



# Forward-Backward asymmetry in top pair production at the ILC

Muhammad Sohail Amjad

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**Forward-Backward asymmetry in top pair production  
at the ILC.**  
par  
**M. Sohail Amjad**

Université Paris-Sud 11

École Doctorale : Particules, Noyaux et Cosmos - ED 517

Laboratoire de l'accélérateur linéaire

Centre Scientifique d'Orsay, Bâtiment 200 - BP 34, 91898 Orsay CEDEX - France

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**Directeur de thèse: M. Roman PÖSCHL (LAL)**

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Prof.	Achille STOCCHI	Président du Jury
Prof.	Klaus DESCH	Rapporteur
Prof.	Hafeez HOORANI	Rapporteur
Prof.	Ben KILMINSTER	Examinateur
Prof.	Marcel VOS	Examinateur
Prof.	Francois RICHARD	Membre Invité



*Dedicated to Prof. Abdus Salam* <sup>1</sup>

---

<sup>1</sup>The legendary Pakistani physicist, renowned for the electroweak theory.



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## *Abstract*

This thesis is done in the framework of the ILC. The determination of the electroweak couplings of the top quark, is one of the tasks at the ILC. The thesis is dedicated to the measurement of the Forward-backward asymmetry in top quark pairs, at 500 GeV, using two beam polarization configurations, in the fully hadronic decay channel. The top quark almost exclusively decays to a  $b$  quark and a  $W$  boson. The 6 jet final state is analyzed using full detector simulation. Two jets with highest b-tag are taken as  $b$  jets and the remaining four jets are used to reconstruct the  $W$ s. The identification of the top and anti-top quarks is done by using the vertex charge of the  $b$  quark. Precisions on the production cross sections are also calculated. It is found that using these parameters, the ILC will be capable of measuring the electroweak couplings of top quark, with a precision of less than 0.5%.

This thesis also includes a chapter on the optimization of the Si-W Electromagnetic calorimeter of the International Large Detector (ILD), one of the two detectors at the ILC. The ECAL of ILD, will consist of alternate layers of Silicon and Tungsten, where Silicon layers are active layers, while Tungsten is passive material. The Silicon layers are divided into wafers, surrounded by guard rings, to avoid the leakage currents. The analysis is focused to optimize the guard ring size. The results indicate that a guard ring of size up to 2mm, does not degrade the energy resolution performance of ECAL, considerably.

The thesis is divided into 6 chapters. The first chapter gives a brief over view of the Standard Model and emphasis on the need of a lepton collider for precision measurements. The second chapter is dedicated to the theoretical aspects of the top quark physics at the ILC. A detailed description of the ILD and its sub-detectors is given in the 3rd chapter. The 4th chapter presents the studies of the optimization of Si-W ECAL guard ring size. The 5th chapter contains the details of analysis of  $t\bar{t}$  production at ILC, the measurement of the  $A_{FB}^t$  and cross section  $\sigma_{t\bar{t}}$ . The last chapter contains summary of the results.



# Contents

<b>Acknowledgements</b>	<b>iv</b>
<b>Abstract</b>	<b>vi</b>
<b>1 Standard Model</b>	<b>1</b>
1.1 Introduction . . . . .	1
1.2 Interactions in the Standard Model . . . . .	3
1.2.1 Electromagnetic Interactions . . . . .	4
1.2.2 Strong Interactions . . . . .	4
1.2.3 Electroweak Interactions . . . . .	5
1.3 Higgs Physics . . . . .	7
1.3.1 Spontaneous Symmetry Breaking . . . . .	7
1.3.2 Higgs Mechanism . . . . .	8
1.3.3 Two Higgs Doublet Models (2HDM) . . . . .	10
1.4 Open Questions in Particle Physics . . . . .	12
1.5 Motivation for a lepton collider . . . . .	13
<b>2 Top quark physics at the ILC</b>	<b>17</b>
2.1 Introduction . . . . .	17
2.2 Searches and Discovery of the top quark . . . . .	18
2.2.1 Properties of Top Quark . . . . .	18
2.3 Electroweak couplings of top quark . . . . .	21
2.4 Cross sections . . . . .	24
2.5 Forward Backward Asymmetry . . . . .	25
<b>3 International Large Detector (ILD)</b>	<b>28</b>
3.1 Introduction . . . . .	28
3.2 The International Linear Collider . . . . .	28
3.3 The Particle Flow Algorithm (PFA) . . . . .	30
3.4 The ILD detector concept . . . . .	31
3.4.1 Vertex Detectors (VTX) . . . . .	31
3.4.2 Central Tracking . . . . .	33
3.4.2.1 Silicon Tracking . . . . .	34
3.4.2.2 The Time Projection Chamber (TPC) . . . . .	35
3.4.3 The ILD Calorimeter System . . . . .	36
3.4.3.1 The Silicon Tungsten Electromagnetic Calorimeter (Si-W ECAL) . . . . .	37

3.4.3.2	Alternatives for ECAL . . . . .	39
3.4.3.3	The Hadronic Calorimeter (HCAL) . . . . .	39
3.4.4	The Magnetic Coil and The Muon Chamber . . . . .	41
3.5	Softwares and tools. . . . .	42
<b>4</b>	<b>Optimization of the Si-W ECAL guard ring size</b>	<b>43</b>
4.1	Introduction . . . . .	43
4.2	Motivation . . . . .	44
4.3	Optimization studies of the guard rings . . . . .	46
4.4	Wafer Scan . . . . .	46
4.5	Physics Channels at the ILC . . . . .	48
4.5.1	$Z \rightarrow q\bar{q}$ Jets at 91 GeV . . . . .	49
4.5.2	$Z \rightarrow e^-e^+$ Channel. . . . .	51
4.6	Summary . . . . .	53
<b>5</b>	<b>Top quark forward backward asymmetry at the ILC</b>	<b>55</b>
5.1	Introduction . . . . .	55
5.2	Asymmetries at hadron colliders . . . . .	55
5.3	Asymmetries at the ILC . . . . .	56
5.4	Production cross sections at the ILC and beam polarizations. . . . .	57
5.5	Studies . . . . .	59
5.6	LCFIPplus . . . . .	60
5.7	Analysis and Kinematic Cuts . . . . .	61
5.8	Standard Model background . . . . .	65
5.9	Charge of the b quark . . . . .	66
5.9.1	Quality of the charge reconstruction . . . . .	67
5.9.2	$\gamma\gamma$ background . . . . .	67
5.10	Mis-tagging of $c$ -jets as $b$ -jets . . . . .	69
5.11	Identification of top quarks . . . . .	71
5.12	Determination of the forward backward asymmetry $A_{FB}^t$ . . . . .	74
5.13	Form Factors . . . . .	76
5.14	Discussion of results . . . . .	78
<b>6</b>	<b>Summary and outlook</b>	<b>81</b>
6.1	The optimization of Si-W ECAL . . . . .	81
6.2	Forward-backward asymmetry in top quark pairs . . . . .	82
<b>A</b>	<b>Vertex Charge</b>	<b>84</b>

# <sup>1</sup> Chapter 1

## <sup>2</sup> Standard Model

### <sup>3</sup> 1.1 Introduction

<sup>4</sup> The Standard Model (SM) is the most comprehensive description of elementary particles  
<sup>5</sup> and their laws of interactions in the world of particle physics today. Along with explaining  
<sup>6</sup> the properties of already discovered particles, it has made deeply tested predictions over  
<sup>7</sup> the years. The model has an excellent success in describing the building blocks of matter.  
<sup>8</sup> According to the model, matter is made up of fermions, spin 1/2 particles which interact  
<sup>9</sup> via bosons. According to current knowledge, these fermions are elementary particles and  
<sup>10</sup> they are further classified into leptons and quarks, depending on the type of interaction,  
<sup>11</sup> in which they take part. There are six leptons and six quarks which are grouped into  
<sup>12</sup> three doublets. The leptons and some of their properties are given in the table below,

Family	Particle	L	B	$Q_e$	Mass
<i>1<sup>st</sup></i>	e	1	0	-1	511keV
	$\nu_e$	1	0	0	<2eV
<i>2<sup>nd</sup></i>	$\mu$	1	0	-1	105.66 MeV
	$\nu_\mu$	1	0	0	<0.19MeV
<i>3<sup>rd</sup></i>	$\tau$	1	0	-1	1.78GeV
	$\nu_\tau$	1	0	0	<18.2MeV

TABLE 1.1: Currently known leptons, in the framework of the Standard Model, along with their properties.

<sup>13</sup> where L,B and  $Q_e$  represent lepton number, baryon number and electric charge respectively. The following table lists the quark doublets and their properties,

<sup>15</sup> The numbers represented here, are taken from [24].

Family	Particle	L	B	$Q_e$	Mass
$1^{st}$	u	0	$1/3$	$2/3$	$2.3^{+0.7}_{-0.5}$ MeV
	d	0	$1/3$	$-1/3$	$4.8^{+0.5}_{-0.3}$ MeV
$2^{nd}$	c	0	$1/3$	$2/3$	$1.275 \pm 0.025$ GeV
	s	0	$1/3$	$-1/3$	$95 \pm 5$ MeV
$3^{rd}$	t	0	$1/3$	$2/3$	$173.07 \pm 0.52$ GeV
	b	0	$1/3$	$-1/3$	$4.18 \pm 0.018$ GeV

TABLE 1.2: Currently known quarks in the Standard Model. The masses represented here are their constituent masses, as the free quarks do not exist.

Interaction	Particle	Charge(electric)	Spin	Mass ( $\text{GeV}/c^2$ )
Weak	Z	0	1	91.2
	$W^\pm$	$\pm 1$	1	80.4
E.M	$\gamma$	0	1	0
Strong	$g$	0	1	0

TABLE 1.3: Gauge bosons of the Standard Model, and their properties. The respective interactions of which these bosons are mediators, are also shown.

- 16 Leptons and quarks interact through force carrier particles. These particles, also called  
 17 the mediators, are spin 1 particles or gauge bosons. The gauge bosons are summarized  
 18 here.
- 19 The elementary particles can be summarized in pictorial form, as presented in figure 1.1.
- 20 The interactions among these particles are divided into three types;
- 21 – Electromagnetic interactions are described by Quantum Electrodynamics (QED).  
 22 The photon ( $\gamma$ ) is the mediator of this interaction.
  - 23 – The weak interaction is the one in which all fermions take part. The associated  
 24 gauge Bosons are  $W^\pm$  and  $Z$ .
  - 25 – Quarks and gluons interact through the strong interaction as they carry a color  
 26 charge. Gluons are the mediators of the strong interaction and are self-interacting  
 27 as well. This interaction is described by Quantum Chromodynamics (QCD).
  - 28 – The Standard Model is completed by the Higgs boson, that couples to all massive  
 29 particles.
- 30 Currently, the Standard Model does not incorporate gravity, though it is regarded as one  
 31 of the fundamental forces of Nature.



FIGURE 1.1: Elementary particles of the Standard Model. The recently discovered Higgs boson is also included.

## 32 1.2 Interactions in the Standard Model

- 33 asym Quantum Field Theory (QFT) is the mathematical basis of the Standard Model.
- 34 The equations of QFT are obtained by the principle of least action and gauge symmetries.
- 35 In the Standard Model, a Lagrangian describes the dynamics of a particular interaction.
- 36 The particles taking part in that interaction are represented as dynamical fields in space-time.
- 37 Generally this Lagrangian  $\mathcal{L}$  is a function of fields and of their derivatives.

The fermion fields, which represent matter particles, are represented by  $\psi$ , which can be further decomposed to left and right parts as follows;

$$\psi^{Left} = \frac{1}{2}(1 - \gamma_5)\psi \quad \psi^{Right} = \frac{1}{2}(1 + \gamma_5)\psi \quad (1.1)$$

- 38 Here  $\gamma_5$  is the 5th gamma matrix.  $(1 \pm \gamma_5)$  is the Chirality operator. Under the weak
- 39 Isospin  $SU(2)$  transformation, the left-handed particles are weak Isospin doublets, while
- 40 the right-handed particles are singlets.

The mathematical model is gauge invariant and is based on  $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$  symmetry. Here  $SU(2)_L \otimes U(1)_Y$  represents the electroweak symmetry;  $SU(2)_L$  is the weak Isospin symmetry group and  $U(1)_Y$  is the component for weak hypercharge symmetry. The weak hypercharge ( $Y$ ) is defined as

$$Q = I_3 + \frac{1}{2}Y, \quad (1.2)$$

- 41 where  $I_3$  is the third component of  $SU(2)_L$  Isospin, and  $Q$  is the electric charge.  $I_3 =$
- 42  $\pm 1/2$  for left-handed fermions, while  $I_3 = 0$  for right-handed fermions.  $SU(3)_C$  repre-
- 43 sents the color symmetry group which is related to strong interactions.

- <sup>44</sup> The Standard Model is a chiral theory, as the Lagrangian contains only massless fields.  
<sup>45</sup> The particles of left Chirality are treated differently, by gauge interactions, from the  
<sup>46</sup> ones of right Chirality. The interactions in the framework of the Standard Model are  
<sup>47</sup> described in this chapter.

### <sup>48</sup> 1.2.1 Electromagnetic Interactions

The laws of electromagnetic interactions are described by QED [8]. The simple Lagrangian for this interaction, involving a fermion field  $\psi$  and a massless photon field  $A_\mu$ , can be written as,

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu D_\mu)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (1.3)$$

- <sup>49</sup> Where  $D_\mu = \partial_\mu - iQeA_\mu$  is the covariant derivative, with  $e$  the electric charge and  $A^\mu$  is  
<sup>50</sup> the covariant four-potential of the electromagnetic field.  $\gamma^\mu$  are the Dirac matrices and  
<sup>51</sup>  $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$  is the electromagnetic field tensor. QED is an abelian gauge theory  
<sup>52</sup> with the symmetry group  $U(1)$ , which implies that the photon is not a self-interacting  
<sup>53</sup> particle. The photon itself does not carry any electric charge.  
<sup>54</sup> The strength of the electromagnetic field is expressed by the running coupling constant  
<sup>55</sup>  $\alpha$ , whose value depends on the momentum transfer during the interaction. The value for  
<sup>56</sup> zero momentum transfer is  $\alpha = \frac{e^2}{4\pi\epsilon_0} \simeq \frac{1}{137}$ .

### <sup>57</sup> 1.2.2 Strong Interactions

- <sup>58</sup> QCD [9], the non-abelian gauge theory, is the mathematical formulation which describes  
<sup>59</sup> the strong interaction among quarks and gluons. The theory is represented by  $SU(3)_c$   
<sup>60</sup> group and because it is a non-abelian theory, gluons can self interact. Unlike the photons,  
<sup>61</sup> which carry no electromagnetic charge, gluons carry color charge themselves. There are  
<sup>62</sup> 3 color charges, carried by quarks and gluons.

The gauge invariant Lagrangian of QCD for a quark field  $q$ , can be written as following,

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu)q - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu} \quad (1.4)$$

- <sup>63</sup> Here  $D_\mu = \partial_\mu - ig_s T_a G_\mu^a$  is the covariant derivative and  $q$  is a massless quark field,  
<sup>64</sup> interacting via the gluon field  $G_\mu^a, a = (1, 2, 3\dots 8)$ .  $T_a$  are the generators of  $SU(3)$  and  $g_s$   
<sup>65</sup> is the dimensionless coupling strength, analogous to 'e' in QED. Both fields are expressed  
<sup>66</sup> in  $SU(3)$  representation.  $G_{\mu\nu}$  is the QCD analog of  $F_{\mu\nu}$  in QED, and is called the strong  
<sup>67</sup> field tensor. It can be expressed as  $G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g f^{abc} G_\mu^b G_\nu^c$ , where  $f^{abc}$  are  
<sup>68</sup> the structure constants of  $SU(3)$ .

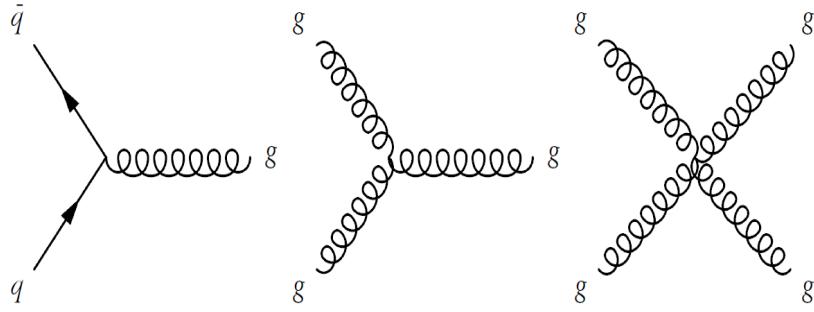


FIGURE 1.2: Vertices of the QCD, at the tree level. The quark-quark, quark-gluon and gluon-gluon couplings are represented in terms of Feynman diagrams.

69 The behavior of the strong coupling constant  $\alpha_s = \frac{g^2}{4\pi}$  is different than that of the  
 70 electromagnetic coupling constant. The force present between two quarks is smaller at  
 71 a smaller distance but it increases by increasing the distance between them, prohibiting  
 72 the existence of free quarks. The energy used to separate the quarks, is converted into  $q\bar{q}$   
 73 pairs. This phenomenon is called "confinement". It implies that the quarks interact with  
 74 other quarks to form hadrons (except the top quark). This is called "hadronization".  
 75 The hadrons are color neutral and can be classified as mesons or baryons depending on  
 76 their spin. Mesons are bosons, consisting of  $q\bar{q}$  pairs, for example pions ( $\pi^+, \pi^-, \pi^0$ ).  
 77 Baryons are fermions consisting of  $qqq$ , for example protons ( $uud$ ) and neutrons ( $udd$ ).  
 78 The other distinct feature of QCD is "asymptotic freedom", which implies that at high  
 79 energies (small distances), quarks propagate as free particles. The basic interactions of  
 80 QCD are shown in figure 1.2.

### 81 1.2.3 Electroweak Interactions

82 Abdus Salam[7], Sheldon Glashow[5], and Steven Weinberg [6] unified the electromagnetic  
 83 and weak interaction, calling it the electroweak interaction [1]. The experimental  
 84 verification of the theory came through the discovery of neutral currents in 1973 [2] and  
 85 later with the discovery of the W and Z bosons at the Super Proton Synchrotron (SPS)  
 86 in 1983.

To start with, the  $\beta$  decay is described by the Fermi theory, which conserves the parity. The parity violation was observed by Madame Wu [38], observing a correlation between direction of electrons and spin of nucleus. This correlation was interpreted as electron being left-handed, thus violating the Parity. The  $V-A$  theory was developed by Feynman and Gell-Mann in 1958. It treats the neutrinos as massless particles, and takes the parity violation into account. It modifies the Fermi theory by subtracting the axial vector

current from the vector current. For example, the neutrino part in the Fermi theory is replaced as

$$\bar{e}(x)\gamma_\mu\nu_e(x) \longrightarrow \bar{e}(x)\gamma_\mu\frac{1}{2}(1-\gamma_5)\nu_e(x) \quad (1.5)$$

$$= \underbrace{\frac{1}{2}\bar{e}(x)\gamma_\mu\nu_e(x)}_{\text{Vector Current}} - \underbrace{\frac{1}{2}\bar{e}(x)\gamma_\mu\gamma_5\nu_e(x)}_{\text{Axial Vector Current}} \quad (1.6)$$

$$= \frac{1}{2} \left( V_\mu^{(e)}(x) - A_\mu^{(e)}(x) \right). \quad (1.7)$$

$$(1.8)$$

The Standard Model electroweak theory is described by the  $SU(2)_L \otimes U(1)_Y$  symmetry group. It contains three massless bosons  $W^i, i = (1, 2, 3)$ , associated with  $SU(2)$  and 1 massless boson associated with  $U(1)$ . The Lagrangian for these bosons can be written as,

$$\mathcal{L}_{EW} = -\frac{1}{4}W^{i\mu\nu}W_{\mu\nu}^i - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} + \bar{\psi}i\gamma^\mu D_\mu\psi \quad (1.9)$$

Here  $B^{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$  and  $W^{i\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu - g\vec{W}_\mu \times \vec{W}_\nu$ . They are field strength tensors for weak hypercharge  $Y$  and Isospin  $I_L$  respectively.  $D_\mu$  is the covariant derivative which can be expressed as,

$$D_\mu = \partial_\mu + i\frac{g}{2}\tau_j W_\mu^j + 2ig'YB_\mu \quad (1.10)$$

- <sup>87</sup> where  $g'$  and  $g$  are the coupling constants related to fields  $B$  and  $W_j, j = (1, 2, 3)$ ,  
<sup>88</sup> respectively. The  $\tau_j$  are Pauli spin matrices in  $SU(2)_L$  space as given below,

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \quad (1.11)$$

The  $W$  boson can be obtained from the  $W$  fields as following,

$$W^{\mu\pm} = \frac{W_1^\mu \mp iW_2^\mu}{\sqrt{2}} \quad (1.12)$$

To obtain the  $Z$  boson ( $Z^\mu$ ) and photon ( $A^\mu$ ) fields we introduce the weak mixing angle  $\theta_W$  and the following combinations of  $W_3^\mu$  and  $B^\mu$  ;

$$Z^\mu = \cos\theta_W W_3^\mu - \sin\theta_W B_\mu \quad (1.13)$$

$$A^\mu = \sin\theta_W W_3^\mu + \cos\theta_W B_\mu \quad (1.14)$$

The couplings of fermions to Z boson are given as,

$$\frac{|q_f|(I_3^f - Q \sin^2 \theta_W)}{\sin \theta_W \cos \theta_W} \quad (1.15)$$

89  $|q_f|$  denotes the fermion charge and  $I_3$  is the third component of Isospin. The term  
90  $Q \sin^2 \theta_W$  allows the coupling of the Z boson to charged right-handed fermions, which  
91 is not the case for pure  $SU(2)_L$  couplings. The vector and axial vector currents behave  
92 differently under the parity transformation. The Z boson couples to the right and left-  
93 handed fermions while the W boson, also called the charged currents, couples to  
94 left-handed fermions only. The W boson makes flavor changing interactions possible in  
95 electroweak sector, through the CKM mechanism [3, 4].

96 The theory is non-abelian like QCD, due to the interaction between Ws.

### 97 1.3 Higgs Physics

98 So far, we have considered massless fields while in fact the gauge bosons,  $W^\pm$  and  $Z$ , as  
99 well as fermions are massive. Mass terms like  $m\psi\bar{\psi}$  are forbidden because they do not  
100 transform as scalars under  $SU(2)_L \otimes U(1)_Y$ . The other option of gauge terms,  $\frac{1}{2}m_A^2 A_\mu A^\mu$ ,  
101 violates the gauge invariance of the Lagrangian. The mass of fermions and bosons can  
102 be generated by spontaneous symmetry breaking and the Higgs Mechanism [10].

#### 103 1.3.1 Spontaneous Symmetry Breaking

The Lagrangian, for a scalar field  $\phi$ , can be written as:

$$\mathcal{L}_\phi = T - V(\phi) = \frac{1}{2}(\partial_\mu \phi)^2 - (\frac{1}{2}\mu^2 \phi^2 + \frac{1}{4}\lambda\phi^4) \quad (1.16)$$

104 The potential  $V(\phi) = \frac{1}{2}\mu^2 \phi^2 + \frac{1}{4}\lambda\phi^4$  has a minimum if  $\lambda > 0$ . The position of this  
105 minimum depends on the sign of  $\mu^2$ .

106 If  $\mu^2 > 0$ : this Lagrangian describes a scalar particle with mass  $\mu$  and a quartic self  
107 coupling. The ground state,  $\phi = 0$ , respects the transformation  $\phi \rightarrow -\phi$ . This solution  
108 is called symmetric, and it is shown in the left part of figure 1.3.

109 When  $\mu^2 < 0$ : there is a whole circle of minima in  $V(\phi)$ , with a radius  $\phi = \pm(\sqrt{-2\mu^2/\lambda})$   
110 as shown in the right part of figure 1.3. The  $\mu$ -term is not a mass term anymore. And  
111 it is with this solution, that we can see spontaneous symmetry breaking.

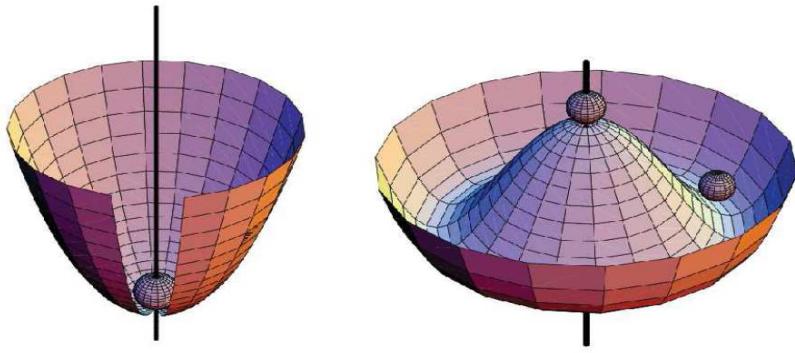


FIGURE 1.3: The potential  $V(\phi)$  for two possible solutions with  $\mu^2 > 0$  (left) and  $\mu^2 < 0$  (right). The image is taken from [11].

### <sup>112</sup> 1.3.2 Higgs Mechanism

The Higgs Mechanism works by applying spontaneous symmetry breaking to a local gauge symmetry. For a complex scalar field Isospin doublet,

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad (1.17)$$

the electroweak sector Lagrangian excluding fermions, can be written as:

$$\mathcal{L}_\phi = D_\mu \phi^\dagger D_\mu \phi + \mu^2 (\phi \phi^\dagger) - \frac{\lambda}{4} (\phi \phi^\dagger)^2 - \frac{1}{4} W^{i\mu\nu} W_{\mu\nu}^i - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} \quad (1.18)$$

The minimum is at  $(\phi^\dagger \phi) = -v^2/\lambda$ . We can expand around this minimum by taking

$$\phi(x) = \begin{pmatrix} 0 \\ \frac{v+H(x)}{2} \end{pmatrix} \quad (1.19)$$

Substituting this value of  $\phi(x)$  to eq. 1.18 and using  $D_\mu = \partial_\mu + i\frac{g}{2}\sigma_j W_\mu^j + 2ig'YB_\mu$ , we get;

$$\mathcal{L}_\phi = \frac{1}{2} (\partial_\mu H \partial^\mu H) - \mu^2 H^2 \quad (1.20)$$

$$- \frac{1}{4} (\partial_\mu W_{i\nu} - \partial_\nu W_{i\mu}) (\partial^\mu W_i^\nu - \partial^\nu W_i^\mu) \quad (1.21)$$

$$+ \frac{1}{8} g^2 v^2 (W_{1\mu} W^{1\mu} + W_{2\mu} W^{2\mu}) \quad (1.22)$$

$$+ \frac{1}{8} v^2 (g W_{3\mu} - g' B_\mu) (g W_3^\mu - g' B^\mu) - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \quad (1.23)$$

$$(1.24)$$

<sup>113</sup> The first two components of the W field have quadratic terms which implies that these fields are massive with mass  $M_W = \frac{gv}{2}$ . The third component of the W field mixes with

the B field. This equation can be further expanded using equations 1.12-1.14, to show that 5 bosons appear in the Lagrangian. The theory, thus, predicts the existence of a massive boson, famously known as Higgs boson, a candidate to which has recently been discovered at the LHC [35, 36], at a mass around 126 GeV.

The discovery marked an excellent success of the LHC, and is the biggest discovery in the domain of the particle physics, in last two decades, after the discovery of the top quark. The two experiments at the LHC, ATLAS and CMS, simultaneously announced the observation of Higgs-like boson. The CMS observed a mass of  $125.3 \pm 0.4(stat) \pm 0.5(syst)$  GeV [35] and ATLAS reported the mass to be  $126.0 \pm 0.4(stat) \pm 0.4(sys)$  GeV [36]. Figure 1.4 shows the respective plots from the two experiments.

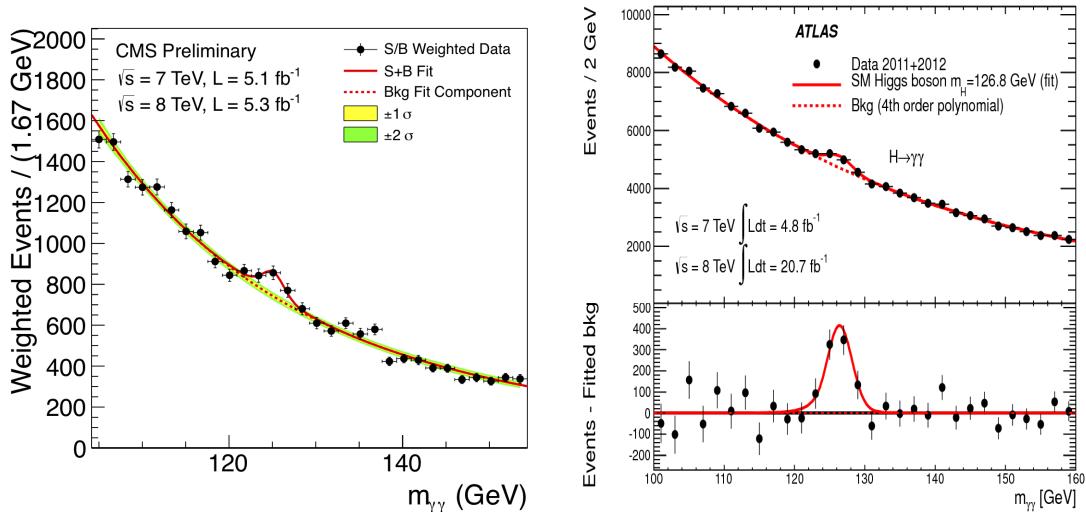


FIGURE 1.4: Left Di-photon ( $\gamma\gamma$ ) invariant mass distribution for CMS data taken in 2011 and 2012 [35]. Right The same from the ATLAS experiment for  $\sqrt{s} = 7$  TeV and  $\sqrt{s} = 8$  TeV combined [36].

The discovery of a low-mass Higgs implies further precise studies of Higgs boson. One of the areas where the hint of new physics could be found, is the Higgs boson couplings to Standard Model particles. Existence of new particles will modify these couplings and the measurements could diverge from the Standard Model predictions.

Figure 1.5 shows the order of the couplings of the Higgs boson to different particles, including the top quark, which feature in the physics program of the ILC, a future linear collider.

This low mass of the Higgs boson has several implications. One of the major problems it brings is the Hierarchy problem. The scalar field  $\phi$  presented in equation 1.16, has a value

$$\langle\phi\rangle = \sqrt{\frac{m_H^2}{2\lambda}}, \quad (1.25)$$

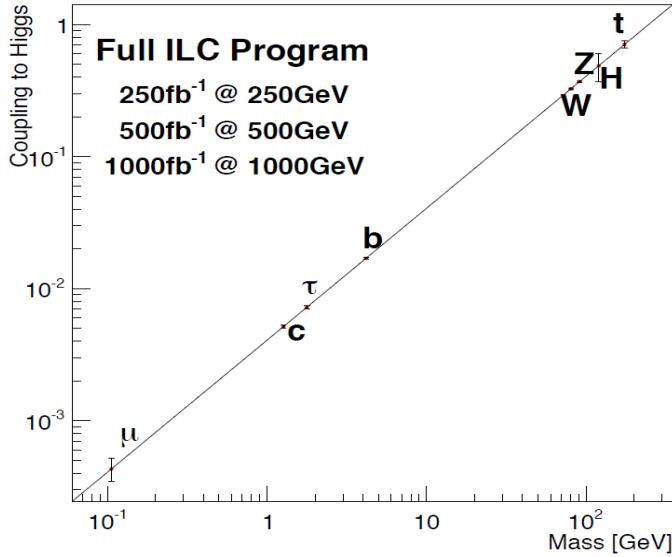


FIGURE 1.5: Higgs boson couplings to different Standard Model particles, as to be measured at the ILC. A precise determination of these couplings could hint at any divergences from the Standard Model predictions, and existence of new physics [40].

where  $\mu^2$  has been replaced by  $m_H^2$ . Since we know experimentally that  $\langle \phi \rangle$  is around 246 GeV, the quantity  $m_H^2$  is of the order of  $(100 \text{ GeV})^2$ . The problem with that is that  $m_H^2$  receives radiative corrections from all the particles, to which it couples. For example the corrections from a fermion  $f$ , of mass  $m_f$  and coupling to Higgs  $\lambda_f$ , could be written as [16]:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{UV}^2 + \dots \quad (1.26)$$

Where  $\Lambda_{UV}$  is the ultraviolet cut-off, which can be interpreted as the scale to which the Standard Model is valid or a scale at which the effects of new physics appear. If the Standard Model is to be valid upto the Planck scale, the corrections to the  $m_H^2$  are around 30 order of the magnitude higher than the required value of  $-(100 \text{ GeV})^2$ . This problem only occurs for the corrections to the mass of Higgs boson, as the masses of fermions and gauge bosons do not have a direct quadratic sensitivity to the  $\Lambda_{UV}$ . However, they do have an indirect dependence on this parameter, as all the particles in Standard Model, obtain their masses via the interaction to the Higgs boson.

### 1.3.3 Two Higgs Doublet Models (2HDM)

Some solutions have been proposed to solve this problem. Conformal solution [12], within the framework of the Standard Model, and extra dimensions solution [13] are a few options along with the composite Higgs models [14], as in technicolor models [15].

144 Another solution is Supersymmetry. Here the focus will be on the Two Higgs Doublet  
145 Model (2HDM), which can be incorporated in Minimal Supersymmetric extension of the  
146 Standard Model (MSSM)[34].

Lets suppose, there exists a complex scalar  $S$ , with mass  $m_S$  and it couples to Higgs with a Lagrangian term  $-\lambda_S |H|^2 |S|^2$ . Then the correction to  $m_H$  could be rewritten as [16]:

$$\Delta m_H^2 = \frac{\lambda_s}{16\pi^2} \left[ \Lambda_{UV}^2 - 2m_S^2 \ln \left( \frac{\Lambda_{UV}}{m_S} \right) + \dots \right]. \quad (1.27)$$

147 Note that the contribution becomes positive here because of the fact the fermions will  
148 have a negative contribution and bosons a positive one. In turn, the total contribution  
149 to the mass will be zero. There are two types of 2HDMs: Type I and Type II, where  
150 the two Higgs doublets couple differently. For example in Type I, one doublet couples to  
151 the quarks, and the other doesn't. While in Type II, one Higgs doublet may couple to  
152 up type quarks, and other to down type quarks. This possibly could explain the mass  
153 hierarchy between the  $b$  and  $t$  quarks. If both of the quarks, obtain their mass via the  
154 coupling to the single Higgs doublet, as is the case in Standard Model, it will be difficult  
155 to explain this anomaly. On the other hand, if the top quark couples to different Higgs  
156 doublet, the hierarchy could be explained.

157 The Higgs sector of the Minimal Supersymmetric Standard Model (MSSM) is a con-  
158 strained Type II 2HDM. The two Higgs doublets can be written as follows:

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}, \quad (1.28)$$

The electroweak symmetry is broken when the neutral components of these Higgs fields obtain a vacuum expectation value. The combination of the VEVs is constrained by the following condition:

$$2(\langle H_1^0 \rangle^2 + \langle H_2^0 \rangle^2) \equiv v^2 \simeq (246 GeV)^2 \quad (1.29)$$

But their ratio is not confined and is defined as:

$$\tan \beta = \langle H_2^0 \rangle / \langle H_1^0 \rangle \quad (1.30)$$

159 Where  $\langle H_2^0 \rangle$  and  $\langle H_1^0 \rangle$  are the vacuum expectation values of the neutral Higgs boson,  
160 which couples to  $u$  type and  $d$  type fermions, respectively. The factor  $\tan \beta$ , is a free  
161 parameter of the SUSY. The searches for SUSY are carried out for different values of  
162  $\tan \beta$ .

163 Due to SUSY breaking, that enters in the loops, there are radiative corrections to the  
164 tree-level structure of the model. In particular, the effective Lagrangian that describes

165 the coupling of the Higgs bosons to the third generation quarks, is modified by the  
 166 Yukawa vertex corrections.

## 167 1.4 Open Questions in Particle Physics

168 The Standard Model had excellent success, ever since it started as the fundamental  
 169 theory for particle physics. The successful predictions of electroweak theory, of existence  
 170 of gauge bosons  $W$  and  $Z$ , the discovery of third family of quarks, predicted using CKM  
 171 mechanism, and Higgs boson, the latest feather in the crown of Standard Model, make it  
 172 a successful model. Precision studies has been carried over various experimental facilities.  
 173 A recent summary of electroweak precision results, after the discovery of Higgs boson, is  
 shown in the figure 1.6.

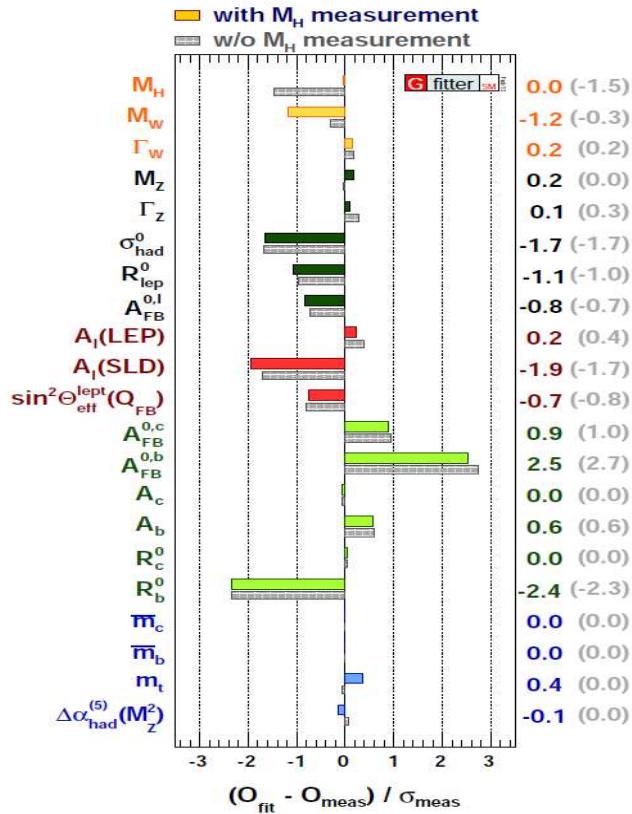


FIGURE 1.6: The figure shows the difference between the measured values of SM parameters, and the predicted values, in units of uncertainty for the fit. The color lines represent the values with mass of the Higgs boson  $m_H$ , while gray lines are without  $m_H$ . The image is taken from [33]

174

175 Despite its success, there are problems which are not understood in the framework of  
 176 the Standard Model. It has not been able to explain the mass hierarchies in, e.g. the

177 quark sector. The heaviest quark  $t$  is 35 times heavier than the next heavier quark  $b$ ,  
178 which happens to be it's Isospin doublet partner as well. This difference of masses is not  
179 explained in the Standard Model.

180 The masses of the particles are introduced by the spontaneous symmetry breaking, as  
181 explained previously. The reason for the EWSB is unknown in the framework of the  
182 Standard Model. Also, the radiative corrections to the Higgs mass, which depend on  
183 top quark mass particle, are larger than the actual Higgs mass. Which implies that the  
184 Higgs mass parameter has to be fine-tuned, in order to cancel the quantum corrections.

185 Another missing explanation from the Standard Model is baryon-anti baryon asymmetry.  
186 In the observed universe, it has been found that the quantity of baryonic matter exceeds  
187 that of antibaryonic matter by large amount. The Standard Model does not offer any  
188 valid explanation for this discrepancy. Though the CP violation proposal is under study,  
189 but the Standard Model CP violation is not sufficient is not sufficient to explain the  
190 excess of matter.

191 One of the most important elements, needed to explain the universe is Gravity. The  
192 Standard Model does not incorporate a quantum field theory for gravity. Though the  
193 possible existence of Graviton, candidate for carrier of gravitational force, is postulated,  
194 it remains unobserved.

195 Related to the Gravitation and astroparticle physics, is another problem of dark matter.  
196 The observed rotation of galaxies and the amount of matter observed are not compatible.  
197 The solution proposed to this problem is existence of the dark matter. A candidate for  
198 the dark matter is missing in the framework of the Standard Model.

199 The inclusion of gravity to the fundamental interactions will require an explanation for  
200 the mass hierarchy. The gravitational mass scale is  $1/\sqrt{G} \simeq 10^{19}$  GeV, where  $G$  is the  
201 Newton constant, while typical masses of electroweak bosons are  $\sim 100$  GeV. Another  
202 way of looking at the hierarchy problem is that if there exists a Grand Unification  
203 Symmetry, it is broken at a scale of  $10^{16}$  GeV, while electroweak symmetry is broken at  
204 100 GeV, which is a difference of 14 orders of magnitude.

## 205 1.5 Motivation for a lepton collider

206 After the discovery of a Higgs-like boson, important parameters to be studied are the  
207 its production cross section, a precise determination of the mass of the Higgs boson  
208 ( $m_H$ ), its branching ratios and couplings to other Standard Model particles. The Higgs  
209 couplings to other Standard Model particles are of the fundamental importance towards

the discovery of any new physics. The precise determination and any deviation from the Standard Model predictions, could well hint at the possible role of Higgs in new physics.

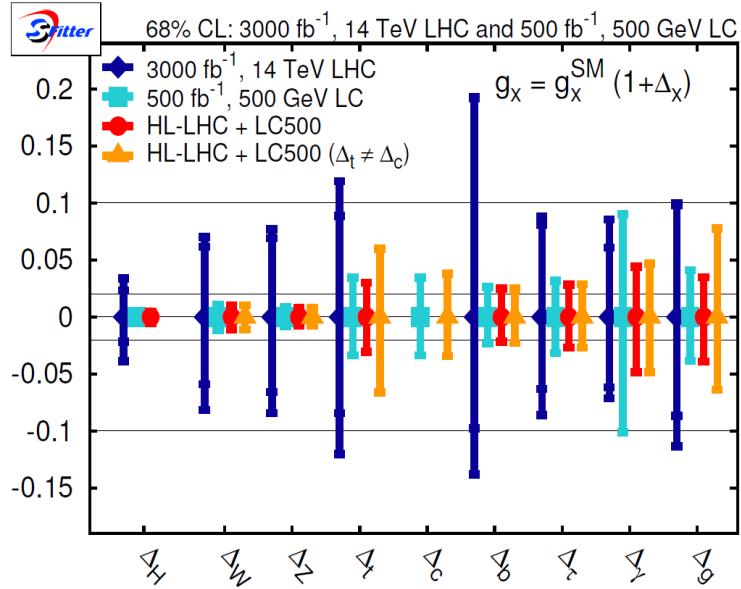


FIGURE 1.7: Comparison of ILC and LHC, for measurements of precision of Higgs couplings to different particles. The plot shows a comparison of precisions (from left to right) of LHC, ILC and High Luminosity LHC, combined with ILC. The inner bars for HL-LHC denote a scenario with improved experimental systematic uncertainties. The image is taken from [56].

As already mentioned, the 2HDM proposes two Higgs doublets instead of one, as in the framework of the Standard Model. The confirmation of the nature of the Higgs boson will require a clean and precise determination of its couplings. Figure 1.7 shows the comparison of precision on couplings of Higgs boson to different particles, as attainable at LHC at nominal center-of-mass energy and the ILC, a proposed future linear collider. Apart from comparing the original precisions, a combination of the two is also shown.

The decay properties of the Higgs boson, make it difficult to precisely analyze all the decay channels at a hadron collider, with the difficulty of separating the decay to  $q\bar{q}$  pairs, from the huge amount of QCD background. The model independent Higgs analysis at the ILC, is through the Higgs recoil method,  $e^-e^+ \rightarrow HZ$ [100]. Given that the ILC could operate at a center-of-mass energy of  $\sqrt{s} = 250$  GeV, which corresponds to the peak cross section for the Higgs boson. The precise reconstruction of the  $Z$  boson means that the Higgs reconstruction can be done precisely in any mode, including decay to quark pairs and invisible decays. It also provides opportunity to investigate the nature of the Higgs boson itself, including the compositeness.

There is a large spectrum of physics processes which could be studied at a lepton collider. For example the two fermion  $e^+e^- \rightarrow f\bar{f}$  process, which is of particular interest, at a

lepton collider. The cross section for such processes can be written as:

$$\frac{d\sigma}{d \cos \theta} = \frac{\pi \alpha^2}{2s} [A_+(1 + \cos \theta)^2 + A_-(1 - \cos \theta)^2] \quad (1.31)$$

Where the coefficients  $A_+ = (1 - P_{e^-})(1 + P_{e^+})$ ,  $A_- = (1 + P_{e^-})(1 - P_{e^+})$  depend on the beam polarizations.  $P_{e^-}$  and  $P_{e^+}$  are the polarization of electron and positron beam respectively.

The models with gravitation effect at TeV scale, propose modification to this cross section. One such example is Randall-Sundrum Models[49]. The proposed future linear collider, ILC, will also be capable of doing the precision measurements in WW, self Higgs coupling and could search for extended Higgs states. A brief summary of different processes, which could be studied at ideal center-of-mass energies, at ILC, is given in figure 1.8.

Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \rightarrow Z$	ultra-precision electroweak
160 GeV	$e^+e^- \rightarrow WW$	ultra-precision W mass
250 GeV	$e^+e^- \rightarrow Zh$	precision Higgs couplings
350–400 GeV	$e^+e^- \rightarrow t\bar{t}$ $e^+e^- \rightarrow WW$ $e^+e^- \rightarrow \nu\bar{\nu}h$	top quark mass and couplings precision W couplings precision Higgs couplings
500 GeV	$e^+e^- \rightarrow f\bar{f}$ $e^+e^- \rightarrow t\bar{t}h$ $e^+e^- \rightarrow Zhh$ $e^+e^- \rightarrow \tilde{\chi}\tilde{\chi}$ $e^+e^- \rightarrow AH, H^+H^-$	precision search for $Z'$ Higgs coupling to top Higgs self-coupling search for supersymmetry search for extended Higgs states

FIGURE 1.8: Tunable center-of-mass energy at ILC, enables study of different processes at nominal center-of-mass energies. The threshold energy makes it possible to precisely measure the mass, width and cross section of different Standard Model particles.

The chiral structure of the Standard Model makes the beam polarization a vital feature of the lepton collider, to study the precision physics. As is evident from the figure 1.6, that the measurement of  $A_{FB}^{0,b}$  is  $\sim 3\sigma$  away from the Standard Model prediction. The  $A_{FB}^{0,b}$ , is a relative measure of number b quarks, in forward hemisphere of the detector, as compared to that in backward hemisphere. The measurement of a higher than predicted value suggests that the coupling of the  $Z$  boson to the heavy fermions could be modified. This modification could be further amplified while studying the  $Zt\bar{t}$  couplings. Though the details on this will be given in 2.3, it is worth mentioning that the direct measurement of this coupling is not possible hadron colliders, due to a different production mechanism

of the top quark pairs. The coupling measurement is only possible through the associated boson production. On the other hand, at a linear collider, such as ILC, the production goes directly through the  $Zt\bar{t}$  vertex. Apart from that, the availability of polarization makes it possible to study the helicity related parameters. Also the production cross section, the left-right and forward-backward asymmetry are variables sensitive to the beam polarization. All these measurements could lead to the understanding of electroweak coupling of the heaviest quark.

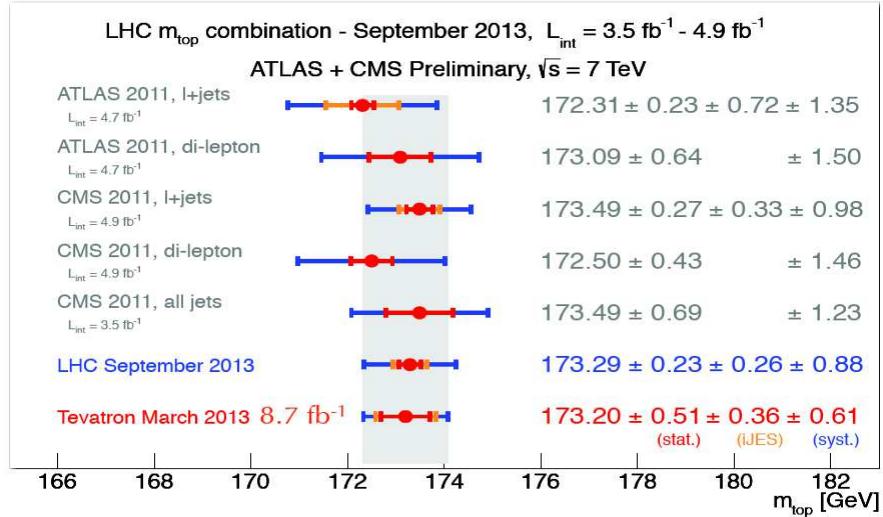


FIGURE 1.9: Recent results on the measurement of the top quark mass, from LHC.

The precise determination of the mass of the top quark, has been a subject of study at the particle colliders since its discovery. The efforts for a more and more precise determination are on going, and the recent results from the LHC experiments are shown in figure 1.9. A very precise determination of this parameter can be made using the top threshold physics. The linear collider operating at a center-of-mass energy of  $\sqrt{s} = 2m_t$  provides an idea opportunity to precisely measure the mass  $m_t$ , width  $\Gamma_t$  and production cross section  $\sigma_{t\bar{t}}$  of the top quark.

259 Chapter 2

260 Top quark physics at the ILC

261 2.1 Introduction

262 The top quark is by far the heaviest known quark. It is much more massive than the  
263 other observed quarks and leptons. It is as massive, as a gold atom. A comparison of  
264 the mass of top quark, with other known quarks is shown in figure 2.1. In this chapter  
265 a review of top quark properties will be given, followed by a specific focus on top quark  
266 physics at linear colliders, specially ILC.

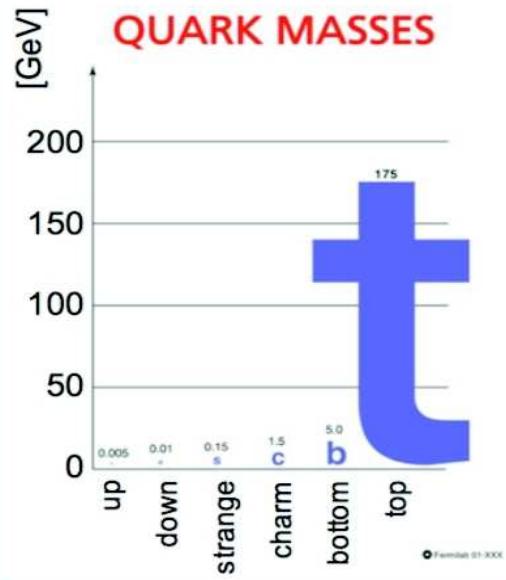


FIGURE 2.1: The mass of the top quark as compared to other quarks in the Standard Model. It is 35 times heavier than the next heavier quark  $b$ .

## <sup>267</sup> 2.2 Searches and Discovery of the top quark

<sup>268</sup> The existence of the third family of quarks was postulated by Makoto Kobayashi and  
<sup>269</sup> Toshihide Maskawa [3]. Their prediction was heavily dependent on the GIM mechanism,  
<sup>270</sup> devised by Glashow, Iliopoulos and Maiani in 1970 [26]. The charm quark was success-  
<sup>271</sup> fully predicted and discovered, through the discovery of  $J/\psi$  mesons which is a  $c\bar{c}$  bound  
<sup>272</sup> state[18, 19]. This discovery confirmed the GIM mechanism and provided a lot of credi-  
<sup>273</sup> bility to the the prediction of the third family. Soon after, the  $\tau$  lepton was discovered  
<sup>274</sup> at SLAC[17], confirming the existence of the third family of leptons. The discovery of  
<sup>275</sup> the b quark did not take a long time. In 1977,  $\Upsilon$ , a  $b\bar{b}$  bound state with a mass of 9.5  
<sup>276</sup> GeV, was discovered at Fermilab, confirming the existence of the b quark[20].

<sup>277</sup> However, the discovery of the top quark was not that swift. The searches for top quark  
<sup>278</sup> went on for a few years. One of the reasons for this was that the mass of the top quark  
<sup>279</sup> could not be predicted in the framework of Standard Model. Search for the top quark  
<sup>280</sup> began in the late 1970s, at SLAC and DESY, but it did not produce any hint of top quark  
<sup>281</sup> production. The first searches were carried out at the lepton colliders. For example, at  
<sup>282</sup> LEP, the indirect measurements put an an upper limit of 45.8 GeV, on the mass of  
<sup>283</sup> top.The limiting factor for the searches at the lepton colliders was center-of-mass energy.  
<sup>284</sup> In the 80s, with the start of hadron colliders, this problem was solved. The dominant  
<sup>285</sup> mode of search initially was  $W \rightarrow tb$ , which put an upper limit of  $\simeq 77\text{GeV}$  on the mass  
<sup>286</sup> of the top quark.

<sup>287</sup> In the early 1980s CERN also became involved through its Super Proton Synchrotron  
<sup>288</sup> (SPS). In 1988, the experiments concluded that the mass of the top quark must be above  
<sup>289</sup> 41 GeV. By the end of the decade this limit was pushed to 77 GeV as CERN came to its  
<sup>290</sup> energy limits with  $p\bar{p}$  collisions. The CDF and D0 collaboration at Fermilab, continued  
<sup>291</sup> searching for the top quark. The D0 experiment started taking data in the beginning  
<sup>292</sup> of 1992 and by the end of the year, the lower limit on the mass was pushed to 91 GeV.  
<sup>293</sup> Finally in March 1995, both experiments simultaneously announced the discovery of the  
<sup>294</sup> top quark [25, 30]. A summary of history of top quark search is given in the following  
<sup>295</sup> table 2.1.

### <sup>296</sup> 2.2.1 Properties of Top Quark

<sup>297</sup> The top quark has a charge +2/3 and spin 1/2 but its most prominent property is its  
<sup>298</sup> mass. It is the Isospin doublet partner of the  $b$  quark. It acquires its mass via Yukawa  
<sup>299</sup> couplings to the Higgs boson. There have been various studies to precisely determine  
<sup>300</sup> the mass of the top quark. Currently the world average is  $173.07 \pm 0.52 \pm 0.72\text{GeV}$  [24].

Year	Collider	$\sqrt{s}$	Beam	Mass Limit ( $\text{GeV}/c^2$ )
<b>Lepton Colliders</b>				
1979-84	PETRA(DESY)	12–46.8 GeV	$e^+e^-$	>23.3
1987-90	TRISTAN(KEK)	61.4 GeV	$e^+e^-$	>30.2
1989-90	SLC (SLAC), LEP(CERN)	91.2 GeV ( $m_Z$ )	$e^+e^-$	>45.8 (indirect measurement)
<b>Hadron Colliders</b>				
1984	SPS(CERN)	630 GeV	$p\bar{p}$	>45
1990	SPS(CERN)	630 GeV	$p\bar{p}$	>69
1991	TEVATRON(FNAL)	1.8 TeV	$p\bar{p}$	>77
1992	TEVATRON(FNAL)	1.8 TeV	$p\bar{p}$	>91
1994	TEVATRON(FNAL)	1.8 TeV	$p\bar{p}$	>131

TABLE 2.1: History of the discovery of the top quark, at various particle colliders. The colliders are classified into lepton and hadron colliders.

- 301 The heavy mass of the top quark implies a short life time, which is of the order of  
 302  $0.5 \times 10^{-24}$  sec. This life time is smaller than the time needed for the formation of QCD  
 303 bound states, which is  $1/\Lambda_{QCD} \simeq 3 \times 10^{-24}$  sec. So, unlike the other quarks, there do  
 304 not exist any  $t\bar{t}$  bound states. The top quark does not hadronize either, so there do not  
 305 exist any hadrons containing top quarks. This property of the top quark provides an  
 306 opportunity to study the properties of a bare quark.  
 307 The short life time also implies that the top quark decays before it can depolarize, hence  
 308 the information on polarization of the top quark, is carried by its decay products.

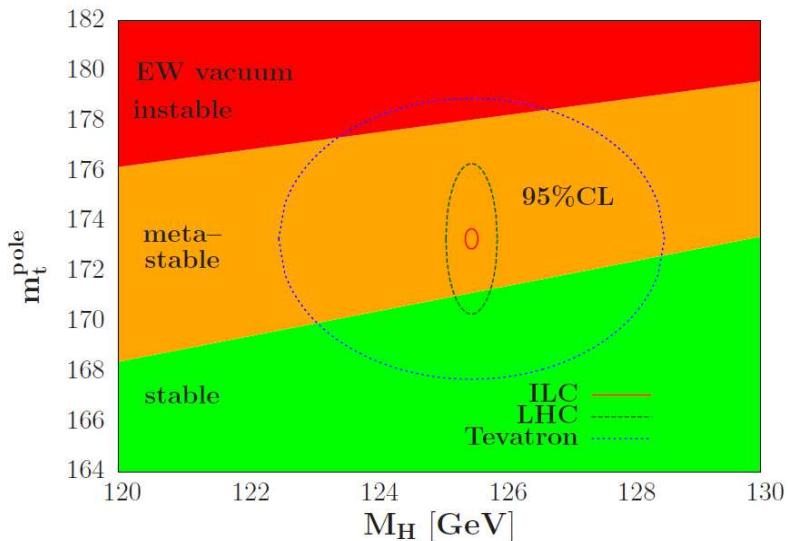


FIGURE 2.2: The stability of the electroweak vacuum, shown in the  $[m_H, m_t]$  plane. The  $2\sigma$  ellipses show the precisions obtained at the LHC and Tevatron, and the one obtainable at the ILC, a future linear collider. The image is taken from [57].

$t\bar{t} \rightarrow b\bar{q}q\bar{b}q\bar{q}$	46.2 %
$t\bar{t} \rightarrow b\bar{q}q\bar{b}l\nu_l$	43.5 %
$t\bar{t} \rightarrow b\nu_l\bar{b}\nu_l$	10.3 %

TABLE 2.2: Fractions of different decay modes of  $t\bar{t}$  pairs.

- 309 It decays through the electroweak interaction, predominantly (99.8 %) into a b quark  
 310 and a W boson ( $t \rightarrow bW^+$ ). From here on, only this decay vertex will be treated. The  
 311 W boson can further decay into two quarks or a lepton and a neutrino. The following  
 312 table presents the probabilities of the different decay modes for  $t\bar{t}$ .
- 313 The first of these is called fully the hadronic decay mode, while the remaining two are  
 314 called semi-leptonic and fully leptonic, respectively.
- 315 The mass of the top quark is also one of the fundamental parameters of the electroweak  
 316 theory. The precise measurement of top quark mass is important for the measurement  
 317 of electroweak precisions. For example, the loop corrections to the Higgs boson mass are  
 318 proportional to  $(m_t/m_W)^4$ [28].
- 319 The importance of the precise determination of the top quark mass can be highlighted in  
 320 many ways. One of them is that it is strongly related to the stability of the electroweak  
 321 vacuum, if the Standard Model is valid upto the Planck scale. The figure 2.2 shows  
 322 the stability curve, in the plane of Higgs boson and top quark masses. Here the pole  
 323 mass of the top quark is used, which is in fact the mass of the fermion propagator of  
 324 the top quark. There exist another scheme to describe the mass of the top quark, called  
 325  $\bar{MS}$  scheme. Along with the close relation of the top quark mass, to the stability of  
 326 electroweak vacuum, the figure also shows the capability of the hadron colliders (LHC  
 327 and Tevatron) and the future linear collider (ILC) to precisely determine the Higgs boson  
 328 and top quark masses.
- 329 Due to large Yukawa couplings, the top quark mass is one of the factors constraining the  
 330 mass of the Higgs boson, recently discovered at LHC. This fact is illustrated in the figure  
 331 2.3. A variation of 1 GeV in mass of the top quark, corresponds to a 10 GeV change in  
 332 the mass of Higgs boson. The uncertainties on the mass of the top quark, thus strongly  
 333 constrained the efforts to predict the mass of Higgs bosons from LEP experimental data.  
 334 This constraint can also be interpreted in a different view, that it helps to verify the  
 335 nature of the Higgs boson. For the Higgs boson to be compatible with the Standard  
 336 Model, its mass should lie in the electroweak fit represented in 2.3. As there are other  
 337 theories, which predict the existence of a light Higgs boson(s), at around the same mass,  
 338 as the one discovered at the LHC. Any deviations from this fit, could hint at the existence

339 of new physics, beyond Standard Model. The discovered Higgs boson's mass lies well  
 within the bound, obtained by the fit using  $W$  boson mass, and the mass of top quark.

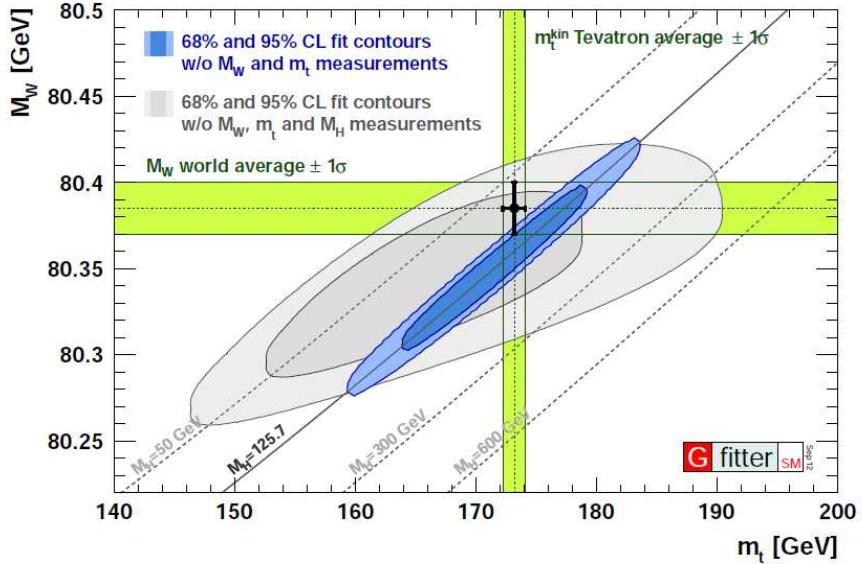


FIGURE 2.3: Indirect constraints on the mass of Higgs boson ( $m_H$ ) with respect to top quark mass( $m_t$ ) and  $W$  boson mass( $m_W$ ). The indirect searches at LEP and Tevatron, excluded some regions for the mass of Higgs boson, which are not shown here. [37].

340

### 341 2.3 Electroweak couplings of top quark

342 Although the top quark was discovered 18 years ago, some of its properties still remain  
 343 undetermined, including the electroweak couplings to gauge bosons. Current data does  
 344 provide some weak constraints on the EW couplings, specially the LEP data which  
 345 constraints the  $t\bar{t}Z$  couplings indirectly. One of the reasons for this is that so far the top  
 346 quark has only been studied at hadron colliders, where the production of the  $t\bar{t}$  pairs is  
 347 predominantly either through  $q\bar{q}$  pairs ( $q\bar{q} \rightarrow g^* \rightarrow t\bar{t}$ ), or gluon-gluon fusion( $gg \rightarrow t\bar{t}$ ).  
 348 As the process  $q\bar{q} \rightarrow Z * / \gamma^* \rightarrow t\bar{t}$  is greatly suppressed, the couplings can only be  
 349 indirectly measured in associate production of top pairs. However, the production of  $t\bar{t}$   
 350 pairs at a lepton collider takes place through electroweak mechanism. The top quark pair  
 351 production goes directly through the  $t\bar{t}Z$  and  $t\bar{t}\gamma$  vertices. Absence of concurrent QCD  
 352 production leads to clean measurement of electroweak couplings of the top quark. The  
 353 production mechanism is  $e^- e^+ \rightarrow (Z/\gamma^*) \rightarrow t\bar{t}$ , represented by the Feynman diagrams,  
 354 in figure 2.4.

The general Lorentz-invariant equation, describing the interaction of a vector boson  $X$  and two top quarks, can be written in terms of form factors. The generalized production

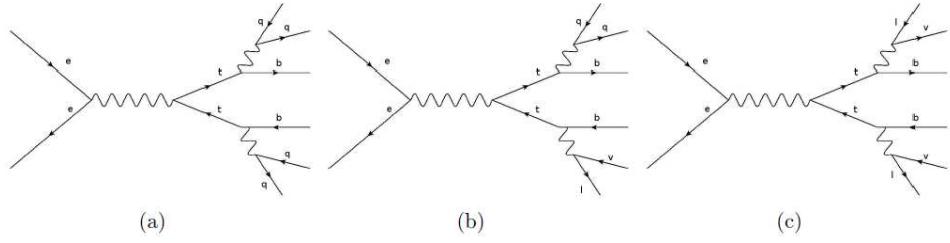


FIGURE 2.4: Feynman diagrams showing the production of  $t\bar{t}$  pairs at an electron collider, and their decay. The three possible decay mechanisms a) fully hadronic, b) semi-leptonic and c) fully leptonic are shown.

vertex  $ttX$  can be written as [29]:

$$\Gamma_{\mu}^{ttX}(k^2, q, \bar{q}) = ie \left\{ \gamma_{\mu} \left( \tilde{F}_{1V}^X(k^2) + \gamma_5 \tilde{F}_{1A}^X(k^2) \right) + \frac{(q - \bar{q})_{\mu}}{2m_t} \left( \tilde{F}_{2V}^X(k^2) + \gamma_5 \tilde{F}_{2A}^X(k^2) \right) \right\} \quad (2.1)$$

Where  $e$  is the electron charge,  $m_t$  is the mass of top quark,  $k^2 = (q + \bar{q})^2$  is the four momentum of the gauge boson,  $q$  and  $\bar{q}$  represent the four vectors of the  $t$  quarks. The  $\gamma_{\mu}$  are Dirac matrices with  $\mu = 0, 1, 2, 3$ . The subscript  $V$  and  $A$  represent the vector and axial vector coupling form factors respectively. The term  $\gamma_5 = i\Pi\gamma_{\mu}$  allows to introduce the axial vector currents into theory.

Using the Gordon identity for the vector and axial vector currents in above equation, one can rewrite it as:

$$\Gamma_{\mu}^{t\bar{t}X}(k^2, q, \bar{q}) = -ie \{ \gamma_{\mu} (F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2)) + \frac{i\sigma_{\mu\nu}}{2m_t} (q + \bar{q})^{\nu} (iF_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2)) \} \quad (2.2)$$

Where  $\sigma_{\mu\nu} = i/2(\gamma_{\mu}\gamma_{\nu} - \gamma_{\nu}\gamma_{\mu})$ . It must be taken into account that the Gordon identity holds only when both top quarks are on-shell. It can easily be seen that form factors  $\tilde{F}_i$  and  $F_i$  in above equations, are related to each other as:

$$\tilde{F}_{1V}^X = -(F_{1V}^X + F_{2V}^X), \quad \tilde{F}_{1V}^X = F_{1V}^X, \quad \tilde{F}_{1A}^X = -F_{1A}^X, \quad \tilde{F}_{2A}^X = -iF_{2A}^X \quad (2.3)$$

In the Standard Model most of these form factors have a zero value and the vector and axial vector couplings of Z, go as  $\frac{I_3 - 2Qs_w^2}{2s_w c_w}$  and  $\frac{I_3}{2s_w c_w}$  respectively, where  $I_3$  is the third component of the Isospin, taking the following values.

$$I_3(e_L, t_L, e_R, t_R) = \left( \frac{-1}{2}, \frac{1}{2}, 0, \frac{-1}{2} \right) \quad (2.4)$$

At the tree level, the non-zero form factors have the following values:

$$F_{1V}^{\gamma} = -\frac{2}{3}, \quad F_{1V}^Z = -\frac{1}{4s_w c_w} \left(1 - \frac{8}{3}s_w^2\right), \quad F_{1A}^Z = \frac{1}{4s_w c_w} \quad (2.5)$$

360 Where  $c_w$  and  $s_w$  represent  $\cos \theta_w$  and  $\sin \theta_w$  respectively, where  $\theta_w$  is the Weinberg  
361 Angle.

362 The above expression for the Born level, six form factors  $F_{1A}, F_{1V}, F_{2V}$  for  $Z$  and  $\gamma$  are  
363 CP conserving form factors, while the two form factors  $F_{2A}$  are the CP violating form  
364 factors.

365  $F_{2V}^{\gamma, Z}$  are the electric and weak magnetic dipole moment form factors, while the  $F_{2A}^{\gamma, Z}$  are  
366 the electric and weak electric dipole moment form factors.

367 The sign of the form factor values are sensitive to the interference between the  $Z$  and  
368  $\gamma$ . This limits the precise determination of the electroweak couplings of top quark, at  
369 the hadron colliders, where the couplings are to be measured in the associated vector  
370 boson production. As is the case at the LHC for example, only the absolute value of the  
371 couplings can be determined.

372 By using the above form factors, and taking into account the helicity of the incoming  
373 electrons, one can write new form factors as follows [39]:

$$\mathcal{F}_{ij}^L = -F_{ij}^{\gamma} + \left(\frac{\frac{-1}{2} + s_w^2}{s_w c_w}\right) \left(\frac{s}{s - m_Z^2}\right) F_{ij}^Z \quad (2.6)$$

$$\mathcal{F}_{ij}^R = -F_{ij}^{\gamma} + \left(\frac{s_w^2}{s_w c_w}\right) \left(\frac{s}{s - m_Z^2}\right) F_{ij}^Z \quad (2.7)$$

374 Where  $L$  and  $R$  represent the helicity of the incoming electrons,  $i = 1, 2$  and  $j = V, A$   
375 refer to the structure of the form factors.  $s$  is the square of the center-of-mass  
376 energy  $\sqrt{s}$ .

By using the similar notations, the decay vertex of the top quark  $t \rightarrow bW$  can be written as follows:

$$\Gamma_{\mu}^{tWb}(k^2, q, \bar{q}) = i \frac{g}{\sqrt{2}} \left\{ \gamma_{\mu} (F_{1L}^W(k^2)P_L + F_{1R}^W(k^2)P_R) + \frac{i\sigma_{\mu\nu}}{2m_t} (q + \bar{q})^{\nu} (iF_{2L}^W(k^2)P_R + F_{2R}^W(k^2)P_L) \right\} \quad (2.8)$$

377 The strong coupling of the top quark to the electroweak symmetry breaking suggest that  
378 top quark studies can be a gateway to new physics. A specific scenario for this case are  
379 Randall-Sundrum Models [49]. These models and composite Higgs models have been  
380 discussed in detail in Volume 1, section 5.3.1 of [40]. Following the Randall-Sundrum

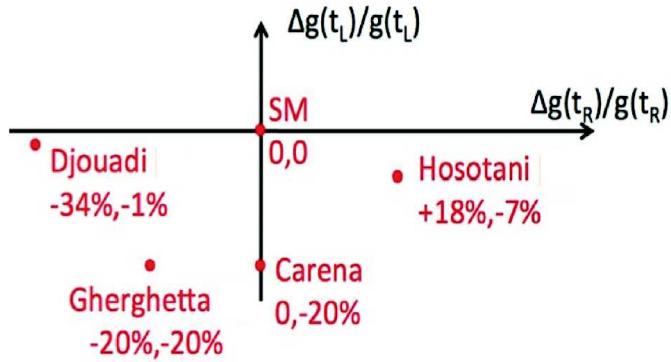


FIGURE 2.5: Divergence of  $t\bar{t}Z$  couplings from Standard Model prediction, as predicted by some models, in Randall-Sundrum scenario.

381 approach, the couplings of the top quark to the Z boson may diverge from the predictions  
 382 of the Standard Model, due to Z-Z' mixing. Various proposals have been made for these  
 383 divergences, for example Djouadi [45], Hosotani [46], Ghergheta [47] and Carena [48], as  
 384 shown in figure 2.5.

## 385 2.4 Cross sections

The production cross section could be written in terms of the above mentioned form factors. The Born level cross section with electron beam polarization  $I = L, R$ , can be expressed as:

$$\sigma_I = 2\mathcal{A}N_c\beta \left[ (1 + 0.5\gamma^{-2})(\mathcal{F}_{1V}^I)^2 + (\mathcal{F}_{1A}^{I'})^2 + 3\mathcal{F}_{1V}^I\mathcal{F}_{2V}^I \right] \quad (2.9)$$

386 Where  $\mathcal{A} = \frac{4\pi\alpha^2}{3s}$ ,  $\alpha(s)$  is the electromagnetic running coupling constant,  $N_c$  represents  
 387 the number of quark colors,  $\gamma$  is the Lorentz factor,  $\beta$  is the velocity and  $\mathcal{F}_{1A}^{I'} = \beta\mathcal{F}_{1A}^I$ .

388 Figure 2.6 shows a prediction for the  $t\bar{t}$  production cross section at the ILC. Different  
 389 curves represent the center-of-mass energy loss mechanisms at the ILC, at the interaction  
 390 point.

391 Further details on the polarized cross sections and beam polarizations will be given in  
 392 5.4.

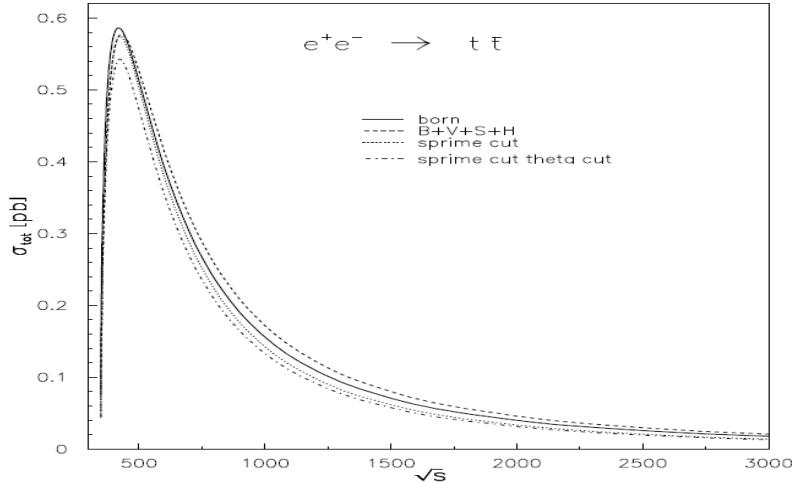


FIGURE 2.6:  $t\bar{t}$  production cross section, as a function of center-of-mass energy. The solid curve is for Born level cross section, while the dashed lines show the electroweak cross section. The dotted and dashed-dotted curves take into effect the loss of beam energy mechanisms such as ISR. The figure is taken from [52].

### <sup>393</sup> 2.5 Forward Backward Asymmetry

The above mentioned form factors can also be used to write the Forward-Backward Asymmetry of top quark pair production, as shown in the following equation:

$$(A_{FB}^t)_I = \frac{-3\mathcal{F}_{1A}^{I'}(\mathcal{F}_{1V}^I + \mathcal{F}_{2V}^I)}{2[(1 + 0.5\gamma^{-2})(\mathcal{F}_{1V}^I)^2 + (\mathcal{F}_{1A}^{I'})^2 + 3\mathcal{F}_{1V}^I\mathcal{F}_{2V}^I]} \quad (2.10)$$

<sup>394</sup> Figure 2.7 shows the  $A_{FB}^t$ , as a function of  $\sqrt{s}$ , for unpolarized electron-positron beams.

However, the  $A_{FB}^t$  is sensitive to beam polarizations. Using Standard Model values for the form factors, the following values for  $A_{fb}^t$  can be deduced, for the respective electron beam polarizations.

$$(A_{FB}^t)_L = 0.38, (A_{FB}^t)_R = 0.47. \quad (2.11)$$

The asymmetric distribution of the fermion in the forward and backward hemispheres of the detectors, is called the Forward-Backward Asymmetry, and it is a characteristic, common to all fermions. The first observations of the parity violation, in the Madame Wu experiment, showed the inhomogeneous distribution of the final state fermions. Since then, it has been observed and measured at various experiments, involving different fermion, notably  $b$  quarks and  $t$  quarks. The definition of  $A_{FB}^t$ , in experimental terms,

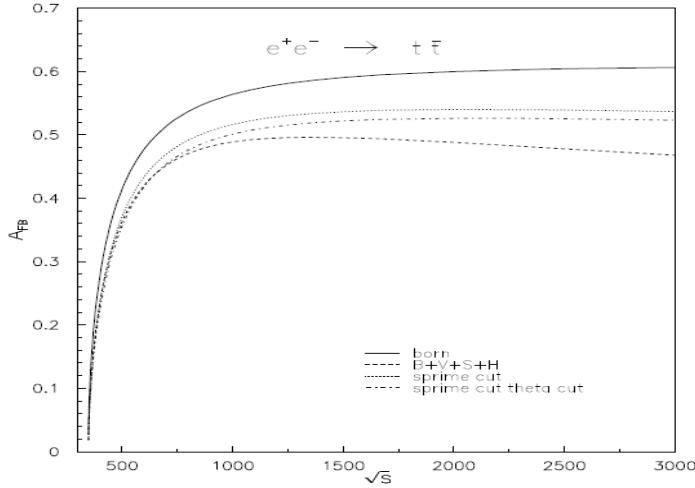


FIGURE 2.7:  $A_{FB}^t$  as a function of  $\sqrt{s}$ . The Born level  $A_{FB}^t$  is shown by solid lines. [52].

can be put as follows:

$$A_{FB}^t = \frac{N(0 < \theta_{top} \leq \frac{\pi}{2}) - N(\frac{\pi}{2} < \theta_{top} \leq \pi)}{N(0 < \theta_{top} \leq \frac{\pi}{2}) + N(\frac{\pi}{2} < \theta_{top} \leq \pi)} \quad (2.12)$$

395 The  $A_{FB}$  for the  $b$  quarks was measured at LEP [43, 44], and was found to be slightly  
 396 above the Standard Model expectations. A deviation of  $3\sigma$  was observed. Also, a mea-  
 397 surement of  $t\bar{t}$  forward backward asymmetry  $A_{FB}^t$  has been made at the Tevatron[22, 23].  
 398 The Standard Model predicts this value to be 0.078[21] but a value of  $0.19 \pm 0.0065$   
 399 (*stat.*)  $\pm 0.024$  (*syst.*) is observed[22], which is  $2\sigma$  off. However, the value of  $A_{FB}^t$  is  
 400 dependent on the production mechanism of the top quark pairs. These measurements  
 401 correspond to the QCD production of the  $t\bar{t}$  pairs, as Tevatron is a  $p\bar{p}$  collider and the  
 402  $t\bar{t}$  production is dominated by  $q\bar{q} \rightarrow t\bar{t}$ . Although LHC is also a hadron collider, but  
 403 higher center-of-mass energy and  $pp$  collisions instead of  $p\bar{p}$  imply that the production is  
 404 dominated by gluon-gluon fusion.

405 These anomalies have significant implications. The  $b\bar{b}$  asymmetry can, for example, be  
 406 explained by the contributions of Kaluza-Klein excitations of electroweak gauge bosons  
 407 in warped extra-dimension models. In these models, the gauge interactions of  $b$  and  $t$   
 408 quarks are different from that of light quarks, due to their different behavior in the extra  
 409 dimensions. But it is more difficult to generate a  $t\bar{t}$  forward backward asymmetry through  
 410 exchanges of Kaluza-Klein gluons because of electroweak precision constraints[45].

411 All measurements of the  $t\bar{t}$  asymmetry were made at hadron collider, so far. A detailed  
 412 review on the measurement of  $A_{FB}^t$  at hadron colliders will be given in Chapter 5. This  
 413 thesis will concentrate on the study of  $A_{FB}^t$ , at the ILC, using fully hadronic decays of

414  $t\bar{t}$  at a 500 GeV center-of-mass energy. The studies are carried out for  $t\bar{t}$  decaying to six  
415 quarks;  $e^-e^+ \rightarrow t\bar{t} \rightarrow (bW^+)(\bar{b}W^-) \rightarrow b\bar{b}q\bar{q}q\bar{q}$ .

416 A linear collider is an ideal machine to study particle physics at a high precision level.  
417 Today, the most advanced proposal for a linear collider is the International Linear Col-  
418 linder. Apart from measuring the electroweak couplings of the top quark, studies have  
419 been made for the capability of the ILC, to measure the top Yukawa couplings in associ-  
420 ated Higgs production, at various center-of-mass energies[53, 54, 55]. The precision level  
421 achievable at the ILC, makes it possible to not only study the top quark in details, but  
422 also the other physics processes including precision Higgs measurement and W physics.  
423 The potential of the ILC to find any hint of the new physics has been shown in the  
424 studies with full detector simulations. The details description of ILC and its detector  
425 will be given in the next chapter.

426 **Chapter 3**

427 **International Large Detector (ILD)**

428 **3.1 Introduction**

429 The physics results achieved at the LHC need to be complemented by high precision  
430 measurements, which are achievable with lepton colliders. At lepton colliders, the full  
431 beam energy is available in the collision while at hadron colliders it is shared among  
432 the constituent quarks of hadrons. Moreover, the undesired QCD background at hadron  
433 collisions, can be avoided at lepton colliders.

434 The best option for a lepton collider, at high energies, is a linear accelerator. Charged  
435 particles moving in a circular path, radiate energy which is proportional to  $\frac{E^4}{m^4} \frac{1}{r^2}$  [58].  
436 This radiation is called synchrotron radiation. Electrons, being lighter than protons,  
437 radiate far more energy in a circular accelerator. Upto a certain limit of beam energy,  
438 circular colliders can be used for electron beams, for example LEP, but for high beam  
439 energies, synchrotron radiation is a very challenging problem to control.

440 At the moment, there are two main proposals for a linear collider: The International  
441 Linear Collider (ILC) and the Compact Linear Collider(CLIC) [59].

442 The ILC [40] is designed to operate at a center-of-mass energy of  $\sqrt{s} = 500$  GeV, later  
443 on extendable to 1 TeV, while CLIC is designed to start operating at 500 GeV and can  
444 be upgraded upto 3 TeV.

445 **3.2 The International Linear Collider**

446 One of the advantages of a linear collider is that it can run at any center-of-mass energy,  
447 accessible within its design. The luminosity is approximately proportional to the energy.

ILC design parameters	
center-of-mass energy $\sqrt{s}$	91-500 GeV
Peak Luminosity	$2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
electron beam polarization $P_{e^-}$	>80%
positron beam polarization $P_{e^+}$	upto 30%
Total Length	~31 km

TABLE 3.1: Major ILC design parameters. The design allows for an upgrade up to a center-of-mass energy of 1 TeV.

- 448 The ILC will collide electrons and positrons, at a center-of-mass energy upto 500 GeV.  
 449 The accelerator required for this purpose is approximately 31 km in length. It is designed  
 450 to generate a total of  $500 \text{ fb}^{-1}$  of data in the first four years of operation. The important  
 451 design parameters for the ILC[40] are summarized in the following table.
- 452 The technology of the ILC is based on 1.3 GHz superconducting RF cavities, which will  
 453 operate at a gradient of 31.5 MV/m. Polarized electrons are produced by a laser illumi-  
 454 nating a photo cathode in a DC gun. A normal conducting structure pre-accelerates  
 455 these beams to 76 MeV. After-wards, they are accelerated to 5 GeV in superconduct-  
 456 ing linacs. Superconducting solenoids rotate the spin vectors into the vertical direction,  
 457 before injecting the beam into damping rings. These damping rings are 6.7 km in cir-  
 458 cumference as shown in figure 3.1. The beams are then injected into the main linacs  
 459 which are  $\sim 11$  km long . Finally, they are focused to very small spot sizes, of the order  
 460 of a few nanometers, at the collision point, using a beam delivery system which is 2.2  
 461 km per side.
- 462 The baseline time structure of the beam consists of bunchtrains of 1312 bunches spaced  
 463 554 nanoseconds, passing the interaction point at a rate of 5Hz. Each bunch train is  
 464 about 0.3 millimeter long, with about 200 milliseconds between bunch trains. These  
 465 parameters are for ILC operating at  $\sqrt{s} = 500 \text{ GeV}$ .
- 466 Beam polarization is one of the assets of the ILC. It enables the study of physics param-  
 467 eters involving the spin of particles, for example helicity. The  $e^-$  beams can be polarized  
 468 upto 80% while the  $e^+$  beams can be polarized upto 30% without using photon collima-  
 469 tors and upto 60% with photon collimators [65]. Longitudinally polarized positron beams  
 470 are generated from the circularly polarized photons, which are produced by the helical  
 471 undulator in the ILC accelerator system. This undulator is installed at the end of the  
 472 main linac beamline. The photons generated by undulator strike the rim of a rotating  
 473 titanium target, which has a thickness of 0.4 radiation lengths. The electron positron  
 474 pairs are generated at this point, and positrons are captured by 0.07 mrad transverse  
 475 dynamic aperture. The polarization of the positron beams is conserved throughout the  
 476 transportation of the positrons to damping rings.

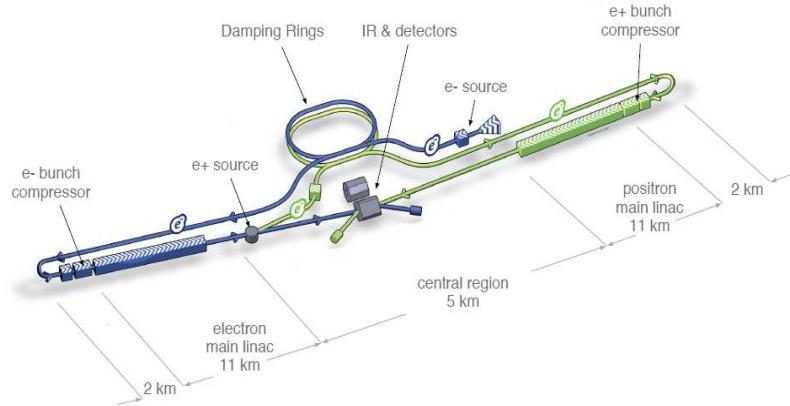


FIGURE 3.1: Accelerator system of the ILC. Damping rings, main linacs and beam delivery system are shown. Blue color represents electron beam system, while green color is for positron beam.[40]

Particle type	Energy fraction	Detector
Charged particles	~60%	Tracker
Photons	~30%	ECAL
Neutral hadrons	~10%	ECAL + HCAL

TABLE 3.2: Constituents of a typical jet, along with fraction of the jet energy carried by them.

477 The ILC is proposed to have two detectors, to complement each other for the physics  
 478 measurements, namely the Silicon Detector (SiD)[60] and the International Large De-  
 479 tector (ILD)[61]. The SiD is a compact detector, based on silicon technology which will  
 480 operate in a magnetic field of 5T. The design of the ILD results in a large sized detector  
 481 with a large TPC used for tracking and highly granular calorimeters. It will operate in  
 482 a lower magnetic field of 3.5 T.

### 483 3.3 The Particle Flow Algorithm (PFA)

484 Precision measurements require a good performance from detectors and reconstruction  
 485 algorithms. The Particle Flow [66] approach will be followed at the ILC to reconstruct  
 486 final state particles. It will be used to reconstruct quark and gluon jets from their  
 487 constituent particles. Typically, a jet is composed of different types of particles. The  
 488 contribution of photons, charged and neutral hadrons to the total jet energy is given in  
 489 the table below.

490 The PFA uses the reconstructed energy from these particles, in each sub-detector as  
 491 shown in the table above, to reconstruct the jet energy. The technique not only requires

492 an excellent particle identification and granularity from the calorimeter, but also the  
 493 complementarity of different subdetectors operating together.

494 While the PFA has been tested at existing experiments for example CMS[70, 71], it  
 495 determines the design of the detectors at the ILC, that will be optimized for its use.  
 496 Within the framework of detector R&D for the ILC, the PFA has been already applied  
 497 to beam test data taken over prototype sub-detectors[69].

### 498 3.4 The ILD detector concept

499 The ILD is a multipurpose  $4\pi$  detector. Its two main features are: The Particle Flow  
 500 approach to identify individual particles [68], and a good tracking and vertexing per-  
 501 formance. The PF approach requires highly granular calorimeters. An excellent perfor-  
 502 mance from the vertex detectors and trackers is necessary to reconstruct the tracks of  
 503 charged particles, and to determine their charge. The R&D for the ILD is driven by  
 504 these factors. A schematic view of the ILD is shown in figure 3.2. It consists of many  
 505 subdetectors, optimized for different tasks. Along with individual performance, the de-  
 506 tectors are required to be complementary to each other. Their detailed description is  
 507 given in the next sections.

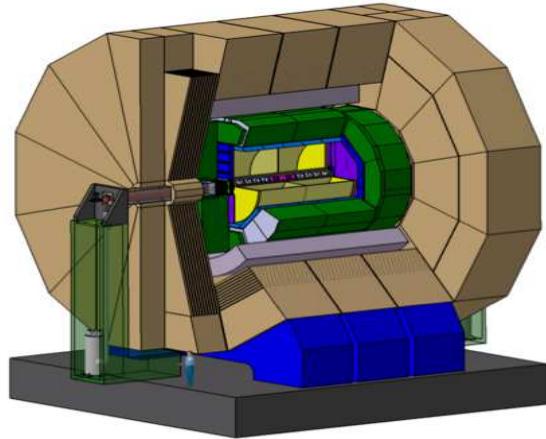


FIGURE 3.2: A Schematic view of the International Large Detector (ILD). The relative dimensional size is exhibited with respect to average height of a human. Different sub-detectors of the ILD are shown in different colors.

#### 508 3.4.1 Vertex Detectors (VTX)

509 The principal goal of a vertex detector is to identify the interaction vertex and vertices of  
 510 short-lived particles such as D or B mesons and  $\tau^\pm$ . Since it is closest to the interaction

511 point, it reconstructs the first point of a track. The vertices of short lived particles are  
 512 traced back by using the track information of their decay products.

513 It also plays a vital role in reconstructing the jet charge and in flavor tagging. In the  
 514 analysis described in this thesis, these two parameters have a central importance. The  
 515 recognition of b-jets and reconstruction of their charge have been used to identify top  
 516 and anti-top quarks. The analysis will be discussed in detail in chapter 5.

517 Taking into account these requirements, the following conditions are to be fulfilled at the  
 518 VTX of the ILD.

- 519 – A single point resolution of less than  $3 \mu\text{m}$  is required.
- 520 – The thickness of the material between the first measured point of a track and the  
 521 IP should be less than 1% of the radiation length  $X_0$ .
- 522 – The first layer of the vertex detector should be  $\sim 15 \text{ mm}$  from the IP.

The impact parameter resolution of the vertex detector,  $\sigma_{ip}$ , can be expressed as follows:

$$\sigma_{ip} = a \oplus \frac{b}{p \cdot \sin^{2/3} \theta} \mu\text{m} \quad (3.1)$$

523 Here,  $p$  is the track momentum, and  $\theta$  is the angle of the track with respect to the beam  
 524 axis. For the VTX at the ILD, the required resolution can be achieved with  $a \leq 5 \mu\text{m}$  &  
 525  $b \leq 10 \mu\text{m}$ . In comparison to previously used vertex detectors, these numbers are almost  
 526 half of the next achieved number in terms of vertex detector resolution. For example,  
 527 for the SLC detector,  $a \simeq 10 \mu\text{m}$  and  $b = 33 \mu\text{m}$ [75].

528 The baseline design of the VTX, which should meet these requirements, is in the R&D  
 529 phase. The VTX consists of 3 concentric layers of double-sided ladders which are  $\sim 2$   
 530 mm apart. Each ladder has a thickness of  $\leq 50 \mu\text{m}$ , divided in pixels. The inner-most  
 531 layer is at 16mm from the IP and the outermost layer is at 60mm. The material of each  
 532 ladder accounts for 0.15%  $X_0$  in total. The VTX provides an overall point resolution of  
 533  $2.8 \mu\text{m}$ . Some parameters of the VTX are listed below. This geometry is called double  
 534 ladder (VTX-DL).

535 The alternative geometry for this baseline design is called single ladder (VTX-SL). It  
 536 consists of 5 equally-spaced single layers. The radius of the first layer, is the same as the  
 537 previous one, while the last layer has a radius of 60mm. The two geometries are shown  
 538 in figure 3.3

Layer No.	Inner Radius (mm)	Length $z$ (mm)	$\cos \theta$	$\sigma$ ( $\mu\text{m}$ )
1	16	62.5	0.97	2.8
2	18	62.5	0.96	6
3	37	125	0.96	4
4	39	125	0.95	4
5	58	125	0.91	4
6	60	125	0.90	4

TABLE 3.3: Dimensions of the different layers of vertex detector and the polar angle covered by them. The respective point resolution is also shown.

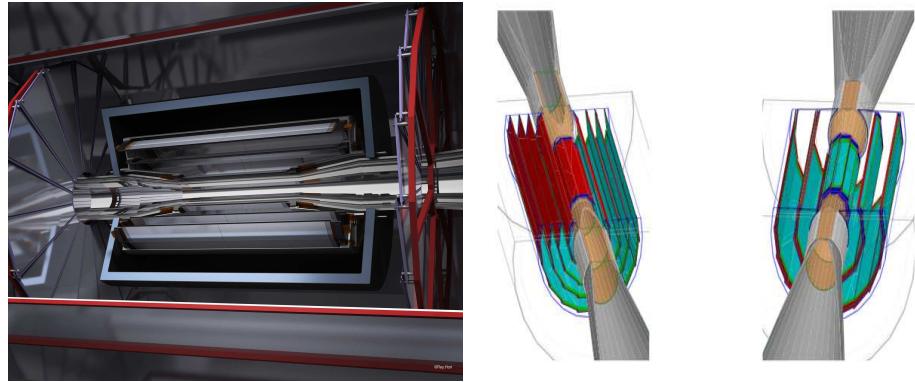


FIGURE 3.3: The vertex detector of the ILD. The left figure shows a view of the VTX around the beam pipe, at the interaction point. The right part shows two proposed geometries; Single Ladder and Double Ladder.

539 There are currently three readout technologies under consideration for VTX. The CMOS  
 540 Pixel Sensor(CPS)[72], Fine Pixel CCD (FPCCD) [73] and Depleted Field Effect Transistor(DEPFET) [74] are the potential options.

542 The performance of the vertex detector with CMOS pixel sensor technology, is shown  
 543 in figure 3.4. The single point resolution is plotted versus the signal to noise ratio [64].  
 544 Various colors represent different in-pixel circuits. The resolution is close to the required  
 545  $\sim 3 \mu\text{m}$ . The chips of the VTX contain 1152 columns, each of 576 pixels. Each pixel  
 546 has a  $18.4 \mu\text{m}$  pitch. The VTX has also been tested for MIP detection efficiency. The  
 547 efficiency is better than 99%.

### 548 3.4.2 Central Tracking

549 Track reconstruction for charged particles at the ILD consists of two parts, namely  
 550 silicon tracking and central tracking. The silicon trackers are the Silicon Internal Tracker  
 551 (SIT), the Silicon External Tracker (SET), the Endcap Tracking Detector (ETD) and the

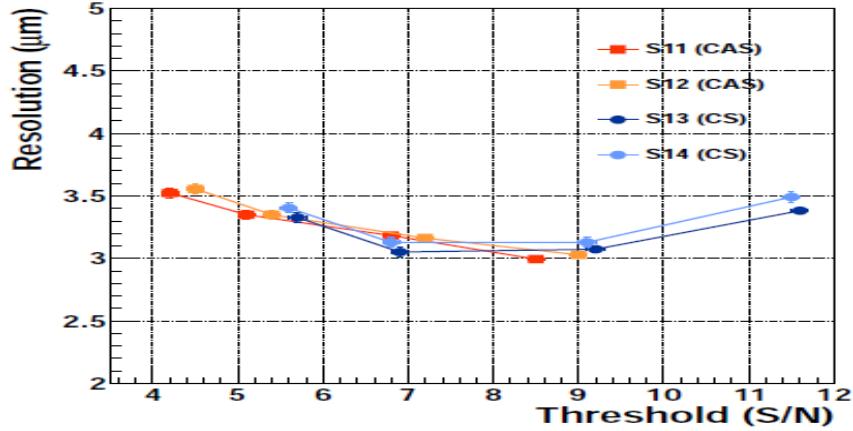


FIGURE 3.4: Single point resolution of the VTX with CMOS Pixel Sensor technology, as a function of the S/N ratio for different in-pixel circuits (S11-S14).

552 Forward Tracking Detector(FTD). The central tracking uses a Time Projection Chamber  
 553 (TPC).

#### 554 3.4.2.1 Silicon Tracking

555 The SIT is placed between the TPC and the VTX. Its role is to provide the link between  
 556 the TPC and the vertex detector. It consists of 2 silicon layers. The SET is located  
 557 in the barrel part, between the TPC and the electromagnetic calorimeter (ECAL). It is  
 558 the third silicon layer in the central barrel region and it provides outermost point of the  
 559 track. The ETD is placed between the TPC end plate and endcap calorimeter system.  
 560 It serves as an entry point to the ECAL. The SIT and SET also provide time-stamping  
 561 of bunches, allowing for bunch tagging of each event. Time stamping of the bunches is  
 562 particularly important to avoid the overlap of events.

563 SIT, SET and ETD consist of microstrip silicon sensors. The baseline sensors are  $10 \times$   
 564  $10\text{cm}^2$ , with a  $50\mu\text{m}$  pitch. The sensors have a very thin edge, (inactive zone), ranging  
 565 between a few 10s of  $\mu\text{m}$  to a few 100  $\mu\text{m}$ . These detectors are shown in figure 3.5. In  
 566 the left part of the figure, the relative position of the silicon trackers can be seen with  
 567 respect to the TPC and the ECAL, while the right part is a detailed 3D implementation  
 568 in Geant4 of the TPC geometry, in a right-handed coordinate system with the origin at  
 569 the interaction point(0,0,0).

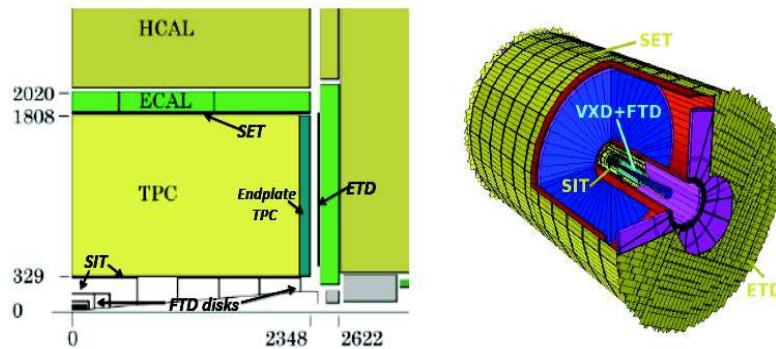


FIGURE 3.5: ILD tracking detectors. The left figure shows a quadrant of the tracking system where ETD, FTD, SIT and SET are visible, with their relative positions to the Vertex Detector (VXD), TPC and ECAL. The right side represents a Geant 4 Implementation of the silicon system.

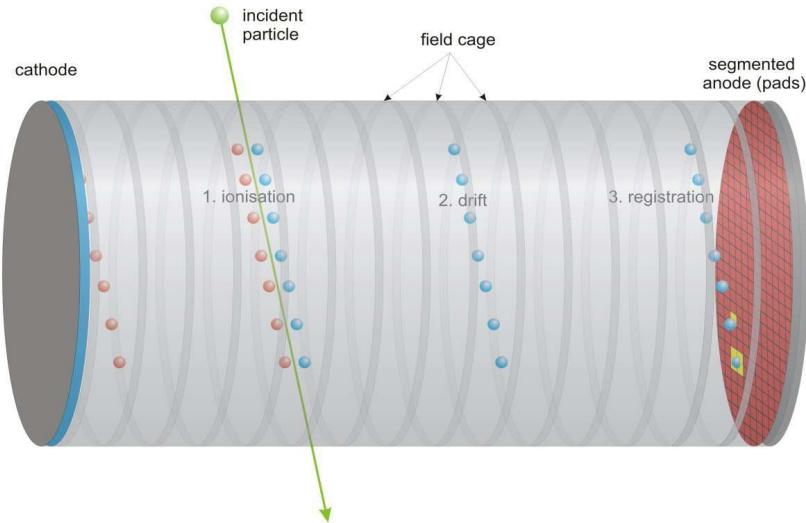


FIGURE 3.6: The working principle of a time projection chamber.

### 570 3.4.2.2 The Time Projection Chamber (TPC)

571 The Time Projection Chamber (TPC) is used to measure the trajectories of particles  
 572 coming out of the vertex detector. The TPC is filled with a gas. When a charged  
 573 particle enters the TPC, it ionizes the molecules of the gas. Due to the applied voltage,  
 574 the released electrons drift towards the anode. At the anode, these electrons are detected  
 575 on the readout plates, which are segmented perpendicular to the drift direction. In order  
 576 to measure precisely the position of particle, the electric field needs to be homogeneous  
 577 throughout the volume of the TPC. The working principle of a TPC is exhibited in figure  
 578 [3.6](#).

579 The TPC of the ILD consists of two identical chambers filled with gas. The cathode is  
 580 placed at the center of the TPC, while anodes occupy the ends of volume. These anodes  
 581 are equipped with a readout system. A high voltage is applied, which creates an electric  
 582 field across the TPC.

583 The TPC is expected to work in a magnetic field of 3.5 T. The main requirements on  
 584 the design of the TPC are characterized by two parameters, the point resolution  $\sigma_p$  and  
 585 double hit separation. The objective is to achieve a point resolution less than  $100 \mu\text{m}$   
 586 and a double hit separation resolution of 2 mm.

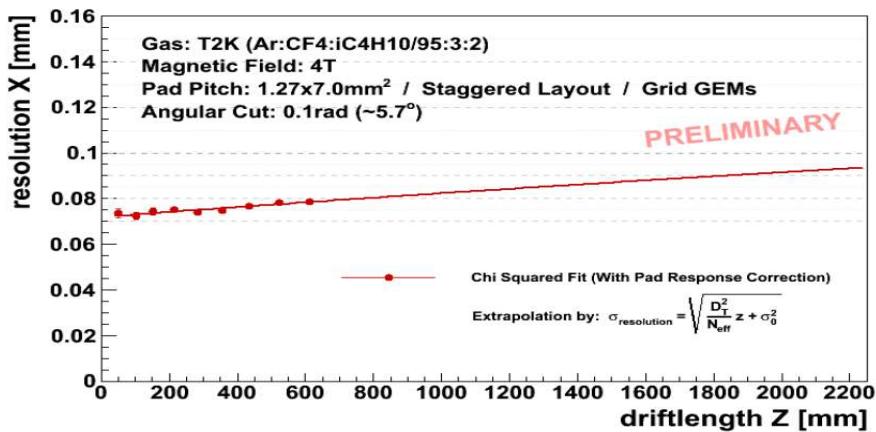


FIGURE 3.7: The single point resolution of the TPC prototype, with GEM readout, measured in a 4T magnetic field. The curve is extrapolated to full drift lengths.

587 The TPC will have an inner radius of 330 mm and an outer radius of 1808 mm. It will  
 588 be 4.7 meters in length along the z-axis. It will cover an angle of  $|\cos \theta| \simeq 0.98$ .

589 The choice of the TPC gas is driven by the requirements on drift velocity and its diffusion  
 590 properties. A drift length of 2 m and a magnetic field of 3.5 T are also taken into account.  
 591 The gas considered for the TPC is called T2K gas, which is a Ar-CF4(3%)-isobutane(2%)  
 592 mixture.

593 A prototype has been developed and has been tested at experimental facilities. Figure  
 594 3.7 shows the performance of this prototype operating in a 4T magnetic field. The single  
 595 points resolution is shown against the drift length. The extrapolation of the curve to full  
 596 drift lengths shows that a point resolution  $\sigma_p \leq 100 \mu\text{m}$  can be achieved [83].

### 597 3.4.3 The ILD Calorimeter System

598 In the PFA, as described earlier, the emphasis is placed on the full tracking of the shower  
 599 particles in the calorimeter, rather than the energy resolution of individual particles. The

calorimeters should enable a full tracking of the shower particles in the calorimeter. The required high granularity implies a large number of cells and readout channels. The calorimeter system of the ILD is expected to have  $\sim 10^8$  channels, with the current baseline design. The R&D for the calorimeter system is mainly done by the CALICE collaboration [76]. The calorimeters are described below, in more detail.

### 3.4.3.1 The Silicon Tungsten Electromagnetic Calorimeter (Si-W ECAL)

The main role of the ECAL is to reconstruct photons and electrons. It must be able to measure their energy, position, and angle. To meet the performance goal, with the PFA, the ECAL needs to have a high granularity and to be placed inside the magnetic field. The latter requirement implies that it should be as thin as possible, for a compact and cost effective detector. In addition, it should also have a minimum insensitive area.

The ILD ECAL will have a barrel and endcap structure, divided into 8 staves in the barrel region. A schematic view of the ECAL and of one module are shown in fig 3.8.

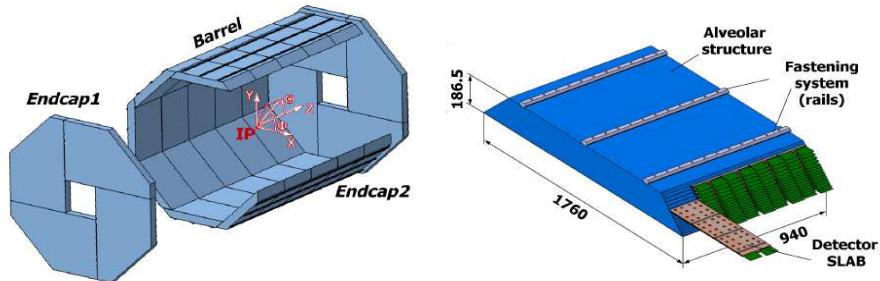


FIGURE 3.8: Si-W ECAL of the ILD. The left part of the figure is a depiction of Barrel Endcap structure of ECAL, while the right part shows one module, with alternate layers.

A Silicon Tungsten Calorimeter is one of the options for ILD. Silicon is chosen as active material, while Tungsten is the absorber material. The choice of absorber material is driven by the compactness of the detector and the need to separate particle which are close together. This implies that the absorber material should have a small radiation length  $X_0$ , a small Molière radius and a high ratio of interaction length  $\lambda_l$  to radiation length  $X_0$ . Tungsten meets these requirements, as outlined below.

- A small Molière Radius  $R_M$  of 9 mm helps to separate particle showers.
- A small radiation length  $X_0 = 3.6$  mm helps to make a compact detector.
- A high  $\lambda_l/X_0 = 27.5$  ratio helps to achieve the longitudinal separation electromagnetic and hadronic showers, by making sure that hadrons only start interacting in the later part of the ECAL.

Number of Si Layers	30
Cell size	$5 \times 5 \text{ mm}^2$
Total Thickness	185 mm
Inner Radius	1843 mm
Outer Radius	2028 mm
Radiation lengths	$24 \text{ X}_0$
Total Surface Area of Silicon	$2500 \text{ m}^2$

TABLE 3.4: Major properties of the Si-W ECAL of the ILD.

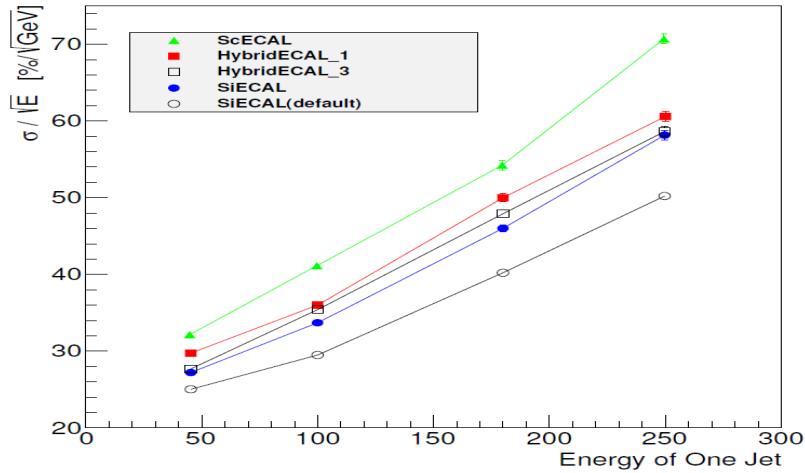


FIGURE 3.9: The performance of Electromagnetic Calorimeter for the ILD. The figure shows the energy resolution of various proposals for ECAL.

624 The important properties of the Si-W ECAL are summarized in the following table.

625 The choice of these parameters ensures 99% containment of 5 GeV electromagnetic showers,  
626 while more than 98% of 50 GeV showers is contained in the ECAL.

627 According to the baseline design, the Si-W ECAL will comprise of 30 readout layers.  
628 Each silicon layer will be  $\sim 300 \mu\text{m}$  thick, and will consist of 4 wafers, per stave. Wafers  
629 of size  $9 \times 9 \text{ cm}^2$  will be segmented into  $16 \times 16$  cells, each cell measuring  $5 \times 5 \text{ mm}^2$ . This  
630 cell size has been decided after dedicated R & D studies to optimize the cell size.

631 The first Si-W ECAL prototype which was developed to test the proof of principle, was  
632 called the physics prototype. It was a 30 layer module with varying absorber thickness.  
633 Various tests at DESY, FNAL, and CERN were done with different incident particles  
634 and with different energy ranges. Analysis of this data determined an electromagnetic  
635 energy resolution of  $\sigma_E/E = (16.6 \pm 0.1) \% / \sqrt{E(\text{GeV})} \oplus (1.1 \pm 0.1) \%$  with a MIP  
636 signal over noise ratio of  $S/N \approx 7.5$ [77] [78]. This value is in good agreement with the  
637 ILD simulations.

638 One of the important objectives of the R&D is to optimize the cost to performance  
 639 ratio of the ECAL. Along with considering alternative options (described in the next  
 640 section), the efforts have also concentrated on minimizing the cost of the Si-W ECAL,  
 641 by optimizing the number of layers (to make a cost effective ECAL without effecting  
 642 the performance) and the size of the guard rings. The guard rings prevent the current  
 643 leakage but are also dead zones which should be minimized. This optimization will be  
 644 discussed in more detail in Chapter 4.

#### 645 3.4.3.2 Alternatives for ECAL

646 Besides the Si-W ECAL design, alternative technologies are proposed that could be more  
 647 cost effective. One of them is the Scintillator ECAL(ScECAL). The idea is to use  $5 \times$   
 648  $45 \text{ mm}^2$  scintillator strips, arranged in alternating directions, to achieve an effective  
 649 granularity, of  $5 \times 5 \text{ mm}^2$ . One of the difficulties with developing the ScECAL, is the  
 650 thickness of the scintillator strips. The silicon strips of a few hundred microns can be  
 651 easily developed while scintillator strip needs to be at least 1mm thick. In order to  
 652 conserve the total thickness of the ECAL, other components have to be made thinner.

653 Another proposal is a hybrid ECAL, which is a combination of the Si-W ECAL and  
 654 ScECAL. Various configurations involving silicon and scintillator layers have been studied  
 655 with the help of detailed simulations.

656 The performance of different options for the ECAL is shown in Figure 3.9. The energy res-  
 657 olution  $\sigma_E/\sqrt{E}$  is plotted versus the jet energy. The default option, Si-W ECAL(SIECAL  
 658 in the figure), has the best resolution.

#### 659 3.4.3.3 The Hadronic Calorimeter (HCAL)

660 The purpose of hadronic calorimeter is to separate the energy deposited by charged and  
 661 neutral hadrons, and to precisely measure the energy deposited by the latter.

662 The HCAL of the ILD will be a barrel and endcap sampling calorimeter as shown in  
 663 fig 3.10. Currently there are two options under study, namely analogue (AHCAL) and  
 664 semi-digital (SDHCAL). It will consist of alternative layers of steel as absorber material,  
 665 and scintillator tiles (AHCAL) or glass RPC (SDHCAL) as active material. Stainless  
 666 steel has been chosen as absorber material. It has an interaction length of  $\lambda_I = 17 \text{ cm}$   
 667 and a radiation length of  $X_0 = 1.8 \text{ cm}$ . The moderate ratio  $\lambda_I/X_0$  allows for a fine  
 668 sampling in the longitudinal direction. Steel is cheap and its rigidity helps to realize a  
 669 self supporting structure, minimizing the dead areas due to auxiliary support structures.  
 670 The HCAL has a total depth of  $\sim 6\lambda_I$ .

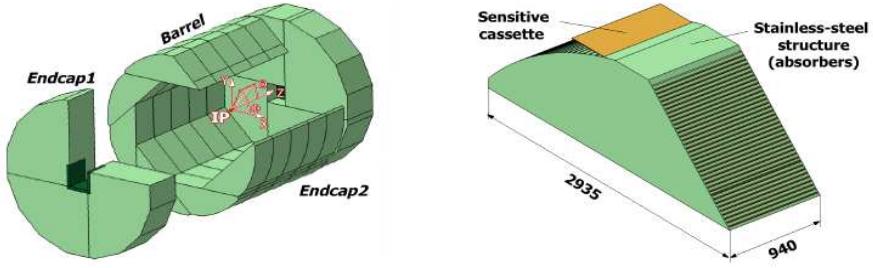


FIGURE 3.10: View of the HCAL. The barrel endcap structure is depicted in the left part, while the right part shows a module of the detector.

671 There are two options for the geometry of the HCAL. The first one has 2 rings in  
 672 longitudinal direction and 16 modules in azimuthal direction, while the second one has  
 673 5 rings along the z-direction and 8 modules.

674 The optimization of the HCAL is driven by two parameters, the total depth and the  
 675 cell size. The total depth contributes to the energy resolution by controlling the shower  
 676 leakages beyond the HCAL. The cell size is important for the separation of particles. It  
 677 also affects the cost of the detector, by increasing the number of readout channels. These  
 678 parameters have been optimized with dedicated studies, using full detector simulations.  
 679 This optimization has also taken into account the possibility of the ILC extension upto 1  
 680 TeV, where highly energetic jets are expected. These studies have shown the capability of  
 681 a 48 layer ( $6\lambda_1$ ) HCAL to absorb hadronic showers at these high energies. These studies  
 682 have also shown that, for the AHCAL, a cell size of  $3 \times 3 \text{ cm}^2$  is the best compromise  
 683 between a good energy resolution and a large number of channels. A smaller size will  
 684 increase the number of readout channels, without providing any substantial gain on  
 685 particle separation. A larger cell size will degrade the particle separation power of the  
 686 HCAL. Similar studies for the SDHCAL resulted in a cell size of  $1 \times 1 \text{ cm}^2$  as the best  
 687 option.

688 The energy resolution performance of the AHCAL physics prototype is shown in the left  
 689 part of Figure 3.11. The resolution shown here is for charged pions. The figure represents  
 690 three types of curves, the ones obtained with simple energy sums and those with local  
 691 and global software compensation techniques. These techniques help to improve the  
 692 resolution by 20%, and the stochastic term is reduced to  $(45 \pm 0.3)\%/\sqrt{E_{beam}(\text{GeV})}$  [84].  
 693 The right part of the figure shows the energy resolution of the SDHCAL as a function of  
 694 beam energy.

695 The physics prototypes were developed to test the proof of principle. After having suc-  
 696 cessfully tested these prototypes, the R&D program focuses on construction and testing

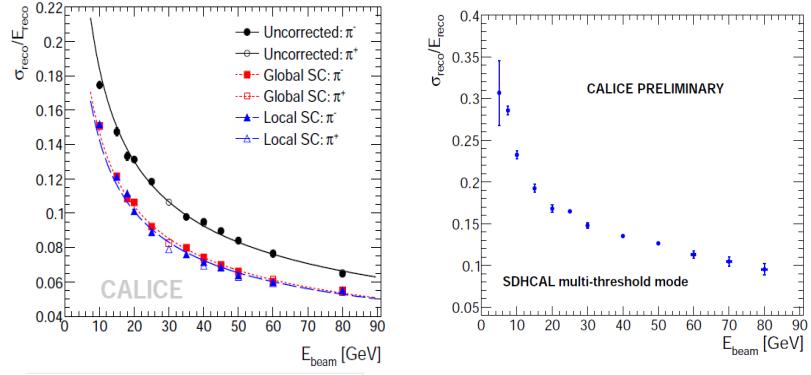


FIGURE 3.11: The HCAL energy resolution with pion showers. The left part shows the resolution as a function of beam energy for the AHCAL prototype, for showers starting in first 5 layers. The right part shows the energy resolution of the SDHCAL prototype.

697 of technological prototypes, and to address the engineering challenges of the proposed  
698 detectors.

#### 699 3.4.4 The Magnetic Coil and The Muon Chamber

700 The ILD is designed to have a nominal magnetic field of 3.5 T with a maximal field of 4  
701 T. The magnetic field is provided by a solenoid magnet, with a diameter of 6.88 m and a  
702 length of 7.35 m, placed between the HCAL and the muon chamber. The superconducting  
703 coil is made of 3 modules, which are electrically and mechanically connected. Each  
704 module has a length of 2.45 m and consists of 4 layers, with 105 turns per layer. An iron  
705 yoke will be used to provide flux return. It will consist of a barrel yoke and two endcap  
706 yokes. The total thickness will be 2.68 m in the barrel and 2.12 m in the endcaps. This  
707 iron yoke will also serve as the main mechanical structure of the ILD.

708 The Muon chamber/tail catcher will be used to detect muons and tails of hadronic  
709 showers. It is placed inside the iron return yoke. The iron serves as absorber material.  
710 The first section of the chamber consists of 10 layers, close together, separated by 10 cm  
711 thick iron layers. The second section of the chamber is used as a muon tracker, and these  
712 three layers are 60cm apart. Since the muon chamber/tail catcher system is situated  
713 after the magnetic yoke, which accounts for  $2 \lambda_I$  itself, it cannot contribute significantly  
714 to the jet energy reconstruction. To compensate for these limitations, the chamber starts  
715 with a sensitive layer, followed closely by several active layers.

### **716 3.5 Softwares and tools.**

717 Software and simulation tools have been developed in the framework of the ILC. ILC-  
718 Soft is the software framework used for analysis and simulation. It provides the main  
719 tools LCIO, GEAR, Mokka and Marlin. This set of tools has been used for the pro-  
720 duction of Monte Carlo events and for the results published in the Detector Baseline

721 Design (DBD)[40]. The reconstruction tools have also been developed and tested with

722 beamtest data. The PFAPandora package is used to apply the PFA to simulated data.

723 Specific analysis oriented processors like LALLeptonFinder[79] and GARLIC[80] are also

724 developed and tested.

725 The analysis presented in this thesis used LCFIPlus[105] and Zfinder processors in dif-  
726 ferent sections. LCFIPlus is used for flavor tagging and locating the secondary ver-

727 tex. The latest version of the software provides a good efficiency for both purposes.

728 ZFinder was used to reconstruct the Z boson from its decay products and to correct for

729 Bremsstrahlung.

730 The analysis tools have been regularly updated and improved. Since the release of LOI

731 [63], the advanced techniques have been implemented to improve the analysis efficiency.

<sup>732</sup> Chapter 4

<sup>733</sup> Optimization of the Si-W ECAL  
<sup>734</sup> guard ring size

<sup>735</sup> 4.1 Introduction

<sup>736</sup> Optimization of the performance-to-cost ratio is one of the important aspects of the R&D  
<sup>737</sup> program for the ILD. The Si-W ECAL [3.4.3.1](#) is the most expensive sub-detector of the  
<sup>738</sup> ILD. An estimation published in the DBD [40], shows that the Si-W ECAL costs upto  
<sup>739</sup> 40% of the total ILD cost. The design and cost of the Si-W ECAL has a strong impact on  
<sup>740</sup> the overall cost of detector. The important parameters to optimize are the inner radius  
<sup>741</sup> of Si-W ECAL, the number of layers, insensitive areas and sampling fraction. The cost of  
<sup>742</sup> the detector varies with the total surface area of the detector and the number of channels,  
<sup>743</sup> while its performance varies with the total thickness and sampling. The ILD Si-W will  
<sup>744</sup> have a highly granular surface area of  $\sim 2500 \text{ m}^2$  in total.

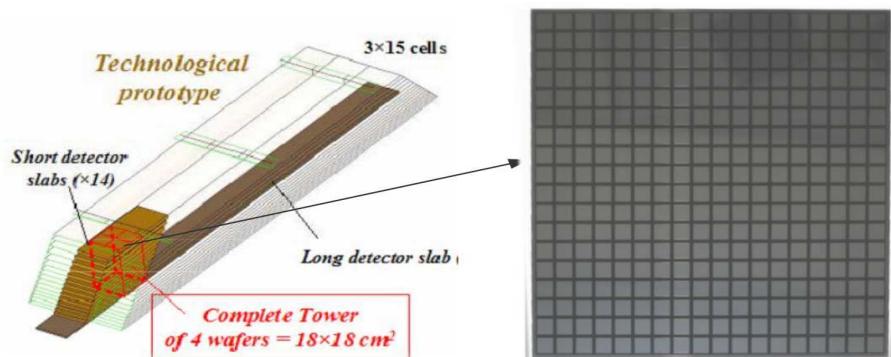


FIGURE 4.1: A schematic 3D view of the technological prototype of the Si-W ECAL. A silicon wafer is highlighted on the right.

Studies have been made to analyze the performance of the ECAL with a reduced number of layers and with different sampling fractions[87, 88]. Preserving the total thickness of absorber material, and varying its thickness in different stacks of layers has been studied. In this chapter, the optimization of the guard ring size will be discussed. The material used for guard rings is less expensive than the silicon used for the active layers. On the other hand, larger size of guard rings will result in an increase in dead zones in the ECAL, degrading its performance. To find a compromise between these two parameters, we study the physics performance of the ECAL, as a function of guard ring size.

Figure 4.1 shows an artistic view of a module of Si-W ECAL technical prototype. The left part shows a stack of layers, with four silicon wafer per layers. These wafers are separated by the guard rings between them. The red lines, drawn on the top layers, represent the position of guard rings. The gap between two consecutive wafers is called interwafer gap. The final design of ECAL of ILD will consist of 8 staves in the barrel region of the ILD. The gap between two staves is called interstave gap.

One wafer is highlighted in the right part, which is a matrix of silicon pixels, each measuring  $5 \times 5 \text{ mm}^2$ . The wafer shown in figure, contains  $18 \times 18$  cells, however, the final design will feature  $16 \times 16$  cells.

The silicon wafers are surrounded by the floating guard rings. These guard rings are used to avoid leakage currents from one wafer to another and to allow the detector to operate in high voltage conditions. They are insensitive zones and their properties have been studied and understood [89]. In the Si-W ECAL of ILD, at their current size, guard rings occupy a total of 4.4% area.

## 4.2 Motivation

During the analysis of beamtest data of physics prototype of Si-W ECAL [96], an energy loss at the interwafer positions was observed. Figure 4.2 shows the mean value of raw energy as a function shower barycenter defined as:

$$(\bar{x}, \bar{y}) = \Sigma(E_i x_i, E_i y_i) / \Sigma E_i \quad (4.1)$$

It was estimated that the energy loss is 15% and 20% in x and y directions respectively. Comparatively smaller energy loss in x direction is due to the staggering of the gaps in this direction. A technique was devised to compensate for the energy loss at these positions and to have a rather uniform response from the calorimeter. This aspect emphasizes on the need of careful studies, to determine the effect of increasing the guard ring size, on

773 energy resolution of the ECAL. During this study we do not apply any corrections to  
 774 the reconstructed energy, in order to see the effects of guard ring size.

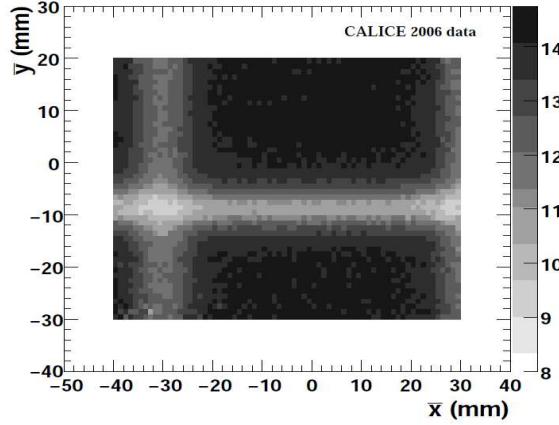


FIGURE 4.2: Energy loss at interwafer gaps of physics prototype of Si-W ECAL, during a beamtest in 2006. The incident beam consisted of electrons at 15 GeV. The figure is taken from [96].

775 The other aspect which makes it important to analyze the effect of guard rings, is the  
 776 cross talk. The analysis of test beam data from physics prototype showed cross talk  
 777 through the guard rings resulting in square events. In case of such events, we observe  
 778 hits all around the edge of wafer, when shower hits the wafer. The frequency of these  
 779 events was found to increase with the energy of primary electrons[102].

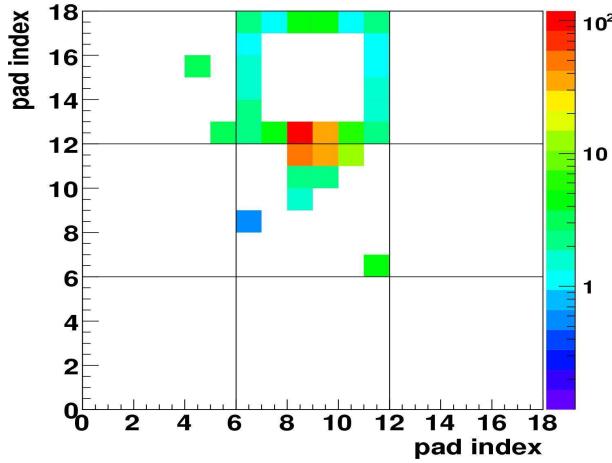


FIGURE 4.3: Example of square event along with normal event .

780 The figure 4.3 shows an example of a square event. The image is taken from [94].

### **781 4.3 Optimization studies of the guard rings**

782 The goal of optimization studies is to study the physics performance of the Si-W ECAL  
 783 with various guard ring sizes. In order to do that, two physics channels are studied. The  
 784 contribution of ECAL to jet energy resolution is studied through the hadronic decay of Z  
 785 boson at 91 GeV. The decay of Z boson to electrons, is used to study the electromagnetic  
 786 energy resolution for various guard ring sizes.

787 The current guard ring size is 1 mm, called the standard size hereafter. The performance  
 788 with this guard ring size will be compared with the previous results for a cross check.

789 A reasonable range for the guard ring size is between 0 and 2 mm but we include larger  
 790 sizes (3, 5 and 8 mm) to see the propagation of effects on the energy resolution. The  
 791 study is performed with Mokka 06-07 [97] and ILCSoft 01-10[98] is used for reconstruc-  
 792 tion. These are the standard simulation and analysis tools in the framework of ILD.  
 793 The analysis part also uses Marlin and MarlinPandora and optimized reconstruction  
 794 algorithms for different physics processes.

795 As described in the previous chapter, there are multiple options for the hadronic calorime-  
 796 ter of the ILD, including AHCAL, DHCAL and sDHCAL. For this study we use the  
 797 AHCAL, as hadronic calorimeter.

### **798 4.4 Wafer Scan**

799 Simulated photons, with an energy of 2 GeV, are sent into a specific part of the Si-W  
 800 ECAL. These photons are smeared in polar angle  $\theta$  and  $\phi$  to target a selected region in  
 801 the ECAL barrel.

802 As a cross check, Figure 4.4 shows the map of a layer hit by photons, where colors  
 803 represent the number of hits in each cell. The inter-wafer and inter-stave gaps can be  
 804 clearly seen. Along the  $z - axis$ , at 0 mm, the interwafer gap is narrower than the  
 805 interstave gaps, at -90 and 90 mm respectively. The actual size of the guard ring for this  
 806 image is 1 mm, but because the reconstruction of the hit position is done at the center  
 807 of the cell, the gap appears to be bigger. It is also observed that gaps in y direction are  
 808 more pronounced than those in  $x$ -direction. This is due to the staggering of the gaps  
 809 in  $x$ -direction. The staggering is the relative shift in the position of layers to avoid the  
 810 projected gaps.

811 After this cross check study, we proceed to look the their effect on the reconstruction of  
 812 energy and hits.

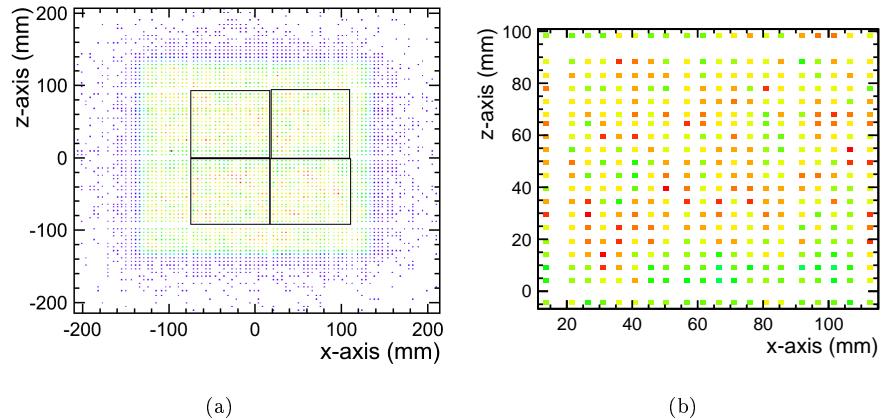


FIGURE 4.4: A silicon layer hit by 2 GeV photons. In (a), the four wafers are separated by black lines, representing the position of the guard rings. The position of the interwafer and interstave gaps can be seen. In (b) a close-up of one wafer is shown.

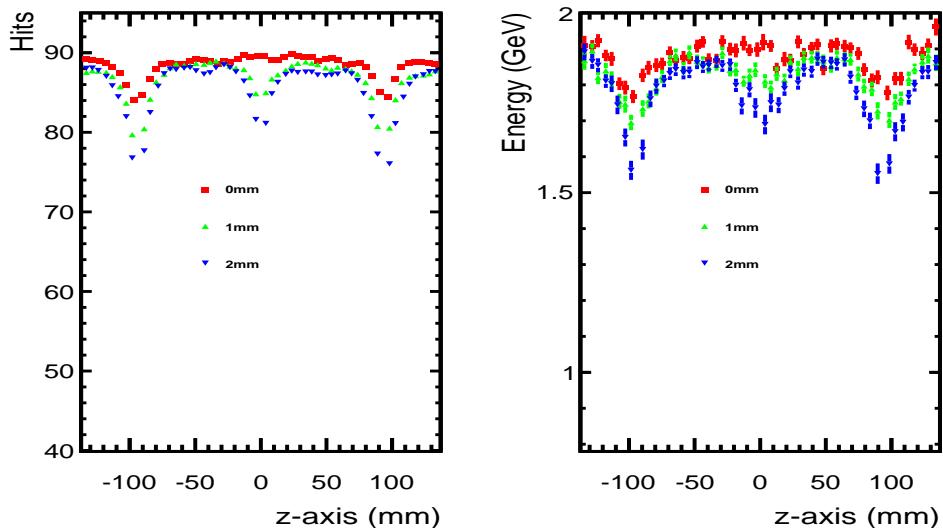


FIGURE 4.5: Reconstructed energy (right) and number of hits (left), for 2 GeV photons, as a function of position. Energy loss and hit loss can be seen at the interwafer and interstave gaps. The colors represent different guard ring sizes.

813 Figure 4.5 shows the number of reconstructed hits and reconstructed energy versus the  
 814 position on z-axis. A drop in the number of hits and in the reconstructed energy is visible  
 815 at the positions of the interwafer and interstave gaps. As expected, this drop increases  
 816 with increasing guard ring size. In the absence of guard rings, the drop only occurs at  
 817 the interstave gaps, as is shown by the red curve, representing the 0 mm guard ring size.

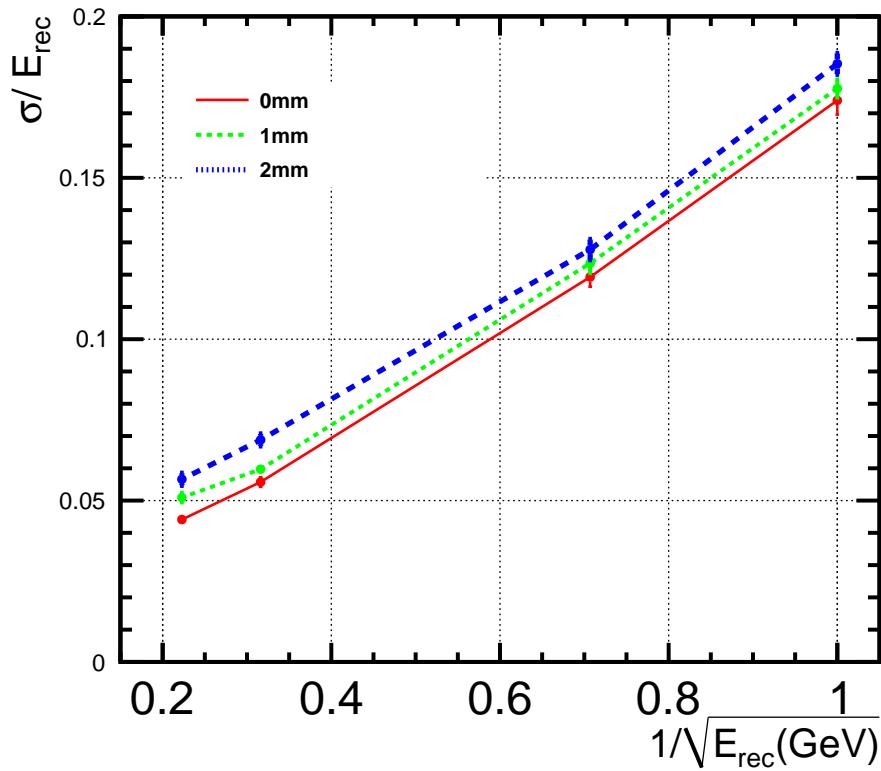


FIGURE 4.6: Variation in the electromagnetic energy resolution of the Si-W ECAL, for different guard ring sizes (0.1 and 2 mm). The energy of the incident photons varies between 1 and 20 GeV.

818 The energy loss at the interwafer and the interstave gaps degrades the electromagnetic  
 819 energy resolution of ECAL. Figure 4.6 shows energy resolution for single photon events.  
 820 It is clear that the energy resolution is degraded by the increase in guard rings size. The  
 821 best energy resolution is naturally obtained without a guard ring as the the inactive area  
 822 due to guard rings is minimum.

## 823 4.5 Physics Channels at the ILC

824 After the systematic studies with single photons we proceed now to study the impact  
 825 of the guard rings on the physics performance of the Si-W ECAL. For this purpose, we  
 826 investigate the hadronic ( $Z \rightarrow uds$ ) and leptonic ( $Z \rightarrow e^+e^-$ ) decays of Z. These two  
 827 channels are of great importance at the ILC physics program.

828 **4.5.1  $Z \rightarrow q\bar{q}$  Jets at 91 GeV**

829 Many of the final states at the ILC will consist of hadronic jets. The ECAL plays an  
830 important part in the reconstruction of these jets. Jets contain photons coming from  
831 the decay of  $\pi^0$ . These photons carry  $\sim 30\%$  of the total jet energy and are to be  
832 reconstructed in the ECAL. They may remain undetected due to non-sensitive detector  
833 parts. Therefore the jet energy resolution might be affected by the guard ring size.

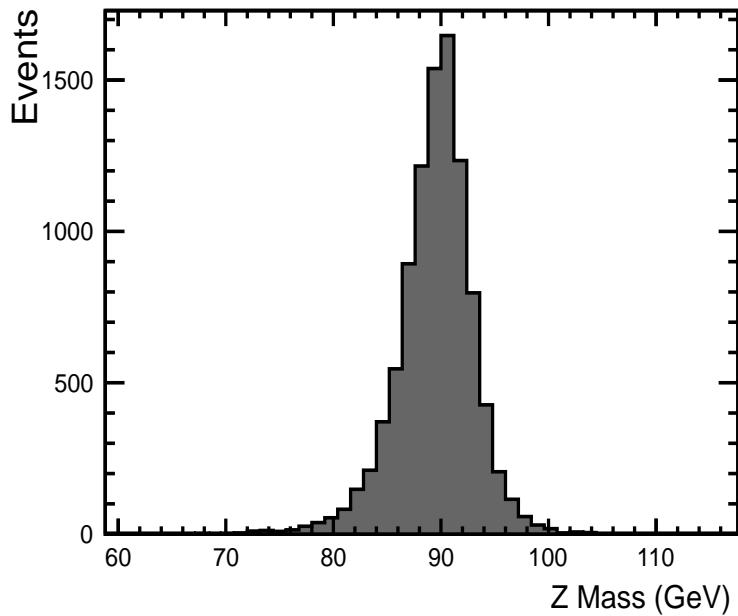


FIGURE 4.7: The reconstructed mass of  $Z$  decaying to  $q\bar{q}$  pairs at  $\sqrt{s} = 91$  GeV.

834 Moreover,  $\sim 50\%$  of hadrons start showering in the ECAL[90]. A good energy resolution  
835 performance requires these showers to be reconstructed precisely. The inactive areas  
836 such as guard rings may compromise these measurements, even though most of the jet  
837 energy is deposited in the HCAL.

838 In order to see the impact on the jet energy resolution, we choose  $Z \rightarrow u\bar{u}/d\bar{d}/s\bar{s}$  at a  
839 center-of-mass energy of 91 GeV. The Durham Jet algorithm [92] is used via the Satoru  
840 Jet Finder to reconstruct the jets. Figure 4.7 shows the reconstructed  $Z$  mass.

841 Two approaches are followed for the analysis: The Gaussian sigma and  $RMS_{90}$ .  $RMS_{90}$   
842 is the rms for the 90% events from the center of a Gaussian distribution. The purpose  
843 to use this approach is to reduce sensitivity to the non gaussian tails.

844 In order to see the effect of increasing guard ring size on the resolution,  $RMS/\sqrt{E}$  and  
845  $RMS_{90}/\sqrt{E}$  are shown as a function of the cosine of the polar angle  $\theta$  of the jets. From

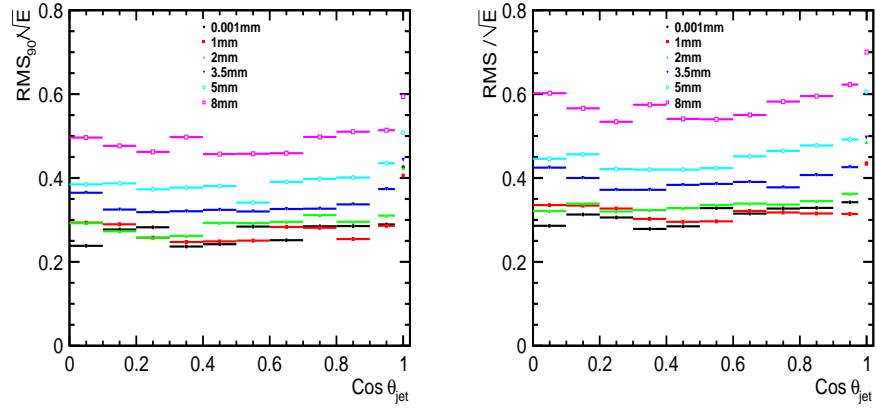


FIGURE 4.8: The jet energy resolution as a function of  $\cos \theta_{jet}$ , where  $\theta_{jet}$  is the polar angle of jets along the z-axis. (a) shows the comparison of  $RMS_{90}/\sqrt{E_{jet}}$  for various guard ring sizes. (b) is for the gaussian sigma ( $RMS/\sqrt{E_{jet}}$ ).

846 figure 4.8, it can be seen that the energy resolution for jets degrades as the guard ring  
 847 size increases, but up to 2 mm there is no significant degradation. For the standard size  
 848 (1mm) the results for the jet energy resolution agree with those already published in the  
 DBD [40].

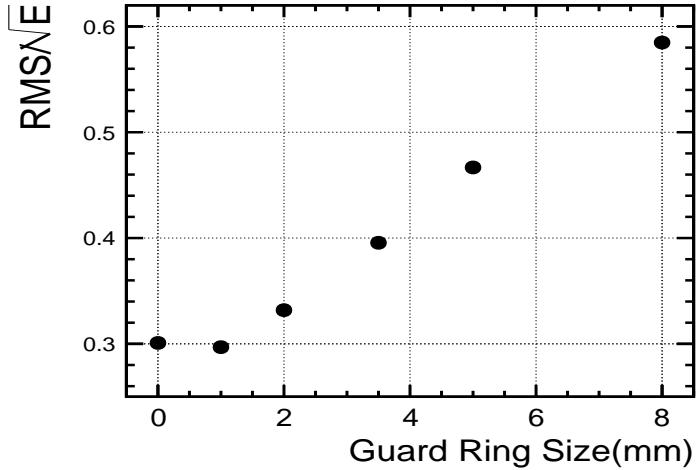


FIGURE 4.9: Jet energy resolution (  $RMS_{90}/\sqrt{E}$  ) as a function of guard ring size.

849  
 850 Figure 4.9 shows the jet energy resolution, integrated over the polar angle, as a function of  
 851 the guard ring size. For a guard ring size in range 0-2 mm, the degradation in resolution  
 852 is very small.

853 **4.5.2  $Z \rightarrow e^-e^+$  Channel.**

854 The leptonic decay of the Z boson is one of the important channels for ILC physics. It  
855 is used for detector calibration, because of the high accuracy with which the Z mass  
856 (91.2 GeV) and its branching ratios are known. It is also a useful channel to evaluate  
857 the performance of the ECAL. At the ILC, this channel will be used to reconstruct the  
858 Higgs mass, by means of the Z recoil mass [100].

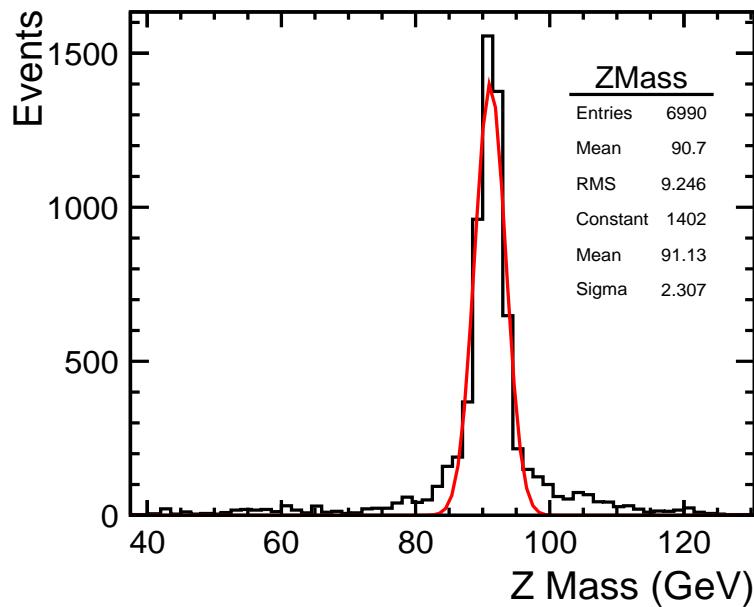


FIGURE 4.10: The Z mass from  $Z \rightarrow e^+e^-$ , fitted with a gaussian.

859 The leptonic decay of the Z bosons creates Bremsstrahlung photons, radiated by the  
860 electrons, that can be only reconstructed in the ECAL. The recovery of these photons is  
861 compromised due to the presence of inactive area.

862 We use polarized electron beams  $(P_{e-}, P_{e+}) = (-0.8, +0.3)$  at  $\sqrt{s} = 250\text{GeV}$ . The  
863 process studied here is  $e^-e^+ \rightarrow ZH$ . The Z is reconstructed from its decay products  
864 using ZFinder[101], an algorithm to reconstruct the Z from electrons. It includes the  
865 recovery of Bremsstrahlung photons.

866 As this channel is very sensitive to modifications in the structure of the ECAL, we want  
867 to assure a good reconstruction. This is verified by a simple calculation for the resolution  
868 on the Z mass. As Z has a very mild boost, we can assume it is at rest and that its decay  
869 electrons have equal energy ( $\frac{M_Z}{2}$ ). The sigma for reconstructed Z mass can be expressed  
870 as:

$$\sigma(M_Z) = \frac{1}{2} \cdot \sigma(E_e) \cdot \left( \frac{M_Z}{E_e} \right)^2 \simeq 2 \cdot \sigma(E_e) \quad (4.2)$$

With the ECAL energy resolution  $\sim 17\%$ , we have

$$\sigma(E_e) = 0.17 \cdot \sqrt{E_e} = 1.15 \text{ GeV} \implies \sigma(M_Z) = 2.30 \text{ GeV} \quad (4.3)$$

871 The value found by the Gaussian fit in figure 4.10, is in agreement with this result. This  
 872 cross check ensures the good performance of analysis and reconstruction tools. It also  
 873 shows that the energy loss due to Bremsstrahlung photons is well recovered by the  
 874 reconstruction algorithm.

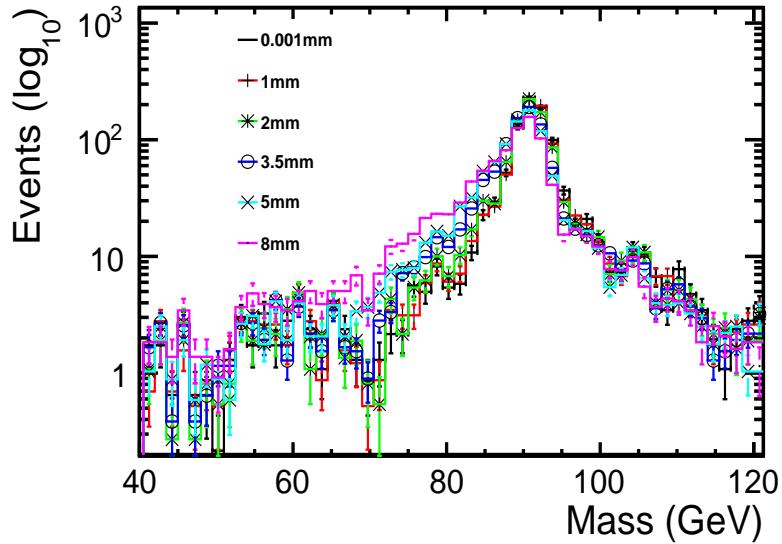


FIGURE 4.11: The distribution of mass of the  $Z$ , reconstructed from  $e^+e^-$ . The log scale is used to show propagation of tails with increasing guard ring size.

875 As is evident from the figure 4.10, the distribution of the mass of  $Z$  has tails on the right  
 876 and left part, due to imperfections in the reconstructions. The propagation of these tails  
 877 with the guard ring size has been studied, as is shown in the figure 4.11. The guard  
 878 ring size within a reasonable range of 0-2mm has very little effect on the tails, however  
 879 larger sizes increase the tails considerably. Although the difference is small for smaller  
 880 sizes, but in order to preserve high precision the smallest possible guard ring size should  
 881 be preferred.

882 As described earlier, the process studied here was  $e^-e^+ \rightarrow ZH$ , which is one of the  
 883 benchmarks at ILC, for the reconstruction of Higgs boson. Although the main focus of

the studies was to reconstruct the Z from it's decay products, for the sake of completeness the result Higgs recoil mass spectrum is also shown in figure 4.12.

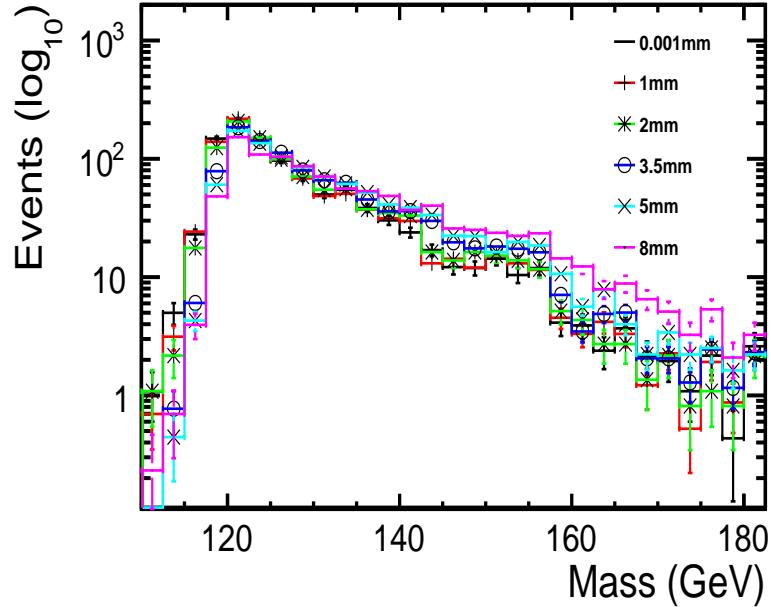


FIGURE 4.12: The Higgs recoil mass distribution, reconstructed using the method from [100]. The plot shows the effect on tails, with increasing guard ring size.

The electromagnetic energy resolution ( $RMS/\sqrt{E}$ ) as a function of the guard ring size is shown in figure 4.13. The effect is more pronounced, specially for smaller guard ring sizes, as compared to the jet energy resolution. But again, we see that the resolution degradation at smaller guard ring sizes is very small( $\sim 2\%$ ). Up to 2 mm, like in the case of jets, the energy resolution of the ECAL is not affected severely.

## 4.6 Summary

We studied the energy resolution of the ECAL for hadronic and leptonic decays of Z for different guard ring sizes ranging from 0 to 8 mm. In the case of jets we have studied the energy resolution as a function of the jet polar angle. We observed that the energy resolution depends on the guard ring size and that it is degraded when we go to larger sizes, as we increase the dead area in the detector. We found that the energy resolution varies very little for typical guard ring sizes i.e. between 0 and 2 mm. The study takes into account the effects on physics performance. The effects on silicon wafers, for example the square events, were not studied during this analysis.

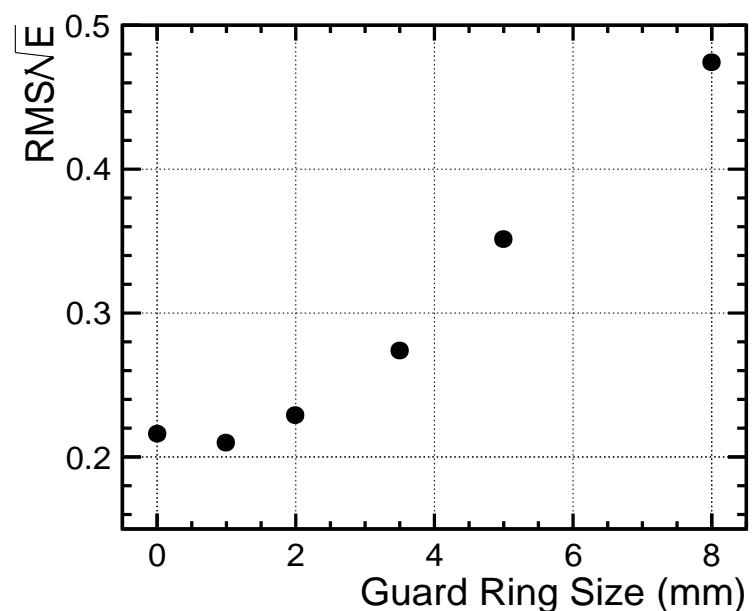


FIGURE 4.13: Electromagnetic energy resolution of ECAL as a function of guard ring size,  
for  $Z \rightarrow e^+e^-$ .

900 Chapter 5

901 Top quark forward backward  
902 asymmetry at the ILC

903 5.1 Introduction

904 As already explained in the section 2.5, the top quark is one of the important topics of  
905 study at the ILC. Due to its large mass, it is most strongly coupled to the mechanism  
906 of the electroweak symmetry breaking. For this and other reasons, the top quark is  
907 expected to be a window to any new physics at the TeV energy scale. In this chapter  
908 we will present the measurement of  $t\bar{t}$  forward backward asymmetry at ILC, in hadronic  
909 decay channel.

910 5.2 Asymmetries at hadron colliders

911 The last few years were marked by a number of publications from the Tevatron experi-  
912 ments which reported on tensions with Standard Model predictions in the measurement  
913 of forward backward asymmetries  $A_{FB}$ . This observable counts the difference in the  
914 number of events in the two hemispheres of the detector. In hadronic collisions, the  
915 polar angle is typically expressed in terms of the rapidity  $y$ , which is invariant under  
916 longitudinal boosts.

917 Usually the analyses use the semi-leptonic decay channel, for example at the LHC and  
918 Tevatron. In this scenario, at least one member of the  $t\bar{t}$  pair is required to decay lepton-  
919 ically to assure the particle identification. The average asymmetry reported by CDF is  
920  $0.201 \pm 0.065$  (stat.)  $\pm 0.018$  (syst.) [112] which agrees with  $0.196 \pm 0.060$  (stat.)  $^{+0.018}_{-0.026}$  (syst.)  
921 as reported by DØ [113]. These values can be compared with an asymmetry of about

0.07 predicted by the Standard Model from NLO QCD and electroweak effects. This result is difficult to verify at the LHC. The LHC is a proton-proton collider, so the two hemispheres are intrinsically symmetric. Further, at the LHC at 7 TeV, only 15% of the interactions arise from  $q\bar{q}$  collisions; the 85% from  $gg$  collisions can have no intrinsic asymmetry. Still, in  $q\bar{q}$  collisions at the LHC, it is likely that the  $q$  is a valence quark while the  $\bar{q}$  is pulled from the sea. This implies that  $t\bar{t}$  pairs produced from  $q\bar{q}$  are typically boosted in the direction of the  $q$ . This offers methods to observe a forward backward asymmetry in  $q\bar{q} \rightarrow t\bar{t}$ . For example, a forward-backward asymmetry in the  $\bar{q}$  reaction translates into a smaller asymmetry  $A_C$  in the variable  $\Delta|y| = |y_t| - |\bar{y}_t|$ . For this observable, CMS measures  $A_C = 0.004 \pm 0.010$  (stat.)  $\pm 0.012$  (syst.) [114], which agrees with the Standard Model predictions within the relatively large uncertainties. So far, the LHC experiments have not provided any independent evidence for asymmetries outside the Standard Model predictions [104, 115]. The theoretical interpretation of these asymmetries is also very uncertain. Many plausible models of the  $t\bar{t}$  asymmetry predict effects in top quark physics at high energy that are excluded at the LHC. For a review of the current situation, see [116, 117].

### 5.3 Asymmetries at the ILC

The top quark physics program at ILC has been discussed in chapter 2. In this chapter, the focus will be on studies carried out to measure the forward backward asymmetry in top pair production at the ILC, with the help of full detector simulations.

Figure 5.1 shows the Born level  $A_{FB}$  for different particles, as a function of center-of-mass energy, with unpolarized beams and neglecting the effect of initial state radiation (ISR).

It can be seen that the value of  $A_{FB}$  for the top quark is around 0.40 at a center-of-mass energy of 500 GeV. This value is however, for unpolarized beams. With polarized beams the values of  $A_{FB}^{top}$  are given below.

$$- \{P_{e^-}, P_{e^+}\} = (-1, +1), A_{FB}^{top} = 0.47$$

$$- \{P_{e^-}, P_{e^+}\} = (+1, -1), A_{FB}^{top} = 0.38$$

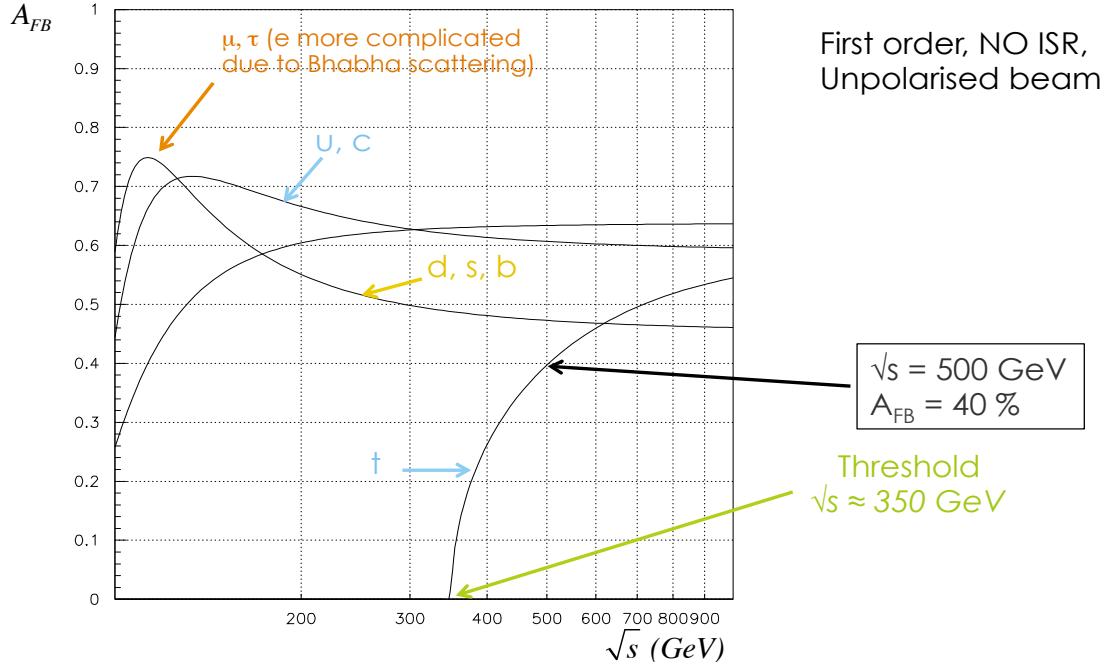


FIGURE 5.1: Forward Backward asymmetry  $A_{FB}$  for different particles produced in  $Z$  decay, as a function of center-of-mass energy  $\sqrt{s}$ .

## 950 5.4 Production cross sections at the ILC and beam polarizations.

951

952 For polarized electron-positron beams, the production cross section for any particle  
 953 through  $e^-e^+ \rightarrow X$ , can be expressed as[107]:

$$\sigma_{P_{e^-}, P_{e^+}} = \frac{1}{4} [(1 - P_{e^-} P_{e^+})(\sigma_{-,+} + \sigma_{+-}) + (P_{e^-} - P_{e^+})(\sigma_{+-} - \sigma_{-,+})] \quad (5.1)$$

954 Here,  $P_{e^-}$  and  $P_{e^+}$  represent the degree of polarization of electron and positron beams  
 955 respectively. This expression assumes  $m_e/E \rightarrow 0$ , which is valid for  $\sqrt{s} \gg m_e$ . In  
 956 this case, the terms like  $\sigma_{+,+}$  and  $\sigma_{--,}$  don't contribute to the cross section due to  
 957 the helicity conservation in the massless limit. The cross section varies for different  
 958 beam polarizations. The cross section for  $t\bar{t}$  production for left-handed electron beam  
 959 polarization is much larger than that for right-handed electron beam.

960 A graphical representation for the production cross section of different Standard Model  
 961 physics channels at ILC, including  $t\bar{t}$ , is shown in figure 5.2, for an energy range between  
 962 0 and 1 TeV.

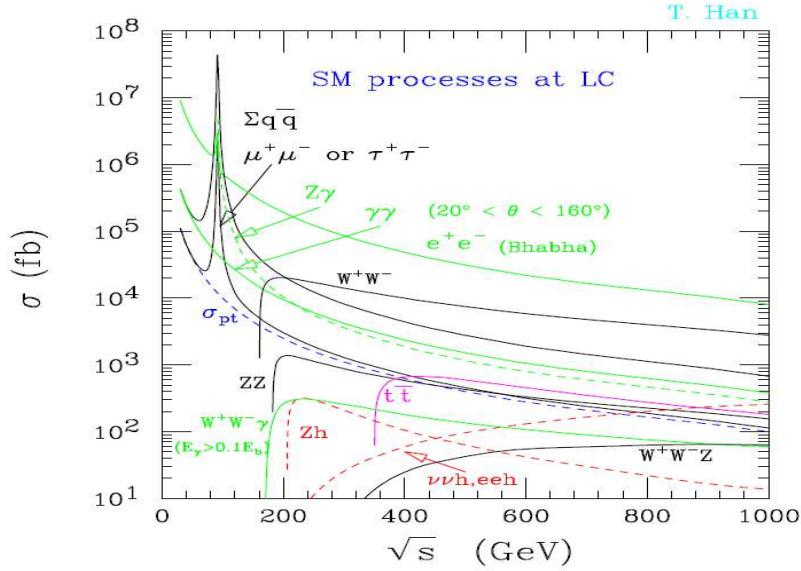


FIGURE 5.2: Unpolarized cross sections for different Standard Model processes at the ILC, as a function of center-of-mass energy  $\sqrt{s}$ . The image is taken from [106].

963 The numerical values for cross sections of some of these processes, including major back-  
 964 ground processes, for  $t\bar{t}$  studies, are shown in Table 5.1. These values are for a center-  
 965 of-mass energy  $\sqrt{s} = 500\text{GeV}$ .

Channel	Unpolarized(fb)	$e_L^- e_R^+$	$e_R^- e_L^+$	$A_{LR}^0(\%)$
$t\bar{t}$	572	1564	724	36.7
$b\bar{b}$	372	1212	276	62.9
$\sum_{u,d,s,c} q\bar{q}$	2208	6032	2793	36.7
$\mu\mu$	456	969	854	6.3
$WW$	6603	26000	150	98.8
$ZZ$	422	1106	582	31.0
$ZWW$	40	151	8.7	89

TABLE 5.1: Production cross-sections of some important channels at the ILC, with unpolarized and fully polarized beams, at a center-of-mass energy  $\sqrt{s} = 500\text{GeV}$ . The last column represents the left-right asymmetry  $A_{LR}^0$ . [120]

966 The fully hadronic decay of  $t\bar{t}$  pairs, is a benchmark in the DBD [40]. It accounts for 46%  
 967 of the total top quark decay. A schematic view of the process is shown in figure 5.3. The  
 968 advantage of using this channel is that the kinematic variables of the top decay can be  
 969 reconstructed more precisely, as the final state can be fully reconstructed. In the semi-  
 970 leptonic or fully leptonic decays, the W boson decays into a lepton and its corresponding  
 971 neutrino. The reconstruction of this W becomes less precise since the neutrino escapes

972 the detector. The hadronic decay channel on the other hand, allows a full exploitation  
 973 of  $t\bar{t}$  sample.

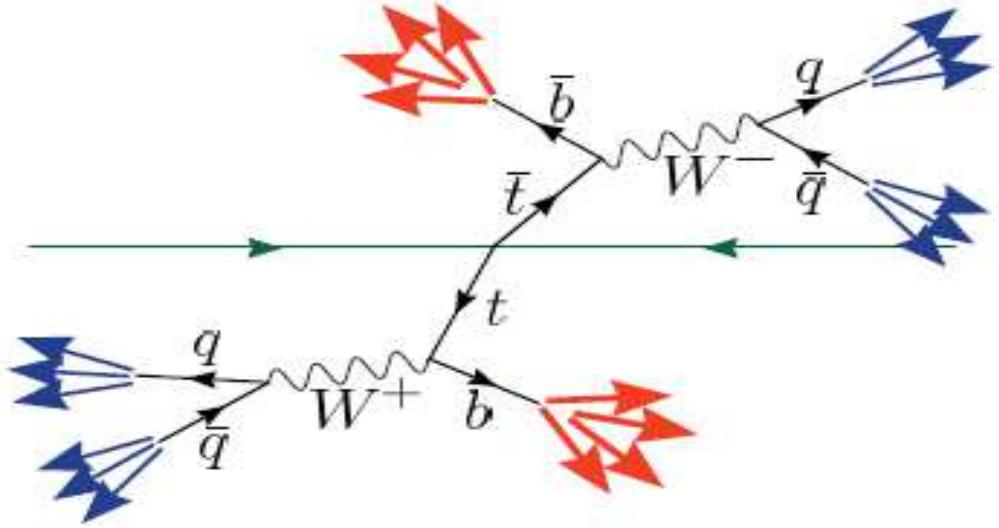


FIGURE 5.3: A schematic view of the fully hadronic decay of top quark pairs.

## 974 5.5 Studies

975 Fully polarized beams are used for the analysis of the fully hadronic decay mode of  
 976 the top quark, to measure the forward backward asymmetry at the ILC, at 500 GeV  
 977 center-of-mass energy. The following two beam polarization configurations are studied.

- 978 – For the left-handed electron configuration  $e_L^- e_R^+$ , we use  $\{P_{e^-}, P_{e^+}\} = (-1, +1)$ .
- 979 – While for the right-handed configuration  $e_R^- e_L^+$ ,  $\{P_{e^-}, P_{e^+}\} = (+1, -1)$

The beams at the ILC, will not be 100% polarized, rather the electron beam can be polarized upto 80%, and the positron beam upto 30%. This implies that the effective polarization  $P_{eff}$ , which is defined as follows,

$$P_{eff} = \frac{|P_{e^-}| + |P_{e^+}|}{1 + |P_{e^-}||P_{e^+}|} \quad (5.2)$$

980 will be around 90%.

981 The  $t\bar{t}$  events are generated by **Whizard** version 1.95 [109, 110]. The parton showering  
 982 and hadronization is done by PYTHIA 6.422 [93]. **Whizard** produces a six-fermion final  
 983 state, of which  $t\bar{t}$  is a sub-sample.

984 An integrated luminosity of  $250 \text{ fb}^{-1}$ , for each polarization configuration, is then sub-  
 985 jected to a full detector simulation. The reconstruction is done with `ILCSoft v01-16`.  
 986 Durham jet algorithm [92] is used for jet clustering.  $K_t$  algorithms [82] are used to re-  
 987 move the gamma gamma background. The `LCFIPplus` package plays a central role in the  
 988 analysis. A brief description of `LCFIPplus` is given in the next section.

## 989 5.6 LCFIPplus

990 `LCFIPplus`[105] is used for jet finding, vertex finding, flavor tagging and reconstruction  
 991 of the vertex charge. Initially designed for the optimization of vertex detector design,  
 992 the software package currently provides tools for reconstruction of all physics processes,  
 993 where locating the vertex and reconstructing its charge is required. The package consists  
 994 of multiple algorithms used for different tasks.

The jet finding part is based on the principle used in the Durham jet algorithm[92]. In the initial part, every hit or track is treated as jet, and starting from one such jet, the near by jets are added to the previous one, thus reducing the number of jets by 1, at each step. At each step, a distance  $Y(i, j)$  between two jets  $i$  and  $j$  is computed for the pair of jets as follows:

$$Y(i, j) = \frac{2\min(E_i, E_j)^2(1 - \cos\theta_{ij})}{Q^2} \quad (5.3)$$

995 Where  $E_i$  and  $E_j$  are the jet energies,  $\theta_{ij}$  is the angle between the two.  $Q^2$  is constant,  
 996 which is typically center-of-mass energy. Two jets with a minimal  $Y(i, j)$  are combined  
 997 into a single jet. The process is continued, till the required number of jets is achieved.

998 After finding the jets, the vertex finding is performed in two steps: namely finding the  
 999 primary vertex, and the secondary vertex. The vertex locator part of the algorithm  
 1000 is a complete re-implementation of the vertex finder ZVTOP, developed at the SLD  
 1001 experiment [111]. For the most part the LCFIVertex algorithm is as the original ZVTOP.  
 1002 Improvements like using the Kalman vertex fit and adjustments to allow the use of  
 1003 ZVTOP for events at center-of-mass energies above the Z resonance are made to adopt  
 1004 to the requirements.

1005 The tracks are combined to form a vertex, using  $\chi^2$  minimization. The tracks with a  $p_t$   
 1006 less than 100 MeV, are discarded. Further parameters taken into account are the number  
 1007 of tracks, the distance from the IP, the probability of secondary vertex and the decay  
 1008 length.

1009 The flavor tagging part of the algorithm uses the secondary vertex information, whenever  
 1010 available. A neural network uses separate sets of variables depending on whether a  
 1011 secondary vertex is found or not. The choice of the neural network architecture and  
 1012 input variables is flexible. The actual choice of these parameters is defined by the external  
 1013 weight files, produced by using dedicated samples, at the time of running the algorithm.  
 1014 These weight files are prepared to optimize the performance of the **LCFIPlus**, for different  
 1015 conditions like number of jets in final state, center-of-mass energy and detector geometry.

1016 The discrimination of different types of jets uses the flavor of hadrons. The fact that *uds*  
 1017 jets do not contain vertices stemming from the decays of heavy flavor hadrons, helps to  
 1018 distinguish *c* jets from them. Significant attention is also paid to sort out the unwanted  
 1019 vertices corresponding to photon conversions, and decay of  $K_s$  and  $\Lambda$  particles.

1020 The discrimination of *b* and *c* jets is done using the output of dedicated neural networks.  
 1021 Three sets of neural networks are trained depending on whether 1, 2 or at least 3 vertices  
 1022 are found for the jet. The discrimination of the *c* jets from the lighter quarks is easy. The  
 1023 "*b* nets" are trained by providing *b* jets as signal sample, and *c* jets and lighter quarks as  
 1024 background. Similarly, "*c* nets" are given *c* jets as signal, and *b* jets and lighter quarks  
 1025 as background.

1026 A good flavor tag is a pre-requisite for the determination of the charge. This part of the  
 1027 reconstruction chain is the most crucial to analysis presented in this thesis. The *b*-quark  
 1028 decay chain is complex, and reconstruction of its charge is a difficult task in a multijet  
 1029 environment.

1030 The measurement of the *b*-jet charge is done using the tracks associated to the vertex.  
 1031 The charge of individual tracks needs to be measured with good accuracy. Charge of all  
 1032 tracks, associated to the vertex of *b*-jet is summed to obtain the charge of *b* quark. During  
 1033 this analysis, the charge was measured at the secondary vertex, whenever available, to be  
 1034 used for identification of *b*-jets. The current version of the **LCFIPlus** is not yet optimized  
 1035 for the charge measurements.

## 1036 5.7 Analysis and Kinematic Cuts

1037 The *t* quark decays nearly exclusively into a *b* quark and a *W* boson. The *b* quarks  
 1038 hadronize into a jet, called *b* jet hereafter, which contains a *B* hadron. The six jet  
 1039 final state is reconstructed using the Durham jet finder [92]. Subsequently the jets are  
 1040 analyzed with the **LCFIPlus** package, which assigns a *b* likeness called b-tag to the jet.  
 1041 Figure 5.4 shows the quality of b-tag as a function of polar angle of the jets. The two  
 1042 jets with the highest b-tag values are considered to be the jets from the *b* quarks. The

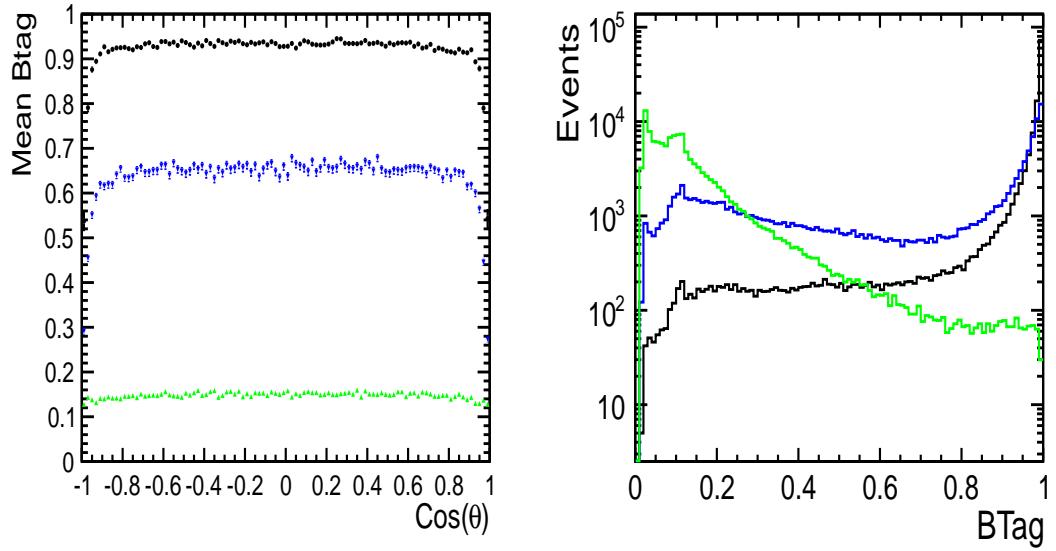


FIGURE 5.4: Left: The b-tag of the first three jets, classified on the basis of b-tag value, shown as a function of  $\cos(\theta)$  of the jets. Right: The distribution of b-tag, for three jets.

1043 likelihood of third jet is also shown in the figure. As the figure shows, the mean value of  
 1044 the second highest b-tag is above 0.3. The right part of figure shows the distribution of  
 1045 b-tag. A little spike for the second  $b$ -jet, can be seen around btag value 0.2. These jets  
 1046 are either in very forward region, or soft  $b$ -jets. The events with b-tag values less than 0.3  
 1047 are rejected, as a pre-selection for charge measurement.

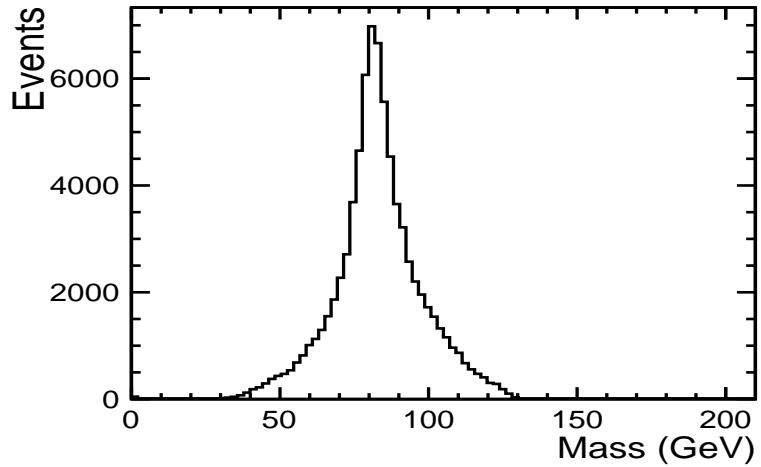


FIGURE 5.5: Reconstructed mass of the  $W$  bosons, from jets. Two  $W$ s are selected from the combination of four jets, for which the variable  $\psi$  has a minimum value

1048 The possibility of  $c$ -jet being mistagged as a  $b$ -jet is also investigated. It was found that  
 1049 around 7% of the  $b$ -jets, could be the mis-tagged  $c$ -jets.

The two  $W$  bosons are reconstructed from the remaining four jets. Different combinations of jets are checked for choosing the two  $W$ s. A variable  $\psi$  is defined as:

$$\psi = |m_{ij} - m_W| + |m_{kl} - m_W| \quad (5.4)$$

1050 Here, ij and kl represent different possible combinations of jets and  $m_W = 80.4$  GeV, is  
 1051 the mass of  $W$  boson. The minimum value of  $\psi$  is used to reconstruct the required  $W$ s.  
 1052 Figure 5.5 represents the mass distribution of the selected  $W$  candidates.

After having reconstructed the jets from  $W$  bosons and  $b$  quark jets, the jets are combined to form  $t$  quarks. Out of two possible combinations of two  $b$  jets with these  $W$ s,  $Top = W_i + b_k$  with  $i, k = (1, 2)$ , two tops are reconstructed with the minimal  $\chi^2$ .

$$\chi^2 = \left( \frac{m_t - 174\text{GeV}}{\sigma_{m_t}} \right)^2 + \left( \frac{E_t - 250\text{GeV}}{\sigma_{E_t}} \right)^2 + \left( \frac{p_b^* - 69\text{GeV}}{\sigma_{p_b^*}} \right)^2,$$

with

$$p_b^* = \gamma p_b (1 - \beta_t \cdot \cos(\theta_{tb}))$$

being the momentum of the  $b$  quark in the rest frame of the  $t$  quark,  $E_t$  the energy of the  $t$  quark candidate and  $m_t$  the reconstructed mass of the  $t$  quark. The variables  $\sigma_{m_t}$ ,  $\sigma_{E_t}$  and  $\sigma_{p_b^*}$  expressed in the above equation are calculated from the distributions of  $m_t$ ,  $E_t$  and  $p_b^*$ , respectively. They take the following values.

$$\sigma_{m_t} = 6.3\text{GeV}, \quad \sigma_{E_t} = 8.0\text{GeV}, \quad \sigma_{p_b^*} = 10\text{GeV}. \quad (5.5)$$

1053 The left part of figure 5.6 represents the value  $\chi^2$  versus reconstructed mass of top, while  
 1054 right part shows  $\chi^2$  versus the reconstructed energy of top. The concentration of events  
 1055 in the bottom part, around the nominal mass and energy values of top quark, shows the  
 1056 discrimination power of the  $\chi^2$  method.

1057 The defined  $\chi^2$  is a quality criterion for the events and only events that satisfy  $\chi_1^2 < 20$   
 1058 and  $\chi_2^2 < 40$  are retained. Systematic studies, performed by varying the  $\chi^2$  cut, will  
 1059 be discussed in section 5.14. Finally, events are selected for which both  $t$  quarks and  
 1060 both  $W$  bosons are in the range  $140 < m_t < 210$  GeV and  $60 < m_W < 100$  GeV. The  
 1061 efficiency of these cuts is given in table 5.3.

1062 The mass distribution of two selected top quarks is shown in figure 5.7.

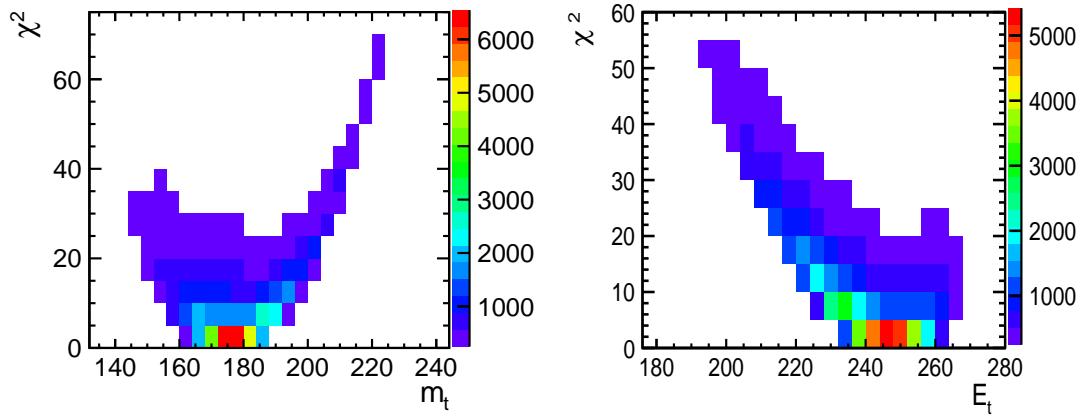


FIGURE 5.6:  $\chi^2$  values plotted against the mass of the top quark candidate Left and it's energy Right. The  $\chi^2$  distribution for maximum events is closed to the nominal values of mass and energy, as expected.

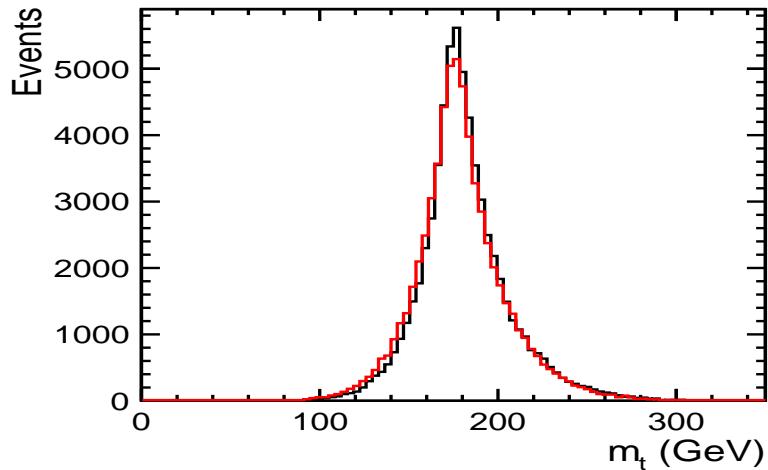


FIGURE 5.7: Mass distribution of the top quarks, selected using the  $\chi^2$  criterian. Two curves represent the  $t$  and  $\bar{t}$  quarks.

1063 All introduced event selection criteria are summarized in Table 5.2.

Selection of the signal events		
Cut number	Cut Name	Type
1	b-tag	$b \text{ tag}_{1,2} > 0.3$
2	$\chi^2$	$\chi^2 < 30$
3	Kinematic	$140 < m_t < 210 \text{ GeV}$

Cuts used for the identification of the top quark charge		
4	Jet Charge Cut	$Q_b < 5$
5	Event Charge	$C \neq 0$

TABLE 5.2: Cuts as applied in this analysis in the sequence as they appear in the text.

1064 The efficiency of the first set of cuts, used to select the signal events, will be given in table  
 1065 5.3. The statistical error obtained for the cross section of  $t\bar{t}$  hadronic decay, using these  
 1066 cuts, is 0.40% for the left-handed beam polarization, and 0.60% for the right-handed  
 1067 polarization.

## 1068 5.8 Standard Model background

1069 The backgrounds studied during the analysis are classified on the basis of the number of  
 1070 fermions. The background processes have already been shown in table 5.1, along with  
 1071 the corresponding cross sections.

1072 The 6-fermion background is divided in two parts. The first part consists of  $ZWW$ , which  
 1073 can have a 6-jet final state. It has been shown that the rejection of this background can  
 1074 be easily done. One of the criteria to recognize such a background is the invariant mass  
 1075 of the  $b\bar{b}$  system. As the figure 5.8 shows, there is a clear peak around the  $Z$  mass.

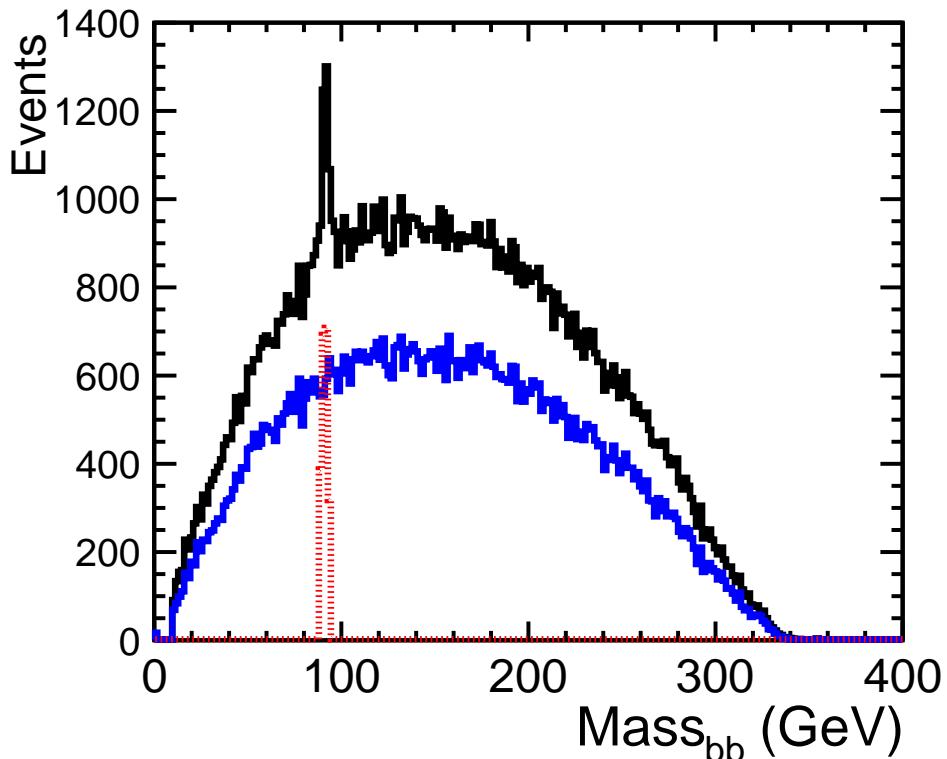


FIGURE 5.8: Mass distribution of  $b\bar{b}$  system. The  $ZWW$  background can be seen peaking at  $Z$  mass. The plot shows solid black line for all events, red dotted line is recognized as  $ZWW$  background. The blue curve shows the events selected after removing the background.

1076 The second part of 6-fermion background studied is the the semi-leptonic decay of  $t\bar{t}$  pairs.  
 1077 The semi-leptonic events can migrate into hadronic due to multiple reasons, mainly hard  
 1078 gluon radiation,  $\gamma\gamma$  background, and jets with multiple vertices. While studying this  
 1079 background, the reconstruction is forced to treat the leptons from the W decay, as jets.

1080 The next type of background processes is 4-fermion background. Two processes are  
 1081 studied namely  $WW$  and  $ZZ$ . The  $WW$  background has the highest cross section, while  
 1082 the  $ZZ$  background can be misleading, specially in cases where  $Z$  decays to  $b\bar{b}$ . Only  
 1083 fully hadronic decay of the  $Z$  and  $W$  bosons are studied.

1084 The requirement of two bjets with a b-tag value higher than 0.3, is a strong cut against the  
 1085  $WW$  background, which has the highest cross section among the background processes.  
 1086 Given that the  $Z$  bosons can decay to  $b\bar{b}$ , this cut is less efficient in this case, but the  
 1087 next cuts on the kinematics of the top quark candidates and  $\chi^2$  give good performance  
 1088 for rejection of this background.

Process	Total Events	b-tag	Kinematic	$\chi^2$	Efficiency
$t\bar{t}_{had} (e_L^- e_R^+)$	162128	104710	80780	56598	34.90%
$t\bar{t}_{had} (e_R^- e_L^+)$	63976	41325	32884	24228	37.87 %
$t\bar{t}_{sl} (e_L^- e_R^+)$	102255	53090	26531	5280	5.16 %
$t\bar{t}_{sl} (e_R^- e_L^+)$	52012	28722	14235	3084	5.92 %
$WW(e_L^- e_R^+)$	$6.5 \times 10^6$	39084	7442	2163	0.03 %
$ZZ(e_L^- e_R^+)$	276500	35027	8770	2929	1.05 %
$ZZ(e_R^- e_L^+)$	145500	18006	4373	1501	1.03 %
$Z \rightarrow q\bar{q} (e_L^- e_R^+)$	$8.11 \times 10^6$	94226	21270.	5530	0.06 %
$Z \rightarrow q\bar{q} (e_R^- e_L^+)$	$4.5 \times 10^6$	31877	7874	2286	0.05 %

TABLE 5.3: Efficiency of different cuts, for he signal and Standard Model background processes. The respective beam polarizations are shown in parentheses. The last column shows the final selection efficiency.

1089 2-fermions background is also studied, for the sake of completeness. The hadronic decay  
 1090 of  $Z$  boson is studied for both polarizations. Despite a high cross section, this process  
 1091 can be easily discriminated because of requirement of 6 jets. The final efficiency for this  
 1092 process is below 0.1%.

1093 The efficiency of various cuts is summarized in the table 5.3. The number for background  
 1094 events are scaled to correspond to the same luminosity of  $250 \text{ fb}^{-1}$ .

## 1095 5.9 Charge of the b quark

1096 The  $b$  quark charge  $Q_b$  at the vertex is determined to identify whether it came from a  $t$   
 1097 or  $\bar{t}$  quark. Technical details of measuring the vertex charge, are given in appendix A.

1098 In this section the quality of charge reconstruction and the rejection of  $\gamma\gamma$  background  
 1099 will be discussed.

### 1100 5.9.1 Quality of the charge reconstruction

1101 The charge at the vertex is reconstructed as the sum of the charge of all particles related  
 1102 to this vertex. For both jets  $|Q_b| < 5$  is required, otherwise the event is rejected. The  
 1103 algorithm gives integral values for the quark charge instead of partial values for the  
 1104 charge of quark.

1105 In order to verify the charge reconstruction it is compared with  $b$  quark and  $\bar{b}$  quark in  
 1106 the event generator record. Additionally, a cross check is performed using  $B$  mesons,  
 1107 which are formed from the  $b$  quark. The Fig. 5.9 shows in its left part the measured jet  
 1108 charges originating from  $b$  or  $\bar{b}$  quarks. The right hand part is the same but now the  
 1109 reference charge is given by a  $B$  meson in the jet. For about 60% events, the charge  
 1110 of the original particle is reconstructed correctly. The distributions are compatible with  
 1111 those shown in Ref. [108]

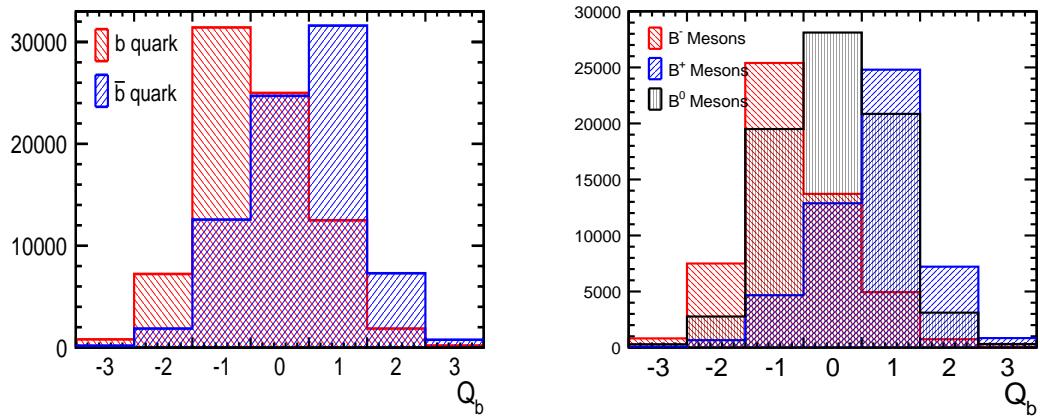


FIGURE 5.9: Left: Reconstructed charge for jets originating from  $b$  or  $\bar{b}$  quarks. Right: The charge of the  $B$  meson is taken as a reference for the verification of the vertex charge measurement.

### 1112 5.9.2 $\gamma\gamma$ background

1113 One of the major backgrounds expected at the ILC stems from photon-photon collisions.  
 1114 These photons are radiated by electrons in the beam and are called Beamstrahlung  
 1115 photons. The cross section for such collisions is a few 100 nb, for incoherent photons.  
 1116 For each bunch crossing, approximately one such collision is expected. These collisions  
 1117 produce low  $p_t$  hadrons. The data samples used for this study take this effect into

account. The samples were simulated with  $\gamma\gamma$  collisions overlaid. The soft quark jets produced in this case are one of the sources of confusion for jet clustering and flavor tagging. Of special importance are the jets produced in the very forward region of the detector. To take away the effects of this background, we use the  $k_t$  algorithm [82] to remove these low  $p_t$  hadrons, before jet clustering and flavor tagging.

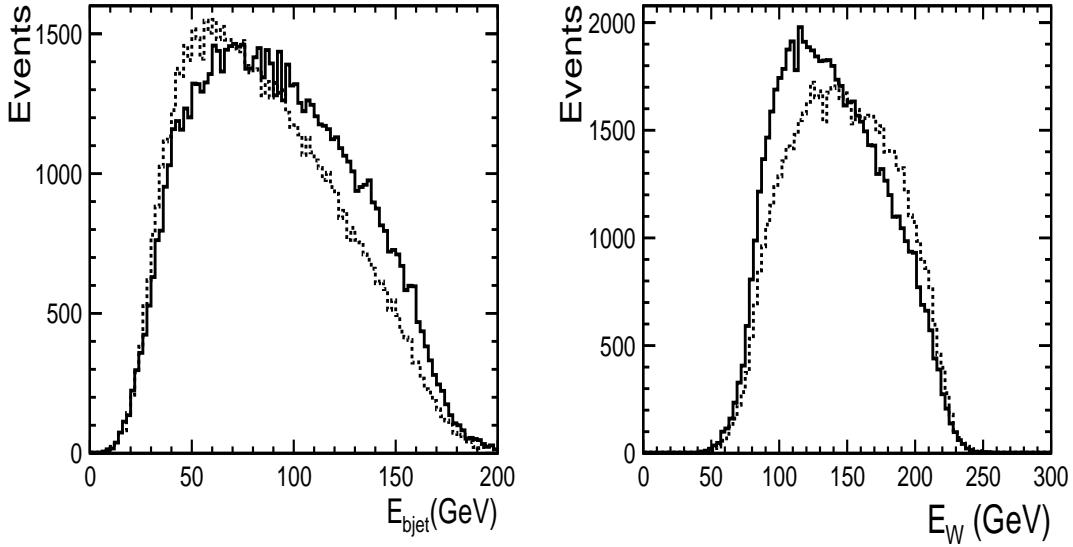


FIGURE 5.10: Comparison of the energy of the  $b$  jets, and  $W$  bosons, in  $t\bar{t}$  decay production, for left-handed and right-handed electron beams. The dotted line represents the right-handed electron beams, while solid lines are for left-handed electron beam case.

The effect of the background on b-charge measurement in both polarization configurations is not the same. The background affects the right-handed electron beam case in a stronger way as compared with the left-handed electron beam. The reason for this is that in case of left-handed electron beams, the  $b$ -jets are more energetic, while they are comparatively soft for right-handed electron beams. This is because of the  $V - A$  structure of the  $tWb$  decay vertex. On the other hand, the energy of the  $Ws$  behaves conversely i.e.  $Ws$  are more energetic in the right-handed electron beam case, as the figure 5.10 shows.

[106]

Figure 5.11 shows the effect of  $\gamma\gamma$  background on the reconstruction of charge, for the right-handed electron beams with polarization  $(P_{e^-}, P_{e^+}) = (+1, -1)$ . However, the effect of background on left-handed polarization has also been studied, and it was found that the removal of background had a smaller effect as compared to right-handed polarization.

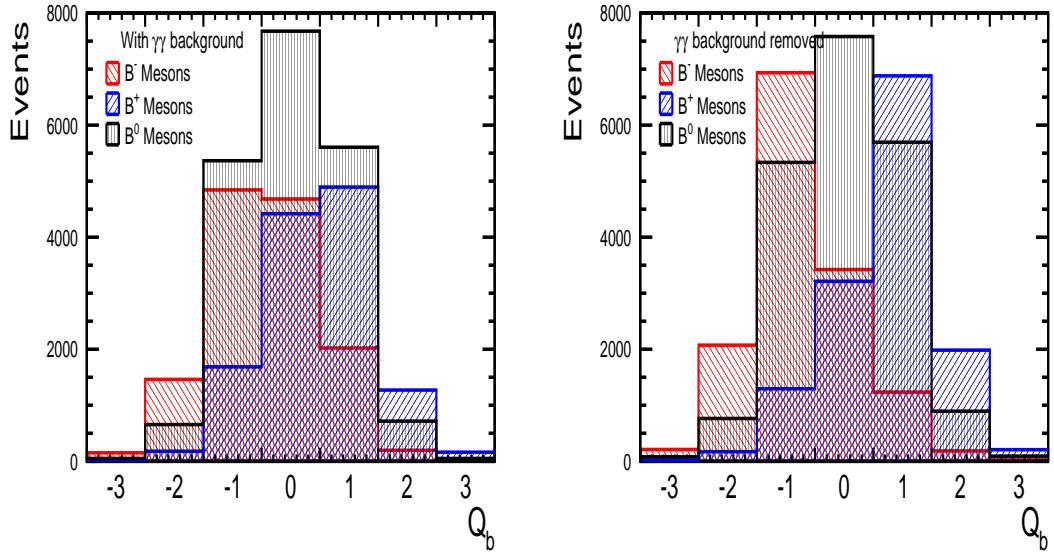


FIGURE 5.11: Left: Reconstructed charge for b-jets, using B-Meson charge for verification, with  $\gamma\gamma$  background. Right: After removing the background using  $k_t$  algorithm.

## 1137 5.10 Mis-tagging of $c$ -jets as $b$ -jets

1138 A clean reconstruction of  $b$ -jets is vital to a good measurement of the direction of top  
 1139 quark, which is in turn used to calculate the forward-backward asymmetry. Separating  
 1140 the  $b$ -jets from  $c$ -jets is a difficult task, and there is always a probability of  $c$ -jet being  
 1141 mistagged as  $b$ -jet. A dedicated study is performed to understand this problem, with  
 1142 the help of the generated events. The studies are performed using the angle between the  
 1143 generated  $b,c$  quarks and the reconstructed  $b$ -jets ( $\theta_{b_{rec}b_{MC}}$ ,  $\theta_{b_{rec}c_{MC}}$ ). Figure 5.12 shows  
 1144 the distribution of the cosine of these angles, versus each other. The figures shown here  
 1145 correspond to the  $b$ -jet, with second highest  $b$ -tag, in the left handed polarization case.

1146 For the purpose of defining the mis-tagging, this figure is sub-divided into three parts,  
 1147 depending on the comparison of cosine of two angles, and later on putting a cut on the  
 1148 value of  $\cos(\theta_{b_{rec}c_{MC}})$ . For convenience, three subdivisions are shown individually, in  
 1149 figure 5.13.

1150 Figure contains three plots corresponding to following scenarios.

- 1151 – First plot from left, contains events where  $\cos(\theta_{b_{rec}c_{MC}})$  is bigger than  $\cos(\theta_{b_{rec}b_{MC}})$ ,  
 1152 implying that the reconstructed  $b$ -jets is closer to the  $c$  quark in generated sample,  
 1153 as compared to  $b$  quarks.

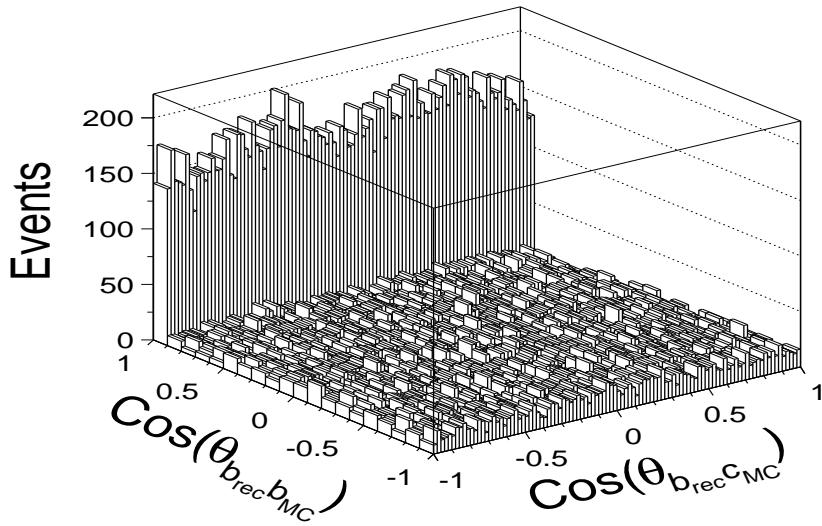


FIGURE 5.12: The *cosine* of the angle between reconstructed  $b$ -jets and generated  $b, c$  quarks. Most of the reconstructed  $b$ -jets are closer to the generated  $b$  quarks.

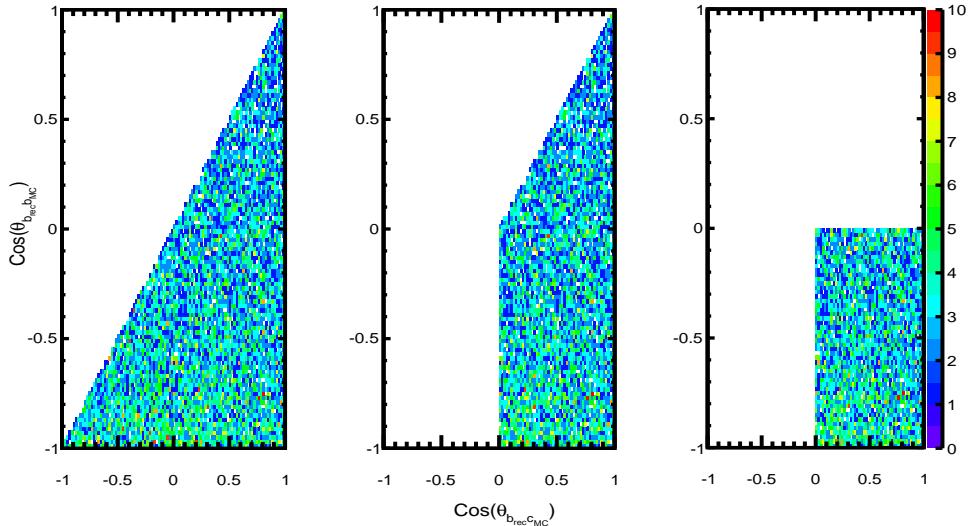


FIGURE 5.13: Subdivisions of figure 5.12. The figures correspond to three scenarios. Left:  $\theta_{b_{\text{rec}}c_{MC}} < \theta_{b_{\text{rec}}b_{MC}}$ , Center:  $\theta_{b_{\text{rec}}c_{MC}} < \theta_{b_{\text{rec}}b_{MC}}$  and  $\theta_{b_{\text{rec}}c_{MC}} < \pi/2$ , and Right:  $\theta_{b_{\text{rec}}c_{MC}} < \theta_{b_{\text{rec}}b_{MC}}$ ,  $\theta_{b_{\text{rec}}c_{MC}} < \pi/2$ , and  $\theta_{b_{\text{rec}}b_{MC}} > \pi/2$ .

- 1154 – The plot in centre show the same, except for a cut, asking for  $\theta_{b_{\text{rec}}c_{MC}}$  less than  $\pi/2$ .
- 1155
- 1156 – Right-most plot contains the events where the reconstructed  $b$ -jet is away from the generated  $b$  quark by more than  $\pi/2$ , while it is closer to the generated  $c$  quark,
- 1157

1158 by less than  $\pi/2$ . Events in this plot are recognized as  $c$ -jets, mistagged as  $b$ -jets  
 1159 (Quadrant 4).

1160 The fraction of events corresponding to each of these plots, are shown in table 5.4 for  
 1161 both polarizations and both  $b$ -jets. In the table, the  $b$ -jet with the highest b-tag value is  
 1162 shown as Jet1, and the jet with second highest b-tag is called Jet2.

Angle	Events Jet1 (%)	Events Jet1 (%)	Events Jet2 (%)	Events Jet2 (%)
	All	Above b-tag 0.3	All	Above b-tag 0.3
<b>left-handed Polarization (<math>e_L^- e_R^+</math>)</b>				
$\theta_{b_{rec}c_{MC}} < \theta_{b_{rec}b_{MC}}$	12	11	13	8
$\theta_{b_{rec}c_{MC}} < \theta_{b_{rec}b_{MC}}$ $\theta_{b_{rec}c_{MC}} < \pi/2$	8	8	9	6
$\theta_{b_{rec}c_{MC}} < \theta_{b_{rec}b_{MC}}$ $\theta_{b_{rec}c_{MC}} < \pi/2$ $\theta_{b_{rec}b_{MC}} > \pi/2$	6	6	6	4
<b>right-handed Polarization (<math>e_R^- e_L^+</math>)</b>				
$\theta_{b_{rec}c_{MC}} < \theta_{b_{rec}b_{MC}}$	12	11	12	8
$\theta_{b_{rec}c_{MC}} < \theta_{b_{rec}b_{MC}}$ $\theta_{b_{rec}c_{MC}} < \pi/2$	8	8	9	6
$\theta_{b_{rec}c_{MC}} < \theta_{b_{rec}b_{MC}}$ $\theta_{b_{rec}c_{MC}} < \pi/2$ $\theta_{b_{rec}b_{MC}} > \pi/2$	5	5	6	4

TABLE 5.4: Percentage number of events, as shown in the figure 5.13, for both polarizations.

1163 From this study, it is concluded that 4-6 % of the  $b$ -jets are mistagged  $c$ -jets. It is seen  
 1164 that requirement of the  $b\text{-tag} > 0.3$  helps to reject the mis-tagged events, more in the case  
 1165 of second  $b$ -jet than the first jet. It is also observed that the effect is almost independent  
 1166 of the polarization.

1167 A part of  $b$ -jets could be indeed very close to the  $c$ -jets, making it difficult to separate  
 1168 the two. For example, the distribution of the *cosine* of the angle, between generated  $b$   
 1169 and  $c$  quarks is shown in left part of figure 5.14. Some of the  $b$  quarks are very close  
 1170 to the  $c$  quarks, which will be difficult to separate. The other reasons, for mis-tagging  
 1171 could be the soft  $b$ -jets and hard gluons, emitted by the  $b$ -jets. The hard radiations alter  
 1172 the direction of  $b$  quarks. A distribution of the angle between two generated  $b$  quarks, is  
 1173 shown in the right part of figure 5.14. Although, most of the  $b\bar{b}$  pairs, are back to back,  
 1174 or close to that, there is a long tail, showing the comparatively small angles between  $b$   
 1175 and  $\bar{b}$  quarks.

## 1176 5.11 Identification of top quarks

1177 For the association of the  $b$  jets  $b_1$  and  $b_2$  having charge  $Q_{b_1}$  and  $Q_{b_2}$  to  $t$  or  $\bar{t}$  the event  
 1178 charge  $C = Q_{b_1} - Q_{b_2}$  is defined. The Fig. 5.15 shows the distribution of the event charge.

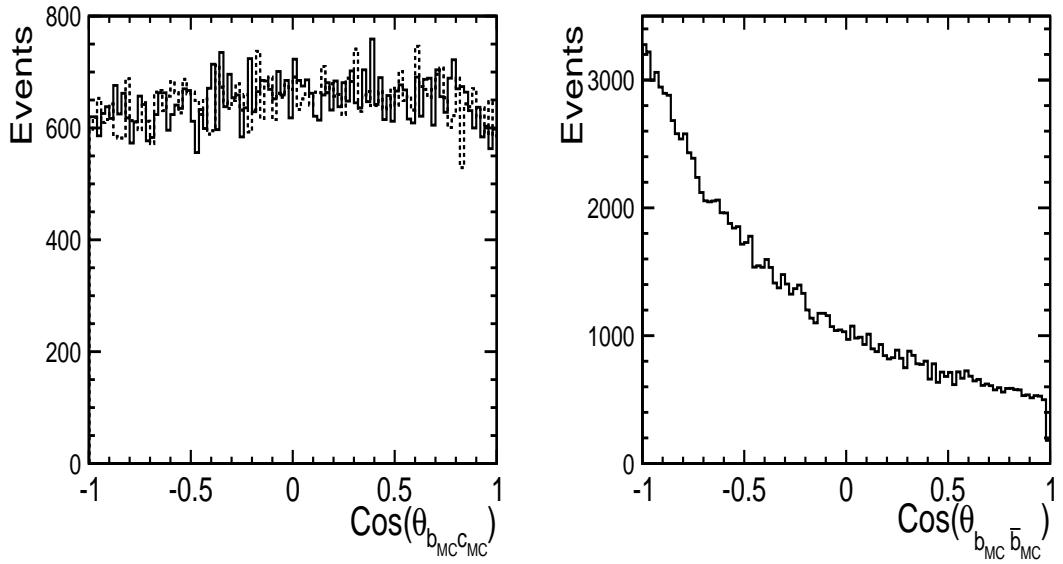


FIGURE 5.14: Left: The distribution of cosine of the angle between generated  $b$  and  $c$  quarks (solid line), and  $\bar{b}$  and  $c$  quarks ( dotted line). Right: Thh distribution of cosine of the angle between generated  $b$  and  $\bar{b}$  quarks.

<sup>1179</sup> As expected, most of the events have a non-zero  $C$  value, which in turn implies that we can distinguish between a  $t$  quark and a  $\bar{t}$  quark. The following criteria are applied

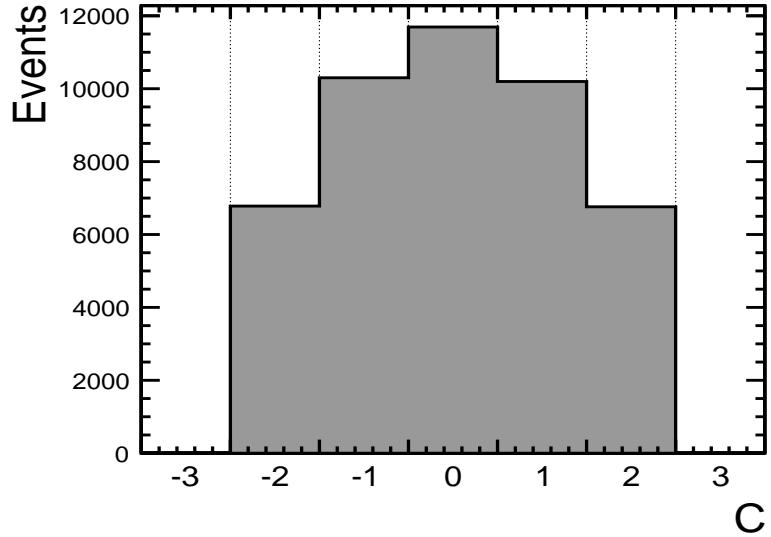


FIGURE 5.15: Event Charge  $C = Q_{b_1} - Q_{b_2}$ , the variable used to identify the charge of top quark.

<sup>1180</sup>

<sup>1181</sup> – In case  $C = 0$  an event is discarded;

- 1182 – If  $C < 0$  the  $b_1$  is assumed to be produced in the decay of a  $t$  quark;  
 1183 – If  $C > 0$  the  $b_1$  is assumed to be produced in the decay of a  $\bar{t}$  quark.

1184 For the signal events, the further cuts are applied, in addition to the previously described  
 1185 cuts. One of the factors, that affects the purity is the wrong charge. The subtraction of  
 1186 events, where the charge is wrongly assigned, is done with the help of the MC events.  
 1187 For this purpose, the reconstructed b jets are compared with the b jets in MC events, by  
 1188 measuring the polar angle between the two. If the two jets do not satisfy the condition  
 1189 of  $\cos(\theta) > 0.9$ , the charge is assumed to be wrong. A distribution of cosine of the angle  
 1190 between  $b$ -jet and  $b$  partons in MC is shown in the figure 5.16. The reconstruction of  
 1191 direction works good for 60% events, while the remaining 40% events can be seen in  
 1192 the tail. One of the reasons for this long tail, and an imperfect reconstruction of the  
 1193 direction are the hard radiations. A  $b$  quark can radiate hard gluons, which can alter its  
 1194 direction. The change of direction is more significant if the  $b$ -jet has a low energy, which  
 1195 is particularly true for the right-handed polarization case.

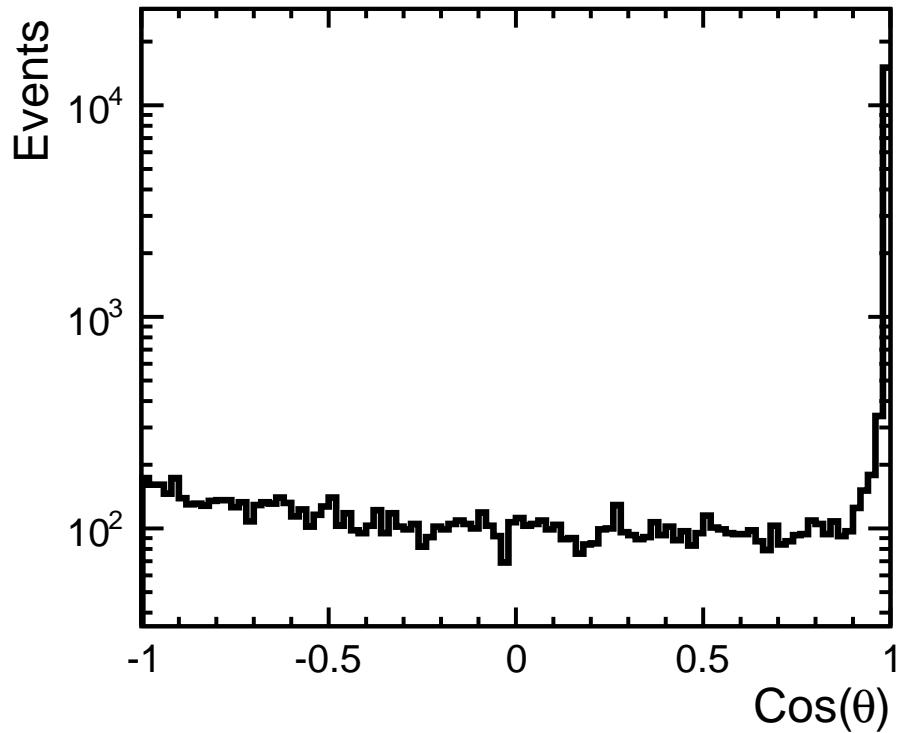


FIGURE 5.16: Cosine of the angle between reconstructed  $b$  jet and the Monte Carlo  $b$  jet.  
 This parameter is used to identify the wrong charge assignments, and remove them.

- 1196 The final selection efficiency, after subtraction of events with wrong charge, is 20% for  
 1197 left-handed electron beams, and 21.41% for the right-handed. This is in agreement with

1198 the one reported in [108]. The quality of reconstruction of top quarks, at the final stage,  
 1199 can be cross checked by comparing them to the top quarks at generator level. A difference  
 1200 of cosine of angle, of the reconstructed top quark, and the MC top quark is shown in  
 1201 figure 5.17.

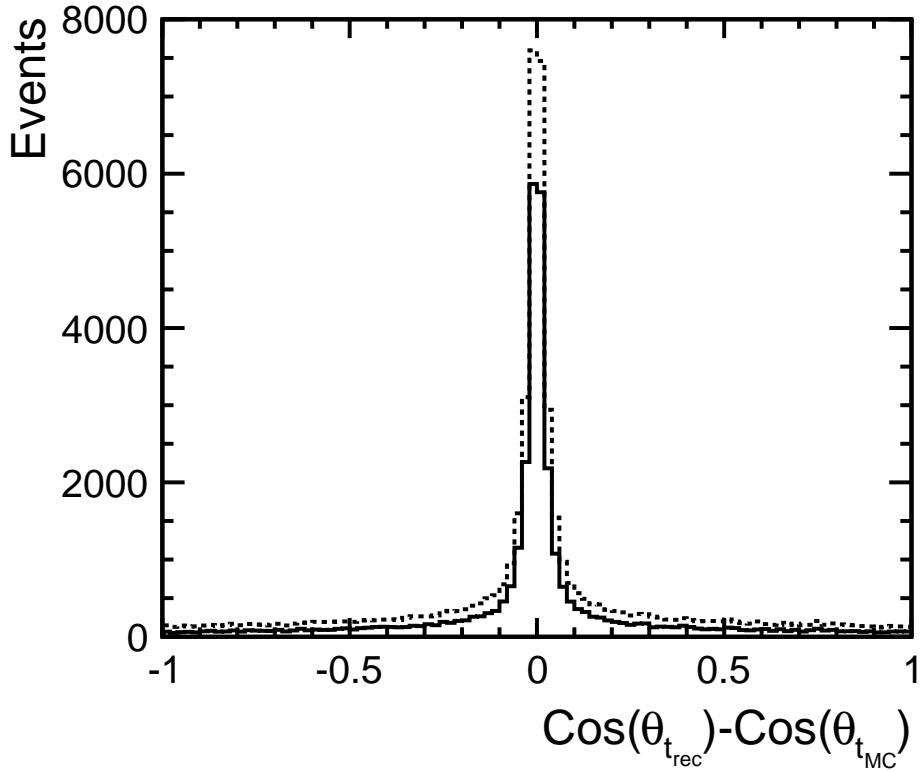


FIGURE 5.17: Difference in Cosine of angle between reconstructed and Monte Carlo  $t$  quarks. The dotted line represented the number of quarks before the subtraction of events with wrong charge, while solid line shows the same after the correction.

1202 **5.12 Determination of the forward backward asymmetry**  
 1203  $A_{FB}^t$

The forward backward asymmetry is defined as follows

$$A_{FB}^t = \frac{N(0 < \theta_{top} \leq \frac{\pi}{2}) - N(\frac{\pi}{2} < \theta_{top} \leq \pi)}{N(0 < \theta_{top} \leq \frac{\pi}{2}) + N(\frac{\pi}{2} < \theta_{top} \leq \pi)}$$

1204 The polar angle  $\theta_{top}$  is defined w.r.t. to the incoming electron beam. The quantity  $N$  is  
 1205 the number of events in the different detector hemispheres.

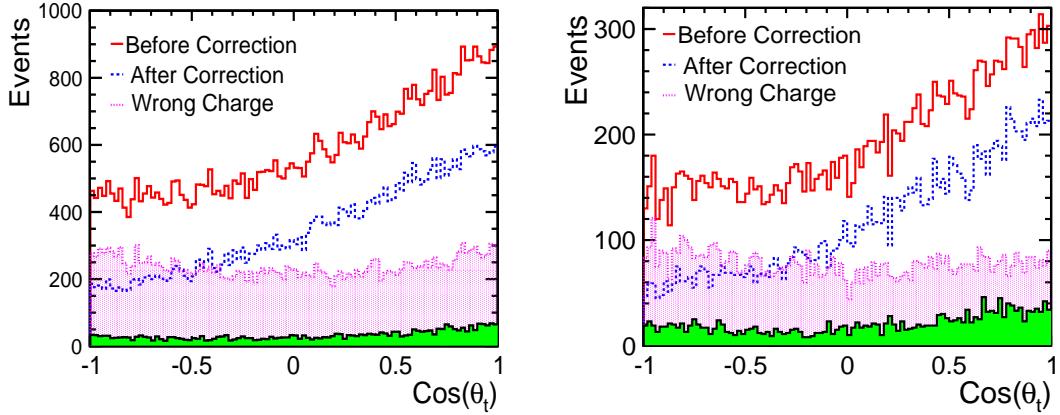


FIGURE 5.18: Left: Asymmetry for  $P, P' = -1, +1$  after application of cuts in Tab. 5.2. The figure shows in addition the generated distribution and the events for which the  $b$  quark charge is incorrectly reconstructed. The bottom fill shows the Standard Model background.

Right: The same as left but for  $P, P' = +1, -1$

1206 A positive value of the asymmetry implies that the forward region of the detector is pop-  
 1207 ulated by the  $t$  quarks, while there are more  $\bar{t}$  in the other hemisphere. For convenience,  
 1208 the asymmetry is given for  $t$  quarks only and the angle of  $\bar{t}$  is inverted by  $\pi$  to add it to  
 1209 the number of  $t$  quarks.

$$\cos \theta_t = -1 * \cos \theta_{\bar{t}}$$

1210 The Fig. 5.18 shows the forward backward asymmetry for the polarization  $P, P' = -1, +1$   
 1211 after the selection described in the previous section. A clear asymmetry is visible. The  
 1212 wrongly assigned charge of  $b$  quark, results in a lower asymmetry. They are shown in  
 1213 the bottom of Fig. 5.18.

For about 60% of the  $t$  quarks the charge is measured correctly, depending on the various cut scenarios. For the final result events with wrong charge assignment are subtracted from the number of observed events. The resulting asymmetries for both beam polarizations are shown in Fig. 5.19 and the results are summarized in Tab. 5.6. Note, that 1/4 of the difference between generated and reconstructed  $A_{FB}^t$  is taken as the systematic error. The error on the  $A_{FB}^t$  is calculated as following:

$$\delta_{A_{FB}} = \sqrt{\frac{1 - A_{FB}^2}{N}} \quad (5.6)$$

1214 Here,  $N$  is the number of events. The statistical error is shown for the number of events  
 1215 expected for  $250 \text{ fb}^{-1}$  and  $P, P' = \pm 0.8, \mp 0.3$

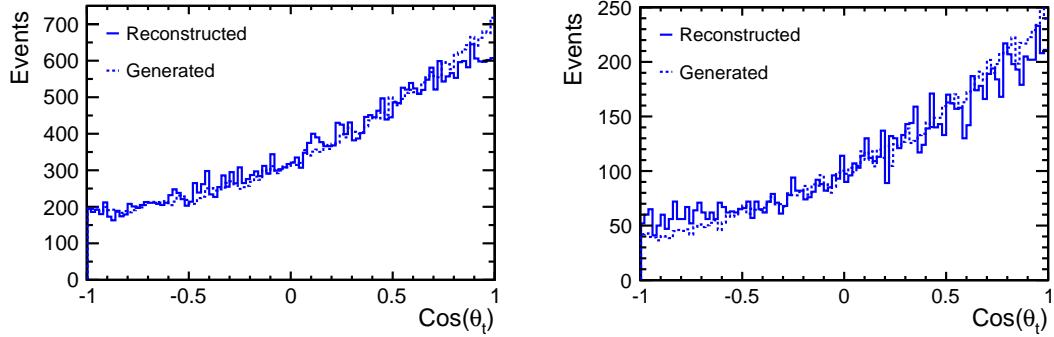


FIGURE 5.19: Left: Angular distribution of top quarks for  $P, P' = -1, +1$  after application of cuts in Tab. 5.2 and correction for events in which the  $b$  quark charge was incorrectly reconstructed. The corrected result is compared with the generated distribution. Right: The same as left but for  $P, P' = +1, -1$

$P, P'$	$(A_{FB}^t)_{gen.}$	$A_{FB}^t$	$\delta_{A_{FB}}$	$(\delta_{A_{FB}}/A_{FB})_{stat.} [\%]$	$(\delta_{A_{FB}}/A_{FB})_{syst.} [\%]$
$-1, +1$	0.352	0.332	0.007	1.9 (corrected to $P, P' = -0.8, +0.3$ )	1.4
$+1, -1$	0.439	0.388	0.009	2.01 (corrected to $P, P' = +0.8, -0.3$ )	2.9

TABLE 5.5: Precisions expected for  $A_{FB}^t$  for different beam polarizations.

### 1216 5.13 Form Factors

1217 The precisions on the form factors, mentioned in 2.3, have been calculated using these  
1218 results. Following four parameters are used to calculate the form factors.

1219  $-\delta_\sigma(e_L^- e_R^+) = 0.40\%$

1220  $-\delta_\sigma(e_R^- e_L^+) = 0.60\%$

1221  $-\delta_{A_{FB}}/A_{FB}(e_L^- e_R^+) = 1.9\%$

1222  $-\delta_{A_{FB}}/A_{FB}(e_R^- e_L^+) = 2.01\%$

1223 While calculating the form factors, the CP violating form factors are fixed to their stan-  
1224 dard model values. The results for hadronic decay channel, are presented in the following  
1225 table, along with semi-leptonic channel. For a comparison, the precisions expected from  
1226 LHC, are also shown. The difference in the calculation method is that for LHC, only  
1227 one form factor was allowed to vary at a time, while for calculations using our results  
1228 for hadronic and semi-leptonic decay channels, two or four forms are allowed to vary  
1229 simultaneously.

1230 The  $\gamma/Z$  mixing at a lepton collider allows to fix the sign of the form factors, while at  
1231 the LHC, the top quark couples either to  $\gamma$  or  $Z$ . This implies that the cross section  $\sigma$  is

Coupling	Standard Model value	LHC $\mathcal{L} = 300 \text{ fb}^{-1}$	ILC (semi-leptonic) $\mathcal{L} = 500 \text{ fb}^{-1}$ $(P_{e-}, P_{e+}) = (\pm 0.8, \mp 0.3)$	ILC (hadronic) $\mathcal{L} = 500 \text{ fb}^{-1}$ $(P_{e-}, P_{e+}) = (\pm 0.8, \mp 0.3)$
$\Delta\tilde{F}_{1V}^{\gamma}$	-0.66	+0.043 -0.041	$\pm 0.002$	$\pm 0.002$
$\Delta\tilde{F}_{1V}^Z$	0.23	+0.240 -0.620	$\pm 0.003$	$\pm 0.003$
$\Delta\tilde{F}_{1A}^Z$	-0.59	+0.052 -0.060	$\pm 0.006$	$\pm 0.010$
$\Delta\tilde{F}_{2V}^{\gamma}$	0.015	+0.038 -0.035	$\pm 0.001$	$\pm 0.001$
$\Delta\tilde{F}_{2V}^Z$	0.018	+0.270 -0.190	$\pm 0.002$	$\pm 0.002$

TABLE 5.6: Precisions expected for different form factors, using semi-leptonic and hadronic decay channels of  $t\bar{t}$ , at  $\sqrt{s} = 500 \text{ GeV}$ , with polarized beams at the ILC. The same for the LHC, is also shown.

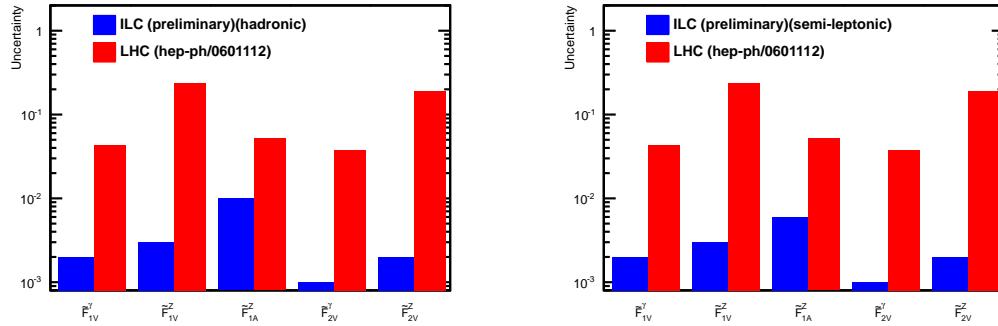


FIGURE 5.20: Left: A comparison of precisions for different form factors, for measurement of electroweak couplings of the top quark, at the ILC, using fully hadronic decay channel, and the LHC. Right: The same using semi-leptonic channel.

1232 proportional to  $(F_{1V}^Z)^2 + (F_{1A}^Z)^2$ . Therefore the precisions expected at the LHC, cannot  
1233 exclude the sign flip of the  $F_{1A}^Z$  or  $F_{1V}^Z$ .

1234 The results for both decay channels are consistent. The value of  $\Delta F_2^i$  depend on the cross  
1235 section, so there is no difference.  $\Delta\tilde{F}_{1A}^Z$  is almost double as compared to the semi-leptonic  
1236 channel, due the comparatively higher  $\delta_{AFB}/A_{FB}$  for the right-handed polarization in  
1237 the hadronic decay channel. But this difference does not appear in  $\Delta\tilde{F}_{1V}^{\gamma}$  because the  
1238 error on  $A_{FB}$  for two polarizations is averaged in this case.

1239 A graphic representation of these form factors is shown in figure 5.20.

## 1240 5.14 Discussion of results

1241 A major source of systematic error is that the final correction for wrongly measured  
 1242  $b$  quark charges is based on Monte Carlo truth information. This is one of the draw  
 1243 backs of this analysis scheme, as it would require a perfect modeling of the final state.  
 1244 However, the effect of systematics have been studied, by varying different cuts, on which  
 1245 the final measurement of the  $A_{FB}$  depends.

1246 The final results are shown to be robust against the  $\chi^2$  cut. The final selection efficiency  
 1247 varies by 7%, while the purity varies by 2% only. The following table shows, the effect  
 1248 of variation of  $\chi^2$ , on purity and efficiency. Note that the values of  $(\delta_{A_{FB}}/A_{FB})_{stat.}$   
 1249 onwards, are corrected for luminosity  $250 \text{ fb}^{-1}$ .

$\chi^2$	$A_{FB}^t$	$\delta_{A_{FB}}$	$(\delta_{A_{FB}}/A_{FB})_{stat.} [\%]$	Purity [%]	Final Efficiency
<b>left-handed Polarization (<math>e_L^- e_R^+</math>)</b>					
30	0.332	0.007	1.9	59.42	20.02
20	0.333	0.008	1.9	60.60	16.00
15	0.330	0.008	2.06	61.68	13.37
<b>right-handed Polarization (<math>e_R^- e_L^+</math>)</b>					
30	0.388	0.009	2.01	59.89	20.42
20	0.412	0.013	2.06	60.35	16.46
15	0.412	0.015	2.4	60.35	13.95

TABLE 5.7: Variation of the  $\chi^2$  for two beam polarizations.

1250 The effect of tightening the b-tag requirement is also studied. A tight cut on the b-tag,  
 1251 increases the purity by 4-5%, while decreasing the efficiency by the same amount. The  
 1252 numbers are given in the following table.

b-tag <sub>1,2</sub>	$A_{FB}^t$	$\delta_{A_{FB}}$	$(\delta_{A_{FB}}/A_{FB})_{stat.} [\%]$	Purity [%]	Final Efficiency [%]
<b>left-handed Polarization (<math>e_L^- e_R^+</math>)</b>					
0.9,0.8	0.326	0.008	1.9	63.90	16.68
<b>right-handed Polarization (<math>e_R^- e_L^+</math>)</b>					
0.9,0.8	0.390	0.013	2.17	63.85	16.80

TABLE 5.8: The purity is increased by tightening the cut on b-tag.

1253 The major source of confusion in the charge measurement are the neutral  $B$  hadrons. A  
 1254 zero jet charge makes the Event Charge  $C$  biased as well, when combined with the other  
 1255 bjet charge. The studies showed that purity of the charge measurement varies for the  
 1256 values of Event Charge  $C$ , mainly because of this problem.

1257 –  $|C| = 1$ , purity = 55.67 % , Efficiency = 8.46 %, for left-handed polarization, while  
 1258  $|C| = 1$ , purity = 56.56% , Efficiency = 8.70 % for right-handed polarization.

- 1259 –  $|C| \geq 1$ , purity = 62.53 %, Efficiency = 11.58 % in case of left-handed polarization,  
 1260 and  $|C| \geq 1$ , purity = 62.63 % , Efficiency = 11.70 %.

1261 One of the outcomes of this aspect of the study was to propose further improvements  
 1262 in the LCFIPplus. Access to the Tertiary vertex will give a better control over precision  
 1263 in charge measurement. The  $B^0$  mesons decay to  $D$  mesons, which in turn decay to  
 1264 leptons. Measuring the charge of lepton will help to improve not only the efficiency, but  
 1265 also the purity. Using the muons for the vertex charge is easier, however the isolation of  
 1266 electrons, in a jet is a difficult task to accomplish.

1267 The results are comparable to those obtained by using semi-leptonic channel [103]. The  
 1268 certainty of the charge measurement of a lepton is higher as compared to doing that for a  
 1269 bjet. The addition of the hadronic channel to the top quark pair decays studies adds to  
 1270 not only statistics, but also helps to calculate the total cross section. The relative error  
 1271 obtained in the hadronic channel is comparable with that in semi-leptonic. Following  
 1272 table shows a comparison of the numbers in both channels.

Channel	$A_{FB}^t$	$\delta_{A_{FB}}$	$(\delta_{A_{FB}}/A_{FB})_{stat.} [\%]$	Final Efficiency [%]
<b>left-handed Polarization (<math>e_L^+ e_R^-</math>)</b>				
hadronic	0.332	0.007	1.9	20.02
semi-leptonic	0.326	0.005	1.7	28.5
<b>right-handed Polarization (<math>e_R^+ e_L^-</math>)</b>				
hadronic	0.388	0.009	2.01	20.42
semi-leptonic	0.419	0.017	1.27	55.91

TABLE 5.9: A comparison of semi-leptonic and hadronic channels.

1273 The performance for the right-handed polarization case, is better in case of semi-leptonic  
 1274 analysis, mainly because of the reason the semi-leptonic relies on the charge of lepton  
 1275 coming from the  $W$  boson, which are more energetic in right-handed polarization electron  
 1276 beams case. The soft b-jets in this case lead to not only mis-identification of the charge,  
 1277 but also cause the problem for the reconstruction of kinematics, specially the direction  
 1278 of top quarks.

1279 On the other hand, in the left-handed case, the performance is comparable, despite the  
 1280 lower efficiency in the case of hadronic decay channel. In this case, the reconstruction  
 1281 of the top quark direction is dominated by the bjets and Ws are comparatively less  
 1282 energetic. This leads to the migration effect, in semi-leptonic analysis. This problem is  
 1283 cured using the  $\chi^2$  method, which has been detailed in [103].

1284 The vertex charge measurement has also been applied to the semi-leptonic analysis,  
 1285 complementarily with the lepton charge. The application yields satisfactory results, and  
 1286 provides an alternative to the  $\chi^2$  method used in that channel. It was found that the

1287 method is equally efficient, and the statistical error obtained is the same as in hadronic  
1288 decay channel. While using the b-jet charge method in the semi-leptonic channel, no  
1289 corrections for the wrong charge assignments were made using the MC data. A cross  
1290 check was performed using the charge of the lepton, only.

1291 Another factor, limiting the efficiency, is that the LCFIPlus algorithm is not optimized  
1292 for the charge measurement. One of the features of this is that while reconstructing the  
1293 jet vertices, low  $p_t$  tracks are dropped, without taking into consideration their effect on  
1294 the total vertex charge. An improvement in the performance for the vertex charge will  
1295 certainly help to improve the results.

1296 The dedicated studies for mis-tagging of  $c$ -jets as  $b$ -jets, showed that around 5% of the  $b$   
1297 jets were the mis-tagged  $c$ -jets. The reasons for this include the hard radiations, emitted  
1298 by  $b$  quarks. The treatment of these hard gluons, in the current versions of **Whizard**,  
1299 could be improved in next versions. This will hopefully, provide a better performance  
1300 for tagging the jets.

1301 It is also proposed that the optimization of different cuts for two polarizations maybe  
1302 done independently and could yield better results. One of the observation in this regard  
1303 is the effect of tightening the b-tag cut, which effects the right-handed polarization more  
1304 than the left-handed. Due to different kinematics in two cases, the kinematic cuts could  
1305 also be differently applied to optimize the performance.

1306 **Chapter 6**

1307 **Summary and outlook**

1308 The International Linear Collider is a proposed future electron positron collider, which  
1309 will operate at a center-of-mass energy between 91 GeV and 500 GeV, later on extendable  
1310 upto 1 TeV. ILC is proposed to have two detectors, namely International Large Detector  
1311 (ILD), and Silicon Detector (SiD). This thesis is done in the framework of the ILD.

1312 The thesis work can be summarized in two parts. The R & D project was aimed to op-  
1313 timize the Si-W Electromagnetic calorimeter's performance, which will be a subdetector  
1314 of the ILD. The physics project was focused on analyzing the top quark production at  
1315 the ILC.

1316 **6.1 The optimization of Si-W ECAL**

1317 The Si-W ECAL of ILC will consist of alternate Silicon and Tungsten layers. The silicon  
1318 makes the active layers, while Tungsten acts as absorber material. Each silicon layers is  
1319 divided into 4 wafers. The analysis focused on analyzing the performance of ECAL as  
1320 a function of the guard ring size, an important component of the silicon wafers, used to  
1321 prevent the current leakages. Several guard ring sizes ranging from 0 mm to 8 mm were  
1322 studied, using two physics channels, namely the hadronic and leptonic decay of the Z  
1323 boson. These are benchmark channels at the ILC, and of fundamental importance for  
1324 many related studies. The precision available on the mass of Z boson, is used to calibrate  
1325 the detectors.

1326 Many final states at the ILC will consist of jets. The jets contain photons, which can  
1327 disappear into inactive zones created by the guard rings, and therefore degrade the jet  
1328 energy resolution of the ECAL. The studies for the hadronic decay channel, were carried  
1329 out at the Z pole mass, with Z decaying to two quarks. The Z decay to electrons

1330  $Z \rightarrow e^-e^+$  was studied for a center-of-mass energy of 250 GeV, in the Higgs-strahlung  
 1331 production. The channel  $e^-e^+ \rightarrow Zh$  will be used for the studies of the Higgs boson at  
 1332 the ILC. The model independent analysis of the properties of the Higgs boson make this  
 1333 channel a benchmark at the ILC.

1334 The results for both the channels were consistent. Cross checks were performed during  
 1335 the analysis, to assure the quality of the analysis, with previously published results. The  
 1336 studies found that a guard ring size in range of 0-2 mm, does not degrade the energy  
 1337 resolution of the ECAL, significantly. The effect of the guard ring size, on the energy  
 1338 resolution of the ECAL, was studied as a function of the polar angle. It was found that  
 1339 the effect was independent of the position of the ECAL layers, in the detectors.

1340 The results will be useful in future discussion with the manufacturers of the Silicon  
 1341 sensors for the ECAL. The studies are on going to analyze whether a guard ring is really  
 1342 needed to avoid the current leakages, or not. If needed, a guard ring of size upto 2mm,  
 1343 will not degrade the performance of the ECAL.

## 1344 6.2 Forward-backward asymmetry in top quark pairs

1345 The top quark is considered as a window to the new physics, due its distinguished prop-  
 1346 erties like large mass, strong Yukawa couplings and link to the electroweak symmetry  
 1347 breaking. Measuring the electroweak couplings of the top quark, could hint at the ex-  
 1348 istence of the new physics beyond Standard Model. The precise determination of these  
 1349 couplings is a benchmark at the ILC. In order to precisely measure the couplings, the  
 1350 forward-backward or left-right asymmetry of the top quark needs to be measured pre-  
 1351 cisely. The hadronic decay channel was analyzed, using the vertex charge. The results  
 1352 of the study are part of the DBD[40].

1353 Two beam polarization configurations  $(P_{e^-}, P_{e^+}) = (-1, +1)$  and  $(P_{e^-}, P_{e^+}) = (+1, -1)$   
 1354 were studied at a center-of-mass energy of 500 GeV. Two parameters, cross section and  
 1355 the forward backward asymmetry were measured. Both are depend on the beam polar-  
 1356 izations.

1357 The 6-jet final states was analyzed using dedicated algorithms and full detector simula-  
 1358 tion. The identification of the top quarks was done by identifying the charge of the  $b$   
 1359 quark, at the vertex. The sum of the charge of all the tracks having a  $p_t$  above 100 MeV,  
 1360 was taken as the vertex charge.

1361 The final selection efficiency was 20% with a charge measurement purity of 60%. The sta-  
 1362 tistical error on the cross section was estimated to be 0.40 % and 0.60% for the left-handed

1363 and right-handed electron beam polarizations respectively. The relative statistical error  
1364  $\delta A_{FB}^t/A_{FB}^t$  was found to be 1.9% for the left-handed electron beam configuration and  
1365 2.01% for the right-handed one. The systematic studies showed the robustness of the  
1366 final results against the various selection cuts.

1367 The analysis allowed for a full exploitation of the  $t\bar{t}$  sample, and will help to calculate  
1368 the total cross section. The precision on the form factors of the electroweak couplings,  
1369 could be calculated more accurately, combined with the semi-leptonic results.

1370 The prospect of vertex charge carries a lot of potential. The technique is also applied to  
1371 the semi-leptonic analysis. The semi-leptonic analysis relies on the charge of the lepton,  
1372 coming from the  $W$  decay. In case of left-handed electron polarizations, the direction  
1373 of the top quark is determined by the direction of the  $b$  quark, which are comparatively  
1374 more energetic. The use of vertex charge, could help to improve the performance.

1375 Apart from the  $t\bar{t}$  studies, the other charge measurements could also benefit from an  
1376 improved measurement of the vertex charge. The benchmark process at the ILC include,  
1377 2 fermion processes, such as the hadronic decay of  $Z$ , and 4 fermion process such as  $ZZ$   
1378 and  $WW$ . The hadronic decay of these bosons, can make use of the vertex charge.

1379 **Appendix A**

1380 **Vertex Charge**

1381 We use the collection `RefindJets`, produced by the jet clustering algorithm. This col-  
1382 lection contains the information on flavor tagging and other jet properties. The problem  
1383 with this collection is that the jet charge is not well reconstructed. The algorithm drops  
1384 some Particle Flow Objects (PFOs) for this collection, hence the charge values related  
1385 to jets contained in this collection are not reliable.

1386 On the other hand, the reliable information on the charge is contained in the collected  
1387 `RefinedVertex`, which is `Vertex` type as an LCIO object, instead of being `ReconstructedParticle`  
1388 type. The PID handler tool which acts to collect the information related to b-tag, does  
1389 not work for the `Vertex` type object, therefore at the vertex, it is impossible to retrieve  
1390 the information on b-tag value.

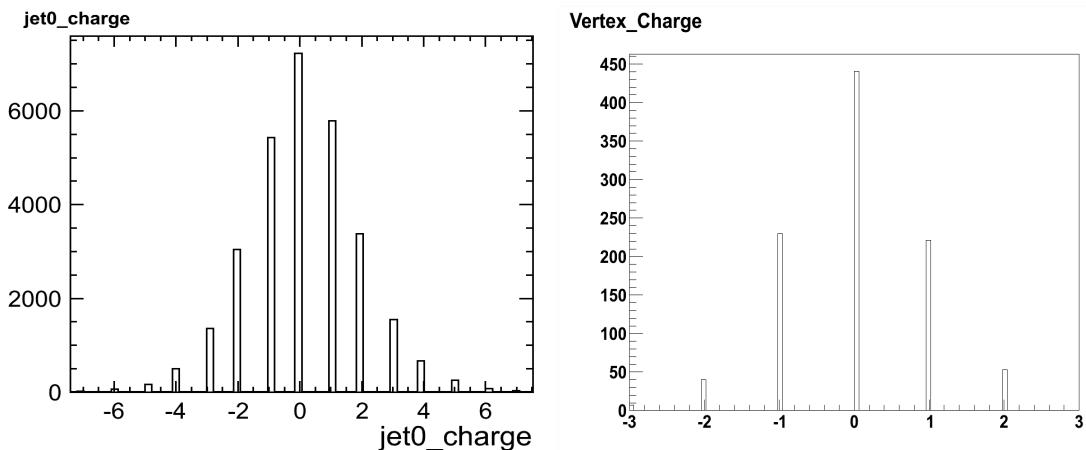


FIGURE A.1: Jet Charge vs Vertex Charge.

1391 To sort this problem out, we use the `LCRelation` tool to pass from `RefindJets` to  
1392 `RefinedVertex` and vice versa. The LC Relation passed through another collection

1393 which related jets to their vertices. The use of `LCRelation` in this way requires that we  
1394 have credible information on the b-tag value of the jet under consideration. We use the  
1395 cut  $b - tag \geq 0.3$  at this stage, which is reasonably good as shown in figure 5.4.

1396 A comparison of the charge of jets, as reconstructed from jets collection and vertex  
1397 collection is shown in figure A.1.

# <sup>1398</sup> Bibliography

- <sup>1399</sup> [1] S. L. Glashow.  
<sup>1400</sup> Nucl. Phys 22(1961) 579  
<sup>1401</sup> S. Weinberg.  
<sup>1402</sup> Phys. Rev.Lett. 19(1967) 1264.
- <sup>1403</sup> [2] J. Hasert *et al.*  
<sup>1404</sup> 1973 Phys. Lett. 46B 138-140.
- <sup>1405</sup> [3] Makoto Kobayahi, Toshihide Maskwa.  
<sup>1406</sup> Progress of Theoretical Physics Vol 49. Feb 1973.
- <sup>1407</sup> [4] Nicola Cabibo.  
<sup>1408</sup> Phys. Rev. Lett. 10 (1963) 531-533.
- <sup>1409</sup> [5] S.L. Glashow.  
<sup>1410</sup> Nuclear Physics, 22(4):579-588, 1961.
- <sup>1411</sup> [6] S. Weinberg.  
<sup>1412</sup> Physical Review Letters, 19(21):1264, 1967.
- <sup>1413</sup> [7] A. Salam.  
<sup>1414</sup> Elementary particle theory. Relativistic groups and analyticity.  
<sup>1415</sup> Nobel Symposium. 1968
- <sup>1416</sup> [8] Quantum Electrodynamics.  
<sup>1417</sup> R.P. Feynman.
- <sup>1418</sup> [9] A. Pich.  
<sup>1419</sup> [arXiv:hep-ph/9505231v1](https://arxiv.org/abs/hep-ph/9505231v1)
- <sup>1420</sup> [10] P. W. Higgs  
<sup>1421</sup> Phys. Rev. Lett. 13, 508-509 (1964) .
- <sup>1422</sup> [11] J. Iliopoulos.  
<sup>1423</sup> [arXiv:1305.6779v](https://arxiv.org/abs/1305.6779v).

- 1424 [12] K. A. Meissner, H. Nicolai  
1425       [arXiv:hep-th/0612165](https://arxiv.org/abs/hep-th/0612165)
- 1426 [13] N. Arkani-Hamed, S. Dimopoulos, G. Dvali.  
1427       [arXiv:hep-ph/9803315](https://arxiv.org/abs/hep-ph/9803315).
- 1428 [14] E. Bertuzzo, T. S. Ray, H. de Sandes, C. A. Savoy.  
1429       [arXiv:1206.2623](https://arxiv.org/abs/1206.2623)  
1430       L. Vecchi.  
1431       [arXiv:1304.4579](https://arxiv.org/abs/1304.4579).
- 1432 [15] K. Lane.  
1433       [arXiv:hep-ph/0202255](https://arxiv.org/abs/hep-ph/0202255)
- 1434 [16] S. P. Martin.  
1435       [arXiv:hep-ph/9709356](https://arxiv.org/abs/hep-ph/9709356).
- 1436 [17] M. L. Perl.  
1437       SLAC-PUB-5937
- 1438 [18] J. J. Aubert *et al.*  
1439       Phys. Rev. Lett. 33, 1404-1406 (1974).
- 1440 [19] J. -E. Augustin *et al.*  
1441       Phys. Rev. Lett. 33, 1406-1408 (1974)
- 1442 [20] L. M. Lederman,  
1443       Scientific American, October 1978, vol. 239, no. 4, pp. 72-80.
- 1444 [21] J. H. Kuhn and G. Rodrigo.  
1445       [arXiv:1109.6830\[hep-ph\]](https://arxiv.org/abs/1109.6830)
- 1446 [22] Oleg Brandt on behalf of the D0 collaboration [arXiv:1209.4364v1\[hep-ex\]](https://arxiv.org/abs/1209.4364v1)
- 1447 [23] [http://www-cdf.fnal.gov/physics/new/top/2009/tprop/Afb/cdfnote\\_9724\\_public\\_v01.pdf](http://www-cdf.fnal.gov/physics/new/top/2009/tprop/Afb/cdfnote_9724_public_v01.pdf)
- 1449 [24] J. Beringer *et al.* (Particle Data Group),  
1450       Phys. Rev. D86, 010001 (2012).
- 1451 [25] CDF Collaboration.  
1452       Phys.Rev.Lett.74:2626-2631,1995. [arXiv:hep-ex/9503002](https://arxiv.org/abs/hep-ex/9503002)
- 1453 [26] S. L. Glashow, J. Iliopoulos, L. Maiani.  
1454       Physical Review D, vol. 2, Issue 7, pp. 1285-1292

- 1455 [27] R. Barate et al.  
1456 Phys. Lett., B565 (2003) 61-75.
- 1457 [28] G. Degrassi *et al.*  
1458 [arXiv:1205.6497v2](https://arxiv.org/abs/1205.6497v2).
- 1459 [29] A. Juste *et al.*  
1460 [arXiv:hep-ph/0601112v2](https://arxiv.org/abs/hep-ph/0601112v2)
- 1461 [30] D0 Collaboration (S. Abachi et al.) [CDF Collaboration]  
1462 Phys. Rev. Lett. 74 (1995) 2632-2637  
1463 [arXiv:hep-ex/9503003](https://arxiv.org/abs/hep-ex/9503003)
- 1464 [31] M. W. Grunewald and A. Gurtu.  
1465 <http://pdg.lbl.gov/2010/reviews/rpp2010-rev-w-mass.pdf>
- 1466 [32] J. Beringer *et al.*  
1467 Phys. Rev. D86, 010001 (2012).  
1468 <http://pdg.lbl.gov/2012/listings/rpp2012-list-z-boson.pdf>
- 1469 [33] M. Baaka, R. Kogler.  
1470 [arXiv:1306.0571\[hep-ph\]](https://arxiv.org/abs/1306.0571[hep-ph])
- 1471 [34] S. Dimopoulos, H. Georgi.  
1472 Nuclear Physics B193 (1981) 150-162.
- 1473 [35] Observation of a new boson at a mass of 125 GeV with the CMS experiment at  
1474 the LHC.  
1475 Physics Letters B, Volume 716, Issue 1, 17 September 2012, Pages 30-61. [arXiv:1207.7235\[hep-ex\]](https://arxiv.org/abs/1207.7235[hep-ex])
- 1477 [36] Observation of a new particle in the search for the Standard Model Higgs boson  
1478 with the ATLAS detector at the LHC.  
1479 Physics Letters B, Volume 716, Issue 1, 17 September 2012, Pages 1-29. [arXiv:1207.7214\[hep-ex\]](https://arxiv.org/abs/1207.7214[hep-ex])
- 1481 [37] M. Baak, R. Kogler (for the Gfitter group).  
1482 [arXiv:1306.0571v2](https://arxiv.org/abs/1306.0571v2)
- 1483 [38] E. Ambler, R. W. Hayward, D. D. Hopps, and R. P. Hudson  
1484 Phys. Rev. 105, 1413-1415 (1957)
- 1485 [39] Carl R. Schmidt .  
1486 [arXiv:hep-ph/9504434](https://arxiv.org/abs/hep-ph/9504434)

- 1487 [40] The International Linear Collider. Technical Desgin Report
- 1488 [41] ATLAS Collaboration.
- 1489 [arXiv:1305.2756](https://arxiv.org/abs/1305.2756)
- 1490 [42] Michael E. Peskin.
- 1491 SLAC-PUB-15178.
- 1492 [43] OPAL Collaboration.
- 1493 [arXiv:hep-ex/0209076v1](https://arxiv.org/abs/hep-ex/0209076v1)
- 1494 [44] DELPHI Collaboration.
- 1495 [arXiv:hep-ex/0403041v1](https://arxiv.org/abs/hep-ex/0403041v1)
- 1496 [45] A. Djouadi,G. Moreau,F. Richard, and R. K. Singh.
- 1497 PHYSICAL REVIEW D 82, 071702(R) (2010)
- 1498 [46] Y. Hosotani and M. Mabe.
- 1499 Physics Letters B, 615(3-4):257-265, 2005.
- 1500 [47] Y. Cui, T. Gherghetta, and J. Stokes.
- 1501 Journal of High Energy Physics, 2010(12):1-21, 2010.
- 1502 [48] M. Carena, E. Ponton, J. Santiago, and C.E.M. Wagner.
- 1503 Nuclear Physics B, 759(1-2):202-227, 2006.
- 1504 [49] L. Randall and R. Sundrum.
- 1505 Phys.Rev. Lett. 83, 3370 (1999) [[hep-ph/9905221](https://arxiv.org/abs/hep-ph/9905221)] .
- 1506 [50] L. Randall and R. Sun drum.
- 1507 [[hep-th/9906064](https://arxiv.org/abs/hep-th/9906064)]
- 1508 [51] Filimon Gournaris. 01-04-2008. IoP HEPP Annual Meeting, Lancaster University.
- 1509 <http://indico.cern.ch/getFile.py/access?contribId=14&sessionId=12&resId=0&materialId=slides&confId=27799>
- 1511 [52] J. Fleischer *et al.*
- 1512 [arXiv:hep-ph/0302259v1](https://arxiv.org/abs/hep-ph/0302259v1)
- 1513 [53] Ikematsu *et al.*
- 1514 Phys.Rev.D84:014033,2011 arXiv:1104.5132
- 1515 [54] H. Tabassam, Victoria Martin.
- 1516 [arXiv:1202.6013v1\[hep-ex\]](https://arxiv.org/abs/1202.6013v1)

- 1517 [55] Tony Price *et al.*  
1518 LC-REP-2013-004.  
1519 <http://www-flc.desy.de/lcnotes/notes/LC-REP-2013-004.pdf>
- 1520 [56] M. Klute *et al.*  
1521 [arXiv:1301.1322\[hep-ph\]](arXiv:1301.1322[hep-ph]).
- 1522 [57] S. Alekhin *et al.*  
1523 [arXiv:1207.0980\[hep-ph\]](arXiv:1207.0980[hep-ph])
- 1524 [58] K. W. Robinson.  
1525 Physical Review, Volume 111, Number 2. July 15 1958.  
1526 <http://ab-abp-rlc.web.cern.ch/ab-abp-rlc/AP-literature/Robinson-1958.pdf>
- 1528 [59] M. Aicheler *et al.*  
1529 [http://project-clic-cdr.web.cern.ch/project-clic-cdr/CDR\\_Volume1.pdf](http://project-clic-cdr.web.cern.ch/project-clic-cdr/CDR_Volume1.pdf)
- 1530 [60] SiD Detector Outline Document.  
1531 <http://hep.uchicago.edu/~oreglia/siddod.pdf>
- 1532 [61] <http://ilcild.org/>
- 1533 [62] International Linear Collider.  
1534 Reference Design Report.  
1535 [http://ilcdoc.linearcollider.org/record/6321/files/ILC\\_RDR\\_Volume\\_3-Accelerator.pdf](http://ilcdoc.linearcollider.org/record/6321/files/ILC_RDR_Volume_3-Accelerator.pdf)
- 1537 [63] The International Large Detector. Letter of Intent.  
1538 <http://ilcild.org/documents/ild-letter-of-intent/LOI/20Feb2010.pdf>
- 1539 [64] The International Large Detector.  
1540 Detector Baseline Design (DBD).  
1541 <https://svnsrv.desy.de/baswebsvn/wsvn/General.ilddbd/tags/V00-01/ildbdb/ILD-master.pdf>
- 1543 [65] W. Li *et al.*  
1544 <http://accelconf.web.cern.ch/accelconf/IPAC2012/papers/tuppr042.pdf>
- 1545 [66] M. A. Thomson.  
1546 Nucl. Instr and Meth. A611 (2009) 25-40. <arXiv:0907.3577>
- 1547 [67] M.A. Thomson.  
1548 <http://www.hep.phy.cam.ac.uk/~thomson/publications/hsw06.pdf>

- 1549 [68] J-C Brient and H. Videau  
1550 :arXiv:hep-ex/0202004
- 1551 [69] The CALICE Collboration.  
1552 [arXiv:1105.3417v3](https://arxiv.org/abs/1105.3417v3)
- 1553 [70] CMS PAS PFT-10-002.  
1554 <http://cms-physics.web.cern.ch/cms-physics/public/PFT-10-002-pas.pdf>
- 1555 [71] F. Beaudette. CMS Collaboration.  
1556 <http://cds.cern.ch/record/1319088>
- 1557 [72] I. Valin, C. Hu-Guo, J. Baudot, G. Bertolone, A. Besson, et al.  
1558 JINST 7 (2012) C01102.  
1559 [http://iopscience.iop.org/1748-0221/7/01/C01102/pdf/1748-0221\\_7\\_01\\_C01102.pdf](http://iopscience.iop.org/1748-0221/7/01/C01102/pdf/1748-0221_7_01_C01102.pdf)
- 1561 [73] E. Kato *et al.*  
1562 [arXiv:1202.3017v1](https://arxiv.org/abs/1202.3017v1)
- 1563 [74] J. Velthuis *et al.*  
1564 Nucl. Instrum. Meth. **A579** (2007) 685-89.
- 1565 [75] D. J. Jackson, D. Su, F. J. Wickens.  
1566 SLAC-PUB-13025. <http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-13025.pdf>
- 1568 [76] <https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome>
- 1569 [77] CALICE Collaboration.  
1570 [arXiv:0805.4833](https://arxiv.org/abs/0805.4833)
- 1571 [78] CALICE Collaboration.  
1572 [arXiv:0811.2354](https://arxiv.org/abs/0811.2354)
- 1573 [79] J. Rouene.  
1574 <http://ilcagenda.linearcollider.org/getFile.py/access?contribId=50&sessionId=10&resId=0&materialId=slides&confId=5468>
- 1576 [80] M. Reinhard, J. C. Brient. [arXiv:0902.3042v1](https://arxiv.org/abs/0902.3042v1)
- 1577 [105] D. Bailey *et al.*  
1578 Nucl. Instrum. Meth. A610 (2009) 573-589. [arXiv:0908.3019](https://arxiv.org/abs/0908.3019)
- 1579 [82] M. Cacciari, G. P. Salam.  
1580 Phys. Lett. B 641:57-61, 2006. [arXiv:hep-ph/0512210](https://arxiv.org/abs/hep-ph/0512210)

- 1581 [83] P. Schade, J. Kaminski.  
1582 Nuclear Instruments and Methods in Physics Research **A628(2011)** 128-132.
- 1583 [84] The CALICE Collaboration.  
1584 JINST **7** (2012) P09017 [arXiv:1207.4210v2](https://arxiv.org/abs/1207.4210v2)
- 1585 [85] International Linear Collider. [www.linearcollider.org](http://www.linearcollider.org). [www.ilcild.org/](http://www.ilcild.org/)
- 1586 [86] CALICE Collaboration.  
1587 <http://twiki.cern.ch/twiki/bin/view/CALICE/WebHome>
- 1588 [87] M.S. Amjad.  
1589 CALICE Collaboration Meeting, Casablanca, Morocco. 2010.
- 1590 [88] T. H. TRAN.  
1591 Presentation at LCWS12. 2012.
- 1592 [89] V. Mishra *et al.*  
1593 PRAMANA journal of physics. Vol. 65, No. 2. August 2005 pp. 259-272.  
1594 <http://www.ias.ac.in/pramana/v65/p259/fulltext.pdf>
- 1595 [90] Naomi van der Kolk.  
1596 Publication in progress.
- 1597 [91] Y. L. Dokshitzer,  
1598 Contribution cited in Report of the Hard QCD Working Group,  
1599 Proc. Workshop on Jet Studies at LEP and HERA, Durham,  
1600 December 1990, J. Phys. G17 (1991) 1537.
- 1601 [92] S. Catani, Y. L. Dokshitzer, M. Olsson, G. Turnock, B. R. Webber.  
1602 Phys. Lett. B269 (1991) 432-438.
- 1603 [93] PYTHIA 6.4 Physics and Manual.  
1604 T. Sjostrand, S. Mrenna, P. Skands.  
1605 [arXiv:hep-ph/0603175](https://arxiv.org/abs/hep-ph/0603175).
- 1606 [94] EUDET-Memo-2009-13.  
1607 P. Sicho et al.  
1608 <http://www.eudet.org/e26/e28/e42441/e68274/EUDET-MEMO-2009-13.pdf>
- 1609 [95] CALICE Collaboration  
1610 [arXiv:0805.4833v2\[physics.ins-det\]](https://arxiv.org/abs/0805.4833v2[physics.ins-det])
- 1611 [96] CALICE Collaboration  
1612 [arXiv:0811.2354\[physics.ins-det\]](https://arxiv.org/abs/0811.2354[physics.ins-det])

- 1613 [97] P. de Freitas et al.  
1614 <http://polzope.in2p3.fr:8081/MOKKA>.
- 1615 [98] ILCSOFT  
1616 <http://ilcsoft.desy.de/portal>
- 1617 [99] Letter of intent. 2009.  
1618 <http://ilcild.org/documents/ild-letter-of-intent>.
- 1619 [100] Hengne Li. 2009  
1620 <http://tel.archives-ouvertes.fr/tel-00430432/fr/>
- 1621 [101] M. A. Thomson,  
1622 ZFinder: A Marlin processor for Bremsstrahlung recovery., (2009)
- 1623 [102] R. Cornat.  
1624 Nuclear Science Symposium Conference Record. NSS'08 IEEE (2008).
- 1625 [103] M.S. Amjad *et al.*,  
1626 [arXiv:1307.8102](https://arxiv.org/abs/1307.8102)
- 1627 [104] K. Lannon, F. Margaroli and C. Neu,  
1628 [arXiv:1201.5873v1\[hep-ex\]](https://arxiv.org/abs/1201.5873v1)
- 1629 [105] D. Bailey *et al.*  
1630 Nucl. Instrum. Meth. A610:573-589,2009. [arXiv:0908.3019](https://arxiv.org/abs/0908.3019)
- 1631 [106] T. Han.  
1632 [arXiv:hep-ph/0508097v1](https://arxiv.org/abs/hep-ph/0508097v1)
- 1633 [107] G. Moortgat-Pick *et al.*  
1634 Phys.Rept.460:131-243,2008 [arXiv:hep-ph/0507011](https://arxiv.org/abs/hep-ph/0507011).
- 1635 [108] Katsumasa Ikematsu *et al.*  
1636 [arXiv:1005.4635v1\[hep-ex\]](https://arxiv.org/abs/1005.4635v1)
- 1637 [109] W. Kilian, T. Ohl, and J. Reuter,  
1638 Eur. Phys. J. **C21** (2011) 1742,  
1639 [arxiv:0708.4233](https://arxiv.org/abs/0708.4233)
- 1640 [110] M. Moretti, T. Ohl, and J. Reuter.  
1641 [arxiv:0102195](https://arxiv.org/abs/0102195).
- 1642 [111] D. J. Jackson.  
1643 Nucl. Instrum. Meth. A 388 (1997) 247.

- 1644 [112] T. Schwarz *et al.*, [CDF Collaboration], CDF-Note 10584,  
1645 [http://www-cdf.fnal.gov/physics/new/top/2011/AfbComb/Afb\\_combo\\_5invfb.pdf](http://www-cdf.fnal.gov/physics/new/top/2011/AfbComb/Afb_combo_5invfb.pdf)
- 1647 [113] V. M. Abazov *et al.* [D0 Collaboration],  
1648 Phys. Rev. D **84**, 112005 (2011) [arXiv:1107.4995\[hep-ex\]](https://arxiv.org/abs/1107.4995).
- 1649 [114] CMS Collaboration, Physics Analysis Summary CMS-PAS-TOP-11-30 (2011).
- 1650 [115] ATLAS Collaboration, ATLAS-CONF-2011-106 (2011).
- 1651 [116] M. I. Gresham, I. -W. Kim and K. M. Zurek,  
1652 Phys. Rev. D **85**, 014022 (2012) [arXiv:1107.4364\[hep-ph\]](https://arxiv.org/abs/1107.4364).
- 1653 [117] J. A. Aguilar-Saavedra,  
1654 [arXiv:1202.2382v1\[hep-ph\]](https://arxiv.org/abs/1202.2382v1).
- 1655 [118] S. J. Brodsky and X. -G. Wu,  
1656 Phys. Rev. Lett. **109**, 042002 (2012) [arXiv:1203.5312\[hep-ph\]](https://arxiv.org/abs/1203.5312).
- 1657 [119] M.S. Amjad *et al.*, LC-REP-2013-007,  
1658 <http://www-flc.desy.de/lcnotes/notes/LC-REP-2013-007.pdf>.
- 1659 [120] P. Doublet.  
1660 PhD-Thesis Université de Paris XI.  
1661 LAL, LAL 11-222 (2011).
- 1662 [121] P. Doublet, F. Richard, R. Poschl, T. Frisson and J. Rouene.  
1663 [arXiv:1202.6659\[hep-ex\]](https://arxiv.org/abs/1202.6659).