

QCD-resummation and non-minimal flavour-violation for supersymmetric particle production at hadron colliders

Ph.D. defense of Benjamin Fuks

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Outline

- 1 **Supersymmetry**
 - Main features of the MSSM
 - mSUGRA with NMFV
 - SUSY particle production at hadron colliders
- 2 **Resummation for slepton-pair hadroproduction in the MSSM**
 - Leading order results: Single-spin asymmetries
 - Next-to-leading order calculations
 - Resummation formalisms
 - Transverse-momentum distributions
 - Invariant-mass distributions
 - Total cross sections
- 3 **Squark and gaugino hadroproduction in NMFV SUSY**
 - Considered benchmark point
 - Squark-antisquark pair production
 - Associated squark-gaugino production
- 4 **Summary and outlook**

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Main features of the MSSM

- High energy extension to Standard Model.
- Symmetry between fermions and bosons.

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle$$

$$Q|\text{Fermion}\rangle = |\text{Boson}\rangle \quad \text{where } Q \text{ is a SUSY generator}$$
- Minimal Supersymmetric Standard Model (MSSM): one SUSY generator.
 ⇒ One SUSY partner for each SM particle.

Particle content of the MSSM

Names		particle	spin	superpartner	spin
(s)quarks (×3 families)	Q	$(u_L d_L)$	1/2	$(\tilde{u}_L \tilde{d}_L)$	0
	\bar{u}	u_R^\dagger	1/2	\tilde{u}_R^*	0
	\bar{d}	d_R^\dagger	1/2	\tilde{d}_R^*	0
(s)leptons (×3 families)	L	(νe_L)	1/2	$(\tilde{\nu} \tilde{e}_L)$	0
	\bar{e}	e_R^\dagger	1/2	\tilde{e}_R^*	0
Higgs(inos)	H_u	$(H_u^+ H_u^0)$	0	$(\tilde{H}_u^+ \tilde{H}_u^0)$	1/2
	H_d	$(H_d^0 H_d^-)$	0	$(\tilde{H}_d^0 \tilde{H}_d^-)$	1/2
gluon/gluino		g	1	\tilde{g}	1/2
W bosons/winos		W^\pm, W^0	1	$\tilde{W}^\pm, \tilde{W}^0$	1/2
B boson / bino		B	1	\tilde{B}	1/2

- Two Higgs doublets (\equiv eight degrees of freedom).
 \Rightarrow 3 Nambu-Goldstone bosons eaten by the Z^0 and W^\pm bosons to get massive.
 \Rightarrow 5 remaining physical Higgses (h^0, H^0, A^0 and H^\pm).
- Mixing of gauginos/Higgsinos (same electric charge, spin and color).
 - * **Charginos:** $(\tilde{W}^\pm, \tilde{H}_{\{u,d\}}^\pm) \Rightarrow (\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)$.
 - * **Neutralinos:** $(\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0) \Rightarrow (\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)$.

Advantages of the MSSM

- Some advantages
 - * **Solution to the hierarchy problem** (stabilization of the Higgs mass).
[Witten (1981); Kaul (1982)]
 - * **Gauge coupling unification** at high energy ($Q \sim 10^{16}$ GeV).
[Ibanez, Ross (1981); Dimopoulos, Raby, Wilczek (1981)]
[Amaldi, de Boer, Fürstenau (1991); Carena, Pokorski, Wagner (1993)]
 - * **R -parity conservation: $R = (-1)^{(3B+L+2S)}$.**
 - ⇒ No B or L violating terms in the Lagrangian (✓ proton lifetime).
 - ⇒ **Lightest SUSY particle stable and neutral** ⇔ **dark matter candidate.**
[Goldberg (1983); Ellis *et al.* (1984)]
 - ⇒ SUSY particle produced in pairs at colliders.
 - ⇒ Large amount of \cancel{E}_T in SUSY decays.
 - * ...
- Problem: more than **100 new free parameters.**

SUSY-breaking

- No SUSY discovery until now:
 - * SUSY must be broken,
 - * SUSY masses at a higher scale than SM masses.

- SUSY-breaking:
 - * Is soft (no additional quadratic divergences).
 - * Occurs in a hidden sector.
 - * **Mediated through the visible sector via a given interaction.**

- Minimal supergravity (mSUGRA):
 - * Gravitational interaction.
 - * Non renormalizable interactions, suppressed by the Planck mass.
 - * Determined by **5** parameters ($m_0, m_{1/2}, A_0, \tan \beta, \text{sgn}(\mu)$).

- Gauge-mediated SUSY-breaking (GMSB):
 - * Gauge interactions.
 - * Couplings to messenger fields.
 - * Determined by **6** parameters ($M_{\text{mes}}, \Lambda, n_q, n_l, \tan \beta, \text{sgn}(\mu)$).

Constrained minimal flavour violation

[Ciuchini, Degrandi, Gambino, Giudice (1998)]

- Squared sfermion mass matrices:

$$M_{\tilde{F}}^2 = \begin{pmatrix} M_{LL,1}^2 & 0 & 0 & m_1 m_{LR,1} & 0 & 0 \\ 0 & M_{LL,2}^2 & 0 & 0 & m_2 m_{LR,2} & 0 \\ 0 & 0 & M_{LL,3}^2 & 0 & 0 & m_3 m_{LR,3} \\ m_1 m_{RL,1} & 0 & 0 & M_{RR,1}^2 & 0 & 0 \\ 0 & m_2 m_{RL,2} & 0 & 0 & M_{RR,2}^2 & 0 \\ 0 & 0 & m_3 m_{RL,3} & 0 & 0 & M_{RR,3}^2 \end{pmatrix}$$

- * All flavour-violating elements of $M_{\tilde{F}}^2$ are **zero**.
 - * **Sfermion mixing**: $(\tilde{f}_L, \tilde{f}_R) \Rightarrow (\tilde{f}_1, \tilde{f}_2)$ with flavour conservation.
 - * Small first- and second-generation fermion masses: $m_1, m_2 \rightarrow 0$.
 - * **Three flavour-conserving mixing angles**, $\theta_{\tilde{t}}$, $\theta_{\tilde{b}}$ and $\theta_{\tilde{\tau}}$.
- Squark sector
 - * Flavour violation is governed by the **CKM matrix**, within the interactions.
 - * e.g. chargino-squark-quark vertex proportional to $V_{qq'}$.

Non-minimal flavour violation

[Gabbiani, Gabrielli, Masiero, Silvestrini (1996)]

- The squared squark mass matrices are

$$M_{\tilde{Q}}^2 = \begin{pmatrix} M_{LL,1}^2 & \Delta_{LL}^{12} & \Delta_{LL}^{13} & m_1 m_{LR,1} & \Delta_{LR}^{12} & \Delta_{LR}^{13} \\ \Delta_{LL}^{21} & M_{LL,2}^2 & \Delta_{LL}^{23} & \Delta_{RL}^{21} & m_2 m_{LR,2} & \Delta_{LR}^{23} \\ \Delta_{LL}^{31} & \Delta_{LL}^{32} & M_{LL,3}^2 & \Delta_{RL}^{31} & \Delta_{RL}^{32} & m_3 m_{LR,3} \\ m_1 m_{RL,1} & \Delta_{RL}^{12} & \Delta_{RL}^{13} & M_{RR,1}^2 & \Delta_{RR}^{12} & \Delta_{RR}^{13} \\ \Delta_{LR}^{21} & m_2 m_{RL,2} & \Delta_{RL}^{23} & \Delta_{RR}^{21} & M_{RR,2}^2 & \Delta_{RR}^{23} \\ \Delta_{LR}^{31} & \Delta_{LR}^{32} & m_3 m_{RL,3} & \Delta_{RR}^{31} & \Delta_{RR}^{32} & M_{RR,3}^2 \end{pmatrix}.$$

- The off-diagonal elements are **24 new free parameters**, parameterized by

$$\Delta_{ij}^{qq'} = \lambda_{ij}^{qq'} M_{ii,q} M_{jj,q'}.$$

- Diagonalization through 6×6 rotation matrices R^u and R^d .

- Physical eigenstates given by

$$\begin{aligned} (\tilde{u}_1, \tilde{u}_2, \tilde{u}_3, \tilde{u}_4, \tilde{u}_5, \tilde{u}_6)^T &= R^u (\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R)^T, \\ (\tilde{d}_1, \tilde{d}_2, \tilde{d}_3, \tilde{d}_4, \tilde{d}_5, \tilde{d}_6)^T &= R^d (\tilde{d}_L, \tilde{s}_L, \tilde{b}_L, \tilde{d}_R, \tilde{s}_R, \tilde{b}_R)^T. \end{aligned}$$

Constraints on non-minimal flavour violation

- Scaling of the off-diagonal terms with the SUSY-breaking scale:

$$\Delta_{LL} \gg \Delta_{LR,RL} \gg \Delta_{RR}$$

[Gabbiani, Masiero (1989)]

- FCNC: upper limits on λ 's.

- * Neutral kaon sector ($\Delta m_K, \varepsilon, \varepsilon'/\varepsilon$)
- * B -meson oscillations,
- * D -meson oscillations (Δm_D),
- * Rare decays ($\text{BR}(b \rightarrow s\gamma), \text{BR}(\mu \rightarrow e\gamma), \text{BR}(\tau \rightarrow e\gamma), \text{BR}(\tau \rightarrow \mu\gamma)$),
- * Electric dipole moments (d_n and d_e).

[Gabbiani, Gabrielli, Masiero, Silvestrini (1996)]

[Ciuchini, Masiero, Paradisi, Silvestrini, Vempati, Vives (2007)]

- Constraints:** $\lambda_{LL}^{ct} \leq 0.1, \lambda_{LL}^{bs} \leq 0.1$, other $\lambda_{ij}^{qq'} = 0$.

- Simplification:** $\lambda_{LL}^{ct} = \lambda_{LL}^{bs} = \lambda$.

⇒ Only **one** new free parameter.

⇒ Analysis of the experimentally allowed parameter space in mSUGRA with NMFV.

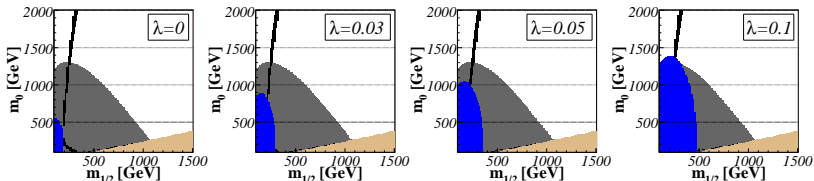
Low-energy, EW precision, and cosmological constraints

- $b \rightarrow s\gamma$:
 - * $\text{BR}(b \rightarrow s\gamma) = (3.55 \pm 0.26) \times 10^{-4}$ [Barbiero *et al.* (2006)].
 - * NMFV contributes at the **one-loop level** (same as the SM contributions).
- $\Delta\rho$:
 - * $\Delta\rho = 0.00102 \pm 0.00086$ (fits of EWPO) [PDG (2006)].
 - * **Sensitive to squark mass splitting** [Veltman (1977)].
 - * Influence on m_W and $\sin^2\theta_W$.
- a_μ
 - * $a_\mu^{\text{SUSY}} = (22 \pm 10) \times 10^{-10}$ (BNL data vs SM) [PDG (2006)].
 - * Squarks contribute at the **two-loop level** only.
 - * Disfavours $\mu < 0$.
- LSP:
 - * **Color singlet and electrically neutral** [Ellis *et al.* (1984)].
- $\Omega_{\text{CDM}} h^2$:
 - * $0.094 < \Omega_{\text{CDM}} h^2 < 0.136$ [Hamann, Hannestad, Sloth, Wong (2007)]
(WMAP, SDSS, SNLS, Baryon Acoustic Oscillations).

Constraints on the NMFV mSUGRA parameter space

SPheno 2.2.3 [Porod (2003)], FeynHiggs 2.5.1 [Heinemeyer, Hollik, Weiglein (2000)].

DarkSUSY 4.1 [Gondolo et al. (2004)].



- $\tan \beta = 10, \mu > 0, A_0 = 0 \text{ GeV}, 0 \leq \lambda \leq 0.1$.
- Region favoured by $a_\mu @ 2\sigma$ (grey)
Reduced squark two-loop vs. slepton one-loop contributions.
- Region excluded by $b \rightarrow s\gamma @ 2\sigma$ (blue)
Very sensitive to λ (same loop-level as the SM one).
- Charged LSP (beige)
- Region favoured by Ω_{CDM} (black)
Not really sensitive to λ .
- Region excluded by $\Delta\rho @ 2\sigma$ (not shown)
Very heavy scalar and gaugino masses excluded.

Benchmark points

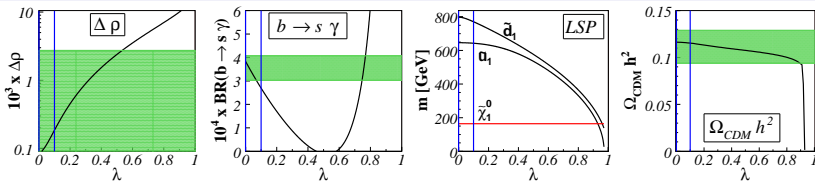
[Bozzi, BF, Herrmann, Klasen (2007)]

- (Some) allowed **benchmark points**:

	m_0 [GeV]	$m_{1/2}$ [GeV]	A_0 [GeV]	$\tan\beta$	$\text{sign}(\mu)$	λ bounds
A	700	200	0	10	+	[0;0.05]
B	100	400	0	10	+	[0;0.1]
C	230	590	0	30	+	[0;0.05]
D	600	700	0	50	+	[0;0.05]

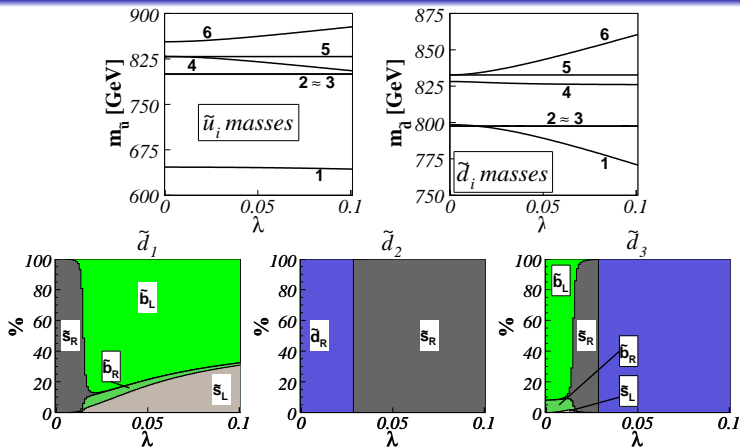
- Benchmarks also allowed for **cMFV scenarios** ($\lambda = 0$).
- In this talk: focus on **benchmark point B**.

Benchmark point BFHK-B: constraints



- $a_\mu \simeq 14 \times 10^{-10}$ (for any λ).
 - * Included in the PDG's 2σ range of $[2; 42] \times 10^{-10}$.
- $\Delta\rho$ (first figure).
 - * Depends strongly on squark flavours, helicities and masses.
 - * Large allowed range ($\lambda \leq 0.52$), due to important experimental errors.
- $b \rightarrow s\gamma$ (second figure).
 - * Very stringent constraint (small error band and large sensitivity on λ).
 - * 2nd allowed region disfavoured by $b \rightarrow s\mu^+\mu^-$ [Gambino, Haisch, Misiak (2005)].
- Cosmological constraints (third and fourth figures).
 - * Small mass difference between LSP and NLSPs at large λ .
 $\Rightarrow \Omega_{CDM}$ falls (co-annihilation and light squark propagated processes).
- **Allowed region: close to (c)MFV ($\lambda \lesssim 0.1$).**

Benchmark point BFHK-B: Mass splitting - flavour content



- Hermitian squark mass matrices depend continuously on the single parameter λ .
 - * The eigenvalues do not cross \Rightarrow **avoided crossings**.
 - * Exchange of the flavour content between the concerned eigenstates.
- Large mixing between 2nd and 3rd generations, even for small λ .

SUSY particles production at hadron colliders

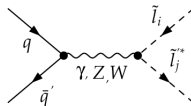
- Slepton-pair production.
 - * Much reduced sensitivity to NMFV (through squark-gluino loops only).
⇒ **cMFV hypothesis**.
 - * Fixed-order calculations at LO and SUSY-QCD NLO.
 - * Precision calculations including soft-gluon resummation.
- Squark- and gaugino-pair production.
 - * Fixed-order LO calculations in NMFV.
 - * QCD loop-corrections for squark-antisquark pair production (cMFV limit).

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Slepton-pair production at hadron colliders

- Drell-Yan like process



$$q\bar{q} \rightarrow \gamma, Z^0 \rightarrow \tilde{l}_i \tilde{l}_i^* \quad \text{and} \quad q\bar{q}' \rightarrow W^\mp \rightarrow \tilde{l}_i \tilde{\nu}_i^* + \text{c.c.}$$

- Sleptons are often light \Rightarrow decays into LSP + SM lepton \Rightarrow clean signal.
- Cross sections given by

$$(\Delta)\sigma = \sum_{a,b} \int_{\tau}^1 dx_a \int_{\tau/x_a}^1 dx_b (\Delta)f_{a/h_1}(x_a, \mu_F) (\Delta)f_{b/h_2}(x_b, \mu_F) (\Delta)\hat{\sigma}_{ab}(z, M; \alpha_s(\mu_R), \frac{M}{\mu_F}, \frac{M}{\mu_R})$$

where $(\Delta)\hat{\sigma}_{ab}$ is computed perturbatively

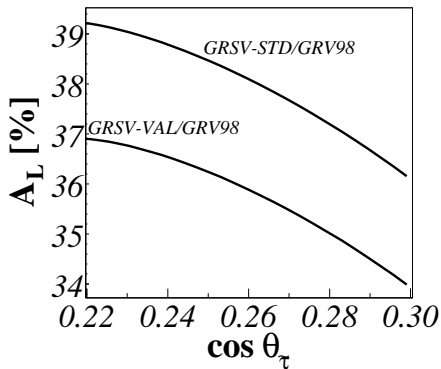
$$(\Delta)\hat{\sigma}_{ab}(z, M; \alpha_s(\mu_R), \frac{M}{\mu_F}, \frac{M}{\mu_R}) = \sum_{n=0}^{\infty} \left(\frac{\alpha_s(\mu_R)}{\pi} \right)^n (\Delta)\sigma_{ab}^{(n)}(z, M; \frac{M}{\mu_F}, \frac{M}{\mu_R}) .$$

Spin asymmetries

- Unpolarized cross section $d\hat{\sigma} = \frac{d\hat{\sigma}_{1,1} + d\hat{\sigma}_{1,-1} + d\hat{\sigma}_{-1,1} + d\hat{\sigma}_{-1,-1}}{4}$.
- Double-spin polarized cross section $d\Delta\hat{\sigma}_{LL} = \frac{d\hat{\sigma}_{1,1} - d\hat{\sigma}_{1,-1} - d\hat{\sigma}_{-1,1} + d\hat{\sigma}_{-1,-1}}{4}$.
- Single-spin cross polarized section $d\Delta\hat{\sigma}_L = \frac{d\hat{\sigma}_{1,1} + d\hat{\sigma}_{1,-1} - d\hat{\sigma}_{-1,1} - d\hat{\sigma}_{-1,-1}}{4}$.
- Double-spin asymmetry for slepton-pair production $A_{LL} = \frac{d\Delta\hat{\sigma}_{LL}}{d\hat{\sigma}} = -1$.
 ⇒ Independent of any SUSY parameter.
 ⇒ Single-spin asymmetry $A_L = \frac{\Delta\sigma_L}{\sigma}$.

Single-spin asymmetry and mixing effects at the Tevatron

$p \bar{p} \rightarrow \tau_1 \tau_1^*$ (Tevatron)

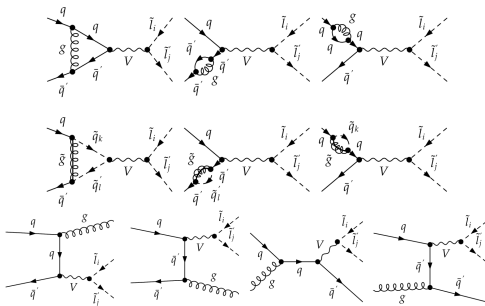


[Bozzi, BF, Klasen (2005)]

- Scenario based on SPS1a' (A_0 varying).
- **Sizeable** asymmetry.
- **Sensitive** to the mixing angle.
- **Large** PDF uncertainties.
- SM lepton pair production: $A_L \approx -0.09$.
 \Rightarrow **discrimination SUSY/SM Drell-Yan**.
- Upgraded Tevatron:
 - * One polarized beam.
[SPIN collaboration (1995)]
 - * Higher luminosity.

NLO calculations

- Feynman diagrams:



- Partonic invariant-mass and transverse-momentum distributions at $\mathcal{O}(\alpha_s)$:

$$\frac{d\hat{\sigma}_{ab}}{dM^2} = \hat{\sigma}_{ab}^{(0)}(M) \delta(1-z) + \frac{\alpha_s}{\pi} \hat{\sigma}_{ab}^{(1)}(M, z) + \mathcal{O}(\alpha_s^2),$$

$$\frac{d^2\hat{\sigma}_{ab}}{dM^2 dq_T^2} = \hat{\sigma}_{ab}^{(0)}(M) \delta(q_T^2) \delta(1-z) + \frac{\alpha_s}{\pi} \hat{\sigma}_{ab}^{(1)}(M, z, q_T) + \mathcal{O}(\alpha_s^2),$$

where $z = M^2/s$.

- Squark mixing included in the SUSY-loops.

q_T and invariant-mass distributions

- Soft and collinear radiations:

- * $\frac{\alpha_s^n}{q_T^2} \ln^m \frac{M^2}{q_T^2}$ or $\alpha_s^n \left(\frac{\ln^m(1-z)}{1-z} \right)_+$ terms in the distributions ($m \leq 2n - 1$).
- * Large at small q_T or $z \lesssim 1$.
- * **Fixed-order theory unreliable** in these kinematical regions.
- * Resummation to all orders needed.
 - $\Rightarrow q_T$ -resummation.
 - \Rightarrow Threshold resummation.
 - \Rightarrow Joint resummation.

- Advantages of resummation:

- * **Reliable** perturbative results.
- * **Correct quantification** of these radiations (even far from critical regions).
- * **Accurate** invariant-mass and q_T spectra.

q_T -distribution \Rightarrow transverse mass \Rightarrow spin and mass determination.

[Lester, Summers (1999); Barr (2006)]

M -distribution and total cross section \Rightarrow accurate mass determination.

[Bozzi, BF, Klasen (2007)]

Main features of the resummation

Reorganization of the cross section

$$d\sigma = d\sigma^{(\text{res})} + d\sigma^{(\text{fin})} .$$

- $d\sigma^{(\text{res})}$
 - * Contains all the logarithmic terms.
 - * Resummed to all orders in α_s .
 - * Exponentiation (Sudakov form factor).
- $d\sigma^{(\text{fin})}$
 - * Remaining contributions.

The resummed component: conjugate spaces (1)

- Conjugate space(s) introduced \Rightarrow **kinematics naturally factorizes**.
- N -moments defined by a Mellin transform

$$F(N) = \int_0^1 dy y^{N-1} F(y).$$

- Inverse transform:

$$F(y) = \oint_{C_N} \frac{dN}{2\pi i} y^{-N} F(N).$$

- N -moment of the hadronic cross section taken with respect to $\tau = M^2/s_h$.
- q_T -spectrum: impact-parameter b -space defined via a Fourier transform.
- The logarithms:

$$\begin{aligned} \left(\frac{\ln(1-z)}{1-z} \right)_+ &\rightarrow \ln^2 \bar{N} \quad \text{with} \quad \bar{N} = N \exp[\gamma_E] \\ \frac{1}{q_T^2} \ln \frac{M^2}{q_T^2} &\rightarrow \ln \bar{b}^2 \quad \text{with} \quad \bar{b} = \frac{bM}{2} \exp[\gamma_E] \end{aligned}$$

The resummed component: conjugate spaces (2)

- Factorization of the hadronic cross sections:

$$\frac{d\sigma^{(\text{res})}}{dM^2}(\tau, M) = \sum_{a,b} \int_{\tau}^1 dx_a \int_{\tau/x_a}^1 dx_b f_{a/h_1}(x_a, \mu_F) f_{b/h_2}(x_b, \mu_F) \hat{\sigma}_{ab}^{(\text{res})}(z; \alpha_s(\mu_R), \frac{M}{\mu_F}, \frac{M}{\mu_R})$$

↓

$$\frac{d\sigma^{(\text{res})}}{dM^2}(N, M) = \sum_{a,b} f_{a/h_1}(N+1, \mu_F) f_{b/h_2}(N+1, \mu_F) \hat{\sigma}_{ab}^{(\text{res})}(N; \alpha_s, \frac{M}{\mu_R}, \frac{M}{\mu_F}),$$

and

$$\frac{d^2\sigma^{(\text{res})}}{dM^2 dq_T^2}(\tau, M, q_T) = \sum_{a,b} \int_{\tau}^1 dx_a \int_{\tau/x_a}^1 dx_b f_{a/h_1}(x_a, \mu_F) f_{b/h_2}(x_b, \mu_F) \hat{\sigma}_{ab}^{(\text{res})}(z, q_T; \alpha_s(\mu_R), \frac{M}{\mu_F}, \frac{M}{\mu_R})$$

↓

$$\frac{d^2\sigma^{(\text{res})}}{dM^2 dq_T^2}(N, M, q_T) = \sum_{a,b} f_{a/h_1}(N+1, \mu_F) f_{b/h_2}(N+1, \mu_F) \int \frac{b}{2} db J_0(b q_T) \mathcal{W}_{ab}^F(N, b; \alpha_s, \frac{M}{\mu_R}, \frac{M}{\mu_F}).$$

- The logarithms are included in the functions $\hat{\sigma}^{(\text{res})}$ and \mathcal{W}^F .

The resummed component: the partonic cross section

- The process-dependence is factorized outside the exponent:

$$\mathcal{W}_{ab}^F(N, b) = \mathcal{H}_{ab}^F(N) \exp \left\{ \mathcal{G}(N, b) \right\},$$

$$\hat{\sigma}_{ab}^{(\text{res})}(N) = \sigma^{(LO)} \tilde{C}_{ab}(N; \alpha_s) \exp \left\{ \mathcal{G}(N, L) \right\}.$$

- \mathcal{H}^F - and \tilde{C} -functions:
 - * Can be computed perturbatively.
 - * Are process-dependent.
 - * Contain all the finite terms in the limit $N \rightarrow \infty$ and $b \rightarrow \infty$ (real and virtual collinear radiation, hard contributions).

The resummed component: the Sudakov form factor

- The Sudakov form factor contains the soft-collinear radiation:

$$\mathcal{G}(N, L; \frac{M^2}{\mu_R^2}) = L g^{(1)}(\alpha_s L) + \sum_{n=2}^{\infty} \left(\frac{\alpha_s}{\pi} \right)^{n-2} g_N^{(n)}(\alpha_s L; \frac{M^2}{\mu_R^2})$$

- The logarithm L is

	q_T	Joint	Threshold
$L = \ln(\dots)$	$1 + \bar{b}^2$	$\bar{b} + \frac{\bar{N}}{1 + \frac{\bar{b}}{4\bar{N}}}$	\bar{N}

- q_T -resummation not justified at small b (large q_T) \Rightarrow **+1** in the log (no change at large b).
- Argument of the log in joint resummation:
 \Rightarrow no subleading terms in perturbative expansions of $\sigma^{(\text{res})}$.
- At NLL accuracy: $g^{(1)}$ and $g^{(2)}$ needed
 $\equiv \alpha_s^n L^{2n}$ and $\alpha_s^n L^{2n-1}$.

The resummed component: improvements and remarks

- q_T -resummation [Catani, de Florian, Grazzini (2001); Bozzi, Catani, de Florian, Grazzini (2006)]
 - * Universal formalism.
 - * Process-independent Sudakov form factor.
 - * Resummation impact only in the relevant kinematical region.

- Threshold resummation [Sterman (1987); Catani, Trentadue (1989, 1991)]
 - * Consistent inclusion of the collinear radiation in the \tilde{C} -function.
[Krämer, Laenen, Spira (1998); Catani, de Florian, Grazzini (2001)]

- Joint resummation [Laenen, Sterman, Vogelsang (2001); Kulesza, Sterman, Vogelsang (2002, 2004)]
 - * Process-independent and universal Sudakov form factor.
[Bozzi, BF, Klasen (*in prep.*)]

The finite component: matching procedure

- Fixed-order theory
 - * Reliable far from the critical kinematical regions ($z \ll 1, q_T \gg 0$).
 - * Spoiled in the critical regions ($z \sim 1, q_T \sim 0$).
- Resummation
 - * Needed in the critical regions.
 - * Not justified far from the critical regions.
- Both contributions important in the intermediate kinematical regions.
- Information from both fixed-order and resummation needed.
- Need to avoid double-counting.
- Consistent matching procedure required:

$$d\sigma^{(\text{fin})} = d\sigma^{(\text{f.o.})} - d\sigma^{(\text{exp})}.$$

Summary: complete resummation formulae

- Invariant-mass spectrum

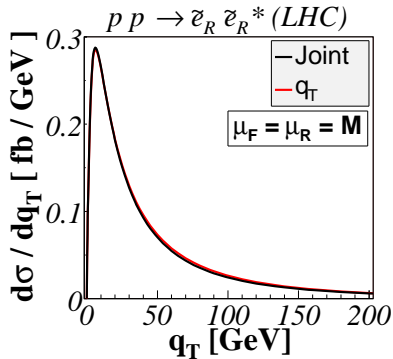
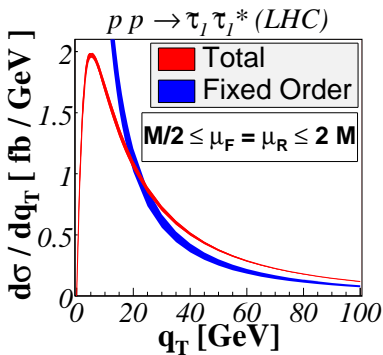
$$\begin{aligned} \frac{d\sigma}{dM^2}(\tau, M) &= \frac{d\sigma^{(\text{F.O.})}}{dM^2}(\tau, M) \\ &+ \oint_{C_N} \frac{dN}{2\pi i} \tau^{-N} \left[\frac{d\sigma^{(\text{res})}}{dM^2}(N, M) - \frac{d\sigma^{(\text{exp})}}{dM^2}(N, M) \right]. \end{aligned}$$

- Transverse-momentum spectrum

$$\begin{aligned} \frac{d^2\sigma}{dM^2 dq_T^2}(\tau, M, q_T) &= \frac{d^2\sigma^{(\text{F.O.})}}{dM^2 dq_T^2}(\tau, M, q_T) \\ &+ \oint_{C_N} \frac{dN}{2\pi i} \tau^{-N} \int \frac{b db}{2} J_0(q_T b) \left[\frac{d^2\sigma^{(\text{res})}}{dM^2 dq_T^2}(N, b) - \frac{d^2\sigma^{(\text{exp})}}{dM^2 dq_T^2}(N, b) \right]. \end{aligned}$$

- * Far from the critical regions, $d\sigma^{(\text{res})} \approx d\sigma^{(\text{exp})} \Rightarrow$ **Perturbative theory.**
- * In the critical regions, $d\sigma^{(\text{F.O.})} \approx d\sigma^{(\text{exp})} \Rightarrow$ **Pure resummation.**
- * In the intermediate regions \Rightarrow **Consistent matching.**

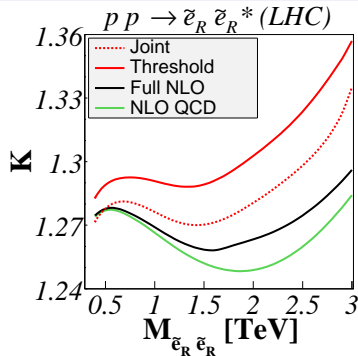
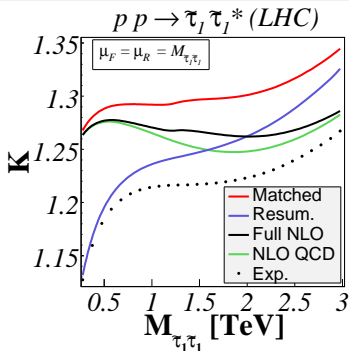
q_T -distribution at the LHC



[Bozzi, BF, Klasen (2006; *in prep.*)]

- * SPS1a and BFHK-B SUSY scenarios (slepton masses ≈ 100 -200 GeV).
- * Finite results at small q_T ; enhancement at intermediate q_T ; **finite total σ** .
- * **Improvement of scale dependences:** (NLL+LO $\lesssim 5\%$; LO 10%).
- * Effects of the threshold-enhanced contributions in the intermediate- q_T region.

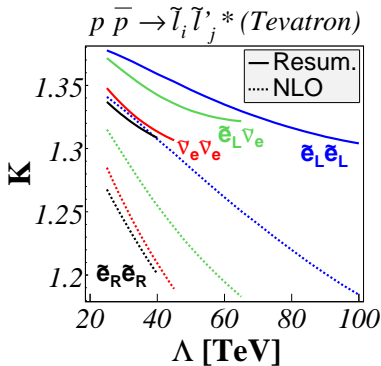
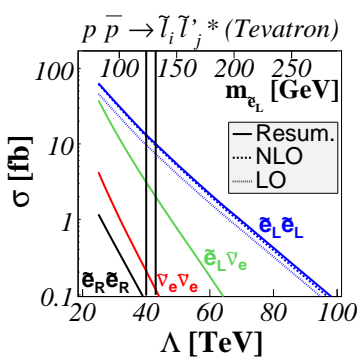
Invariant-mass distribution at the LHC



[Bozzi, BF, Klasen (2007; *in prep.*)]

- * SPS1a and BFHK-B SUSY scenarios (slepton masses $\approx 100\text{-}200$ GeV).
- * Normalization to LO cross section.
- * Small M : $d\sigma^{(\text{res})} \approx d\sigma^{(\text{exp})}$; Large M : $d\sigma^{(\text{F.O.})} \approx d\sigma^{(\text{exp})}$.
- * Reduced SUSY-loop effects.
- * Joint-exponent reproduces q_T -exponent.
 \Rightarrow some differences with threshold-resummation (however under control).

Threshold-resummed total cross sections at the Tevatron



[Bozzi, BF, Klasen (2007)]

- * SPS7 slope.
- * $\sigma \sim 0.1 - 100$ fb (\Rightarrow 1 to 1000 events).
- * NLO and threshold-resummation effects important.
- * Resummation more important for heavier sleptons.
- * Shift in $m_{\tilde{e}_L}$ if deduced from total σ measurement.

Outline

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 - Next-to-leading order calculations
 - Resummation formalisms
 - Transverse-momentum distributions
 - Invariant-mass distributions
 - Total cross sections
- 3 Squark and gaugino hadroproduction in NMFV SUSY
 - Considered benchmark point
 - Squark-antisquark pair production
 - Associated squark-gaugino production
- 4 Summary and outlook

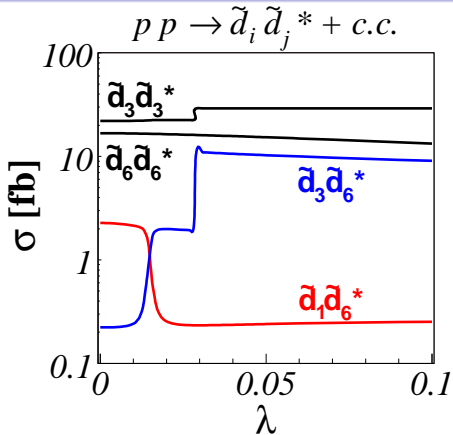
The benchmark point BFHK-B

- Benchmark point for our numerical studies:

m_0 [GeV]	$m_{1/2}$ [GeV]	A_0 [GeV]	$\tan\beta$	$sign(\mu)$	λ bounds
100	400	0	10	+	[0;0.1]

- * Light sleptons (200-300 GeV) and rather light gauginos (150-550 GeV).
- * Not too heavy squarks (650-850 GeV) and heavy gluino (900 GeV).
- * Collider friendly.

Neutral current squark-antisquark pair production



[Bozzi, BF, Herrmann, Klasen (2007)]

- Diagonal pairs:

- * Gluon-fusion initiated diagrams.
- * Strong production
⇒ Large cross sections.
- * Quite insensitive to λ
(flavour-independent $g\tilde{q}\tilde{q}$ vertex).

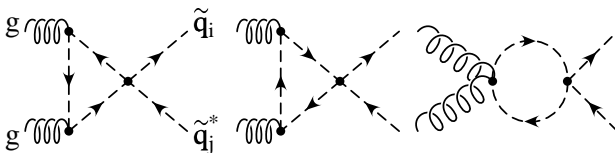
- Non-diagonal pairs:

- * Only $q\bar{q}$ annihilation diagrams (EW + heavy gluino).
- * Show sharp transitions with λ
(Avoided crossings - mass flips).
Example: $\tilde{d}_1 \tilde{d}_6^*$ and $\tilde{d}_3 \tilde{d}_6^*$



QCD-loops for squark-antisquark pair production (1)

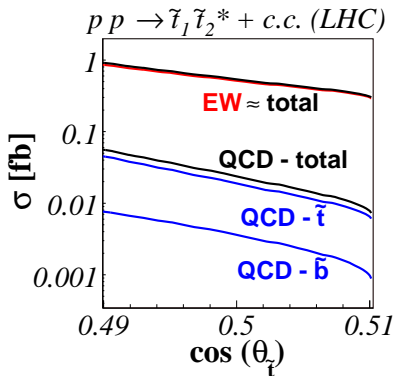
- cMFV limit taken, non-diagonal stop-pair production.
- Gluon fusion subprocesses (enhanced at the LHC).
- $\mathcal{O}(\alpha_s^4)$ diagrams



- * Gluino neglected (loops with heavy top quarks and gluino).
- * Strong coupling (enhancement).
- * Heavy SUSY propagators (suppression).
- * Comparable to $\mathcal{O}(\alpha^2)$ diagrams ?

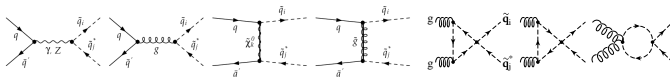
- Loop-contributions proportional to mixing.
⇒ Only third generation considered.

QCD-loops for squark-antisquark pair production (2)

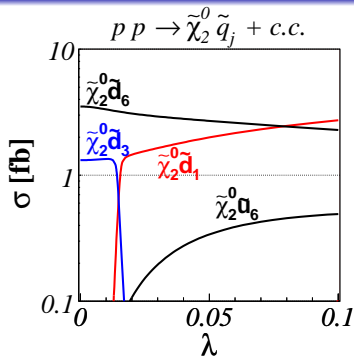


[Bozzi, BF, Klasen (2005)]

- SPS5 SUSY scenario (A_0 varying).
- Dominant Z diagram.
- \tilde{g} and $\tilde{\chi}^0$ t -channels suppressed (negligible top densities).
- QCD-loop effects reduced. (heavy propagators).
- Small sbottom contributions. (small mixing).

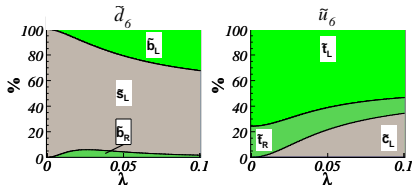
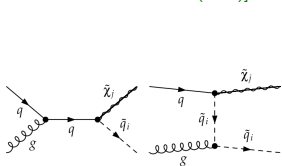


Associated squark-neutralino production



[Bozzi, BF, Herrmann, Klasen (2007)]

- Semi-strong production (10^{-1} fb to 10^2 fb).
- Quite sensitive to flavour violation (due to the $q\tilde{q}\tilde{\chi}$ vertex).
- \tilde{d}_1 - \tilde{d}_3 mass flip.
- $\tilde{d}_6\tilde{\chi}_2^0$ cross section decreases with λ (see \tilde{d}_6 strange/bottom content).
- $\tilde{u}_6\tilde{\chi}_2^0$ cross section increase with λ (see \tilde{u}_6 charm/top content).



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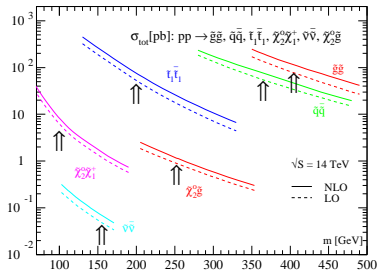
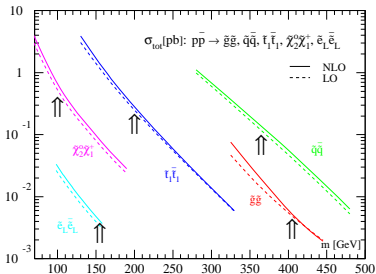
Conclusion and outlook

- Slepton-pair production at hadron colliders.
 - * Mixing effects in LO polarized cross sections.
 - * Full NLO SUSY-QCD calculations, including squark mixing.
 - * Threshold, q_T and joint resummations.
 - * Comparison with the Monte Carlo approach.
 - * Study of other SUSY particle production processes.
 - * Resummation vs. Monte Carlo for other BSM theories (Z').

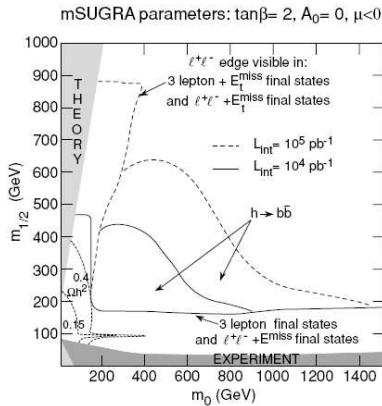
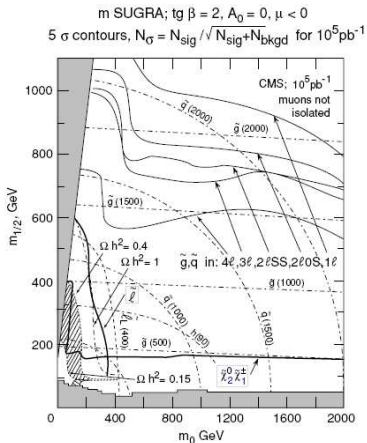
- Study of NMFV effects in the framework of mSUGRA.
 - * Implementation of a flexible computer program, XSUSY.
 - Interface with DarkSUSY, FeynHiggs, SPheno and SuSpect.
 - mSUGRA, GMSB and AMSB scenarios within NMFV.
 - Search for regions allowed by experimental data.
 - Cross sections at LO for “all” sparticle pair-production processes.
 - SUSY particle decays at LO.
 - * Inclusion of next-to-leading order, three-body decays.
 - * Full experimental study
(heavy-flavour tagging efficiencies, detector resolutions, background,...)

Appendix

SUSY cross sections



SUSY cross sections



[Abdullin et al. (2002)]

Minimal flavour violation (in the squark sector)

[D'Ambrosio, Giudice, Isidori, Strumia (2002); Altmannshofer, Buras, Guadagnoli (2007)]

- Flavour structure generated by the **Yukawa couplings**
 ≡ different renormalizations of the quark and squark mass matrices.
 ⇒ Additional flavour violation at the weak scale through RG running.
- Flavour-violating terms of the Lagrangian:
 - * Rewritten as **functions of the Yukawa couplings**.
 - * **Not set to zero** as for cMFV.
- The squared squark mass matrices are

$$M_{\tilde{Q}}^2 = \begin{pmatrix} M_{LL,1}^2 & \Delta_{LL}^{12} & \Delta_{LL}^{13} & m_1 m_{LR,1} & \Delta_{LR}^{12} & \Delta_{LR}^{13} \\ \Delta_{LL}^{21} & M_{LL,2}^2 & \Delta_{LL}^{23} & \Delta_{RL}^{21} & m_2 m_{LR,2} & \Delta_{LR}^{23} \\ \Delta_{LL}^{31} & \Delta_{LL}^{32} & M_{LL,3}^2 & \Delta_{RL}^{31} & \Delta_{LR}^{32} & m_3 m_{LR,3} \\ m_1 m_{RL,1} & \Delta_{RL}^{12} & \Delta_{RL}^{13} & M_{RR,1}^2 & \Delta_{RR}^{12} & \Delta_{RR}^{13} \\ \Delta_{LR}^{21} & m_2 m_{RL,2} & \Delta_{RL}^{23} & \Delta_{RR}^{21} & M_{RR,2}^2 & \Delta_{RR}^{23} \\ \Delta_{LR}^{31} & \Delta_{LR}^{32} & m_3 m_{RL,3} & \Delta_{RR}^{31} & \Delta_{RR}^{32} & M_{RR,3}^2 \end{pmatrix}$$

- The off-diagonal elements depend **only on the Yukawa couplings**.
- The diagonalizing matrices depend **only on the CKM matrix**.

Benchmark points

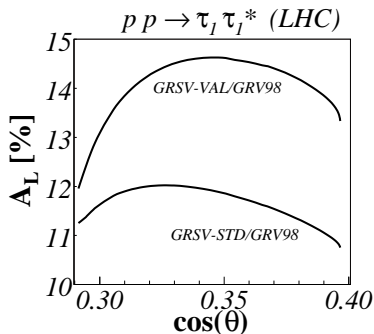
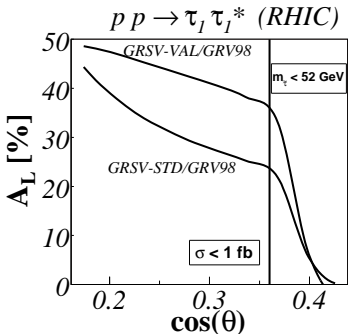
[Bozzi, BF, Herrmann, Klasen (2007)]

- (Some) allowed **benchmark points**:

	m_0 [GeV]	$m_{1/2}$ [GeV]	A_0 [GeV]	$\tan \beta$	$\text{sign}(\mu)$	λ bounds
A	700	200	0	10	+	[0;0.05]
B	100	400	0	10	+	[0;0.1]
C	230	590	0	30	+	[0;0.05]
D	600	700	0	50	+	[0;0.05]

- Benchmarks also allowed for:
 - * cMFV scenarios ($\lambda = 0$).
 - * MFV scenarios (λ ranging from zero to $5 \times 10^{-3} \dots 1 \times 10^{-2}$).
- In this talk: focus on **benchmark point B**.

Single-spin asymmetry and mixing effects at RHIC/LHC



[Bozzi, BF, Klasen (2005)]

- **RHIC**: SPS7-like scenario (Λ varying); strong θ_τ dependence; small $\cos \theta_\tau$ inaccessible and large $\cos \theta_\tau$ excluded by LEP.
- **LHC**: SPS4-like scenario (A_0 varying); reduced mixing angle dependence.
- **Both**: SM asymmetry of different sign, but large PDFs uncertainties.

Inverse transforms

- There are **singularities** in the integrand in the (b, N) spaces

$$\oint_{C_N} \frac{dN}{2\pi i} \tau^{-N} \int \frac{b db}{2} J_0(q_T b) \left[\frac{d^2 \sigma^{(\text{res})}}{dM^2 dq_T^2}(N, b) - \frac{d^2 \sigma^{(\text{exp})}}{dM^2 dq_T^2}(N, b) \right].$$

- * e.g. argument of the logarithm, Landau pole, PDFs, ...
 - * Must be avoided when getting back to physical space.
 - * **Prescription required.**
- Inverse b -transform:
 - * Integration contour diverted in the complex plane.
 - * Bessel function replaced by more convenient auxiliary functions.
[Laenen, Sterman, Vogelsang (2000)]
 - Inverse Mellin transform:
 - * Specific contour avoiding all the poles.
 - * Minimal prescription and principal value resummation.
[Catani, Mangano, Nason, Trentadue (1996); Contopanagos, Sterman (1994)]

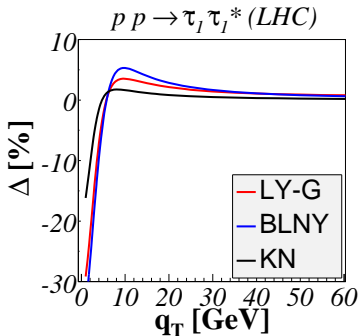
The resummed component: non perturbative effects

- Important non-perturbative (NP) effects for q_T -distributions (large- b region).
≡ intrinsic q_T of the partons, inside the hadrons.
- Resummation formula

$$\mathcal{W}_{ab}^F(N,b) = \mathcal{H}_{ab}^F(N) \exp \left\{ \mathcal{G}(N,b) + F_{ab}^{\text{NP}} \right\}.$$

- NP form factor obtained from experimental data:
 - * Ladinsky-Yuan (LY-G) [Ladinsky, Yuan (1994)].
 - * Brock-Landry-Nadolsky-Yuan (BLNY) [Landry, Brock, Nadolsky, Yuan (2003)].
 - * Konyshov-Nadolsky (KN) [Konyshov, Nadolsky (2006)].

q_T -distribution at the LHC

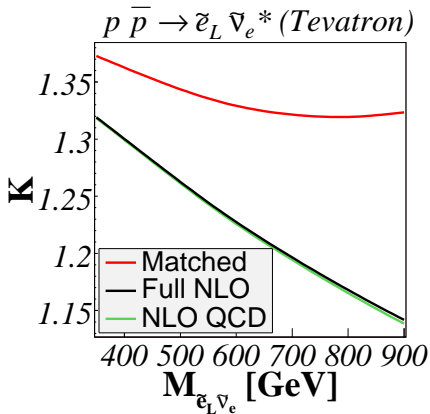


[Bozzi, BF, Klasen (2006)]

- * SPS1a scenario (slepton masses $\approx 100\text{-}200$ GeV).
- * Importance of the NP effects:

$$\Delta = \frac{d\sigma^{(\text{res.}+\text{NP})}(\mu = M) - d\sigma^{(\text{res.})}(\mu = M)}{d\sigma^{(\text{res.})}(\mu = M)}.$$

- * Non-perturbative effects under good control for $q_T > 5$ GeV.

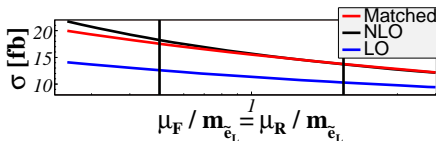
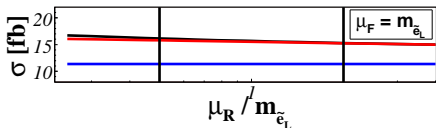
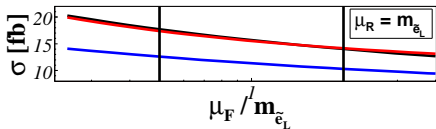
K-factors for associated $\tilde{e}_L \tilde{\nu}_e$ production at the Tevatron

[Bozzi, Fuks, Klasen (2007)]

- SPS1a' SUSY scenario.
- Normalization to LO cross section.
- Close to the threshold:
 - * Resummation effects important (even at low M).
 - * σ^{NLO} dominated by the logs.
 - * $\hat{\sigma} = \hat{\sigma}^{(res)}$ at the permille level.
 - * $\hat{\sigma}^{(f.o.)} = \hat{\sigma}^{(res)}|_{f.o.}$ at the same level.
- SUSY-loop effects reduced.

Dependence of the total σ on unphysical scales (1)

$$p \bar{p} \rightarrow \tilde{\nu}_L \tilde{\nu}_L^* \text{ (Tevatron)}$$

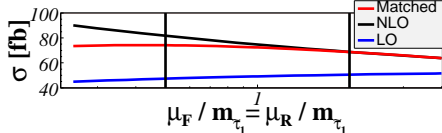
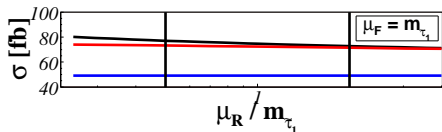
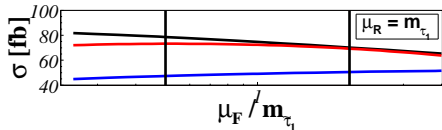


[Bozzi, Fuks, Klasen (2007)]

- SPS7 SUSY scenario.
- Theoretical uncertainty estimated by variations of μ_F and μ_R .
- μ_R dependence
 - * Absent at LO.
 - * Introduced at NLO.
 - * Tamed by resummation.
- μ_F dependence
 - * Reduced at NLO.
 - * Further stabilized by resummation.
- Total theoretical uncertainty.
 - * LO: 20%
 - * NLO: 29%
 - * Resummed: 23%

Dependence of the total σ on unphysical scales (2)

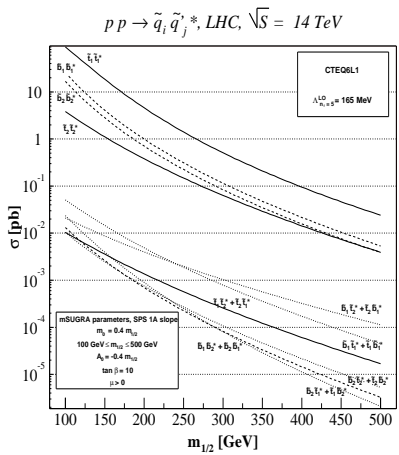
$$pp \rightarrow \tau_1 \tau_1^* \text{ (LHC)}$$



[Bozzi, Fuks, Klasen (2007)]

- SPS7 SUSY scenario.
- Theoretical uncertainty estimated by variations of μ_F and μ_R .
- μ_R dependence
 - * Absent at LO.
 - * Introduced at NLO.
 - * Tamed by resummation.
- μ_F dependence
 - * Overcompensated at NLO.
 - * Stabilized by resummation.
- Total theoretical uncertainty.
 - * LO: 7%
 - * NLO: 17%
 - * Resummed: 8%

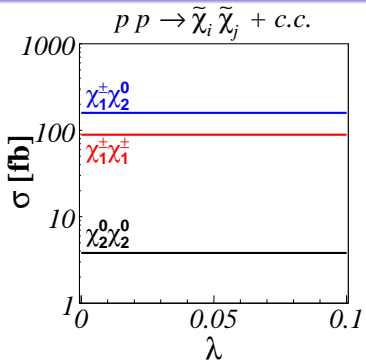
Neutral current squark-antisquark pair production (cMFV)



[Bozzi, BF, Klasen (2005)]

- SPS1a slope SUSY scenario.
- Only stop and sbottom mixing.
- **Diagonal production:**
 - * Large gluon luminosity (LHC).
 - * \exists gluon fusion channels.
 - \Rightarrow **enhanced.**
- **Non-diagonal production:**
 - * Weak production.
 - * One heavy final mass.
 - \Rightarrow **Phase-space suppressed.**
- **Mixed production:**
 - * Weak production.
 - * Light masses possibility.
 - * Charged final state.
 - \Rightarrow **Favoured over non-diagonal channels.**

Gaungino-pair production



- Light gauginos (rather large cross sections).
- Insensitive to flavour violation (sum over all the squark physical states).

[Bozzi, BF, Herrmann, Klasen (2007)]

