

# Transverse-momentum, threshold and joint resummations for slepton-pair production at hadron colliders

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# Outline

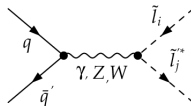
- 1 Introduction and motivations
- 2 Resummation formalisms
  - Main features of the resummation
  - The resummed component
  - Matching procedure
- 3 Applications
  - $q_T$ -distribution
  - Invariant-mass distribution
  - Total cross sections
- 4 Summary and outlook

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# Slepton-pair production at hadron colliders

- Drell-Yan like process



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

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

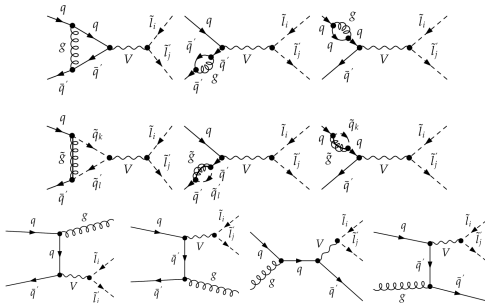
$$\sigma = \sum_{a,b} \int_{\tau}^1 dx_a \int_{\tau/x_a}^1 dx_b f_a/h_1(x_a, \mu_F) f_b/h_2(x_b, \mu_F) \hat{\sigma}_{ab}(z, M; \alpha_s(\mu_R), \frac{M}{\mu_F}, \frac{M}{\mu_R})$$

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

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

# Next-to-leading order calculations

- Feynman diagrams:



- Squark mixing included in the SUSY-loops.
- 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  $z = M^2/s$ .

# $q_T$ 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.
  - ⇒  $q_T$ -resummation.
  - ⇒ Threshold resummation.
  - ⇒ 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 ⇒ transverse mass ⇒ spin and mass determination.

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

$M$ -distribution and total cross section ⇒ accurate mass determination.

[Bozzi, BF, Klasen (2007)]

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# 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  $\alpha_s$ .
  - \* Exponentiation (Sudakov form factor).
- $d\sigma^{(\text{fin})}$ 
  - \* Remaining contributions.



# The resummed component: conjugate spaces

- Conjugate spaces: Mellin, impact-parameter  $\Rightarrow$  kinematics naturally factorizes.
- Factorization of the hadronic cross sections:

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

$$\downarrow$$

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

and

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

$$\downarrow$$

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

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

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

# 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 and **are process-dependent**.
  - \* Contain real and virtual collinear radiation, and hard contributions.
- The Sudakov form factor contains the soft-collinear radiation:
  - \* Can be computed perturbatively and **is process-independent**.
- Used formalisms:
  - \* Universal  $q_T$ -resummation. [Catani, de Florian, Grazzini (2001); Bozzi, Catani, de Florian, Grazzini (2006)]
  - \* Threshold resummation including collinear radiation. [Sterman (1987); Catani, Trentadue (1989, 1991); Krämer, Laenen, Spira (1998); Catani, de Florian, Grazzini (2001)]
  - \* Universal joint resummation. [Laenen, Sterman, Vogelsang (2001); Kulesza, Sterman, Vogelsang (2002, 2004); Bozzi, BF, Klasen (2007)]

# 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

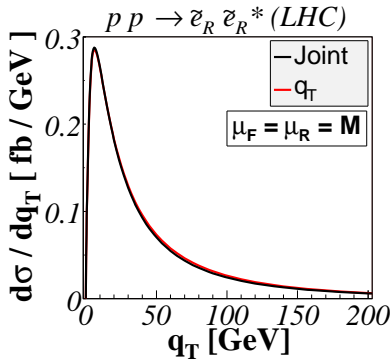
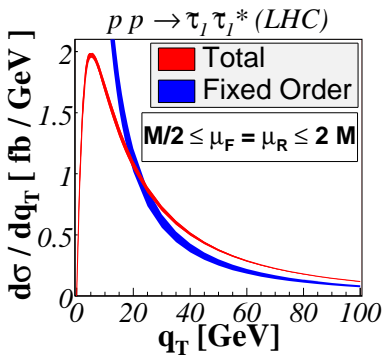
$$\begin{aligned} \frac{d^2\sigma}{dM^2 dq_T^2}(\tau, M, q_T) &= \frac{d^2\sigma^{(\text{F.O.})}}{dM^2 dq_T^2}(\tau, M, q_T) \\ &+ \oint_{C_N} \frac{dN}{2\pi i} \tau^{-N} \int \frac{b db}{2} J_0(q_T b) \left[ \frac{d^2\sigma^{(\text{res})}}{dM^2 dq_T^2}(N, b) - \frac{d^2\sigma^{(\text{exp})}}{dM^2 dq_T^2}(N,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

- \* 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.**

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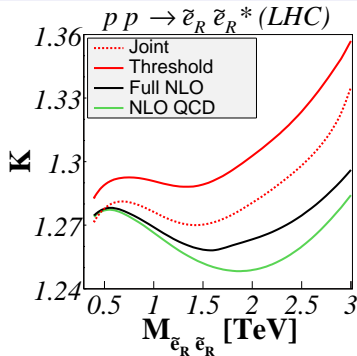
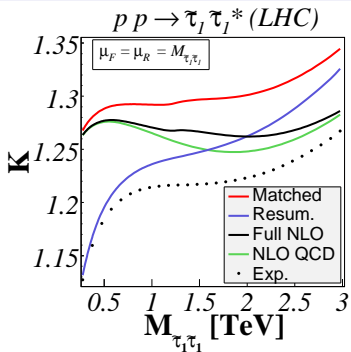
# $q_T$ -distribution at the LHC



[Bozzi, BF, Klasen (2006; 2007)]

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

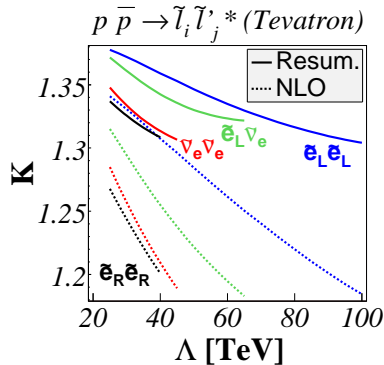
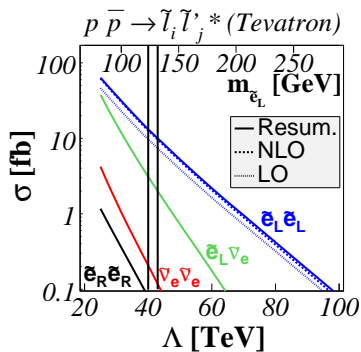
# Invariant-mass distribution at the LHC



[Bozzi, BF, Klasen (2007)]

- \* 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.
- \* NLO and threshold-resummation effects important.
- \* Resummation more important for heavier sleptons.
- \* Shift in  $m_{\tilde{e}_L}$  if deduced from total  $\sigma$  measurement.



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# Summary and outlook

- 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.  
(for other BSM theory; see Qiang Li's talk in *Tools* session)