QCD resummation in the framework of supersymmetry

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With G. Bozzi & M. Klasen [PRD **74** (2006) 015001; NPB **777** (2007) 157; NPB **794** (2007) 46]
With J. Debove & M. Klasen [PLB **688** (2010) 208; NPB **842** (2011) 51; NPB **849** (2011) 64]
With M. Klasen, D. Lamprea & M. Rothering [JHEP **1210** (2012) 081]

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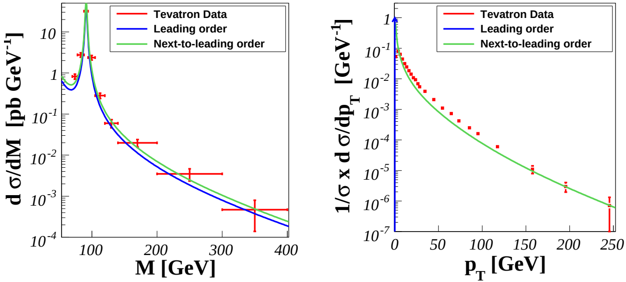
Outline

1. Motivation for precision calculations
2. Soft gluon resummation and Monte Carlo generators
3. Resummation for electroweak superpartner production at the LHC
4. Summary - conclusions

Need for precision: Drell-Yan process at the Tevatron

- **Confrontation between theory and Tevatron data** [DØ collaboration (2005, 2008)].



- * LO calculation: **Disagreement between theory and experiment.**
- * NLO invariant-mass distribution: **good agreement**.
- * NLO p_T-distribution:
  - ◇ **Very good agreement in the large-p_T region**.
  - ◇ **Underestimation in the intermediate-p_T region**.
  - ◇ **Divergence in the small-p_T region**.

- **How to improve NLO predictions** [in particular for the small-p_T region]?

Investigation of the next-to-leading order contributions

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

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

where $z = M^2/s$.

- **$\hat\sigma^{(1)}$ contains different pieces.**
  * **Real gluon emission** diagrams (in the soft limit).

$$iM \approx g_s T^a \left[\frac{\epsilon^*\cdot k_2}{k_2^0\mathbf{k_g^0}(\mathbf{1}+\cos\theta)} - \frac{k_1\cdot\epsilon^*}{k_1^0\mathbf{k_g^0}(\mathbf{1}-\cos\theta)}\right]\mathbf{iM}^{\mathrm{Born}}$$

  * **Virtual loop** contributions (in the soft limit).

$$iM \approx (i\,g_s^2)\int \mathrm{d}k_g\,\frac{k_1\cdot k_2}{k_g^2\,(k_1^0\mathbf{k_g^0}(\mathbf{1}-\cos\theta))(k_2^0\mathbf{k_g^0}(\mathbf{1}+\cos\theta))}\mathbf{iM}^{\mathrm{Born}}$$

Soft and collinear radiation diverges and factorizes.

The problem of the soft and collinear radiation

- **Sum of the two contributions.**

$$\mathrm{d}\sigma^{(1)} = \mathrm{d}\sigma^{(1,\mathrm{loop})} + \mathrm{d}\sigma^{(1,\mathrm{real})} \ .$$

  * **Cancellation** of the poles.
  * **Infrared behaviour:** logarithmic terms in the distributions,

$$\alpha_s \left(\frac{\ln(1-z)}{1-z} \right)_+ \qquad \text{and} \qquad \frac{\alpha_s}{p_T^2} \ln \frac{M^2}{p_T^2} \ .$$

  * **Problems at $z = \frac{M^2}{s} \lesssim 1$ or small p_T.**

The fixed-order theory is unreliable in these kinematical regions.

Improvements

Improvements of the next-to-leading order calculation.

- Matching with a resummation calculation.
  - * **Correct treatment** of the soft and collinear radiation.
    - ► Taken into account to all orders.
  - * **Perturbative method**.
  - * **Parton-level calculation.**
  - * Three formalisms:
    - - p_T**-resummation**: resums $\frac{\alpha_s}{p_T^2} \ln \frac{M^2}{p_T^2}$.
    - - **Threshold resummation**: resums $\left(\frac{\ln(1-z)}{1-z}\right)_+$.
    - - **Joint resummation**: resums both logarithms.
- Matching with a parton shower algorithm.
  - * **Approximation of the resummation calculation**.
  - * **Suitable for a proper description of the collision**.

Resummation philosophy

- **We consider an infrared sensitive quantity R.**
  * Depends on a **hard scale M**.
  * Depends on a **scale m measuring the distance from the critical region** (where the logs are large).
  * Contains **large ratios of scales**.

- **Resummation to all orders**.

$$R(M^2, m^2) = H\big(M^2/\mu^2\big)\ S\big(m^2/\mu^2\big)$$

  * **Separation** of the two scales $\equiv$ **refactorization**.
  * Remark: refactorization holds in conjugate spaces (*e.g.*, **Mellin space**).
  * S and H obey to

$$\frac{\partial H}{\partial \ln \mu^2} = -\frac{\partial S}{\partial \ln \mu^2} = \gamma_S(\mu^2)\ .$$

  * **Choice of $\mu = M$, introduction of the Sudakov form factor**.

$$\mathbf{R(M^2, m^2) = H(1)S(1)\exp\bigg[-\int_{m^2}^{M^2}\frac{dq^2}{q^2}\gamma_S(q^2)\bigg]}\ .$$

  * **No large ratios of scale anymore**.

A resummed cross section

- **Based on factorization properties (in conjugate space)**.
  * Mellin N-space (N conjugate to M^2/S_h).
  * Impact parameter b-space (conjugate to p_T).

$$\mathrm{d}\sigma^{(\mathrm{res})}(N,b) = \sum_{a,b} f_{a/h_1}(N+1)\, f_{b/h_2}(N+1)\, \mathcal{W}_{ab}(N,b),$$

$$\mathcal{W}_{ab}(N,b) = \mathcal{H}_{ab}(N) \exp\Big\{\mathcal{G}(N,b)\Big\}.$$

- The $\mathcal{H}$-coefficient:
  * Contains **real and virtual collinear radiation, hard contributions**.
  * **Can be computed perturbatively as series in α_s**, from fixed-order results.
  * Is process-dependent.

- The Sudakov form factor $\mathcal{G}$:
  * Contains **the soft-collinear radiation** (the logarithmic terms).
  * Resummed to all orders in α_s (exponentiated).
  * **Can be computed perturbatively as series in α_s log.**
  * **Is process-independent (universal)**.

The finite component - matching to the fixed order

- **Fixed-order calculations**.
  * **Reliable far from the critical kinematical regions**.
  * **Spoiled in the critical regions**.
- **Resummation**.
  * **Needed in the critical regions.**
  * **Not justified far from the critical regions.**
- **Intermediate kinematical regions:** both should contribute.

Information from both fixed order and resummation is required.
$\Rightarrow$ consistent matching procedure.

- **Matching procedure:**
  * Addition of both resummation (NLL) and fixed-order results (NLO).
  * Subtracting the **expansion** in α_s of the resummed result.
  * No double-counting of the logarithms.

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{(\mathrm{F.O.})} + \mathrm{d}\sigma^{(\mathrm{res})} - \mathrm{d}\sigma^{(\mathrm{exp})}.$$

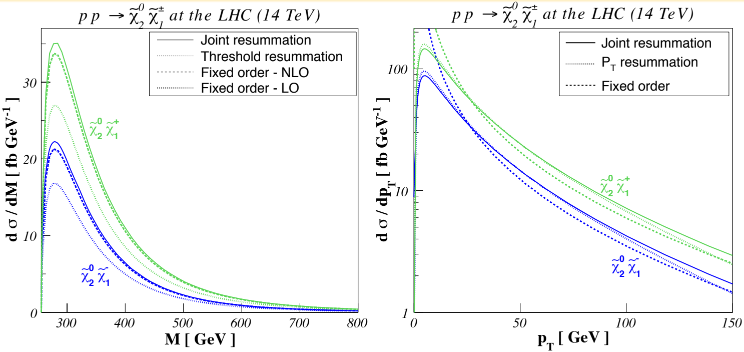
Merging multiparton matrix elements and showers

- **Matrix elements in the context of automated Monte Carlo tools**.
  - * Based on **fixed order theory**.
  - * **Technical limit** on the number of final state particles.
  - * Valid for **hard / well separated** partons ⇒ **hard / well separated jets**.
  - * All **spin and color information** correctly handled.
  - * Event generation **for the final state of interest with 0,1,2,... extra jets**.
- **Parton showers**.
  - * **Resummation of the large (leading) logarithms**.
  - * **High** final state multiplicity.
  - * Valid for **soft and/or collinear** partons ⇒ **soft and/or collinear jets**.
  - * **Approximate** spin and color information.

Complementary procedures.

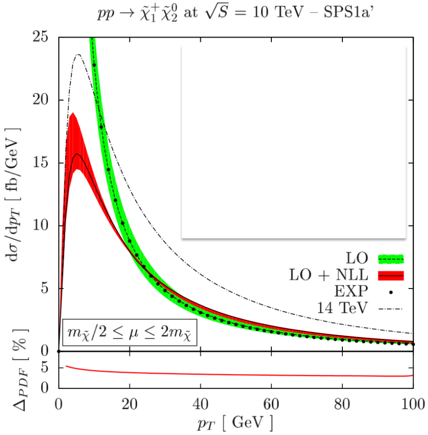
- Need to **combine them without double counting**.
- MLM merging procedure ≡ phase-space cutoff.

Main resummation effects



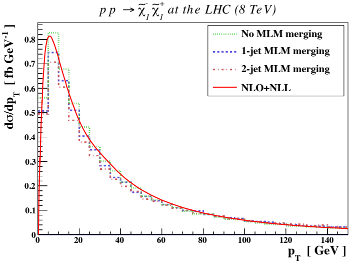
- **Scenario**: LM9: 150 GeV gauginos; 1.5 TeV squarks.
- **Mass spectrum.**
  - * Resummation/NLO: **additional increase of the K-factor** (few percents).
  - * Resummation **effects reduced due to parton densities**.
  - * Resummation formalism choice: few percents.
- **Transverse-momentum distribution:**
  - * Resummation: **finite results at small p_T**.
  - * Effects even **far from the critical regions**.
  - * Good agreement between the two resummation formalisms.

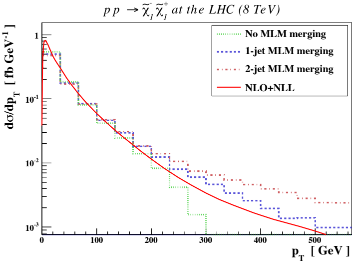
Theoretical uncertainties: the example of the p_T spectrum



- **Scenario**: $\approx$ 180 GeV gauginos.
- **Matching efects**
  - * **Small p_T**: expansion $\approx$ fixed-order.
  - * **Large p_T**: expansion $\approx$ resummation.
  - * **Intermediate p_T**: enhancement.
- **Scale dependence** ($M/2 \leq \mu_R = \mu_F \leq 2M$).
  - * **Reduction** of the uncertainties.
  - * Less than **5%** for $p_T > 5$ GeV.
- **Parton densities dependence** (44 CTEQ sets).
  - * **4-5%** uncertainties for all p_T.
  - * Depends on the final state mass.

MLM merging and resummation





- **Scenario**: 300 GeV charginos; MadGraph + Pythia; LHC (8 TeV).
- **Resummation vs. MLM merging up to two extra jets**.
  - * **Normalization** to the resummed result (for the total cross section).
  - * Lower p_T-range: **very good agreement** between all results.
  - * Higher p_T-range: **too soft spectrum** if no merging is performed.
  - * Merging with two extra jets: **harder spectrum**.

Summary - conclusions

- **Soft and collinear radiation:**
  - Large logarithmic corrections in p_T- and invariant-mass spectra.
  - **Need for resummation (or parton showers)**.
- **p_T, threshold and joint resummations have been implemented.**
  - Reliable perturbative results.
  - Correct quantification of the soft-collinear radiation.
  - **Important effects**, even far from the critical regions.
  - **Theoretical uncertainties under good control.**
- **Comparison with Monte Carlo generators**
  - **Multiparton matrix elements merging with parton showers**, *e.g.*, MLM.
    - **Same precision level as resummation**.
    - **Traditional approach now employed at the experimental level**.