Precision predictions for Beyond the Standard Model processes.

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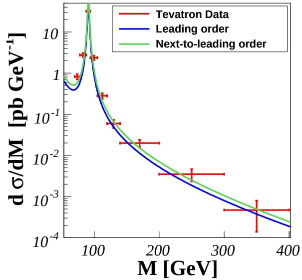
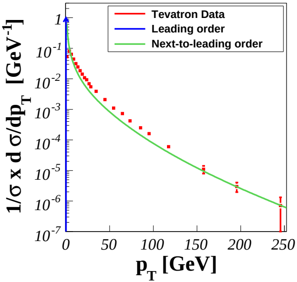
Outline

1. Motivation for precision calculations
2. Resummation formalism
3. Numerical results, including uncertainties, for supersymmetry and Z'
4. Summary - conclusions

Need for precision: Drell-Yan process at the Tevatron

- **Confrontation between theory and Tevatron data** [D∅ 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.

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

  * **Virtual loop** contributions.

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

Soft and collinear radiation diverges and factorizes.

The problem of the soft and collinear radiation

- **Sum of the two contributions.**

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

  - * **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 $z \lesssim 1$ 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.
  - **Perturbative method**.
  - **Parton-level calculation.**
  - Three formalisms:
    - p_T**-resummation**: universally resums $\frac{\alpha_s}{p_T^2} \ln \frac{M^2}{p_T^2}$.
    - **Threshold resummation**: universally resums $\left(\frac{\ln(1-z)}{1-z}\right)_+$.
    - **Joint resummation**: universally resums both logs.

  [Catani, de Florian, Grazzini (2001); Bozzi, Catani, de Florian, Grazzini (2006); Sterman (1987); Catani, Trentadue (1989,1991); Bozzi, BenjF, Klasen (2008)]

- Matching with a parton shower algorithm.
  - **Approximation of the resummation calculation**.
  - **Suitable for a proper description of the collision**.

The resummed component

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

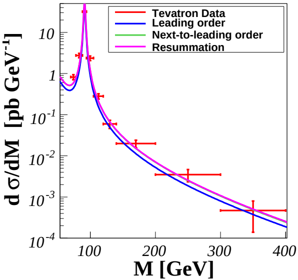
Information from both fixed order and resummation is required.
$\Rightarrow$ consistent matching procedure.

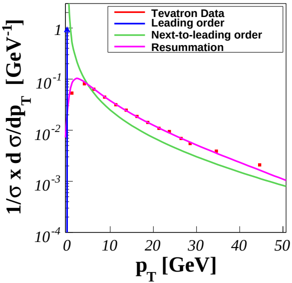
- **Matching procedure:**
  - Addition of both resummation and fixed-order results.
  - Subtracting the **expansion** in α_s of the resummed result.
  - No double-counting of the logarithms.

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

Resummation vs. Tevatron data

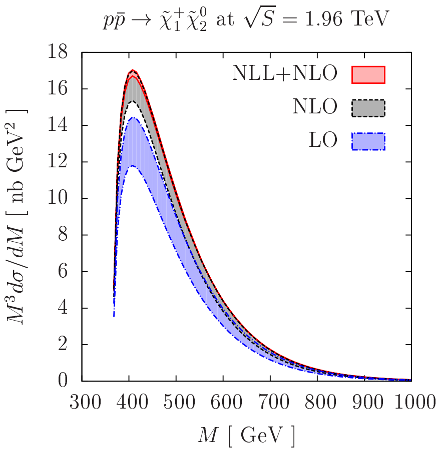
- **Confrontation between theory and Tevatron data** [DØ collaboration (2005, 2008)].





* Invariant-mass distribution: **good agreement**.
  (no change with respect to next-to-leading order).
* p_T-distribution: **good agreement**.
  (big improvement with respect to next-to-leading order).

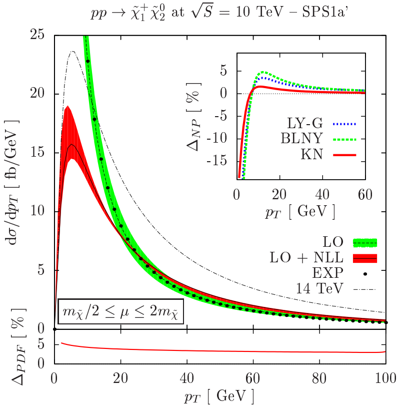
Chargino-neutralino associated production: mass-spectrum



[Debove, BenjF, Klasen (in prep.)]

- **Scenario**: ≈ 180 GeV gauginos.
- **Invariant-mass spectrum**
  - * **NLO**: 20-25% increase.
  - * **Resummation**: moderate increase.
- **Scale dependence** ($M/2 \leq \mu_R = \mu_F \leq 2M$).
  - * **LO: very large dependence**.
  - * **NLO: large dependence**.
  - * **Resummation: reduced dependence**. (higher order terms in the Sudakov).

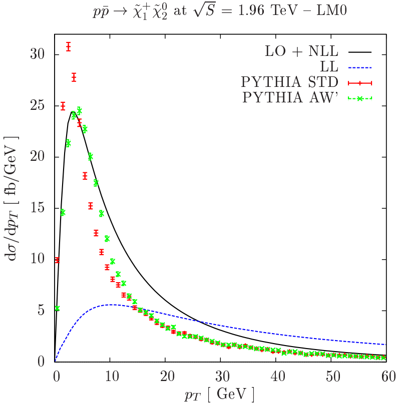
Chargino-neutralino associated production: p_T-spectrum



[Debove, BenjF, Klasen (2010)]

- **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.
  - * Similar to **weak boson** production.
- **Non perturbative effects at low p_T.**
  - * Intrinsic p_T of the partons.
  - * **Under control** for $p_T > 5$ GeV.
- **Uncertainties under control for $p_T > 5$ GeV.**

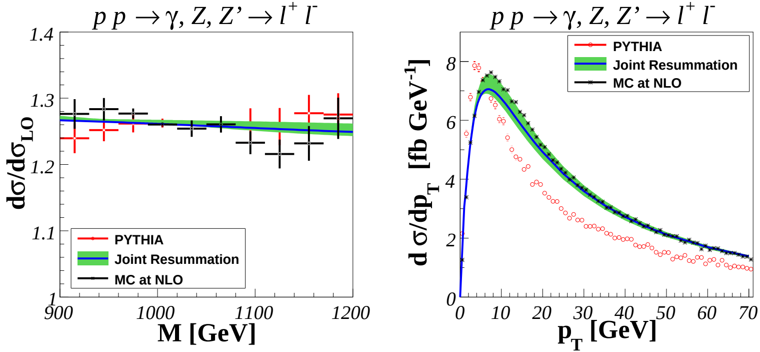
Comparison: PYTHIA and p_T-resummation



[Debove, BenjF, Klasen (2010)]

- **Scenario** $\approx$ 110 GeV gauginos.
- PYTHIA **predictions**.
  - * Used for SUSY **experimental analyses**.
  - * **Leading log** Sudakov form factor.
  - * **Two tunes**.
    - ◇ CDF-AW.
    - ◇ Our tune AW'.
- **Two set of resummed predictions.**
  - * **Leading logaritmic** approximation.
  - * **Next-to-leading logaritmic** results.
- PYTHIA **results**.
  - * **Improves** the LL picture.
  - * **Intrinsic** p_T helps to reproduce NLL.
  - * **Underestimation** for intermediate p_T.
  - * **Direct impact for experimental analyses**.

Comparison: PYTHIA, MC@NLO and joint resummation



[BenjF, Klasen, Ledroit, Li, Morel (2008)]

- 1 TeV Z'; PYTHIA (LO/LL$_+$), MC@NLO (NLO/LL), resummation (NLO/NLL).
- **Mass-spectrum normalized to leading order:**
  - * PYTHIA (*power shower*): mass-spectrum multiplied by a K-factor of 1.26.
  - * **Good agreement between MC@NLO and resummation**.
- **Transverse-momentum distribution:**
  - * **PYTHIA spectrum much too soft, peak not well predicted**.
  - * **Good agreement between MC@NLO and resummation**.

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.
  - * **Uncertainties from scales and parton densities under good control**.
  - * **Reduced dependence on non-perturbative effects.**
- **Comparison with Monte Carlo generators**
  - * **Significant shortcomings in normalization and shapes for PYTHIA**.
  - * **MC@NLO reaches (almost) the same precision level as resummation.**
    BUT: easier implentation in the analysis chains of any experiment.