Precision predictions for hadroproduction processes beyond the Standard Model

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Outline

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Simple questions... and a proposal for answers

- **One of the LHC purposes: which model of new physics is the correct one?**
  - * We need **data** [which are hopefully coming ~~this~~ next year].
  - * We need **theoretical predictions**.
  - * **Reliable** predictions seem reasonnable. [that's the aim of this talk].

Confront data and theory.

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Confront data and theory.

- **How to make reliable predictions? - toy case**
  - Process: **Drell-Yan lepton pair production at the Tevatron**.
  - Considered observables:
    - the lepton-pair **invariant-mass distribution** $\frac{\mathrm{d}\sigma}{\mathrm{d}M}$.
    - the lepton-pair **transverse-momentum distribution** $\frac{\mathrm{d}\sigma}{\mathrm{d}p_T}$.
  - No new physics [for the moment, the talk's topic is not changed...].

Fixed-order perturbative theory

- **QCD factorization theorem**.

$$\sigma = \sum_{ab} \int \mathrm{d}x_a \, \mathrm{d}x_b \, f_{a/p_1}(x_a; \mu_F) \, f_{b/p_2}(x_b; \mu_F) \, \hat{\sigma}_{ab}$$

  * **Long-distance and short-distance physics factorize**.
  * Long-distance physics: parton densities f_a, f_b.
  * Short-distance physics: hard scattering matrix-element $\hat{\sigma}_{ab}$.
  * Introduction of the unphysical factorization scale μ_F.

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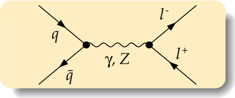
- **Partonic cross section: QCD parturbation theory**.

$$\hat{\sigma} = \hat{\sigma}^{(0)} + \alpha_s \hat{\sigma}^{(1)} + \ldots .$$

First guess: leading order predictions

- **Easy naive approach: matrix element calculation at leading order**:



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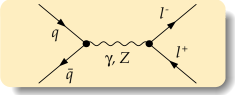
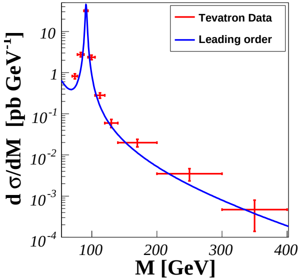
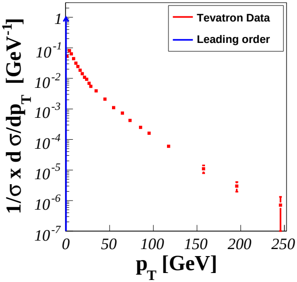


- **Confrontation between theory and Tevatron data**. [DØ collaboration (2005, 2008)]

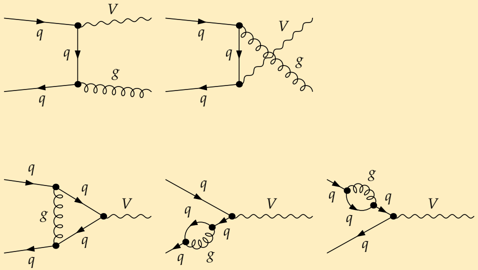




Disagreement between theory and experiment.

Second try: next-to-leading order predictions (1)

- **Improvement of the predictions: next-to-leading order calculation**.



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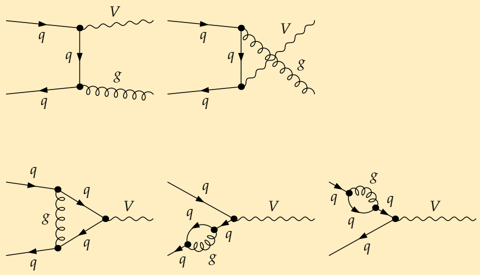

- **Partonic invariant-mass and transverse-momentum distributions at $\mathcal{O}(\alpha_s)$,**

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

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where $z = M^2/s$.

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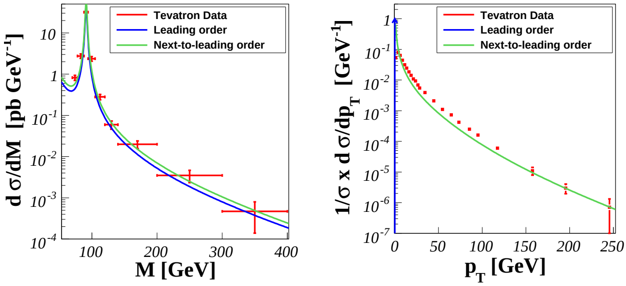

* Invariant-mass distribution: **good agreement**.
* p_T-distribution:
  - ◇ **good agreement in the large-p_T region**.
  - ◇ **diverges in the small-p_T region**.

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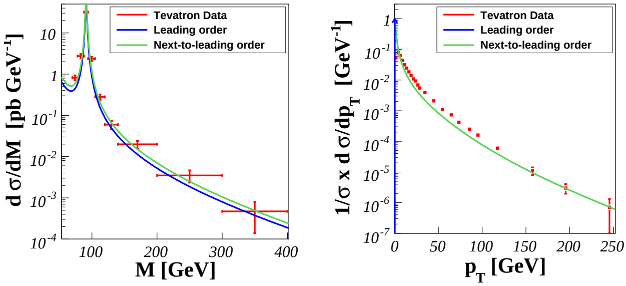

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- **How to improve NLO predictions?** [in particular for the small-p_T region.]

Investigation of the next-to-leading order contributions (1)

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

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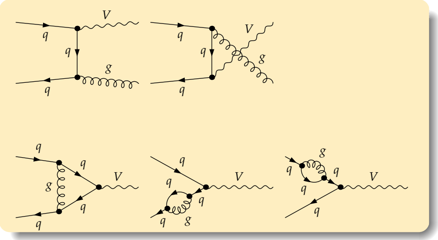
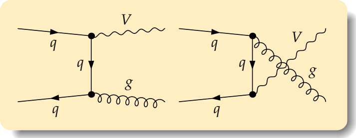
- **$\hat\sigma^{(1)}$ contains two different pieces**.
  * **Real gluon emission** diagrams.
  * **Virtual loop** contributions.



Investigation of the next-to-leading order contributions (2)

- **Amplitude for soft real gluon emission.**



$$iM = g_s T^a \ \bar{v}(k_2) \left[\frac{\not\epsilon(k_g) \left(\not k_g + \not k_2\right) \Gamma^\mu_{qqV}}{2k_2 \cdot k_g} - \frac{\Gamma^\mu_{qqV} \left(\not k_g + \not k_1\right) \not\epsilon(k_g)}{2k_1 \cdot k_g} \right] u(k_1)$$

$$\approx g_s T^a \left[\frac{\epsilon \cdot k_2}{k_2 \cdot k_g} - \frac{k_1 \cdot \epsilon}{k_1 \cdot k_g} \right] \bar{v}(k_2) \ \Gamma^\mu_{qqV} u(k_1)$$

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

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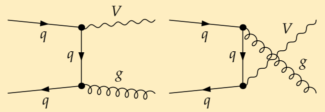

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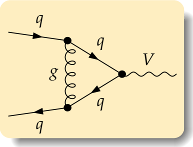
Soft and collinear radiation diverges and factorizes.

Investigation of the next-to-leading order contributions (3)

- **Amplitude for the virtual contribution (soft gluons in the loop).**



$$
\begin{aligned}
iM &= (i\, g_s^2)\bar{v}(k_2) \int \mathrm{d}k_g \frac{\gamma_\nu \left(\not{k}_2 + \not{k}_g\right) \Gamma^\mu_{qqV} \left(\not{k}_1 - \not{k}_g\right) \gamma^\nu}{k_g^2\, (2k_1 \cdot k_g)(2k_2 \cdot k_g)} u(k_1) \\
&\approx (i\, g_s^2) \int \mathrm{d}k_g \frac{k_1 \cdot k_2}{k_g^2\, (k_1 \cdot k_g)(k_2 \cdot k_g)} iM^{\mathrm{Born}} \\
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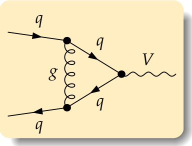

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The virtual contributions diverge and factorize.

The problem of the soft and collinear radiation (1)

- **Sum of the two contributions.**

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

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

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

* **Problems at $z \lesssim 1$ or small p_T.**

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

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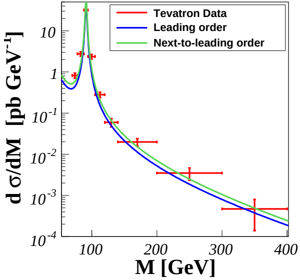
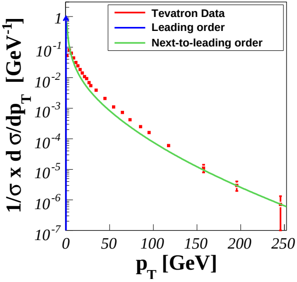
- **Confrontation between theory and Tevatron data**. [D∅ collaboration (2005, 2008)]





* Invariant-mass distribution:

  - ◇ Convolution with the steeply falling parton densities at large z.
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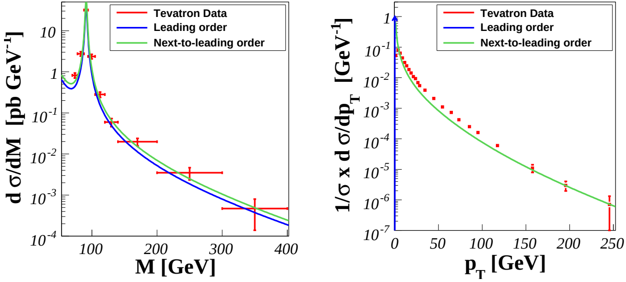

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* p_T-distribution:
  - ◇ **Next-to-leading order calculation reliable for the large p_T**.
  - ◇ Behaviour in the small-p_T region: $\propto \frac{\alpha_s}{p_T^2} \ln \frac{M^2}{p_T^2}$.

Improvements

Improvements of the next-to-leading order calculation.

- Matching with a resummation calculation.
  - **Correct treatment** of the soft and collinear radiation.
  - **Perturbative method**.
  - Soft and collinear radiation taken into account to all orders.
  - **Parton-level calculation.**
- Matching with a parton shower algorithm.
  - **Approximation of the resummation calculation**.
  - **Suitable for a proper description of the collision**.

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Parton showers (1)

- **The parton splitting factorizes** $\Rightarrow$ **iterative splitting**.

$$a(t) \longrightarrow b(z) + c$$
$$b(t') \longrightarrow d(z') + e$$
$$d(t'') \longrightarrow \dots$$

where t is the ordering variable and z the momentum fraction.

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  * **Conservation of probability** for the branching of a parton:

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  * Solving the equation defines the **Sudakov form factor**,

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  * Logarithmic dependence $\Leftrightarrow$ **leading-log approximation**.

Parton showers (2)

Evolution equation for the parton a to the cut-off scale t_0

$$\phi_a(t,E) = \Delta_a(t,t_0) + \sum_b \int_{t_0}^{t} \frac{\alpha_s(t')}{4\pi} \frac{\mathrm{d}t'}{t'} \mathrm{d}z\, \Delta_a(t,t')\, P_{ab}(z)\, \phi_b\big(t', zE\big)\, \phi_c\big(t', (1-z)E\big)$$

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- **Derivation of a parton shower algorithm**
  - * **Ordered Markov chain** (t-variable)

$$Q_0^2 \ll t_1 \ll t_2 \ll \ldots \ll t_N \ll Q^2$$

  - * Choice of t: different shower algorithms.

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  - **Leading logarithms,**
  - **Large number of colors,**
  - **Collinear and/or soft-collinear radiation.**

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- **Improvements require matrix exponentiation $\Rightarrow$ soft-gluon resummation.**

Main features of the resummation

- **Reorganization of the cross section:**

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

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

The resummed component (1)

- **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).

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

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

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- The $\mathcal{H}$-coefficient:
  - Contains **real and virtual collinear radiation, hard contributions**.
- The Sudakov form factor $\mathcal{G}$:
  - Contains **the soft-collinear radiation**.

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  - Is process-dependent.

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  - Is process-dependent.
- The Sudakov form factor $\mathcal{G}$:
  - Contains **the soft-collinear radiation**.
  - **Can be computed perturbatively as series in $\alpha_s \log$.**
  - Is process-independent (universal).
  - Contains the full color and spin structure.

References

- **p_T-resummation** [Catani, de Florian, Grazzini (2001); Bozzi, Catani, de Florian, Grazzini (2006)]
  * Universal formalism ≡ process-independent Sudakov form factor.
  * Resums $\frac{\alpha_s}{p_T^2} \ln \frac{M^2}{p_T^2}$.
- **Threshold resummation** [Sterman (1987); Catani, Trentadue (1989,1991)]
  * Resums $\left(\frac{\ln(1-z)}{1-z}\right)_+$.
- **Joint resummation** [Bozzi, BenjF, Klasen (2008)]
  * Universal formalism ≡ process-independent Sudakov form factor.
  * Resums both types of logarithms.

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

The finite component - matching to the fixed order (2)

- **Matching procedure:**
  - * Addition of both resummation and fixed-order results.
  - * Subtracting the **expansion** in α_s of the resummed result.
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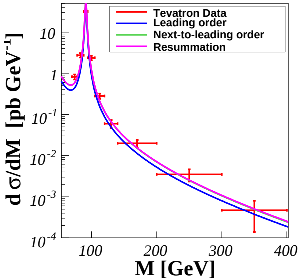
- **Effects of the matching procedure**:
  - * Far from the critical regions, $\mathrm{d}\sigma^{(\mathrm{res})} \approx \mathrm{d}\sigma^{(\mathrm{exp})}$ $\equiv$ **perturbative theory.**
  - * In the critical regions, $\mathrm{d}\sigma^{(\mathrm{F.O.})} \approx \mathrm{d}\sigma^{(\mathrm{exp})}$ $\equiv$ **pure resummation.**
  - * In the intermediate regions: **both contribute.**

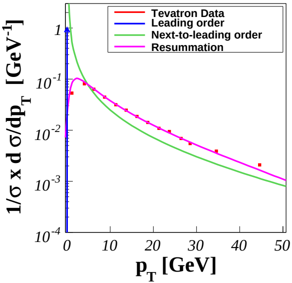
Outline

1. Models and motivation
   - Motivation for resummation calculations
2. Parton showers and resummation
   - Parton showers
   - Transverse-momentum, threshold and joint resummation formalisms
   - Matching to the fixed order
3. Numerical results, with uncertainties
   - The Drell-Yan and the Tevatron
   - Grand Unified Theories and Z' bosons
   - The Minimal Supersymmetric Standard Model (MSSM)
4. Summary - conclusions

Resummation vs. Tevatron data

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





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

Grand Unified Theories and Z' bosons

- **Generalities of the Grand Unified Theories**.
  * **Unification** of the Standard Model gauge groups:

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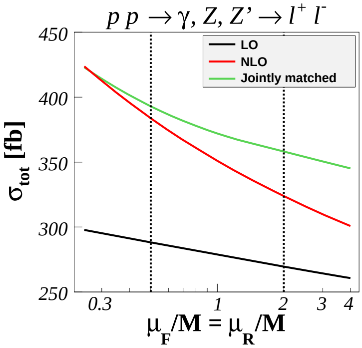
  - * **Breaking to the SM gauge groups**

$$\begin{aligned} E_6 &\to SO(10) \times \mathbf{U(1)}_\psi \\ &\to SU(5) \times \mathbf{U(1)}_\chi \times \mathbf{U(1)}_\psi \\ &\to \mathbf{SU(3)_C} \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y} \times \mathbf{U(1)}_\chi \times \mathbf{U(1)}_\psi. \end{aligned}$$

Additional bosons Z_ψ and $Z' \equiv Z_\chi$.

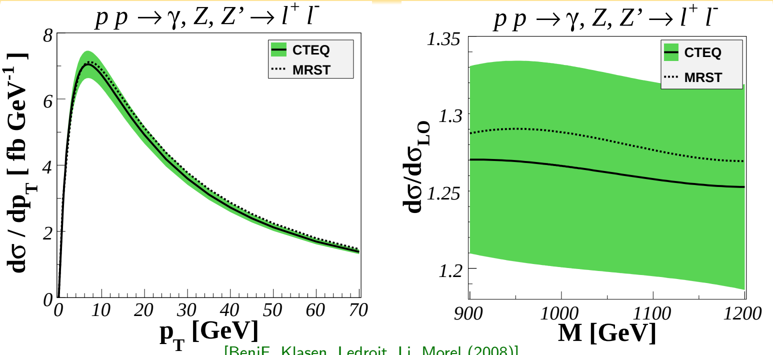
Uncertainties: Z' production, scale variations



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

- **Scenario**.
  - 1 TeV Z'.
  - LHC collider @ 14 TeV.
- **Total cross section** (900 GeV $\leq M \leq$ 1200 GeV).
  - Leading order: full dependence related to μ_F ($\sim$ 7%).
  - Next-to-leading order: introduction of μ_R and the qg channel ($\sim$ 17%).
  - **Resummation: reduction of scale dependence ($\sim$ 9%).**

Uncertainties: parton densities



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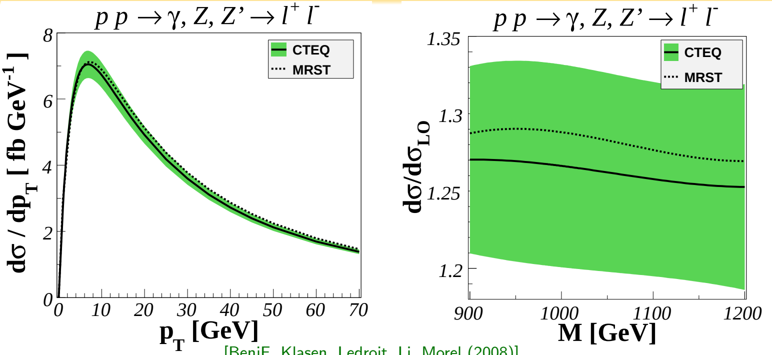

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  - p_T-spectrum: similar shapes but a bit **harder for MRST**.
  - Mass-spectrum: different shapes.
- **Variations along 20 directions for the CTEQ densities**.
  - Variations along the PDF fits: **modest uncertainties** ($\sim$ 10%).
  - Similar to scale dependence.

Non-perturbative effects

- **Important non-perturbative effects in the p_T-distributions**.
  - Intrinsic p_T of the partons inside the hadrons.
  - **Modification of the Sudakov form factor**,

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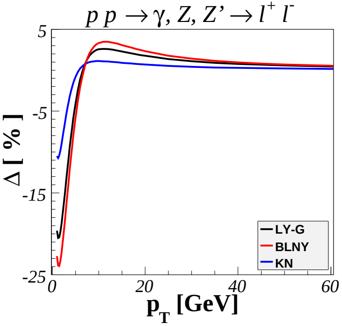

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- **Non-perturbative effects under good control for $p_T > 5$ GeV.**

Monte Carlo and resummation for BSM processes

- **Soft and collinear radiation $\equiv$ Sudakov form factor**.
  - * Parton showers in general: leading logarithms, color,...
  - * Momentum conservation at each branching: **(leading logs)**$_+$, e.g. PYTHIA.
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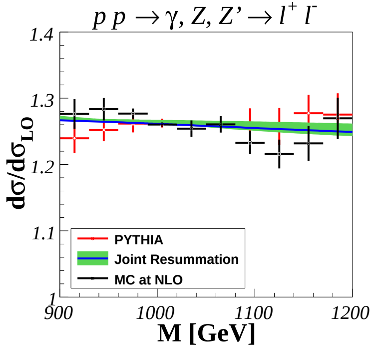
  - * **Resummation: next-to-leading order.**
- **Comparison: resummation vs. PYTHIA vs. MC@NLO.**
  - * **PYTHIA**: virtuality-ordered showers; nice process library.
  - * **MC@NLO**: angular-ordered showers; precision MC generator.
  - * **Resummation**: best precision.

Comparison: PYTHIA, MC@NLO and joint resummation



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- 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.
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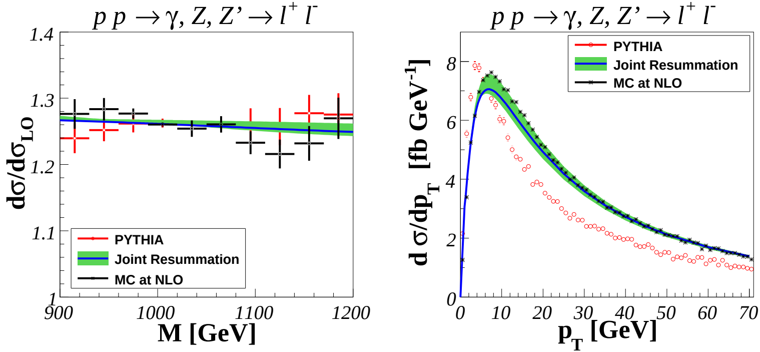

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- **Transverse-momentum distribution:**
  - **PYTHIA spectrum much too soft, peak not well predicted**.
  - **Good agreement between MC@NLO and resummation**.

The Minimal Supersymmetric Standard Model (MSSM)

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

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle$$
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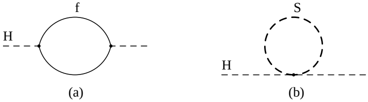
- The MSSM: **one** single supersymmetric (SUSY) generator Q.

The MSSM: one SUSY partner for each SM particle.

* Quarks ⇔ squarks.
* Leptons ⇔ sleptons.
* Gauge/Higgs bosons ⇔ gauginos/higgsinos ⇔ charginos/neutralinos.
* Gluon ⇔ gluino.

Some features of the MSSM

- **Introduction of the SUSY particles in the theory**.
  - * **Solution to the hierarchy problem** (stabilization of the Higgs mass).



◇ Fermionic loop (Fig. a):

$$\Delta M_H^{(a)} = -\frac{y_f^2}{16\,\pi^2}\left[2\,\mathbf{\Lambda^2} + 6\,m_f^2 \ln\frac{\Lambda}{m_f} + \ldots\right]$$

◇ Scalar loop (Fig. b):

$$\Delta M_H^{(b)} = \frac{\lambda_s}{16\,\pi^2}\left[\mathbf{\Lambda^2} - 2\,m_s^2 \ln\frac{\Lambda}{m_s} + \ldots\right]$$

◇ MSSM: two scalars per fermion and $\lambda_S = y_f^2$.
◇ Sum: **logarithmic divergences**.

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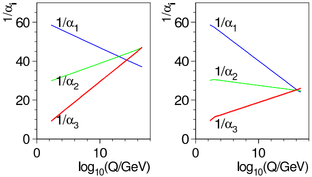

[Fig. from de Boer, Sander (2004)].

- ◇ SUSY particles added in the RGE.
- ◇ Gauge couplings unify at $Q \sim 10^{16}$ GeV.

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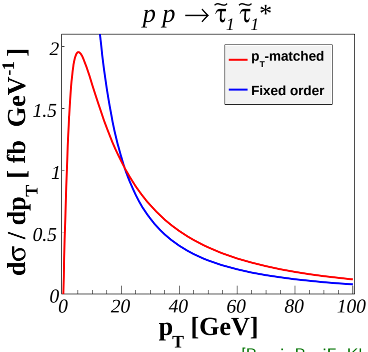
  * **Dark matter candidate** $\Leftrightarrow$ lightest SUSY particle stable and neutral.
- **No SUSY discovery until now!**
  * **SUSY must be broken.**
  * SUSY masses at a higher scale than Standard Model (SM) masses.
  * More than **100 new free parameters**.
  * Simplified benchmark scenarios:
    - ◇ Minimal supergravity (mSUGRA).
    - ◇ Gauge-mediated SUSY-breaking (GMSB).
    - ◇ ...

Resummation for slepton pair production at the LHC



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- **SUSY scenario**: slepton masses ≈ 100-200 GeV.
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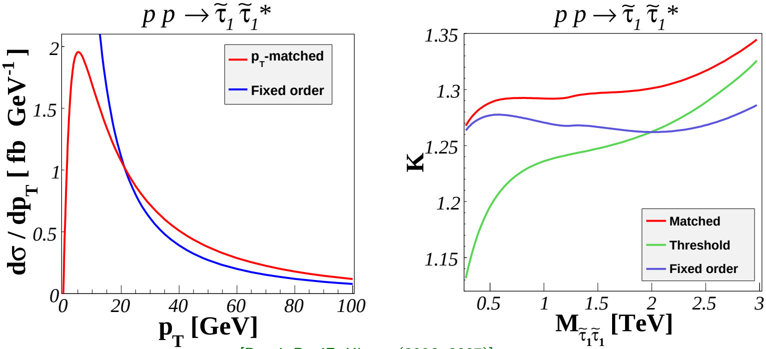

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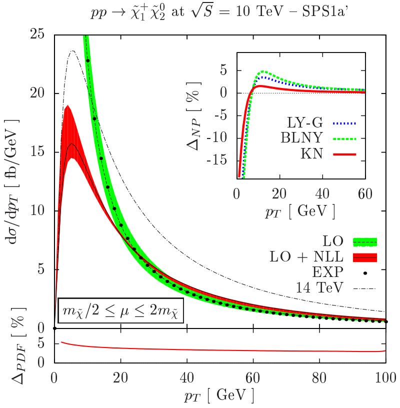
Uncertainties: chargino-neutralino associated production



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- **Scenario**.
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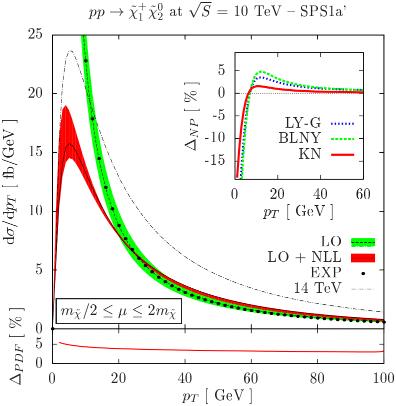

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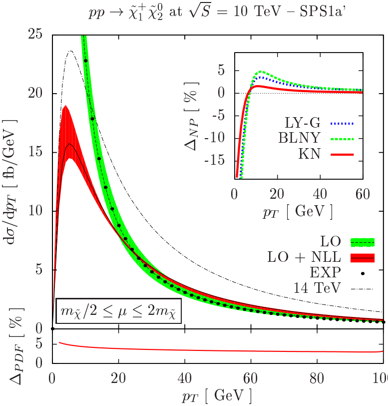

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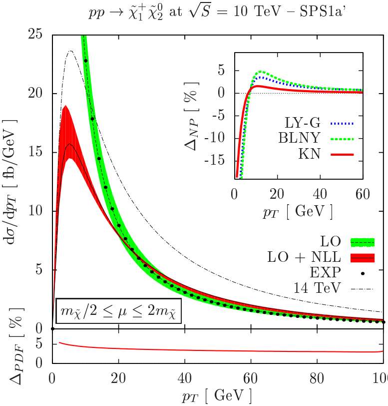

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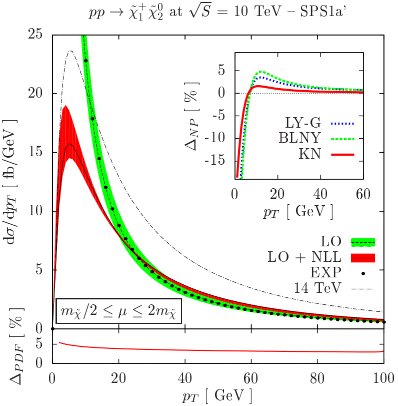

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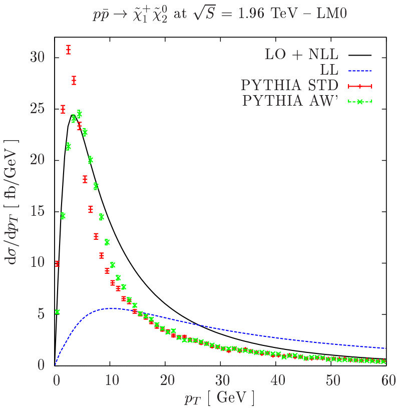
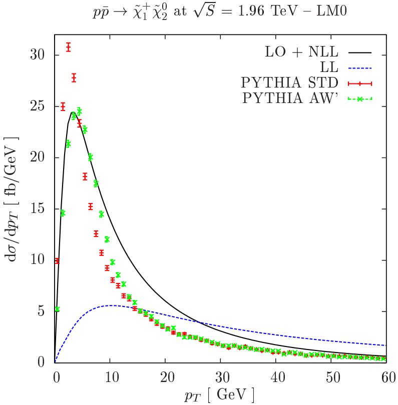


[Debove, BenjF, Klasen (2009)]

- **Scenario**.
  - * ≈ 110 GeV gauginos.
  - * Tevatron collider.
- 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.

Comparison: PYTHIA and p_T-resummation



[Debove, BenjF, Klasen (2009)]

- **Scenario**.
  - * ≈ 110 GeV gauginos.
  - * Tevatron collider.
- 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**.

Outline

Summary - conclusions

- **Considered processes**: slepton-pair, gaugino-pair and Z' production.
- **Soft and collinear radiation:**
  - Large logarithmic corrections in p_T- and invariant-mass spectra.
  - **Need for resummation (or parton showers)**.
- **$\mathbf{p_T}$, 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.
- **Implementation of other processes in the precision tools.**