# QCD resummation for Drell-Yan-like processes beyond the Standard Model.

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# Outline

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# Supersymmetry and the MSSM

- High energy extension to Standard Model.

- Symmetry between fermions and bosons.

$$Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle$$
$$Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle \quad \text{where } Q \text{ is a SUSY generator.}$$

- 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) | $L$ | $(\nu\, e_L)$ | 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 (≡ eight degrees of freedom).
  ⇒ 3 Nambu-Goldstone bosons *eaten* by the $Z^0$ and $W^\pm$ bosons to get massive.
  ⇒ 5 remaining physical Higgses ($h^0$, $H^0$, $A^0$ and $H^\pm$).

- Mixing of gauginos/Higgsinos/sfermions (same electric charge, spin and color).
  * Charginos: $(\tilde{W}^\pm,\, \tilde{H}^\pm_{\{u,d\}}) \Rightarrow (\tilde{\chi}_1^\pm,\, \tilde{\chi}_2^\pm)$.
  * Neutralinos: $(\tilde{B}^0,\, \tilde{W}^0,\, \tilde{H}_u^0,\, \tilde{H}_d^0) \Rightarrow (\tilde{\chi}_1^0,\, \tilde{\chi}_2^0,\, \tilde{\chi}_3^0,\, \tilde{\chi}_4^0)$.
  * Sfermions: $(\tilde{f}_L,\, \tilde{f}_R) \Rightarrow (\tilde{f}_1,\, \tilde{f}_2)$.

# Advantages of the MSSM

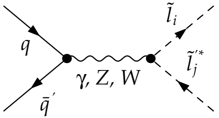
- Some advantages
  - * Solution to the hierarchy problem (stabilization of the Higgs mass).
    [Witten (1981); Kaul (1982)]
  - * Gauge coupling unification at high energy ($Q \sim 10^{16}$ GeV).
    [Ibanez, Ross (1981); Dimopoulos, Raby, Wilczek (1981)]
    [Amaldi, de Boer, Fürstenau (1991); Carena, Pokorski, Wagner (1993)]
  - * $R$-parity conservation: $R = (-1)^{(3B+L+2S)}$.
    - $\Rightarrow$ No $B$ or $L$ violating terms in the Lagrangian (✓ proton lifetime).
    - $\Rightarrow$ Lightest SUSY particle stable and neutral $\Leftrightarrow$ dark matter candidate.
      [Goldberg (1983); Ellis *et al.* (1984)]
    - $\Rightarrow$ SUSY particles produced in pairs at colliders.
    - $\Rightarrow$ Large amount of $\not{E}_T$ in SUSY decays.
  - * ...
- Problem: SUSY breaking $\Rightarrow$ 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):
  * Breaking to gravitational interaction.
  * Non renormalizable couplings, suppressed by the Planck mass.
  * Determined by 5 parameters ($m_0$, $m_{1/2}$, $A_0$, $\tan\beta$, $\mathrm{sgn}(\mu)$).

# Slepton pair production at hadron colliders

- Drell-Yan-like process.
- Tree-level Feynman diagrams:




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

- Sleptons are often light ⇒ decays into LSP + SM lepton ⇒ clean signal.
- Large background from $WW$ and $t\bar{t}$ production.
  ⇒ Importance of accurate theoretical predictions.

# Grand Unified Theories and $Z'$ bosons (1)

- Motivation: unification of the Standard Model (SM) gauge groups:
  $\Rightarrow$ Simple Lie group $G \supset SU(3)_C \times SU(2)_L \times U(1)_Y$.
- Breaking to the SM at high energy scale:
  $\Rightarrow$ Appearance of additional $U(1)$ symmetries $\Leftrightarrow$ extra neutral gauge bosons $Z'$.
- Theoretical model: [Green, Schwarz (1984); Hewett, Rizzo (1989)]
  - Ten-dimensional string theories $E_8 \times E_8$:
    - ◇ Anomaly-free.
    - ◇ Contains chiral fermions (as in the SM).
  - Compactified to $E_6$.
  - Breaking to the SM gauge groups:

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

  - Additional bosons $Z_\psi$ and $Z_\chi$.
  - Mixing between $Z_\psi$, $Z_\chi$ and $Z$.

# Grand Unified Theories and $Z'$ bosons (2)

- Toy model:
  - * Considered gauge group:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi .$$

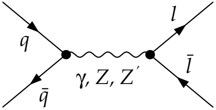
  - * No mixing between $U(1)$-bosons $\Rightarrow Z^0 \equiv Z^{SM}$, $Z' \equiv Z_\chi$, $Z'' \equiv Z_\psi$.
  - * Unification of coupling constants:
    $\Rightarrow g_\chi$ ($\equiv U(1)_\chi$) related to $g'$, $g$ and $e$ ($\equiv$ SM):

$$g_\chi = \sqrt{\frac{5}{3}} g' = \sqrt{\frac{5}{3}} g \tan\theta_W = \sqrt{\frac{5}{3}} \frac{e}{\cos\theta_W} .$$

  - One single free parameter: the $Z'$ mass.

# $Z'$ production at hadron colliders

- Drell-Yan-like process.
- Tree-level Feynman diagrams:

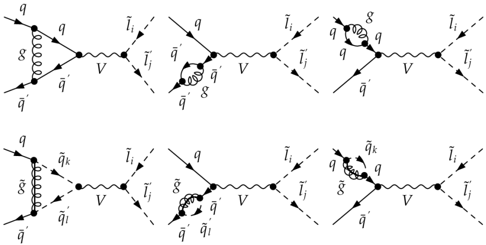



$$q\bar{q} \to \gamma, Z^0, Z' \to l\bar{l}.$$

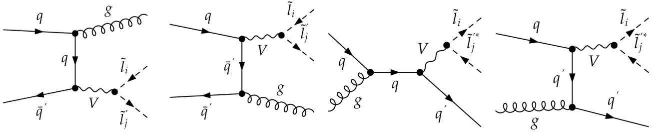
- Signal: additional peak in the Drell-Yan spectrum (clean).
- Irreducible background fron SM Drell-Yan.

# Next-to-leading order calculations

- (SUSY-)QCD one-loop Feynman diagrams:




- Real gluon emission and quark-gluon initiated Feynman diagrams:




- $Z'$ production: - Same diagrams except for the SUSY loops.
  - Sleptons are replaced by leptons.

# Soft and collinear radiation - need for resummation

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

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

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

where $z = M^2/s$.

- Soft and collinear radiation:
  * $\alpha_s^n \left(\frac{\ln^m(1-z)}{1-z}\right)_+$ and $\frac{\alpha_s^n}{q_T^2}\ln^m\frac{M^2}{q_T^2}$ terms in the distributions ($m \leq 2\,n-1$).
  * Large at small $q_T$ or $z \lesssim 1$.
  * Fixed-order theory unreliable in these kinematical regions.

- Resummation to all orders needed.
  * $q_T$, threshold, or joint resummation.
  * Reliable perturbative results.
  * Correct quantification of the soft-collinear radiation.

# Outline

# Main features of resummation

- Reorganization of the cross section:

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

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

# Conjugate spaces: definitions

- Conjugate space(s) introduced:
  - Kinematics naturally factorizes.
  - Hadronic cross sections: convolutions $\longrightarrow$ products.
- Mellin transform ($\equiv N$-moments):

$$F(N) = \int_0^1 \mathrm{d}y\, y^{N-1}\, F(y).$$

  - $N$ variable conjugate to $\tau = M^2/s_h$.
- Fourier transform:

$$F(b) = \int_0^\infty \mathrm{d}x\, e^{-ibx}\, F(x).$$

  - $q_T$-spectrum only.
  - Impact-parameter $b$ conjugate to $q_T$.
- The logarithms:

$$\left(\frac{\ln(1-z)}{1-z}\right)_+ \quad \longrightarrow \quad \ln^2 \overline{N} \quad \text{with} \quad \overline{N} = N \exp[\gamma_E]\ ,$$

$$\frac{1}{q_T^2} \ln \frac{M^2}{q_T^2} \quad \longrightarrow \quad \ln \overline{b}^2 \quad \text{with} \quad \overline{b} = \frac{b\,M}{2} \exp[\gamma_E]\ .$$

# Conjugate spaces: factorization

- Mass spectrum:

$$\frac{\mathrm{d}\sigma^{(\mathrm{res})}}{\mathrm{d}M^2}(\tau) = \sum_{a,b} \iint \mathrm{d}x_a\,\mathrm{d}x_b\, f_{a/h_1}(x_a)\, f_{b/h_2}(x_b)\, \hat{\sigma}^{(\mathrm{res})}_{ab}(z)$$

$$\Downarrow$$

$$\frac{\mathrm{d}\sigma^{(\mathrm{res})}}{\mathrm{d}M^2}(N) = \sum_{a,b} f_{a/h_1}(N+1)\, f_{b/h_2}(N+1)\, \hat{\sigma}^{(\mathrm{res})}_{ab}(N).$$

- $q_T$-spectrum:

$$\frac{\mathrm{d}^2\sigma^{(\mathrm{res})}}{\mathrm{d}M^2\mathrm{d}q_T^2}(\tau, q_T) = \sum_{a,b} \iint \mathrm{d}x_a\mathrm{d}x_b\, f_{a/h_1}(x_a)\, f_{b/h_2}(x_b)\, \hat{\sigma}^{(\mathrm{res})}_{ab}(z, q_T)$$

$$\Downarrow$$

$$\frac{\mathrm{d}^2\sigma^{(\mathrm{res})}}{\mathrm{d}M^2\mathrm{d}q_T^2}(N, q_T) = \sum_{a,b} f_{a/h_1}(N+1)\, f_{b/h_2}(N+1) \int \frac{b}{2}\,\mathrm{d}b\, J_0(b\, q_T)\, \mathcal{W}^F_{ab}(N, b).$$

- The logarithms are included in the functions $\hat{\sigma}^{(\mathrm{res})}$ and $\mathcal{W}^F$. (≡ partonic cross sections).

# The resummed partonic cross sections

- The process-dependence is factorized outside the exponent:

$$\mathcal{W}^F_{ab}(N,b) = \mathcal{H}^F_{ab}(N)\exp\left\{\mathcal{G}(N,b)\right\},$$
$$\hat{\sigma}^{(\mathrm{res})}_{ab}(N) = \sigma^{(LO)}\,\tilde{C}_{ab}(N)\,\exp\left\{\mathcal{G}(N)\right\}.$$

- $\mathcal{H}^F$- and $\tilde{C}$:
  - * Can be computed perturbatively as series in $\alpha_s$.
  - * Are process-dependent.
  - * Contain all the finite terms in the limits $N \to \infty$ and $b \to \infty$. ($\equiv$ real and virtual collinear radiation, hard contributions).
- The Sudakov form factor $\mathcal{G}$:
  - * Can be computed perturbatively as series in $\alpha_s L$ ($L \equiv \ln[\ldots]$).
  - * Is process-independent (universal).
  - * Contain the soft-collinear radiation.

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

# The logarithms

- Exact expressions of the logarithms in conjugate space(s):

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

- Logarithms for $q_T$-resummation:
  * $\ln \bar{b}^2$ large at small $b$ ($\equiv$ large $q_T$).
  * Resummation not justified at small $b$.
  * $\ln \bar{b}^2 \longrightarrow \ln \left[\bar{b}^2 + 1\right]$.
    - ◇ No change at large $b$.
    - ◇ Resummation effects suppressed at small $b$.

- Logarithms for joint resummation:
  * $q_T$- and threshold resummation limits reproduced for large $\bar{b}$ and $\bar{N}$.
  * No subleading terms in perturbative expansions of $\sigma^{(\mathrm{res})}$.

# References

- $q_T$-resummation [Catani, de Florian, Grazzini (2001); Bozzi, Catani, de Florian, Grazzini (2006)]
  - Universal formalism $\equiv$ 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 [Bozzi, BF, Klasen (2008)]
  - Universal formalism $\equiv$ process-independent Sudakov form factor.
  - Correct perturbative expansion of the resummed cross section.
    [Kulesza, Sterman, Vogelsang (2002)]

# Matching to the fixed order

- Fixed-order calculations:
  * 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 calculations:
  * Needed in the critical regions.
  * Not justified far from the critical regions.
- Intermediate kinematical regions:
  * Both fixed order and resummation contribute.
- Information from both fixed order and resummation is required.
  * No double-counting.
    $\Rightarrow$ Consistent matching procedure.

# The matching procedure

- Matching procedure:
  * Adding both resummation and fixed-order results.
  * Subtracting the expansion in $\alpha_s^m$ of the resummed result.
  * No double-counting of the logarithms.

    $\Rightarrow$ Consistent matching.
- Invariant-mass and transverse momentum spectra:

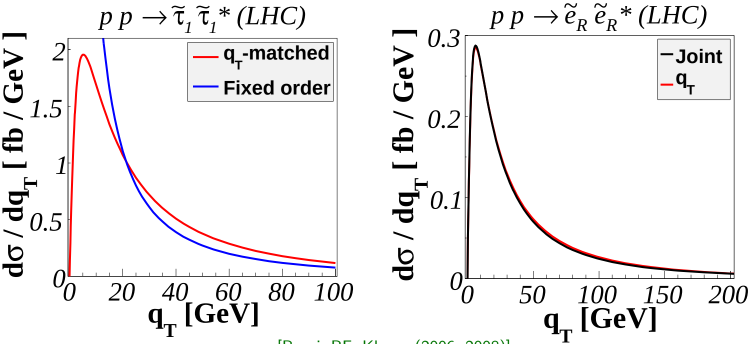
$$\frac{\mathrm{d}\sigma}{\mathrm{d}M^2}(\tau) = \frac{\mathrm{d}\sigma^{(\mathrm{F.O.})}}{\mathrm{d}M^2}(\tau) + \oint_{C_N} \frac{\mathrm{d}N}{2\pi i}\,\tau^{-N}\left[\frac{\mathrm{d}\sigma^{(\mathrm{res})}}{\mathrm{d}M^2}(N) - \frac{\mathrm{d}\sigma^{(\mathrm{exp})}}{\mathrm{d}M^2}(N)\right],$$

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}M^2\,\mathrm{d}q_T^2}(\tau, q_T) = \frac{\mathrm{d}^2\sigma^{(\mathrm{F.O.})}}{\mathrm{d}M^2\,\mathrm{d}q_T^2}(\tau, q_T) + \oint_{C_N} \frac{\mathrm{d}N}{2\pi i}\,\tau^{-N}\int \frac{b\mathrm{d}b}{2} J_0(q_T\, b)$$
$$\times \left[\frac{\mathrm{d}^2\sigma^{(\mathrm{res})}}{\mathrm{d}M^2\,\mathrm{d}q_T^2}(N,b) - \frac{\mathrm{d}^2\sigma^{(\mathrm{exp})}}{\mathrm{d}M^2\,\mathrm{d}q_T^2}(N,b)\right].$$

- Summary:
  * 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

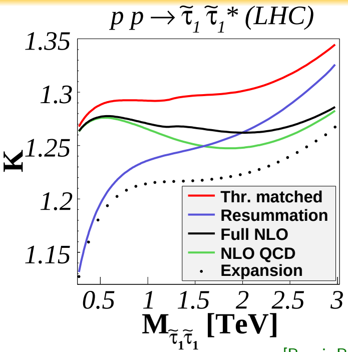
# Transverse-momentum spectra

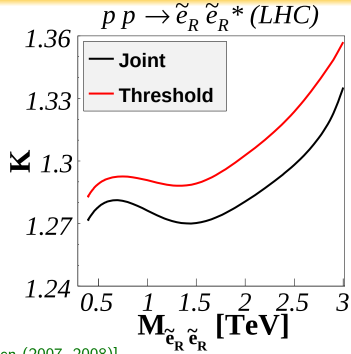



[Bozzi, BF, Klasen (2006, 2008)]

- SPS1a and BFHK-B SUSY scenarios (slepton masses ≈ 100-200 GeV).
- Resummation effects:
  - * Finite results at small $q_T$.
  - * Resummation effects important even at intermediate $q_T$.
- Threshold-enhanced contributions: small effects in the intermediate-$q_T$ region.

# Invariant-mass distributions (normalized to leading order)

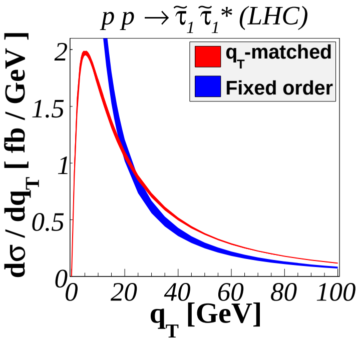


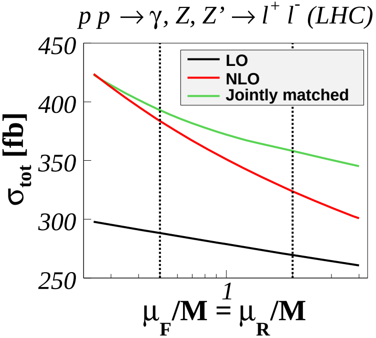




[Bozzi, BF, Klasen (2007, 2008)]

- SPS1a and BFHK-B SUSY scenarios (slepton masses ≈ 100-200 GeV).
- Reduced SUSY-loop effects.
- Resummation effects:
  - * Small $M$: $\mathrm{d}\sigma^{(\mathrm{res})} \approx \mathrm{d}\sigma^{(\mathrm{exp})}$ ≡ perturbative theory.
  - * Large $M$: $\mathrm{d}\sigma^{(\mathrm{F.O.})} \approx \mathrm{d}\sigma^{(\mathrm{exp})}$ ≡ pure resummation.
- Joint vs. threshold resummation: differences under control.

# Factorization and renormalization scale dependence

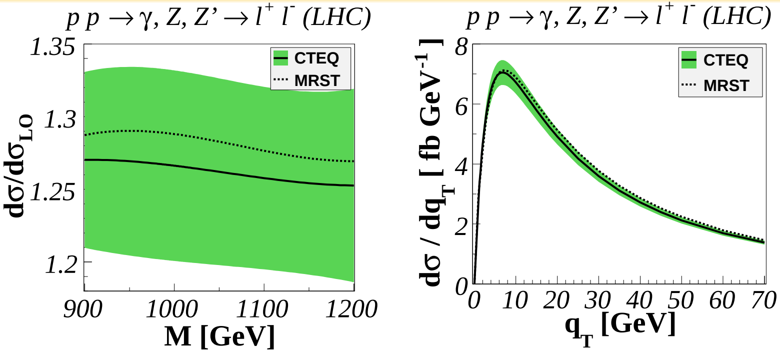



[Bozzi, BF, Klasen (2006); BF, Klasen, Ledroit, Li, Morel (in press)]

- SPS1a SUSY scenario (slepton masses $\approx$ 100-200 GeV); $Z'$ mass of 1 TeV.
- $q_T$-spectrum (integrated over $M$, $M/2 \leq \mu_R, \mu_F \leq 2M$).:
  - Improvement of scale dependence: (from 10% to 5%).
- Total cross section (integrated over $q_T$ and $M$, 900 GeV $\leq M \leq$ 1200 GeV):
  - Leading order: full dependence related to $\mu_F$ ($\sim$ 7%).
  - Next-to-leading order: introduction of $\mu_R$ and the $qg$ channel ($\sim$ 17%).
  - Resummation: reduction of scale dependence ($\sim$ 9%).

# Dependence on parton densities




[BF, Klasen, Ledroit, Li, Morel (in press)]

- $Z'$ mass of 1 TeV.
- CTEQ vs. MRST: different parameterizations of the densities.
  - * Mass-spectrum: different shapes.
  - * $q_T$-spectrum: similar shapes but a bit harder for MRST.
- Uncertainties induced by variations along 20 directions for the CTEQ densities:
  - * Modest uncertainties ($\sim$ 10%).
  - * Similar to scale dependence.

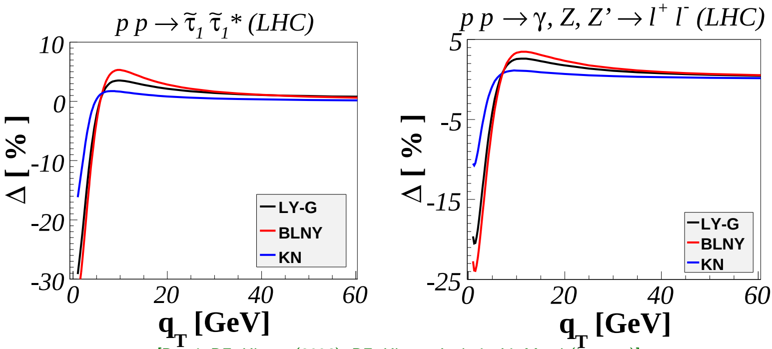
# Uncertainties from non-perturbative effects (1)

- Important non-perturbative (NP) effects for $q_T$-distributions (large-$b$ region).
  - * Intrinsic $q_T$ of the partons inside the hadrons.
  - * Modification of the resummation formula

$$\mathcal{H}^F_{ab}(N) \exp\Big\{\mathcal{G}(N,b)\Big\} \to \mathcal{H}^F_{ab}(N) \exp\Big\{\mathcal{G}(N,b) + F^{\rm NP}_{ab}\Big\}.$$

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

# Uncertainties from non-perturbative effects (2)




[Bozzi, BF, Klasen (2006), BF, Klasen, Ledroit, Li, Morel (in press)]

- SPS1a SUSY scenario (slepton masses ≈ 100-200 GeV); $Z'$ mass of 1 TeV.
- Importance of the NP effects:

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

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

# Outline

# The PYTHIA Monte Carlo generator: parton showering

[Sjöstrand, Mrenna, Skands (2006)]

- Space-like initial-state showers:
  - * At the branching $a \longrightarrow bc$,
    - ◇ $a$ and $b$ have virtualities $Q^2_{\{a,b\}} = -p^2_{\{a,b\}} > 0$ and $c$, $Q^2_c = p^2_c \geq 0$.
    - ◇ $Q_a < Q_b \Rightarrow$ increasing virtualities $\Rightarrow$ iterations until the scale $Q_{\max}$.
    - ◇ $c$ is time-like $\Rightarrow$ decreasing virtualities to the cut-off $Q_0$.
    - ◇ The branching rates depend on the Sudakov form factor.
  - * Backwards evolution scheme:
    - ◇ Start from the hard-scattering partons at $Q_{\max}$ and stop at $Q_0$. .
    - ◇ Reconstruction of the preceding branching.
      $\Rightarrow$ falling sequence of virtualities.
- PYTHIA $\equiv$ leading order + leading logarithms + momentum-conservation.

# The PYTHIA MC generator: the power shower

- $Q_0 \approx 1$ GeV, close to typical hadron mass.
- $Q_{\mathrm{max}}$ is not uniquely defined
  * Can match the hard scale $\Rightarrow$ too soft $q_T$-spectrum.
  * Can be increased to the hadronic center-of-mass energy $\Rightarrow$ power shower.
- Power shower:
  * Need to be matched to matrix elements (hard parton emission).
    $\equiv$ Inclusion of correction factors.
  * Problem with respect to the QCD factorization theorem.
  * Better agreement with matrix elements results at high-$q_T$.

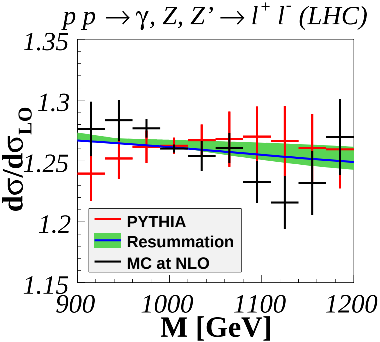
[Miu, Sjöstrand (1999)]

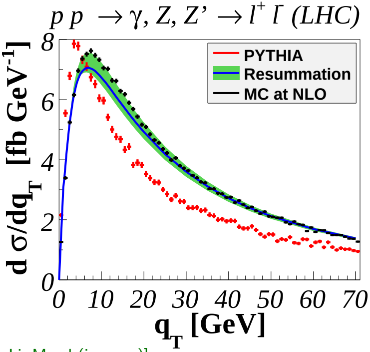
# The MC@NLO Monte Carlo generator

[Frixione, Webber (2002)]

- Initial-state parton showers with HERWIG: [Corcella *et al.* (2001)]
  - * The branchings are ordered by emission angles.
    - ◇ Determined from the Sudakov form factor.
    - ◇ Backwards evolution scheme.
    - ◇ The minimum value is determined by the cut-off $Q_0$.
  - * Non-perturbative stage below $Q_0$:
    Forced splittings of gluons and sea quarks.
- Matching to matrix elements to include hard/wide-angle radiation.
  - * Next-to-leading order (NLO) matrix elements.
  - * Need for a prescription to avoid double-counting (soft-collinear emission).
    - ◇ Two samples, with and without prior NLO real emission.
    - ◇ Based on dipole subtraction method.
      $\Rightarrow$ Monte Carlo counterterm.
      $\Rightarrow$ Two non-divergent samples and no double-counting.
- MC@NLO $\equiv$ next-to-leading order + leading logarithms.

# Comparison: PYTHIA, MC@NLO and joint resummation




[BF, Klasen, Ledroit, Li, Morel (in press)]

- 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.

# Outline

# Summary - conclusions

- Considered processes: slepton-pair and $Z'$ production at hadron colliders.
- Soft and collinear radiation:
  * Large logarithmic corrections in $q_T$- and invariant-mass spectra.
  * Need to be resummed to all orders in $\alpha_s$.
- $q_T$, 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.
- Check of 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.
- Download links for the MC@NLO and resummation codes:
  * `http://lpsc.in2p3.fr/klasen/software/`
  * `http://pheno.physik.uni-freiburg.de/~fuks/resum.html`