Precision predictions for Z' production at the LHC

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Rencontres de Moriond
QCD and High Energy Interactions
March 10, 2008

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Outline

Grand Unified Theories and Z' bosons

- Theoretical model: [Green, Schwarz (1984); Hewett, Rizzo (1989)]
  * Ten-dimensional string theories $E_8 \times E_8$:
    - Anomaly-free and contain chiral fermions.
    - Compactified to E_6.
  * Breaking to the Standard Model (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_ψ and Z_χ.
- Toy model: $Z' \equiv Z_\chi$, with mass of 1 TeV.

Soft and collinear radiation - need for resummation

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

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

  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 $z \lesssim 1$ or small q_T.
  * Fixed-order theory unreliable in these kinematical regions.

- Resummation to all orders needed.
  * Joint resummation considered.
  * Reliable perturbative results.
  * Correct quantification of the soft-collinear radiation.

Outline

Conjugate spaces

- Conjugate spaces introduced:
  - * Mellin transform: N variable conjugate to $\tau = M^2/s_h$.
  - * Fourier transform: Impact-parameter b conjugate to q_T.
- Hadronic cross sections: convolutions → products.

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

- Expression of the logarithms in conjugate spaces:

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

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

$$\Rightarrow\quad L = \ln\left(\bar{b} + \frac{\bar{N}}{1+\frac{\bar{b}}{4\,\bar{N}}}\right).$$

- No additional subleading terms in perturbative expansions of $\sigma^{(\mathrm{res})}$.
  [Kulesza, Sterman, Vogelsang (2002)]

The resummed partonic cross sections

- The process-dependence is factorized outside the exponent:
  [Bozzi, BF, Klasen (2008)]

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

- The $\mathcal{H}$-coefficient:
  * Can be computed perturbatively as series in α_s, from fixed-order results.
  * Is process-dependent.
  * Contains 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 $\alpha_s L$.
  * Is process-independent (universal).
  * Contains the soft-collinear radiation.

Matching to the fixed order

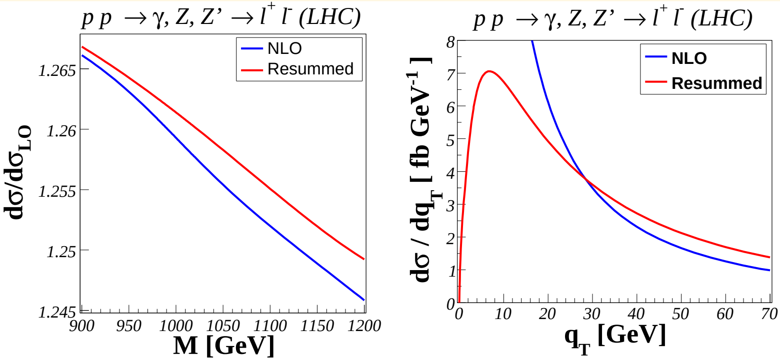
- Matching procedure:
  - * Adding both resummation and fixed-order results.
  - * Subtracting the expansion in α_s^m of the resummed result.
  - * No double-counting of the logarithms.
    $\Rightarrow$ Consistent matching.
- Master formula:

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

- 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

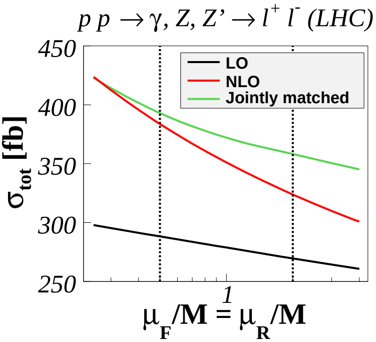
Invariant-mass and transverse-momentum spectra



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

- Invariant-mass spectrum:
  - Resummation effect reduced (far from the critical regions).
- Transverse-momentum spectrum:
  - Finite results at small q_T.
  - Resummation effects important even at intermediate q_T.

Factorization and renormalization scale dependence



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

- Total cross section:
  - * 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 ($\sim 9\%$).

    $\equiv$ Nice stabilization of the theoretical prediction.

PYTHIA, MC@NLO and joint resummation

- PYTHIA: [Sjöstrand, Mrenna, Skands (2006)]
  - * Parton showers ordered by virtualities.
    - ◇ Backwards evolution scheme.
    - ◇ Momentum conservation at each branching.
    - ◇ Branching rates ⇔ (Leading logarithmic) Sudakov form factor.
  - * Matched with leading-order matrix elements.

  ≡ Leading order + leading logarithms + momentum-conservation.

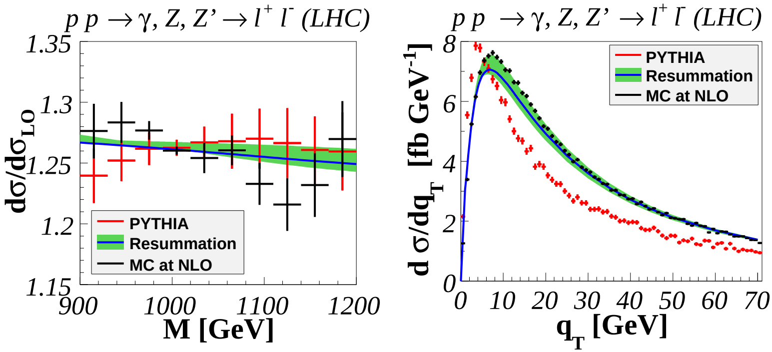
- MC@NLO: [Frixione, Webber (2002)]
  - * Parton showers ordered by angles (HERWIG [Corcella *et al.* (2001)]).
    - ◇ Backwards evolution scheme.
    - ◇ Branching rates ⇔ (Leading logarithmic) Sudakov form factor.
  - * Matched with next-to-leading-order matrix elements.

  ≡ Next-to-leading order + leading logarithms.

- Joint resummation: [Bozzi, BF, Klasen (2008)]

  ≡ Next-to-leading order + next-to-leading logarithms.

Comparison: PYTHIA, MC@NLO and joint resummation



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

- PYTHIA (*power shower*): mass-spectrum multiplied by a K-factor of 1.26.
- PYTHIA q_T-spectrum much too soft, peak not well predicted.
- Good agreement between MC@NLO and resummation.

Outline

Summary - conclusions

- Soft and collinear radiation in Z' production at hadron colliders:
  * Reliable perturbative results $\Leftrightarrow$ Resummation.
  * Joint resummation has been implemented.
- Effects:
  * Important, even far from the critical regions.
  * Uncertainties from scales under good control.
- 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: MC@NLO and resummation codes:
  * `http://lpsc.in2p3.fr/klasen/software/`
  * `http://pheno.physik.uni-freiburg.de/~fuks/resum.html`