Precision predictions for Z' production at the LHC

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Outline

1. Introduction
   - Grand Unified Theories and $Z'$ bosons
   - Soft and collinear radiation - need for resummation

2. Joint resummation formalism
   - Joint resummation formalism
   - Matching to the fixed order

3. Results
   - Invariant-mass and transverse-momentum spectra
   - Comparison: PYTHIA, MC@NLO and joint resummation

4. Summary - conclusions
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4 **Summary - conclusions**
Theoretical model: \[\text{[Green, Schwarz (1984); Hewett, Rizzo (1989)]}\]

* Ten-dimensional string theories $E_8 \times E_8$:
  \begin{itemize}
  \item Anomaly-free and contain chiral fermions.
  \item Compactified to $E_6$.
  \end{itemize}

* Breaking to the Standard Model (SM) gauge groups:

\[
E_6 \rightarrow SO(10) \times U(1)_\psi \\
\rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi \\
\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi.
\]

* Additional bosons $Z_\psi$ and $Z_\chi$.

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 $\mathcal{O}(\alpha_s)$:

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

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

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 ($m \leq 2n - 1$).
  - 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.
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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 $\rightarrow$ products.

$$\frac{d^2\sigma^{\text{(res)}}}{dM^2 dq_T^2}(N, b) = \sum_{a,b} f_{a/h_1} (N + 1) f_{b/h_2} (N + 1) W_{ab}(N, b).$$

- Expression of the logarithms in conjugate spaces:

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

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

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

- No additional subleading terms in perturbative expansions of $\sigma^{\text{(res)}}$.

[Kulesza, Sterman, Vogelsang (2002)]
The resummed partonic cross sections

- The process-dependence is factorized outside the exponent:
  \[ \mathcal{W}_{ab}(N, b) = \mathcal{H}_{ab}(N) \exp \left\{ \mathcal{G}(N, b) \right\}. \]

- The \( \mathcal{H} \)-coefficient:
  * Can be computed perturbatively as series in \( \alpha_s \), 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 $\alpha_s^m$ of the resummed result.
  * No double-counting of the logarithms.
  $\Rightarrow$ Consistent matching.

- **Master formula:**

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

- **Summary:**
  * Far from the critical regions, $d\sigma^{(\text{res})} \approx d\sigma^{(\text{exp})} \equiv$ perturbative theory.
  * In the critical regions, $d\sigma^{(F.O.)} \approx d\sigma^{(\text{exp})} \equiv$ pure resummation.
  * In the intermediate regions: both contribute.
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Invariant-mass and transverse-momentum spectra

- **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 $q_T$.

[BF, Klasen, Ledroit, Li, Morel (in press)]
Factorization and renormalization scale dependence

\[ p p \rightarrow \gamma, Z, Z' \rightarrow l^+ l^- (LHC) \]

- **Total cross section:**
  - **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 (\( \sim 9\% \)).
  - 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 $\Leftrightarrow$ \textit{(Leading logarithmic)} Sudakov form factor.
  - Matched with leading-order matrix elements.
  \equiv \text{Leading order} + \text{leading logarithms} + \text{momentum-conservation}.

- **MC@NLO**: [Frixione, Webber (2002)]
  - Parton showers ordered by angles (HERWIG [Corcella \textit{et al.} (2001)]).
    - Backwards evolution scheme.
    - Branching rates $\Leftrightarrow$ \textit{(Leading logarithmic)} Sudakov form factor.
  - Matched with next-to-leading-order matrix elements.
  \equiv \text{Next-to-leading order} + \text{leading logarithms}.

- **Joint resummation**: [Bozzi, BF, Klasen (2008)]
  \equiv \text{Next-to-leading order} + \text{next-to-leading logarithms}.
Comparison: PYTHIA, MC@NLO and joint resummation

PYTHIA \((\text{power shower})\): 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.

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