Electroweak and QCD aspects in V+jets

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Introduction

Motivation
- Vector boson event yield at the LHC allows for sensitive evaluation of perturbative QCD
- Compare to new MC predictions to steer future calculations
- Improvements in V+jets MC performance will propagate to BSM searches

Talk Outline:
- $Z + \text{Jets}^*$ differential cross section measurements at 13TeV (arXiv:1804.05252)
- Measurement of pure EWK $Z + 2 \text{ jets}$ at 13TeV (arXiv:1712.09814)
- $W + \text{Jets}$ differential cross section measurements at 13TeV (arXiv:1707.05979)
MC Z + Jets Signal Predictions

Madgraph5_amc@nlo (MG5_aMC) + Pythia 8

- **LO matrix elements in Madgraph**
  - Up to 4 outgoing partons
  - Parton showering in Pythia (CUETP8M1 tune)
  - $k_T$-MLM jet merging scheme

- **NLO matrix elements in Madgraph**
  - Up to 2 partons at NLO, 4 at LO
  - Parton showering in Pythia (CUETP8M1 tune)
  - FxFx jet merging scheme
MC Calculations and Samples

- **GENEVA 1.0-RC2 (GE)**
  - NNLO matrix elements + NNLL resummation
  - Parton showering in Pythia 8 (CUETP8M1 tune)
  - FxFx jet merging scheme

- **NNLO Z + 1 Jet Calculation**
  - N-jettiness subtraction scheme
  - Multi-parton interaction and hadronization estimated in MG5_aMC and Pythia 8

<table>
<thead>
<tr>
<th>MC Sample</th>
<th>0j</th>
<th>1j</th>
<th>2j</th>
<th>3j</th>
<th>4j</th>
<th>&gt;4j</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO MG5_aMC</td>
<td>LO</td>
<td>LO</td>
<td>LO</td>
<td>LO</td>
<td>LO</td>
<td>PS</td>
</tr>
<tr>
<td>NLO MG5_aMC</td>
<td>NLO</td>
<td>NLO</td>
<td>NLO</td>
<td>LO</td>
<td>LO</td>
<td>PS</td>
</tr>
<tr>
<td>GE</td>
<td>NNLO</td>
<td>NLO</td>
<td>LO</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>NNLO fixed order</td>
<td>-</td>
<td>NNLO</td>
<td>-</td>
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Z+Jets Phase Space

Data Sample = 2.19 fb\(^{-1}\) at 13 TeV

Leptons (e and \(\mu\))
- \(71.0\,\text{GeV} < m_{ll} < 111.0\,\text{GeV}\)
- \(p_T > 20\,\text{GeV}\)
- \(|\eta| < 2.4\)

Jets
- Anti-\(k_T\) clustering algorithm with \(R=0.4\)
- \(p_T > 30\,\text{GeV}\)
- \(|y| < 2.4\)
- \(\Delta R(\ell,\text{jets}) < 0.4\)

Unfolding done to account for detector resolution
Jet Multiplicity + Leading Jet $p_T$

- **Jet Multiplicity**
  - Discrepancies at high multiplicities where jets in acceptance are from PS
  - GE fails to describe data in PS region

- **Jet $p_T$**
  - Higher order improve shape and normalization compared to LO MG5_aMC
  - Reduced systematic error for fixed order NNLO calculation

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Pt Balance

\[ p_{T}^{bal}(n_{jets}) = |\vec{p}_{T}(Z) + \sum_{i}^{n} \vec{p}_{T}(j_{i})| \]

- Greater than zero due to missed hadronic activity
- Sensitive to modeling of soft gluon radiation
- GE discrepancy in \( \geq 2 \) jets caused by PS jets out of acceptance
Measurement of EWK production of $Z + 2$ jets with 35.9$fb^{-1}$ (a)

- Distinct signature of large $m_{jj}$ and $\Delta \eta_{jj}$
- Boosted decision tree used for signal extraction

MC Predictions

- EWK Signal: LO MG5_aMC
- $\alpha_s^2$ background: LO/NLO MG5_aMC given in (b)
- Pythia 8 with CUETP8M1 tune

arXiv:1712.09814

(a) Production modes: vector boson fusion, bremsstrahlung-like, and multiperipheral.

(b) Strong production modes.
BDT Results

<table>
<thead>
<tr>
<th>Sample</th>
<th>ee</th>
<th>Initial</th>
<th>BDT &gt; 0.92</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total background</td>
<td>159890 ± 510</td>
<td>411890 ± 890</td>
<td>283 ± 29</td>
</tr>
<tr>
<td>EW Zjj signal</td>
<td>2833 ± 10</td>
<td>6665 ± 16</td>
<td>505 ± 43</td>
</tr>
<tr>
<td>Data</td>
<td>163640</td>
<td>422499</td>
<td>194.9 ± 2.6</td>
</tr>
</tbody>
</table>

Signal strength determined from fit of the BDT' output

EWK $Z + 2$ jets fiducial cross section:

- Measurement: $\sigma(EWjj) = 552 \pm 19\,(stat) \pm 55\,(syst)\,fb$
- Prediction: $\sigma_{LO}(EWjj) = 543 \pm 24\,fb$
Conclusion

$Z + \text{Jets differential cross section}$

- NLO MG5$_\text{aMC}$ best global description of data
- Extend the reach of the ME to higher multiplicities $\rightarrow$ reduce dependence on the parton shower
- Improvements in systematic uncertainties in NNLO fixed order calculation

Most precise measurement of EWK + 2 Jets production:

- $\sigma(\text{EWjj}) = 552 \pm 19(\text{stat}) \pm 55(\text{syst}) \text{fb}$
Background processes

- Simulated with NLO POWHEG or MG5_aMC + Pythia 8
- $t\bar{t}$ corrected with data driven method

Data Unfolding

- Account for limited detector resolution
- Background samples subtracted from data
- NLO MG5_aMC sample used for unfolding
Jet $p_T + \text{Multiplicity exclusive}$

Measurement
$\text{NLO} + \text{PS}) \leq \text{MG5}_a\text{MC} + \text{PY8} (\text{LO} + \text{PS}) \leq \text{MG5}_a\text{MC} + \text{PY8} (\text{NNLO})$

$\text{CMS}(13 \text{ TeV})$

$2.19 \text{ fb}^{-1}$

Anti-$k_T$ ($R = 0.4$) jets
$p_T > 30 \text{ GeV}, |y| < 2.4$
$Z/\gamma^* \rightarrow \ell^+\ell^-, N_{\text{jets}} \geq 1$

Measurement
Prediction

$\sigma_{\text{dN/dp}_T}$ [pb/GeV]

$\sigma_{\text{dN/dp}_T}$ [GeV]

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- Most powerful variables: $m_{jj}$, $\Delta \eta_{jj}$
- Others include quark-gluon likelihood (QGL), $p_{Tjj}$

![Dielectron CMS Data](image1)

![Dimuon CMS Data](image2)