Inclusive W, Z and W/Z+jets production at the LHC

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Indiana University

on behalf of the ATLAS and CMS Experiments

March 26, 2015
Introduction

W, Z + X measurements span 5 decades in $\sigma$

CMS Preliminary

Mar 2014

Production Cross Section, $\sigma$ [pb]

- 7 TeV CMS measurement ($L \leq 5.0 \text{ fb}^{-1}$)
- 8 TeV CMS measurement ($L \leq 19.6 \text{ fb}^{-1}$)
- 7 TeV Theory prediction
- 8 TeV Theory prediction

Fiducial W and Z as with $W \rightarrow l\nu$, $Z \rightarrow ll$ and kinematic selection
Excellent agreement with theory
Z $p_T$

- Probes QCD ISR, $p_T$ distribution of partons in proton
- gluon PDF
- important input for searches with W and Z backgrounds, and particularly for W mass through improved parton shower tunes

Backgrounds subtracted, Data unfolded to particle level in
- 3 rapidity regions and
- 3 definitions of final state kinematics:
  - Born, bare and dressed

Uncertainties < 1% below Z $p_T \sim 100$ GeV
Z $p_T$

Born-level combined result compared with predictions from

- FEWZ and DYNLO: Fixed-order calculation, CT10 PDFs
- ResBos (NNLL): Resummed multiple and collinear gluon emissions, CT10 PDFs,
- NLO+NNLL: Banfi et al, CTEQ6m PDFs

Divergence at low $p_T$ expected from lack of resummation; dynamic scale choice improves shape at high $p_T$

Uncertainties defined by resummation, renormalization and factorization scale variations

Inclusion of scale uncertainties covers difference between data and prediction
**W p_T**

- Similar approach, but QCD background more challenging than in Z
- Differential cross sections measured at Born level, compared with theory
  - Powheg: NLO QCD
- Measurement uncertainties: 3-25%
- Within uncertainties, all predictions describe data
W+jets

Important process for studying pQCD, and to validate main background to many SM & BSM searches

- Measurements of $W+(n \geq 0, \ldots, 7)$ jets unfolded to particle level
- Signal and background processes simulated with MC, apart from data-driven $tt$, Multijets estimate
- Data confronted with NLO fixed-order, resummed calculations and MEPS programs

**W selection:**
- Lepton $p_T > 25$ GeV
- Lepton $|\eta| < 2.5$
- $E_T^{\text{miss}} > 25$ GeV
- $m_T > 40$ GeV

**Jet selection:**
- Jet $p_T > 30$ GeV
- Jet $|y| < 4.4$
- $\Delta R(\text{lep}, \text{jet}) > 0.5$
W+jets

- W+jets measurements which reach 1 TeV of jet transverse energy
- Painstaking analysis of ~40 distributions, should be valuable to Monte Carlo developers
- Theory generally can describe data, but there are several regions with 2-3σ excursions
Z+jets

- Important test of pQCD and validation of SM backgrounds to NP searches
- Unfolded total and differential cross sections as function of jet variables using \( \sim 20 \text{ fb}^{-1} \) of pp collision data at \( \sqrt{s} = 8 \text{ TeV} \), allows detailed analysis of QCD dynamics
- Data compared to predictions from:
  - Sherpa2+Blackhat: NLO accuracy for \( n_{\text{jets}} \leq 2 \)
  - Madgraph normalized to NNLO
- Data rates very well described up to accuracy of matrix element calculation (4), and agreement within errors for all multiplicities

ATLAS results: [JHEP07(2013)032](http://dx.doi.org/10.1007/JHEP07(2013)032)
Z+jets

- Some discrepancy between measurement and predictions for $100 < p_{T}^{\text{jet}} < 450$ GeV in 1 jet bin
- First Z+5 jet differential cross section measurements

![Graph showing comparison between data and predictions for the differential cross section. The graph includes bins for different values of $p_{T}^{\text{jet}}$ and $\eta$ values, with comparisons to different theoretical models such as MadGraph, Sherpa, and others. The y-axis shows the ratio of theory to data, and the x-axis shows the leading jet $p_{T}$ in GeV, with a range from 0 to 100 GeV. The legend indicates various theoretical predictions and the experimental data.}
Z+jets

Double differential measurement:

$$\frac{d^2\sigma}{dp_T^j dy^j} = \frac{1}{\mathcal{L} \times \epsilon} \times \frac{N}{2 \times \Delta |y^j| \times \Delta p_T^j}$$

in muon channel and over full rapidity acceptance of detector

~10% disagreement between measurement and Madgraph for leading jet $p_T^{\text{jet}} > 100$ GeV and all $y$

Overall good description of data by MC models
W+jets \quad (R\text{-}jets) \quad Z+jets

- Increased precision due to cancellation of many systematic effects
- Probes difference between kinematics of the jet system recoiling against W or Z
- Very good description by NLO pQCD

1-15% uncertainty over jet bins considered
\[ \frac{Z/\gamma^*+\text{jets}}{\gamma+\text{jets}} \]

- Ratio expected to be constant above \( p_T \) region where \( Z \) mass effects are important.

- Test for potential large log effects at high energy, not always included in perturbative calculations.

- 4 kinematic regimes: \( n_{\text{jets}} \geq 1, 2, 3 \) and \( n_{\text{jets}} \geq 1 \) with \( HT > 300 \) GeV; \( p_T^{Z/\gamma^*} \) always \( > 100 \) GeV - BSM searches phase spaces.

- Fiducial measurement in agreement with theory; MadGraph can describe shape of ratio in \( p_T \) but predicts \( \sim 20\% \) normalization difference (at LO). Higher order effects are expected to be smaller than experimental uncertainties.

\[
R_{\text{dilep}} = \frac{\sigma_{Z\to ll}(p_T^{Z} > 314 \text{ GeV})}{\sigma_{\gamma}(p_T^{\gamma} > 314 \text{ GeV})} = 0.0322 \pm 0.0008(\text{stat}) \pm 0.0020(\text{syst})
\]

Thursday, March 26, 15
Bulk of $p_T^Z/H_T$ distribution contain events with $Z$ balanced by hard jets inside acceptance; tail includes events with additional radiation outside acceptance.

Blackhat fails to describe data above 1 in ratio due to lack of soft or forward jets, but describes data below 1, indicating no evidence for missing large-log contributions.
Z+b(b) - CMS

- Z+b sensitive to b-quark content of proton; Z+2b important background in Higgs and BSM searches
- b-tagging: simple secondary vertex (SSV) algorithm; mistags estimated from template fit to secondary vertex mass
- data in best agreement with predictions from 5-flavor NLO predictions

<table>
<thead>
<tr>
<th>Cross section</th>
<th>Measured</th>
<th>MADGRAPH (5F)</th>
<th>aMC@NLO (5F)</th>
<th>MCFM (parton level)</th>
<th>MADGRAPH (4F)</th>
<th>aMC@NLO (4F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{Z+1b}$ (pb)</td>
<td>$3.52 \pm 0.02 \pm 0.20$</td>
<td>$3.66 \pm 0.22$</td>
<td>$3.70^{+0.23}_{-0.26}$</td>
<td>$3.03^{+0.30}_{-0.36}$</td>
<td>$3.11^{+0.47}_{-0.81}$</td>
<td>$2.36^{+0.47}_{-0.37}$</td>
</tr>
<tr>
<td>$\sigma_{Z+2b}$ (pb)</td>
<td>$0.36 \pm 0.01 \pm 0.07$</td>
<td>$0.37 \pm 0.07$</td>
<td>$0.29^{+0.04}_{-0.04}$</td>
<td>$0.29^{+0.04}_{-0.04}$</td>
<td>$0.38^{+0.06}_{-0.10}$</td>
<td>$0.35^{+0.08}_{-0.06}$</td>
</tr>
<tr>
<td>$\sigma_{Z+b}$ (pb)</td>
<td>$3.88 \pm 0.02 \pm 0.22$</td>
<td>$4.03 \pm 0.24$</td>
<td>$3.99^{+0.25}_{-0.29}$</td>
<td>$3.23^{+0.34}_{-0.40}$</td>
<td>$3.49^{+0.52}_{-0.91}$</td>
<td>$2.71^{+0.52}_{-0.41}$</td>
</tr>
<tr>
<td>$\sigma_{Z+b/Z+j}$ (%)</td>
<td>$5.15 \pm 0.03 \pm 0.25$</td>
<td>$5.35 \pm 0.11$</td>
<td>$5.38^{+0.34}_{-0.39}$</td>
<td>$4.75^{+0.24}_{-0.27}$</td>
<td>$4.63^{+0.69}_{-1.21}$</td>
<td>$3.65^{+0.70}_{-0.55}$</td>
</tr>
</tbody>
</table>
**Z+b(b) - ATLAS**

- Additional, unfolded differential cross sections in a variety of kinematic variables
- Comparable measurement & theory uncertainties

Results comparable between two experiments

Discrepancy with MCFM at $\Delta \phi = \pi$ due to fixed-order nature of calculation

QCD radiation and soft corrections not fully captured by non-perturbative corrections applied to theory
W/Z reconstructed as single jets

- New heavy resonances can decay to highly boosted W and Z bosons.
- Proof of principle that W and Z hadronic decay products can be distinguished from partonic jets.
- Hadronically decaying W and Z bosons reconstructed as broad single jets with \( p_T > 320 \) GeV and \( |\eta| < 1.9 \), in pp collisions at \( \sqrt{s} = 7 \) TeV.
  - anti-\( k_T \) clustering algorithm with \( R = 0.6 \)
  - Likelihood discriminant derived from three jet shape variables
    - thrust minor
    - sphericity
    - aplanarity

Thrust Minor
Sphericity
W/Z reconstructed as jets

- Cross section extracted from fit to jet mass, using massless jet constituents:
  \[
  m_{\text{jet}} = \sqrt{\left(\sum_i E_i\right)^2 - \left| \sum_i \vec{p}_i \right|^2}
  \]
- Result:
  \[
  \sigma_{W^+Z} = 8.5 \pm 0.8 \text{ (stat.)} \pm 1.5 \text{ (syst.) pb}
  \]
  
  NLO QCD prediction: \( \sigma_{W^+Z} = 5.1 \pm 0.5 \text{ pb} \)

### Systematic Uncertainties

<table>
<thead>
<tr>
<th>Sources</th>
<th>( \sigma_{W^+Z} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC modelling</td>
<td>4.4 %</td>
</tr>
<tr>
<td>Background pdf</td>
<td>8.8 %</td>
</tr>
<tr>
<td>Signal pdf</td>
<td>5 %</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>3.7 %</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>Jet mass scale</td>
<td>2.2 %</td>
</tr>
<tr>
<td>Jet mass resolution</td>
<td>12.6 %</td>
</tr>
<tr>
<td>( t\bar{t} ) contribution</td>
<td>2.8 %</td>
</tr>
<tr>
<td>Single-top and diboson contrib.</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>( W ) and ( Z ) relative yield</td>
<td>2.9 %</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.8 %</td>
</tr>
<tr>
<td>Total</td>
<td>18 %</td>
</tr>
</tbody>
</table>
Conclusions and Prospects

- Run I measurements being finalized as preparations for Run II data gear up.

- No major excursions of data from predictions - so no big hints of new physics in Run I dataset; but many measurements that MC theorists can dig into.

- Run II will continue to provide precision measurements in kinematic regions where new physics will be searched for.
  - also for rare processes that will come into reach with higher $\sqrt{s}$ and larger luminosity

- Phase I upgrades (after Run II) will include dedicated hardware for triggering highly boosted W, Z (and top quark) bosons that decay hadronically.

Full set of results and associated documentation:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
Backup
W+jets

![Graphs showing predicted versus data for different generators like BH+S, LoopSim, ALPGEN, SHERPA, and MEPS@NLO.]
W+jets

W+≥2 jets

ATLAS

HEJ

ALPGEN

SHERPA

MEPS@NLO

\( p_T (\text{2nd leading jet}) \) [GeV]

\( |y| (\text{2nd leading jet}) \)
\textbf{Z+J/\Psi}

- Clean signature to investigate double parton scattering (DPS)
- DPS dominates at low opening angle between Z and J/\Psi

Assuming DPS dominates first bin of $\Delta \phi$ distribution, can set an upper limit on the level of DPS in signal and, correspondingly, a lower limit on $\sigma_{\text{eff}}$

see Monday’s talk by L. Gladilin
W mass

Summary slide from M. Boonekamp’s 2015 Moriond EW talk:

Summary

- Detector calibration is at the level required for a first competitive measurement.

- Physics modeling of W production is a major challenge. Factorizing the longitudinal and transverse QCD degrees of freedom is not maintainable.
  - A consistent treatment should rely on a combined PDF / resummation analysis.
  - Most relevant effects to disentangle:
    - valence PDFs; 2nd generation partons; resummation parameters
  - Theoretical estimates of PDF uncertainties give $\delta M_W \approx 20 - 30$ MeV. Precise estimates at the analysis level will strongly depend on the measurement procedure

- DY measurements are critical to constrain the models.
  - W&Z cross sections; W charge asymmetry; W+charm of particular importance for the PDFs
  - $p_T^Z$ can be measured very accurately, but PDF flavour decomposition is a pre-requisite for a correct interpretation of this measurement.
  - Measuring $p_T^W$ provides less ambiguous constraints. Needs a significant low-pile-up data sample
  - Existing measurements are %-level or below: check experimental consistency ahead of higher-level interpretation!
**EW Z+2jets**

**Motivations:**
- testbed for VBF Higgs
- measurement of TGC for space-like momentum transfer (complementary to diboson production)

**Representative LO EW Zjj contributions**

VBF Z production is Z+2jets at tree level

VBF component (left) cannot be calculated independently without breaking gauge invariance
EW Z+2jets

- Inclusive (Strong + EW) Zjj measured in 5 fiducial regions
- Theoretical predictions calculated with Powheg Box and Sherpa 1.4.3
EW Z+2jets

- Signal extraction performed using template fit to the dijet mass spectrum, varying the signal EW Zjj and background normalization independently.
- Number of EW Zjj events $N_{EW}$ extracted from fit and converted to cross section

$$\sigma_{EW} = \frac{N_{EW}}{\int L dt \cdot C_{EW}}$$

- Result significance is evaluated using pseudoexperiments: background is excluded at >5$\sigma$ confidence.
- Measurement is systematics dominated; largest contributions from
  - Control region statistics
  - Jet Energy Scale (experimental)
  - Signal modeling, background modeling and signal/background interference (theoretical)

Weighted average:

$$\sigma_{EW} = 54.7 \pm 4.6 \text{ (stat)} \pm 9.8 \text{ (syst)} \pm 1.5 \text{ (lumi)} \text{ fb}.$$ 

Powheg prediction:

$$46.1 \pm 0.2 \text{ (stat)} \pm 0.3 \text{ (scale)} \pm 0.8 \text{ (PDF)} \pm 0.5 \text{ (model)} \text{ fb}.$$ 

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta N_{EW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electrons</td>
</tr>
<tr>
<td>Lepton systematics</td>
<td>$\pm 8.9 %$</td>
</tr>
<tr>
<td>Control region statistics</td>
<td>$\pm 5.6 %$</td>
</tr>
<tr>
<td>JES</td>
<td>$\pm 5.6 %$</td>
</tr>
<tr>
<td>JER</td>
<td>$\pm 0.4 %$</td>
</tr>
<tr>
<td>Pileup jet modelling</td>
<td>$\pm 0.3 %$</td>
</tr>
<tr>
<td>JVF</td>
<td>$\pm 1.1 %$</td>
</tr>
<tr>
<td>Signal modelling</td>
<td>$\pm 8.9 %$</td>
</tr>
<tr>
<td>Background modelling</td>
<td>$\pm 7.5 %$</td>
</tr>
<tr>
<td>Signal/background interference</td>
<td>$\pm 6.2 %$</td>
</tr>
<tr>
<td>PDF</td>
<td>$\pm 1.5 %$</td>
</tr>
</tbody>
</table>

First 5$\sigma$ validation of the EW Zjj process!
Z+b(b)

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\sigma(Zb)$ [%]</th>
<th>$\sigma(Zbb)$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>b-jet tagging efficiency</td>
<td>3.4</td>
<td>9.8</td>
</tr>
<tr>
<td>c-jet mistag rate</td>
<td>0.2</td>
<td>2.3</td>
</tr>
<tr>
<td>light-jet mistag rate</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>JES</td>
<td>2.9</td>
<td>4.7</td>
</tr>
<tr>
<td>JER</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>b-jet template shape</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>c-jet template shape</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>light-jet template shape</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>b-jet template scale factor</td>
<td>N/A</td>
<td>2.3</td>
</tr>
<tr>
<td>MPI</td>
<td>2.5</td>
<td>0.8</td>
</tr>
<tr>
<td>gluon splitting</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>background normalisation</td>
<td>1.1</td>
<td>3.6</td>
</tr>
<tr>
<td>$tt$ modelling</td>
<td>0.0</td>
<td>2.9</td>
</tr>
<tr>
<td>MC sample size</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>lepton efficiency, scale and resolution $E_T^{miss}$</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>luminosity</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>7.7</strong></td>
<td><strong>14.0</strong></td>
</tr>
</tbody>
</table>
### R-Jets

<table>
<thead>
<tr>
<th>(N_{\text{jets}})</th>
<th>((W \rightarrow e\nu)/(Z \rightarrow ee))</th>
<th></th>
<th>((W \rightarrow \mu\nu)/(Z \rightarrow \mu\mu))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\geq 0)</td>
<td>(\geq 1)</td>
<td>(\geq 2)</td>
</tr>
<tr>
<td>Electron</td>
<td>0.89</td>
<td>0.92</td>
<td>0.93</td>
</tr>
<tr>
<td>JES</td>
<td>0.094</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>JER</td>
<td>0.25</td>
<td>2.4</td>
<td>3.5</td>
</tr>
<tr>
<td>(E_T^{\text{miss}})</td>
<td>0.19</td>
<td>1.7</td>
<td>1.2</td>
</tr>
<tr>
<td>(\tau\tau)</td>
<td>0.024</td>
<td>0.23</td>
<td>1.0</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>0.81</td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>0.12</td>
<td>0.57</td>
<td>0.58</td>
</tr>
<tr>
<td>Unfolding</td>
<td>0.20</td>
<td>0.56</td>
<td>0.86</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.062</td>
<td>0.26</td>
<td>0.27</td>
</tr>
<tr>
<td>Total</td>
<td>1.3</td>
<td>4.1</td>
<td>4.8</td>
</tr>
</tbody>
</table>

*Table 5* Systematic uncertainties in percent on the measured \(W + \text{jets} / Z + \text{jets}\) cross-section ratio in the electron and muon channels as a function of the inclusive jet multiplicity \(N_{\text{jets}}\).
Table 1: Break down of the uncertainties on the cross section measurements as a function of jet multiplicity. The column denoted *Tot. Unc.* contains the total uncertainty; the column denoted *stat* contains the statistical uncertainty; the remaining columns contain the different systematic uncertainties.

<table>
<thead>
<tr>
<th>N(_{\text{jets}})</th>
<th>Tot. Unc. [%]</th>
<th>stat [%]</th>
<th>JEC [%]</th>
<th>JER [%]</th>
<th>PU [%]</th>
<th>Bgrnd [%]</th>
<th>Lumi [%]</th>
<th>Unf [%]</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>= 1</td>
<td>5.4</td>
<td>0.11</td>
<td>4.5</td>
<td>0.55</td>
<td>0.29</td>
<td>0.05</td>
<td>2.6</td>
<td>1.5</td>
<td>1.3</td>
</tr>
<tr>
<td>= 2</td>
<td>6.9</td>
<td>0.24</td>
<td>6.3</td>
<td>0.36</td>
<td>0.32</td>
<td>0.25</td>
<td>2.6</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>= 3</td>
<td>9.0</td>
<td>0.58</td>
<td>8.5</td>
<td>0.35</td>
<td>0.37</td>
<td>0.54</td>
<td>2.6</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>= 4</td>
<td>11</td>
<td>1.3</td>
<td>11</td>
<td>0.28</td>
<td>0.46</td>
<td>0.93</td>
<td>2.6</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>= 5</td>
<td>15</td>
<td>3.0</td>
<td>15</td>
<td>0.52</td>
<td>0.75</td>
<td>1.3</td>
<td>2.6</td>
<td>2.6</td>
<td>1.5</td>
</tr>
<tr>
<td>= 6</td>
<td>21</td>
<td>7.5</td>
<td>19</td>
<td>0.48</td>
<td>1.5</td>
<td>2.1</td>
<td>2.6</td>
<td>2.2</td>
<td>1.4</td>
</tr>
<tr>
<td>= 7</td>
<td>27</td>
<td>19</td>
<td>17</td>
<td>2.40</td>
<td>4.1</td>
<td>3.0</td>
<td>2.6</td>
<td>2.5</td>
<td>1.6</td>
</tr>
</tbody>
</table>

The estimate of the total systematic uncertainty on the cross section measurements is made by varying independently and in both directions (up and down) each of the contributing factor. These different systematic uncertainties are added in quadrature assuming they are independent.