ATLAS: Vector-boson production plus $N$-jets

Arantxa Ruiz Martínez (CERN)

on behalf of the ATLAS Collaboration

Jet vetoes and multiplicity observables (JVMO 2014)

IPPP Durham, 16-18 July 2014
Summary of ATLAS measurements

Standard Model Production Cross Section Measurements

ATLAS Preliminary
Run 1 \( \sqrt{s} = 7, 8 \) TeV

LHC pp \( \sqrt{s} = 7 \) TeV

- Theory
- Data 4.5 - 4.7 fb\(^{-1}\)

LHC pp \( \sqrt{s} = 8 \) TeV

- Theory
- Data 20.3 fb\(^{-1}\)

Standard Model Production Cross Section Measurements Status: July 2014

ATLAS Preliminary Run 1 \( \sqrt{s} = 7, 8 \) TeV

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JVMO 2014

17 July 2014
Recent ATLAS results:

- $W + \text{jets}$ cross section (ATLAS-CONF-2014-035) **NEW!**
- $Z + \text{jets}$ cross section (JHEP 07 (2013) 032)
- $W + \text{jets}/Z + \text{jets}$ cross section ratio (ATLAS-CONF-2014-034) **NEW!**
- $Z + b$-jets cross section (arXiv:1407.3643) **NEW!**
- $W + b$-jets cross section (JHEP 06 (2013) 084)
- $W + c$-jets cross section (JHEP 05 (2014) 068)
$W$+jets cross section

For the production of a massive gauge boson accompanied by jets, jet transverse momenta up to 1 TeV are now, for the first time, accessible and allow access to a kinematic region where higher order EWK effects can become as important as those from higher-order pQCD corrections.

$W$+jets cross section measurement at 7 TeV (4.6 fb$^{-1}$)

- Cross sections are shown as a function of the jet multiplicity up to 7 jets.
- Differential cross sections are measured wrt the jet $p_T$ and $y$ for events with multiplicities up to 5 jets.
- Differential cross sections are measured as a function of:
  - the scalar $p_T$ sum of the jets ($S_T$)
  - the scalar $p_T$ sum of the jets, lepton and neutrino ($H_T$)
  - the angular separation and invariant mass of the two leading jets in $p_T$
- The data are compared to predictions from BLACKHAT+SHERPA, HEJ, ALPGEN, SHERPA and MEPS@NLO.
Fiducial phase space at particle level:

- **Lepton:**
  - Electron channel: $p_T > 25$ GeV, $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$)
  - Muon channel: $p_T > 25$ GeV, $|\eta| < 2.4$
  - Combined: $p_T > 25$ GeV, $|\eta| < 2.4$

- **$W \rightarrow \ell \nu$ criteria:**
  - Exactly one lepton
  - $E_T^{\text{miss}} > 25$ GeV
  - $m_T > 40$ GeV

- **Jet criteria:**
  - $p_T > 30$ GeV
  - $|y| < 4.4$ GeV
  - Jet overlap removal: $\Delta R(\ell, \text{jet}) > 0.5$
$W$ + jets cross section

Background estimation:

- Multijet (data-driven):
  - Template from data events failing nominal lepton identification or isolation
  - Normalization from fit to $E_T^{miss}$ distribution ($15 < E_T^{miss} < 80$ GeV)

- $t\bar{t}$ (data-driven):
  - Template from control region with $\geq 3$ jets and $\geq 1$ $b$-jet
  - Fit to the transposed aplanarity variable

- Simulated samples: single top, dibosons

Dominant systematic uncertainties:

- Jet energy scale (JES)
- At high jet multiplicities, $t\bar{t}$ background estimate
Inclusive jet multiplicities:

- BLACKHAT+SHERPA is in good agreement for all jet multiplicities up to 5 jets.
- ALPGEN and SHERPA predictions show different trends for jet multiplicities > 4 jets, however both are in agreement within systematics.
- MEPS@NLO describes the jet multiplicity with a similar level of agreement.
$W^+\text{jets cross section}$

- BLACKHAT+SHERPA, exclusive sums and LoopSim underestimate the data at high transverse momenta by $\sim 2\sigma$
- ALPGEN, SHERPA and MEPS@NLO are in fair agreement with the data
**W+jets cross section**

- BLACKHAT+SHERPA is significantly lower than the data
- Better agreement by BLACKHAT+SHERPA exclusive sums and LoopSim
- MEPS@NLO agrees well with the data above 200 GeV
Differential jet cross sections are accessible for large jet multiplicities and for energy regimes up to 1 TeV, which allows the modelling of the $Z+jets$ process to be probed for typical phase-space regimes expected from new phenomena and from Higgs boson production, for example via vector-boson fusion (VBF).

$Z+jets$ cross section measurement at 7 TeV (4.6 fb$^{-1}$)

- Updates from the 2010 publication:
  - Extension to higher jet multiplicities and $p_T$, forward region
  - New variables: jet $p_T$ ratio, $H_T$, $S_T$, $Z$ $p_T$
  - Exclusive jet multiplicity ratios
  - Observables after VBF preselection, veto efficiencies

- Background estimation:
  - Data-driven multijet and semi-data-driven dileptonic $t\bar{t}$
  - Simulated samples: single top, dibosons
Event selection:

- **Lepton:**
  - Electron channel:
    - $p_T > 20$ GeV,
    - $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$)
  - Muon channel:
    - $p_T > 20$ GeV,
    - $|\eta| < 2.4$
  - $Z \rightarrow \ell\ell$ criteria:
    - Exactly 2 OS leptons
    - $\Delta R(\ell,\ell) > 0.2$
    - $66 \leq m_{\ell\ell} \leq 116$ GeV

- **Jet criteria:**
  - $p_T > 30$ GeV
  - $|y| < 4.4$ GeV
  - Jet overlap removal:
    - $\Delta R(\ell,jet) > 0.5$
Z+jets cross section

Inclusive jet multiplicities and ratios $R_{\geq(n+1)}/\geq n$:

- Data are consistent with BLACKHAT+SHERPA, ALPGEN and SHERPA
- MC@NLO parton shower underestimates the observed rate for additional jet emission by a factor of 2, which leads to large offsets for higher jet multiplicities
Exclusive jet multiplicities at the LHC are expected to be described by means of two benchmark patterns (predicted in JHEP 10 (2012) 162 and PLB 224 (1989) 237):

- 'Staircase scaling' with $R_{n+1}/n$ constant
- 'Poisson scaling' with $R_{n+1}/n$ inversely proportional to $n$

$\left(\mathcal{H}_{T}^{\text{jet}}\right.\text{leading jet} > 150 \text{ GeV}$)
**$W$+jets/$Z$+jets cross section ratio**

$W$+jets/$Z$+jets cross section ratio ($R_{jets}$) at 7 TeV (4.6 fb$^{-1}$)

- Directly probes the difference between the kinematic distributions of the jet system recoiling against the $W$ or $Z$ bosons
- Is a more precise test of perturbative QCD (pQCD), since some experimental uncertainties and effects from non-perturbative processes, such as hadronization and multi-parton interactions, are greatly reduced in the ratio
- In the ratio, the systematic uncertainties that are positively correlated between the numerator and denominator cancel at the level of their correlations

**Graphs:**

- **Left graph:** Relative uncertainty breakdown for $W$+jets events with $N_{jets}$.
- **Right graph:** Mean relative systematic variation for $W$+jets events with $N_{jets}$.

**Notes:**

- The graphs provide a detailed view of the relative uncertainty and mean relative systematic variation across different jet multiplicities ($N_{jets}$).

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**ATLAS-CONF-2014-034**

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\( W + \text{jets} / Z + \text{jets} \) cross section ratio

- **BLACKHAT+SHERPA** describes the data within theoretical uncertainties, although it does not include all contributions for events with at least 4 jets.
- **ALPGEN** agrees with data, except in the 0 jet bin, where it deviates from the data by 2\( \sigma \) of the exp. uncertainties.
- **SHERPA** is about 1\( \sigma \) of the exp. uncertainties greater than the measurement at high multiplicities, where the effects of hard QCD radiation are tested.
At low jet $p_T (< 200$ GeV), the $R_{\text{jets}}$ distribution falls as the leading jet $p_T$ increases: different shapes in $W+\text{jets}$ and $Z+\text{jets}$

At low $p_T$, predictions present different trends from data, ALPGEN shows the best agreement

Differences between predictions at high leading-jet rapidity due to the effects of the parton shower and PDF sets
Heavy flavour production typically suffer from large theoretical uncertainties → $Z + b$-jets provide important experimental constraints to improve predictions

- Important bkg for $ZH$ with $H \rightarrow b\bar{b}$
- Jet selection:
  - $p_T > 20$ GeV, $|y| < 2.4$, $b$-tagging with 75% efficiency operating point
- Two schemes employed in pQCD:
  - 4-flavour number scheme (4FNS): light quarks and gluons in initial state only, $b$-quark typically massive
  - 5-flavour number scheme (5FNS): introduces initial state $b$-PDF, $b$-quark typically massless
Z + b-jets cross section

Measurement as a function of:

- **b-jet $p_T$:** good shape description by theoretical predictions, aMC@NLO 4FNS underestimates the data

- **$\Delta\phi(Z,b)$:** sensitive to additional radiation, bad description by MCFM at $\pi$, much better agreement by ALPGEN, SHERPA and aMC@NLO

- **$\Delta R(b,b)$:** sensitive to $b$-production mechanism, all predictions with reasonable description of the data except at low $\Delta R(b,b)$
$W + b$-jets cross section

$W + b$-jets cross section at 7 TeV (4.6 fb$^{-1}$)

- LO Feynman diagrams:

\[
W + b\bar{b} + X \quad W + b + X
\]

- Important bkg for $ZH$ with $H \to b\bar{b}$

- $W + b$-jets cross section as a function of the jet multiplicity

- $W + b$-jets cross section as a function of the $p_T$ of the leading $b$-jet
$W + c$-jets cross section

$W + c$-jets cross section at 7 TeV (4.6 fb$^{-1}$)

- $W$ boson in association with a single charm quark is produced at LO by the scattering of a gluon and a down-type quark ($d, s, b$)

- Directly sensitive to the $s$-quark distribution function in the proton at $Q$ on the order of $m_W$

- Select signal as Opposite Sign – Same Sign (OS–SS) events where pair produced quarks ($Wb\bar{b}$, $Wc\bar{c}$) are subtracted automatically!

![Feynman diagrams for $W + c$-jets production](image)
Other recent vector-boson production measurements

Hadronic $W/Z$ cross section (arXiv:1407.0800)
- Reconstruct hadronic decay product as a single merged jet in the final state
- Boost the jet constituents to the jet CoM frame:
  - QCD jets: isotropic topology
  - $W/Z$ jets: back-to-back topology
- Build likelihood ratio discriminant with different jet shape variables: thrust, sphericity and aplanarity

$Z \rightarrow b \bar{b}$ cross section (arXiv:1404.7042)
- Separate signal and control regions with a Neural Network single discriminant $S_{NN}$ based on $\eta_{dijet}$ and $\Delta \eta$(dijet, balancing jet)

$Z/\gamma^*$ $p_T$ distribution (arXiv:1406.3660)
- Measurement used to tune the PYTHIA8 and POWHEG+PYTHIA8 generators
### Data/theory ratio of Vector Boson + X measurements

#### Vector Boson + X Cross Section Measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Reference</th>
<th>Data/theory Ratio</th>
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<tr>
<td>(\sigma_{\text{fid}}(\gamma+X) [</td>
<td>\eta</td>
<td>^2 &lt; 1.37] )</td>
</tr>
<tr>
<td>(- [1.52 &lt;</td>
<td>\eta</td>
<td>^2 &lt; 2.37] )</td>
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<tr>
<td>(- [n_{\text{jet}} \geq 1] )</td>
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<td>(- [n_{\text{jet}} \geq 2] )</td>
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<td>JHEP 07, 032 (2013)</td>
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<td>4.6</td>
</tr>
<tr>
<td>(\sigma_{\text{fid}}(Z \rightarrow bb))</td>
<td>ATLAS-STDMD-2012-15</td>
<td>4.6</td>
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<tr>
<td>(\sigma_{\text{fid}}(Z_{\text{EWK}}))</td>
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<td>(\sigma_{\text{fid}}(W))</td>
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#### ATLAS Preliminary

Run 1 \(\sqrt{s} = 7, 8\) TeV

- **LHC pp \(\sqrt{s} = 7\) TeV**
  - Theory
  - Data
  - stat + syst
- **LHC pp \(\sqrt{s} = 8\) TeV**
  - Theory
  - Data
  - stat + syst

### References

- PRD 89, 052004 (2014)
- JHEP 07, 032 (2013)
- ATLAS-STDMD-2012-15
- ATLAS-CONF-2014-035
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- ATLAS-CONF-2014-034
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Conclusions

- Vector-boson production in association with light and heavy-flavor jets is one of the basic measurements of the LHC physics programme:
  - Essential for the understanding of basic physics
  - Test of the current theoretical predictions
  - Input to more refined generators and PDF sets
  - Background for new physics searches

- Extending the measured phase space with new results:
  - New variables, extending the reach in jet $p_T$, multiplicity
  - Exploring more complex final states: $W/Z +$ heavy flavor jets
  - New measurements of cross-section ratios

- Theoretical predictions also advancing greatly:
  - Some “tuning” needed to perfectly match the data
  - Heavy flavor matching and modeling is a hot topic

- Stay tuned for new results at 8 TeV and 13/14 TeV soon!
BACKUP
Backup: $W + \text{jets}$ cross section

Template fits

- Data, $\sqrt{s} = 7\text{ TeV}, 4.6\text{ fb}^{-1}$
- EWK + top processes
- Multijets
- $N_{\text{jets}} = 1$

- Data, $\sqrt{s} = 7\text{ TeV}, 4.6\text{ fb}^{-1}$
- EWK + top processes
- Multijets
- $N_{\text{jets}} = 1$

- Data, $\sqrt{s} = 7\text{ TeV}, 4.6\text{ fb}^{-1}$
- EWK + top processes
- Multijets
- $N_{\text{jets}} = 1$

- $W \rightarrow \mu, N_{\text{jets}} = 3$
- Data
- Fit Result
- $W$ plus EWK
- $t\bar{t}$
- Multijets

- $W \rightarrow \mu, N_{\text{jets}} = 5$
- Data
- Fit Result
- $W$ plus EWK
- $t\bar{t}$
- Multijets

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Backup: $W+jets$ cross section

Breakdown for different jet multiplicities:

- At low multiplicities, very high signal purity
- At high multiplicities, large contribution from $t\bar{t}$

<table>
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<tr>
<th>$N_{jet}$</th>
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<th>3</th>
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<tr>
<td>MultiJet</td>
<td>4%</td>
<td>11%</td>
<td>12%</td>
<td>11%</td>
<td>7%</td>
<td>6%</td>
<td>5%</td>
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<tr>
<td>$t\bar{t}$</td>
<td>&lt;1%</td>
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<td>3%</td>
<td>18%</td>
<td>46%</td>
<td>63%</td>
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<tr>
<td>$W \rightarrow \tau\nu$, diboson</td>
<td>2%</td>
<td>3%</td>
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<td>$Z \rightarrow ee$</td>
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<td>7%</td>
<td>7%</td>
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<td>88 300</td>
<td>27 700</td>
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<td>91 212</td>
<td>28 076</td>
<td>85 14e</td>
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<tr>
<td>Total Predicted</td>
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<td>99 749</td>
<td>30 400</td>
<td>93 25</td>
<td>26 37</td>
<td>663</td>
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Exclusive jet multiplicities:

- BLACKHAT+SHERPA is in good agreement for all jet multiplicities up to 5 jets.
- ALPGEN and SHERPA predictions show different trends for jet multiplicities > 4 jets, however both are in agreement within systematics.
- MEPS@NLO describes the jet multiplicity with a similar level of agreement.
Summary of theoretical predictions

<table>
<thead>
<tr>
<th>Program</th>
<th>Max. number of partons at approx. NNLO (N_{\text{jets}}+2)</th>
<th>NLO (N_{\text{jets}}+1)</th>
<th>LO (N_{\text{jets}})</th>
<th>Parton/Particle level</th>
<th>Distributions shown</th>
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<td>3</td>
<td>parton level with corrections</td>
<td>Leading jet (p_T) and (H_T) for (W + \geq 1) jet</td>
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<td>BLACKHAT+SHERPA</td>
<td>–</td>
<td>5</td>
<td>6</td>
<td>parton level with corrections</td>
<td>All</td>
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<td>BLACKHAT+SHERPA exclusive sums</td>
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<td>–</td>
<td>–</td>
<td>4</td>
<td>particle level</td>
<td>All</td>
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</table>
Background estimation:

- **Multijet (data-driven):**
  - Sample dominated by QCD obtained reverting electron identification, trigger, and sign requirement (electrons) or isolation cuts (muons)
  - Extract normalization by fitting di-lepton mass distribution using two template distributions: QCD from data, signal+other background distributions from MC

- **Dileptonic $t\bar{t}$ (semi-data-driven):**
  - Shape from $e^\pm\mu^\mp$ events in data
  - Normalization to $e^\pm e^\mp/\mu^\pm\mu^\mp$ final states derived from MC

- **Simulated samples:** single top, dibosons

**Dominant systematic uncertainties:**

- Jet energy scale (JES)
### Breakdown for different jet multiplicities:

#### $Z \rightarrow ee$ channel

<table>
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<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>648</td>
<td>106</td>
<td>24.4</td>
<td>5.6</td>
<td>1.41</td>
<td>0.19</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>diboson</td>
<td>1830</td>
<td>1164</td>
<td>492</td>
<td>109</td>
<td>18.5</td>
<td>3.0</td>
<td>0.27</td>
<td>0.03</td>
</tr>
<tr>
<td>$t\bar{t}$, single top</td>
<td>2120</td>
<td>1670</td>
<td>1187</td>
<td>508</td>
<td>163</td>
<td>48</td>
<td>13.0</td>
<td>4.4</td>
</tr>
<tr>
<td>multi-jet</td>
<td>6400</td>
<td>1250</td>
<td>310</td>
<td>71</td>
<td>16.1</td>
<td>3.5</td>
<td>0.81</td>
<td>0.3</td>
</tr>
<tr>
<td>total expected</td>
<td>1239000</td>
<td>193000</td>
<td>44300</td>
<td>9600</td>
<td>2010</td>
<td>393</td>
<td>70</td>
<td>13.9</td>
</tr>
<tr>
<td>data (4.6 fb$^{-1}$)</td>
<td>1228767</td>
<td>191566</td>
<td>42358</td>
<td>8941</td>
<td>1941</td>
<td>404</td>
<td>68</td>
<td>17</td>
</tr>
</tbody>
</table>

#### $Z \rightarrow \mu\mu$ channel

<table>
<thead>
<tr>
<th></th>
<th>$\geq 0$ jets</th>
<th>$\geq 1$ jet</th>
<th>$\geq 2$ jets</th>
<th>$\geq 3$ jets</th>
<th>$\geq 4$ jets</th>
<th>$\geq 5$ jets</th>
<th>$\geq 6$ jets</th>
<th>$\geq 7$ jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>1710000</td>
<td>260000</td>
<td>56800</td>
<td>11700</td>
<td>2300</td>
<td>430</td>
<td>75</td>
<td>12.1</td>
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<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>123</td>
<td>42.1</td>
<td>12.0</td>
<td>3.2</td>
<td>&lt; 0.5</td>
<td>&lt; 0.5</td>
<td>&lt; 0.5</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>1069</td>
<td>152</td>
<td>36.1</td>
<td>7.5</td>
<td>1.56</td>
<td>0.29</td>
<td>0.09</td>
<td>0.09</td>
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<tr>
<td>diboson</td>
<td>2440</td>
<td>1620</td>
<td>682</td>
<td>149</td>
<td>25.8</td>
<td>3.9</td>
<td>0.41</td>
<td>0.10</td>
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<tr>
<td>$t\bar{t}$, single top</td>
<td>2690</td>
<td>2130</td>
<td>1500</td>
<td>639</td>
<td>194</td>
<td>54</td>
<td>17.2</td>
<td>7.3</td>
</tr>
<tr>
<td>multi-jet</td>
<td>3900</td>
<td>650</td>
<td>295</td>
<td>83</td>
<td>23</td>
<td>5.7</td>
<td>2.1</td>
<td>0.18</td>
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<tr>
<td>total expected</td>
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<td>265000</td>
<td>59400</td>
<td>12600</td>
<td>2540</td>
<td>490</td>
<td>95</td>
<td>19.8</td>
</tr>
<tr>
<td>data (4.6 fb$^{-1}$)</td>
<td>1678500</td>
<td>257169</td>
<td>56506</td>
<td>12019</td>
<td>2587</td>
<td>552</td>
<td>122</td>
<td>31</td>
</tr>
</tbody>
</table>
Backup: \( Z + \text{jets cross section} \)

Scaling pattern also investigated for a VBF preselection (2 jets with \( m_{jj} > 350 \text{ GeV} \) and \( |\Delta y_{jj}| > 3.0 \)) → Exclusive jet multiplicities and ratios \( R_{(n+1)/n} \):

- BLACKHAT+SHERPA prediction is consistent with data
- ALPGEN overestimates \( R_{3/2} \)
- SHERPA describes the multiplicity well
Backup: $Z+$jets cross section

Fraction of events that pass a veto on a central ($|\eta| < 2.4$) third jet after the VBF preselection:

- **ALPGEN** predicts too small efficiency, the overestimate of $R_{3/2}$ in ALPGEN leads to an underestimate of the veto efficiency

- **SHERPA** has a good agreement with data
Particle-level phase space

| Lepton $p_T$ and pseudorapidity $\eta$ | $p_T > 25$ GeV, $|\eta| < 2.5$ |
| $W$ transverse mass and neutrino $p_T$ | $m_T > 40$ GeV, $p_T > 25$ GeV |
| $Z$ invariant mass and lepton-lepton angular separation | $66 < m_{\ell\ell} < 116$ GeV, $\Delta R_{\ell\ell} > 0.2$ |
| Jet $p_T$, rapidity and jet-lepton angular separation | $p_T > 30$ GeV, $|y| < 4.4$, $\Delta R_{j\ell} > 0.5$ |

- In the ratio, the systematic uncertainties that are positively correlated between the numerator and denominator cancel at the level of their correlations.
- The impact on the ratio of a given source of uncertainty was estimated by simultaneously applying the systematic variation due to this source to both $W$+jets and $Z$+jets events and performing the full measurement chain with the systematic variations applied.
- The systematic uncertainties on the $t\bar{t}$ and multijet background estimates were considered to be uncorrelated.
- The uncertainty on the integrated luminosity was treated as correlated.
Backup: $W + b$-jets cross section

$W + b$-jets cross section at 7 TeV (4.6 fb$^{-1}$)

- Particle-level phase space:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton transverse momentum</td>
<td>$p_T^\ell &gt; 25$ GeV</td>
</tr>
<tr>
<td>Lepton pseudorapidity</td>
<td>$</td>
</tr>
<tr>
<td>Neutrino transverse momentum</td>
<td>$p_T^\nu &gt; 25$ GeV</td>
</tr>
<tr>
<td>W transverse mass</td>
<td>$m_T &gt; 60$ GeV</td>
</tr>
<tr>
<td>Jet transverse momentum</td>
<td>$p_T &gt; 25$ GeV</td>
</tr>
<tr>
<td>Jet rapidity</td>
<td>$</td>
</tr>
<tr>
<td>Jet multiplicity</td>
<td>$n \leq 2$</td>
</tr>
<tr>
<td>$b$-jet multiplicity</td>
<td>$n_b = 1$ or $n_b = 2$</td>
</tr>
<tr>
<td>Jet-lepton separation</td>
<td>$\Delta R(\ell, \text{jet}) &gt; 0.5$</td>
</tr>
</tbody>
</table>

- The results are compared to the NLO predictions of MCFM and POWHEG, and to ALPGEN scaled by the NNLO normalization factor for the $W$ cross section:
  - ALPGEN and POWHEG implement a **4-flavour number scheme (4FNS)**
  - MCFM includes a **5-flavour number scheme (5FNS)** to account for the presence of $b$-quarks in the IS originated from parton distribution functions
Backup: $W + c$-jets cross section

$W + c$-jets cross section at 7 TeV (4.6 fb$^{-1}$)

- $W$ boson in association with a single charm quark is produced at LO by the scattering of a gluon and a down-type quark ($d, s, b$)

\[ g\bar{s} \rightarrow W^+ \bar{c} \quad \text{and} \quad gs \rightarrow W^- c \]

These initial states are dominant, while the reaction initiated by a $d$-quark contributes about 10% → Directly sensitive to the $s$-quark PDF!

- Event selection:
  
  - $W \rightarrow \ell\nu$:
    - Electron channel: $p_T > 25$ GeV, $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$), $E_T^{\text{miss}} > 25$ GeV, $m_T > 40$ GeV
    - Muon channel: $p_T > 20$ GeV, $|\eta| < 2.4$, $E_T^{\text{miss}} > 20$ GeV, $m_T > 60$ GeV
  
  - $c$-jet:
    - Jet with $p_T > 25$ GeV, $|\eta| < 2.5$
    - Soft muon with $p_T > 4$ GeV, $|\eta| < 2.5$
    - $\Delta R(\ell, \text{jet}) < 0.5$
Backup: $W + c$-jets cross section

- Select signal as Opposite Sign – Same Sign (OS–SS) events where pair produced quarks ($Wb\bar{b}$, $Wc\bar{c}$) are subtracted automatically!

- Data and aMC@NLO comparison for different PDF sets:
  - Best agreement with ATLAS-epWZ12 and NNPDF2.3coll predictions
  - CT10, HERAPDF1.5 and MSTW2008 also are in agreement
  - NNPDF2.3 less favoured

- Ratio of strange to down sea quarks compared to HERA-PDF1.5 and ATLAS-epWZ12 → Data favour PDFs with symmetric light sea over the whole $x$ range