Chiara Debenedetti
UCSC, SCIPP
on behalf of the ATLAS collaboration
- Drell-Yan pairs transverse momentum and $\Phi^*_\eta$ precision measurement @ 8 TeV - arXiv: 1512.02192

- Measurement of angular coefficients in Z-boson events @ 8 TeV - still no arXiv record

- $W,Z$ cross section and cross-section ratio measurement @ 13 TeV - arXiv:1603.09222
Drell-Yan lepton pairs transverse momentum and $\phi_\eta^*$ precision measurement

L=20.3 fb$^{-1}$
Data collected by ATLAS @ 8 TeV in 2012
Motivation

- Testing different aspects of QCD:
  - soft gluon resummation
  - fixed-order perturbative QCD predictions
  - parton shower models

\[ \Phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \cdot \sin(\theta^*_\eta) \]
\[ \cos(\theta^*_\eta) = \tanh[(\eta^- - \eta^+)/2] \]

\[ \Phi^*_\eta \text{ only direction dependent} \rightarrow \text{no resolution effects present at low } p_T^{\ell\ell} \]

- Fiducial volume defined as: 
  \[ p_T^{\ell} > 20 \text{ GeV}, |\eta_\ell| < 2.4 \]

- MC signal: Powheg+Pythia

- Backgrounds: multi-jet data-driven and others from MC

```
| l = e, \mu |
```

combination @ Born level
Results: QCD predictions comparison

- Comparisons with RESBOS under Z $m_{\ell\ell}$ peak and for integrated rapidity:
  - Low $\Phi^*_\eta$ and $p_T^{\ell\ell}$: dominated by soft-gluon-resummation effects $\rightarrow$ RESBOS predictions consistent with the data within theoretical uncertainties
  - High $\Phi^*_\eta$ and $p_T^{\ell\ell}$: sensitive to hard parton emissions $\rightarrow$ RESBOS differs from data

- Detailed comparisons with RESBOS in bins of rapidity and invariant mass for $\Phi^*_\eta$:
  - in Z peak region disagreement for $\Phi^*_\eta \approx 2$
  - low $m_{\ell\ell}$ disagreement for $\Phi^*_\eta \approx 0.4$
  - good agreement in other regions
  - ratio of high $m_{\ell\ell}$ to low $m_{\ell\ell}$ shows disagreement above $\Phi^*_\eta \sim 0.5$

Known: RESBOS lacking NNLO QCD corrections for $\gamma^*$ and Z/$\gamma^*$ interference

Good description of RESBOS in evolution of the $(1/\sigma)d\sigma/d\Phi^*_\eta$ measurement with $|y_{\ell\ell}|$

More plots in the backup slides!

C. Debenedetti - UCSC/SCIPP - PHENO2016 - Vector boson measurement @ ATLAS
Results: comparison to PS approach

- In the Z mass peak region and above, for $p_T^{\ell\ell}$ within 5 and 100 GeV description of MC's compatible with data at 10% level
- Low mass and high $p_T^{\ell\ell}$ → worse agreement
- Powheg+Pythia tuned with AZNLO tune (using 7 TeV ATLAS data) provides best description under the Z mass peak for $p_T^{\ell\ell} < 50$ GeV
- Sherpa differences with respect to data have same size of Powheg, but opposite trend

- Same study performed for $(1/\sigma)d\sigma/d\Phi^*_\eta$ show similar behaviour for the different mass bins
- PS MC's describe well (maximal discrepancies of 5%) the evolution of $(1/\sigma)d\sigma/dp_T^{\ell\ell}$ over $|y^{\ell\ell}|$

More plots in the backup slides!

C. Debenedetti - UCSC/SCIPP - PHENO2016 - Vector boson measurement @ ATLAS
Results: compare to fixed-order QCD

- Low $p_T$ discrepancies expected because soft gluon emissions dominant
- Good shape description for $p_T > 30$ GeV, but normalisation systematically 15% lower than data
- Recent NNLO calculations (http://moriond.in2p3.fr/QCD/2016/TuesdayMorning/Huss.pdf) show improved agreement with data

Not sensitive to EW corrections (much smaller than data/DYNNNLO discrepancy)
Measurement of angular coefficients in Z-boson events

L=20.3 fb⁻¹
Data collected by ATLAS @ 8 TeV in 2012
- **Measurement of production dynamics through a spin 1 Z via spin correlation between initial and final state partons**

- Use **Collins-Soper (CS) reference frame** → defines lepton θ and Φ

- **The fully differential DY cross section can be reorganised by factorising the dynamic of the boson production, and the kinematic of the decay → very precise measurement of \( A_i \) coefficients, that can be expressed as a function of θ and Φ**

\[
\begin{align*}
\langle \frac{1}{2} (1 - 3 \cos^2 \theta) \rangle &= \frac{3}{20} (A_0 - \frac{2}{3}); & \langle \sin 2\theta \cos \phi \rangle &= \frac{1}{5} A_1; & \langle \sin^2 \theta \cos 2\phi \rangle &= \frac{1}{10} A_2; \\
\langle \sin \theta \cos \phi \rangle &= \frac{1}{4} A_3; & \langle \cos \theta \rangle &= \frac{1}{4} A_4; & \langle \sin^2 \theta \sin 2\phi \rangle &= \frac{1}{5} A_5; \\
\langle \sin 2\theta \sin \phi \rangle &= \frac{1}{5} A_6; & \langle \sin \theta \sin \phi \rangle &= \frac{1}{4} A_7.
\end{align*}
\]

- **Lam-Tung relationship** predicts \( A_0=A_2 \) up to NLO QCD (expect \( A_0>A_2 \) @ higher orders)

- **\( A_{5,6,7} \)** expected to be 0 up to NLO QCD, and slightly divergent from zero @ high \( p_T \) for NNLO QCD

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### Analysis strategy

- **Select three different lepton pair combinations:**
  - 2 central electrons ($e_{CC}$), two central muons ($\mu_{CC}$), one forward and one central electron ($e_{CF}$)

- **Fiducial volume:**
  - $p_T^{\ell} > 25$ GeV and $|\eta^{\ell}| < 2.4$ (central leptons)
  - $p_T^{\ell} > 20$ GeV, $2.5 < |\eta^{\ell_e}| < 4.9$ (forward electrons)
  - $80 < m_{\ell\ell} < 100$ GeV, measurement functions of $p_T^Z$ and also binned in $y^Z$

- **Signal MC:** Powheg+Pythia
- **Backgrounds estimated from MC, but multijet data-driven**
- Select **three different lepton pair combinations**:
  - 2 central electrons (e_{CC}), two central muons (μ_{CC}),
    one forward and one central electron (e_{CF})
  - Fiducial volume:
    - p_T >25 GeV and |η_ℓ|<2.4 (central leptons)
    - p_T >20 GeV, 2.5<|η_ℓ|<4.9 (forward electrons)
    - 80<m_{ℓℓ}<100 GeV, measurement functions of p_T and also binned in y_Z

- **Fold polynomials** to reco phase space (t_{ij}) and fit them to reco data to the full phase space A_i’s

\[ N_{\exp}^n(A_i,\sigma,\theta) = \left( \sum_{j=1}^{23} \sigma_j \times L \times \left[ t_{b,j}(\beta) + \sum_{i=0}^{7} A_{i,j} \times t_{i,j}(\beta) + \sum_{B} T_B(\beta) + T_{fakes} \right] \right) \times \gamma^n \]

**Perform maximum likelihood fit on the reco data to extract the A_i’s:**

\[
\mathcal{L}(A_i,j,\sigma^φ_j | N) = \prod_{n=0}^{N_{\text{bins}}} \left( P(N_{\text{obs}}^n | N_{\exp}^n(A_i,\sigma,\theta)) \times \gamma^n \right) \times \prod_{m=0}^{M} G(0 | \beta^m,1)
\]

- Signal MC: Powheg+Pythia
- Backgrounds estimated from MC, but multijet data-driven

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Results

- In general, comparison with Powheg+MINLO and DYNNLO (both $O(\alpha_s)$ for $A_i$ vs $p_T$ predictions) show good agreement with data.

- $A_2$ has a slower rise in data in $p_T$ than predictions.

- $A_0-A_2$, confirms Lam-Tung breaking @ higher orders than NLO $\rightarrow$ very sensitive probe of higher order QCD corrections!

- For $p_T > 50$ GeV, a factor of 2 higher than predictions (PDF cannot cover for this, probably due to higher order effects).

- $A_{5,6,7}$ all deviate from 0 @ high $p_T$, compatible with predictions within the errors but limited sensitivity.
W,Z cross sections and cross-section ratios

$L = 81 \text{ pb}^{-1} @ 13 \text{ TeV}$

Data taken with 50 ns bunch spacing in early Summer 2015
Motivation and strategy

- Benchmark for understanding of EW and QCD processes
  - Precise predictions available @ NNLO QCD with NLO EW corrections (DYNNLO+FEWZ +SANC)

- High precision in the measurement reachable because of leptonic final states, and large production cross sections

- First tests of PDF’s @ 13 TeV
  - Cancellation of experimental uncertainties in the ratios providing constraints on the PDF’s

- Calculate total and fiducial cross sections, and fiducial-cross-section ratios

\[
\sigma_{W,Z}^{\text{fid}} \times \text{BR}(W, Z \rightarrow l\nu, ll) = \sigma_{W,Z}^{\text{tot}} \times \text{BR}(W, Z \rightarrow l\nu, ll) \cdot A_{W,Z} = \frac{N - B}{C_{W,Z} \cdot \mathcal{L}_{W,Z}}
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\]

geometric and phase space fiducial acceptance

Fiducial phase space: \( \ell = \mu, e \)
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\]

- Top-quark and EW backgrounds
  - estimated from simulation
  - dominant contributions:
    - W analysis: \( Z \rightarrow \mu \mu \) 5%, \( W \rightarrow \tau \nu \) 2%, \( Z \rightarrow ee, ttbar \) 1%
    - Z analysis: \( ttbar \) 0.5%, EW background 0.2%

- QCD multijet background \( \rightarrow \) data driven
  - in Z channel negligible (<0.1%)
  - in W channel evaluated with repeated template fit approach in slices of isolation, and extrapolated to the signal region: \( \sim 10\% \) in electron channel and \( \sim 4\% \) in muon channel
Combination and xsec measurement

Combination of the different channels

- Use HERAverager and account for correlations in the systematics and for MJ use: \( \delta(W^\pm)^2 = \delta(W^+)^2 + \delta(W^-)^2 + 2\rho\delta(W^+)\delta(W^-) \)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Predicted cross section ( \times BR(W \rightarrow \ell\nu, Z \rightarrow \ell\ell) ) [nb]</th>
<th>Measured cross section ( \times BR(W \rightarrow \ell\nu, Z \rightarrow \ell\ell) ) [nb]</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>(value ( \pm ) PDF ( \pm ) scale ( \pm ) other)</td>
<td>(value ( \pm ) stat ( \pm ) syst ( \pm ) lumi)</td>
</tr>
<tr>
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<td>Fiducial</td>
<td>Total</td>
</tr>
<tr>
<td>( W^- )</td>
<td>( 3.40^{+0.09}_{-0.11} \pm 0.04 \pm 0.06 )</td>
<td>( 8.54^{+0.21}_{-0.24} \pm 0.11 \pm 0.12 )</td>
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<td>( W^\pm )</td>
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<td>( 20.08^{+0.53}_{-0.54} \pm 0.26 \pm 0.28 )</td>
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<tr>
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<td>( W^+/W^- )</td>
<td>( 1.30 \pm 0.01 )</td>
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Good agreement with predictions!

- DYNNLO compared to data considering different PDF choices
- Agreement with NNLO predictions, lumi uncertainty is large, covering all the PDFs spread

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Cross-section ratios

\[ R_{W^+/W^-} = \sigma_{W^+}^{\text{fid}} / \sigma_W^{\text{fid}} \]

\[ R_{W/Z} = \sigma_{W}^{\text{fid}} / \sigma_Z^{\text{fid}} \]

- (partial) **cancellation of some uncertainties** (lumi, lepton ID and trigger systematics)
  - improved discriminating power between different pdf predictions

- Sensitivity to different aspects:
  - \( W^+ / W^- \) to \( u - d_v \) at low \( x \)
  - \( W^+ / Z \) to strange quark distribution

- \( W^+ / W^- \) more discriminant power, **favours CT14nnlo and MMHT14nnlo PDFs**

- \( W/Z \) compatible with all PDFs within uncertainties
Conclusions

- **Drell-Yan pairs transverse momentum and $\Phi_{\eta}$ precision measurement @ 8 TeV** - arXiv:1512.02192
  - Good agreement with RESBOS until high $p_T$ or $\Phi_{\eta'}$ where divergences start
  - Powheg+Pythia with AZNLO tune provides best description of $p_T^{\ell\ell}$ in Z mass peak region
  - Fixed order NNLO QCD predictions systematically show 15% difference in normalisation to data, and no sensitivity to EW correction is observed

- **Measurement of angular coefficients in Z-boson events @ 8 TeV** - coming soon on arXiv!
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  - $A_0$-$A_2$ sensitive to higher order corrections (confirmed Lam-Tung breaking @ NLO)
  - $A_{5,6,7}$ different from 0 @ high $p_T$ and consistent with predictions

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  - Fiducial and total cross sections in agreement within uncertainties with predictions, and different PDF choices
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Thanks for listening!
Drell-Yan lepton pairs transverse momentum and $\phi_{\eta}^*$ precision measurement

$L=20.3 \, fb^{-1}$ collected by ATLAS @ 8 TeV
Background composition

- **Under the Z peak**
  dominated by $\gamma\gamma \rightarrow \ell\ell$ and multijet $\sim 1\%$

- **Low $m_{\ell\ell}$**
  - high $p_T^{\ell\ell}$ and $\Phi_{\eta}^*$ dominated by $tt$ and $VV$ $\sim 20\%$
  - low $p_T^{\ell\ell}$ dominated by $Z \rightarrow \tau\tau$ and multijet $\sim 20\%$

- **High $m_{\ell\ell}$**
  - high $p_T^{\ell\ell}$ and $\Phi_{\eta}^*$ dominated by $tt$ $\sim 30\%$
  - low $p_T^{\ell\ell}$ dominated by $\gamma\gamma \rightarrow \ell\ell$ $\sim 20\%$
Systematic uncertainties

Data statistical uncertainty is dominant

Lumi uncertainty 2.8%

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Data vs RESBOS (i)

\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

- Data - statistical uncertainty
- Data - total uncertainty
- ATLAS

\begin{align*}
\text{Data vs RESBOS} \\
\phi_{\eta}^* & \quad \phi_{\eta}^* \\
66 \text{ GeV} \leq m_{ll} < 116 \text{ GeV}, 0 \leq |y| < 0.4 & \quad 66 \text{ GeV} \leq m_{ll} < 116 \text{ GeV}, 0.4 \leq |y| < 0.8 \\
66 \text{ GeV} \leq m_{ll} < 116 \text{ GeV}, 0.8 \leq |y| < 1.2 & \quad 66 \text{ GeV} \leq m_{ll} < 116 \text{ GeV}, 1.2 \leq |y| < 1.6 \\
66 \text{ GeV} \leq m_{ll} < 116 \text{ GeV}, 1.6 \leq |y| < 2.0 & \quad 66 \text{ GeV} \leq m_{ll} < 116 \text{ GeV}, 2.0 \leq |y| < 2.4 \\
46 \text{ GeV} \leq m_{ll} < 66 \text{ GeV}, 0 \leq |y| < 0.8 & \quad 116 \text{ GeV} \leq m_{ll} < 150 \text{ GeV}, 0 \leq |y| < 0.8 \\
46 \text{ GeV} \leq m_{ll} < 66 \text{ GeV}, 0.8 \leq |y| < 1.2 & \quad 116 \text{ GeV} \leq m_{ll} < 150 \text{ GeV}, 0.8 \leq |y| < 1.6 \\
46 \text{ GeV} \leq m_{ll} < 66 \text{ GeV}, 1.6 \leq |y| < 2.4 & \quad 116 \text{ GeV} \leq m_{ll} < 150 \text{ GeV}, 1.6 \leq |y| < 2.4
\end{align*}
Data vs RESBOS (ii)

ATLAS $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

- Data - statistical uncertainty
- Data - total uncertainty
- RESBos

$0.4 < |y| < 0.8$

$0.8 < |y| < 1.2$

$1.2 < |y| < 1.6$

$1.6 < |y| < 2.0$

$66 \text{ GeV} < m_{ll} < 116 \text{ GeV}$

$2.0 < |y| < 2.4$

$46 \text{ GeV} < m_{ll} < 66 \text{ GeV}$

$1.6 < |y| < 2.4$
Data vs RESBOS (ili)

\begin{align*}
\text{Data - statistical uncertainty} & \quad \text{Data - total uncertainty} \\
\text{ATLAS} & \quad \sqrt{s} = 8 \text{ TeV, } 20.3 \text{ fb}^{-1}
\end{align*}

\begin{align*}
0 < |y| & < 0.8 \\
0.8 < |y| & < 1.6 \\
1.6 < |y| & < 2.4
\end{align*}

\begin{align*}
116 \text{ GeV} < m & < 150 \text{ GeV} \\
1.6 < |y| & < 2.4
\end{align*}
Results: comparison to PS approach

Monte Carlo / Data

$\vec{t}\vec{s} = 8$ TeV, 20.3 fb$^{-1}$

**ATLAS**

- Data (stat uncert.)
- Sherpa
- PowhegPythia (AU2)
- PowhegPythia (AZNLO)

### 12 GeV $\leq m_\ell < 20$ GeV, $|y_\ell| < 2.4$

### 46 GeV $\leq m_\ell < 66$ GeV, $|y_\ell| < 2.4$

### 20 GeV $\leq m_\ell < 30$ GeV, $|y_\ell| < 2.4$

### 66 GeV $\leq m_\ell < 116$ GeV, $|y_\ell| < 2.4$

### 30 GeV $\leq m_\ell < 46$ GeV, $|y_\ell| < 2.4$

### 116 GeV $\leq m_\ell < 150$ GeV, $|y_\ell| < 2.4$

### 66 GeV $\leq m_\ell < 116$ GeV

### 2.0 $\leq |y_\ell| < 2.4$

### $0.4 \leq |y_\ell| < 0.8$

### $0.8 \leq |y_\ell| < 1.2$

### $1.2 \leq |y_\ell| < 1.6$

### $1.6 \leq |y_\ell| < 2.0$

### $|y_\ell| < 0.4$

**Data (total uncert.)**

**PowhegPythia (AU2)**

**PowhegPythia (AZNLO)**

**Sherpa**

**ATLAS**
Data vs PS MC’s for $\phi^*\eta$

**ATLAS** $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

- $46$ GeV $\leq m_{ll} < 66$ GeV, $|y_{ll}| < 2.4$
- $66$ GeV $\leq m_{ll} < 116$ GeV, $|y_{ll}| < 2.4$
- $116$ GeV $\leq m_{ll} < 150$ GeV, $|y_{ll}| < 2.4$

**Monte Carlo / Data**

- Data - statistical uncertainty
- Data - total uncertainty
- SHERPA
- POWHEG/PHOENIX (AU2)
- POWHEG/PHOENIX (AZNLO)
- HERWIG
- ATLAS $\mu = 8$ TeV, 20.3 fb$^{-1}$

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New NNLO available predictions (http://moriond.in2p3.fr/QCD/2016/TuesdayMorning/Huss.pdf) show *improved agreement with the data*

- Up to 5-10%
Measurement of angular coefficients in Z-boson events

L=20.3 fb$^{-1}$ collected by ATLAS @ 8 TeV in 2012

Not yet on arXiv - hot from the press!!!
Analysis motivation

\[ \frac{1}{2} (1 - 3 \cos^2 \theta) = \frac{3}{20} (A_0 - \frac{2}{3}); \quad \langle \sin 2\theta \cos \phi \rangle = \frac{1}{5} A_1; \quad \langle \sin^2 \theta \cos 2\phi \rangle = \frac{1}{10} A_2; \]
\[ \langle \sin \theta \cos \phi \rangle = \frac{1}{4} A_3; \quad \langle \cos \theta \rangle = \frac{1}{4} A_4; \quad \langle \sin^2 \theta \sin 2\phi \rangle = \frac{1}{5} A_5; \]
\[ \langle \sin 2\theta \sin \phi \rangle = \frac{1}{5} A_6; \quad \langle \sin \theta \sin \phi \rangle = \frac{1}{4} A_7. \]

- **A_0** and **A_2**: fractions of transverse and longitudinal polarisations
  - Lam-Tung relationship predicts \( A_0 = A_2 \) up to NLO QCD (expect \( A_0 > A_2 \) @ higher orders)
- **A_1**: interference between transverse and longitudinal polarisation
- **A_3** and **A_4**: product of vector-axial couplings, sensitive to \( \sin^2 \theta_W \)
  - \( A_4 \) only one present @ LO QCD
- **A_5,6,7**: expected to be 0 up to NLO QCD, and slightly divergent from zero @ high \( p_T \) for NNLO QCD
Lepton selections sculpt $A_i$ distributions → **fold polynomials** to reco phase space, modelling acceptance, efficiencies and migration effects with MC → $t_{ij}$

- Build also **background templates** $T_B$
- Fit folded templates to reco data to the full phase space $A_i$'s

$$N_{exp}^n (A, \sigma, \theta) = \left\{ \sum_{j=1}^{23} \sigma_j \times L \times \left[ t_{8,j}(\beta) + \sum_{i=0}^{7} A_{i,j} \times t_{i,j}(\beta) \right] + \sum_{B} T_B(\beta) + T_{Fakes} \right\} \times \gamma^n$$

**Perform maximum likelihood fit on the reco data to extract the $A_i$'s:**

$$\mathcal{L}(A_{i,j}, \sigma_j \Phi | N) = \prod_n \left\{ P(N_{obs}^n \mid N_{exp}^n (A, \sigma, \theta) P(N^n_{eff} \mid \gamma^n N_{obs}^n) \right\} \times \prod_m G(0 \mid \beta^m, 1)$$
### Background fractions

#### e⁺e⁻: \(y^2\)-integrated

<table>
<thead>
<tr>
<th>(p_T^\parallel [\text{GeV}])</th>
<th>Background fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
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<tr>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>100</td>
<td>0.2</td>
</tr>
</tbody>
</table>

#### \(\mu\mu\): \(y^2\)-integrated

<table>
<thead>
<tr>
<th>(p_T^\parallel [\text{GeV}])</th>
<th>Background fraction</th>
</tr>
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<tr>
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<td>10</td>
<td>0.1</td>
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<tr>
<td>100</td>
<td>0.2</td>
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</tbody>
</table>

#### \(\tau\tau\): \(y^2\)-integrated

<table>
<thead>
<tr>
<th>(p_T^\parallel [\text{GeV}])</th>
<th>Background fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>100</td>
<td>0.2</td>
</tr>
</tbody>
</table>

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**ATLAS Preliminary**

8 TeV, 20.3 fb\(^{-1}\)

- **ee\(_{cc}\):** \(y^2\)-integrated
- **\(\mu\mu\):** \(y^2\)-integrated
- **\(\tau\tau\):** \(y^2\)-integrated

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Systematic uncertainties

**Data stat**

**Lepton systematics**

**PDF uncertainty**

**MC signal statistics**
W, Z cross sections and cross-section ratios

$L = 81 \text{ pb}^{-1} @ 13 \text{ TeV}$

Data taken with 50 ns bunch spacing in early Summer 2015
Event selection:
Primary vertex: hard scatter vertex with at least 2 tracks associated
Trigger (e): isolated electron with $p_T > 24$ GeV OR electron with $p_T > 60$ GeV
Trigger ($\mu$): isolated muon with $p_T > 20$ GeV OR muon with $p_T > 50$ GeV

Good electron:
Pass likelihood medium ID
Isolation: 90% efficient track-calor combined working point
$p_T > 25$ GeV, $|\eta| < 2.47$, excluding calorimeter crack region ($1.37 < |\eta| < 1.52$)

Good muon:
Pass medium ID
Isolation: 90% efficient track-calor combined working point
$p_T > 25$ GeV, $|\eta| < 2.4$

W selection:
Only one good electron or muon
Calibrated missing energy > 25 GeV
$m_T^W > 50$ GeV

Z selection:
Exactly two good electron or muon
$66$ GeV < $m_{\ell\ell}$ < $116$ GeV

NB: uniform cuts across the channels (important for uncertainty reduction in ratio)
Multijet background extraction in W analysis

**QCD multijet background:**
- in Z analysis negligible (<0.1%), in W analysis sizeable contribution, estimated using data

**Use repeated template fit approach**
- slice in intervals of isolation, to obtain statistically independent templates

- Evaluation performed in 2 Fit Regions ($m_T$ relaxed, $E_T^{\text{miss}}$ relaxed), for different kinematic distributions ($E_T^{\text{miss}}, m_T, p_T^\ell$, $d\Phi(E_T^{\text{miss}}, \ell)$) → extract yields

- Different extracted yields extrapolated to signal region (small isolation values)

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- slice in intervals of isolation, to obtain *statistically independent* templates

- Evaluation performed in 2 Fit Regions ($m_T$ relaxed, $E_T^{\text{miss}}$ relaxed), for *different kinematic distributions* ($E_T^{\text{miss}}$, $m_T$, $p_T^\ell$, $d\Phi(E_T^{\text{miss}}, \ell)$) → extract yields

- Different extracted *yields* extrapolated to signal region (small isolation values)
- No differential cross section evaluated:
  - plots only illustrative of the data/MC agreement

- Signal modelled with Powheg+Pythia8, MJ shape and yield from data-driven estimate, other backgrounds from simulation (Powheg+Pythia - check ttbar)

- Systematic band shows experimental uncertainties, but does not include 5% luminosity uncertainty
Systematic uncertainties

<table>
<thead>
<tr>
<th>$\delta C/C$ [%]</th>
<th>$Z \rightarrow e^+e^- W^+ \rightarrow e^+\nu W^- \rightarrow e^-\nu\bar{\nu}$</th>
<th>$Z \rightarrow \mu^+\mu^- W^+ \rightarrow \mu^+\nu W^- \rightarrow \mu^-\nu\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton trigger</td>
<td>0.1 0.3 0.3</td>
<td>0.2 0.6 0.6</td>
</tr>
<tr>
<td>Lepton reconstruction, identification</td>
<td>0.9 0.5 0.6</td>
<td>0.9 0.4 0.4</td>
</tr>
<tr>
<td>Lepton isolation</td>
<td>0.3 0.1 0.1</td>
<td>0.5 0.3 0.3</td>
</tr>
<tr>
<td>Lepton scale and resolution</td>
<td>0.2 0.4 0.4</td>
<td>0.1 0.1 0.1</td>
</tr>
<tr>
<td>Charge identification</td>
<td>0.1 0.1 0.1</td>
<td>– – –</td>
</tr>
<tr>
<td>JES and JER</td>
<td>– 1.7 1.7</td>
<td>– 1.6 1.7</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>– 0.1 0.1</td>
<td>– 0.1 0.1</td>
</tr>
<tr>
<td>Pile-up modelling</td>
<td>&lt; 0.1 0.4 0.3</td>
<td>&lt; 0.1 0.2 0.2</td>
</tr>
<tr>
<td>PDF</td>
<td>0.1 0.1 0.1</td>
<td>&lt; 0.1 0.1 0.1</td>
</tr>
<tr>
<td>Total</td>
<td>1.0 1.9 1.9</td>
<td>1.1 1.8 1.8</td>
</tr>
</tbody>
</table>

- Contribute to the cross-section measurement via the C factor mainly

- **Lumi uncertainty 5%**
Putting everything together...

A factors obtained at Born level with DYNNLO
- dominant uncertainty from different PDF sets (CT14nnlo, NNPDF3.0, MMHT14nnlo68CL, ABM12)
- Measurement in electron channel higher for W, but larger uncertainties, and within 1σ
Lepton universality

Check of lepton universality: good agreement with SM expectations and previous precision measurements

\[ R_W = \frac{\sigma_{W^\pm \rightarrow e^\pm e^-}}{\sigma_{W^\pm \rightarrow \mu^\pm \mu^-}} \]

\[ R_Z = \frac{\sigma_{Z \rightarrow e^+e^-}}{\sigma_{Z \rightarrow \mu^+\mu^-}} \]

ATLAS
13 TeV, 81 pb^{-1}

68% CL ellipse area

Data
R_{W} PDG average
R_{Z} PDG average
Standard Model

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Cross-section dependence on $\sqrt{s}$

Consistent with NNLO QCD
Z+jets cross section

$L = 81 \text{ pb}^{-1} @ 13 \text{ TeV}$

Data taken with 50 ns bunch spacing in early Summer 2015
Motivation and strategy

- Helps to understand **QCD effects in high-multiplicity final states**
- Z+jets important background to several searches, Higgs boson and top quark production
- Same fiducial phase space as Z inclusive analysis for leptons, with extra jets requirement of $p_T>30$ GeV and $|y|<2.5$
  - Look at events with up to 4 jets in the final state

- Sherpa 2.1 signal MC
- MC-based background estimate

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**Results**

- **Bin-by-bin extraction of fiducial cross sections at particle level** (see inclusive analysis)
  - Combination of lepton channels using HERAverager

- Comparison to Sherpa (NLO) and Madgraph (LO) → **good agreement** also in ratio

- Reach precision of 10-20% up to 4 jets