Rencontre de Vietnam 2018 - windows on the universe -

Standard Model Physics at LHC

Ludovica Aperio Bella
on behalf of ATLAS CMS and LHCb experiments
SM measurements play essential roles in testing our current understanding of the laws that govern the universe. Measurements of the SM at LHC are looking at unexplored territory:

- Testing the validity of SM in challenging & previously unaccessible regions
  - High energy, rare processes
  - Difficult modelling: high-order/EW corrections
- Tune MC generators, constraints PDFs, ...

Constrain, or observe, new physics contributions

- Rare production processes
- Processes sensitive to anomalous couplings

Background to all direct searches & Higgs measurements
SM measurements validity range

Standard Model Production Cross Section Measurements

ATLAS Preliminary
Run 1, 2 \( \sqrt{s} = 7, 8, 13 \) TeV

LHC pp \( \sqrt{s} = 7 \) TeV
- Data 4.5 – 4.9 fb\(^{-1}\)
- LHC pp \( \sqrt{s} = 8 \) TeV
- Data 20.2 – 20.3 fb\(^{-1}\)
- LHC pp \( \sqrt{s} = 13 \) TeV
- Data 3.2 – 79.8 fb\(^{-1}\)

# events in 2016 dataset
Precision measurements of [differential] V+Jets production cross sections stringent tests of SM predictions
- sensitive to higher order (QCD and EWK effects)
- sensitive to non perturbative effects (e.g. particle emission, parton shower)
- also explicitly EWK production mode (VBF, soft QCD modelling)
- Comparison of the measurements with predictions motivates additional Monte Carlo (MC) generator development and improves our understanding of the prediction uncertainties.

(Up to) triple differential \( \gamma(+) \text{jets} \)

<table>
<thead>
<tr>
<th>CMS Preliminary</th>
<th>2.26 fb(^{-1}) (13 TeV)</th>
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<tbody>
<tr>
<td>(</td>
<td>y</td>
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<td></td>
<td>JETPHOX NNPDF3.0</td>
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<td></td>
<td>JETPHOX CT14</td>
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<td></td>
<td>JETPHOX MMHT14</td>
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<tr>
<td></td>
<td>JETPHOX HERAPDF2.0</td>
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<tr>
<td></td>
<td>NNPDF3.0 total theoretical unc.</td>
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Sensitivity to (gluon) PDFs

\[ \frac{\text{Theory}}{\text{Data}} \]

\( E_T (\text{GeV}) \)

<table>
<thead>
<tr>
<th>Data</th>
<th>ATLAS</th>
<th>CMS</th>
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<tbody>
<tr>
<td>(W( ^+ ) + 1 jets)/(W( ^+ ) + ≥ 1 jets)</td>
<td>(W( ^+ ) + 1 jets)/(W( ^+ ) + ≥ 1 jets)</td>
<td>(W( ^+ ) + 1 jets)/(W( ^+ ) + ≥ 1 jets)</td>
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<tr>
<td>( p_T^\gamma &gt; 30 \text{ GeV},</td>
<td>y</td>
<td>&lt; 4.4 )</td>
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<tr>
<td>Data</td>
<td>BH-S</td>
<td>NNLO</td>
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<tr>
<td>Data</td>
<td>SHERPA ( 2.1 ) NLO</td>
<td>BH-S</td>
</tr>
<tr>
<td>Data</td>
<td>SHERPA ( 2.1 ) LO</td>
<td>SHERPA ( 2.1 ) NLO</td>
</tr>
<tr>
<td>Data</td>
<td>ALPGEN+HERWIG</td>
<td></td>
</tr>
</tbody>
</table>

Sensitivity to valence quark and gluon PDFs at high x

\[ \frac{\text{Data}}{\text{Pred.}} \]

\( p_T (\text{GeV}) \)
Unique measurement of the triple differential cross section: \( d^3\sigma/dy_mll dq_c \) in a wide kinematic range, \( m_{ll} \ [46,200] \text{ GeV and } y_{ll} < 3.6 \), using \( \sqrt{s} = 8 \text{ TeV} \) ATLAS data.

- The measurement is designed to be sensitive to both PDFs and \( \sin^2\theta_W \).
- In the Z-peak region, the data accuracy is better than 0.5% in a wide region of \( |y_{ll}| < 1.4 \).
- The measurement is used to compute single- and double-differential \( d\sigma/dm_{ll} \) and \( d^2\sigma/dm_{ll}dy_{ll} \) cross sections.
- The results are well described by modified Powheg predictions.
- as well as forward-backward asymmetry (\( A_{FB} \)).

Triple-differential distributions of the forward-backward asymmetry, \( A_{FB} \), compare with the predictions from the inclusive NNLO\( JET \) calculations using the MMHT14 PDF set for \( \sin^2\theta_W = 0.2348 \).
Differential cross-section measurements of W and Z production in the forward acceptance.

LHCb offers a complementary phase space region with respect to ATLAS and CMS for Standard Model tests in electroweak sector

$sin^2\theta_W$ measurement with $\sqrt{s} = 7, 8$ TeV $Z \rightarrow \mu\mu$ events

$sin^2\theta_W^{\text{eff}} = 0.23142 \pm 0.00073 \pm 0.00052 \pm 0.00056,$

stat.  sys.  PDF
LHC data has extensive and growing portfolio of pdf-sensitive measurements of same process at different CM energies, and ratio measurements (EG. of different processes, or same process at different energies) with partially cancelling systematics can provide significant pdf constraints

NNLO QCD calculations available for important physics processes – developments in grid technology (APPLfast) mean these data should be useable in rigorous NNLO pdf fits in the near future.

→ ATLAS-epWZ16 pdf (available on lhapdf)
Tests of the consistency of the EW sector in the SM through higher precision measurements of its fundamental parameters ($\sin^2 \theta_W$ and $m_W$) it is one of the goal of LHC physics program.

• This requires specific efforts in the experimental community and the theory community
  - using high $|y^{ll}|$ events to enhance sensitivity to weak mixing angle
  - validate use of improved Born approximation at the LHC for precision Z physics.
  - low-$\mu$ runs in 2017/2018 to measure precisely $p_T^W$
  - precision DY measurements require ultimate performance of detector for electrons/muons and hadronic recoil
  - improve theoretical predictions and uncertainty estimates for $p_T^W/p_T^Z$

Full EW fit: $\sin^2 \theta'_{\text{eff}} = 0.23150 \pm 0.00006$

Indirect determination from EW fit: $\sin^2 \theta'_{\text{eff}} = 0.23149 \pm 0.00007$

Lepton collider average (LEP/SLC): $\sin^2 \theta'_{\text{eff}} = 0.23152 \pm 0.00016$
\[
\sin^2 \theta^\ell_{\text{eff}} = 0.23101 \pm 0.00036 \text{ (stat)} \pm 0.00018 \text{ (syst)} \pm 0.00016 \text{ (theo)} \pm 0.00031 \text{ (PDF)}
\]

- Exploit forward-backward asymmetry \((A_{FB})\) in Drell-Yan \(ee/\mu\mu\) events
  - Fit mass (Tevatron) or mass & rapidity (CMS) dependence of observed \(A_{FB}\) to SM predictions as function of \(\sin^2 \theta^\ell_{\text{eff}}\)
  - Extract from angular coefficient \(A_4\) (ATLAS) in mass/rapidity bins

Using Bayesian Reweighting used for equiprobable NNPDF replicas from the measured forward-backward asymmetry.
\[ \sin^2\theta_{\text{eff}}^{\text{lept}} \] -- key SM parameter

- Exploit forward-backward asymmetry (A_{FB}) in Drell-Yan ee/\mu\mu events
  - Fit mass (Tevatron) or mass & rapidity (CMS) dependence of observed A_{FB} to SM predictions as function of \( \sin^2\theta_{\text{eff}}^{\text{lept}} \)
  - Extract from angular coefficient \( A_4 \) (ATLAS) in mass/rapidity bins

ATLAS-CONF-2018-037

\[
\frac{d^3\sigma}{dp_T^2\,dy \,dm^2 \,d\cos\phi} = \frac{3}{16\pi} \frac{d^3\sigma^{U+L}}{dp_T^2\,dy \,dm^2} \text{\{1 + cos}^2\theta \text{\} + \frac{1}{2} A_0 (1 - 3 \cos^2\theta) + A_1 \sin2\theta \cos\phi + A_2 \sin\theta \cos\phi + A_3 \cos\theta + A_4 \sin\theta \sin\phi + A_5 \sin^2\theta \sin\phi \sin\phi + A_6 \sin^2\theta \sin^\phi \sin^\phi + A_7 \sin\theta \sin\phi}.\]

- ATLAS extraction is using angular coefficient (A) (3 channels: \( \mu\mu, ee, \text{ee}_{\text{cf}} \) at 8\, TeV) is technically more challenging than AFB, but some advantages
  - Angular variables can constrain experimental systematics
  - Measurements in full phase space via analytical extrapolation of the spherical harmonics.
    - Reduced theory uncertainties
    - Possibly more sensitive to NLO EW effects that can break harmonic decomposition compared to AFB (but can be accounted for with corrections)

Measurement of the Angular coefficient in m and Y bins simultaneously reduce considerably the dominant source of experimental systematic uncertainties and theory unc. arising from PDF uncertainties.
### ATLAS uncertainty breakdown of WMA

**Central value**

<table>
<thead>
<tr>
<th>Channel</th>
<th>$ee\text{CC}$</th>
<th>$\mu\mu\text{CC}$</th>
<th>$ee\text{CF}$</th>
<th>$ee\text{CC} + \mu\mu\text{CC}$</th>
<th>$ee\text{CC} + \mu\mu\text{CC} + ee\text{CF}$</th>
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<tr>
<td>Central value</td>
<td>0.231148</td>
<td>0.23123</td>
<td>0.23166</td>
<td>0.23119</td>
<td>0.23140</td>
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**Uncertainties**

<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>$ee\text{CC}$</th>
<th>$\mu\mu\text{CC}$</th>
<th>$ee\text{CF}$</th>
<th>$ee\text{CC} + \mu\mu\text{CC}$</th>
<th>$ee\text{CC} + \mu\mu\text{CC} + ee\text{CF}$</th>
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<tr>
<td>Total</td>
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<td>59</td>
<td>43</td>
<td>49</td>
<td>36</td>
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<td>Stat.</td>
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<td>40</td>
<td>29</td>
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<tr>
<td>Syst.</td>
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<td>44</td>
<td>32</td>
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**Uncertainties in measurements**

<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>$ee\text{CC}$</th>
<th>$\mu\mu\text{CC}$</th>
<th>$ee\text{CF}$</th>
<th>$ee\text{CC} + \mu\mu\text{CC}$</th>
<th>$ee\text{CC} + \mu\mu\text{CC} + ee\text{CF}$</th>
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<tr>
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<td>9</td>
<td>7</td>
<td>6</td>
<td>4</td>
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<td>4</td>
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<td>3</td>
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<td>Lepton resolution</td>
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<td>Lepton efficiency</td>
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<td>3</td>
<td>2</td>
<td>4</td>
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<td>0</td>
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<td>2</td>
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<td>25</td>
<td>22</td>
<td>18</td>
<td>16</td>
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**Uncertainties in predictions**

<table>
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<tr>
<th>Uncertainties</th>
<th>$ee\text{CC}$</th>
<th>$\mu\mu\text{CC}$</th>
<th>$ee\text{CF}$</th>
<th>$ee\text{CC} + \mu\mu\text{CC}$</th>
<th>$ee\text{CC} + \mu\mu\text{CC} + ee\text{CF}$</th>
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<tbody>
<tr>
<td>PDF (predictions)</td>
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<td>22</td>
<td>33</td>
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<td>5</td>
<td>6</td>
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<td>3</td>
<td>3</td>
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**Note:**

- $ee\text{CF}$ is the most precise channel with 1.5 M of events (13.5M $ee+\mu\mu$).
- Measurement uncertainty: $36 \times 10^{-5}$.
New analysis techniques, including in-situ PDF profiling and categorisation statistical and systematic uncertainties are significantly reduced relative to previous CMS and ATLAS measurements.
The challenges of the W Boson mass at LHC

Need excellent understanding of detector and MC simulation

Energy under the electron cone

In-cone FSR

Underlying event

Soft Recoil

Min Bias

Zero Bias

Hard Recoil

\[ p_T^W \]

\[ E_T \]
• At LO $p_{Tl}$ has a Jacobian peak at $m_W/2$, $m_T$ has an endpoint at $m_W$

• Method:  
  Fit the distribution of $p_{Tl}$ and $m_T$ using MC templates generated with different $m_W$ in 16 category. 
  
  • $m_T$ less sensitive to W boson $p_T$, but more sensitive to hadronic recoil resolution  
  • $p_{Tl}$ not directly dependent on recoil, but more sensitive to $p_T^W$

• Different effects modify the reconstructed $p_{Tl}$ and $m_T$ distributions:  
  • Initial and final state radiation (QED);  
  • The W boson $p_T^W$ distribution (QCD);  
  • Detector response.
The final combination gives
\[ m_W (\text{Partial Comb.}) \]

Taking into account the correlation of different combinations are performed,
\[ \text{Stat. Uncertainty} \cdot \text{Full Uncertainty} \]

\[ m_W (\text{Full Comb.}) \]

\[ \Delta \chi^2 = 6.8 \, \text{MeV} \, (\text{approx. } 50\%) \quad \text{and of} \quad \text{mod. syst} = 13.6 \, \text{MeV} \]

Combined Result
\[ m_W = 80370 \pm 19 \, \text{MeV} \]
W mass physics modelling

- QCD uncertainties are evaluated by varying parameters of Pythia-8 AZ tune and of the NNLO calculation.
- Largest uncertainties on $m_W$ from PDF variations in NNLO calculation: 13-15 MeV, largely anti-correlated between $W^+$ and $W^-$.
- Uncertainties from missing higher-order electroweak corrections are small.

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<tbody>
<tr>
<td>80369.5</td>
<td>6.8</td>
<td>6.6</td>
<td>6.4</td>
<td>2.9</td>
<td>4.5</td>
<td>8.3</td>
<td>5.5</td>
<td>9.2</td>
<td>18.5</td>
<td>29/27</td>
</tr>
</tbody>
</table>

Stat. = 6.8 MeV  exp. syst = 10.6 MeV  mod. syst = 13.6 MeV

$m_W = 80370 \pm 19$ MeV
The modelling of the W/Z $p_T$ ratio in pp collisions is an open issue in QCD: Only (N)LL parton shower predictions are in agreement with the data, all other higher order predictions fail to describe the observed distributions.

A measurement able to resolve $W$ $p_T$ in bins of 5 GeV with 1% uncertainty would provide a direct probe of the W/Z $p_T$ ratio and a crucial experimental input to understand this issue. In order to resolve $W$ $p_T$ at 5 GeV we need to achieve a experimental resolution of the Hadronic recoil of the same order.

Both ATLAS and CMS collected $\sim500$ pb$^{-1}$ of data collected with low Pileup! fantastic opportunity for W boson transverse momentum measurement!
Another fundamental goal of LHC physics program is to tests of the consistency of the SM through **direct exploration of the EW symmetry breaking mechanism using diboson production**. This requires eventually very large datasets and specific efforts from the theory community.

**Multi-bosons production at LHC:**
- Measure cross-section of process predicted by SM but never observed before
- *EW and QCD higher order corrections are very important!*
- Sensitive probe of BSM gauge iterations.
- Probe anomalous triple/quartic gauge couplings (*aTGC,QGC*)

**Study vector-boson scattering (VBS) processes**
- Key test of EWSB
- Sensitive to anomalous QGC
- Enhanced in beyond-SM scenarios (e.g. modified Higgs sector or new resonances)
What about predictions?

Same-sign WW process is the only diboson process to-date for which NLO (EW and QCD) corrections have been computed. (PhysRevLett.118.261801)

Main impact of improved calculation arises from NLO EW corrections which are negative and correspond to ≈ -15% in the fiducial region of interest.

\[ \sigma_{\text{LO}}^{\text{fid}} = 1.64 \text{ fb with } \approx 10\% \text{ uncertainty} \]

\[ \sigma_{\text{NLO}}^{\text{fid}} = 1.36 \text{ fb with } \approx 2\% \text{ uncertainty} \]

Overall a 20% reduction of the fiducial cross section which is unambiguous at this order only in terms of final-state leptons and partons.
Observation @ CMS in 2017 (5.5σ observed, 5.7σ expected)

Measured fiducial cross section:

\[ \sigma_{\text{fid}}(W^\pm W^\mp jj) = 3.83 \pm 0.66 \text{ (stat)} \pm 0.35 \text{ (syst)} \text{ fb.} \]

in agreement with LO prediction

Observation @ ATLAS (6.9σ observed, 4.6σ expected (Sherpa))

Same-sign WW: \( \sigma_{\text{fid}} = 2.91^{+0.51}_{-0.47} \text{ (stat)} \pm 0.27 \text{ (sys)} \text{ fb.} \)

Fiducial cross sections at LO for same-sign WWjj EW process:

Sherpa v2.2.2: 2.0 ± 0.3 fb
Powheg+Pythia8: 3.1 ± 0.5 fb
Vector boson scattering (VBS) processes are sensitive to anomalous QGC. The first observation of these processes was made at ATLAS.

Enhanced in beyond-SM scenarios, such as the ATLAS-CONF-2018-033, VBS processes form a distinct experimental signature characterized by two vector bosons. This is distinguishable from QCD-induced production through kinematic variables.

The EW WZ final state is an important subclass of processes contributing to WZ plus two jet (WZjj) production. It proceeds via QCD radiation of partons from the incoming quark or gluon lines, shown in Fig. 1 (b), leading to forward and high-momentum jets in addition to the vector bosons. They are part of an important subclass of processes contributing to WZjj production that proceeds via EW WZ production.

An excess of events with respect to the SM prediction could indicate contributions from additional EW WZjj production (or QCD WZ), and is distinguishable from the EW-induced component via kinematic selections.

The discovery of a scalar boson with couplings consistent with the standard model (SM) Higgs boson provides evidence that the W and Z bosons acquire mass through the Higgs mechanism. Given the mass of the Higgs boson, the couplings to the quark and gluon sectors are expected to include interactions with the Higgs and vector bosons, modifying their effective couplings. Characterizing the self-interactions of the vector bosons is thus of great importance.

Measurements of EW processes in the WZ sector modifying the quartic coupling can be parameterized in terms of dimension-eight effective operators, which we refer to as EW-induced WZjj production (or QCD WZ), and is distinguishable from the EW-induced component via kinematic selections.

Only LO predictions exist for WZjj EW production. What about predictions? Sherpa v2.2.2 predicts 0.32 ± 0.03 fb, while ATLAS observed 5.6σ expected events.

**1st observation + differential measurements of EW processes in the WZ**

**higher-order calculations of diboson EW production, existing to-date only for same-sign WW EW production**

**WZjj EW**

\[ \sigma_{\text{fid}} = 0.57 \pm 14 \text{(stat)} \pm 0.05 \text{(sys)} \pm 0.04 \text{(th.)} \text{ fb} \]

What about predictions?

Sherpa v2.2.2: 0.32 ± 0.03 fb

Only LO predictions exist for WZjj EW production.

L. Aperio Bella
Vector boson scattering (VBS), in which vector bosons are radiated from the incoming quarks, is used to train and optimize a boosted decision tree (BDT) on simulated events to exploit differences in their kinematic properties. New physics in the EW sector modifying the quartic coupling can be parameterized in terms of dimension-eight effective couplings. Characterizing the self-interactions of the vector bosons is thus of great importance subclass of processes contributing to WZ plus two jet (WZjj) production that proceeds via QCD radiation of partons from the incoming quark or gluon lines, shown in Fig. 1 (b), leading to contributions at $\mathcal{O}(aQGC)$.

The discovery of a scalar boson with couplings consistent with the standard model (SM) Higgs sector is expected to include interactions with the Higgs and vector bosons, modifying their effective couplings. Characterizing the self-interactions of the vector bosons to the Higgs and their triple and quartic self-interactions are expected.

1 Introduction

The discovery of a scalar boson with couplings consistent with the standard model (SM) Higgs provides evidence that the W and Z bosons by the ATLAS and CMS collaborations [1, 2] provides evidence that the W and Z bosons leptonic decay modes by the CMS and ATLAS collaboration at 7, 8 and 13 TeV [3–6], and limits effective couplings. Characterizing the self-interactions of the vector bosons to the Higgs and their triple and quartic self-interactions are expected.

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Figure 1: Representative Feynman diagrams for the EW- (top row and bottom left) and QCD- (bottom right) induced WZ production, is used to extract the signal significance and to measure the cross section in a phase space with enhanced contribution, or simply EW WZ production. An additional contribution to the WZjj state proceeds by QCD-induced production (or QCD WZ), and is distinguishable from the EW-induced component via kinematic variables. New physics in the EW sector modifying the quartic interactions (a) of the vector bosons. This is distinguishable from QCD-induced production (b) through kinematic variables.

A total of 36 discriminating variables including observables sensitive to parton emissions between the data, filled histograms the expected signal and background contributions. No data beyond the fit within the respective uncertainties. This approach constrains the yield of the QCD-induced production (or QCD WZ), and is distinguishable from the EW-induced component via kinematic variables. New physics in the EW sector modifying the quartic interactions (a) of the vector bosons. This is distinguishable from QCD-induced production (b) through kinematic variables.

Electrons are measured in the pseudorapidity range $2.4 < \eta < 3.0$. A total of 36 discriminating variables including observables sensitive to parton emissions between the data, filled histograms the expected signal and background contributions. No data beyond the fit within the respective uncertainties. This approach constrains the yield of the QCD-induced production (or QCD WZ), and is distinguishable from the EW-induced component via kinematic variables. New physics in the EW sector modifying the quartic interactions (a) of the vector bosons. This is distinguishable from QCD-induced production (b) through kinematic variables.
**WZ Inclusive+differential cross section** measurements from both ATLAS & CMS

*Good agreement between data & predictions*
WZ Inclusive+differential cross section measurements from both ATLAS & CMS

Good agreement between data & predictions

@ATLAS first measurement measurement of WZ polarisation use lepton angular distributions, template fits to $(q \cdot \cos \theta)$,
• Measurements in EW sectors are keys in continuing testing the SM & searching for new physics.
• Outstanding SM results using Run1 data but very impressing new results using Run2 data @13TEV!
• Numerous very interesting new results
  • Approaching LEP single experiment sensitivity for weak mixing angle measurement
  • On the road of detailed vector-boson scattering studies in different channel
• Great potential in the future!
Backup
weak mixing angle extraction HL-LHC
Energy evolution of $\sigma_{\text{tot}}$ and $\sigma_{\text{el}}$

Elastic cross section from the nuclear part of the integrated fit function
First measurement of W/Z polarisation in diboson processes

- Helicity fractions $f_0$ (longitudinal polarisation) and $f_L/f_R$ (transverse polarisation)
- Evidence for longitudinally polarised Ws at $4.2\sigma$ (3.8$\sigma$ expected)
- Theory predictions are LO EW with $\sin^2\theta_W = 0.23152$ (PDG 2016)
• Examples of differential distributions for WZ EW signal region: $\Delta y_{jj}$ (left) and $m_{jj}$ (right), compared to Sherpa predictions rescaled to their post-fit values.
W mass measurement with ATLAS

Combined Result

Different combinations are performed, taking into account the correlation of $m_T$ and $p_T^{ll}$ (approx. 50%) and of systematics. The final combination gives (assuming same mass for $W^+$ and $W^-$):

- **Experiment Systematic Uncertainty (exp. syst)**: $10.6$ MeV
- **Model Systematic Uncertainty (mod. syst)**: $13.6$ MeV
- **Statistical Uncertainty (stat)**: $6.8$ MeV

$m_W = 80370 \pm 19$ MeV

Comparison with previous results and SM

- The ATLAS measurement has the same precision of the previous most-precise single measurement (CDF) and is consistent with previous results.
- Word Combination uncertainty varies between 11 and 14 MeV, depending on assumed correlation between ATLAS and Tevatron. PDG assumes 7 MeV of correlated uncertainty (J. Erler, Moriond 2017). A detailed study of this correlation (mainly PDFs) would be very important.
- Good agreement with predicted $m_W$ from SM EWK fit.

PDG, April 2017

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stat. = 6.8 MeV  exp. syst = 10.6 MeV

mod. syst = 13.6 MeV
Properties of EW Zjj signal events:
well-separated jets in rapidity with large mjj, and central decay of Z boson
suppressed color flow in the region between the two jets (low hadronic activity in the rapidity interval)