Inclusive and differential W and Z at CMS and ATLAS

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on behalf of the ATLAS and CMS Collaborations

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- Production of $Z/\gamma^*$ and $W$ via Drell-Yan process

- purely leptonic decays are a very clean experimental signature
- observables sensitive to both QCD and EW sectors of the Standard Model
  - theory cross sections computed up to NNLO in QCD and NLO in EW
  - total and differential cross-sections (absolute or normalized) are sensitive to the proton structure (PDFs)

- EW production of $Z$ and $W$ bosons
  - vector boson fusion, bremsstrahlung-like and other diagrams
  - sensitive to triple gauge boson couplings
    - possible new physics contributions
• In the SM, 3 parameters define the EW sector
  - U(1), SU(2) couplings and VEV: (g, g’, v) can be connected to observables
    - e.g. at tree level:
      \[
      M_W = \frac{v|g|}{2}, \quad M_Z = \frac{v\sqrt{g^2 + g'^2}}{2}, \quad \cos\theta_W = \frac{m_W}{m_Z}
      \]
    - mass of the W (Z) measured at LHC and Tevatron (LEP) with millions of events
    - weak mixing angle \(\theta_W\) from precision Z measurements

• The same 3 parameters regulate triple- / quartic-couplings, but are measured with lower precision
  - sensitive to new physics

• Higgs boson and top enter the EW picture through radiative corrections

• Stringent consistency tests can be done via a global EW fit (e.g. \(M_W - M_{\text{top}} - m_H\))
The 5D differential cross section can be decomposed as 1+8 harmonic polynomials $P_i(\cos\theta^*, \phi^*)$, multiplied by dimensionless angular coefficients $A_i(p_T^Z, y_Z, m_Z)$.

- all hadronic dynamics and EW fundamental parameters dependence is in $A_i$

\[
\frac{d\sigma}{dp_T^Z dy_Z dm_Z d\cos\theta d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^Z dy_Z dm_Z} \times \left\{ (1 + \cos^2\theta) + \frac{1}{2} A_0 (1 - 3 \cos^2\theta) + A_1 \sin 2\theta \cos\phi \\
+ \frac{1}{2} A_2 \sin^2\theta \cos 2\phi + A_3 \sin \theta \cos \phi + A_4 \cos \theta \\
+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin \phi + A_7 \sin \theta \sin \phi \right\}.
\]

- ATLAS has a measurement of $A_0 - A_7$ [JHEP 08 (2016) 159]. CMS reported $A_0 - A_4$ [PLB750 (2015) 154]

The path to full 5D is step-by-step in increasing number of variables.

<table>
<thead>
<tr>
<th>differential in:</th>
<th>sensitive to:</th>
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</thead>
<tbody>
<tr>
<td>di-lepton mass $m_{\ell\ell}$</td>
<td>proton PDFs</td>
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<tr>
<td>di-lepton rapidity $y_{\ell\ell}$</td>
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<tr>
<td>di-lepton $p_T^{\ell\ell}$</td>
<td>higher order QCD predictions</td>
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<tr>
<td>angular distributions ($\cos\theta^<em>, \sin\phi^</em>$)</td>
<td>weak mixing angle $\theta_W$ (and PDFs)</td>
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Angular coefficients results

- Measurement with 8 TeV data from ATLAS and CMS are more precise than the calculations
  - violation of Lam-Tum relation $A_0=A_2$ by higher order QCD corrections

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**Figure 1**: Comparison of the five angular coefficients $A_0$, $A_1$, $A_2$, $A_3$, and $A_4$ for $Z+j$ collisions at 8 TeV. The plots show the measured values compared to theoretical predictions from POWHEG+MINLO and DYNNLO (NNLO) frameworks, with shaded bands indicating the total uncertainties.

**Figure 2**: Comparison of the five angular coefficients $A_0$, $A_1$, and $A_2$ for $Z+j$ collisions at 8 TeV, with data points and theoretical predictions from MadGraph, Powheg, and FEWZ,NNLO.

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**Figure 3**: Comparison of the angular coefficients $A_3$, $A_4$, and $A_5$ for $Z+j$ collisions at 8 TeV, with data points and theoretical predictions from POWHEG+MINLO and DYNNLO (NNLO) frameworks.

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**Further References**:

- ATLAS Collaboration: *High-Precision Measurements of Angular Coefficients for $Z+j$ Production at the ATLAS Experiment*. JHEP [2016] 159
- CMS Collaboration: *Precision Measurements of Angular Coefficients for $Z+j$ Production at the CMS Experiment*. PLB 750 (2015) 154

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**Acknowledgements**: We wish to thank our colleagues and collaborators for their contributions to this work.
• ATLAS measures DY production w.r.t. 3 kinematic variables

\[ \frac{d^3}{dm_{\ell\ell} \ d|y_{\ell\ell}| \ d\cos\theta^*} \]

improves both \( \theta_W \) and PDF sensitivities

sensitivity to proton PDFs

- the \( \theta_W \) measurements at colliders typically limited by the PDFs
- this measurement is designed to be simultaneously sensitive to \( \theta_W \) and PDFs
  - limiting the leading systematic uncertainties

• \( d^3\sigma \) measured in fiducial region, unfolded to Born-level
  - phase space defined by lepton \( p_T, \eta, \) and \( m_{\ell\ell} \) ranges
  - \( d^3\sigma \) up to \( |y_{\ell\ell}| < 2.4 \) with \( ee+\mu\mu \) and up to 3.6 with \( ee \)
The primary result of the 3D Drell-Yan measurement shows:

- 3 of 7 mass ranges shown
- Asymmetry between $\pm \cos\theta^*$ (filled region) reflects parity violation in Z-boson decays
  - Asymmetry is zero and flips sign at $m_{ee} \sim M_Z$

**Figure 7**

3σ $\sigma_{\Delta}$

$M_{ee} < M_Z$

$M_{ee} \sim M_Z$

$M_{ee} > M_Z$
• From 3D differential x-s, derive 2D, 1D integrated results:
  - \( \frac{d\sigma}{d m_{\ell\ell}}, \frac{d^2\sigma}{d m_{\ell\ell} d |y_{\ell\ell}|} \)
  - \( A_{FB} \), which makes more clear the parity violation effects:
    \[
    A_{FB}(m_{\ell\ell}, |y_{\ell\ell}|) = \frac{\int d\sigma(\cos \theta^* > 0) - \int d\sigma(\cos \theta^* < 0)}{\int d\sigma(\cos \theta^* > 0) + \int d\sigma(\cos \theta^* < 0)}
    \]

• Good agreement with POWHEG, with NNLO QCD and NLO EW \( K \)-factors

• Large sensitivity from the electron channel with one fwd electron
  - possible to simultaneously extract \( \sin^2\theta_{\text{eff}} \) and PDFs with improved precision

**AFB (one lepton central, one forward)**
$\sin^2 \theta_W$ measurements

- $A_{FB}$ depends on the interference of vector and axial currents
  - at LO EW, $\sin^2 \theta_W = 1 - m_W/m_Z$.
  - beyond, tree level couplings are replaced by effective couplings, measuring:
    $$\sin^2 \theta_{\text{eff}}^\ell = k_Z^\ell \sin^2 \theta_W$$

- $A_{FB}$ depends on quark flavor $\Rightarrow$ sensitivity to PDFs

- $\theta^*$ is the angle between the lepton and quark
  - at LHC (pp) use the direction of the di-lepton system in the laboratory frame as the positive axis
  - dilution of asymmetry when not true
  - quarks are mainly originated from valence and tend to have larger $x$ than antiquarks
    - dependence on PDFs from large-$x$ antiquarks

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CMS measures $A_{FB}$ in 6 bins of rapidity and 12 bins of dilepton mass (8 TeV)
- Extract $\sin^2\theta_{\text{eff}}$ by fitting the measured $A_{FB}$ with different templates

Using Bayesian weighting method with NNPDF3.0 replicas: $w \propto \exp\{\chi^2/2\}$
- uncertainty related to PDFs reduces from 0.00057 to 0.00030 (factor $\sim$2)

$\mu\mu$

\[ \sin^2\theta_{\text{eff}} = 0.23101 \pm 0.00053 \]
\[ \sin^2\theta_{\text{eff}} = 0.23101 \pm 0.00036 \text{ (stat)} \pm 0.00018 \text{ (syst)} \pm 0.00016 \text{ (theo)} \pm 0.00031 \text{ (PDF)} \]
ATLAS measures as $A_{FB} = 3/8 A_4$, fitting the $A_i$ with templates (8x8 bins in ($\cos\theta^*,$ $\phi^*$) for each $y_{ll}$, $m_{ll}$ bin

- then $A_4 = a \times \sin^2 \theta_{eff} + b$ in each bin. Sensitivity enhanced by using central-forward $ee$

$\sin^2 \theta_{eff} = 0.23140 \pm 0.00036$

$\sin^2 \theta_{eff} = 0.23101 \pm 0.00021$ (stat) $\pm 0.00016$ (syst) $\pm 0.00024$ (PDF)
PDFs from $W^\pm$ charge asymmetry

- Related to the larger number of valence $u$ quarks than $d$ quarks in the proton
- Rapidity distributions constrains quark and anti-quark PDFs
  - constraints from Run1, first ones at 13 TeV coming
• QCD sector of the SM can be tested with associate V + jets production
  - NNLO in QCD, NLO in EWK: theory has O(1%) precision, experiment often sub-% level
• Z, W + light jets measured up to 7 jets, good agreement with NLO QCD
  - jet multiplicities test higher order terms, PDFs
  - also studied correlations (e.g. m_{j\ell}, |\Delta Y_{j\ell}|...) sensitive to ME/PS matching, non-perturbative effects modeled with PS, etc.
**EW Z and W production**

- EW W, Z production is one interesting mechanism
  - VBF understanding important for Higgs measurements and new physics searches
  - EW production $\ll$ QCD one, but can be disentangled
    - typical handles: two forward jets with high di-jet mass
- ATLAS and CMS measure measure inclusive x-sec at 13 TeV
  - also used to constrain anomalous VVV couplings

**W+2jets**

**Z+2jets**

$\sigma_{EW}(Wjj) = 6.23 \pm 0.12 \text{ (stat)} \pm 0.61 \text{ (syst)} \text{ pb}$ [submitted to EPJ C]

$\sigma_{EW}(lljj) = 534 \pm 20 \text{ (stat)} \pm 57 \text{ (syst)} \text{ fb}$ [EPJ C (2018) 78]


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• Valuable consistency check of the SM

\[ m_W^2 \left( 1 - \frac{m_W^2}{m_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_\mu} (1 + \Delta r) \]

\[ \Delta m_W^{\text{theory}} = 8 \text{ MeV} < \Delta m_W^{\exp} = 15 \text{ MeV} \]
\[ \Delta m_t^{\text{theory}} = 2.1 \text{ GeV} > \Delta m_t^{\exp} = 0.76 \text{ MeV} \]

m_W particularly sensitive on M_{top} and M_{Higgs}

improve on m_W

need \Delta m_W / m_W \sim 10^{-4} !

• Measurement at LHC affected by PDFs more than Tevatron (need sea quarks in pp vs p\bar{p} collisions)
  - 25% of W produced by s and c quarks (vs 5% at Tevatron)
  - reduction of PDF uncertainties vital !

• First and only m_W measurement at LHC so far from ATLAS
  - 2 template fit to m_T(W), p_T(lep)
  - but none of the variables is Lorentz-invariant: 
    **modelling uncertainties** of longitudinal (PDFs) and transverse (q_T) d.o.f. in W production
• precision 0.02%, dominating uncertainty from theory: QCD, PDF
  - \( m_W = 80370 \pm 7 \text{ (stat.)} \pm 11 \text{ (exp. syst.)} \pm 14 \text{ (mod. syst.)} \text{ MeV} = 80370 \pm 19 \text{ MeV} \)
  - ATLAS measurement competes with Tevatron combination

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<tbody>
<tr>
<td>( m_T-p_T, W^\pm, e-\mu )</td>
<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>
</tr>
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**ATLAS W mass result**

- way forward under study at LHC EW WG: advisable a less model-dependent Z to W extrapolation
- direct measurement of \( p_T(W) \), W angular coefficients (e.g. low PU data taken in 2017)
- e.g. PDF in-situ constraints from W data (e.g. JHEP12 (2017) 130). More finely grained W \( p_T \) in the low \( p_T \) region

**ATLAS**

\( \sqrt{s} = 7 \text{ TeV, 4.1 fb}^{-1} \)

\( p_T^\mu \) in \( W^+ \) events

**ATLAS**

\( \sqrt{s} = 7 \text{ TeV, 4.7 fb}^{-1} \)

\( pp \rightarrow Z+X \)

\( 1/\sigma \frac{d\sigma}{dp_T} [\text{GeV}^{-1}] \)

**\( p_T(Z) \) modelling**

\( 1/\sigma \frac{d\sigma}{dp_T} [\text{GeV}^{-1}] \)

\( p_T^Z \) [GeV]

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Conclusions

- A rich research program is being pursued at the LHC
- Given no direct indications of new physics, EW sector is the main area for tests of the Standard Model of particle physics
- LHC Run2 has just ended. Only a fraction of Run2 data has been used for EW measurements
  - expect a stream of precision measurements with 13 TeV during the LHC shutdown
- Several improved theoretical calculations exists

- Advanced experimental techniques aim in a reduced theory-dependent approach
  - a measurement becomes a full program of simultaneous measurements
  - sometimes it will require full Run2 statistics, it always takes time

- precision may be the path for discoveries
The End
- CMS and ATLAS results consistent with the mean value of LEP and SLD and other available measurements
  - statistical uncertainties still dominate

- Measurements at the LHC will improve with Run 2 data and beyond
- PDF uncertainties could be reduced including more recent LHC data and performing a global fit
PDF constraints

- PDFs affect $A_{FB}$ mainly off the $Z$ pole, with opposite sign below and above $M_Z$
- Max sensitivity for $\sin^2\theta_{eff}$ for $m_{\ell\ell} \sim M_Z$
- Using Bayesian weighting method with NNPDF3.0 replicas: $w \propto \exp\{\chi^2/2\}$
  - uncertainty related to PDFs reduces from 0.00057 to 0.00030 (factor $\sim$2)
  - equivalent to ATLAS profiling of the PDF nuisances

![Diagram showing $A_{FB}$ vs. $m_{\ell\ell}$ for various $\sin^2\theta_{eff}$ values]

$\Delta A_{FB}$ vs. $m_{\ell\ell}$ (GeV)

**Figure 5**

18.8 ($\mu\mu$) + 19.6 (ee) fb$^{-1}$ (8 TeV)

**Table**

<table>
<thead>
<tr>
<th>Nominal NNPDF3.0</th>
<th>Weighted NNPDF3.0</th>
</tr>
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<tbody>
<tr>
<td>Entries</td>
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<tr>
<td>Mean</td>
<td>0.23102</td>
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<tr>
<td>Std Dev</td>
<td>0.00057</td>
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<tr>
<td>Entries</td>
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**EPJ C (2018) 78:701**

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**Production Cross Section, $\sigma$ [pb]**

- **Z and W + jets** production can be used to test high-order QCD calculations
  - the DY process almost factorized wrt the strong interaction production
  - LO predicts W and Z at rest
  - the transverse boost of the V ($= W, Z$) can be modelled:
    - at small $p_T$ needs soft gluon emission: resummation (non perturbative)
    - higher $p_T$, with perturbative QCD

- Many measurements of V+jets at LHC are compared with the most recent calculations:
  - NNLO in QCD, NLO in EWK: theory has O(1%) precision, experiment often sub-% level

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**CMS Preliminary**

*November 2017*

**Vector Boson + X fid. Cross Section Measurements**

Status: March 2018

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