Measurements of the Vector boson production with the ATLAS Detector

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on behalf of the ATLAS experiment

11 September 2017
W and Z boson production:
- clear signature
- large statistics
- small background contamination

W and Z boson are background to:
- SM measurements
- Higgs measurements
- new physics searches

Precision measurements of W and Z boson production useful to:
- test SM and extract SM parameters $\rightarrow m_W$, $\sin^2 \theta_W$, etc.
- probe the proton structure $\rightarrow$ constrain PDFs
- test perturbative QCD $\rightarrow$ probe state-of-the-art theory predictions
# Outline

Selection of recent results obtained with 7, 8 and 13 TeV ATLAS data

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Public ATLAS Standard Model results available at: [link](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublications)
W & Z cross section @ 7 TeV


- \( W(\rightarrow \nu e)/W(\rightarrow \mu \nu) \) & \( Z(\rightarrow ee)/Z(\rightarrow \mu \mu) \)
  - High precision measurements (few %)
  - Good agreement between data and SM
  - In agreement with lepton universality
  - W boson measurement:
    - As precise as previous best measurement
    - Higher precision than LEP combined

- \( W(\rightarrow l\nu)/Z(\rightarrow ll) \)
  - High precision measurement:
    - Possibility to check agreement with predictions of different PDFs
  - All predictions higher than data:
    - Need for improvement in the proton description
W & Z cross section @ 7 TeV

- **W charge asymmetry**
- Good agreement with theory predictions
- Experimental accuracy at the <1% level

\[
A_\ell = \frac{d\sigma_{W^+}/d|\eta_\ell| - d\sigma_{W^-}/d|\eta_\ell|}{d\sigma_{W^+}/d|\eta_\ell| + d\sigma_{W^-}/d|\eta_\ell|}
\]

- **Z cross section vs rapidity |y_{ll}|**
- Good agreement for |y_{ll}| > 1
- General disagreement for |y_{ll}| < 1
- Discrepancy can be interpreted as enhanced strangeness PDFs

**ATLAS**

- Data
- ABM12
- CT14
- HERAPDF2.0
- JR14
- MMHT2014
- NNPDF3.0

- Uncorr. uncertainty
- Total uncertainty

**Z/γ* → ℓ+ℓ⁻**

- 66 < m_{ℓ⁻} < 116 GeV
- p_T > 20 GeV
- |y_{ll}| < 2.5

**Theory/Data**

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Exploiting results of this measurement:

- New ATLAS PDF: \textbf{ATLAS-epWZ16}
- Constrain strange quark PDF (most sensitive region: $Q^2 = 1.9 \text{ GeV}^2$, $x = 0.023$)
- $R_s$ compatible with unsuppressed strangeness at low $x$

\[
R_s = \frac{s + \bar{s}}{u + d}
\]

\[
R_s = \frac{s + \bar{s}}{u + d} = 1.13 \pm 0.05 \text{ (exp)} \pm 0.02 \text{ (mod)} \pm 0.01 \text{ (par)}
\]
W/Z cross section @ 7 TeV

- W/Z ratio is sensitive to strange quark PDF
- Definitely accessing the proton structure
- New PDF developed: *ATLAS-epWZ16*
- Smaller uncertainties than ATLAS-epWZ12
W & Z cross section @ 13 TeV


- \(W^+, W^-, W^\pm, Z\) separate cross sections
- High precision measurements:
  - Z: 1% (± 2.1% luminosity)
  - W: 2% (± 2.1% luminosity)
- Theoretical predictions uncertainty:
  - dominated by PDF (Z: 7%, W: 6%)
- Possible to constrain PDFs!
W & Z cross section @ 13 TeV

**W^+/W^- ratio**
- High precision measurement (< 1%)
- Luminosity uncertainty canceled in ratio
- Discriminate among PDFs
  - CT14 & MMHT14: best description

**W/Z ratio**
- Luminosity uncertainty canceled in ratio
- Results compatible with all PDFs (within uncertainties)
- ATLAS-epWZ12 (based on ATLAS data fits) gives the best description
tt/Z cross section ratio @ 7, 8, 13 TeV

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**Systematics cancel out in the ratio**

**Results more precise than prediction!**

**Good agreement with different PDF**

**Best sensitivity at 8 and 7 TeV**

**Measured also tt/Z double ratio**

- $13/8$ TeV, $13/7$ TeV, $8/7$ TeV
Exploiting the tt/Z results:

- Profile ATLAS-epWZ12 to constrain:
  - light sea quark PDF
  - gluon PDF
Z+jets cross section @ 13 TeV

Z+jets cross section @ 13 TeV

Jet $p_T$ spectrum

- Z+jets cross section
- State-of-the-art predictions:
  - NNLO ($Z+\geq 1\text{jet Njetti}$)
  - NLO (BlackHat+Sherpa)
  - LO (various)

- LO MG5_aMC+PY8 CKKWL & FxFx too hard jet $p_T$ spectrum
- LO Alpgen+PY6, NLO Sherpa 2.2, NLO BlackHat+Sherpa, NNLO Njetti, show good agreement with data

- LO predicts too hard jet spectrum ($p_T > 200$ GeV)
Z+jets cross section @ 13 TeV

Jet multiplicity

- Z+jets cross section
- State-of-the-art predictions:
  - NNLO \(Z+\geq 1\text{jet}\quad N_{\text{jetti}}\)
  - NLO (BlackHat+Sherpa)
  - LO (various)

- Reasonable agreement up to 3 jets
- LO MG5_aMC+PY8 CKKW \(L\) seems OK
- LO Alpgen+PY6, NLO Sherpa 2.2, NLO MG5_aMC+PY8 FxFx systematic trend deviating from data

- Mismodeling for high jet multiplicity \(N_{\text{jets}} \geq 4\)
3D Z cross section @ 8 TeV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2016-04/
3D Z cross section @ 8 TeV to be published soon

- Triple differential Z boson cross section as a function of: $m_{ll}$, $|y_{ll}|$, $\cos \theta^*$
- Collin-Soper frame:
  - rest frame of the (Z boson) di-lepton system
- lepton $\cos \theta^*$: measured from z-axis, symmetric to the 2 incoming partons
  \[
  \cos \theta^* = \frac{p_{Z,\perp}}{m_{ll}|p_{Z,\perp}|} \frac{p_1^+ p_2^- - p_1^- p_2^+}{\sqrt{m_{ll}^2 + p_{T,\perp}^2}}
  \]
- $A_{FB}$ (forward-backward asymmetry)
  - related to weak mixing angle $\sin^2 \theta_W$
  - change sign at $m_Z$
  - increase with $y_{ll}$
  \[
  A_{FB} = \frac{d^3\sigma(\cos \theta^* > 0) - d^3\sigma(\cos \theta^* < 0)}{d^3\sigma(\cos \theta^* > 0) + d^3\sigma(\cos \theta^* < 0)}
  \]
- Overall good agreement with Powheg+Pythia8
- Precision: 0.5% ($\pm$ 1.9% luminosity)
- Prediction tends to underestimate data
3D Z cross section @ 8 TeV to be published soon

- \( A_{FB} \) change signs at \( m_Z \):
  - from positive...
    - \( m_{ll} \): 66-80 GeV
    - \( \cos \theta^* > 0 \)
    - \( \cos \theta^* < 0 \)
  - ... to == 0 ...
    - \( m_{ll} \): 80-91 GeV
    - \( \cos \theta^* > 0 \approx \cos \theta^* < 0 \)
  - ... then negative!
    - \( m_{ll} \): 102-116 GeV
    - \( \cos \theta^* < 0 \)
    - \( \cos \theta^* > 0 \)
Z leptons angular coefficients @ 8 TeV

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Z leptons angular coefficients @ 8 TeV

- DY leptons angular correlations ($\theta$ and $\phi$)
  - described by angular coefficients $A_0 \ldots A_7$
  - $A_i$ measured in 3 $Y_z$ bins and integrated in $Y_z$

- Results:
  - Evidence for higher than zero $A_0 - A_2$
  - Evidence for non zero $A_{5,6,7}$

\[
\left\langle \frac{1}{2} (1 - 3 \cos^2 \theta) \right\rangle = \frac{3}{20} (A_0 - \frac{2}{3});
\]
\[
\left\langle \sin 2\theta \cos \phi \right\rangle = \frac{1}{5} A_1;
\]
\[
\left\langle \sin^2 \theta \cos 2\phi \right\rangle = \frac{1}{10} A_2;
\]
\[
\left\langle \sin \theta \cos \phi \right\rangle = \frac{1}{4} A_3;
\]
\[
\left\langle \cos \theta \right\rangle = \frac{1}{4} A_4;
\]
\[
\left\langle \sin^2 \theta \sin 2\phi \right\rangle = \frac{1}{5} A_5;
\]
\[
\left\langle \sin 2\theta \sin \phi \right\rangle = \frac{1}{5} A_6;
\]
\[
\left\langle \sin \theta \sin \phi \right\rangle = \frac{1}{4} A_7.
\]
Lam-Tung relation broken: \( A_0 - A_2 > 0 \)
Confirm needs for higher order corrections
Data almost factor 2 larger than predictions:
- pQCD calculations: DYNNLO (NNLO)
- MC’s at V+j NLO: POWHEG+MINLO Z+j
- Sherpa 2.1 better than Sherpa 1.4
Several recently published predictions:
- improve data/MC comparison
- do not fully explain \( A_0 - A_2 \) at high \( p_T \)
anti-\( k_t \) splitting scales @ 8 TeV

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anti-$k_t$ splitting scales @ 8 TeV

- $Z(\rightarrow ll) + \text{jets}$: jet clusterization in steps with anti-$k_t$ algorithm
  - Inputs: charged particle tracks ($p_T > 400$ MeV, $|\eta| < 2.5$)
  - Associating tracks with minimum distance criteria:
    - distance between tracks or between tracks and beam axes

Clusterization steps:
0) $p_n$ tracks as input
1) minimum distance between $p_1$ and $p_2$ tracks $\rightarrow$ track $p_{12}$
2) minimum distance between $p_0$ and axes $\rightarrow$ jet $j_2$
3) minimum distance between $p_{12}$ and axes $\rightarrow$ jet $j_1$

$\mathbf{d}_k = \min(d_{ij}, d_{ib})$

- $0^{\text{th}}$ splitting scale ($\sqrt{d_0}$): $p_T$ of the leading $k_t$-jet
- $N^{\text{th}}$ splitting scale ($\sqrt{d_N}$): distance at which an $N$-jet event resolved as $(N+1)$
**anti-$$k_t$$ splitting scales @ 8 TeV**  

- Theoretical predictions: **Sherpa (MEPS@NLO), Powheg+Pythia8 (NNLOPS)**
- Measurements provided from 0\(^{th}\) to 7\(^{th}\) splitting scales
- Observe significant differences between measurement and predictions
- Compatible results for: Z(\(\rightarrow\)ee) and Z(\(\rightarrow\)\(\mu\mu\)) channels; R = 0.4 and R = 1.0

- Low splitting scales (0\(^{th}\))
  - MEPS@NLO better from 10 GeV

- High splitting scales (7\(^{th}\))
  - NNLOPS better up to 3 GeV

---

**ATLAS**  
\(\sqrt{s} = 8\) TeV, 20.2 fb\(^{-1}\)  
Z \(\rightarrow\) e\(^+\)e\(^-\), R = 0.4

**Data (2012)**  
- MEPS@NLO  
- NNLOPS

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\(\sqrt{s} = 8\) TeV, 20.2 fb\(^{-1}\)  
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- MEPS@NLO  
- NNLOPS
Summary
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- ATLAS precision measurements with 7, 8 and 13 TeV data
  - Very high precision: 1-2%
  - $W(\rightarrow ev)/W(\rightarrow \mu v)$ ratio: higher precision than LEP combined
- Possibility to cancel out systematics with cross section ratios
  - $W^+/W^-$ ratio, $W/Z$ ratio, $tt/Z$ ratio
- Higher precision than theoretical predictions:
  - Improve PDFs not compatible with data results
  - Provide inputs for new PDFs: *new* ATLAS-epWZ16
  - Underline the needs for higher order corrections
- Remaining discrepancies motivate further work to improve modelling and precision

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Summary

- ATLAS precision measurements with 7, 8 and 13 TeV data
  - Very high precision: 1-2%
  - $W(\rightarrow e\nu)/W(\rightarrow \mu\nu)$ ratio: higher precision than LEP combined
- Possibility to cancel out systematics with cross section ratios
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- Higher precision than theoretical predictions:
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  - Underline the needs for higher order corrections
- Remaining discrepancies motivate further work to improve modelling and precision
- ATLAS precision measurements are a powerful mean to improve our understanding of perturbative QCD!

Thanks for your attention!
Drell-Yan production

ATLAS/CMS and LHC-b complementary:

- Probes Bjorken-\( x \) in range \( 10^{-4} < x < 1 \)
- Low & high \( x \) accessed by off-shell data

- Total and differential cross-sections in boson (lepton) kinematics (\( y, p, f^*, ... \))
- Cross-section ratios (\( W^+/W^-, W/Z, ... \))

Excellent detector calibration:

- Typical experimental systematics \(~1\%\)
- Luminosity systematics (2-3\%) and also other contributions cancel in ratios
General information on measurement methods

Total and fiducial cross-section:

\[ \sigma_{W/Z}^{\text{fid}} = \frac{N_{W/Z} - B_{W/Z}}{C_{W/Z} L_{\text{int}}} \]

- \( N_{W/Z} \) - candidate events in data
- \( B_{W/Z} \) - background events
- \( C_{W/Z} \) - efficiency correction factor
- \( L_{\text{int}} \) - luminosity

\[ \sigma_{W/Z}^{\text{tot}} = \frac{\sigma_{W/Z}^{\text{fid}}}{A_{W/Z}} \]

- \( A_{W/Z} \) - acceptance

“Particle level” measurements:
- unfolding with MC corrects
- for detector effects;
- leptons “dressed” with QED FSR

Main systematic uncertainties:
- jet energy scale
- background (on W)
- unfolding
ATLAS W & Z cross sections
Selected candidates:
W→ev: ~13M
W→μν: ~16M
Z→ee: 1M (CC), 320k (CF)
Z→μμ: 1.6M

Background contamination:
W→lν: ~7-9%
Z→ll: ~1-3%

\( \sqrt{s} = 7 \text{ TeV}, 4.6 \text{ fb}^{-1} \)

\( W^+ \rightarrow e^+\nu \)

\( Z \rightarrow e^+e^- \)

All predictions (but HERAPDF2.0) lower than measurements, with large PDF uncertainties

Large strange-quark component in W production which is theoretically not well constrained

Uncertainty on measured shape is 0.1-0.2%: discrepancy in shape
Profiling results:
- significantly reduced uncertainties
- central values are increased towards unity

Unsuppressed strange fraction:
- in contradictions to most contemporary PDF sets (strange fraction around 0.5)
- however: large parametrisation uncertainty
**tt/Z double ratio measurement**

- 13/8 TeV, 13/7 TeV, **8/7 TeV (this slide)**
- Further reduce uncertainties
- Discrepancy between data and MC for 8/7 TeV ratio
- Room for improvements
  - Mainly in the tt cross section

**tt/Z cross section ratio @ 7, 8, 13 TeV**

**Z(8 TeV)/Z(7 TeV)**

**tt(8 TeV)/tt(7 TeV)**
6 cross sections used to profile ATLAS-epWZ12 PDF set
Relative jet topology (mostly back-to-back) modelled by all

- **MG5_aMC+PY8 CKKWL** overestimates contribution at large $H_T$ (hard jets)
- **BlackHat+Sherpa** (fixed order NLO) underestimates at $H_T > 300$ GeV due to missing contribution from higher parton multiplicities (higher orders in pQCD)
  - solved with **Njetti NNLO**
anti-\(k_t\) splitting scales @ 8 TeV

- Measurements provided from 0\(^{th}\) to 7\(^{th}\) splitting scales
- Observe significant differences between measurement and predictions
- Compatible results for:
  - \(Z(\rightarrow ee)\) and \(Z(\rightarrow \mu\mu)\) channels
  - \(R = 0.4\) and \(R = 1.0\)

\(1^{st}\) splitting scale

\(Z(\rightarrow \mu\mu), R = 0.4\)

\(Z(\rightarrow ee), R = 1.0\)

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Astonishing precision at 7 TeV (compared to 13 TeV)

\[ R_W = \frac{\sigma_W^{e^- \gamma^* \to e^-} / \sigma_W^{e^- \gamma^* \to \mu^- \mu^+}}{1} \]

\[ R_Z = \frac{\sigma_Z^{e^- \gamma^* \to e^-} / \sigma_Z^{e^- \gamma^* \to \mu^+ \mu^-}}{1} \]

**ATLAS**
13 TeV, 81 pb\(^{-1}\)
68\% CL ellipse area

Data
- **Green**
- **Red** \( R_W \) LEP \( e^+ e^- \rightarrow W^+ W^- \)
- **Blue** \( R_Z \) LEP+SLD \( e^+ e^- \rightarrow Z \)
- **Orange** Standard Model

Standard Model
- **Star**

**7 TeV**

\( 7 \) TeV

\( 13 \) TeV, 4.6 fb\(^{-1}\)

**95\% CL ellipse area**

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