# Inclusive Single Gauge Boson Production at 7, 8 and 13 TeV

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Rencontres de Moriond: EW

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#### Detectors





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Experiment	$\sqrt{s}$ / TeV	Integrated Luminosity / fb <sup>-1</sup>
ATLAS	7	5.6
	8	22.6
	13	3.9
CMS	7	5.6
	8	22.6
	13	3.8
LHCb	7	1.0
	8	2.0
	13	0.3

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## Coverage



- ATLAS and CMS have precision tracking in central region where most of W & Z boson production occurs.
- LHCb provides precision coverage for η > 2 - can make complementary measurements.
- ATLAS and CMS have forward calorimetry can measure electrons and jets.

## Production cross-sections

- Inclusive single gauge boson production at ATLAS, CMS and LHCb.
- Factorisation theorem:

 $\sigma_{AB \to X} = \sum_{a, b} \int_0^1 dx_1 \int_0^1 dx_2 f_a(x_1, Q^2) f_b(x_2, Q^2) \cdot \sigma(ab \to X)$ 

- Cross-section measurements and ratios are sensitive to PDFs.
  - Partonic calculations give percent level accuracy; but PDF uncertainty usually larger.
- Measurements used to constrain PDFs - important for other LHC measurements.
- Together the LHC experiments cover wide range in  $x Q^2$  plane.



LHC 13 TeV Kinematics

#### Production cross-sections

- Results not just of use for constraining PDFs.
- Can probe pQCD and parton emission in hard collision by measuring boson transverse momentum.
  - Can compare results to different MC event generators test different approaches.
- Can also probe angles of leptons in Z boson decay.
  - Can probe boson polarisation and electroweak mixing more on this later in the talk!
- Showing a selection of results focusing on most recent! Nowhere near exhaustive apologies if your favourite measurement is absent.

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• Measurements made for electrons and muons in fiducial cross-section (also extrapolated to total cross-section measurements).



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- Measured cross-sections compared to theoretical predictions from different PDF sets good agreement observed.
- Measurement will provide constraints in future PDF fits.



- Measured cross-section ratios compared to theoretical predictions from different PDF sets good agreement observed.
- Spread of PDF predictions shows importance of measurements in providing constraints.



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- Measurements made in fiducial cross-section (chosen based on optimal detector coverage; different for muons and electrons).
- Measurements also made for total cross-section extrapolate from fiducial region. For Z boson production measurement require  $60 < m_{\ell\ell} < 120$  GeV.



• Measured cross-section ratios compared to theoretical predictions from different PDF sets.

CMS-PAS-SMP-15-004

• Excellent agreement seen with NNLO QCD calculations.





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## 13 TeV Production - LHCb

• Z analysis requires both muons satisfy  $p_{\rm T}$  > 20 GeV, 2.0 <  $\eta$  < 4.5 and 60 <  $m_{\mu\mu}$  < 120 GeV.



- Differences between PDF sets suggest that with more data LHCb can play important role constraining PDFs.
- Good agreement is seen between the fiducial cross-section and NNLO predictions.

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## 13 TeV Production - LHCb

#### Rapidity

#### **Transverse Momentum**



- Data also agrees with predictions from different PDF sets as a function of the boson rapidity.
- Transverse momentum distribution shows good agreement between Pythia 8 and LHCb data.

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# 8 TeV Differential Cross-sections - ATLAS arXiv:1512.02192

- Measured the differential cross-section for the Drell-Yan process as a function of the boson transverse momentum and  $\phi_{\eta}^{*}$ .
- Extended acceptance in di-lepton mass, measurements made as a function of mass, rapidity, transverse-momentum and φ<sup>\*</sup><sub>n</sub>.
- Comparison of  $p_T$  distribution to RESBOS (NLO+NNLL):



# 8 TeV Differential Cross-sections - ATLAS arXiv:1512.02192

*p*<sub>T</sub> distribution in different bins of rapidity (for events close to Z peak), compared to different event generators:



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## 8 TeV Differential Cross-sections - ATLAS arXiv:1512.02192

• Fixed order predictions give worse agreement than RESBOS and generators interfaced with parton showers.



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## 8 TeV Differential Cross-sections - CMS

- arXiV:1603.01803
- Measure the inclusive W boson cross-section differentially as a function of the muon  $\eta$  separately for positively and negatively charged muons.
- Measured for  $p_{\rm T}^{\mu} > 25$  GeV.



## 8 TeV Differential Cross-sections - CMS

• Charge asymmetry as a function of the lepton  $\eta$  shows good agreement with all PDF sets.



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## 8 TeV Differential Cross-sections - LHCb JHEP 01 (2016) 155

- W analysis requires muon with  $p_{\rm T} > 20$  GeV and 2.0  $< \eta < 4.5$ .
- Z analysis requires both muons satisfy this and 60  $< m_{\mu\mu} <$  120 GeV.
- Measured fiducial cross-sections agree well with NNLO pQCD predictions using different PDF sets.



## 8 TeV Differential Cross-sections - LHCb JHEP 01 (2016) 155

- Measure the cross-section ratio differentially, and take fiducial cross-section ratios with respect to 7 TeV measurements.
- Good agreement seen with predictions at NNLO in pQCD from different PDF sets.



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## Measurements of boson decay

- In frame where boson is at rest, can write differential cross-section as:  $\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta^*\,\mathrm{d}\phi^*} \propto \left[ (1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin(2\theta^*)\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*) + A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^* \right]$ 
  - ▶ in Collins-Soper frame, where θ\*, φ\* are the angles of the negatively charged lepton relative to the direction which bisects the proton directions.
- Different coefficients contain different information:
  - $A_0$ ,  $A_1$ ,  $A_2$  probe polarisation.
  - ► A<sub>0</sub> A<sub>2</sub> = 0; deviations from this arise from higher-order effects like multi-gluon emission.
  - ► A<sub>3</sub>, A<sub>4</sub> also contain information about vector and axial-vector couplings of the Z boson.
- Can also measure forward (cos(θ\*) > 0) v backward (cos(θ\*) < 0) asymmetries probe A<sub>4</sub> and electroweak mixing.

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## Angular coefficients - CMS

• CMS measurement of angular coefficients as a function of boson transverse momentum (also determined as function of rapidity).



- No one model perfectly captures the measured distributions.
- Measurement important to test modelling of production a key step towards a measurement of  $m_{W}$ .

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## $A_{\rm fb}$ - LHCb

- At y = 0 complete ambiguity to axis forward-backward asymmetry diluted. Asymmetry increases as |y| increases.
- LHCb probes a larger asymmetry, despite seeing fewer events than ATLAS and CMS.
- Limiting systematic momentum scale / alignment.



JHEP 11 (2015) 190

### Measuring the weak mixing angle

- Fit the A<sub>FB</sub> distribution with templates generated from simulation with different values of sin<sup>2</sup>(θ<sup>eff.</sup><sub>lept.</sub>).
  - ATLAS:  $0.2308 \pm 0.0005(stat.) \pm 0.0006(syst.) \pm 0.0009(PDF)$
  - LHCb:  $0.2314 \pm 0.0007(stat.) \pm 0.0005(syst.) \pm 0.0006(theory)$



## Conclusions

- Results on single gauge boson production sensitive to PDFs.
  - ATLAS, CMS and LHCb results all provide constraints in PDF fits.
  - New results available at 13 TeV.
- Results also probe pQCD and parton emission in hard collisions:
  - transverse momentum distributions well modelled for some regions of phase space, but significant disagreement seen in some regions (e.g.  $p_T > M_Z$ ).
- Can also probe boson polarisation and electroweak mixing by considering angular distributions of the boson decay.
  - CMS have precision measurements of angular coefficients.
  - Also precise determinations of  $\sin^2(\theta_{lept.}^{eff.})$  at the LHC.

## **Backup Slides**

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#### 8 TeV Differential Cross-sections - ATLAS



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arXiv:1512.02192

#### 8 TeV Differential Cross-sections - ATLAS

#### arXiv:1512.02192



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## A<sub>fb</sub> - ATLAS

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#### 8 TeV Differential Cross-sections - CMS

#### arXiV:1603.01803



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## Angular coefficients - CMS

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## 13 TeV Production - LHCb



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## 8 TeV Differential Cross-sections - LHCb JHEP 01 (2016) 155



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