

# New LHCb results on Z and W production in the forward region

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DIS 2015

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# Overview

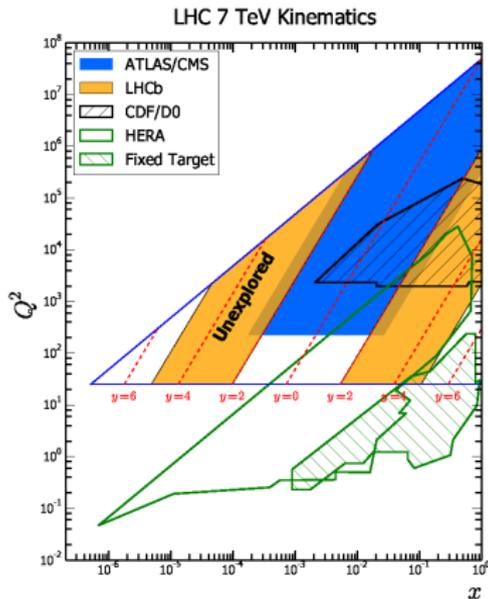
- Studying electroweak bosons in the forward region,  $2 < \eta < 4.5$
- Focus on inclusive W/Z production:
  - $Z \rightarrow \mu\mu$  and  $W \rightarrow \mu\nu$  at  $\sqrt{s} = 7$  TeV with  $1\text{fb}^{-1}$ . LHCb-PAPER-2015-001
  - $Z \rightarrow ee$  at  $\sqrt{s} = 8$  TeV with  $2\text{fb}^{-1}$ . [arXiv:1503.00963](https://arxiv.org/abs/1503.00963)
- $Z + b$ -jet production at  $\sqrt{s} = 7$  TeV with  $1\text{fb}^{-1}$ . [JHEP 01 \(2015\) 064](https://arxiv.org/abs/1408.064)

# Parton density functions

$$\sigma_{pp \rightarrow V} = \sum_{a,b} \int dx_1 dx_2 \underbrace{f_a(x_1, Q^2) f_b(x_2, Q^2)}_{PDFs} \hat{\sigma}_{ab}(x_1, x_2, Q^2)$$

- PDFs parameterised as functions of  $x$  and  $Q^2$ .
- Two distinct regions (orange) low- and high- $x$  due to forward acceptance  $2 < \eta < 4.5$ .
- $x$  constrained by kinematics:  

$$x_{\pm} = \frac{M}{\sqrt{s}} e^{\pm y}$$
- High- $x$  well known HERA, Tevatron. Low- $x$  unexplored LHCb.
- $W/Z$ :  $Q^2 \sim 10^4$  and  $x \sim 10^{-4}$  or  $x \sim 10^{-1}$ .



# Testing the SM

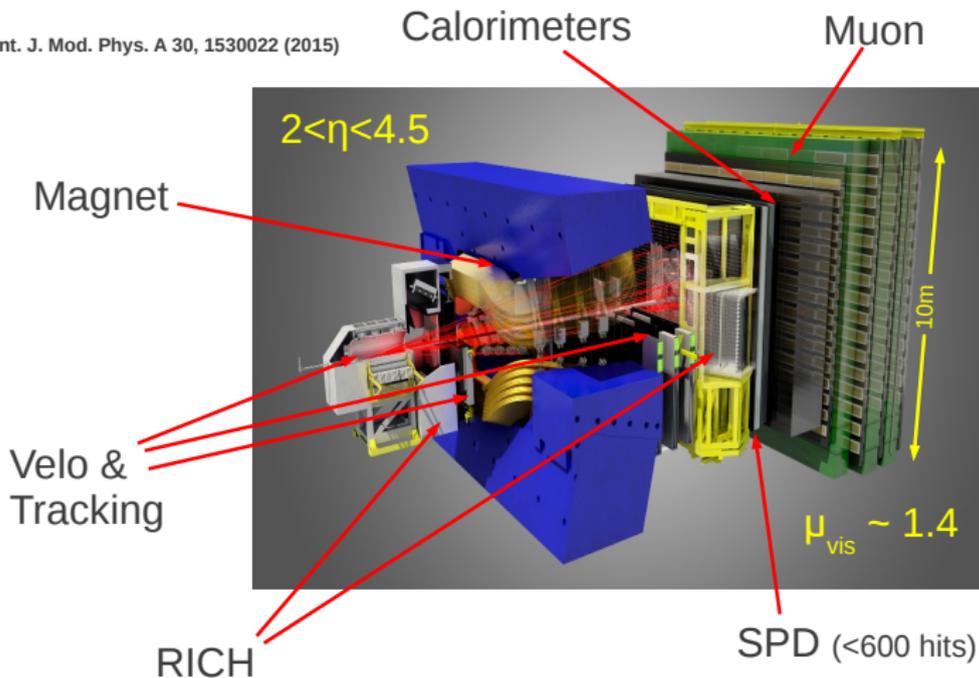
$$\sigma_{pp \rightarrow V} = \sum_{a,b} \int dx_1 dx_2 \underbrace{f_a(x_1, Q^2) f_b(x_2, Q^2)}_{PDFs} \hat{\sigma}_{ab}(x_1, x_2, Q^2)$$

Measure ratios of cross-sections:  $R_{W/Z} = \frac{\sigma_W}{\sigma_Z}$ ,  $R_W = \frac{\sigma_{W^+}}{\sigma_{W^-}}$

- Experimental precision
  - Luminosity cancels in the ratio. Largest uncertainty on cross-sections removed.
  - Correlated systematic uncertainties means relative uncertainty much reduced.
- Theoretical precision
  - Largest uncertainty on predicted cross-section is due to PDFs.
  - Since these are correlated the relative uncertainty on the ratio is reduced.
  - Scale and  $\alpha_s$  uncertainties almost fully correlated. These also reduced.

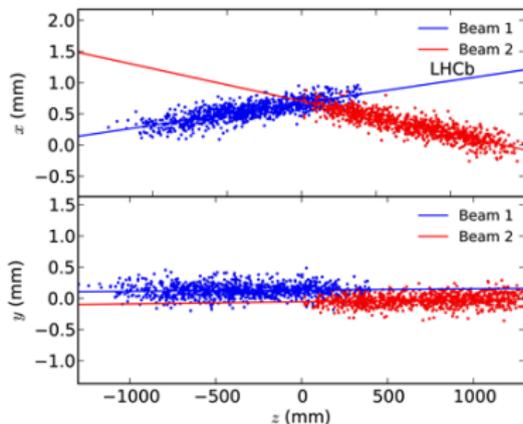
# LHCb detector

Int. J. Mod. Phys. A 30, 1530022 (2015)

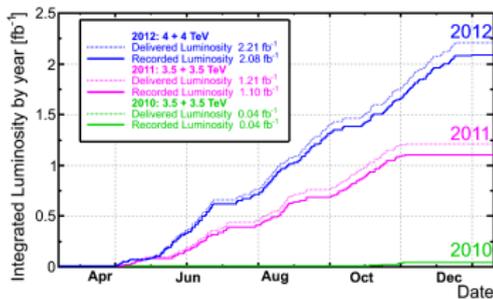


# Precision luminosity

## 2014 JINST 9 P12005



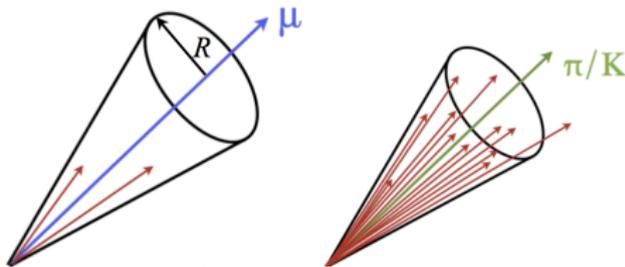
- Luminosity measured at LHCb using Van der Meer scans (VDM) and Beam-Gas Imaging (BGI).
- Inject Ne gas to increase rate for BGI.
- $\frac{\sigma_f}{\mathcal{L}}$ : 1.7%(1.1%) in 2011(2012).



- "This represents the most precise luminosity measurement achieved so far at a bunched-beam hadron collider".

# Selecting electroweak bosons

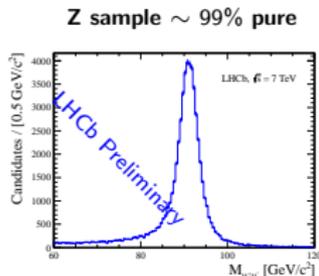
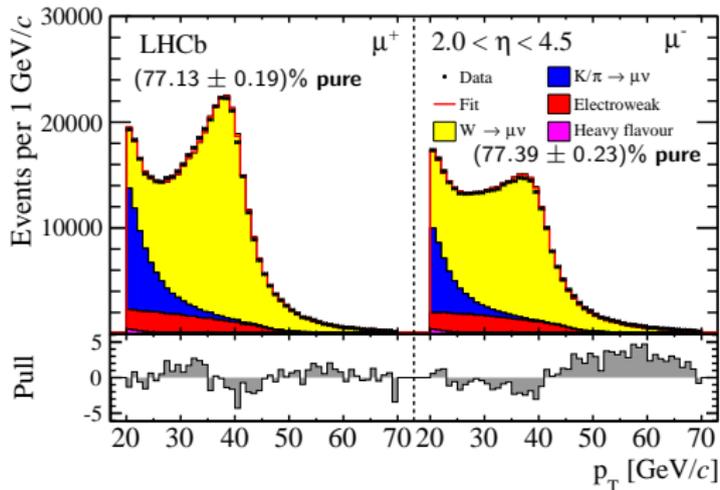
JHEP 12 (2014) 079; LHCb-PAPER-2015-001



- Common to  $W$  and  $Z$ :
  - High  $p_T$  ( $> 20 \text{ GeV}/c$ ).
  - $2 < \eta < 4.5$ .
  - Good track-fit quality.
  - Isolated muons consistent with primary interaction point.
  - Candidate event triggered by muon trigger.
  - Residual backgrounds include:  $\pi/K$  decay-in-flight, decays of heavy flavour hadrons, other QCD and electroweak.
- $W$ : 1 muon
- $Z$ : 2 muons.  $60 < M_{\mu\mu} < 120 \text{ GeV}/c^2$

# Purity estimation

JHEP 12 (2014) 079; LHCb-PAPER-2015-001; Comput. Phys. Comm. 178 (2008) 852



- $\sim 800,000$   $W$  candidates.
- Fit muon  $p_T$  distribution.

- **Signal:** RESBOS shape, normalisation free in  $\eta$  and charge.
- **Electroweak:** ( $Z \rightarrow \mu\mu$ ,  $W \rightarrow \tau\nu$ ,  $Z \rightarrow \tau\tau$ ): RESBOS/PYTHIA shapes and normalisation ( $9.82 \pm 0.16$ )% from data.
- **Decay-in-flight:** Data shape. Normalisation free in  $\eta$  and charge.
- **Heavy flavour:** Data shape ( $IP > 100\mu m$ ) and normalisation ( $0.48 \pm 0.03$ )%.

Phys. Rev. D50 (1994) 4239; Phys. Rev. D56 (1997) 5558; Phys. Rev. D67 (2003) 073016

# Fiducial cross-sections

Nucl.Instrum.Meth. A602 (2009) 432-437  
CERN-ATS-2013-040

- Cross-sections defined in fiducial region: muons with  $2 < \eta < 4.5$ ,  $p_T > 20 \text{ GeV}/c$  and in the case of the Z boson an invariant mass  $60 < M_Z < 120 \text{ GeV}/c^2$ .

$$\sigma_{VB} = \frac{\rho N}{\mathcal{A}\epsilon\mathcal{L}}$$

- The cross-section measured in bin  $i$  of  $y_Z$ ,  $p_{T,Z}$  and  $\phi_Z^*$  or W muon  $\eta^\mu$ .

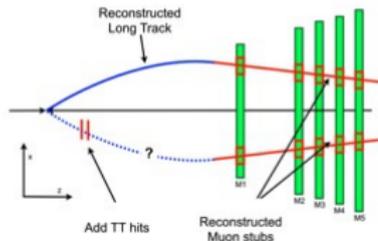
$$\phi_Z^* = \frac{\tan((\pi - |\Delta\phi|)/2)}{\cosh(\Delta\eta/2)}.$$

- Total cross-sections obtained by summing the differential cross-sections.
- Dominant uncertainties are the luminosity, W purity  $\rho$  and efficiency due to 600 SPD hit threshold.
- $\sim 1\%$  uncertainty for beam energy since results quoted at specific  $\sqrt{s}$ .

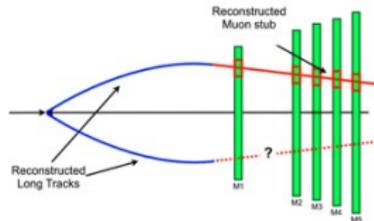
# Efficiencies

- Muon reconstruction efficiencies: tag-and-probe with the  $Z$  resonance.
- Efficiencies studied as function of muon kinematics and detector occupancy.

## Track efficiency from Tag & Probe



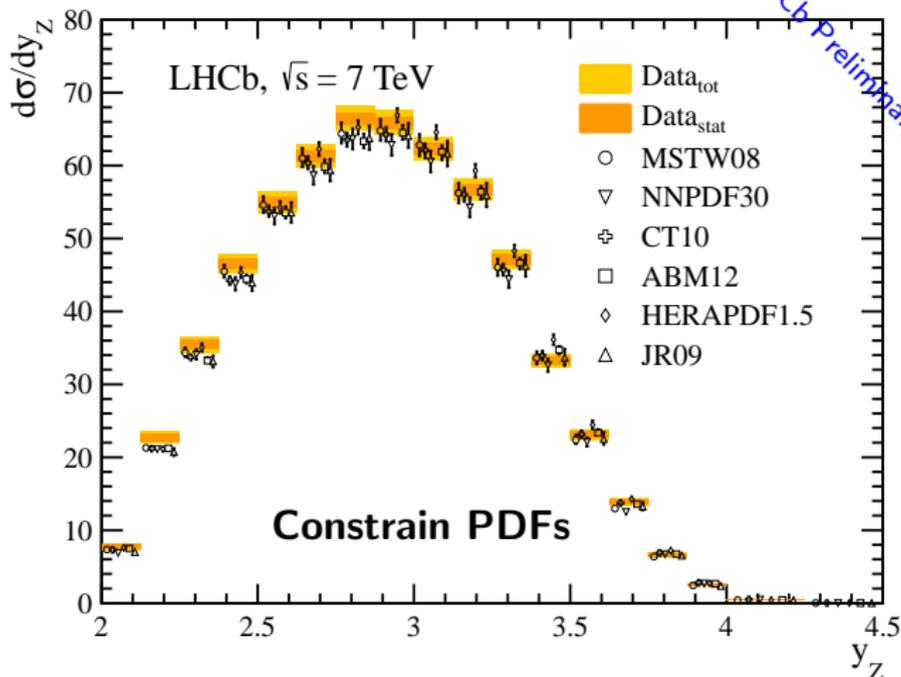
## Muon ID from Tag & Probe



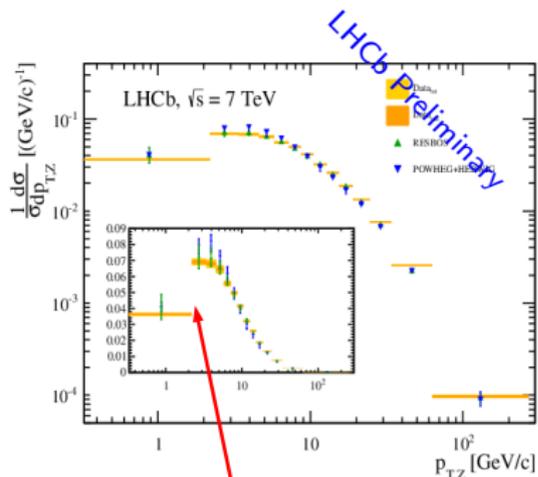
- Must also correct for threshold at 600 SPD sub-detector hits in muon trigger.
- Evaluated in previous  $W$  boson analysis [JHEP 12 \(2014\) 079](#) to be  $(95.9 \pm 1.1)\%$ .
- New method  $(94.0 \pm 0.2)\%$ . Update  $W$  cross-sections to profit from increased precision.
- Systematic uncertainty accounting for differences between  $W^\pm$  and  $Z \sim 0.3\%$ .

# Differential cross-sections: $y_Z$

Phys. Rev. D86 (2012) 094034; LHCb-PAPER-2015-001



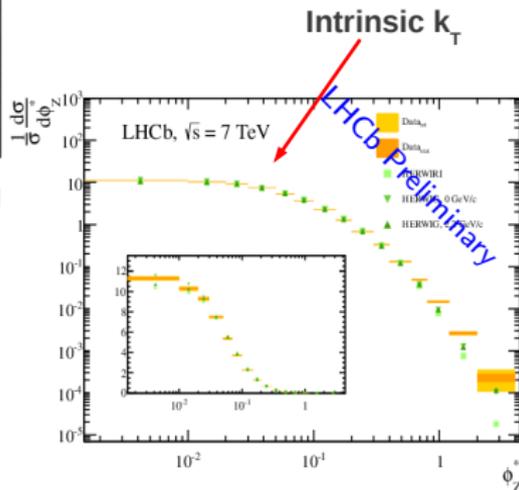
# Differential cross-sections: $p_{T,Z}$ and $\phi_Z^*$



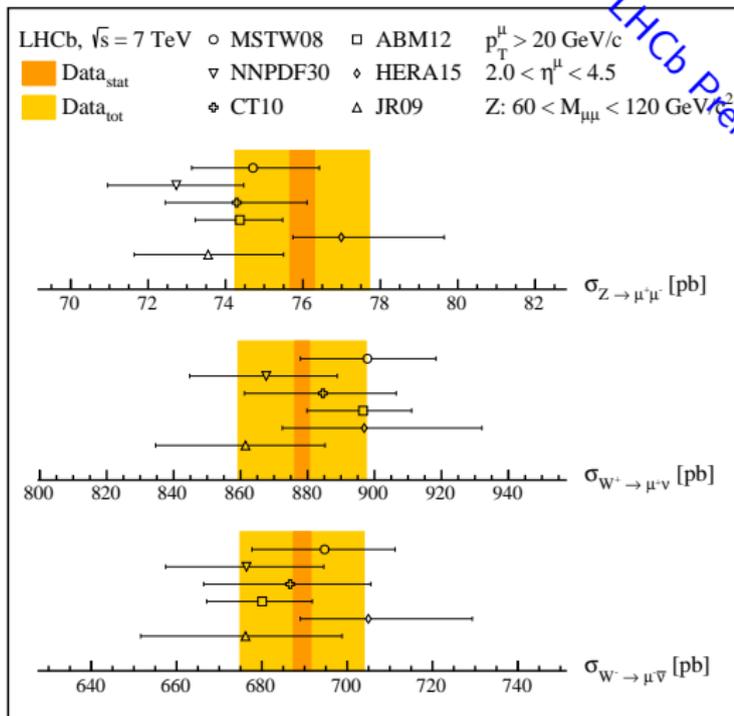
JHEP 11 (2004) 040  
 JHEP 06 (2002) 029  
 Phys. Rev. D81 (2010) 076008

Phys. Rev. D50 (1994) 4239  
 Phys. Rev. D56 (1997) 5558  
 Phys. Rev. D67 (2003) 073016

## Testing QCD

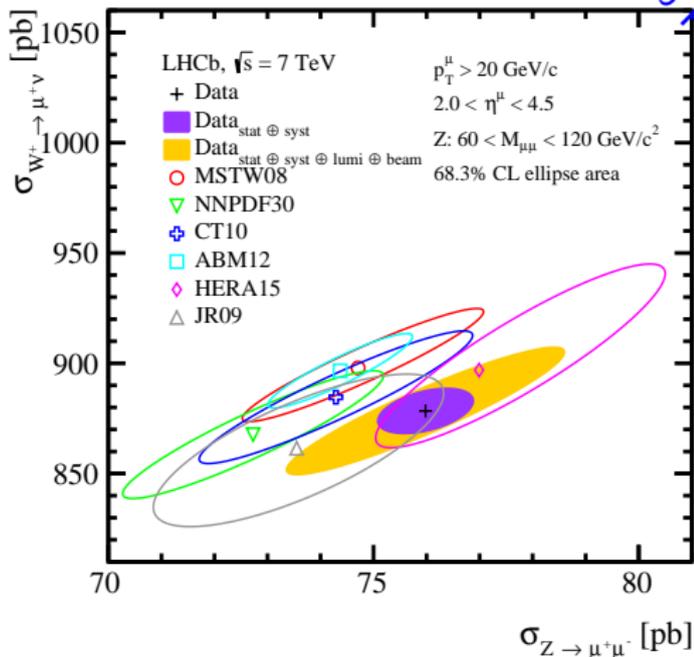


# Results: cross-sections



LHCb Preliminary

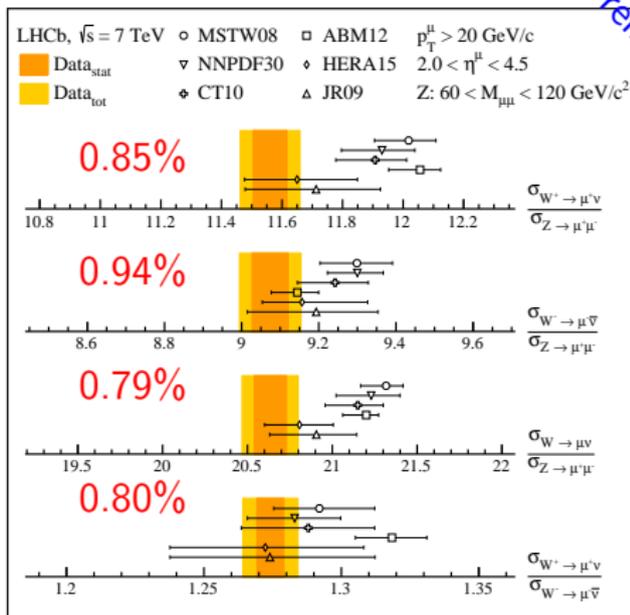
# Results: confidence ellipse



LHCb Preliminary

# Results: cross-section ratios

LHCb Preliminary



- Luminosity uncertainty cancels. Sub 1% precision.
- Sensitivity to choice of PDF.
- Overall agreement with SM.

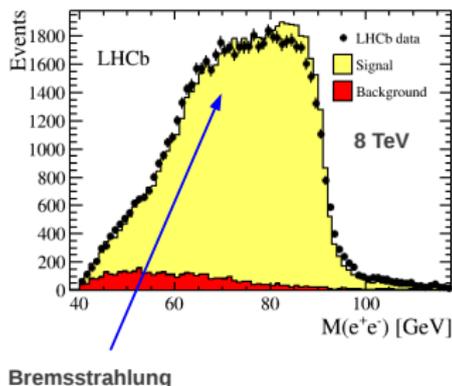
# $Z \rightarrow ee$ at $\sqrt{s} = 8$ TeV

arXiv:1503.00963

- Aim: Measure 'fiducial' cross-section with  $p_T^e > 20$  GeV/c,  $2 < \eta^e < 4.5$  and  $60 < M_{ee} < 120$  GeV/c<sup>2</sup>.

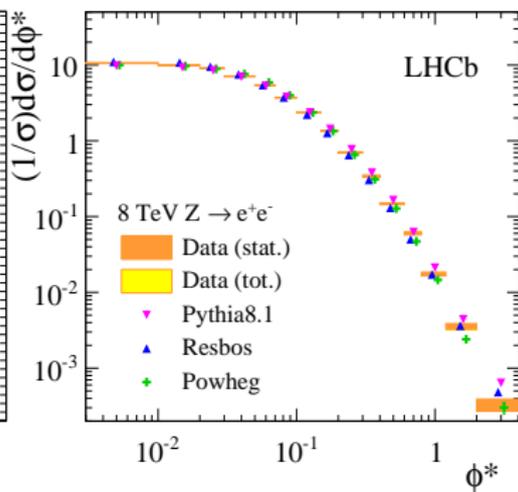
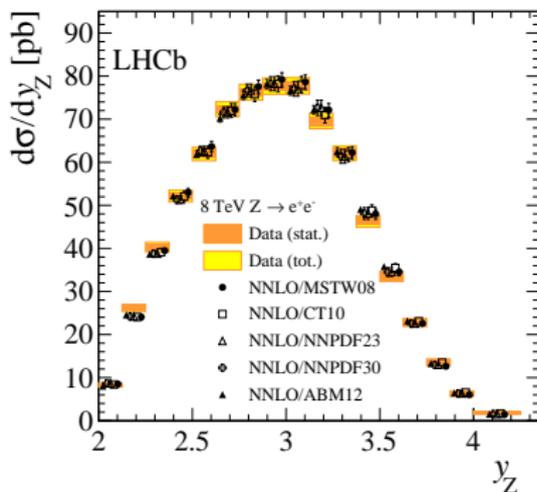
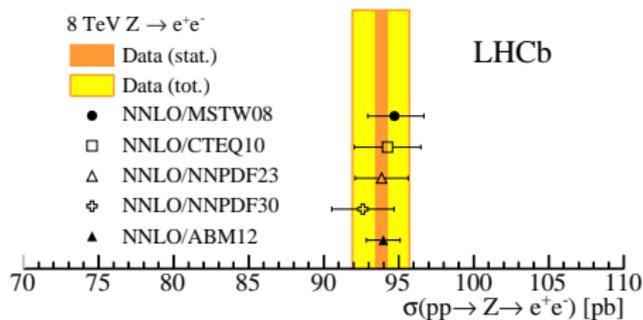
- Similar analysis procedure to 7 TeV analysis.
- 8 TeV: Profit from better simulation of bremsstrahlung.
- Use  $\phi^*$  variable (directions known better than momenta).

$$\phi_Z^* = \frac{\tan((\pi - |\Delta\phi|)/2)}{\cosh(\Delta\eta/2)}$$



# $Z \rightarrow ee$ at $\sqrt{s} = 8$ TeV: Results

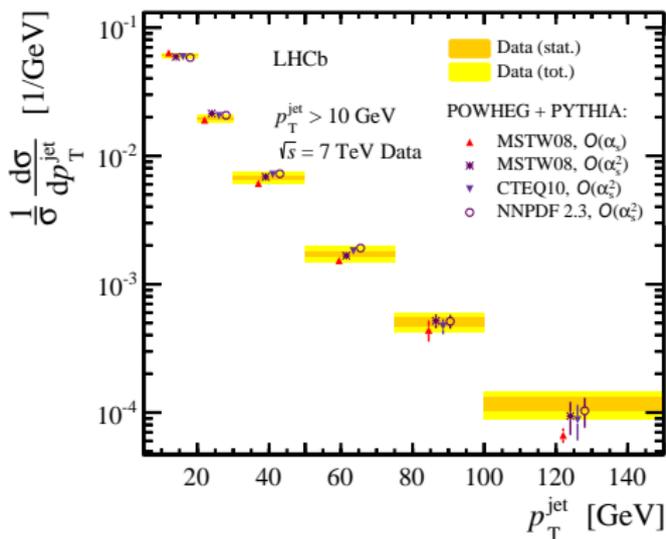
arXiv:1503.00963



# Z + jet at 7 TeV

JHEP 01 2014 033

- Particle flow
  - Charged tracks
  - Calorimeter clusters
  - *anti* -  $k_T$  algorithm  
 $R = 0.5$
- Select Z
  - $p_T^\mu > 20$  GeV/c
  - $2 < \eta^\mu < 4.5$
  - $60 < M_{\mu\mu} < 120$  GeV/c<sup>2</sup>
- Select jet
  - $p_T^{\text{jet}} > 10(20)$  GeV/c
  - $2 < \eta^{\text{jet}} < 4.5$
  - $R(\mu^\pm, \text{jet}) > 0.4$



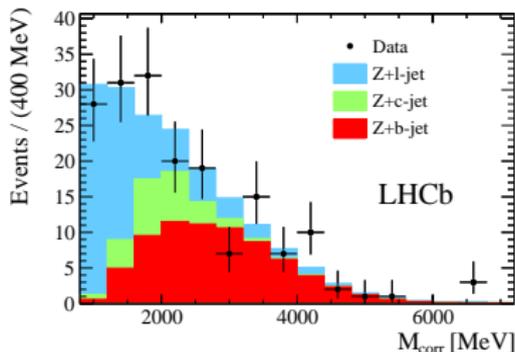
# Z + b-jet at 7 TeV

JHEP 01 2015 064

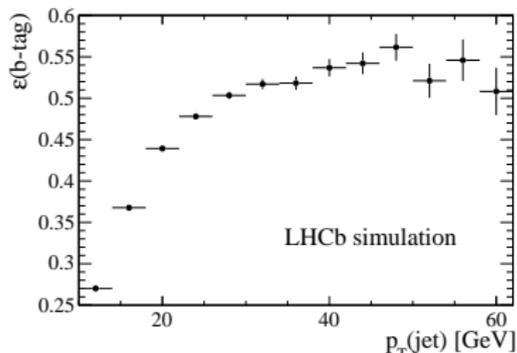
$$\sigma(Z + b\text{-jet}) = \frac{\varepsilon(Z + \text{jet})}{\varepsilon(Z + b\text{-jet})} \frac{1}{\varepsilon(b\text{-tag})} \frac{N(Z + b\text{-jet})}{Z + \text{jet}} \sigma(Z + \text{jet})$$

- Strategy: Normalise to Z + jet.
- Topological secondary vertices: 2,3,4 particles (charged,  $K^0$ ,  $\Lambda$ ) within jet.
- Template fit to

$$M_{\text{corr}} = \sqrt{M^2 + p^2 \sin^2 \theta} + p \sin \theta.$$



- $\varepsilon(b\text{-tag})$  determined from simulation.
- Variation in  $\varepsilon(b\text{-tag})$  and  $M_{\text{corr}}$  template 15%.

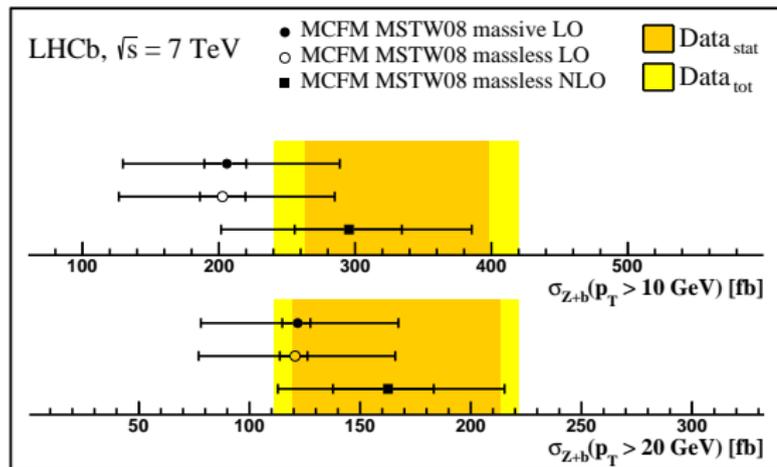


# $Z + b\text{-jet}$ at 7 TeV: Results

JHEP 01 2015 064;

Nucl. Phys. Proc. Suppl. 205-206 (2010) 10;

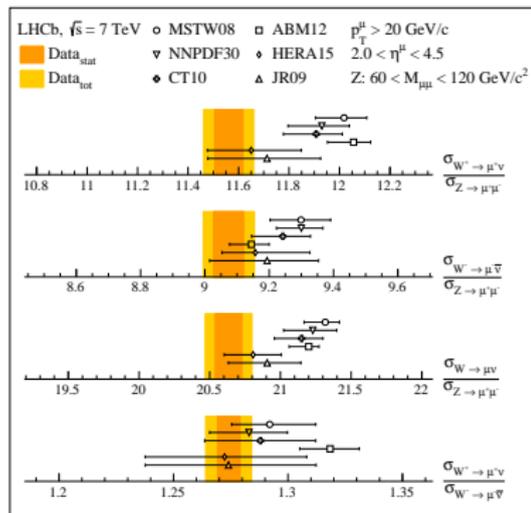
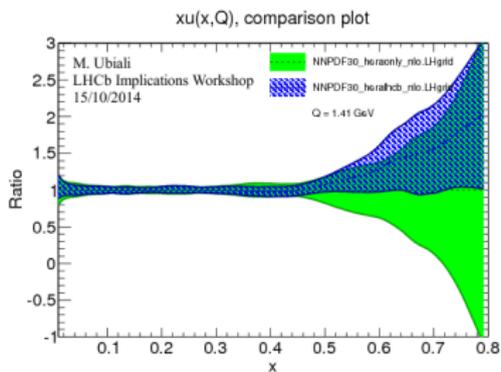
Comput. Phys. Comm. 178 (2008) 852



- Compare to MCFM.
- Convert  $b\text{-quark}$  at parton level to  $b\text{-jet}$  using PYTHIA8.

# Conclusions

- Variety of measurements involving  $W$  and  $Z$  bosons during run-1 at LHCb.
- These help constrain PDFs.
- Control of systematic uncertainty has lead to some of these measurements being particularly precise, sub 1%.
- Push SM to its limits!



# Acknowledgements

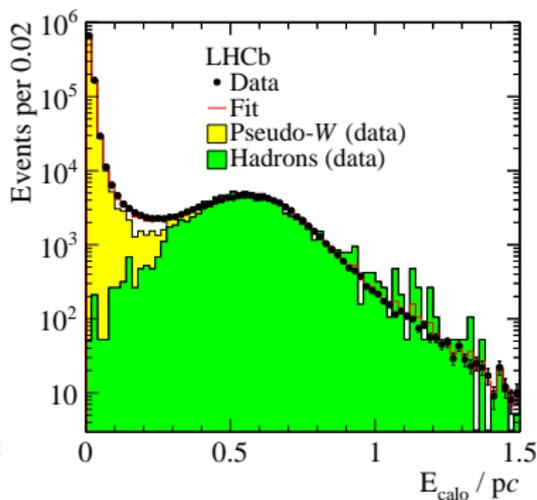
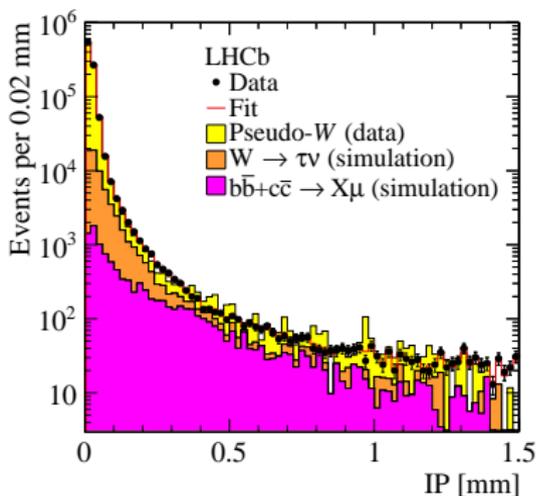


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# BACKUP

# Reducing $W$ backgrounds

JHEP 12 (2014) 079



# EW normalisation

$$N_{Z \rightarrow \mu\mu}^{1\mu} = N_{Z \rightarrow \mu\mu}^{2\mu} \cdot \mathcal{A}_{m_{\mu\mu}}^Z \cdot \mathcal{F}_{Z \rightarrow \mu\mu}^{1\mu/2\mu} \cdot \frac{\epsilon_{RECO}^W}{\epsilon_Z^{RECO}} \cdot \epsilon_{SEL}^W$$

- $N_{Z \rightarrow \mu\mu}^{2\mu}$  from Pseudo-W.
- $\mathcal{A}_{m_{\mu\mu}}^Z$  mass window acceptance correction.
- $\mathcal{F}_{Z \rightarrow \mu\mu}^{1\mu/2\mu}$  fraction of events with one muon inside to two muons ( $\sim 2$ ).
- $\frac{\epsilon_{RECO}^W}{\epsilon_Z^{RECO}} = \frac{1}{(2 - \epsilon_{TRG}) \cdot \epsilon_{TRK} \cdot \epsilon_{ID}}$

## Z cross-section systematics

<b>Source</b>	<b>Uncertainty (%)</b>
Statistical	0.39
Trigger efficiency	0.07
Identification efficiency	0.23
Tracking efficiency	0.53
FSR	0.11
Purity	0.22
GEC efficiency	0.26
Systematic	0.68
Beam energy	1.25
Luminosity	1.72
Total	2.27

## Cross-section ratios systematics

Source	Uncertainty (%)			
	$R_{WZ}$	$R_{W+Z}$	$R_{W-Z}$	$R_W$
Statistical	0.45	0.48	0.50	0.38
Trigger efficiency	0.15	0.16	0.13	0.07
Identification efficiency	0.12	0.12	0.12	0.03
Tracking efficiency	0.24	0.23	0.26	0.08
FSR	0.16	0.21	0.17	0.21
Purity	0.41	0.49	0.55	0.62
GEC efficiency	0.27	0.28	0.29	0.18
Systematic	0.60	0.67	0.72	0.69
Beam energy	0.26	0.19	0.34	0.15
Total	0.79	0.85	0.94	0.80