



# Latest LHCb measurements of Electroweak Boson Production in Run-1



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On behalf of the LHCb collaboration

European Organisation for Nuclear Research (CERN)

CERN Seminar

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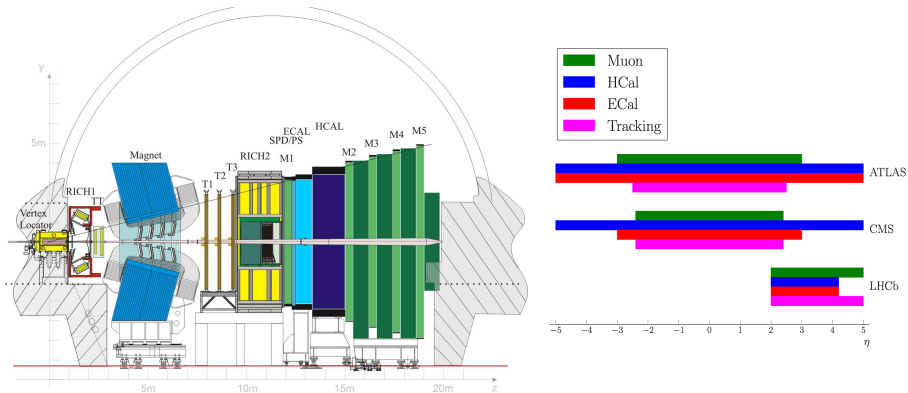
# Introduction

- Talk will focus on two recent **LHCb measurements** involving electroweak boson production (where the bosons decay to muons):
  - ▶ **W and Z boson production<sup>1</sup> cross-sections** in proton-proton collisions at 8 TeV, in muonic final states.
    - ★ Allows constraints on parton distribution functions.
    - ★ Ratios with the 7 TeV results allow tests of the Standard Model.
  - ▶ Measurement of the **forward-backward asymmetry in Z boson decays** to a dimuon final state.
    - ★ Probes the vector and axial-vector couplings.
    - ★ Allows for experimental determination of  $\sin^2(\theta_W^{\text{eff}})$ .
- But before all that I'll start by discussing the LHCb detector, trigger, and data samples.

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<sup>1</sup>For simplicity we consider virtual photon ( $\gamma^*$ ) production and interference terms to be included in the label 'Z'.

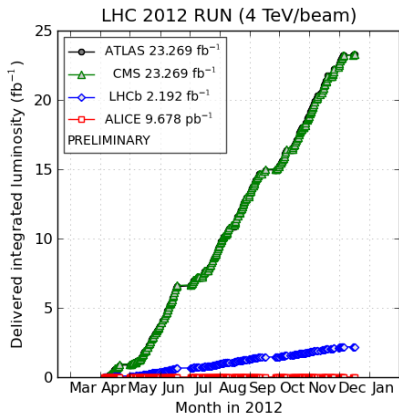
- Single arm spectrometer, fully instrumented in **forward region** ( $2.0 < \eta < 4.5$ ).



- Designed for **flavour physics**.
- **Overlap with GPDs in  $2.0 < \eta < 2.5$ ,**  
LHCb unique precision coverage in  $2.5 < \eta < 4.5$ .

- Whilst designed for flavour physics - has all the components and sub-detectors necessary for other physics analyses.
  - ▶ Excellent vertex resolution (VELO) - 0.01-0.05 mm in transverse plane,
  - ▶ Tracking detectors, ECAL, HCAL, Muon chambers,
  - ▶ Ring Imaging Cherenkov (RICH) detectors for particle ID,
  - ▶ Trigger on low  $p_T$  objects - e.g. single lepton ( $p_T > 10$  GeV).
- allows complementary studies of EW physics to ATLAS and CMS. The region of overlap also allows comparison of results.
- However, reduced angular acceptance means that standard variables like missing  $E_T$  not available.

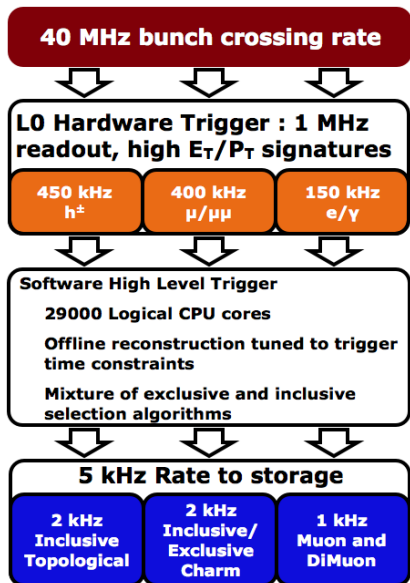
- LHCb runs at a **reduced luminosity** in comparison to ATLAS and CMS.



(generated 2013-01-29 18:28 including fill 3453)

- Total recorded  $\sim 3 \text{ fb}^{-1}$ ,
- On average bunch crossings at LHCb contain  $< 2 \text{ } pp$  interactions,
- Advantages associated with reduced luminosity and low pileup environment - events are very clean, high efficiency jet flavour tagging.
- Analyses discussed here based on  $\sqrt{s} = 7$  and 8 TeV data.

# The LHCb Trigger



- **Hardware trigger** selects events containing muons with  $p_T > 1.8$  GeV
- **Software trigger** for electroweak physics at LHCb select events containing a muon or electron with  $p_T > 10$  GeV.
- Software trigger also selects dimuon final states.
- Software trigger significantly improved in LS1.

# Why study Electroweak production physics at LHCb?

- Benchmark measurements to study PDFs (as recommended by PDF4LHC group).
- LHCb probes a region of phase space where the vector boson is produced in the **forward region**.
- $x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$ 
  - ▶ As you move forward in rapidity you probe regions at high and low Bjorken  $x$ ,
  - ▶ Note cutoff - if you move sufficiently far forward it becomes impossible to produce massive particles.

- **Factorisation theorem:**

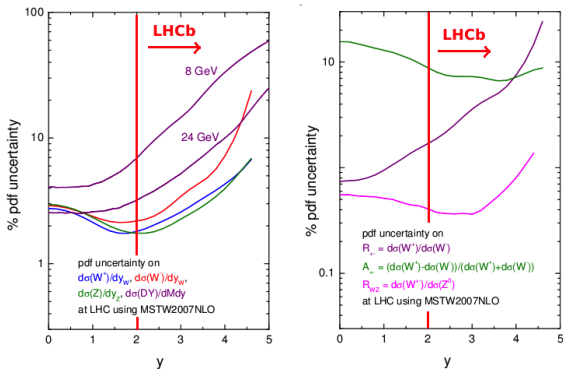
$$\sigma_{AB \rightarrow X} = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 f_a(x_1, Q^2) f_b(x_2, Q^2) \cdot \sigma(ab \rightarrow X)$$

PDFs

Partonic Interaction

# PDF physics at LHCb

- Uncertainty on partonic collisions  $\sim 1\%$ .
- PDF uncertainty at LHCb can be much larger:  $\sim 10\%$ .



Adapted from Thorne *et al.*, 2008: [arXiv:0808.1847](https://arxiv.org/abs/0808.1847)

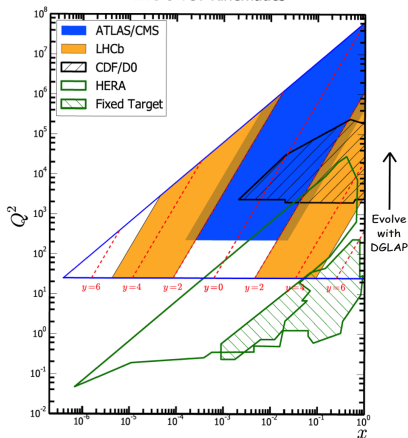
- LHCb has ability to **constrain PDFs** in some distributions and ratios, and to **test the Standard Model** in others.



# PDF physics at LHCb

- Why is the PDF uncertainty so large?

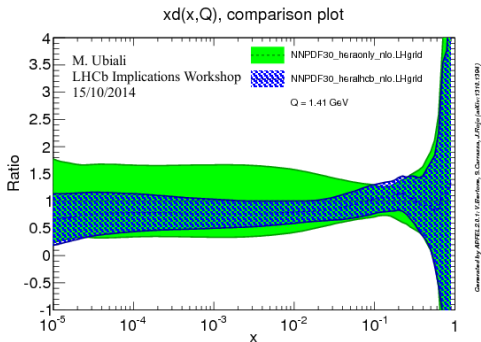
LHC 8 TeV Kinematics



- Collisions at LHCb probe collisions taking one parton which is well constrained by previous measurements, and one parton which is largely unconstrained.
- There is a large PDF uncertainty at low  $x$ .
- Measurements at LHCb have ability to constrain PDFs in a region which is unprobed by GPDs.

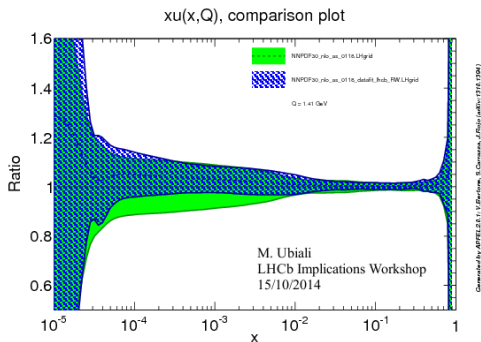
# Impact of existing LHCb results on PDFs

- Many LHCb 7 TeV results on electroweak boson production now included in PDF fits.
- Large impact on pre-LHC PDF knowledge.
- Shown here NNPDF down quark PDF and uncertainties (normalised so central value pre-LHC is unity):
  - ▶ Green: PDF fit using HERA data
  - ▶ Blue: PDF fit using HERA data and 7 TeV LHCb data



# Impact of existing LHCb results on PDFs

- Shown here NNPDF up quark PDF and uncertainties:
  - ▶ Green: PDF fit including LHC data (but no LHCb data)
  - ▶ Blue: PDF fit including LHC data (and 7 TeV LHCb data)



- Even when results from other LHC experiments are included in PDF fits, LHCb still noticeably reduces PDF uncertainties - **LHCb measurements of clear use in PDF fits.**

# Measurements of Production Cross-sections at LHCb

# Z production - dimuon channel

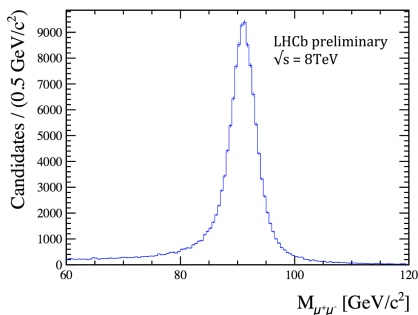
- Measure the **total cross-section** and the **differential cross-section** as a function of:
  - ▶ Z boson **rapidity**,
  - ▶ Z boson **transverse momentum**,
  - ▶ Z boson  $\phi^*$ .
- ▶ where  $\phi^*$  is a variable which is correlated with transverse momentum:  
 $\phi^* = \tan(\phi_{\text{acop}}) / \cosh(\Delta\eta/2)$ ,  $\phi_{\text{acop}} = \pi - \Delta\phi$ ,
- ▶ as an angular variable, 'easier' to measure at hadron colliders than energies (resolution is better)
- ▶  $\phi^* \sim p_T/M$

EPJ C71 1600 (2011)

# Z production - Introduction

- Search for:  $pp \rightarrow Z/\gamma^*(\rightarrow \mu\mu)X$ ,
- Studied in:
  - ▶ 2011 data ( $\mathcal{L} = 1.0 \text{ fb}^{-1}$ ,  $\sqrt{s} = 7 \text{ TeV}$ ) [JHEP 08 \(2015\) 039](#)
  - ▶ 2012 data ( $\mathcal{L} = 2.0 \text{ fb}^{-1}$ ,  $\sqrt{s} = 8 \text{ TeV}$ ) [LHCb-PAPER-2015-049](#)
- Fiducial acceptance:
  - ▶  $60 < M^{\mu\mu} < 120 \text{ GeV}$ ,
  - ▶  $2.0 < \eta^{\mu} < 4.5$ ,
  - ▶  $p_{\text{T}}^{\mu} > 20 \text{ GeV}$ .
- Selected tracks required to pass the fiducial requirements.
- Trigger requires at least one muon candidate to be responsible for event passing each stage of the trigger.
- Additional requirements to select high quality tracks which are associated with hits in the muon detectors.
- Select  $\sim 150\text{k events}$  in 2012 data.

# Z production - Purity



- Largest background is **heavy flavour** contribution (with  $b \rightarrow \mu X$ ), estimated from data using background enriched sample (using isolation/vertex requirements).
- **Hadron misID** - estimated from data using randomly triggered data and known misID rates.
- Other electroweak processes (e.g.  $Z \rightarrow \tau\tau$ ,  $\tau \rightarrow \mu X$ ) contribute at a lower level, number taken from simulation.

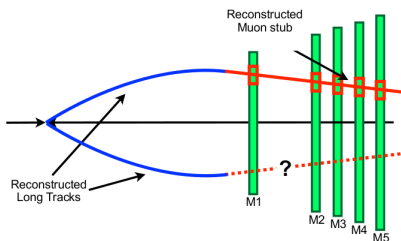
Purity of sample is  $(99.3 \pm 0.2)\%$

# Z production - Muon Reconstruction Efficiencies

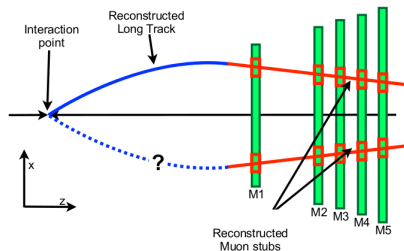
Also need to measure efficiencies with which events pass selection:

- all efficiency numbers determined using **data-driven methods**,
- evaluated as a function of  $\eta$ ,  $\phi$ ,  $p_T$ ,  $p$ , pile-up, date, charge, magnet polarity,
- determined directly from data using **tag-and-probe methods**.
- correct for efficiencies by applying weights.

Probe muon identification



Probe tracking efficiency





## Z production - Event level efficiencies

- The **single muon trigger path** also requires that the occupancy of the 'SPD' sub detector is not too high.
  - ▶ Removes of small subset of events which would dominate processing time.
- Efficiency determined using two different methods:
  - ▶ **Dimuon trigger path** has looser occupancy requirements: provides alternative selection route. Can use this to estimate 'global event cut' (GEC) efficiency.
  - ▶ Occupancy distribution completely measured for Z boson events containing one  $pp$  interaction. By mixing these events with randomly triggered events, can 'generate' pile-up effects, and measure GEC efficiency.
- Measured as a function of the kinematic distributions ( $\sim 3\%$  variation with boson rapidity).
- **Efficiency is  $(93.0 \pm 0.3)\%$** ; methods give consistent results.

# Z production - Measuring Cross-sections

- Correct result to **Born level in QED** (correct for QED FSR from the muons)
  - ▶ enables comparison between different decay modes of the Z,
  - ▶ corrections taken from simulation (effect consistent between Herwig++ and Pythia at level of 0.2%),
- also correct for small bin-to-bin migrations from detector resolution effects e.g. in Z transverse momentum.
  - ▶ **Bayesian unfolding** used as default approach.
  - ▶ Cross-checked using different initial models, and different unfolding techniques.
  - ▶ Do not unfold boson rapidity - the muon directions are determined to extremely high precision.

$$\sigma = \frac{\rho f_{\text{mig}} f_{\text{FSR}}}{\mathcal{L}} \sum_{\text{events}} \epsilon_Z^{-1}$$

## Z production - Uncertainties

- Systematic uncertainties in Z boson production cross-section measurement:

	Uncertainty (%)
Statistical	0.27
Purity	0.21
Tracking	0.48
Identification	0.21
Trigger	0.05
GEC	0.34
FSR	0.13
Systematic	0.67
Beam energy	1.15
Luminosity	1.16
Total	1.79

- Largest 'experimental' systematic uncertainty associated with **tracking efficiency**.
- Determined from data using **tag-and-probe method**.
- Consider accuracy by applying it to simulated data and comparing with 'true' efficiency - apply difference as uncertainty.
- Statistical precision of determination and other sources also applied as uncertainty.

# Z production - Uncertainties

- Luminosity

2012 JINST 7 P01010

- ▶ determined using Van der Meer scan and beam-gas interactions.
- ▶ Consistent luminosity estimates from the two measurements.
- ▶ Uncertainties set on each individual method.
- ▶ Most precise luminosity determination at a bunched beam hadron collider.

- Beam energy

CERN-ATS-2013-040

- ▶ Beam energy uncertainty also considered: beam energy known at level of 0.65%.
- ▶ This uncertainty applies to all LHC experiments.
- ▶ Cross-sections known to evolve with the centre-of-mass energy: particularly sensitive at LHCb.
- ▶ Obviously the measured cross-section has no such uncertainty, but rather than apply to theoretical predictions, port the beam energy uncertainty to an equivalent effect on the cross-section.

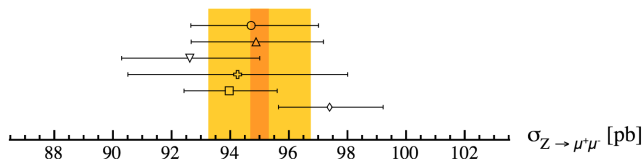
# Z production - Results

The measured cross-section at LHCb is:

$$\sigma(Z \rightarrow \mu\mu) = 95.0 \pm 0.3 \text{ (stat.)} \pm 0.7 \text{ (syst.)} \pm 1.1 \text{ (beam)} \pm 1.1 \text{ (lumi) pb}$$

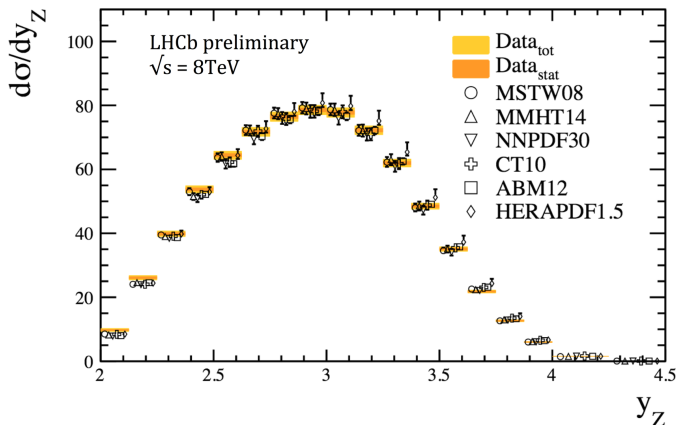
LHCb preliminary  $\sqrt{s} = 8\text{TeV}$   
Data<sub>stat</sub> Data<sub>tot</sub>

○	MSTW08	⊕	CT10	$p_T^\mu > 20 \text{ GeV}/c$
△	MMHT14	□	ABM12	$2.0 < \eta^\mu < 4.5$
▽	NNPDF30	◇	HERA15	$Z: 60 < M_{\mu\mu} < 120 \text{ GeV}/c^2$



# Z production - Results

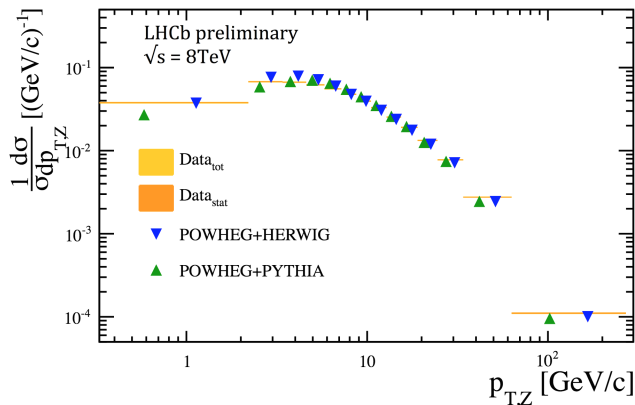
## Z boson rapidity distribution



- The boson rapidity is very sensitive to the PDFs - how forward the boson is provides information about the Bjorken- $x$  values of the colliding partons.

# Z production - Results

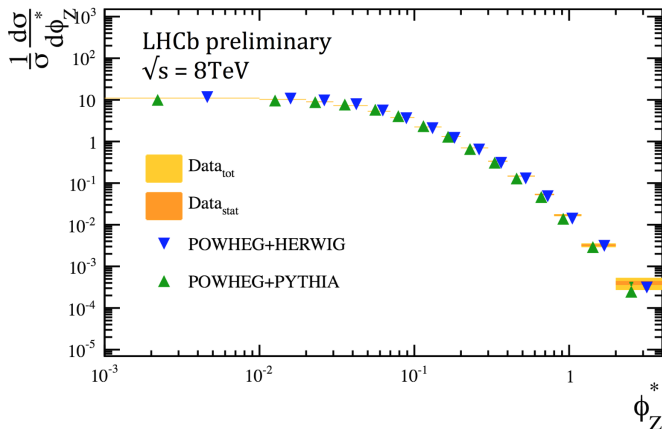
## Z boson transverse momentum distribution



- The transverse momentum of the boson provides information about the importance of higher order effects in pQCD, parton shower approximations, and modelling of the intrinsic  $k_T$  of the partons.

# Z production - Results

## Z boson $\phi^*$ distribution



- The  $\phi^*$  distribution is correlated with the boson  $p_T$ , and is more easily measured experimentally.



## W production - muon channel

- Search for:  $pp \rightarrow W(\rightarrow \mu\nu)X$ ,
  - ▶ study each charge separately
- Ability to **constrain PDFs**, especially in charge asymmetry.



- Ratio with  $Z$  has ability to **test SM** at level  $< 1\%$ .
- Same fiducial acceptance for muons as  $Z$  analysis:  $2.0 < \eta < 4.5$ ,  $p_T > 20$  GeV.
- Studied in:
  - ▶ 2011 data ( $\mathcal{L} = 1.0 \text{ fb}^{-1}$ ,  $\sqrt{s} = 7$  TeV) [JHEP 12 \(2014\) 079](#)
  - ▶ 2012 data ( $\mathcal{L} = 2.0 \text{ fb}^{-1}$ ,  $\sqrt{s} = 8$  TeV) [LHCb-PAPER-2015-049](#)
- Note that LHCb does not have  $4\pi$  coverage - so cannot use missing  $E_T$  and associated methods to select  $W$  bosons.

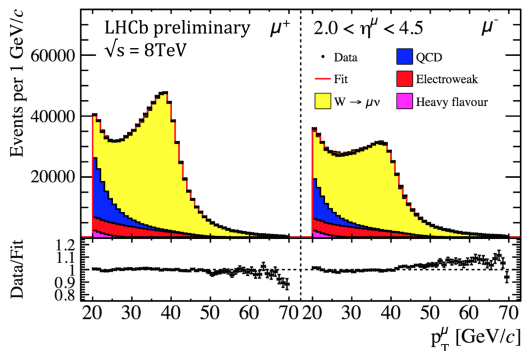
## W production - Selecting Events

Selection for  $W \rightarrow \mu\nu$ :

- $20 < p_T^\mu < 70$  GeV,
- $2.0 < \eta < 4.5$ ,
- trigger on **single muon**,
- track and muon-identification requirements **same as in Z boson analysis**.
- no other muon with  $p_T^\mu > 2$  GeV in the event,
- isolation requirement on muon (reduces QCD background).
- require that muons come from a proton-proton interaction and are not associated with secondary decays (reduces background from  $\tau$  or semi-leptonic decays of heavy flavour mesons).

Select > 1.7M candidate W boson decays.

# W production - Purity



- Determine number of signal events by fitting templates to  $p_T^\mu$  spectra as a function of  $\eta$ .
  - Fit templates from simulation (signal) and data (most significant backgrounds).
  - $W^+$  purity 79%,  $W^-$  purity 78%.
- templates varied to set systematic uncertainties associated with template shapes and purity of sample.
  - reconstruction and selection efficiencies checked for any dependence on the muon charge - none seen.

# W production - Uncertainties

- **Systematic uncertainties** from different sources:

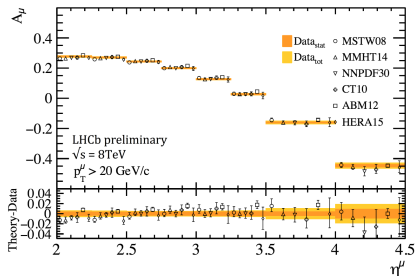
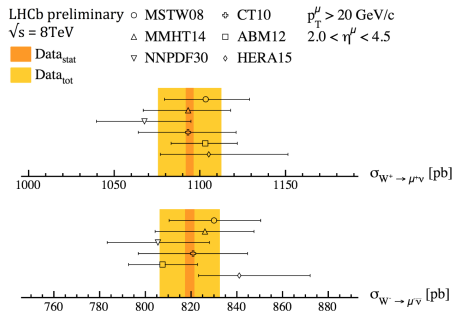
Source	Uncertainty (%)		
	$\sigma_{W^+}$	$\sigma_{W^-}$	$\sigma_Z$
Statistical	0.19	0.23	0.27
Purity	0.28	0.21	0.21
Tracking	0.26	0.24	0.48
Identification	0.11	0.11	0.21
Trigger	0.14	0.13	0.05
GEC	0.40	0.41	0.34
Selection	0.24	0.23	—
Acceptance	0.08	0.08	—
FSR	0.14	0.11	0.13
Momentum scale	0.05	0.12	—
Systematic	0.65	0.62	0.67
Beam energy	1.00	0.86	1.15
Luminosity	1.16	1.16	1.16
Total	1.67	1.59	1.79

- Largest 'experimental' uncertainty from efficiency of **global event cuts**.
  - ▶ Determined as before on Z boson events, so same uncertainty as there.
  - ▶ Additional uncertainties associated with how well the efficiency measured in Z boson events ports to W boson events.
- Uncertainty from fit folded into the purity and the statistical uncertainties: not a dominant uncertainty.

# W production - Results

Measured cross-sections (left)

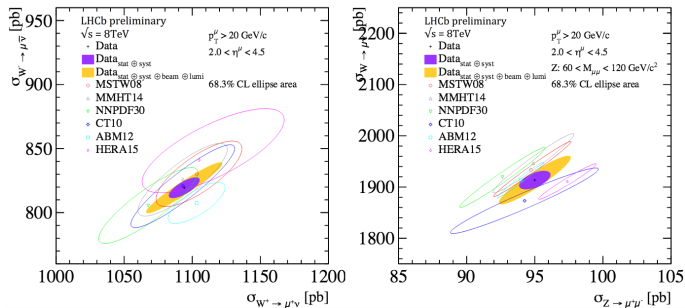
$A_{\mu} = (\sigma(W^+) - \sigma(W^-))/(\sigma(W^+) + \sigma(W^-))$  as a function of  $\eta^{\mu}$  (right)



- systematic uncertainties on data largely cancel in asymmetry.
- LHCb occupies interesting region of phase space where the asymmetry changes sign.
- result is sensitive to ratio of up valence PDF to down valence PDF.

# Cross-section ratios

- Many theoretical and experimental uncertainties cancel, so ratio measurements allows for precision tests of the Standard Model at levels below 1%.
- Some uncertainties remain - correlations fully accounted for.



Theoretical uncertainties shown on this slide are due to PDFs.

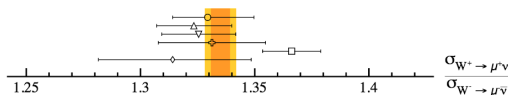
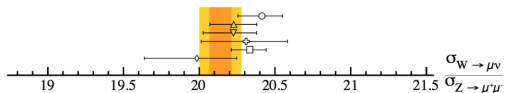
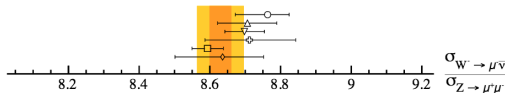
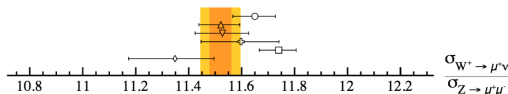
Scale variations not included.

# Cross-section ratios

- Overall cross-section ratios at 8 TeV show good agreement with predictions from different PDF sets.

LHCb preliminary  $\sqrt{s} = 8\text{TeV}$   
 Data<sub>stat</sub> (orange) Data<sub>tot</sub> (yellow)

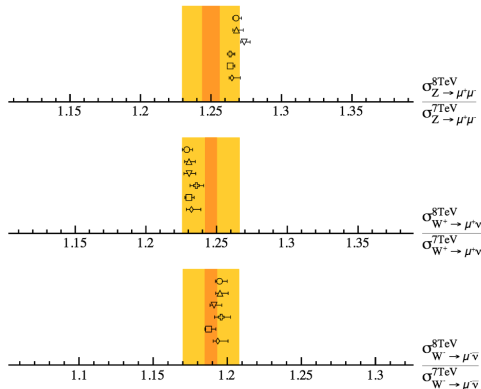
$\circ$  MSTW08  $\diamond$  CT10  $p_T^\mu > 20\text{ GeV}/c$   
 $\triangle$  MMHT14  $\square$  ABM12  $2.0 < \eta^\mu < 4.5$   
 $\nabla$  NNPDF30  $\diamond$  HERA15  $Z: 60 < M_{\mu\mu} < 120\text{ GeV}/c^2$



# Cross-section ratios

- PDF uncertainties largely cancel in ratios of 8 TeV cross-section measurements with 7 TeV measurements.
- Luminosity correlated between two years at level of 0.55

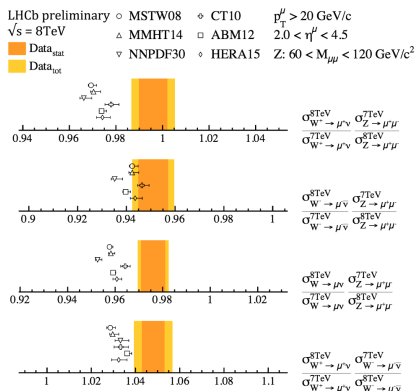
LHCb preliminary  $\circ$  MSTW08  $\diamond$  CT10  $p_T^\mu > 20 \text{ GeV}/c$   
 $\sqrt{s} = 8\text{TeV}$   $\triangle$  MMHT14  $\square$  ABM12  $2.0 < \eta^\mu < 4.5$   
  $\text{Data}_{\text{stat}}$   $\nabla$  NNPDF30  $\diamond$  HERA15  $Z: 60 < M_{\mu\mu} < 120 \text{ GeV}/c^2$   
  $\text{Data}_{\text{tot}}$





# Cross-section ratios

- Can also consider ratios of ratios:
- Further removes many experimental uncertainties - largest remnant systematic uncertainty due to W boson purity.
- precision test of Standard Model at **per mille** level.



- Broad **agreement with Standard Model** - measurements are correlated (if one ratio deviates, others are expected to as well); all individual measurements agree with predictions at  $2\sigma$  level or better.

# Decays of directly produced Z bosons at LHCb to 2

**muons:**  
 $A_{FB}$  and  $\sin^2(\theta_W^{\text{eff}})$

## Asymmetries in Z boson decays

- The angular distribution of Z boson decays contains information on the **vector** and **axial-vector** couplings:

$$\frac{d\sigma}{d\cos\theta^*} = A(1 + \cos^2\theta^*) + B\cos\theta^*$$

- ▶ at leading order, where  $A$  and  $B$  depend on the invariant mass of the dimuon pair, the initial state quark colour charge, and the vector and axial-vector couplings, and where  $\theta^*$  is the angle of the  $\mu^-$  in the Collins-Soper frame.
- measurements sensitive to  $A$  and  $B$  probe vector and axial-vector couplings, and through them the Weinberg mixing of the Z boson.
- measure  $A_{FB} = (N_F - N_B)/(N_F + N_B)$ , where  $N_F$  is the number of forward decays ( $\cos\theta^* > 0$ ), and  $N_B$  the number of backward decays.
- measurement probes the relative vector and axial-vector couplings, and the **effective (leptonic) weak mixing angle**,  $\sin^2(\theta_W^{\text{eff}})$ .
- sensitivity enhanced by Z boson and virtual photon interference.

# Asymmetries in Z boson decays

- Want to study couplings of Z boson,
- The 2 best measurements of the leptonic  $\sin^2(\theta_W^{\text{eff}})$  differ by  $\sim 3$  standard deviations.

## LEP + SLD

Phys. Rept. 427 (2006) 257

## LEP $A_{\text{FB}}(\text{b})$

Phys. Rept. 427 (2006) 257

## SLD $A_{\text{LR}}$

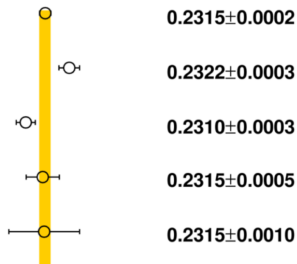
Phys. Rev. Lett. 84 (2000) 5945

## D0

Phys. Rev. Lett. 115 (2015) 041801

## CDF

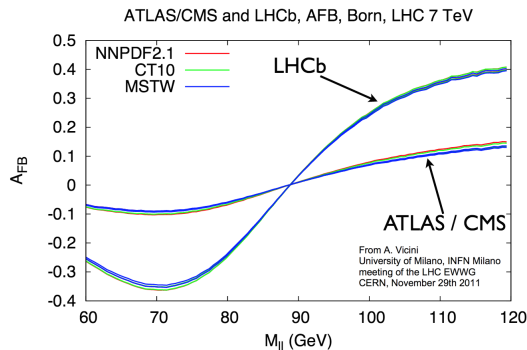
Phys. Rev. Lett. D89 (2014) 072005



# Asymmetries in Z boson decays

- Why perform these measurements at LHCb?
  - ▶ At a boson rapidity of 0, the measured  $A_{FB}$  is 0, for all dimuon invariant masses, due to the symmetric initial state.
  - ▶ At **low rapidities, reduced sensitivity** of  $A_{FB}$  to  $\sin^2(\theta_W^{\text{eff}})$ : little ability to estimate which proton contained the colliding quark and which contained the colliding anti-quark.
  - ▶ At **higher rapidities,  $A_{FB}$  is larger**: the proton travelling towards LHCb tends to contain the quark, and the proton travelling away from LHCb tends to contain the anti-quark.
    - ★ This is because the high- $x$  parton will tend to be the quark and not the anti-quark, entirely due to PDFs: there are few high- $x$  anti-quarks.

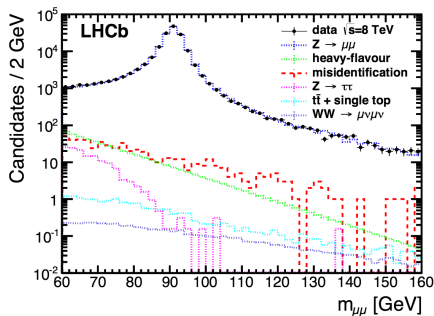
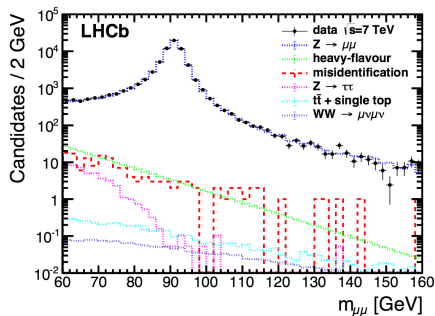
# Asymmetries in Z boson decays



- With enhanced  $A_{FB}$  in the forward region there is enhanced sensitivity to  $\sin^2(\theta_W^{\text{eff}})$ .
- Even with larger PDF uncertainties on the cross-sections, the increased magnitude of  $A_{FB}$  reduces theoretical uncertainties associated with extracting  $\sin^2(\theta_W^{\text{eff}})$ .

# Asymmetries in Z boson decays - Selecting Events

- Selection very similar to that of the inclusive Z boson cross-section analysis.
  - ▶ Increase the boson mass window to  $60 < M < 160$  GeV - increases sensitivity to  $\sin^2(\theta_W^{\text{eff}})$ .
  - ▶ Dominant background shapes constrained using data; along with simulation of signal shape, describe data well.



# Asymmetries in Z boson decays - Unfolding

- Unfold the measured  $A_{FB}$  distribution for detector effects:
  - ▶ Apply **momentum scale/curvature bias corrections** (determined using data). Correct for any residual misalignment or imperfect knowledge of the magnetic field, which could provide a curvature bias or momentum scale effect, affecting the invariant mass distribution.
  - ▶ Apply correction factors (determined using data) to account for **muon reconstruction efficiency** varying with the muon pseudorapidity.
  - ▶ Unfold the data to correct for the **dimuon invariant mass resolution** using the Bayesian method.
- No correction is applied to the  $A_{FB}$  distribution to account for muon QED FSR. Instead, theoretical distributions include this effect.



## Asymmetries in Z boson decays - Uncertainties

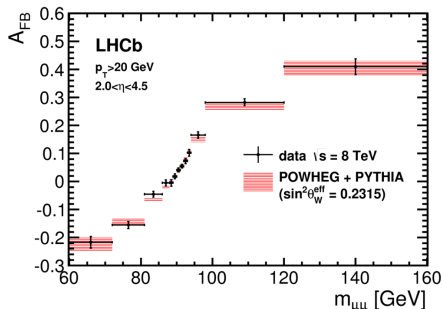
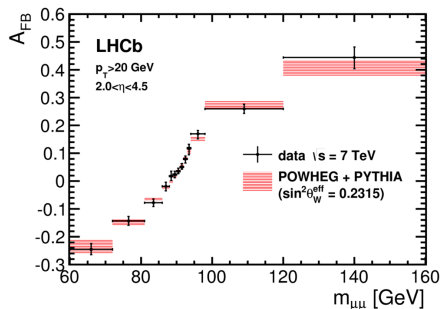
- Dominant experimental uncertainty from the **momentum scale and curvature bias corrections**.
  - ▶ determined from uncertainties on the magnetic field map measurements and the precision with which the residual corrections are determined.
- Mean (absolute) shift in  $A_{FB}$  from experimental uncertainties:

Source of uncertainty	$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 8 \text{ TeV}$
curvature/momentum scale	0.0102	0.0050
data/simulation mass resolution	0.0032	0.0025
unfolding parameter	0.0033	0.0009
unfolding bias	0.0025	0.0025

- Impact of uncertainties on reconstruction efficiencies and background asymmetries are negligible.

# Asymmetries in Z boson decays - Results

- The measured  $A_{FB}$  distribution agrees with theoretical predictions in both 7 and 8 TeV data.
  - ▶ On these plots, the theoretical predictions are produced according to values of  $\sin^2(\theta_W^{\text{eff}})$  corresponding to the current world average.



# Asymmetries in Z boson decays - Measuring $\sin^2(\theta_W^{\text{eff}})$

- Determine  $\sin^2(\theta_W^{\text{eff}})$  by **comparing with simulation** produced using different values of  $\sin^2(\theta_W^{\text{eff}})$ .
  - ▶  $\chi^2$  comparison of the data with simulation to determine the best value.
  - ▶ Simulation produced using **POWHEG-BOX** interfaced with **Pythia8**, using **NNPDF2.3**.
  - ▶  $\alpha_S(M_Z)$  set to 0.118

# Asymmetries in Z boson decays - Theoretical Uncertainties

- Many different sources of theoretical uncertainty considered which can affect the extraction of  $\sin^2(\theta_W^{\text{eff}})$ :
  - ▶ **PDF uncertainties** - the extraction is repeated using simulation produced from each of the different NNPDF 68% cl replicas in turn. The uncertainties are larger than those found from simply changing the PDF set to CT10.
  - ▶ **Renormalisation and factorisation scales** are varied by factors of 0.5 and 2, to probe the effect of higher order contributions.
  - ▶  $\alpha_S$  is varied by  $\pm 0.002$ , covering the current uncertainty on the world average.
  - ▶ The uncertainty associated with **FSR** is found by varying the generator used for FSR: results from FEWZ, Pythia and Herwig++ are considered.
  - ▶ The  $A_{FB}$  shapes were found to be consistent between different generators.

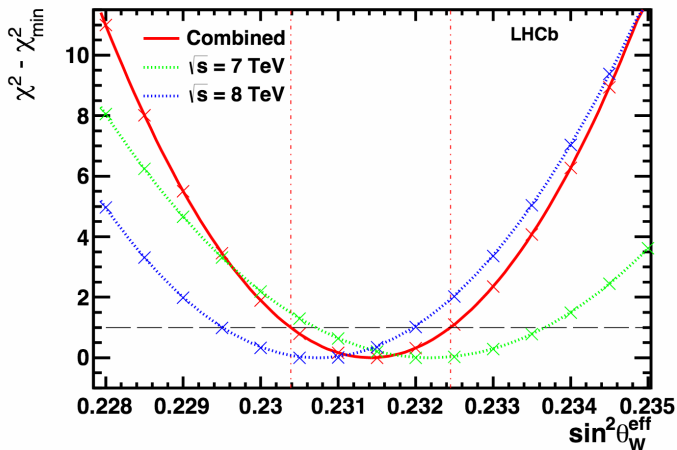
# Asymmetries in Z boson decays - Theoretical Uncertainties

- Average shift in  $A_{FB}$  from the theoretical uncertainties.

Uncertainty	average $\Delta A_{FB}^{\text{pred}} $
PDF	0.0062
scale	0.0040
$\alpha_s$	0.0030
FSR	0.0016

- Largest theoretical uncertainty from PDF knowledge.
- Comparable to LHCb experimental uncertainties.

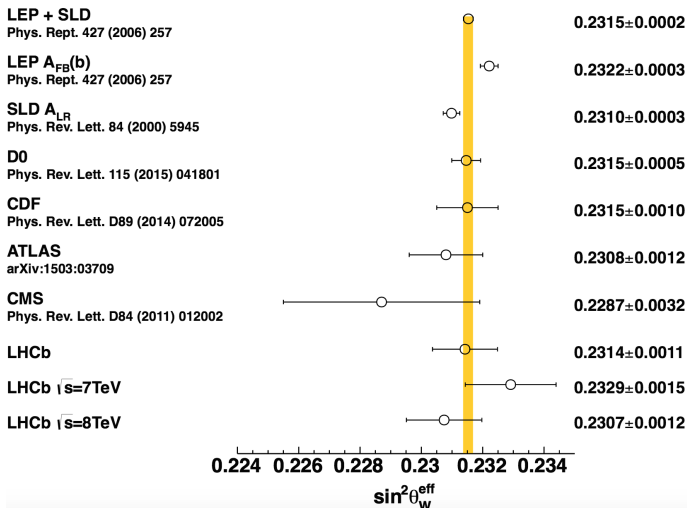
# Asymmetries in Z boson decays - Results



**LHCb measures:**

$$\sin^2(\theta_W^{\text{eff}}) = 0.23142 \pm 0.00073 \text{ (stat.)} \pm 0.00052 \text{ (syst.)} \pm 0.00056 \text{ (theo.)}$$

# Asymmetries in Z boson decays



# Asymmetries in Z boson decays - The Future

- Can we expect the LHCb precision to improve?
  - ▶ **Yes** - the result is currently dominated by statistical uncertainties.
  - ▶ **Yes** - PDF uncertainties will reduce with new PDF sets which are constrained by LHC data (including the cross-section results discussed earlier).
  - ▶ **Yes** - the measurement can be binned in the boson rapidity to maximise the input from the most sensitive regions. This was not done yet as the measurement is currently statistically limited.
- Note - with the change in collision energy to 14 TeV the dilution of  $A_{FB}$  from imperfect knowledge of the initial state quark direction slightly increases at LHCb by 5%.



# Conclusions

# Conclusions

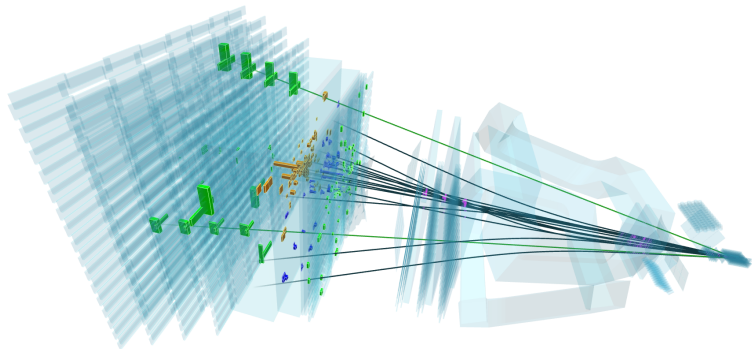
- At the LHC, LHCb uniquely occupies the **low- $x$  phase space** at electroweak energy scales.
- This allows LHCb to make **complementary measurements** to ATLAS and CMS.
- LHCb results on electroweak boson production are useful for **constraining parton distribution functions**.
- Many LHCb results already included in most recent PDF fits.
- LHCb has performed the most precise inclusive W & Z boson production cross-section measurements at the LHC.
- Ratios of measurements allow **tests of the Standard Model** at per mille precision.
- Results in proton-proton collisions at 7 and 8 TeV currently **agree with the Standard Model**.

# Conclusions

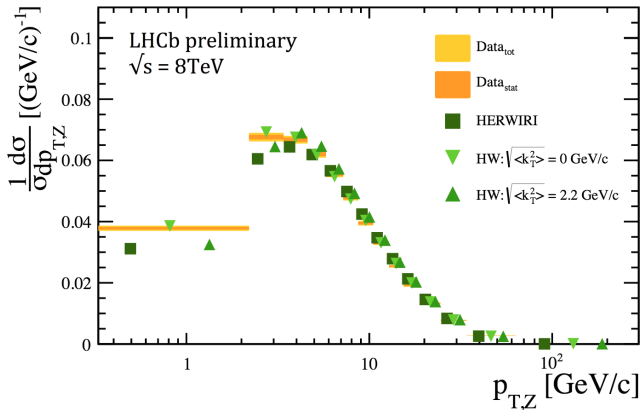
- The angular distributions associated with decays of directly produced neutral electroweak bosons can be used to **extract the value of  $\sin^2(\theta_W^{\text{eff}})$** .
  - ▶ Probes the **vector and axial-vector couplings** of neutral electroweak bosons in the Standard Model.
  - ▶ This parameter currently has a  $\sim 3\sigma$  discrepancy between the two best measurements.
- The forward region probes a larger  $A_{FB}$  than the central region - due to better knowledge of the directions of the incoming quarks and anti-quarks.
  - ▶ Important measurement for LHCb to make!
- LHCb result using 7 and 8 TeV data is **currently the most precise measurement at the LHC, consistent with the world average**.
  - ▶ And the result is not limited by PDF knowledge.

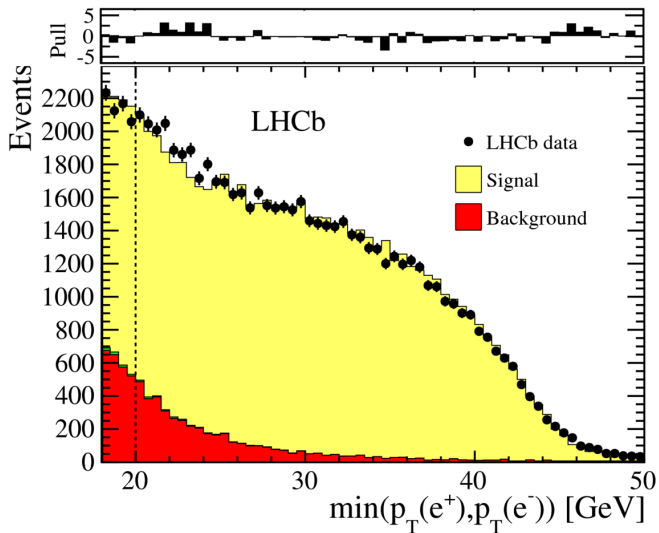


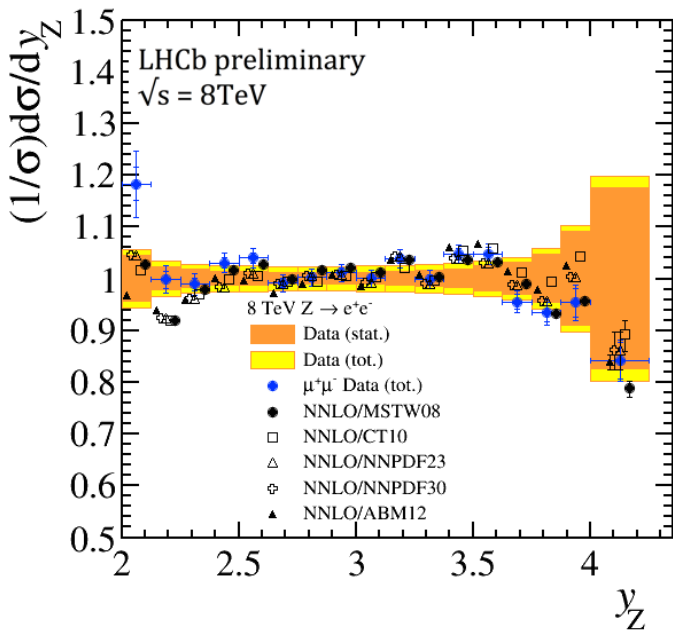
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Run 157596  
Sat, 11 Jul 2015 02:01:18



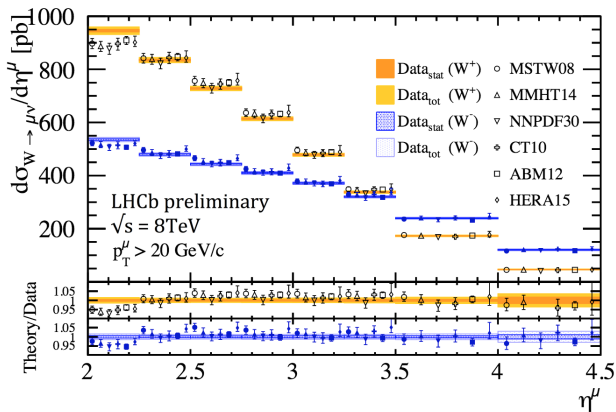
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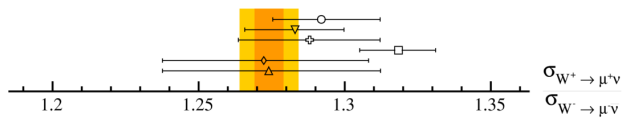
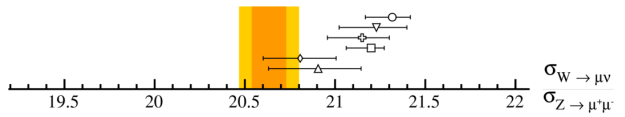
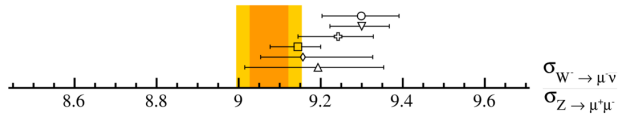
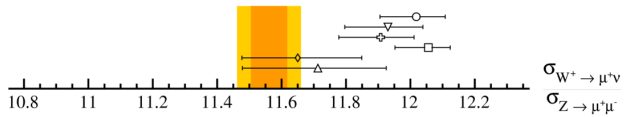




Source	Uncertainty (%)			
	$R_{W^\pm}$	$R_{W+Z}$	$R_{W-Z}$	$R_{WZ}$
Statistical	0.30	0.31	0.33	0.36
Purity	0.25	0.28	0.21	0.22
Tracking	0.06	0.22	0.24	0.23
Identification	0.01	0.11	0.11	0.11
Trigger	0.04	0.10	0.09	0.09
GEC	0.13	0.21	0.22	0.21
Selection	0.10	0.24	0.23	0.23
Acceptance	0.11	0.21	0.19	0.17
FSR	0.18			
Momentum scale	0.07	0.05	0.12	0.08
Systematic	0.38	0.55	0.52	0.50
Beam energy	0.14	0.15	0.29	0.21
Total	0.50	0.65	0.68	0.65

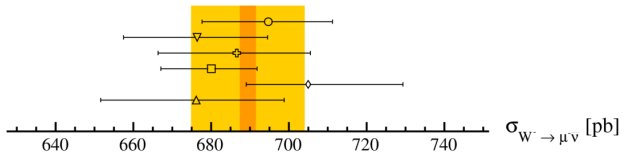
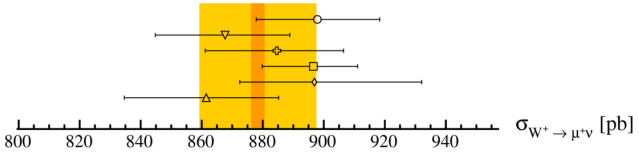
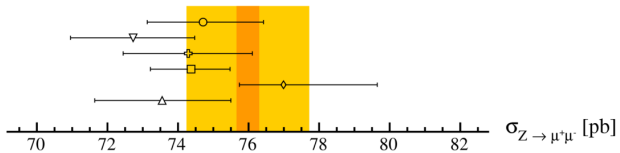
LHCb,  $\sqrt{s} = 7$  TeV

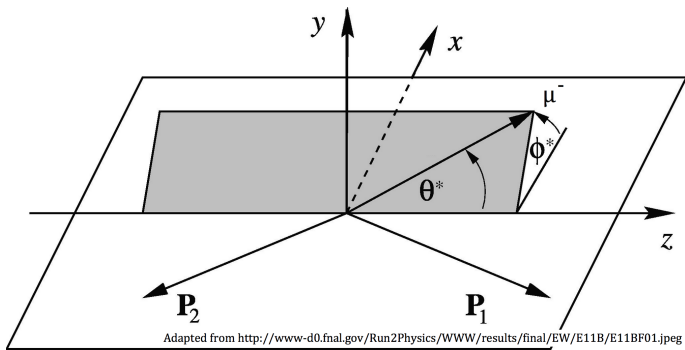
○ MSTW08	□ ABM12	$p_T^\mu > 20$ GeV/c
■ Data <sub>stat</sub>	▽ NNPDF30	$2.0 < \eta^\mu < 4.5$
■ Data <sub>tot</sub>	⊕ CT10	$Z: 60 < M_{\mu\mu} < 120$ GeV/c <sup>2</sup>
	△ JR09	



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	◇ HERA15	
	△ JR09	





# PDF Sets

- CT10 - arXiv:1101.0561
- NNPDF30 - arXiv:1410.8849
- MMHT14 - arXiv:1411.2560
- MSTW08 - arXiv:0901.0002
- ABM12 - arXiv:1310.3059
- HERA1.5 - arXiv:0911.0884
- JR09 - arXiv:0810.4274

# Theoretical Predictions

- Pythia8 - arXiv:1410.3012
- Pythia6 - arXiv:hep-ph/0603175
- Herwig++ - arXiv:0803.0883
- Herwiri - arXiv:1001.1434
- Powheg - arXiv:1002.2581
- MC@NLO - arXiv:1010.0819
- FEWZ - arXiv:1011.3540

## Further References

- A. Vicini, PDF effects on the measurement of the weak mixing angle, Talk at the LHC EW WG,

<https://indico.cern.ch/event/145744/contribution/9/attachments/138185/196081/ViciniPDFsin2thetaW.pdf>

- R. Thorne *et al.*, Parton Distributions and QCD at LHCb, Proceedings of DIS 2008, arXiv:0808.1847