Recent EW measurements at LHCb

Ronan Wallace
LHCb Implications Workshop
November 3rd, 2015

Overview

- Today:

Topic	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	Ref.
$W(Z) \to \mu\nu(\mu\mu)$	7	1	JHEP08(2015)039
$W(Z) \to \mu\nu(\mu\mu)$	8	2	LHCb-PAPER-2015-049
$A_{\mathrm{FB}}/sin^2\theta_W^{\mathrm{eff}}$	7/8	3	arXiv:1509.07645

- Also:

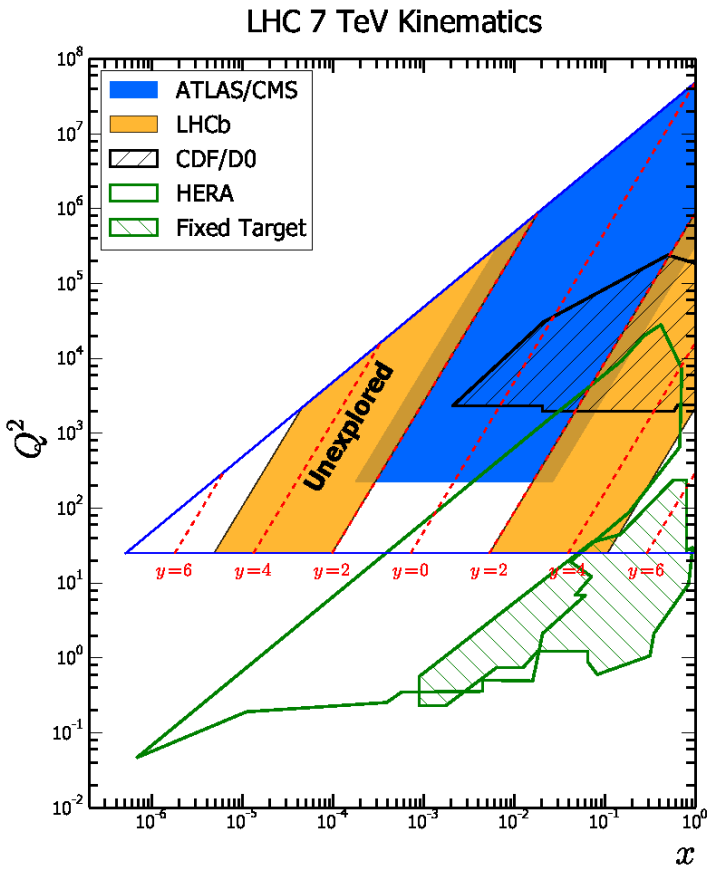
Topic	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	Ref.
$Z \to ee$	7	1	JHEP02(2013)106
$Z \to ee$	8	2	JHEP05(2015)109
$Z \to \tau\tau$	7	1	JHEP01(2013)111

EW motivations: Parton density functions

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

CERN-LHCb-PROC-2014-057

- 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: $Q^2 \sim 10^4$ (GeV/c^2)^2 and $x \sim 10^{-4}$ or $x \sim 10^{-1}$.



EW motivations: Testing the SM

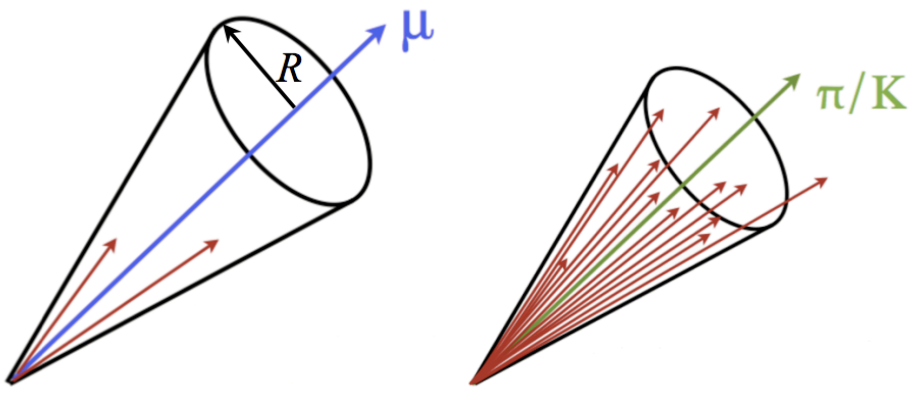
$$\sigma_{pp\to V} = \sum_{a,b} \int dx_1 dx_2 \underbrace{f_a\left(x_1, Q^2\right) f_b\left(x_2, Q^2\right)}_{PDFs} \hat{\sigma}_{ab}(x_1, x_2, Q^2)$$

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 α_s uncertainties almost fully correlated. These also reduced.

Selecting electroweak bosons

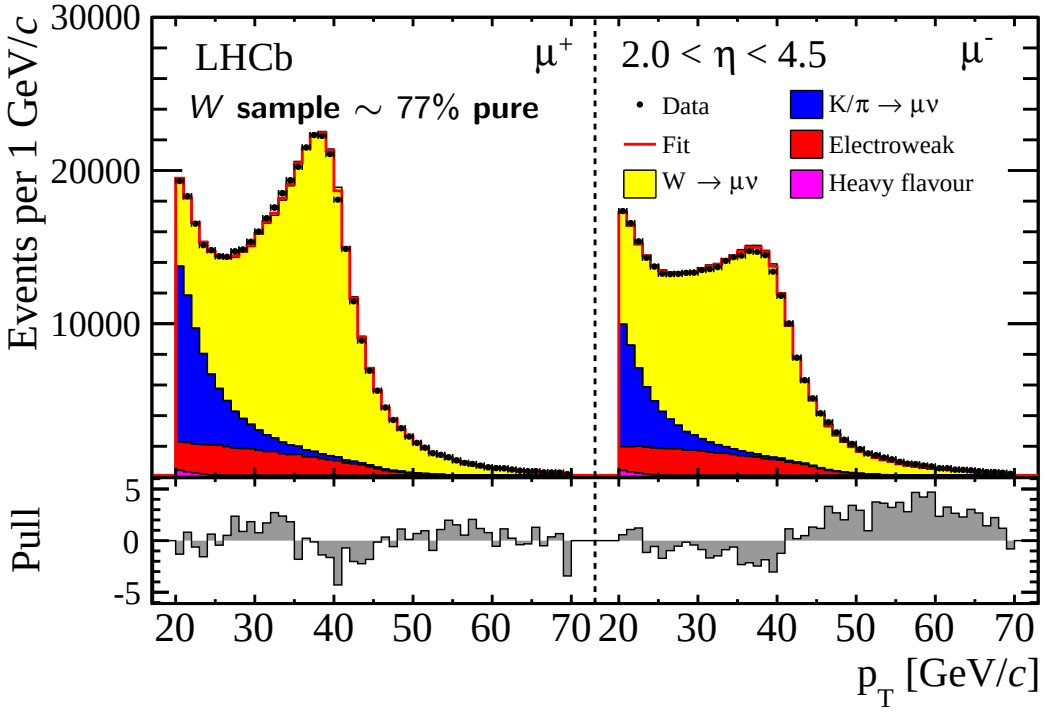
JHEP 12 (2014) 079; JHEP 08 (2015) 039



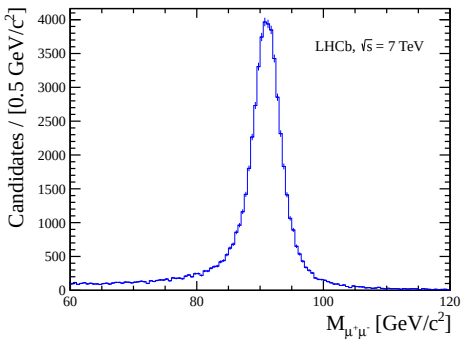
- Common to W and Z:
  - High p_T (> 20 GeV/c).
  - $2 < \eta < 4.5$.
  - Good track-fit quality.
  - Isolated muons consistent with primary interaction point.
  - Candidate event triggered by muon trigger.
  - Residual backgrounds include: π/K decay-in-flight, decays of heavy flavour hadrons, other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

Purity estimation

JHEP 12 (2014) 079; JHEP 08 (2015) 039; Comput. Phys. Comm. 178 (2008) 852



Z sample ~ 99% pure



- ~ 0.8(1.7) M W candidates in 7(8) TeV samples.
- Fit muon p_T distribution.

- **Signal**: RESBOS shape, normalisation free in η and charge.
- **Electroweak**: ($Z \to \mu\mu$, $W \to \tau\nu$, $Z \to \tau\tau$): RESBOS/PYTHIA shapes and normalisation from data.
- **Decay-in-flight**: Data shape. Normalisation free in η and charge.
- **Heavy flavour**: Shape ($IP > 100\mu m$) and normalisation from data.
- Large pulls at high muon p_T negligible impact on cross-section

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

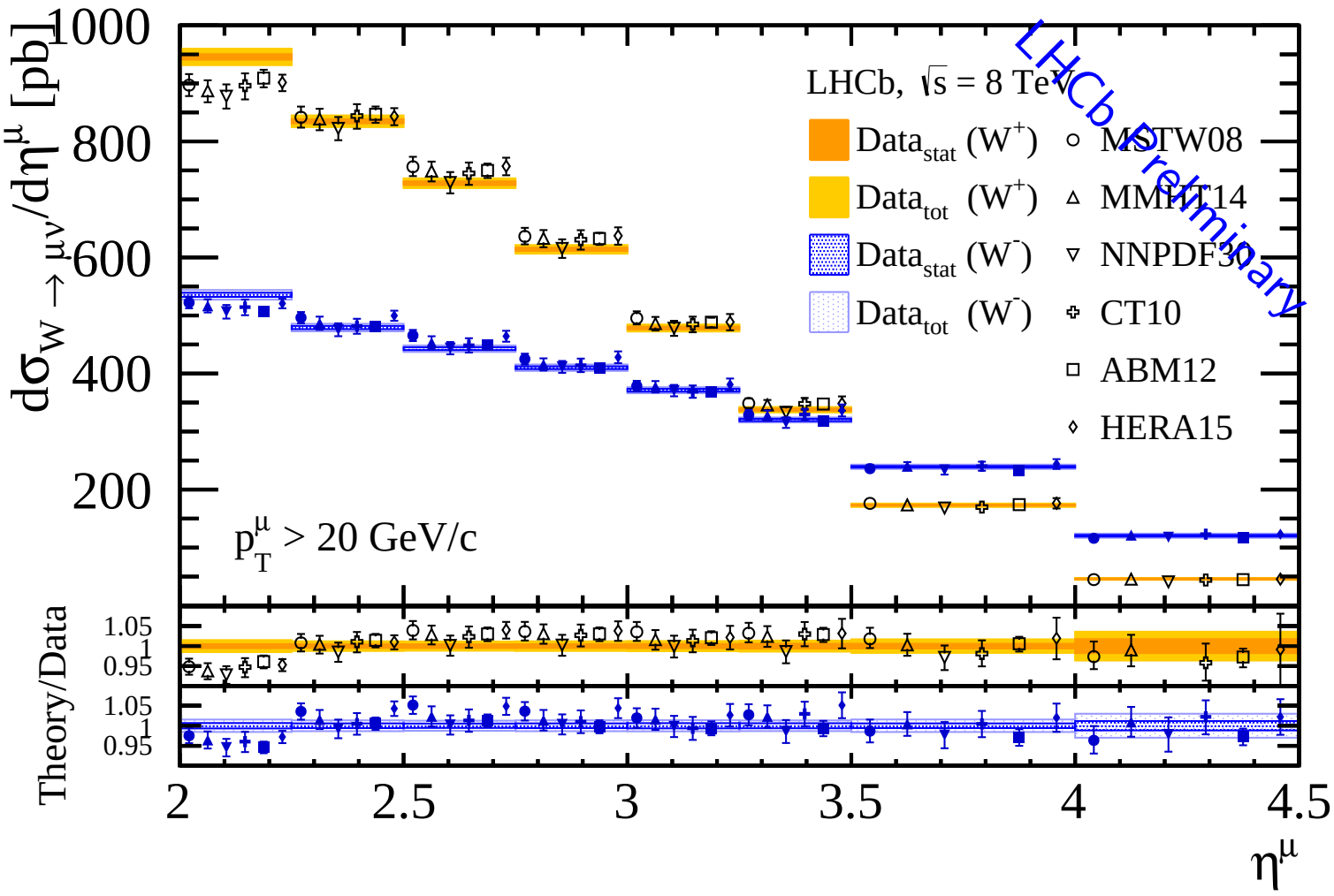
- Cross-sections defined in fiducial region: muons with $2 < \eta < 4.5$, $p_T > 20\ GeV/c$ and in the case of the Z boson an invariant mass $60 < M_Z < 120\ GeV/c^2$.

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

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

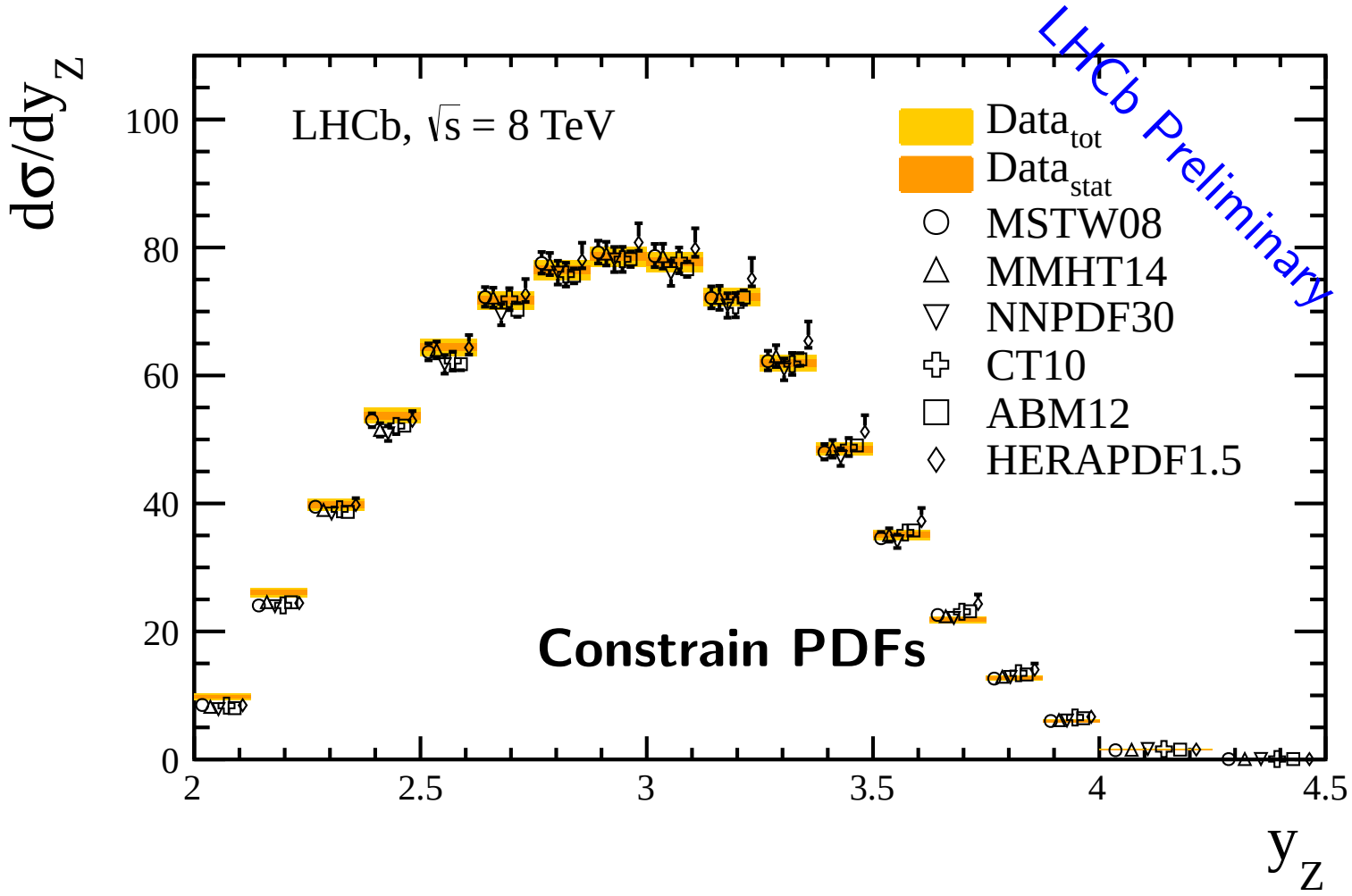
Differential cross-sections: η^{μ} at 8 TeV

LHCb-PAPER-2015-049



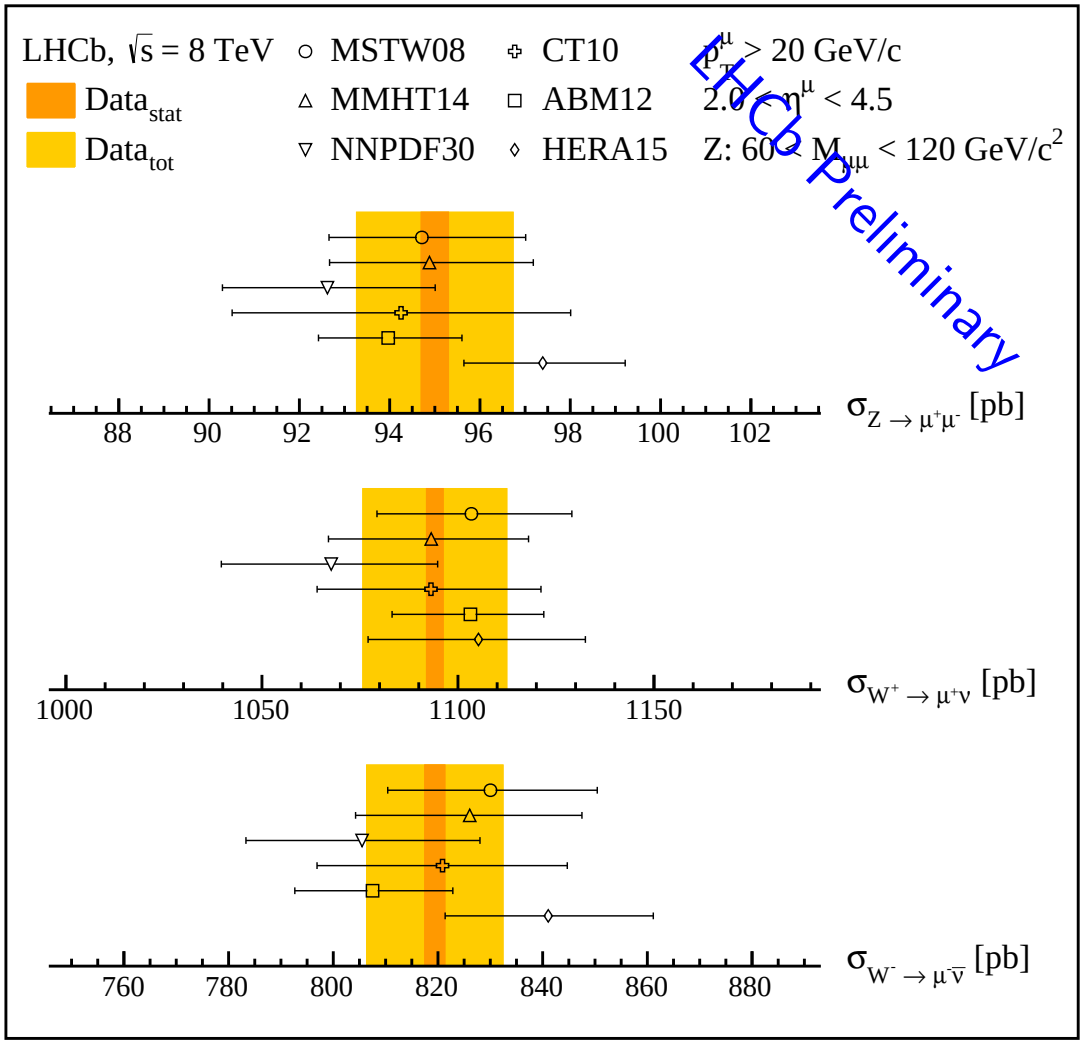
Differential cross-sections: y_Z at 8 TeV

LHCb-PAPER-2015-049



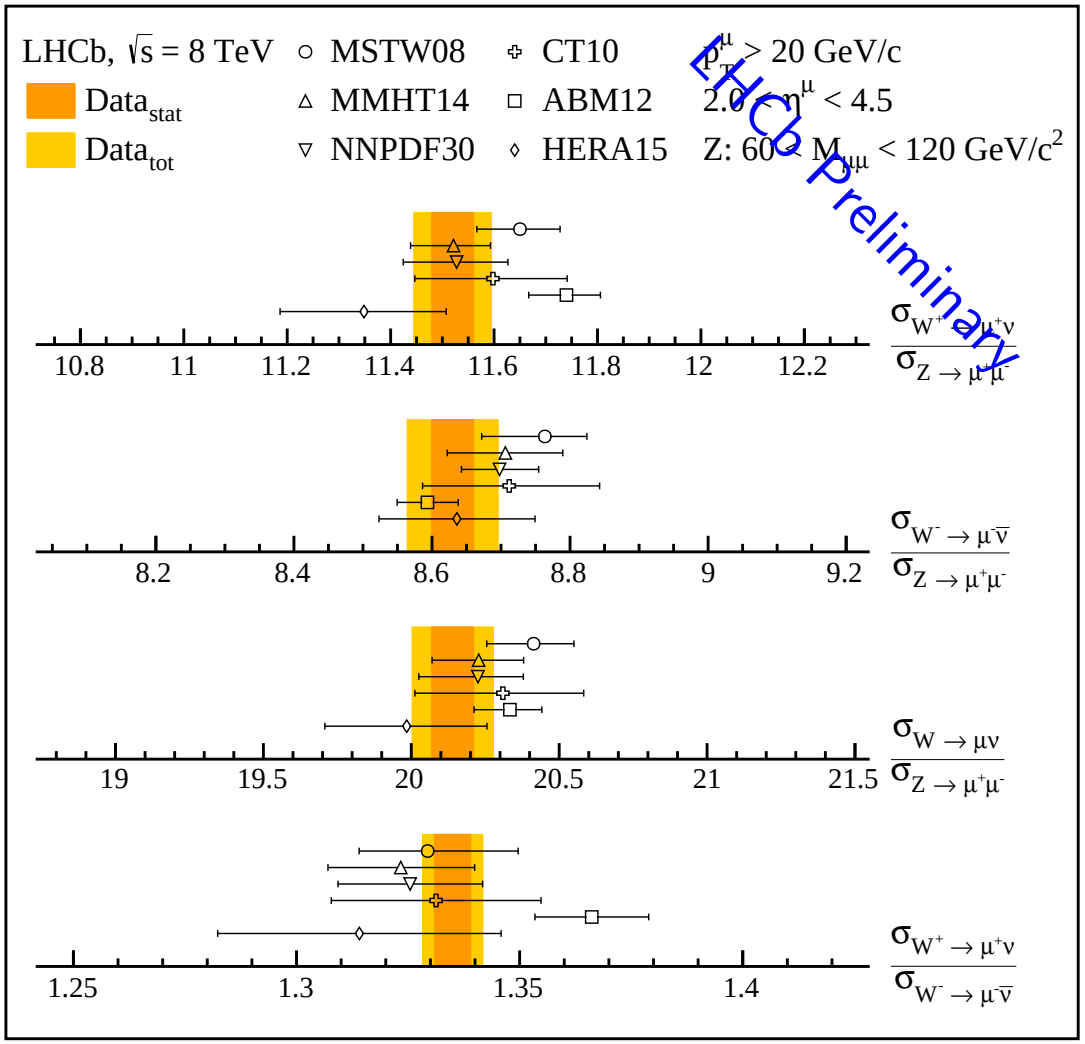
Cross-sections at 8 TeV

LHCb-PAPER-2015-049



Cross-section ratios at 8 TeV

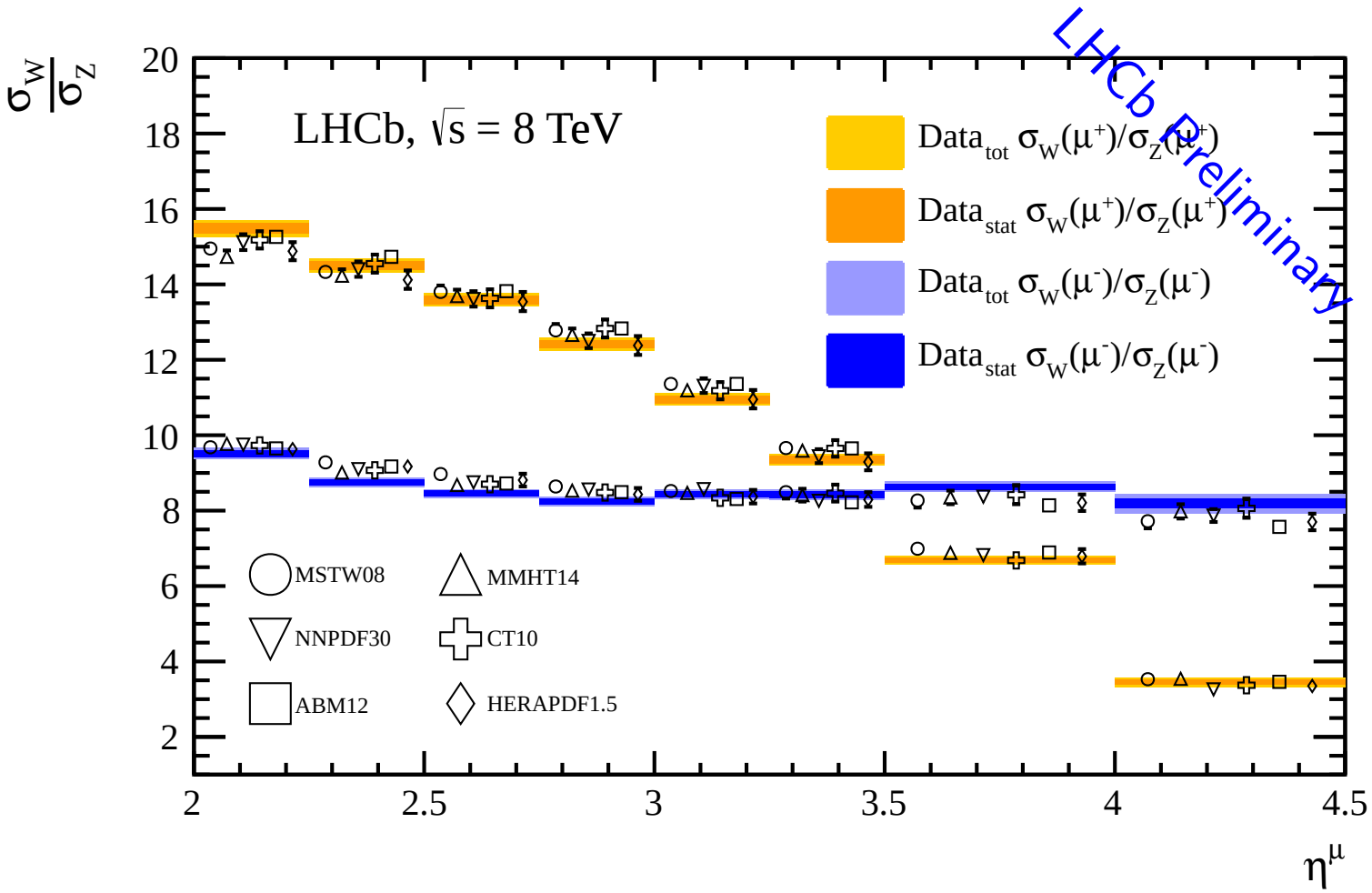
LHCb-PAPER-2015-049



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

Cross-section ratios at 8 TeV

LHCb-PAPER-2015-049



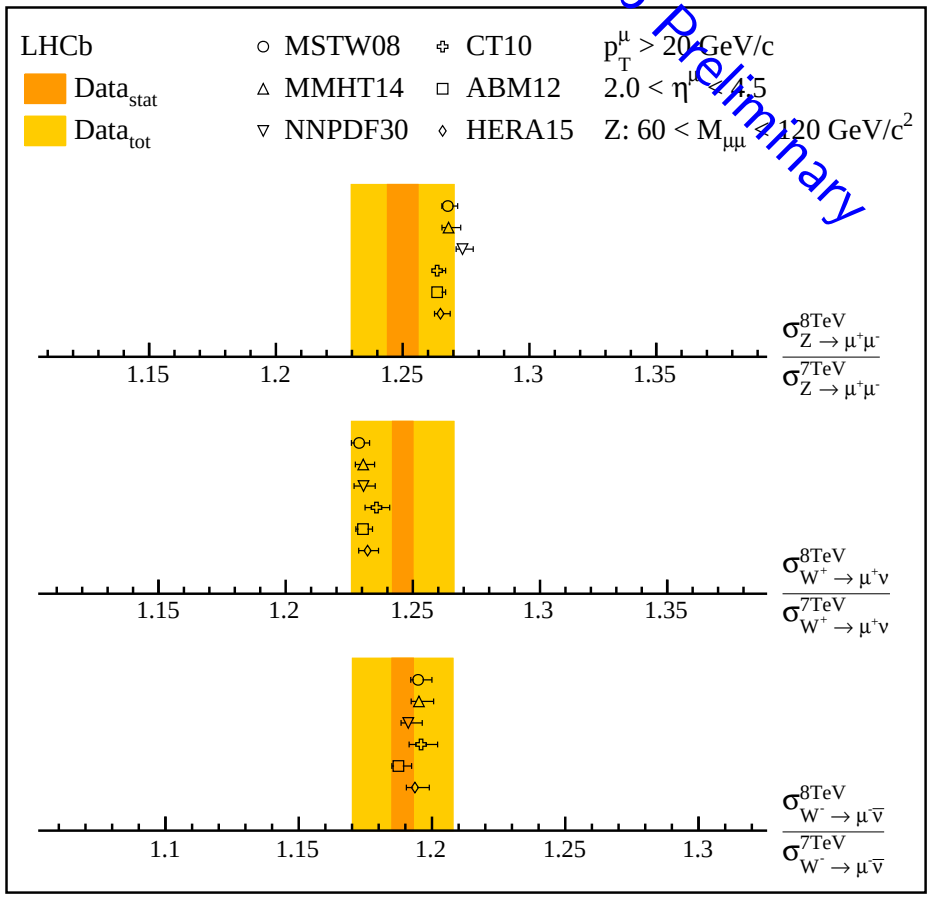
– Differential in lepton η about all we can do. Differential in lepton p_T if W fit pulls can be improved.

Combining measurements on different data sets

- Similar measurements all performed on 7 TeV data set.
- Combine the two to check for interesting effects (BSM) with energy evolution.
- Correlated uncertainty?
- Uncertainties due to statistically independent sample are uncorrelated.
- Uncertainties reflecting common methods are correlated.
- Luminosity uncertainty: 55% correlated.

Cross-section ratios at different $\sqrt{s}$

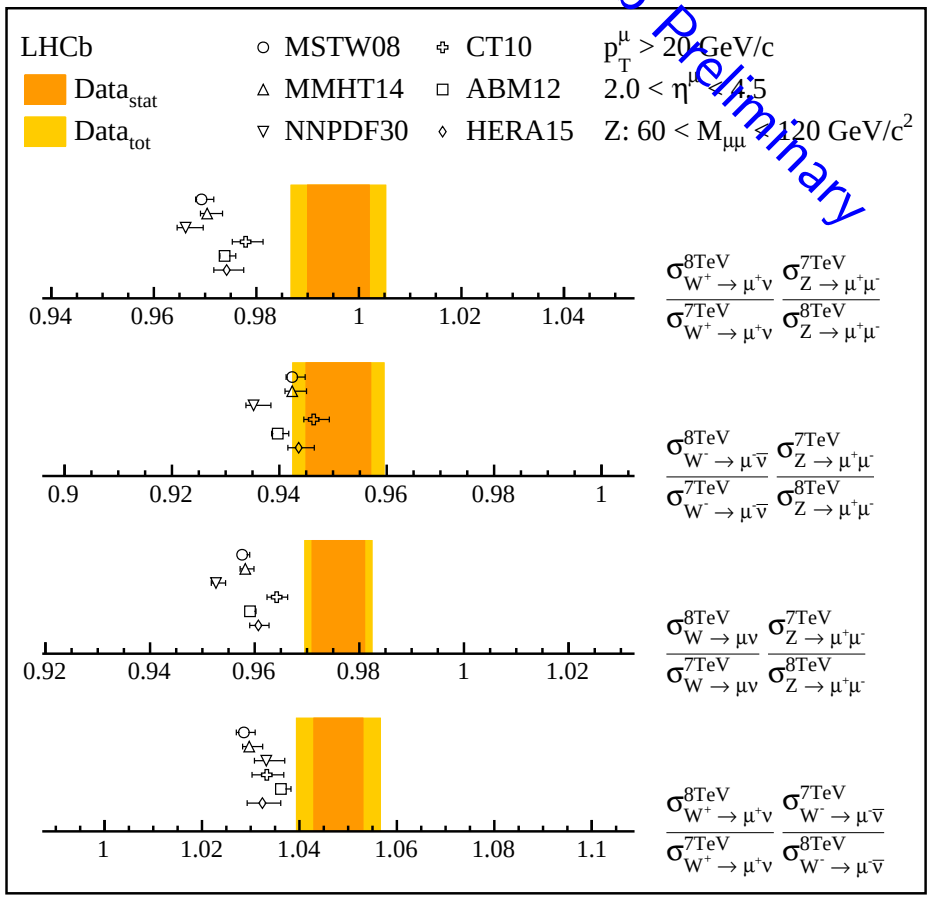
LHCb-PAPER-2015-049



- Measurement uncertainty dominated by luminosity 1.5%
- PDF uncertainty rather small.

Double ratios of cross-sections at different $\sqrt{s}$

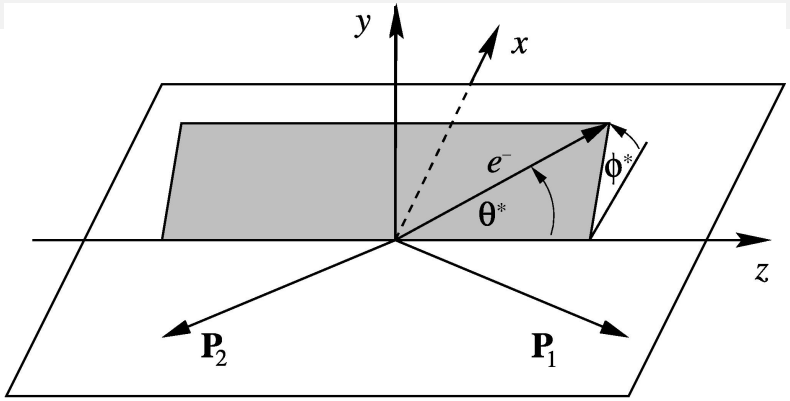
LHCb-PAPER-2015-049



- Sub-percent precision (statistically dominated). Precise test of SM.
- Some sensitivity to choice of PDF.
- Maximal deviations about 2σ.

Definitions for A_{FB} and $sin^2(\theta_W^{\mathrm{eff}})$

FERMILAB-THESIS-2005-22



- Collins-Soper frame: Dimuon CM frame where z-axis parallel to $\vec{P_1} - \vec{P_2}$
- θ^* the polar angle of positively charged lepton in Collins-Soper frame.

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

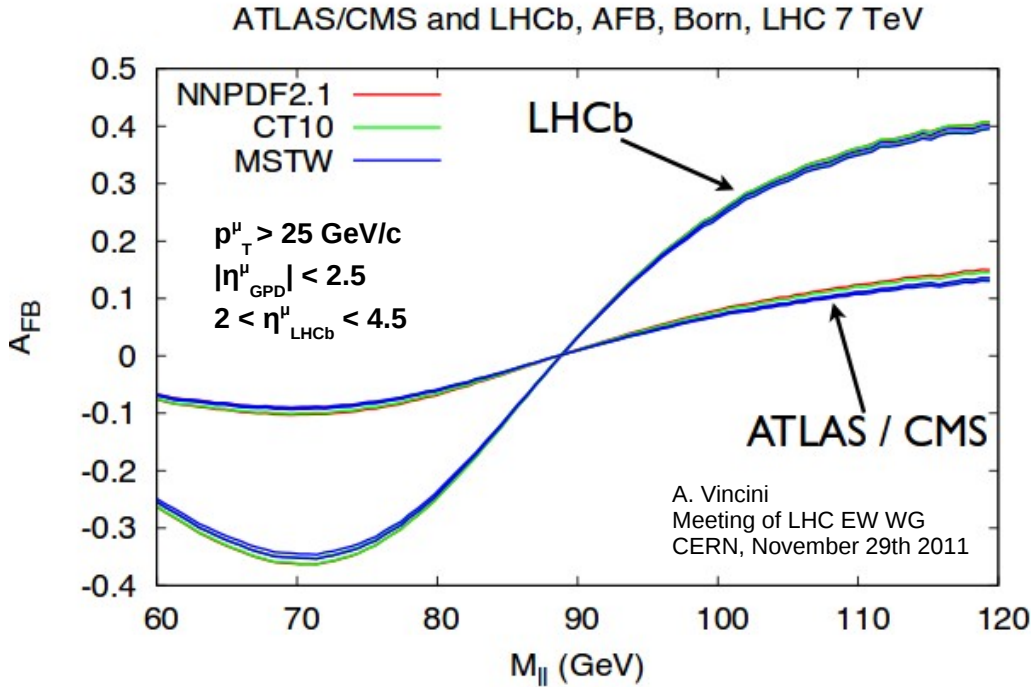
- Forward: Count N_{F} with $cos\ \theta^* > 0$. Backward: Count N_{B} with $cos\ \theta^* < 0$.

$$B \propto A_{\mathrm{FB}} \equiv \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}} \propto sin^2\theta_W^{\mathrm{eff}}$$

- A_{FB} can be related to $sin^2\theta_W^{\mathrm{eff}}$ when the direction of the initial colliding quark is known.
- $sin^2\theta_W^{\mathrm{eff}}$ extracted from fits to A_{FB} as function of mass.

Benefits of forward geometry

https://indico.cern.ch/event/145744/contribution/9

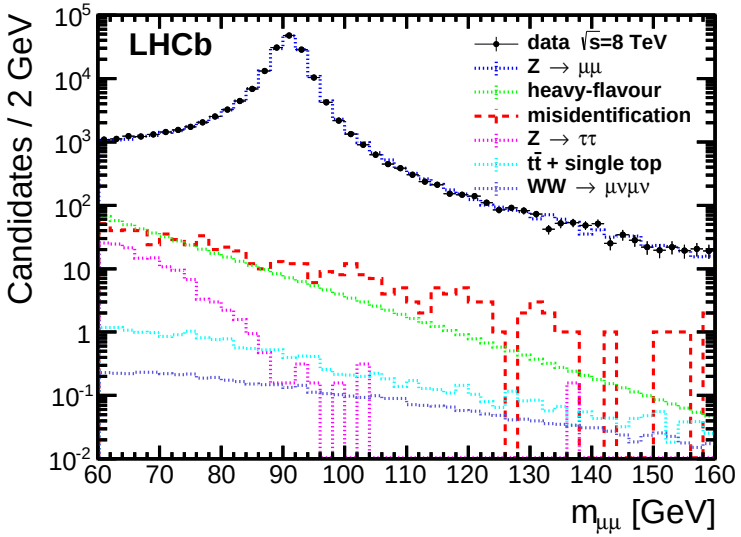


- At $y = 0$ $A_{\mathrm{FB}} = 0$ due to symmetric initial state.
- Dilutes ability of A_{FB} to determine $sin^2\theta_W^{\mathrm{eff}}$ since direction of initial quark is unknown.
- Forward Z boson in LHCb due to colliding quark travelling into LHCb.
- Assignment of forward and backward decays leads to correct assignment 90% of the time.

Measurement of A_{FB}

LHCb-PAPER-2015-039

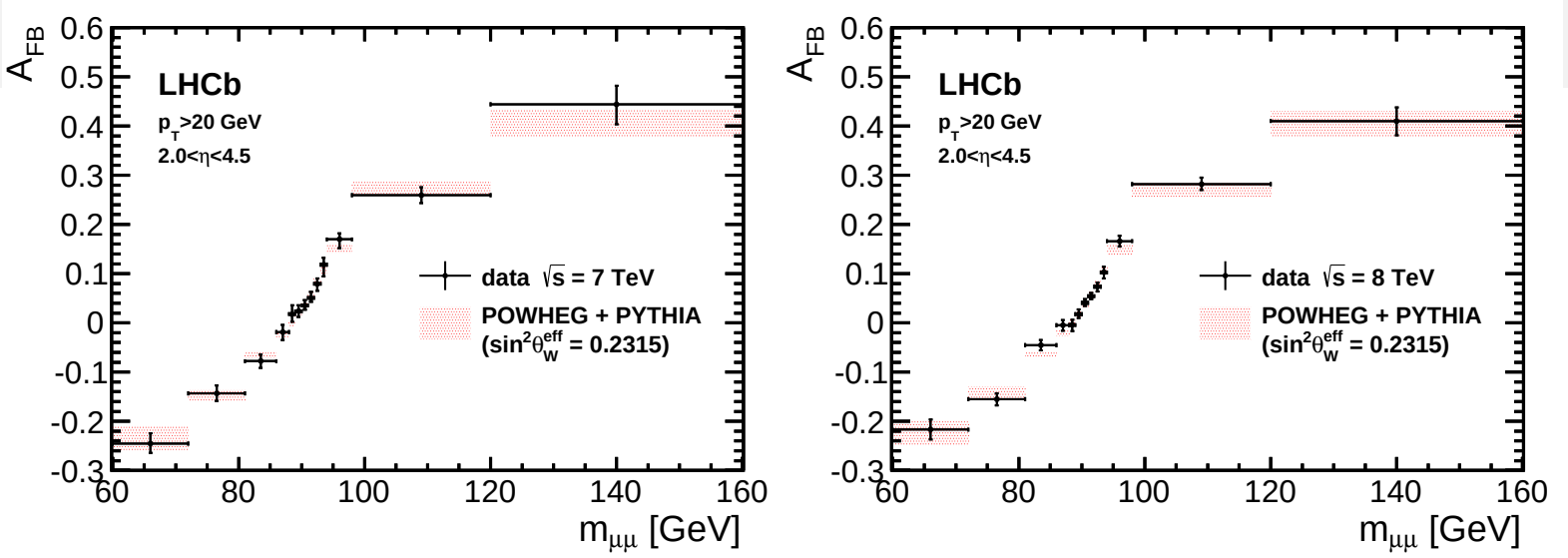
- Sample of Z bosons with extended mass range (160 GeV/c^2)
- Correct muon momenta for magnetic field scale and detector misaligment.
- Unfold for resolution effects: train on calibrated simulation.
- Correct for backgrounds.



- No correction for dilution of A_{FB} due to knowledge of intial quark.
- No FSR corrections (compare to prediction with FSR instead).
- Uncertainties due to efficiencies/backgrounds negligible.

Source of uncertainty	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ 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

Measurement of A_{FB}



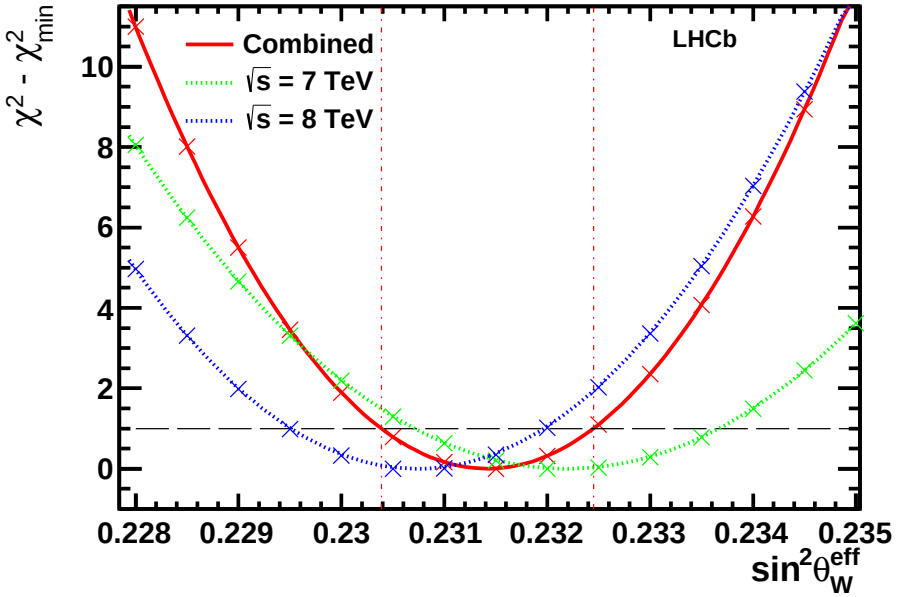
$$A_{FB} = 0.412 \pm 0.027(stat.)^{+0.005}_{-0.009}(sys.) \pm 0.026(theo.)$$

- Most precise result at LHC.
- Statistically limited.
- Theoretical uncertainty required for extraction of $sin^2\theta_W^{eff}$.

Uncertainty	average $\Delta\lvert A_{FB}^{pred}\rvert$	Method
PDF	0.0062	NNPDF replicas (68% CL)
scale	0.0040	$\frac{M_Z}{2} < \mu < 2M_Z$
α_s	0.0030	0.118±0.002
FSR	0.0016	FEWZ/HERWIG++/PYTHIA

Extracting $sin^2\theta_W^{\text{eff}}$

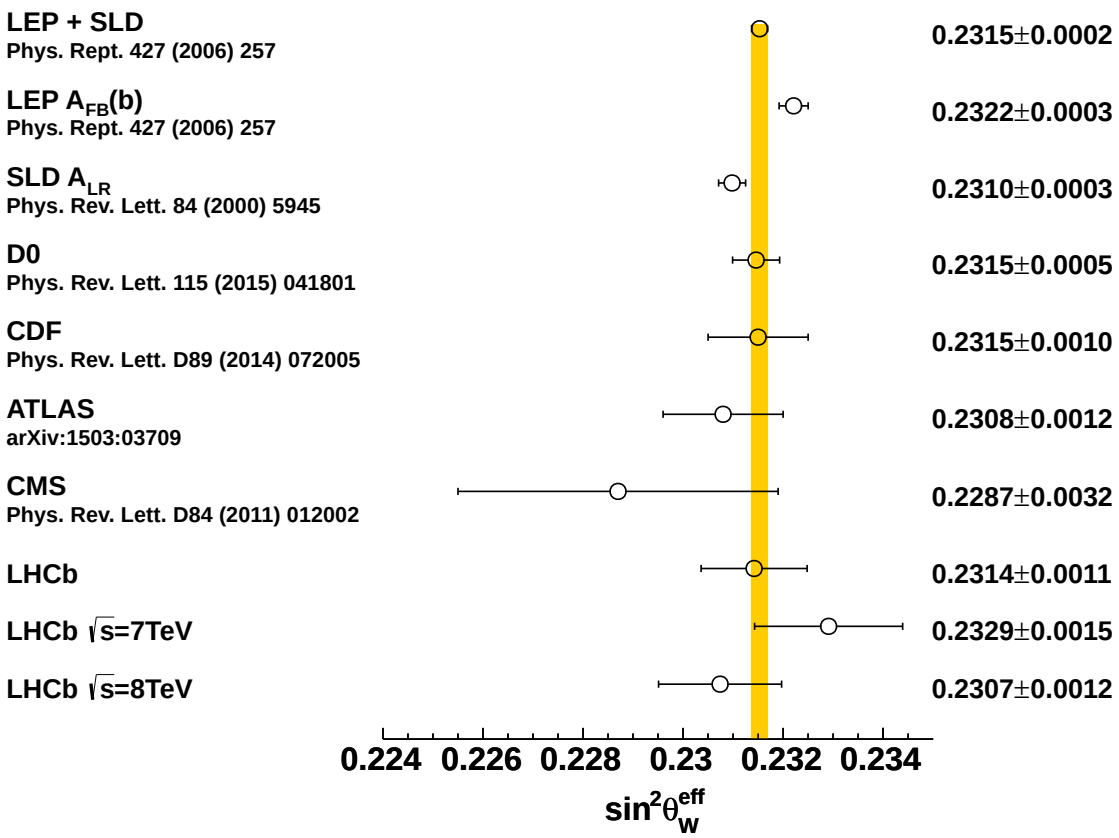
- Generate POWHEG+PYTHIA samples with different values of $sin^2\theta_W^{\text{eff}}$
- Construct a χ^2 from generated and measured distributions. Value from minimum.
- Uncertainty: Interval in $sin^2\theta_W^{\text{eff}}$ corresponding to unit change in χ^2.



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

- Most precise result at LHC.
- Statistically limited.

Measurements of $sin^2\theta_W^{\text{eff}}$



Conclusions

- Measurements of electroweak boson cross-sections and $sin^2\theta_W^{\text{eff}}$ have been presented.
- Stringent test of the SM. Can also help to constrain proton PDFs.
- No evidence of deviation from SM behaviour.
- Most precise measurements statistically limited.
- Important to make these measurements at 13 TeV and 14 TeV with the next phase of LHC.
- Double differential A_{FB} in mass and rapidity with increased stats.

Points of discussion?

- Extraction of W boson signal: alternative variables to fit?.
- W/Z ratio vs η: charge dependent shapes. Other distributions?
- Are there new ways to exploit LHCb's precision in dilepton final-states?
- What other measurements can be used to constrain PDFs?

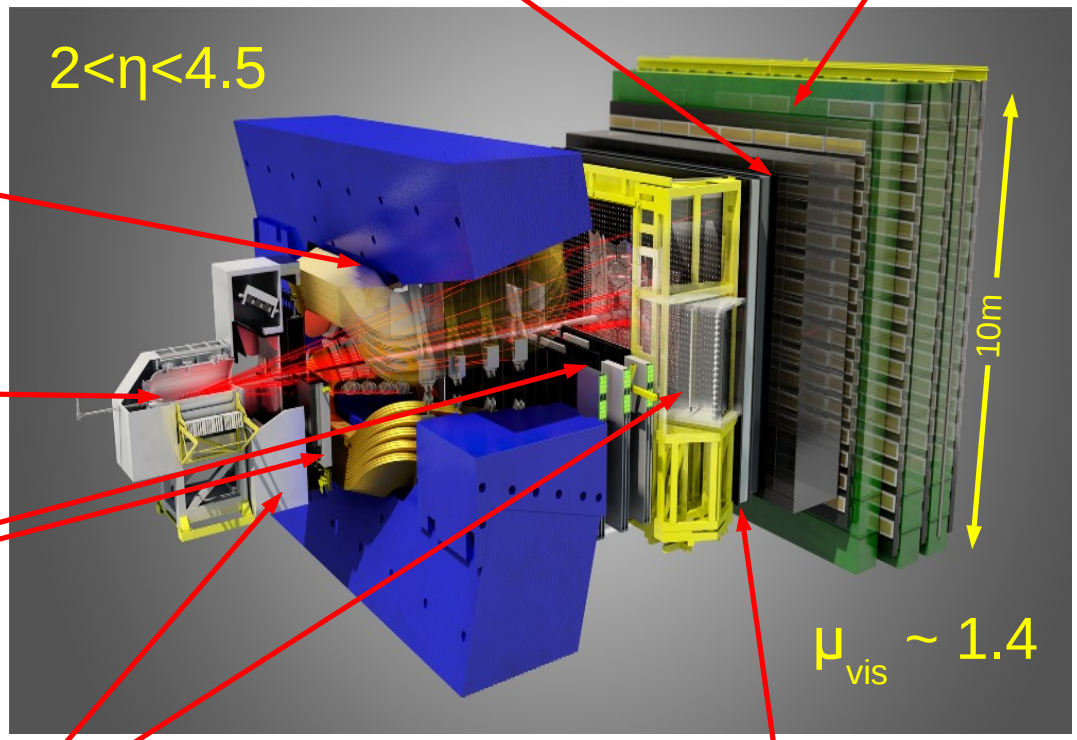
Acknowledgements

These slides were produced as part of the output of the DGGP, funded under the Programme for Research in Third Level Institutions (PRTLI) Cycle 5 and co-funded by the European Regional Development Fund.

BACKUP

LHCb

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



Calorimeters

Muon

Magnet
4 Tm

Velo
δ_{IP}~(15+29/p_T) μm

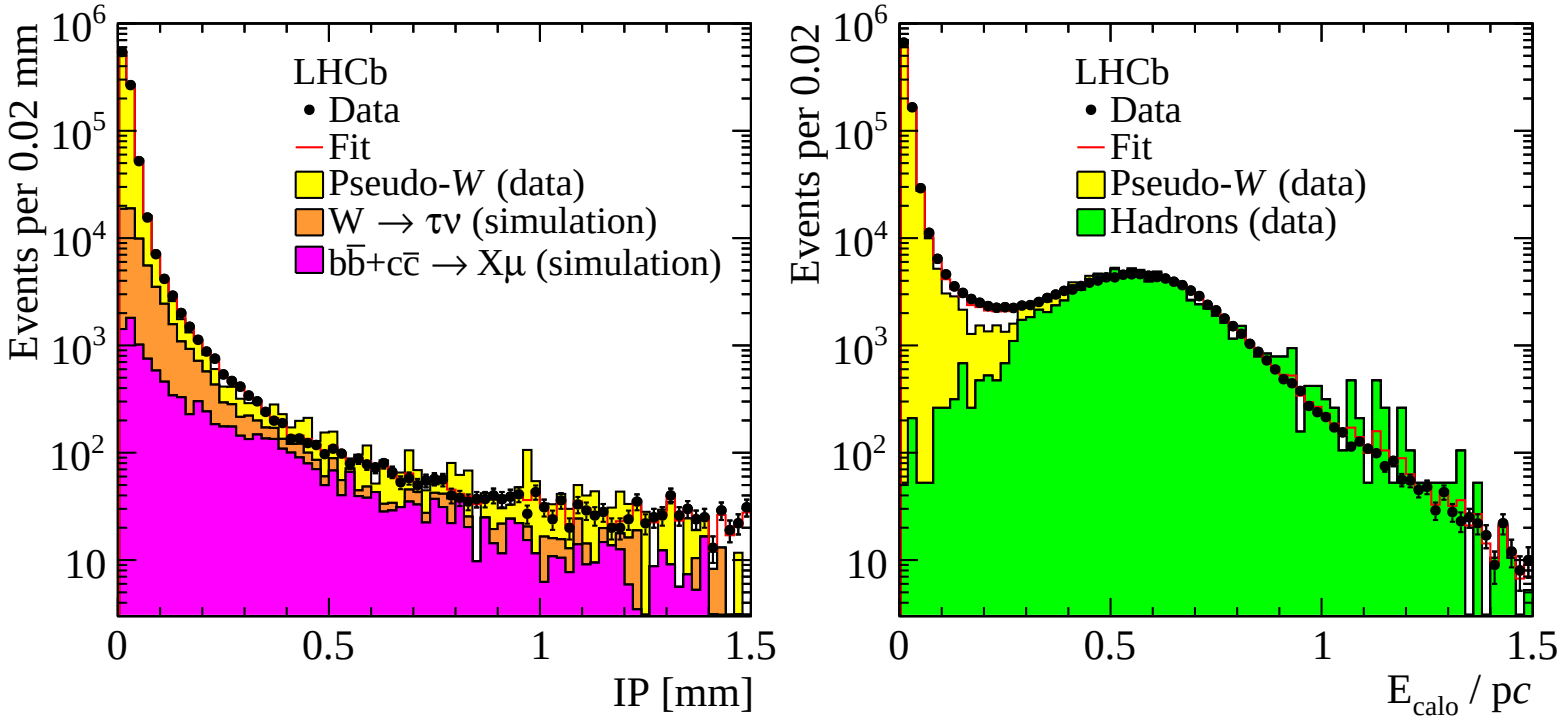
Tracking
δ_p/p < 1 %

RICH

SPD (<600 hits)

Reducing W backgrounds

JHEP 12 (2014) 079



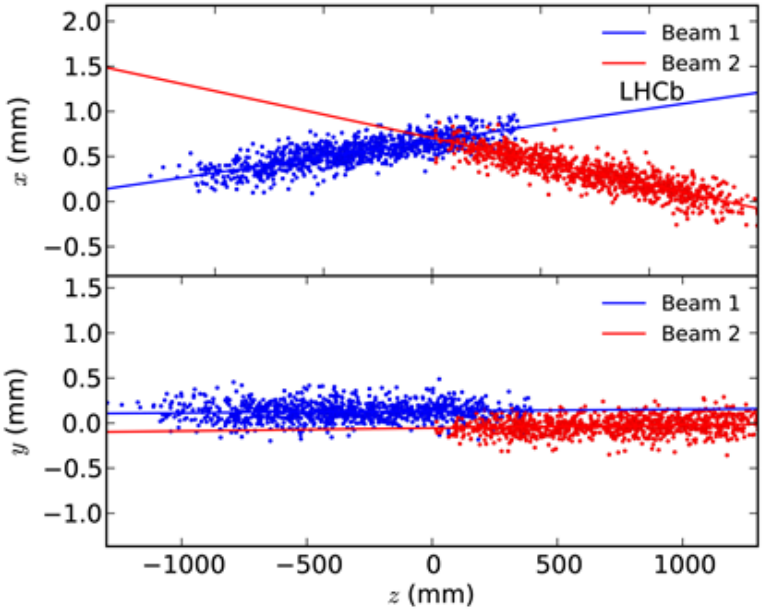
EW normalisation

$$N^{1\mu}_{Z\to\mu\mu} = N^{2\mu}_{Z\to\mu\mu} \cdot \mathcal{A}^{Z}_{m_{\mu\mu}} \cdot \mathcal{F}^{1\mu/2\mu}_{Z\to\mu\mu} \cdot \frac{\varepsilon^{W}_{RECO}}{\varepsilon^{Z}_{RECO}} \cdot \varepsilon^{W}_{SEL}$$

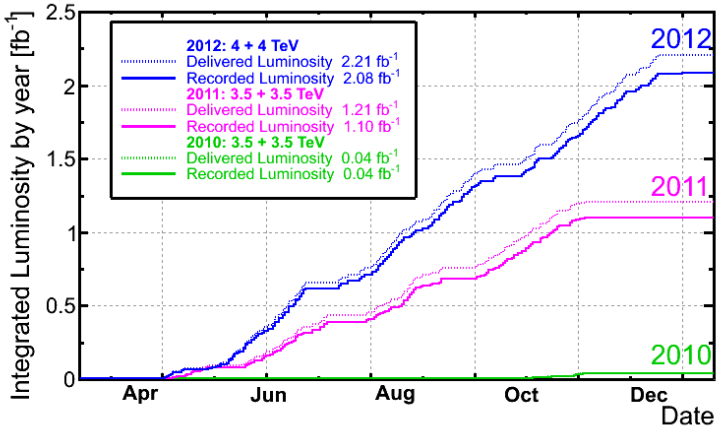
- $N^{2\mu}_{Z\to\mu\mu}$ from Pseudo-W.
- $\mathcal{A}^{Z}_{m_{\mu\mu}}$ mass window acceptance correction.
- $\mathcal{F}^{1\mu/2\mu}_{Z\to\mu\mu}$ fraction of events with one muon inside to two muons (~ 2).
- $\frac{\varepsilon^{W}_{RECO}}{\varepsilon^{Z}_{RECO}} = \frac{1}{(2-\varepsilon_{TRG})\cdot\varepsilon_{TRK}\cdot\varepsilon_{ID}}$

Precision luminosity

2014 JINST 9 P12005



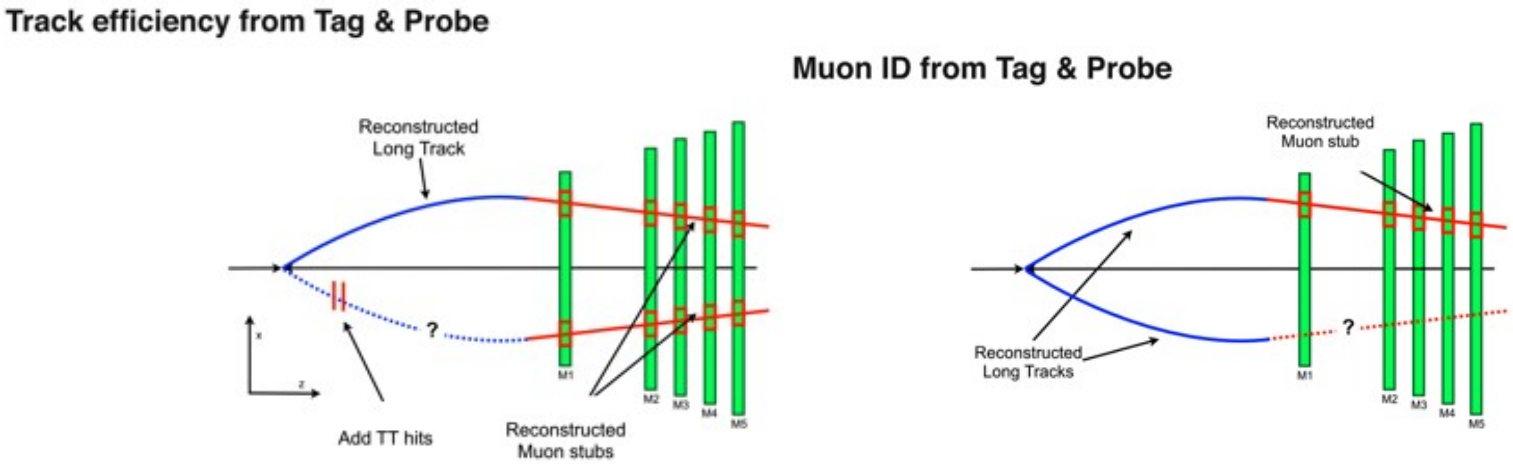
- Luminosity levelling (< 2 pp interactions per bunch crossing).
- Luminosity measured at LHCb using Van der Meer scans (VDM) and Beam-Gas Imaging (BGI).
- Inject Ne gas to increase rate for BGI.
- $\frac{\sigma_{\mathcal{L}}}{\mathcal{L}}$: 1.7%(1.1%) in 2011(2012).



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

Efficiencies

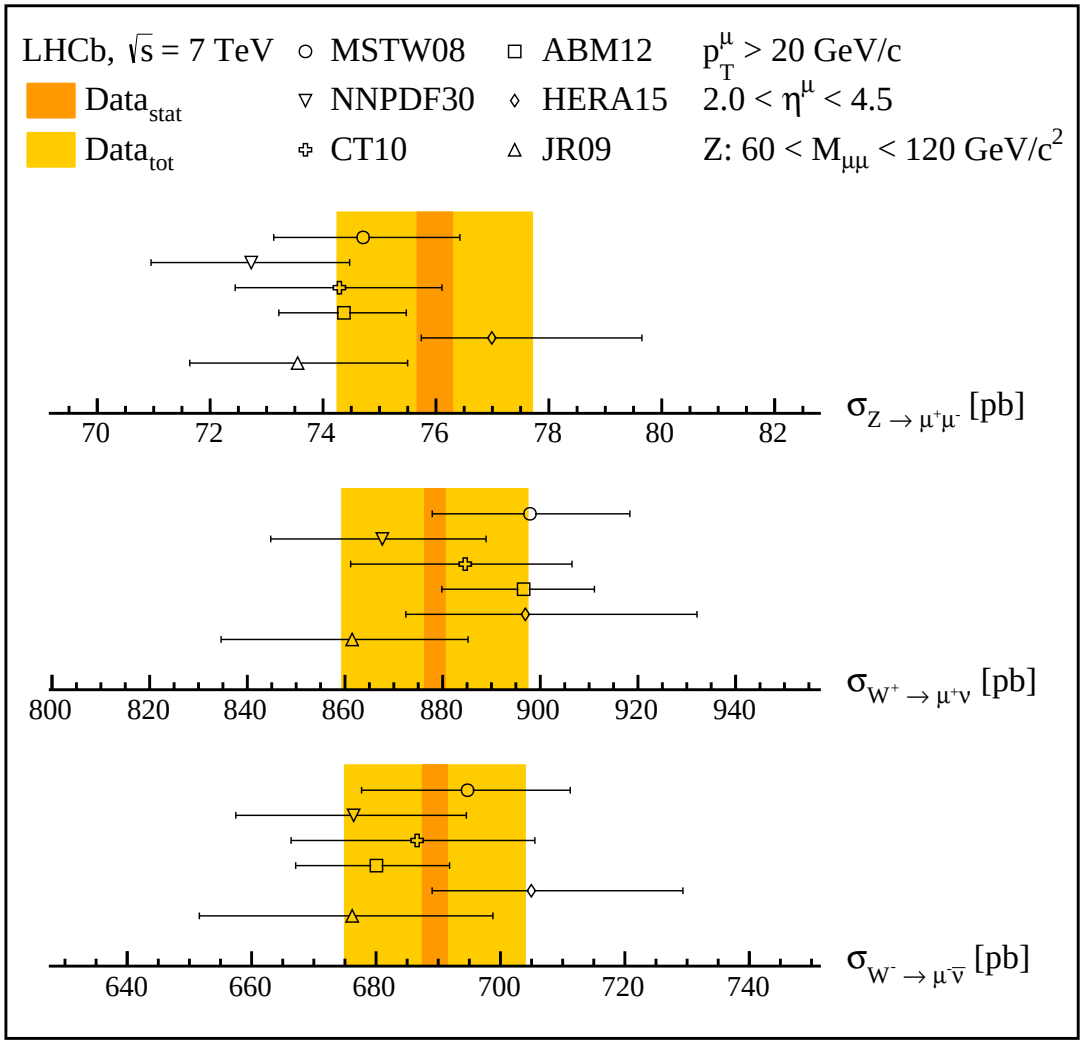
- Muon reconstruction efficiencies: tag-and-probe with the Z resonance.
- Efficiencies studied as function of muon kinematics (η, p_T)and detector occupancy.



- Must also correct for threshold at 600 SPD sub-detector hits in muon trigger.

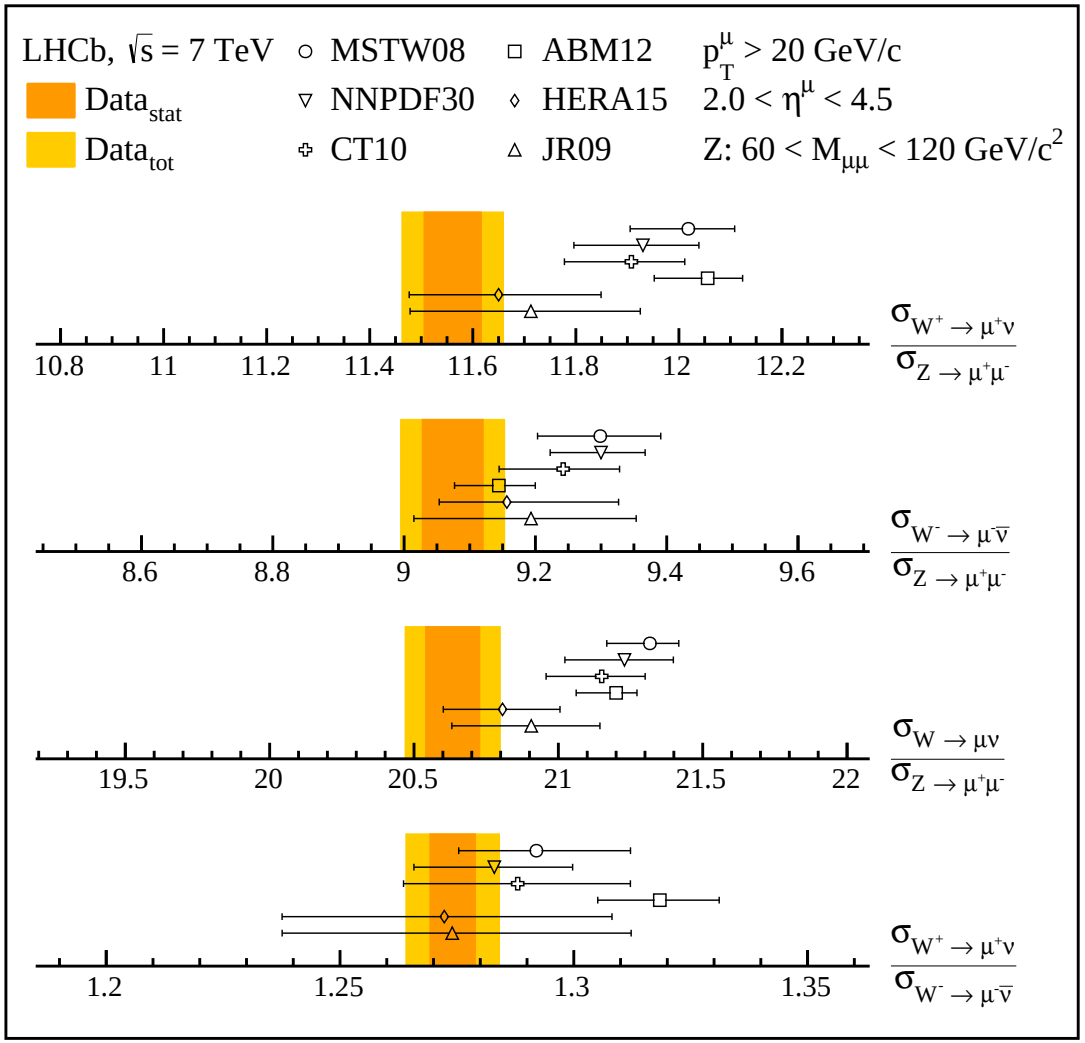
Cross-sections at 7 TeV

JHEP08(2015)039



Cross-section ratios at 7 TeV

JHEP08(2015)039



Z cross-section systematics at 7 TeV

Source	**Uncertainty (%)**
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 at 7 TeV

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

Beyond Standard Model

JHEP08(2012)010

$$
\begin{aligned}
R^{X}_{E_1/E_2} &= \frac{\sigma_X(E_1)}{\sigma_X(E_2)} \\
&= \frac{\sigma_X^{SM}(E_1) + \sigma_X^{BSM}(E_1)}{\sigma_X^{SM}(E_2) + \sigma_X^{BSM}(E_2)} \\
&= \frac{\sigma_X^{SM}(E_1)}{\sigma_X^{SM}(E_2)} \left[\frac{\sigma_X^{SM}(E_2) + \frac{\sigma_X^{BSM}(E_1)\sigma_X^{SM}(E_2)}{\sigma_X^{SM}(E_1)}}{\sigma_X^{SM}(E_2) + \sigma_X^{BSM}(E_2)} \right] \\
&= \frac{\sigma_X^{SM}(E_1)}{\sigma_X^{SM}(E_2)} \left[\frac{1 + \frac{\sigma_X^{BSM}(E_1)}{\sigma_X^{SM}(E_1)}}{1 + \frac{\sigma_X^{BSM}(E_2)}{\sigma_X^{SM}(E_2)}} \right] \\
&\approx \frac{\sigma_X^{SM}(E_1)}{\sigma_X^{SM}(E_2)} \left[1 + \frac{\sigma_X^{BSM}(E_1)}{\sigma_X^{SM}(E_1)} - \frac{\sigma_X^{BSM}(E_2)}{\sigma_X^{SM}(E_2)} \right]
\end{aligned}
$$

$$
\left(1 + \frac{\sigma_X^{BSM}(E_2)}{\sigma_X^{SM}(E_2)} \right)^{-1} \sim 1 - \frac{\sigma_X^{BSM}(E_2)}{\sigma_X^{SM}(E_2)}.
$$