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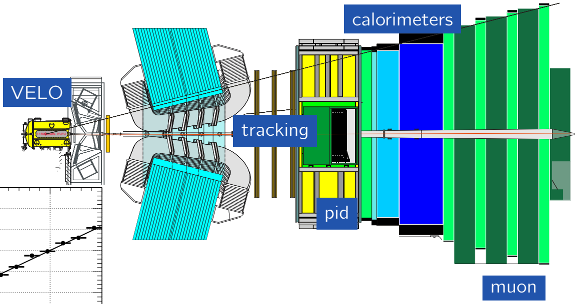
Electroweak Physics in the Forward Region at the LHC

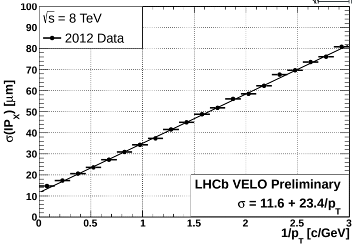
XXX Rencontres de Physique de La Vallée d'Aoste - La Thuile

LHCb

[*JINST* 3 (2008) S08005]

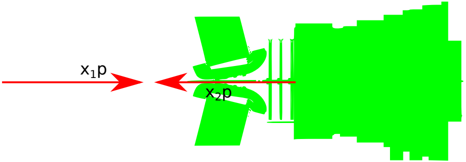
- optimised to study $\mathcal{CP}$ Violation in B and D decays at the LHC
- fully instrumented between $2.0 \leq \eta \leq 5.0$
- excellent tracking, PID and vertexing capabilities (muon id efficiency ~98%)

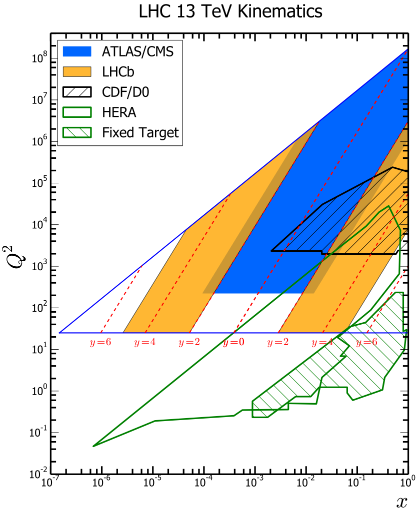




- 2011 - 1.0 fb^{-1} - 7 TeV
- 2012 - 2.0 fb^{-1} - 8 TeV
- 2015 - 300 pb^{-1} - 13 TeV

introduction

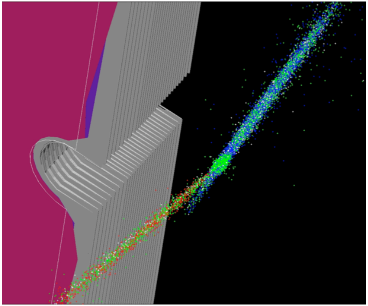




- LHCb's forward acceptance provides interesting possibilities to study Parton Density Functions
- two distinct large and small-x regions covered
- small x-region unexplored by previous experiments
- measurements of W, Z and Drell-Yan production at LHCb can constrain the PDFs in this region
  - W and Z (x of $\sim 10^{-4}$ and 10^{-1})
  - low-mass Drell-Yan (x down to 10^{-6}) can be explored with low mass triggers

precision luminosity at LHCb

[*JINST* 9 (2014) P12005]



Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.
Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

- luminosity measured at LHCb using two methods: Van der Meer Scan (VDM) and Beam-Gas Imaging (BGI)
- beams scanned across each order in VDM scan to trace beam profile
- in BGI method neon injected in beam-pipe to reconstruct beams using collision vertices

- BGI and VDM methods combined to achieve precision of 1.7% in 2011 and 1.2% in 2012
- “the most precise luminosity measurement achieved so far at a bunched-beam hadron collider”

Measurements

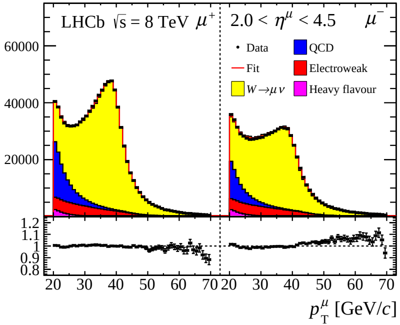
1. Inclusive W production at $\sqrt{s} = 7$ and 8 TeV
2. Inclusive Z production at $\sqrt{s} = 7$ and 8 TeV
3. Measurement of forward backward asymmetry in Z decays
4. W production in association with heavy flavour jets at 7 and 8 TeV
5. Z production at $\sqrt{s} = 13$ TeV NEW!

$W \to \mu\nu$

[*JHEP* 08 (2015) p. 039] , [*JHEP* 01 (2016) p. 155]

- single high-p_{T} muon final state
  - prompt, isolated
- $p_{\mathrm{T}}^{\mu} > 20$ GeV, $2.0 < \eta^{\mu} < 4.5$
- purity determined by fit to muon p_{T} spectrum in bins of pseudorapidity

Shape	Source
$W \to \mu\nu$	Simulation
QCD	Data
$\gamma/Z^{*} \to \mu\mu$	Simulation
$W \to \tau\nu$, $Z \to \tau\tau$	Simulation
Heavy Flavour	Data

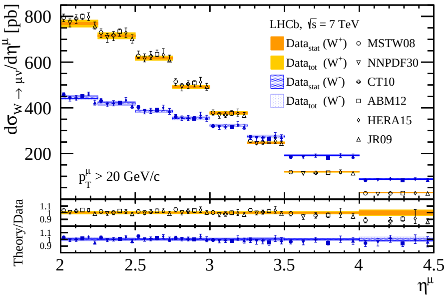


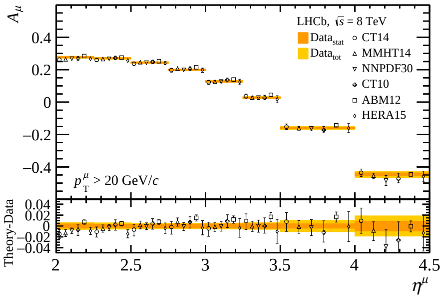
Purity ∼ 77%

- Signal and Decay In Flight templates float free in fit
- other shapes normalised using data-driven methods

$W \rightarrow \mu\nu$ - Results

[*JHEP* 08 (2015) p. 039] , [*JHEP* 01 (2016) p. 155]



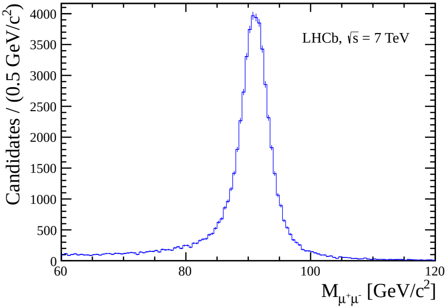


- experimental precision of 2-4% - dominated by luminosity and beam energy uncertainty
- compared to NNLO predictions calculated using FEWZ
- good agreement with predictions for variety of PDF sets

$Z \to \mu\mu$

[*JHEP* 08 (2015) p. 039] , [*JHEP* 01 (2016) p. 155]

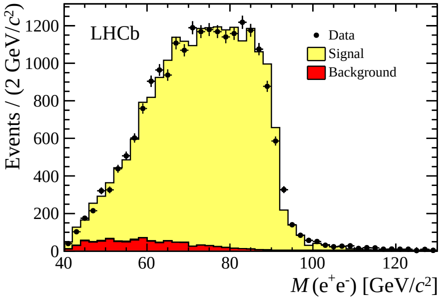
- two identified muons
- $p_{\mathrm{T}}^{\mu} > 20$ GeV
- $2 < \eta^{\mu} < 4.5$
- $60 < M_{\mu\mu} < 120$ GeV
- principle backgrounds from Heavy Flavour, Mis-id, other electroweak ($Z \to \tau\tau$, WW,$t\bar{t}$)
- purity $> 99\%$



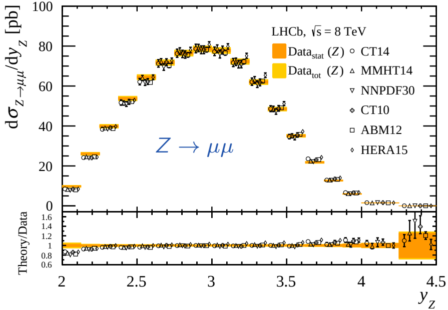
$Z \rightarrow ee$

[*JHEP* 02 (2013) p. 106] , [*JHEP* 05 (2015) p. 109]

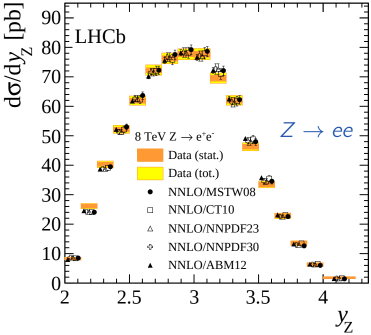
- Two identified electrons
- $p_{\mathrm{T}}^{e} > 20$ GeV
- $2 < \eta^{e} < 4.5$
- $M_{ee} > 40$ GeV
- Mass peak smeared by Bremsstrahlung (calorimeter saturation)
- Dominant background from electron mis-id
- Purity $\sim$ 95%
- Transferred to same fiducial region as $Z \rightarrow \mu\mu$ using acceptance factor from simulation

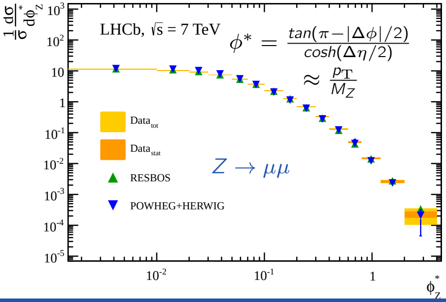


$Z \to \ell\ell$ results



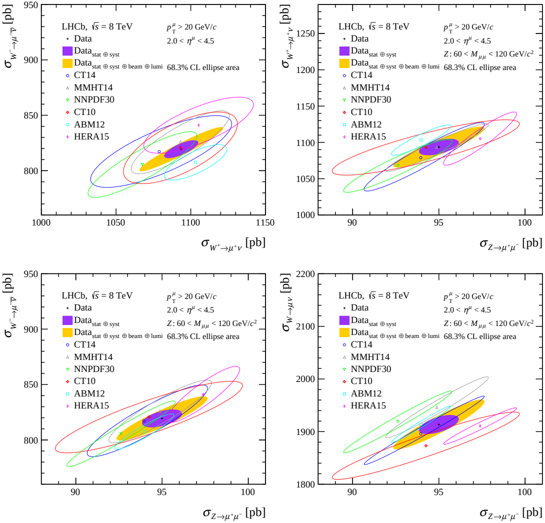
- experimental precision of 2-4% - dominated by luminosity and beam energy uncertainty
- good agreement with NNLO predictions
- RESBOS and POWHEG + HERWIG describe ϕ^* distribution well
  - ϕ^* acts a proxy for p_{T} but depends on well measured track angles





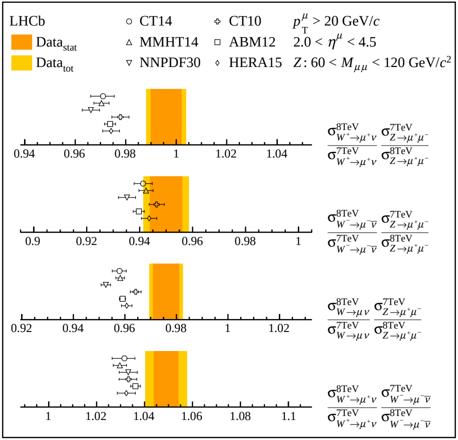
W/Z ratios

[*JHEP* 08 (2015) p. 039]



- ratios of W and Z production in muon final states
- many experimental uncertainties cancel
- can cancel/highlight theoretical uncertainties
- precise constraints on PDFs / tests of the SM

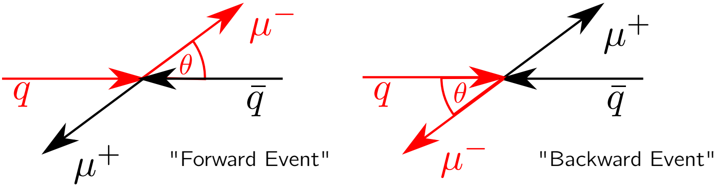
W/Z double ratios



- ratios at different centre-of-mass energies
  - study of the evolution of the cross-sections with $\sqrt{s}$
  - further cancellation of uncertainties
  - double ratios most precise test of the SM
  - some deviations from predictions
- can also study ratios differentially [1509.03993 [hep-ph]]

forward-backward asymmetry

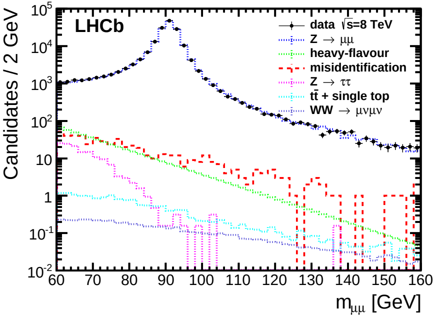
- forward backward asymmetry, A_{FB}, present in $q\bar{q} \to Z/\gamma^* \to \ell\ell$ decays due to presence of vector and axial vector couplings

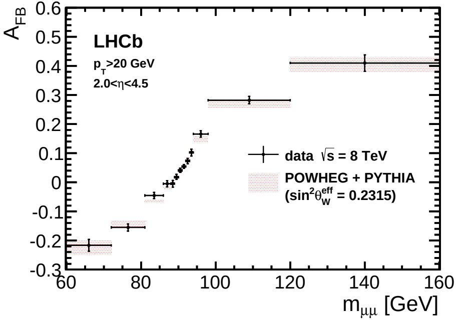


- A_{FB} sensitive to effective weak mixing angle, $\sin^2 \theta_W^{eff}$
- LHC is a symmetric pp collider - positive axis defined to be along boost direction of Z
- dilution due to lack of knowledge of quark direction
- higher valence quark content in forward region gives larger A_{FB} and greater sensitivity to $\sin^2 \theta_W^{eff}$.

A_{FB} at LHCb

[*JHEP* 11 (2015) p. 190]



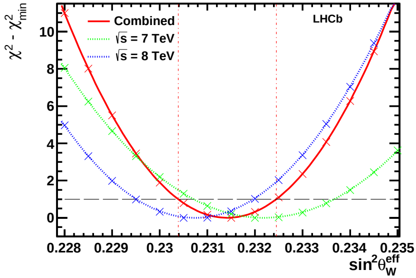


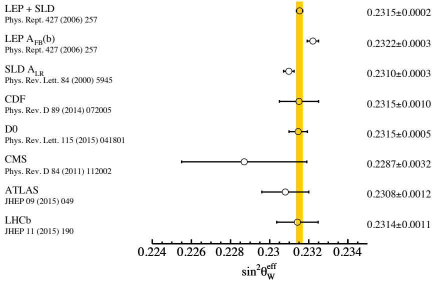
- selection similar to inclusive $Z \rightarrow \mu\mu$ analysis
  - mass range extended up to 160 GeV
- A_{FB} measured as a function of dimuon invariant mass
  - unfolded for detector effects
- dominant uncertainty due to muon momentum scale calibration

extraction of $sin^2\theta_W^{eff}$.

[*JHEP* 09 (2015) p. 049]

- extraction of $\sin^2\theta_W^{eff}$ performed using template fit to shapes obtained with different values
  - generated using POWHEG + PYTHIA



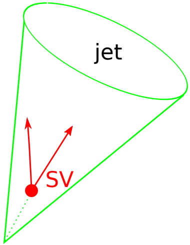


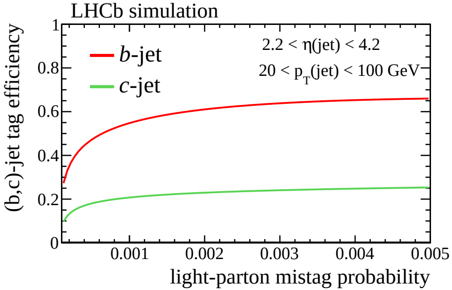
- most precise measurement at the LHC
- largest systematic uncertainty due to PDFs
- statistically limited
- for more details, see talk by L. Sestini in YSF

heavy flavour tagging at LHCb

[*JINST* 10 (2015) P06013]

- heavy flavour tagging at LHCb performed using secondary vertex tagging
- reconstruct 2-body vertices in event
- merge into *n*-body vertices (SV) by linking vertices with shared tracks
- reconstruct jets and tag those containing SVs
- two separate BDTs trained to separate light from heavy-flavour jets, and *b* from *c* jets
  - based on SV and jet kinematics



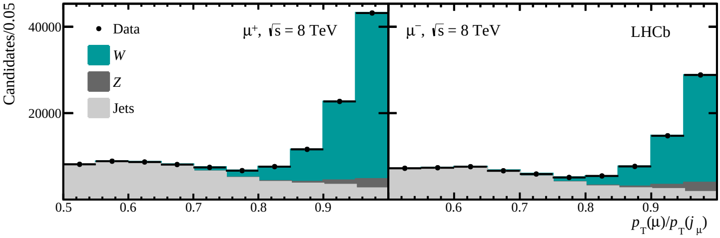


- light-jet mistag rate $< 1\%$ for inclusive b-tag and c-tag efficiencies of 65% and 25% respectively
- validated using b- and c-jet enriched data samples

$W + (b, c, l)$-jet measurements [LHCb]

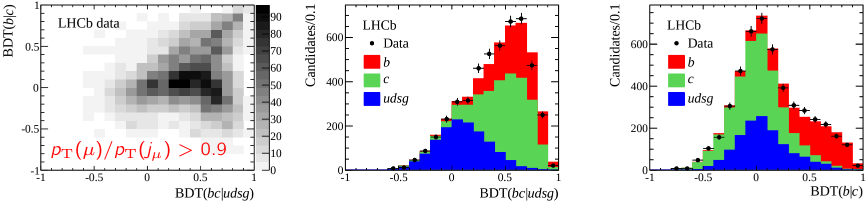
[*Phys. Rev.* D92 (2015) p. 052001]

- measurements of W production in association with light and heavy flavour jets performed at LHCb
- W reconstructed through presence of single high-p_T muon as in inclusive analysis
- jet inputs taken from ParticleFlow and clustered using anti-k_T algorithm (R=0.5)
  - jet $p_{\rm T} > 20$ GeV, $2.2 < \eta^j < 4.2$
- require $p_{\rm T}(j_\mu + j) > 20$ GeV
  - j_μ - reconstructed jet containing muon
  - proxy for missing energy in the system
- purity determined using fit to muon isolation spectrum, $p_{\rm T}(\mu)/p_{\rm T}(j_\mu)$



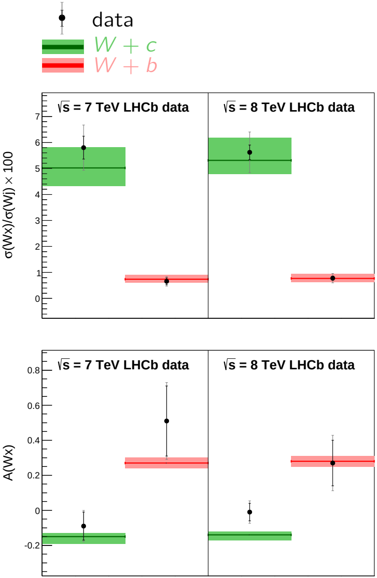
$W + (b, c, l)$-jet measurements

[*Phys. Rev.* D92 (2015) p. 052001]



- jets SV tagged and $b-$ and $c-$jet content extracted from fits to 2D BDT distributions in each bin of $p_{\mathrm{T}}(\mu)/p_{\mathrm{T}}(j_\mu)$
- measurements performed of
  - ratios ($W^{\pm}j/Zj$, $W(b,c)/Wj$)
  - asymmetries (Wb, Wc)
- builds on previous measurements of Zj [*JHEP* 01 (2014) p. 033] and Zb [*JHEP* 01 (2015) p. 064]

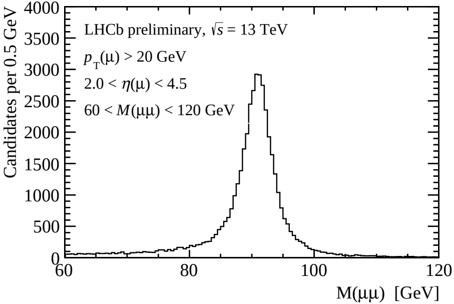
results

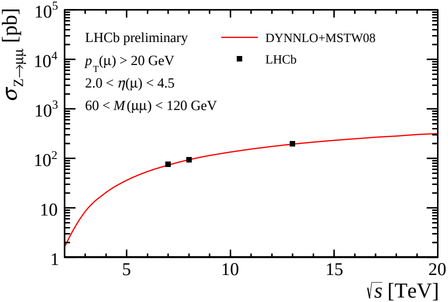


- good level of data/theory agreement observed
- experimental measurements dominated by statistical uncertainties
- b- and c-tagging uncertainties determined from data ($\approx 10\%$)
- measured $W + c$ asymmetries $\approx 2\sigma$ smaller than SM expectations

Z boson production at 13 TeV NEW

[LHCb-CONF-2016-002]

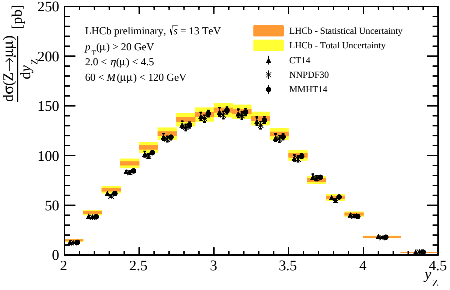


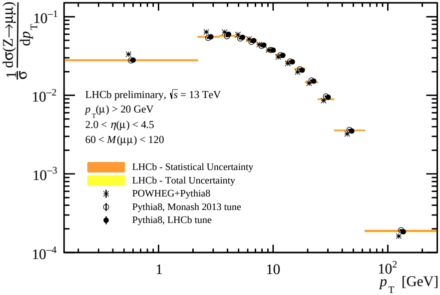


- preliminary measurement performed of $Z \to \mu\mu$ production at 13 TeV
  - approximately 300 pb^{-1} of data
- same techniques and fiducial region as in Run-I analysis
- probes lower x values than Run-I measurements
- measurement limited by knowledge of luminosity (3.9%)

Z boson production at 13 TeV NEW

[LHCb-CONF-2016-002]





- differential measurements of (left) rapidity and (right) Z p_{T}
- compared to NNLO predictions for different PDF sets for rapidity and Pythia8 and POWHEG+Pythia8 for p_{T} spectrum

conclusions and outlook

- large program of electroweak physics performed in Run-I at LHCb
- precise W and Z boson measurements
- advances in heavy flavour tagging
- still more results to come!
- first Run-II measurement of Z production at LHCb presented
- analysis of 13 TeV data is underway!
- looking forward to new results!

references

Generators

- FEWZ [*Comput. Phys. Commun.* 182 (2011) pp. 2388–2403]
- DYNNLO [*Phys. Rev. Lett.* 98 (2007) p. 222002]
- POWHEG [*JHEP* 07 (2008) p. 060]
- PYTHIA [*JHEP* 05 (2006) p. 026] , [*Comput. Phys. Commun.* 178 (2008) pp. 852–867]
- HERWIG [*Eur. Phys. J.* C58 (2008) pp. 639–707]

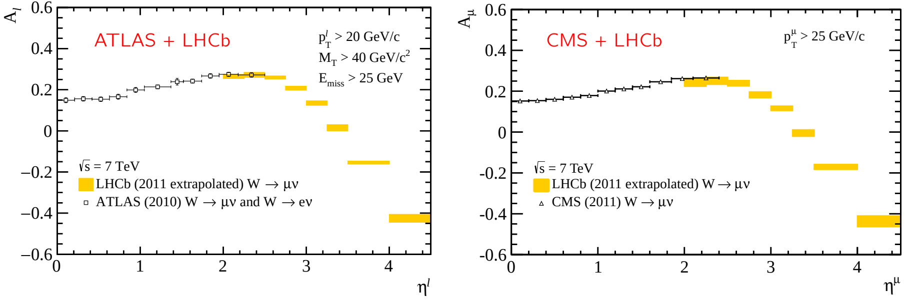
PDF sets

- CT10, CT14 [*Phys. Rev.* D89 (2014) p. 033009] , [*Phys. Rev.* D93 (2016) p. 033006]
- NNPDF2.3, 3.0 [*Nucl. Phys.* B867 (2013) pp. 244–289] , [*JHEP* 04 (2015) p. 040]
- MSTW08, MMHT14 [*Eur. Phys. J.* C63 (2009) pp. 189–285] , [*Eur. Phys. J.* C75 (2015) p. 204]
- ABM12 [*Phys. Rev.* D89 (2014) p. 054028]
- JR09 [*Phys. Rev. D* 79 (2009) p. 074023]

BACKUP

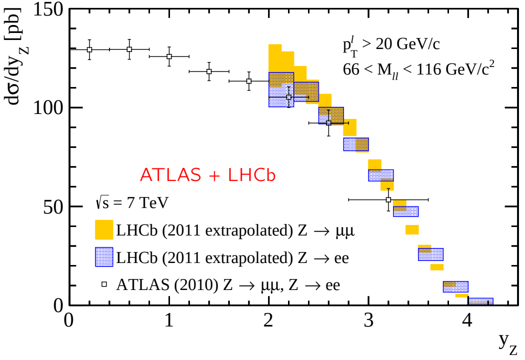
BACKUP

$W \to \mu\nu$ - comparison with central region [*JHEP* 08 (2015) p. 039]



- LHCb result extrapolated to ATLAS and CMS fiducial regions using simulation
  - ATLAS $\mathrm{M_T} > 40$ GeV, $E_{\mathrm{miss}} > 25$ GeV
  - CMS - $p_{\mathrm{T}} > 25$ GeV
- good agreement in overlap region

$Z \to \ell\ell$ - comparison with central region [*JHEP* 08 (2015) p. 039]



- LHCb result extrapolated to ATLAS regions using simulation
  - 66$< M_{\ell\ell} <$ 116 GeV
- good agreement in overlap region

kinematic range

- Measurements performed as a function of di-lepton mass in different kinematic ranges

Exp.	Channel	$M_{\ell\ell}$	p_{T}^{ℓ}	η^{ℓ}
LHCb	dimuon	$60 - 160$ GeV	> 20 GeV	$2 < \eta < 4.5$
CMS	dimuon	$40 - 2000$ GeV	> 20 GeV	$\lvert\eta\rvert < 2.4$
CMS	dielectron	$40 - 2000$ GeV	> 20 GeV	$\lvert\eta\rvert < 2.4$
CMS	central-fwd electron	$40 - 300$ GeV	$> 30, 20$ GeV	$\lvert\eta\rvert < 2.4$, $3.0 < \eta < 5$
ATLAS	dimuon	$40 - 2000$ GeV	> 25 GeV	$\lvert\eta\rvert < 2.4$
ATLAS	dielectron	$40 - 1000$ GeV	> 25 GeV	$\lvert\eta\rvert < 2.47$
ATLAS	central-fwd electron	$40 - 250$ GeV	> 25 GeV	$\lvert\eta\rvert < 2.47$, $2.5 < \eta < 4.9$

A_{FB} Systematics

Table 1: Weighted average of the absolute systematic uncertainties for A_{FB}, for different sources, given separately for $\sqrt{s} = 7$ and 8 TeV.

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

Table 4: Weighted average of the absolute systematic uncertainties for $A_{\mathrm{FB}}^{\mathrm{pred}}$, for the different sources of theoretical uncertainty. The value quoted for the PDF uncertainty corresponds to the 68% confidence range, while for the others the maximum and minimum shifts are given. The correlations among the invariant mass bins are not taken into account.

Uncertainty	average $\Delta\lvert A_{\mathrm{FB}}^{\mathrm{pred}}\rvert$
PDF	0.0062
scale	0.0040
α_s	0.0030
FSR	0.0016

$$\sin^2\theta_W^{eff} = 0.23142 \pm 0.00073 \pm 0.00052 \pm 0.00056$$