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on behalf of the ATLAS, CMS and LHCb Collaborations

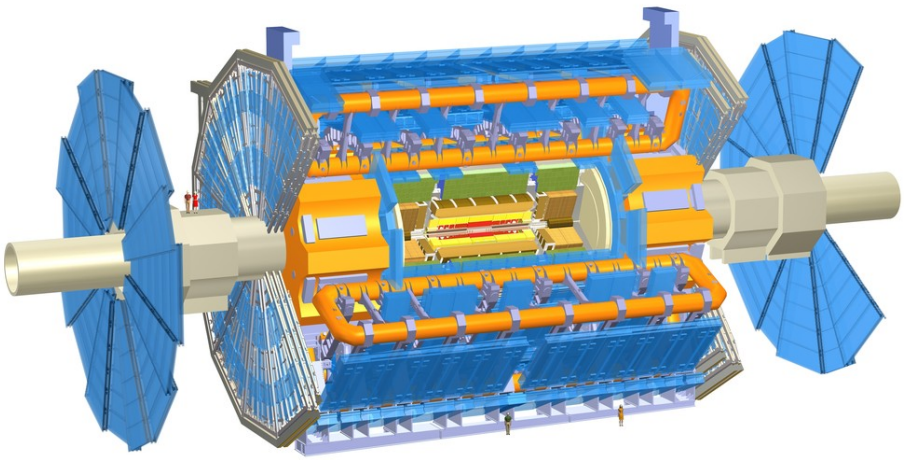
University of Liverpool

Forward EW Physics at the LHC

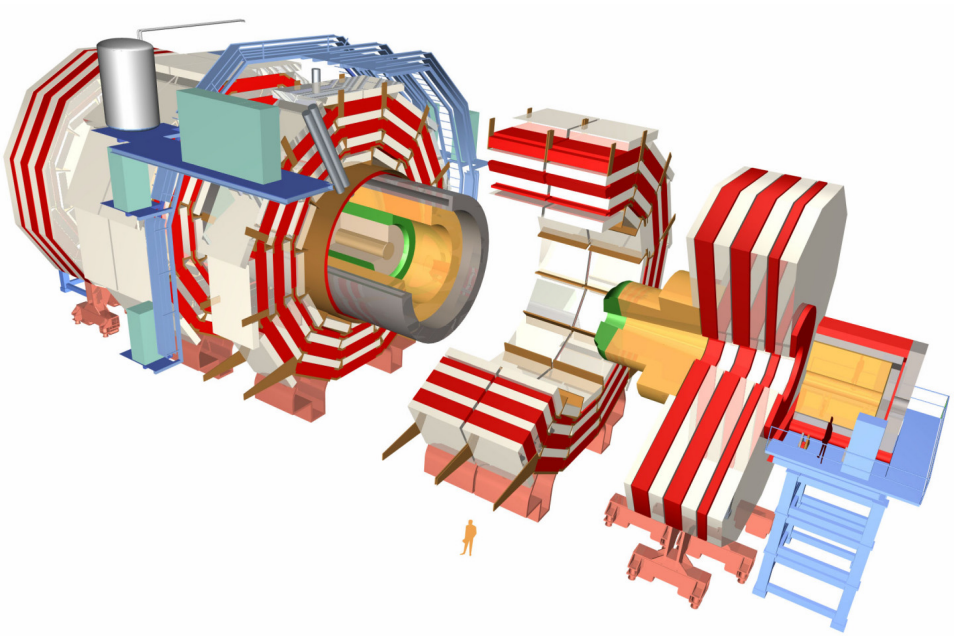
September 2nd
LHCP 2015 - St. Petersburg

detectors at the LHC

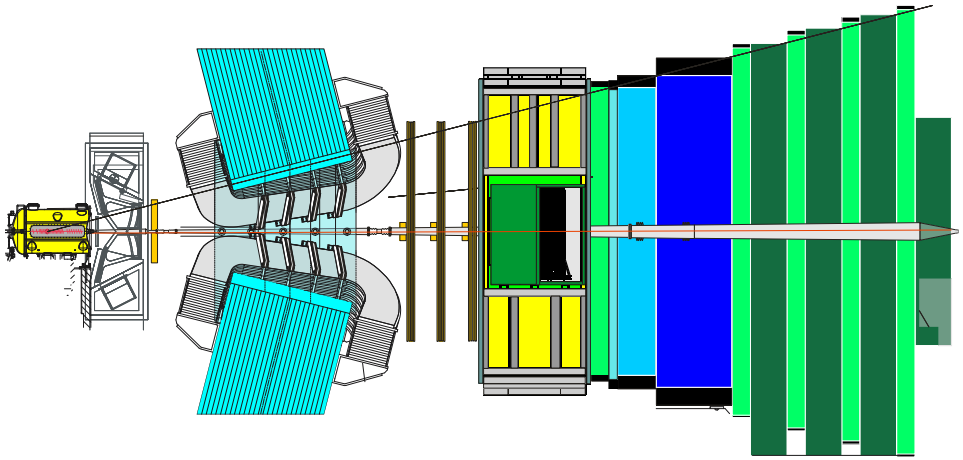
ATLAS - general purpose detector [*JINST*(2008)3:S08003]



CMS - general purpose detector [*JINST*(2008)3:S08004]

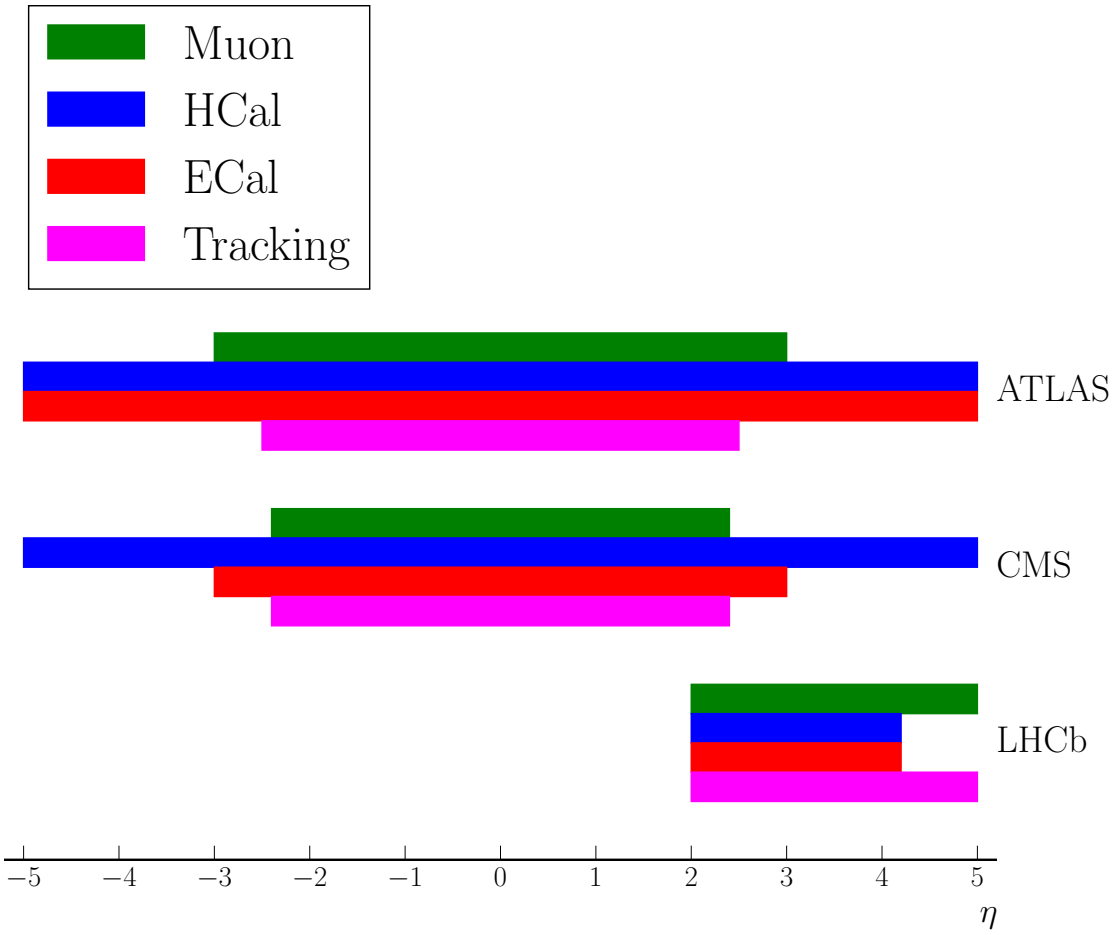


LHCb - optimised for B-Physics [*JINST*(2008)3:S08005]



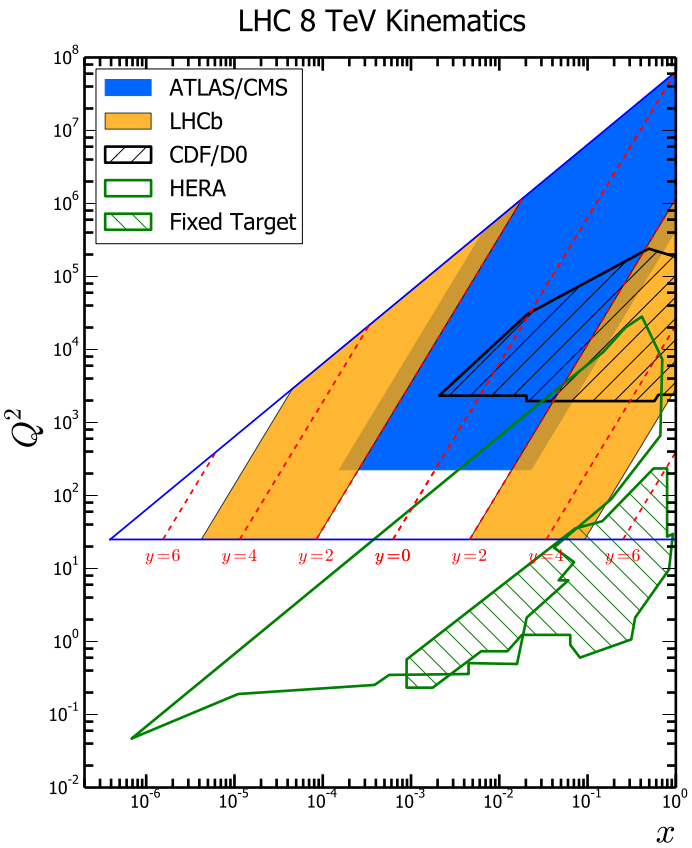
Lumi.	$\sqrt{s}$	ATLAS	CMS	LHCb
2010	7 TeV	45 pb^{-1}	41 pb^{-1}	36 pb^{-1}
2011	7 TeV	5.6 fb^{-1}	5.6 fb^{-1}	1.1 fb^{-1}
2012	8 TeV	22 fb^{-1}	22 fb^{-1}	2.1 fb^{-1}
2015	13 TeV			

rapidity coverage



- LHCb fully instrumented in the forward region
- ATLAS and CMS have calorimetry in forward region (forward electrons/jets)

why look forward?



- forward coverage gives access to unique kinematic region
  - constrains high- and low-x PDFs
- can identify large rapidity gaps in di-jet production
  - sensitivity to electroweak production of W and Z bosons
- larger valence quark component at high-x
  - better defined quark direction
  - greater sensitivity to $q\bar{q}$ asymmetries

overview

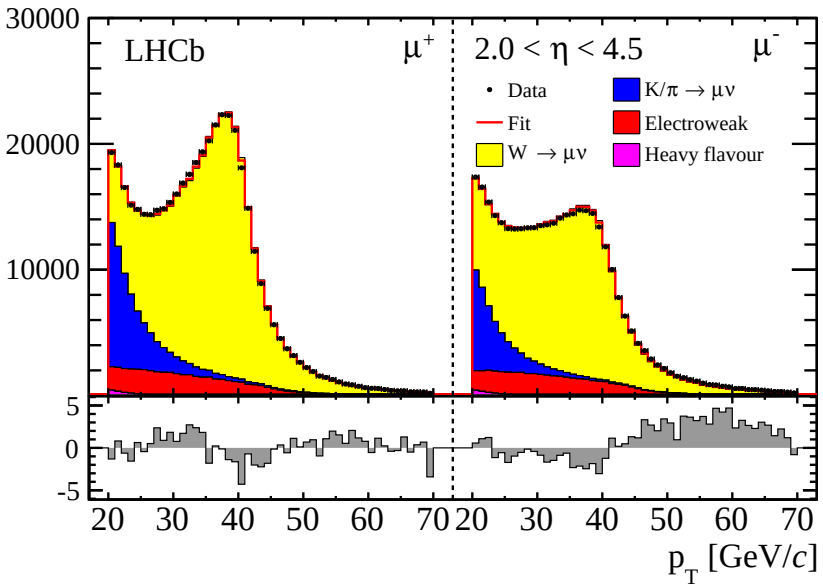
talk will cover three main areas:

- single boson production in the forward region (LHCb)
- single boson production in association with forward jets (ATLAS, CMS, LHCb)
- forward-backward asymmetry in $Z \to \ell\ell$ events (ATLAS, CMS, LHCb)

$W \to \mu\nu$ [LHCb]

- 1.0 fb^{-1} of 2011 data at 7 TeV [*JHEP*(2015)08:p. 039]
- 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

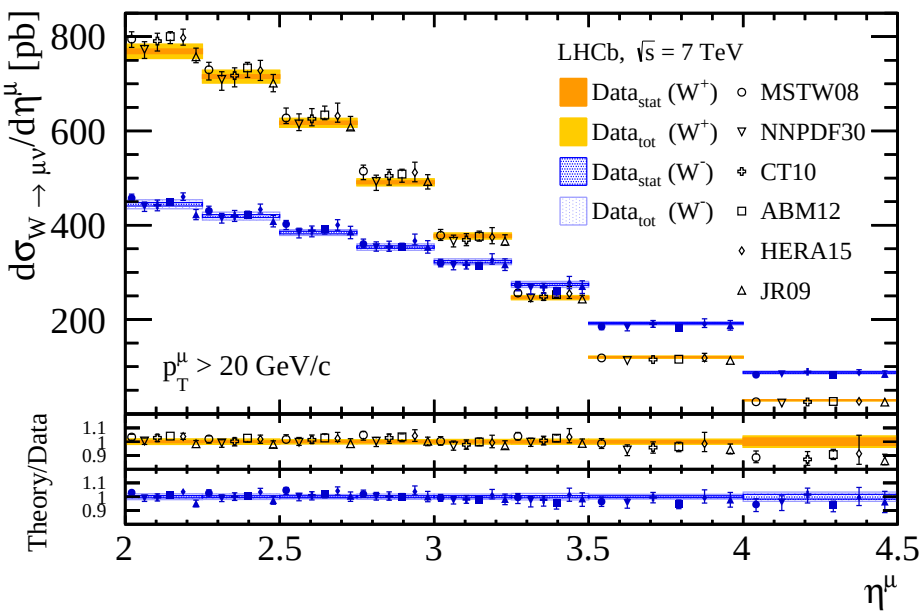
Shape	Source
$W \to \mu\nu$	Simulation
K/π Decay In Flight	Data
$\gamma/Z^* \to \mu\mu$	Simulation
$W \to \tau\nu$, $Z \to \tau\tau$	Simulation
Heavy Flavour	Data

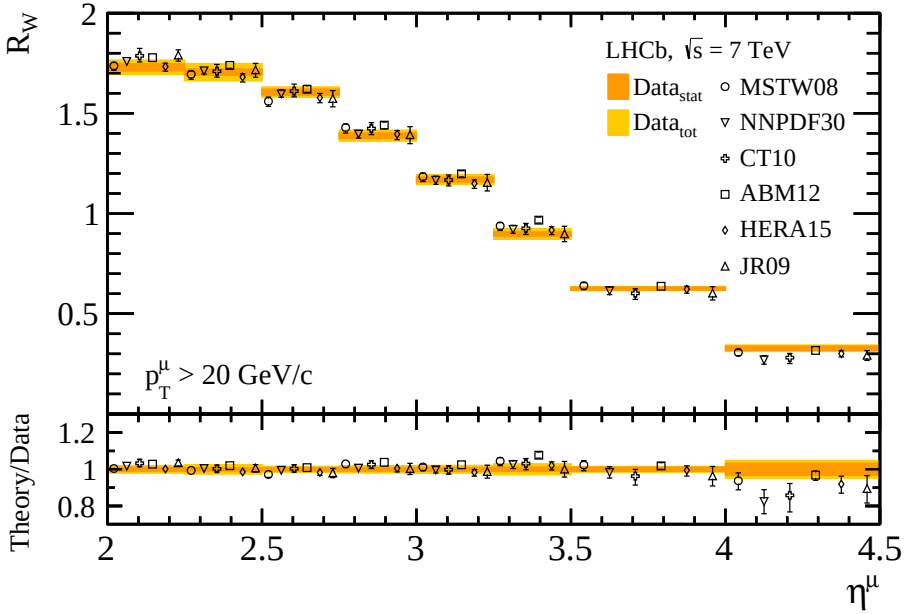


- Signal and Decay In Flight templates float free in fit
- other shapes normalised using data-driven methods

Purity $\sim$ 77%

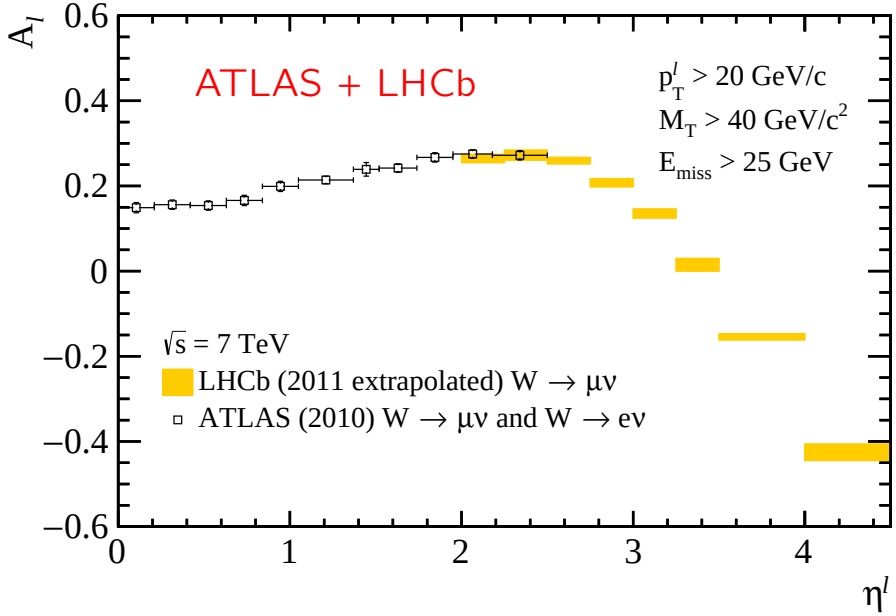
$W \to \mu\nu$ - Results [*JHEP*(2015)08:p. 039]

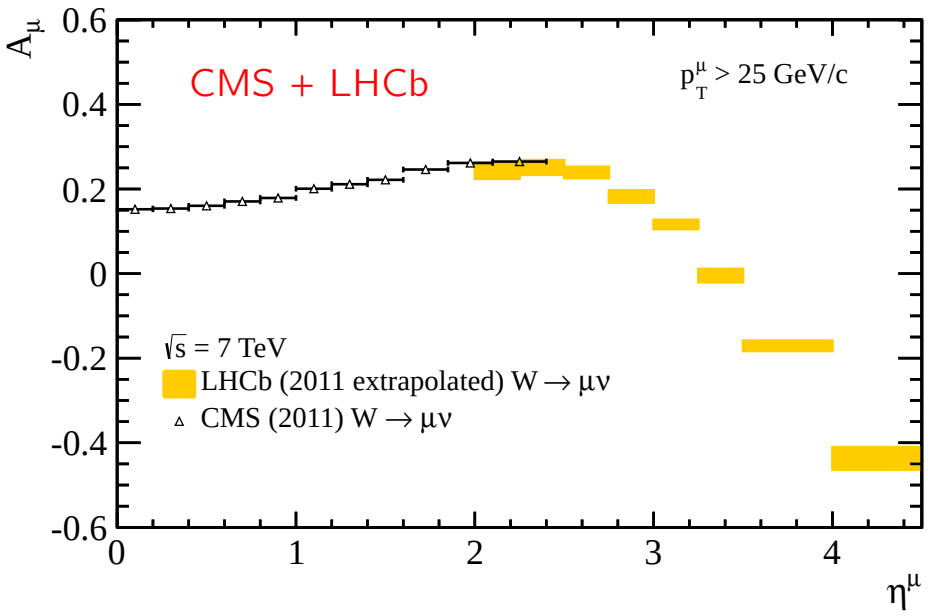




- experimental precision of 2-4% - dominated by luminosity and beam energy uncertainty
- data corrected for FSR using Pythia interfaced with PHOTOS
- compared to NNLO predictions calculated using FEWZ
- good agreement with predictions for variety of PDF sets

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





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

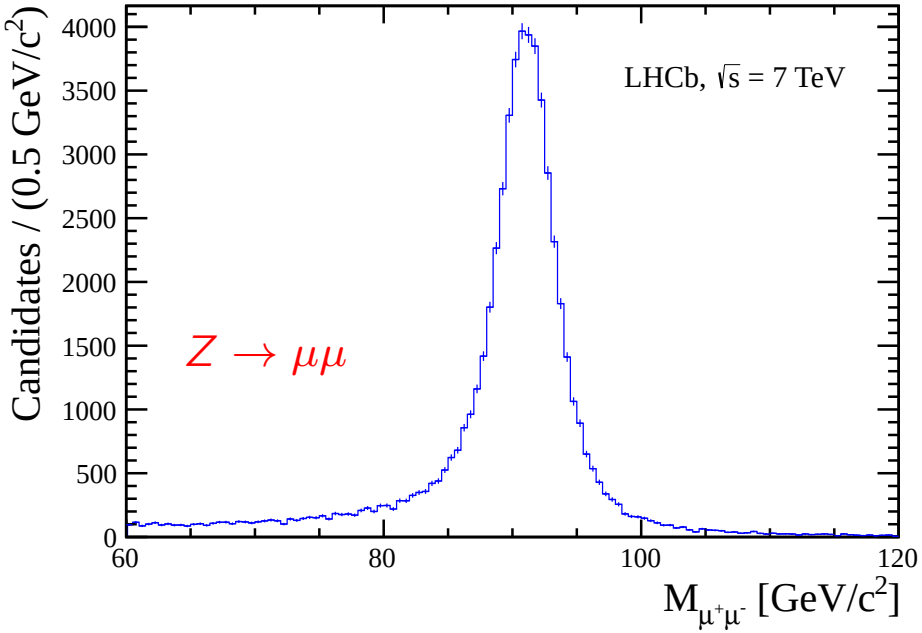
$Z \to \ell\ell$ [LHCb]

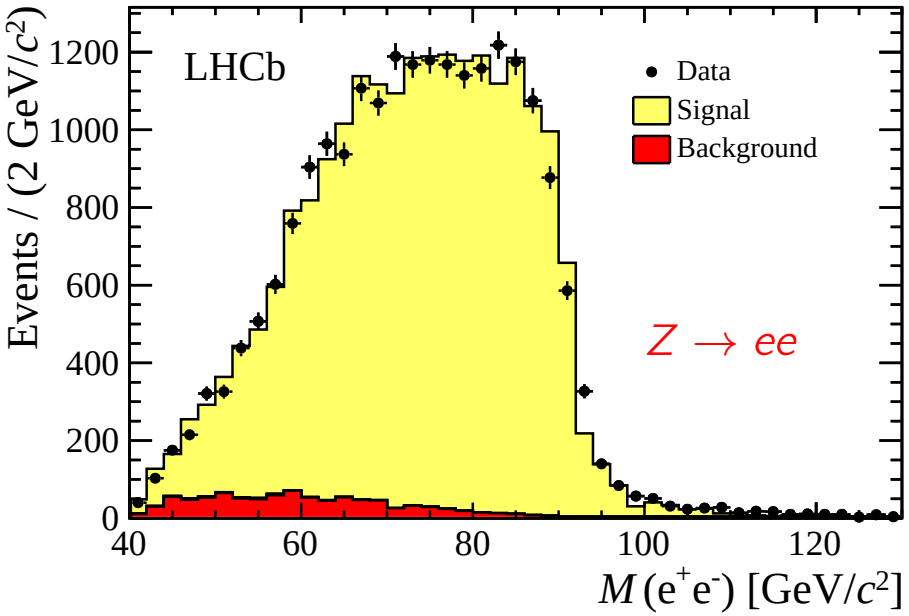
- measurements performed at 7 TeV for muon [*JHEP*(2015)08:p. 039] and electron [*JHEP*(2013)02:p. 106] channels, and 8 TeV for electron [*JHEP*(2015)05:p. 109] channel

Selection:

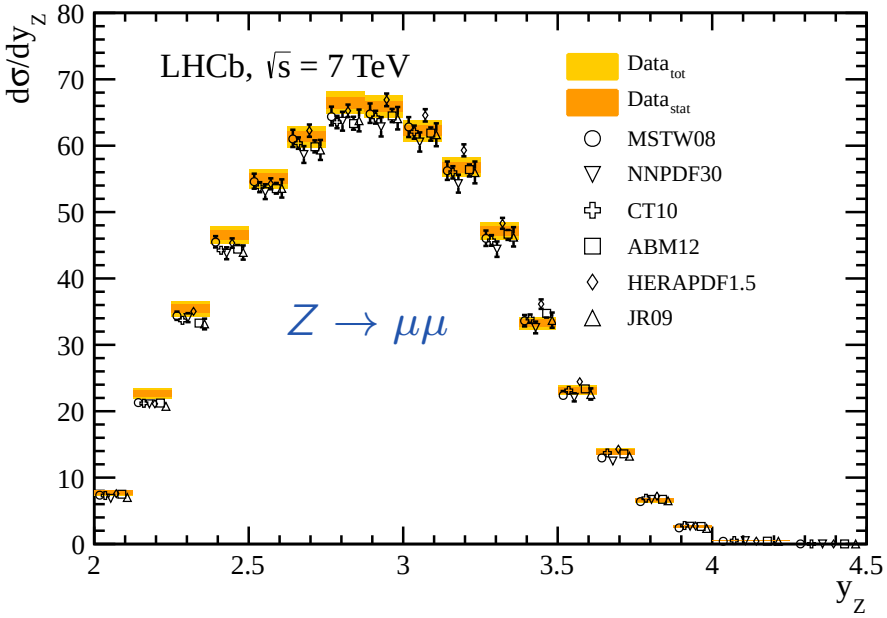
- two identified muons/electrons
- $p_{\mathrm{T}}^{\ell} > 20$ GeV
- $2 < \eta^{\ell} < 4.5$
- $60 < M_{\mu\mu} < 120$ GeV, $M_{ee} > 40$ GeV

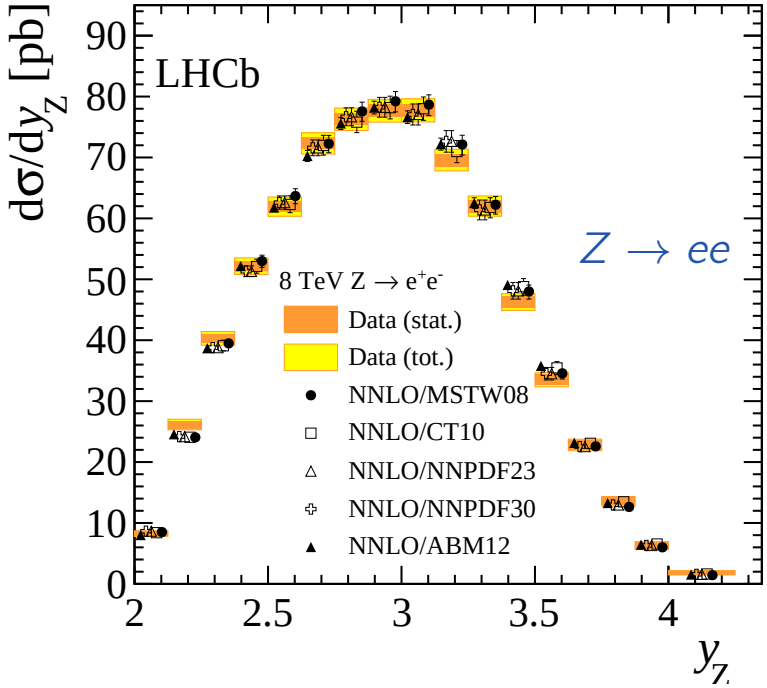
- $Z \to ee$ mass peak smeared by Bremsstrahlung
- purity $> 99\%$ ($\mu\mu$)
- purity $\sim 95\%$ (ee)



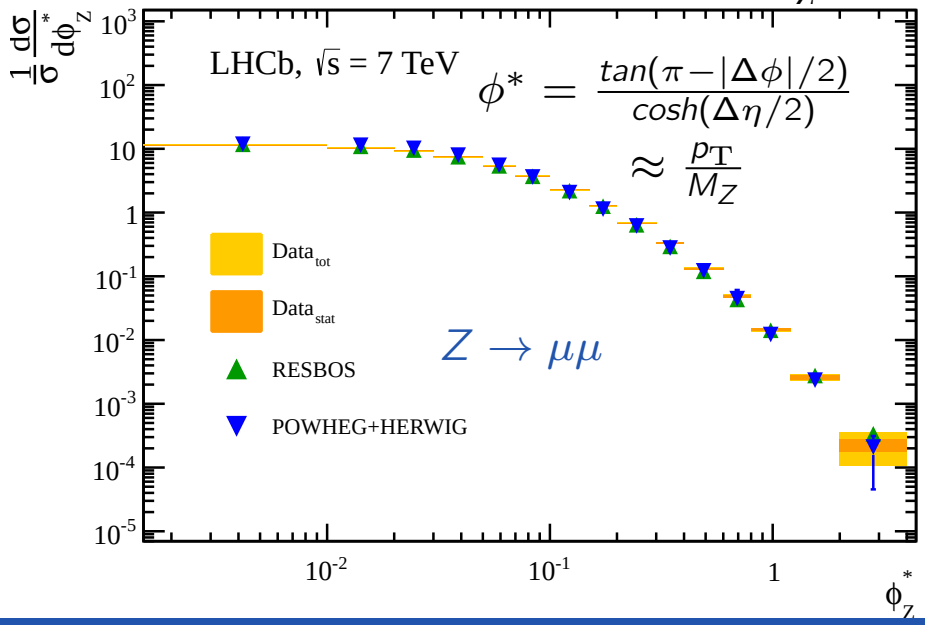


$Z \to \ell\ell$ results [LHCb] [*JHEP*(2015)08:p. 039] , [*JHEP*(2013)02:p. 106] , [*JHEP*(2015)05:p. 109]

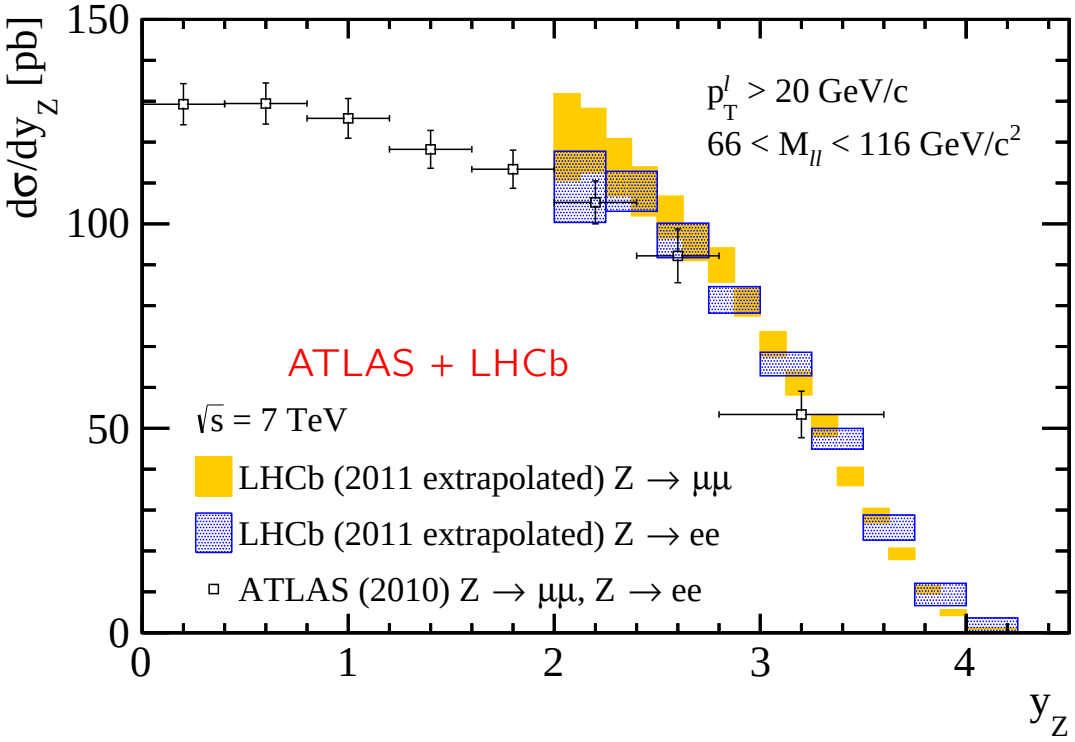




- experimental precision of 2-4% - dominated by luminosity and beam energy uncertainty
- good agreement with NNLO predictions
- RESBOS and POWHEG + PYTHIA describe ϕ^* distribution well

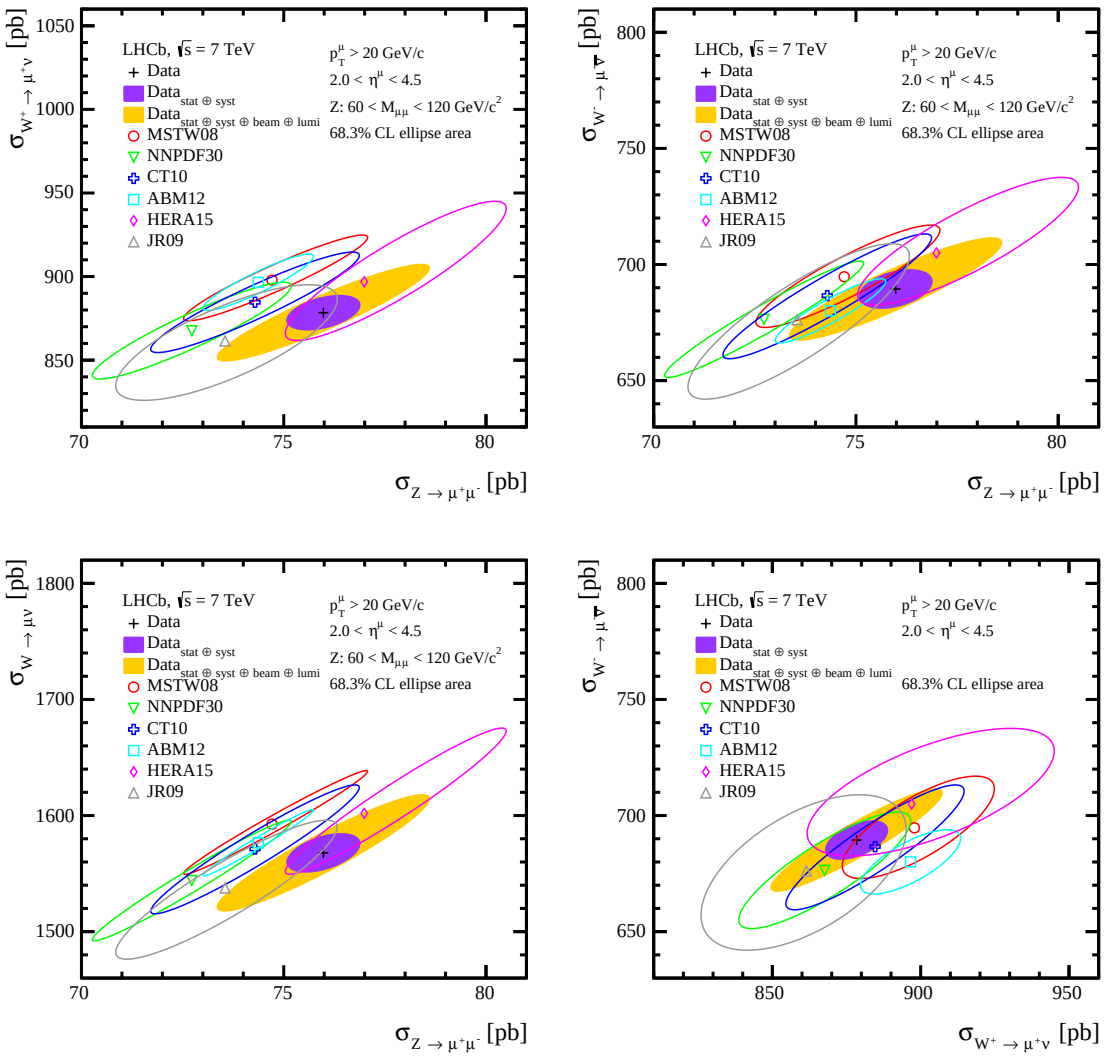


$Z \to \ell\ell$ - comparison with central region [*JHEP*(2015)08:p. 039]



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

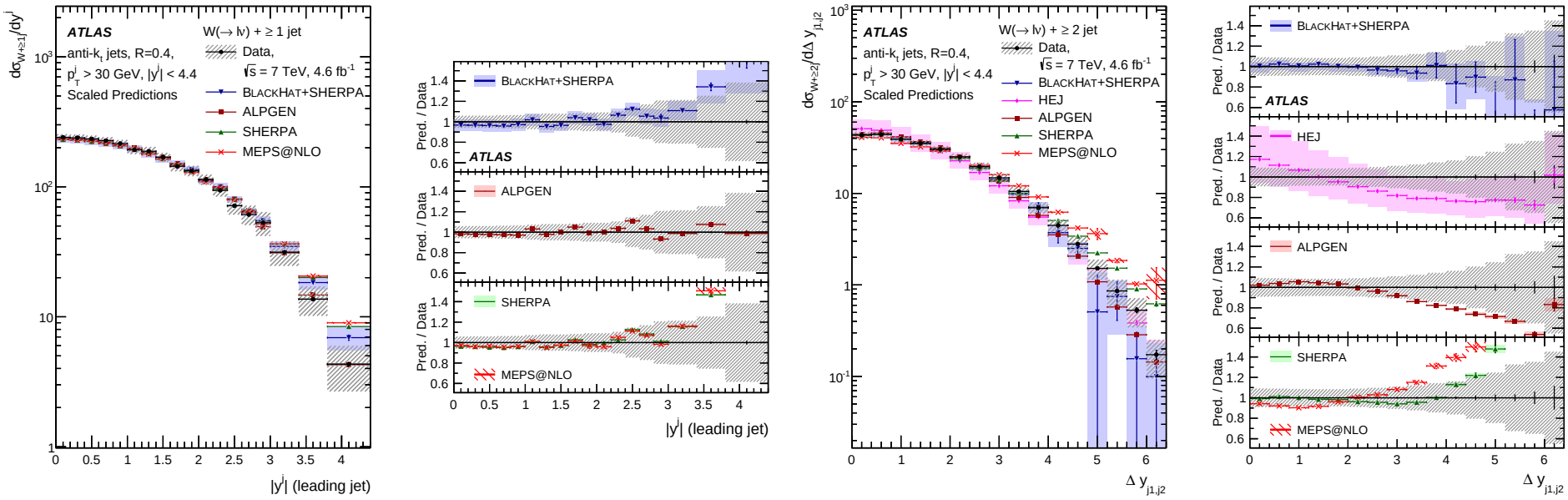
W/Z ratios [LHCb] [*JHEP*(2015)08:p. 039]



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

W/Z+forward(backward) jets [ATLAS]

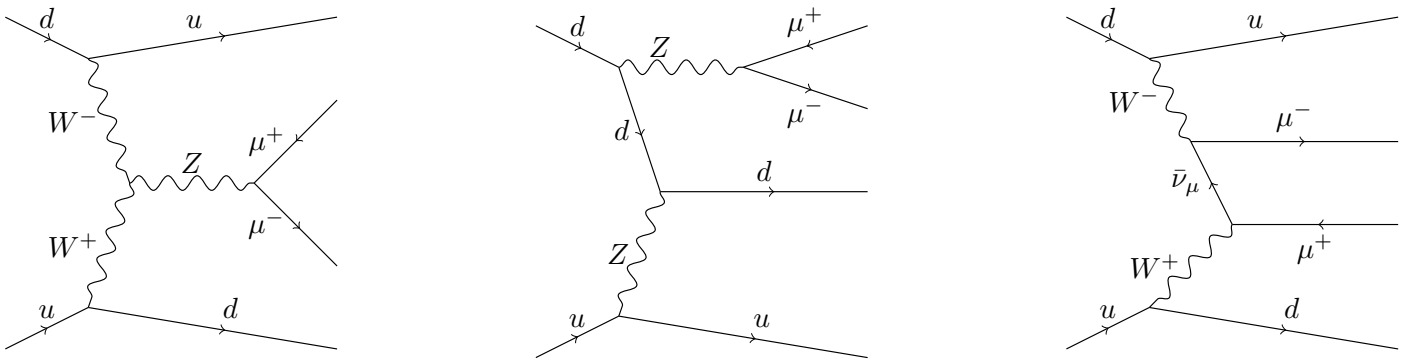
- CMS inclusive jet measurements use central jet rapidity range ($|y_j| < 2.4$)
- ATLAS inclusive Wj [*Eur. Phys. J.*(2015)C75:p. 82] and Zj [*JHEP*(2013)07:p. 032] measurements extend up to jet rapidities of 4.4
  - anti-k_T algorithm, $R = 0.4$



- some disagreements observed in forward region
- improvements in description expected with tuning using ATLAS results (e.g. Sherpa 2.2)

electroweak W/Z production [ATLAS,CMS]

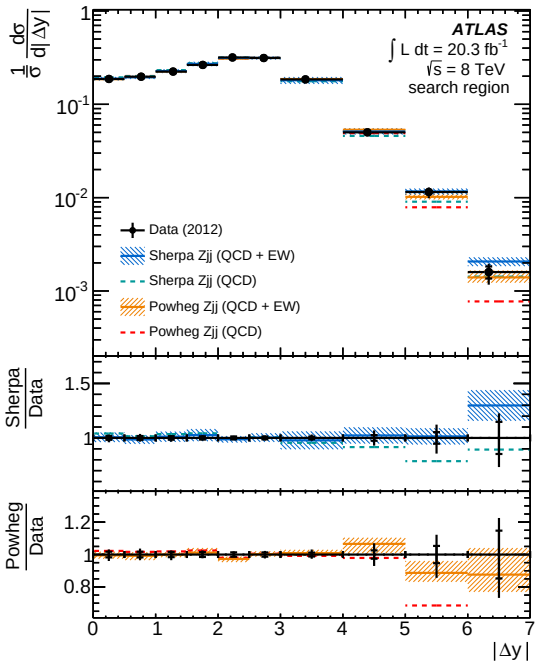
- electroweak W/Z production can occur through vector-boson fusion (VBF), Z-boson bremsstrahlung and non-resonant production

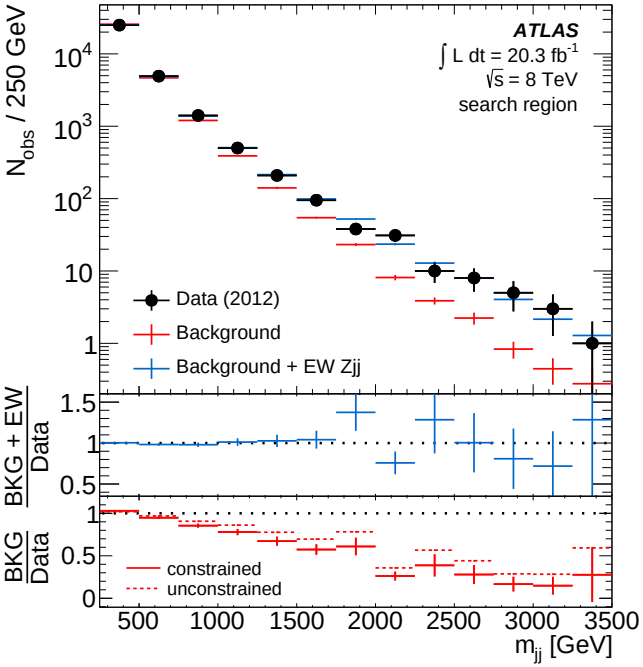


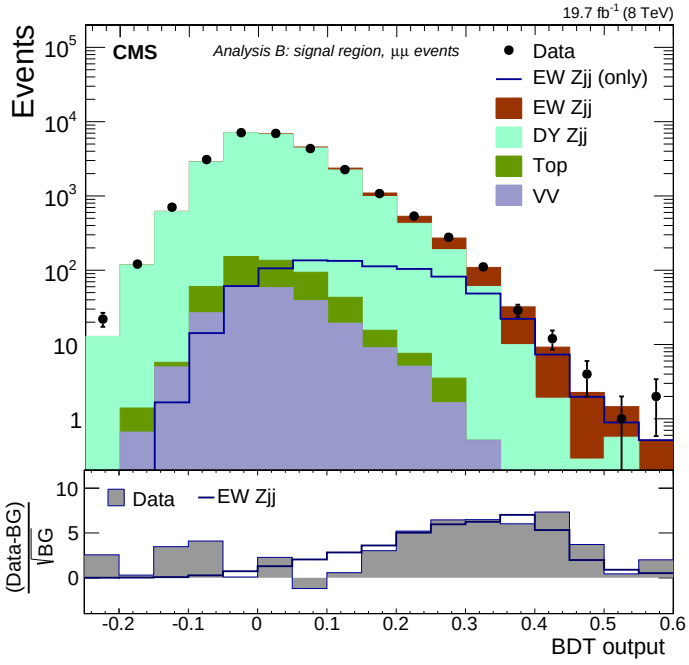
- VBF relevant for Higgs production and sensitive to anomalous triple-gauge couplings
- can be identified by presence of two jets and large rapidity gap
  - colour flow - suppression of soft gluon radiation
- measurements performed by CMS and ATLAS using jets with rapidities up to 4.7
- note: electroweak production of di-bosons not covered here [*Phys. Rev. Lett.*(2014)113:p. 141803] [*Phys. Rev. Lett.*(2015)114:p. 051801] (see talk by A. Bocci)

electroweak *Zjj* production [ATLAS, CMS]

- ATLAS [*JHEP*(2014)04:p. 031]
  - define search region
  - balanced *Zjj* system, rapidity gap between jets
- CMS [*JHEP*(2013)10:p. 062] , [*Eur. Phys. J.*(2015)C75:p. 66]
  - separation achieved using BDT



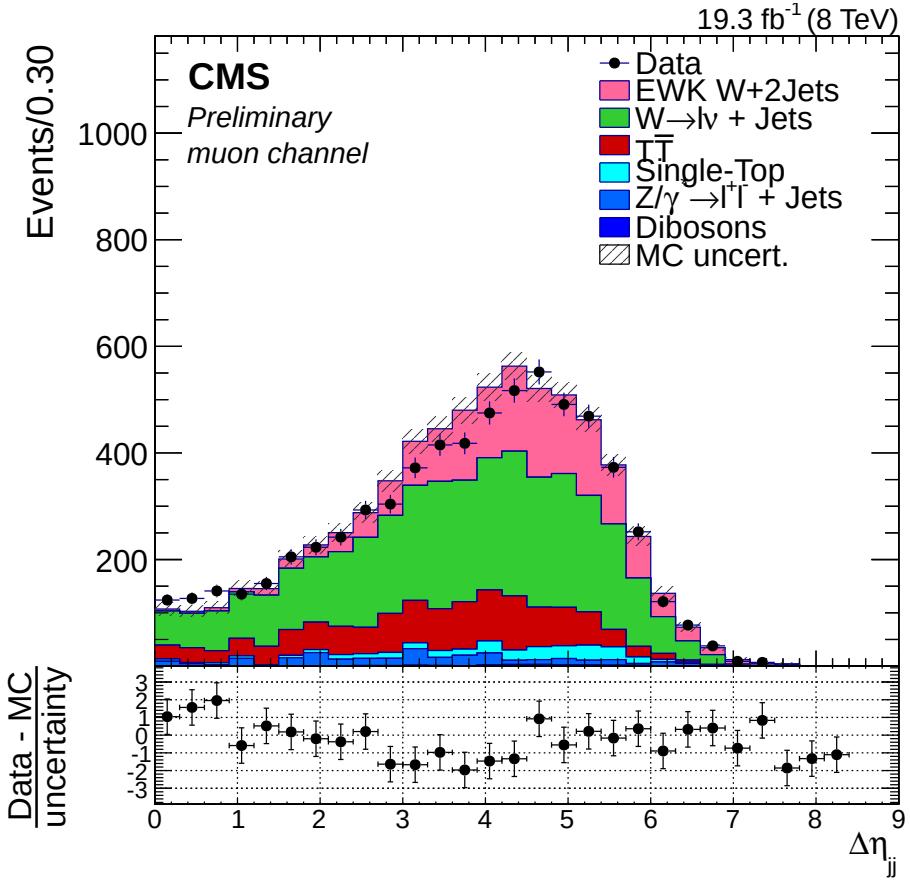


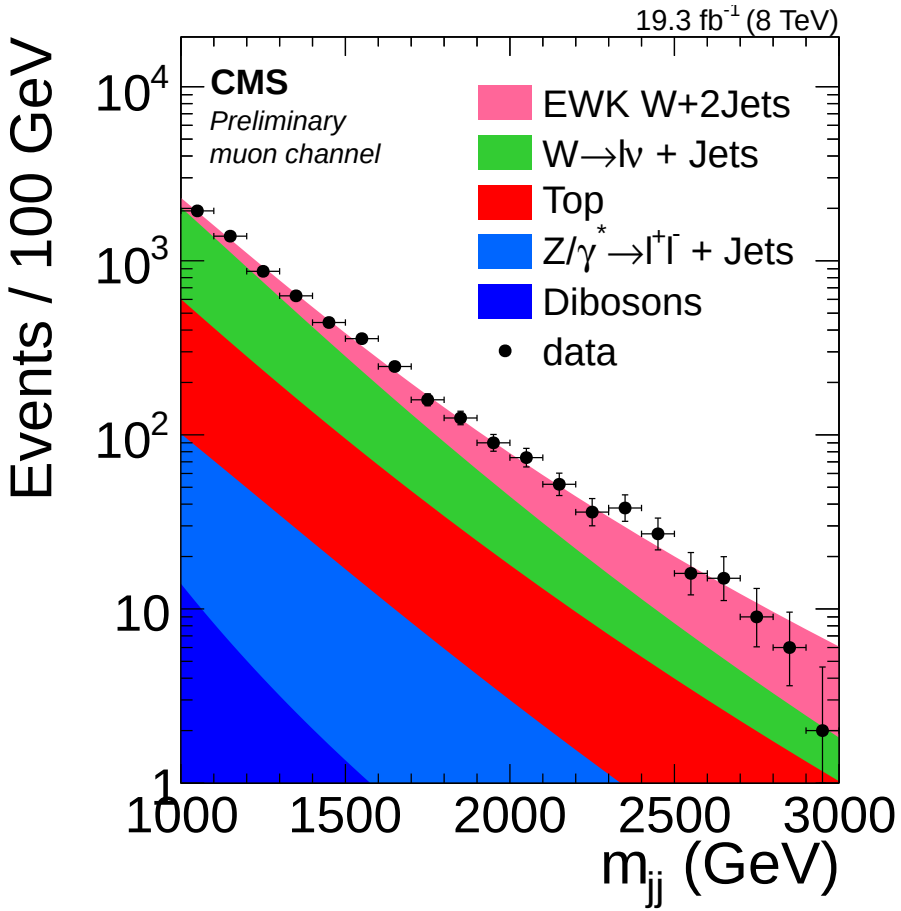


- both experiments measure significance $> 5\sigma$
- measured ewk production cross-sections in agreement with theoretical predictions (POWHEG, MADGRAPH)

electroweak *Wjj* production [CMS]

- CMS also perform measurement of electroweak *Wjj* production using similar strategy to *Zjj* analysis in both muon and electron channels [CMS-PAS-SMP-13-012]

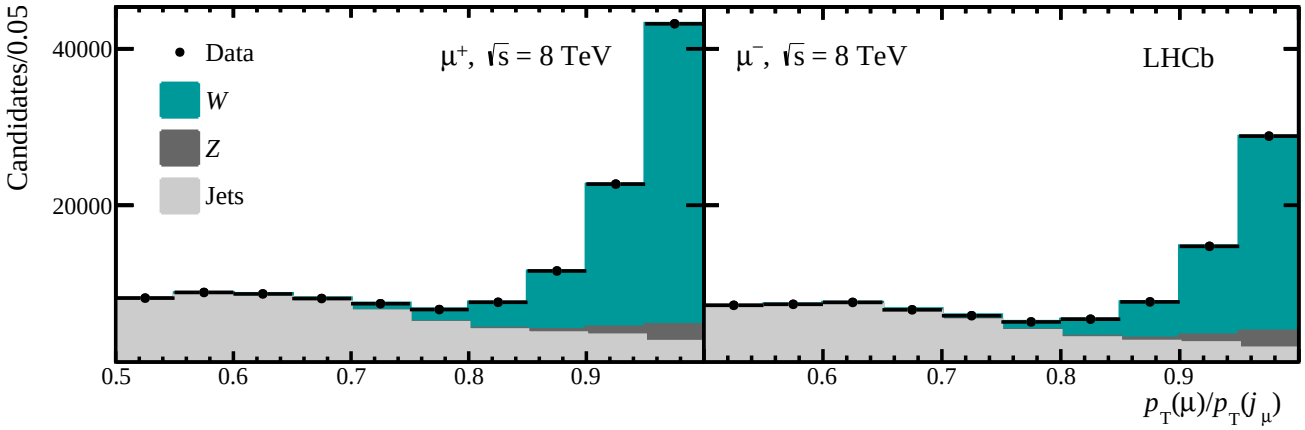




- cross-section extracted from fit to M_{jj}
- good agreement with SM expectation from MADGRAPH+PYTHIA

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

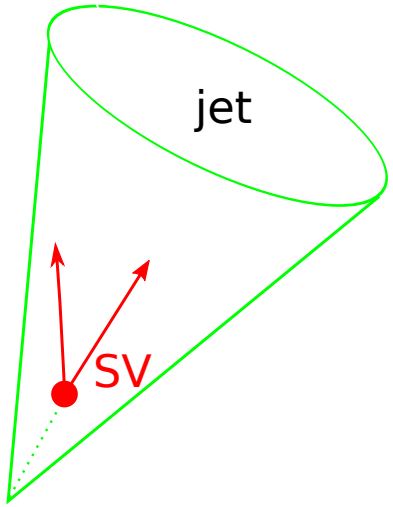
- measurements of W production in association with light and heavy flavour jets performed at LHCb [1505.04051 [hep-ex]]
- W reconstructed through presence of single high-p_T muon
- jets reconstructed using ParticleFlow and anti-k_T algorithm (R=0.5)
- purity determined using fit to muon isolation spectrum

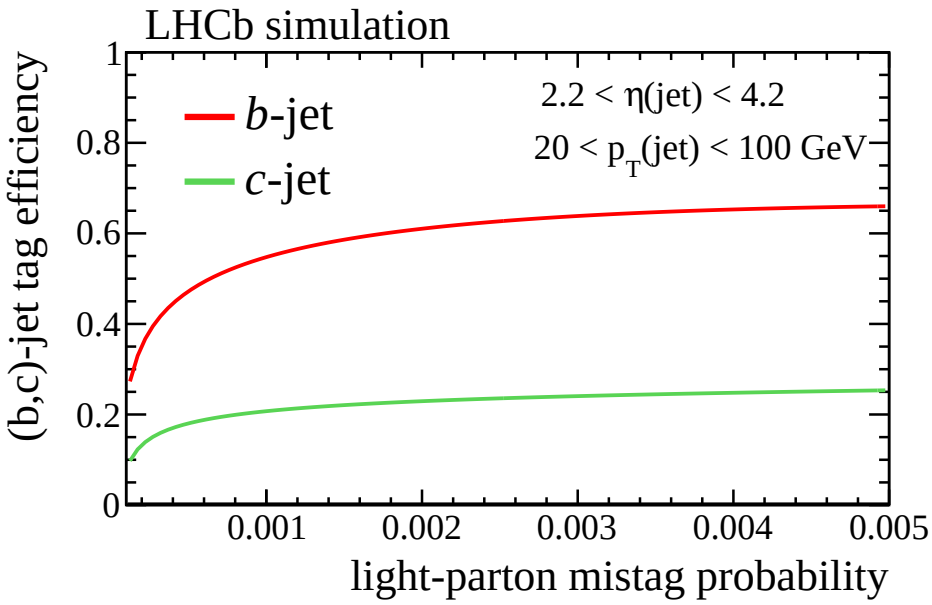


- measurements of
  - ratios ($W^{\pm}j/Zj$, $W(b, c)/Wj$)
  - asymmetries (Wb, Wc)
- builds on previous measurements of Zj [*JHEP*(2014)01:p. 033] and Zb [*JHEP*(2015)01:p. 064]
- jets tagged using secondary vertex tagger

heavy flavour tagging [*JINST*(2015)10:P06013]

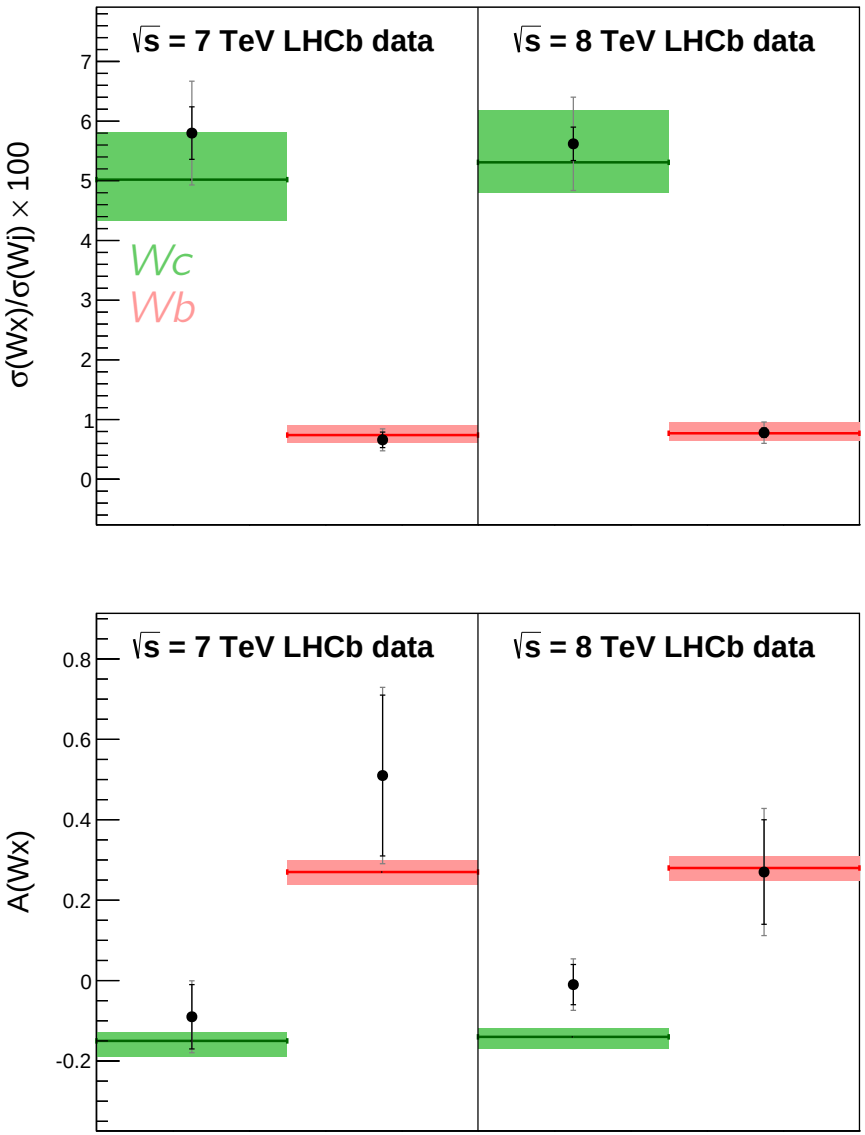
- reconstruct 2-body vertices
- merge into *n*-body vertices (SV) by linking vertices with shared tracks
- two separate BDTs trained to separate light from heavy-flavour jets, and *b* from *c* jet
  - based on SV and jet kinematics





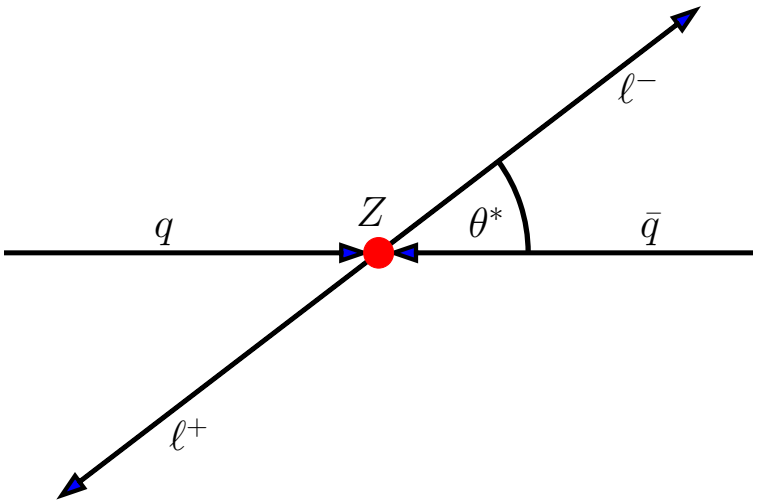
- light-jet mistag rate $< 1\%$ for inclusive b-tag and c-tag efficiencies of 65% and 25% respectively
- validated using b- and c-jet enriched data samples

results [1505.04051 [hep-ex]]



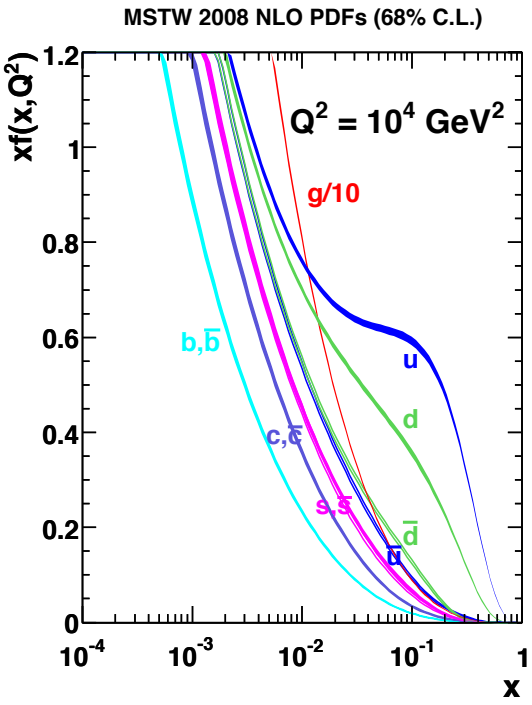
- good level of data/theory agreement observed
- experimental measurements dominated by statistical uncertainties
- b- and c-tagging uncertainties determined from data ($\approx 10\%$)
- measured Wc asymmetries $\approx 2\sigma$ smaller than SM expectations

forward-backward asymmetry



- lepton forward-backward asymmetry in Z boson decays arises through $q\bar{q}$ annihilation
- forward defined with respect to quark direction : $N_F = N(\cos\theta^* > 0)$

$$A_{\mathrm{FB}} = \frac{N_F - N_B}{N_F + N_B}$$



- quark direction not known at the LHC
- positive axis can be defined to be along boost direction of Z
  - some dilution due to "mis-identification" of quark direction
- greater sensitivity in forward region due to higher Bjorken-x
  - larger valence quark contribution
  - valence quarks tend to be produced with more momentum than sea anti-quarks
  - asymmetry less diluted

kinematic range

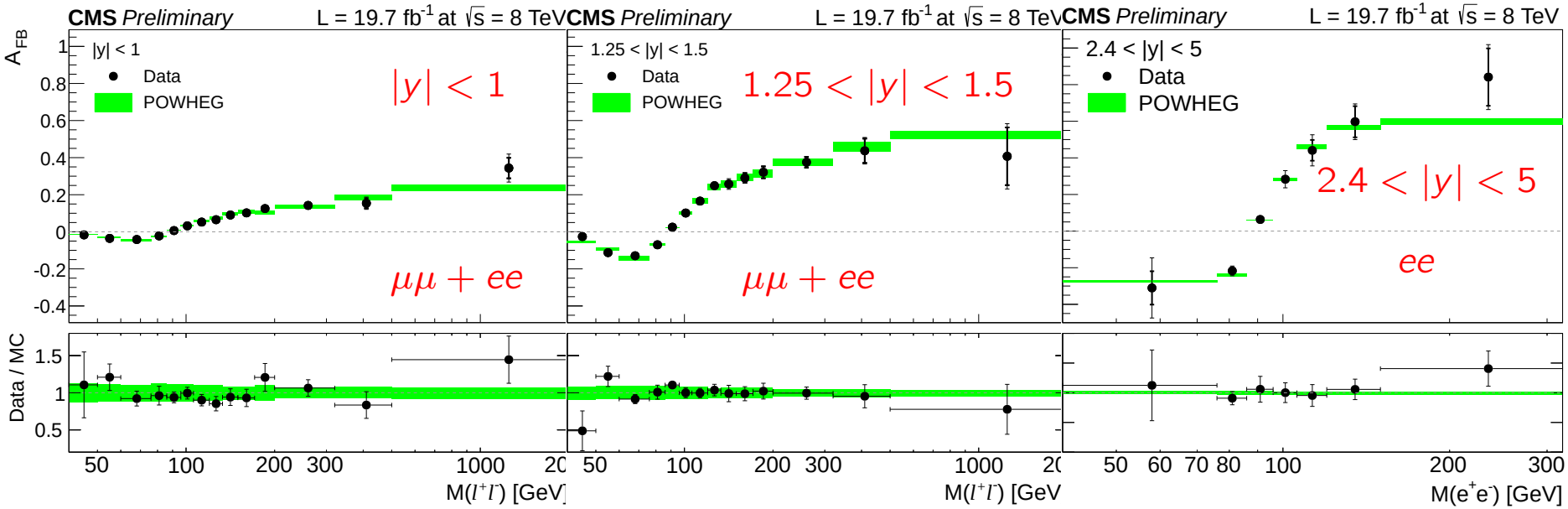
- Measurements performed as a function of di-lepton mass in different kinematic ranges

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	$\lvert\eta\rvert < 2.47$, $2.5 < \eta < 4.9$

- LHCb performs measurement using two forward muons [LHCb-PAPER-2015-039 (prelim.)]
- ATLAS [1503.03709 [hep-ex]] and CMS [*Phys. Lett.*(2013)B718:pp. 752–772] , [CMS-PAS-SMP-14-004] with three distinct channels
  - Two central muons
  - Two central electrons
  - One central electron and one forward electron (reconstructed in calorimeters)
- Measurements performed at 7 TeV (ATLAS, CMS, LHCb) and 8 TeV (CMS, LHCb)
  - Forward electrons only included in 8 TeV CMS result

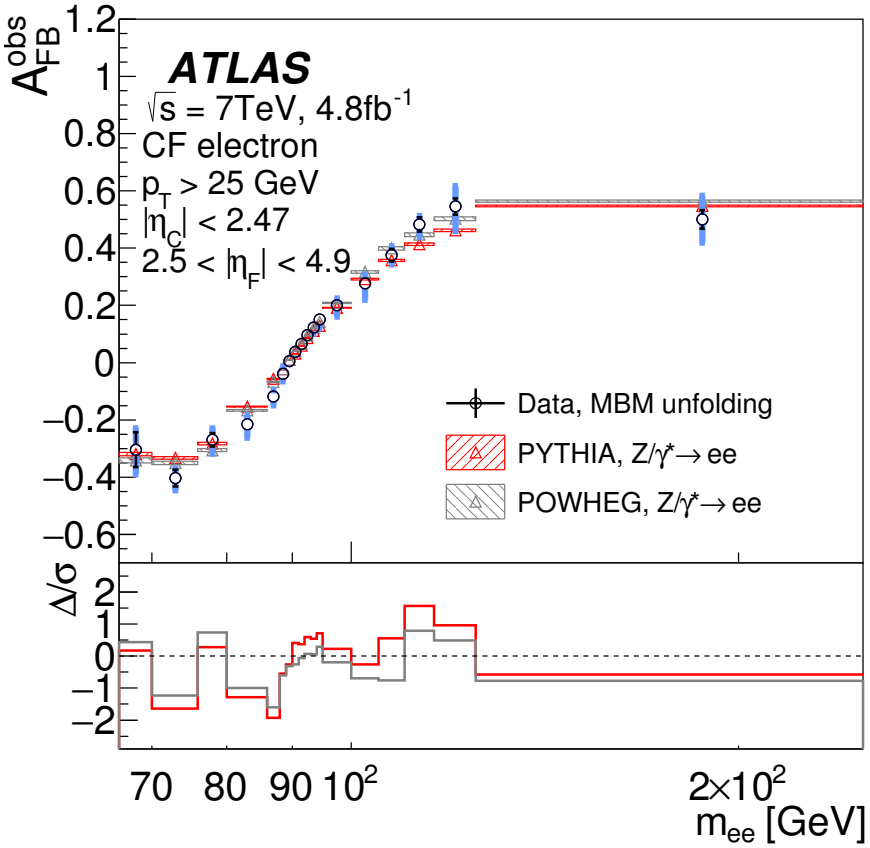
CMS[CMS-PAS-SMP-14-004]

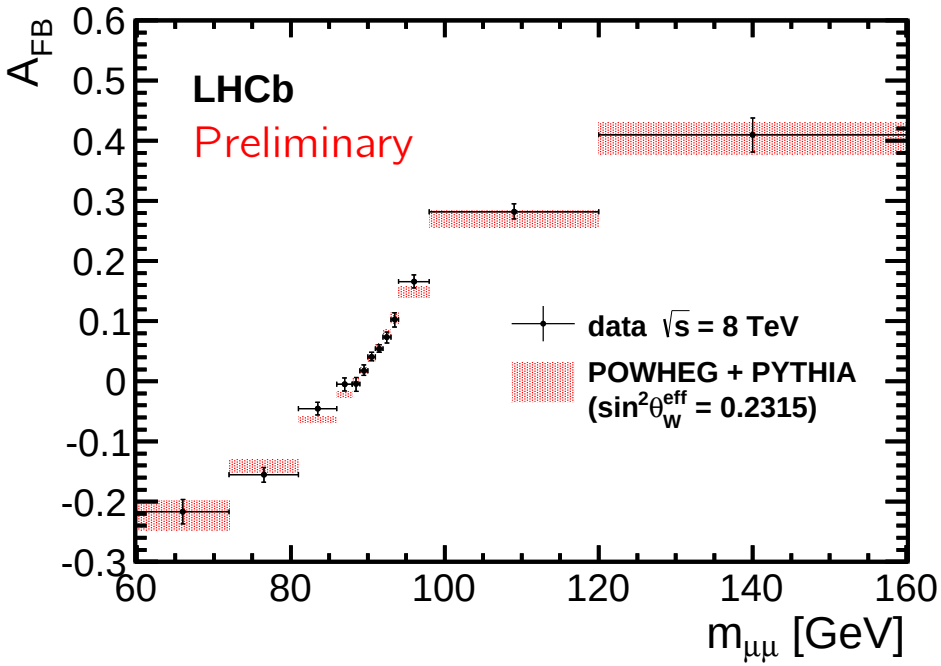
- CMS measurement performed double-differentially as a function of rapidity and mass



- distributions background subtracted and corrected for detector effects and FSR
- increasing asymmetry moving forward in rapidity
- dominant uncertainty due to background estimation

ATLAS, LHCb [1503.03709 [hep-ex]] ,[LHCb-PAPER-2015-039 (prelim.)]

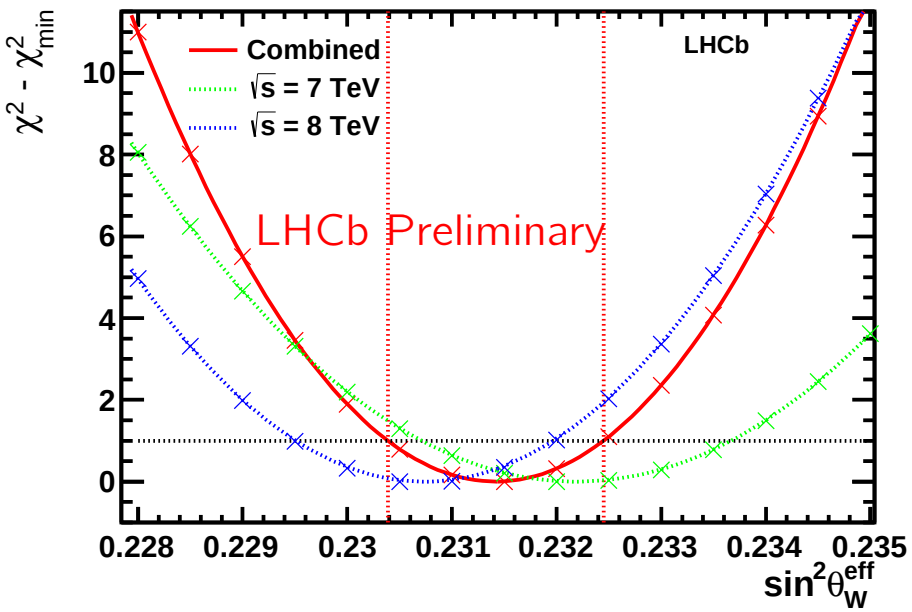


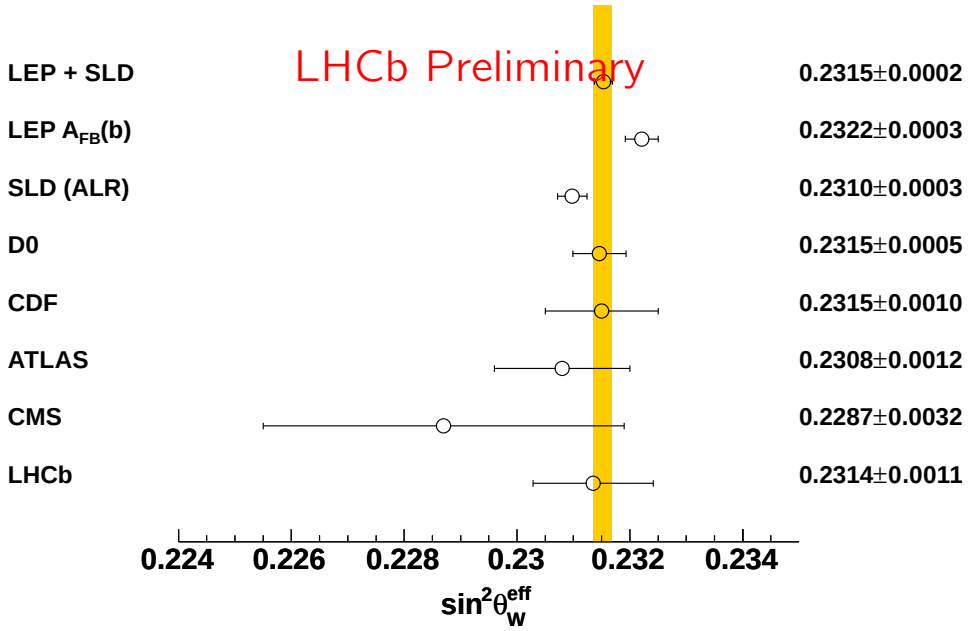


- (left) ATLAS central-forward electrons compared to PYTHIA and POWHEG
  - unfolded for bin-to-bin mass migrations (detector effects and FSR)
- (right) LHCb forward-forward muons
  - unfolded for detector effects
- dominant uncertainty due to unfolding (ATLAS) and energy scale (LHCb)

extraction of $sin^2\theta_W^{eff}$. [1503.03709 [hep-ex]] ,[LHCb-PAPER-2015-039 (prelim.)]

- ATLAS and LHCb extend their measurement to include extraction of $\sin^2\theta_W^{eff}$.
  - χ^2 minimisation to template shapes of different $\sin^2\theta_W$ values with PYTHIA (ATLAS) and POWHEG + PYTHIA (LHCb)
- ATLAS measurement further corrected for dilution effects (PYTHIA)





- Dominant uncertainty due to PDFs (ATLAS) and statistics (LHCb)
- CMS measurement of $\sin^2\theta_W^{eff}$. [*Phys. Rev.*(2011)D84:p. 112002] not covered here

conclusion

- range of EWK measurements performed by all three experiments in the forward region
- precision measurements for PDF constraints, electroweak production and forward-backward asymmetries
- some measurements statistically limited (LHCb)
- looking forward to extra statistics in run-II
- thanks to the LHC and the experiments!