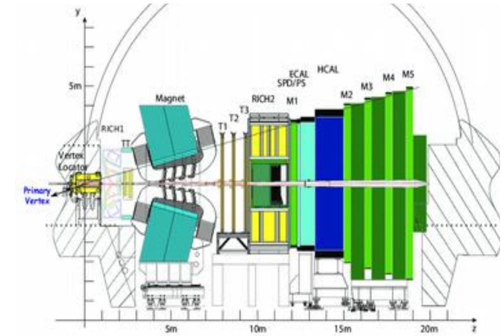
# Gauge Boson Physics in the Forward Region at LHCb

**Alexandru T. Grecu**
***on behalf of the **LHCb** collaboration**
Horia Hulubei National Institute for Physics and Nuclear Engineering
(IFIN-HH), Bucharest, Romania

*QCD@LHC, ETH & University of Zürich*
*Zürich, Switzerland, 22nd – 26th August 2016*

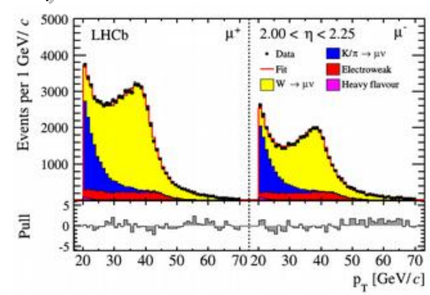
# Outline

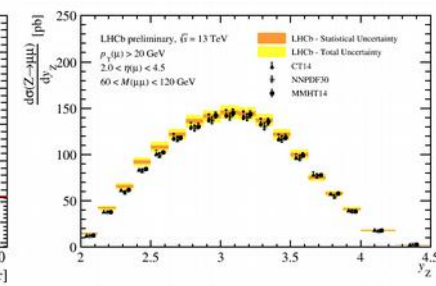
- The LHCb Detector and the Forward Region



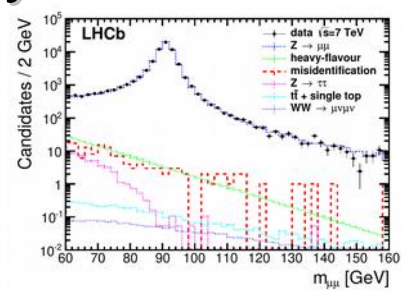

- W±/Z Production in pp Collisions at 7, 8, 13 TeV

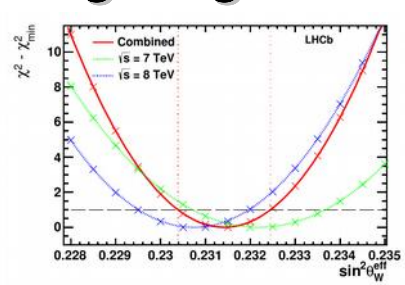
Inputs for proton PDF tuning.
Katharina Müller's talk in plenary session tomorrow morning.

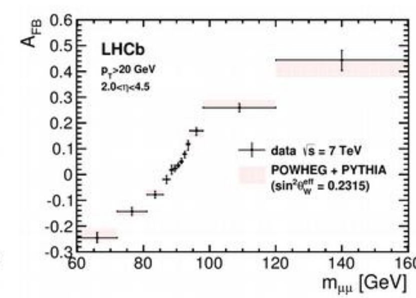



- Z Production Asymmetry and the Weinberg Angle




Electroweak boson production with jets and top measurements

Wouter Hulsbergen's talk tomorrow

# The LHCb detector and the Forward Region

JINST 3 (2008) S080005; IJMP A30 (2015) 1530022

**Full coverage for 2 < η < 5** – complementary to ATLAS and CMS phase space

**Excellent luminosity determination**: %-level uncertainty

Van der Meer scan & Beam-Gas Imaging – SMOG system [JINST 9 (2014) 12005]

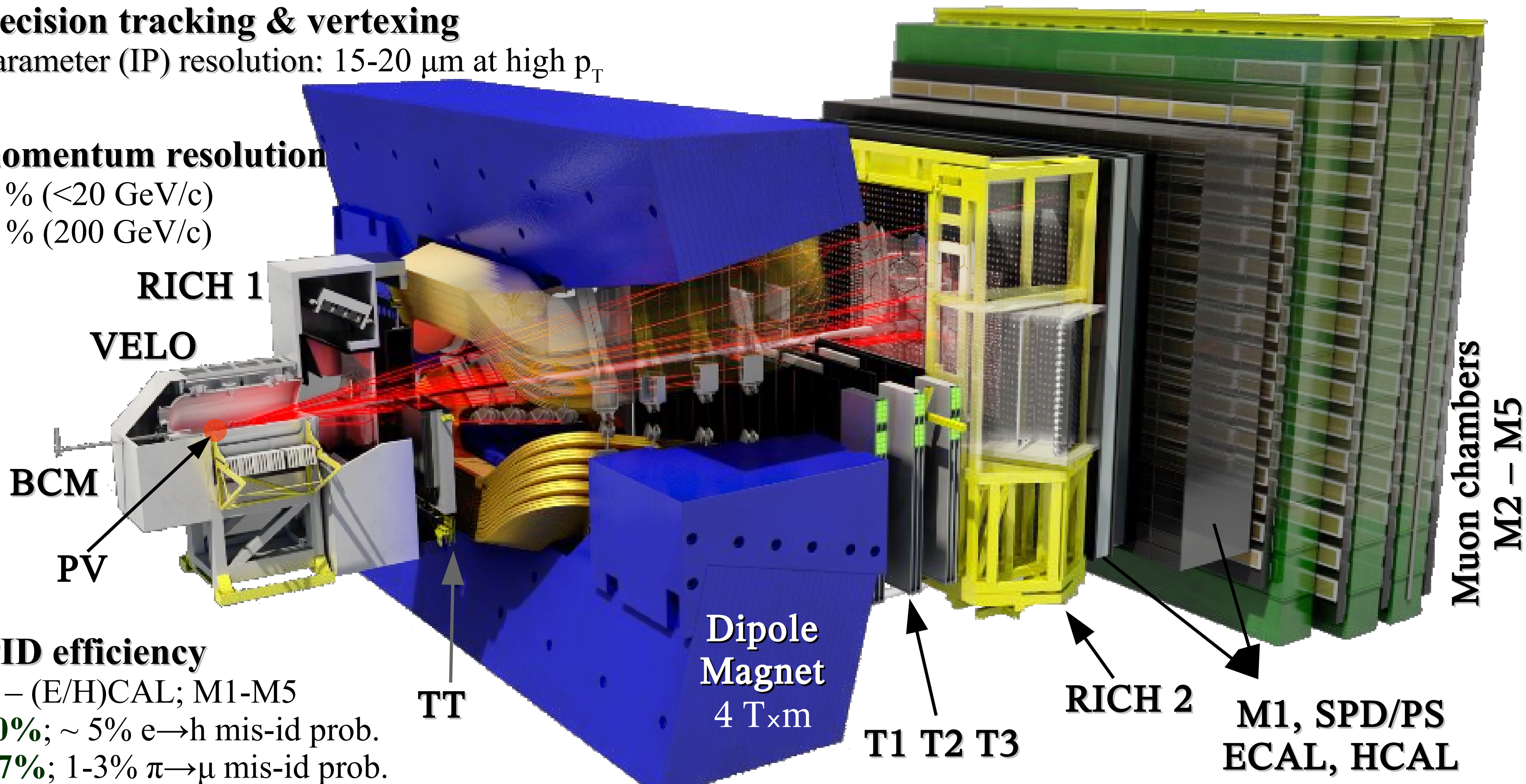
**High precision tracking & vertexing**

Impact Parameter (IP) resolution: 15-20 μm at high $p_T$

**Good momentum resolution**

Δp/p: 0.5 % (<20 GeV/c)

1.0 % (200 GeV/c)




**Good PID efficiency**

e, γ; μ – (E/H)CAL; M1-M5

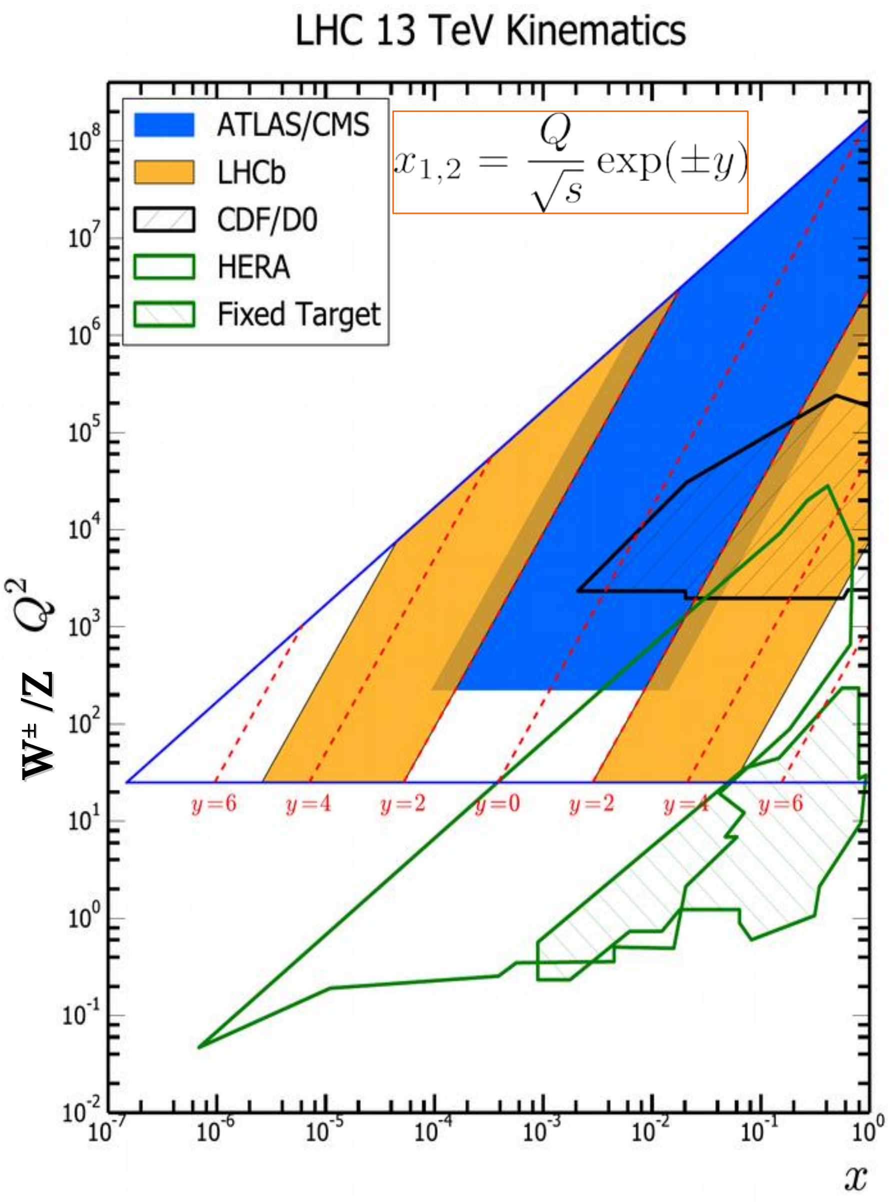
- **e: ~ 90%**; ~ 5% e→h mis-id prob.
- **μ: ~ 97%**; 1-3% π→μ mis-id prob.

More numbers in back-up slides...

# The LHCb detector and the Forward Region

## Probing Parton Density Functions (PDFs) in the Forward Region

- probe two distinct regions in (x-Björken, $Q^2$) space
- access previously unexplored region of low-x, high-$Q^2$
- at $W^{\pm}/Z$ scale: $x \sim 10^{-4}$ and $10^{-1}$




## Integrated Luminosity

- 7 TeV (2011): 1.0/fb ± 1.7%
- 8 TeV (2012): 2.0/fb ± 1.2%
- 13 TeV (2015): 0.3/fb ± 3.9% (improve in 2016)

# $Z \rightarrow \ell^+ \ell^-$

## $Z \rightarrow \mu^+ \mu^-$

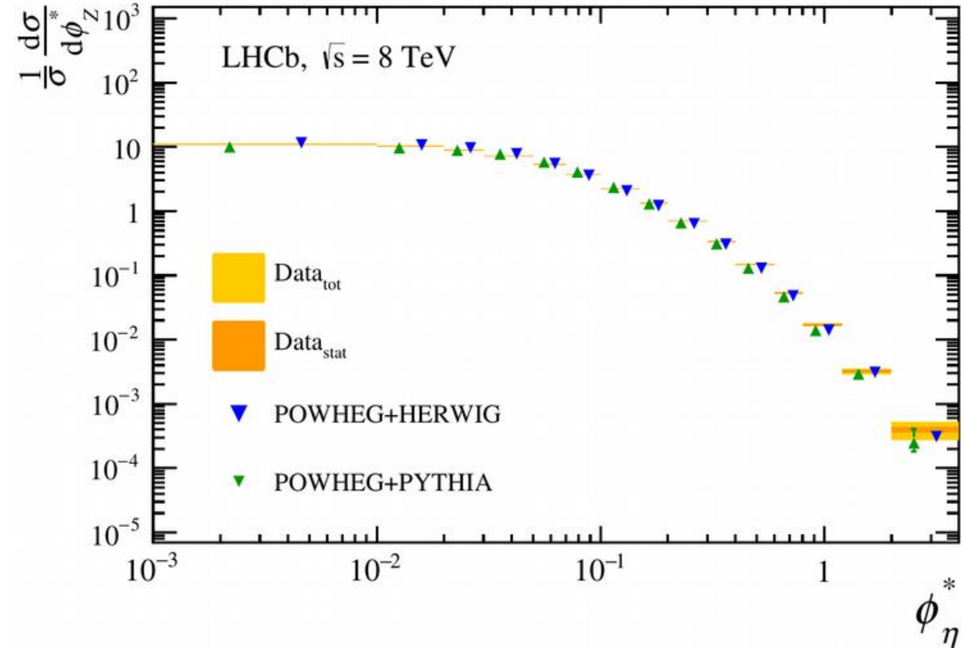
- 7 TeV: JHEP 08 (2015) 039*
- 8 TeV: *JHEP 01 (2016) 155*
- 13 TeV: arXiv: 1607.06495

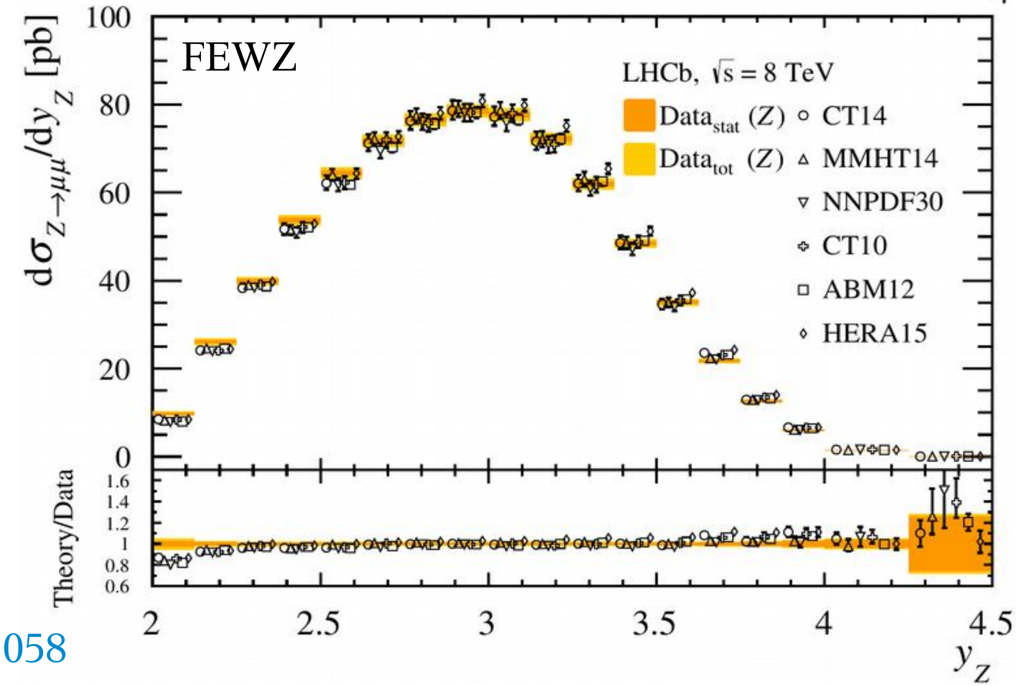
- Selection: 2 muons, $2 < \eta_\mu < 4.5$, $p_T > 20$ GeV/c, $60 < M_{\mu\mu} < 120$ GeV/c$^2$
- **Signal purity ~ 99%**
- Differential cross-sections in y(Z), $p_T$(Z); $\phi^*$(Z)

$$\phi^* = \frac{\tan\left(\frac{\pi - |\Delta\phi|}{2}\right)}{\cosh\left(\frac{\Delta\eta}{2}\right)} \simeq \frac{p_T^{(\mu\mu)}}{M_{\mu\mu}}$$

- Total uncertainty on cross-section:
  - 7 TeV: 2.3 % (main: lumi + beam energy)
  - 8 TeV: 1.8 % (main: lumi + beam energy)

- Good overall agreement to NLO (POWHEG) and NNLO (FEWZ) predictions w/ different PDFs



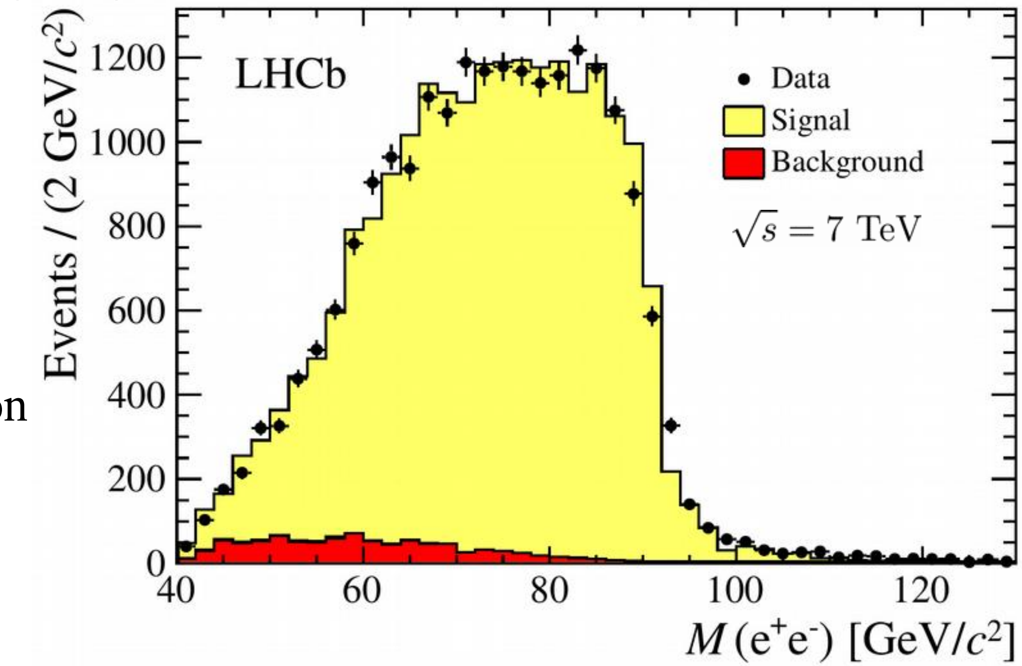




* Superseeds JHEP 06 (2012) 058

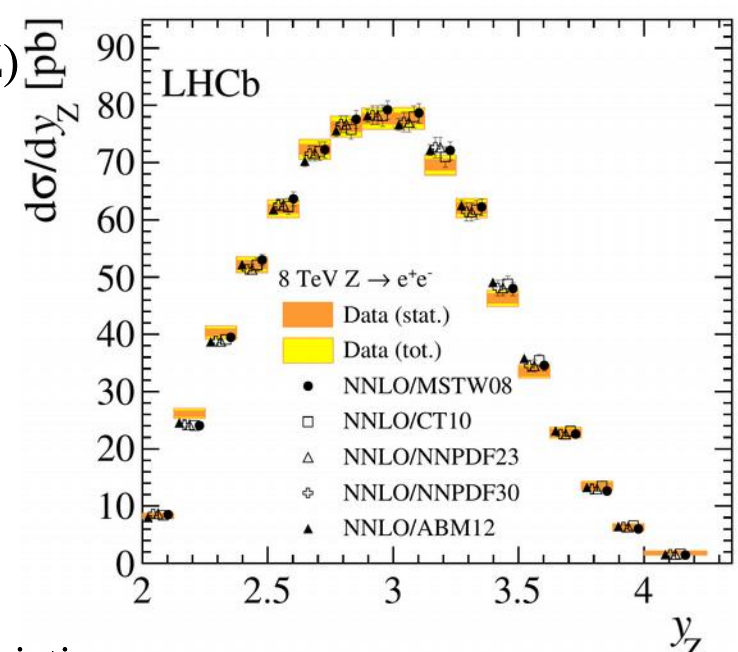
# $Z \rightarrow \ell^+ \ell^-$

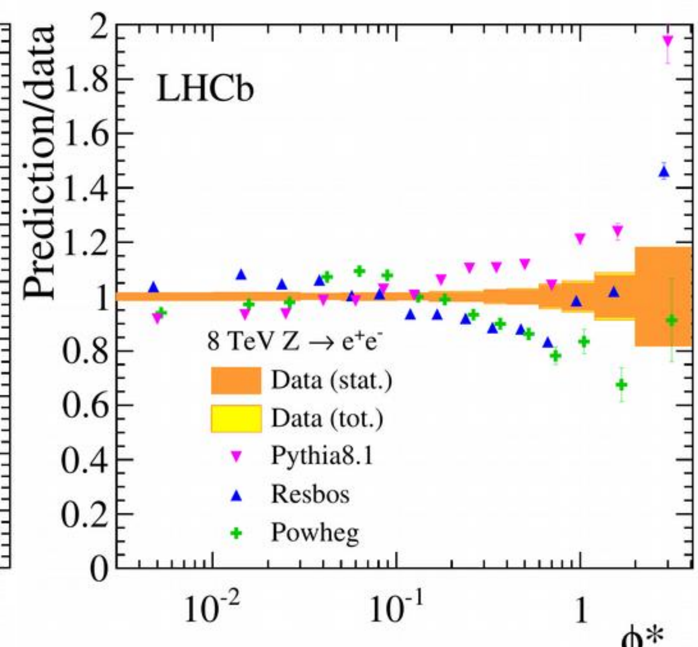
## $Z \rightarrow e^+ e^-$

- ✓ 7 TeV: JHEP 02 (2013) 106*
- ✓ 8 TeV: *JHEP 05 (2015) 109*
- ✓ 13 TeV: arXiv: 1607.06495




- Selection: 2 electrons, $2 < \eta_e < 4.5$, $p_T > 20$ GeV/c, $M_{ee} > 40$ GeV/$c^2$
- Bremsstrahlung recovery limited by ECAL saturation at $p_T > 10$ GeV/c → $p_T$ not well known
- Results corrected to Born level using simulation
- **Signal purity** ~ 95% (electron mis-ID – main bkg)
- Diff. cross-section in y(Z), $\phi^*$(Z)
- ➔ Good agreement to NNLO estimation w/ PDFs in $y_Z$ distribution
- ➔ (N)LO models overestimate low $\phi^*$ and underestimate at high values. RESBOS seems to agree better.



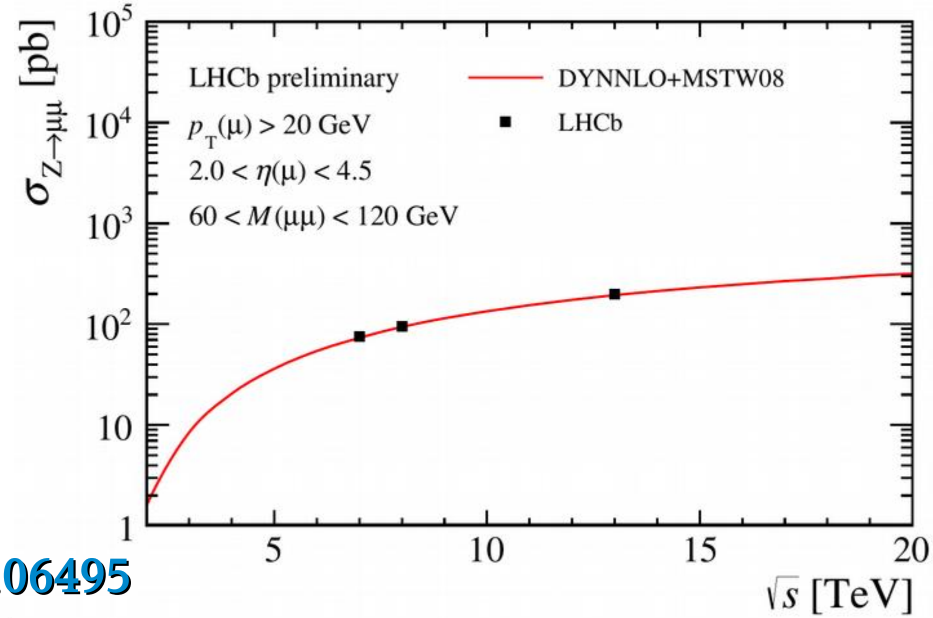




*Older measurements w/ higher uncertainties: JHEP 06 (2012) 058, JHEP 01 (2013) 011

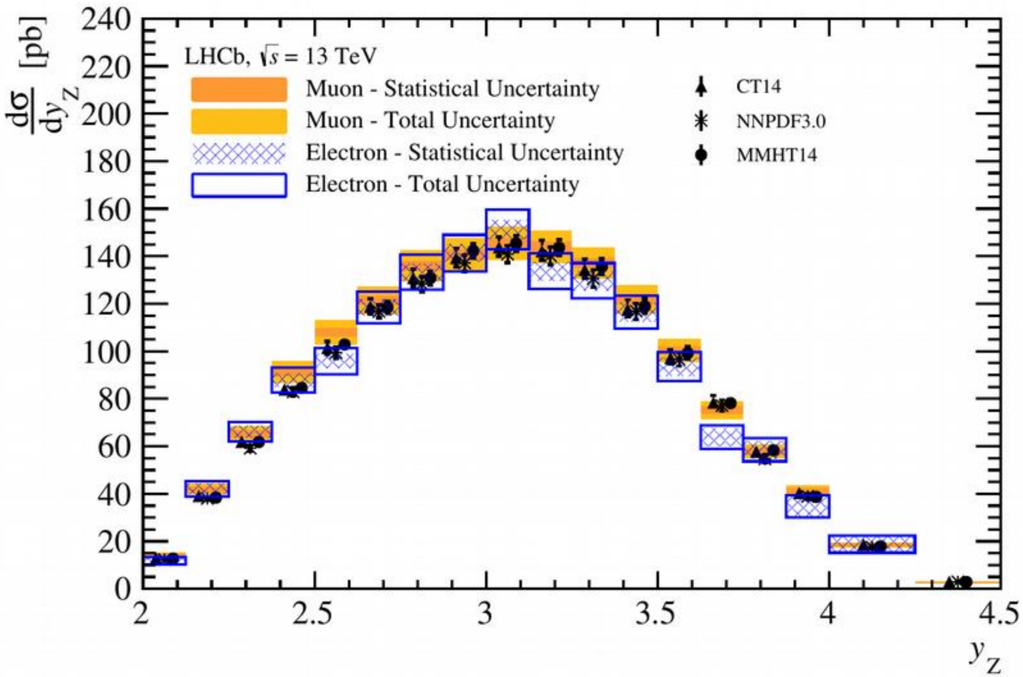
# $Z \rightarrow \ell^+ \ell^-$ @ 13 TeV

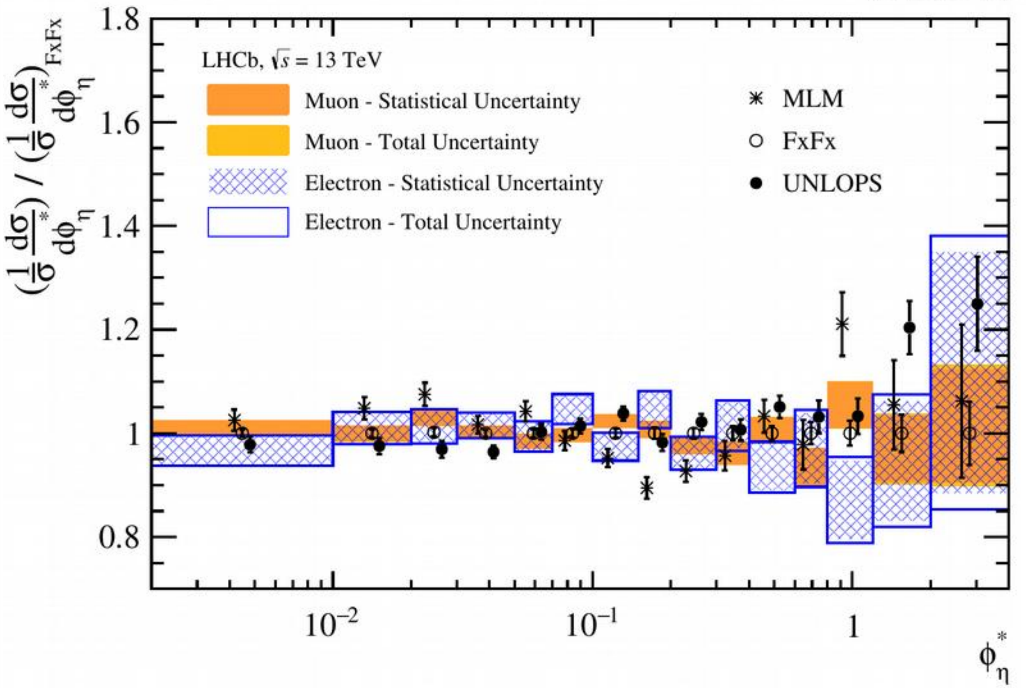
New !

- Limited data set (2015): 0.3 $fb^{-1}$ (sizable stat. error)
- Probe lower x-Björken values than Run I
- Systematic error: 2.4/2.5%$^{(\mu\mu/ee)}$ ⊕ lumi: 3.9%
- Good agreement:
  - ✓ σ(Z→ee) vs. σ(Z→μμ) – back-up slides
  - ✓ $y_Z$ distribution vs. NNLO pQCD + PDFs
  - ✓ $P_T$, $\phi^*$ distributions vs. higher order pQCD + matching schemes




arXiv: 1607.06495

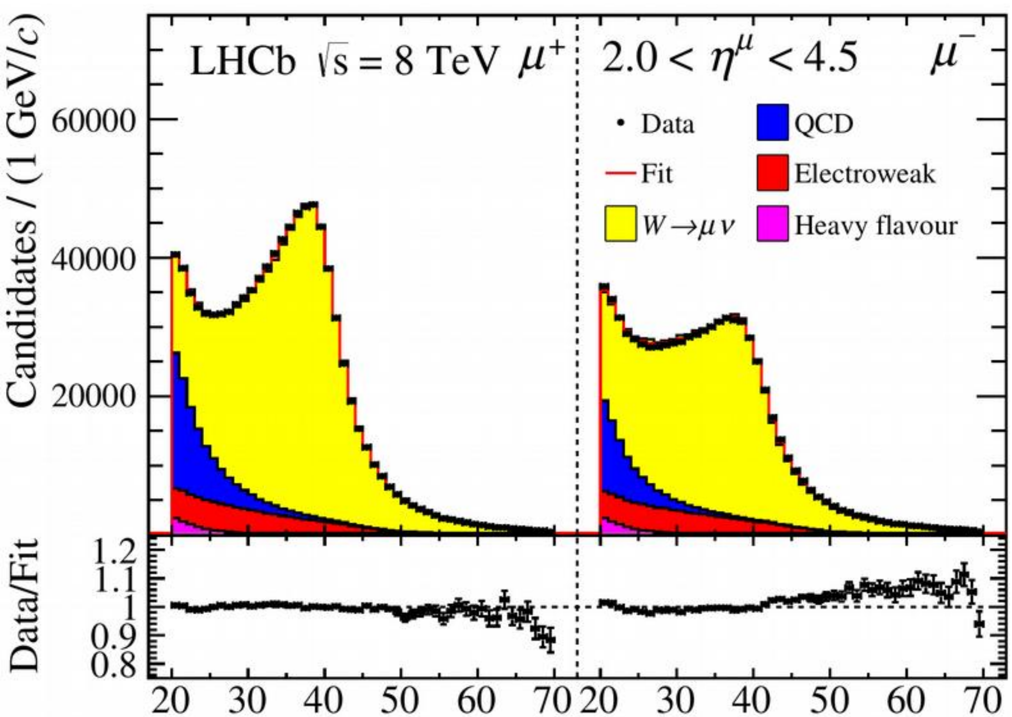


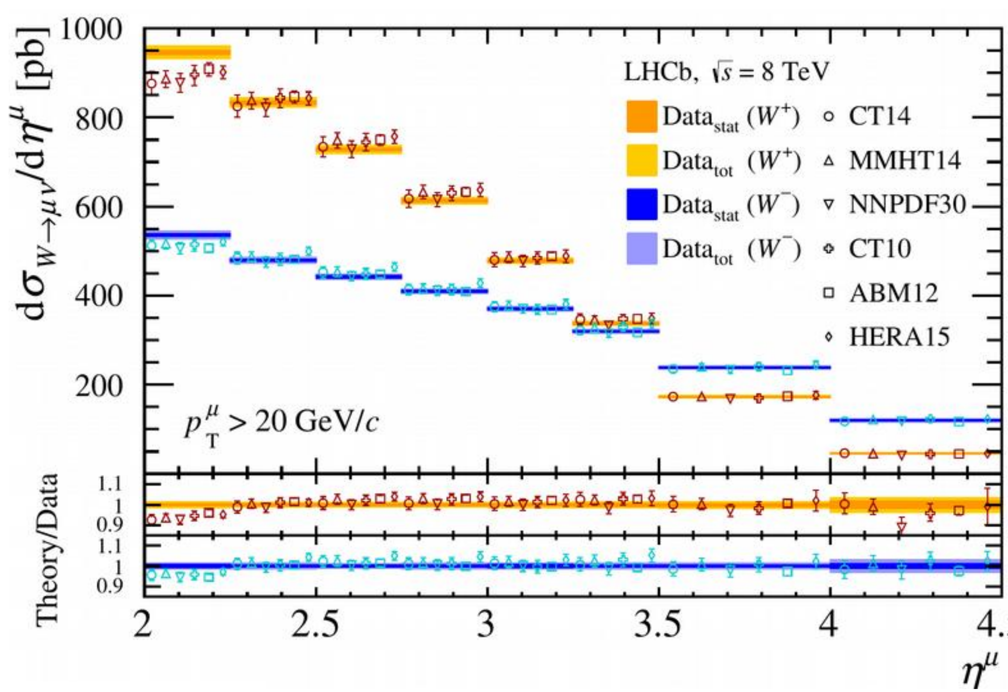



# $W \to \mu\ \nu_\mu$

- ✓ 7 TeV: JHEP 08 (2015) 039*
- ✓ 8 TeV: *JHEP 01 (2016) 155*

- Similar selection as $Z \to \mu\mu$ papers;
  additionally: prompt, isolated muons w/ small E(CALO)/pc; veto on second lepton
- **Signal purity:** ~ 77 – 79%
- Signal estimated from fit to $p_T^{(\mu)}$ spectrum in $\eta^{(\mu)}$ bins
- Backgrounds: decay of heavy hadron, hadron mis-ID (from data); EW sources (from MC)
- Errors (2 – 4%) dominated by uncertainties on luminosity and beam energy
- Data agrees w/ NNLO predictions (FEWZ) using a set of PDFs



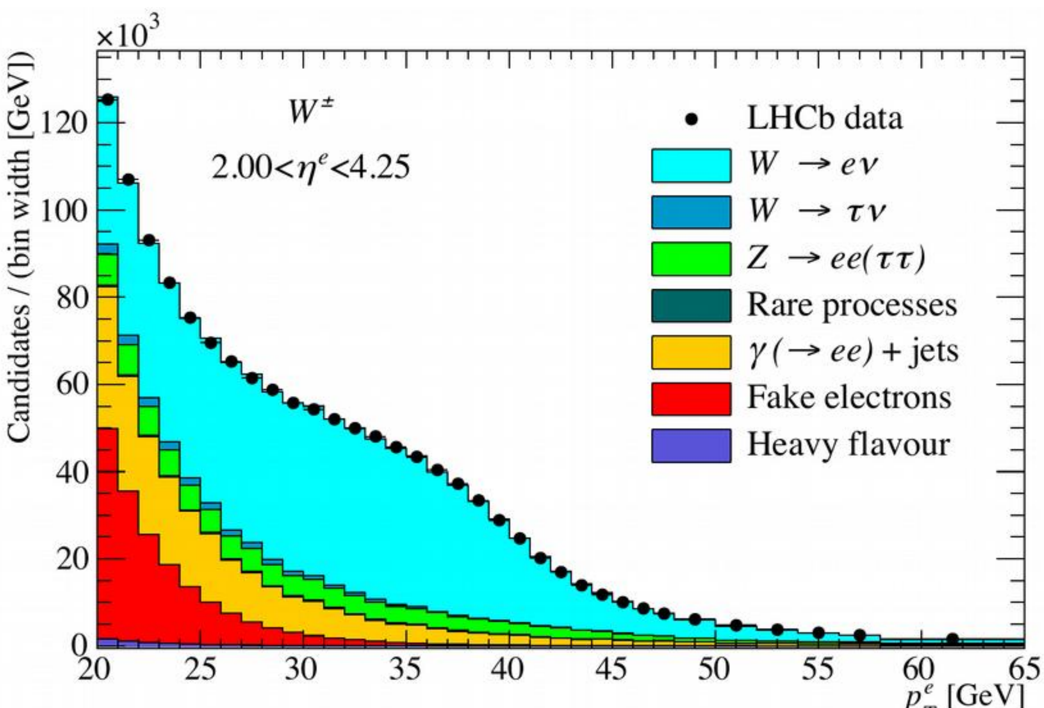



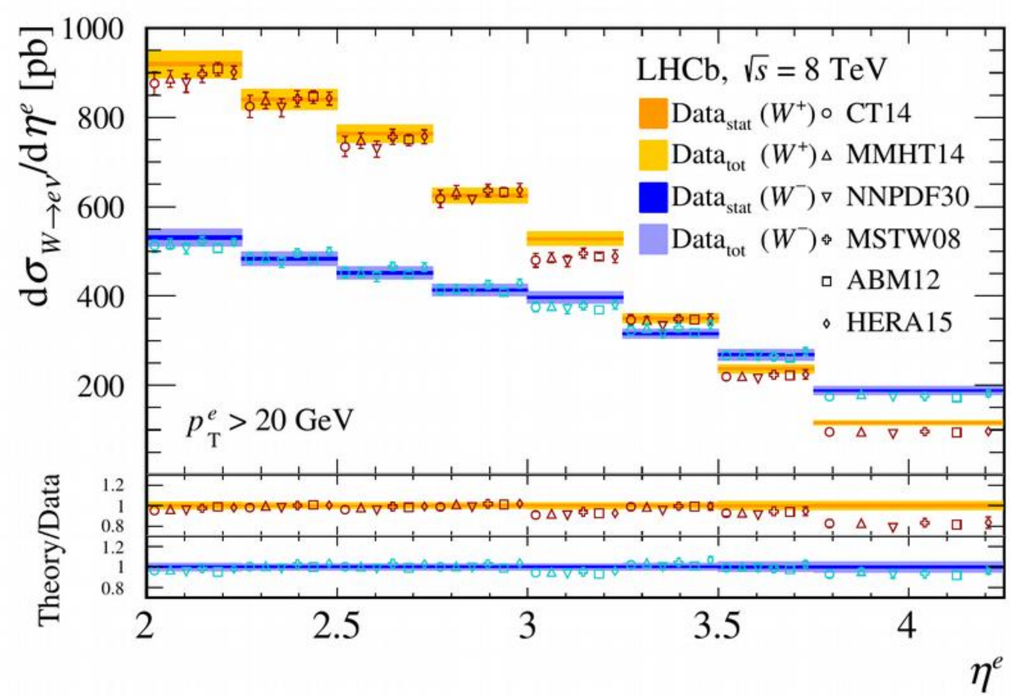

*Superseeds JHEP 12 (2014) 079

# $W \rightarrow e\,\nu_e$

✓ 8 TeV: arXiv: 1608.01484

- Slightly different (from Z → ee) kinematic region: $2 < \eta^e < 4.25$ (CALO acc.), $p_T^{\,e} > 20$ GeV/c
- Additional selection: energy deposition in CALO sub-systems consistent with electron; isolation criteria keeping bremsstrahlung photons
- Similar fit to $p_T^{\,e}$ spectrum to determine signal yield. Backgrounds: EW processes (simulation); fake electrons, heavy flavour hadron decays (data)
- **Signal purity:** 64% ($W^+$); 56% ($W^-$)
- Systematic uncertainty dominated by purity, efficiency, beam energy and lumi evaluation.
- Satisfactory agreement with NNLO predictions with different parametrisations of PDFs. Small tension in $W^+$ distribution at high $\eta^e$ (large PDF uncertanty region)

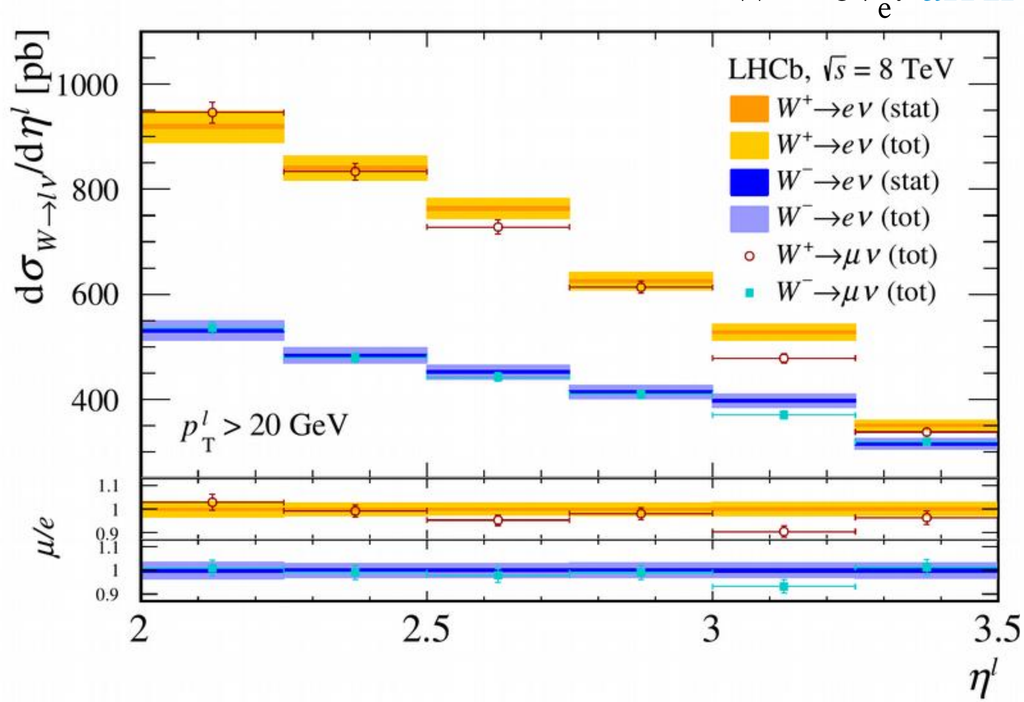


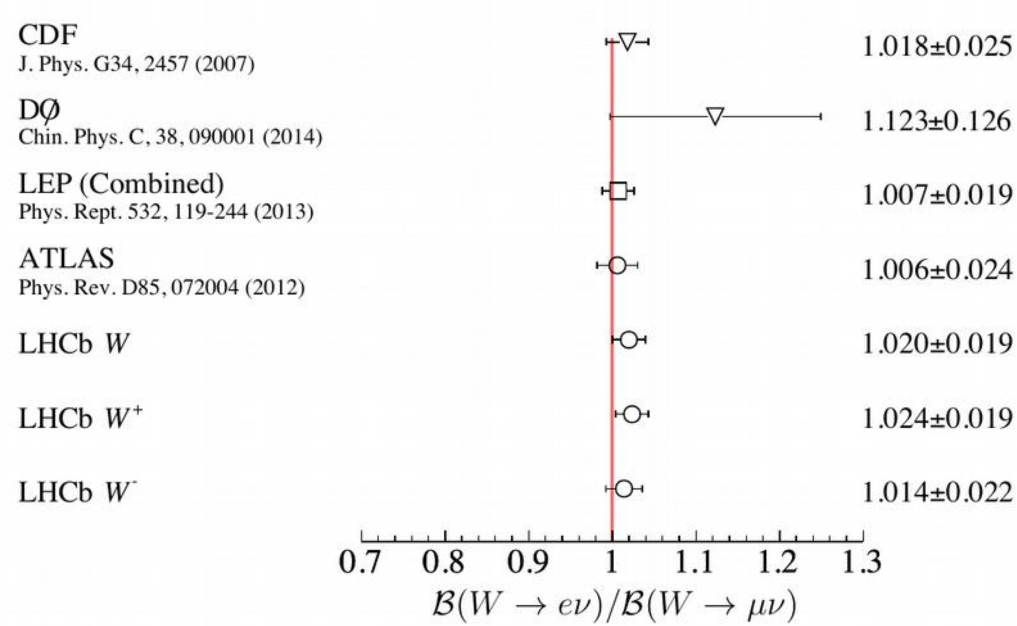



# Test of Lepton Universality

- Measurements coincide in kinematic region: $p_T^\ell > 20$ GeV/c; $2.00 < \eta^\ell < 3.50$
- Overall good agreement (also in charge asymmetries and cross-section ratios). Almost 3 σ tension in bin $3.00 < \eta^\ell < 3.25$ for $W^+$.
- Ratios of branching fractions exceed each previous determinations; comparable to combined LEP result.

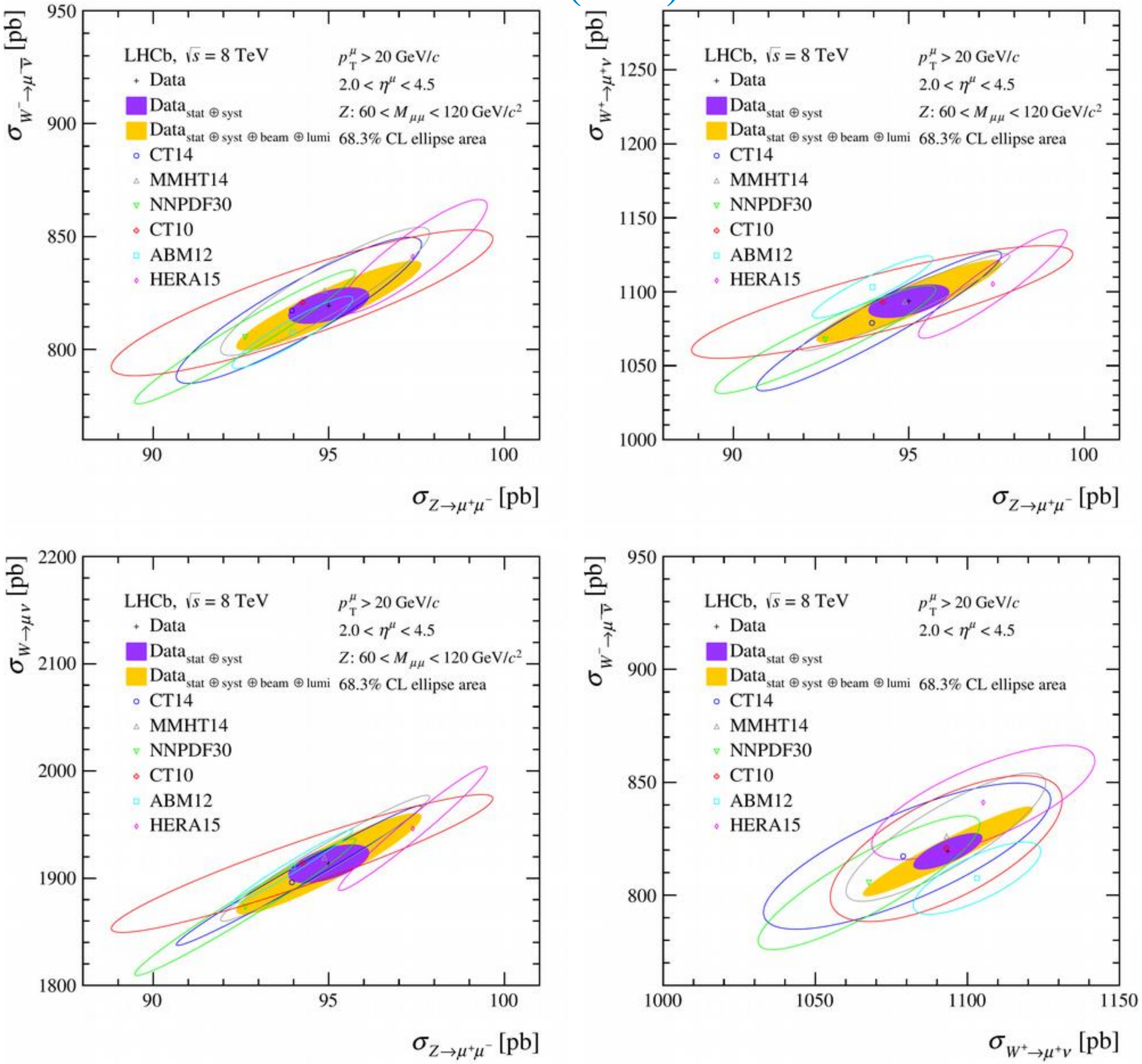
$W \to \mu\nu$: JHEP 01 (2016) 155
$W \to e\nu_e$: *arXiv: 1608.01484*



# W and Z Cross-sections

JHEP 01 (2016) 155




Correlation between cross-sections → systematic uncertainties cancel/reduce for asymmetries/ratios.

$$A_\ell = \frac{\sigma(W^+ \to \ell^+\nu_\ell) - \sigma(W^- \to \ell^-\bar{\nu}_\ell)}{\sigma(W^+ \to \ell^+\nu_\ell) + \sigma(W^- \to \ell^-\bar{\nu}_\ell)}$$

$$R_{W^\pm} = \sigma(W^+)/\sigma(W^-),$$
$$R_{W^+Z} = \sigma(W^+)/\sigma(Z),$$
$$R_{W^-Z} = \sigma(W^-)/\sigma(Z),$$
$$R_{WZ} = \frac{\sigma(W^+) + \sigma(W^-)}{\sigma(Z)}$$

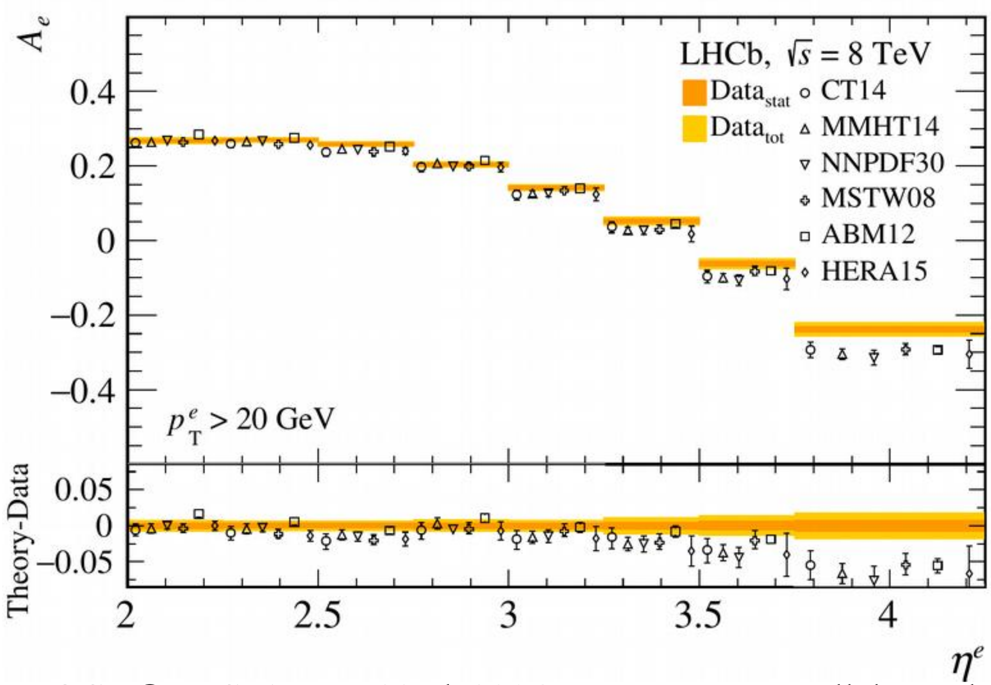
- Experimental uncertainties:
  - ✗ Luminosity
  - ✗ Efficiencies
  - ✗ Purity evaluation

- Theoretical uncertainties:
  - ✗ PDF uncertainties
  - ✗ scale uncertainties

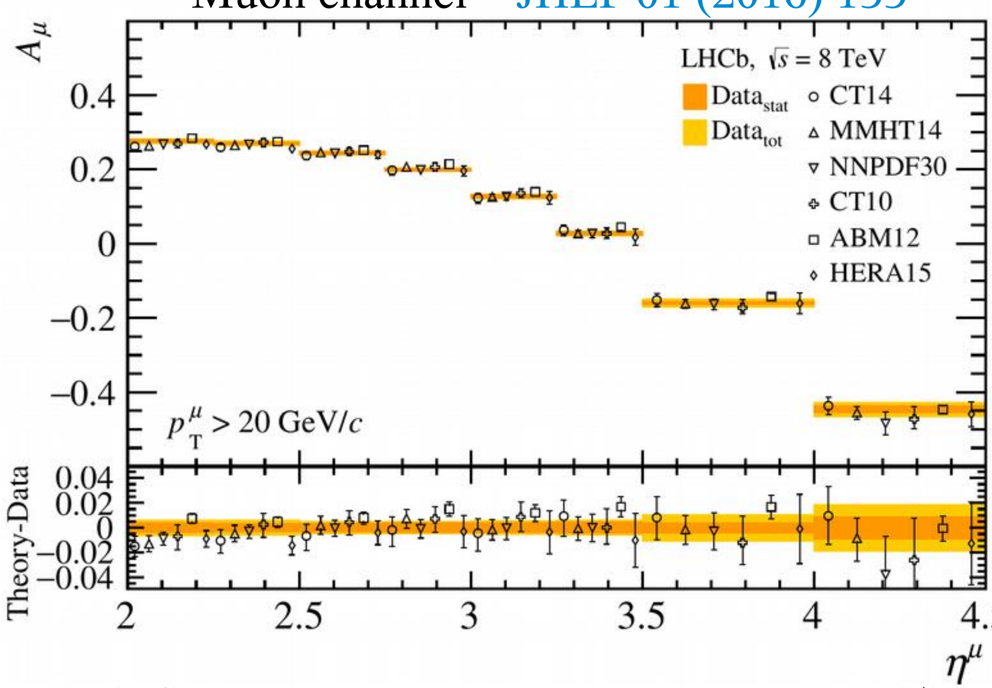
# Charge Asymmetries in W Leptonic Decays

- Charge asymmetries for W and $R_{W\pm}$ probe differences between distributions of *u* and *d* valence quarks in protons
- Good agreement with NNLO theory predictions configured with a series of PDFs
  For electron decay channels, difference at high η due to observed tension in $W^+$ cross-section

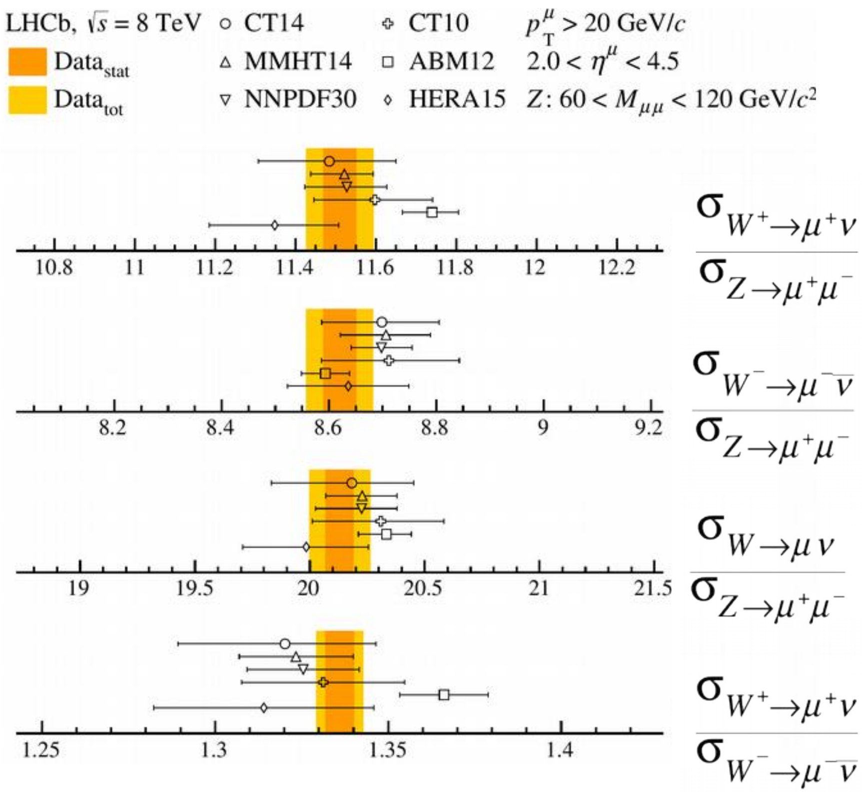
Electron channel – arXiv: 1608.01484



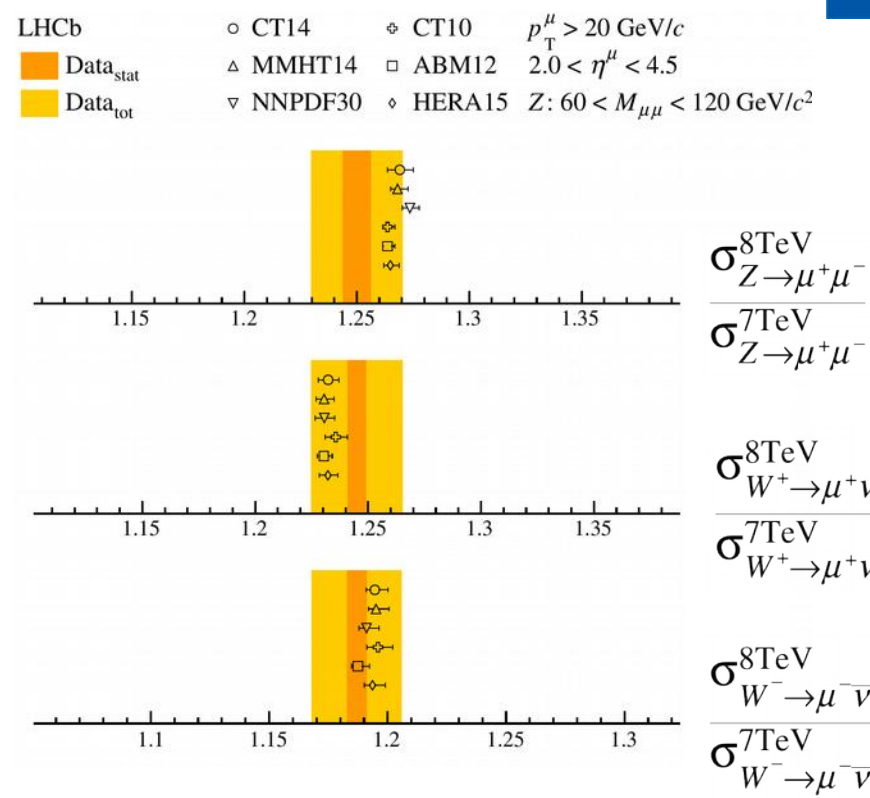

Muon channel – JHEP 01 (2016) 155



# Cross-section Ratios




JHEP 01 (2016) 155




- $R_{W\pm}$ smaller uncertainties (mainly statistical) than theoretical predictions
- Probing strange content of proton $R_{W\pm Z}(\eta)$
- PDF uncertainties very much reduced in cross-section ratios at different $\sqrt{s}$

- Smaller experimental errors recommend ratios for strict testing of pQCD models and improvement of PDFs* at high/low-x where their uncertainties are largest

*Talks by Katharina Müller and Voica Rădescu in plenary session tomorrow morning.

# Z Production Asymmetry. Weinberg Angle

Weinberg (weak mixing) angle $\theta_W$ free MSM parameter of electroweak(EW) Lagrangian:

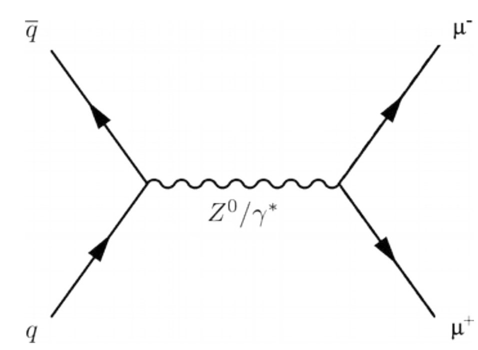
$$\mathcal{L}_{\mathrm{EW}} = \sum_{\psi} \bar{\psi}\gamma^{\mu}\left(i\partial_{\mu} - \frac{g'}{2}Y_{\mathrm{W}}B_{\mu} - \frac{g}{2}{}_{\mu}\right)\psi, \qquad \cos\theta_{\mathrm{W}} = \frac{g}{\sqrt{g^2+g'^2}} = \frac{M_W}{M_Z}$$

- Z couplings differ for left- and right-handed fermions → asymmetry in angular distribution of negative and positive daughter leptons

- $\mathbf{sin^2\theta^{eff}_W}$ defined as function of the ratio of vector(V) and axial-vector(A) effective (including higher order EW corrections) couplings of the Z boson to daughter leptons ~ $\mathbf{sin^2\theta_W}$.

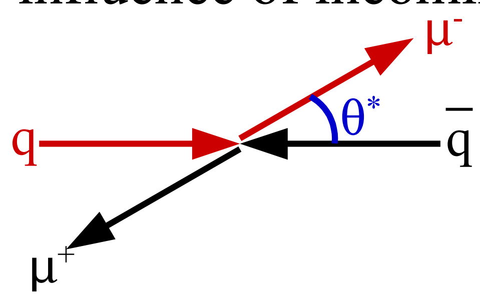
- $\mathbf{sin^2\theta^{eff}_W}$ measurements at $e^-e^+$ colliders differ by 3 standard deviations. Measured also at hadron colliders by D0, CDF, ATLAS, CMS.

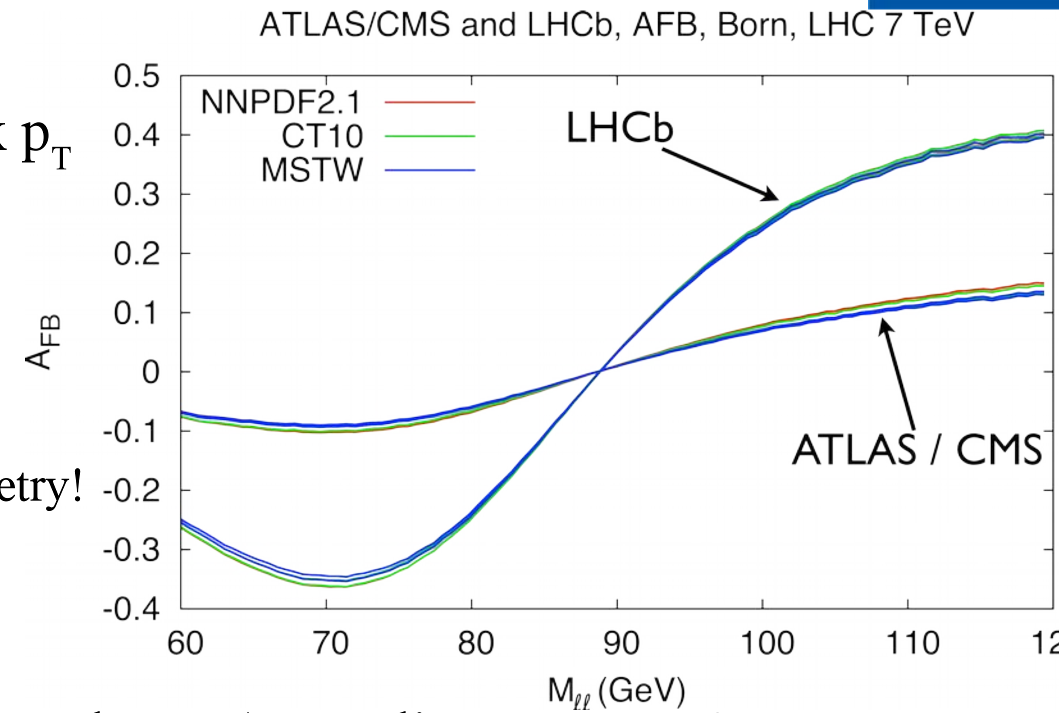
- LHCb measured Z asymmetry in the process $\mathbf{q\bar{q} \to Z/\gamma^* \to \mu^-\mu^+}$



# Z Production Asymmetry. Weinberg Angle

- **Collins-Soper** (dimuon rest) frame
  – minimize influence of incoming quark $p_T$




- Z angular distribution:

generates asymmetry! (→ $B\cos\theta^*$)

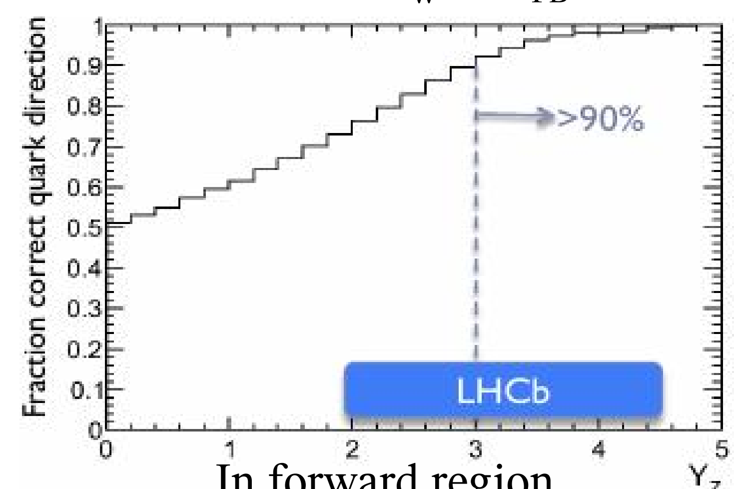
$$\frac{d\sigma}{d\cos\theta^*} = A(1+\cos^2\theta^*) + B\cos\theta^*$$

A, B ~ dimuon mass, color charge of quarks, V-A couplings; B ~ $\mathbf{\sin^2\theta_W}$ ~ $A_{FB}$

- forward-backward asymmetry:

$$A_{\mathrm{FB}} = \frac{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}{N(\cos\theta^* > 0) + N\cos\theta^* < 0)}$$

- Symmetric pp collisions @ LHC
  - high-x valence quark + sea anti-quark → Z boson
  - initial quark direction inferred from Z momentum
  - "dilution" of $A_{FB}$ sensitivity to $\mathbf{\sin^2\theta^{eff}_W}$

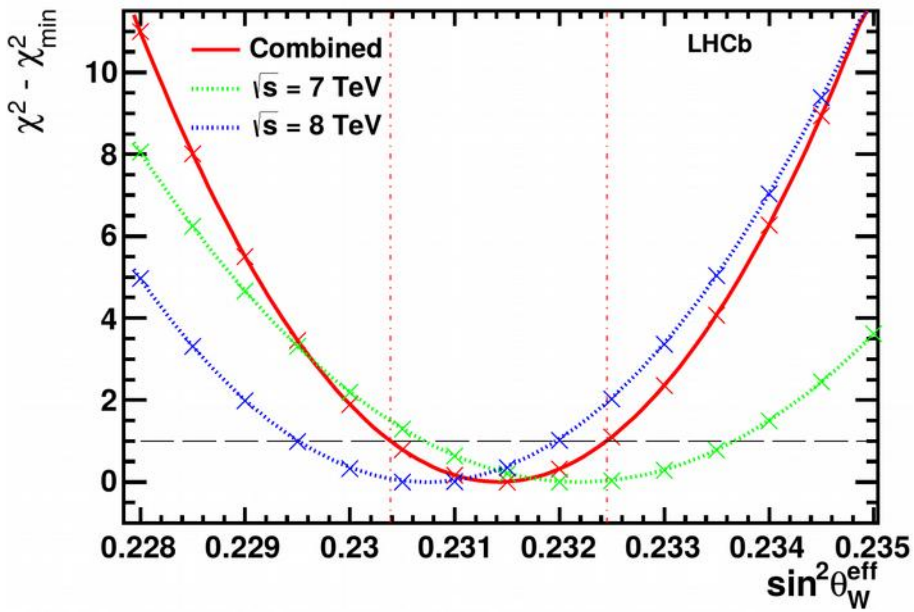



In forward region
better precision on $A_{FB}$

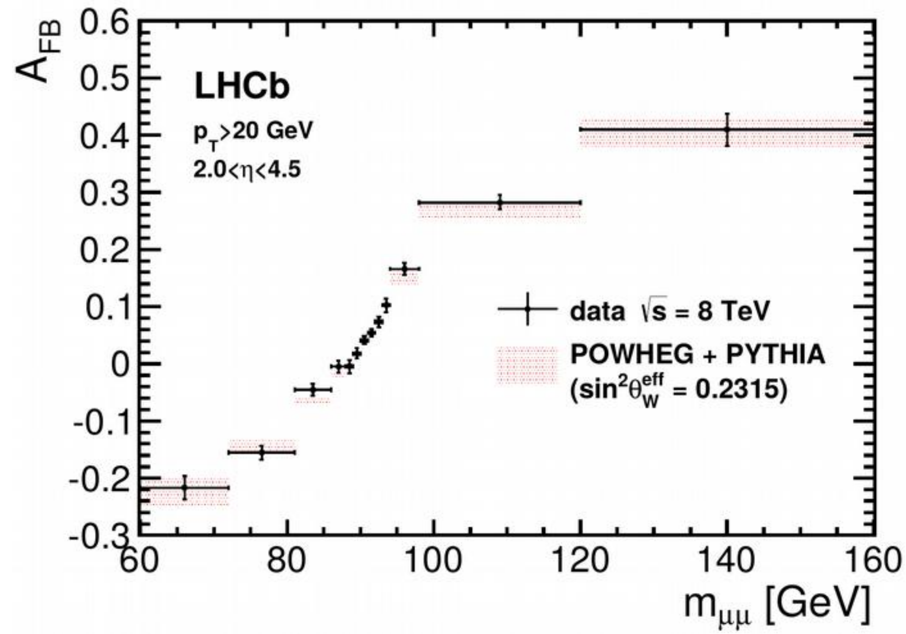
A. Vicini, WG on EW @ LHC, 28-30 Nov. 2011, CERN

# Z Production Asymmetry. Weinberg Angle

JHEP 11 (2015) 190

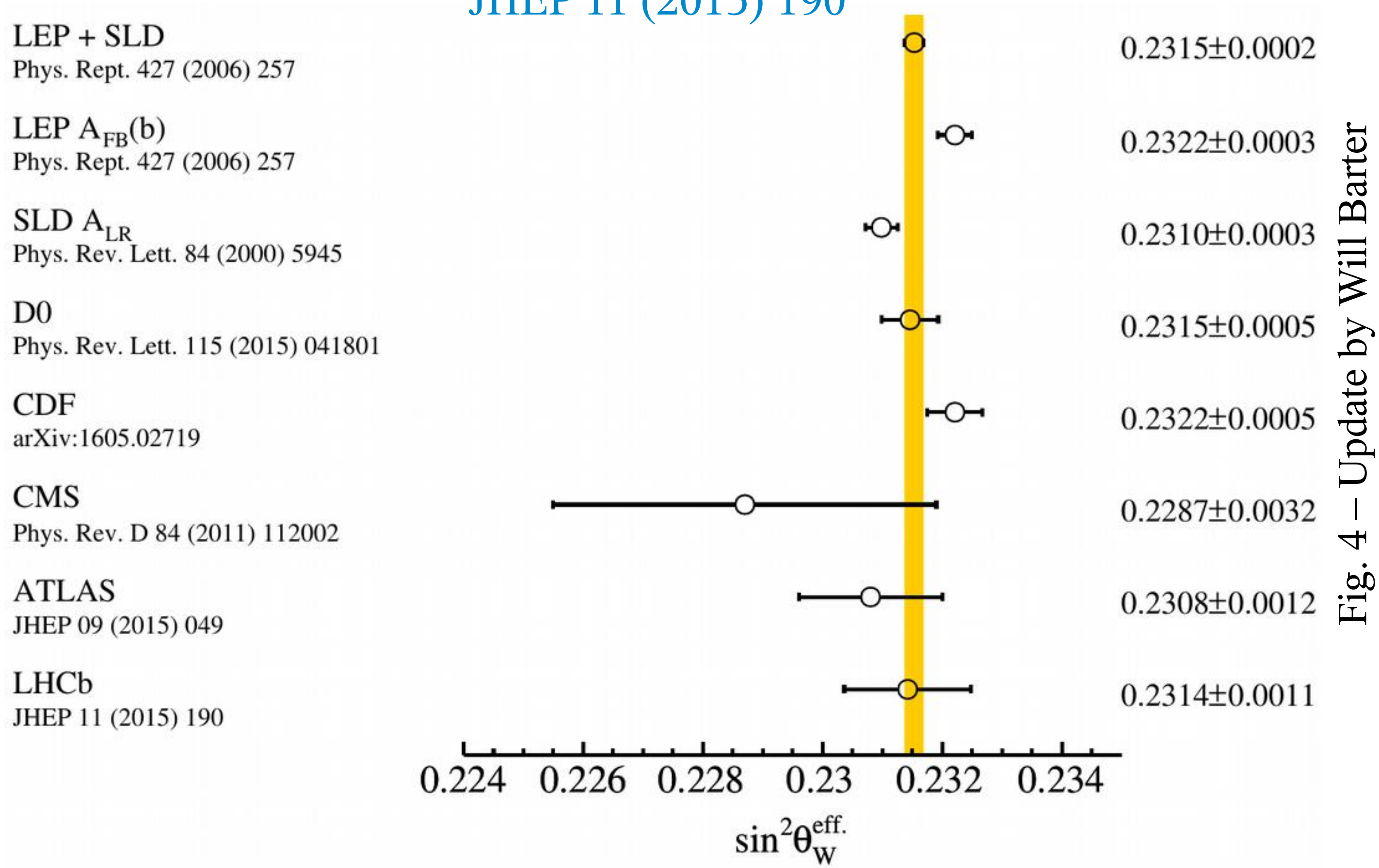



- Same selection as inclusive
  Z → μμ measurement
- $\sin^2\theta^{eff}_W$ estimated from comparison to simulation (POWHEG+PYTHIA, NNPDF2.3) considering the min. of a $\chi^2$ w/ respect to measured $A_{FB}$
- Statistically limited – more data expected in Run II → double differential $A_{FB}$ ( $m_{\mu\mu}$, $\eta_\mu$ )
- Main systematic error:
  momentum scale uncertainty
- $A_{FB}$ distributions in good agreement with SM predictions



# Z Production Asymmetry. Weinberg Angle

JHEP 11 (2015) 190




Measurement for combined 7 and 8 TeV data sets (~ 3 $fb^{-1}$):

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

PDFs, scale, $\alpha_s$, FSR

**LHCb result consistent with world average; most precise from hadron colliders !**

# Conclusions & Outlook

- LHCb acceptance complementary to ATLAS and CMS
  – sensitivity to high and low Björken-x
  – very low experimental uncertainties

- Many precision measurements involving EW boson production
  – constraints on PDFs
  – more stringent tests on SM pQCD models
  – testing the lepton universality at precisions comparable to LEP
  – most precise determination at hadron colliders of weak mixing angle empiric SM parameter

- More to follow:
  – increased precision with more data ~ 2/fb/year in LHC Run II
  – measurements of cross-sections and ratios at higher energies to infer the existence of physics beyond Standard Model

Thank you!

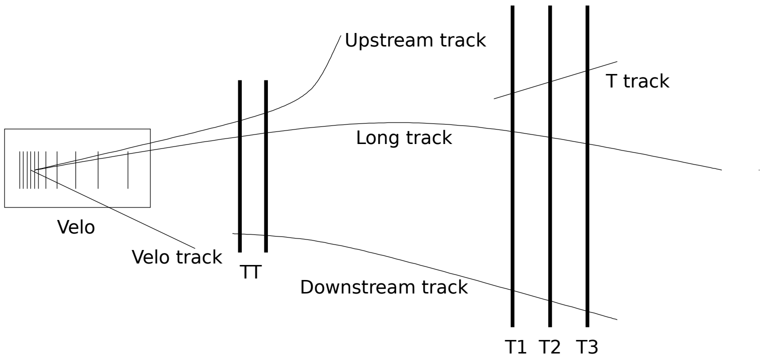
# BACKUPS

# The LHCb detector and the Forward Region

## LHCb Detector Performance

IJMP A30 (2015) 1530022

- Impact Parameter (IP) resolution: (15 + 29/$p_T$[GeV/c]) μm, i.e., ~ 20 μm at high $p_T$
- Momentum resolution: Δp/p ~ 0.5 % (p < 20 GeV/c) → 1.0 % (p ~ 200 GeV/c)
- ECAL resolution (nominal): 1 % + 10 %/ √(E[GeV])
- Invariant mass resolution:
  - ~8 MeV/$c^2$ for B → J/ψ X decays with constraint on J/ψ mass
  - ~22 MeV/$c^2$ for two-body B decays
  - ~100 MeV/$c^2$ for Bs → φ γ, dominated by photon contribution
- Trigger efficiencies:
  - ~90 % for dimuon channels
  - ~30 % for multi-body hadronic final states
- Track reconstruction efficiency: ~ 96% for Long Tracks
- Particle ID efficiency:
  - Electron ID ~ 90 % for ~ 5 % e→h mis-id probability
  - Kaon ID ~ 95 % for ~ 5 % π→K mis-id probability
  - Muon ID ~ 97 % for 1-3 % π→μ mis-id probability
- Integrated luminosity for datasets:
  - 7 TeV (2011): 1.0/fb ± 1.7%
  - 8 TeV (2012): 2.0/fb ± 1.2%
  - 13 TeV (2015): 0.3/fb ± 3.9% (to improve in 2016)
- Data taking efficiency: 90% (99% good for physics analyses)



# $Z \to \ell^+ \ell^-$

Total cross-sections (at Born level):

- 7 TeV: JHEP 02 (2013) 106; JHEP 08 (2015) 039

$$\sigma(Z \to ee) = 76.0 \pm 0.8\ (\text{stat}) \pm 2.0\ (\text{sys}) \pm 2.6\ (\text{lumi}) \pm 0.4\ (\text{FSR})\ \text{pb}$$

$$\sigma(Z \to \mu\mu) = 76.0 \pm 0.3\ (\text{stat}) \pm 0.5\ (\text{sys}) \pm 1.0\ (\text{beam}) \pm 1.3\ (\text{lumi})\ \text{pb}$$

- 8 TeV: JHEP 05 (2015) 109

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

$$\sigma(Z \to \ell\ell) = 94.9 \pm 0.2\ (\text{stat}) \pm 0.6\ (\text{sys}) \pm 1.1\ (\text{beam}) \pm 1.1\ (\text{lumi})\ \text{pb}\ ;\ \ell = e\ \&\ \mu$$

- 13 TeV: arXiv: 1607.06495

$$\sigma(Z \to ee) = 190.2 \pm 0.9\ (\text{stat}) \pm 4.7\ (\text{sys}) \pm 7.7\ (\text{lumi})\ \text{pb}$$

$$\sigma(Z \to \mu\mu) = 198.0 \pm 1.7\ (\text{stat}) \pm 4.7\ (\text{sys}) \pm 7.4\ (\text{lumi})\ \text{pb}$$

$$\sigma(Z \to \ell\ell) = 194.3 \pm 0.9\ (\text{stat}) \pm 3.3\ (\text{sys}) \pm 7.6\ (\text{lumi})\ \text{pb}$$

# $W^{\pm} \rightarrow \ell\, \nu$

## Total cross-sections (at Born level):

- 7 TeV: JHEP 08 (2015) 039; arXiv: 1608.01484

$$\sigma(W^+ \rightarrow \mu^+ \nu) = 878.0 \pm 2.1\ (\text{stat}) \pm 6.7\ (\text{sys}) \pm 9.3\ (\text{beam}) \pm 15.0\ (\text{lumi})\ \text{pb}$$

- $\sigma(W^- \rightarrow \mu^- \bar{\nu}) = 689.5 \pm 2.0\ (\text{stat}) \pm 5.3\ (\text{sys}) \pm 6.3\ (\text{beam}) \pm 11.8\ (\text{lumi})\ \text{pp}$

- 8 TeV: JHEP 01 (2016) 155

$$\sigma(W^+ \rightarrow \mu^+ \nu) = 1093.6 \pm 2.1\ (\text{stat}) \pm 7.2\ (\text{sys}) \pm 10.9\ (\text{beam}) \pm 12.7\ (\text{lumi})\ \text{pb}$$

$$\sigma(W^- \rightarrow \mu^- \bar{\nu}) = 818.4 \pm 1.9\ (\text{stat}) \pm 5.0\ (\text{sys}) \pm 7.0\ (\text{beam}) \pm 9.5\ (\text{lumi})\ \text{pb}$$

$$\sigma(W^+ \rightarrow e^+ \nu_e) = 1124.4 \pm 2.1\ (\text{stat}) \pm 21.5\ (\text{sys}) \pm 11.2\ (\text{beam}) \pm 13.0\ (\text{lumi})\ \text{pb}$$

$$\sigma(W^- \rightarrow e^- \bar{\nu}_e) = 809.0 \pm 1.9\ (\text{stat}) \pm 18.1\ (\text{sys}) \pm 7.0\ (\text{beam}) \pm 9.4\ (\text{lumi})\ \text{pb}$$

$$\sigma(W \rightarrow e\, \nu) = 1933.3 \pm 2.9\ (\text{stat}) \pm 38.2\ (\text{sys}) \pm 18.2\ (\text{beam}) \pm 22.4\ (\text{lumi})\ \text{pb}$$

# $Z \rightarrow \ell^+ \ell^-$ @ 13 TeV

New !

- Good agreement:
  - Measurements slightly larger than NNLO pQCD (+ different PDF sets) at low $y_Z$
  - Lower systematic effects in $p_T$, $\phi^*$ distributions (statistically dominated)
  - PYTHIA 8 predictions better than (POWHEG + PYTHIA8 – NLO)
  - No significant difference between LHCb and Monash 2013 tunes

arXiv: 1607.06495