Electroweak Results in LHCb

Federico Betti on behalf of the LHCb collaboration

LHC Days in Split

September 22, 2016

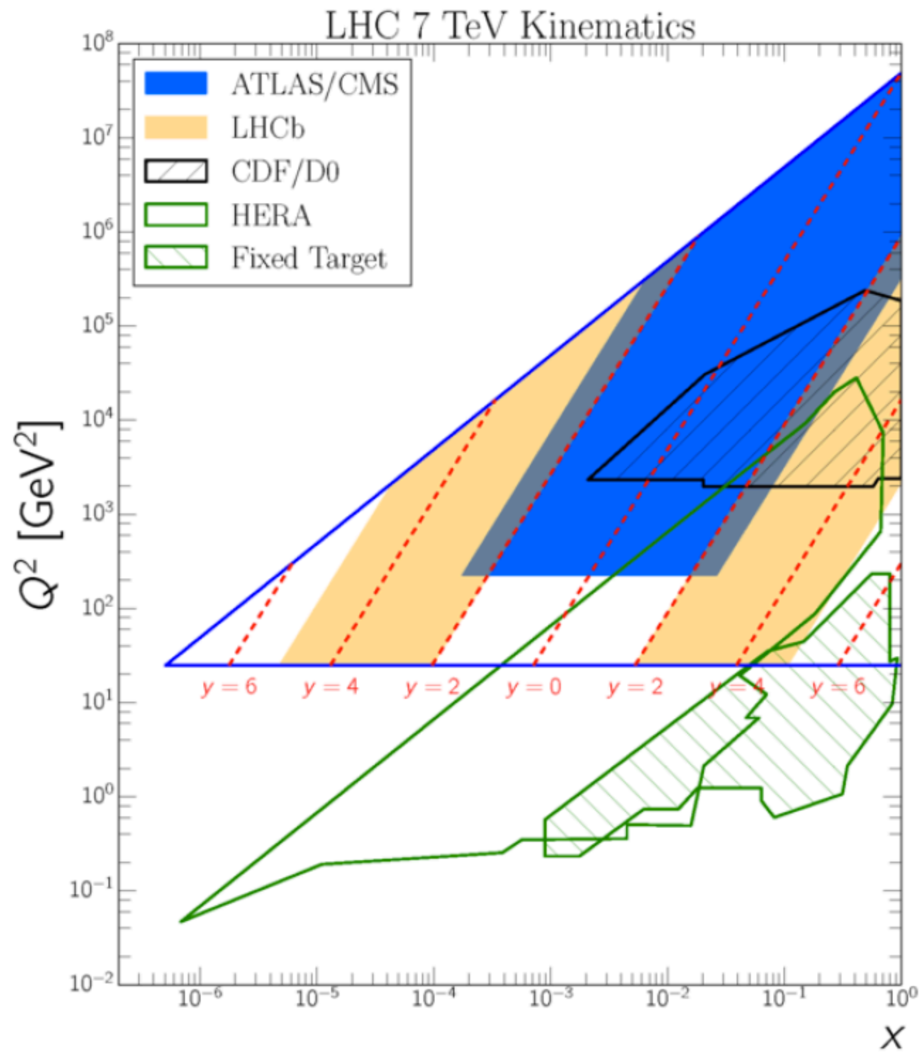
Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

Outline

- Motivations to study EW bosons processes
- The LHCb detector
- $Z \to ll$ forward production
- $W \to l\nu$ forward production
- Cross-section ratios and W charge asymmetries
- W/Z production with jets
- Z production asymmetries

Motivations

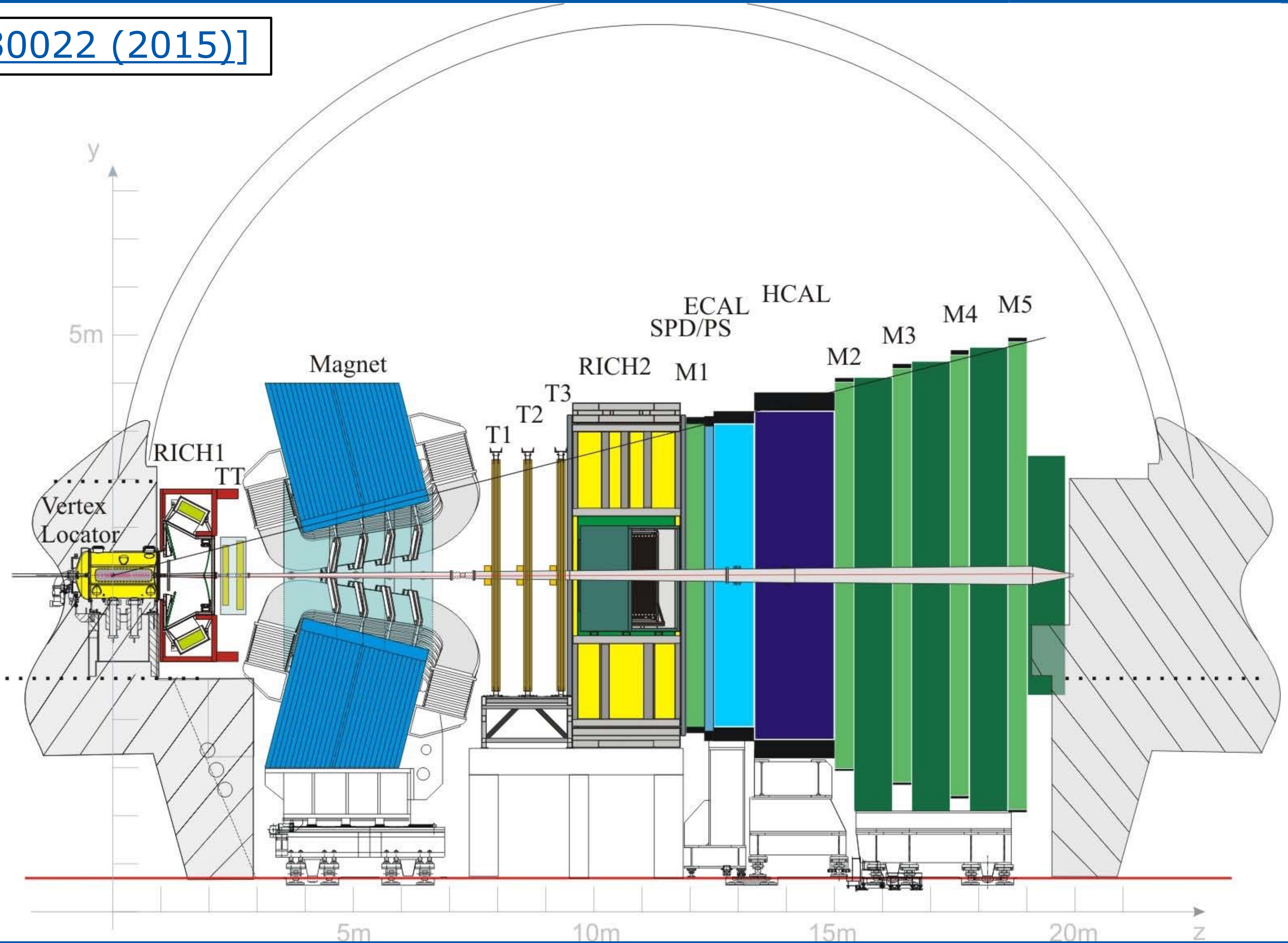
- Measurements of EW bosons production cross section constrain **PDFs** in protons
- LHCb acceptance → access to Bjorken−$\boldsymbol{x} \approx \mathbf{10^{-4}}$
- W/Z cross-section ratio → **tests of the SM**
- A_{FB} in Z production → precise measurement of $\boldsymbol{\sin^2 \theta_W^{eff}}$



The LHCb detector

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

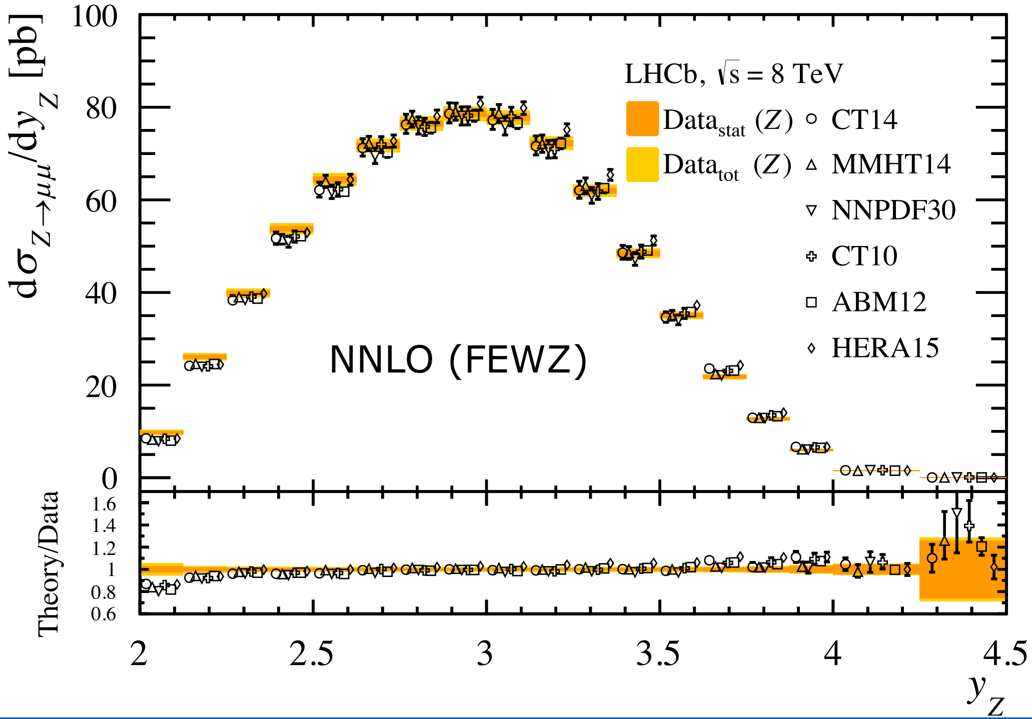
- Single arm spectrometer in $2 < \eta < 5$ range
- Excellent **vertex** resolution ($13\ \mu m$ in transverse plane for primary vertex)
- Excellent **IP** resolution ($\sim 13\ \mu m$ on the transverse plane)
- Very good **momentum** resolution ($\delta p/p \sim 0.5\% - 0.8\%$)
- Excellent **PID** capabilities
- Very good **trigger** efficiency ($\sim 90\%$)



$Z \rightarrow \mu^+\mu^-$ forward production

- Two muons with $2.0 < \eta < 4.5$, $p_T > 20\ \mathrm{GeV}$, $60 < m(\mu\mu) < 120\ \mathrm{GeV}$
- Signal **purity** ≈ 99%
- **Differential** cross-sections in bins of y_Z, $p_{T,Z}$, ϕ^*_Z $\quad \phi^*_Z \equiv \frac{\tan(\phi_{\mathrm{acop}}/2)}{\cosh(\Delta\eta/2)}$
- Total **uncertainties** (dominated by **lumi** + **beam** energy) on total cross-section
  1. @ 7 TeV: 2.3% [JHEP 08 (2015) 039]
  2. @ 8 TeV: 1.8% [JHEP 01 (2016) 155]

Good overall **agreement** with predictions at NLO and **NNLO** for various PDFs

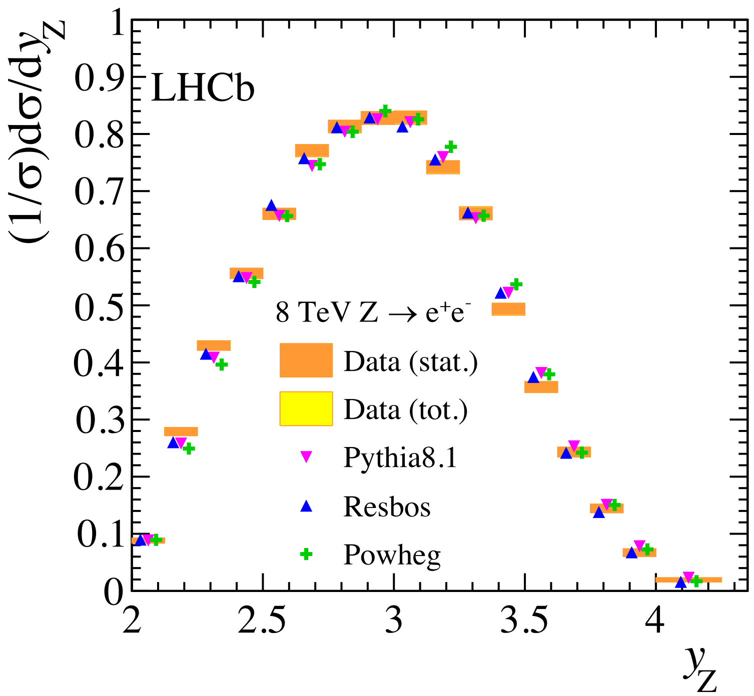


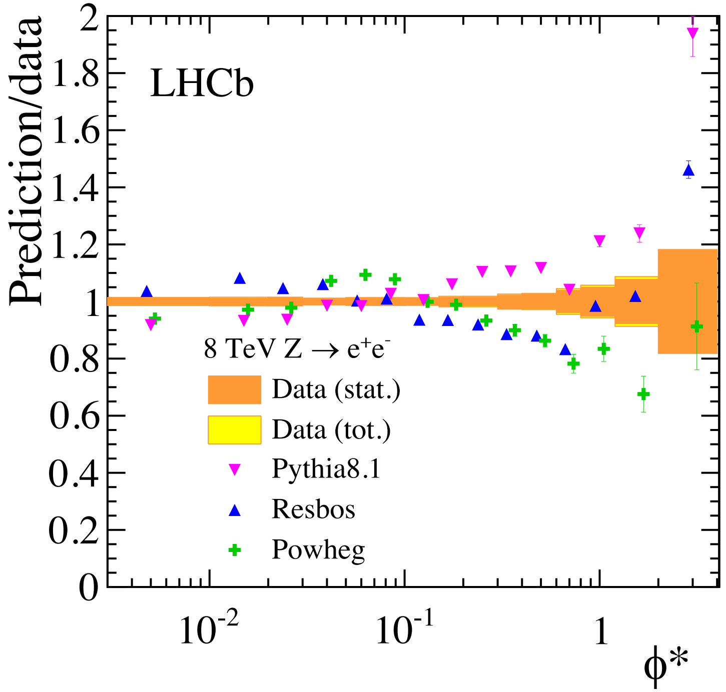
$Z \to e^+e^-$ forward production

- Two electrons with $2.0 < \eta < 4.5$, $p_T > 20$ GeV, $60 < m(ee) < 120$ GeV
- ECAL saturation ➔ limited **bremmstrahlung** recovery ➔ p_T not well known
- Results corrected to the **Born** level using MC
- Total **uncertainties** (dominated by **lumi**) on total cross-section
    1. @ 7 TeV: 4.4% [JHEP 02 (2013) 106]
    2. @ 8 TeV: 2% [JHEP 05 (2015) 109]

Rapidity distribution **well modelled** by NNLO predictions

Necessary **higher order** calculations to describe ϕ^* distribution



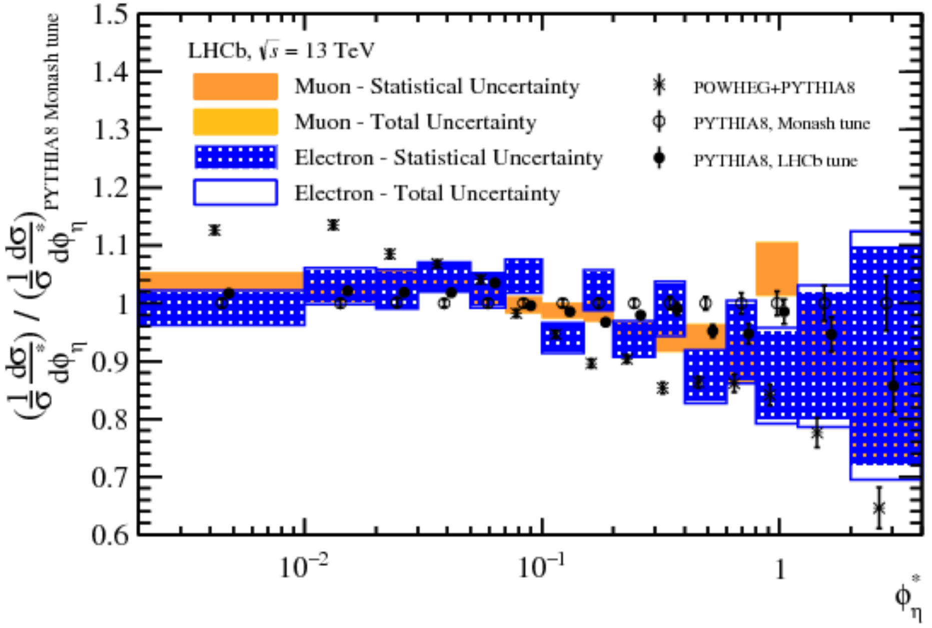


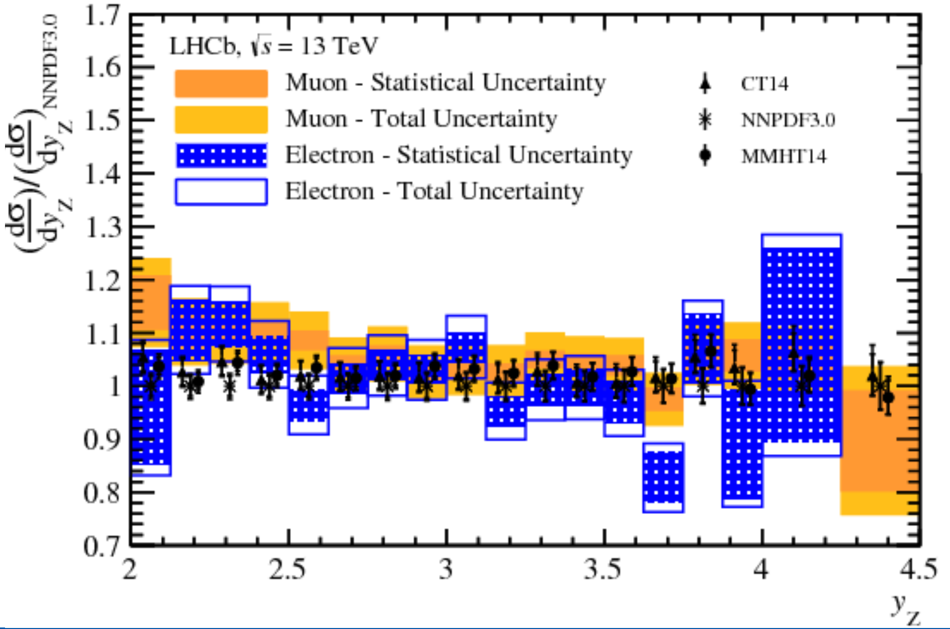
$Z \to l^+l^-$ forward production @ 13 TeV

[arXiv:1607.06495]

- $\mathbf{0.3\ fb^{-1}}$ dataset
- Same analysis strategy as in Run I
- Dominated by **lumi** uncertainty (3.9%)

- **No discrepancies** in y_Z (wrt $\mathcal{O}(\alpha_s^2)$ pQCD) and $p_{T,Z}$, ϕ_η^* (wrt higher orders pQCD) distributions
- No specific PDFs are favoured



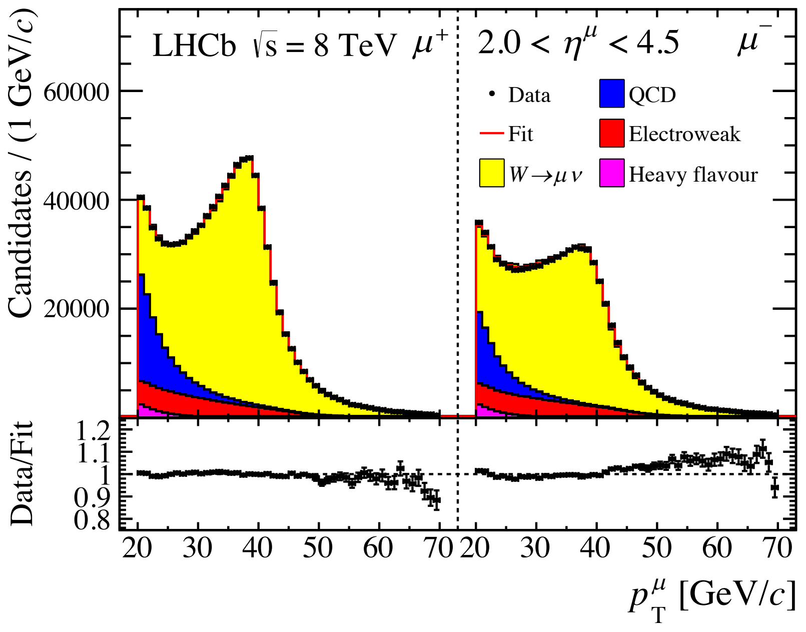


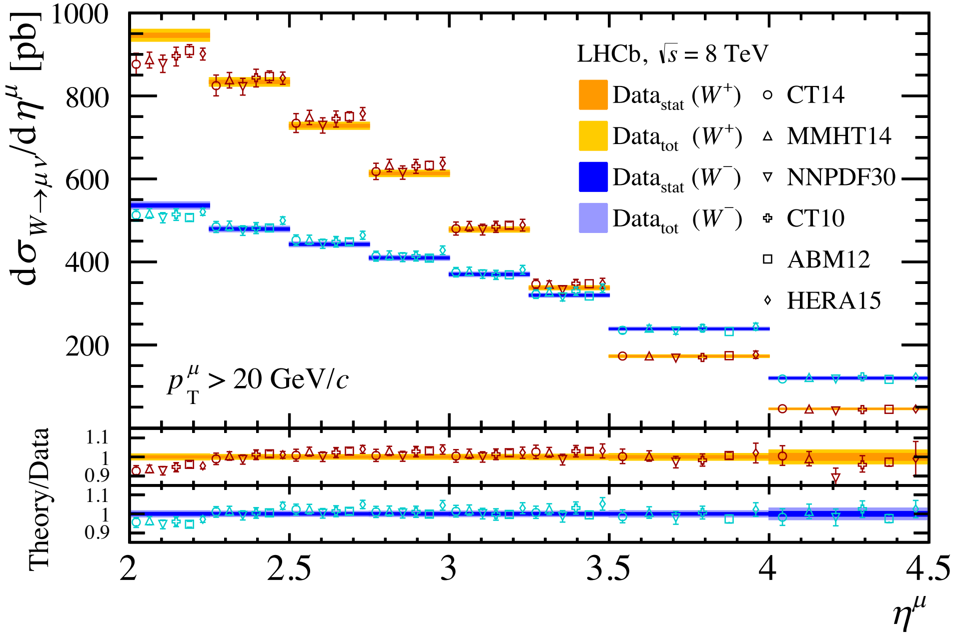
$W \to \mu\nu$ forward production

- Muon with $2.0 < \eta < 4.5$, $p_T > 20$ GeV
- **Isolated** muon, $E_{calo}/p < 4\%$, **veto** on other muon
- **Backgrounds**: heavy hadron decays, hadron mis-ID, EW processes
- **Purity** ≈ 77% from fit to $p_T(\mu)$

@7 TeV: [JHEP 12 (2014) 079]
@8 TeV: [JHEP 01 (2016) 155]

- Error dominated by **lumi** and beam **energy** uncertainties
- **Agreement** with NNLO predictions



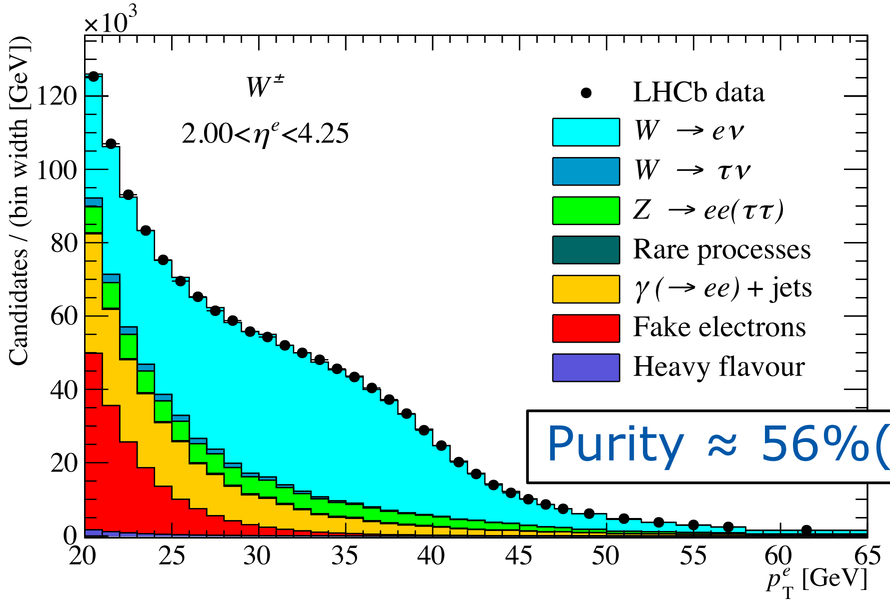


$W \rightarrow e\nu$ forward production (@ 8 TeV)

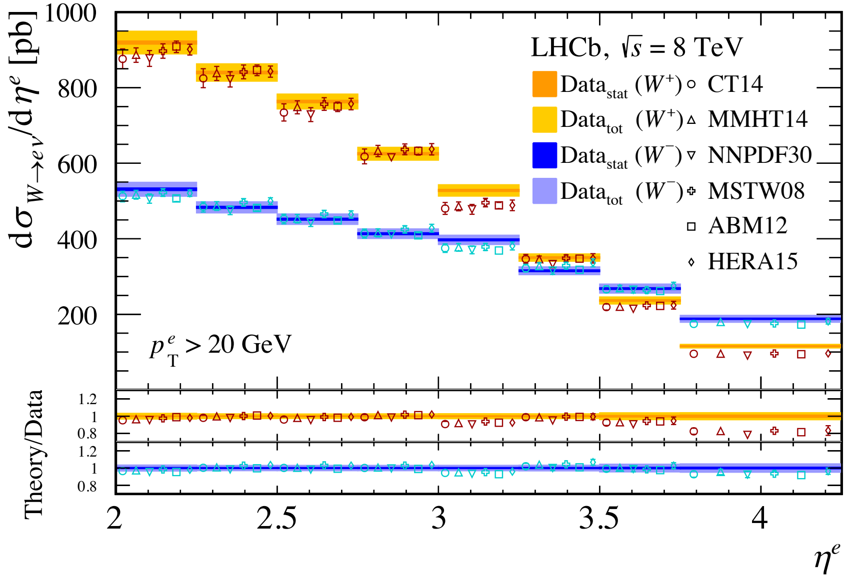
[arXiv:1608.01484]

- $2 < \eta < 4.25$ because of **ECAL acceptance**, $p_T > 20$ GeV
- ECAL **saturation** ➔ p_T not well known, but still useful to determine signal **yield**
- Cuts on **IP** and **isolation** requirements
- Similar backgrounds as $W \rightarrow \mu\nu$

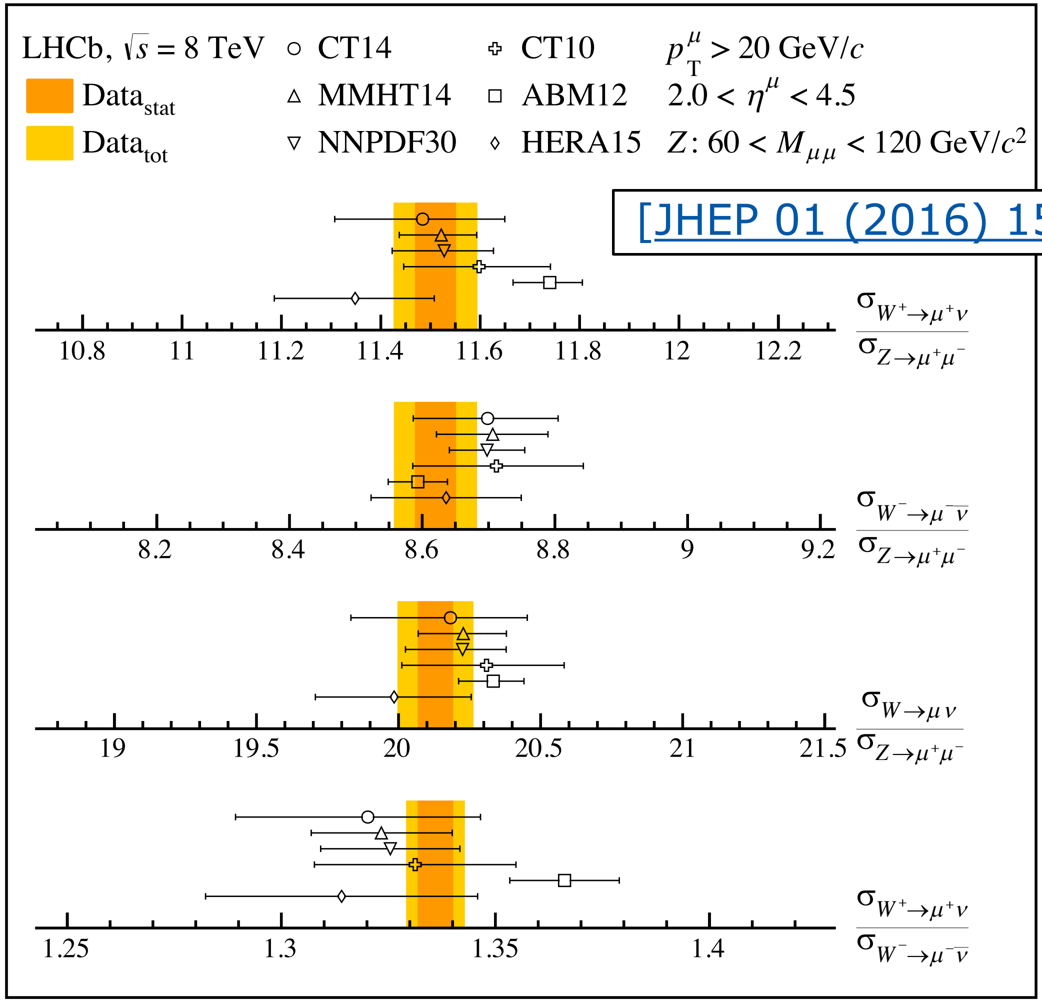
- 2.5% uncertainty, mainly due to **systematics**
- **Agreement** with NNLO calculations in pQCD



Purity ≈ 56%(W^-)-64%(W^+)



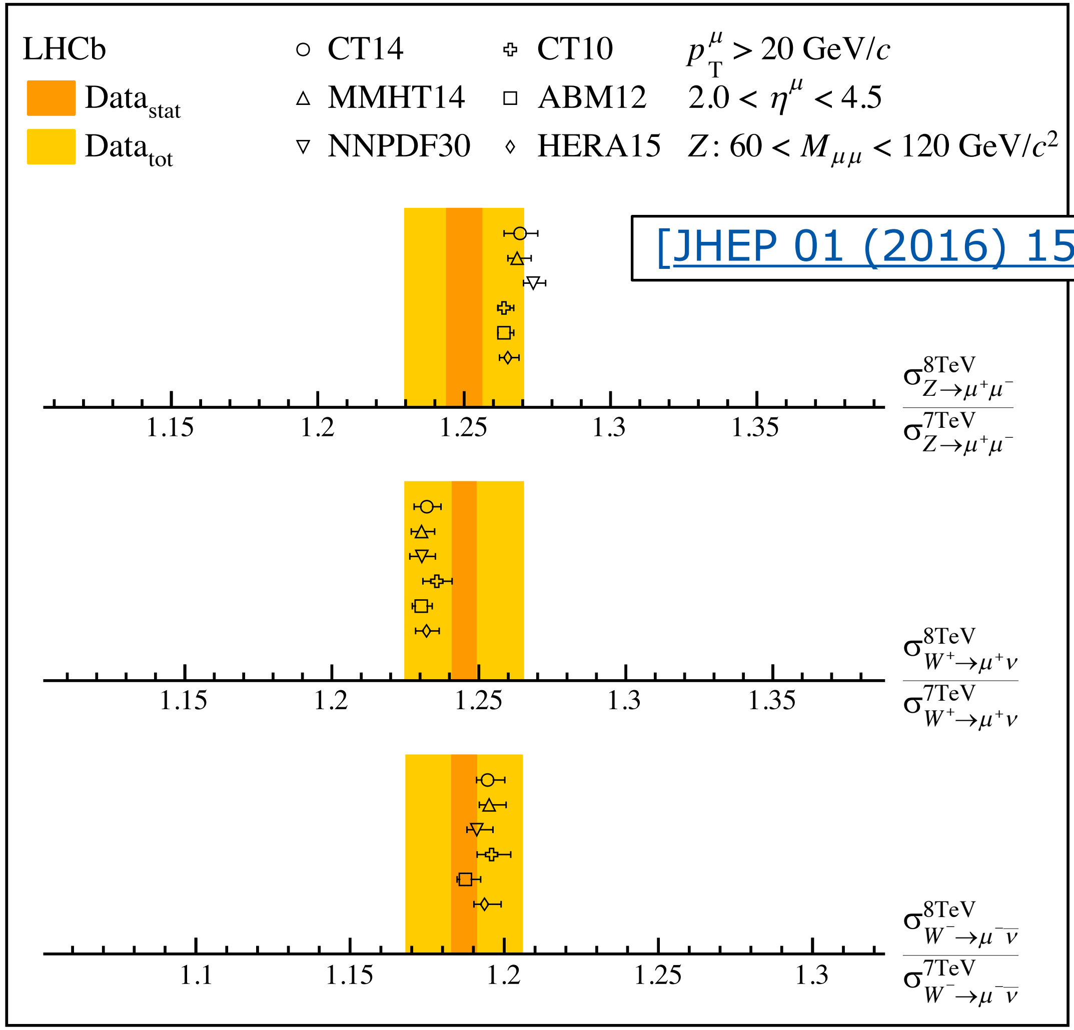
Cross-section ratios (W/Z)



[JHEP 01 (2016) 155]

- Many **uncertainties** are reduced/canceled in cross-section ratios
- Dominant uncertainties on the ratios are due to **purity** and samples **size**
- Test of the SM at **percent** level
- **Consistent** with $\mathcal{O}(\alpha_s^2)$ calculations
- More data from **Run II** will be very useful

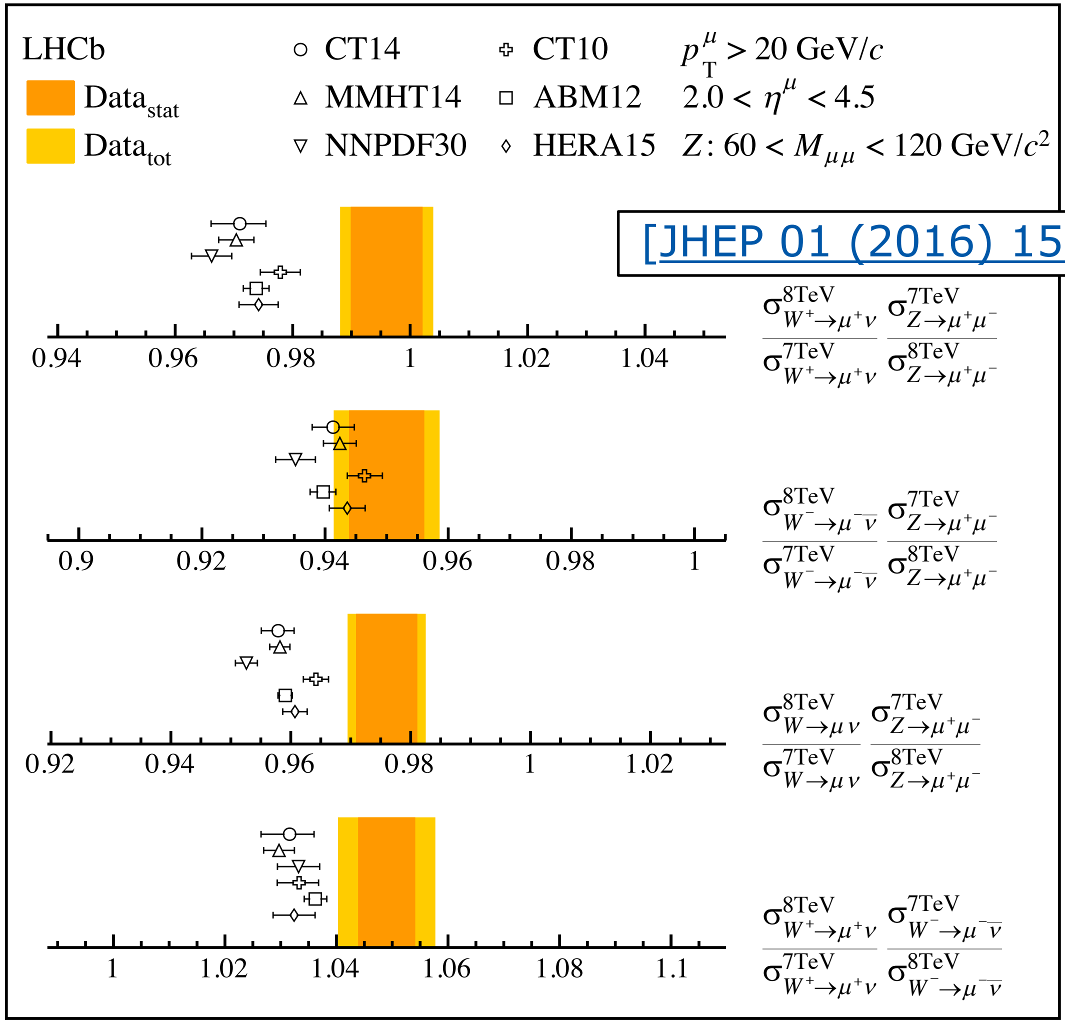
Cross-section ratios (8/7 TeV)



[JHEP 01 (2016) 155]

- Dominant uncertainty is due to **luminosity**
- **Per-mille** precision in theoretical predictions
- **Agreement** with expectations

Cross-section double ratios



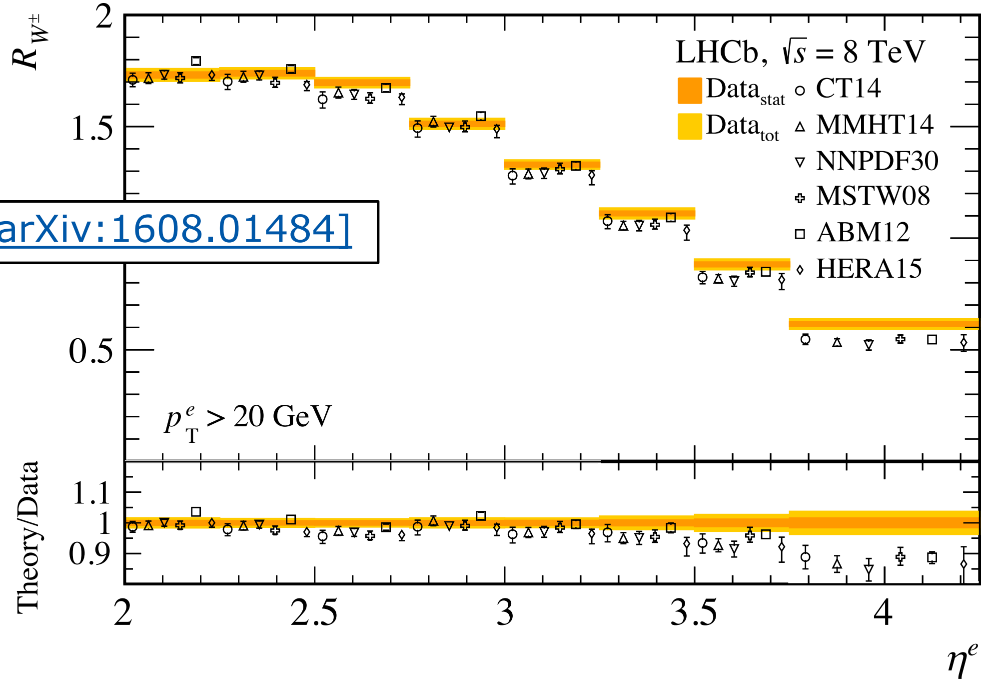
[JHEP 01 (2016) 155]

- Here the **luminosity** uncertainties cancel
- **Per-mille** precision in theoretical predictions
- **2σ** deviation for some ratios → **motivation** to extend the analysis at higher energies

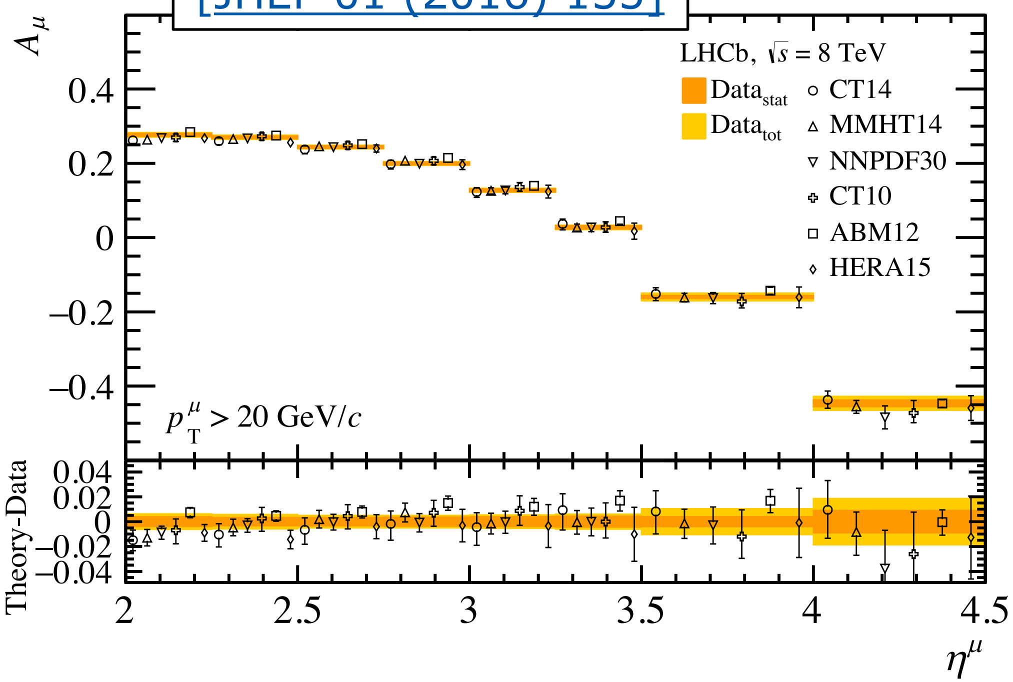
W charge asymmetries

- $\boldsymbol{\sigma(W^{+})/\sigma(W^{-})}$ useful to constrain the ratio between up and down valence quark in proton
- Good **agreement** with the SM

[arXiv:1608.01484]

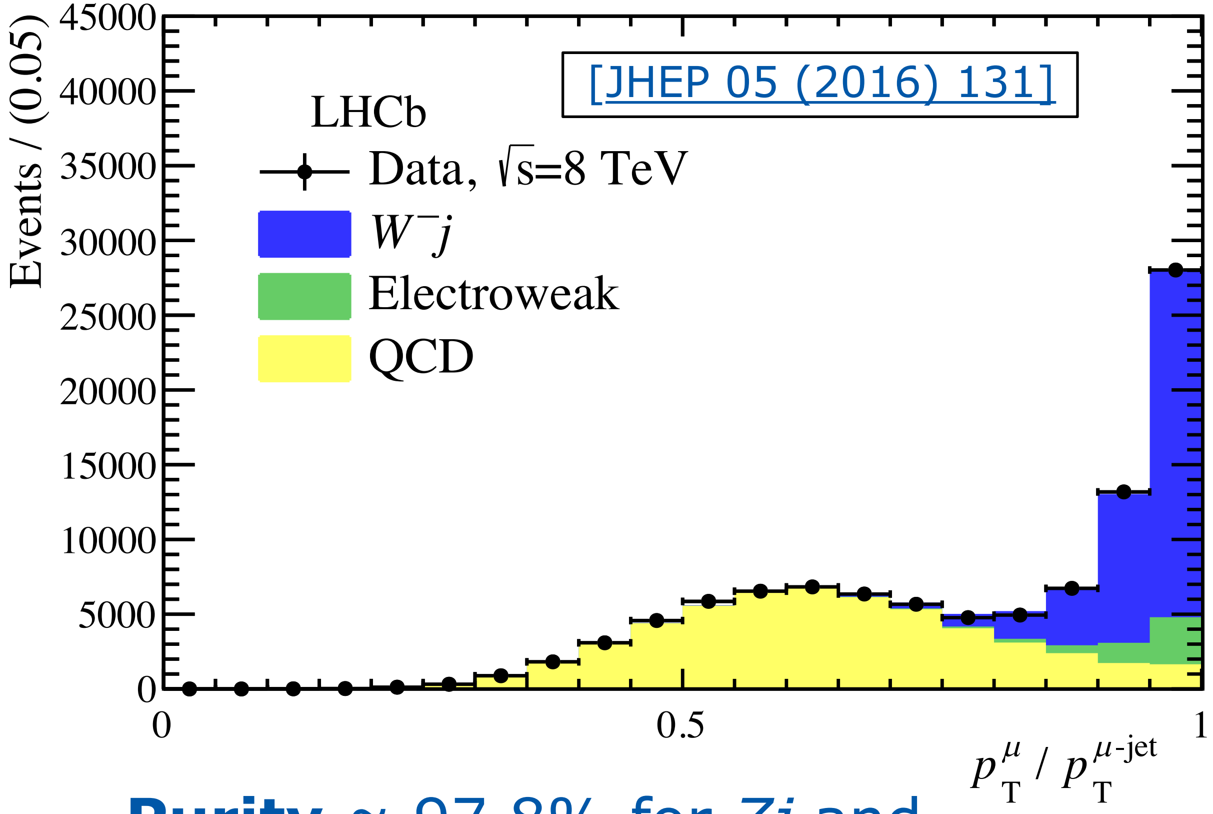


[JHEP 01 (2016) 155]



W+jet and Z+jet @ 8 TeV

- More sensitivity to the **gluon** PDF
- **Leptons**: same selection as for $W \to \mu\nu$ and $Z \to \mu\mu$
- **Jets**: reconstructed with anti-k_T algorithm, $p_T >$ 20 GeV, $2.2 < \eta^{jet} < 4.2$, pick highest p_T jet
- Measure **differential** cross-section in bins of:
  1. p_T^{jet}, η^{jet}, y^Z, $|\phi^Z - \phi^{jet}|$ for *Zj*
  2. p_T^{jet}, η^{jet}, η^{μ} for *Wj*

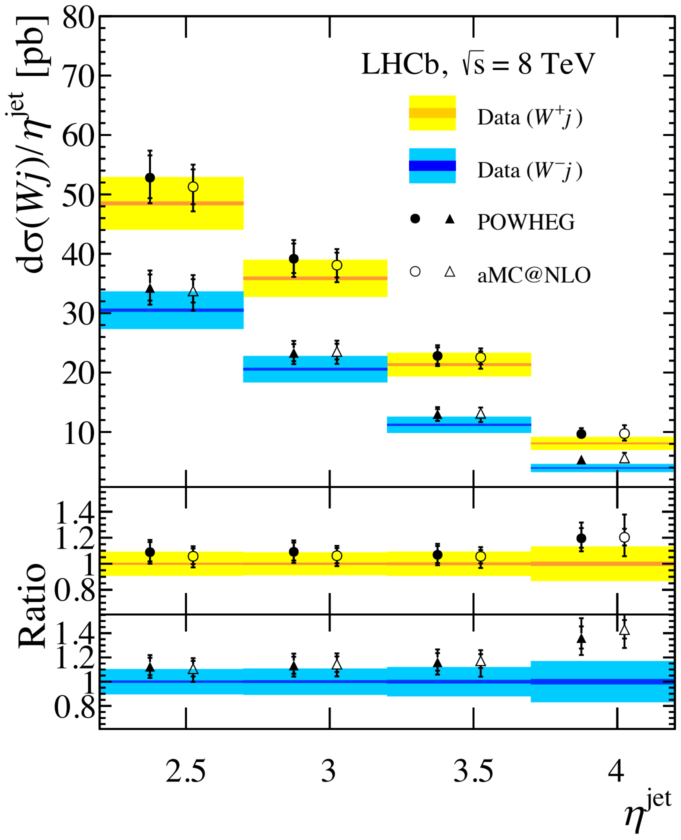


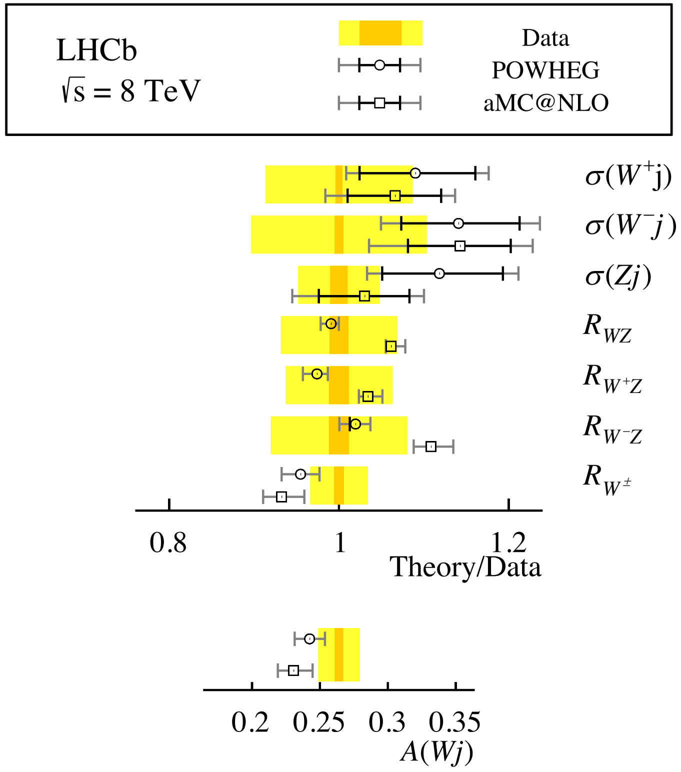
Purity ≈ 97.8% for *Zj* and 46.7(36.5)% for $W^+j(W^-j)$

W+jet and Z+jet @ 8 TeV

[JHEP 05 (2016) 131]

- **Uncertainties** on cross-sections: 9% (W^+j), 11% (W^-j), 5% (Zj)
- Uncertainty dominated by **jet energy** scale and **purity**
- **Good agreement** with predictions at $\mathcal{O}(\alpha_s^2)$ for all distributions

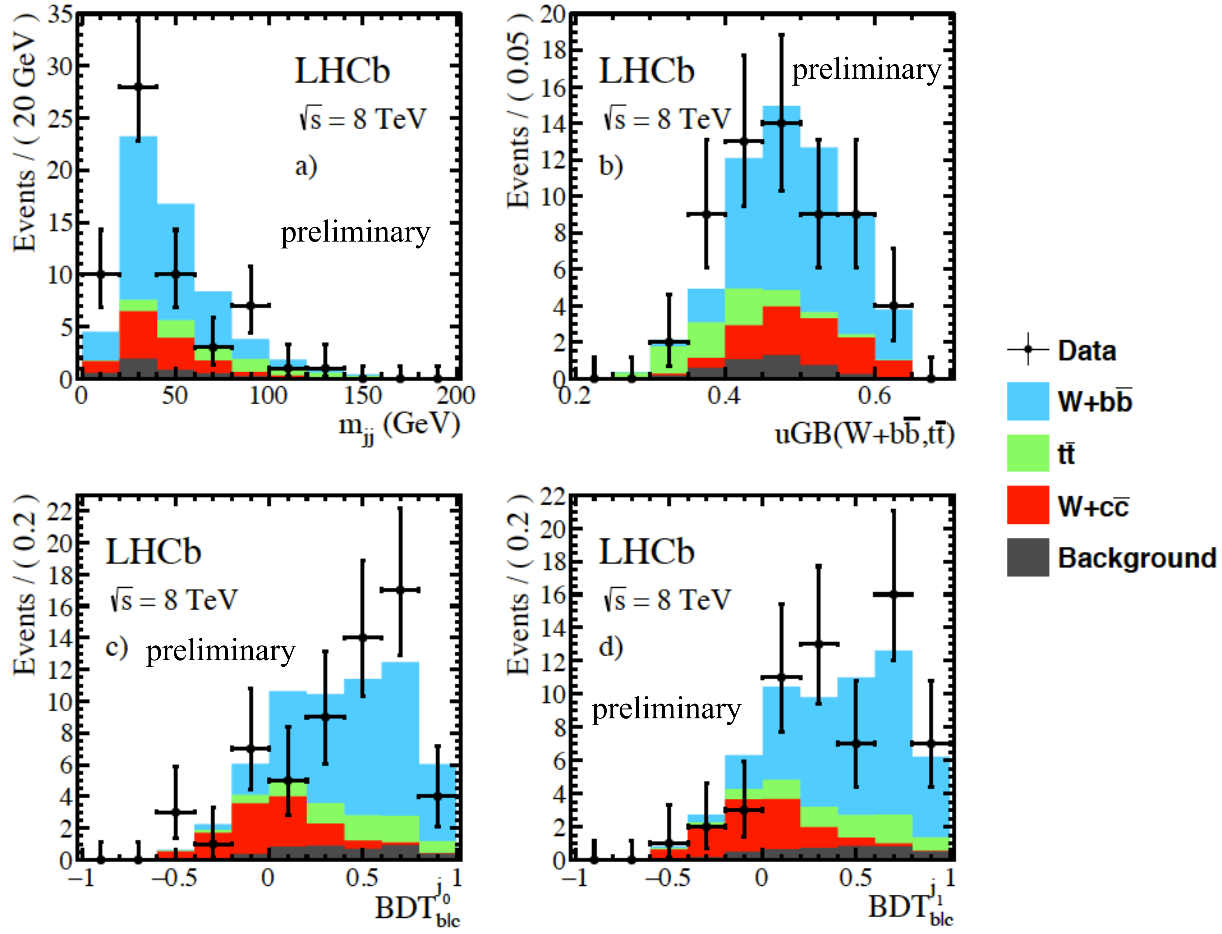




$W + b\bar{b}$, $W + c\bar{c}$, $t\bar{t}$ @ 8 TeV

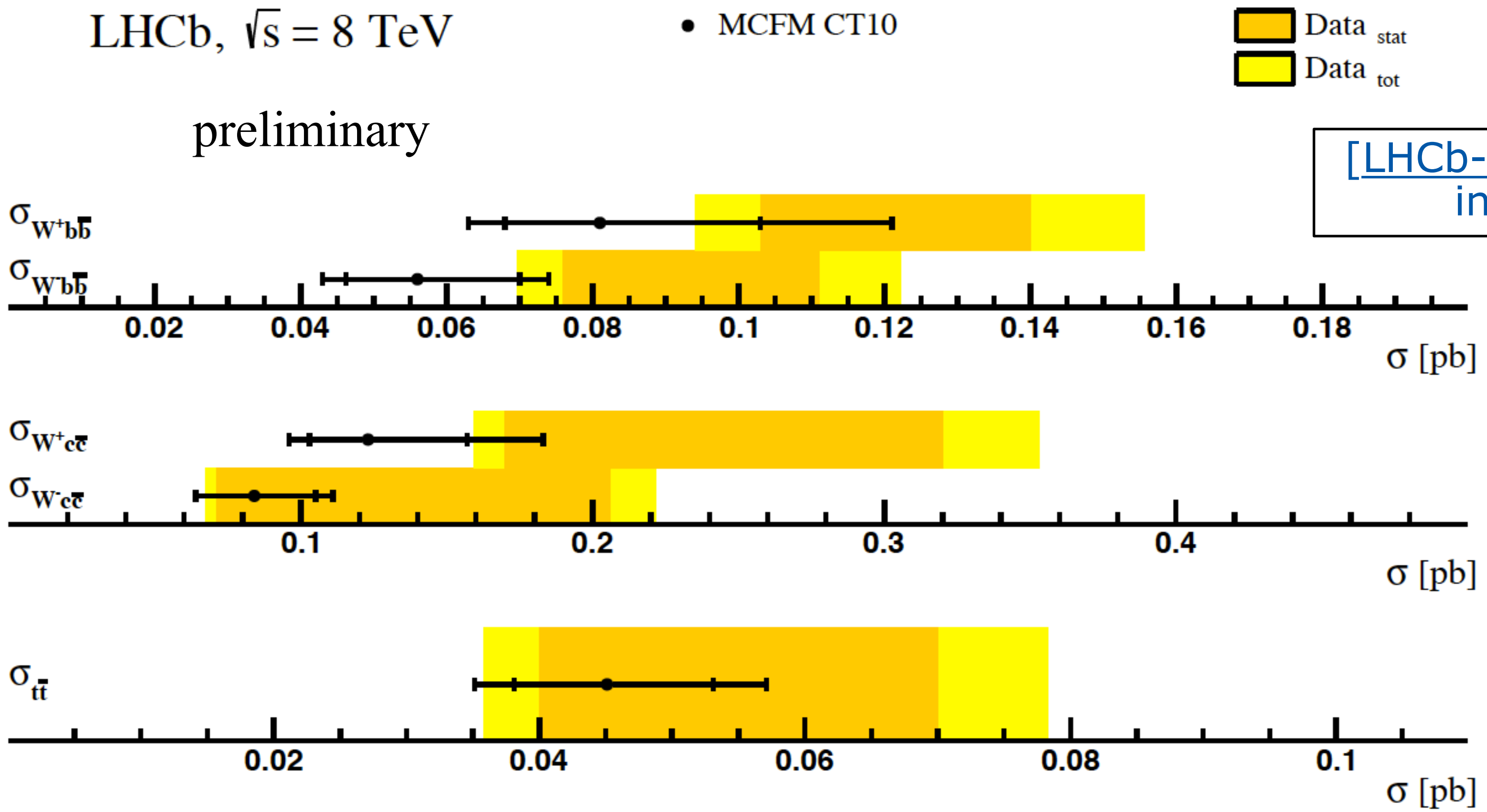
[LHCb-PAPER-2016-038] in preparation

- **Selection** similar to Wj analysis
- $12.5\,\mathrm{GeV} < p_T^{jet} < 100\,\mathrm{GeV}$ and $\Delta R > 0.5$ between the 3 objects
- **Backgrounds**: $Z + b\bar{b}$, $Z + c\bar{c}$, $Z(\tau\bar{\tau}) + b/c$, $Z(b\bar{b}) + W/Z$, QCD multi-jet
- **Four-dimensional** fit in:
  1. m_{jj}
  2. uGB to discriminate $W + b\bar{b}$ from $t\bar{t}$
  3. BDT to discriminate b/c from light-quark jet (for each jet)



$W + b\bar{b}$, $W + c\bar{c}$, $t\bar{t}$ @ 8 TeV

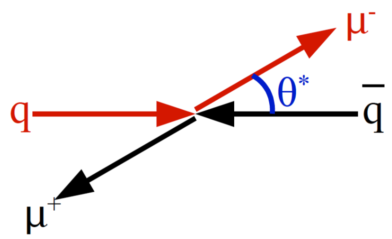
Agreement with the predictions @ NLO (using MCFM)



[LHCb-PAPER-2016-038]
in preparation

Z production asymmetry

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

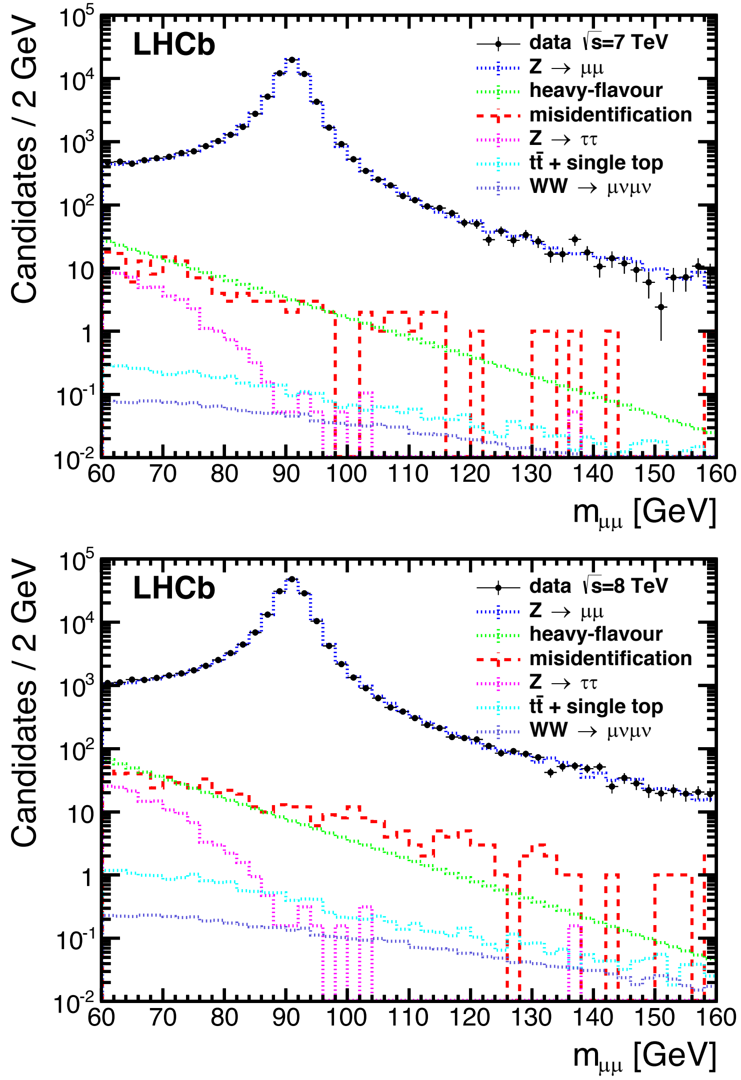


- θ^* is μ^- polar angle in **Collins-Soper** frame
- A_{FB} depends on **V-A** coupling → sensitive to $\sin^2\theta_W^{eff}$
- High sensitivity at **high rapidities** → LHCb is a good place to study A_{FB}!
- **Same selection** as in $Z \to \mu\mu$ analysis, $m(\mu\mu)$ extended to 160 GeV
- **Combination** of 7 TeV and 8 TeV results

Z production asymmetry

- Asymmetry is **unfolded** to correct for detector effects and bin-to-bin migrations
- $\sin^2 \theta_W^{eff}$ determined comparing simulation with measured A_{FB}, using the χ^2 minimization
- Significant **uncertainties** from:
  1. **Curvature** correction
  2. Detector **alignment**
  3. **Momentum** scale

[JHEP 11 (2015) 190]

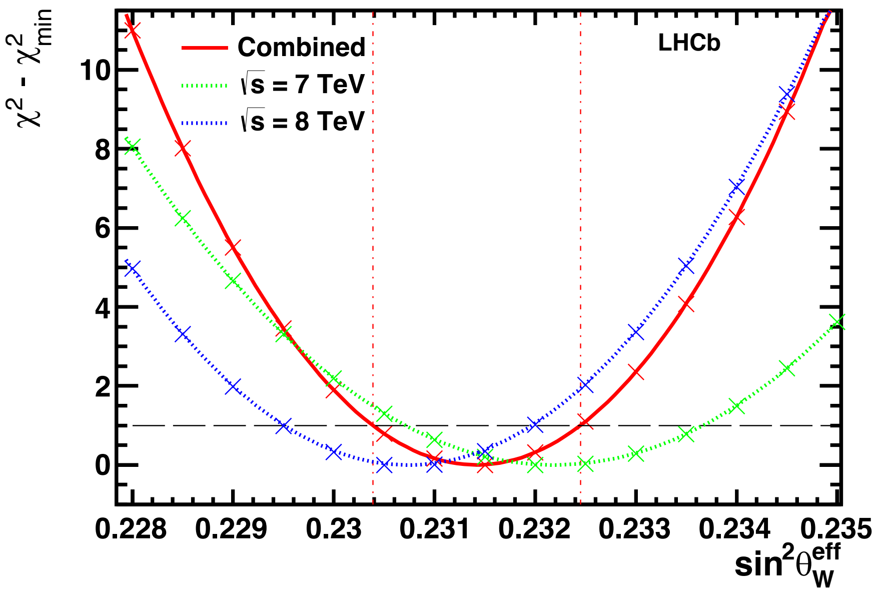


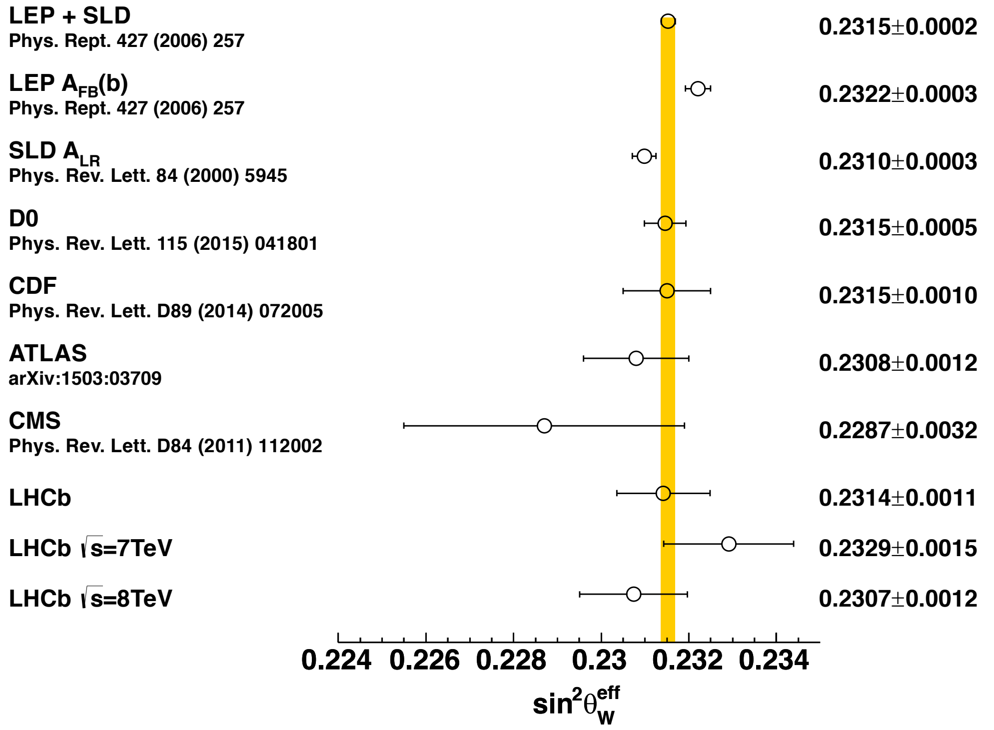
Z production asymmetry

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

- **Consistent** with the world average
- **Statistically** limited → more data expected from Run II

[JHEP 11 (2015) 190]





Conclusions

- LHCb acceptance: sensitivity to high and low **Bjorken-x**
- Precise EW bosons production measurements which agree with the **SM** and put constraints on the **PDFs**
- Very precise measurement of $\boldsymbol{sin^2 \theta_W^{eff}}$
- Expectations from Run II: **increased precision** with $2\ \mathrm{fb}^{-1}$/year and new cross-section **ratios** available at higher energy

Backup slides

$Z \to l^+ l^-$ forward production

- @ 7 TeV:
  - $\sigma(Z \to \mu^+\mu^-) = 76.0 \pm 0.3(\text{stat}) \pm 0.5(\text{syst}) \pm 1.0(\text{beam}) \pm 1.3(\text{lumi})$ pb
  - $\sigma(Z \to e^+e^-) = 76.0 \pm 0.8(\text{stat}) \pm 2.0(\text{syst}) \pm 2.6(\text{lumi}) \pm 0.4(\text{FSR})$ pb
- @ 8 TeV:
  - $\sigma(Z \to \mu^+\mu^-) = 95.0 \pm 0.3(\text{stat}) \pm 0.7(\text{syst}) \pm 1.1(\text{beam}) \pm 1.1(\text{lumi})$ pb
  - $\sigma(Z \to e^+e^-) = 93.81 \pm 0.41(\text{stat}) \pm 1.48(\text{syst}) \pm 1.14(\text{lumi})$ pb
- @ 13 TeV:
  - $\sigma(Z \to l^+l^-) = 194.3 \pm 0.9(\text{stat}) \pm 3.3(\text{syst}) \pm 7.6(\text{lumi})$ pb

$W \to l\nu$ forward production

- @ 7 TeV:
  - $\sigma(W^+ \to \mu^+\nu) = 878.0 \pm 2.1(\text{stat}) \pm 6.7(\text{syst}) \pm 9.3(\text{beam}) \pm 15.0(\text{lumi})$ pb
  - $\sigma(W^- \to \mu^-\nu) = 689.5 \pm 2.0(\text{stat}) \pm 5.3(\text{syst}) \pm 6.3(\text{beam}) \pm 11.8(\text{lumi})$ pb
- @ 8 TeV:
  - $\sigma(W^+ \to \mu^+\nu) = 1093.6 \pm 2.1(\text{stat}) \pm 7.2(\text{syst}) \pm 10.9(\text{beam}) \pm 12.7(\text{lumi})$ pb
  - $\sigma(W^- \to \mu^-\nu) = 818.4 \pm 1.9(\text{stat}) \pm 5.0(\text{syst}) \pm 7.0(\text{beam}) \pm 9.5(\text{lumi})$ pb
  - $\sigma(W^+ \to e^+\nu) = 1124.4 \pm 2.1(\text{stat}) \pm 21.5(\text{syst}) \pm 11.2(\text{beam}) \pm 13.0(\text{lumi})$ pb
  - $\sigma(W^- \to e^-\nu) = 809.0 \pm 1.9(\text{stat}) \pm 18.1(\text{syst}) \pm 7.0(\text{beam}) \pm 9.4(\text{lumi})$ pb