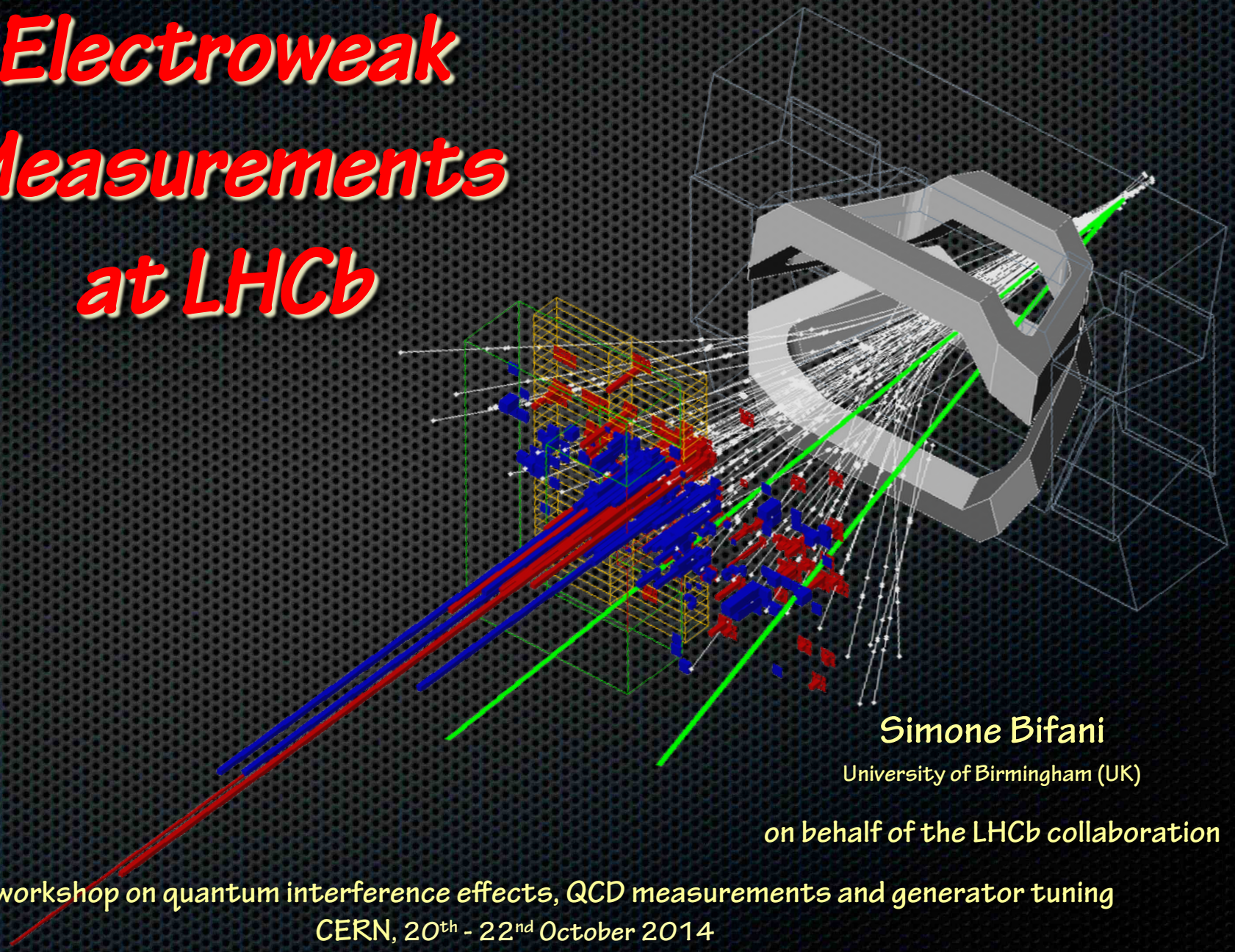
Electroweak Measurements at LHCb



Simone Bifani

University of Birmingham (UK)

on behalf of the LHCb collaboration

LHCb workshop on quantum interference effects, QCD measurements and generator tuning

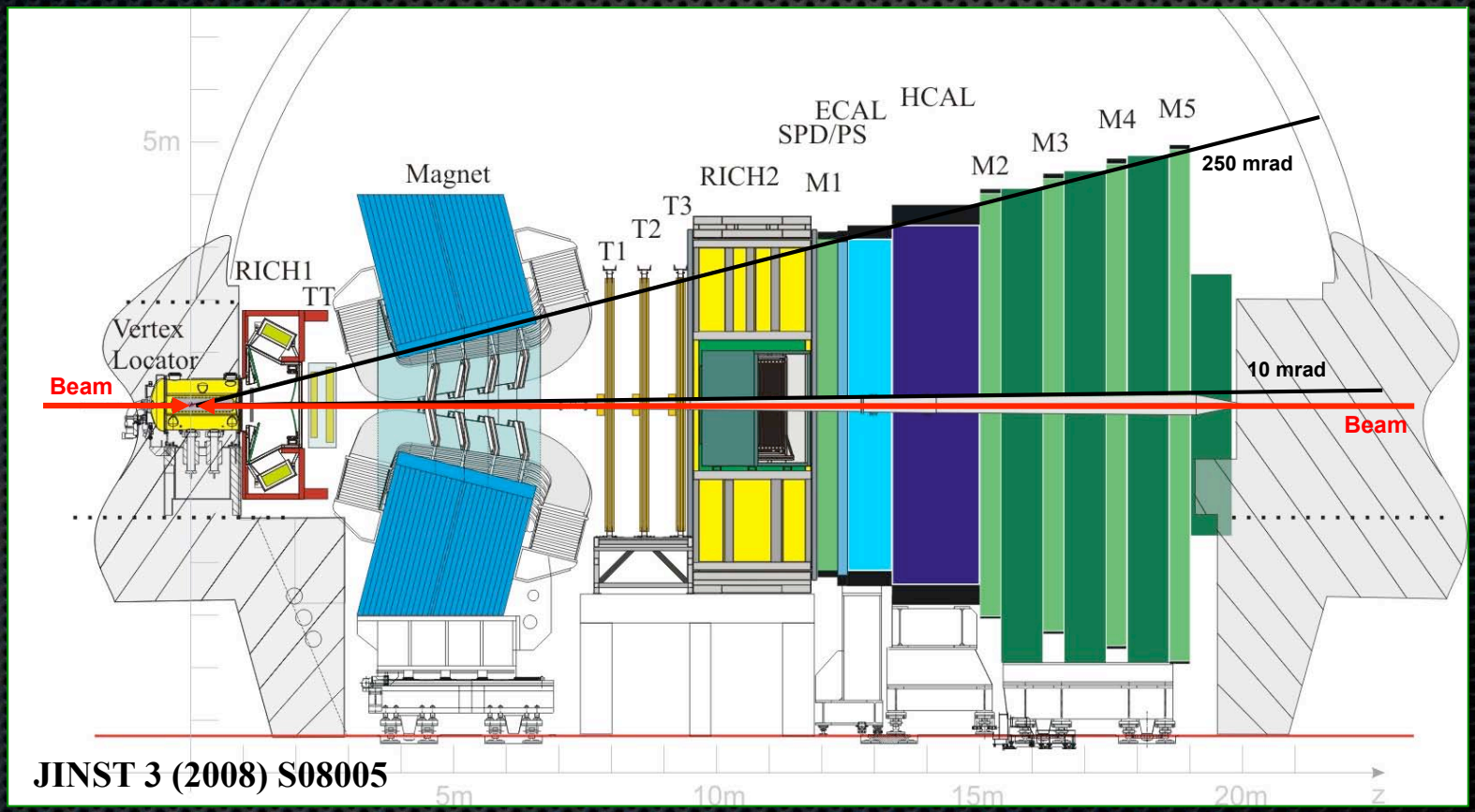
CERN, 20th - 22nd October 2014

Outline

- Introduction
- Analyses
  - $W \to \mu\nu$
  - $Z \to ll$ ($l = \mu, e, \tau$)
  - $Z \to \mu\mu$ in pA
- Prospects
- Summary

LHCb – A Forward Spectrometer

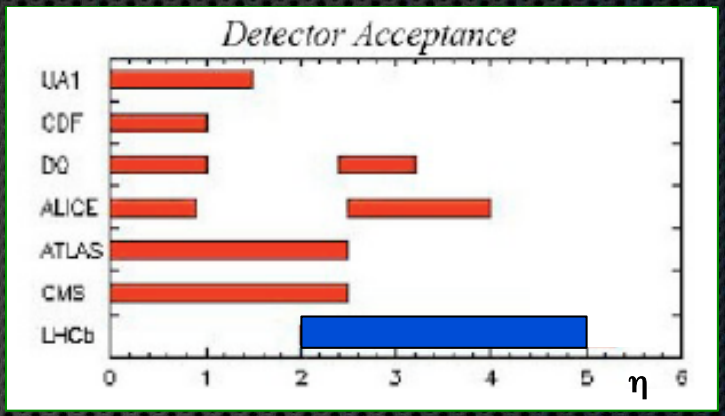
- Designed to look at CP violation in B decays @ LHC
- Fully instrumented within $2.0 < \eta < 5.0$

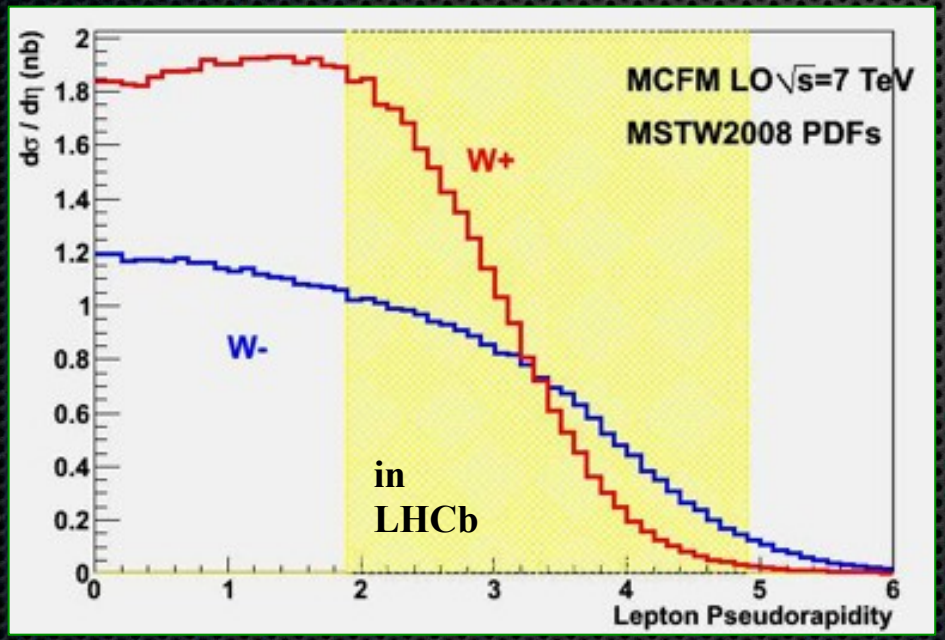


JINST 3 (2008) S08005

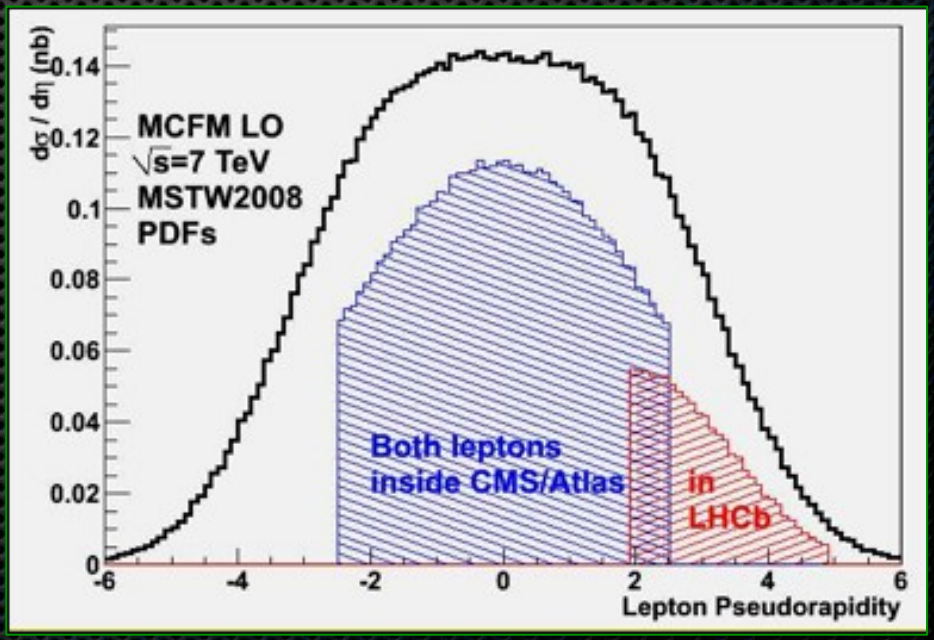
LHCb – A Forward Spectrometer

- Overlap with ATLAS & CMS
  $2.0 < \eta < 2.5$
- Complementary range
  $2.5 < \eta < 5.0$





17%(16%) of W^+(W^-) within LHCb

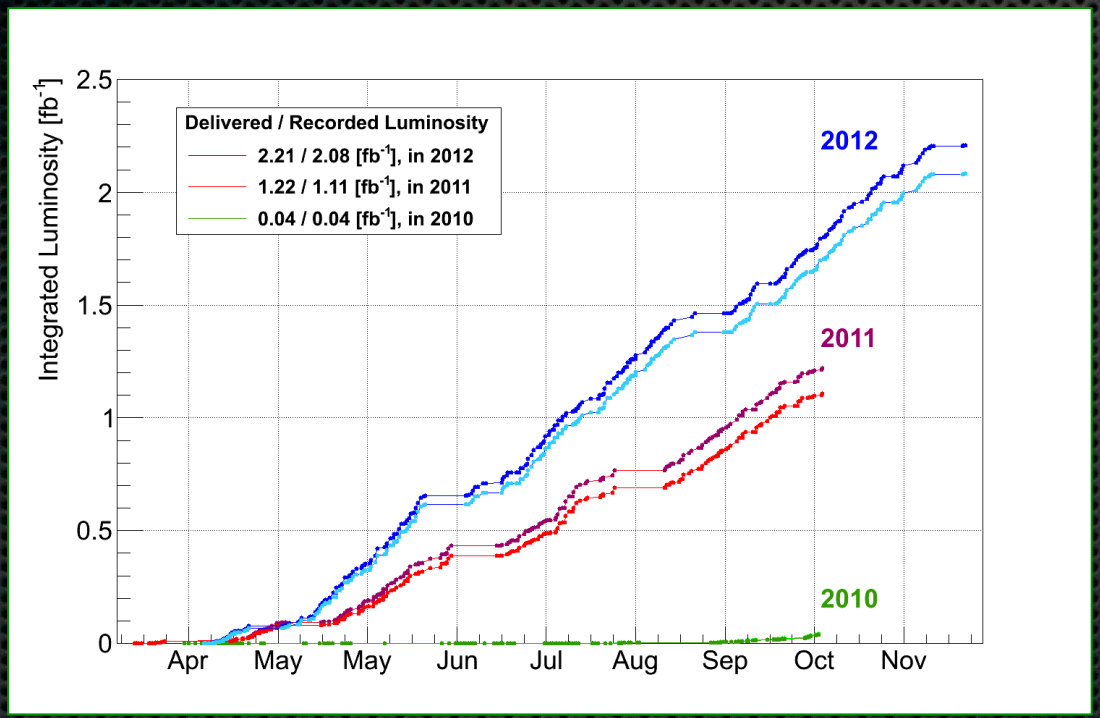


8% of Z within LHCb

Datasets

› Analyses based on 2011(2013) pp(pA) data samples at 7(5) TeV

› 2012 pp data at 8 TeV are currently being analysed



» $\int L_{2011} \sim 1\ fb^{-1}$

» $\int L_{2013} \sim 1.6\ nb^{-1}$

› Due to luminosity levelling, same running conditions throughout fills

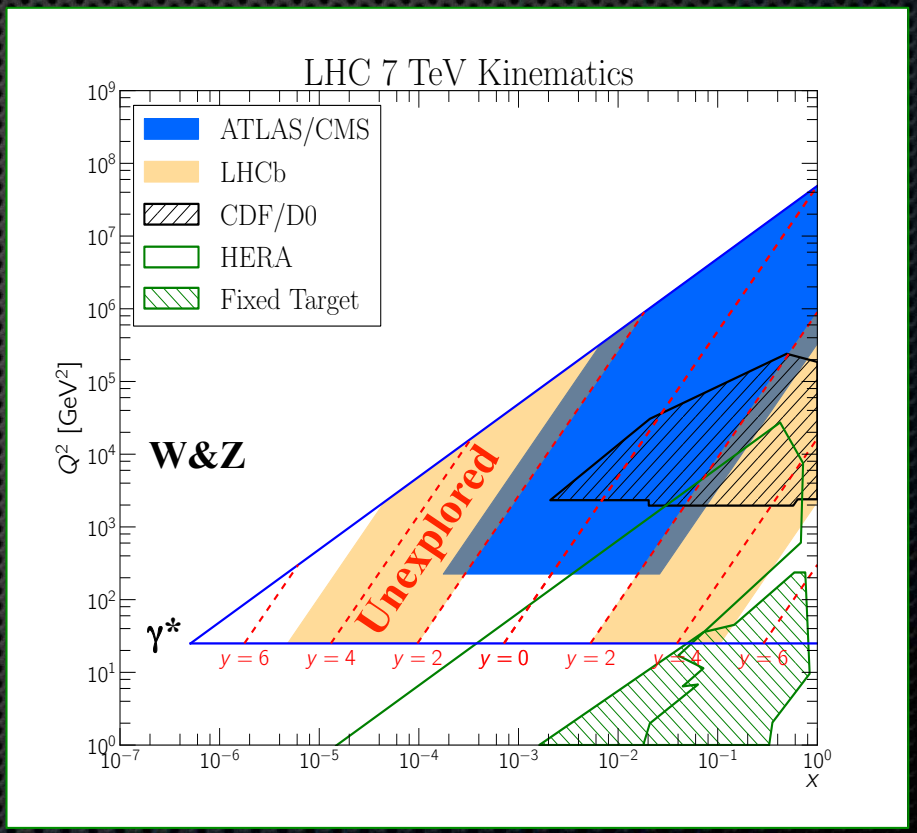
› EW trigger thresholds unchanged during years

W & Z Production and PDFs

- LHCb's forward acceptance provides very interesting possibilities to study the proton Parton Density Functions

- Take large-x from one proton and a small-x from the other
  → probe two distinct regions in the (x, Q^2) space

- Can probe the low-x, high-Q^2 region inaccessible to other experiments
  - W and Z
    (x of 10^{-4} and 10^{-1})
  - Low-mass Drell-Yan
    (x down to 10^{-6})

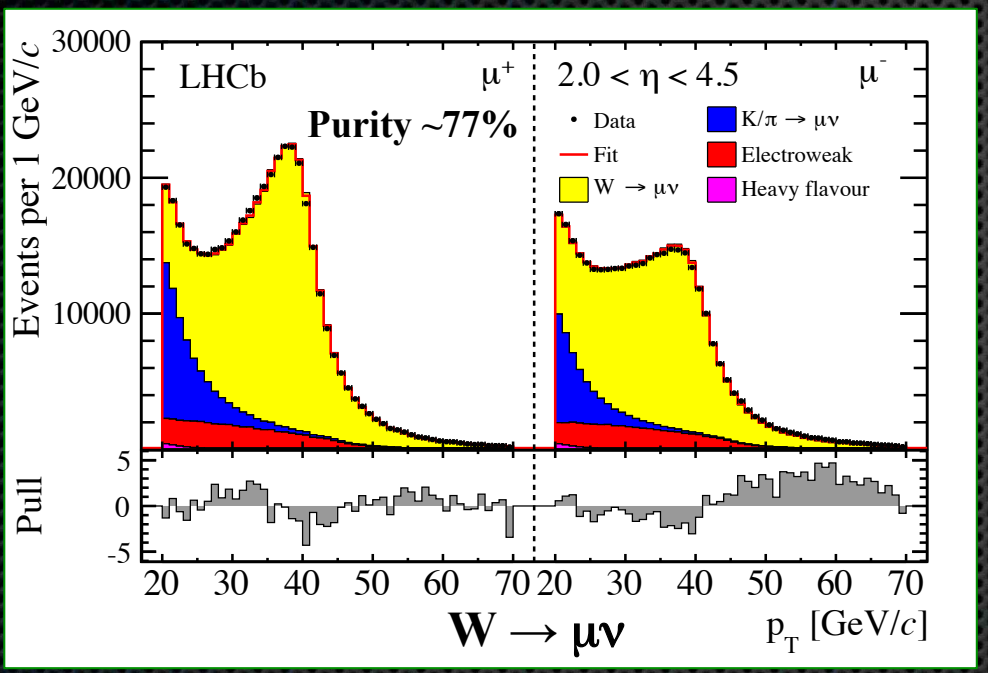


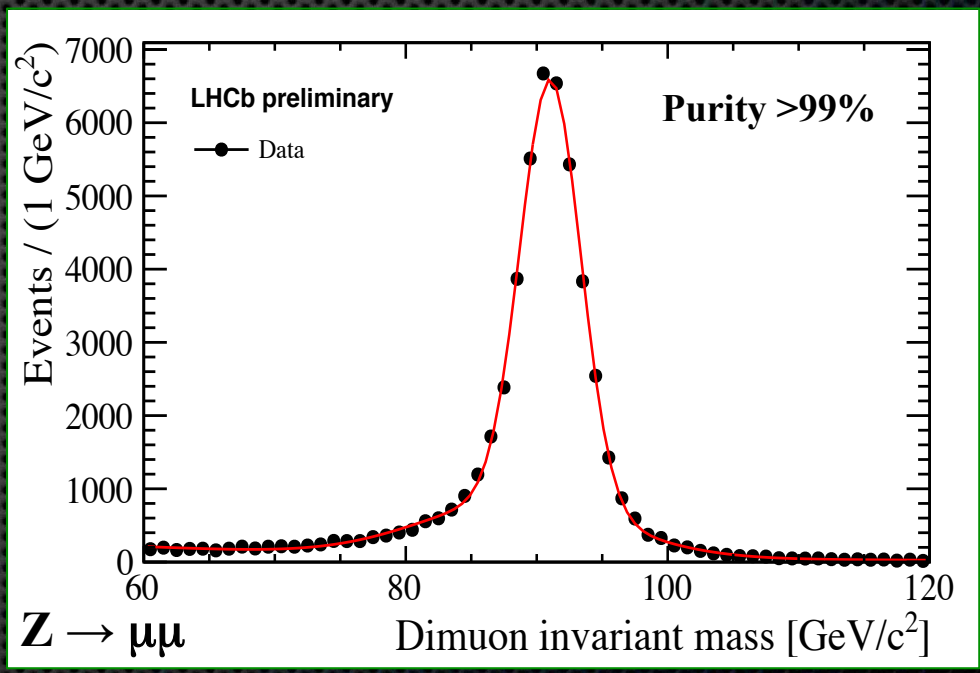
$$x_{1,2} = \frac{M}{\sqrt{s}} \cdot e^{\pm y} \qquad Q^2 = M^2$$

W & Z Production at LHCb

arXiv:1408.4354
LHCb-CONF-2013-007

› LHCb has measured the W and Z production cross-section at 7 TeV using several final states



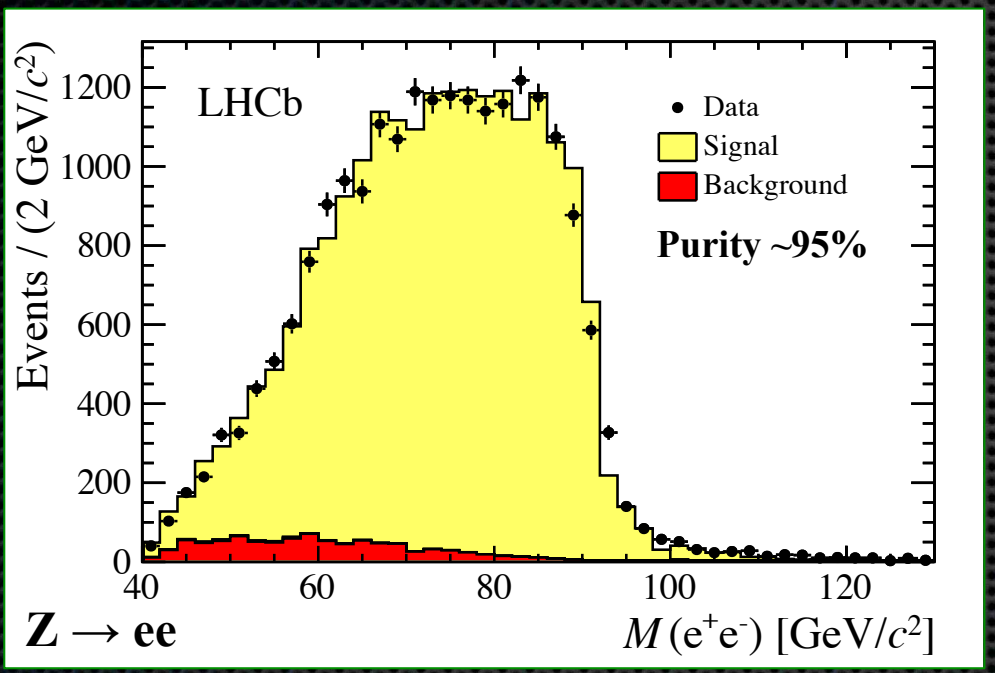


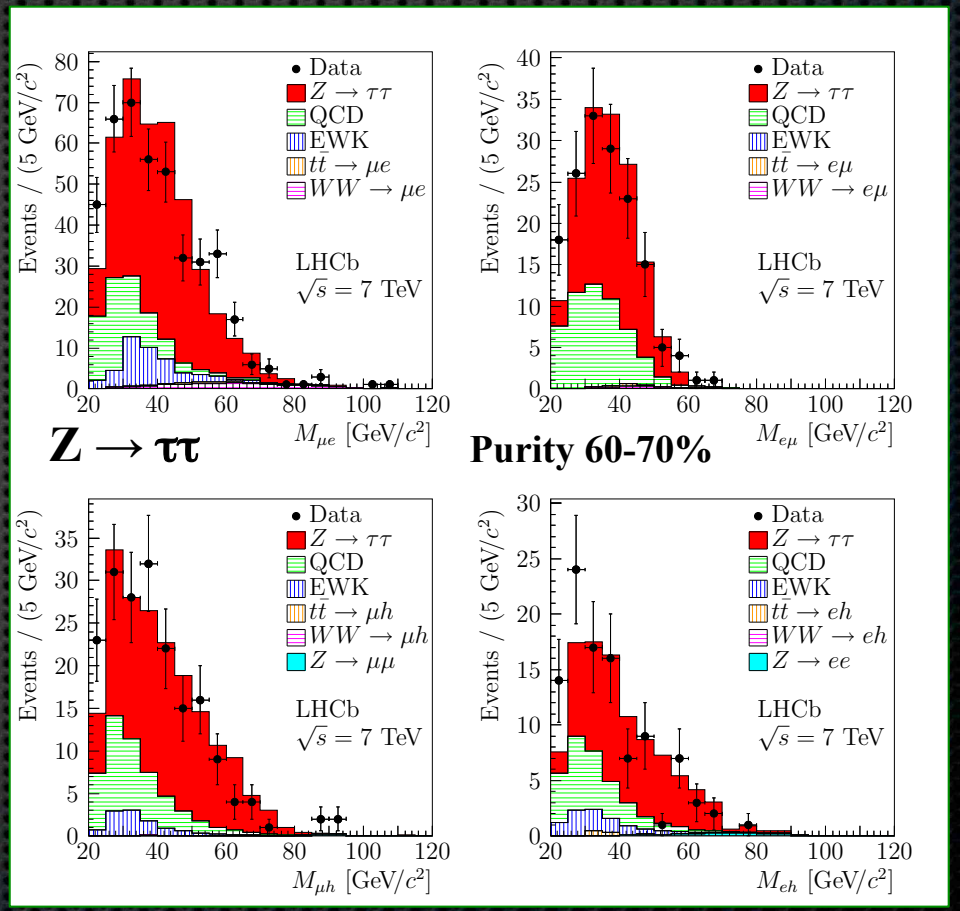
› 2011 Z->μμ analysis with much reduced systematic uncertainty currently under review

W & Z Production at LHCb

JHEP 02 (2013) 106
JHEP 01 (2013) 111

› LHCb has measured the W and Z production cross-section at 7 TeV using several final states

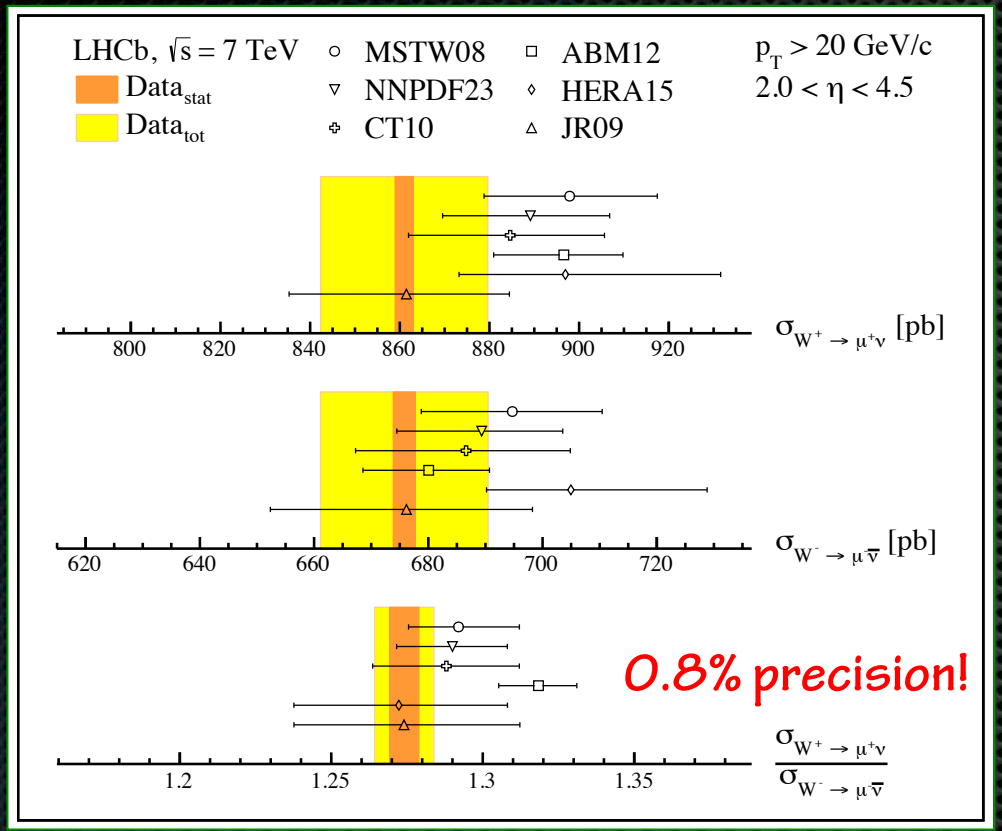


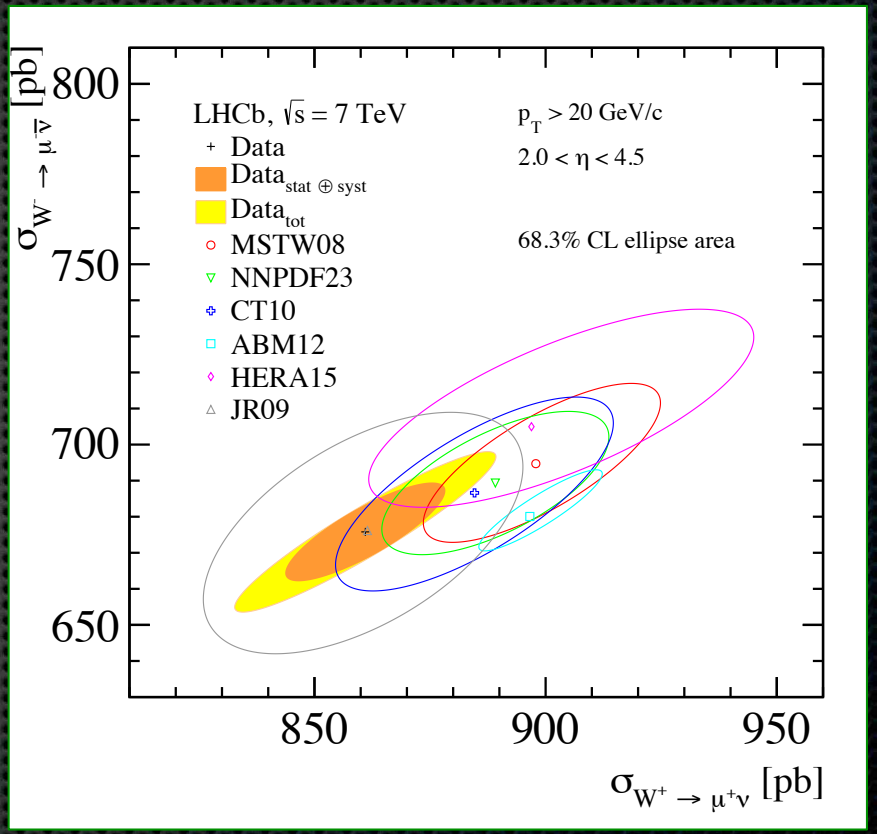


Results – $W \to \mu\nu$

arXiv:1408.4354

› **Fiducial volume**: $p_{T,\mu} > 20$ GeV/c, $2.0 < \eta_\mu < 4.5$





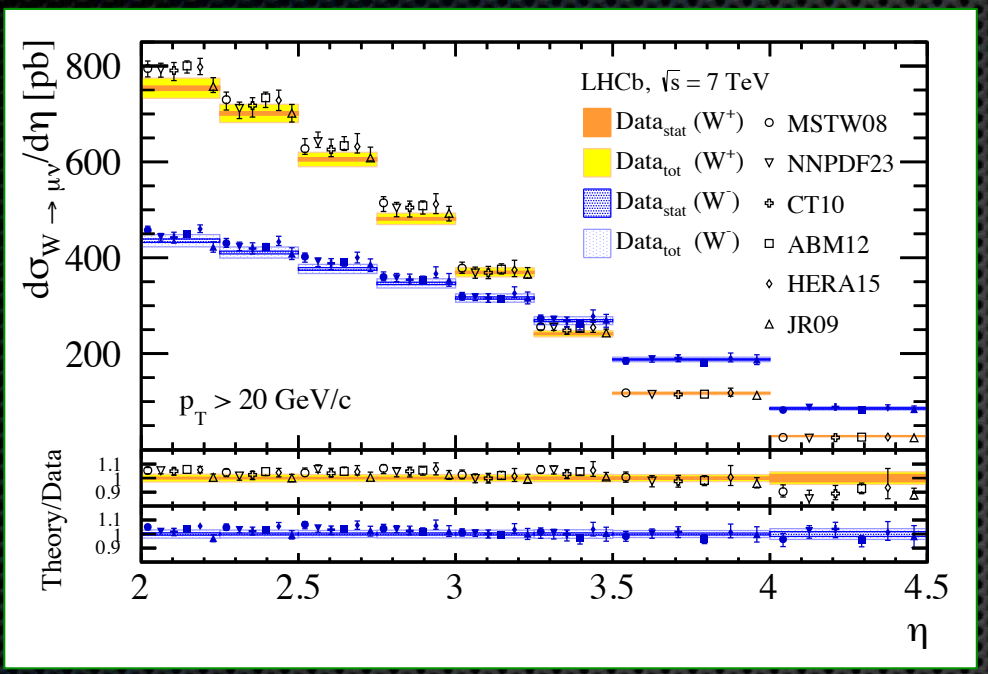
› Results in general agreement with NNLO predictions

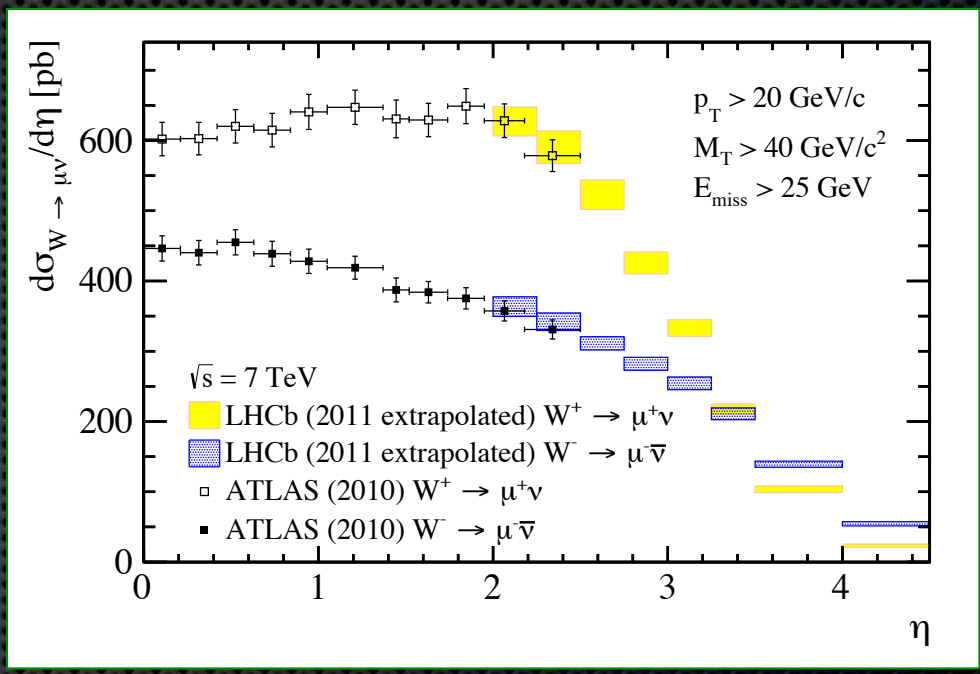
› Main systematics: template fit, reconstruction efficiencies

› Luminosity uncertainty down to 1.7%

Results – $W \to \mu\nu$

arXiv:1408.4354



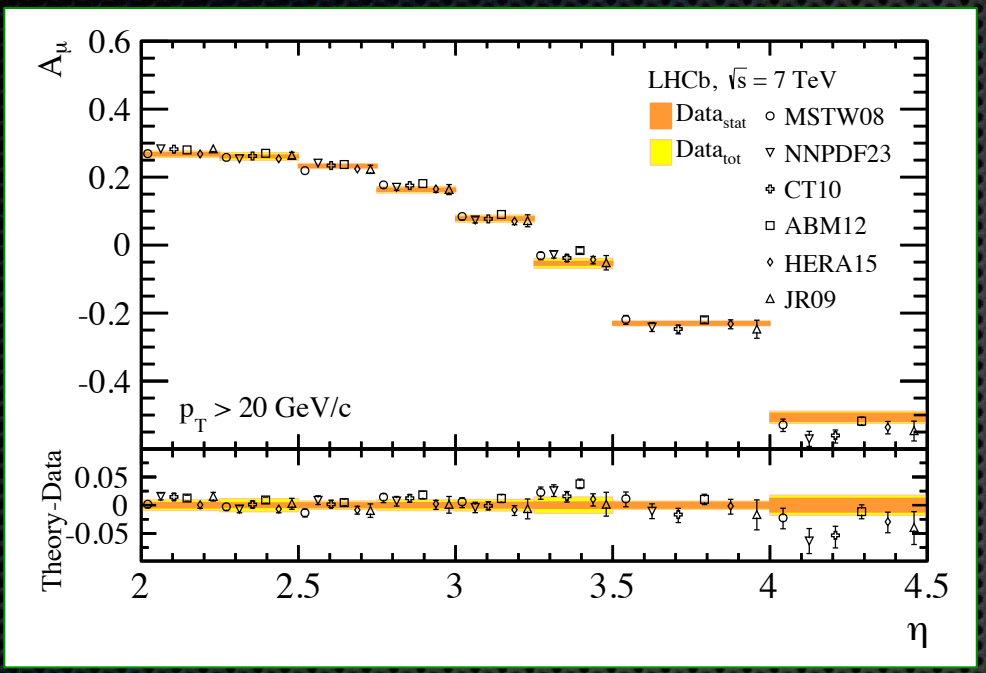


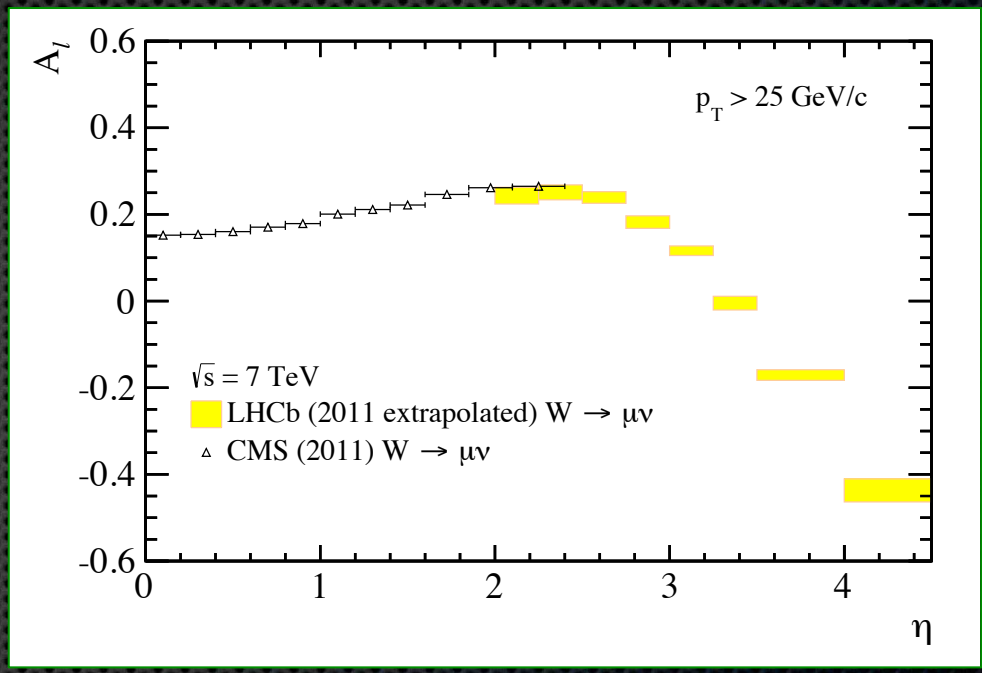
- Good agreement with NNLO
- Good agreement with ATLAS (after adapting to ATLAS cuts)

Results – $W \to \mu\nu$

arXiv:1408.4354

› Lepton charge asymmetry





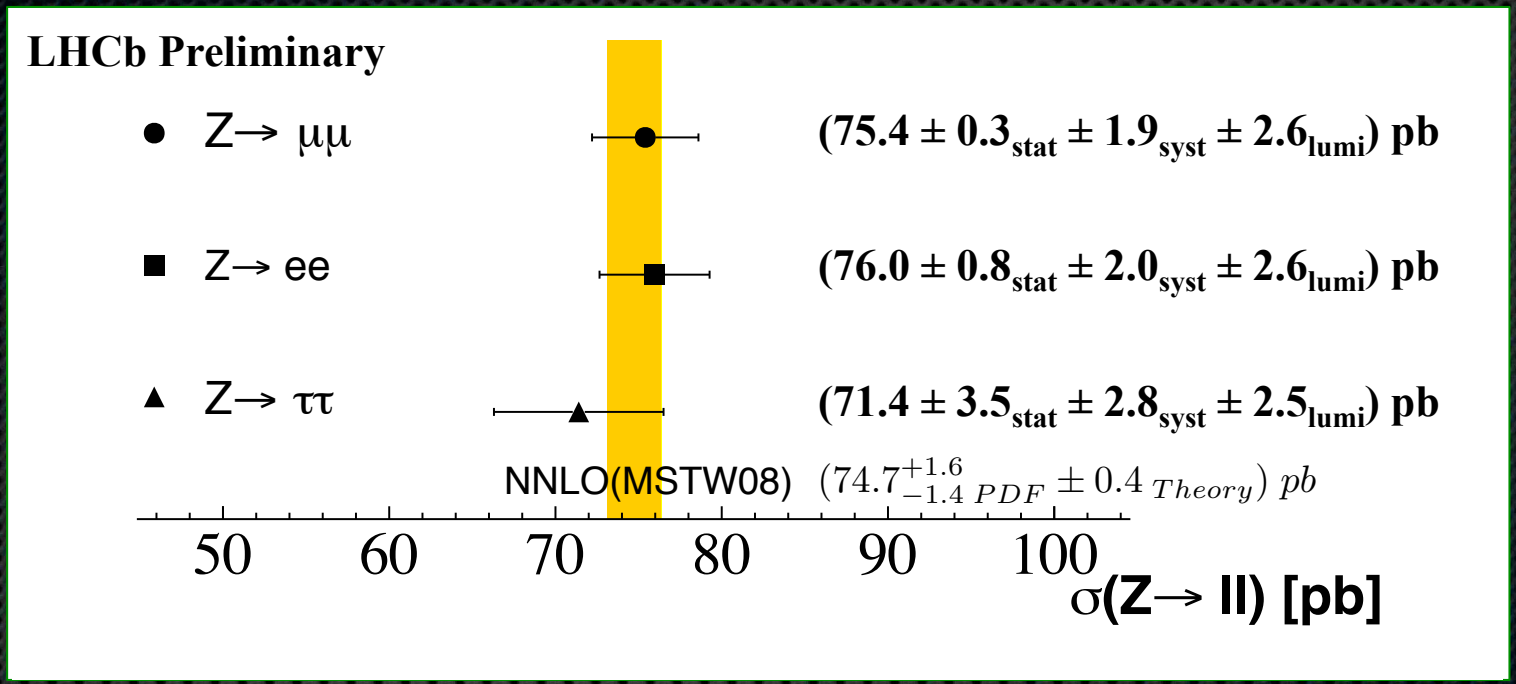
› Good agreement with NNLO

› Good agreement with CMS (after adapting to CMS cuts)

Results – Z → ll

LHCb-CONF-2013-007

› **Fiducial volume**: $p_{T,l} > 20\ GeV/c$, $2.0 < \eta_l < 4.5$, $60 < M_{ll} < 120\ GeV/c^2$



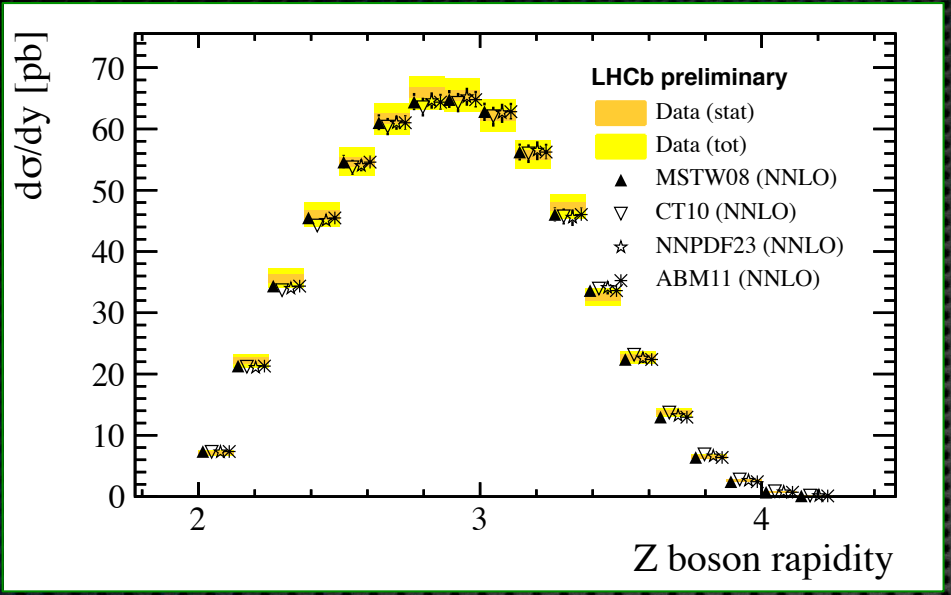
› Results agree with each other and NNLO predictions

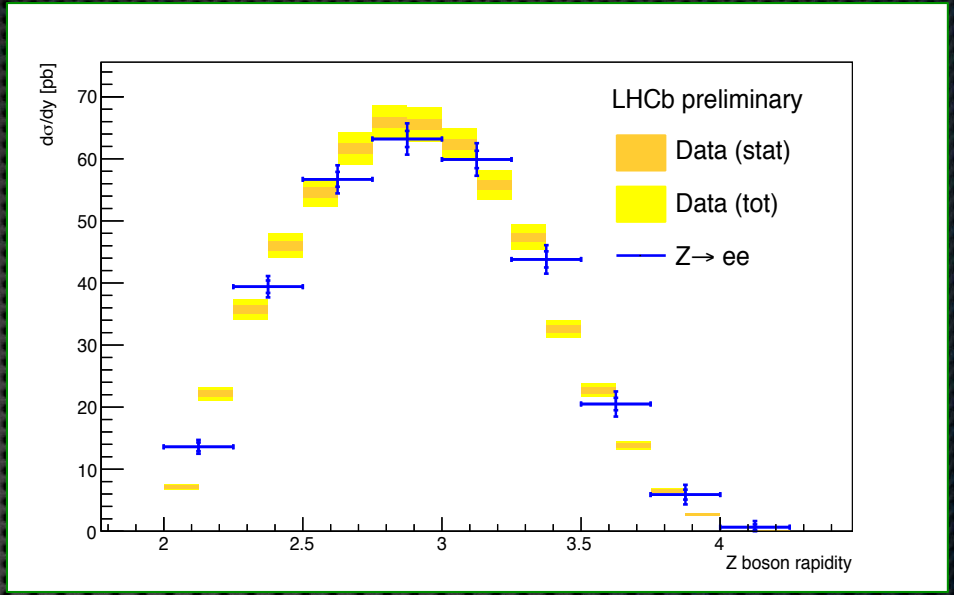
› Measurements limited by statistics (ττ) or luminosity (ee, μμ)

› Main systematics: reconstruction (μμ), tracking efficiency (ee), backgrounds and efficiency (ττ)

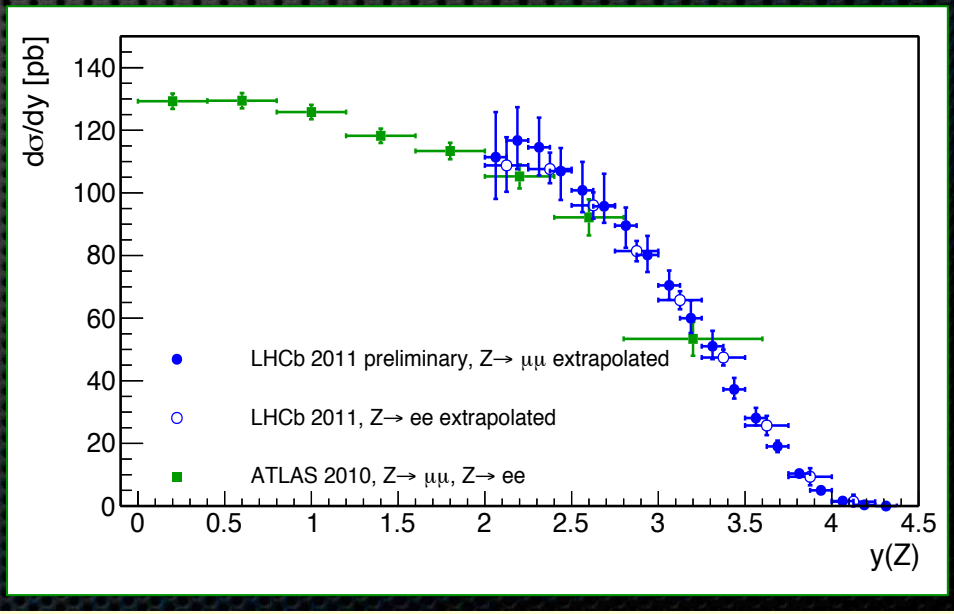
Results – $Z \to ll$

LHCb-CONF-2013-007



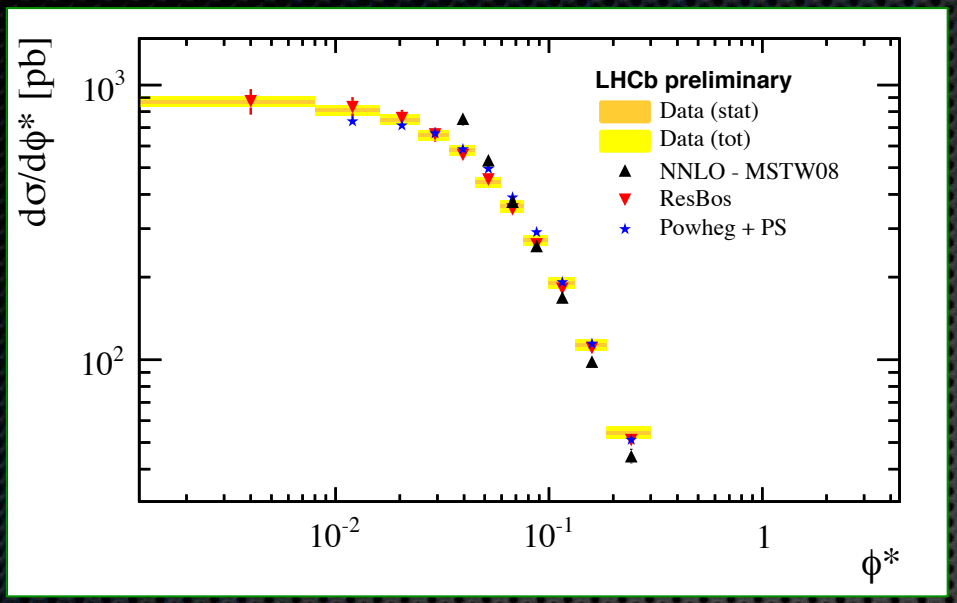


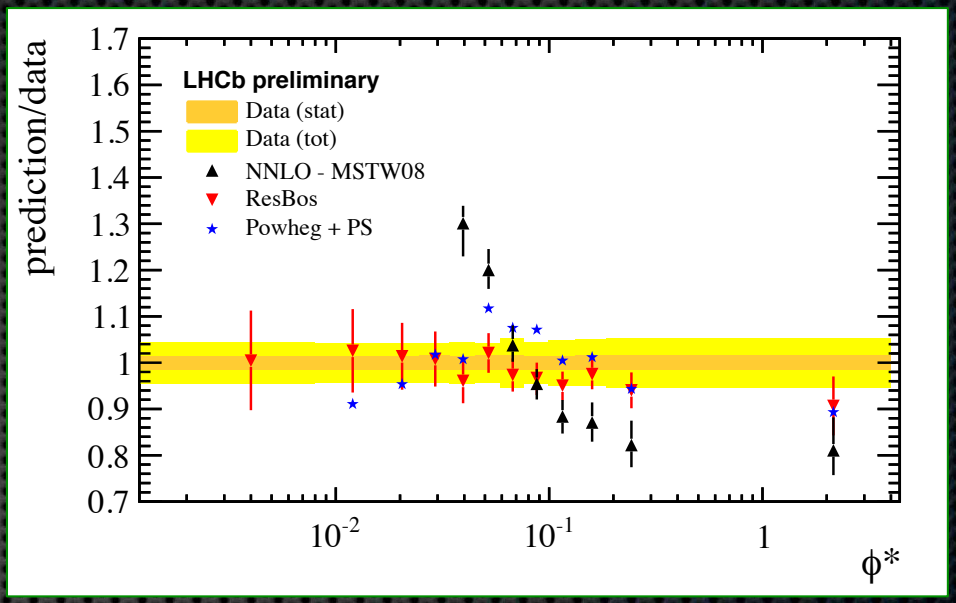
- Good agreement with NNLO
- Good agreement between μμ and ee final states
- Good agreement with ATLAS (after adapting to ATLAS cuts)



Results – $Z \to ll$

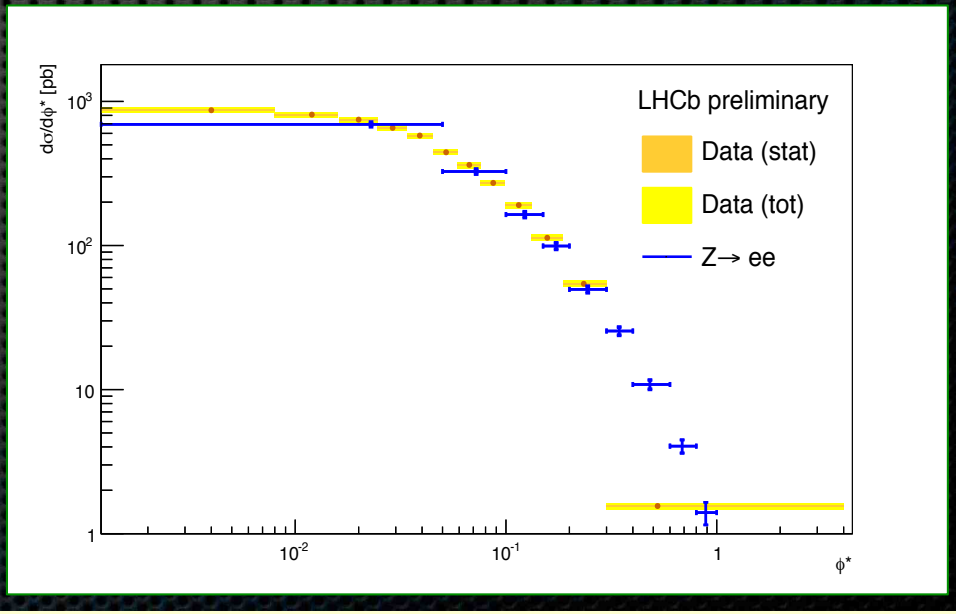
LHCb-CONF-2013-007





$$\phi^* = \frac{\tan\left((\pi - |\Delta\phi|)/2\right)}{\cosh\left(\Delta\eta/2\right)} \approx \frac{p_T}{m_Z}$$

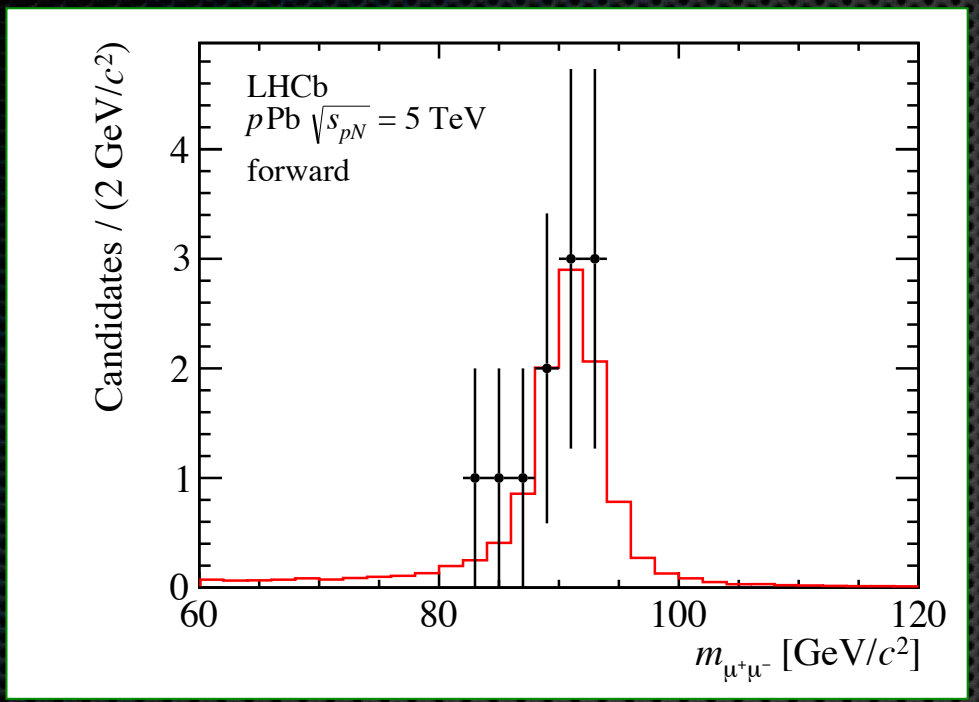
- NNLO fails to describe ϕ^*
- Better agreement when compared to ResBos and POWHEG

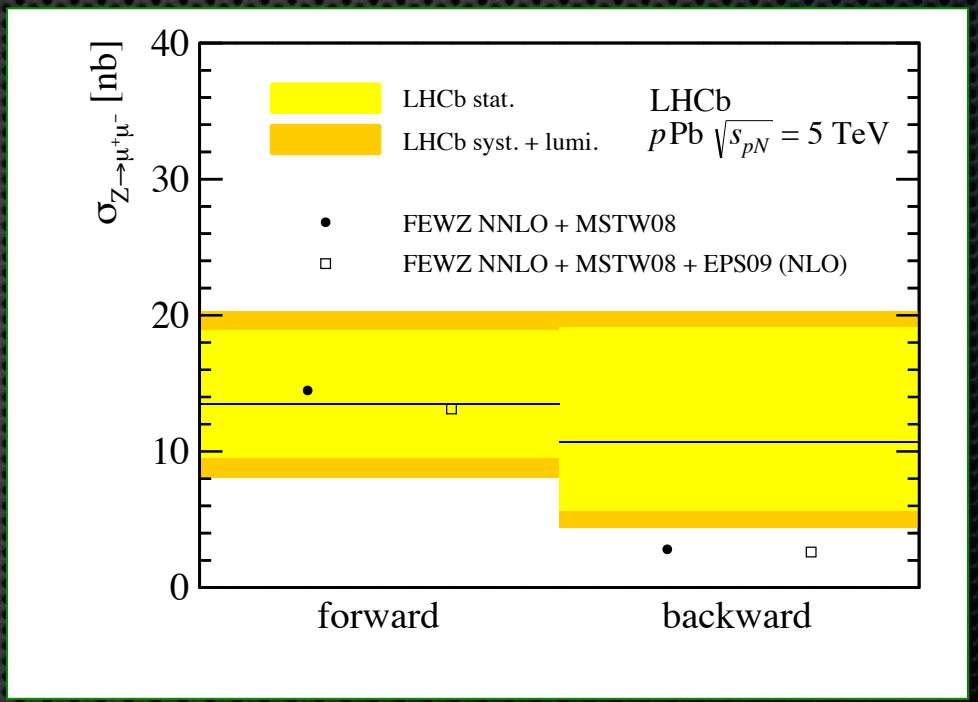


$Z \to \mu\mu$ in pA

LHCb-PAPER-2014-022

› Sensitive to nPDF in a region where there is no experimental input

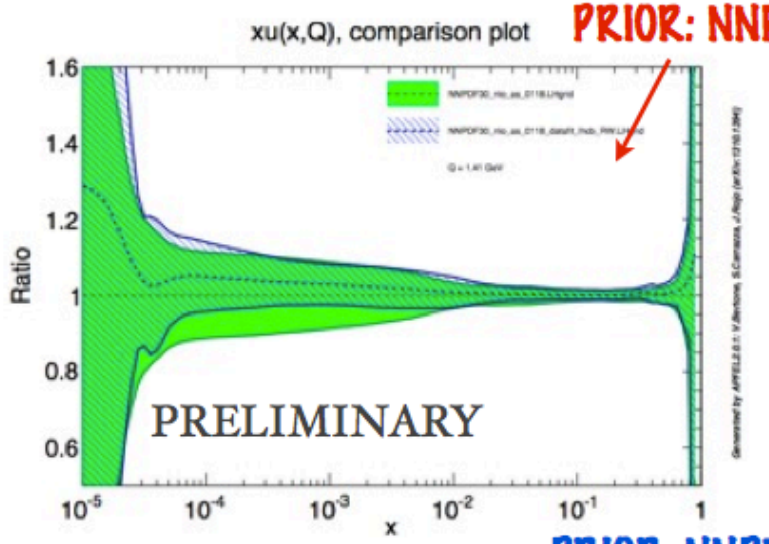


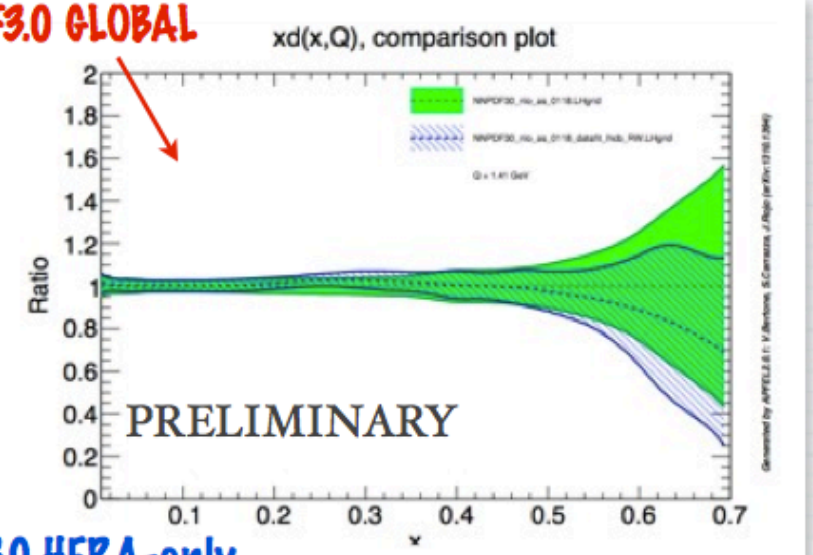


› Forward (pA): $\sigma(Z\to\mu\mu) = (13.5^{+5.4}_{-4.0\ stat} \pm 1.1_{syst})$ pb

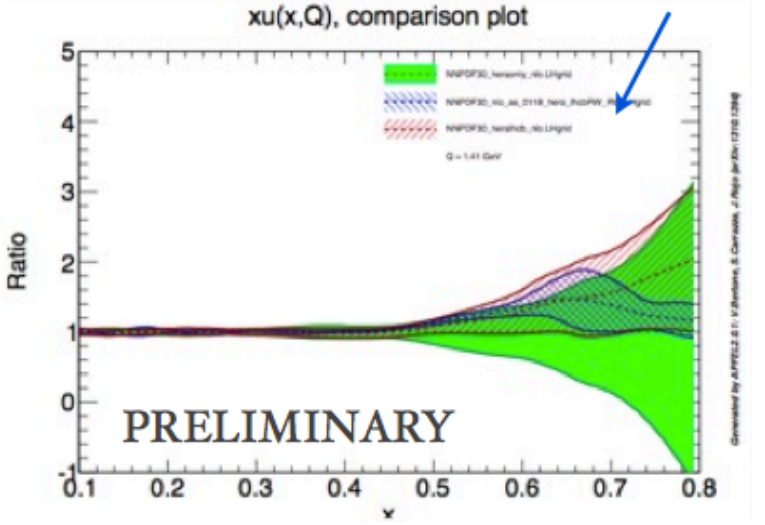
› Backward (Ap): $\sigma(Z\to\mu\mu) = (10.7^{+8.4}_{-5.1\ stat} \pm 1.0_{syst})$ pb

Impact on PDFs





PRIOR: NNPDF3.0 HERA-only



* Reweighting using NNPDF3.0 prior
  Nucl.Phys. B855 (2012) 608
* Large impact of precise W measurements on global fit: visible reduction of u/d uncertainty
* Even larger impact on HERA only fit
  RED: HERA prior + LHCb (old)
  BLUE: HERA prior + LHCb (new)

10/18

› M.Ubiali @ LHCb Impication Workshop

Prospects

- Updates with 8 TeV data for all analyses
- Perform inclusive, differential and associated measurements with Run-II data @ 13(14) TeV

- Measurement of event properties, multiplicities and multiplicity ratios in Z events with identified particles (p, pbar, $K^{\pm}$, Lambda->$p\pi$, K_S->$\pi\pi$, maybe ρ and ϕ)

- What should we measure with higher priority that would be an important input for MC tuning?

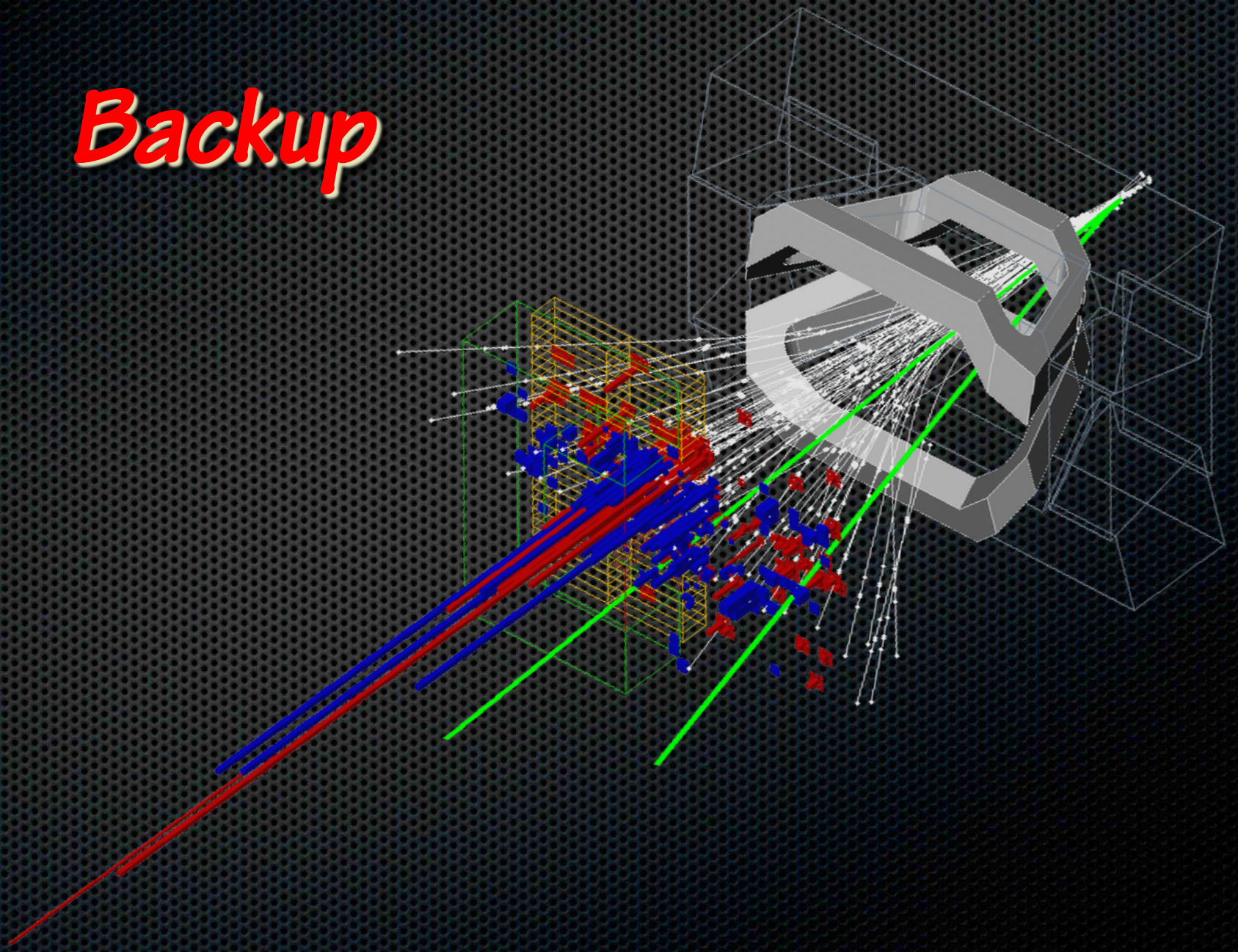
Summary

- LHCb probes a unique region in η and low p_T reach at LHC and can provide important inputs to PDFs in the forward region

- W and Z production cross-sections measured by using a variety of final states
- Results consistent with theoretical predictions calculated at NNLO

- Many other measurements expected soon!

Backup

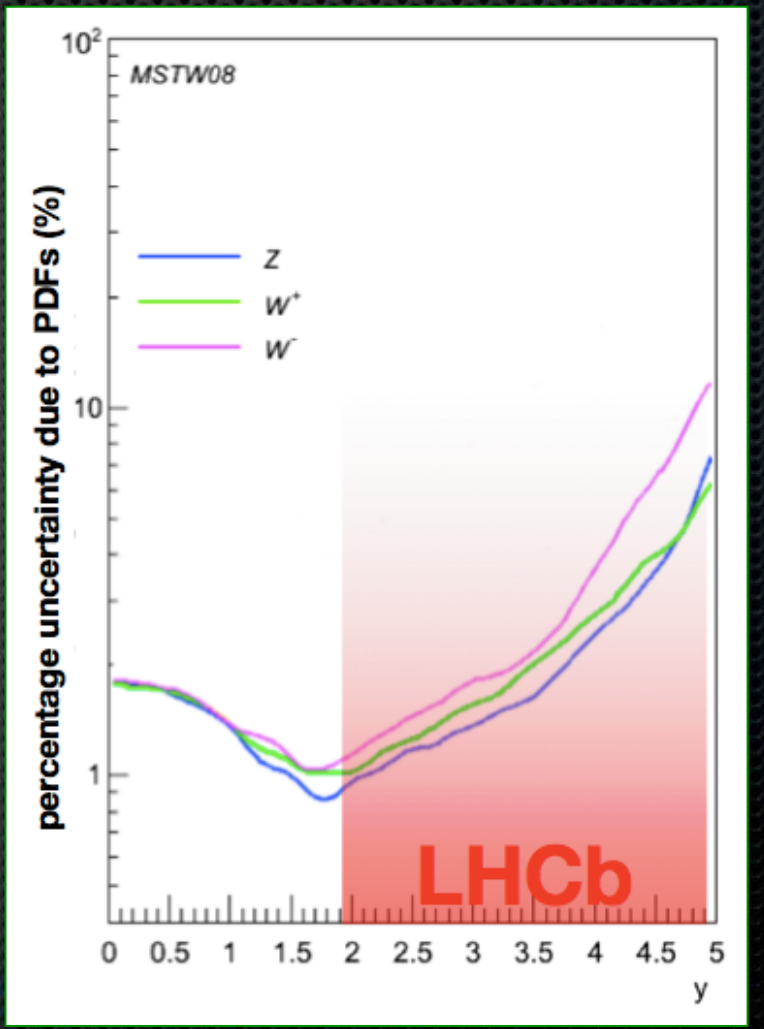


W & Z Production and PDFs

- **Theoretical predictions**
  - Partonic cross-sections known at NNLO to few %
  - PDF uncertainty dominates at large rapidities (1% for y<2, 6-8% at y~5)

$$\underbrace{\sigma(x,Q^2)}_{\text{hadronic } x-\text{sec.}} = \sum_{a,b} \int_0^1 dx_1\, dx_2 \underbrace{f_a(x_1 Q^2) f_b(x_2 Q^2)}_{\text{PDFs } 2-8\%} \underbrace{\hat{\sigma}(x_1, x_2, Q^2)}_{\text{partonic } x-\text{sec.: NNLO } 1\%}$$

- **Experimental measurements**
  - Muon modes provide clean signature and easily reconstructible final states
  - Electron and tau modes provide complementary measurements and test lepton universality



Cross-section measurements @ LHCb can constrain PDFs

W & Z Production and PDFs

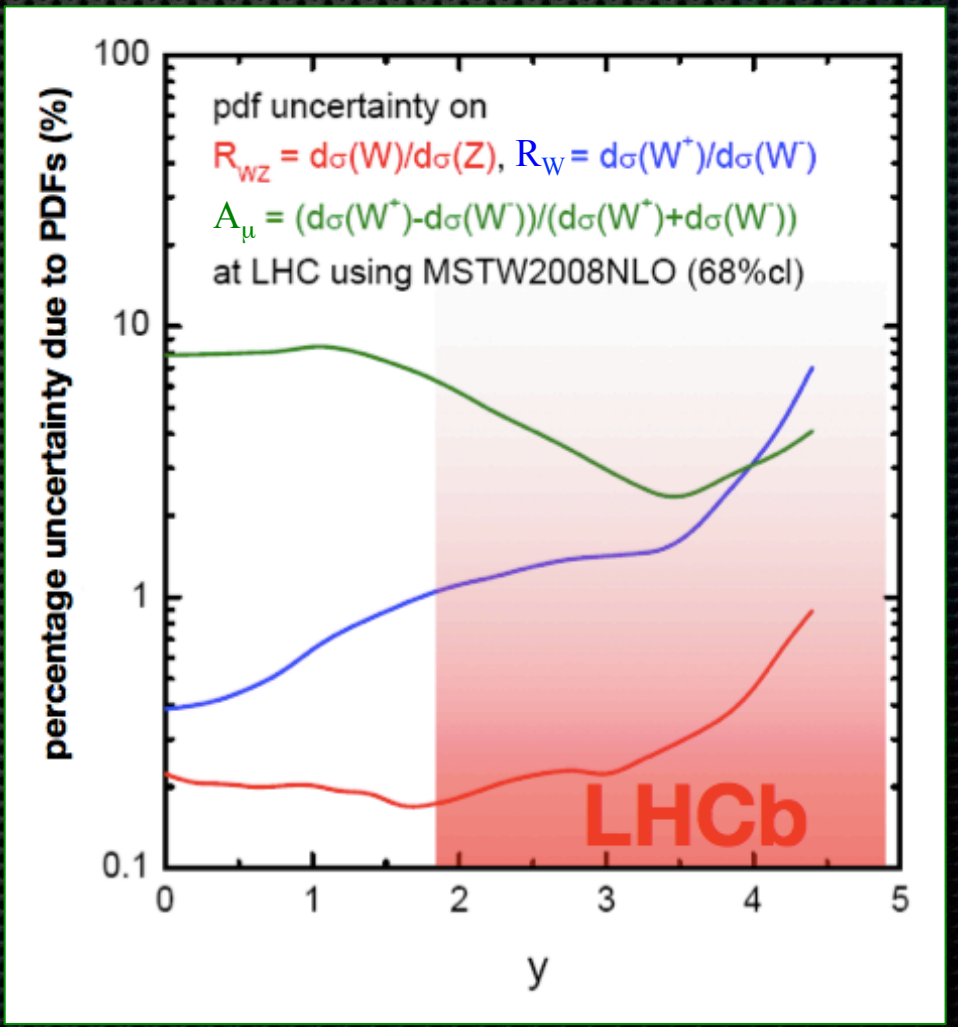
› Cancel or highlight PDF uncertainties with ratios

» $A_\mu = (d\sigma_{W+} - d\sigma_{W-}) / (d\sigma_{W+} + d\sigma_{W-})$
tests u_V and d_V difference

» $R_W = d\sigma_{W+} / d\sigma_{W-}$
tests d_V/u_V ratio

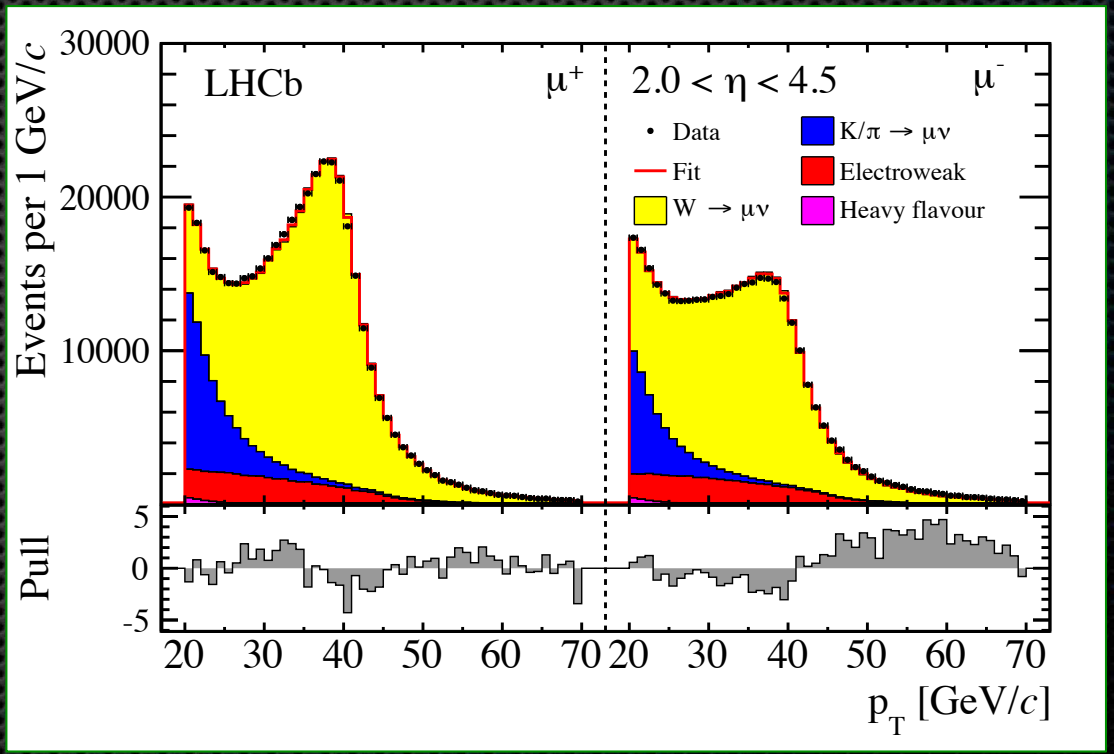
» $R_{WZ} = d\sigma_W / d\sigma_Z$
almost insensitive to PDFs
precise test of SM

Many systematic errors cancel



$W \to \mu\nu$

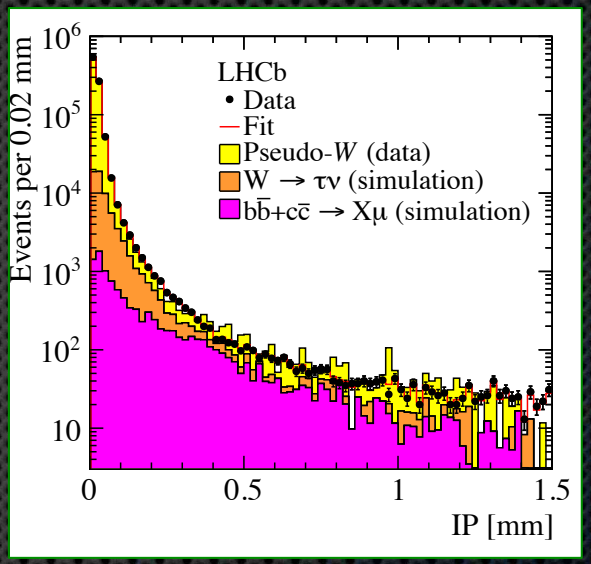
- Single muon trigger: $p_T > 10$ GeV/c
- $\int L \sim 37$ pb^{-1} (2010)
- **1 reconstructed & isolated muon**
  - $p_T > 20$ GeV/c
  - $2.0 < \eta < 4.5$
  - Cone p_T (R=0.5) < 2 GeV/c
  - Extra muon veto ($p_T > 2$ GeV/c)
  - Impact parameter < 40 μm
  - E / pc < 4%
- **Backgrounds**
  - $Z/\gamma^* \to \mu\mu$ (MC)
  - $W \to \tau\nu$ and $Z \to \tau\tau$ (MC)
  - Heavy flavour (Data)
  - K/π decay in flight (Data)
- $N_{Candidates} = 147k^+ \; 116k^-$
- Purity ~ $79\%^+ \; 78\%^-$

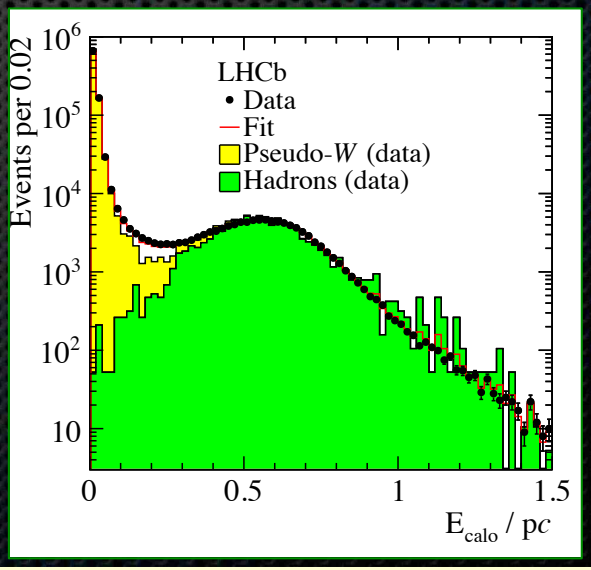


Template fit in 5 η bins
W and Z muon p_T spectrum at NNLO

$W \to \mu\nu$

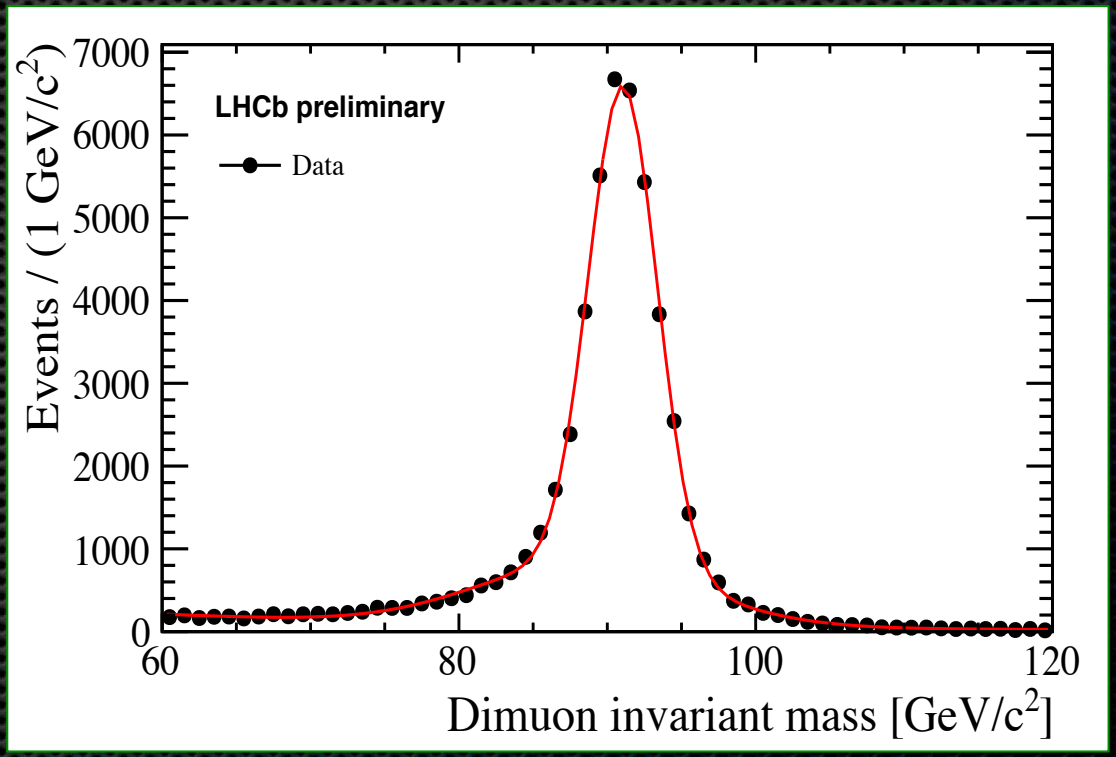
- Specific cuts implemented to reduce each background component
- $Z/\gamma^* \to \mu\mu$
  - Veto on 2nd muon with $p_T > 2$ GeV/c
- $W \to \tau\nu$, $Z \to \tau\tau$ and **Heavy flavour**
  - Impact parameter < 40 μm
- **K/π punchthrough**
  - E / pc < 0.04
- Largest residual backgrounds
  - Decays in flight of K/π
  - $Z \to \mu\mu$ events with one muon outside the acceptance





$Z \to \mu\mu$

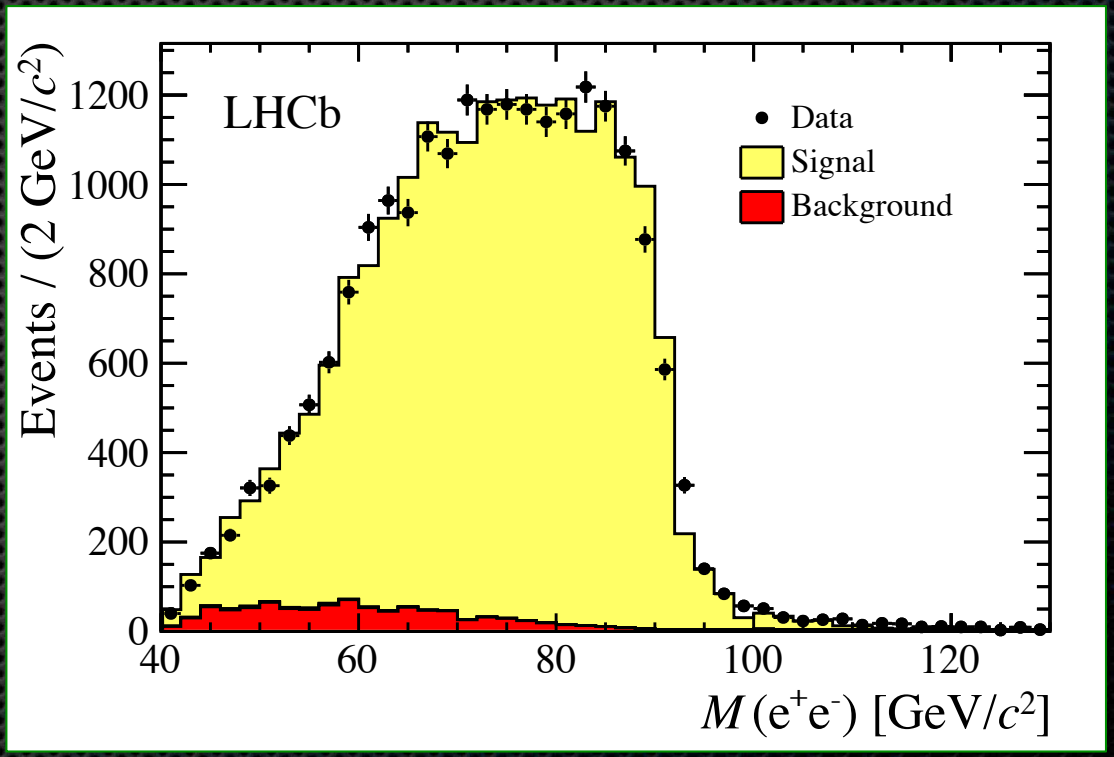
- Single muon trigger: $p_T > 10$ GeV/c
- $\int L \sim 1$ fb^{-1} (2011)
- **2 reconstructed muons**
  - $p_T > 20$ GeV/c
  - $2.0 < \eta < 4.5$
  - $60 < M_{\mu\mu} < 120$ GeV/c^2
- **Backgrounds**
  - Heavy flavour (Data)
  - K/π mis-ID (Data)
  - $Z \to \tau\tau$ (MC)
  - $t\bar{t}$ (MC)
  - WW (MC)



- $N_{Candidates} = 52626$
- Purity > 99%

$Z \rightarrow ee$

- Single electron trigger: $p_T > 15$ GeV/c
- $\int L \sim 945$ pb^{-1} (2011)
- 2 reconstructed electrons
  - $p_T > 20$ GeV/c
  - $2.0 < \eta < 4.5$
  - $E_{ECal} / pc > 0.1$
  - $E_{HCal} / pc < 0.05$
  - $M_{ee} > 40$ GeV/c^2
- Backgrounds
  - K/π mis-ID (Data)
  - Heavy flavour (Data)
  - $Z \rightarrow \tau\tau$ (MC)
  - $t\bar{t}$ (MC)



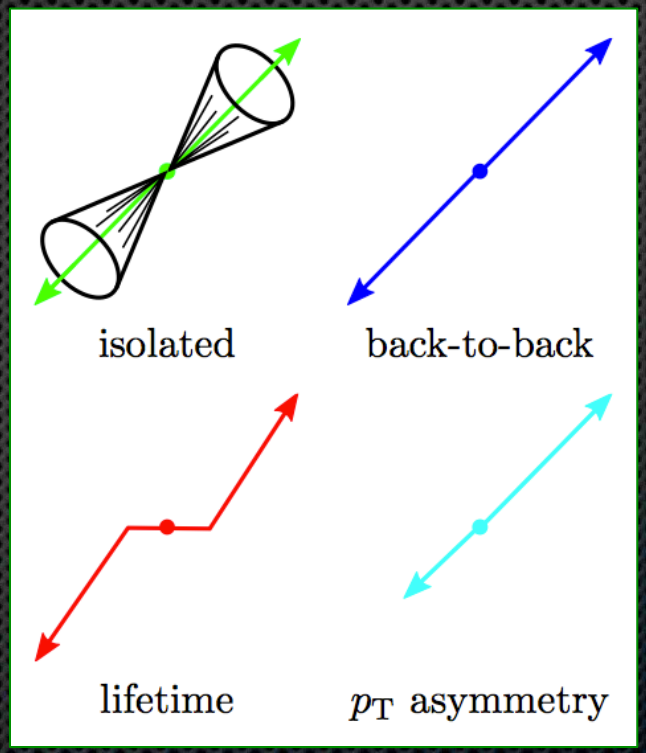
Mass peak distorted by bremsstrahlung

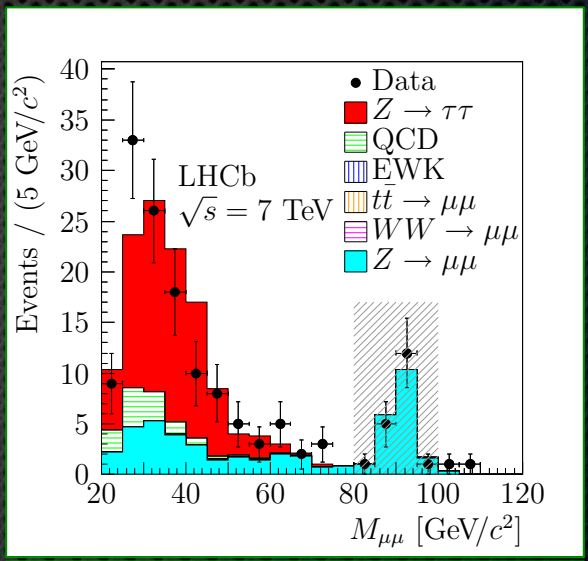
- $N_{Candidates} = 21420$
- Purity ~95%

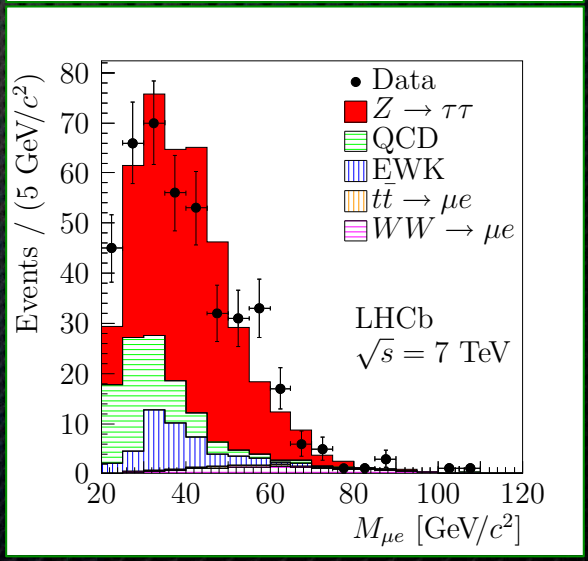
$Z \to \tau\tau$

- **Single lepton trigger:** $p_{T,\mu(e)} > 10(15)$ GeV/c
- **5 final states:** μμ, μe, eμ, μh, eh
  - $p_{T,1} > 20$ GeV/c, $p_{T,2} > 10$ GeV/c
  - $2.0 < \eta_l < 4.5$, $2.25 < \eta_h < 3.75$
  - $M_{12} > 20$ GeV/c^2
- **Backgrounds**
  - QCD (Data)
  - EW (Data)
  - $t\bar{t}$ (MC)
  - WW (MC)
  - Z→ll (MC)
- $N_{Candidates} = 990$
- Purity ~60-70%

$\int L \sim 1$ fb^{-1} (2011)







Cross-Section

- The cross-section for boson production can be expressed as

$$\sigma \cdot \mathcal{BR} = \frac{1}{\int \mathcal{L}} \cdot \frac{N_{Candidates} \cdot \rho}{\mathcal{A} \cdot \varepsilon_{Trigger} \cdot \varepsilon_{Tracking} \cdot \varepsilon_{ParticleID} \cdot \varepsilon_{Selection}} \cdot f_{FSR}$$

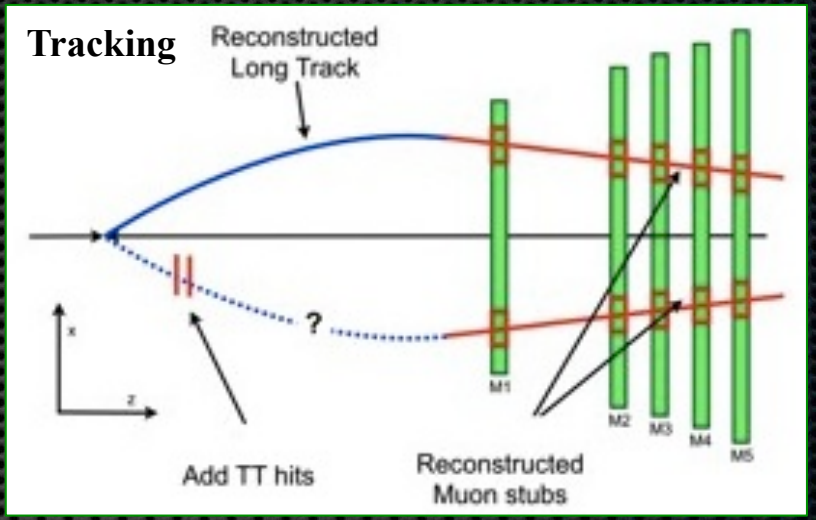
- Measurements performed in the forward region ($2.0<\eta<4.5$) for leptons with $p_T>20$ GeV/c: Acceptance = 1 for $Z\to\mu\mu$ and $W\to\mu\nu$, but obtained from MC for $Z\to ee$ and $Z\to\tau\tau$

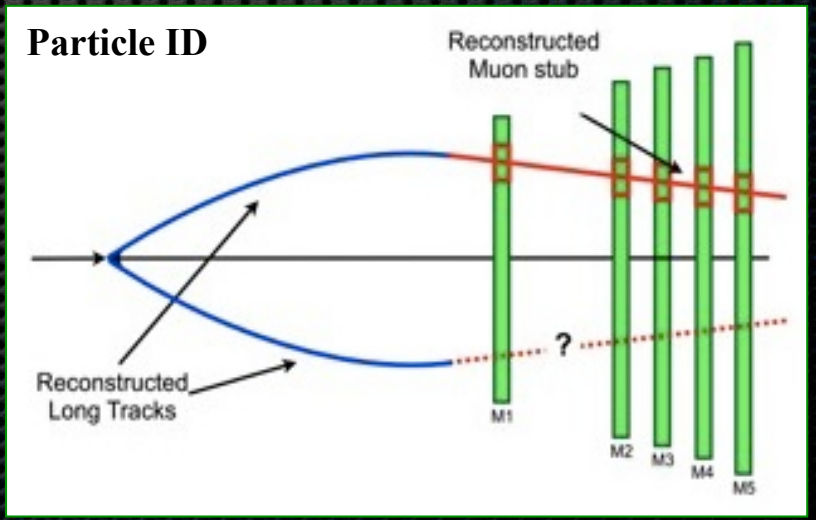
- Efficiencies determined mostly from data and cross checked with simulation

- FSR correction evaluated using HERWIG++ and PHOTOS+PYTHIA

Reconstruction Efficiencies

- **Trigger**
  - Tag: triggered muon
  - Probe: offline identified muon
- **Tracking**
  - Tag: identified muon track
  - Probe: trajectory from muon stub and minimal tracking information
- **Particle ID**
  - Tag: identified muon
  - Probe: reconstructed track





$W \to \mu\nu$

Table 1: Summary of the systematic uncertainties on the inclusive cross-sections and their ratio.

Source	$\Delta\sigma_{W^+\to\mu^+\nu}$ [%]	$\Delta\sigma_{W^-\to\mu^-\bar{\nu}}$ [%]	ΔR_W [%]
Template shape	0.28	0.39	0.59
Template normalisation	0.10	0.10	0.06
Reconstruction efficiency	1.21	1.20	0.12
Selection efficiency	0.33	0.32	0.18
Acceptance and FSR	0.18	0.12	0.21
Luminosity	1.71	1.71	—

$Z \to ll$

Luminosity $\sim 3.5\%$

$Z \to \mu\mu$

- Muon tracking efficiency $\sim 1.1\%$
- Other reconstruction efficiencies $\sim 1.1\%$
- Total $\sim 2.1\%$

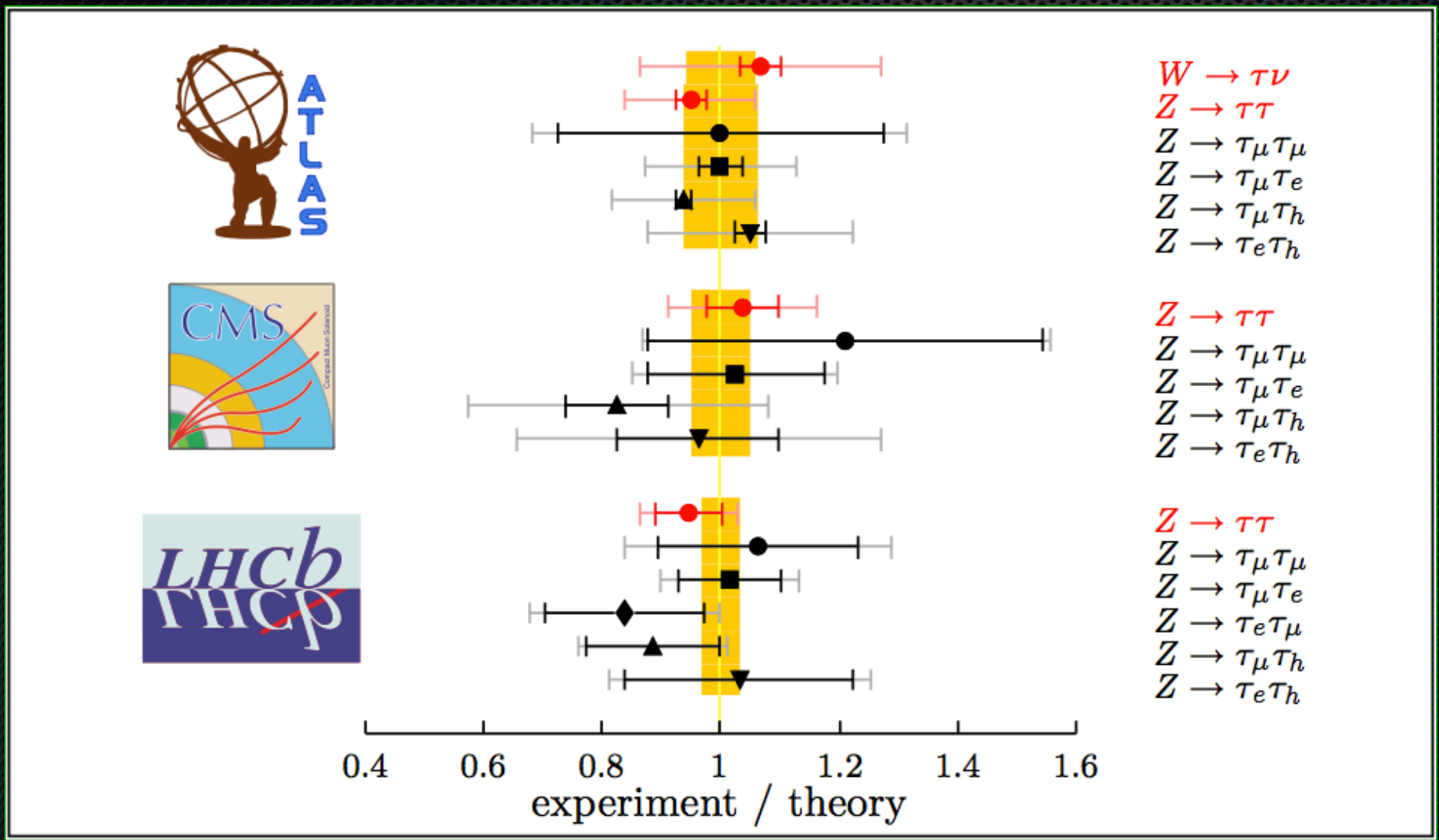
$Z \to ee$

- Electron tracking efficiency $\sim 1.6\%$
- Kinematic efficiency $\sim 1.4\%$
- Total $\sim 2.7\%$

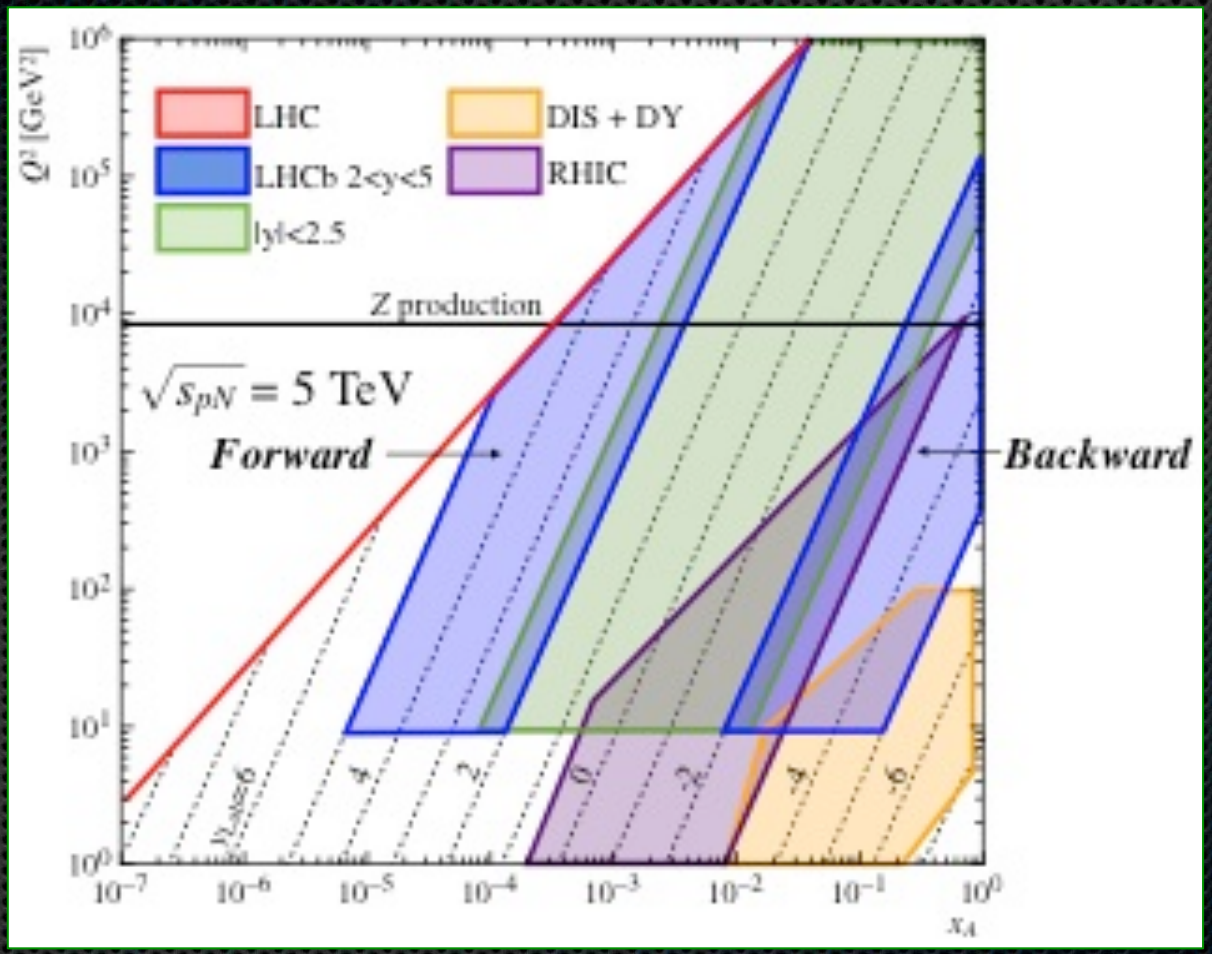
$Z \to \tau\tau$

- In $\tau_\mu\tau_\mu$ channel background dominant $\sim 10\%$
- In $\tau_e\tau_\mu$ or $\tau_e\tau_\mu$ channel reconstruction dominant $\sim 4.7 - 6.2\%$
- In $\tau_\mu\tau_h$ $\tau_e\tau_h$ channel selection dominant $\sim 4.5 - 4.7\%$
- All channels total $\sim 3.9\%$
- Stat. uncertainty is $\sim 4.9\%$

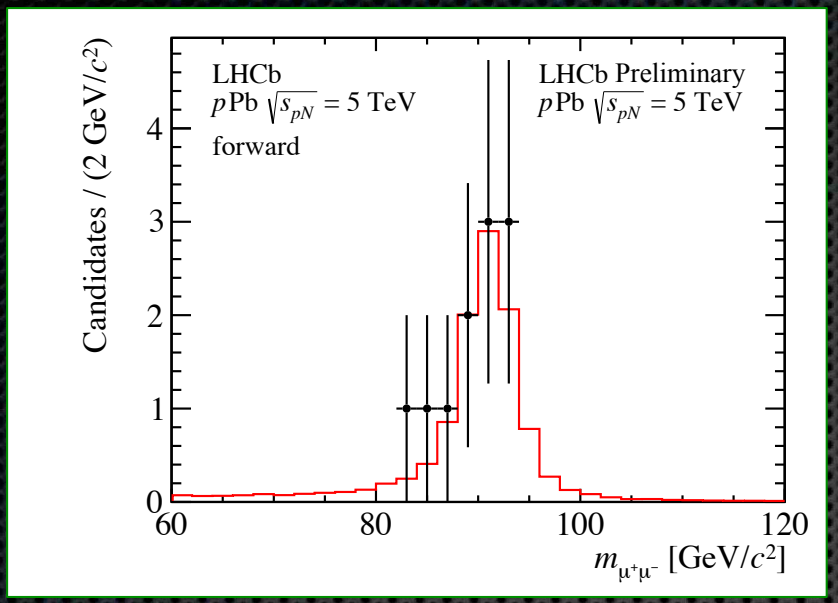
$Z \to \tau\tau$

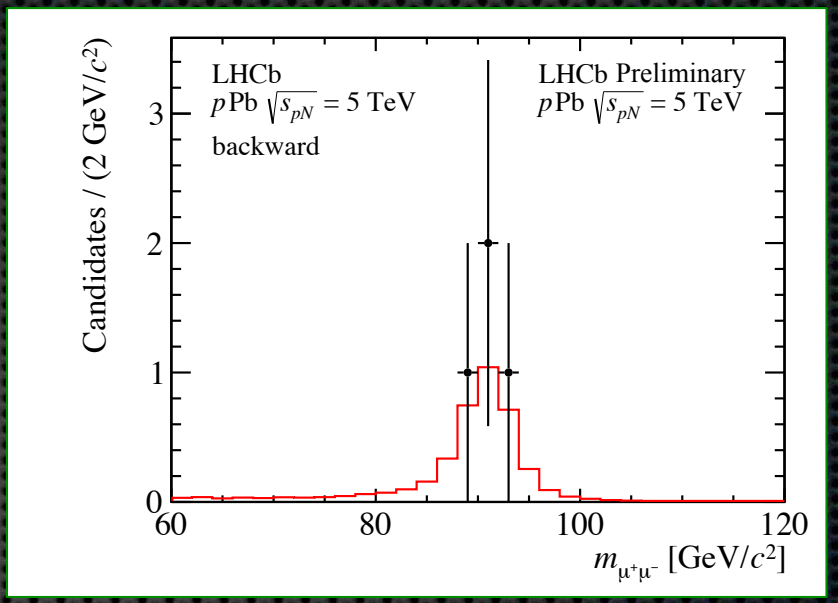

ATLAS
CMS
LHCb
$W \to \tau\nu$
$Z \to \tau\tau$
$Z \to \tau_\mu\tau_\mu$
$Z \to \tau_\mu\tau_e$
$Z \to \tau_\mu\tau_h$
$Z \to \tau_e\tau_h$
$Z \to \tau\tau$
$Z \to \tau_\mu\tau_\mu$
$Z \to \tau_\mu\tau_e$
$Z \to \tau_\mu\tau_h$
$Z \to \tau_e\tau_h$
$Z \to \tau\tau$
$Z \to \tau_\mu\tau_\mu$
$Z \to \tau_\mu\tau_e$
$Z \to \tau_e\tau_\mu$
$Z \to \tau_\mu\tau_h$
$Z \to \tau_e\tau_h$
0.4
0.6
0.8
1
1.2
1.4
1.6
experiment / theory

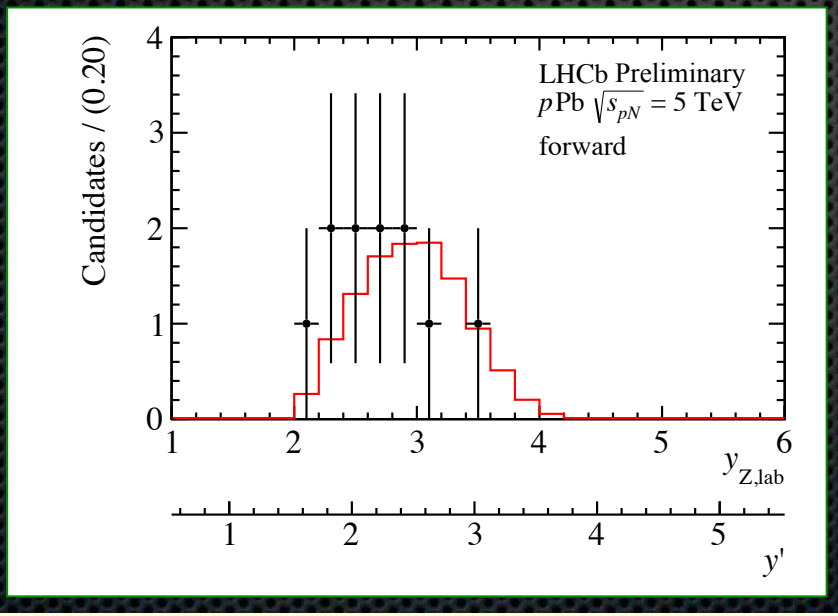
$Z \to \mu\mu$ in pA

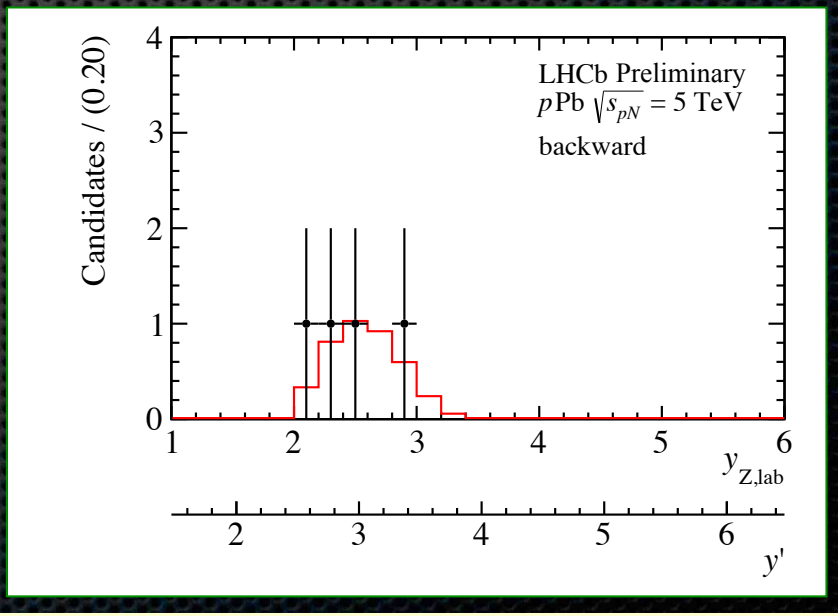


$Z \to \mu\mu$ in pA









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