UNIVERSITY OF LIVERPOOL

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on behalf of the LHCb Collaboration

University of Liverpool

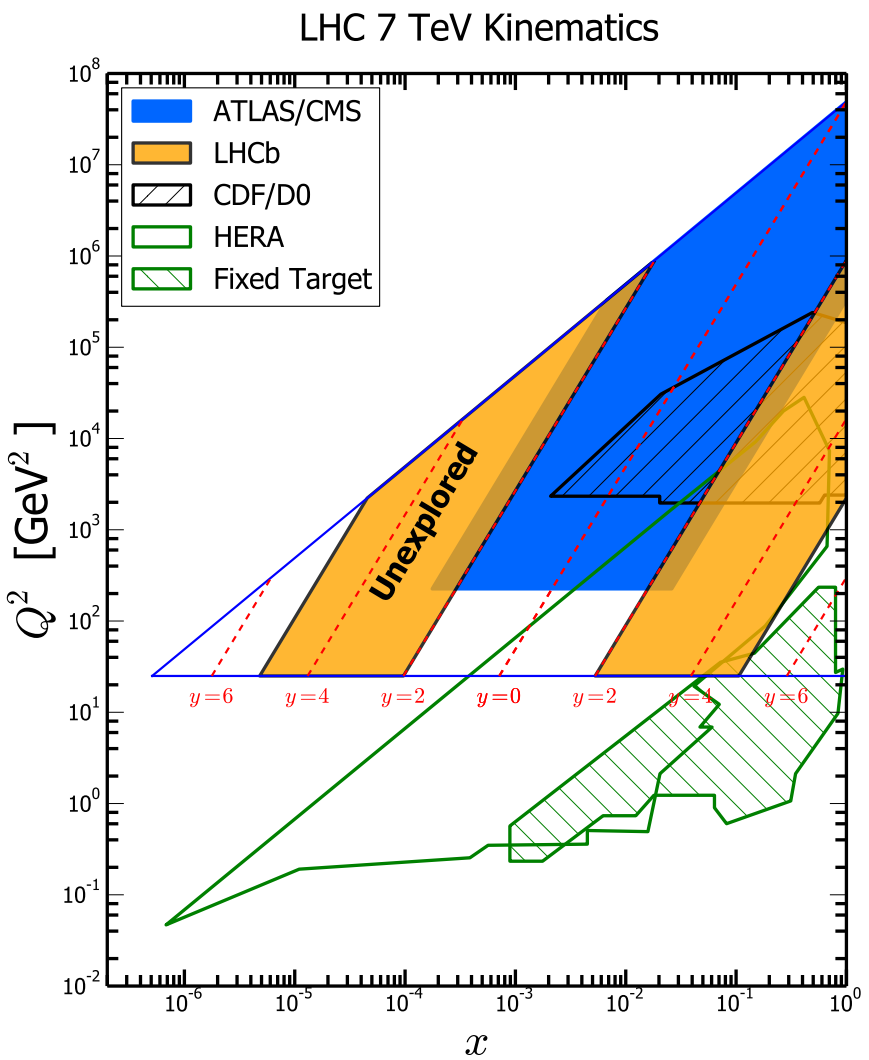
EW boson production at LHCb

Implications of LHCb Measurements and Future Prospects – October 15th, 2014

Outline

Parton Density Functions

- LHCb's forward acceptance provides interesting possibilities to study the Parton Density Functions (PDFs)
- PDFs parameterised as $(x,\ Q^2)$
- 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 $10^{-1} - 10^{0}$)
  - Low-mass Drell-Yan (x down to 10^{-6} at $M_{\mu\mu} \sim 5$ GeV)

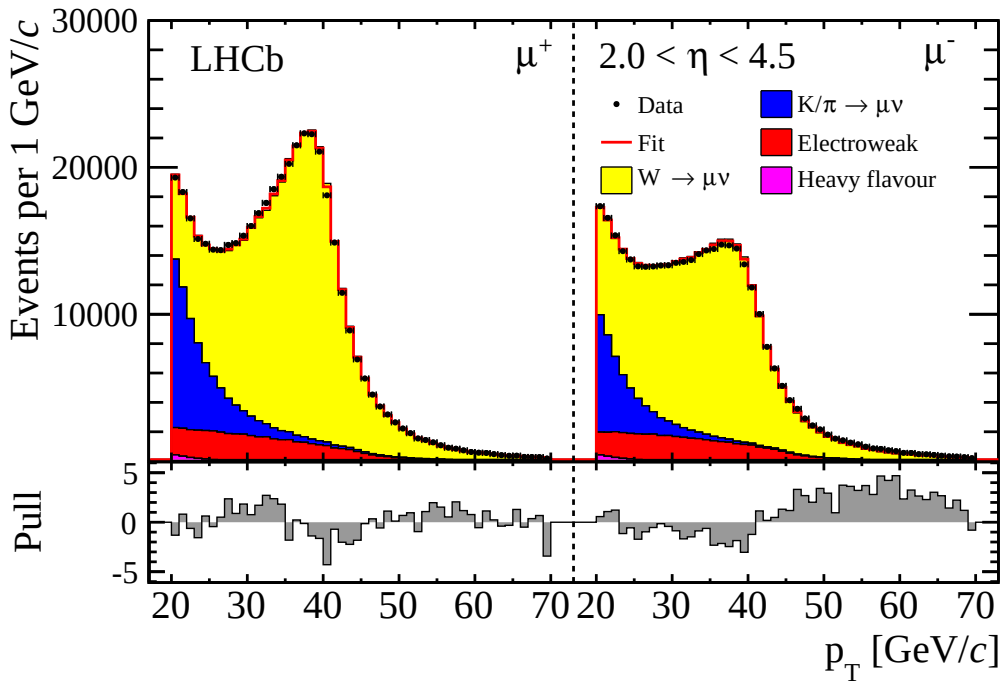


$W \to \mu\nu$

LHCb-PAPER-2014-033

- Updated measurement with 996 pb^{-1} of 2011 data at $\sqrt{s} = 7$ TeV
- Single high-p_{T} muon final state
  - $p_{\mathrm{T}}^{\mu} > 20$ GeV
  - $2.0 < \eta^{\mu} < 4.5$
  - Prompt
  - Isolated
- 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



805,593 events selected
Purity $\sim$ 77%

- Signal and Decay In Flight templates float free in fit
- Other shapes normalised using data-driven methods
- Fit performed in eight η^{μ} bins

$W \to \mu\nu$ – Systematic Uncertainties

LHCb-PAPER-2014-033

- Measurement updated from 2010 result [JHEP 1206 (2012) 058]

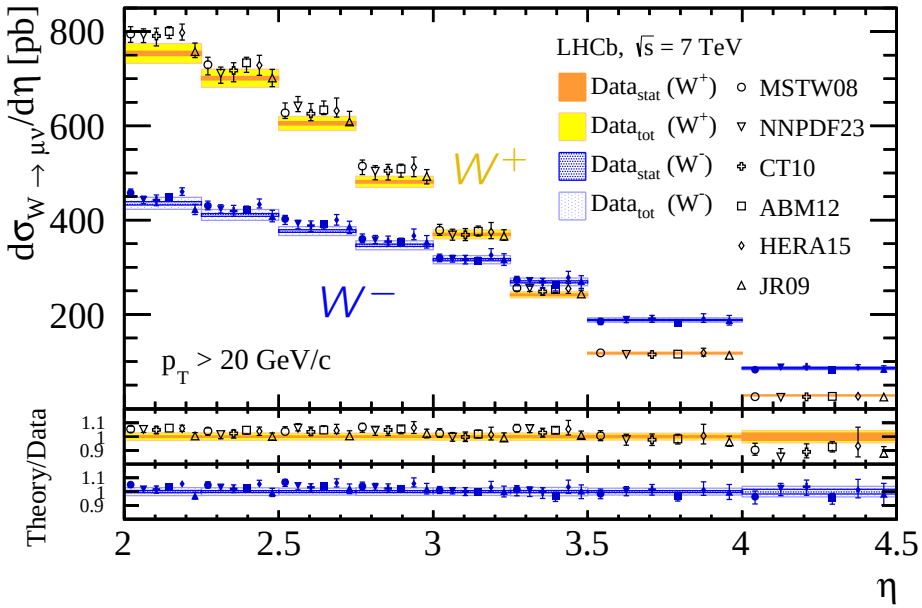
Source		2010	2011
Statistical		1.1%	0.3%
Systematic	Purity	1.1%	0.3%
	Template Shape	1.0%	0.3%
	Reconstruction Efficiency	2.1%	1.2%
	Selection Efficiency	1.8%	0.3%
	Total	3.1%	1.3%
Luminosity		3.5%	1.7%

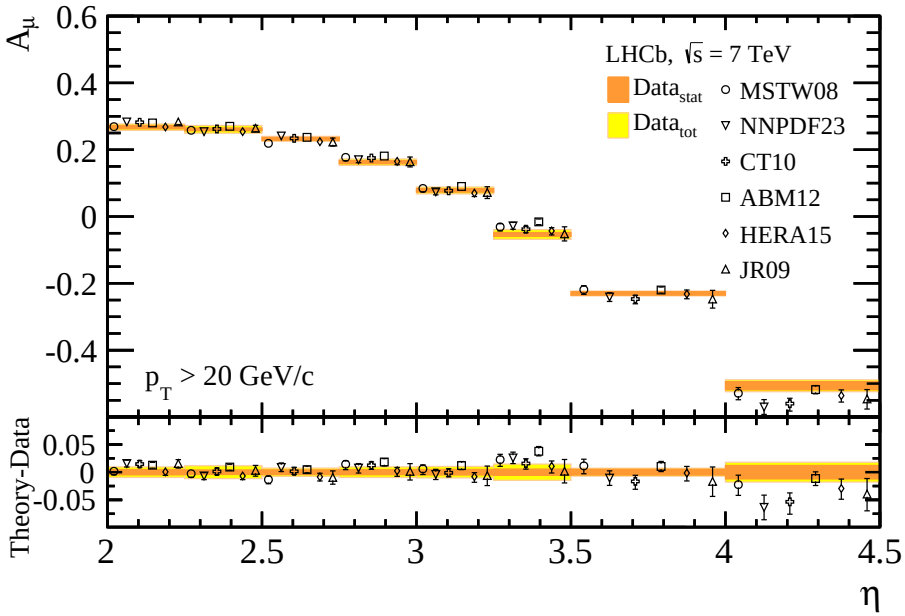
- Reduction in systematic uncertainties
  - Detector effects better understood
  - Larger statistics available for data-driven efficiency determinations
- Precision of luminosity significantly increased
  - "the most precise luminosity measurement achieved so far at a bunched-beam hadron collider" [LHCb-PAPER-2014-047]
- Expect similar improvements soon for updated $Z \to \mu\mu$ measurement

$W \to \mu\nu$ – Differential Distributions

LHCb-PAPER-2014-033

$$A_\mu = \frac{W^+ - W^-}{W^+ + W^-}$$



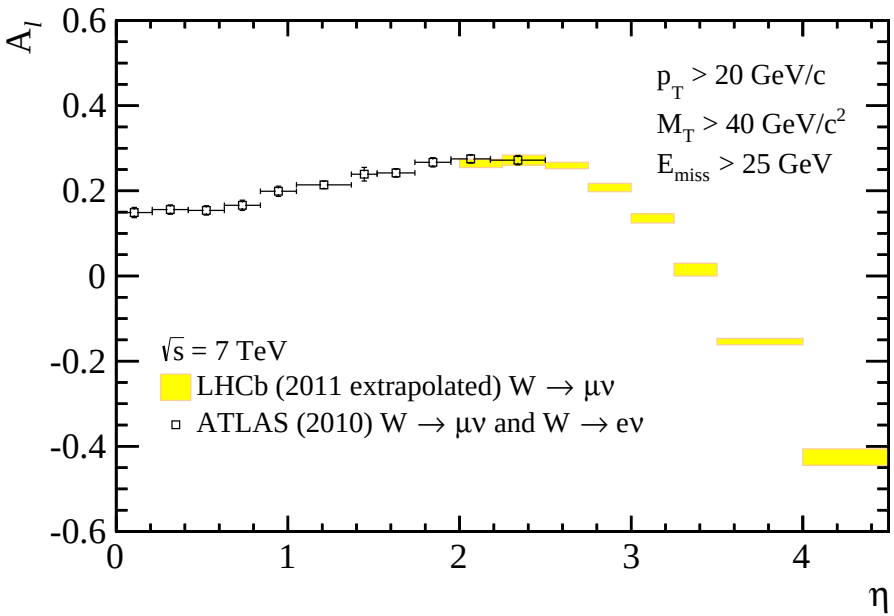


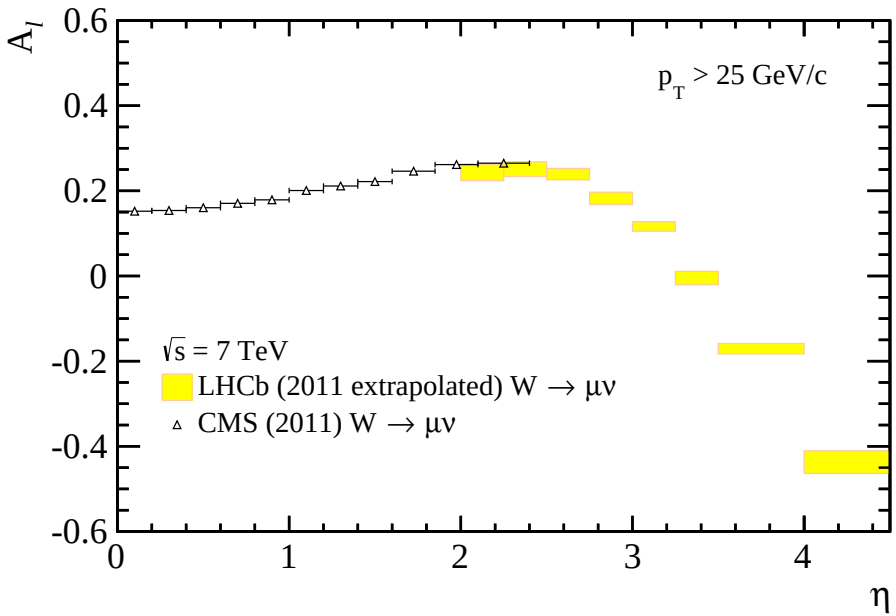
- Experimental uncertainty on differential cross-sections $\sim 2.5 - 4.2\%$
- Data corrected for FSR using Pythia interfaced with PHOTOS
- Compared to NNLO predictions calculated using FEWZ
- Good agreement with predictions for variety of PDF sets

$W \to \mu\nu$ – ATLAS/CMS Comparison

LHCb-PAPER-2014-033
(Supplementary Material)

- LHCb result extrapolated to ATLAS and CMS fiducial regions using simulation
  - ATLAS - $M_T > 40$ GeV, $E_T^{miss} > 25$ GeV
  - CMS - $p_T > 25$ GeV



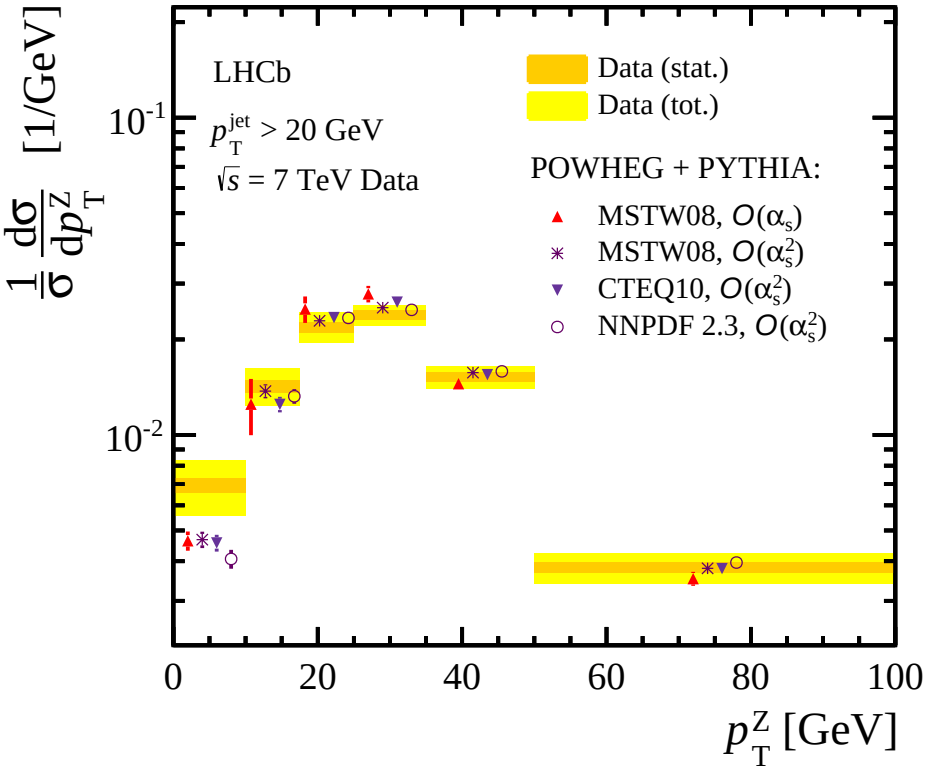


- Good agreement in overlap regions

Z+jet

J. High Energy Phys. 01 (2014) 033

- Associated production of Z boson and jets important test of PDFs and perturbative QCD
- Important benchmark for other jet studies
- Measurement performed at $\sqrt{s} = 7$ TeV



Jet Reconstruction at LHCb

- Particle flow
  - Charged tracks
  - Calorimeter clusters
- Anti-k$_T$ algorithm - $R = 0.5$

$Z + jet$ selection

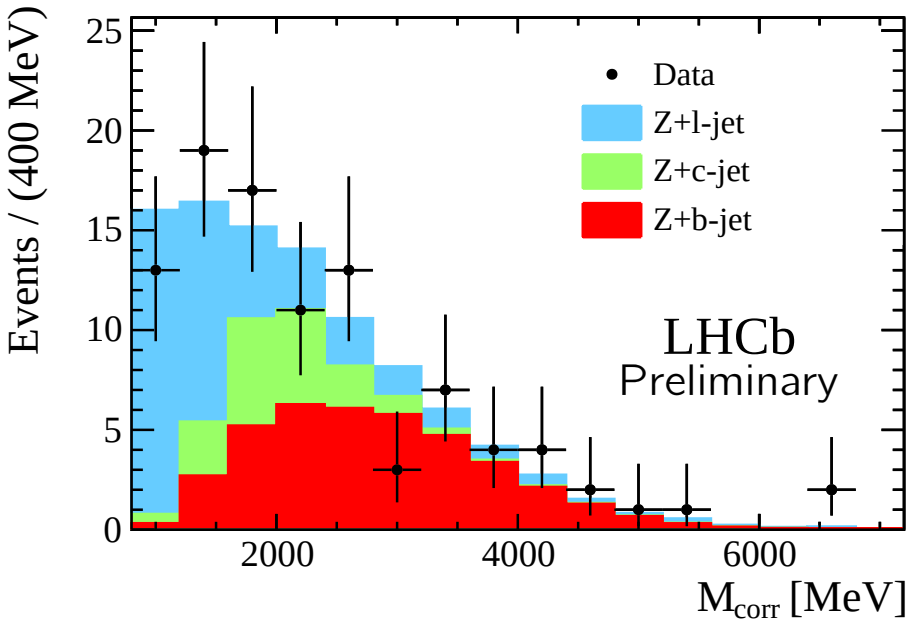
- $p_T^\mu > 20$ GeV, $2 < \eta^\mu < 4.5$
- $60 < M_{\mu\mu} < 120$ GeV
- $p_T^j > 10(20)$ GeV
- $\Delta R(\mu^\pm, jet) > 0.4$

- Jet energy resolution 10-15%
- Data compared to theory predictions using POWHEG + Pythia (Parton Shower)
- In general $\mathcal{O}(\alpha_s^2)$ predictions describe the data well

$Z + b$-jet NEW

LHCb-PAPER-2014-055
(Preliminary)

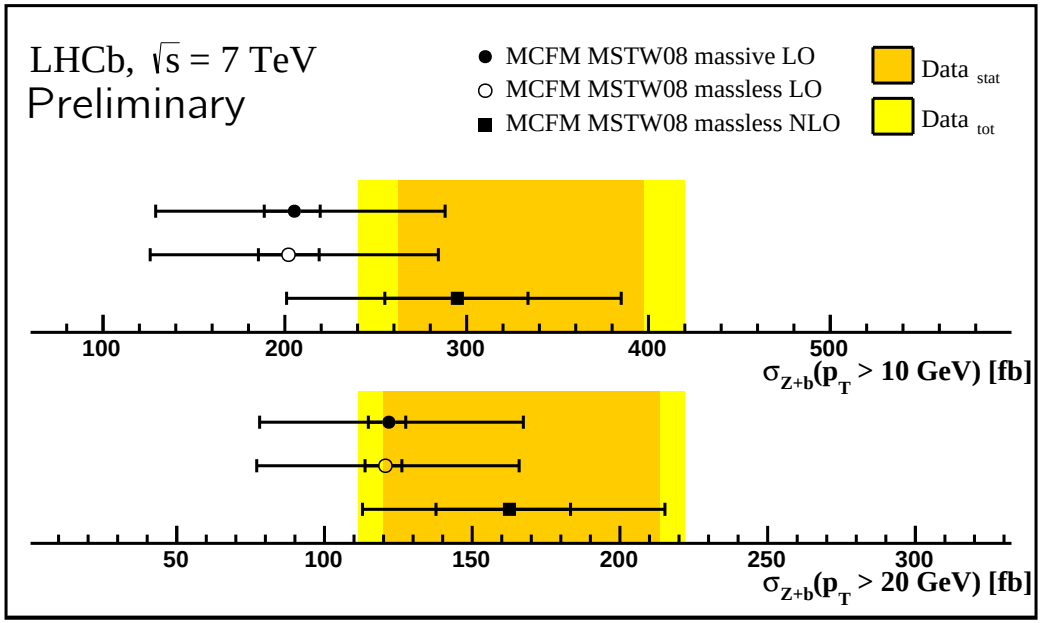
- Z+jet measurement is extended to perform measurement of $Z + b$-jet production at LHCb
- Jet is b-tagged by searching for secondary vertices within reconstructed jet
- B-tagging efficiency of ∼50-55% at high p_{T}
- Purity of selected sample is determined by performing template fit to M_{corr} of the vertex
  - $M_{\mathrm{corr}} = \sqrt{M^2 + p^2 sin^2\theta} + p \sin\theta$
  - Represents mass of secondary vertex corrected for missing particles
- Templates taken from simulation



$Z + b$-jet$^{\mathrm{NEW}}$ – Results

LHCb-PAPER-2014-055

(Preliminary)

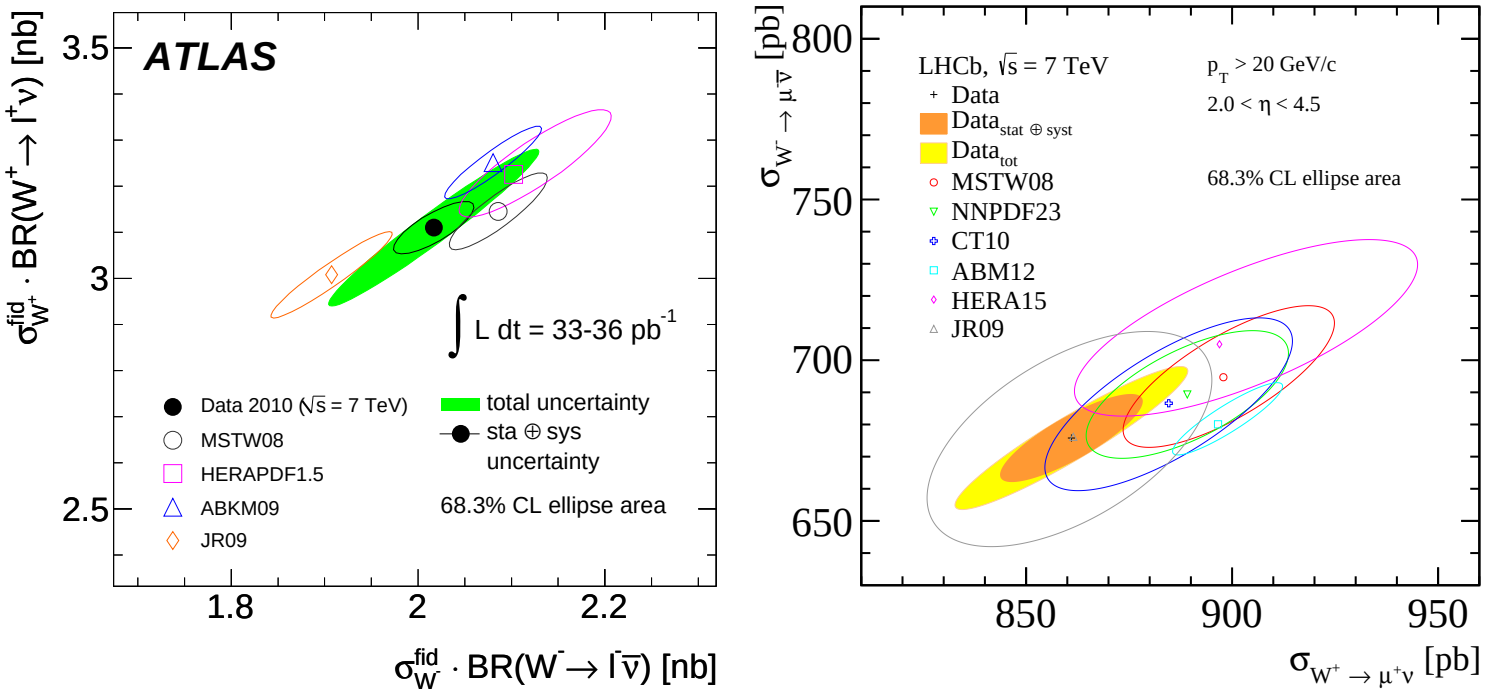


- Measurement uncertainty dominated by b-tagging and purity determination ($\sim$15%)
- Measurement compared to theory predictions calculated using MCFM using both massless (L0, NLO) and massive (LO) b-quarks
- MCFM predictions corrected for fragmentation and hadronization using Pythia 8
- Good agreement with predictions

Outlook

- What's still to come from LHCb?
- Host of measurements underway
  - Improved measurement of $Z \to \mu\mu$ at 7 TeV
  - W and Z measurements at $\sqrt{s} = 8$ TeV
  - Measurements of W production in association with b and c jets
  - Top production (see Victor Coco's talk)
  - Low-mass Drell-Yan production
  - A_{FB} in $\gamma^*/Z \to \mu\mu$ events
- Non-exhaustive list!

Summary



- LHCb has a unique rapidity coverage
  - Can provide important inputs to PDFs in the forward region
- Updated measurement of inclusive $W \to \mu\nu$ production at 7 TeV presented
  - Systematic uncertainties reduced by almost a factor of 3
- First measurement at LHCb using b-tagging also presented!
- Many other measurements expected soon!

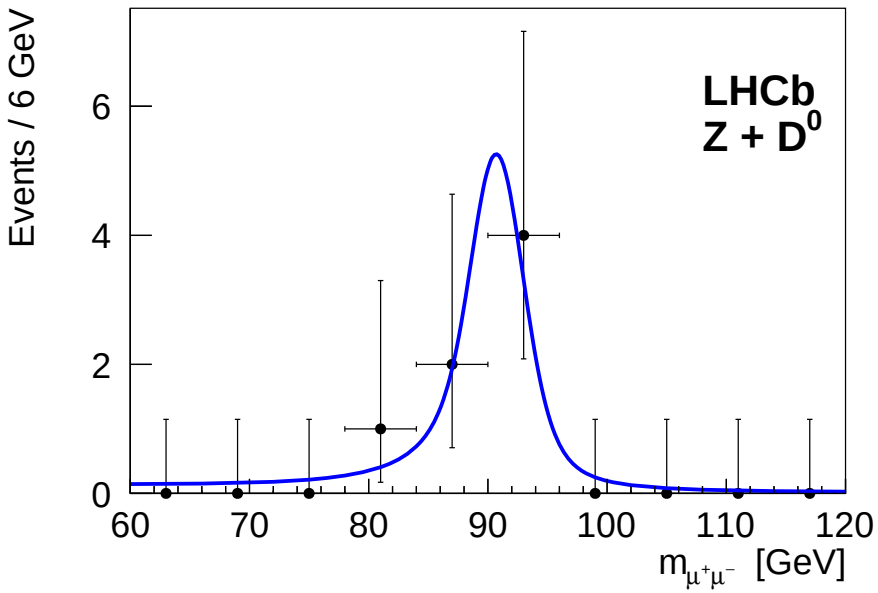
BACKUP

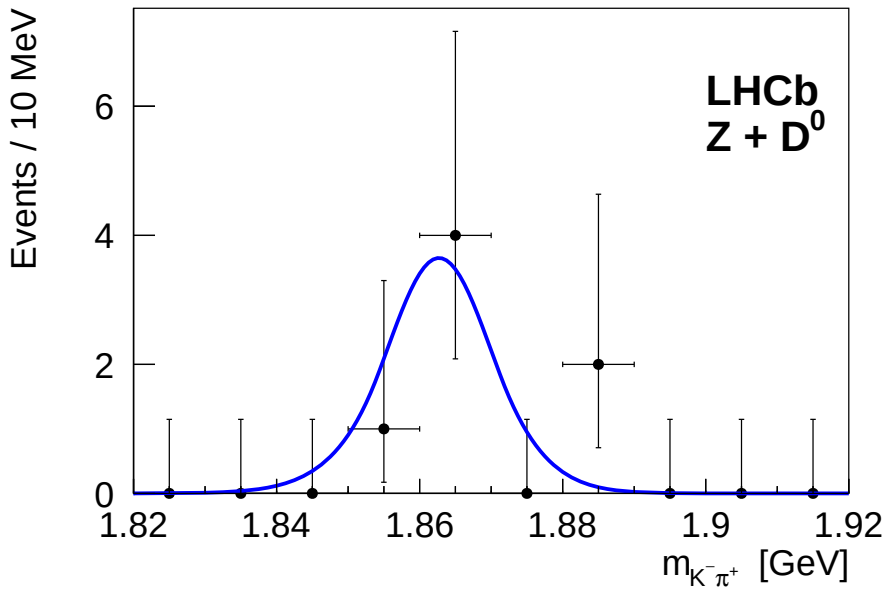
BACKUP

$Z + D$

J. High Energy Phys. 04 (2014) 091

- Associated production of a Z boson and a D-meson
  - Test charm PDF, production mechanism and DPS
- D-mesons reconstructed in channels
  - $D^0 \to K^-\pi^+$
  - $D^\pm \to K^\mp\pi^\pm\pi^\pm$

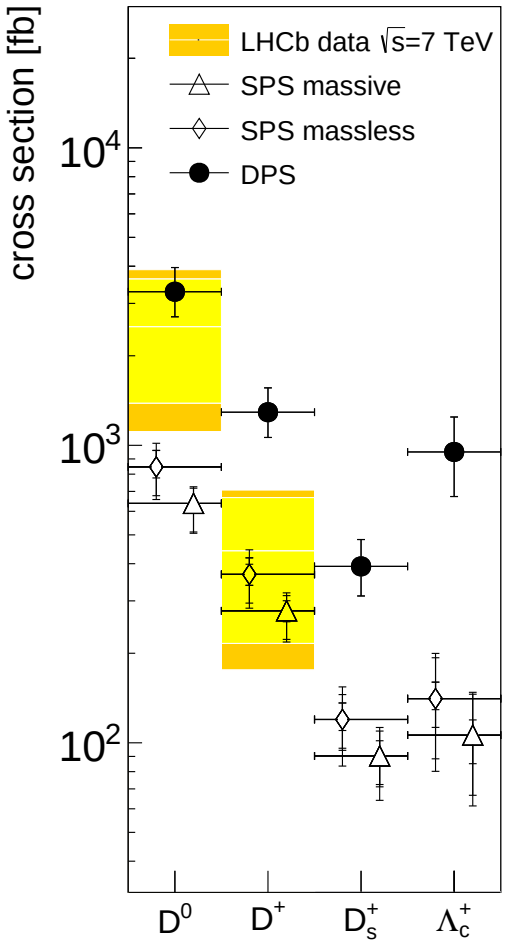




- Fiducial Region:
  - $2.0 < \eta^\mu < 4.5$, $p_{\mathrm{T}}^\mu > 20$ GeV, $60 < M_{\mu\mu} < 120$ GeV
  - $2.0 < y^D < 4.0$, $2 < p_{\mathrm{T}}^D < 12$ GeV
- 11 Candidates observed - 7 D^0 and 4 $D^\pm$
- Purity $\sim 95\%$

$Z + D$ – Results

J. High Energy Phys. 04 (2014) 091

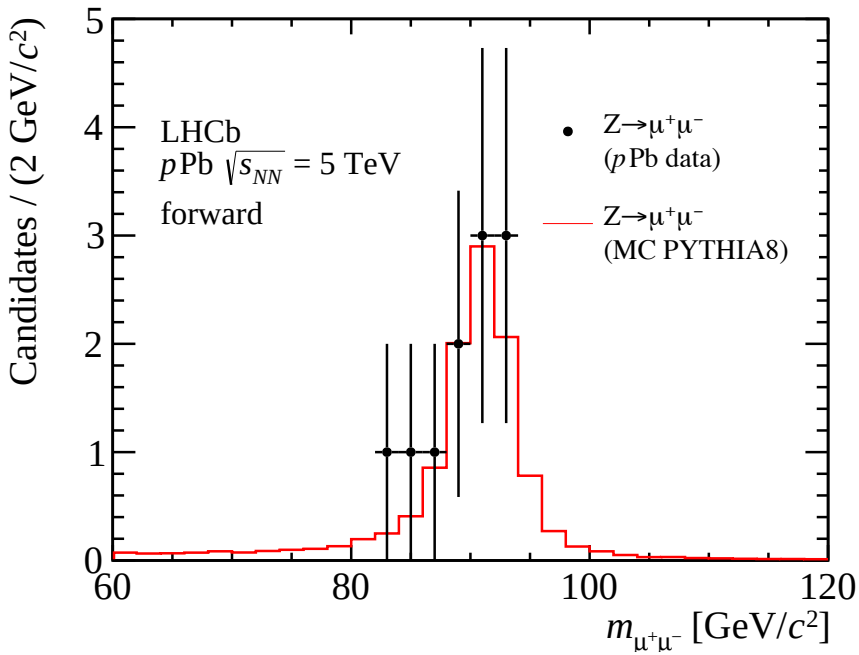


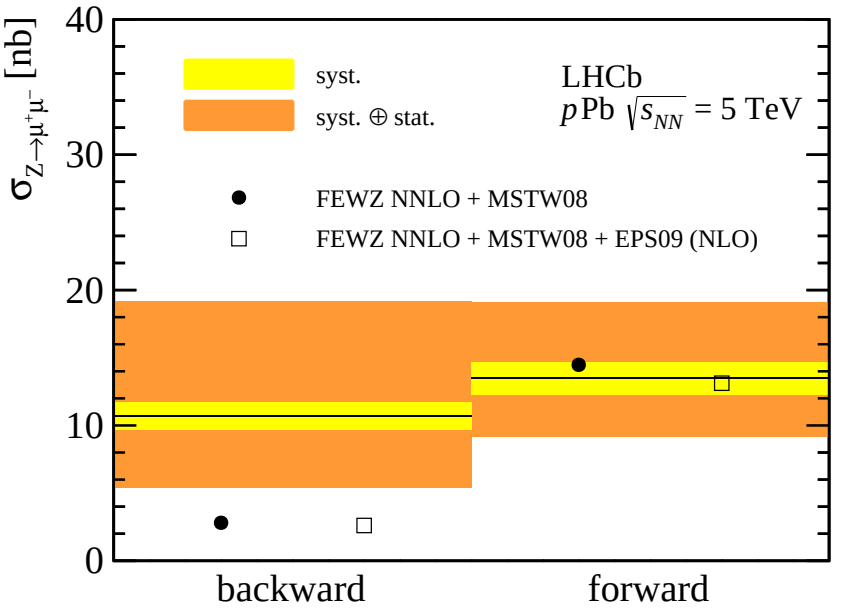
- Contributions from single- and double-parton scattering events
- Single parton scattering determined from MCFM at parton-level and corrected to hadron level
- Double parton scattering determined assuming factorisation of Z and D cross-sections
- $\sigma_{Z\to\mu\mu,D^0} \times \mathcal{B}_{Z\to\mu\mu} = 2.50 \pm 1.12 \pm 0.22$ pb
- $\sigma_{Z\to\mu\mu,D^\pm} \times \mathcal{B}_{Z\to\mu\mu} = 0.44 \pm 0.23 \pm 0.03$ pb

Z in pA collisions

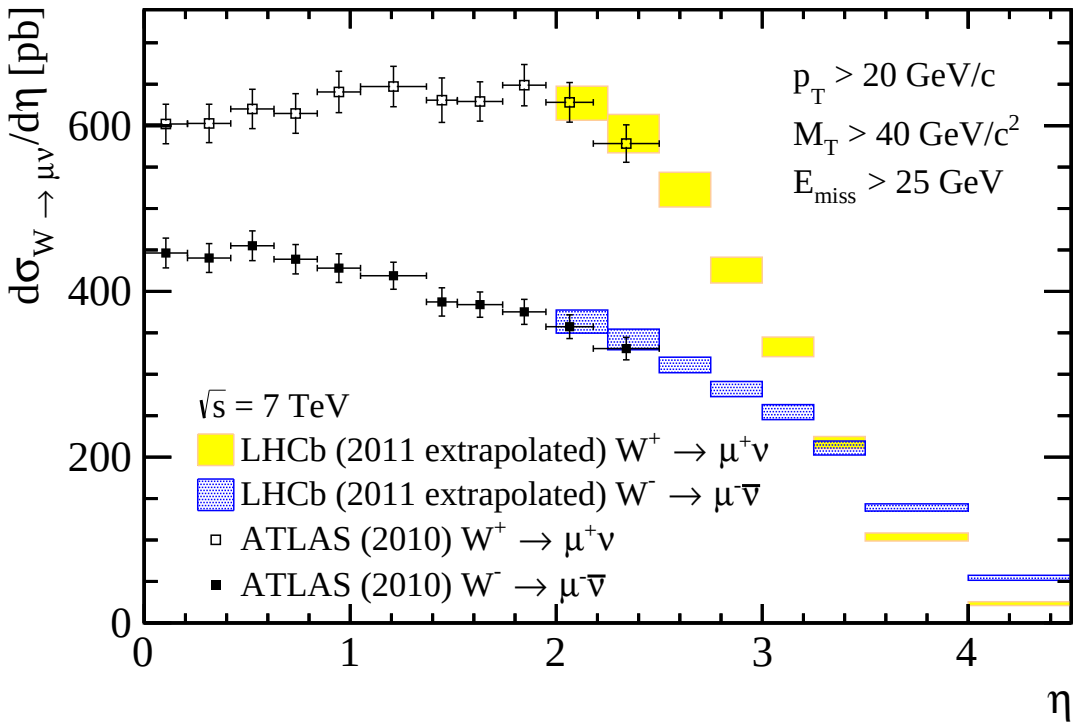
LHCB-PAPER-2014-022

- 1.6 nb^{-1} of pA data collected by LHCb in 2013 at $\sqrt{s_{\rm NN}} = 5$ TeV
- Z production important input for nucleon PDF
- $Z \to \mu\mu$ selection as in inclusive Z and $Z + j$ analysis
- 15 candidates selected (11 forward + 4 backward)
- Purity $> 99\%$
- Dominated by statistical uncertainty





$W \to \mu\nu$ – ATLAS Comparison



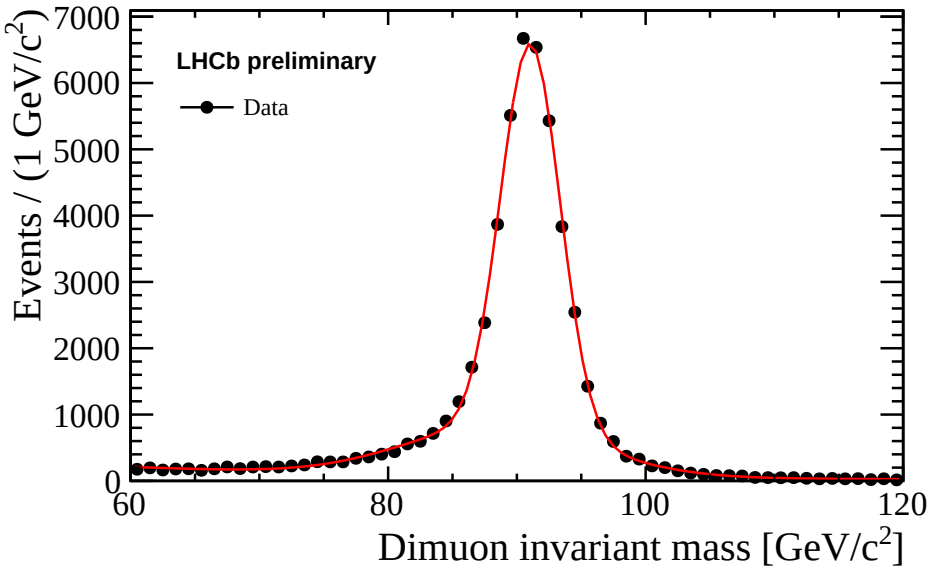
$Z \to \mu\mu$, $Z \to ee$

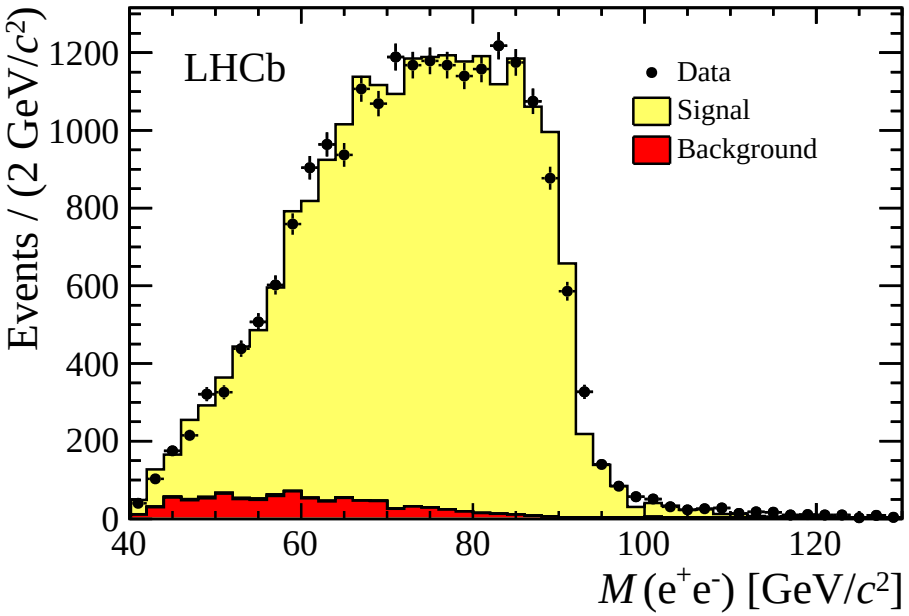
LHCb-CONF-2013-007, LHCb-PAPER-2012-036

Selection:

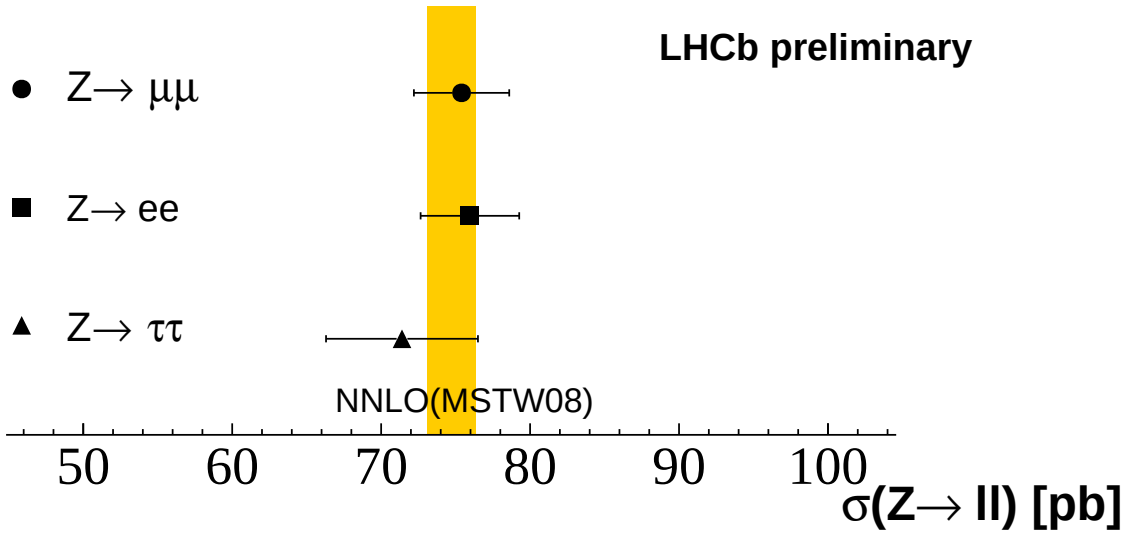
- Two identified muons/electrons
- $p_{\mathrm{T}}^{\ell} > 20$ GeV
- $2 < \eta^{\ell} < 4.5$
- $60 < M_{\mu\mu} < 120$ GeV, $M_{ee} > 40$ GeV

- $Z \to ee$ mass peak smeared by Bremsstrahlung
- $N = 52626$, Purity $> 99\%$ $(\mu\mu)$
- $N = 21420$, Purity $\sim 95\%$ (ee)



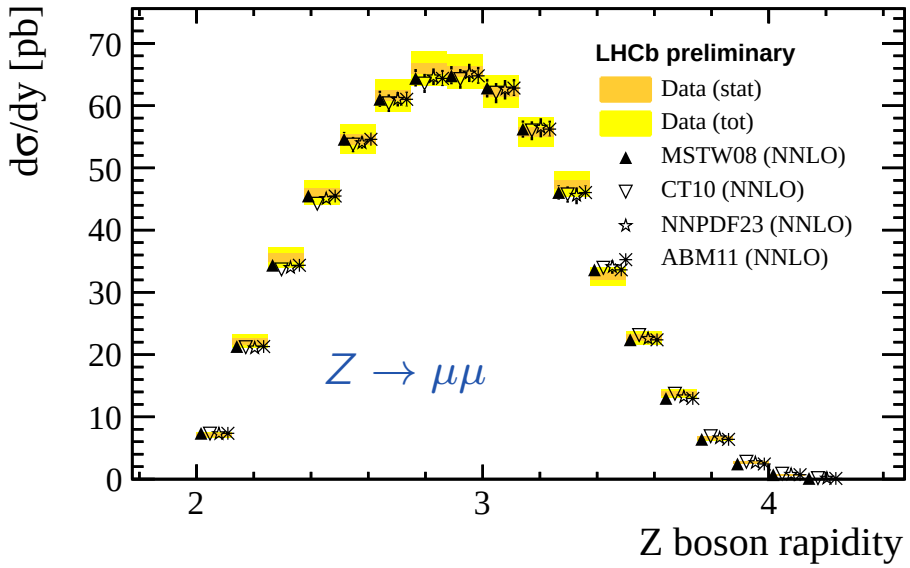


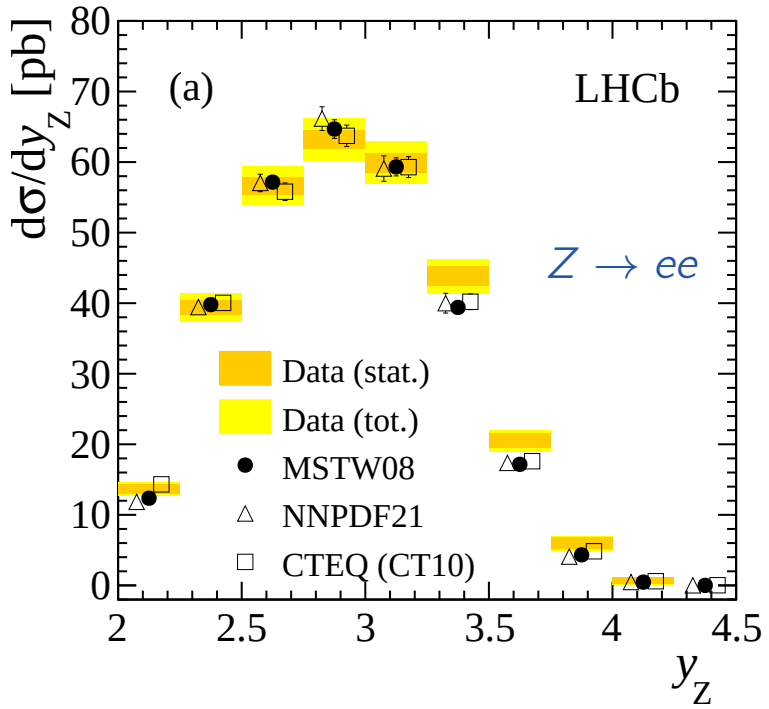
Z Results



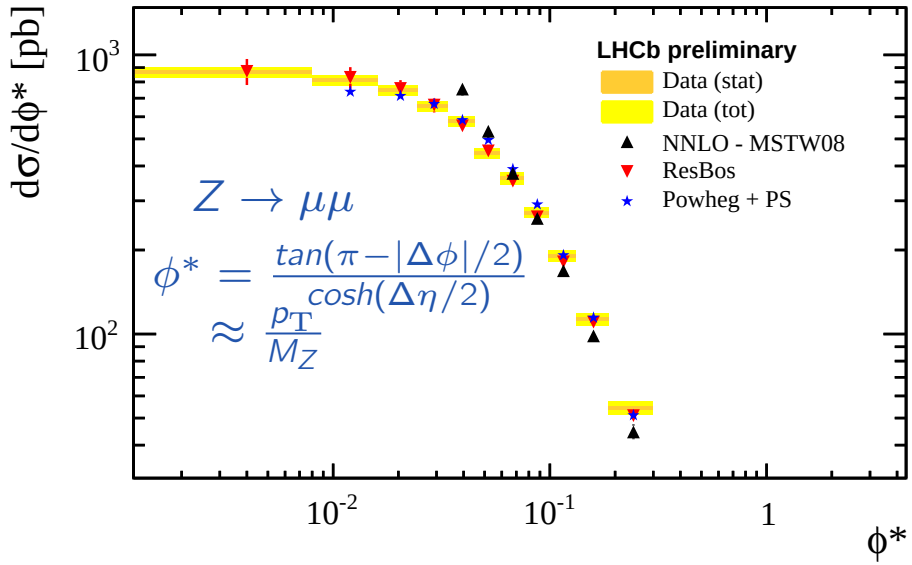
- Measurements agree with NNLO predictions
- Limited by statistics ($\tau\tau$) or luminosity (ee, $\mu\mu$)
- Main systematics: reconstruction efficiency ($\mu\mu$), tracking efficiency (ee), backgrounds and efficiency ($\tau\tau$)

Z Results

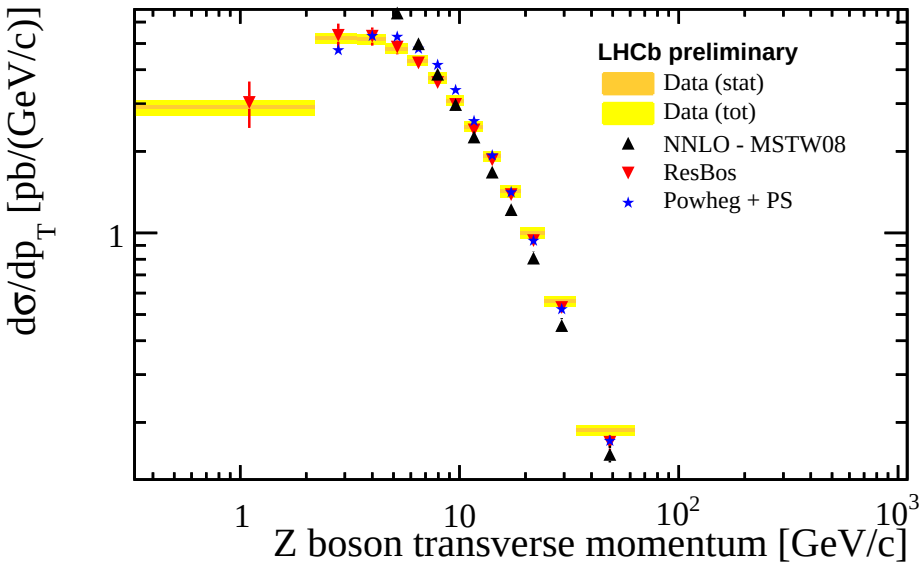


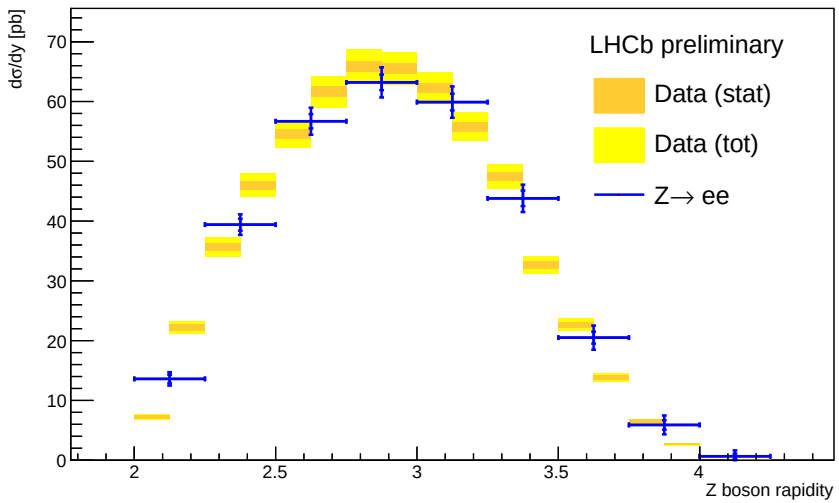


- Good agreement with NNLO predictions
- Good agreement between electron and muon channels
- Resbos and Powheg+PS describe ϕ^* distribution well

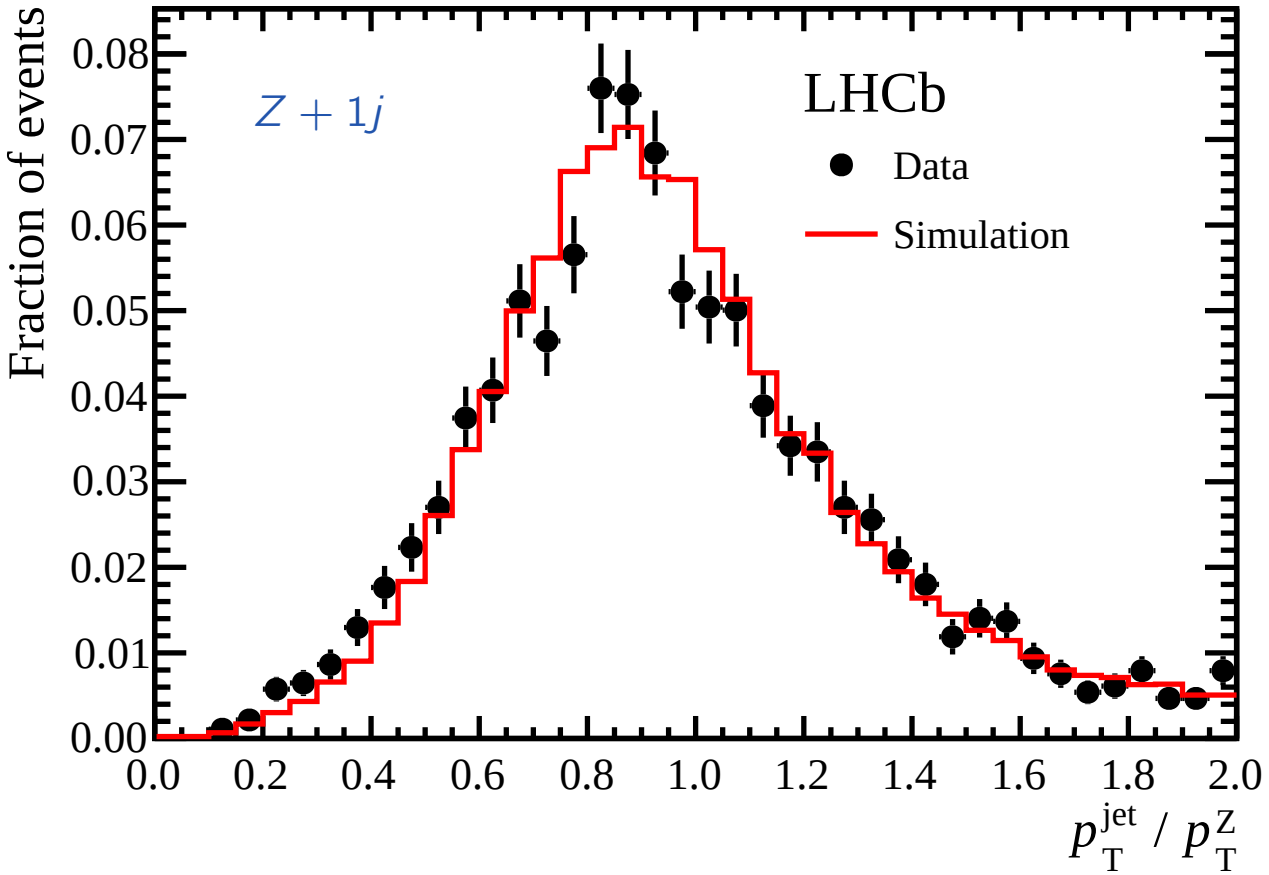


$Z \to \mu\mu$


LHCb preliminary
Data (stat)
Data (tot)
NNLO - MSTW08
ResBos
Powheg + PS
dσ/dp_T [pb/(GeV/c)]
Z boson transverse momentum [GeV/c]

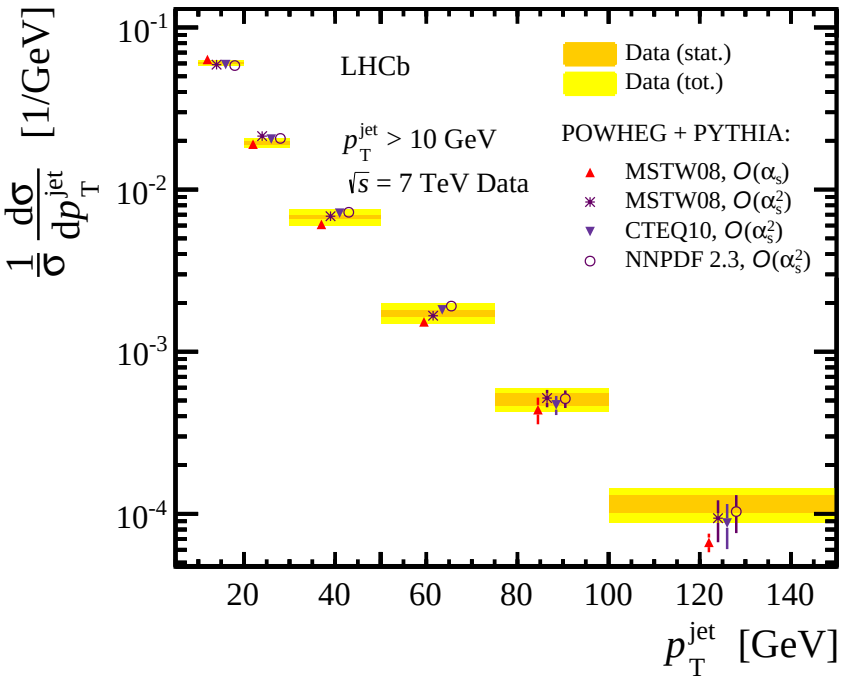

LHCb preliminary
Data (stat)
Data (tot)
Z→ ee
dσ/dy [pb]
Z boson rapidity

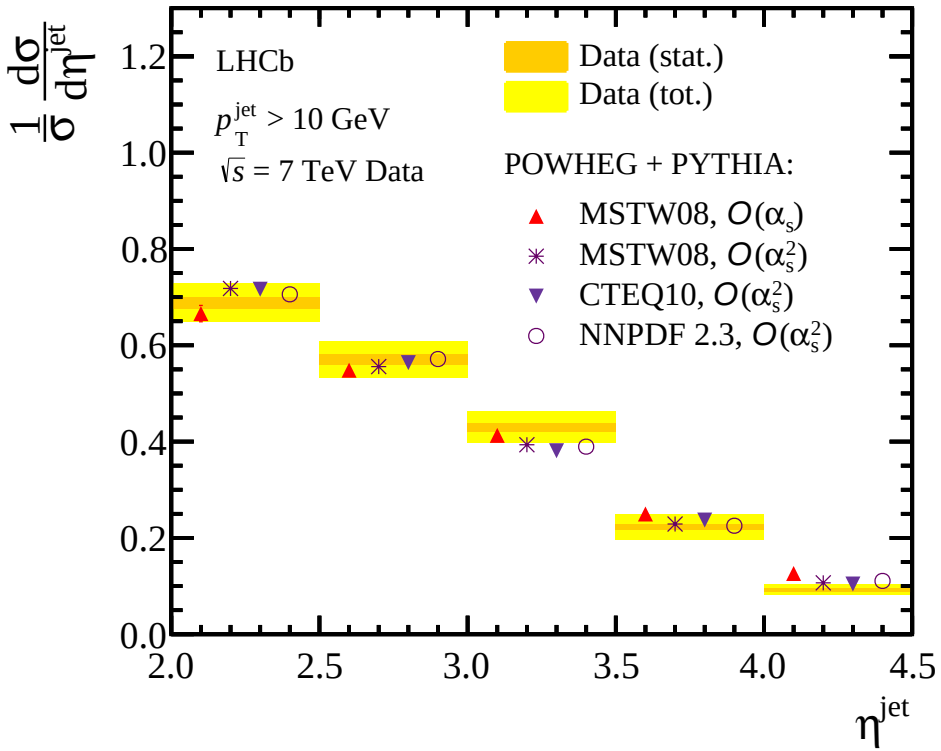
Z+jet – p_{T} balance



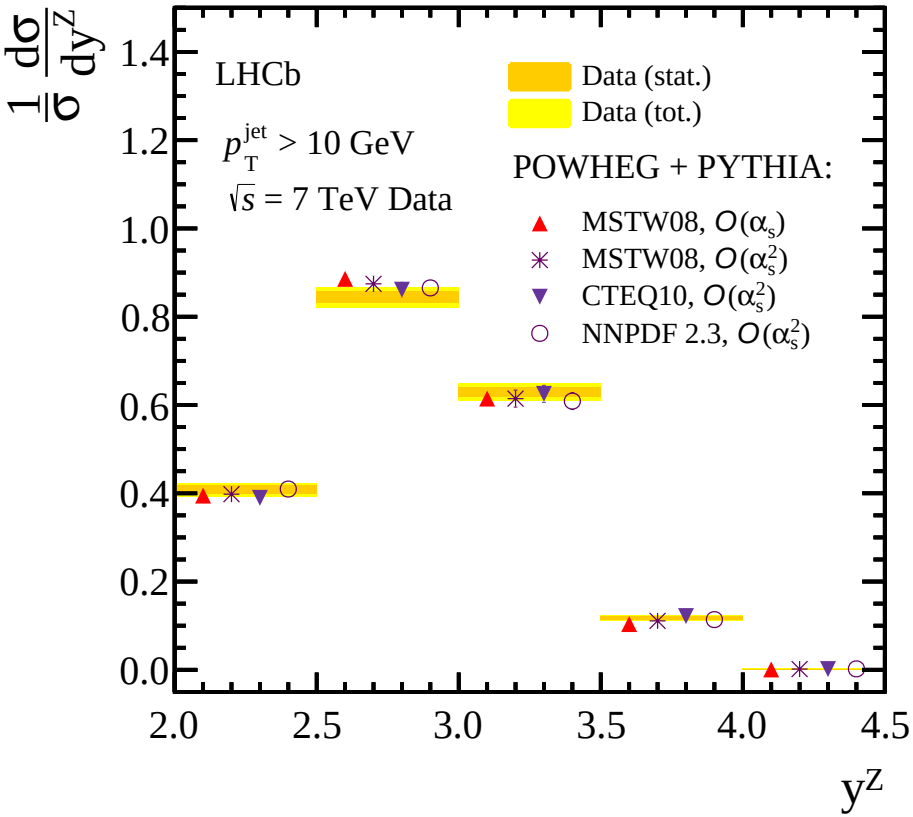
- Simulation describes p_{T} balance between jet and Z boson well in Z+1-jet events

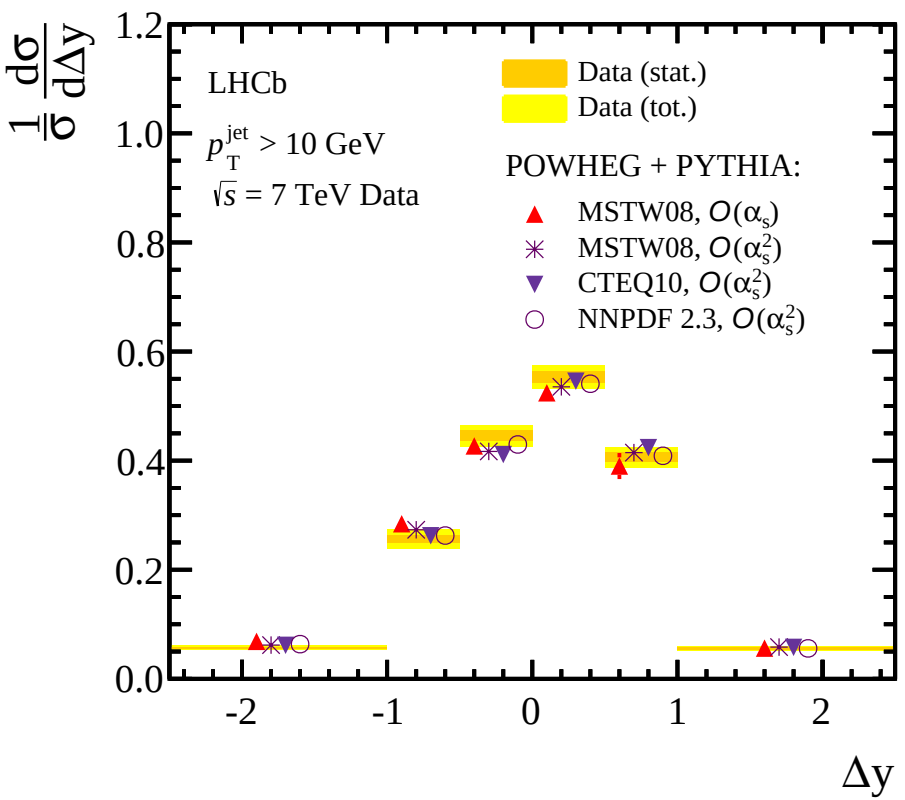
$Z + jet$


LHCb
Data (stat.)
Data (tot.)
$p_T^{jet} > 10$ GeV
$\sqrt{s} = 7$ TeV Data
POWHEG + PYTHIA:
MSTW08, $O(\alpha_s)$
MSTW08, $O(\alpha_s^2)$
CTEQ10, $O(\alpha_s^2)$
NNPDF 2.3, $O(\alpha_s^2)$
$\frac{1}{\sigma}\frac{d\sigma}{dp_T^{jet}}$ [1/GeV]
p_T^{jet} [GeV]


LHCb
Data (stat.)
Data (tot.)
$p_T^{jet} > 10$ GeV
$\sqrt{s} = 7$ TeV Data
POWHEG + PYTHIA:
MSTW08, $O(\alpha_s)$
MSTW08, $O(\alpha_s^2)$
CTEQ10, $O(\alpha_s^2)$
NNPDF 2.3, $O(\alpha_s^2)$
$\frac{1}{\sigma}\frac{d\sigma}{d\eta^{jet}}$
η^{jet}

$Z + jet$


$\frac{1}{\sigma}\frac{d\sigma}{dy^Z}$
LHCb
$p_T^{jet} > 10$ GeV
$\sqrt{s}$ = 7 TeV Data
Data (stat.)
Data (tot.)
POWHEG + PYTHIA:
MSTW08, $O(\alpha_s)$
MSTW08, $O(\alpha_s^2)$
CTEQ10, $O(\alpha_s^2)$
NNPDF 2.3, $O(\alpha_s^2)$
y^Z


$\frac{1}{\sigma}\frac{d\sigma}{d\Delta y}$
LHCb
$p_T^{jet} > 10$ GeV
$\sqrt{s}$ = 7 TeV Data
Data (stat.)
Data (tot.)
POWHEG + PYTHIA:
MSTW08, $O(\alpha_s)$
MSTW08, $O(\alpha_s^2)$
CTEQ10, $O(\alpha_s^2)$
NNPDF 2.3, $O(\alpha_s^2)$
Δy