UNIVERSITY OF LIVERPOOL

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Overview of PDF–sensitive measurements from Run I at LHCb and plans for Run II

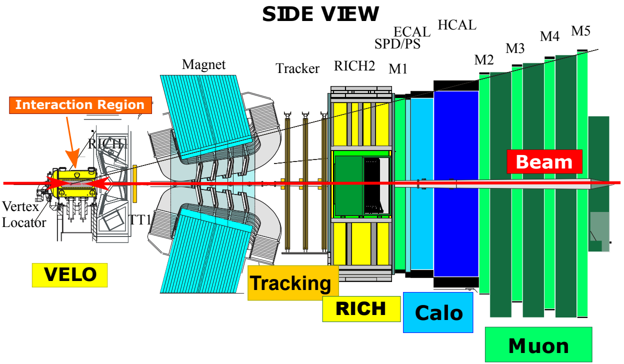
Parton Distributions for the LHC – February 17th, 2015

Outline

1. Introduction
2. Inclusive $W \to \mu\nu$ production
3. Inclusive Z production
4. Z production in association with jets
5. Central Exclusive Production
6. Outlook

LHCb

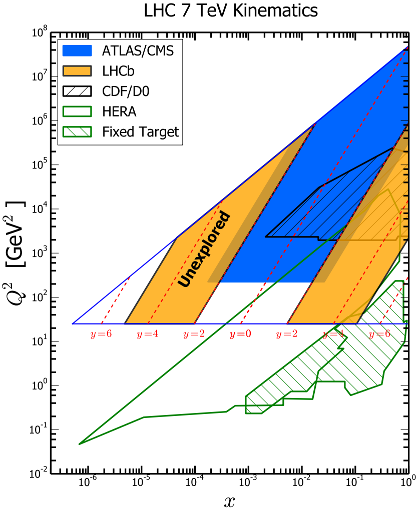
- Forward arm spectrometer at the LHC
- Designed to study $\mathcal{CP}$ violation in B Decays
- Fully instrumented between $2.0 \leq \eta \leq 5.0$
- ATLAS/CMS precision coverage - $|\eta| < 2.5$
- Unique Region $2.5 \leq \eta \leq 5.0$
- VELO also provides backward coverage $(-3.5 < \eta < -1.5)$



2010 - 37.1 pb^{-1} - 7 TeV	2011 - 1.0 fb^{-1} - 7 TeV	2012 - 2.0 fb^{-1} - 8 TeV

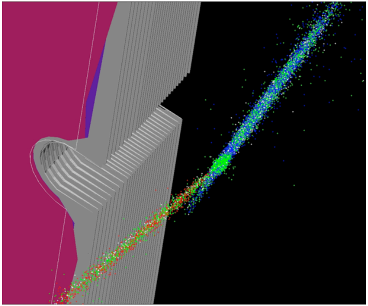
Parton Density Functions

- 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)



Precision Luminosity at LHCb

JINST 9 (2014) 12, P12005



Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.

Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

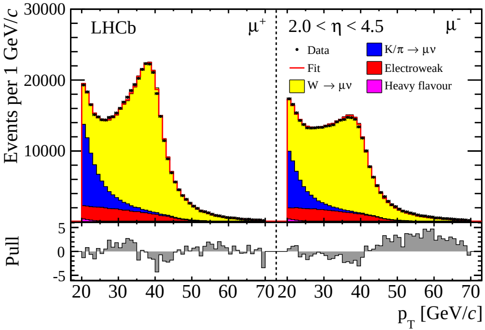
- Luminosity measured at LHCb using two methods: Beam-Gas Imaging (BGI) and Van der Meer Scan (VDM)
- In BGI method neon injected in beam-pipe to reconstruct beams using collision vertices
- Both methods combined to trace beam profile and determine luminosity

- Updated luminosity measurement uses improved two-dimensional description of beam density profile
- BGI and VDM methods combined to achieve precision of 1.7% in 2011 and 1.2% in 2012
  - To be compared to previous precision of 3.5%
- "the most precise luminosity measurement achieved so far at a bunched-beam hadron collider"

$W \to \mu\nu$

- Updated measurement with 996 pb^{-1} of 2011 data at $\sqrt{s} = 7$ TeV
- Single high-p_{T} muon final state
  - $p_{\text{T}}^{\mu} > 20$ 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

JHEP 1412 (2014) 079

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

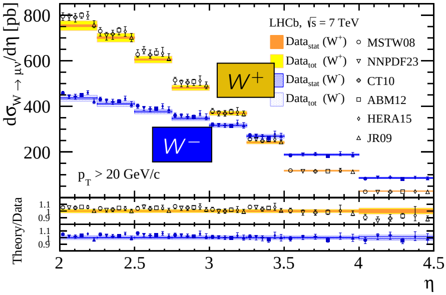
Source		2010	2011
Statistical		1.1%	0.3%
Systematic	Purity	1.1%	0.3%
	Template Shape	1.0%	0.3%
	Reconstruction Efficiency	2.1%	1.2%
	Selection Efficiency	1.8%	0.3%
	Total	3.1%	1.3%
Luminosity		3.5%	1.7%

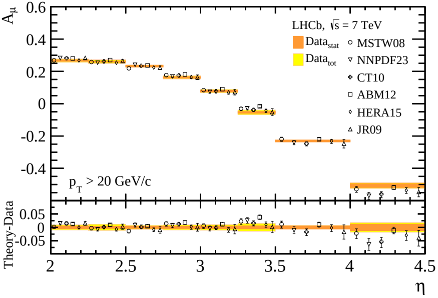
- Reduction in systematic uncertainties
  - Detector effects better understood
  - Larger statistics available for data-driven efficiency determinations
- Precision of luminosity significantly increased

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

JHEP 1412 (2014) 079

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





- 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

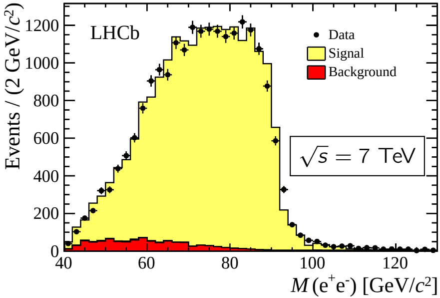
$Z \to ee$

JHEP 1302 (2013) 106, LHCb-PAPER-2015-003

- Measurements of $Z \to ee$ production published at 7 and 8 TeV*new*

Selection:

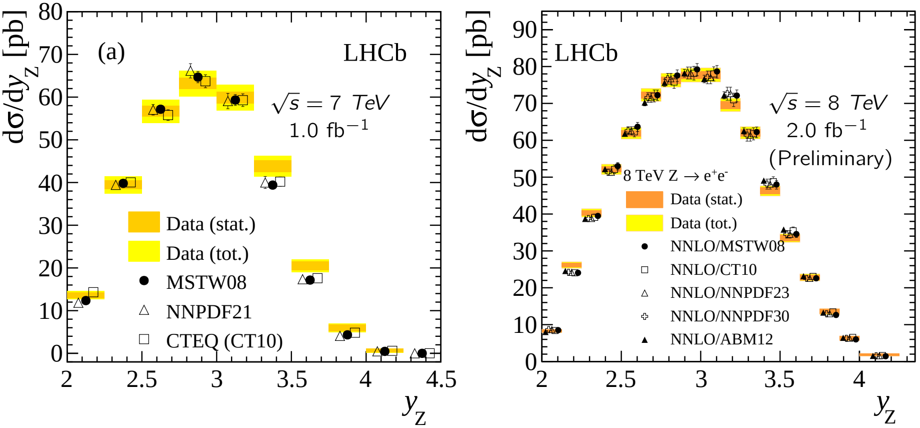
- Two identified electrons
- $p_{\mathrm{T}}^{\ell} > 20$ GeV
- $2 < \eta^{\ell} < 4.5$
- $M_{ee} > 40$ GeV
- $Z \to ee$ mass peak smeared by Bremsstrahlung
- Purity $\sim 95\%$



- Measurement corrected to 60-120 GeV mass range using simulation
- Leading systematic due to luminosity in 2011 (3.5%) and electron reconstruction efficiency in 2012 (1.6%)

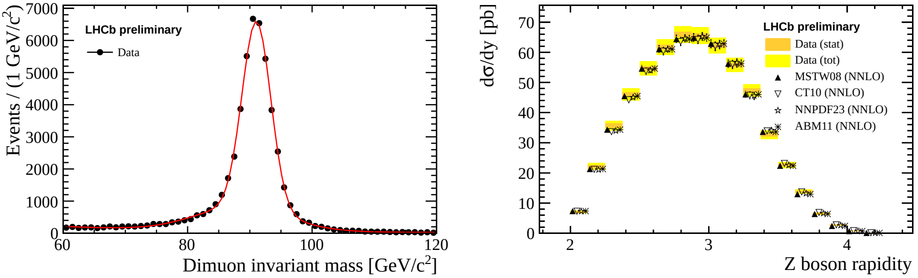
$Z \rightarrow ee$ Results

JHEP 1302 (2013) 106, LHCb-PAPER-2015-003



- Extra statistics in 2012 allow finer binning
- Good agreement with FEWZ NNLO predictions with variety of PDF sets

$Z \to \mu\mu$



- Preliminary measurement at $\sqrt{s} = 7$ TeV with 1.0 fb^{-1} performed
- Purity $> 99\%$
- Good agreement with NNLO predictions using range of PDF sets
- Measurement precision ($\sim 4\%$) dominated by luminosity and reconstruction efficiency
- Updated measurement at 7 TeV expected soon
- Significant reduction in systematic uncertainties combined with reduction in luminosity uncertainty
- Will include precision determination of W/Z ratio

Z+jet

J. High Energy Phys. 01 (2014) 033

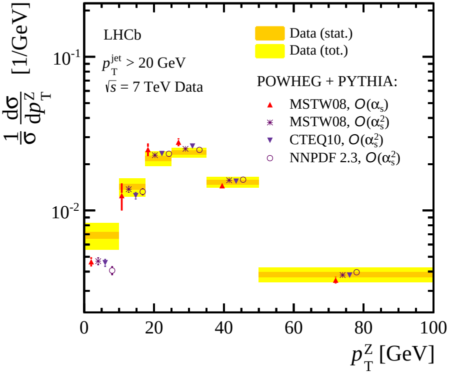
- Associated production of Z boson and jets important test of PDFs and perturbative QCD
- Important benchmark for other jet studies
- Measurement performed at $\sqrt{s} = 7$ TeV

Jet Reconstruction at LHCb

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

$Z + jet$ selection

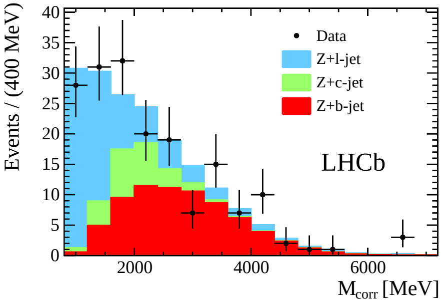
- $p_{\mathrm{T}}^{\mu} > 20$ GeV, $2 < \eta^{\mu} < 4.5$
- $60 < M_{\mu\mu} < 120$ GeV
- $p_{\mathrm{T}}^{j} > 10(20)$ GeV
- $\Delta R(\mu^{\pm}, jet) > 0.4$



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

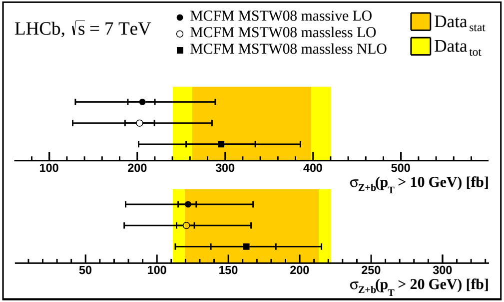
$Z + b$–jet

- 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 – Results

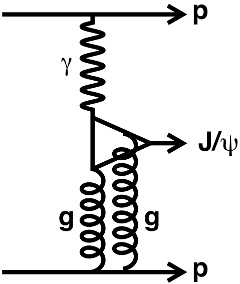
JHEP 1501 (2015) 064



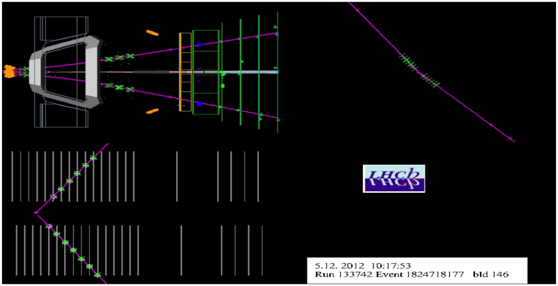
- Measurement uncertainty dominated by b-tagging and purity determination (∼15%)
- Measurement compared to theory predictions calculated using MCFM using both massless (L0, NLO) and massive (LO) b-quarks
- MCFM predictions corrected for fragmentation and hadronization using Pythia 8
- Good agreement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

Central Exclusive Production

- Exchange of neutral, colourless particles - protons remain intact



$pp \to pp + J/\psi$

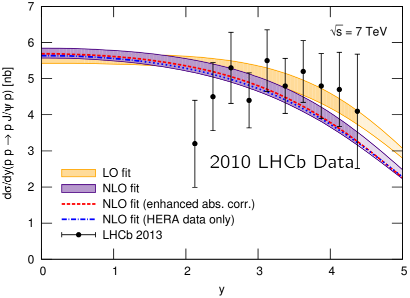


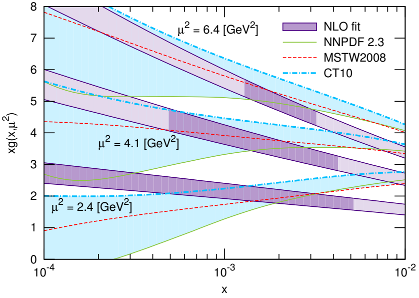
- Experimental signature - events with just two muon tracks in the final state
- LHCb is ideal environment to perform measurements
  - Relatively low number of pile-up collisions
  - Backward VELO coverage can be exploited to identify rapidity gap

Central Exclusive Production – PDFs

JHEP11(2013)085

- Production cross-section $\propto (xg(x, \bar{Q}^2))^2$
- Gluon PDF can be constrained with measurements of exclusive $J\psi$ and $\psi(2S)$ production



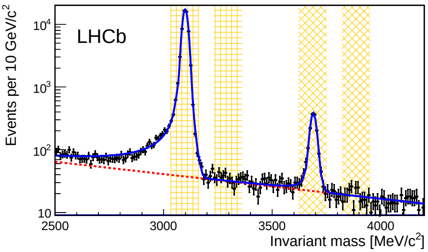


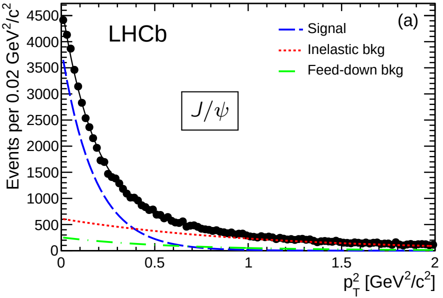
- Predictions at LO and NLO from Jones, Martin, Ryskin, Teubner
- Gluon PDF may rise faster than predicted by global PDFs - increased cross-section for central exclusive channels
- LHCb probes x down to $\sim 10^{-5}$

Exclusive Production at LHCb

JPhys(2014)G41 055002

- Analysis performed using 2011 dataset (7 TeV)
- Select single PV events with exactly two tracks in the LHCb acceptance
- Veto on backward tracks (rapidity gap) and photons ($\chi_c \to J/\psi\gamma$)

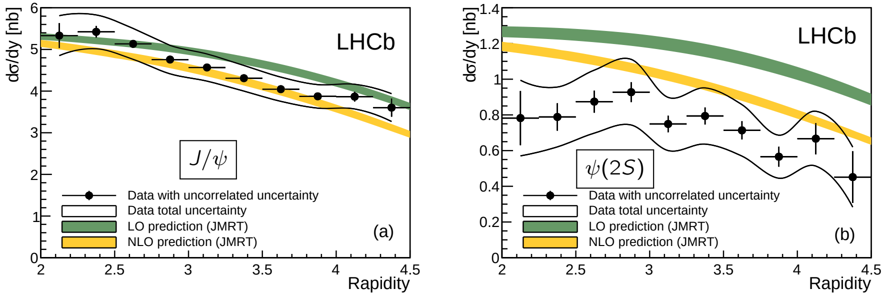




- Low non-resonant background
- Exclusive component determined using fit to p_{T}^2 distribution
- Purity $\sim 60\%$ for J/ψ and $\sim 52\%$ for $\psi(2S)$
  - Dominated by inelastic contribution
  - Non resonant background 0.8% for J/ψ, 17% for $\psi(2s)$
  - Feed-down background 2.5% for J/ψ, negligible for $\psi(2S)$

Exclusive Production at LHCb

- Measurements of J/ψ and $\psi(2S)$ production in 2011 data compared to JMRT predictions

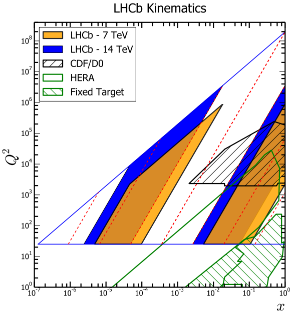


- Experimental uncertainties largely correlated between bins
- Slightly better agreement with NLO predictions

Still to come from Run-I

- Expect a number of Run-I results soon
- Updated measurement of $Z \to \mu\mu$ production at $\sqrt{s} = 7$ TeV
- $W \to \mu\nu$ and $Z \to \mu\mu$ measurements at $\sqrt{s} = 8$ TeV
- Low-mass Drell-Yan production
- Measurements of W production in association with light, beauty and charm jets
- Top production
- Many CEP analyses in the pipeline

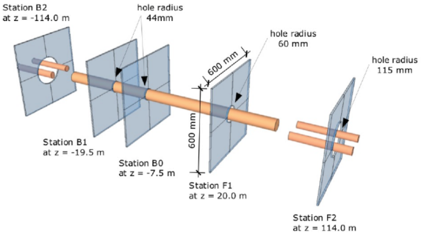
Run–II Prospects from LHCb – Electroweak Physics



- Increased energy opens up a new range of (x, Q^2) phase-space for precision W/Z measurements
- Potential to study QCD di-jet production to probe gluon PDF
- Increased cross-sections for statistically limited measurements
  - e.g. associated W and Z production with light and heavy quark jets

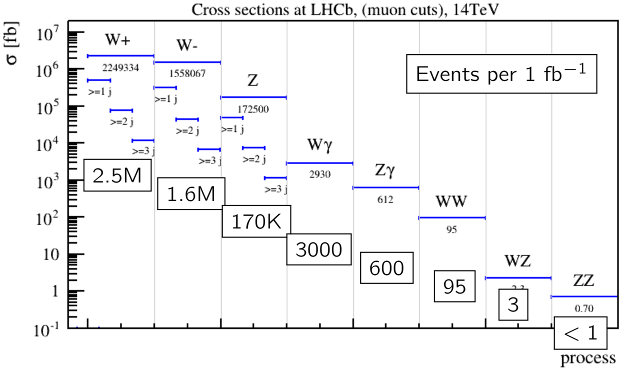
- Large boost in expected number of top events in LHCb acceptance
  - Will no longer be statistically limited with Run-II data
  - Can be used to constrain the gluon PDF (see Rhorry's talk)
- New energies also open up the possibility to measure ratios of cross-sections at different energies
  - Can be used as probe of PDFs where other uncertainties cancel [JHEP08(2012)010]
  - Particularly interesting to cancel theoretical uncertainties in exclusive J/ψ production

Run–II Prospects – CEP



- High Rapidity Shower Counters for LHCb (HERSCHEL) were installed ahead of Run-II
- Scintillation Counters installed up- and down-stream of the LHCb detector
- Extends LHCb coverage into very forward region
  - Detect showers from high rapidity particles interacting with the beam pipe
  - Reject inelastic backgrounds where proton disassociates
- Will be incorporated into the hardware trigger to improve trigger efficiency

Summary



- LHCb has a unique rapidity coverage
  - Can provide important inputs to PDFs in the forward region
- Updated measurements of $W \to \mu\nu$ and $Z \to ee$ presented
  - Improved luminosity uncertainty
  - Systematic uncertainties on $W \to \mu\nu$ reduced by almost a factor of 3
- Still expect many results from Run-I data
- Looking forward to exploiting LHCb's potential with Run-II

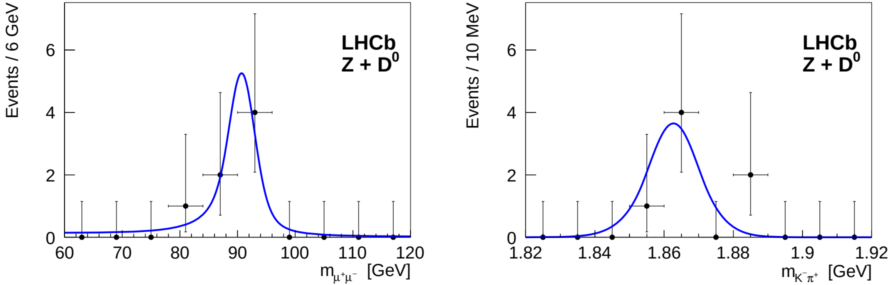
BACKUP

BACKUP

$Z + D$

J. High Energy Phys. 04 (2014) 091

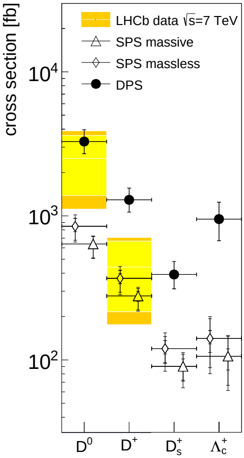
- Associated production of a Z boson and a D-meson
  - Test charm PDF, production mechanism and DPS
- D-mesons reconstructed in channels
  - $D^0 \to K^- \pi^+$
  - $D^\pm \to K^\mp \pi^\pm \pi^\pm$



- 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

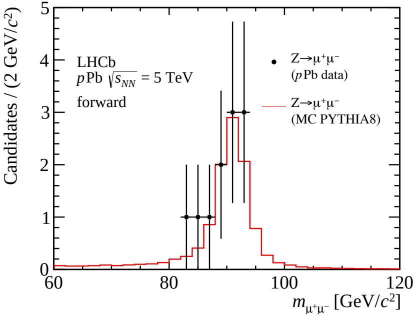
J. High Energy Phys. 04 (2014) 091

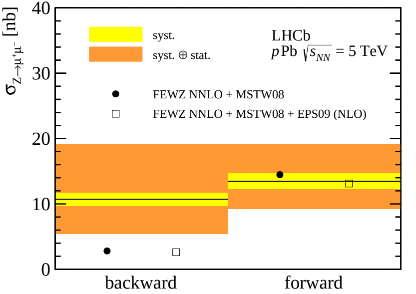


- Contributions from single- and double-parton scattering events
- Single parton scattering determined from MCFM at parton-level and corrected to hadron level
- Double parton scattering determined assuming factorisation of Z and D cross-sections
- $\sigma_{Z\to\mu\mu,D^0} \times \mathcal{B}_{Z\to\mu\mu}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

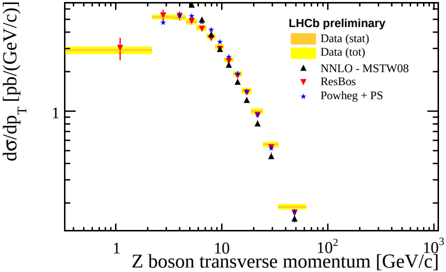
LHCB-PAPER-2014-022

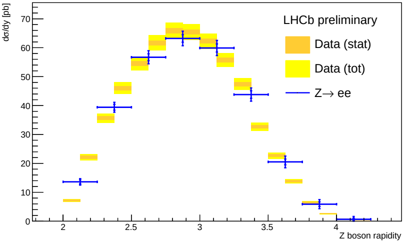




- 1.6 nb^{-1} of pA data collected by LHCb in 2013 at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV
- Z production important input for nucleon PDF
- $Z \to \mu\mu$ selection as in inclusive Z and $Z + j$ analysis
- 15 candidates selected (11 forward + 4 backward)
- Purity $> 99\%$
- Dominated by statistical uncertainty

$Z \to \mu\mu$

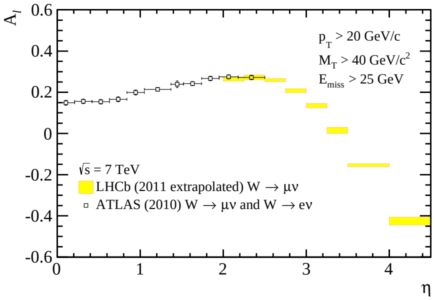

LHCb preliminary
Data (stat)
Data (tot)
NNLO - MSTW08
ResBos
Powheg + PS
dσ/dp_T [pb/(GeV/c)]
Z boson transverse momentum [GeV/c]

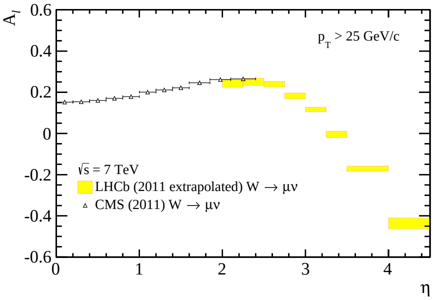

LHCb preliminary
Data (stat)
Data (tot)
Z→ ee
dσ/dy [pb]
Z boson rapidity

$W \to \mu\nu$ – ATLAS/CMS Comparison

LHCb-PAPER-2014-033 (Supplementary Material)

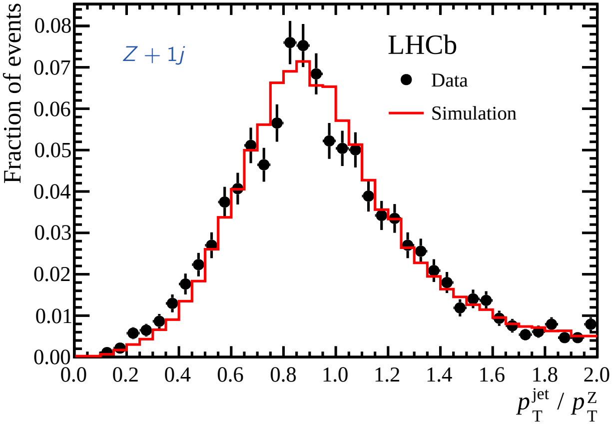
- LHCb result extrapolated to ATLAS and CMS fiducial regions using simulation
  - ATLAS - $M_T > 40$ GeV, $E_T^{miss} > 25$ GeV
  - CMS - $p_T > 25$ GeV





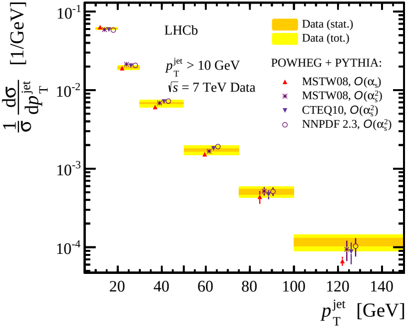
- Good agreement in overlap regions

Z+jet – p_{T} balance

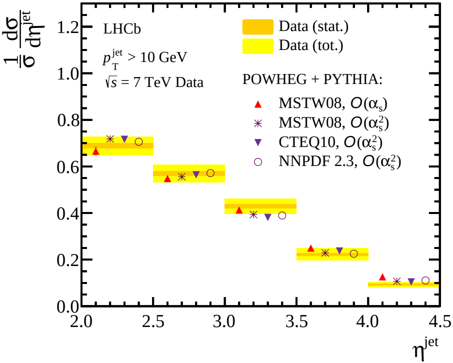


- Simulation describes p_{T} balance between jet and Z boson well in Z+1-jet events

$Z + jet$

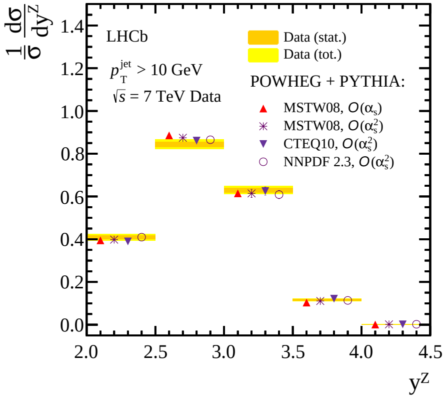


LHCb
p_T^{jet} > 10 GeV
$\sqrt{s}$ = 7 TeV Data
Data (stat.)
Data (tot.)
POWHEG + PYTHIA:
MSTW08, $O(\alpha_s)$
MSTW08, $O(\alpha_s^2)$
CTEQ10, $O(\alpha_s^2)$
NNPDF 2.3, $O(\alpha_s^2)$
$\frac{1}{\sigma}\frac{d\sigma}{dp_T^{jet}}$ [1/GeV]
p_T^{jet} [GeV]

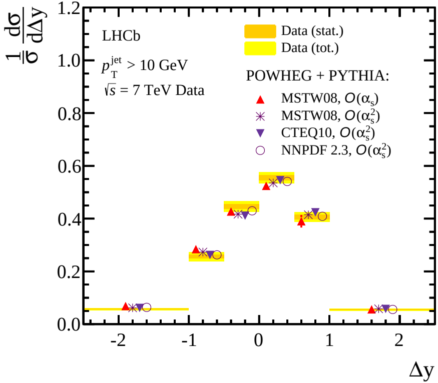


LHCb
p_T^{jet} > 10 GeV
$\sqrt{s}$ = 7 TeV Data
Data (stat.)
Data (tot.)
POWHEG + PYTHIA:
MSTW08, $O(\alpha_s)$
MSTW08, $O(\alpha_s^2)$
CTEQ10, $O(\alpha_s^2)$
NNPDF 2.3, $O(\alpha_s^2)$
$\frac{1}{\sigma}\frac{d\sigma}{d\eta^{jet}}$
η^{jet}

$Z + jet$



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, $O(\alpha_s^2)$
$\frac{1}{\sigma}\frac{d\sigma}{dy^Z}$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
2.0
2.5
3.0
3.5
4.0
4.5
y^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, $O(\alpha_s^2)$
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta y}$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
-2
-1
0
1
2
Δy