Forward electroweak physics at LHCb

Lake Louise Winter Institute 2016

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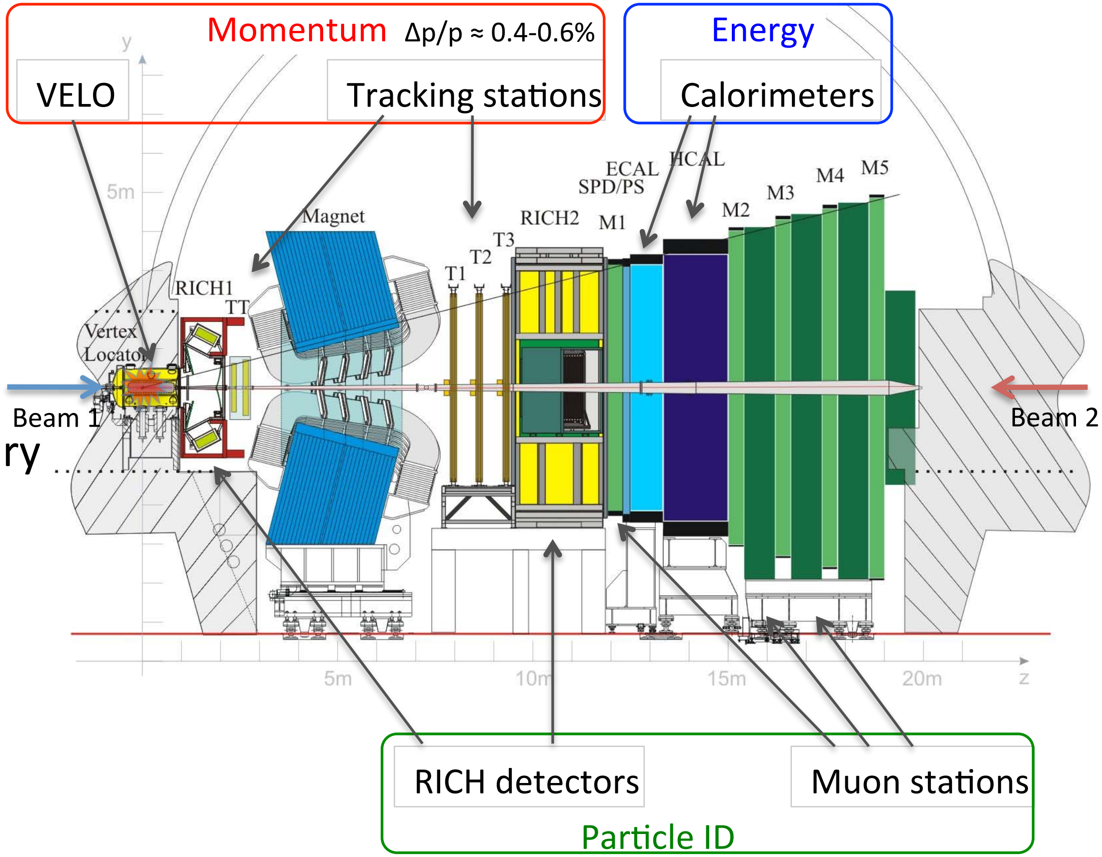
On behalf of the LHCb collaboration

- Forward spectrometer designed for flavour physics
- Overlap with GPDs in $2.0 < \eta < 2.5$
- LHCb unique coverage in $2.5 < \eta < 4.5$
- Can trigger on low p_T and low mass objects
- Precision vertex measurement (primary and secondary ~20 µm, ~45 fs)
- Allows precision electroweak studies complementary to ATLAS and CMS



This talk emphasize

Measurement of the forward W and Z boson production in pp collisions at √s = 8 TeV (JHEP 01 (2016) 155)

Precision luminosity measurements at LHCb (2014 JINST 9 P12005)

Important recent electroweak results are presented in next slide

Why Electroweak production at LHCb?

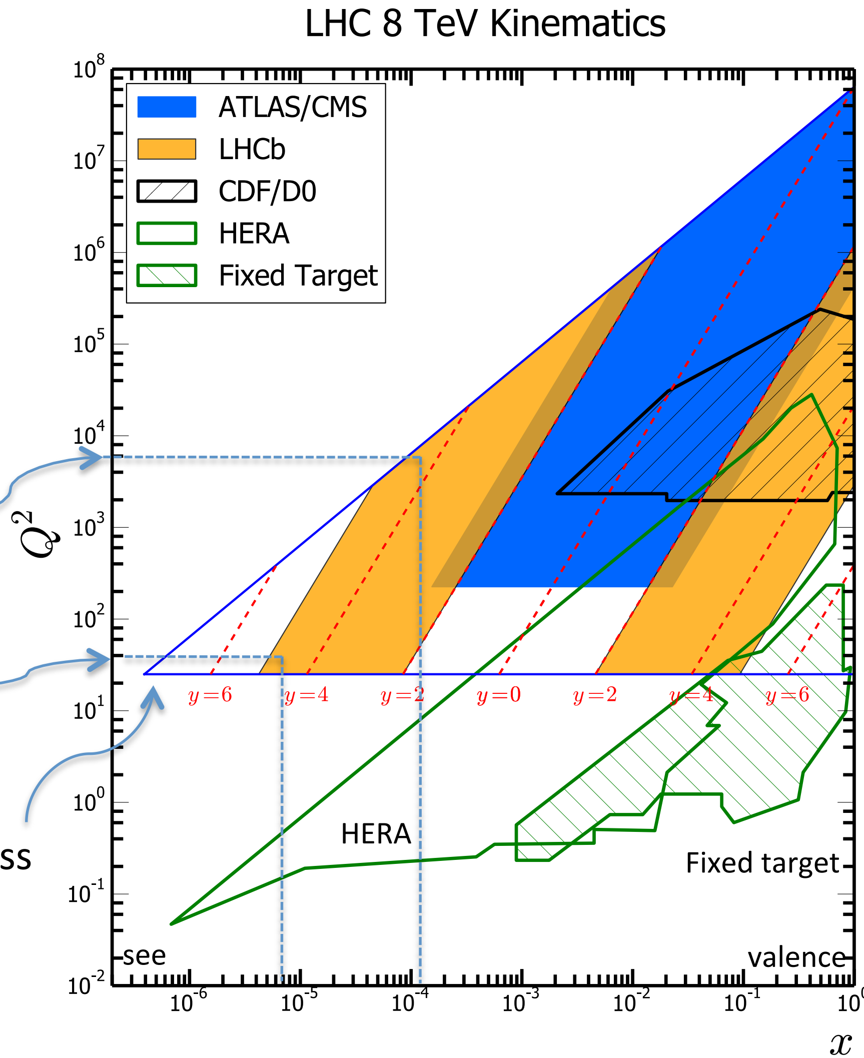
LHCb probes 2 regions:
High x: PDFs are well known
Low x: PDFs are essentially unknown

There is a large PDF uncertainty at low x.

Z/W
Q^2 (~10^4 GeV^2)
$x \approx 10^{-4}$

Low mass DY γ*
Q^2 (25 GeV^2)
$x \approx 8\times10^{-6}$

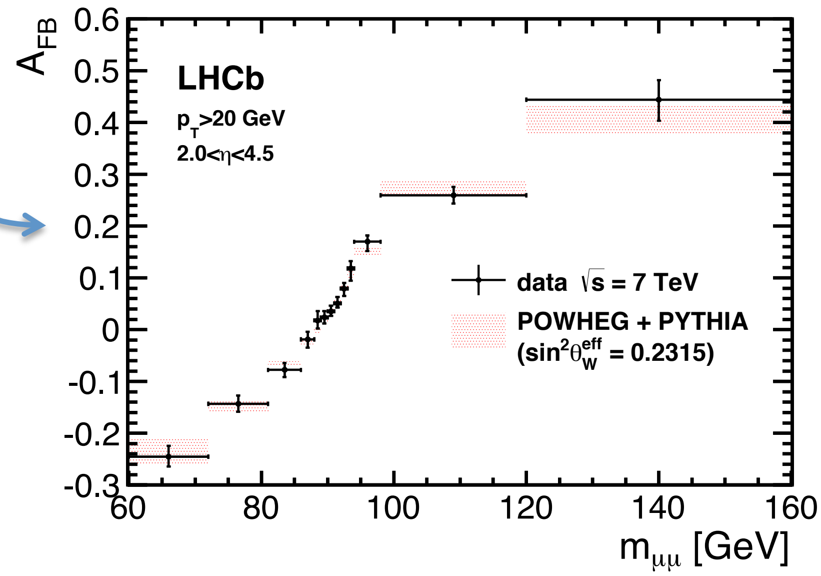
Minimal
triggered mass

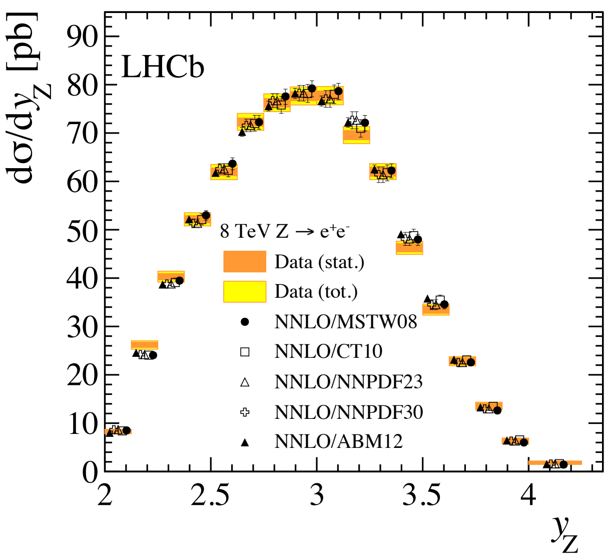


Measurements at LHCb have the ability to
constrain PDFs in a region which is unprobed by GPDs.

Measurement of the forward-backward asymmetry in *Z/γ → $\mu^+\mu^-$ decays and determination of the effective weak mixing angle** (JHEP 11 (2015) 190)

- Z couplings differ for left- and right-handed fermions -> asymmetry in the angular distribution of leptons produced in Z decays.
- Asymmetry depends on the weak mixing angle (θ_W).



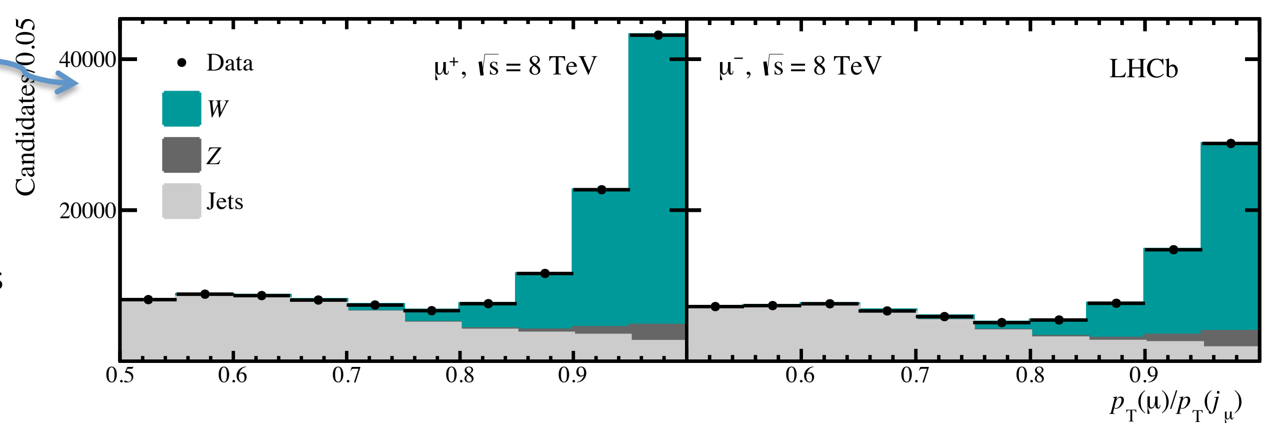


Measurement of the forward Z→ e+e− production at √s = 8 TeV (JHEP 05 (2015) 109)

- Statistically independent sample, with substantially different sources of systematic uncertainties compared to $Z \rightarrow \mu^+\mu^-$

Study of W boson production in association with beauty and charm (Phys. Rev. D 92, 052001 (2015))

- W+jet production provide important tests of the Standard Model
- Ratio of the W+c to W+jet production at LHCb provides important constraints on the s quark PDF (at Q ≈ 100 GeV and x ≈ 10^{-5})



Cross-section measurement

What are the major ingredients (simplified):

$$\sigma = \frac{\rho}{\int L\,dt}\frac{N}{efficiencies}$$

Purity ρ = the number of signal events / total number of events **N**

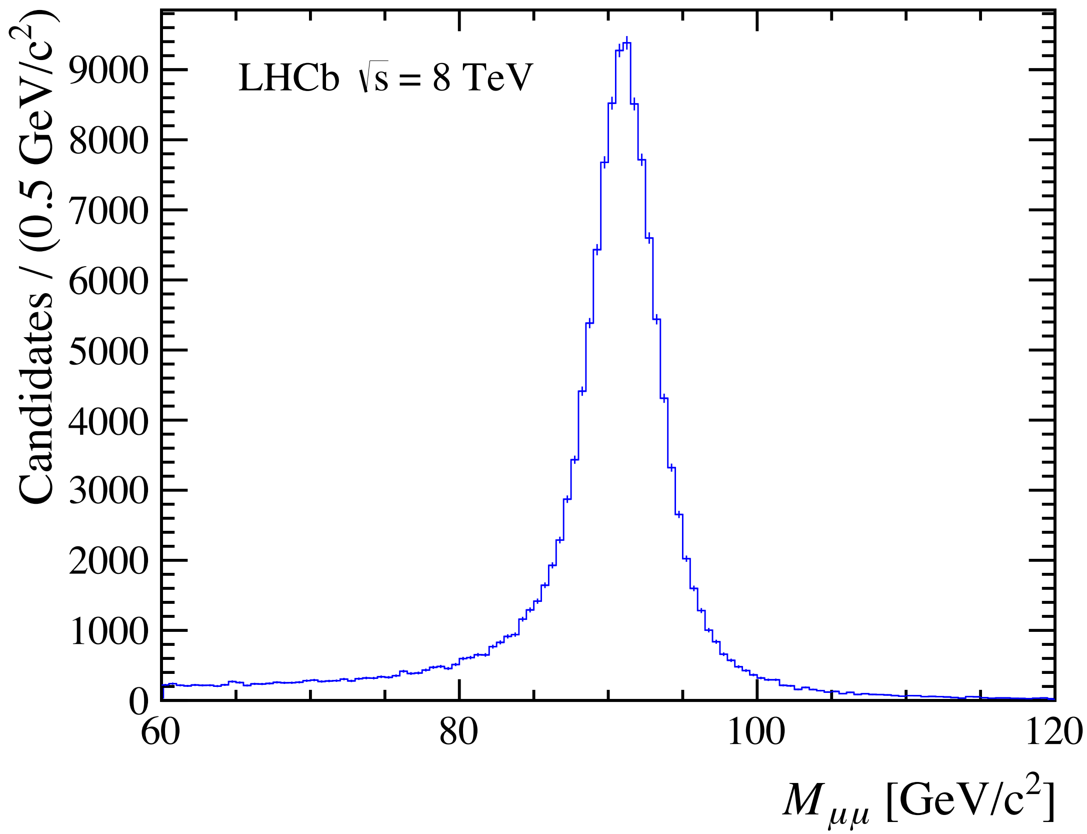
Experimental **efficiencies** (tracking, identification, trigger, selection) are calculated per event for Z or per bin of η^{μ} for W
(all determined from data)

Luminosity is measured in dedicated fills with 2 independent methods:
"van der Meer scan" (VDM) and Beam-Gas Imaging (BGI)
(2014 JINST 9 P12005)

Z→μμ cross section

2012 data (∫L =2.0 fb^{-1}, $\sqrt{s}$ = 8 TeV)
JHEP 01 (2016) 155

Fiducial acceptance:
$60 < M_{\mu\mu} < 120$ GeV/c^2
$2.0 < \eta^{\mu} < 4.5$,
$p_{T\mu} > 20$ GeV/c.



The largest sources of background are decays of heavy flavour hadrons ($b\bar{b}$, $c\bar{c}$) and hadron misidentification (plus Z→ττ; W-pair; Top-pair)

The sample purity is determined by using a mixture of data-driven and simulation-based methods

ρ = (99.3 ± 0.2)%
N = 1.36 M candidates

Uncertainties:

	Z→μμ
Statistical	0.27%
Systematic	0.67%
Beam energy	1.15%
Luminosity	1.16%

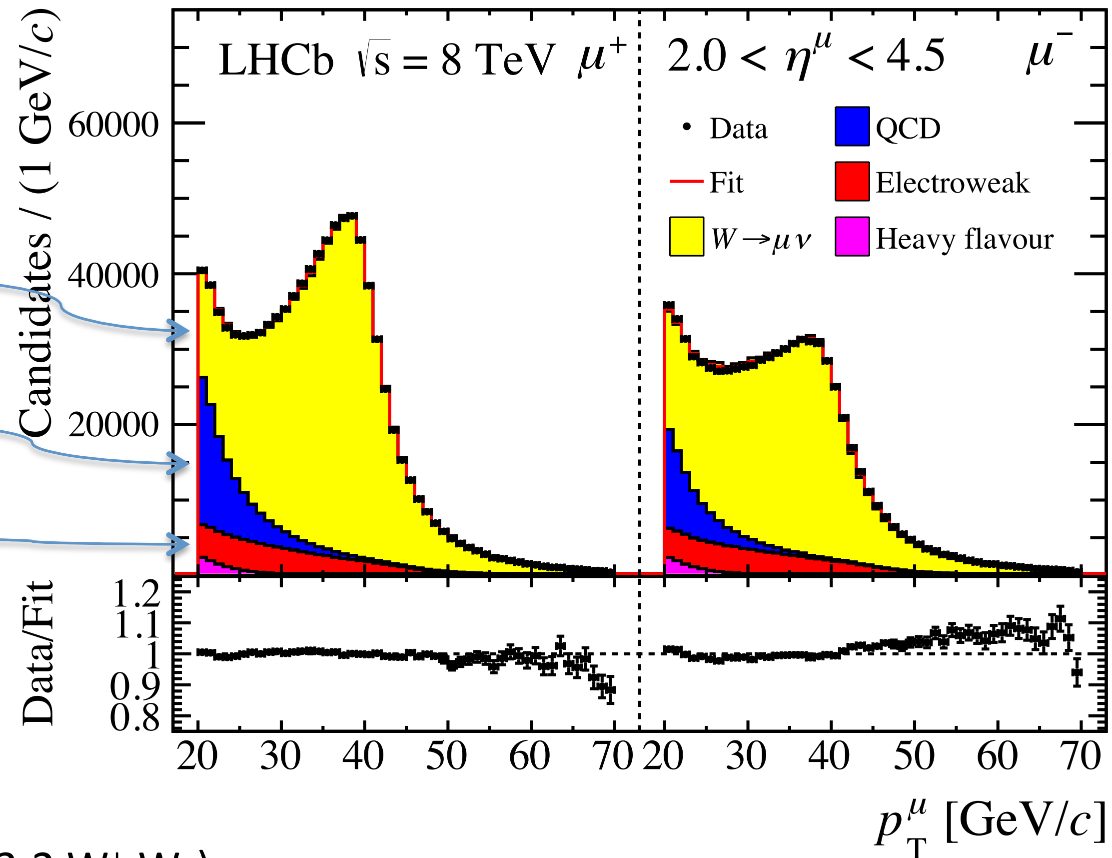
W→μν cross-section

Fiducial acceptance:
$2.0 < \eta^{\mu} < 4.5$,
$p_{T\mu} > 20$ GeV/c.

W→μν (shape from simulation)

Hadronic decay
(shape from data)

Z/γ* with 1 muon in acceptance
(shape from simulation)



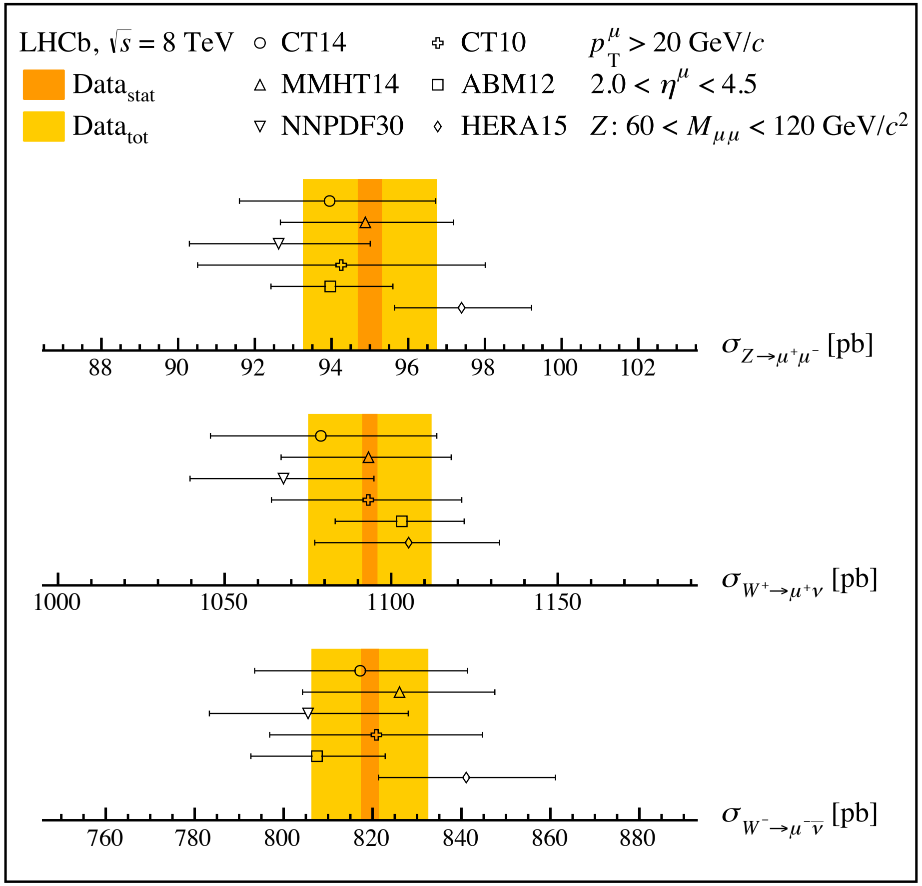
1.73 M W→μν events candidates (3:2 W^+:W^-)
W^+ purity 79%, W^- purity 78%.

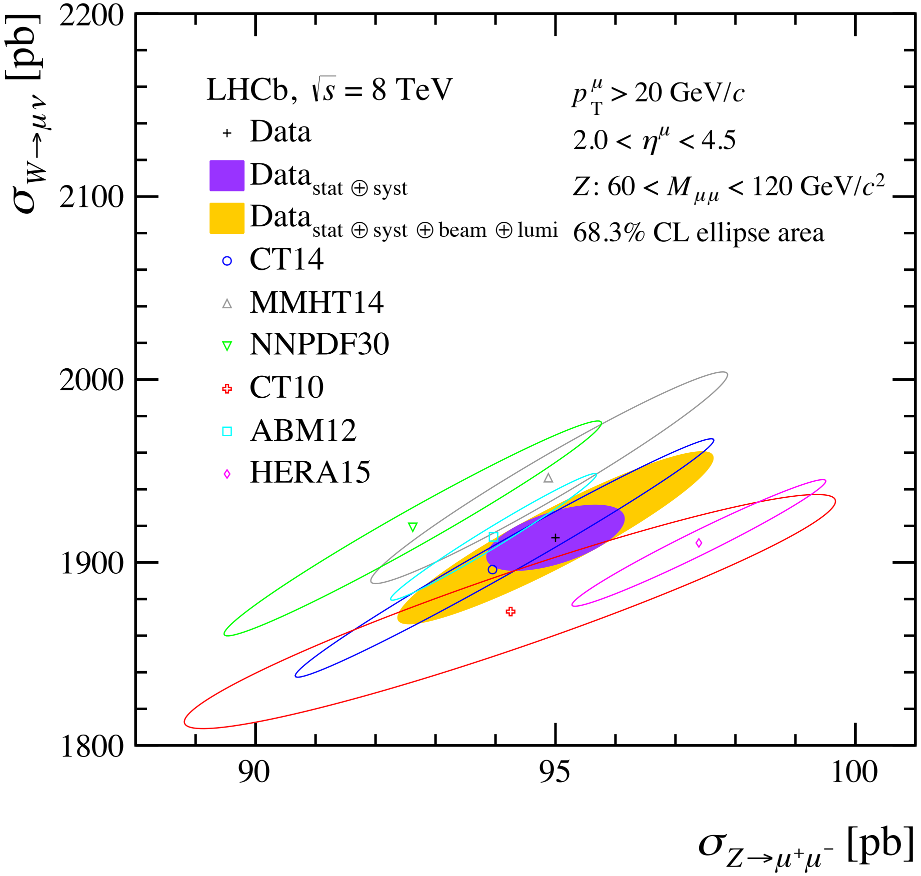
LHCb cannot use missing E_T to select W candidates
Signature: single muon High-p_T, isolated
(no other muon with $p_{T\mu} > 2$ GeV in the event)

Uncertainties:

	$W^+\to\mu^+\nu$	$W^-\to\mu^-\bar{\nu}$
Statistical	0.19%	0.23%
Systematic	0.65%	0.61%
Beam energy	1.00%	0.86%
Luminosity	1.16%	1.16%

W and Z cross-sections





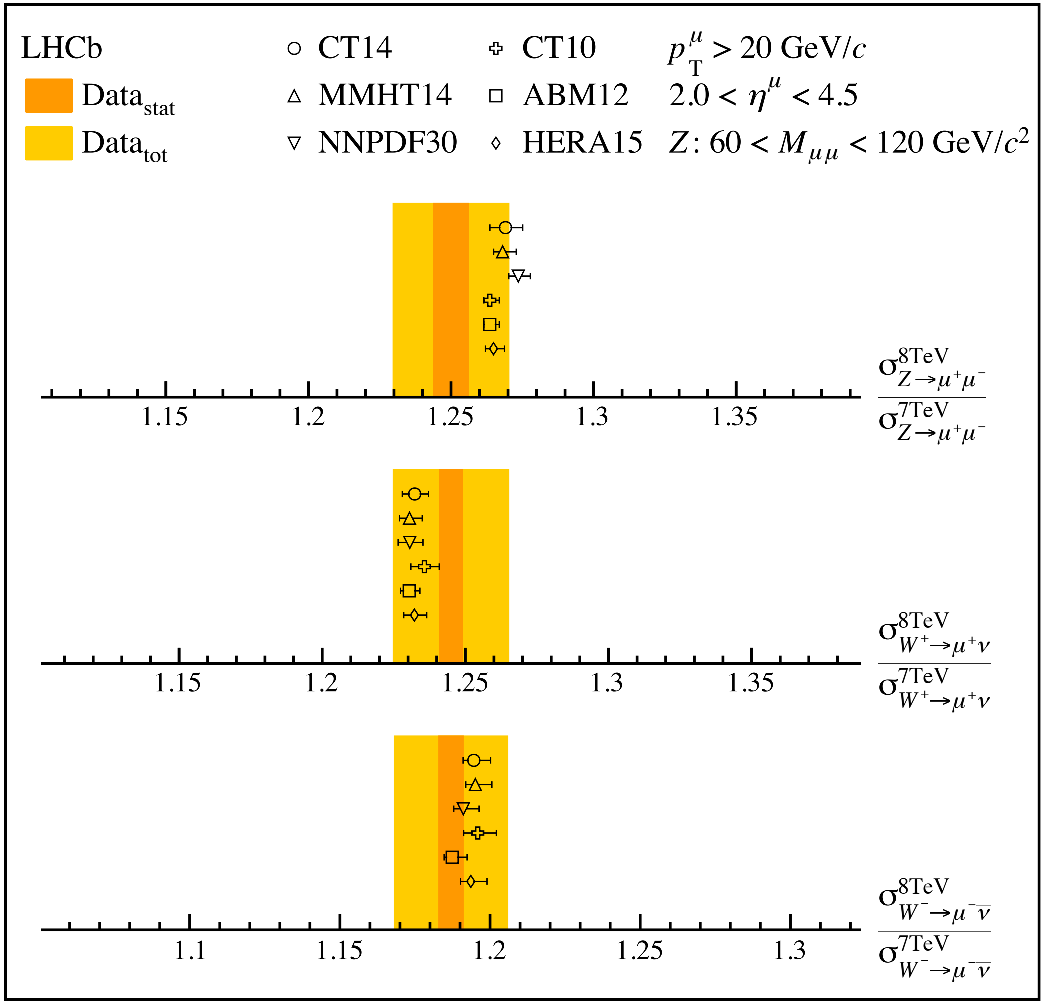
Cross-sections determined with a 0.7–0.8% precision (excluding beam energy and luminosity)

Two-dimensional plots of electroweak boson cross-sections compared to NNLO predictions

Ratios at different $\sqrt{s}$

PDF uncertainties largely cancel in ratios of 8 TeV cross-section measurements with 7 TeV measurements.

Luminosity correlated between two years at level of 0.55



First measurements of this kind at the LHC!

Luminosity determination

Measured by experiments (VDM or beam-gas)

LHC instrumentation

$$L = f \cdot N_1 N_2 \cdot Overlap$$

- Bunch intensity (N_1N_2) measured by LHC instrumentation (uncertainties: ~0.3%).
- Overlap integral depends on beams properties (e.g. beam width, position, angle, shape)

Determined with 2 independent methods:

1. Classic "van der Meer scan" (VDM) used by all 4 LHC experiments
2. Beam-gas imaging (BGI): **new method exclusive to LHCb**

Beam-Gas Imaging (BGI)

$$Overlap = \int \rho_1(x,y,z,t)\rho_2(x,y,z,t)\, dxdydzdt$$

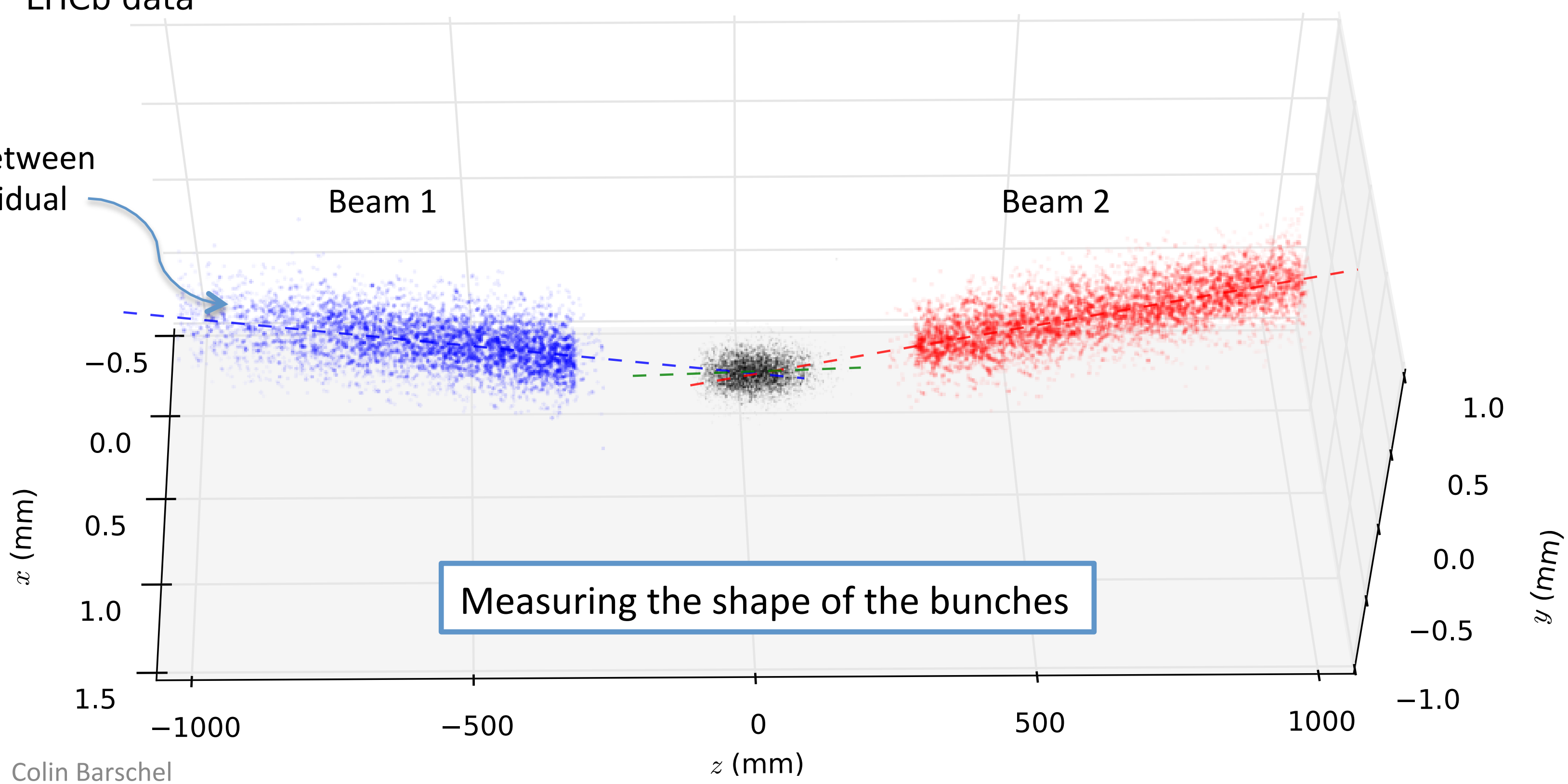
Single bunch density function of colliding bunch pair
(e.g. double Gaussian profile)

Overlap integral depends on:
- Single bunch profiles (X,Y width, shape)
- Beam crossing angle
- Offset (head-on or displaced)

All parameters are measured using interactions between beam and residual gas (injected neon)

LHCb data

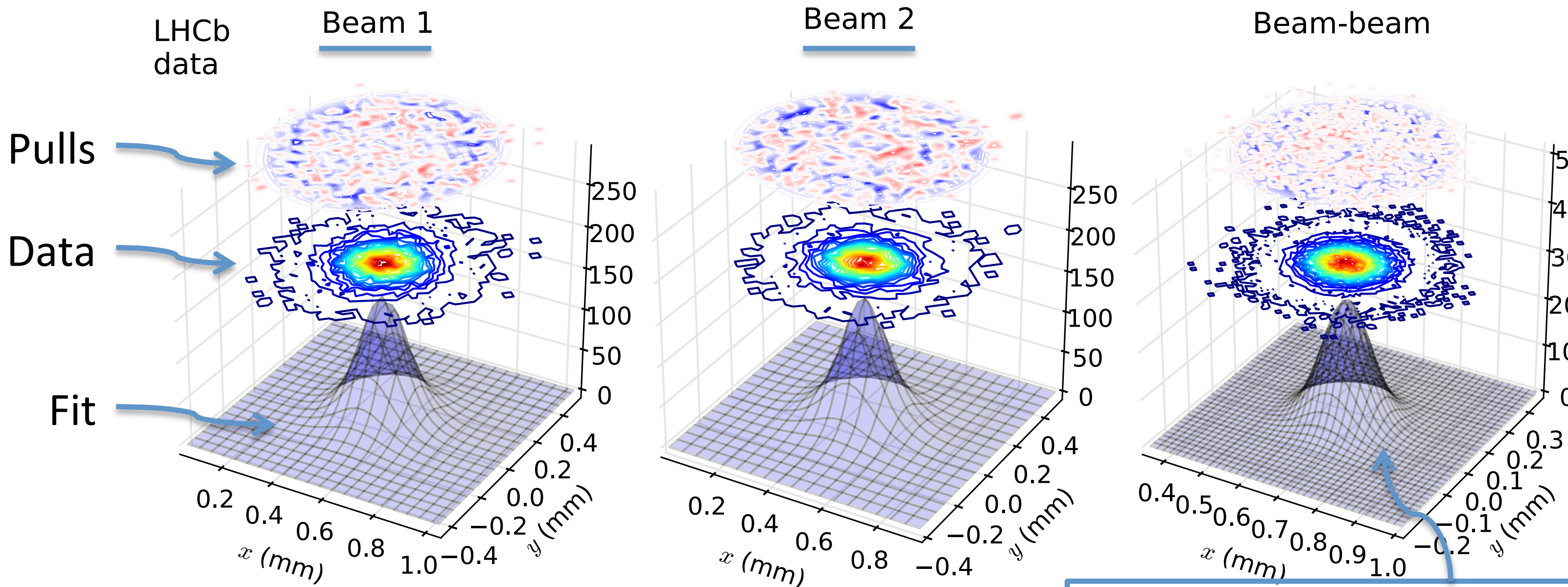
Interaction between beam and residual gas nuclei



Measuring the shape of the bunches

Beam-gas imaging global fit

-Fit single beams and beam spot measured in one global fit (showing only 3 slices out of 24)
-Free parameters are: beam widths (double Gaussian, weight), position, angle
(only amplitudes are free parameters for beam spot -> strong fit constrain)



Shape and position of luminous region is fully predicted by single beam parameters

Method	Absolute calibration			Relative calibration	Total
	σ_{vis} (mb)	Weight	Uncertainty	uncertainty	uncertainty
pp at $\sqrt{s} = 8\,\text{TeV}$					
BGI	60.62 ± 0.87	0.50	1.43% (0.59%)		
VDM	60.63 ± 0.89	0.50	1.47% (0.65%)		
Average	60.62 ± 0.68		1.12%	0.31%	1.16%

2014 JINST 9 P12005

Conclusion

W and Z boson cross-sections measured at $\sqrt{s}$ = 8 TeV using final states containing muons

- Most precise inclusive W & Z boson production cross-section measurements at the LHC!
- Ratios at different centre-of-mass energies using Run-I data measured for the first time at the LHC!
- Presented results made possible by the most precise luminosity determination at the LHC!

- Results in proton-proton collisions at 7 and 8 TeV currently agree with the Standard Model.
- Ratios of measurements allow tests of the Standard Model at per mille precision.
- Many LHCb results already included in most recent PDF fits.

BACKUP

Why Electroweak production at LHCb?

Collision between proton *A* and *B* with partons *a* and *b*

$$\sigma_{AB\to X} = \int dx_a\, dx_b\; f_{a/A}(x_a,Q^2) f_{b/B}(x_b,Q^2)\; \sigma_{ab\to X}$$

Measured cross-section
e.g. $pp \to Z/\gamma^*(\to \mu\mu)X$

Proton structure
parameterized with the PDFs

uncertainty at LHCb can be
large: ~10%

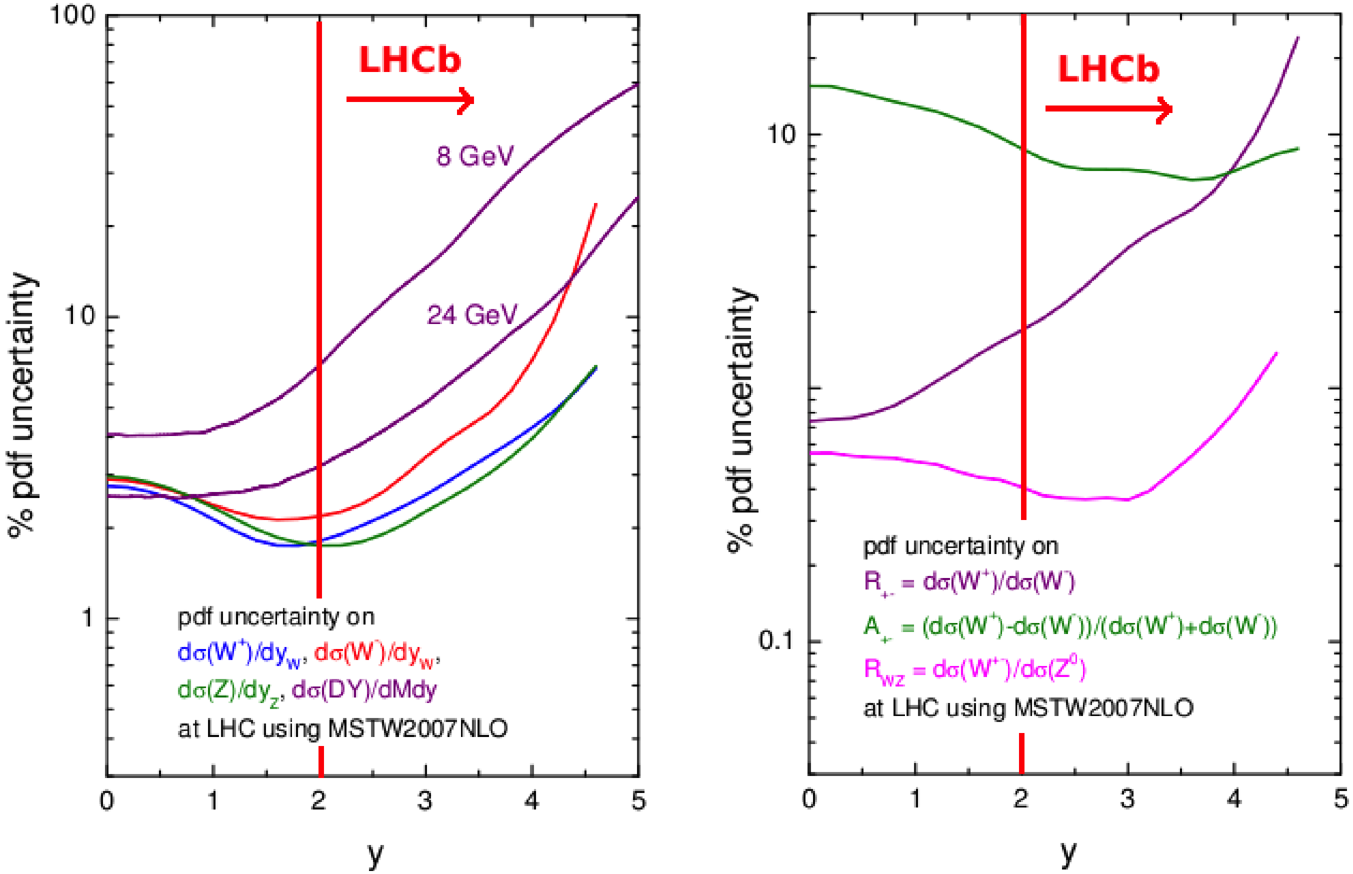
Partonic cross-section
$ab \to X$

Uncertainty ~1%.

LHCb probes a region of phase space where the vector boson is produced in the forward region.
→ Explores regions at high and low momentum fraction where the uncertainties are large

LHCb results at 7 TeV on electroweak boson production now included in PDF fits.

PDF uncertainties



Adapted from Thorne et al., 2008: arXiv:0808.1847
LHCb has ability to constrain PDFs in some distributions and ratios, and to test the Standard Model in others.

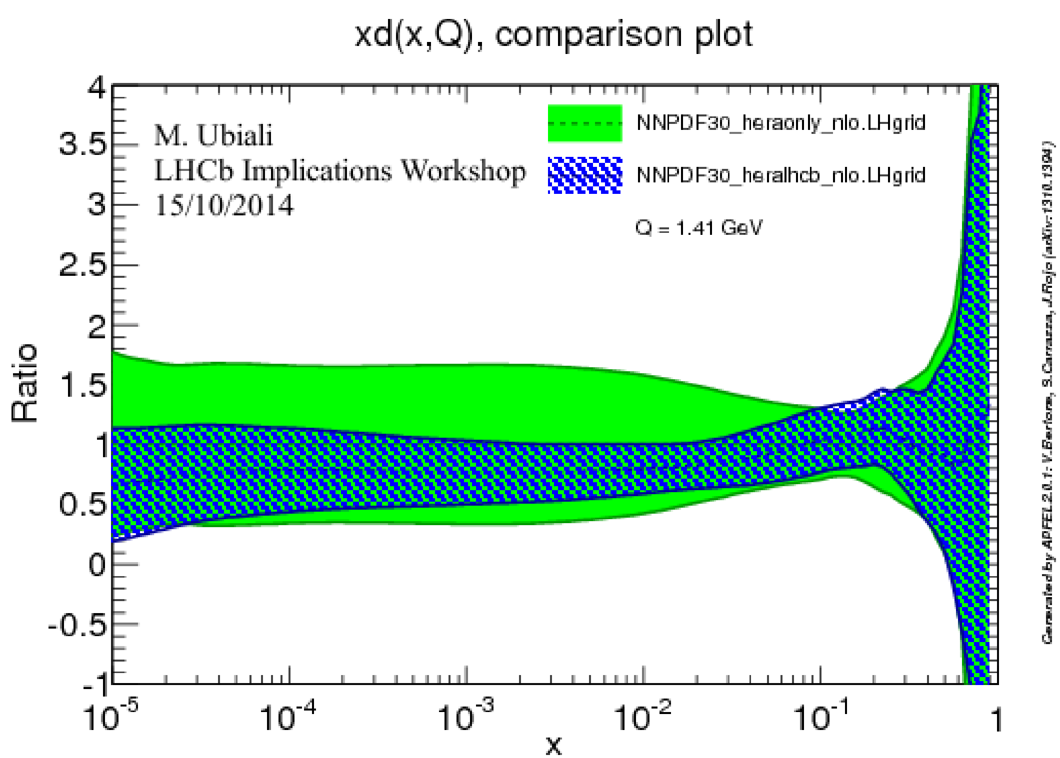
Many LHCb 7 TeV results on electroweak boson production now included in PDF fits.
Large impact on pre-LHC PDF knowledge.

Impact of existing LHCb results on PDFs

- Many LHCb 7 TeV results on electroweak boson production now included in PDF fits.
- Large impact on pre-LHC PDF knowledge.
- Shown here NNPDF down quark PDF and uncertainties (normalised so central value pre-LHC is unity):

Green: PDF fit using HERA data

Blue: PDF fit using HERA data and 7 TeV LHCb data



Cross-section definition

Fiducial region: $p_{\mathrm{T}}^{\mu} > 20\,\mathrm{GeV}/c$, $2 < \eta^{\mu} < 4.5$ and, in the case of the Z boson, $60 < M_{\mu\mu} < 120\,\mathrm{GeV}/c^2$

- The W cross-section is measured in bin i of muon η

$$\sigma_{W^\pm\to\mu^\pm\nu}(i) = \frac{\rho^{W^\pm}(i)}{\mathcal{L}} \cdot \frac{f_{\mathrm{FSR}}^{W^\pm}(i)}{\varepsilon_{\mathrm{GEC}}(i)} \cdot \frac{N^W}{\mathcal{A}^{W^\pm}(i)\cdot\varepsilon_{\mathrm{REC}}^{W}(i)\cdot\varepsilon_{\mathrm{SEL}}^{W^\pm}(i)}$$

$$\varepsilon_{\mathrm{REC}}^{W}(i) = \varepsilon_{\mathrm{TRK}}^{\mu}(i)\cdot\varepsilon_{\mathrm{ID}}^{\mu}(i)\cdot\varepsilon_{\mathrm{TRG}}^{\mu}(i)$$

- The Z cross-section is measured in bin i of boson y, p_{T} and ϕ^*

$$\sigma_{Z\to\mu^+\mu^-}(i) = \frac{\rho^Z}{\mathcal{L}} \cdot \frac{f_{\mathrm{FSR}}^{Z}(i)}{\varepsilon_{\mathrm{GEC}}(i)} \cdot \sum_j U_{ij}\left(\sum_k \frac{1}{\varepsilon_{\mathrm{REC}}^{Z}(\eta_k^{\mu^+},\eta_k^{\mu^-})}\right)_j$$

$$\begin{aligned}\varepsilon_{\mathrm{REC}}^{Z}(\eta_k^{+},\eta_k^{-}) = &\left(\varepsilon_{\mathrm{TRK}}^{\mu}(\eta_k^{+})\cdot\varepsilon_{\mathrm{TRK}}^{\mu}(\eta_k^{-})\right)\cdot\\ &\cdot\left(\varepsilon_{\mathrm{ID}}^{\mu}(\eta_k^{+})\cdot\varepsilon_{\mathrm{ID}}^{\mu}(\eta_k^{-})\right)\cdot\\ &\cdot\left(\varepsilon_{\mathrm{TRG}}^{\mu}(\eta_k^{+})+\varepsilon_{\mathrm{TRG}}^{\mu}(\eta_k^{-})-\varepsilon_{\mathrm{TRG}}^{\mu}(\eta_k^{+})\cdot\varepsilon_{\mathrm{TRG}}^{\mu}(\eta_k^{-})\right)\end{aligned}$$

- The total cross-sections is obtained by summing the differential measurements

Cross-section results

The total cross-sections are measured to be

$$\sigma_{W^+\to\mu^+\nu} = 1093.6 \pm 2.1 \pm 7.2 \pm 10.9 \pm 12.7\,\text{pb}\,,$$
$$\sigma_{W^-\to\mu^-\overline{\nu}} = 818.4 \pm 1.9 \pm 5.0 \pm 7.0 \pm 9.5\,\text{pb}\,,$$
$$\sigma_{Z\to\mu^+\mu^-} = 95.0 \pm 0.3 \pm 0.7 \pm 1.1 \pm 1.1\,\text{pb}\,,$$

where the first uncertainties are statistical, the second are systematic, the third are due to the knowledge of the LHC beam energy and the fourth are due to the luminosity

Source	Uncertainty [%]		
	$\sigma_{W^+\to\mu^+\nu}$	$\sigma_{W^-\to\mu^-\overline{\nu}}$	$\sigma_{Z\to\mu^+\mu^-}$
Statistical	0.19	0.23	0.27
Purity	0.28	0.21	0.21
Tracking	0.26	0.24	0.48
Identification	0.11	0.11	0.21
Trigger	0.14	0.13	0.05
GEC	0.40	0.41	0.34
Selection	0.24	0.23	—
Acceptance and FSR	0.16	0.14	0.13
Systematic	0.65	0.61	0.67
Beam energy	1.00	0.86	1.15
Luminosity	1.16	1.16	1.16
Total	1.67	1.59	1.79

Ratios results

The W boson cross-section ratio is measured as

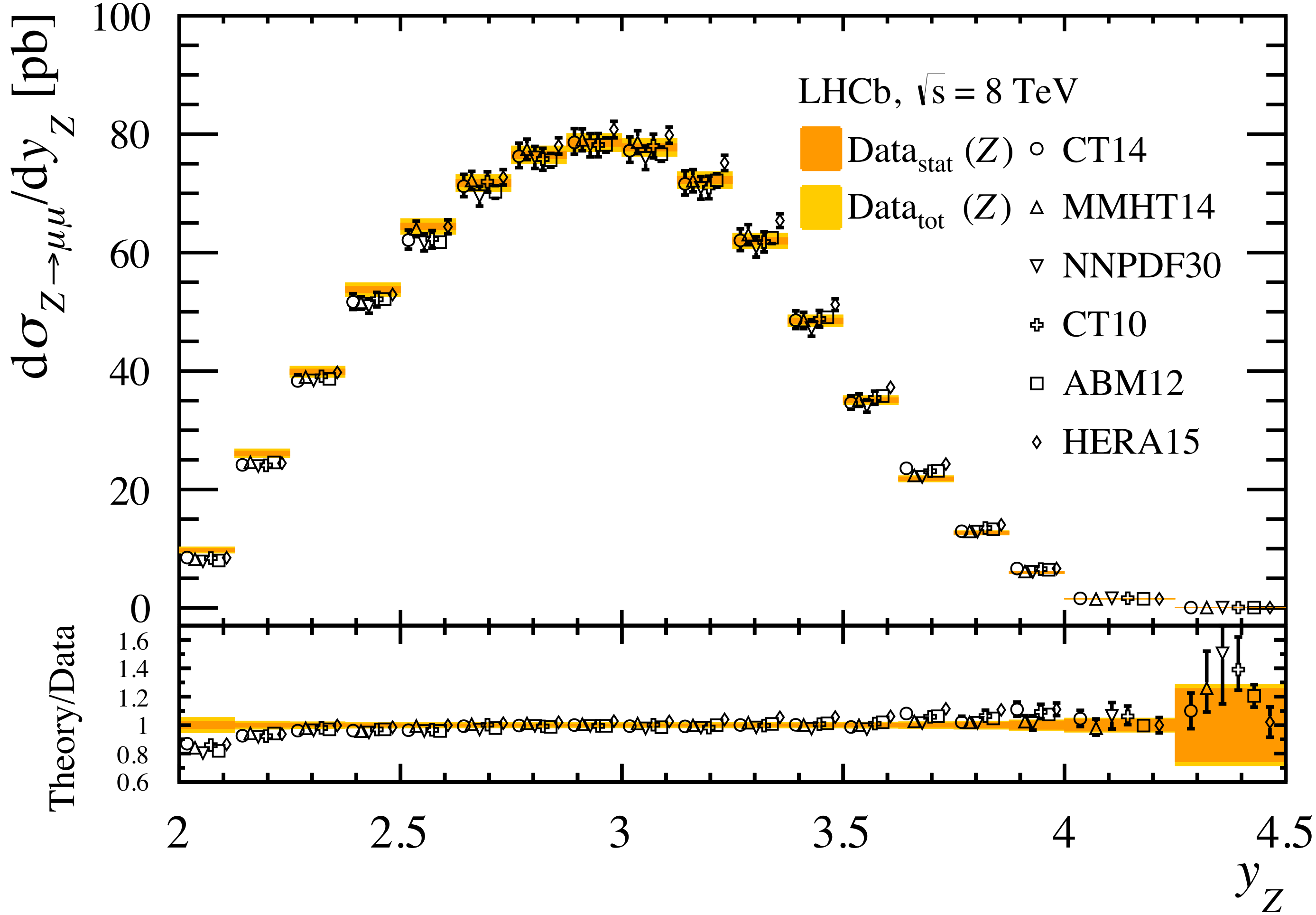
$$R_{W^\pm} = 1.336 \pm 0.004 \pm 0.005 \pm 0.002\,,$$

where the first uncertainty is statistical, the second is systematic and the third is due to the knowledge of the LHC beam energy. The W to Z boson production ratios are found to be

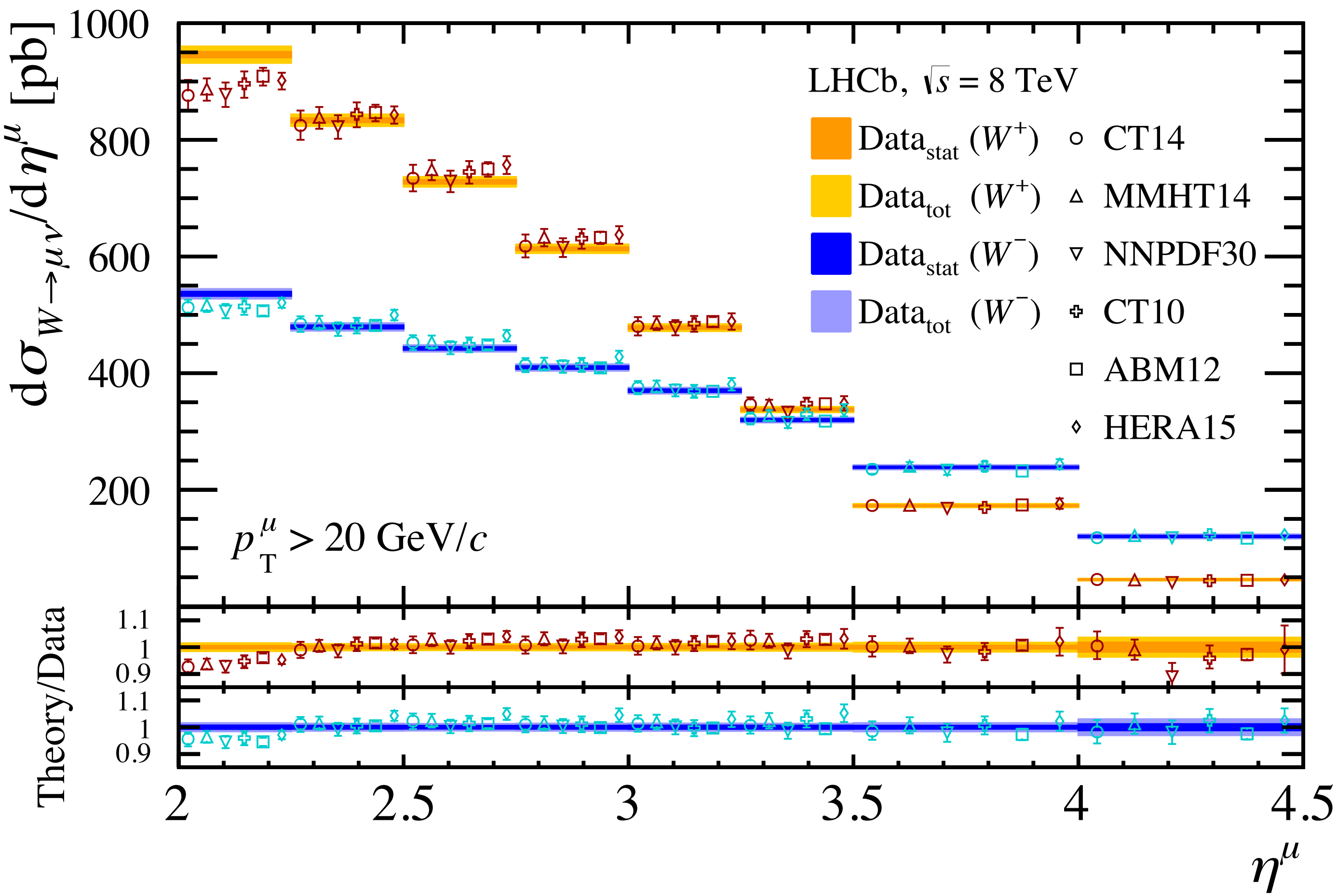
$$\begin{aligned} R_{W^+Z} &= 11.51 \pm 0.04 \pm 0.07 \pm 0.02\,, \\ R_{W^-Z} &= 8.62 \pm 0.03 \pm 0.05 \pm 0.02\,, \\ R_{WZ} &= 20.13 \pm 0.06 \pm 0.11 \pm 0.04\,. \end{aligned}$$

Source	Uncertainty [%]			
	$R_{W^\pm}$	R_{W^+Z}	R_{W^-Z}	R_{WZ}
Statistical	0.30	0.33	0.36	0.31
Purity	0.25	0.35	0.30	0.30
Tracking	0.05	0.22	0.24	0.23
Identification	0.01	0.11	0.11	0.11
Trigger	0.04	0.10	0.09	0.09
GEC	0.13	0.22	0.23	0.21
Selection	0.10	0.24	0.24	0.23
Acceptance and FSR	0.21	0.21	0.19	0.17
Systematic	0.37	0.59	0.56	0.54
Beam energy	0.14	0.15	0.29	0.21
Total	0.50	0.69	0.73	0.66

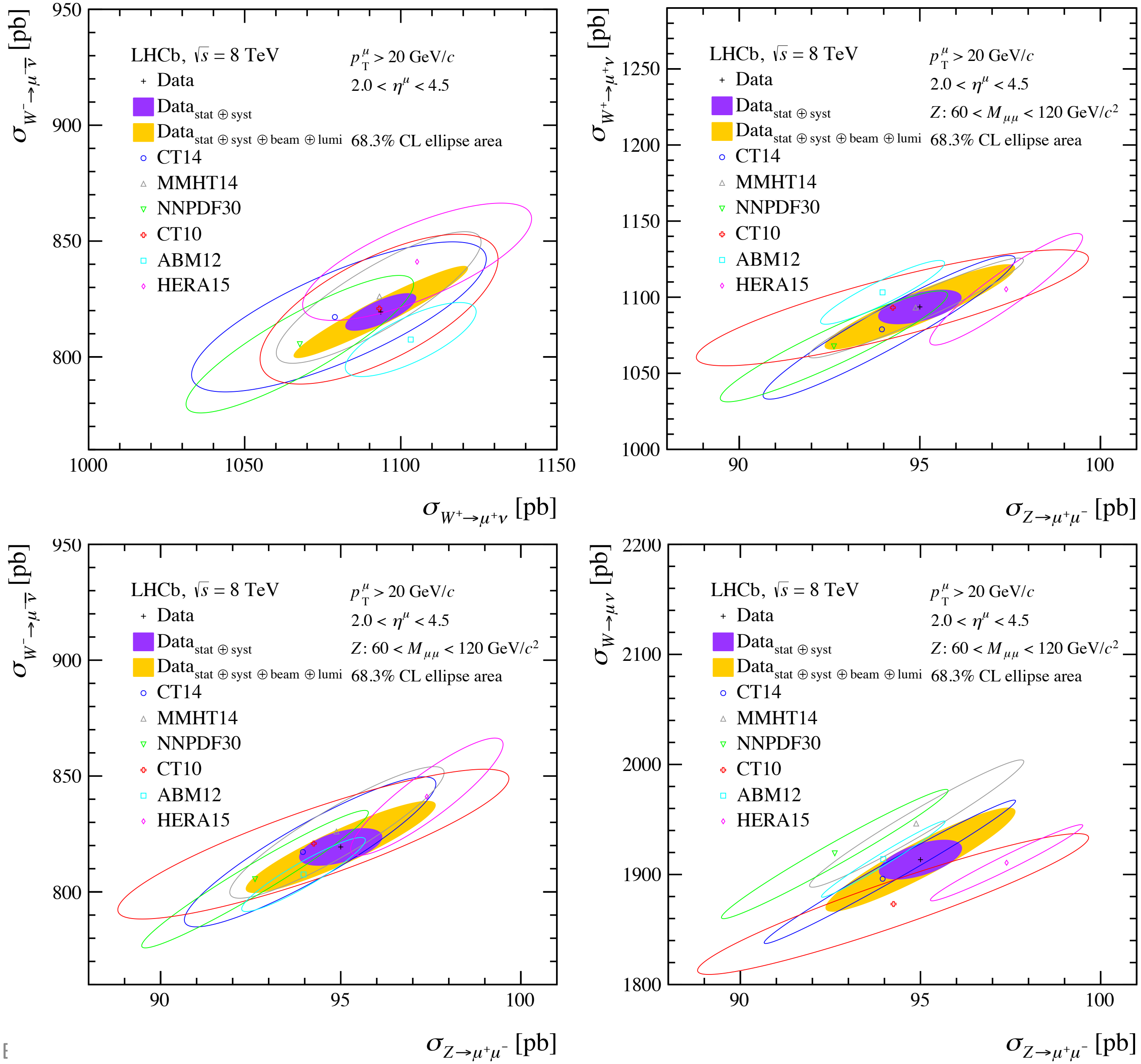
Differential Z boson production cross-section in bins of boson rapidity



Differential W+ and W− boson production cross-section in bins of muon pseudorapidity

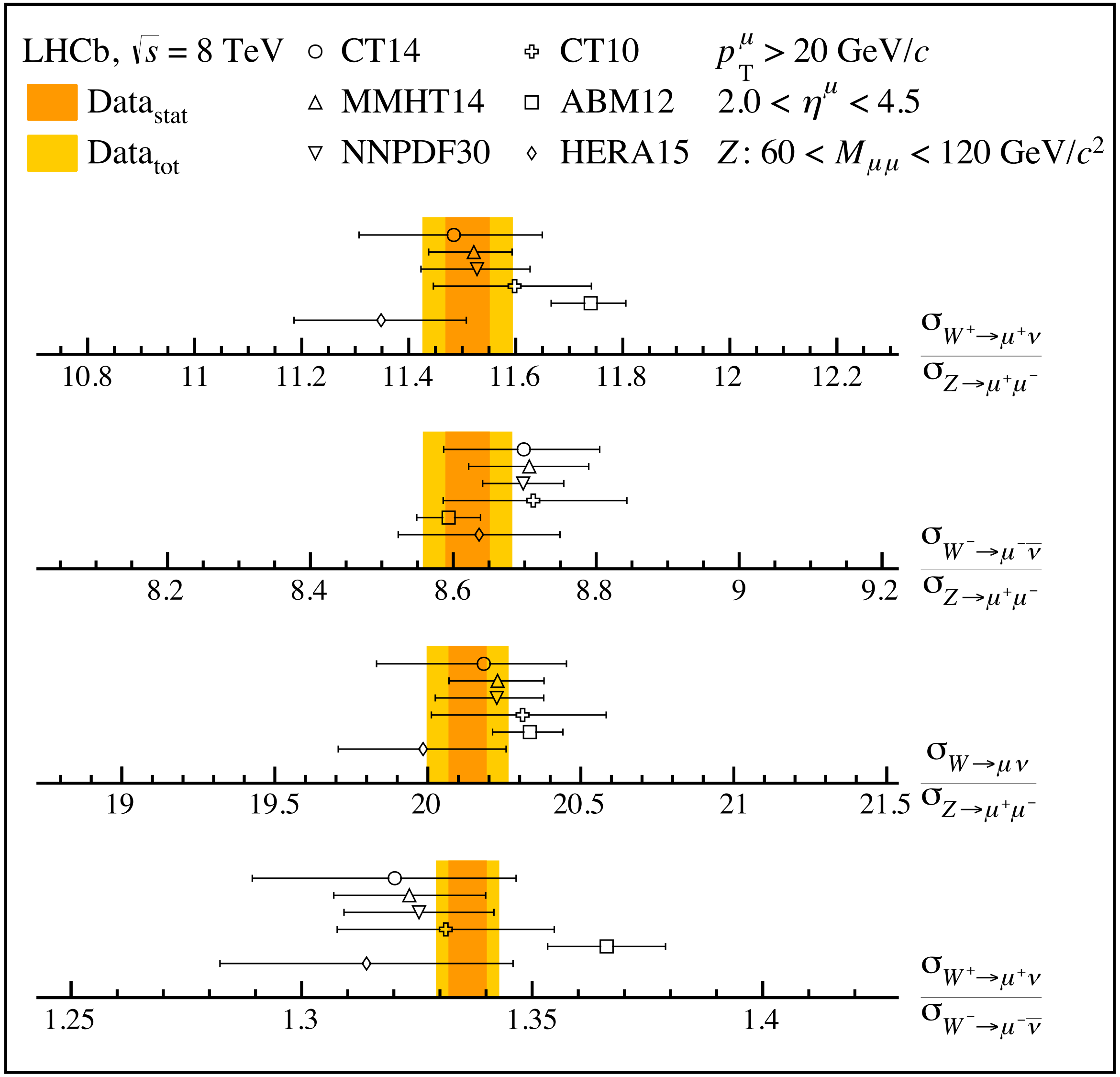


Two-dimensional plots of electroweak boson cross-sections compared to NNLO predic- tions for various parameterisations of the PDFs. The uncertainties on the theoretical predictions correspond to the PDF uncertainty only. All ellipses correspond to uncertainties at 68.3% CL.



Ratios

Cross-section ratios determined with a 0.5–0.8% precision
(good agreement with predictions from different PDF sets.)



Resolution unfolding

Beam gas vertices are measured with the VELO detector

Measured beam width is a convolution of true beam widths with the resolution

Resolution depends on:

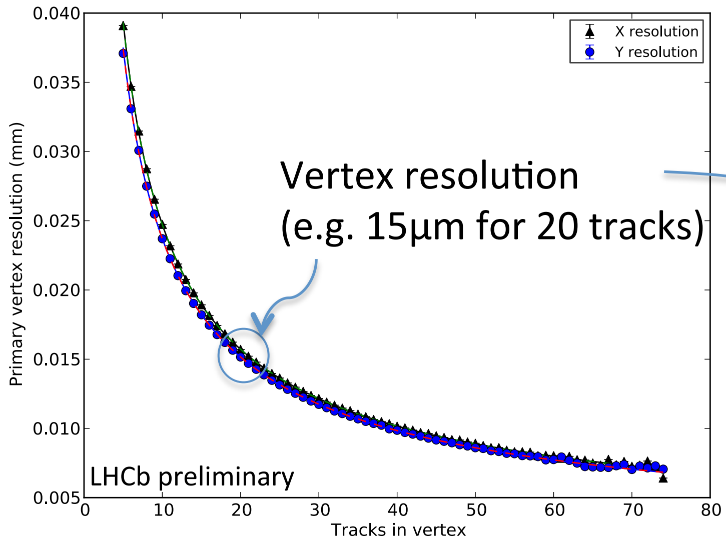
•Z position of vertex

•Number of tracks

•Beam gas or beam beam events have different track distributions

→ Additional parameterization needed for beam gas events and Z position

Parameterization example
for pp resolution

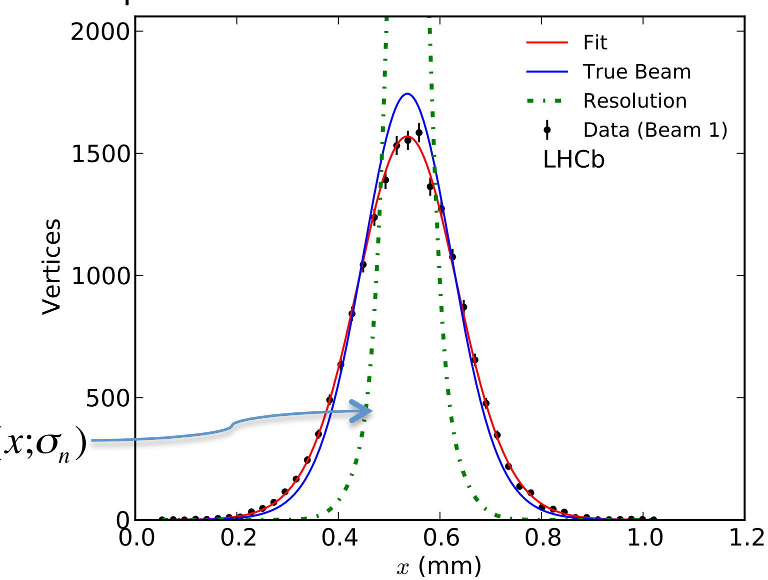


Vertex resolution
(e.g. 15µm for 20 tracks)

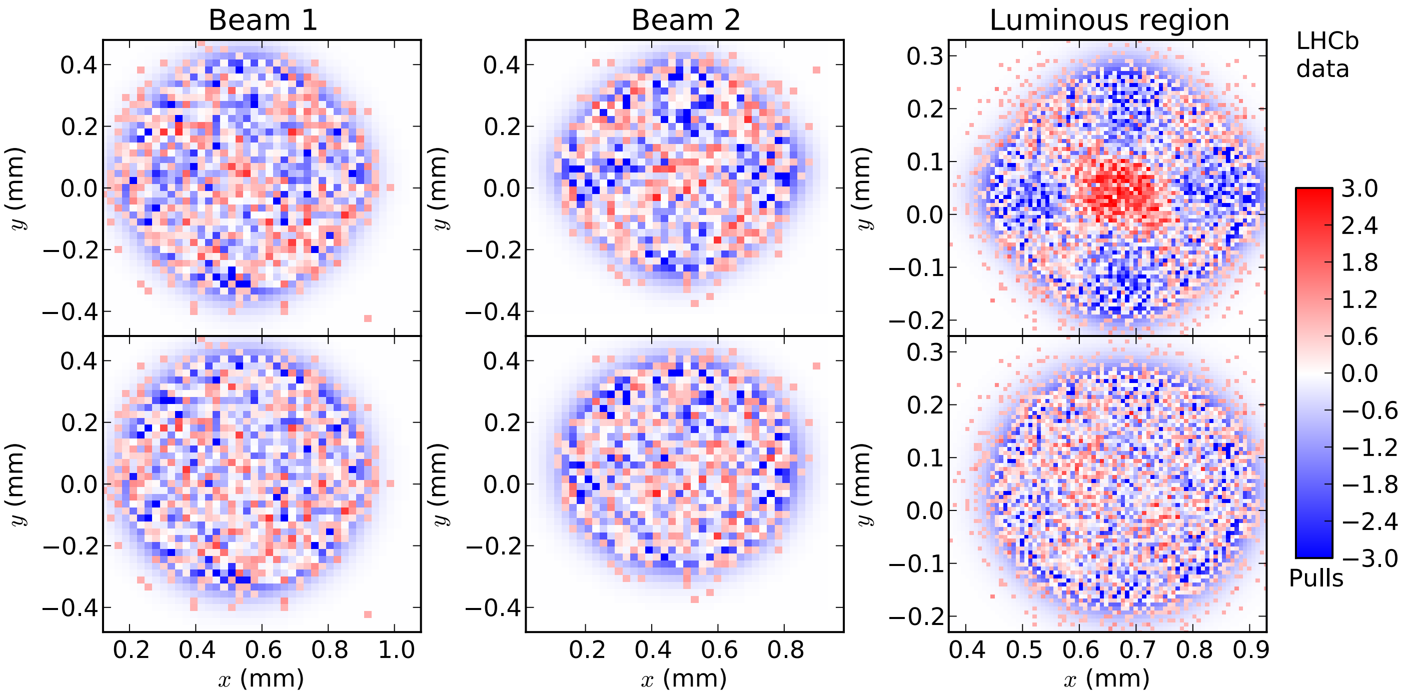
Resolution
distribution

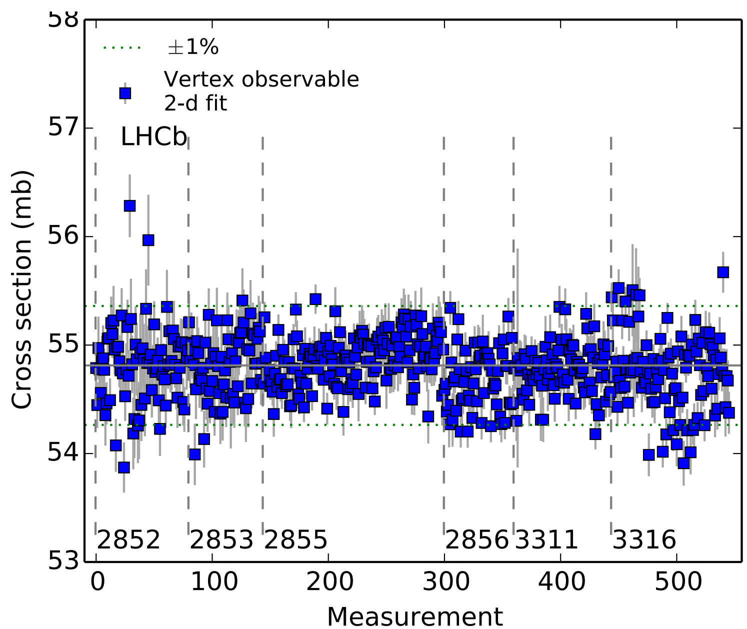
$$R(x) = \sum_{n-1}^{N} c_n g_n(x;\sigma_n)$$

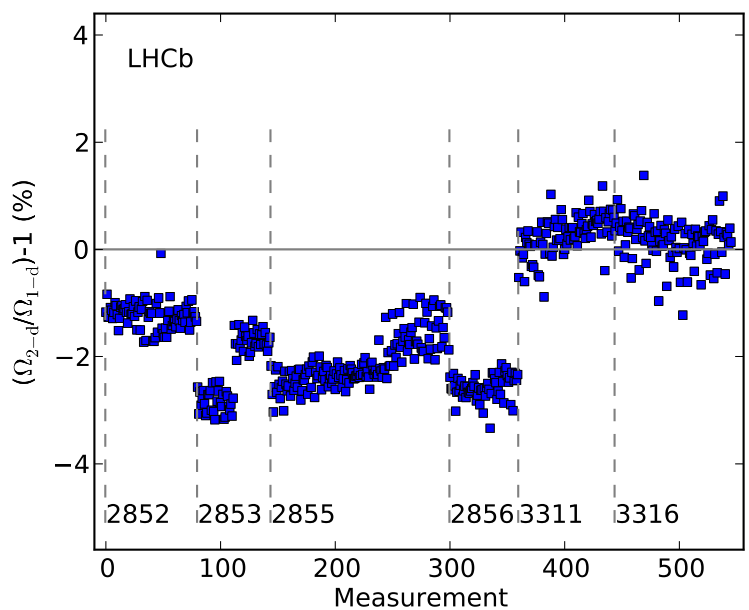
Deconvolution example
Beam width: 90µm



Beam factorizability

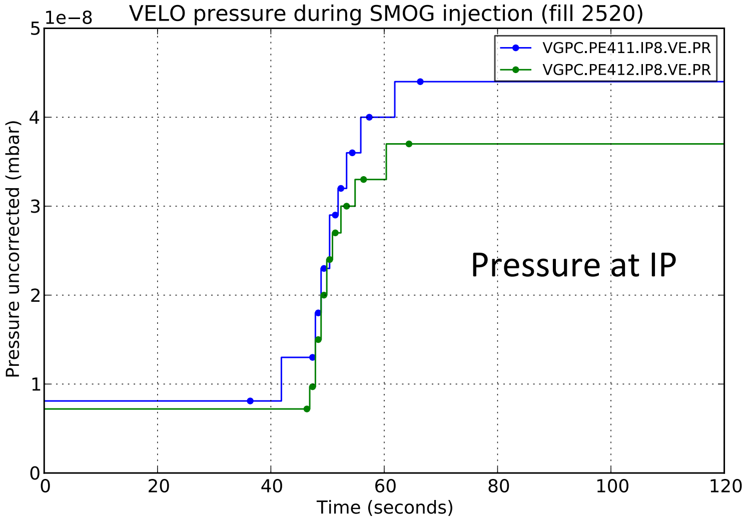






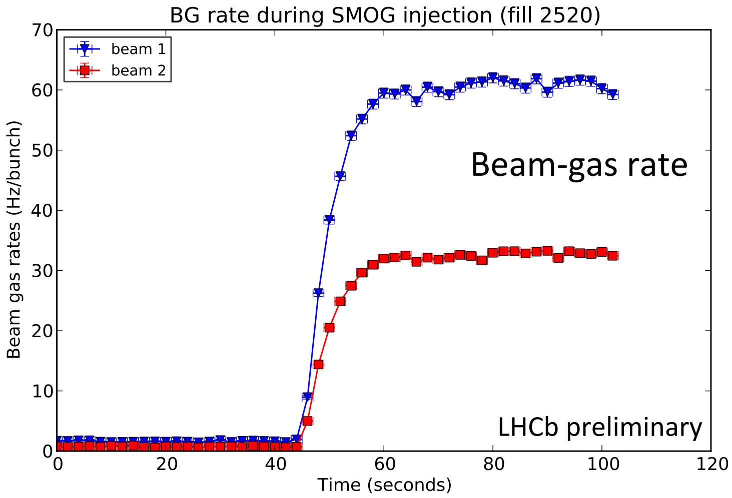
Gas injection to increase beam gas rate

•To increase the accuracy of the beam gas method a larger beam gas rate is necessary
•In 2012 a gas injection system (called SMOG) has been used in dedicated fills
•By injecting neon at the Interaction Point (IP), the vacuum is degraded: from ≈ 10^{-9} mbar to ≈ 10^{-7} mbar



•Shortened integration time ≈20 minutes vs. 2-3 hours
•Higher fit accuracy and better shape description

Additionally:
•Measure single bunch relative intensity in a statistical way (independent of LHC devices)
•Measure charges outside nominal filled LHC bunches (so-called "ghost charges", not seen by LHC instrument)
•Measure beam size evolution over time



LHCb provides this data to the other experiments and to the LHC