Precision weak boson production cross section measurements at LHCb

Colin Barschel
on behalf of the LHCb collaboration

La Thuile 2013

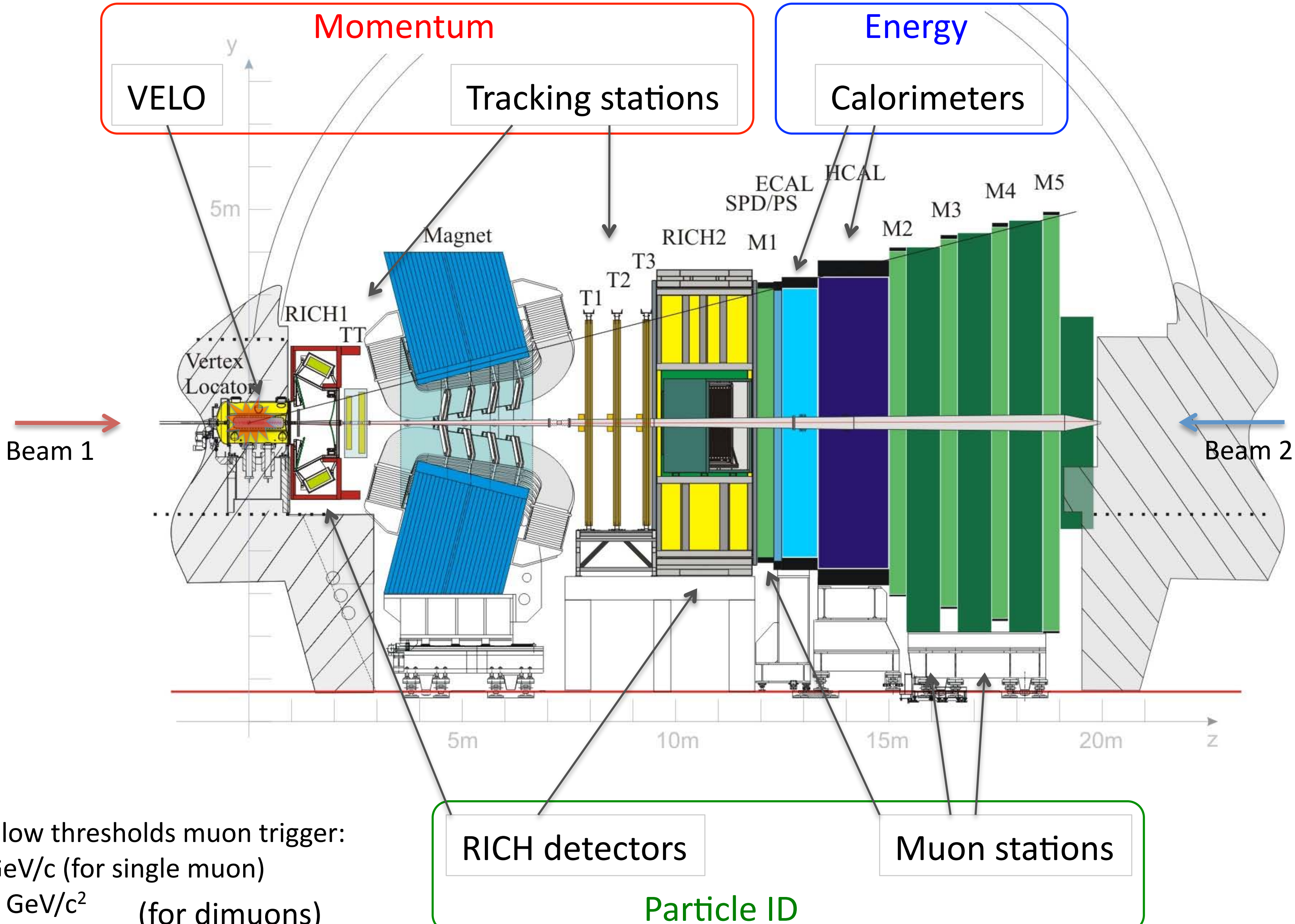
Outline

W→μν
Z→μμ
Z→ee

$$\sigma = \frac{N}{\int L}$$

Beam-gas imaging
A novel method exclusive to LHCb

LHCb detector



Uniquely low thresholds muon trigger:

$p_T > 1.5$ GeV/c (for single muon)

$M_{\mu\mu} > 2.7$ GeV/c^2 (for dimuons)

$p_T^2 > 1.4$ (GeV/c)^2

LHCb explored kinematics

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

$Q^2 = M^2$

$x_{1,2} = (M/\sqrt{s})\, e^{\pm y}$

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

Hadronic cross-section

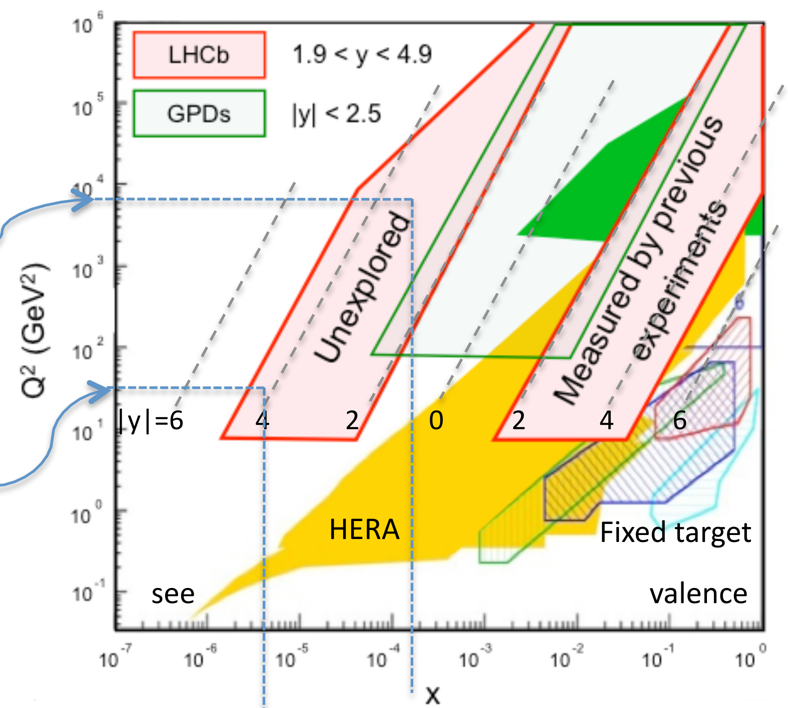
Proton structure parameterized with the PDFs
PDFs: **O(2-8%)**

Partonic cross-section
NNLO: O(2-8%) in forward region

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

Z/W
Q^2 (10'000 GeV^2)
x= 1.7×10^{-4}

Low mass DY γ*
Q^2 (25 GeV^2)
x= 8×10^{-6}



Low mass + high rapidity → low x

PDF uncertainties are large (5-8%) at large rapidities 2<y<5 accessible to LHCb
LHCb electroweak measurements provide valuable input for the PDF fits

Cross-section measurement

What are the major ingredients:

$$\sigma = \frac{\rho}{\int L\, dt} \sum_{i=1}^{Nevents} \frac{1}{efficiencies}$$

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

Experimental **efficiencies** (tracking, identification, trigger) are calculated per event: as function of η and p_T of the two leptons -> mostly determined from data

Luminosity is measured in dedicated fills with 2 independent methods:
"van der Meer scan" (VDM) and Beam-Gas Imaging (BGI)
Present uncertainty is 3.5% (LHCB-PAPER-2011-015)

+ Acceptance; final state radiation corrections

W→μν cross-section

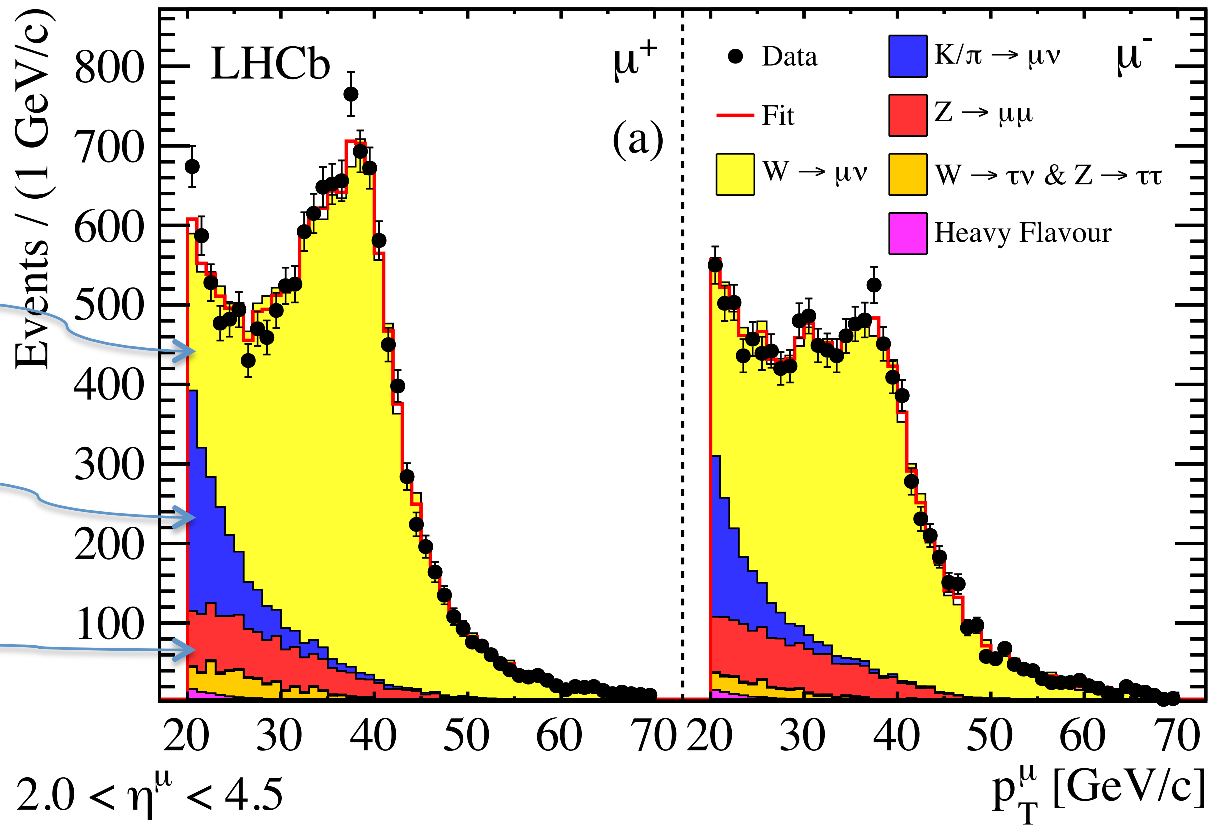
∫L 37.5 pb^{-1} (2010)
Data: single μ with p_T > 10 GeV/c
20<$p_{T\mu}$<70 GeV/c; 2.0<η_μ<4.5

W→μν (shape from simulation)

K, π decay in flight
(shape from data)

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

Purity determination (full η range)



N_{W+} = 14660
ρ_{W+} = 78.8%

N_{W-} = 11618
ρ_{W-} = 78.4%

Uncertainties:

	$W^+\to\mu^+\nu$	$W^-\to\mu^-\bar{\nu}$
statistical	1.1%	1.2%
systematic	3.2%	2.9%
luminosity	3.5%	3.5%

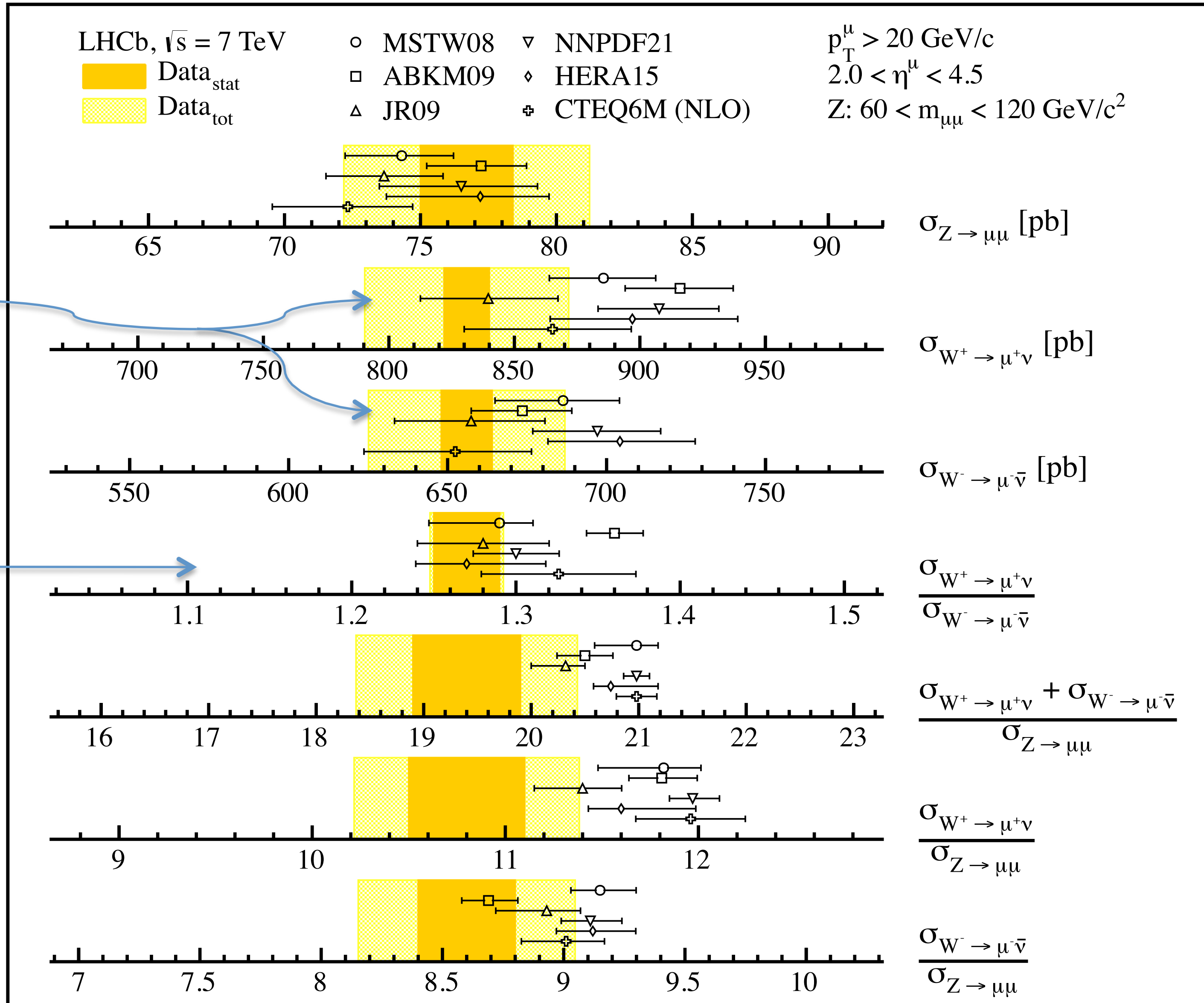
W analysis already limited by luminosity with 2010 data only

W→μν cross-section

Published in:
LHCb-PAPER-2012-008
JHEP06 (2012) 058 (arXiv:1204.1620)

Reduce luminosity uncertainty: valuable input to PDFs

Ratio: most systematic uncertainties cancel
→ Precise measurement 1.7%

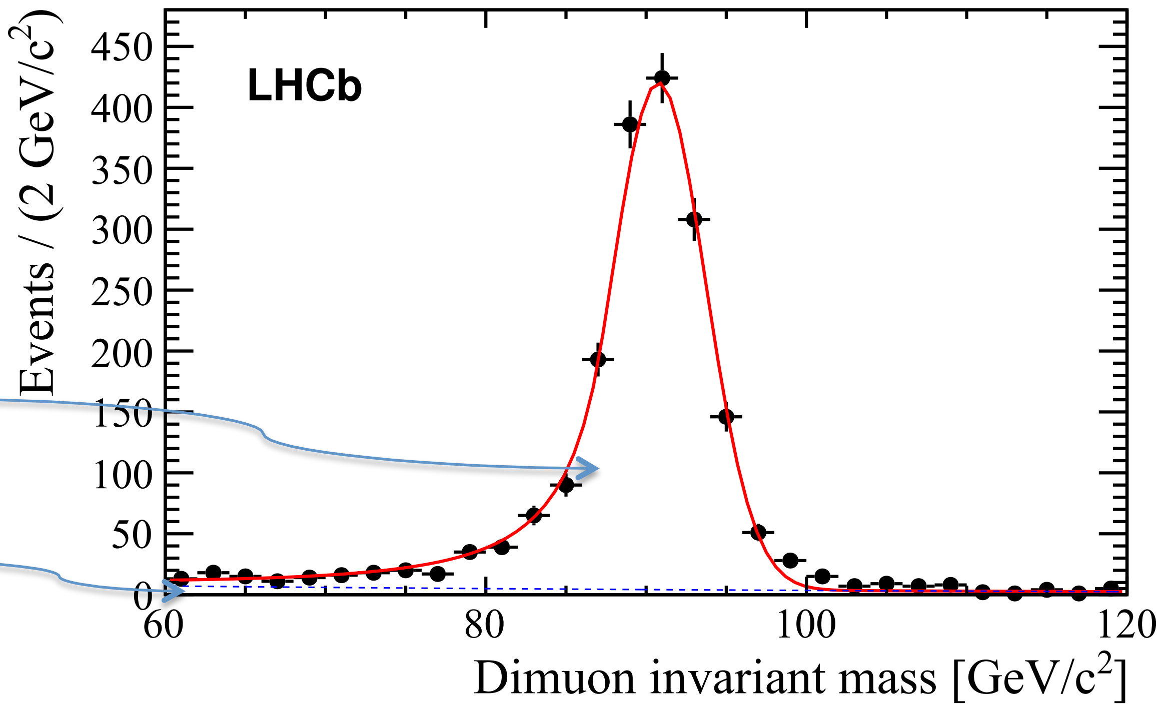


Prediction: NNLO with DYNNLO; PDF uncertainties at 68% CL

Z→μμ cross section

$\int L$ 37.5 pb^{-1} (2010)
Data: single μ with p_T > 10 GeV/c
Selection: two muons
$p_{T\mu}$>20 GeV/c; 2.0<η_μ<4.5
60 < M(μμ) < 120 GeV/c^2

Z mass peak



Z→μμ signal

Low background:
Z→ττ; W-pair; Top-pair; QCD

N_Z = 1966
Bkg = 4.8±1.0
ρ_Z = 99.7%

Uncertainties:

	Z→μμ
statistical	2.2%
systematic	4.3%
luminosity	3.5%

Dominated by efficiencies
Determined from data -> of statistical nature

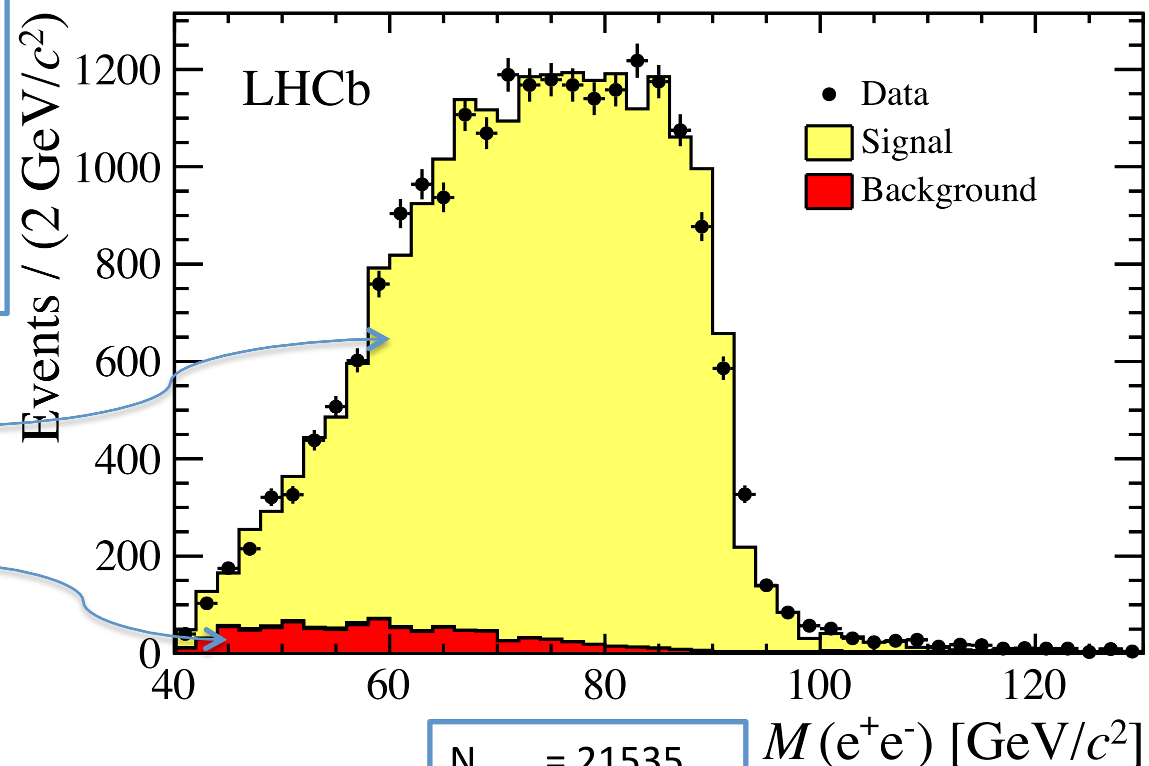
Z→ee cross section

∫L 1 fb^{-1} (2011)
Data:
single electron with p_T > 15 GeV/c
Selection: two electrons
p_{Te}>20 GeV/c; 2.0<η_e<4.5
M(ee) > 40 GeV/c^2

Z mass peak

Z→ee signal

Low background:
Z→ττ; Top-pair; QCD



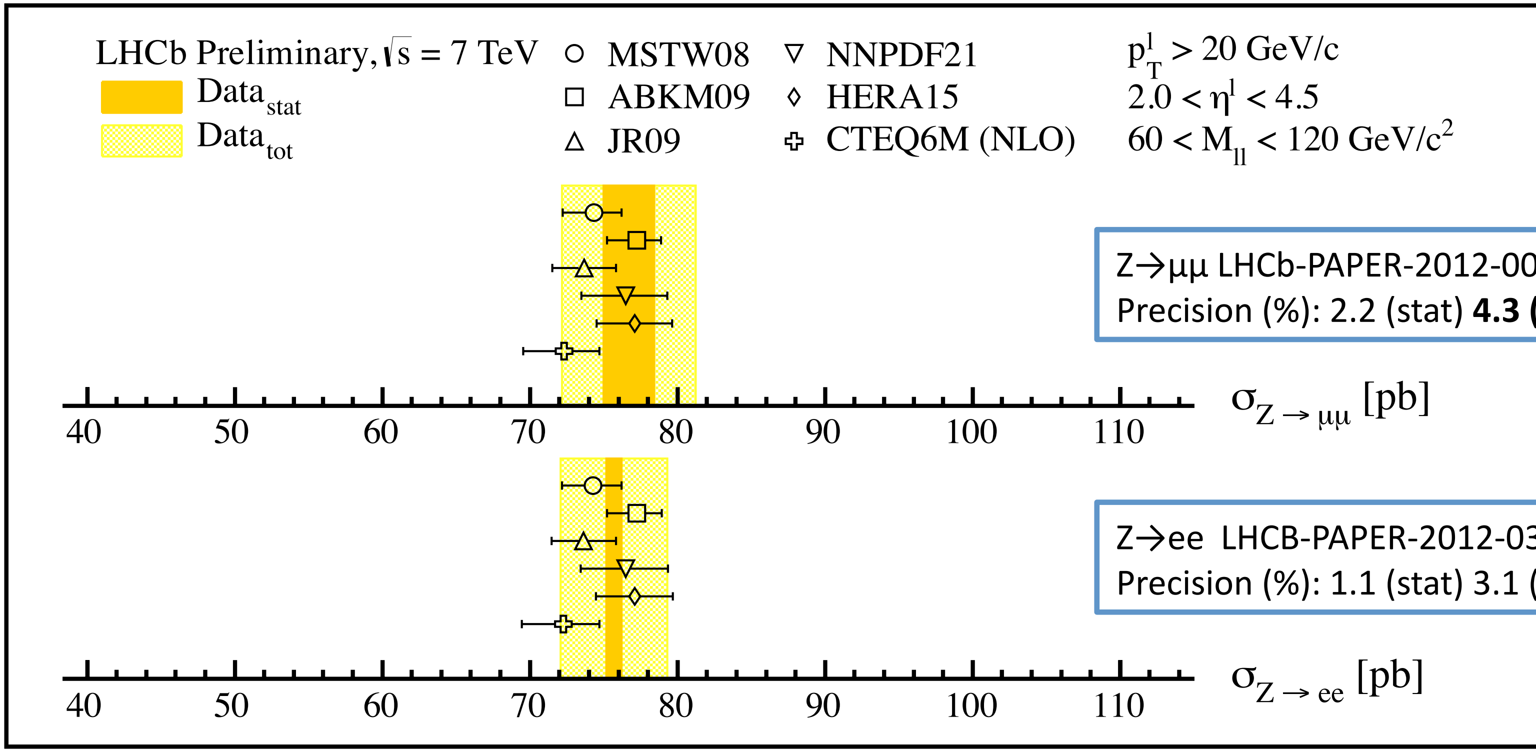
N_Z = 21535
Bkg = 473
ρ_Z = 97.8%

Uncertainties:

	Z→ee
statistical	1.1%
systematic	3.1%
luminosity	3.5%

Detector characteristics prevent a sharp Z peak
Calorimeter saturates; good momentum measurement but energies are underestimated due to bremsstrahlung.
Still possible to select Z→ee with high purity

Z→dilepton cross section



Z→μμ LHCb-PAPER-2012-008
Precision (%): 2.2 (stat) **4.3 (sys)** 3.5 (lumi)

Z→ee LHCB-PAPER-2012-036
Precision (%): 1.1 (stat) 3.1 (sys) **3.5 (lumi)**

NNLO with DYNNLO; PDF uncertainties at 68% CL

Other measurements not shown here:

Z→ττ ∫L 1028 pb^{-1}
Precision (%): **5.0 (stat)** 3.9 (sys) 3.5 (lumi)
LHCb-PAPER-2012-029 arXiv:1210.6289 (JHEP)

γ*→μμ ∫L 37 pb^{-1} 5 ≤ Mμμ ≤ 120 GeV/c^2
With ∫L 1 fb^{-1} analysis will be limited by luminosity in higher mass bins
LHCb-CONF-2012-013

With the full 2011 and 2012 data set

Uncertainties on electroweak cross sections are now mostly dominated by systematic uncertainties

-Most systematic uncertainties are of statistical nature -> will improve with more data

-Ideally the major electroweak cross section measurements should be limited by the detector performance

Measurements should not be dominated by luminosity uncertainty (now 3.5%)

    -Precision on integrated luminosity of 2% (or less) is therefore necessary

> Precision EW measurements are only possible together with a precision luminosity measurement

$$N_1 N_2 \cdot Overlap$$

$$N = \int L \, \sigma$$

Number of signal events

Integrated luminosity

Signal event cross section

LHC instrumentation

Measured by experiments (VDM or beam-gas)

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

•Bunch intensity (N_1N_2) measured by LHC instrumentation. Uncertainties: 2.8% in 2010; O(0.3%) in 2011, 2012
•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) $L = f \cdot N_1 N_2 \cdot \boxed{Overlap}$

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

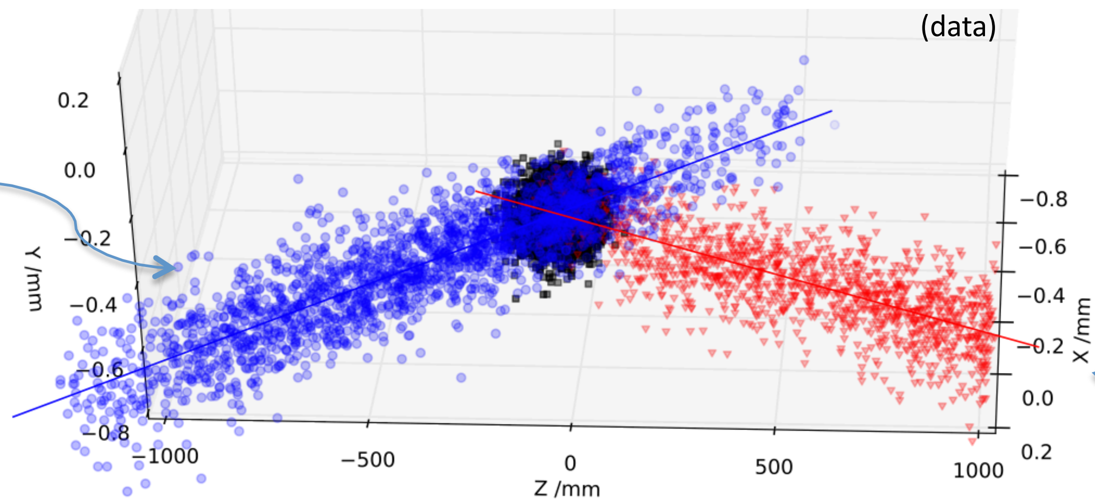
Single bunch density function of colliding bunch pair
(e.g. double Gaussian profile)

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

Interaction between beam and residual gas molecule

Beam 1



Beam 2

Measuring the shape of the bunches

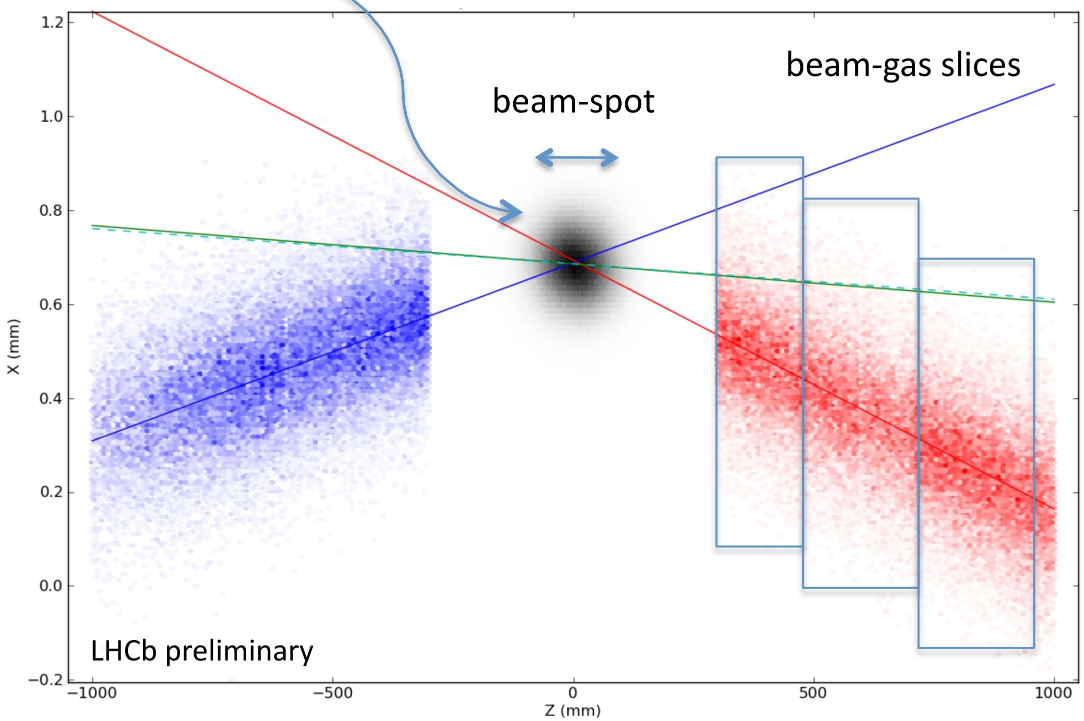
2010 results published in JINST 7 (2012) P01010 [arXiv:1110.2866 [hep-ex]]

Global fit

Measurement per 20 minutes and per bunch pair (≈10^5 beam gas and 10^6 beam beam vertices)

-Fit single beams and beam spot in one global fit
-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 beam spot is fully predicted by single beam parameters

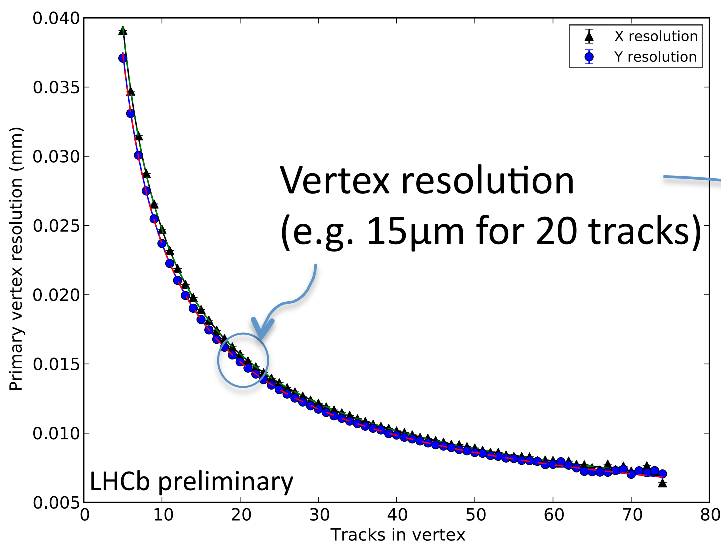


Vertex resolution

Beam gas vertices are measured with the VErtex LOcator (VELO) detector
-Geometry and proximity to the beam permits to achieve high precision in vertex position

Knowledge of the resolution is important:
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

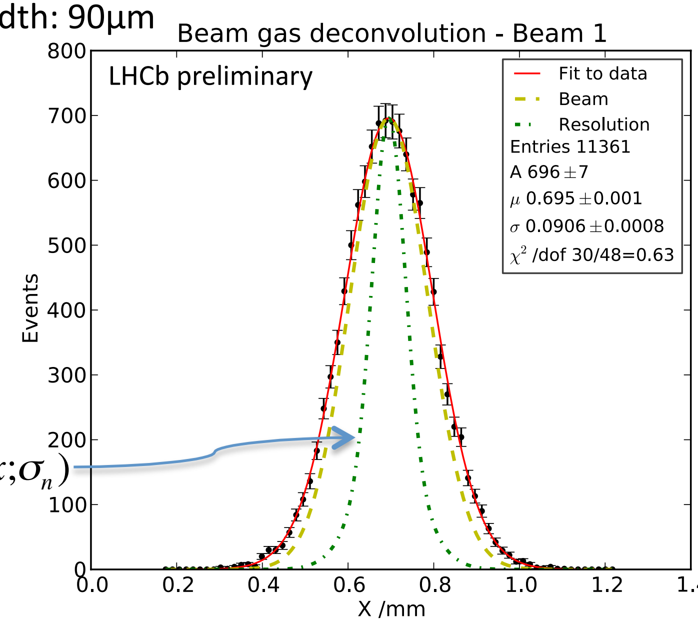
Parameterization example
for pp resolution



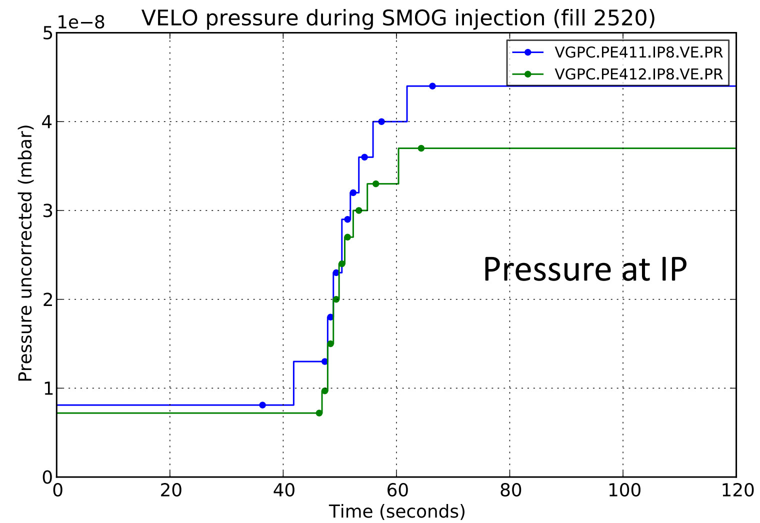
Resolution distribution

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

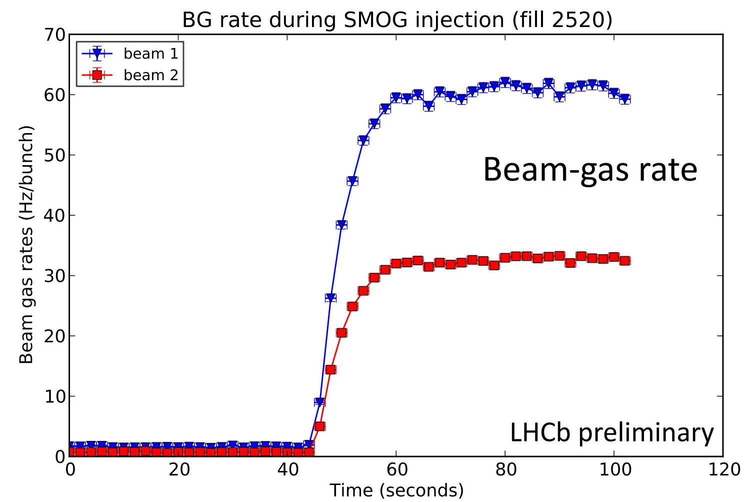
Deconvolution example
Beam width: 90µm



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

Luminosity uncertainties

Final analysis is underway

Major uncertainties for beam gas method

Statistical and fit uncertainty	O(1%) per bunch pair ≈1000 measurements in 2012
Knowledge of the vertex resolution Affects beam width	Resolution uncertainty of 5% and 10 m β* optics: O(1-2%) on cross section
X/Y factorizability*	O(1%)
Crossing angle correction	O(0.2%)

*VDM method used by other experiments assumes "factorizable beams" i.e. X shape does not depend on Y position.
→ Not true! Can be seen and measured with beam gas at LHCb

Luminosity uncertainties not related to beam gas method

Stability of luminosity counters over full dataset	O(0.5%)
Beam total intensity scale	O(0.3%) (was 2.8% in 2010!) (LHC device)
Single bunch intensity (measured by LHCb or LHC device)	O(0.2%)
Ghost charges correction	O(0.1%) → Measured by LHCb for all experiments

Conclusion and outlook

Luminosity: (LHCB-PAPER-2011-015)
•High accuracy of beam gas method possible in 2012 with gas injections (SMOG)
•No gas injection in 2011 but beam gas method still possible with less accuracy
•Uncertainty on beam intensity absolute scale is now reduced by x10 for 2011 and 2012
•Combine van der Meer and beam gas methods (independent methods → strong constrain)

→ Ideally no measurement should be limited by the luminosity uncertainty

LHCb electroweak measurements

1 fb^{-1} in 2011 (√s 7 TeV)
- W/Z production
- Low mass Drell-Yan $\gamma^* \rightarrow \mu\mu$

} will improve using full dataset (≈30× more data)
In some cases limited by present luminosity uncertainty

- $Z \rightarrow ee$ → limited by present luminosity uncertainty

2 fb^{-1} in 2012 (√s 8 TeV)
- New kinematics
- Twice the data
- High precision luminosity

References

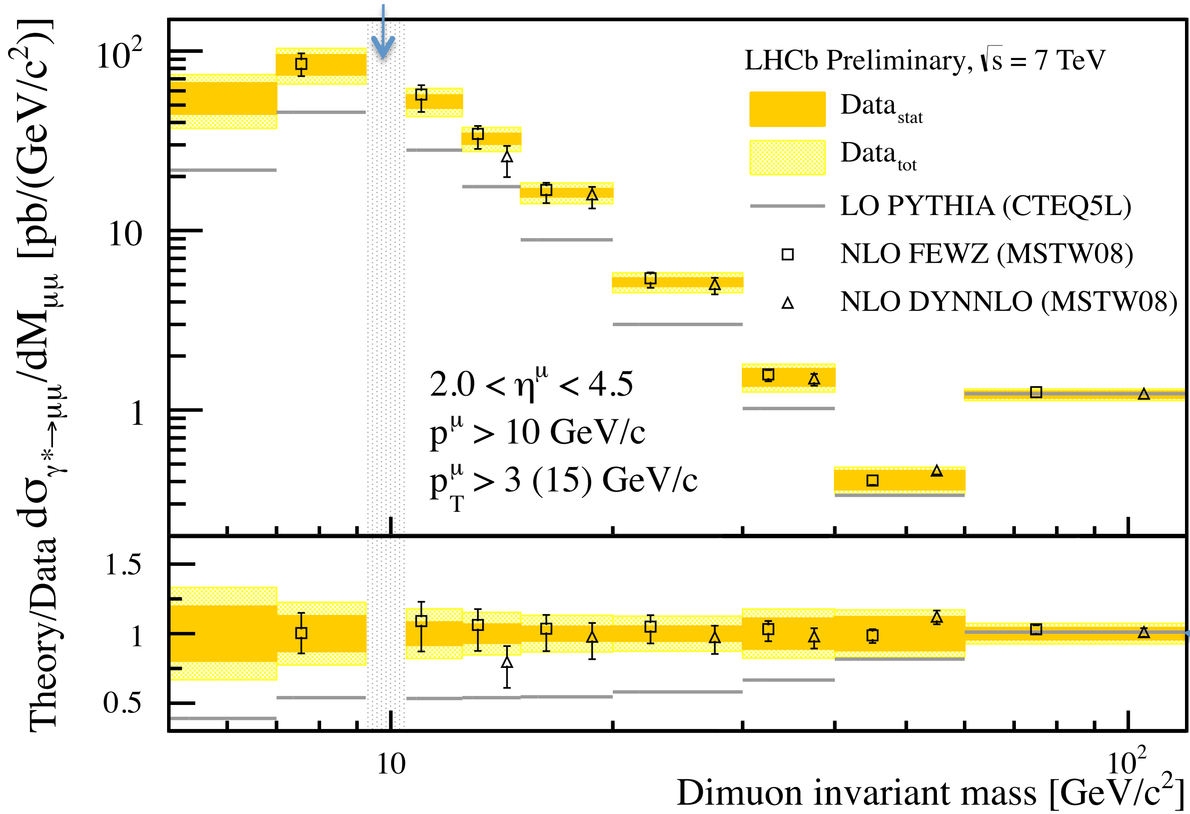
1. Inclusive W and Z production in the forward region at s√ = 7 TeV, LHCb Collaboration, 2012, J. High Energy Phys. 06 (2012) 058, LHCB-PAPER-2012-008
2. Measurement of the cross-section for Z→e+e− production in pp collisions at s√=7 TeV, LHCb Collaboration, 2012, LHCB-PAPER-2012-036
3. Inclusive low mass Drell-Yan production in the forward region at s√ = 7 TeV, LHCb Collaboration, 2012, LHCb-CONF-2012-013
4. A study of the Z production cross-section in pp collisions at s√ = 7 TeV using tau final states, LHCb Collaboration, 2012, LHCB-PAPER-2012-029
5. "Absolute luminosity measurements with the LHCb detector at the LHC", LHCb Collaboration, 2012 LHCB-PAPER-2011-015, *J. Instrum.* 7 (2012) P01010
6. Results of the LHC DCCT Calibration Studies, C. Barschel et al. ,2012, CERN-ATS-Note-2012-026
7. "LHC Bunch Current Normalisation for the April-May 2010 Luminosity Calibration Measurements" G. Anders et al. (BCNWG note1), CERN-ATS-Note-2011-004 PERF
8. "LHC Bunch Current Normalisation for the October 2010 Luminosity Calibration Measurements" A. Alici et al. (BCNWG note2), CERN-ATS-Note-2011-016 PERF
9. "Study of the Relative LHC Bunch Populations for Luminosity Calibration", G. Anders et al. (BCNWG note3), CERN-ATS-Note-2012-028 PERF.
10. "Study of the LHC Ghost Charge and Satellite Bunches for Luminosity Calibration", A. Alici et al. (BCNWG note4), CERN-ATS-Note-2012-029 PERF

Backup slides

Low mass Drell-Yan production cross-section $\gamma^* \to \mu\mu$

Results compared to NLO calculations (data not corrected for FSR)
Theoretical errors include the NLO prediction uncertainties and PDFs uncertainties (at 68% C.L.)
Bins $M_{\mu\mu}$ > 40 GeV/c² have a cut of p_T > 15 GeV/c (for both data and predictions)
Cross-section in Z bin compatible with previous Z cross-section measurement LHCb-PAPER-2012-008
With more data: result in higher mass bin will be limited by present luminosity precision

ϒ resonance excluded



PYTHIA cross-section normalized to highest mass bin

References:
DYNNLO: S. Catani *et al.*, Phys. Rev. Lett. 103 (2009) 082001. [arXiv:0903.2120 [hep-ph]]
FEWZ: R. Gavin *et al.*, Comput. Phys. Commun. (2011)182:2388-2403. [arXiv:1011.3540v1 [hep-ph]]

LHCb-CONF-2012-013

Drell-Yan production cross-section (in mass bins)

Results vs. different PDF sets with NLO from FEWZ (data not corrected for FSR)
Only PDF uncertainties at 68% C.L. are shown
Bins $M_{\mu\mu}$ > 40 GeV/c² have a cut of p_T > 15 GeV/c (for both data and predictions)