# Measurements with electroweak bosons at LHCb

PANIC August 28, 2014

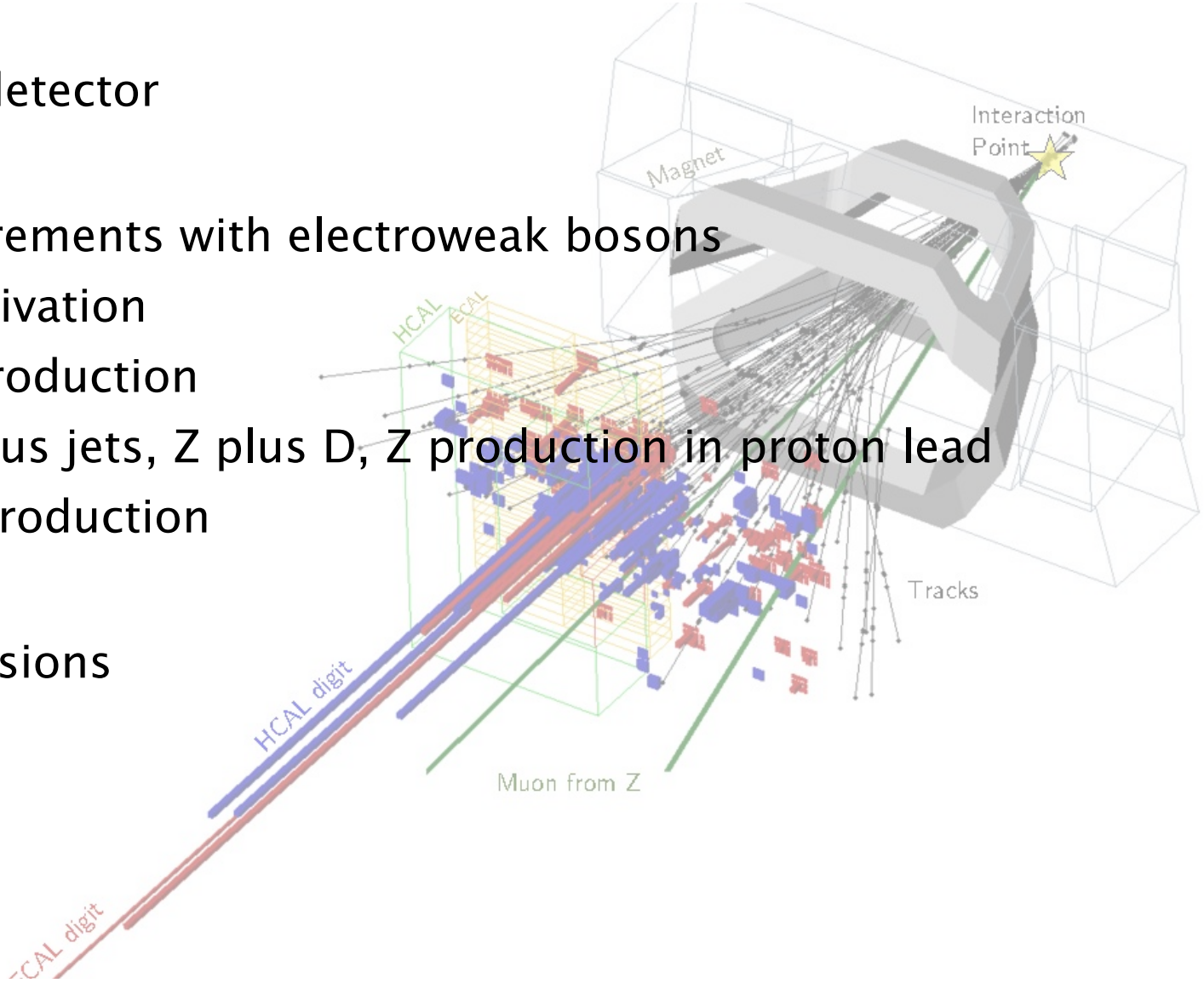
Katharina Müller

on behalf of the LHCb collaboration

University of Zurich[UZH]

# Outline

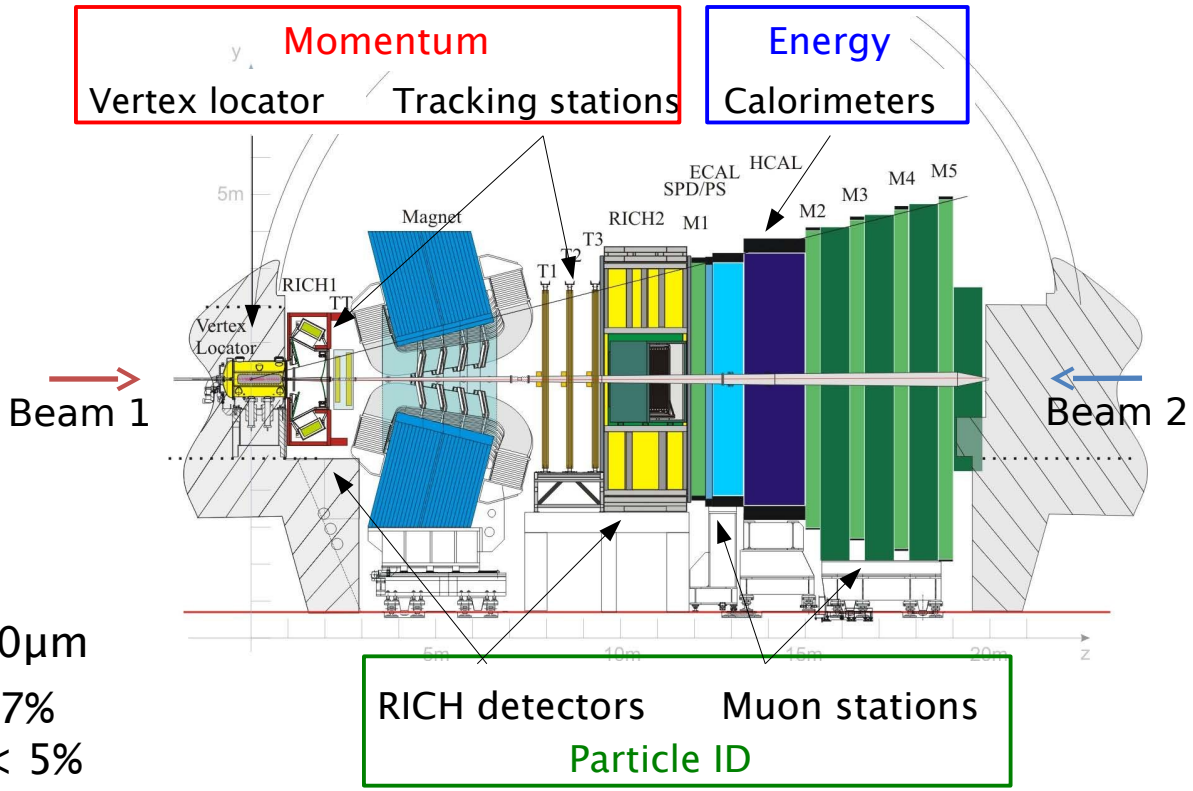
- LHCb detector
- Measurements with electroweak bosons
  - Motivation
  - Z production
  - Z plus jets, Z plus D, Z production in proton lead
  - W production
- Conclusions



# LHCb Detector

JINST3 (2008) S08005

Fully instrumented in the forward region ($2 < \eta < 5$)
some detection capability in backward region ($-3.5 < \eta < -1.5$)

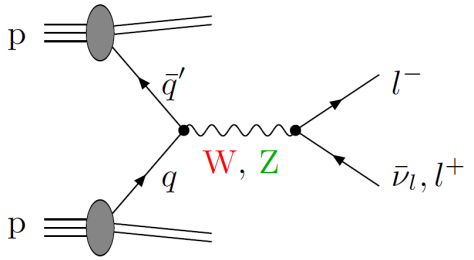



- Tracking: $\sigma_p/p \sim 0.4$–$0.6\%$
- Vertex resolution:
  $\sigma_{xy} \sim 15\mu m$, $\sigma_z \sim 80\mu m$
- Muon ID $\epsilon = 97\%$; mis-id: 0.7%
- Kaon ID $\epsilon = 90\%$; $\pi$ mis-id $< 5\%$

- Analyses based on
  - 2011 1 $fb^{-1}$ @ 7 TeV: Z plus jet, Z plus D, W production
  - 2013 proton-lead runs 2 $nb^{-1}$ @ 5 TeV: Z in proton lead

# Measurements with electroweak bosons

LHCb probes two distinct regions in $x$–$Q^2$: $x_{1,2} = (Q/\sqrt{s})\, e^{\pm y}$



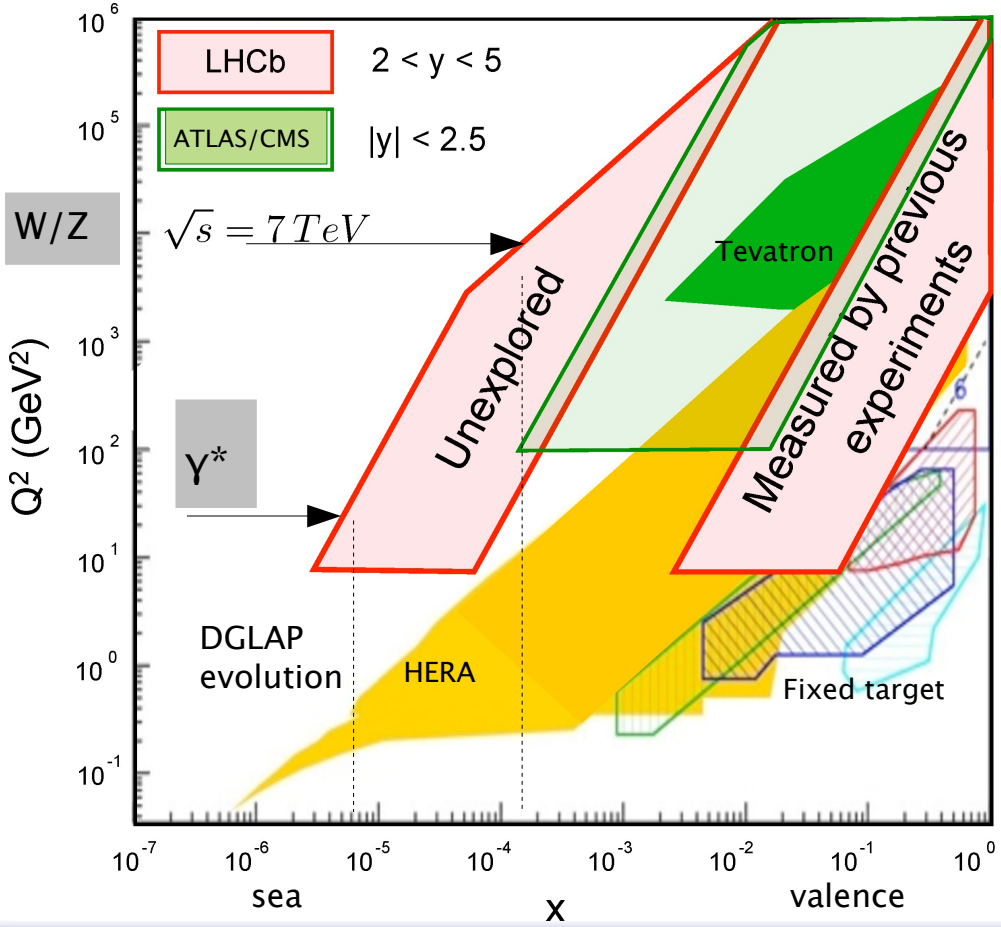

## Forward kinematics:

@ first order, collision of a sea and a valence quark

- asymmetry in production rate for $W^+$ and $W^-$
- sensitivity to parton distribution functions (PDF)

## Unique region at low x

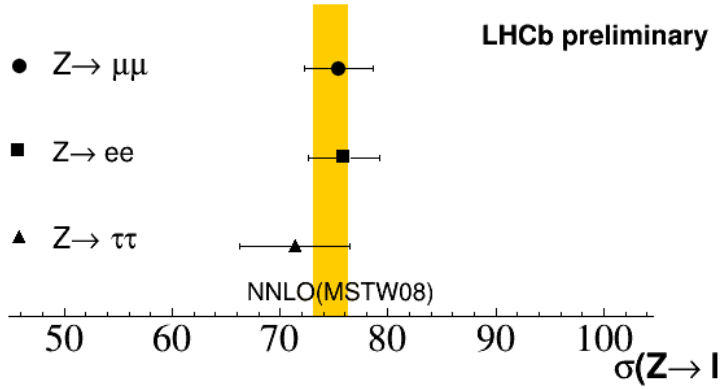
- W, Z production: $x = 1.7 \cdot 10^{-4}$
- complementary to ATLAS/CMS
- input to PDF fits in previously unprobed region

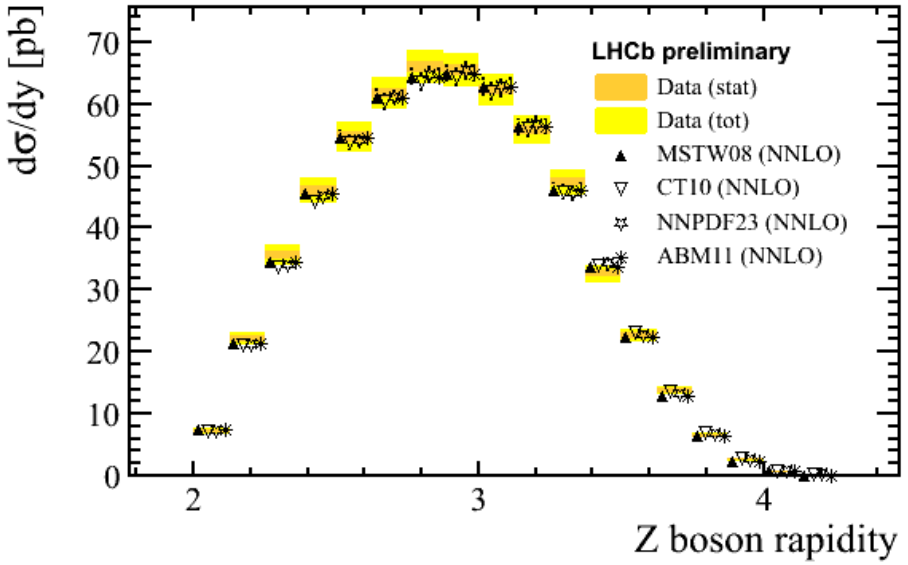


# Inclusive Z measurements



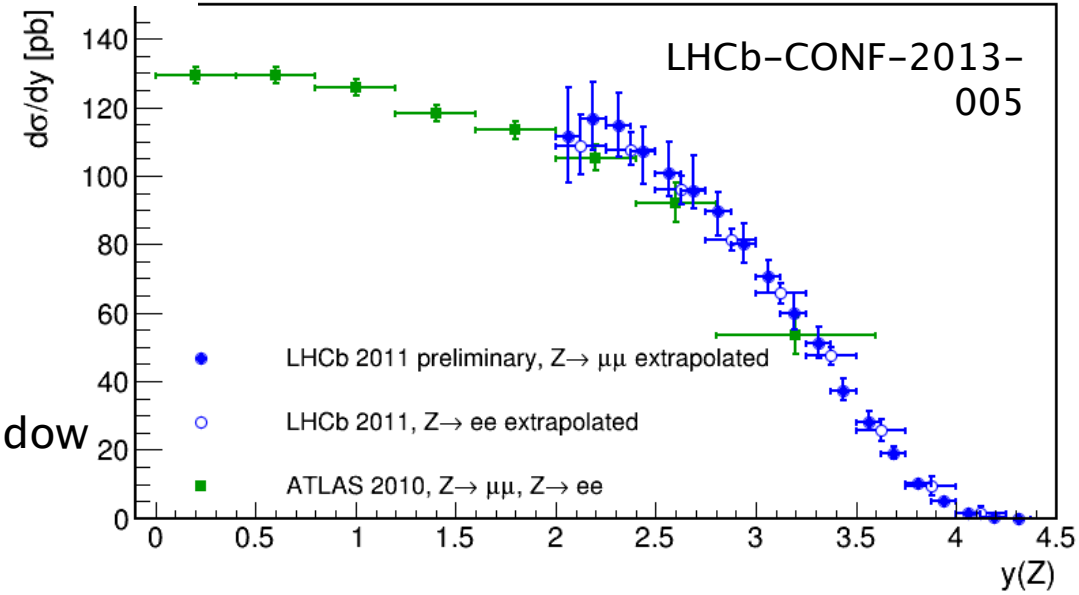
Fiducial volume:
$2<\eta<4.5$, $p_T>20$ GeV
$60<M_{ll}<120$ GeV$^2$



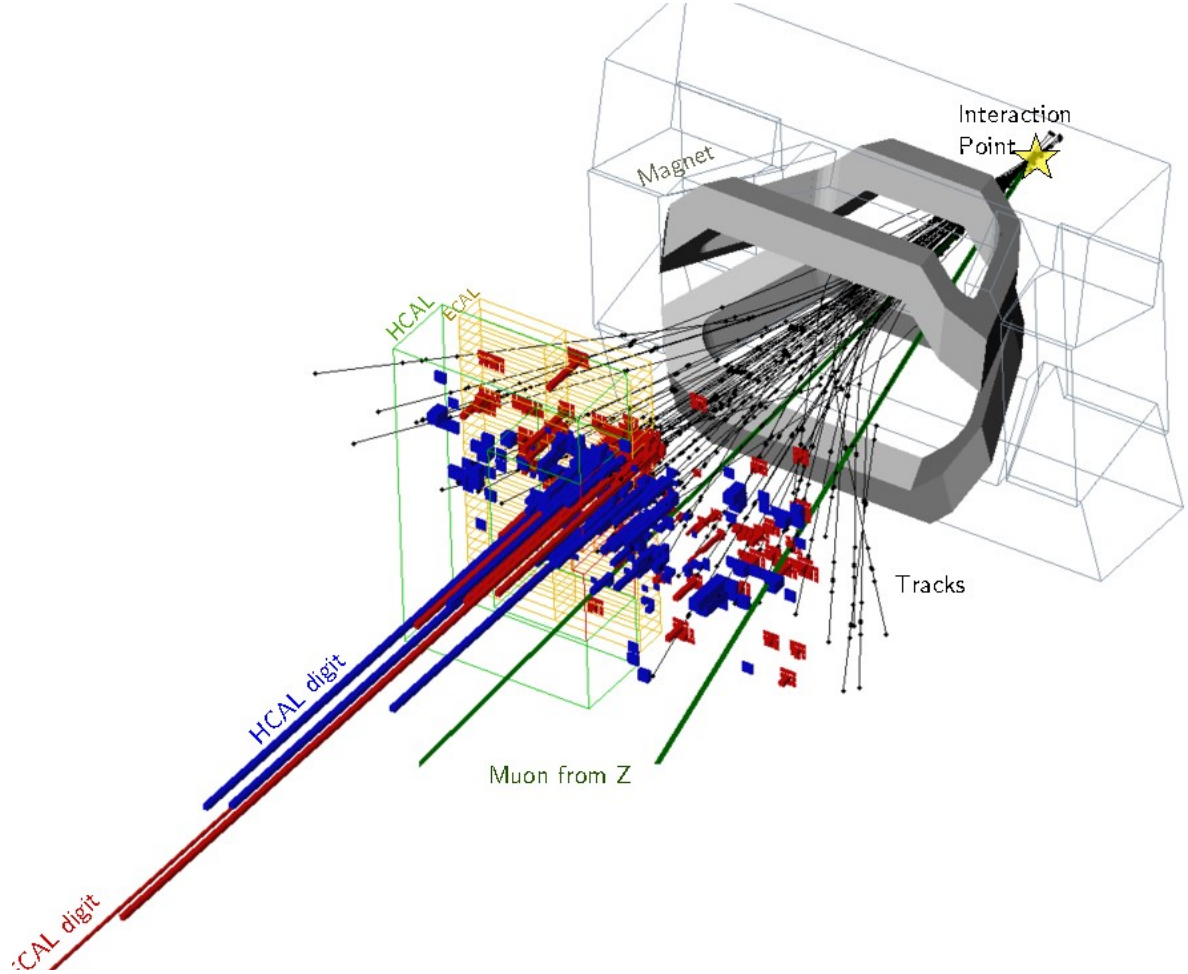




Good agreement
- between different channels
- with NNLO predictions
- with ATLAS in overlap region

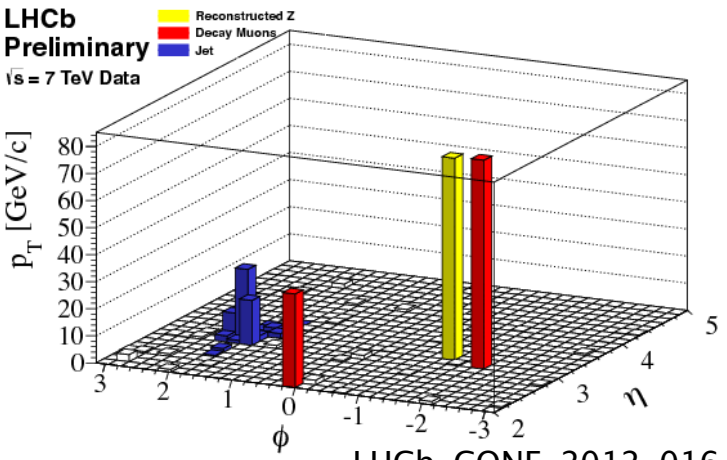
extrapolation to ATLAS:
accounts for acceptance of
the leptons and a different mass window



# Z plus jet production




Sensitivity to gluon content of proton
Test of pQCD




LHCb-CONF-2012-016

# Z plus jet



## Jet reconstruction

- anti-$k_T$ algorithm(R=0.5)
- particle-flow objects:
  charged tracks and neutral clusters

## Z plus jet selection

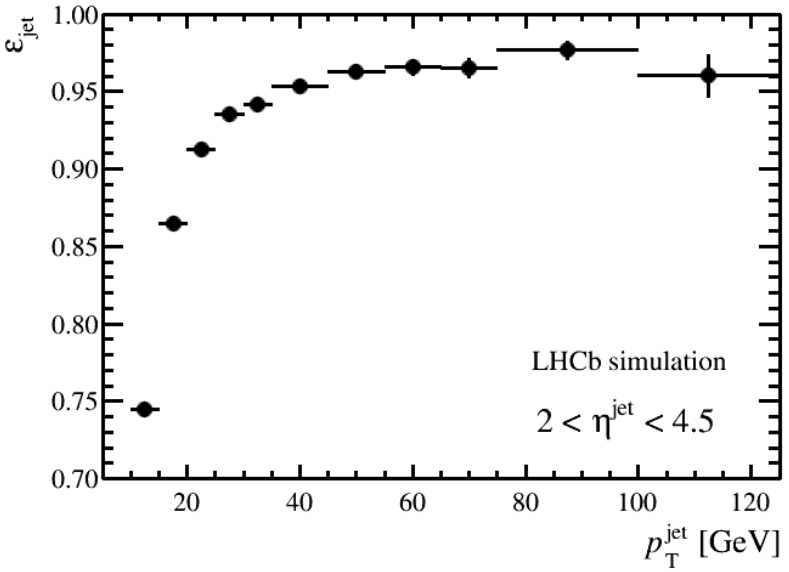
- standard selection for the Z
- jet $2<\eta<4.5$, $p_T>10$ (20 GeV)
- jet-muon separation: $\Delta r(\text{jet},\mu)>0.4$

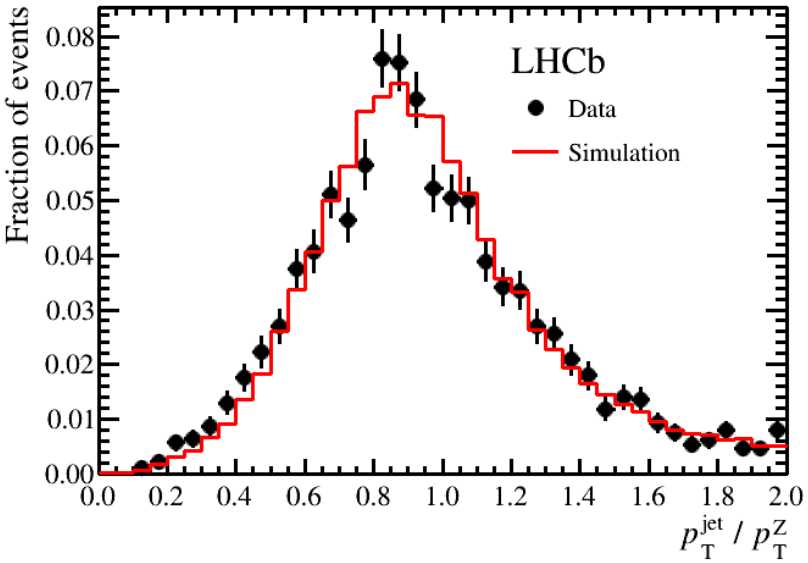
## Jet energy correction

- from simulation: 0.9-1.1
- validated in data: Z plus 1 jet events
- simulation describes data well

## Dominant systematic uncertainties

- jet energy scale and resolution
- jet reconstruction efficiency



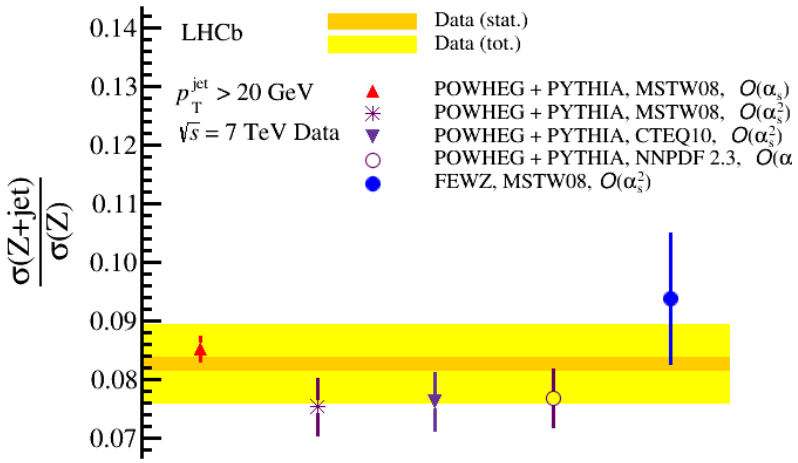
# Z plus jet production



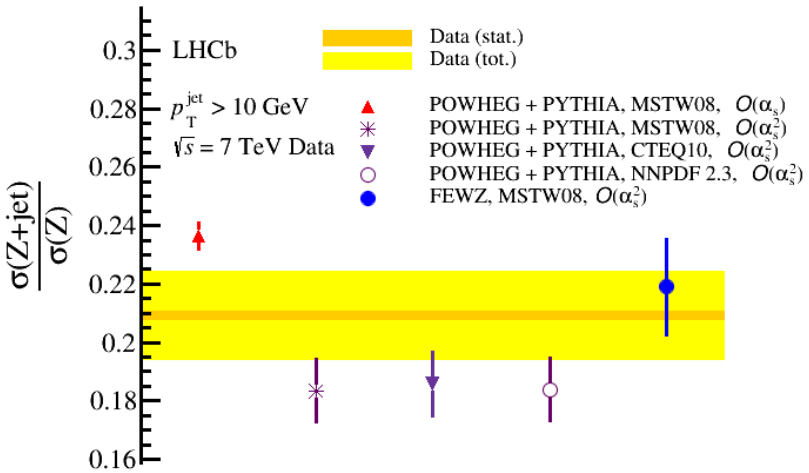
$p_{T(jet)}$>10 GeV: σ = 16.0 ± 0.2(stat) ± 1.2(syst) ± 0.6(lumi) pb

$p_{T(jet)}$>20 GeV: σ = 6.3 ± 0.1(stat) ± 0.5(syst) ± 0.2(lumi) pb

$p_{T(jet)}$>20 GeV




$p_{T(jet)}$>10 GeV




Predictions:

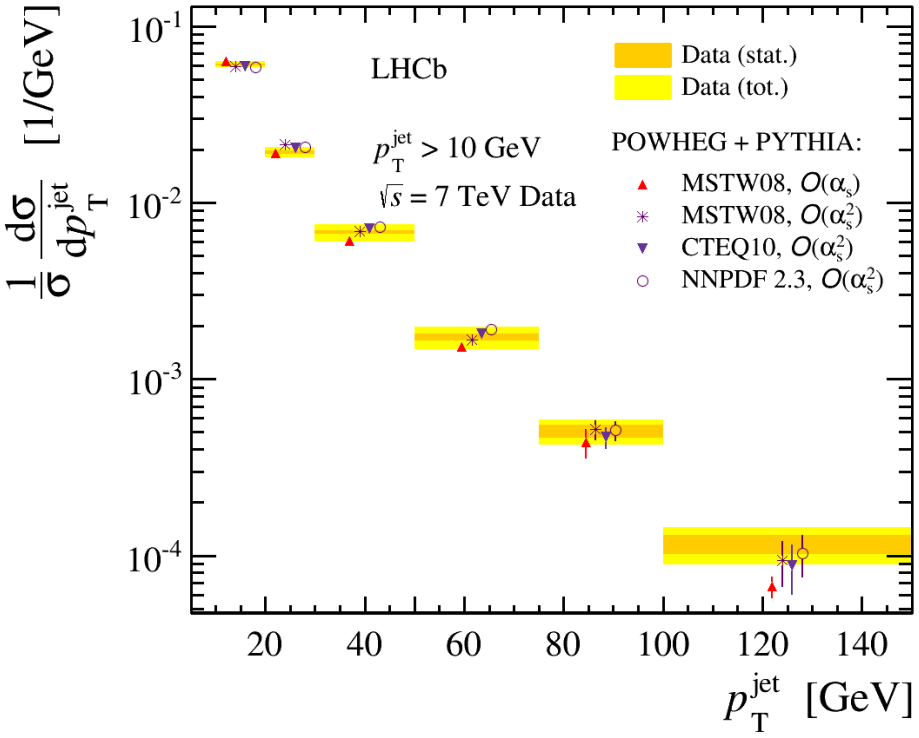
POWHEG+PYTHIA at $O(\alpha_s)$ and $O(\alpha_s^2)$ and different PDF sets

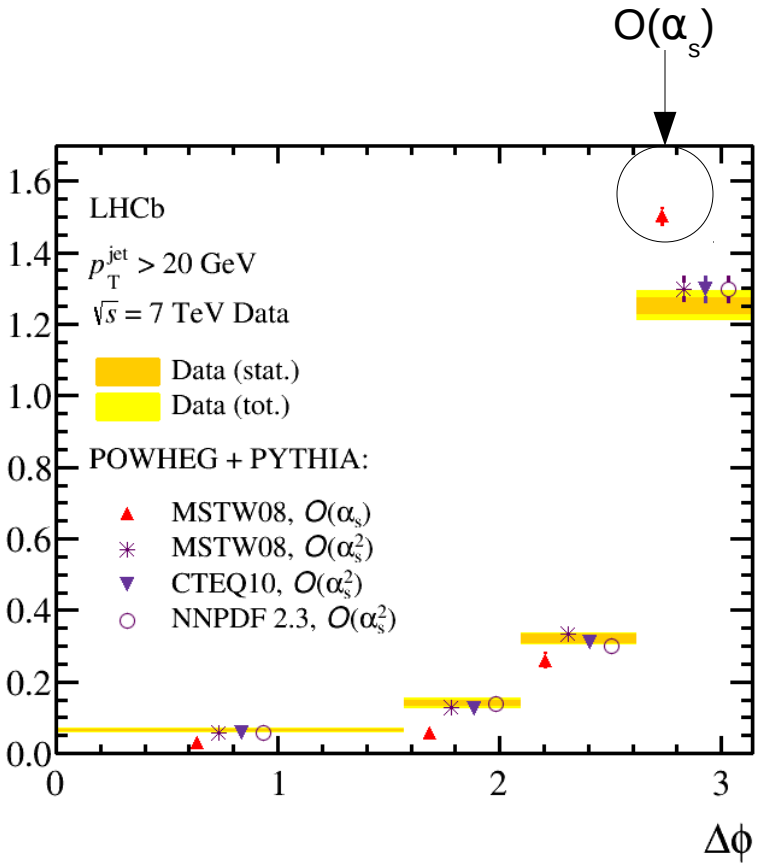
FEWZ $O(\alpha_s^2)$ not corrected for hadronisation and underlying event

FEWZ: Y. Li and F. Petriello, Phys. Rev. D86 (2012) 094034,
POWHEG: JHEP 01 (2011) 095
PYTHIA: JHEP05 (2006) 026

# Z plus jet: differential cross sections

JHEP01 (2014) 033




Results not corrected for FSR

Shapes well described by NLO predictions

LO fails to describe Δφ(Z,jet)

# Z plus D

JHEP04 (2014) 091

Yields information on charm PDF and charm production mechanisms
Contribution from single-(SPS) and double-parton scattering (DPS)

## Selection

standard Z selection
$D^0 \to K^- \pi^+$, $D^+ \to K^- \pi^+\pi^+$
$2 < p_T^D < 12$ GeV, $2 < \eta^D < 4$

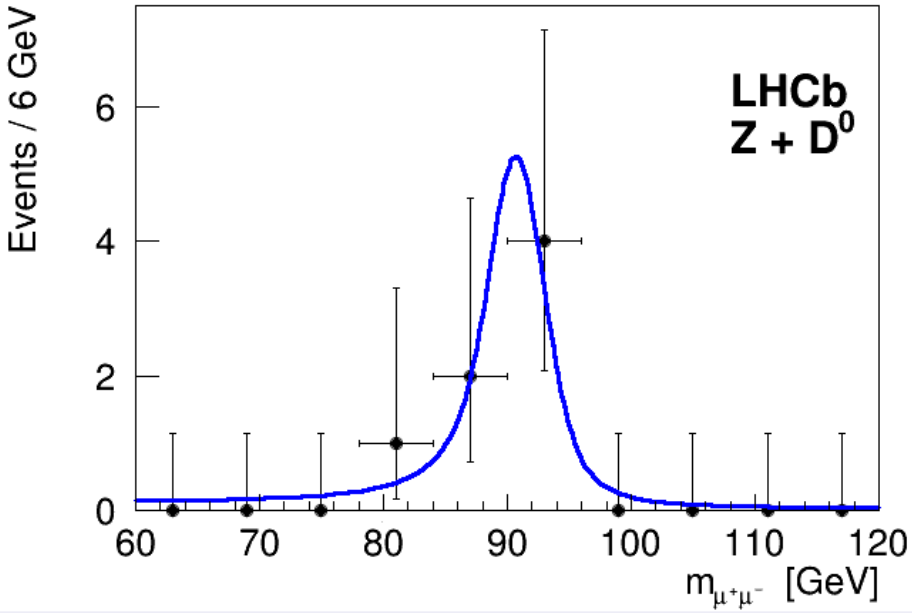
Z and D from same vertex

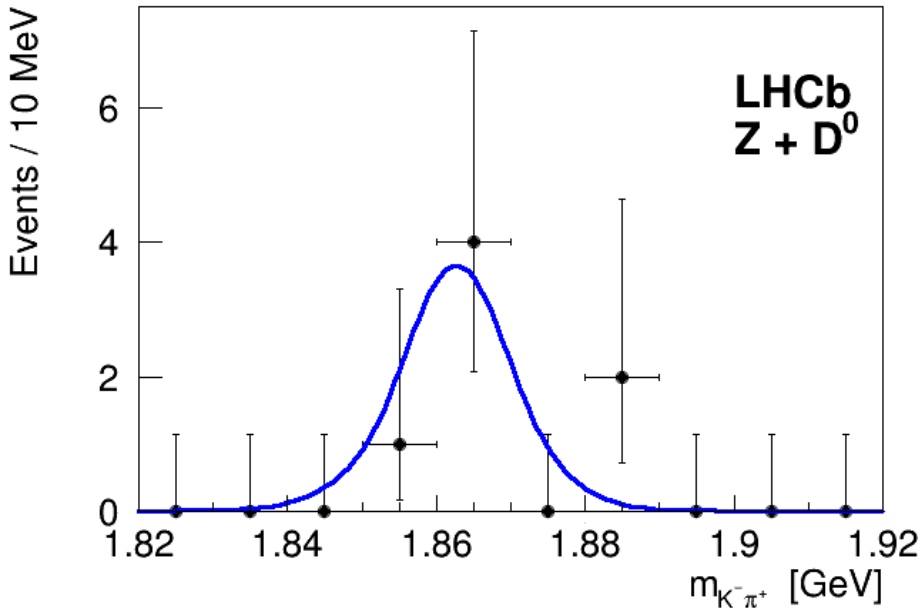
## Background: purity>95%

charmed hadrons from B-decays (dominant)
real Z and D from different vertices
combinatorial background

7 Z plus $D^0$ and 4 Z plus $D^+$ candidates

no $\Lambda_c^+ \to pK\pi$, $D_s^+ \to \Phi\pi^+$



# Z plus D: Results



$\sigma(Z\rightarrow\mu\mu,D^0) = 2.50 \pm 1.12(stat) \pm 0.22(syst)$ pb

$\sigma(Z\rightarrow\mu\mu,D^+) = 0.44 \pm 0.23(stat) \pm 0.03(syst)$ pb

## Predictions

Single parton scattering (SPS) from MCFM

Double parton scattering (DPS):

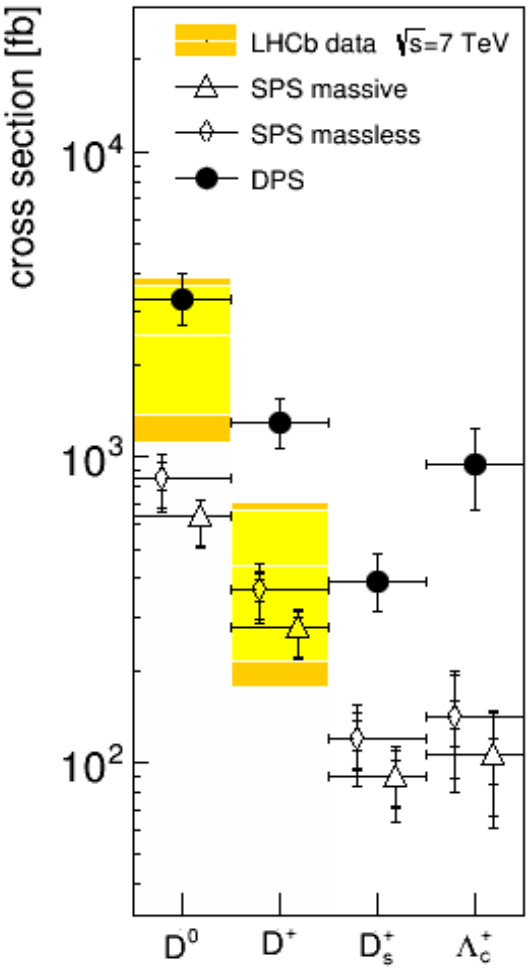
$$\sigma(DPS)=(\sigma(Z\rightarrow\mu\mu)\,\sigma(D))/\sigma_{eff}$$

$$\sigma_{eff} = 14.5 \pm 1.7\,^{+1.7}_{-2.5}\ \text{mb}\quad (CDF)$$

Sum of SPS and DPS expected to describe signal

- consistent for Z plus $D^0$
- Z plus $D^+$ below expectation

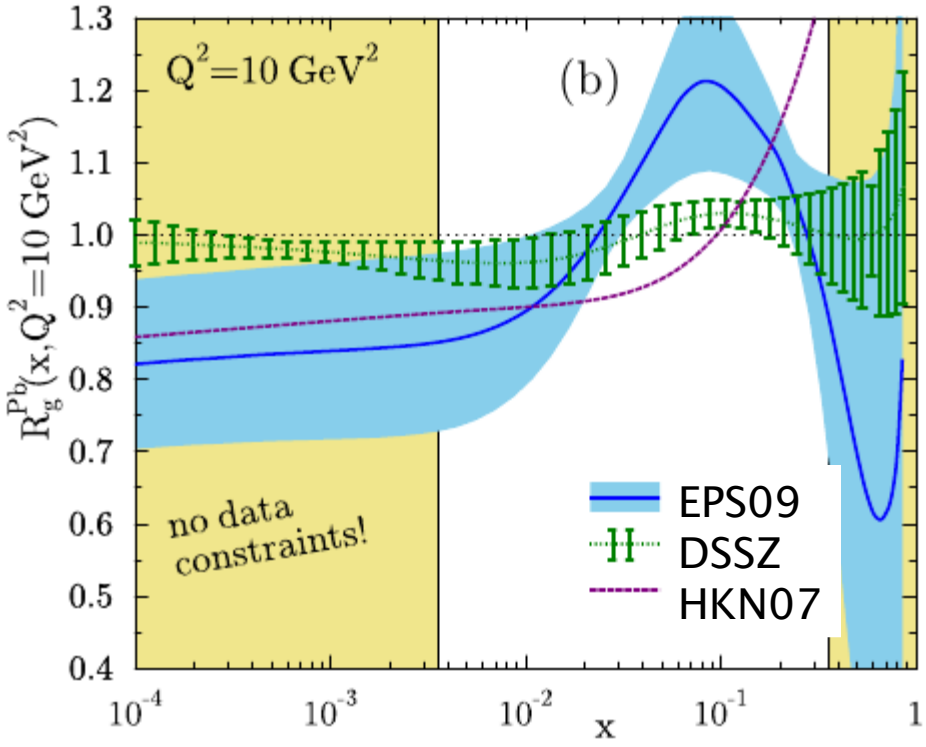
→ differential measurements with high statistics will allow to disentangle SPS and DPS contributions

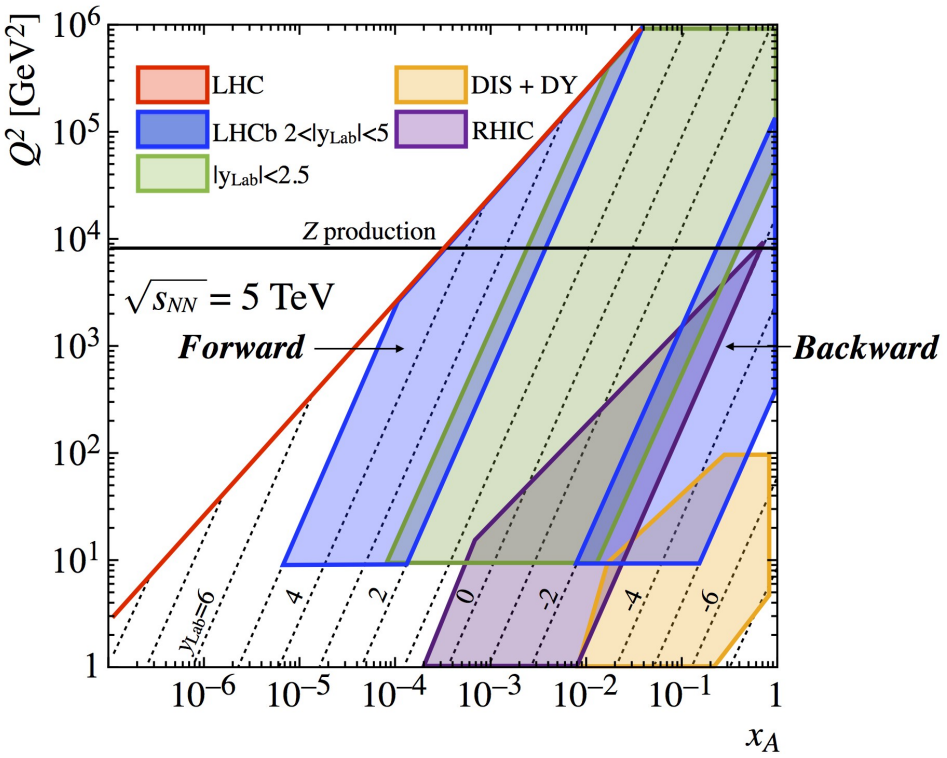



MCFM- Monte Carlo for Femtobarn processes: J. M. Campbell and R. K. Ellis, Nucl. Phys. Proc. Suppl. 205-206 (2010) 10, arXiv:1007.3492.

# Z production in pA

Ratio of nuclear PDF (gluon) for Pb to bare proton PDF [arXiv:1401.2345]




Nuclear PDF (nPDF) poorly constrained at high and low $x_A$, where measurements at LHCb have a good sensitivity.

$x_A$:momentum fraction of a parton inside the nucleon

Forward: proton beam in LHCb direction, backward: lead beam in LHCb direction

EPS09: JHEP 04 (2009) 065, DSSZ : Phys. Rev. D 85 (2012),HKN07: Phys. Rev. C 76 (2007) 065207

# Z production in proton-lead

arXiv:1406.2885, accepted by JHEP

## Forward: pA collisions

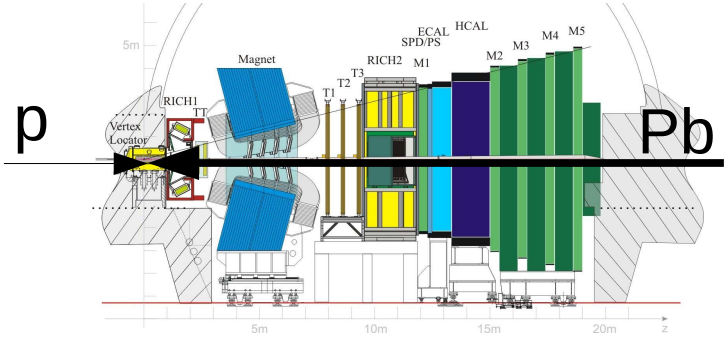
Proton beam: $E_p = 4$ TeV

$^{208}_{82}$Pb beam: $E_N = Z\,E_p \approx 1.58$ TeV

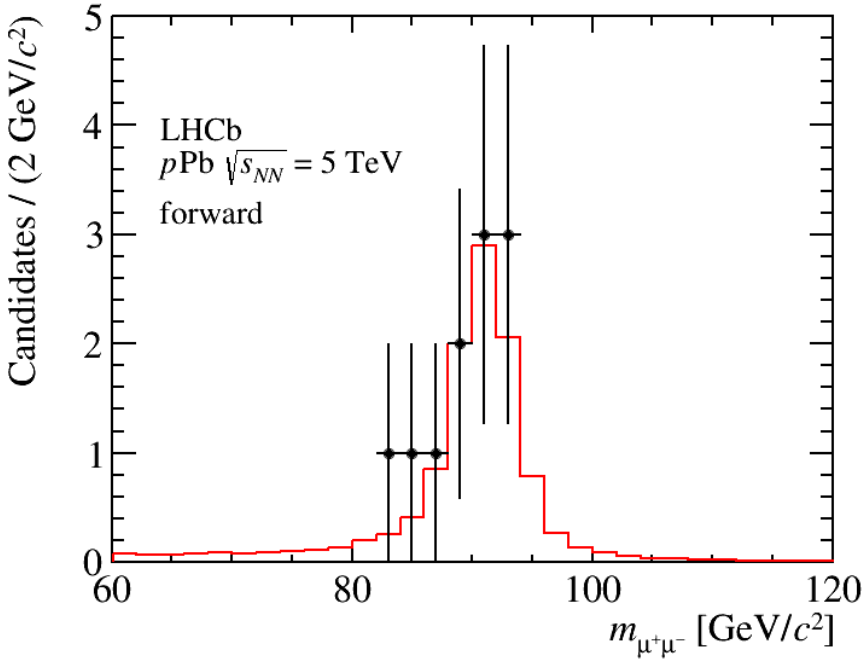
cms energy: $\sqrt{s}_{pN} \approx 5.02$ TeV

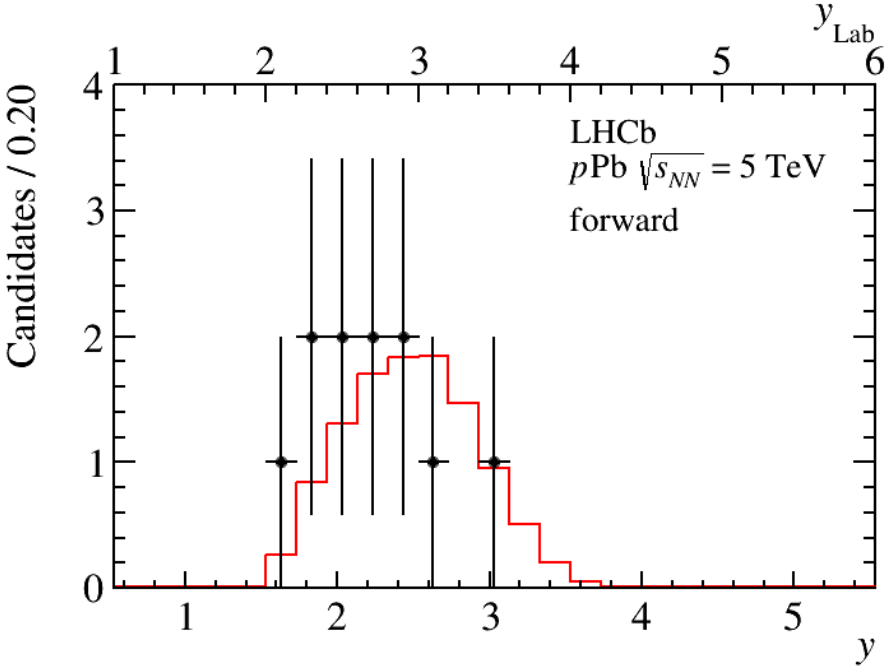
Shift in rapidity: $\Delta y = -1/2 \ln Z/A \approx 0.47$

Luminosity: $1.099 \pm 0.021$ nb$^{-1}$




## 11 candidates



# Z production in proton-lead

arXiv:1406.2885, accepted by JHEP

## Backward: Ap collisions

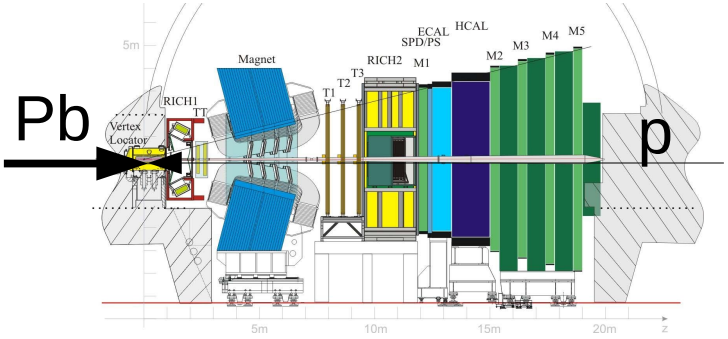
Proton beam: $E_p = 4$ TeV

$^{208}_{82}$Pb beam: $E_N = Z\,E_p \approx 1.58$ TeV

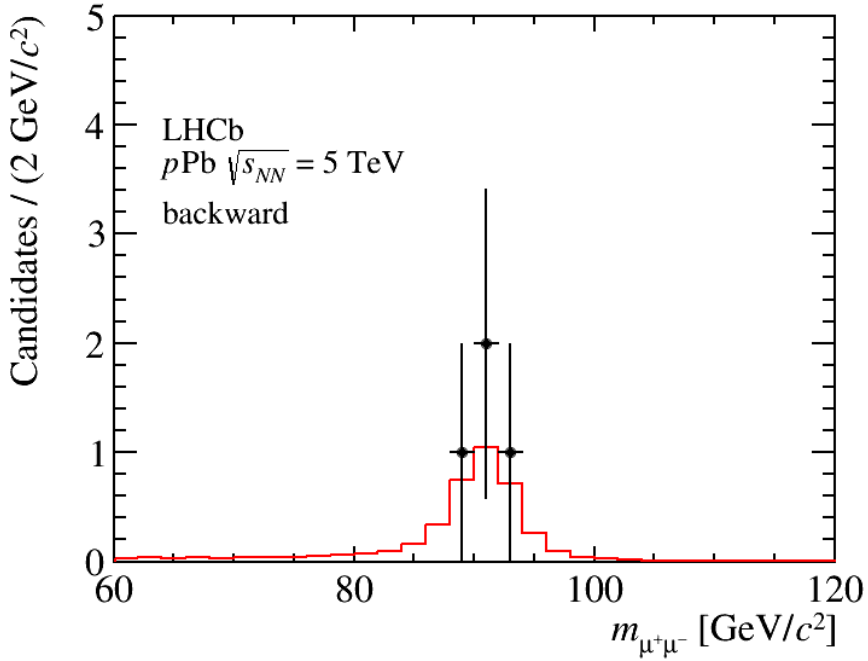
cms energy: $\sqrt{s}_{pN} \approx 5.02$ TeV

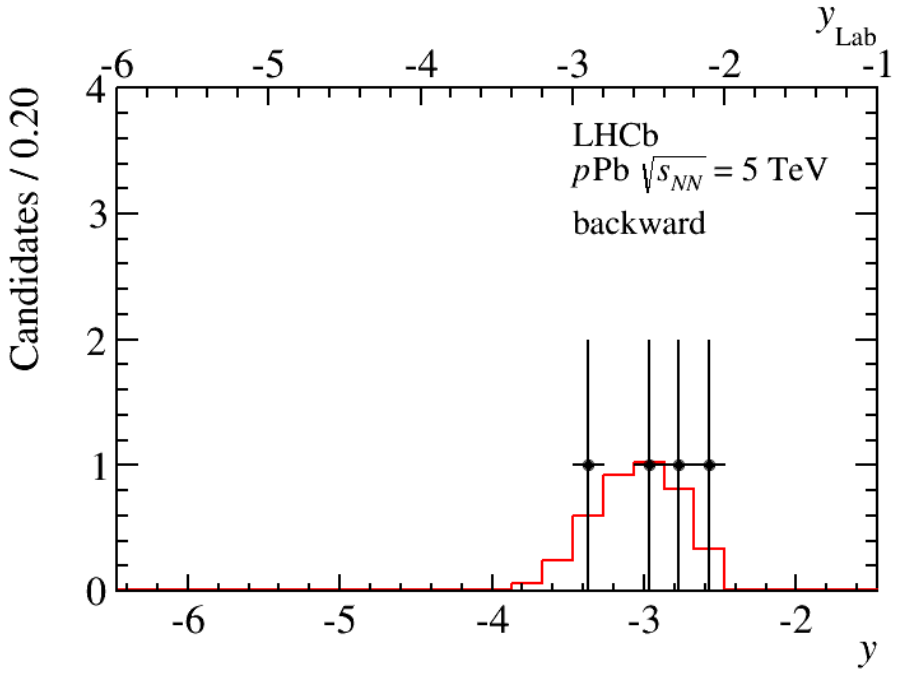
Shift in rapidity: $\Delta y = -1/2 \ln Z/A \approx 0.47$

Luminosity: $0.521 \pm 0.011$ nb$^{-1}$




## 4 candidates



# Z production in proton-lead

arXiv:1406.2885, accepted by JHEP

Efficiencies, purity from data (purity >0.995)
Cross sections:

forward:

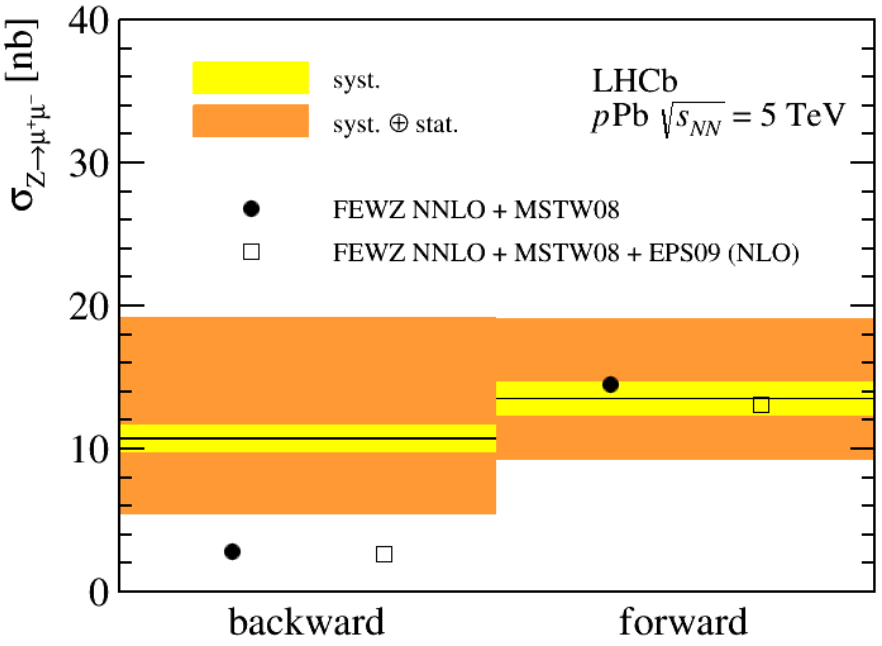
$\sigma_{Z(\to\mu+\,\mu-)} = 13.5^{+5.4}_{-4.0}$ (stat.) ± 1.2(syst.) nb

backward:

$\sigma_{Z(\to\mu+\mu-)} = 10.7^{+8.4}_{-5.1}$ (stat.) ± 1.0(syst.) nb

Theoretical predictions:
NNLO calculations (FEWZ)
nuclear modification: EPS09(NLO)

→ future higher statistics measurements will provide important information on nuclear PDFs

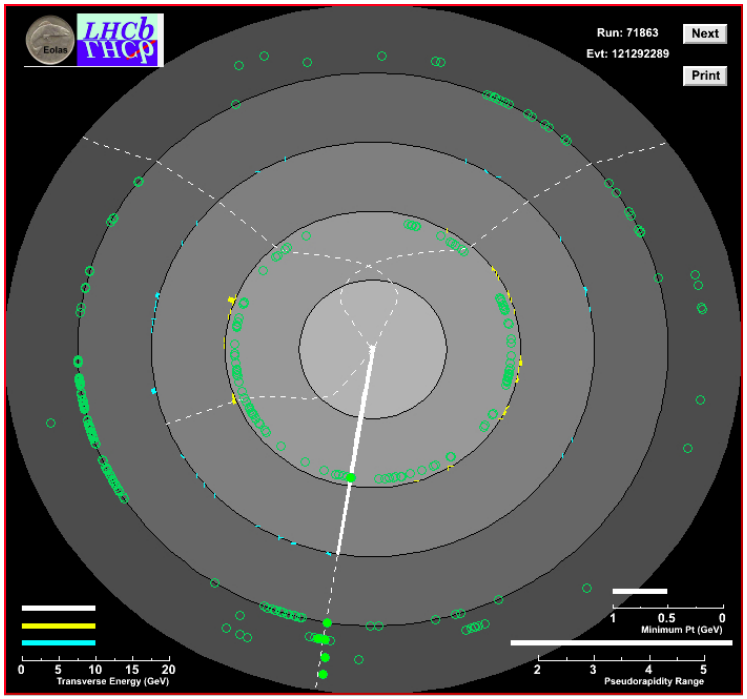



Fiducial volume
muons: $p_T$>20 GeV, 2<η<4.5
mass: 60<M(μμ)<120 GeV$^2$

FEWZ: Y. Li and F. Petriello, Phys. Rev. D86 (2012) 094034, arXiv:1208.5967.

EPS09: K. Eskola, H. Paukkunen, and C. Salgado, JHEP 04 (2009) 065, arXiv:0902.4154.

# W production in pp @ 7 TeV




W selection: one (isolated) muon

Muon: one muon
$20 < p_T < 70$ GeV/c, $2.0 < \eta_\mu < 4.5$

Isolation $E_T^{cone} < 2$ GeV
$p_T^{cone} < 2$ GeV/c

Cuts against background:

- from semi-leptonic decays of heavy flavour
  Impact parameter < 40 μm
- γ*/Z: No other muon with $p_T > 2$GeV
- K/π punch through
  E(Calorimeter)/p<0.04

Main background:
kaon, pion decay in flight
γ*/Z→μμ, one muon in acceptance

# W production

arXiv 1408.4354

## Purity from fit to $p_T$ distribution

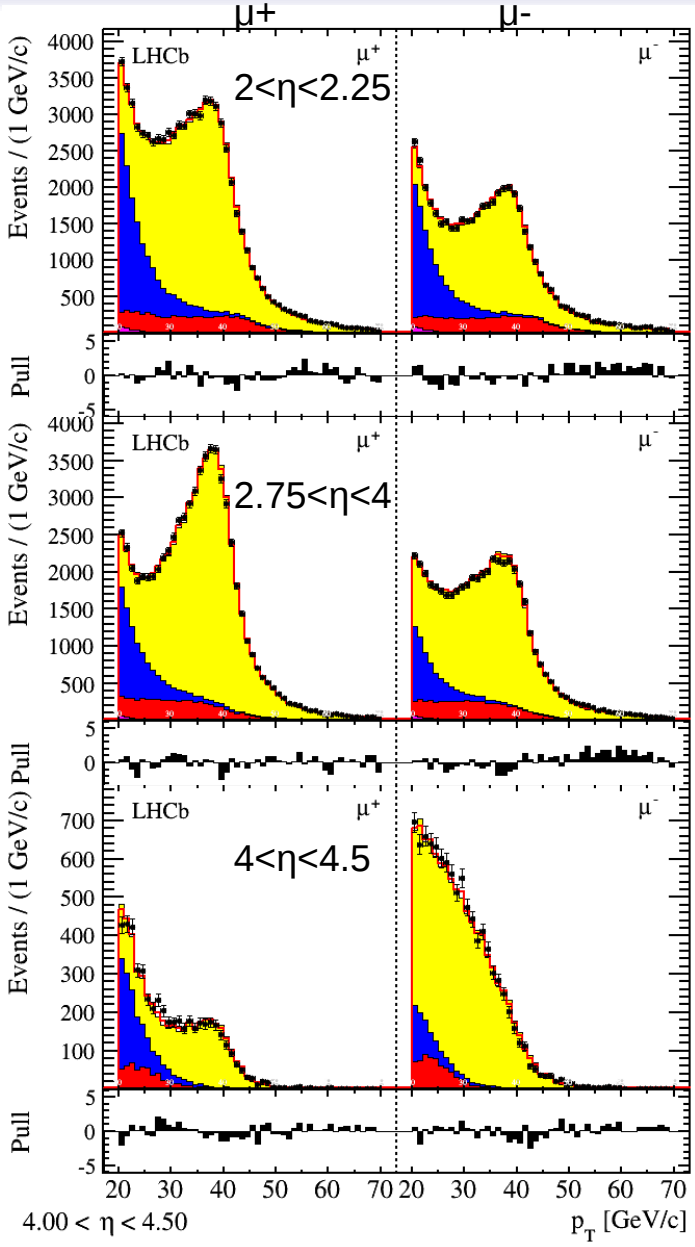
simultaneously in 8 η bins and both charges

| | Shape | Norm. |
|---|---|---|
| W →μν | simulation | fit |
| K/π decay in flight | data | fit |
| γ*/Z→μμ | simulation | fixed |
| W→τν , Z→ττ | simulation | fixed |
| Heavy Flavour | data | fixed |

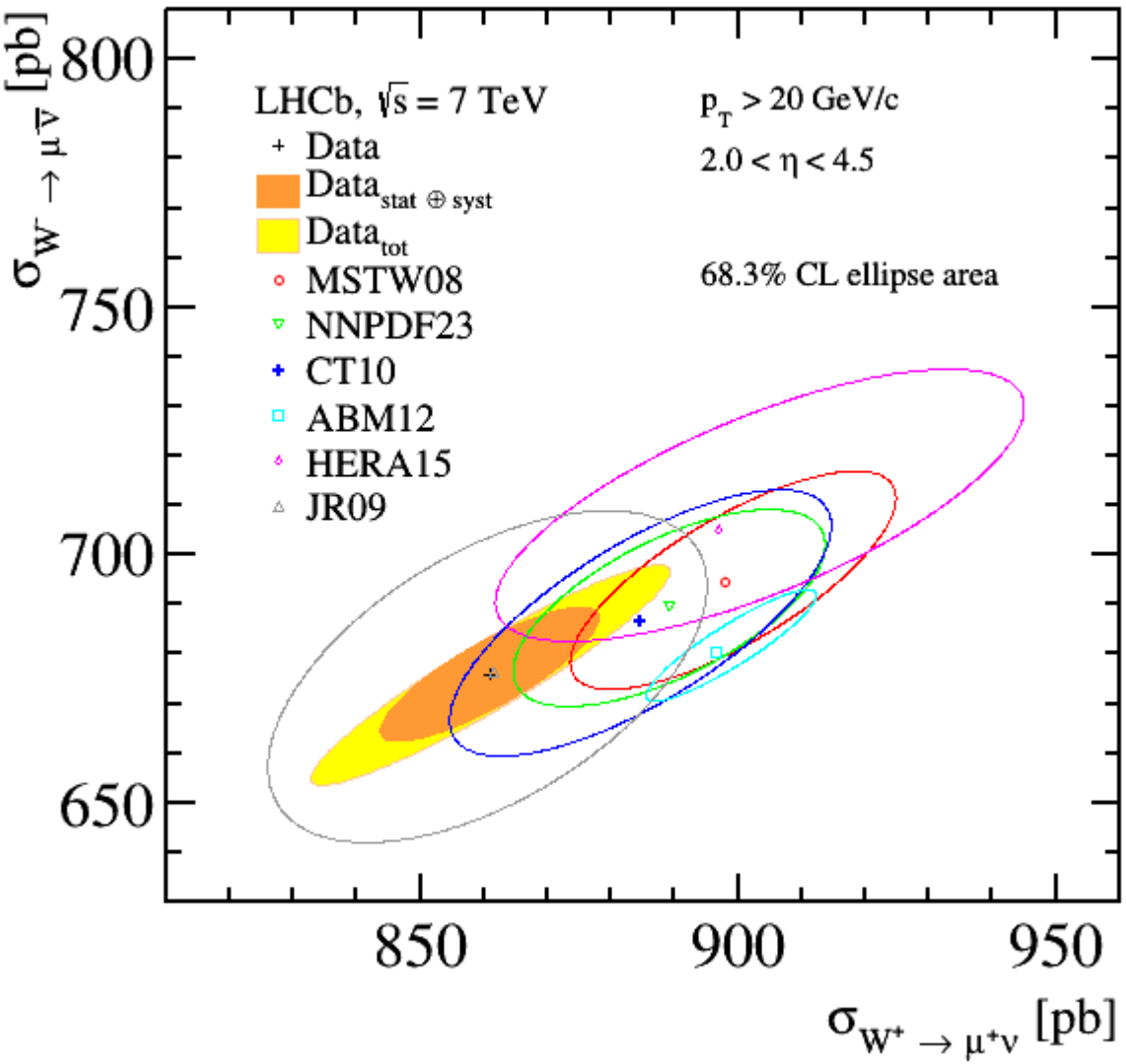
Normalisation
- signal and decay in flight: fitted
- others : fixed from data

Purity: (77.17 ± 0.19)% for $W^+$

(77.40 ± 0.23)% for $W^-$

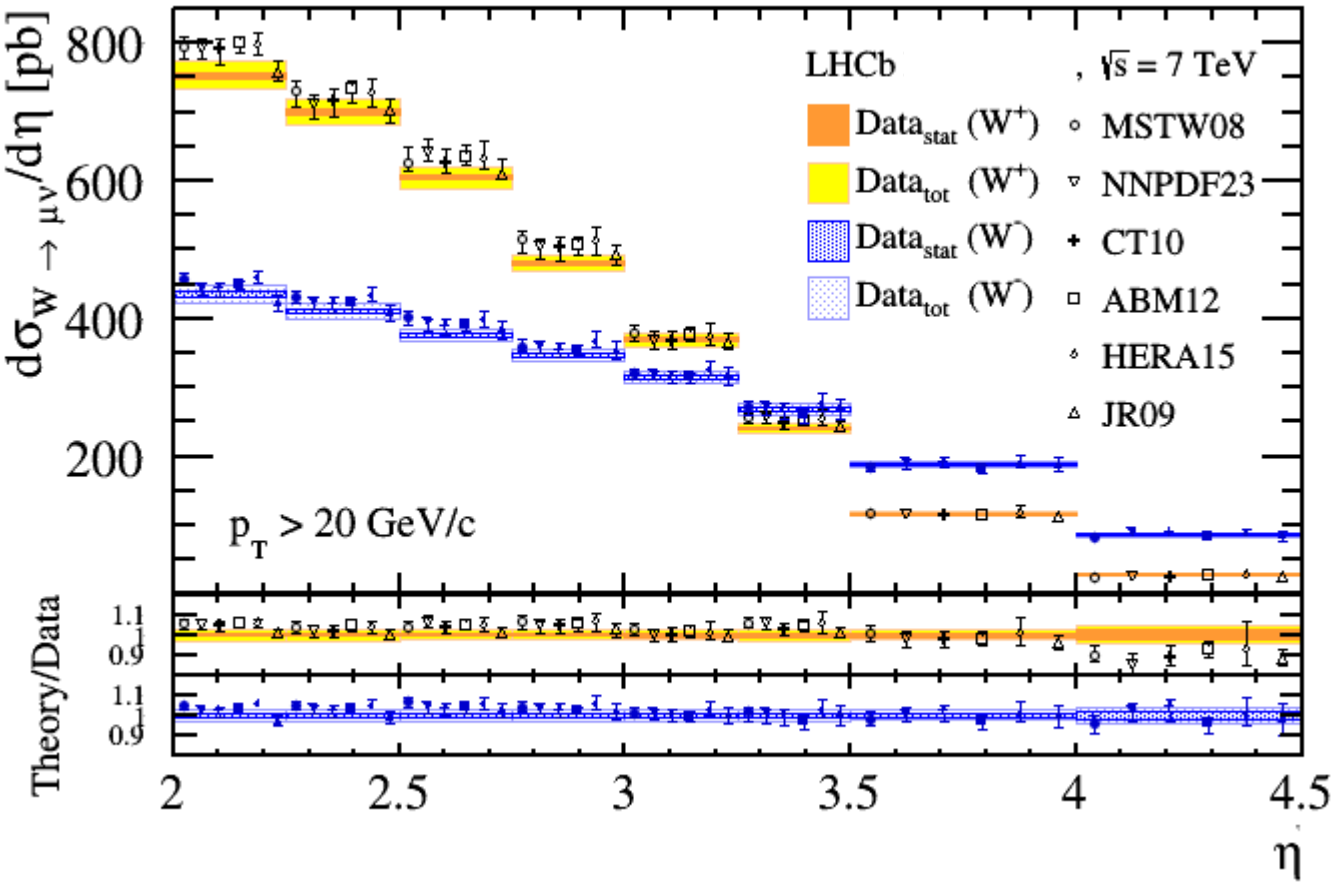


arXiv 1408.4354



# W cross section

arXiv 1408.4354

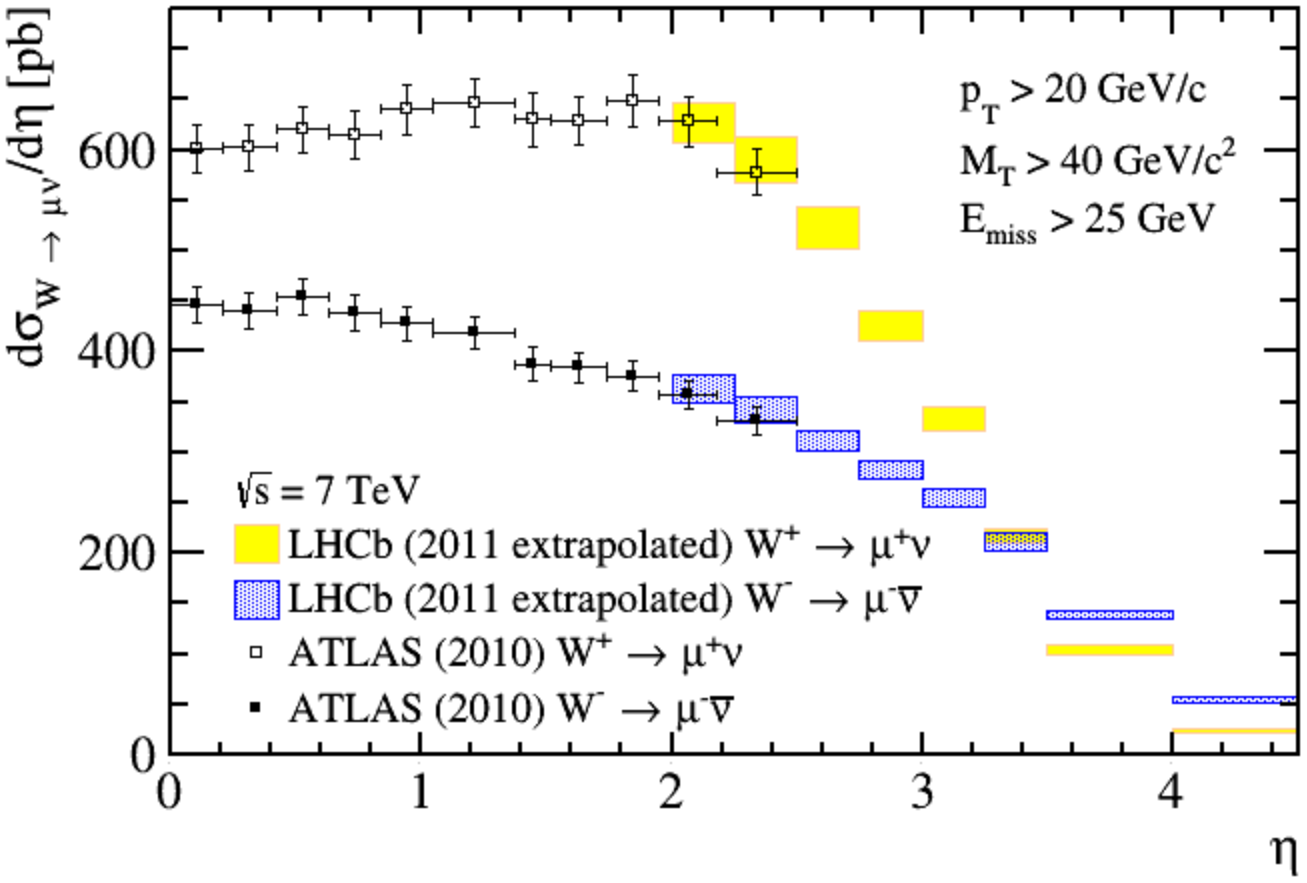



Comparison to NNLO predictions with six different PDF sets

# W cross section – comparison to ATLAS

LHCb-PAPER-2014-022

supplementary material, not on arXiv



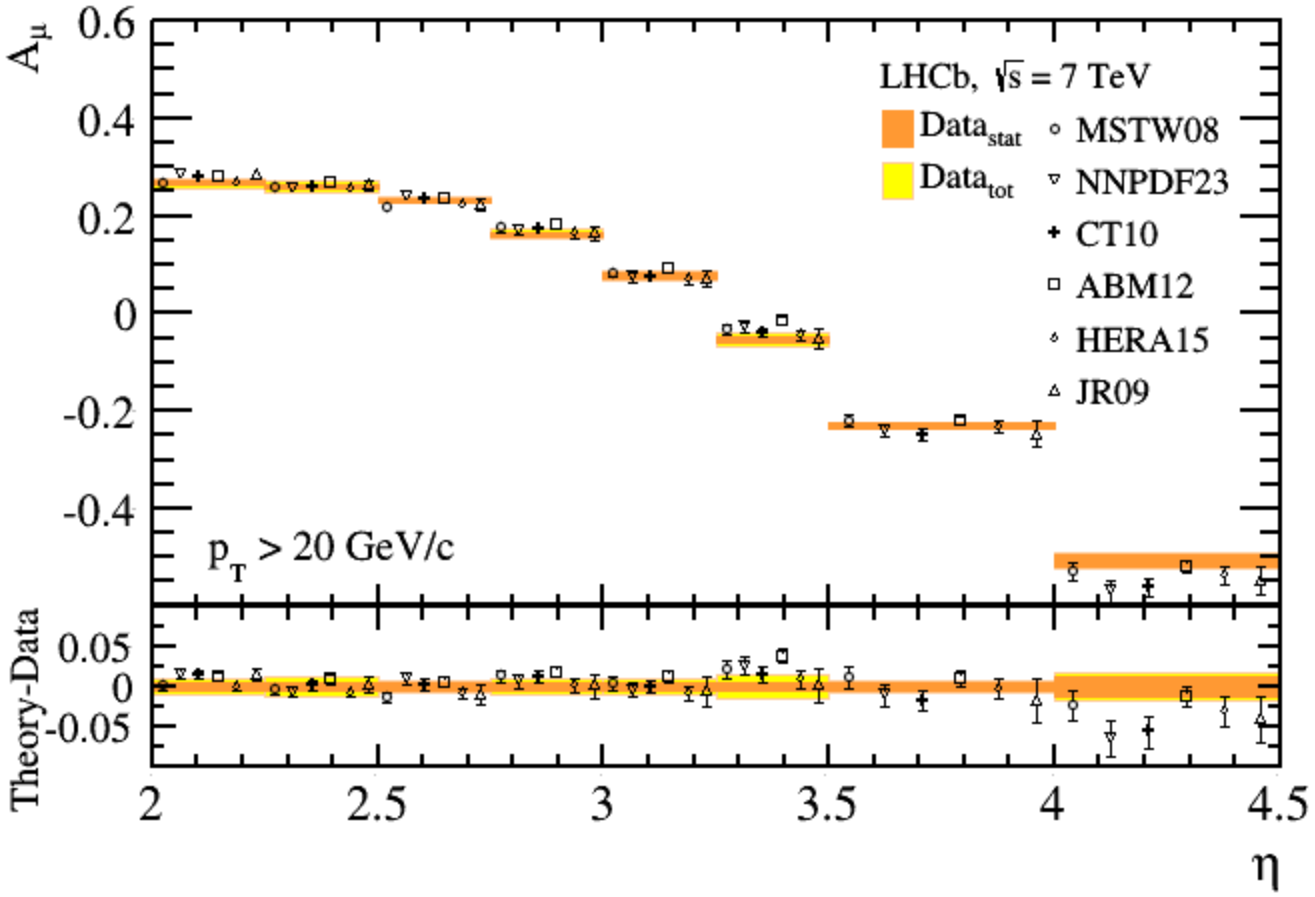

Comparison to ATLAS: LHCb measurements corrected to account for the additional cuts: $E_{Tmiss}$>25 GeV, $M_T$>40 GeV

→ good agreement in overlap region

# W: lepton charge asymmetry

arXiv 1408.4354

$$A_W = (d\sigma(W^+) - d\sigma(W^-)) / (d\sigma(W) + d\sigma(W^-))$$



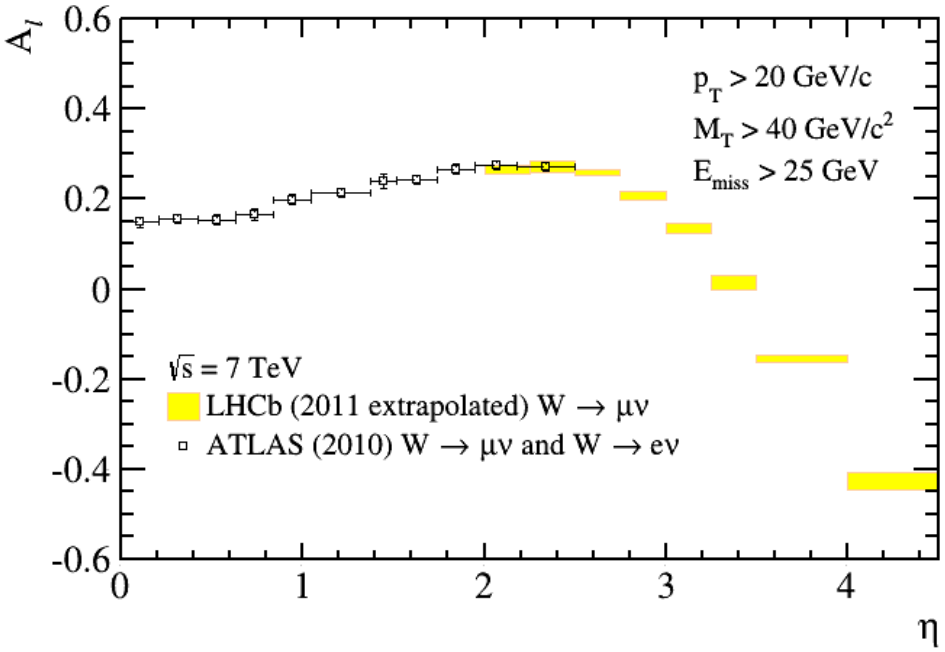
# W: lepton charge asymmetry



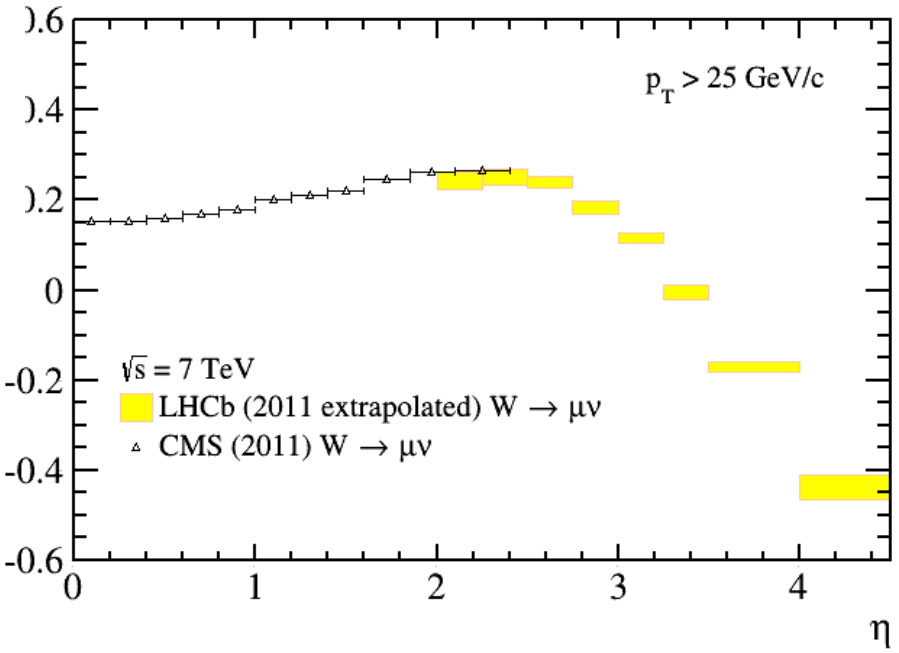
supplementary material, not on arXiv

## Comparison to ATLAS for $p_T$>20 GeV

corrected for cut on $M_T$>40 GeV and $E_{T,miss}$>25 GeV




## Comparison to CMS for $p_T$>25 GeV



# Conclusions

Z production

Z plus jet: first LHCb measurement with jets

Z plus D: first observation in pp collisions

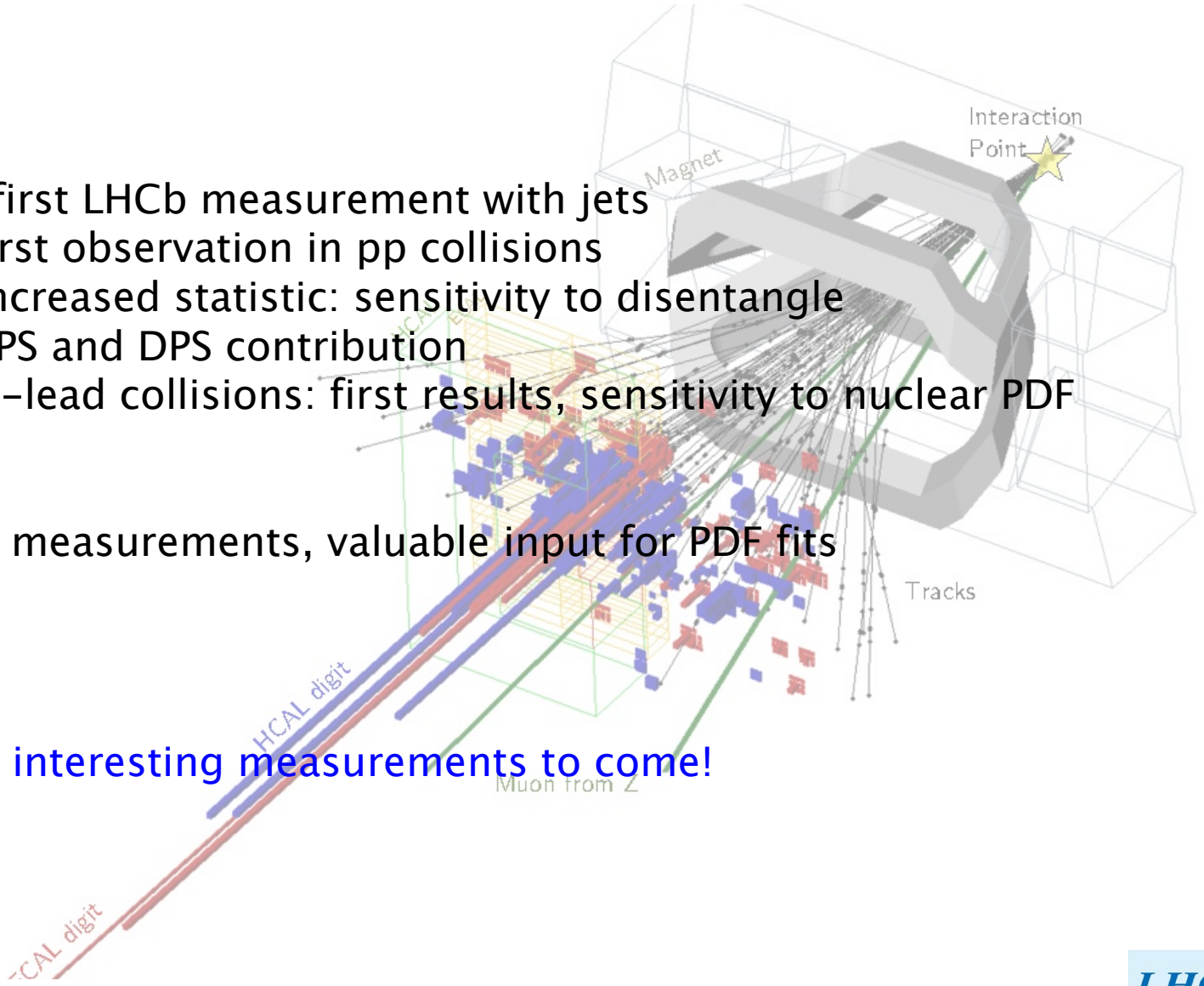
increased statistic: sensitivity to disentangle SPS and DPS contribution

Z in proton-lead collisions: first results, sensitivity to nuclear PDF

W production

Precise new measurements, valuable input for PDF fits

→ Many more interesting measurements to come!



# Backup slides

# LHCb running

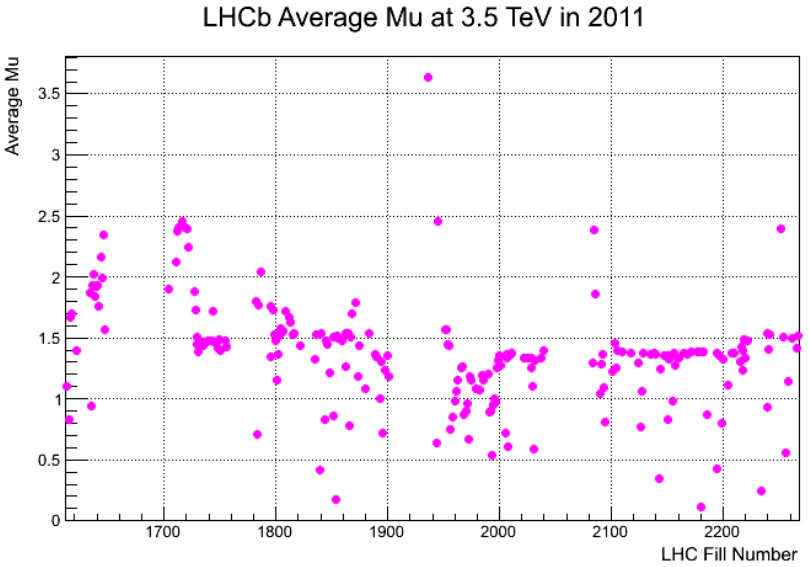
2010 36 $pb^{-1}$@ 7 TeV

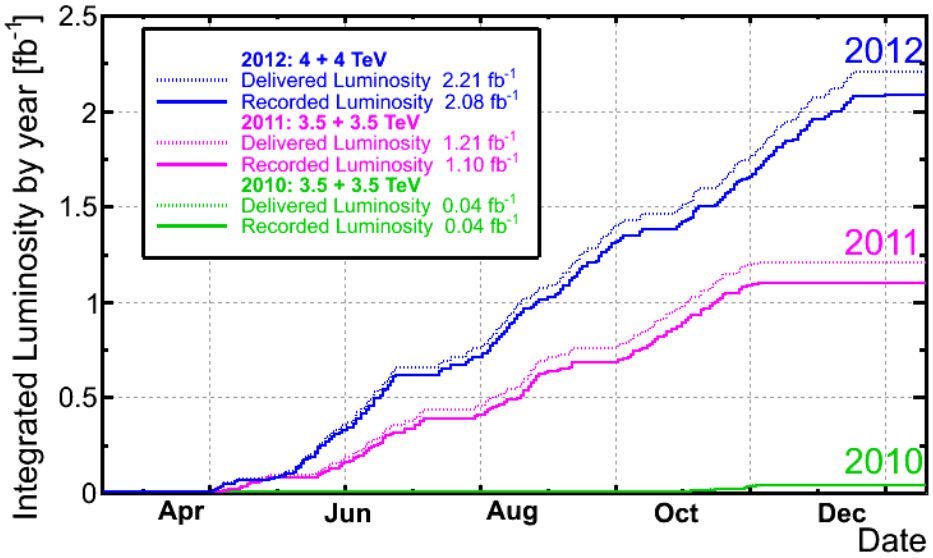
2011 1 $fb^{-1}$ @ 7 TeV

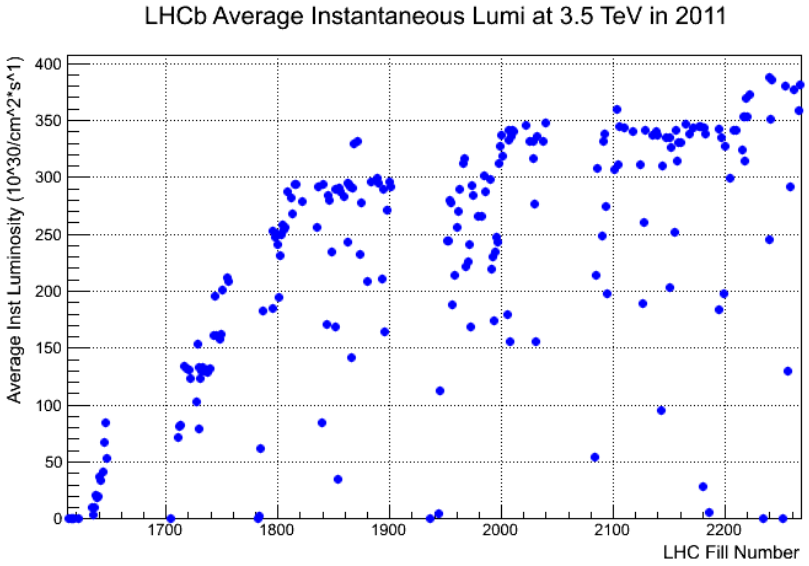
2012 2 $fb^{-1}$ @ 8 TeV

2013 2 $nb^{-1}$ @ 5 TeV proton-lead

Since 2011: Luminosity levelling:
Continuous adjusting of beam overlap
→ roughly constant luminosity
→ stable running conditions
High data taking efficiency:>90%



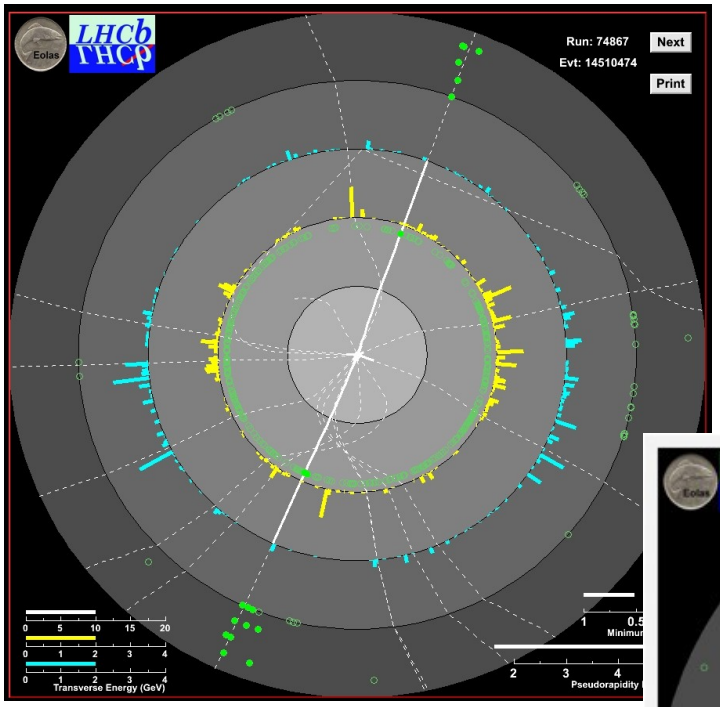



# Systematic uncertainties for W measurement

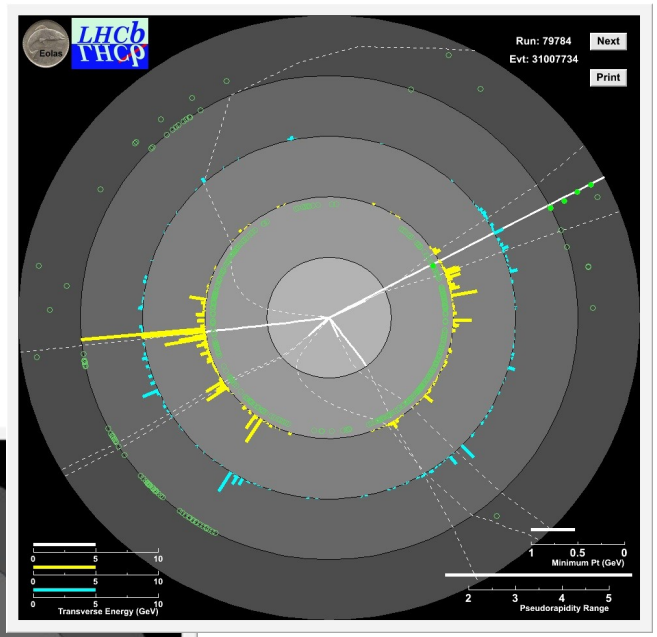
| Source | $\Delta\sigma_{W^+\to\mu^+\nu}$ [%] | $\Delta\sigma_{W^-\to\mu^-\overline{\nu}}$ [%] | $\Delta R_W$ [%] |
|---|---|---|---|
| Template shape | 0.28 | 0.39 | 0.59 |
| Template normalisation | 0.10 | 0.10 | 0.06 |
| Reconstruction efficiency | 1.21 | 1.20 | 0.12 |
| Selection efficiency | 0.33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

# Inclusive Z measurements

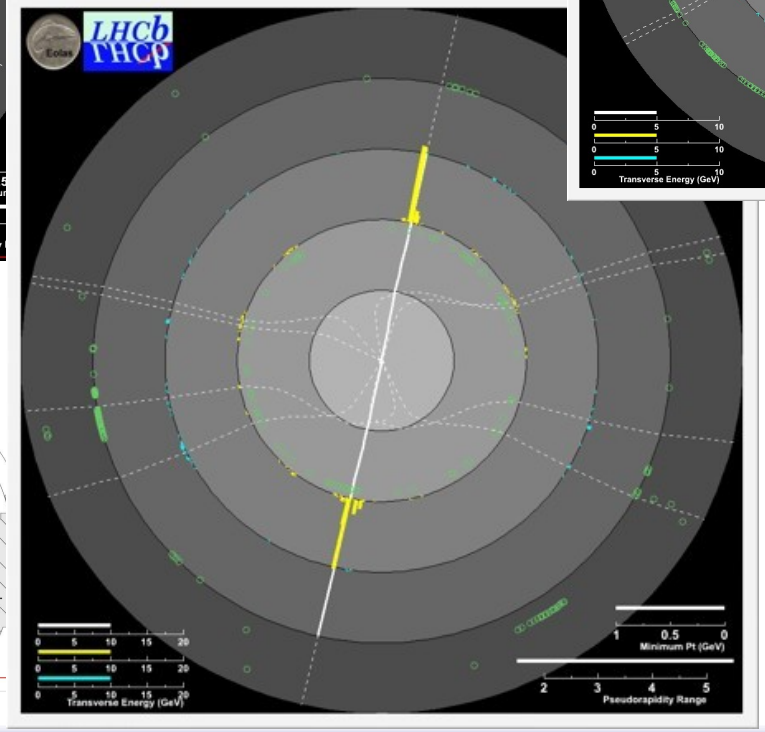
Z → μμ



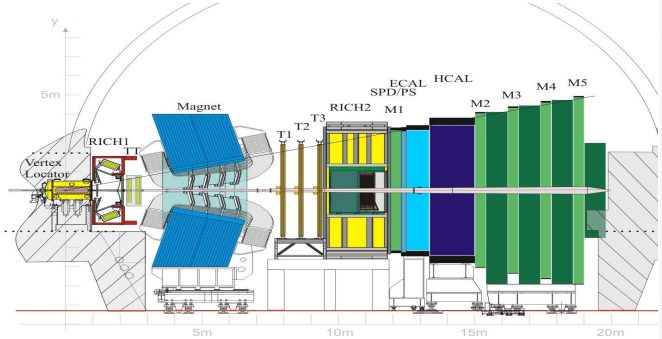

Z→ττ → eμ




Z→ee




φ–z view (Radius=z)

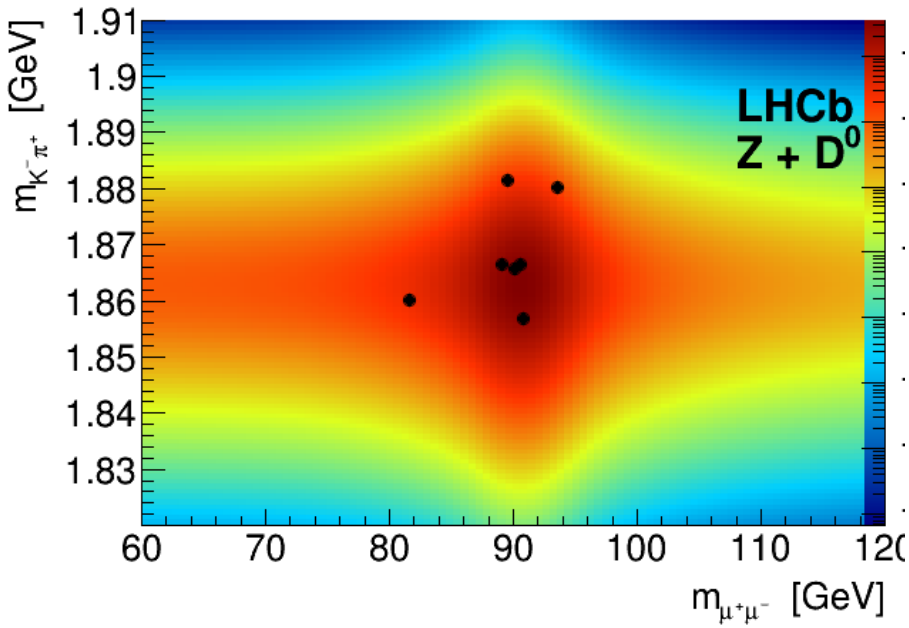


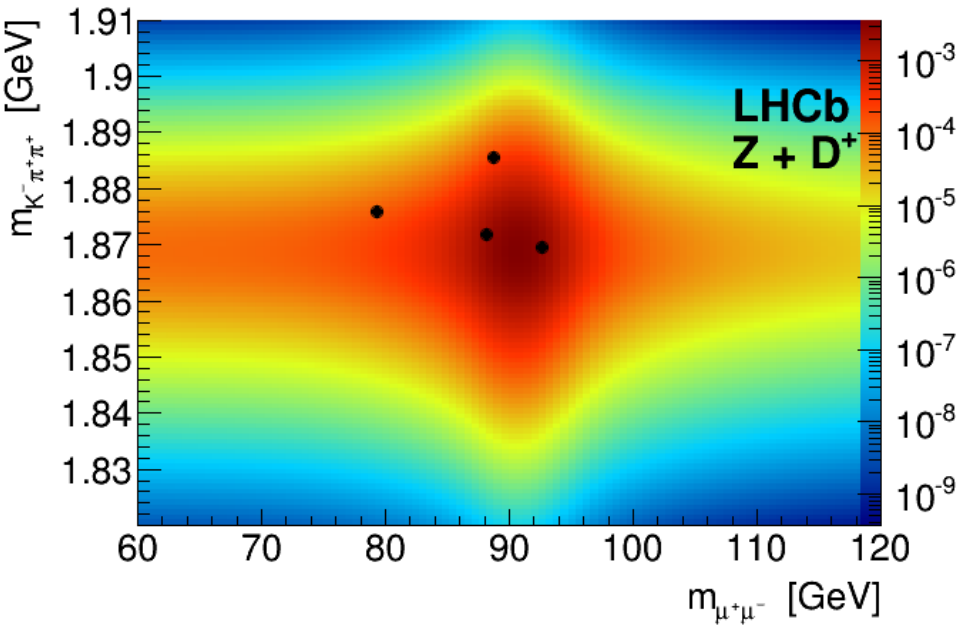
# Z plus D: backgrounds

JHEP04 (2014) 091

- charmed hadrons from B-decays (dominant)
- real Z and D from different vertices
- combinatorial background: from 2d fit to mass distributions

2D mass distribution with PDF for signal and background



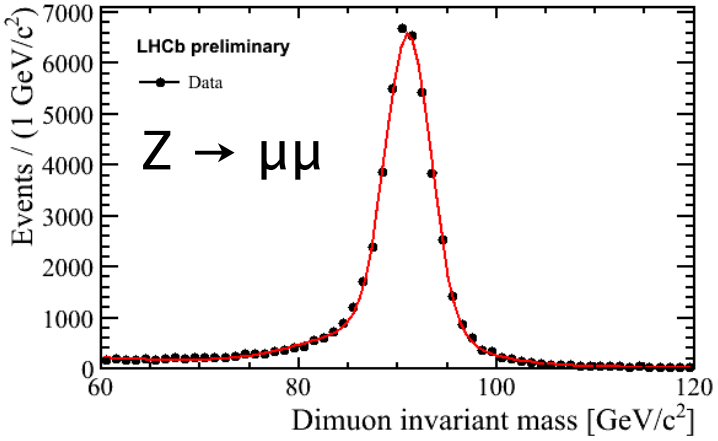




- purity is high about 95%

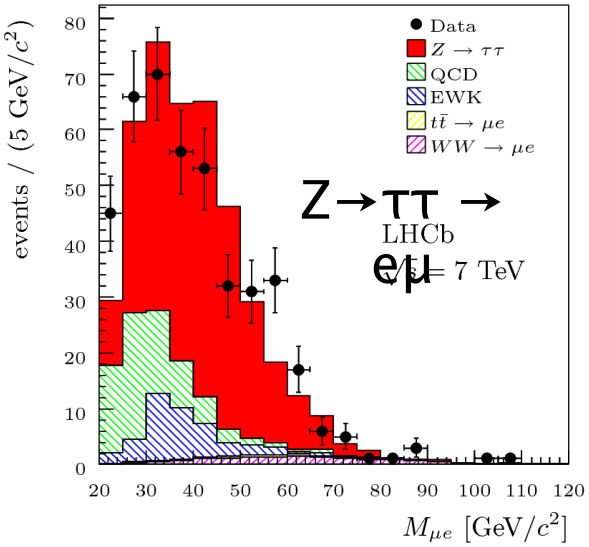
# Inclusive Z measurements at 7 TeV

LHCb-CONF-2013-007

LHCb-CONF-2013-007




JHEP 01 (2013) 111

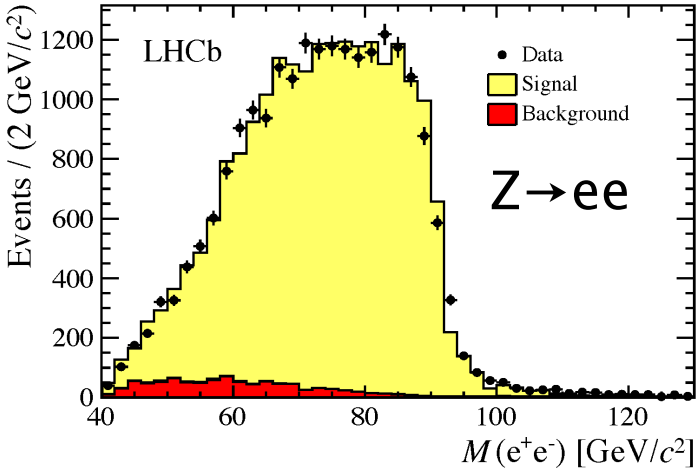



Fiducial volume

leptons: $p_T$>20 GeV, 2<η<4.5

mass: 60<$M_{ll}$<120 GeV$^2$

J. High Energy Phys. 02




Background

muon < 0.3%

electron ~ 4.5%

tau 28-37

→ the following analyses are all based on the di-muon final state
backgrounds:semileptonic decays of heavy quarks, misidentified hadrons