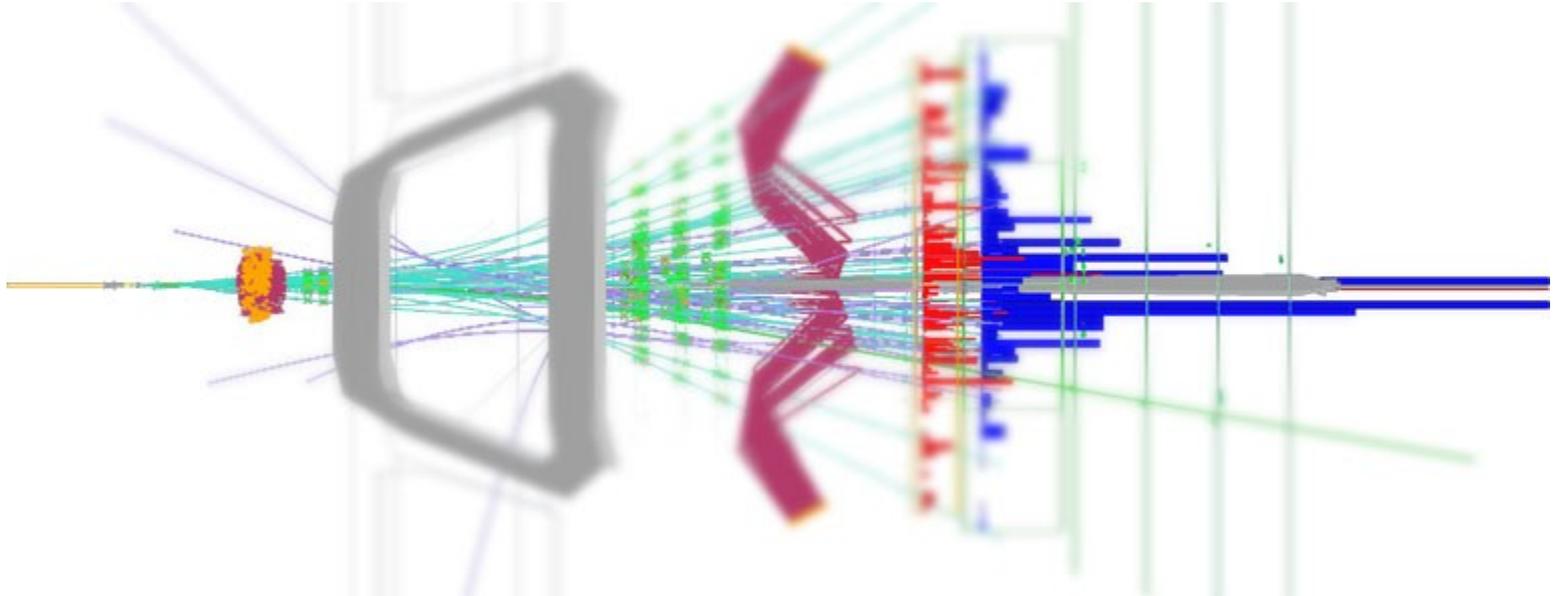


Electroweak results at LHCb

Katharina Müller
on behalf of the LHCb collaboration



Introduction

$Z \rightarrow \mu\mu$, $Z \rightarrow ee$, $Z \rightarrow \tau\tau$

$W \rightarrow \mu\nu$

Low mass Drell-Yan $\gamma^*/Z \rightarrow \mu\mu$

$Z \rightarrow \mu\mu$ plus Jets

Conclusion



University of
Zurich^{UZH}
Physik Institut

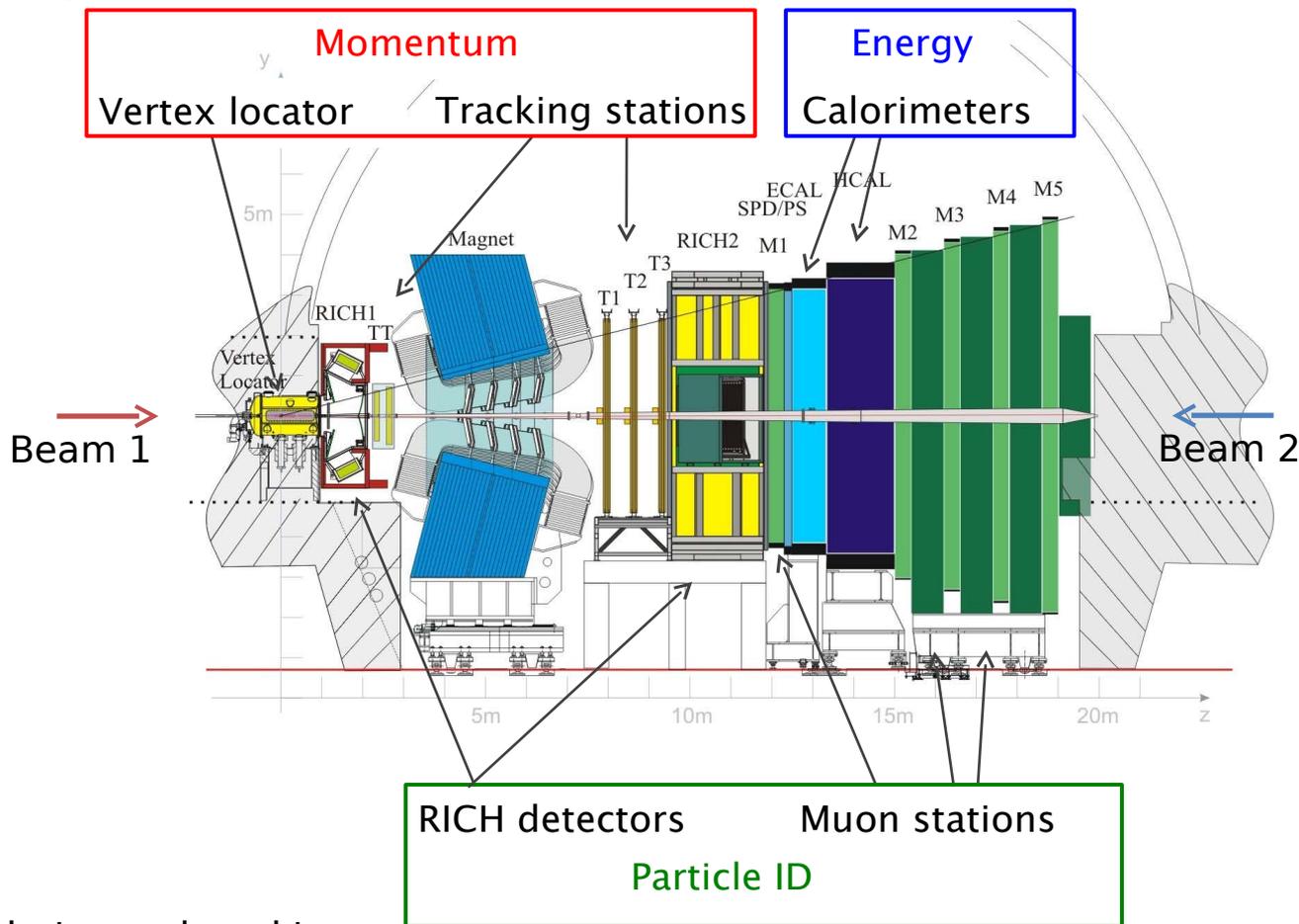




Introduction

LHCb detector

- Forward spectrometer designed to search for new physics in B and D decays
- Fully instrumented in the forward region ($2 < \eta < 5$)
- Some detection: $-3.5 > \eta > -1.5$



- Excellent vertex resolution and tracking
- Particle identification
- Trigger: $p_{\mu} > 3 \text{ GeV}/c$, $p_T^{\mu} > 0.5 \text{ GeV}/c$, $M_{\mu\mu} > 2.5 \text{ GeV}/c^2$

2010: 37pb⁻¹ of data

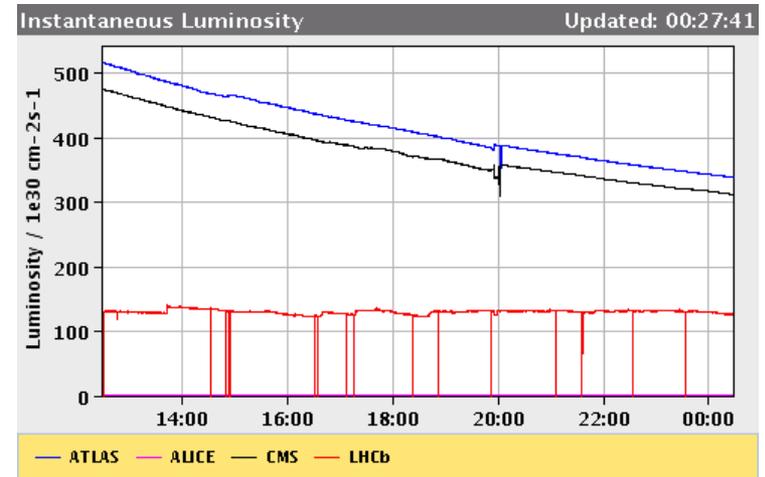
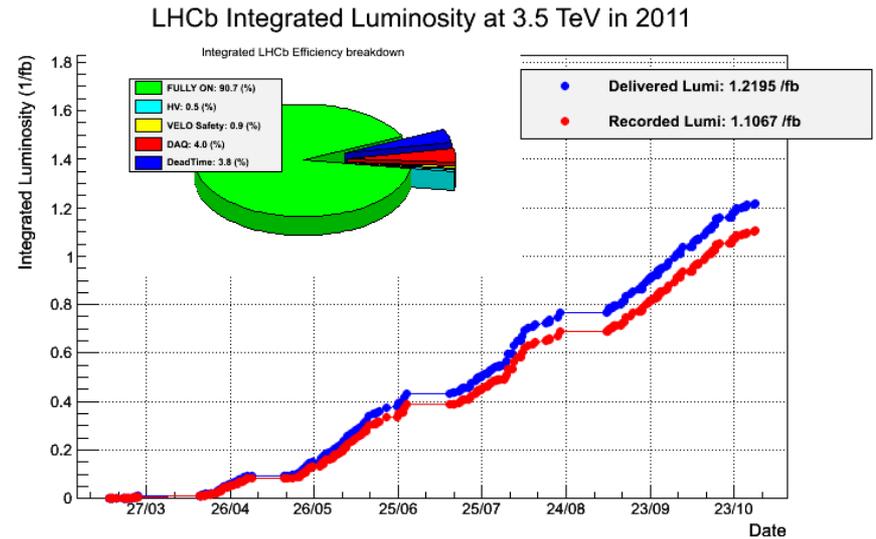
2011: 1 fb⁻¹ of data

> 90% data taking efficiency

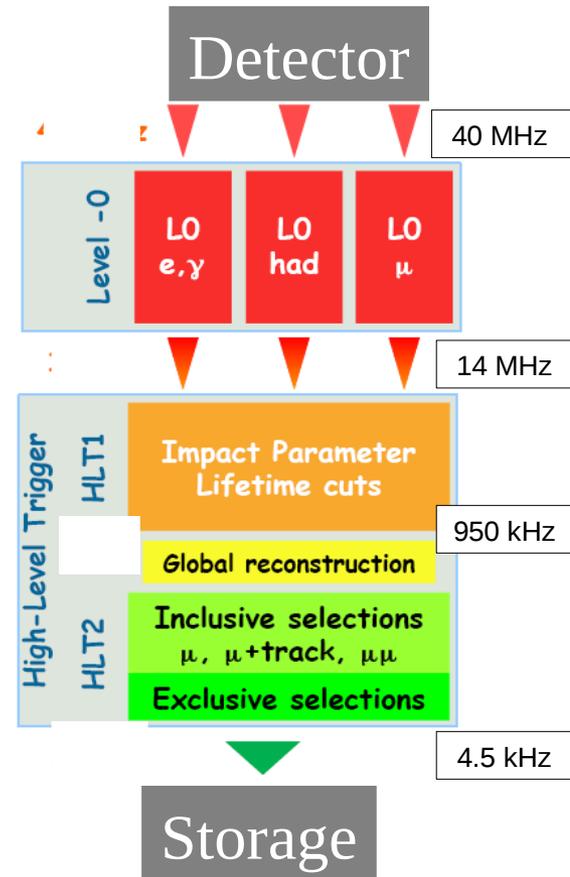
Luminosity levelling :

- Continuous adjust of beam overlap
- Low average number of interactions (1.5)
- Stable running conditions
- Roughly constant luminosity over a fill
- Thanks to LHC team for excellent work!

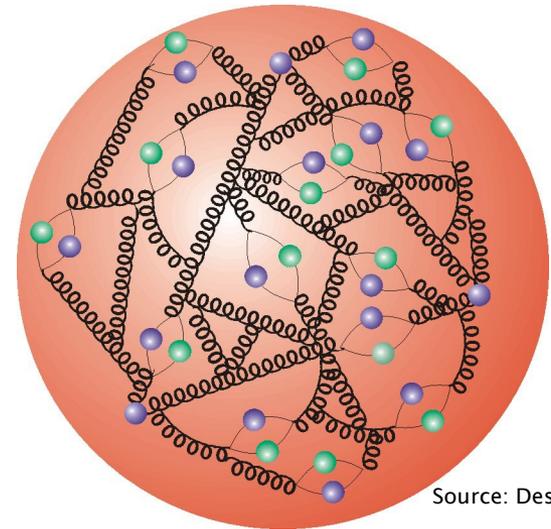
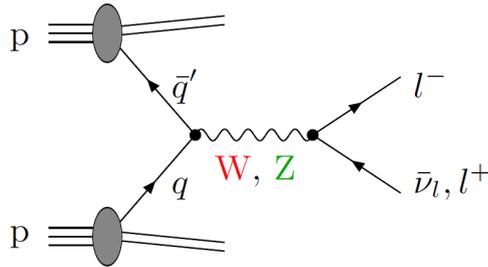
W/Z → μμ, low mass Drell–Yan analyses: 2010 dataset
Z → ee, Z plus Jet analyses: 2011 dataset
Z → ττ analysis: 2011 plus part of 2011 dataset



- Hardware trigger: L0 40 → 14 MHz
- Two software trigger stages
14 MHz → 950 kHz
950 → 4.5 kHz
- Output rate 4.5 kHz (2 x design)
- Size per event: 60 kB



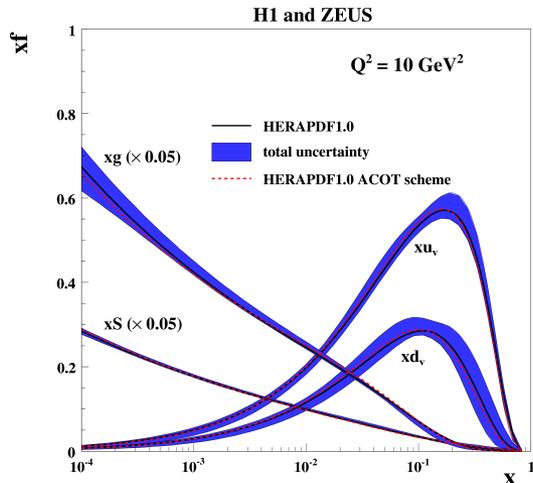
W and Z production at LHCb



Source: Desy, Hamburg

LHCb forward kinematics:
 @ first order, collision of a sea and a valence quark

- Asymmetry in production rate for W^+ and W^-
- Sensitivity to structure of the proton: parton distribution functions (PDF)



PDF : $f_q(x, Q^2)$
 Probability, that proton contains a parton q with momentum fraction x
 Q : invariant mass of parton interaction

JHEP 1001 (2010) 109
 arXiv:0911.0884 [hep-ex]

DGLAP evolution equations: evolution of PDFs in Q^2

ATLAS & CMS:

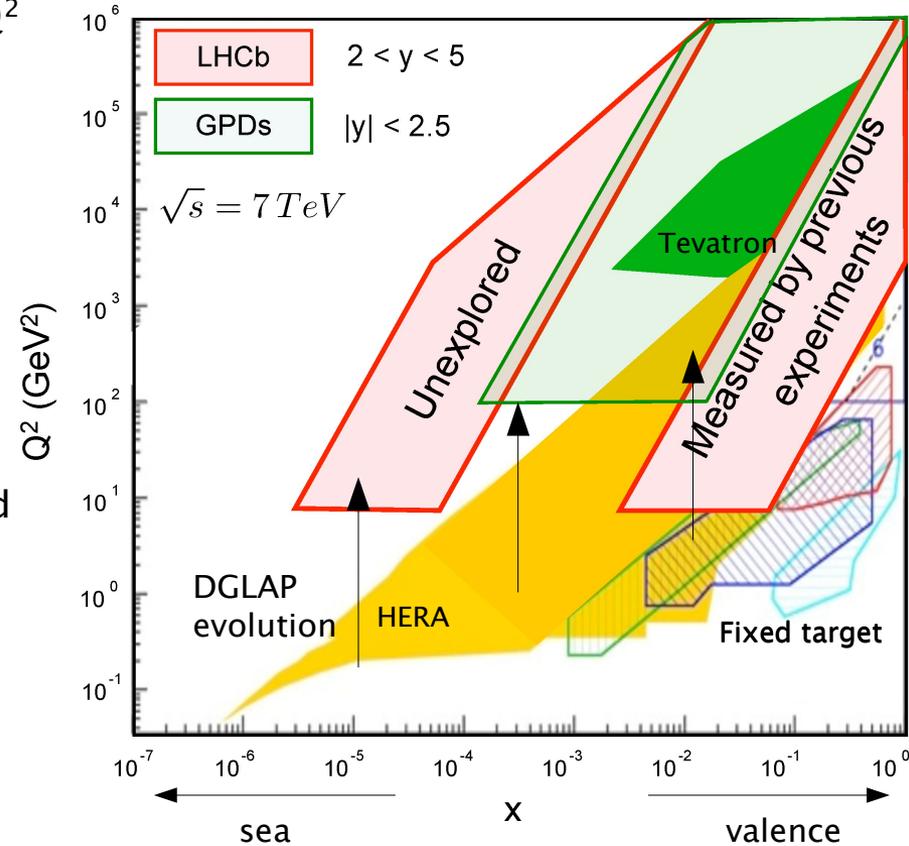
- Collision between two partons with similar x
- PDF already measured or modest DGLAP extrapolation

LHCb

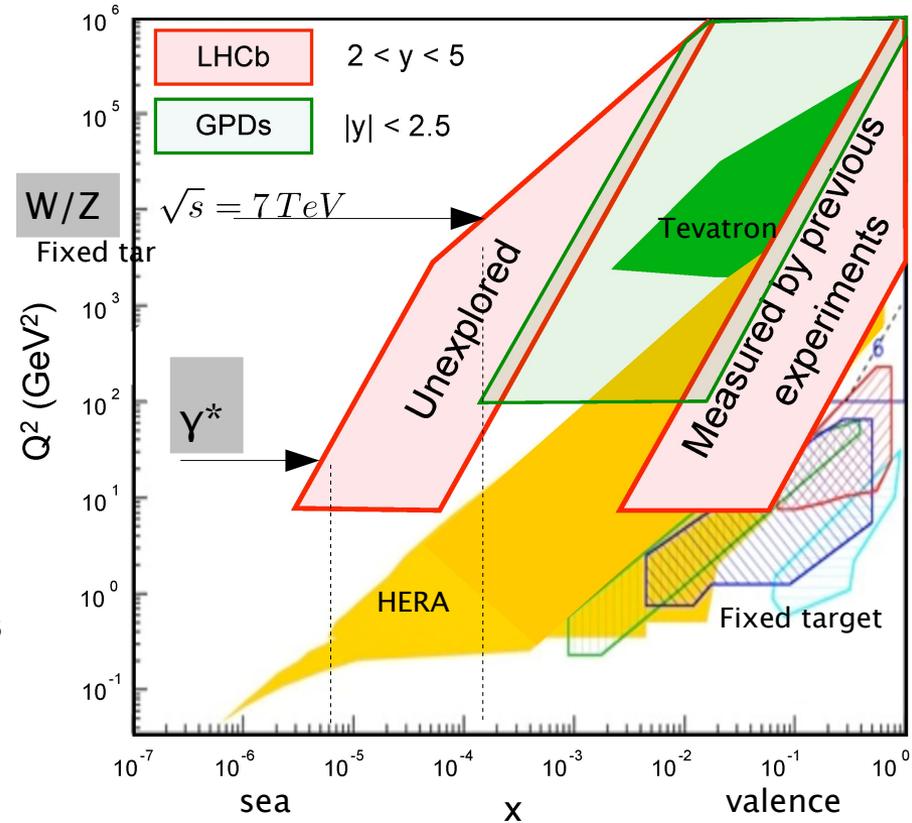
- Collision between parton at high and low x
- One parton well understood
- One parton unknown or large DGLAP evolved

Overlap region between GPDs and LHCb

- Between 2 and 2.5



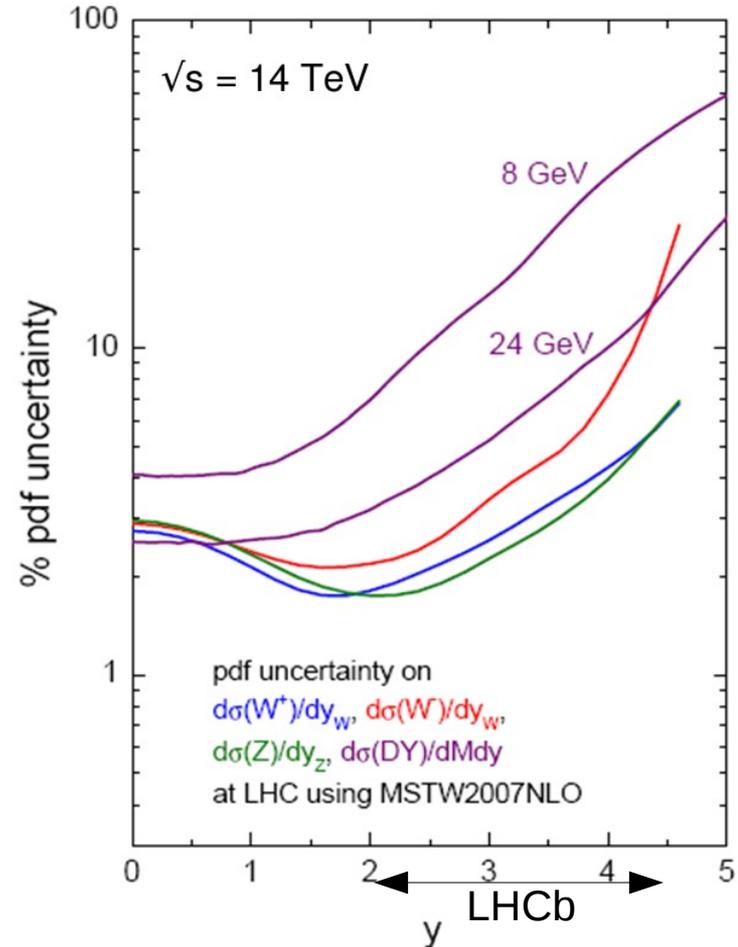
- LHCb probes two distinct regions in $x-Q^2$
- $Q^2=M^2, \quad x_{1,2}=(M/\sqrt{s}) e^{\pm y}$
- Unique region at low x
- SM predictions known at NNLO order
- Important input for PDF fits
- Medium Q^2 ($10'000 \text{ GeV}^2$):
Z and W : $x= 1.7 \cdot 10^{-4}$
- Low Q^2 (25 GeV^2): Drell-Yan (γ^*): $x= 8 \cdot 10^{-6}$



$$\underbrace{\sigma(x, Q^2)}_{\text{hadronic } x\text{-sec.}} = \sum_{a,b} \int_0^1 dx_1 dx_2 \underbrace{f_a(x_1 Q^2) f_b(x_2 Q^2)}_{\text{PDFs } 2\text{--}8\%} \underbrace{\hat{\sigma}(x_1, x_2, Q^2)}_{\text{partonic } x\text{-sec.: NNLO } 1\%}$$

Theoretical predictions

- Cross-sections known to NNLO to %-level
- PDF uncertainty dominates at large rapidities
3% at $y < 2$, 6–8% at $y \sim 5$
- Low mass Drell-Yan: uncertainties much larger



Plot from Thorne et al. (arXiv:0808.1847)

Cancel or highlight PDF uncertainties with ratios

- Many systematic uncertainties cancel
- Theoretical uncertainties partially cancel
- $A_W = (d\sigma(W^+) - d\sigma(W^-)) / (d\sigma(W^+) + d\sigma(W^-))$

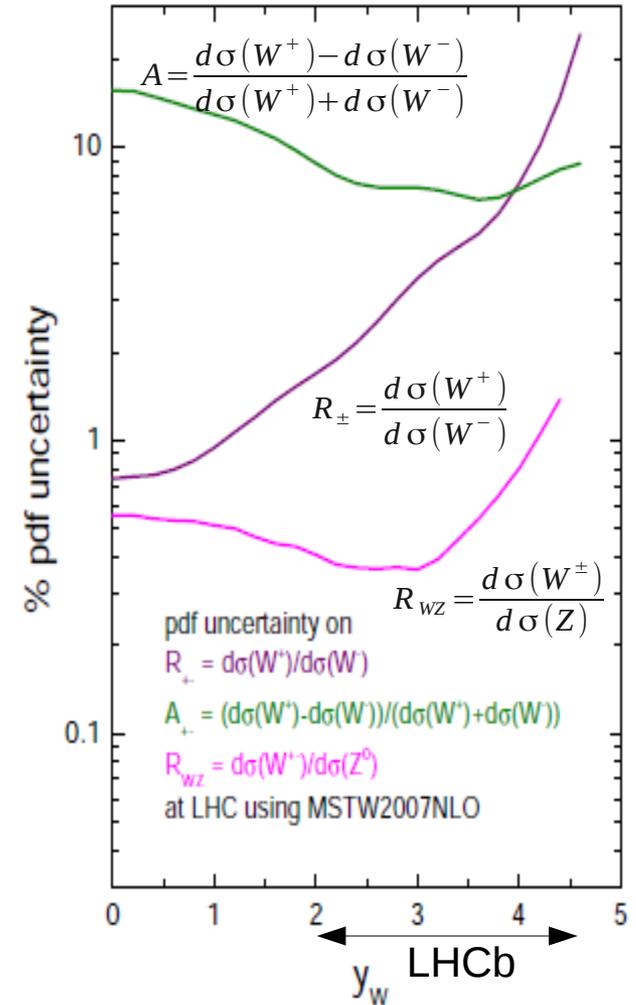
tests valence quarks: difference btw. u_v and d_v

$$R_{+-} = d\sigma(W^+) / d\sigma(W^-)$$

tests valence quarks: u_v/d_v ratio

$$R_{WZ} = d\sigma(W^{+-}) / d\sigma(Z)$$

almost insensitive to PDFs
precise test of SM

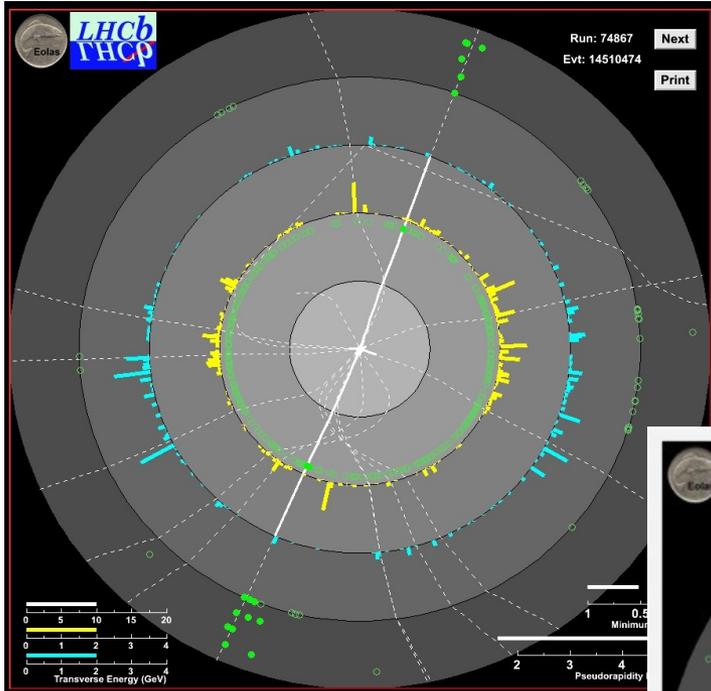


Plot from Thorne et al. (arXiv:0808.1847)

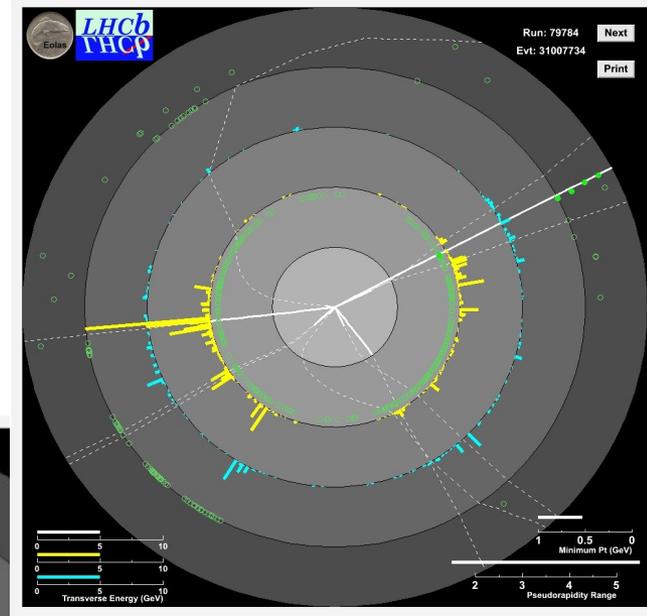
Z Analysis

$Z \rightarrow \mu\mu$, $Z \rightarrow ee$, $Z \rightarrow \tau\tau$

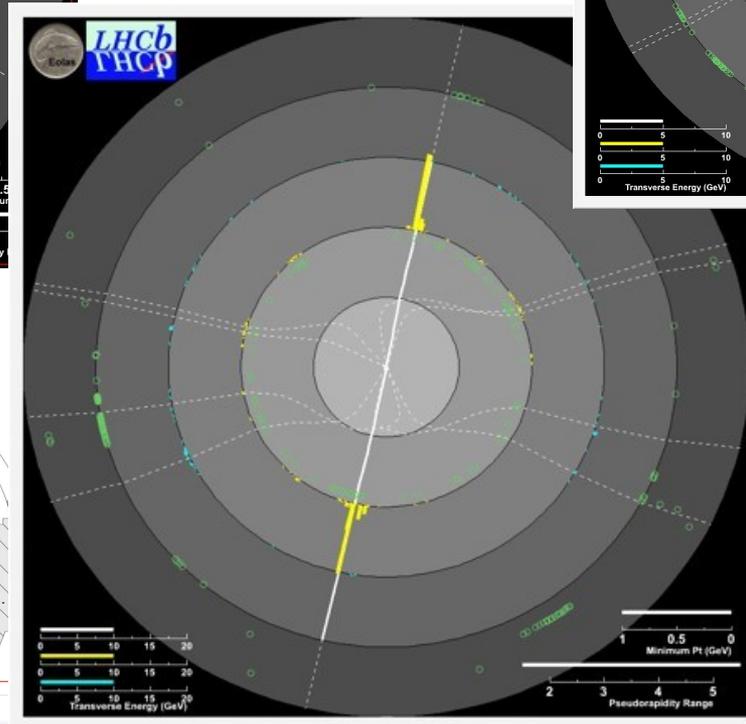
$Z \rightarrow \mu\mu$



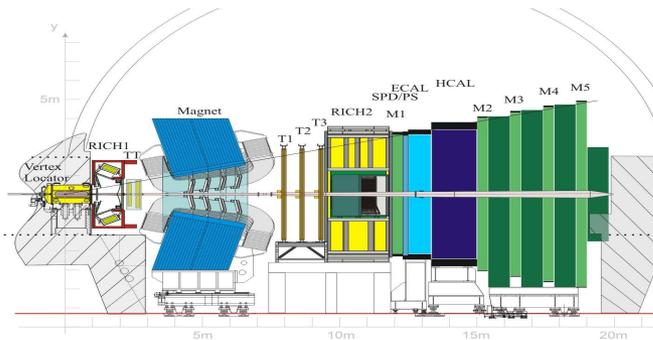
$Z \rightarrow \tau\tau \rightarrow e\mu$



$Z \rightarrow ee$



ϕ -z view (Radius=z)



Data

- 2010 L = 37 pb⁻¹
- Trigger: single μ , $p_T > 10$ GeV/c

Two muons

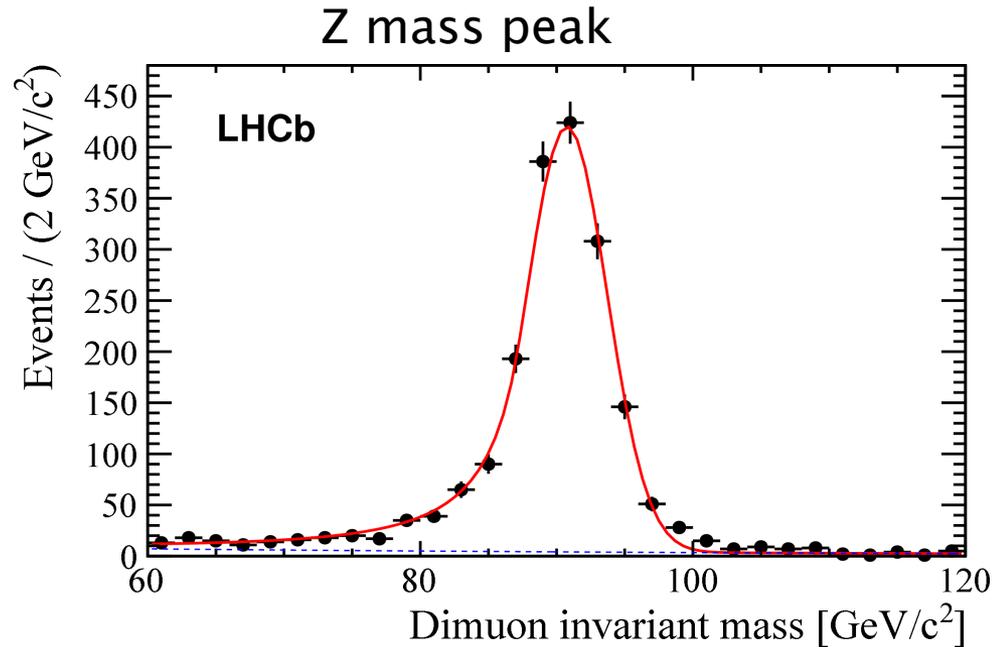
- $p_T > 20$ GeV/c
- $2.0 < \eta_\mu < 4.5$

Z selection

- $60 < M(\mu\mu) < 120$ GeV/c²

Background: low

- Z $\rightarrow \tau\tau$ (MC: 0.3‰)
- W-pair (MC: 0.1‰)
- Top-pair (MC: 0.3‰)
- QCD background (Data: 2‰)
Semileptonic decays of heavy flavour or
K/ π misidentification
Non isolated muons



Candidates:	1966
Background:	4.8 ± 1.0
Purity:	99.7%

arXiv: 1204.1620 LHCb-PAPER-2012-008, accepted by JHEP

Data

- 2011 L = 1 fb⁻¹
- Trigger: single electron, p_T > 15 GeV/c

Two electrons

- p_T > 20 GeV/c
- 2.0 < η_μ < 4.5
- Energy from momentum measurement
Saturation in calorimeter
Resolution worse, Bremsstrahlung

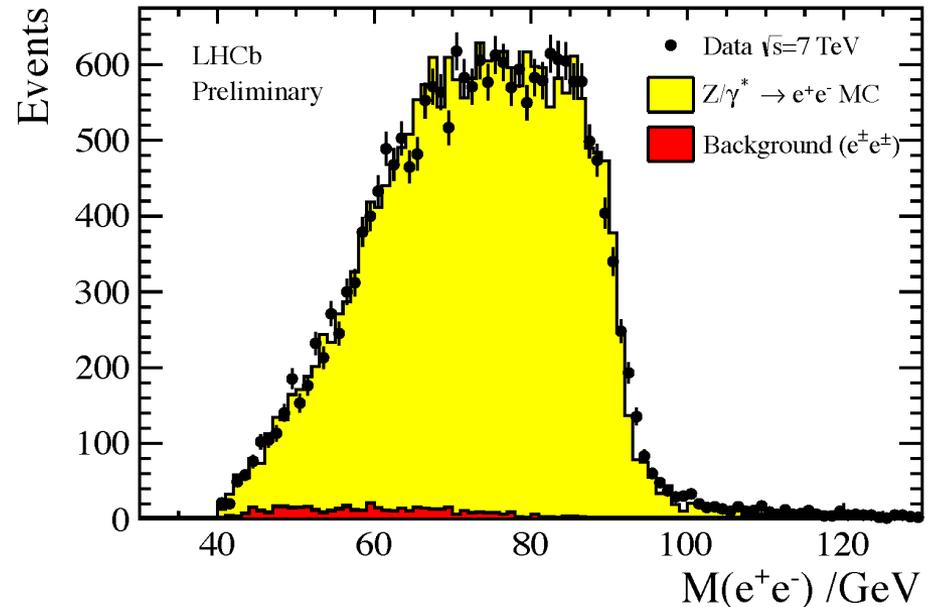
Z selection

- M(ee) > 40 GeV/c²

Background: low

- Z \rightarrow ττ (MC, 0.1%)
- Top-pair (MC, <0.1%)
- QCD (Data, 2.2% same sign electrons)

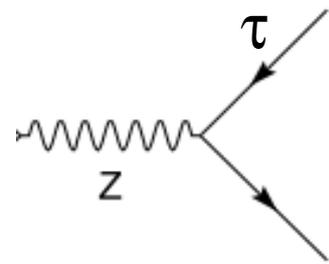
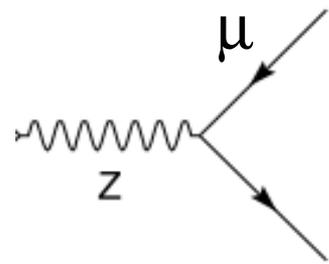
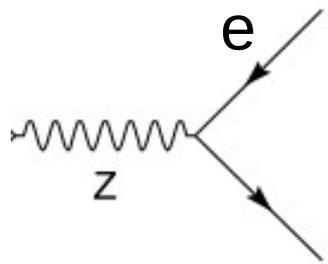
Z mass peak



Candidates: 21535

Background: 473

Purity: 97.8%



Electroweak tests using Z → ττ

- Couplings the same?
- Other production mechanisms for ττ - Higgs?

Two final states:

- Z → ττ → μμνν
- Z → ττ → μeνν
- Use well known single muon trigger

Electron-electron and hadronic channels will follow

Data

- 2010 + 2011 Data (1/4), L 250 pb⁻¹
- Two final states considered μμ and μe
- Single Muon Trigger, p_T > 10 GeV/c
- p_T^μ > 20 GeV/c , p_T^{2nd μ/e} > GeV/c

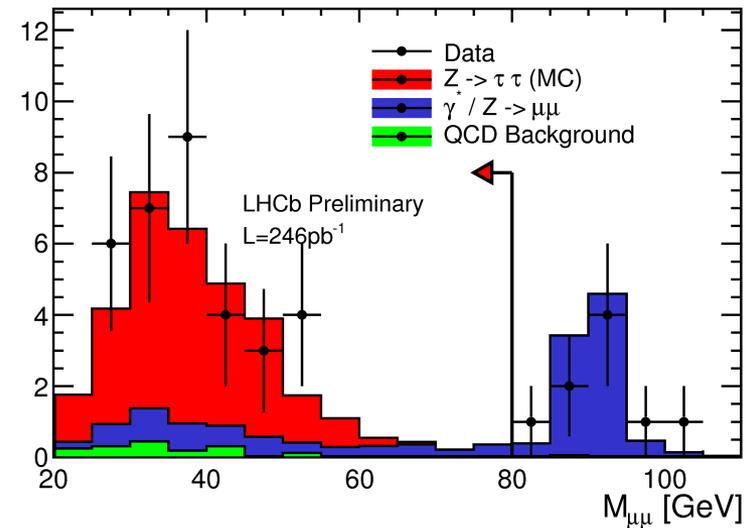
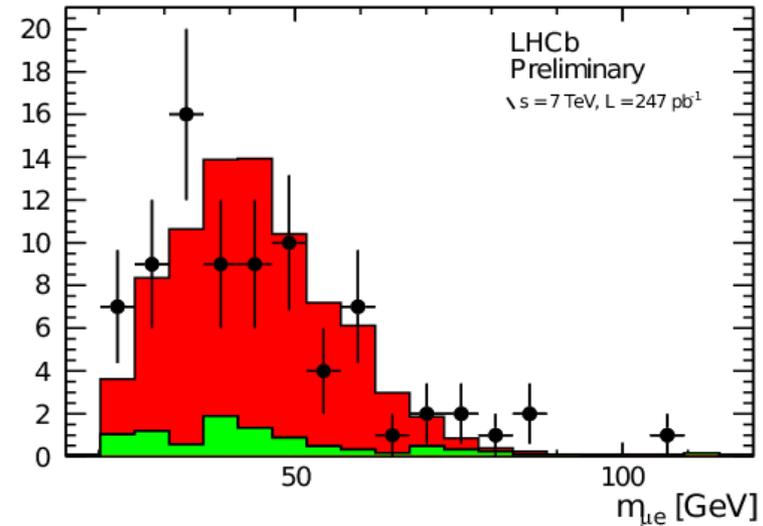
Background

- Electroweak processes (WW, WZ, ZZ)
Leptons back-to-back ΔΦ > 2.7
- QCD: leptons isolated
- Z → μμ (μμ only):
p_T not balanced
Cut on impact parameter

QCD background from data

Z → μμ from MC normalised to data

	μe	μμ
Candidates:	81	33
Background:	12.4 ± 2.7	7.1 ± 2.0
Purity:	85%	78%



Z analysis

Efficiencies

$$\sigma = \frac{\rho N}{A L \epsilon} f_{FSR}$$

ρ : purity
 A : acceptance
 L : luminosity
 ϵ : efficiency
 N : candidates
 f_{FSR} : final state radiation

Efficiencies mostly from data
tracking, identification and trigger: tag and probe in Z sample

Tag:

well identified, triggered muon/electron

Probe:

Identification: fully reconstructed track

Tracking: muon-stub -TT hits

Trigger: identified muon/electron

Electron tracking from MC

Selection ($Z \rightarrow \tau\tau$) from MC

$\mu\mu$: $\epsilon_{sel} = 0.172 \pm 0.014$

μe : $\epsilon_{sel} = 0.46 \pm 0.03$

Acceptance:

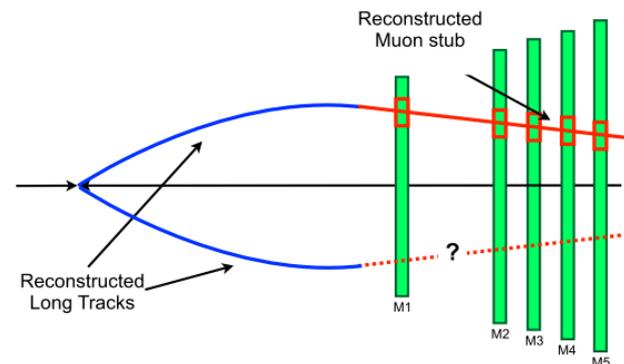
Result within fiducial range of measurement

$Z \rightarrow \mu\mu$: >0.99

$Z \rightarrow ee$: 0.4-0.6

$Z \rightarrow \tau\tau$: 0.25 (μe), 0.39 ($\mu\mu$)

Muon identification



Typical efficiencies

Tracking: 90%

Muon identification: >99%

Electron identification: 95%

Muon Trigger: 88%

Electron Trigger: 85%

Corrected event-wise as function of η_μ

Checked for charge bias

Precision:	Z → μμ	Z → ee	Z → ττ μe μμ
Statistical [%]	2.2	0.7	17 12
Luminosity[%]	3.5	3.5	5.1
Systematic[%]	4.3	3.1	16 10
Luminosity[fb]	37.5	945	247

Systematic uncertainties will reduce with more statistics

Dominant systematic uncertainties:

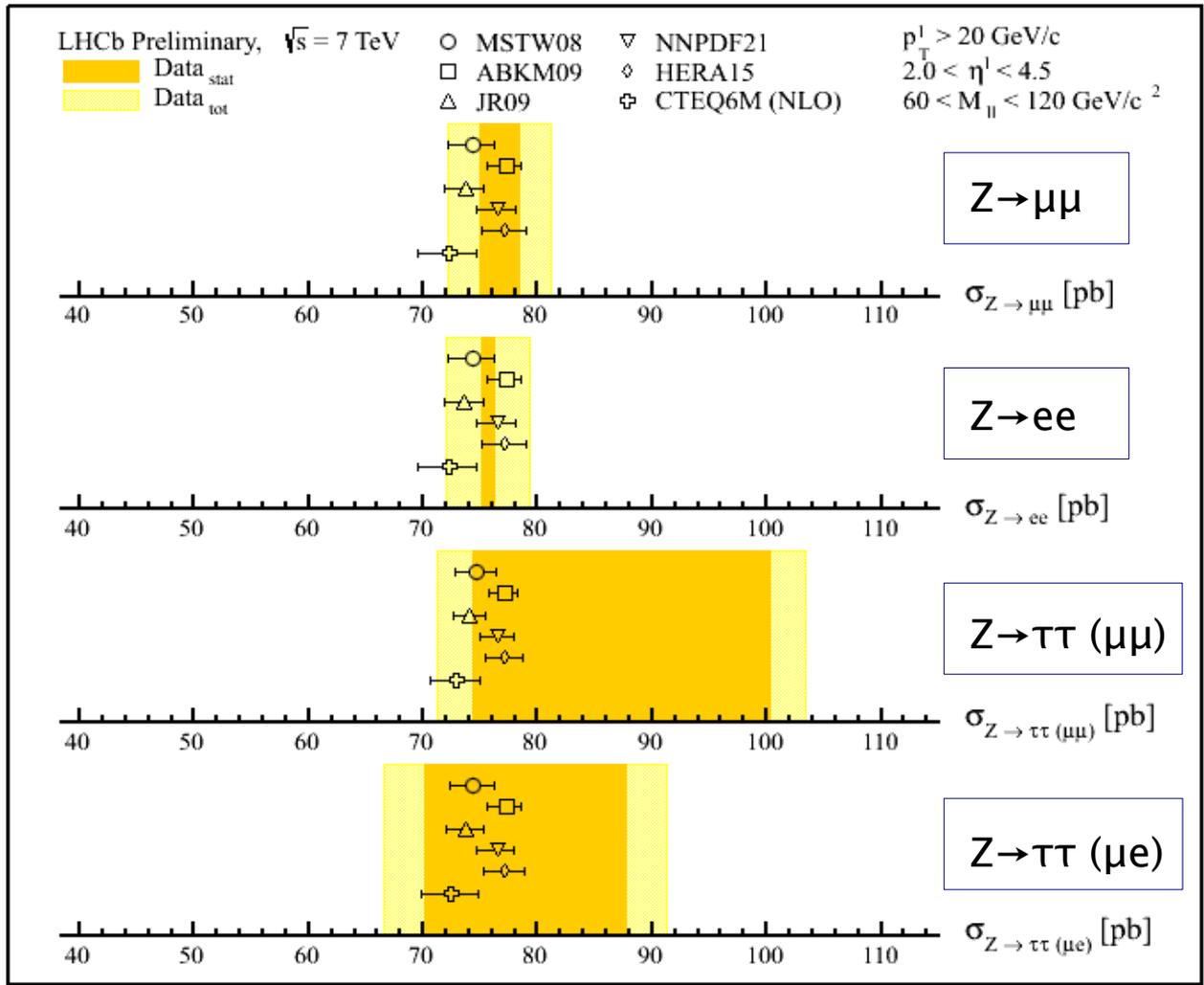
- Efficiencies 4.3%
- Purity 0.1%
- FSR corr. 0.02%

- Z → ττ : limited by statistics
- Z → μμ : limited by efficiency uncertainty (statistical)
- Z → ee : luminosity uncertainty

Results compared to NNLO predictions (DYNNLO) with 6 recent PDF sets

- MSTW08. A. Martin, W. Stirling, R. Thorne and G. Watt
arXiv:0901.0002
- ABKM09: S. Alekhin, J. Blumlein, S. Klein and S. Moch
arXiv:0908.2766
- JR09: P. Jimenez-Delgado and E. Reya
arXiv:0810.4274
- NNPDF D. Ball et al.
arXiv:1002.4407
- HERA15 H1 and ZEUS collaboration
arXiv: 0911.0884
- CTEQ6M P. M. Nadolsky et al. (NLO)
arXiv:0802.0007

NNLO (DYNNLO) PDF uncertainties at 68% CL



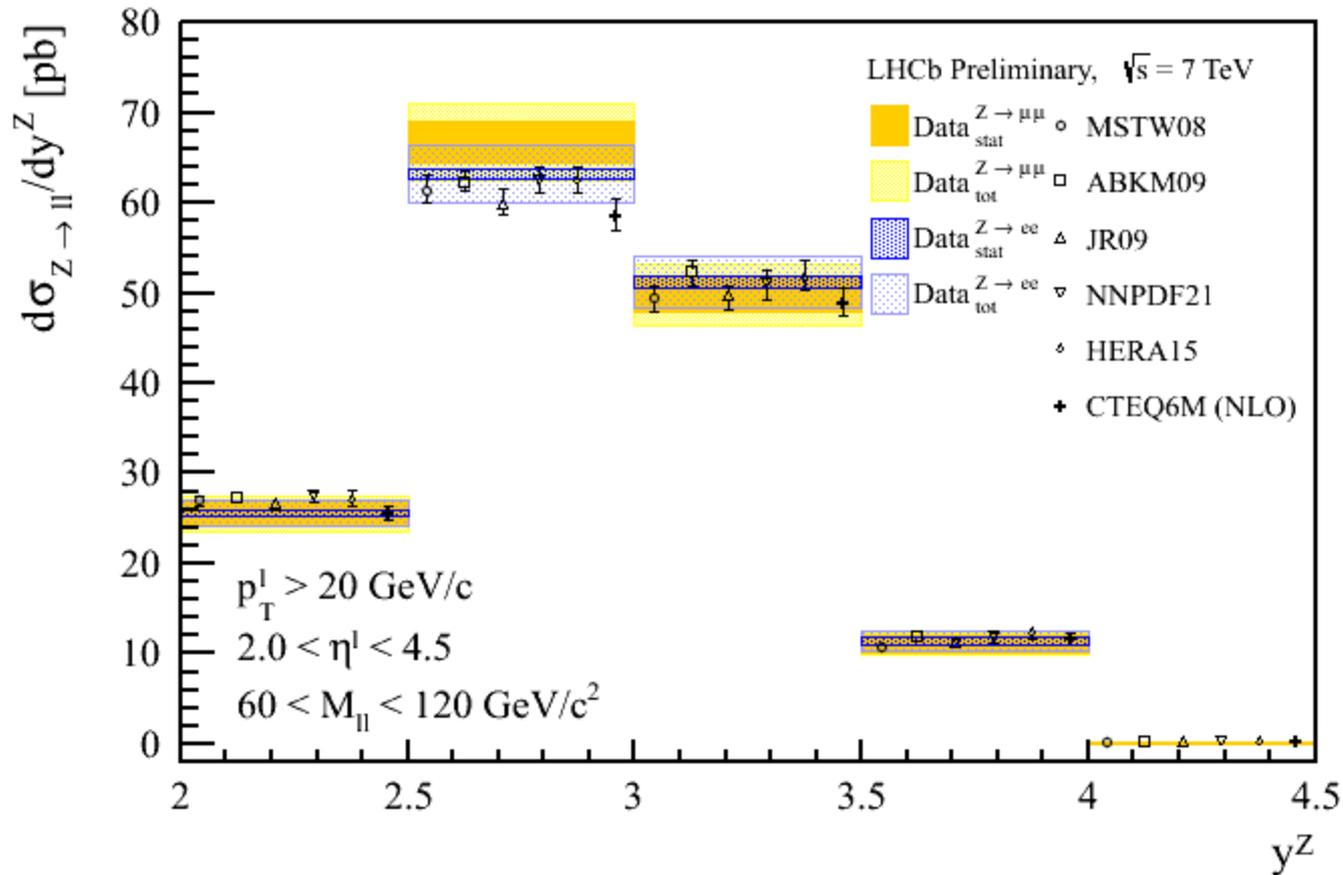
arXiv: 1204.1620

LHCb-CONF-2012-011

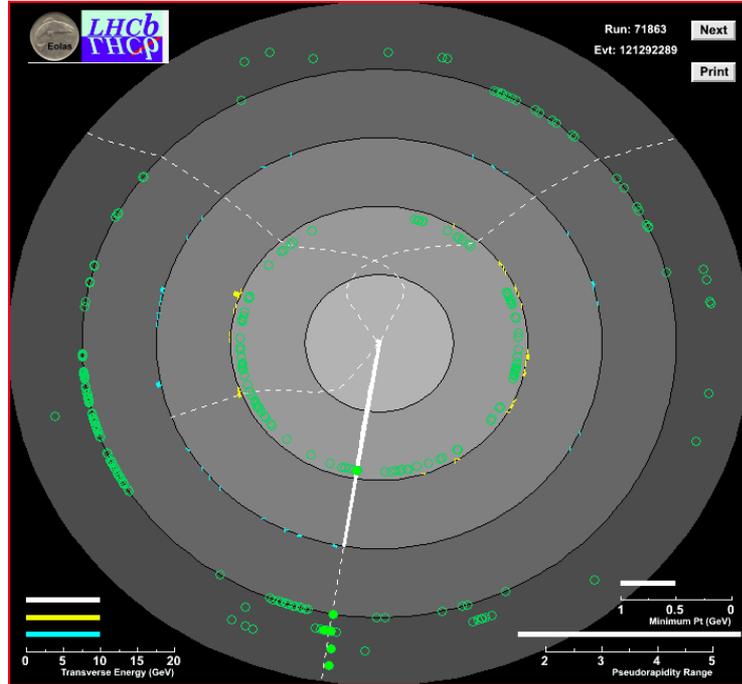
LHCb-CONF-2011-041

LHCb-CONF-2011-041

NNLO (DYNNLO) PDF uncertainties at 68% CL



Z → μμ and Z → ee in agreement with each other and with NNLO

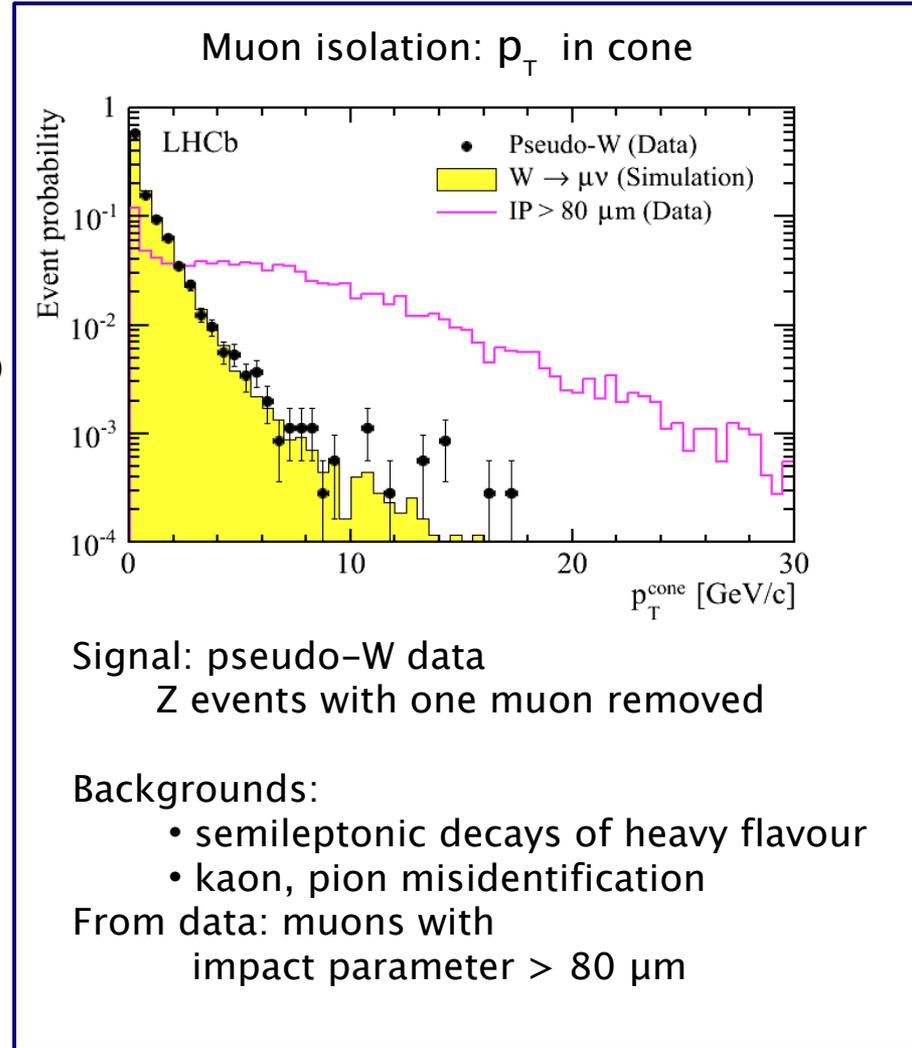
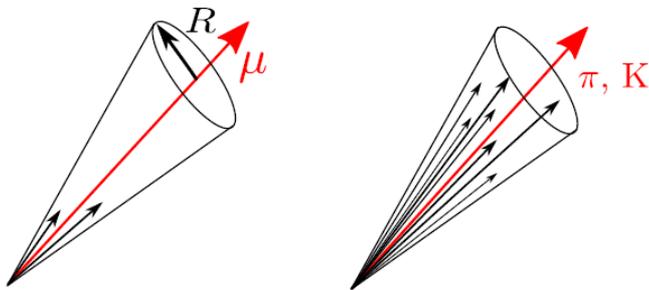


W selection: one (isolated) muon

Data: 2010 L = 37 pb⁻¹
 Single μ, p_T > 10 GeV/c

Muon: one muon
 20 < p_T < 70 GeV/c, 2.0 < η_μ < 4.5

Isolation E_T^{cone} < 2 GeV (Cone R < 0.5 around muon)
 p_T^{cone} < 2 GeV/c

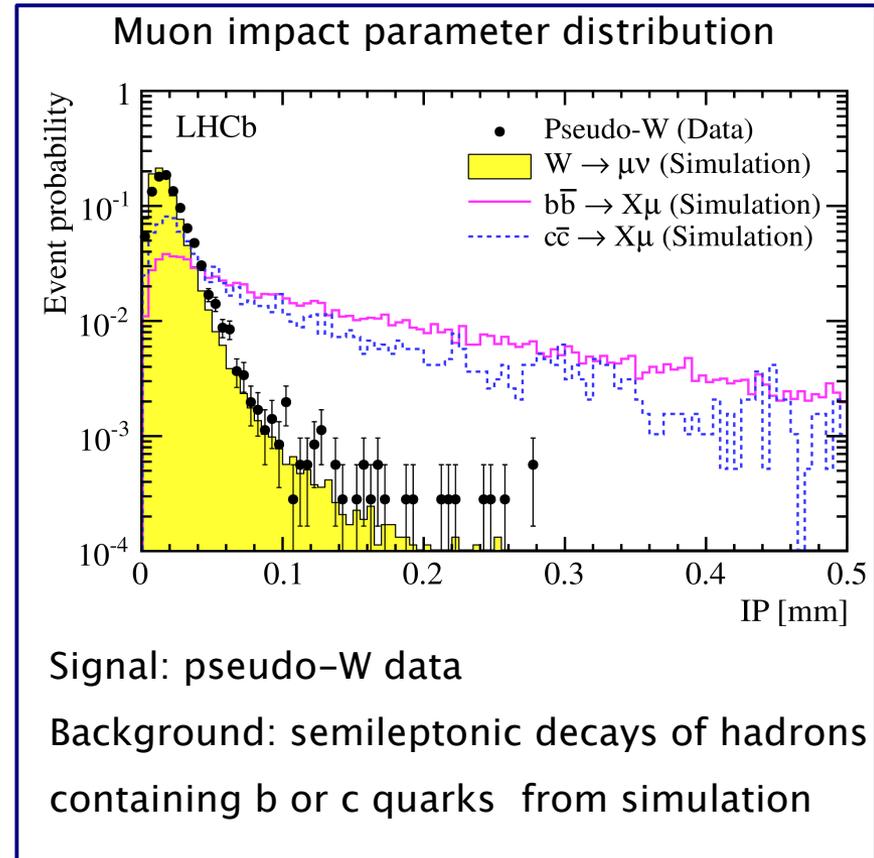


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Cuts against background:
• from semi-leptonic decays of heavy flavour
Impact parameter < 40 μm



Data: 2010 L = 37 pb⁻¹
 Single μ, p_T > 10 GeV/c

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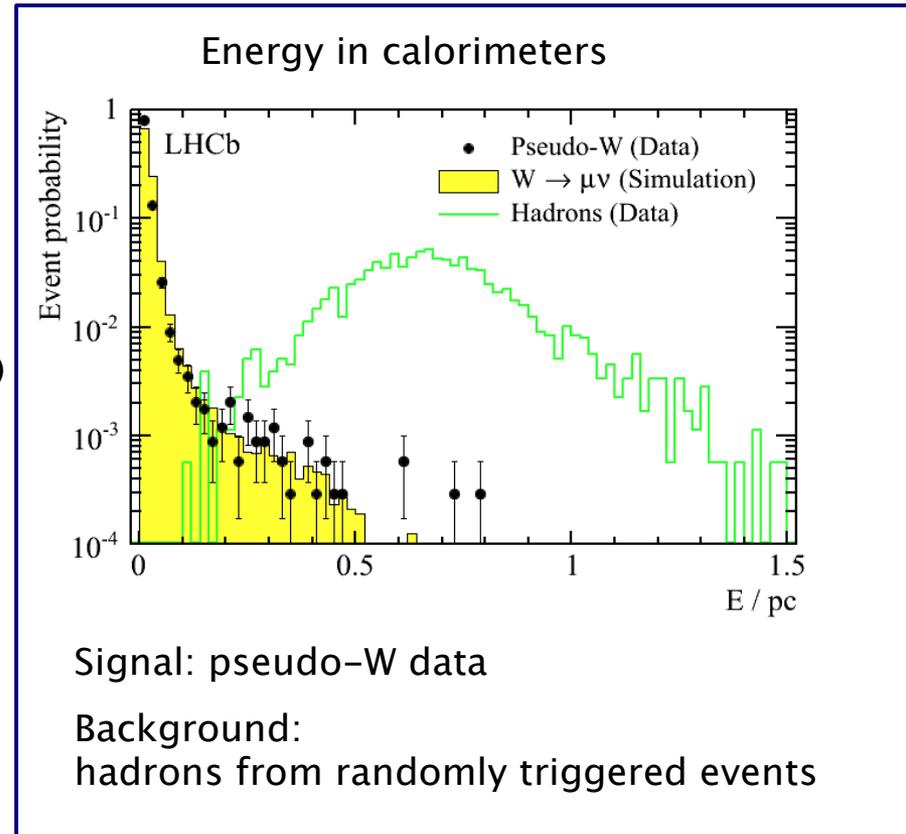
Cuts against background:

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

Candidates: N_{W+} = 14660
 N_{W-} = 11618

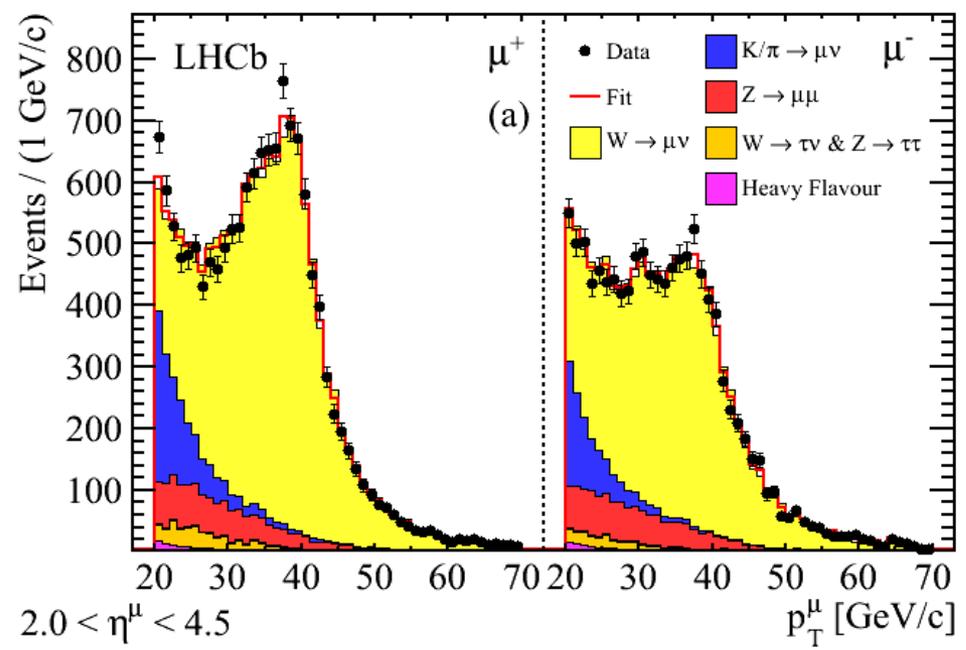
Main background:

Kaon, pion decay in flight
 γ*/Z → μμ, one muon in acceptance



Purity: fit to positively and negatively charged muon p_T distribution

	Shape
W $\rightarrow \mu\nu$	Simulation
K/ π decay in flight	Data
$\gamma^*/Z \rightarrow \mu\mu$	Simulation
W $\rightarrow \tau\nu$, Z $\rightarrow \tau\tau$	Simulation
Heavy Flavour	Data

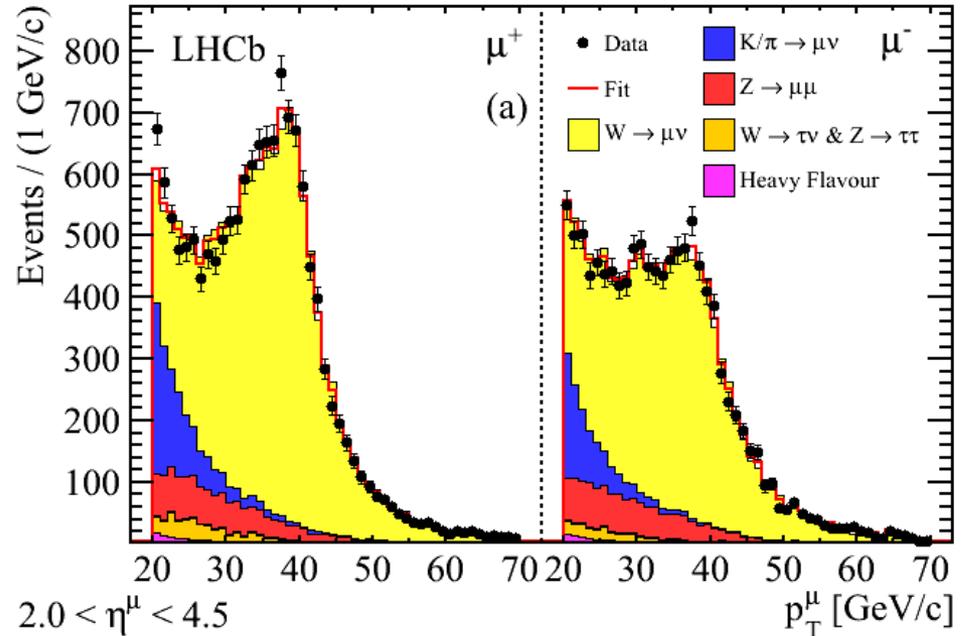


Purity: fit to positively and negatively charged muon p_T distribution

	Shape	Norm.
$W \rightarrow \mu\nu$	Simulation	Fit
K/π decay in flight	Data	Fit
$\gamma^*/Z \rightarrow \mu\mu$	Simulation	Fixed
$W \rightarrow \tau\nu, Z \rightarrow \tau\tau$	Simulation	Fixed
Heavy Flavour	Data	Fixed

Normalisation

- Signal and decay in flight: fitted
- Others : fixed from data



	W+	W-
Purity	78.8%	78.4%



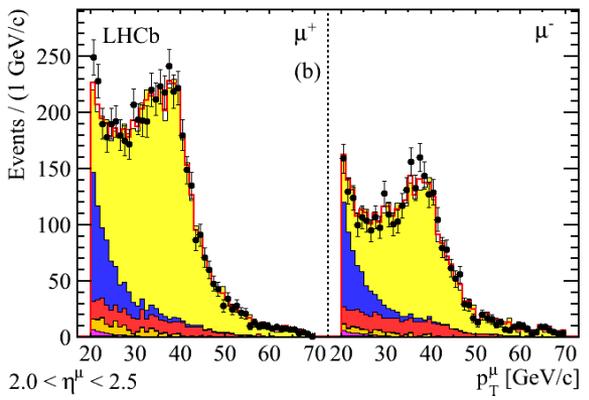
W Analysis

W purity

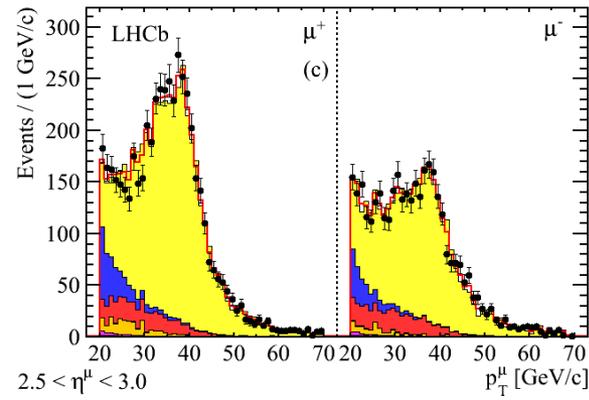
arXiv: 1204.1620

Purity: fit to positively and negatively charged muon p_T distribution in 5 η bins (15 free parameters: 10 signal, 5 background)

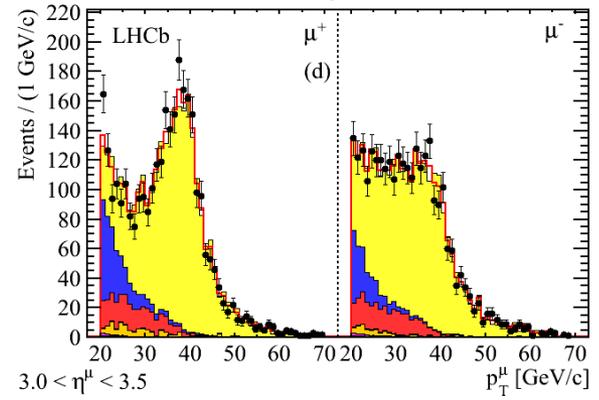
2.0 <math>\eta^\mu < 2.5 </math>



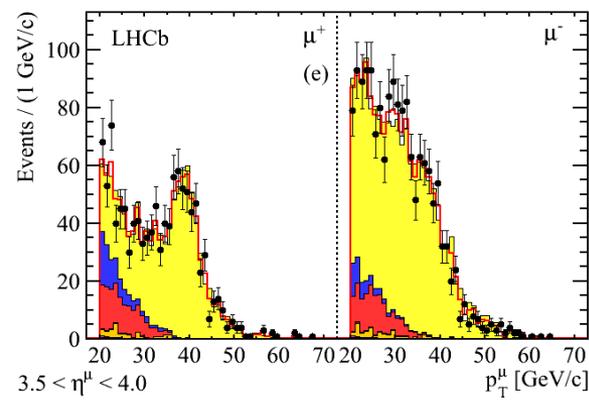
2.5 <math>\eta^\mu < 3.0 </math>



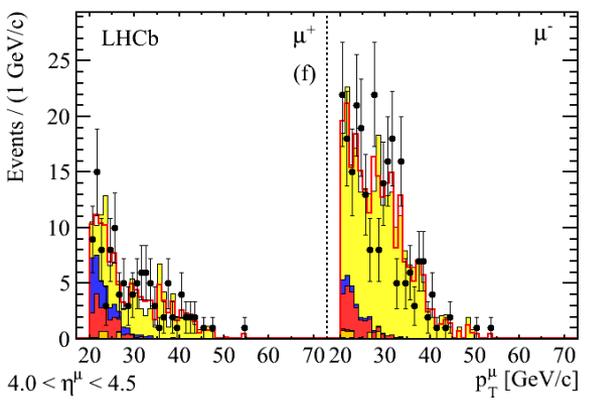
3.0 <math>\eta^\mu < 3.5 </math>



3.5 <math>\eta^\mu < 4.0 </math>



4.0 <math>\eta^\mu < 4.5 </math>

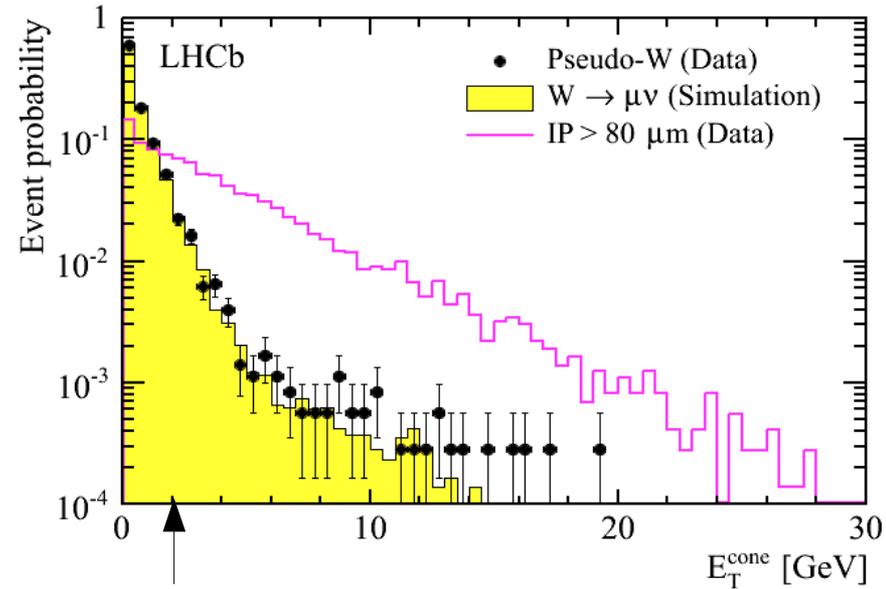


arXiv: 1204.1620

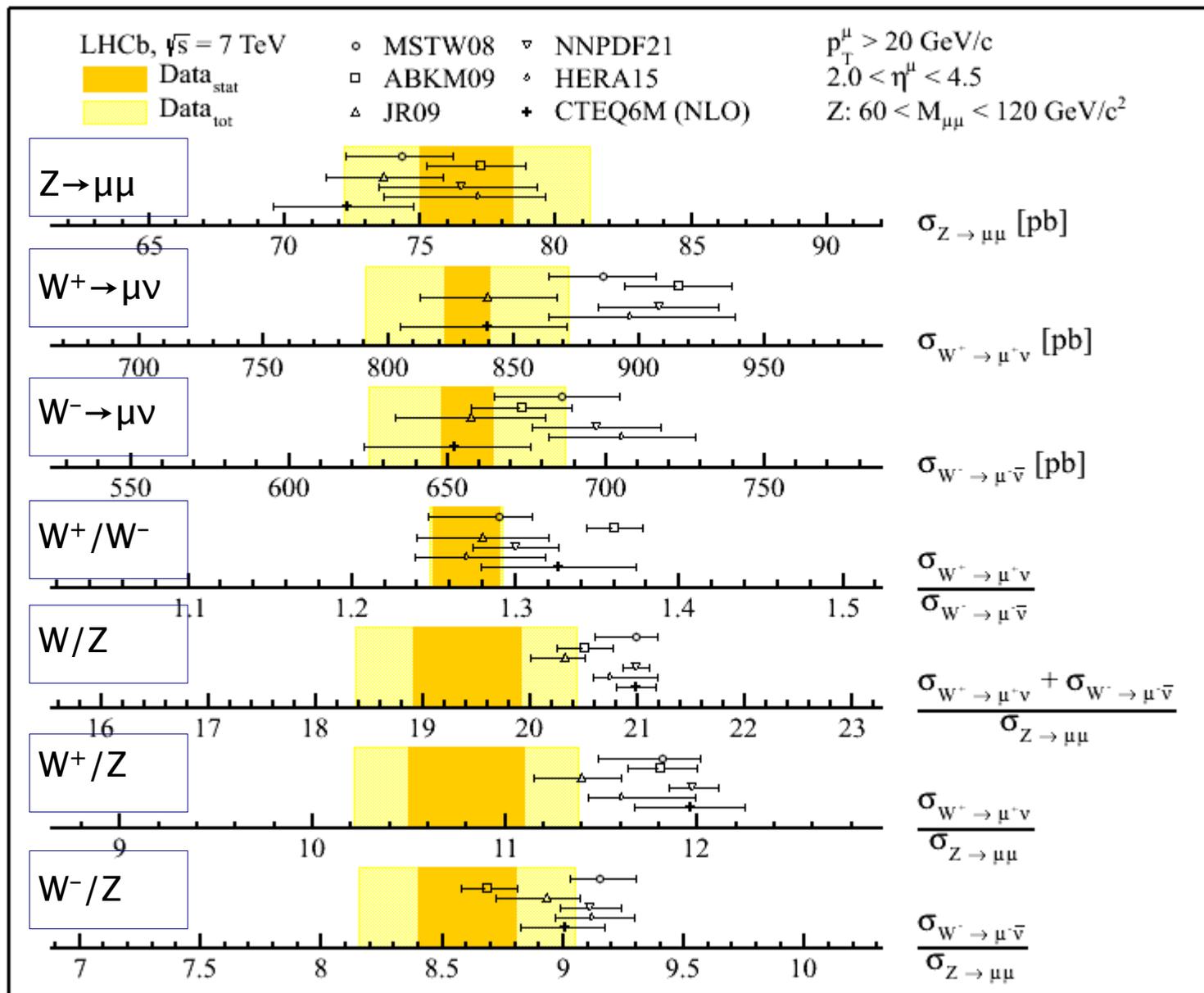
$$\sigma = \frac{\rho N}{A L \epsilon} f_{FSR}$$

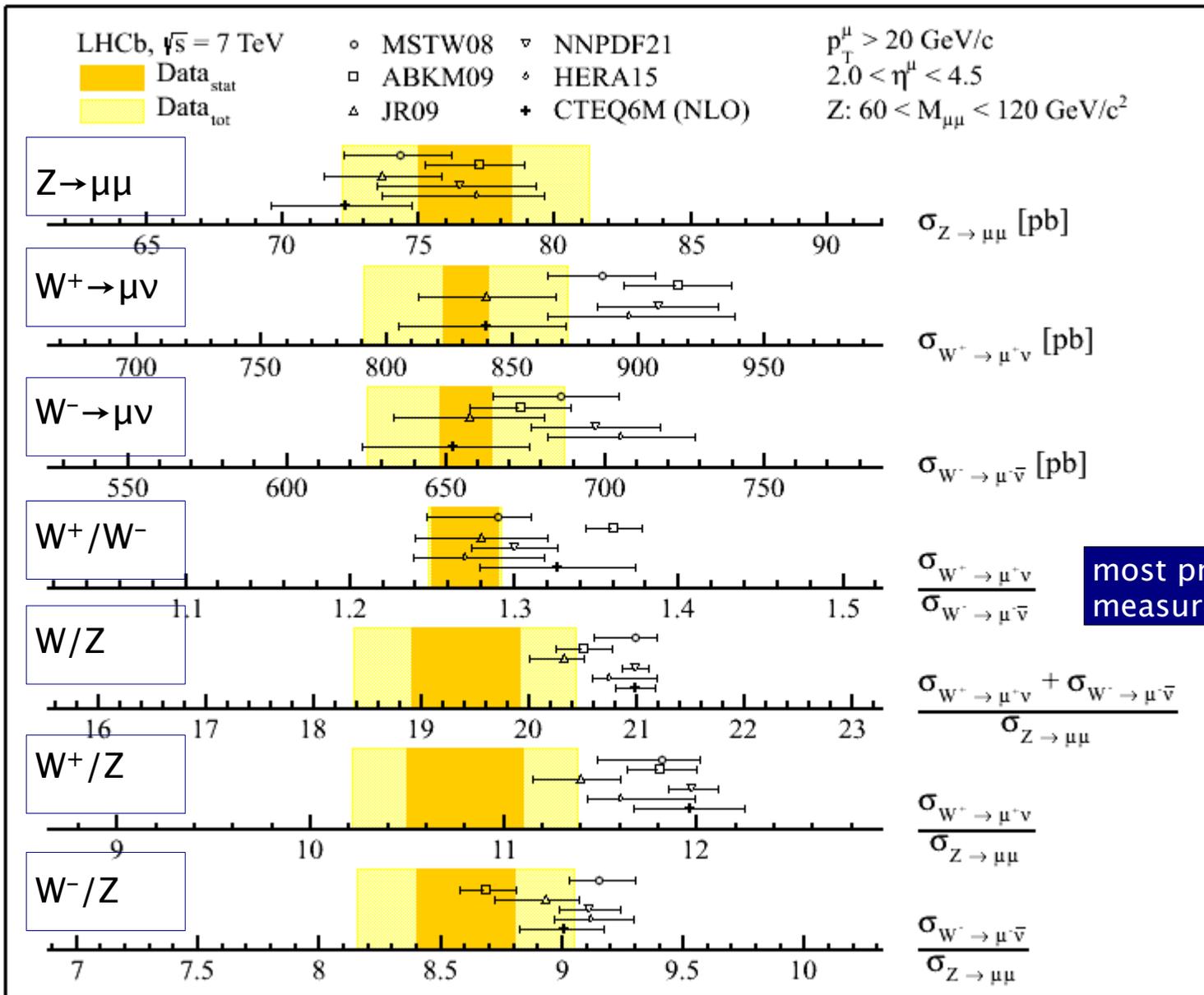
W selection: $(E/p), IP, P_T^{\max}, E_T^{\text{cone}}$
 from pseudo-W events: $\epsilon_{\text{sel}} = 0.3-0.7$

Acceptance: $p_T > 20 \text{ GeV}, 2 < \eta < 4.5$
 $W \rightarrow \mu\nu: > 0.99$



Source	$\Delta\sigma_{W^+ \rightarrow \mu^+ \nu}$ (%)	$\Delta\sigma_{W^- \rightarrow \mu^- \bar{\nu}}$ (%)
Signal purity	± 1.2	± 0.9
Template shape (fit)	± 0.9	± 1.0
Efficiency (trigger, tracking, muon id)	± 2.2	± 2.0
Additional selection	± 1.8	± 1.7
FSR correction	± 0.01	± 0.02
Total	± 3.2	± 2.9
Luminosity	± 3.5	± 3.5



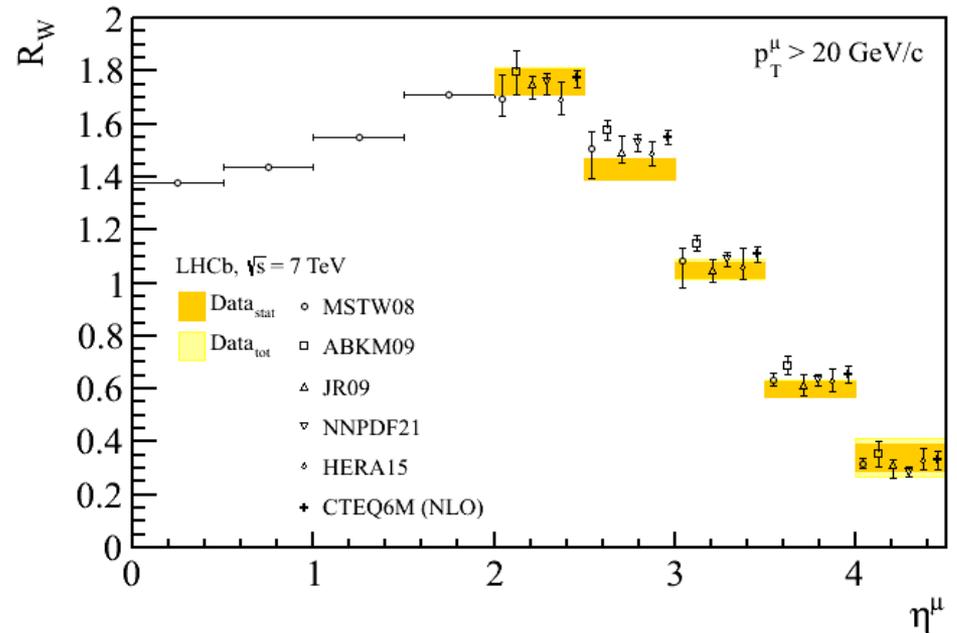
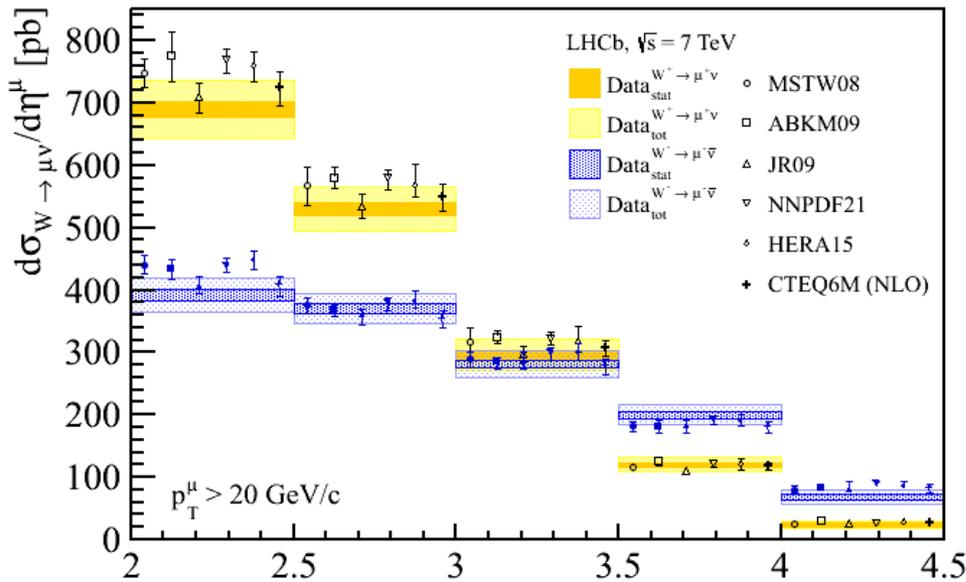


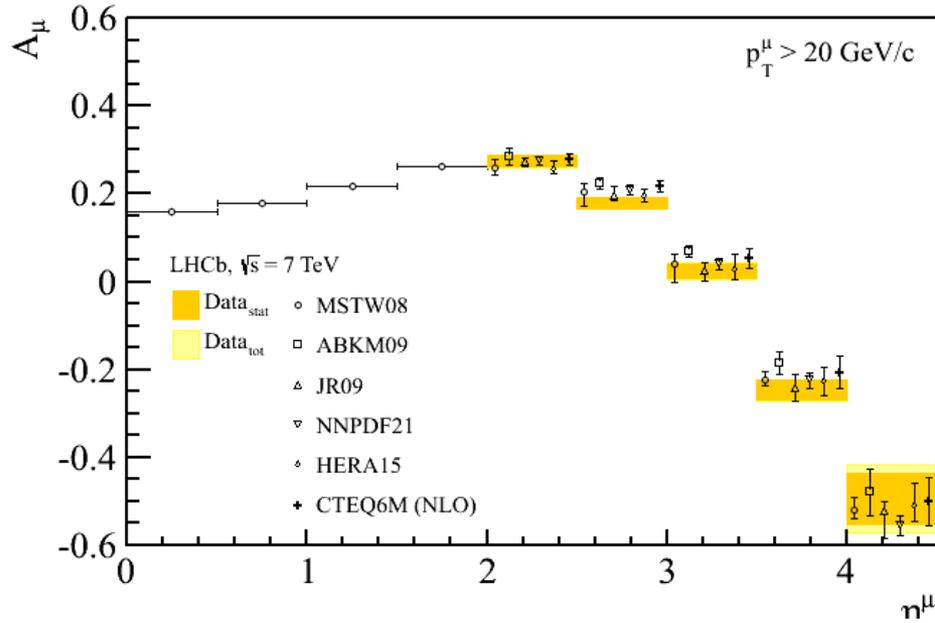
most precise measurement: 1.7%

W analysis

Differential W cross section and W ratio

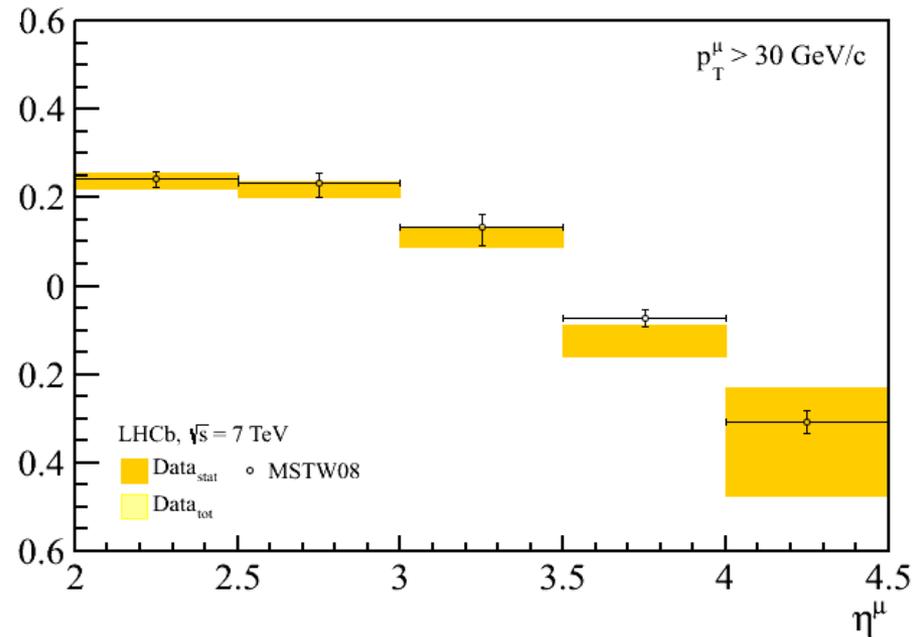
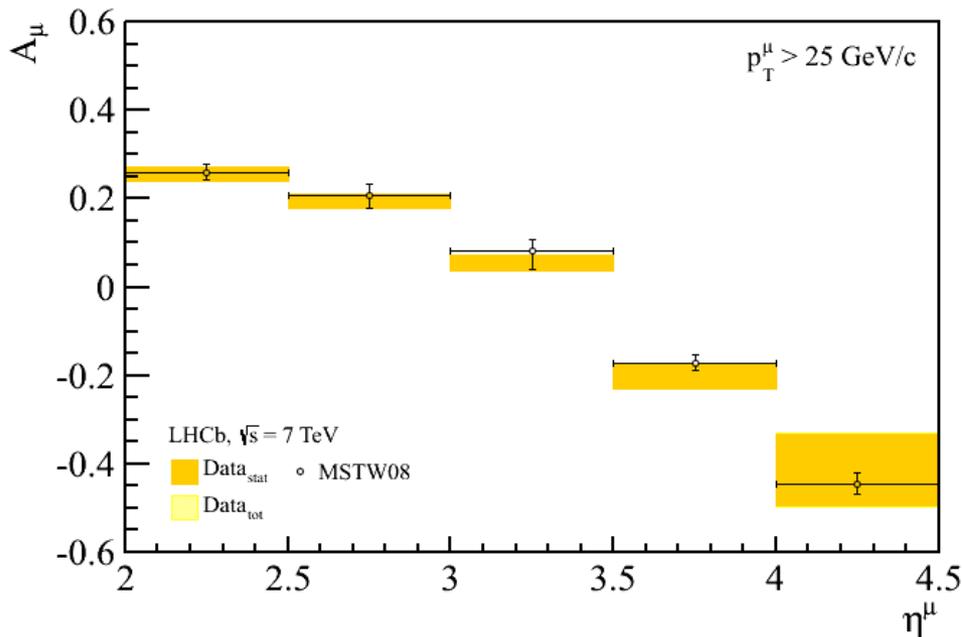
arXiv: 1204.1620



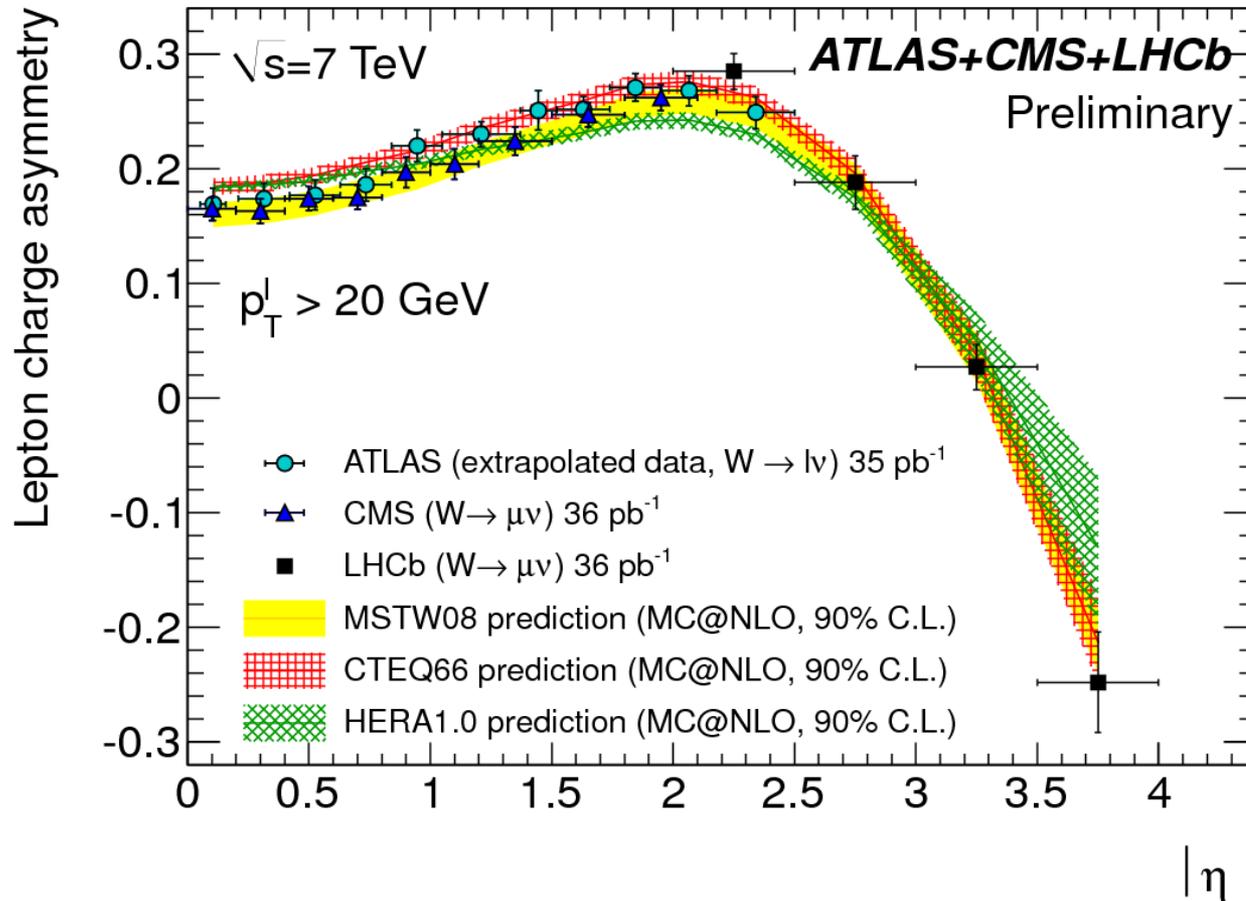


W lepton charge asymmetry for different p_T thresholds

$$A_\mu = \frac{\sigma(W^+ \rightarrow \mu^+ \nu_\mu) - \sigma(W^- \rightarrow \mu^- \bar{\nu}_\mu)}{\sigma(W^+ \rightarrow \mu^+ \nu_\mu) + \sigma(W^- \rightarrow \mu^- \bar{\nu}_\mu)}$$

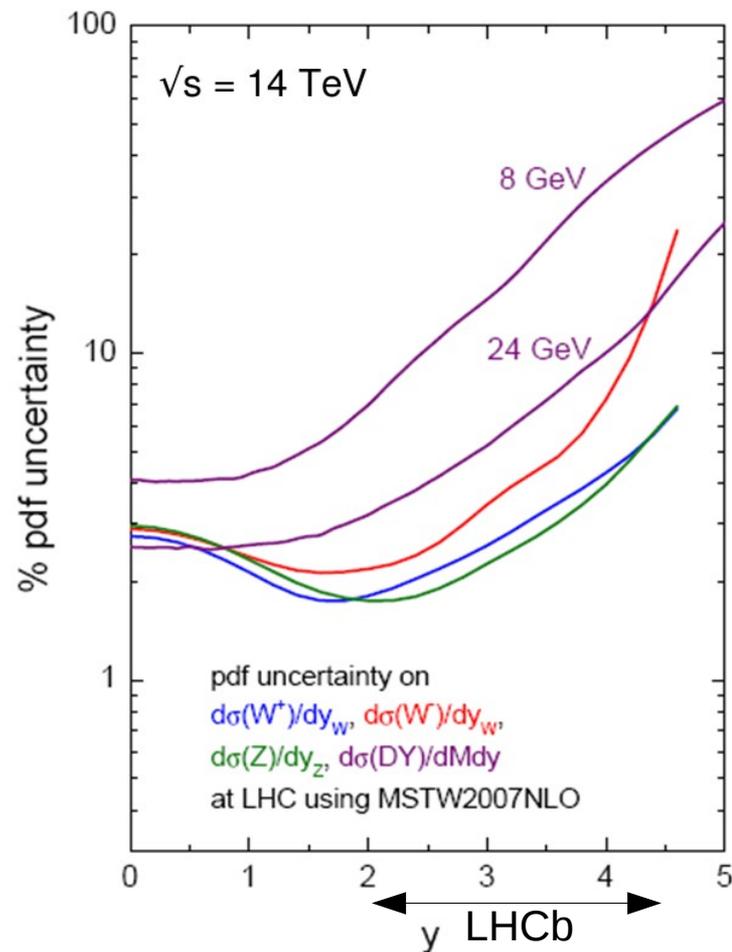
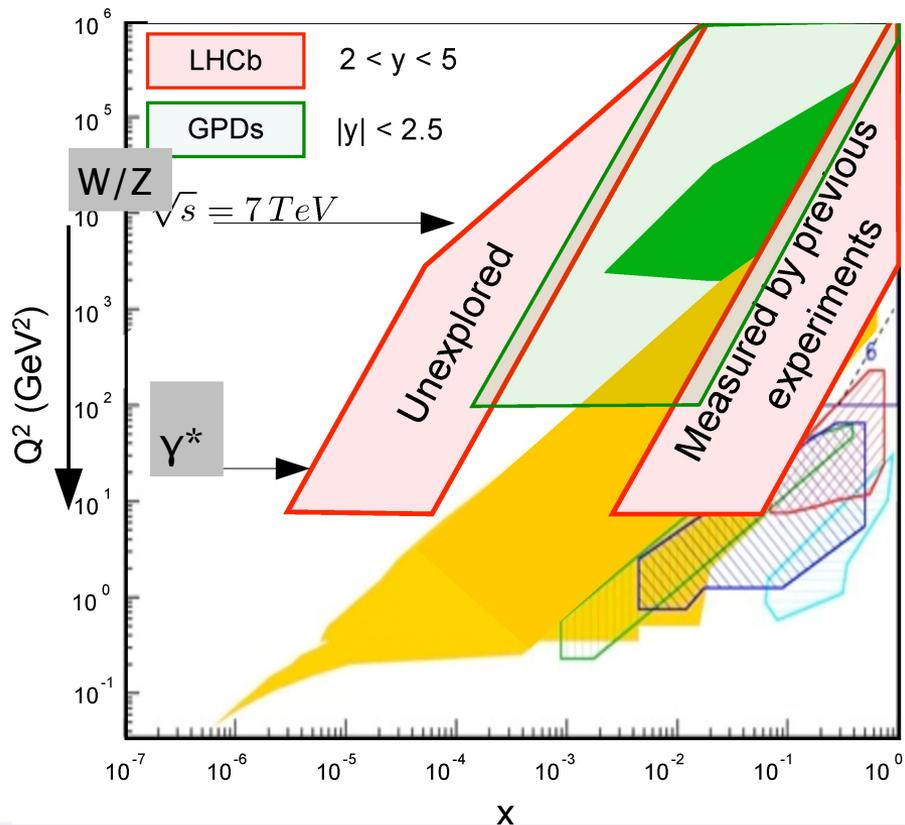


Combined plot with all three experiments
 (very early preliminary analyses)



Low mass Drell-Yan

- W/Z measurements probe
 $Q^2 = 10'000 \text{ GeV}^2, x = 1.7 \cdot 10^{-4}$
- Low mass Drell-Yan (γ^*)
 $Q^2 = 25 \text{ GeV}^2, x = 8 \cdot 10^{-6}$



Data

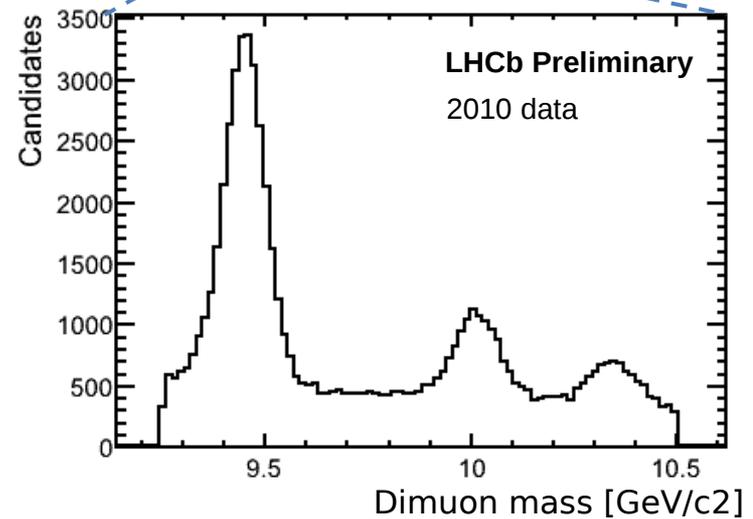
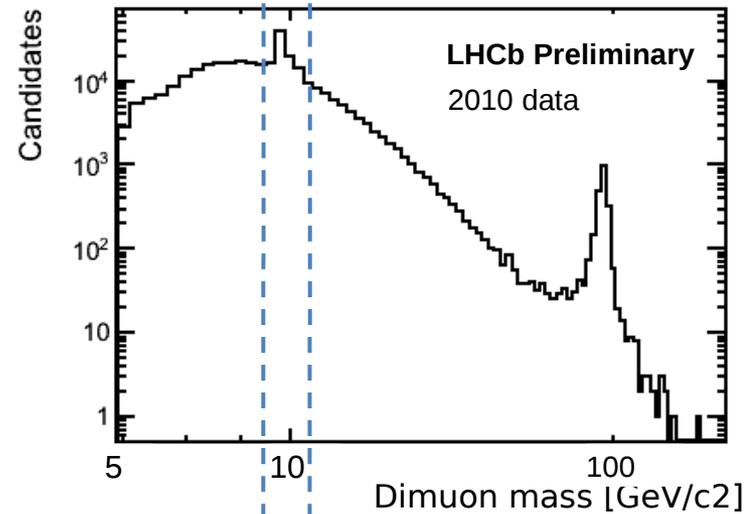
- 2010 L = 37.1 pb⁻¹
- Trigger: di-muon, p_T > 2.5 GeV/c

Muon

- two identified muons
- p_T > 3 GeV/c
- p_T > 15 for M_{μμ} > 40 GeV/c²
- p > 10 GeV/c
- 2.0 < η_μ < 4.5

Mass selection

- 5 < M_{μμ} < 120 GeV/c²



Background

- Semileptonic decays of heavy flavour events
- K/π misidentification
- Radiative tail of Upsilon ($M < 10 \text{ GeV}/c^2$)

Background large at low masses

Signal extraction

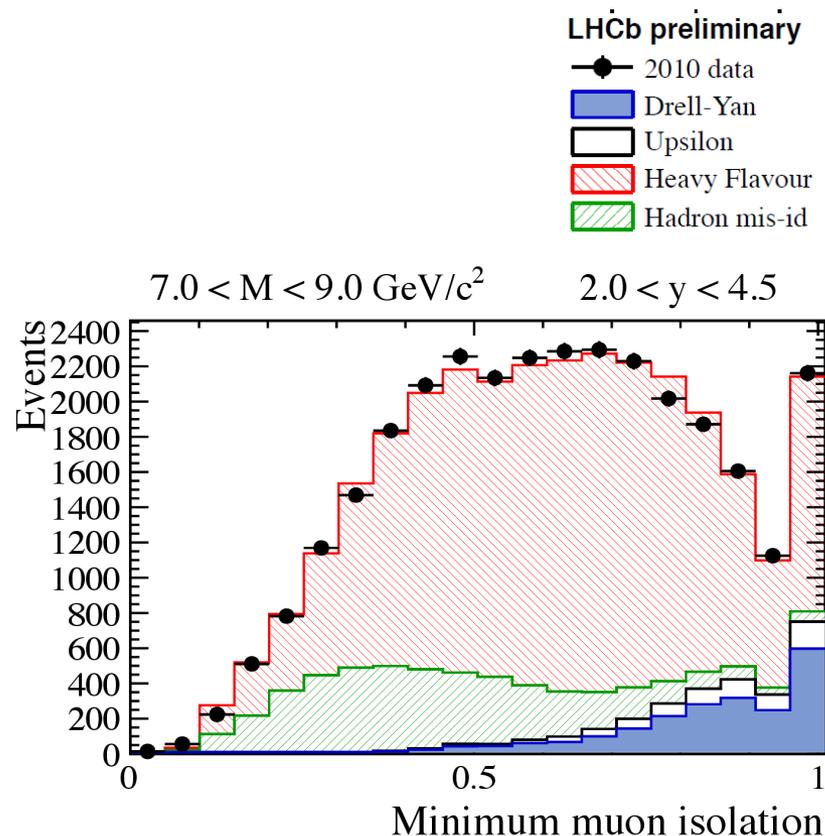
- Template fit to minimum muon isolation
- Muon isolation: $p_T(\mu)/p_T(\mu\text{-Jet})$
- Fit for 9 mass bins
- Fit for 5 η bins (two mass ranges)

Templates

- Signal: simulation
- Background: data

Efficiencies

- From data (similar to W/Z)

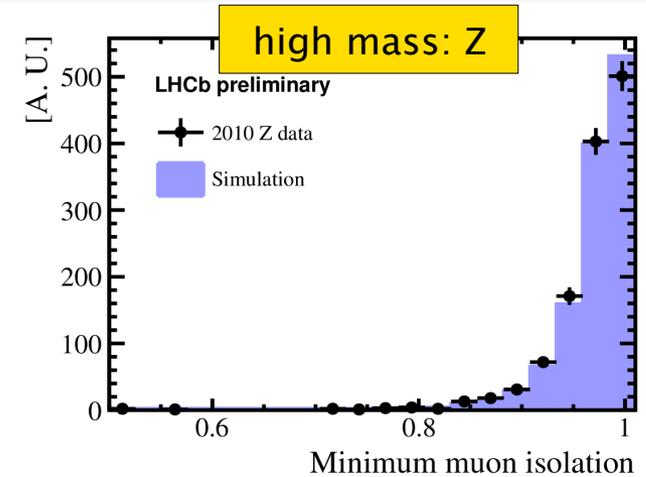
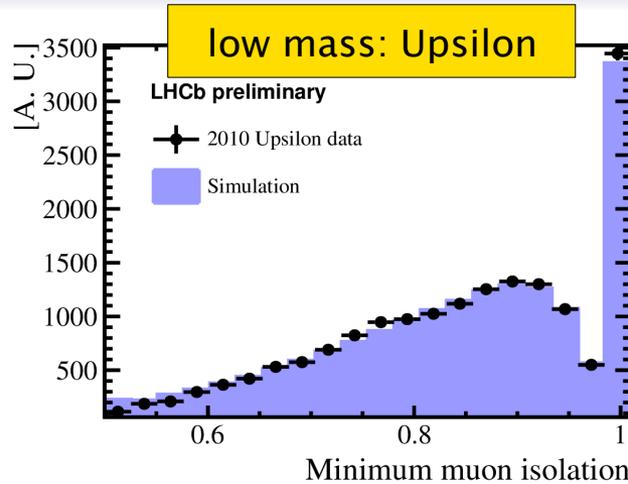


DY Analysis

Purity-Templates

LHCb-CONF-2012-013

Signal template:
Compare data and MC



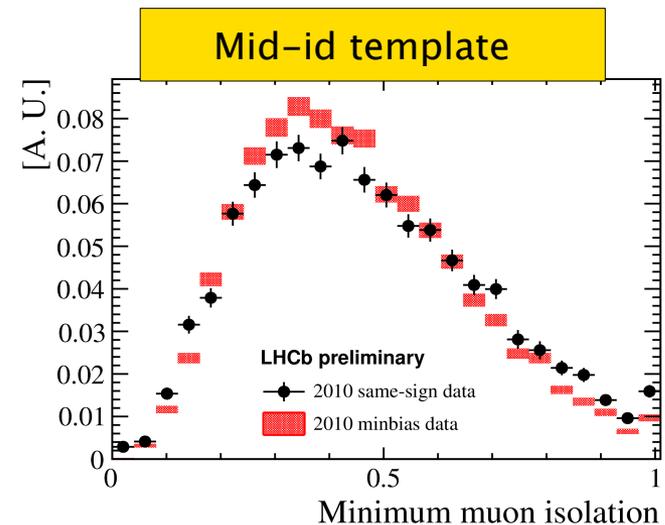
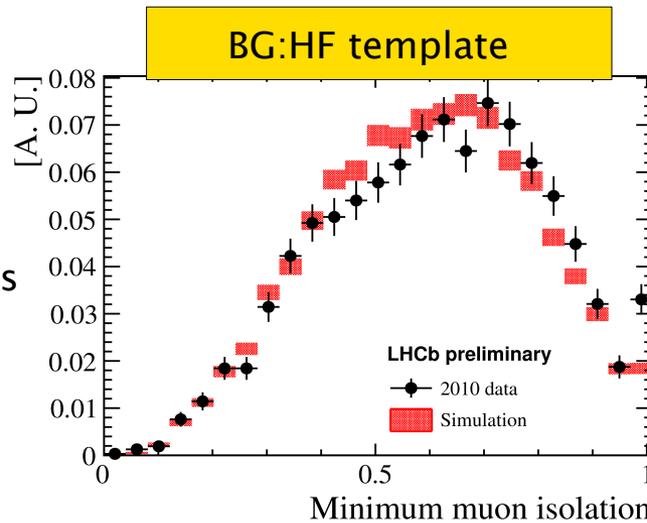
Background templates:

1) Heavy Flavour

- data: IP cut
- simulation

2) Kaon-Pion mis-id

- data: minimum bias
- data: same sign

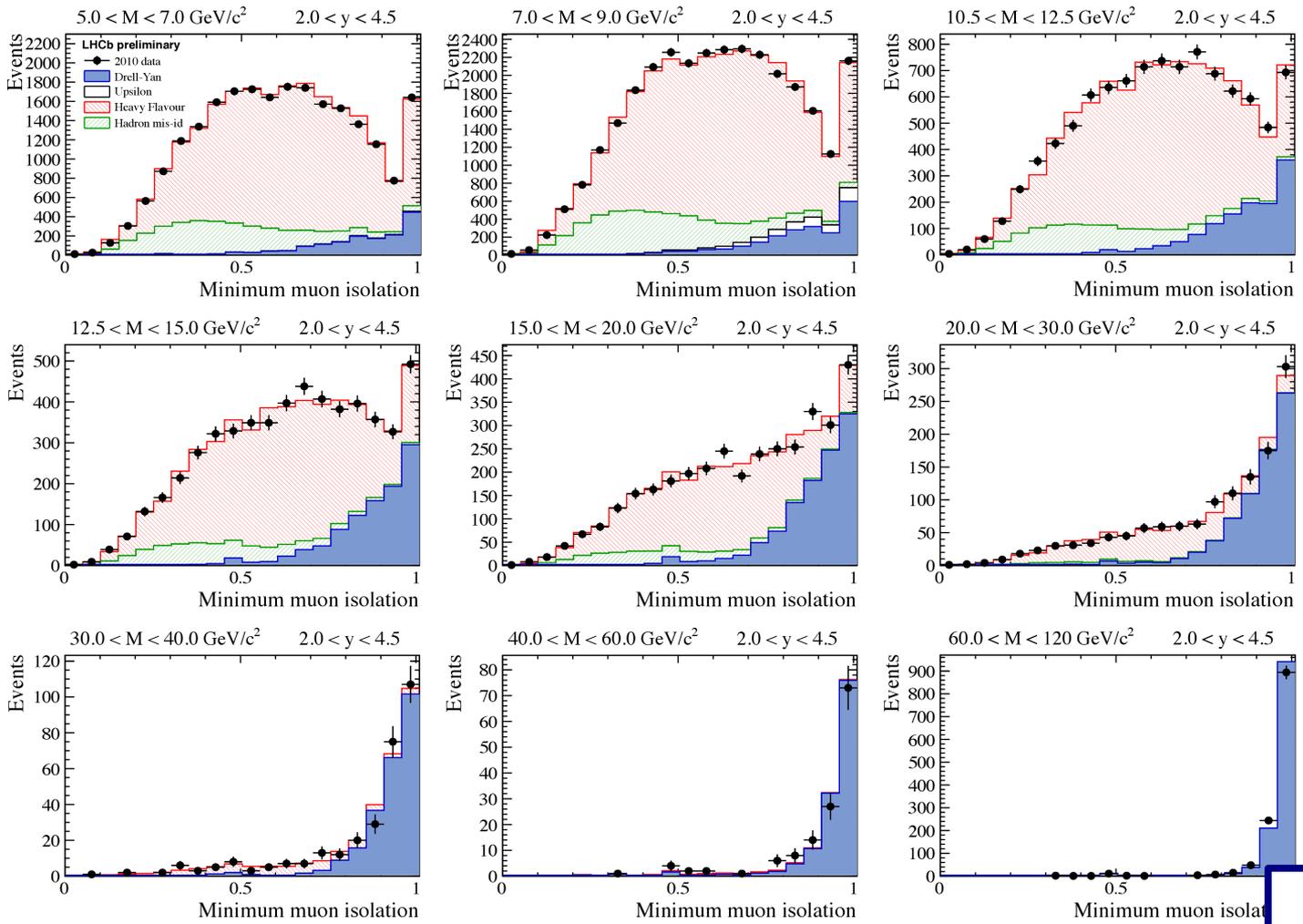
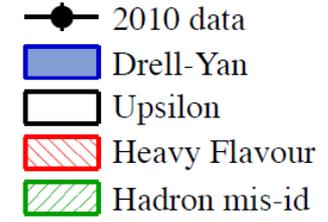


Systematic uncertainties due to templates:

Background: Difference in fitted signal fraction when using different background templates

Signal: distort signal template

LHCb preliminary

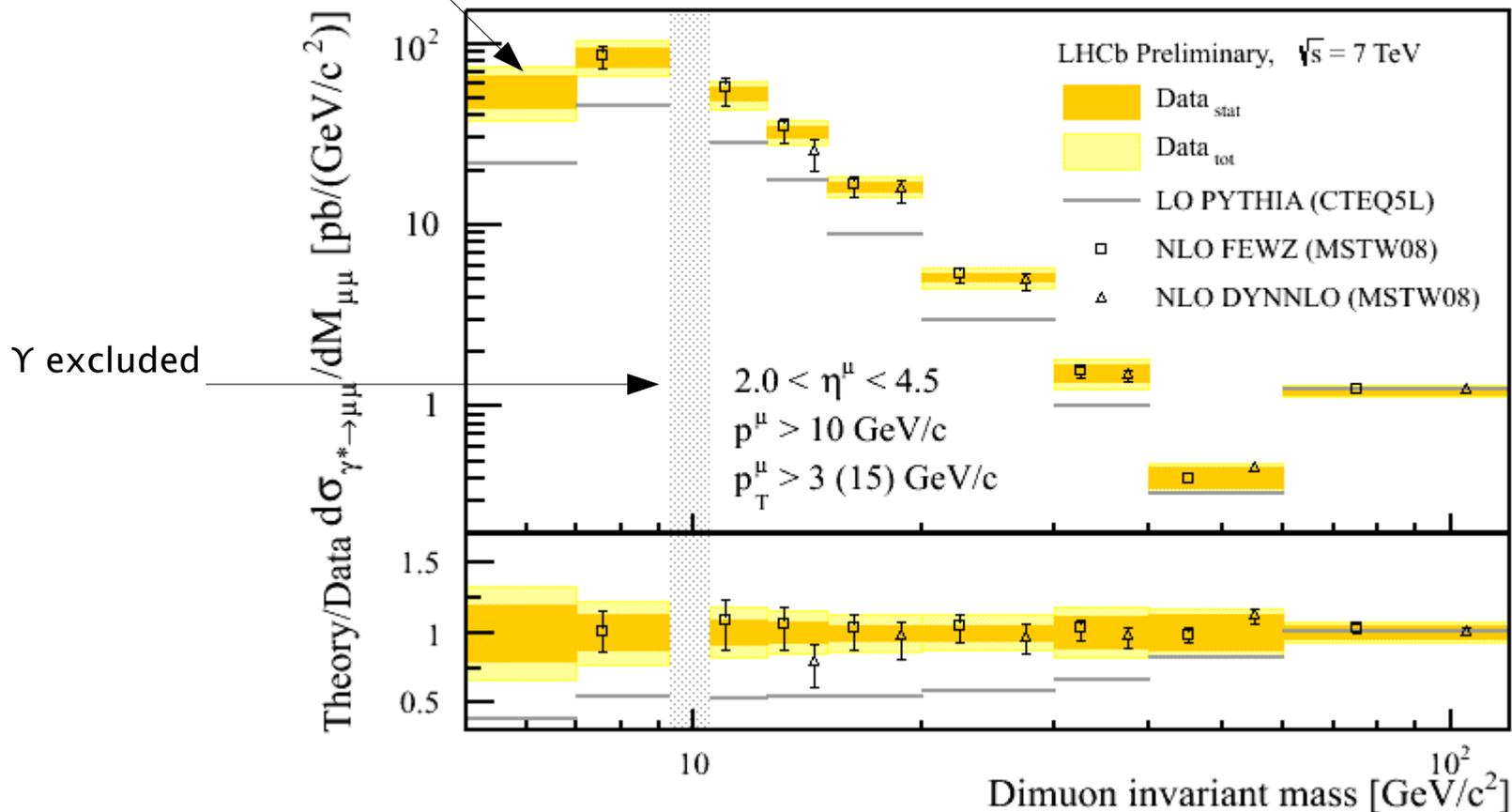


Systematic uncertainties

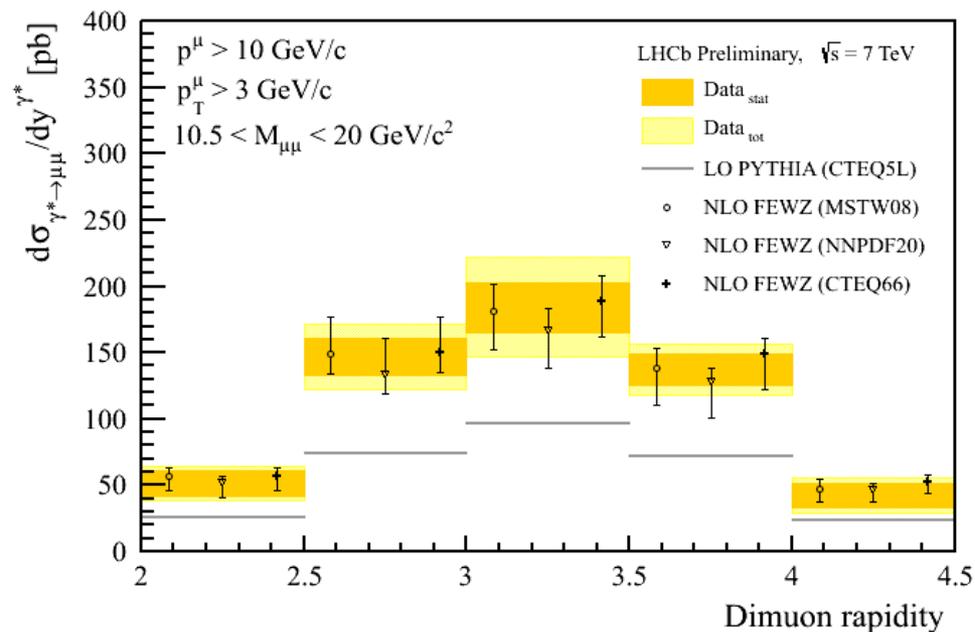
- At low masses: shapes used for template fit 24%
- Efficiencies

Mass [GeV/c ²]	Purity [%]
5–7.5	6.8
7.5–9	9.0
12.5–15	20.4
20–30	54.9
40–60	91.4

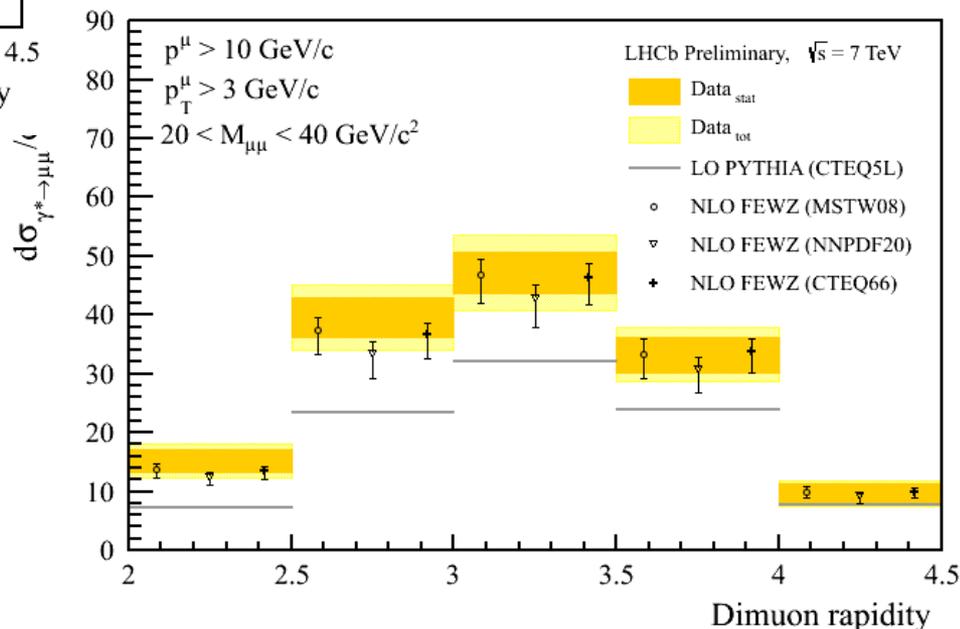
Shape influenced by p_T cut



Compared to NLO predictions (FEWZ and DYNNLO) and PYTHIA
 FEWZ predictions above 7 GeV/c², DYNNLO above 12.5 GeV/c²



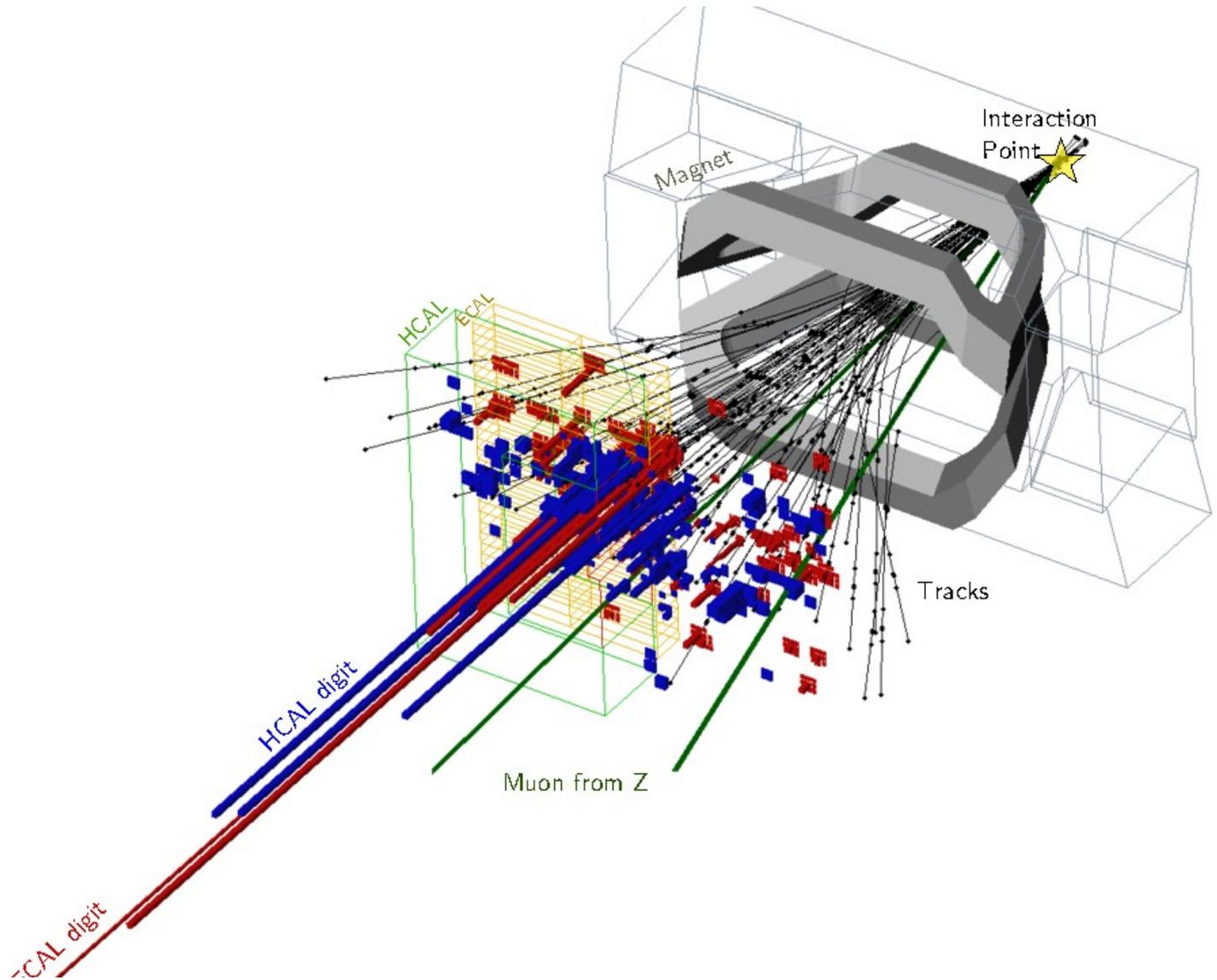
Differential in di-muon rapidity



Compared to NLO predictions (FEWZ) and PYTHIA



Z plus jet analysis



Data

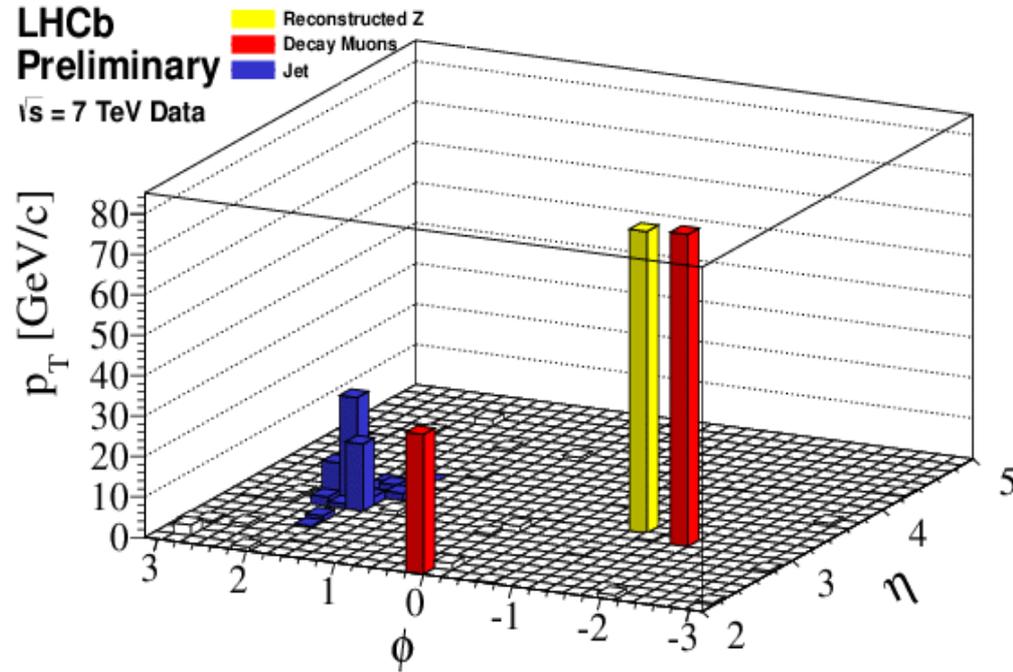
- 2011 L = 1 fb⁻¹
- Z → μμ selection
- 60 < M(μμ) < 120 GeV/c²

Jet reconstruction

- Anti-k_T algorithm (R=0.5)
- Energy flow objects: tracks, photons, neutral hadrons, V0
- Energy mainly from tracks
- Measurement on hadron level

Jet selection

- p_T(jet) > 10 GeV/c
- 2.0 < η_μ < 4.5
- ΔR(μ,jet) > 0.4
- Jet identification



p_T(jet) = 75 GeV/c
 p_T(μ⁺) = 35 GeV/c
 p_T(μ⁻) = 77 GeV/c
 M(μμ) = 97 GeV/c²

Data

- 2011 L = 1 fb⁻¹
- Z → μμ selection
- 60 < M(μμ) < 120 GeV/c²

Jet reconstruction

- Anti-k_T algorithm (R=0.5)
- Energy flow objects:
tracks, photons, neutral hadrons, V⁰
- Energy mainly from tracks
- Measurement on hadron level

Jet selection

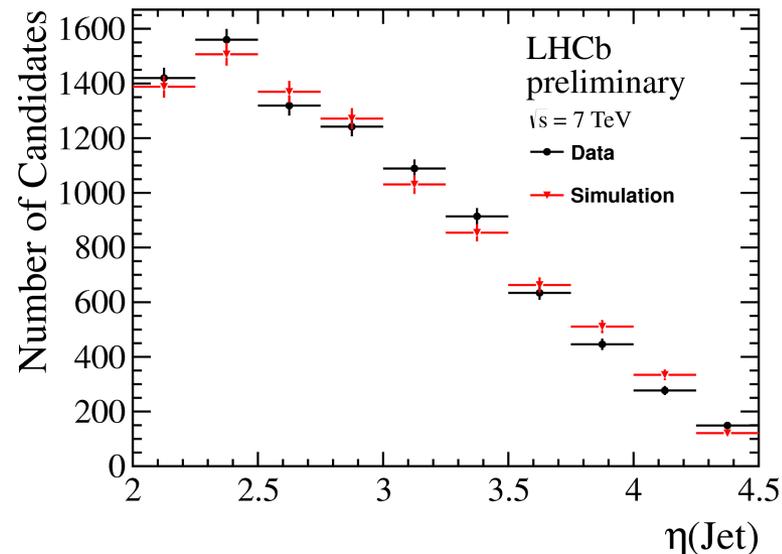
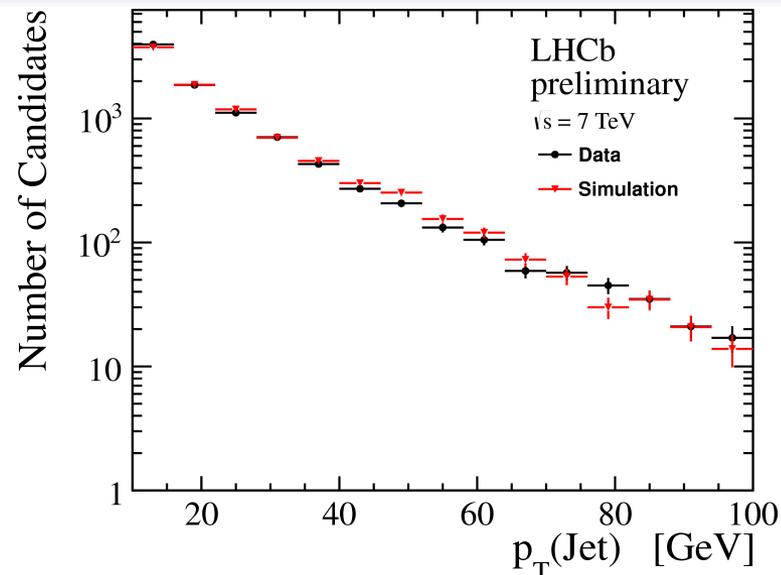
- p_T(jet) > 10 GeV/c
- 2.0 < η_μ < 4.5
- ΔR(μ, jet) > 0.4
- Jet identification

No efficiency correction in these plots

Good agreement between data and simulation on detector level

→ LHCb has the potential for good jet measurements

→ Simulation describes the data well

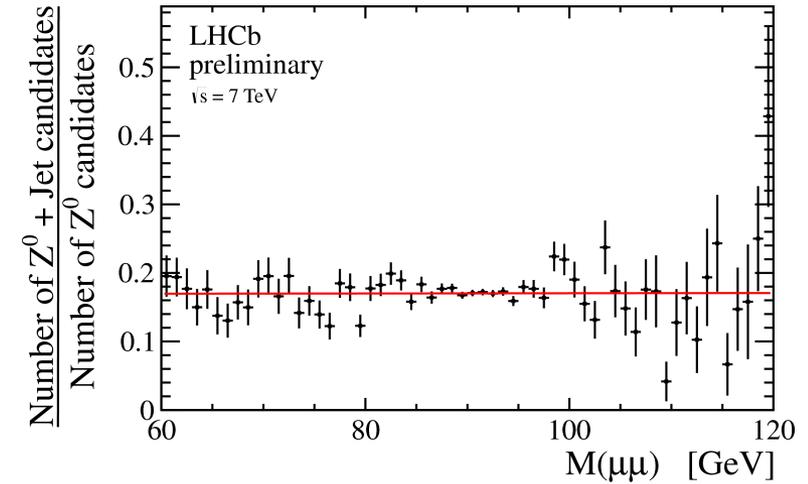
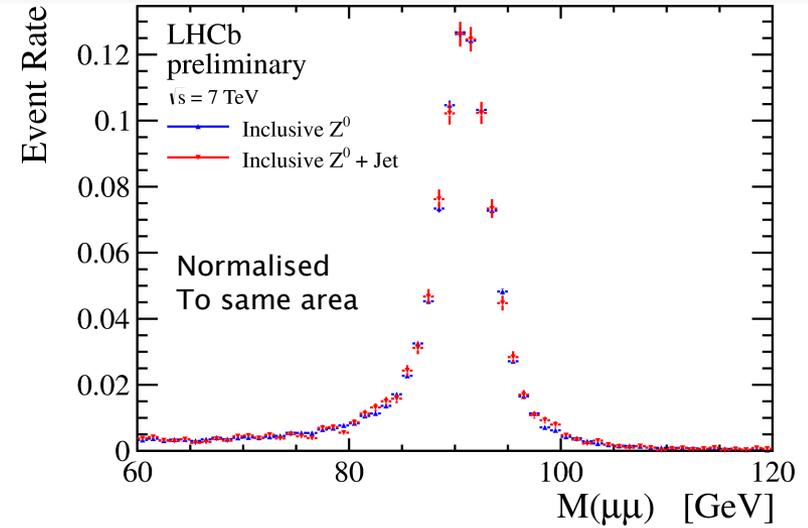


Backgrounds

- Similar to $Z \rightarrow \mu\mu$ analysis

Efficiencies

- Studied as a function of track multiplicity
- Jet finding efficiency: from simulation, reweighted to measured jet multiplicity



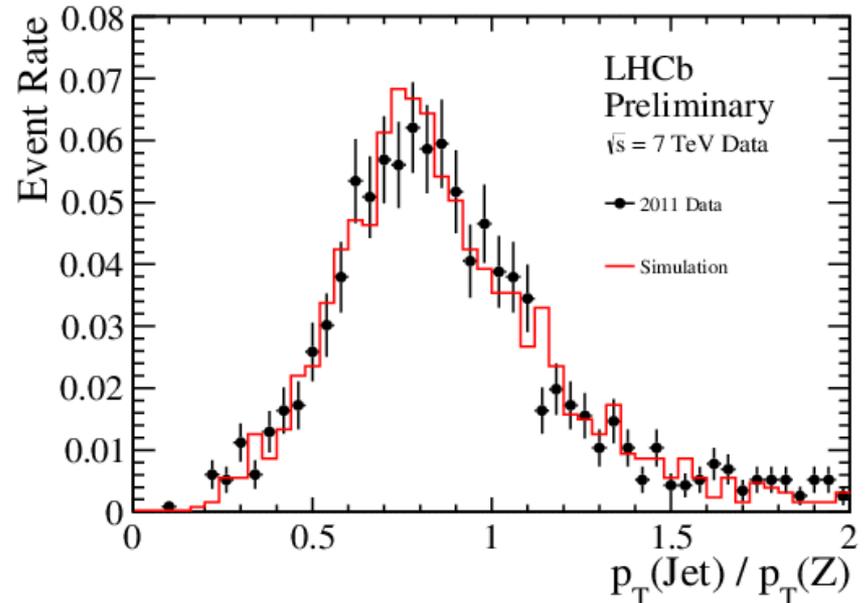
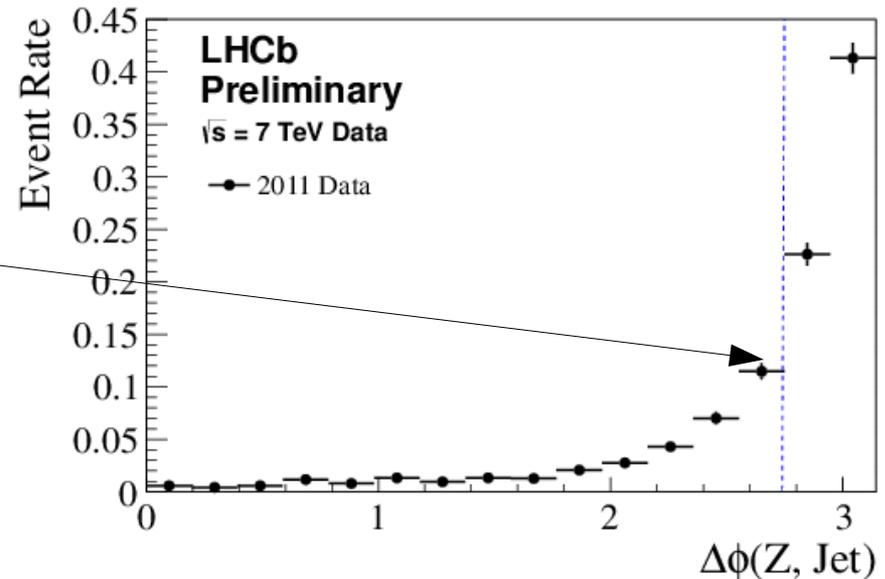
No evidence for enhanced background contribution

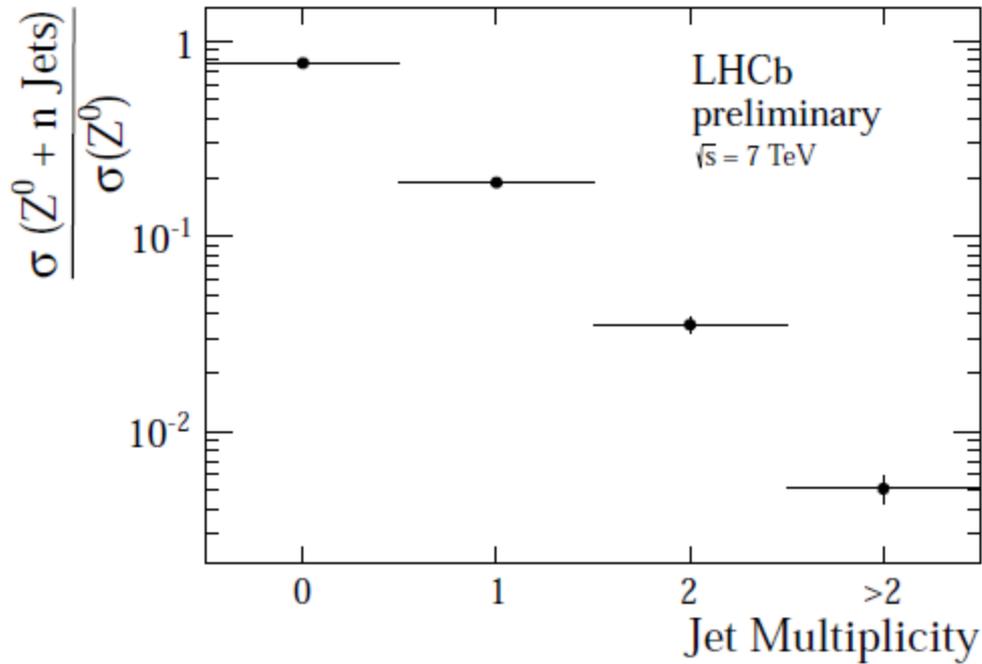
Jet energy scale and resolution

- Jet energy correction from simulation
- Cross check energy scale with data
- From events with Z and jet back-to-back
 Expect balance between jet and Z p_T
- $p_T(\text{Jet})/p_T(\text{Z})$ compare data with simulation
 → Good agreement observed
 → Energy scale: known with 3% precision
 → Energy resolution: compare width in simulation and data
 → Energy resolution 17% @ $p_T(\text{Jet})=30 \text{ GeV}$

Systematic uncertainties

- Energy scale dominant

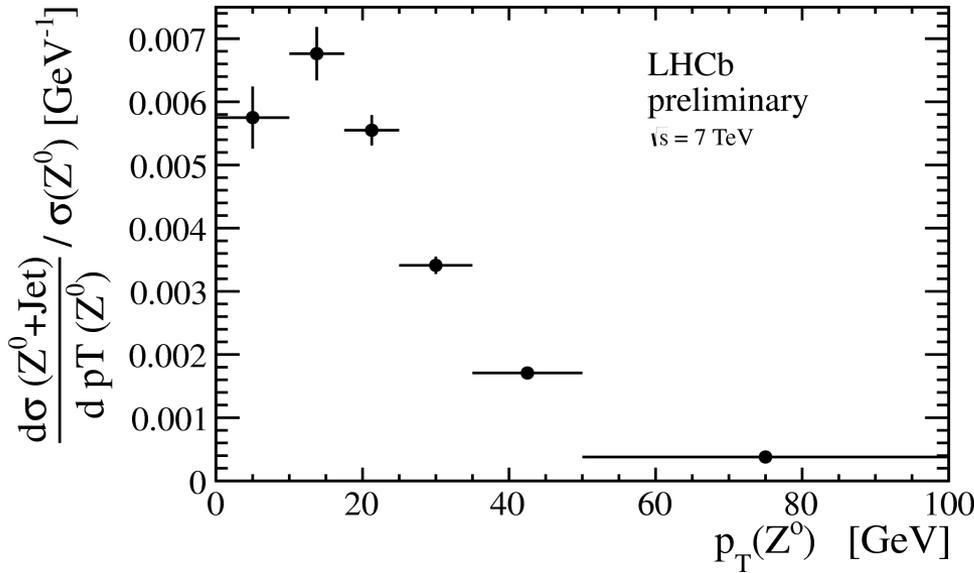




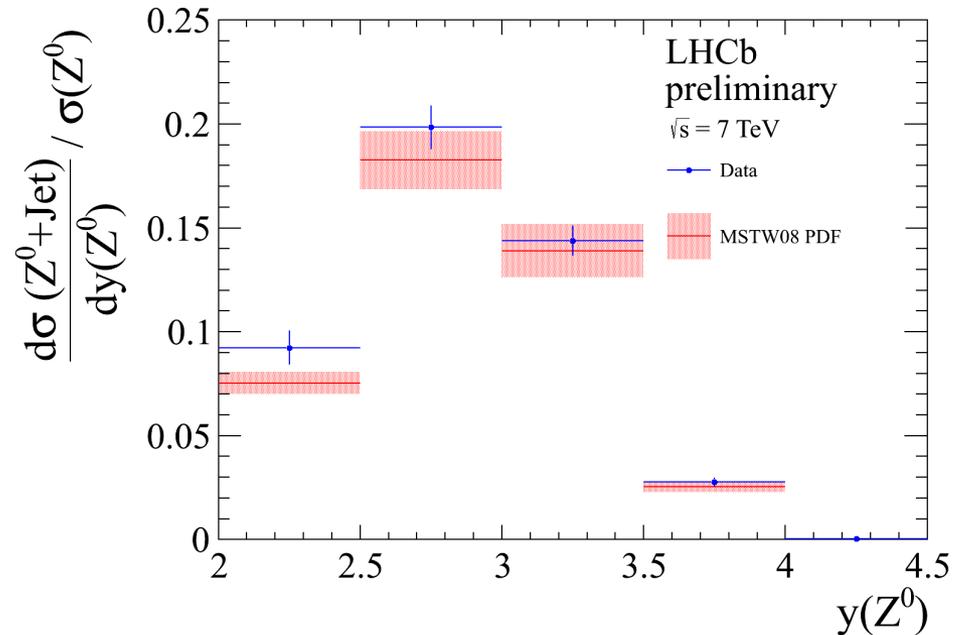
Fraction of events with at least one jet:

LHCb preliminary:
 $0.229 \pm 0.006(\text{stat}) \pm 0.009(\text{syst})$

NLO: FEWZ with MSTW0 (parton level)
 $0.212^{+0.006}_{-0.009}(\text{PDF}) \pm 0.016(\text{scale})$



Normalised to total Z cross section
Result on hadron level
Migrations small <4%



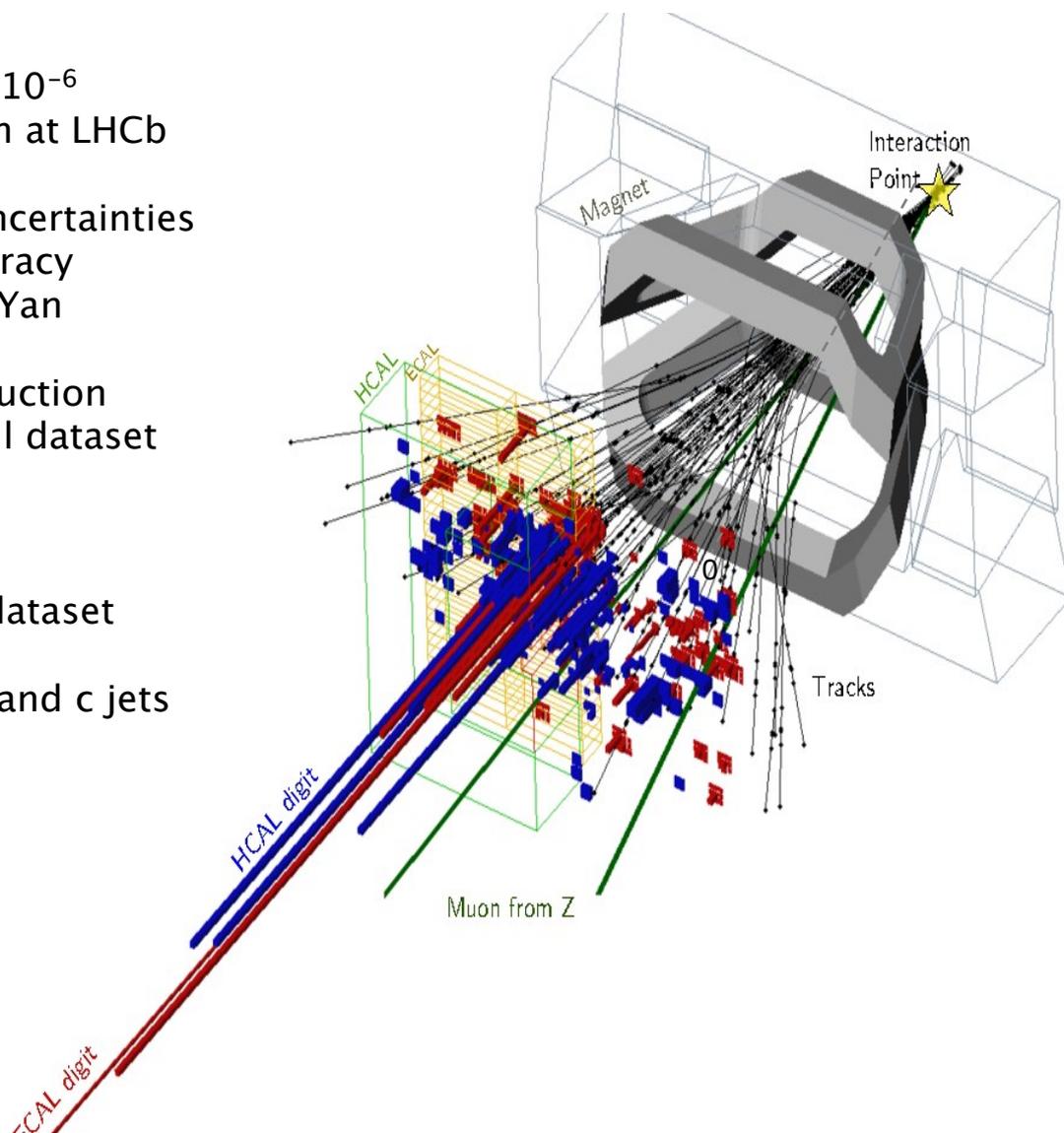
Summary & Outlook

Summary

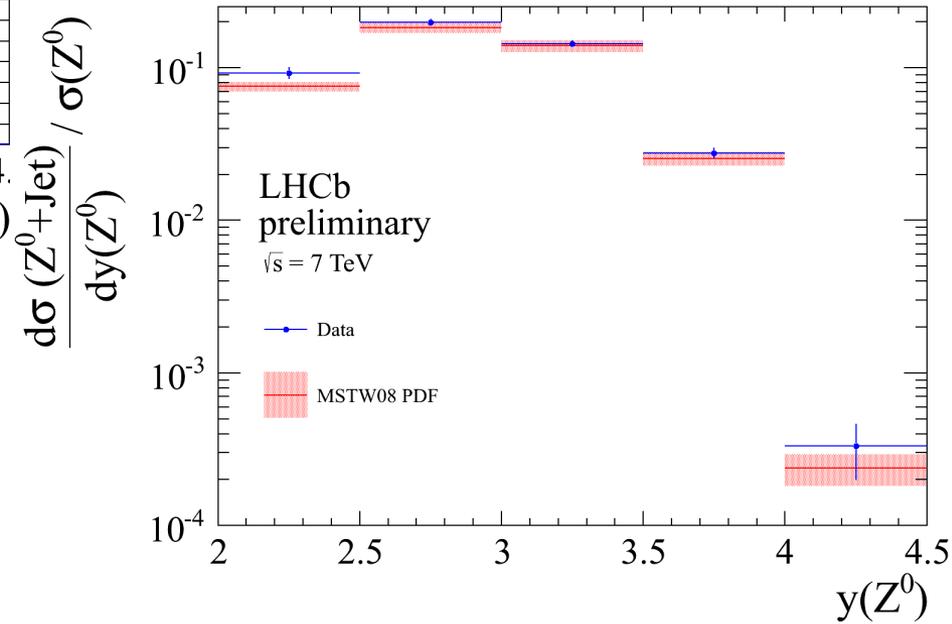
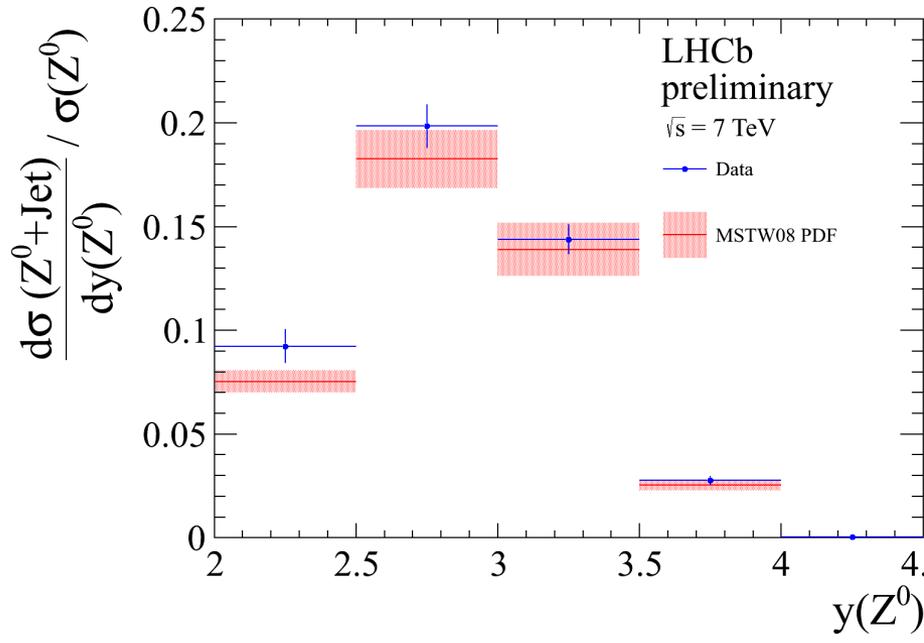
- Unique kinematic range down to $x=8 \cdot 10^{-6}$
- First measurements of W/Z production at LHCb
- In agreement with NNLO predictions
- Precision comparable to theoretical uncertainties
- Ratio W^+/W^- cross section: 1.7% accuracy
- First measurement of low mass Drell-Yan production, $M > 5\text{GeV}/c^2$
- First measurements of Z plus jet production
- Many of these results don't use yet full dataset

Outlook

- Precision will improve with full 2011 dataset
- 2012: 8 TeV running, new kinematics
- W, Z production in association with b and c jets



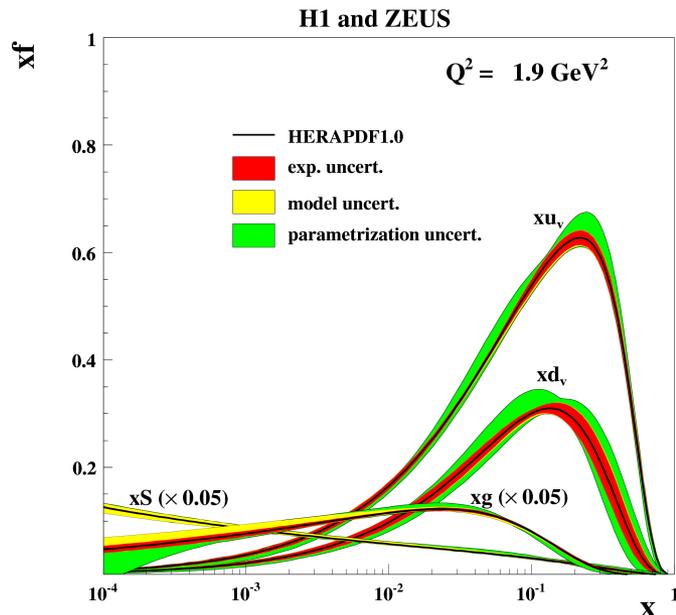
Backup



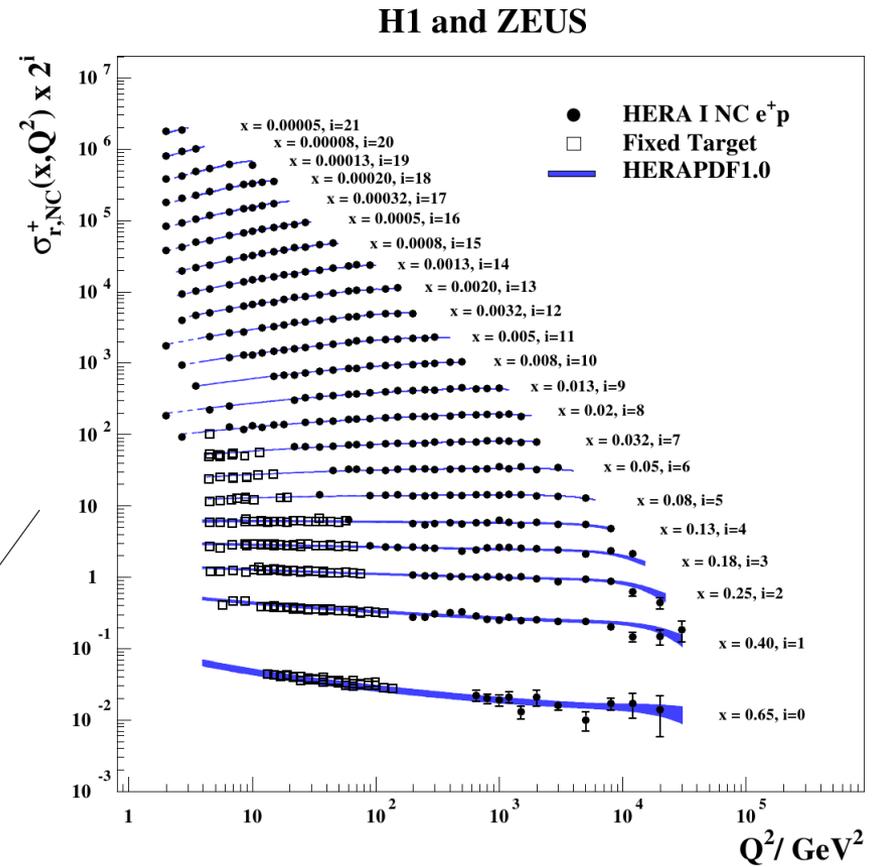
Result on hadron level
 Migrations small <4%

Knowledge of PDFs of the proton:
HERA, Tevatron and fixed target data

HERA: probe the structure of the proton
in a large kinematic range with ep
scattering



PDF-fits



W charge asymmetry

W rapidity cannot be measured
 W lepton charge asymmetry for different
 p_T thresholds

$$A_\mu = \frac{\sigma(W^+ \rightarrow \mu^+ \nu_\mu) - \sigma(W^- \rightarrow \mu^- \bar{\nu}_\mu)}{\sigma(W^+ \rightarrow \mu^+ \nu_\mu) + \sigma(W^- \rightarrow \mu^- \bar{\nu}_\mu)}$$

