Electroweak boson production at LHCb

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(for the LHCb Collaboration)

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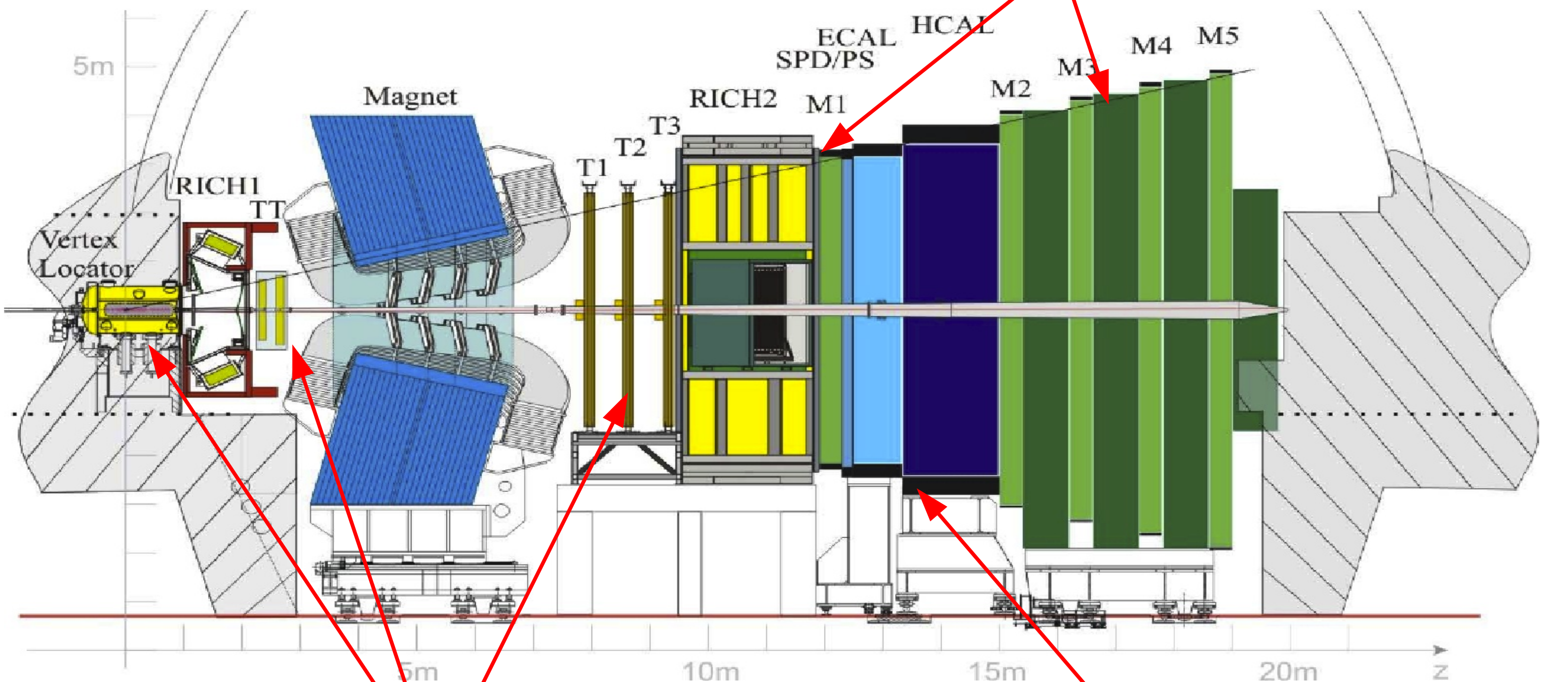
- Introduction
- $Z \rightarrow \mu\mu$, $Z \rightarrow ee$, $Z \rightarrow \tau\tau$
- $W \rightarrow \mu\nu$
- Conclusion

The LHCb detector

Muon chambers:
Muon identification
Low trigger threshold: $m(\mu\mu) > 2.5$ GeV/c^2
(makes low mass D-Y analysis possible)



High-precision tracking system:
$\Delta p/p = 0.4\%$ at 5 GeV/c,
0.6% at 100 GeV/c
Impact Parameter resolution:
20 μm for high pT tracks

Electromagnetic and Hadronic Calorimeters:
Used in electroweak analyses for
electron and hadron identification

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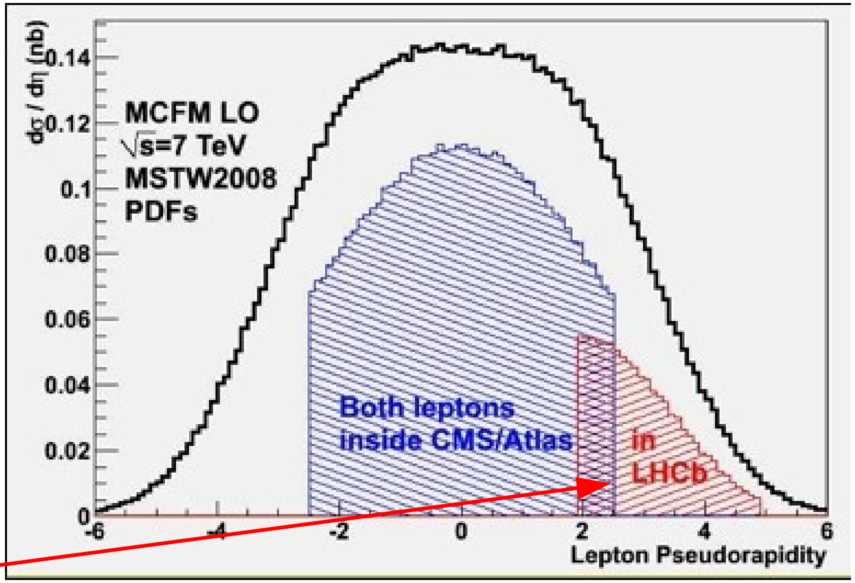
The LHCb detector coverage

- LHCb instrumented region:

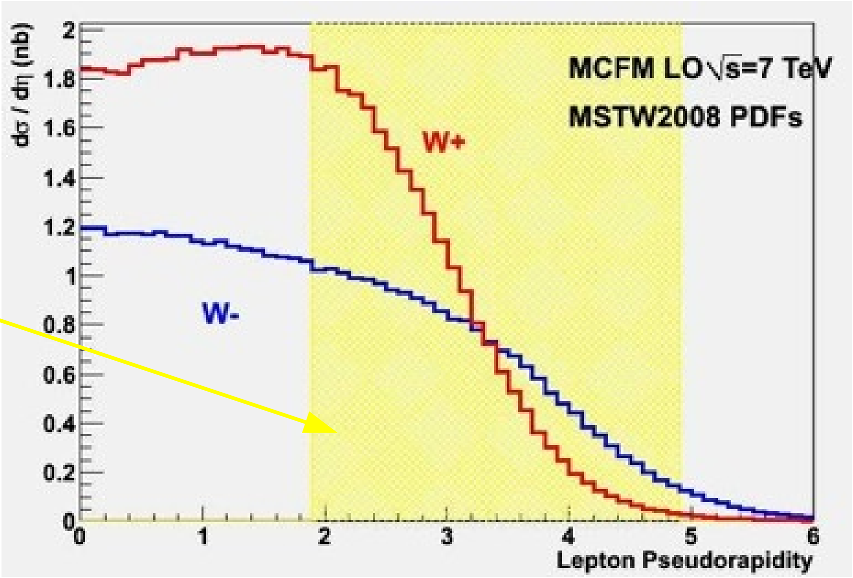
  1.9 < η < 2.5 : overlap with ATLAS and CMS

  2.5 < η< 5 : Unique to LHCb



- 8% of Z decaying leptonically have both leptons inside LHCb

- 16% of W bosons produced inside LHCb

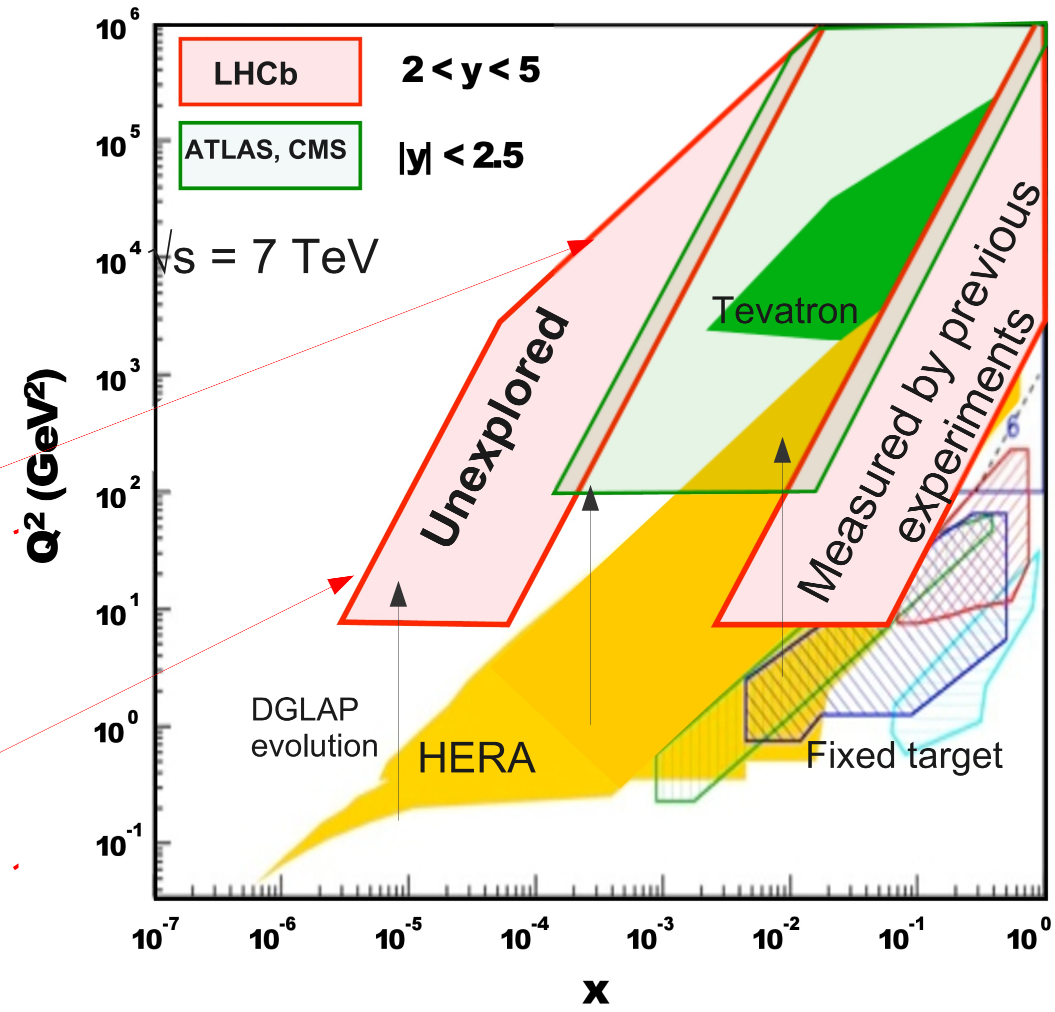


LHCb sensitivity to PDFs

- LHCb probes PDFs at low and high x:

Z, W cross-sections probe unexplored domain
$10^{-4} < x < 10^{-3}$ at $Q \approx 100$ GeV

low mass γ* cross-section probes down to $x = 8.10^{-6}$ at Q = 5 GeV



plot from Thorne et al. ArXiv:0808.1847

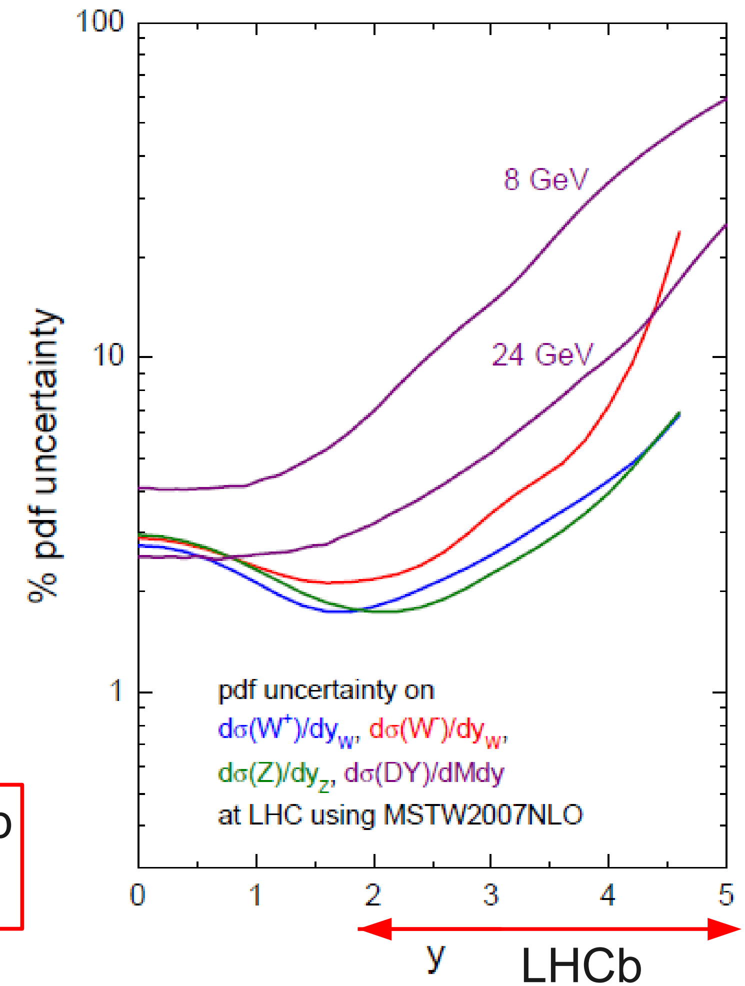
LHCb sensivity to PDFs

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

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

- Electroweak measurements constrain poorly known PDFs and test NNLO partonic cross-sections
  - $W^{+,-}$ and Z differential cross-sections and ratios
  - $\gamma^* \to \mu\mu$ diff. cross-sections:

    PDF uncertainties higher at low γ^* mass



PDF uncertainties are higher in the LHCb kinematic region

LHCb electroweak measurements available

- Z cross section measurements:
  - NEW! $Z \rightarrow \mu\mu$: 1 fb^{-1} LHCb-CONF-2013-007
  - $Z \rightarrow ee$: 1 fb^{-1} JHEP02 (2013) 106, arXiv:1212.4620
  - $Z \rightarrow \tau\tau$: 1 fb^{-1} JHEP01 (2013), 111, arXiv:1210.6289

  (Z stands for Z/γ^* all along the slides)
- $W^{+,-}$ cross section measurement:
  - $W \rightarrow \mu\nu$: 37 pb^{-1} JHEP06(2012)058, arXiv:1204.1620
- Comparison of W and Z LHCb measurement to ATLAS and CMS:
  - NEW! LHCb-CONF-2013-05
- $\gamma^* \rightarrow \mu\mu$ differential cross section at low mass:
  - 37 pb^{-1} LHCb-CONF-2012-013
- Z + jet cross section measurement:
  - Muon channel: 1 fb^{-1} LHCb-CONF-2012-016

} Not discussed today :(

All measurements made at $\sqrt{s}$ = 7 TeV

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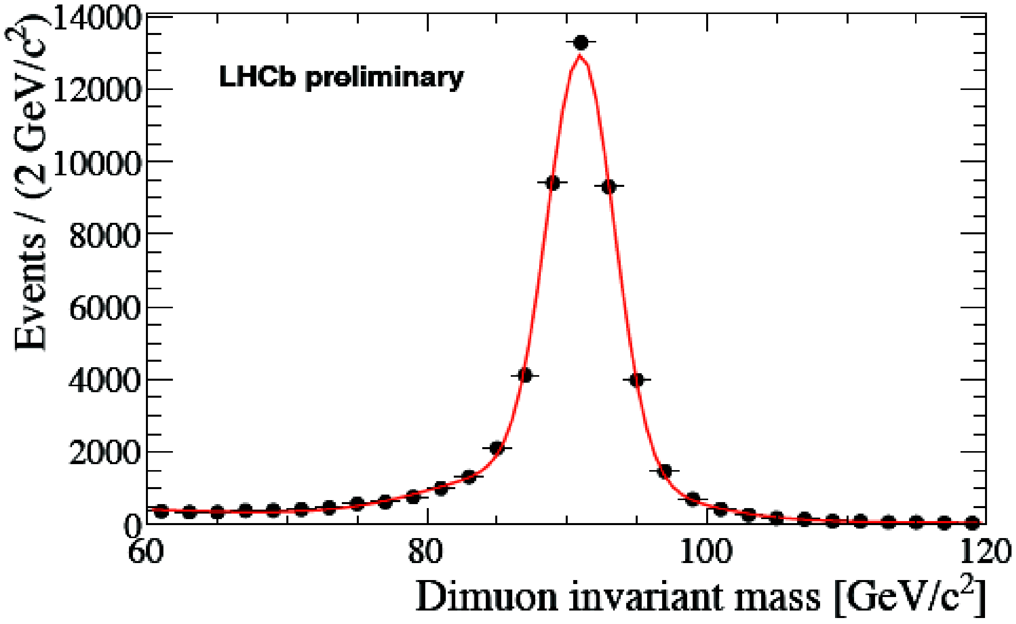
- $W \to \mu\nu$
- Conclusion

$Z \rightarrow \mu\mu$

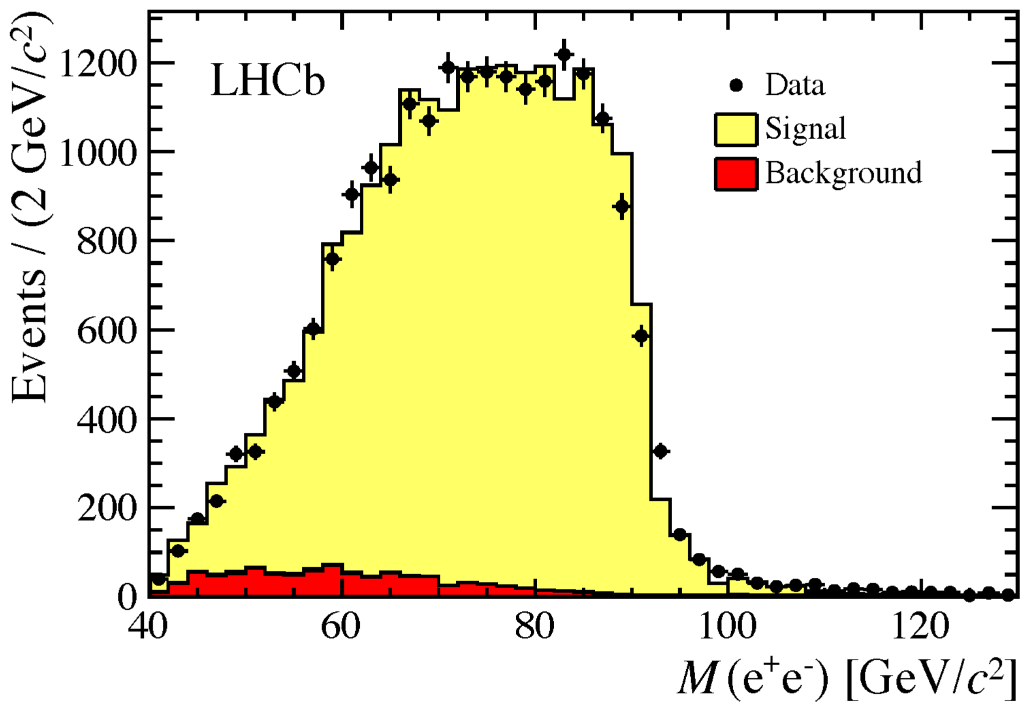


- Trigger: single muon
  - p_T > 10 GeV/c
- Muon selection:
  - 2 < η < 4.5
  - p_T > 20 GeV/c
  - 60 < M(Z) < 120 GeV/c2
- 52632 observed $Z \rightarrow \mu\mu$ candidates
- Backgrounds:
  - Heavy Flavour: 93 ± 13 events (from data)
  - Hadron mis-id: 25 ± 5 events (from data)
  - Electroweak and top: 35 ± 3 events (from simulation)

Purity: 0.9969 ± 0.0003

Z → ee

- Trigger: single electron
  - p_T > 10 or 15 GeV/c
- Electron selection:
  - 2 < η < 4.5
  - p_T > 20 GeV/c
  - M(ee) > 40 GeV/c2



- Backgrounds:
  - Hadron mis-id, Heavy Flavour: from same-sign $e^{\pm}e^{\pm}$ data
  - Z→ττ and top: from simulation
- Purity: 95%

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$Z \rightarrow \tau\tau$

- Trigger:

  $p_T(\mu)$ > 10 GeV/c or $p_T(e)$ > 15 GeV/c

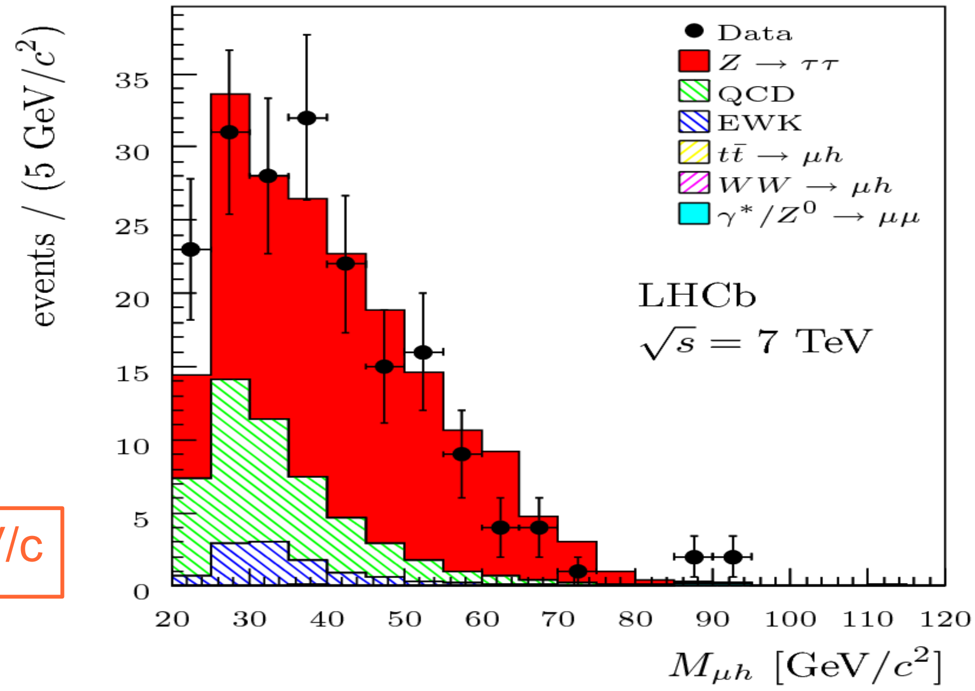
- Channels and selection:

  $Z \rightarrow \tau_\mu\tau_\mu, \tau_\mu\tau_e, \tau_e\tau_\mu$

  $Z \rightarrow \tau_\mu\tau_h, \tau_e\tau_h$ (1-prong)

$p_T(e/\mu)$ > 20 GeV/c	$p_T(e/\mu/h)$ > 5 GeV/c

2 < η(e/μ) < 4.5 ; 2.25 < η(h) < 3.75
60 < M(ττ) < 120 GeV/c^2



- Main backgrounds:
  - QCD and W+jet: from same sign ττ data
  - Z/γ*→μμ : from Z→μμ resonance and low impact parameter sidebands
- Purity: 65-70% in all channels
- Analysis extended to H→ ττ search (see P. Ilten's slides)

Z cross-section determination

- For Z → μμ, in a bin Δ, sum over range of the selected events:

$$\sigma(\Delta) = \frac{\rho\, fFSR(\Delta)\, fMGR(\Delta)}{LA} \sum_k \frac{1}{\varepsilon\,(\eta_k^{\mu+}, \eta_k^{\mu-}, PV_k)}$$

Number of Primary Vertices in event k

- ρ : Purity
- L: Luminosity = 1.013 ± 0.036 fb^{-1}
- A: Acceptance from simulation (~ 1)
- f_{FSR}: Final State Radiation correction (Herwig++)
- f_{MGR}: Correction factor for bin-bin migrations (Pythia + Geant simulation)
- ε : Event by event efficiencies depending on number of Primary Vertices and muon η
  - $\varepsilon = \varepsilon_{trigger}.\varepsilon_{tracking}.\varepsilon_{identification}$

Efficiencies

- $\varepsilon = \varepsilon_{trigger} . \varepsilon_{tracking} . \varepsilon_{lepton\ identification}$
- Determined with tag & probe methods in the Z data sample

  Tag: well identified e/μ

  Probe:

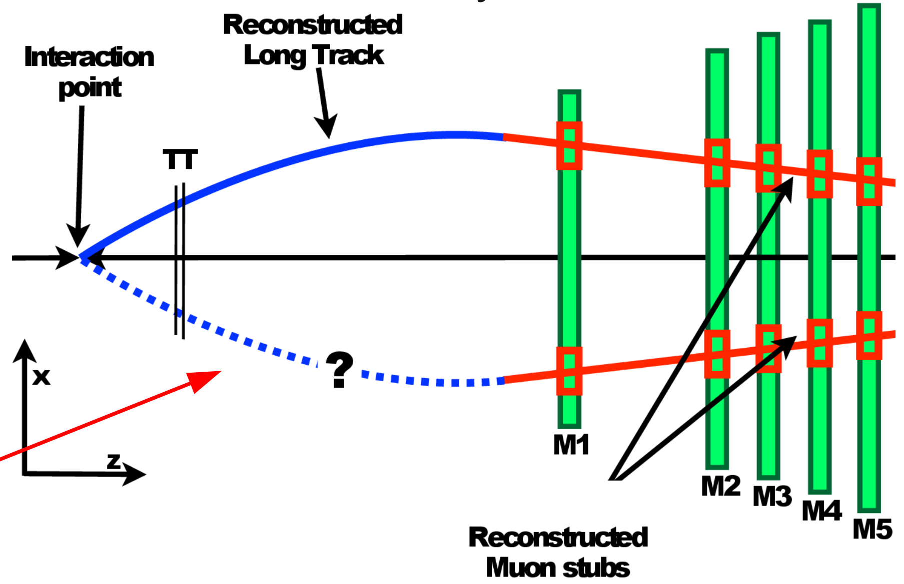
  trigger eff.: identified e/μ

  muon tracking eff.: muon stubs

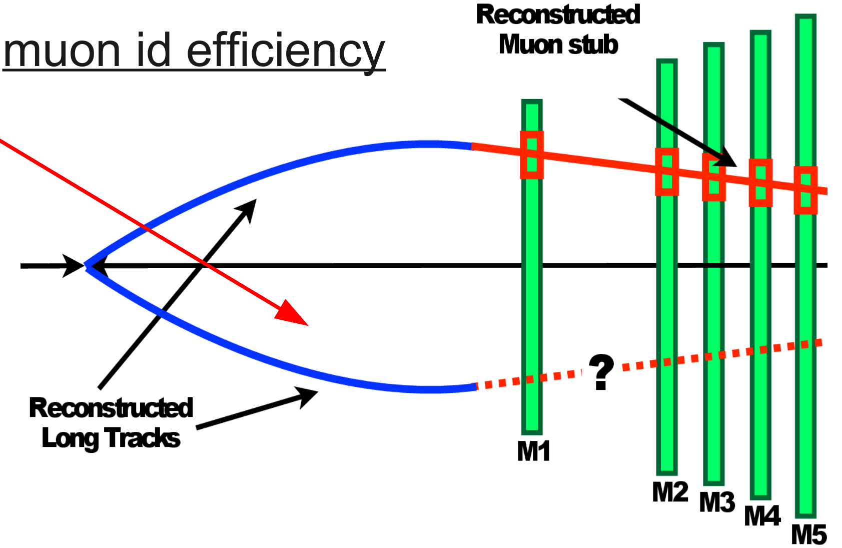
  identification eff.: reconstructed track

  Electron tracking eff. from MC
- Typical efficiencies:
  - Muon tracking: 90%
  - Muon id: 99%
  - Muon trigger for $Z \to \mu\mu$: 90%
  - electron id: 92%

muon track efficiency



muon id efficiency



$Z \to \mu\mu$: Systematic uncertainties

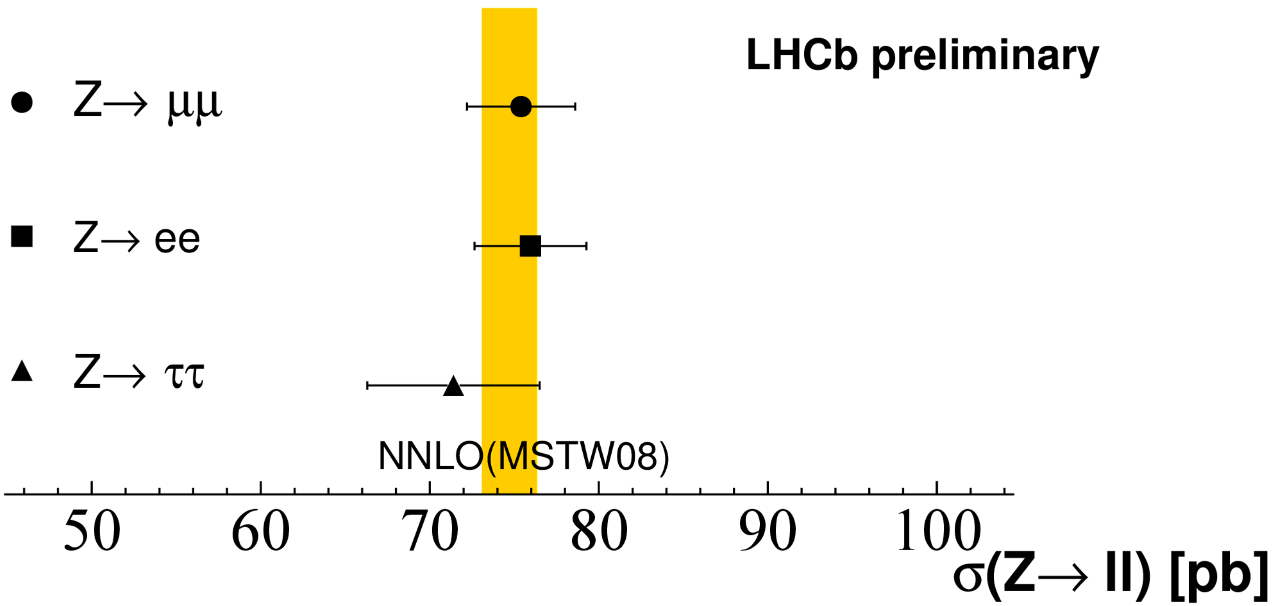
LHCb preliminary

Source	Uncertainty (%)
Tracking efficiency	± 1.1
Global Event Cut efficiency	± 1.1
Muon trigger efficiency	± 0.5
Muon-id efficiency	± 0.5
Magnet polarity	± 1.6
Bin-to-bin migrations	± 0.7
FSR corrections	± 0.2
Signal purity	± 0.03
TOTAL	± 2.5
Luminosity	± 3.5

Mostly statistically based : will decrease with more data

Systematic uncertainties for other Z channels in backup

Z cross-sections: Results



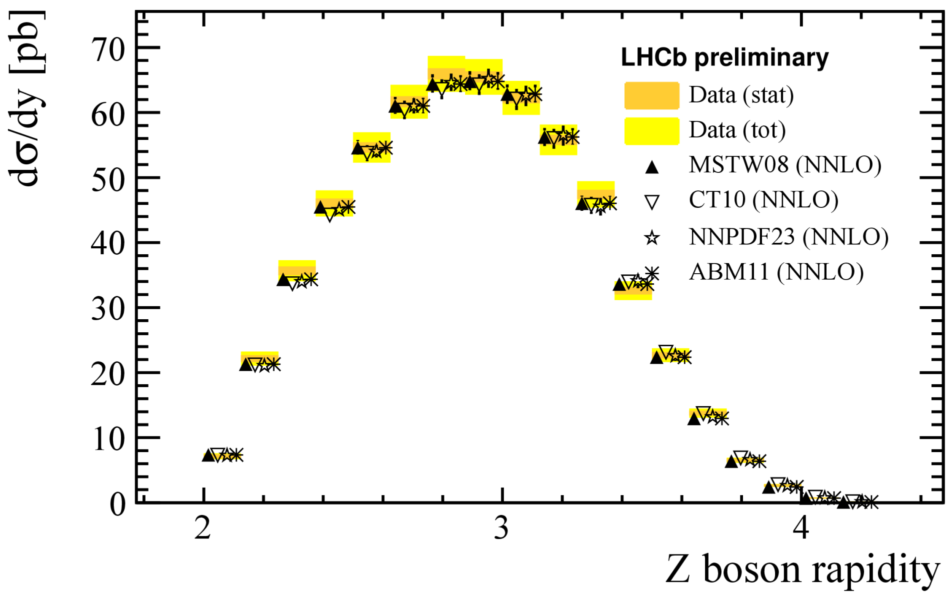
Inclusive Z cross section for leptons with $p_T > 20$ GeV/c and $2.0 < \eta < 4.5$ and $60 < \text{mass}(Z) < 120$ GeV/c^2 :

$\sigma(pp\to Z\to\mu\mu) = 75.4 \pm 0.3(\text{stat}) \pm 1.9(\text{sys}) \pm 2.6(\text{lum})$ pb
$\sigma(pp\to Z\to ee) = 76.0 \pm 0.8(\text{stat}) \pm 2.0(\text{sys}) \pm 2.6(\text{lum})$ pb
$\sigma(pp\to Z\to\tau\tau) = 71.4 \pm 3.5(\text{stat}) \pm 2.8(\text{sys}) \pm 2.5(\text{lum})$ pb

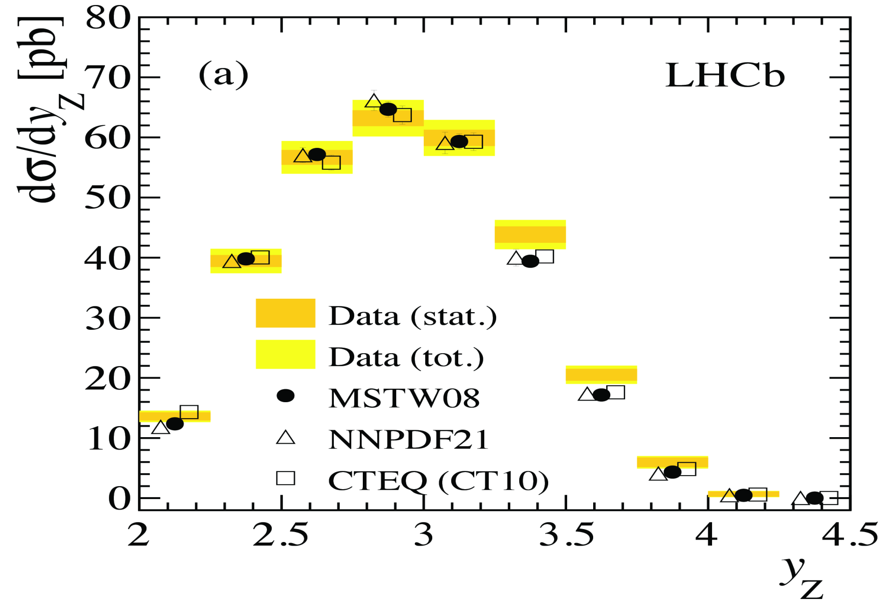
Good agreement between channels and with NNLO prediction from FEWZ using MSTW08 PDF

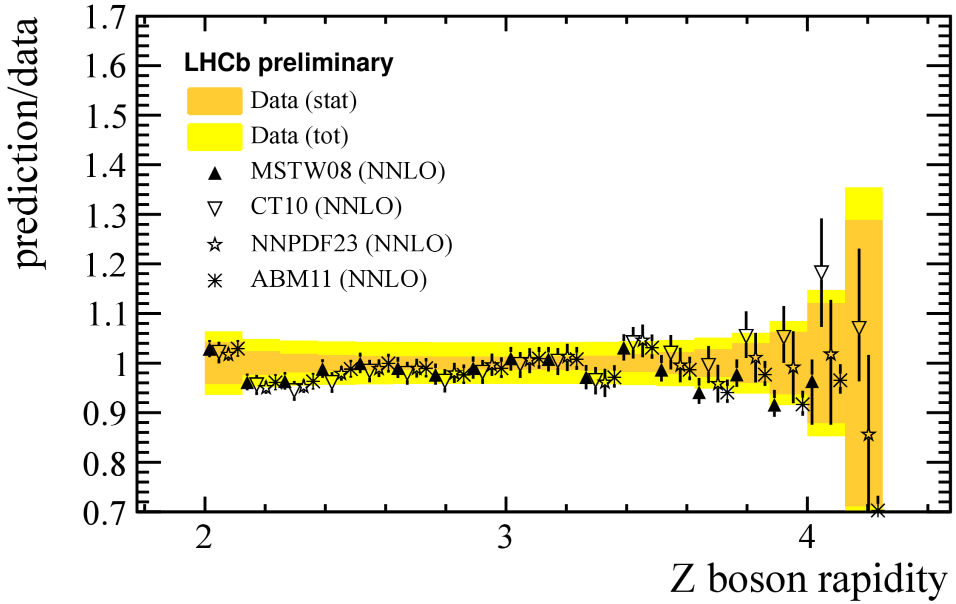
dσ(Z)/dy

Z→μμ



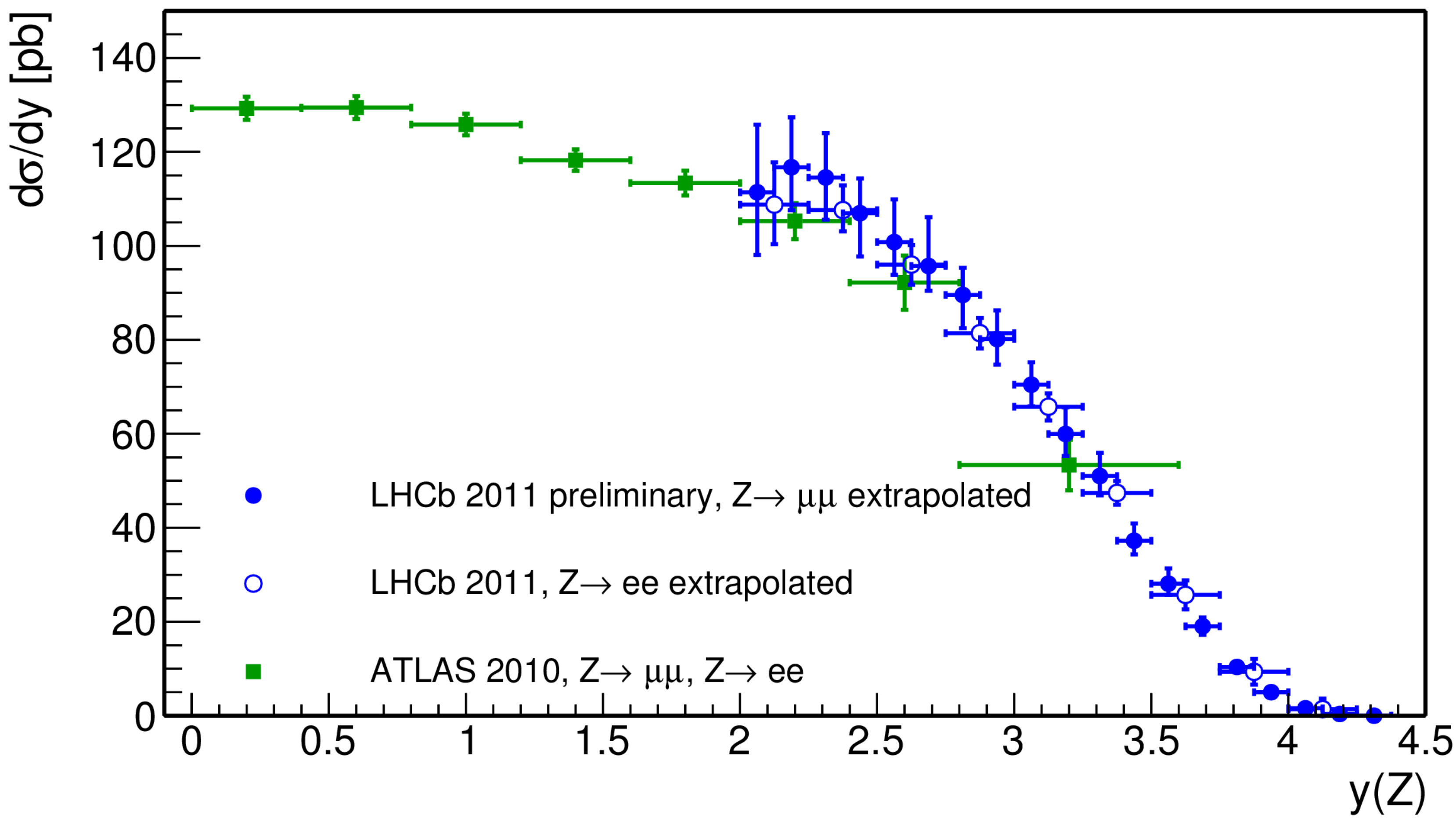
Z→ee





- Good agreement with NNLO predictions from FEWZ using several PDFs
- Present LHCb systematic error comparable with PDF systematics

dσ(Z)/dy



- LHCb cross sections extrapolated to the ATLAS fiducial volume with FEWZ at NLO
- Agreement with ATLAS result observed

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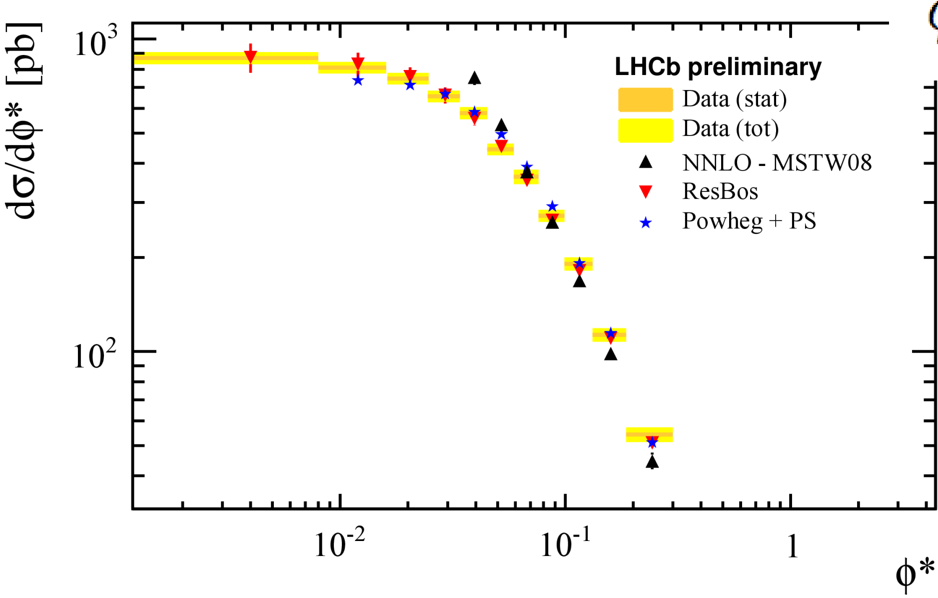
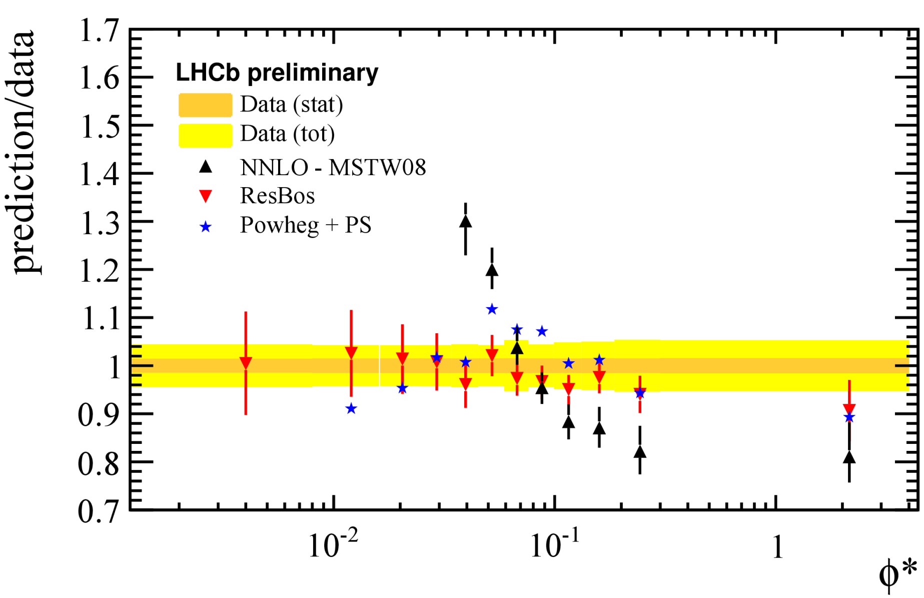
dσ(Z)/dΦ*

Z→μμ

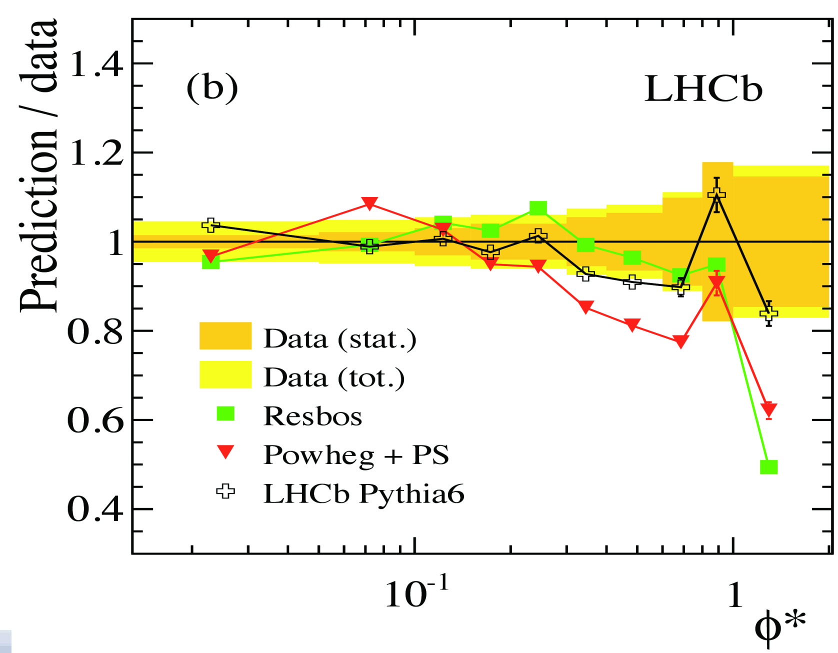


$$\phi^* = tan(\phi_{acop}/2)/cosh(\Delta\eta/2) \simeq p_T/M$$

- Φ* : variable less dependent on momentum resolution
- Φ* distributions described better by Resbos and Powheg than by NNLO (FEWZ)



Z→ee



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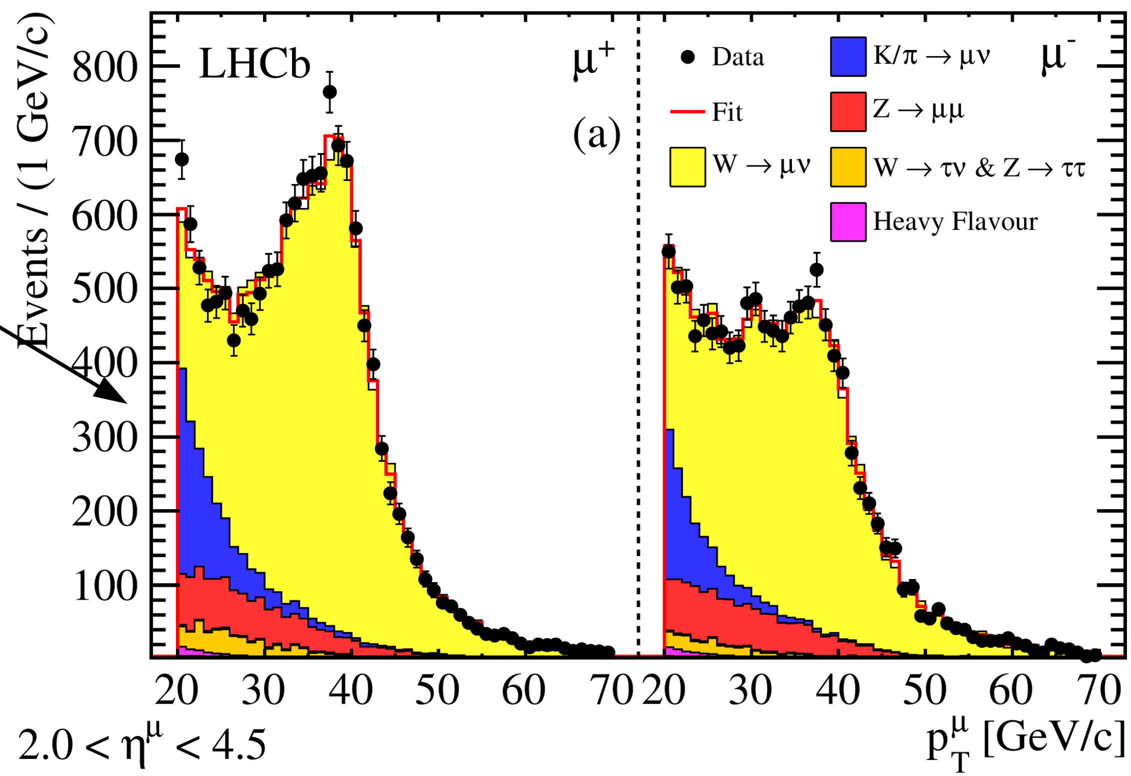
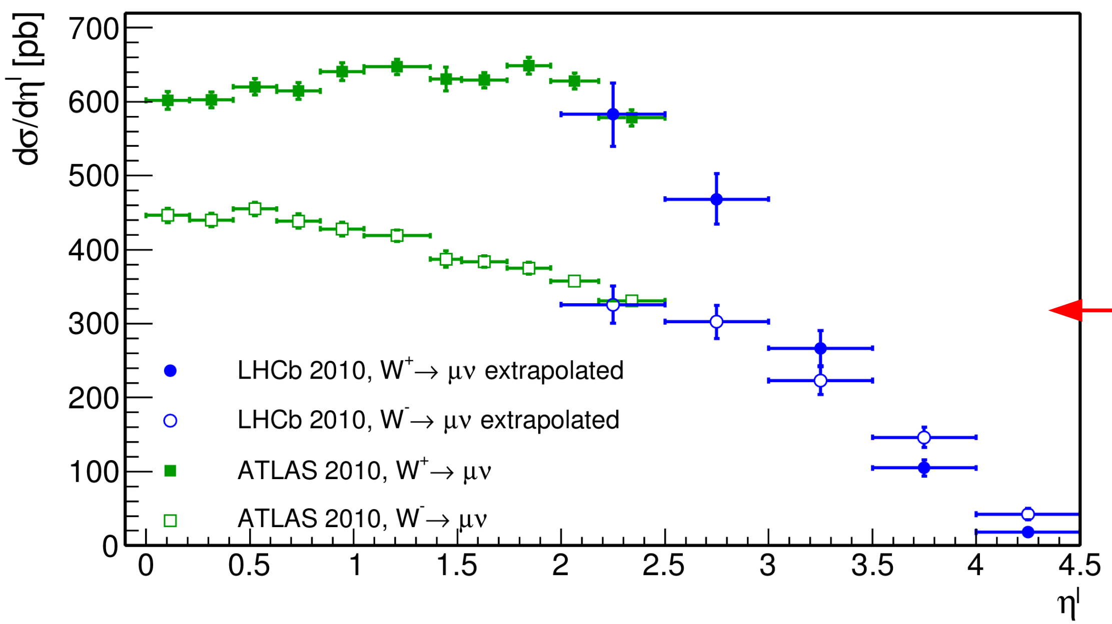
W→μν analysis summary

- Trigger: single muon p_T>10 GeV/c
- Dataset: 37 pb^{-1}, $\sqrt{s}$ = 7 TeV
- Fiducial volume:
  - $2 < \eta(\mu) < 4.5$
  - $20 < p_T(\mu) < 70$ GeV/c
- Purity:
  - from a template fit to the muon p_T distribution
  - around 78% in both W^+ and W^- samples
- N candidates:
  - 14610 W^+
  - 11618 W^-

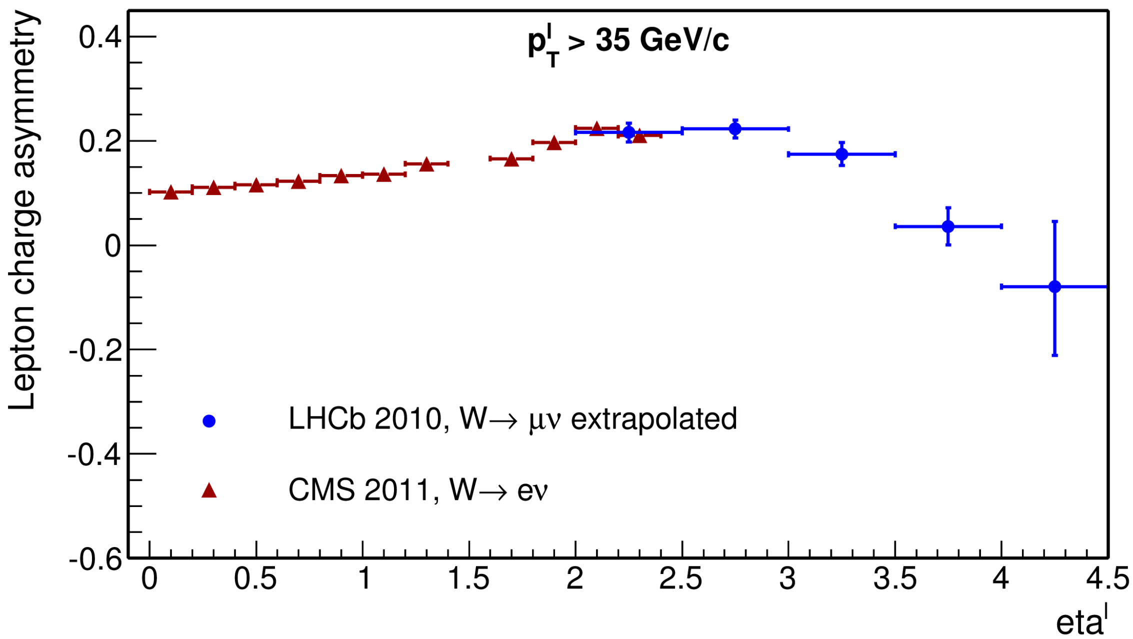


W→μν analysis summary



- $W^{+,-}$ cross sections extrapolated and compared to ATLAS
- Good agreement in overlap region

- W Lepton charge asymmetry extrapolated and compared to CMS
- Good agreement in overlap region



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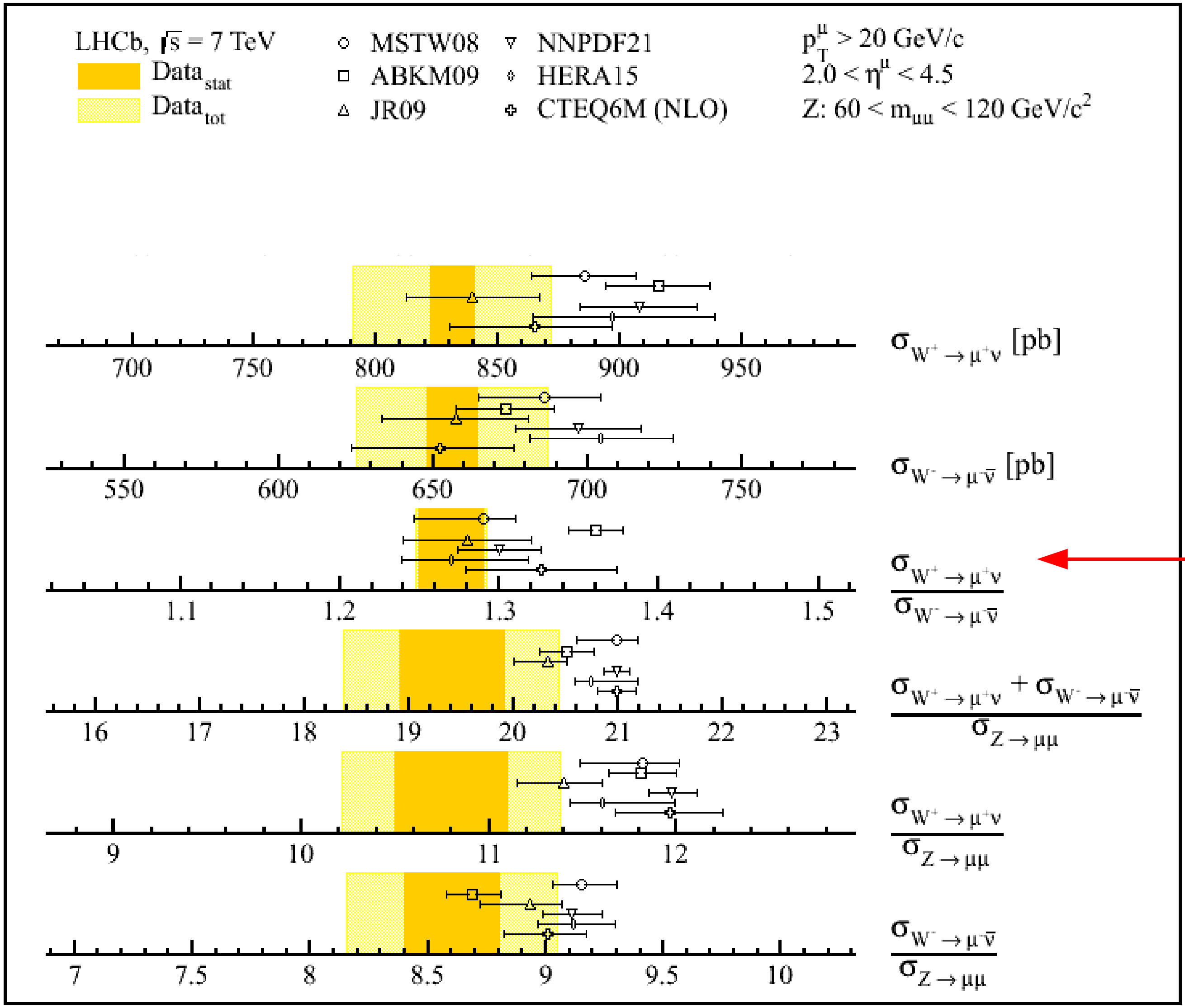
Summary of W measurements and comparison with PDF predictions



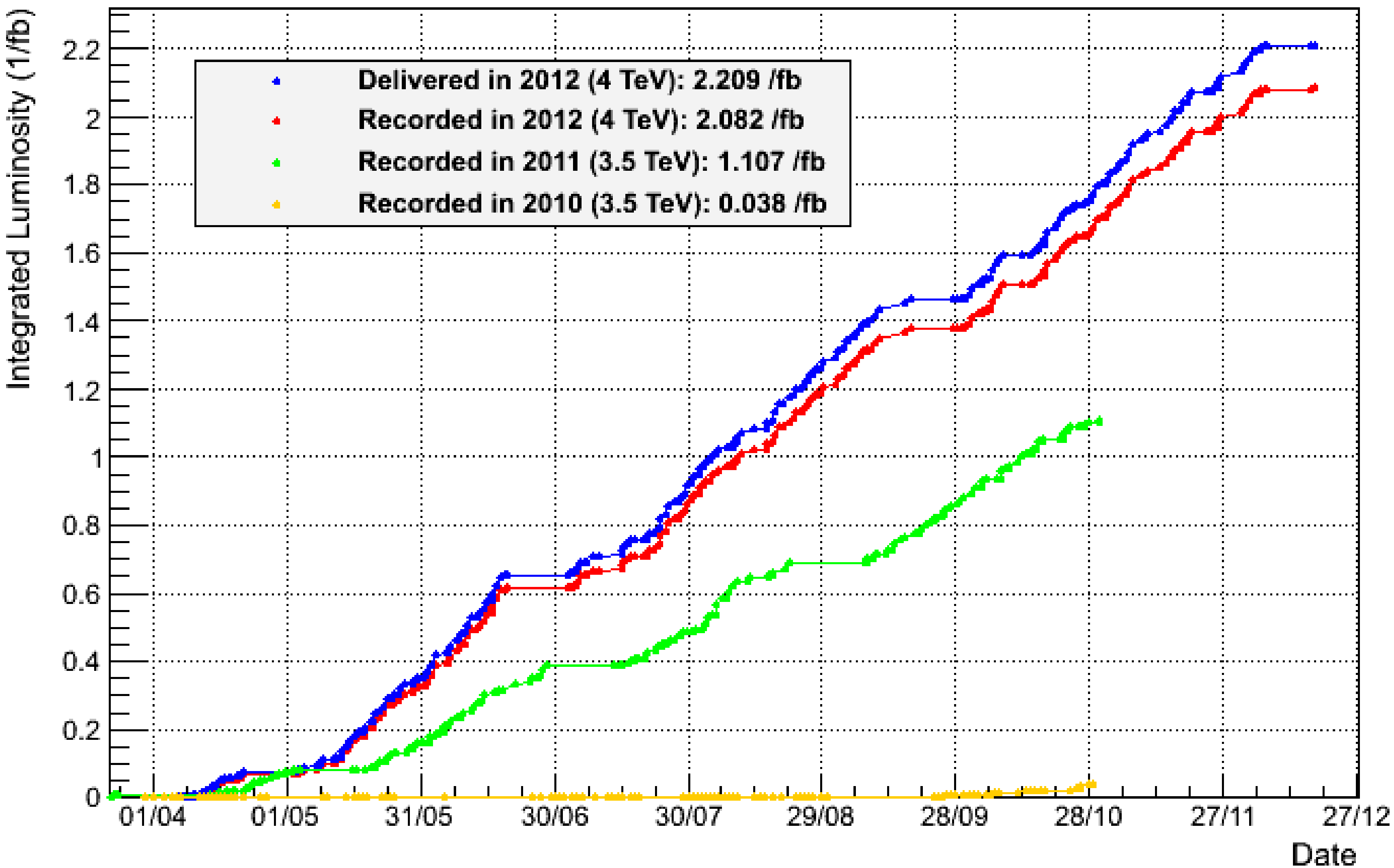
$\sigma(W^+)/\sigma(W^-)$ ratio most precise! (1.7 %)

Conclusion and outlook

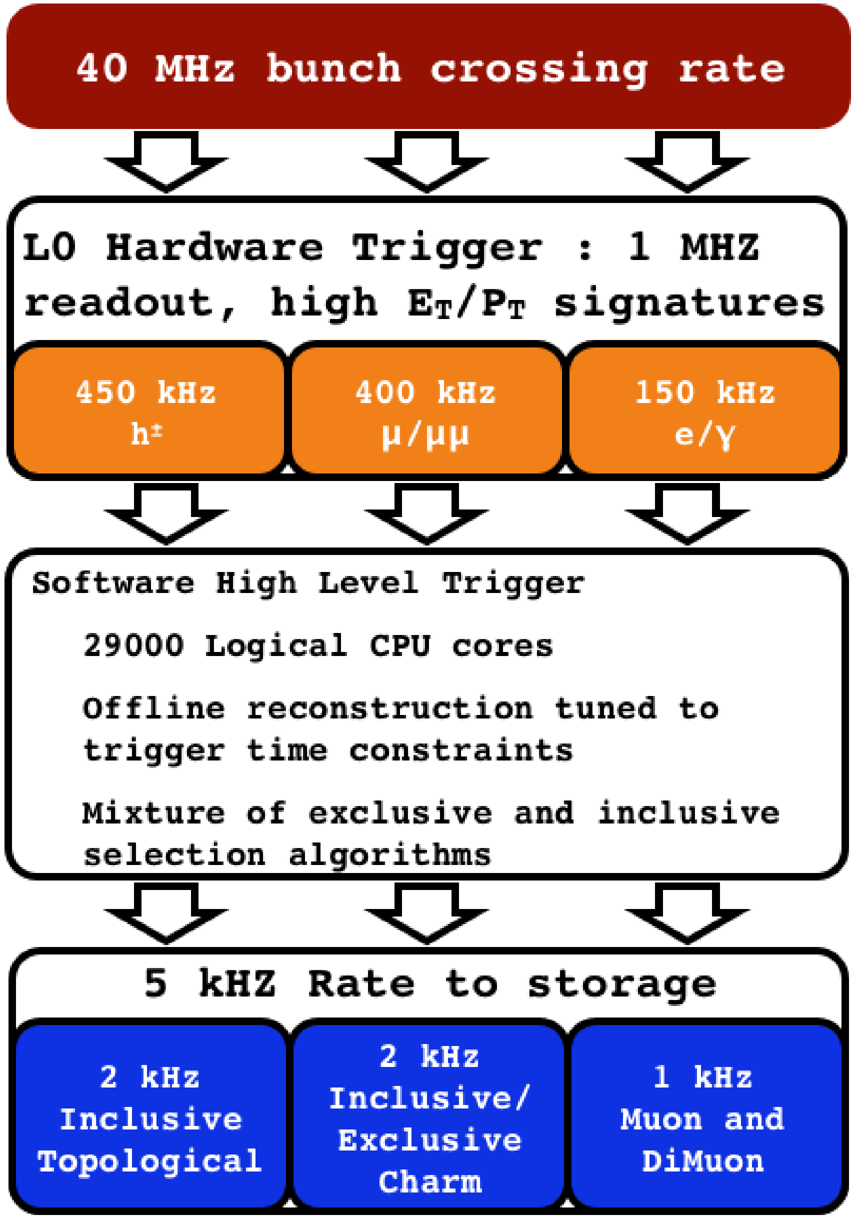
- Electroweak boson cross section measurements at LHCb have been presented in $Z \rightarrow \mu\mu$, ee, $\tau\tau$ channels and $W \rightarrow \mu\nu$, as well as ratios
- These results have been compared to fixed-order QCD calculations with different PDFs
  - NNLO in agreement with measured inclusive cross-section and Z rapidity distributions
  - RESBOS and POWHEG model Z p_T and Φ^* best
- Future improvements include:
  - 1 fb^{-1} $W \rightarrow \mu\nu$ measurements at 7 TeV forthcoming
  - 8 TeV dataset analysis (~2 fb^{-1})
    - Profit from more precise luminosity measurement
    - Sensitivity to lower x with low mass DY
  - Most systematics are statistically based
    - Reduced with more data

Backup

LHCb Integrated Luminosity pp collisions 2010-2012



LHCb Trigger overview



Global Event Cut (GEC)

- At LHCb, Global Event Cuts are applied in the trigger in order to prevent very large events from dominating the processing time
- Most important cut is on the multiplicity of SPD hits:
  - $N_{SPD} < 600$ in the single electron and muon trigger cases (used for $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$)
- Efficiency measured from data:
  - Using $Z \rightarrow \mu\mu$ events triggered alternatively with a dimuon trigger, for which a looser GEC is set ($N_{SPD} < 900$)
  - 95% in the electron case
  - 96% in the muon case

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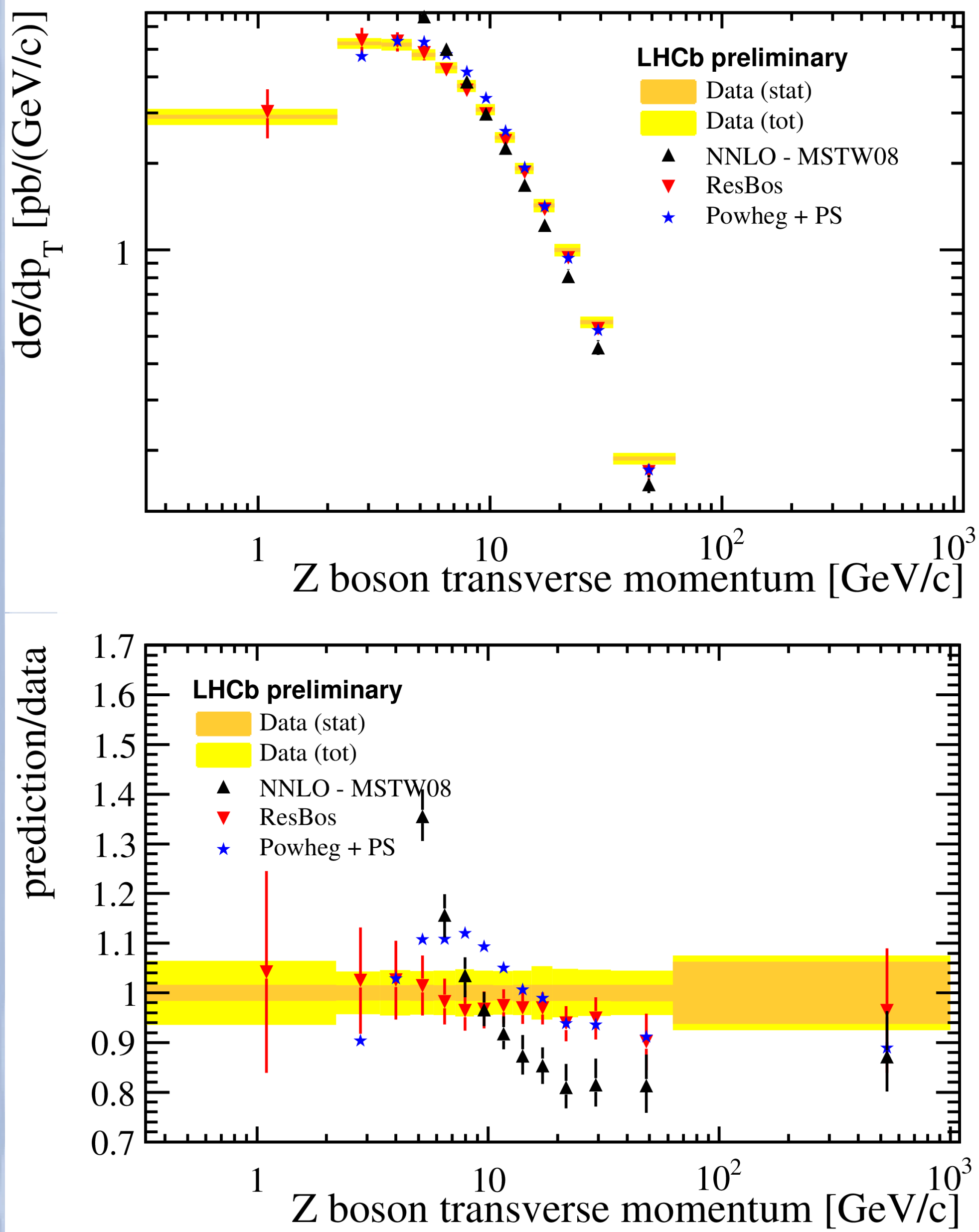
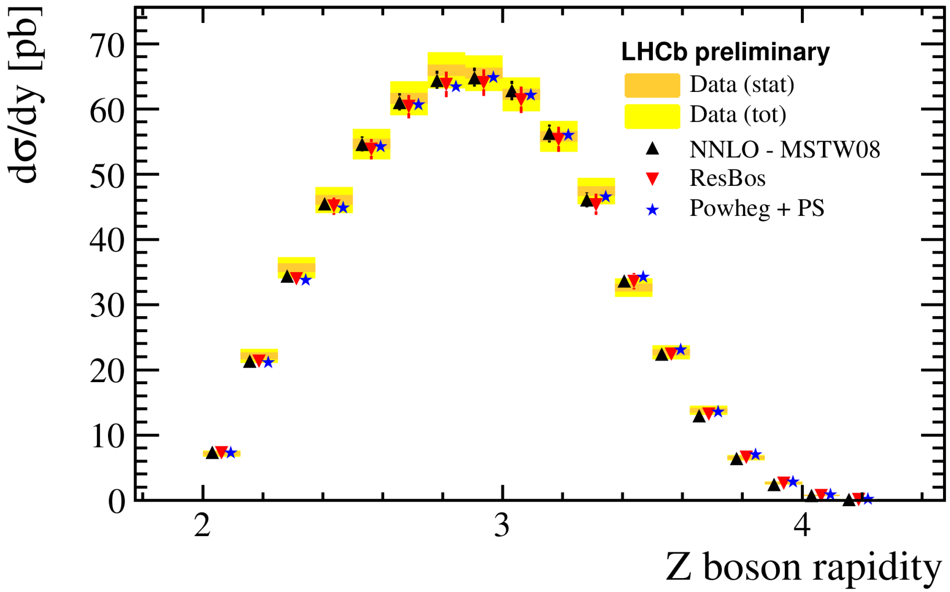
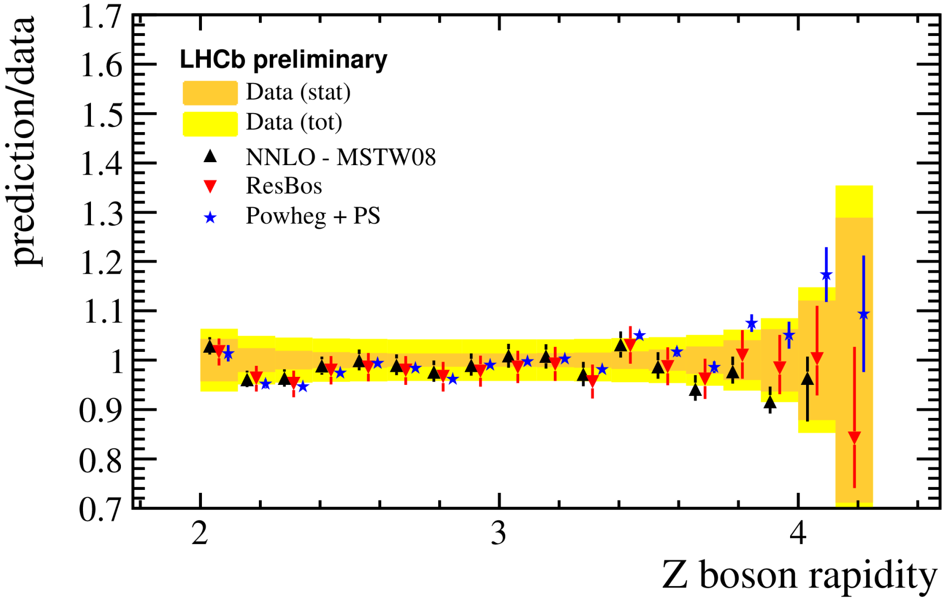
dσ(Z→μμ)/dp_T



- Observed Z p_T distributions compared to NLO (Resbos, Powheg) and NNLO calculations (FEWZ)
- Good agreement observed

dσ(Z→μμ)/dy





- Observed Z rapidity distributions compared to NLO (Resbos, Powheg) and NNLO calculations (FEWZ)
- Good agreement observed

$Z \rightarrow ee$: efficiencies and uncertainties

$$\sigma(pp \rightarrow Z \rightarrow e^+e^-) = \frac{N(e^+e^-) - N(e^\pm e^\pm)}{\epsilon_{GEC} \cdot \epsilon_{trig} \cdot \epsilon_{track} \cdot \epsilon_{kin} \cdot \epsilon_{PID} \cdot \int \mathcal{L}dt} \cdot f_{FSR} \cdot f_{MZ}$$

f_{MZ}: correction factor to make up for dielectron events outside the mass range 60 < M(ee) < 120 GeV which pass the event selection.
Estimated from simulation.

Quantity	**Valeur ± uncertainty** LHCb
N_{bkg} from same sign ev. = $N(e^\pm e^\pm)$	974 ± 78
ε_{GEC}	0.947 ± 0.004
ε_{trig}	0.715 ± 0.021 (I) / 0.899 ± 0.003 (II)
ε_{track}	0.913 ± 0.015
ε_{kin}	0.500 ± 0.007
ε_{PID}	0.844 ± 0.011
f_{FSR}	1.049 ± 0.005
F_{MZ}	0.967 ± 0.001
Luminosity (pb^{-1})	581 ± 20 (I) / 364 ± 13 (II)

Two data periods: I and II

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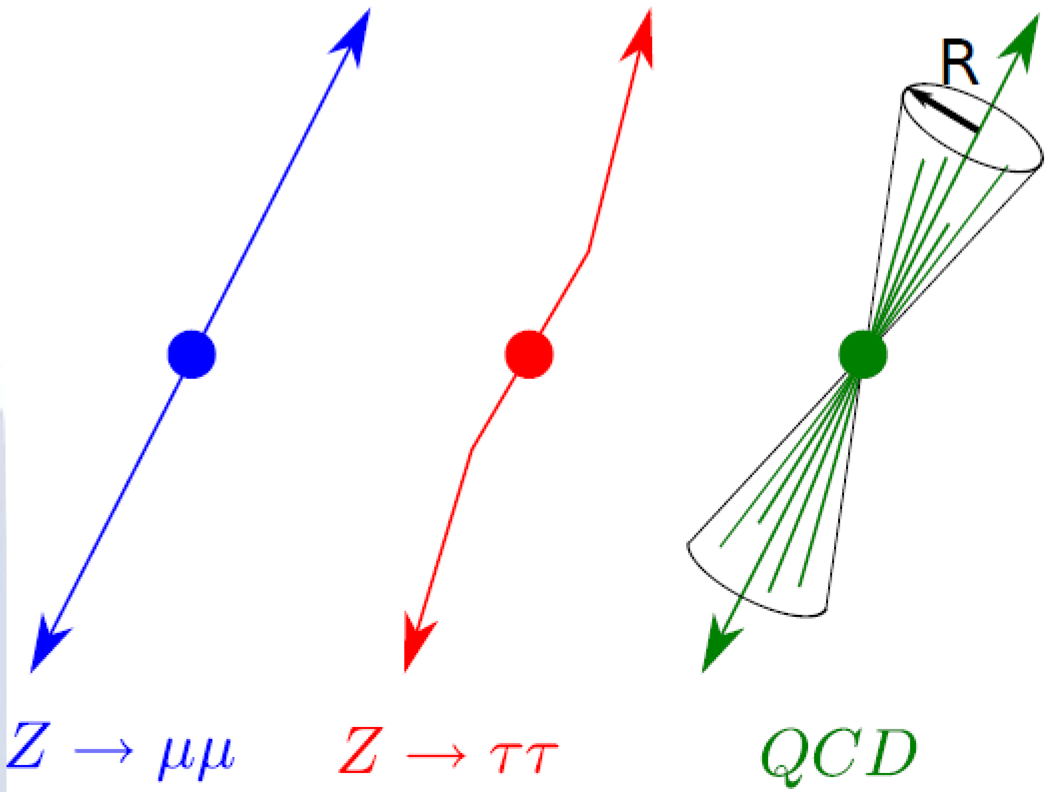
$Z \rightarrow \tau\tau$: Tau identification



$$R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.5$$

$$I = \frac{p_T^{\ell} - p_T^{cone}}{p_T^{\ell} + p_T^{cone}} \qquad A_{p_T} = \frac{p_T^1 - p_T^2}{p_T^1 + p_T^2}$$

$$I_{pT} = p_T^{\,l} - p_T^{\,cone}$$

- Use the fact that Tau tracks are produced isolated with large impact parameters:

$I_{pT} < 1$ GeV/c for $\tau_l\tau_l$

$I_{pT} < 2$ GeV/c for $\tau_l\tau_h$

IPS: Impact Parameter Significance:
Sum of the IP of the two taus divided by their combined uncertainty

IPS > 9 for $\tau_l\tau_h$ and $\tau_\mu\tau_\mu$

$A_{PT} > 0.3$ for $\tau_\mu\tau_\mu$

$Z \rightarrow \tau\tau$: Systematic uncertainties

Table 2: Systematic uncertainties expressed as a percentage of the cross-section for each $Z \rightarrow \tau\tau$ analysis stream. Contributions from acceptance $\mathcal{A}$, branching fractions $\mathcal{B}$, number of background events N_{bkg}, reconstruction efficiencies ε_{rec}, and selection efficiencies ε_{sel} are listed. The superscripts on $\varepsilon_{\text{trk}}{}^{(i)}$ and $\varepsilon_{\text{id}}{}^{(i)}$ indicate the first or second τ lepton decay product candidate. The percentage uncertainties on the cross-section for N_{bkg} are quoted for each individual background, as well as the total background. The efficiency uncertainties are split in a similar fashion.

Stream		$\Delta\sigma_{pp\rightarrow Z\rightarrow\tau\tau}$ [%]				
		$\tau_\mu\tau_\mu$	$\tau_\mu\tau_e$	$\tau_e\tau_\mu$	$\tau_\mu\tau_h$	$\tau_e\tau_h$
$\mathcal{A}$		1.48	1.61	1.32	1.10	1.11
$\mathcal{B}$		0.46	0.32	0.32	0.32	0.33
N_{bkg}	N_{QCD}	4.33	0.80	3.08	0.40	0.92
	N_{EWK}	4.22	1.54	1.52	0.40	0.72
	$N_{t\bar{t}}$	0.02	0.08	0.12	0.00	0.58
	N_{WW}	0.02	0.14	0.13	0.09	0.08
	N_Z	8.00	–	–	0.22	0.23
Total N_{bkg}		10.03	1.75	3.44	0.61	1.32
ε_{rec}	ε_{GEC}	0.10	0.10	0.10	0.10	0.10
	ε_{trg}	0.88	0.71	2.29	0.72	4.30
	$\varepsilon_{\text{trk}}{}^{(1)}$	0.71	0.74	3.67	0.79	3.67
	$\varepsilon_{\text{trk}}{}^{(2)}$	0.34	3.67	0.61	1.76	1.68
	$\varepsilon_{\text{id}}{}^{(1)}$	0.38	0.28	1.72	0.29	1.73
	$\varepsilon_{\text{id}}{}^{(2)}$	0.78	0.18	0.56	0.03	0.09
Total ε_{rec}		1.47	4.21	4.73	2.08	6.15
ε_{sel}	ε_{kin}	–	1.04	2.89	–	1.91
	$\varepsilon_{I_{p_T}}$	1.79	1.91	3.19	1.65	2.75
	$\varepsilon_{\lvert\Delta\Phi\rvert}$	1.08	1.03	1.86	0.60	0.97
	ε_{IPS}	2.70	–	–	1.92	2.85
	$\varepsilon_{A_{p_T}}$	2.03	–	–	–	–
Total ε_{sel}		3.97	2.41	4.69	2.60	4.50
Total systematic		11.13	5.41	7.56	3.88	7.88

LHCb

$Z \rightarrow \tau\tau$: Acceptance, efficiencies, number of events

LHCb

Table 1: Acceptance factors, branching fractions, selection efficiencies, numbers of background and observed events for each $Z \rightarrow \tau\tau$ analysis stream.

Stream	$\mathcal{A}$	$\mathcal{B}$ [%]	ε_{sel}	N_{bkg}	N
$\tau_\mu\tau_\mu$	0.405 ± 0.006	3.031 ± 0.014	0.138 ± 0.006	41.6 ± 8.5	124
$\tau_\mu\tau_e$	0.248 ± 0.004	6.208 ± 0.020	0.517 ± 0.012	129.7 ± 4.9	421
$\tau_e\tau_\mu$	0.152 ± 0.002	6.208 ± 0.020	0.344 ± 0.016	56.6 ± 3.3	155
$\tau_\mu\tau_h$	0.182 ± 0.002	16.933 ± 0.056	0.135 ± 0.004	53.3 ± 0.8	189
$\tau_e\tau_h$	0.180 ± 0.002	17.341 ± 0.057	0.082 ± 0.004	36.6 ± 0.9	101

Hadron identification efficiency: Obtained from minimum bias data
- Assuming the highest p_T track to be a hadron, compute the probability for it to pass the hadron identification efficiency requirements (E(HCAL)/p > 0.05)

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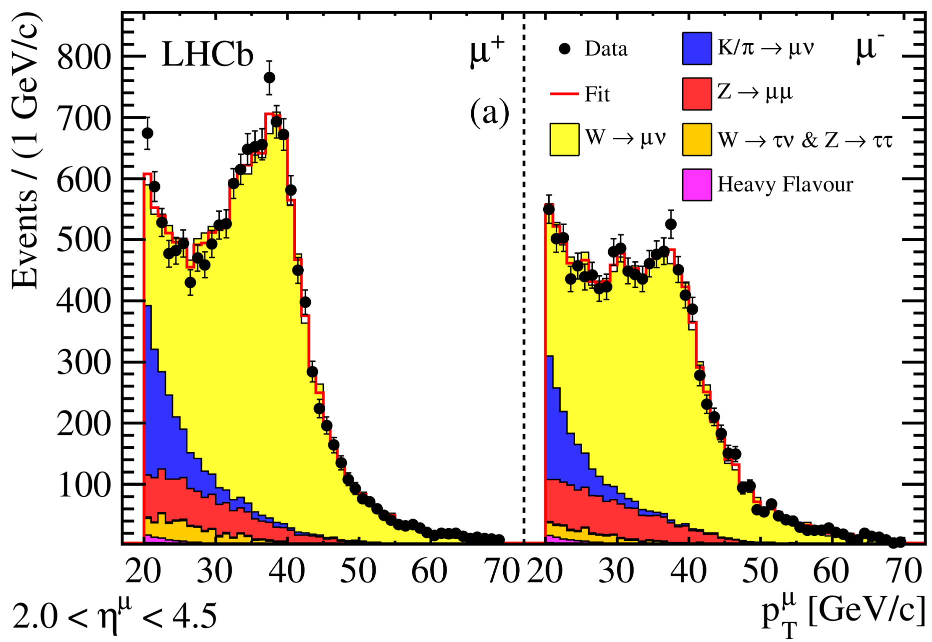
W→μν analysis

- Purity:

  - from a template fit to the muon pT distribution:

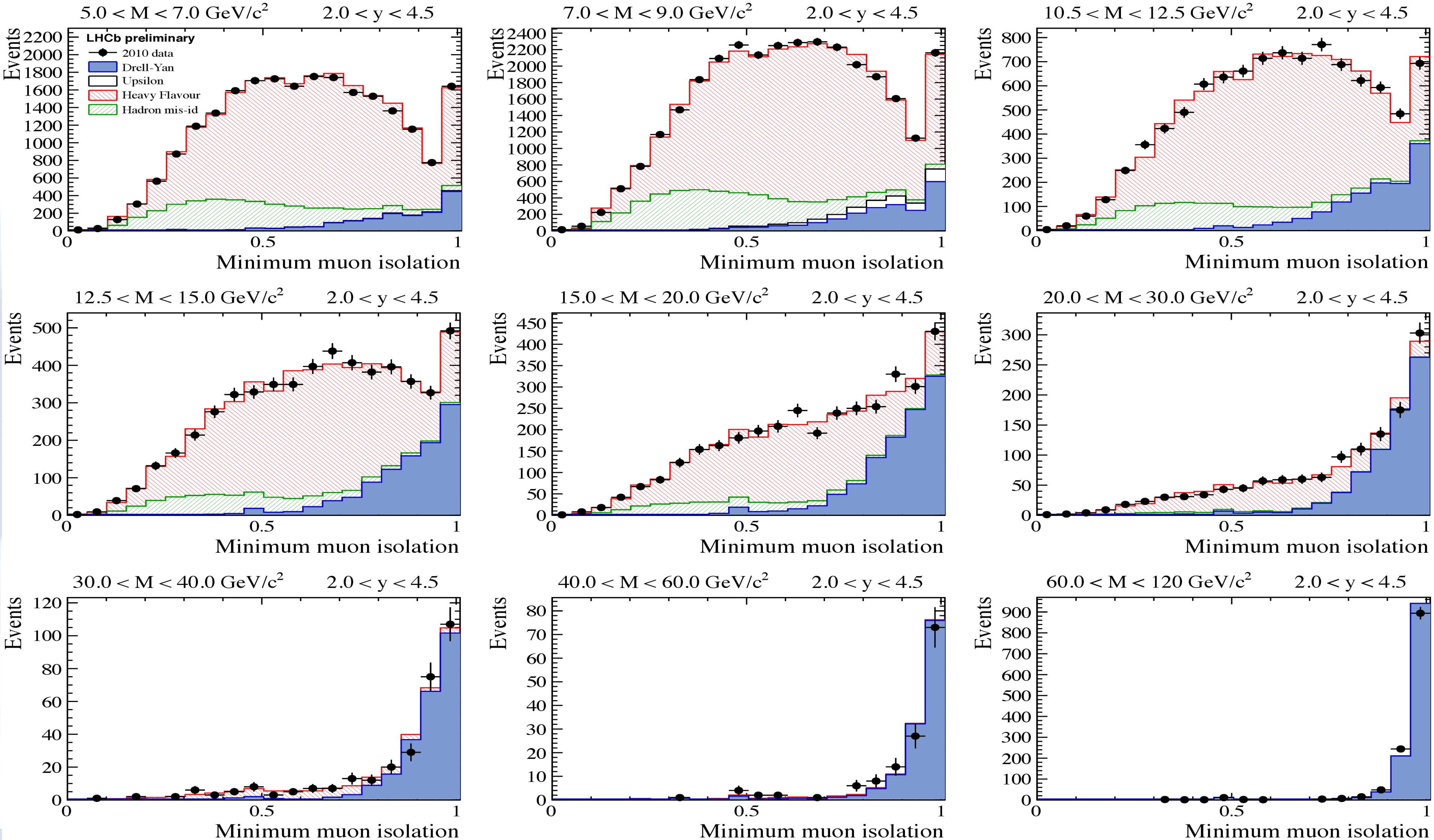
	Shape	Norm.
W →μν	Simulation	Fit
K/π decay in flight	Data	Fit
γ*/Z→μμ	Simulation	Fixed
W→τν , Z→ττ	Simulation	Fixed
Heavy Flavour	Data	Fixed



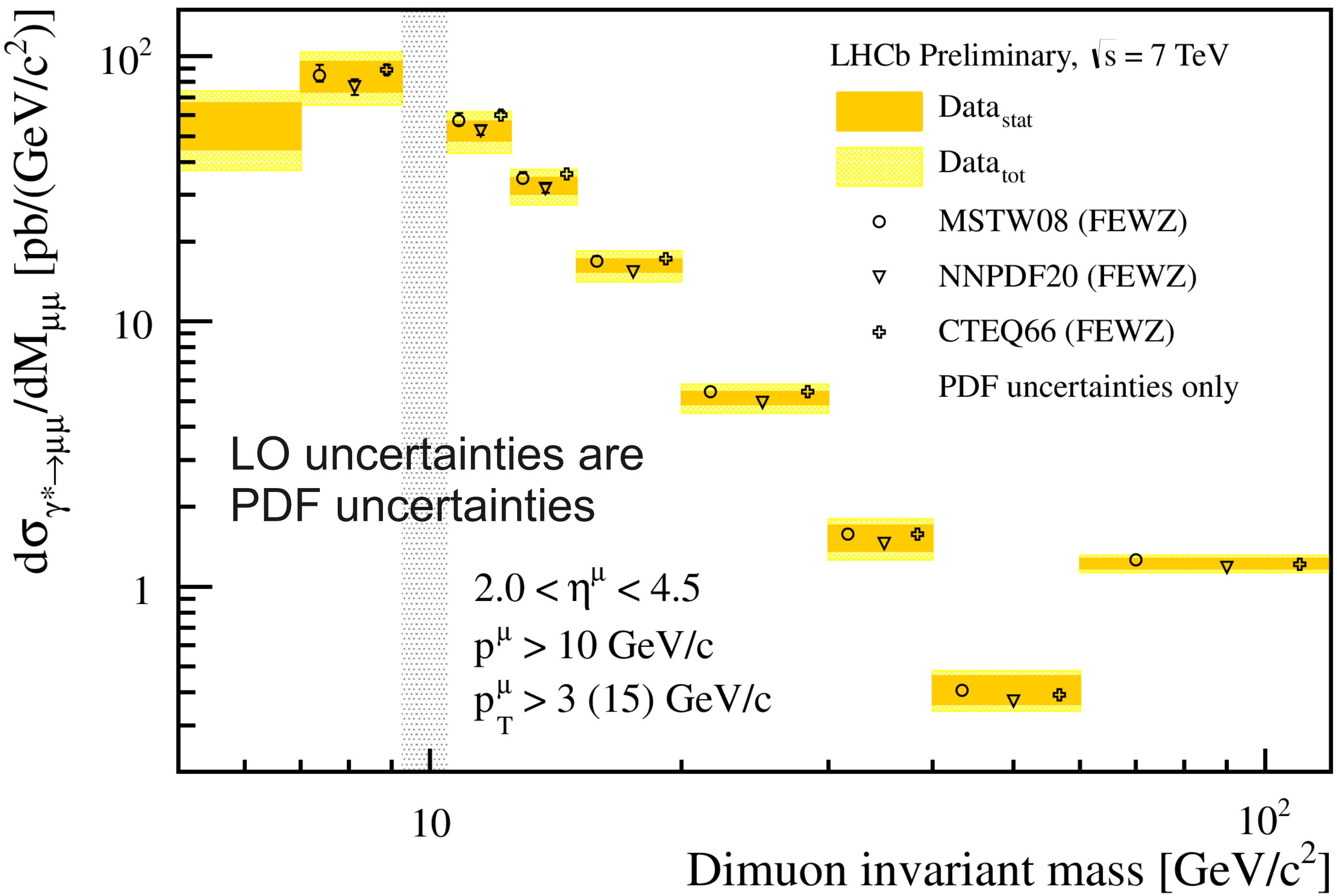
  - around 78% in both W^+ and W^- samples

Drell-Yan γ* → μμ

37 pb^{-1} , $2 < \eta(\mu) < 4.5$, $5 < M(\mu\mu) < 120$ GeV/c^2
Signal purity from template fits to the minimum muon isolation distributions:



Drell-Yan γ* → μμ mass distribution



- Mass region around Upsilon (ϒ) meson excluded
- The NLO FEWZ predictions reproduce the data well