UNIVERSITÀ DEGLI STUDI DI PADOVA

INFN Istituto Nazionale di Fisica Nucleare

LHCb

Electroweak Physics at LHCb

State of the art and future prospects

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on behalf of the LHCb Collaboration

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Overview

What to talk about

- LHCb detector
- Latest Electroweak Physics measurements at LHCb:
  - W and Z cross-section measurements
  - W/Z+jet production
  - $Z + c$-jet production
  - W mass

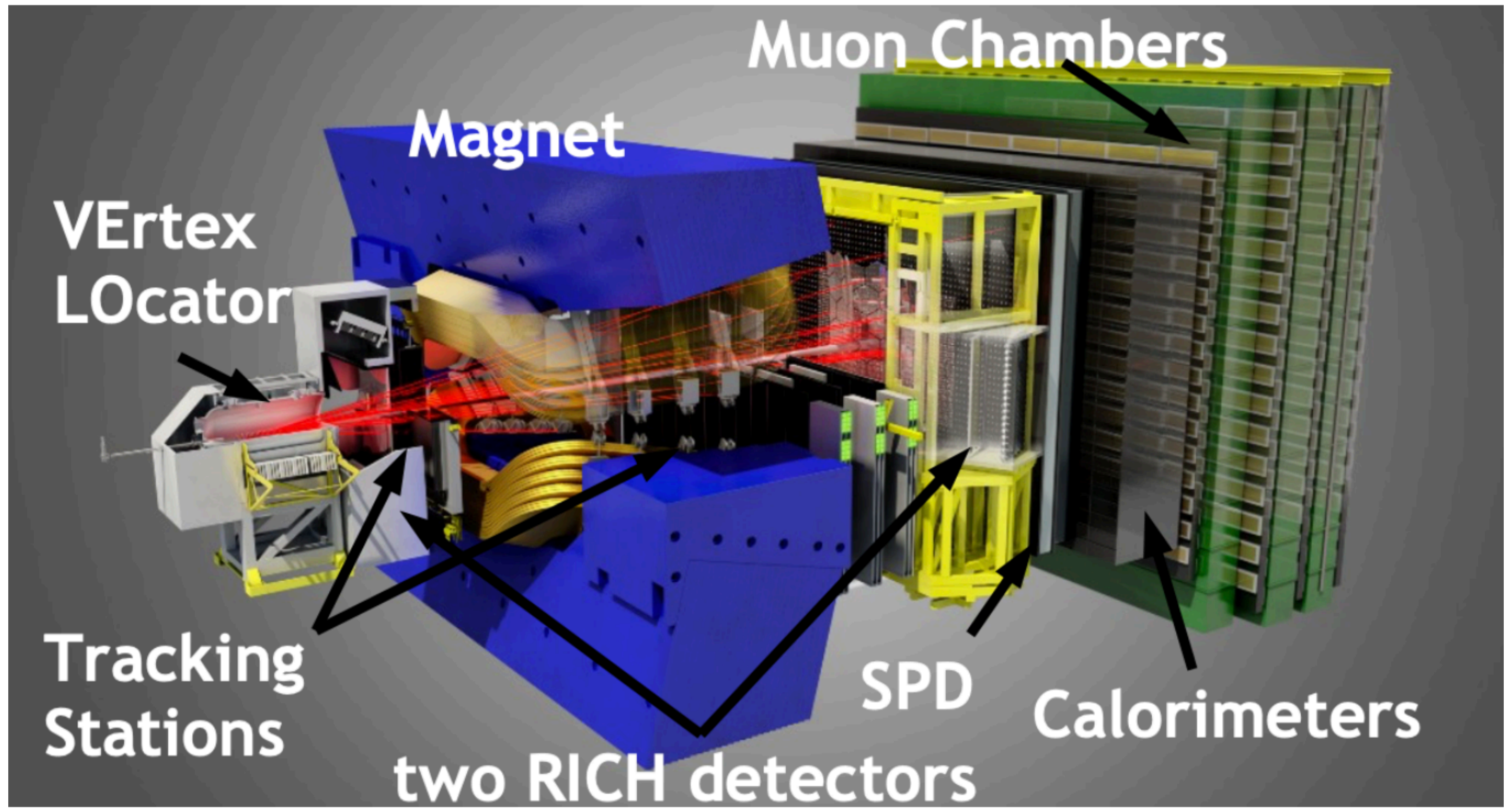
NEW

- Future prospects

LHCb detector

A “general purpose forward detector”

- LHCb, originally designed for b- and c-hadron physics, is now considered a general purpose forward detector
- Track momentum resolution: 0.4% at 5 GeV and 0.6% at 100 GeV
- Muon ID efficiency: 97% with 1-3% $\mu \to \pi$ misidentification
- Electron ID efficiency: 90% with 5% $h \to e$ misidentification
- Electron reconstruction: bremsstrahlung recovery and well-measured direction
- Excellent vertex reconstruction system: tagging of b- and c-jets with reconstruction of secondary vertices formed by tracks inside the jet cone



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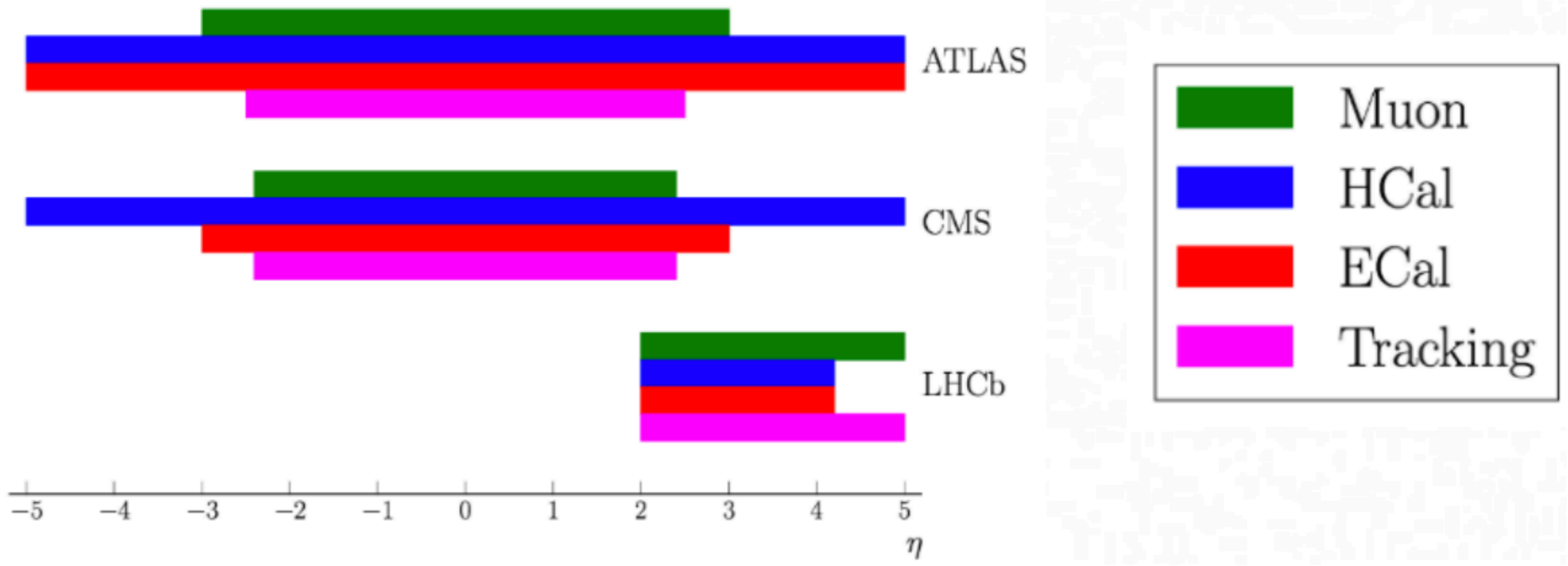
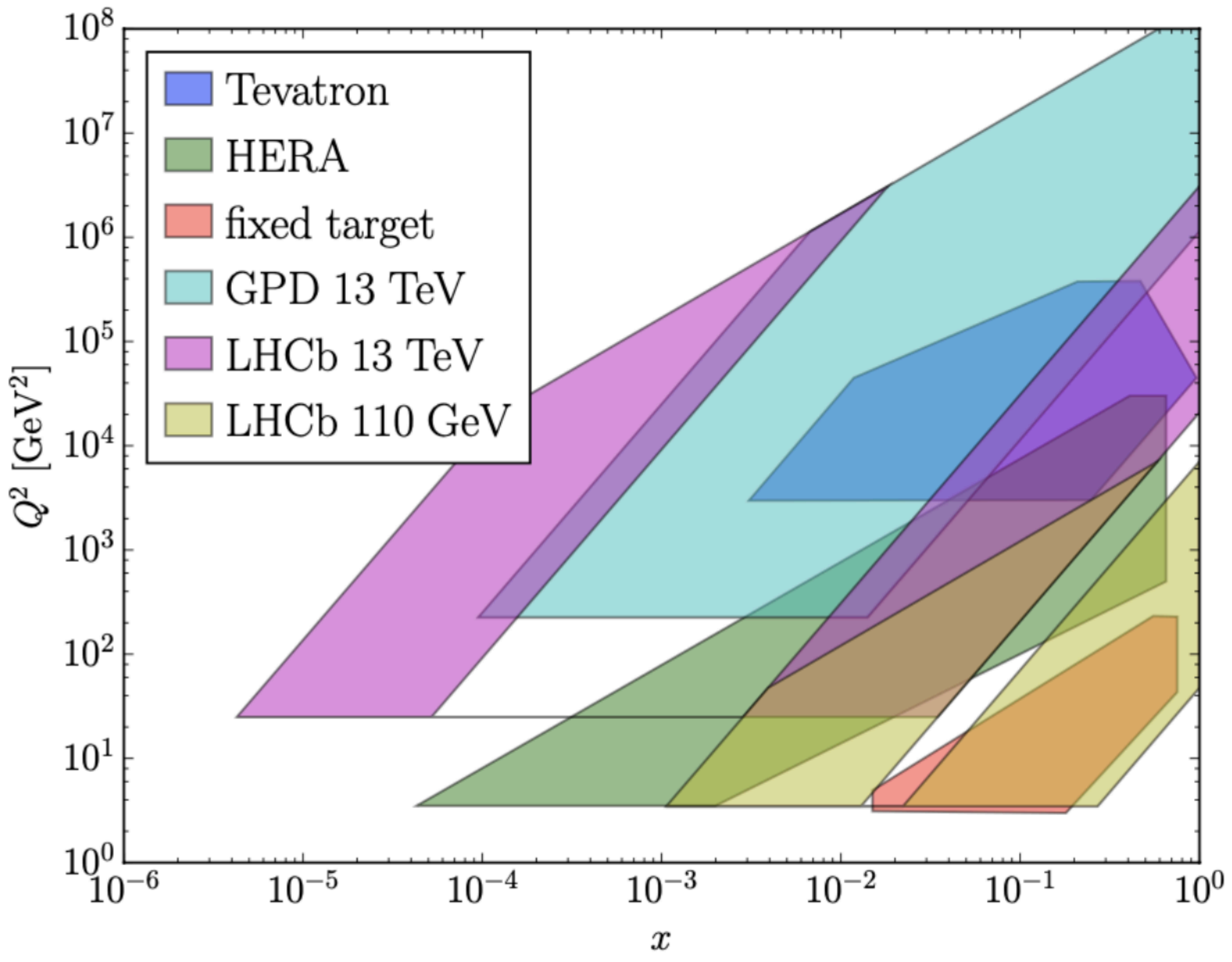


LHCb detector

Studying the forward region

- LHCb allows to test perturbative QCD (pQCD) predictions in a phase space $(2 < \eta < 5)$ complementary to General Purpose Detectors
- Parton distribution functions (PDFs) and proton structure can be studied in regions not accessible by other LHC experiments
  - **At high x values**
  - **At low x values and high Q^2, unexplored by other experiments**
- Interesting region to study Electroweak (EW) and Jet Physics

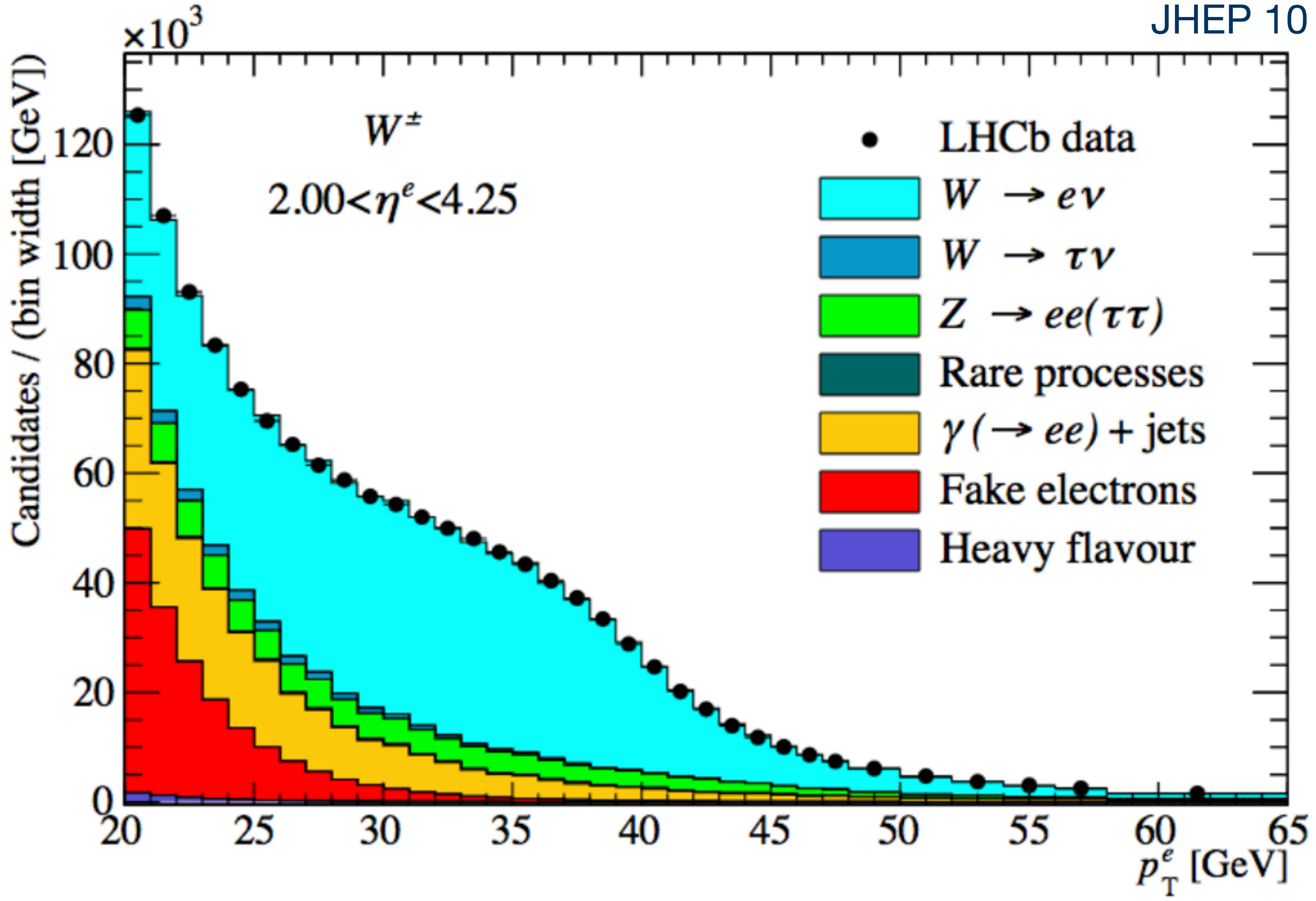


Electroweak Physics

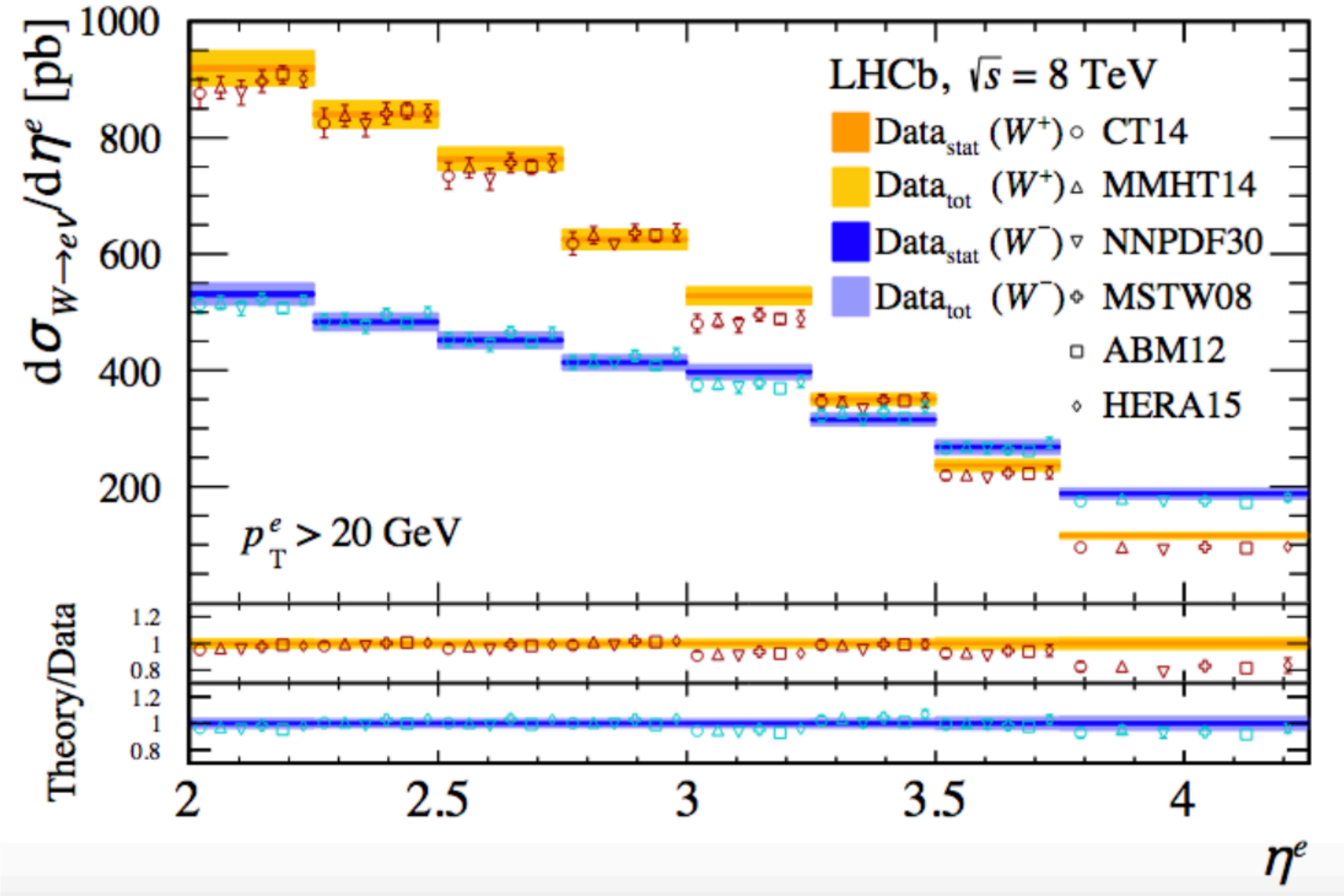
W production

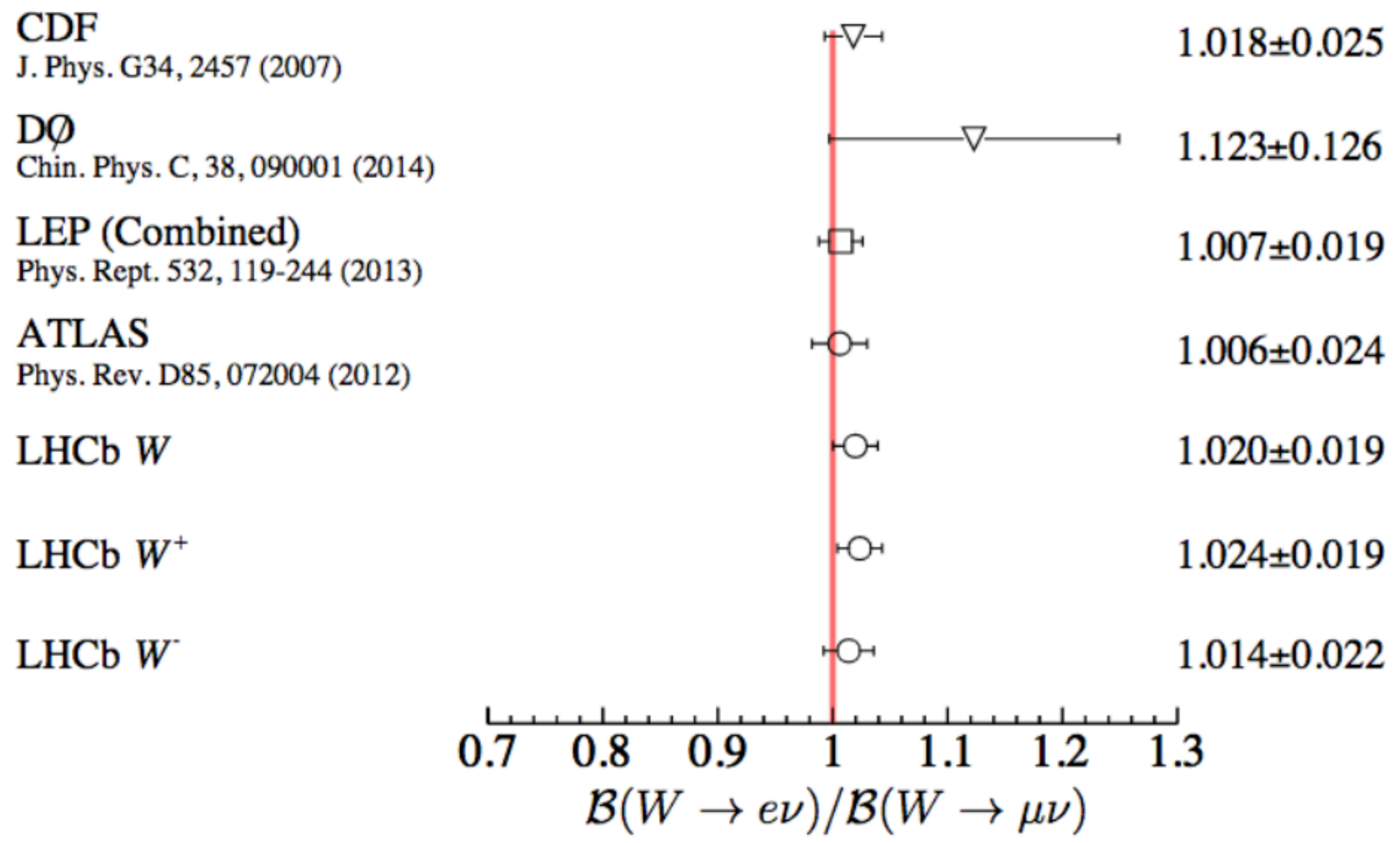
$W \to e\nu$ at $\sqrt{s} = 8$ TeV

JHEP 10 (2016) 030



- Important measurement to validate the high $p_T(e)$ reconstruction and identification at LHCb
- Fiducial region: $p_T(e) > 20$ GeV, $2.0 < \eta(e) < 4.25$
- Fit to the electron p_T distribution to extract the W yield
- Differential cross section as a function of the electron η is compatible with the prediction

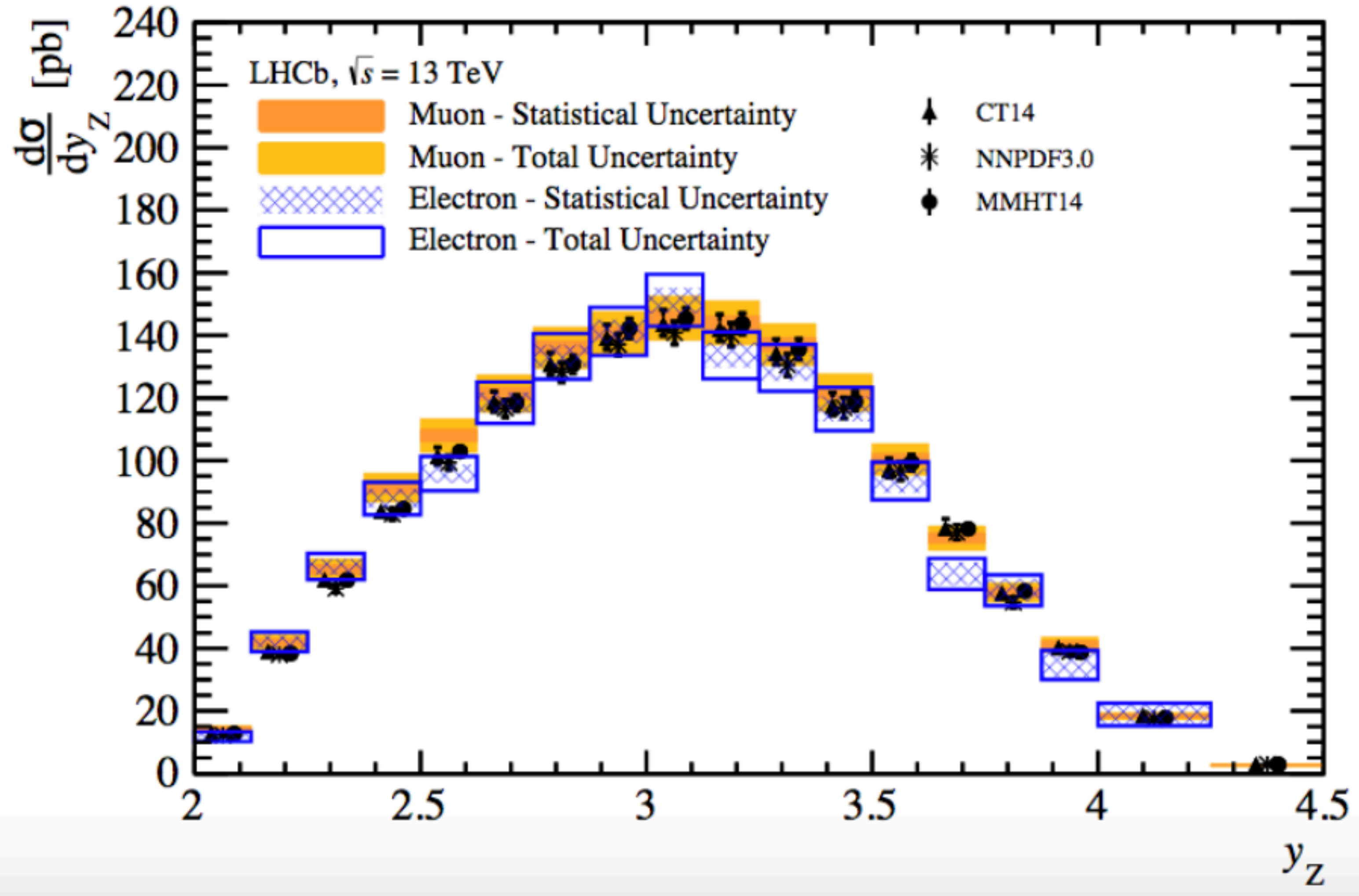


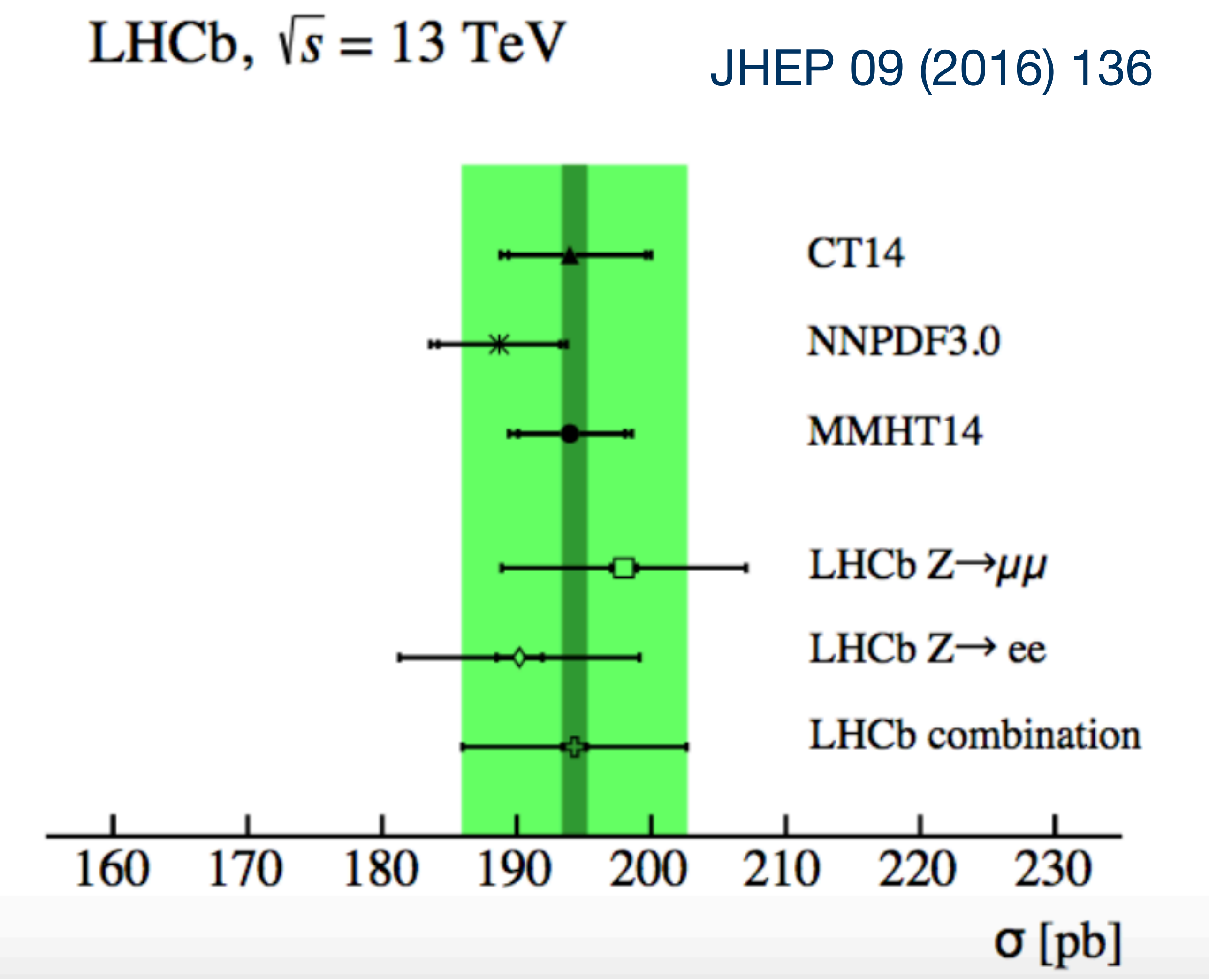


Z production

$Z \to \mu\mu$ and $Z \to ee$ at $\sqrt{s} = 13$ TeV

- Lepton final states $Z \to \mu\mu$ and $Z \to ee$, 294 pb^{-1}
- Fiducial region: $2.0 < \eta(\mu/e) < 4.5$, $p_T(\mu/e) > 20$ GeV, $60 < M_{\mu\mu/ee} < 120$ GeV
- High purity samples: 99.2% for $Z \to \mu\mu$ and 92.2% for $Z \to ee$
- $Z \to \mu\mu$ and $Z \to ee$ measured cross-section are compatible within the uncertainties





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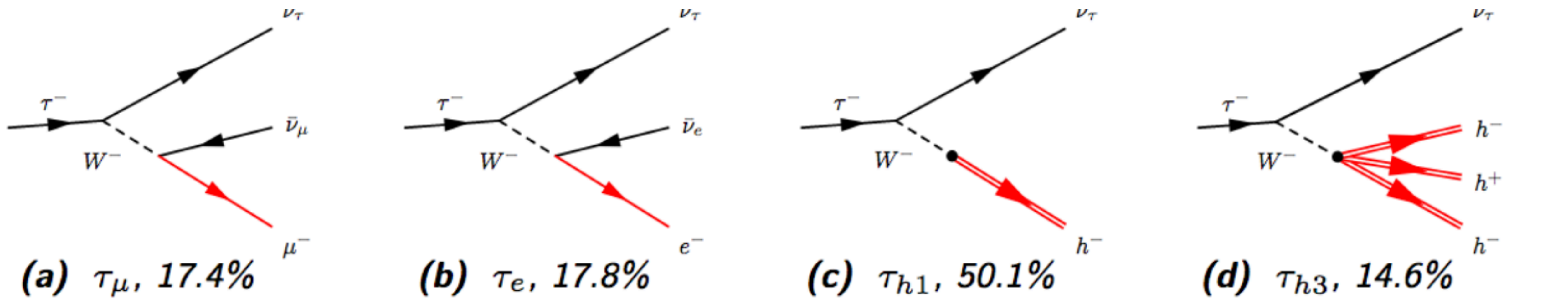
Z production

$Z \to \tau\tau$ at $\sqrt{s} = 8$ TeV



- τ lepton is reconstructed in 4 final states
- Analysis with 8 TeV data, ~ 2 fb^{-1}, fiducial region: $2.0 < \eta < 4.5$, $p_T > 20$ GeV, $60 < M_{\tau\tau} < 120$ GeV
- Combined cross sections from all channel, taken in to account uncertainties correlation: $\sigma(pp \to Z \to \tau\tau) = 95.8 \pm 2.1 \pm 4.6 \pm 0.2 \pm 1.1$ pb
- All ratios consistent with 1

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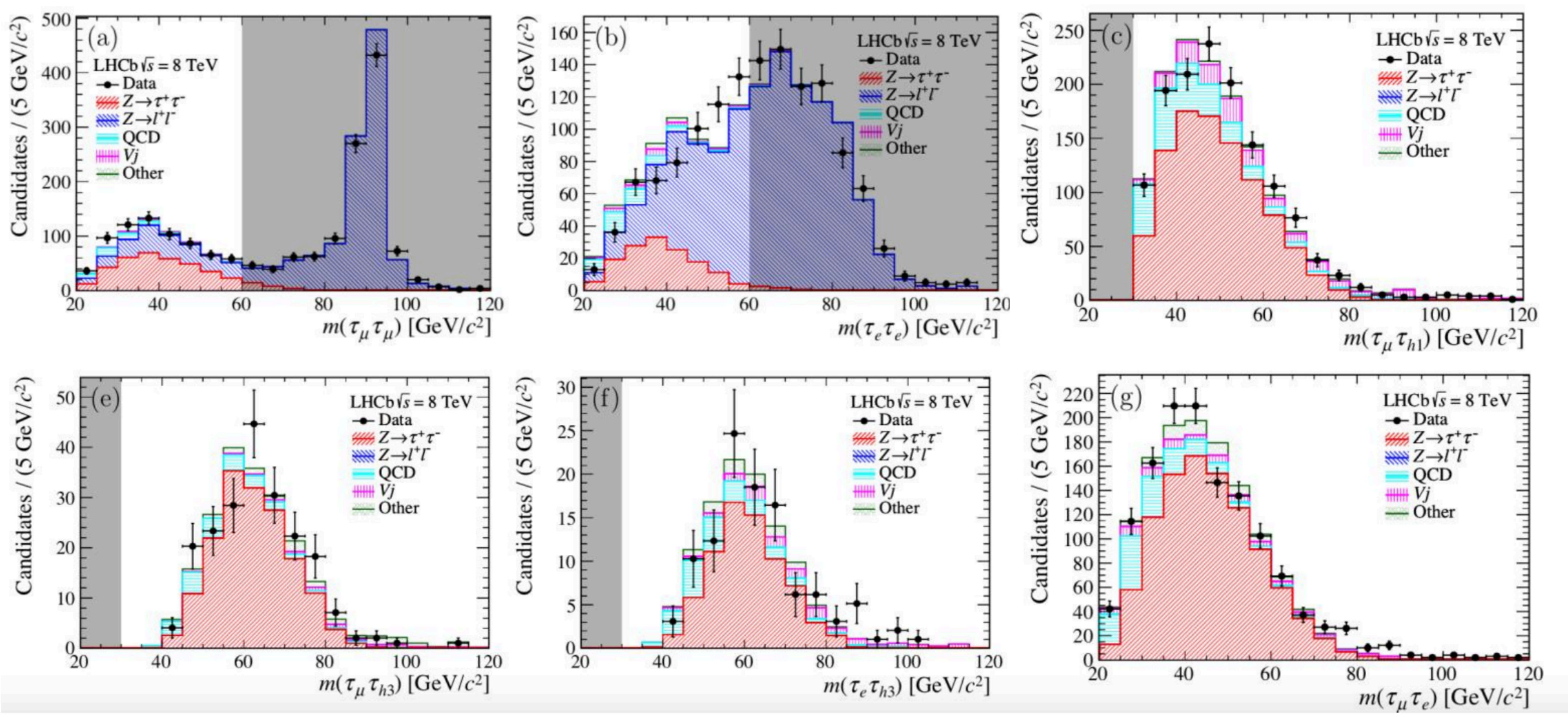
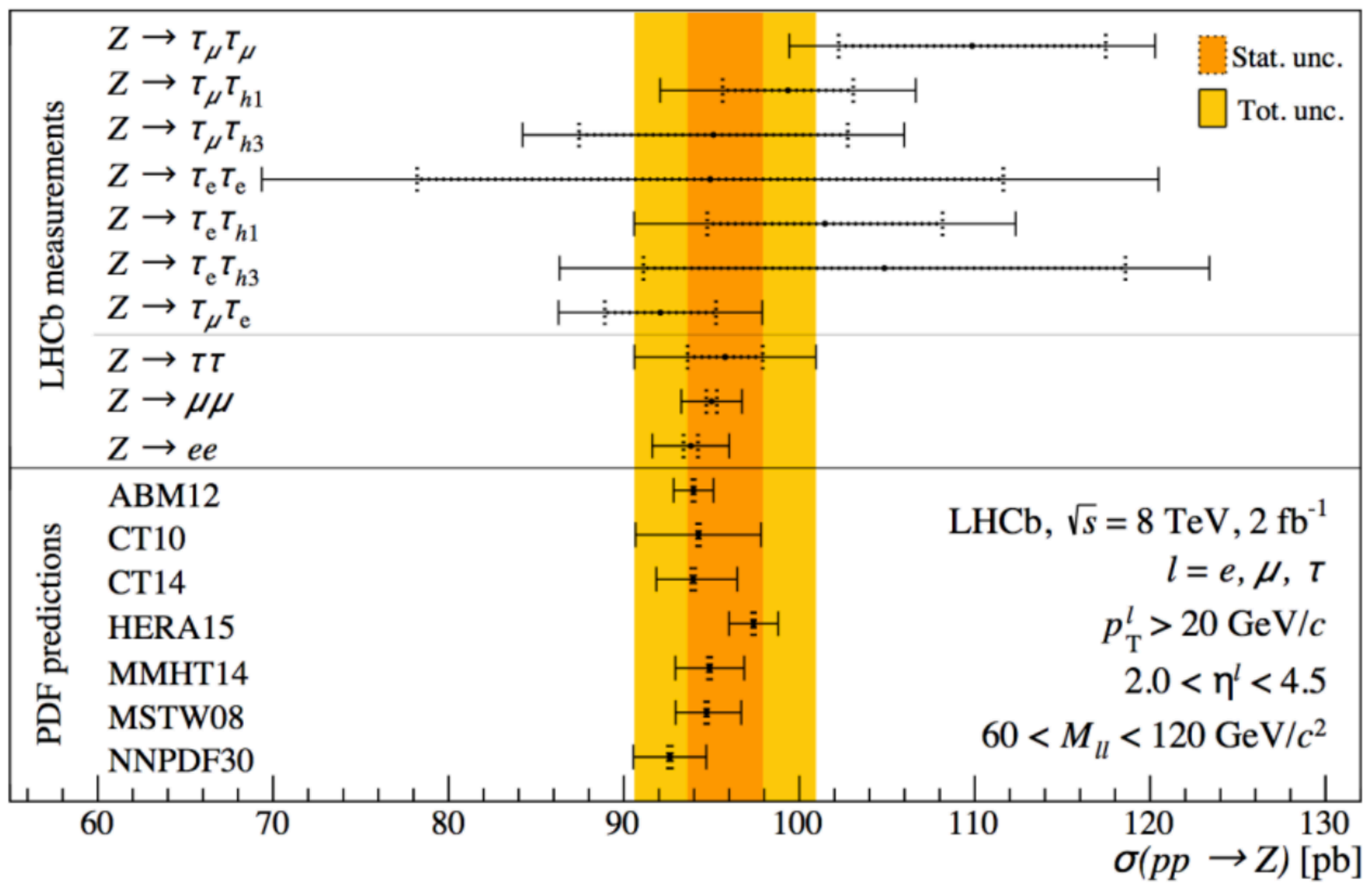
$$\frac{\sigma^{8\text{TeV}}_{pp\to Z\to\tau^+\tau^-}}{\sigma^{8\text{TeV}}_{pp\to Z\to\mu^+\mu^-}} = 1.01 \pm 0.05$$

$$\frac{\sigma^{8\text{TeV}}_{pp\to Z\to\tau^+\tau^-}}{\sigma^{8\text{TeV}}_{pp\to Z\to e^+e^-}} = 1.02 \pm 0.06$$



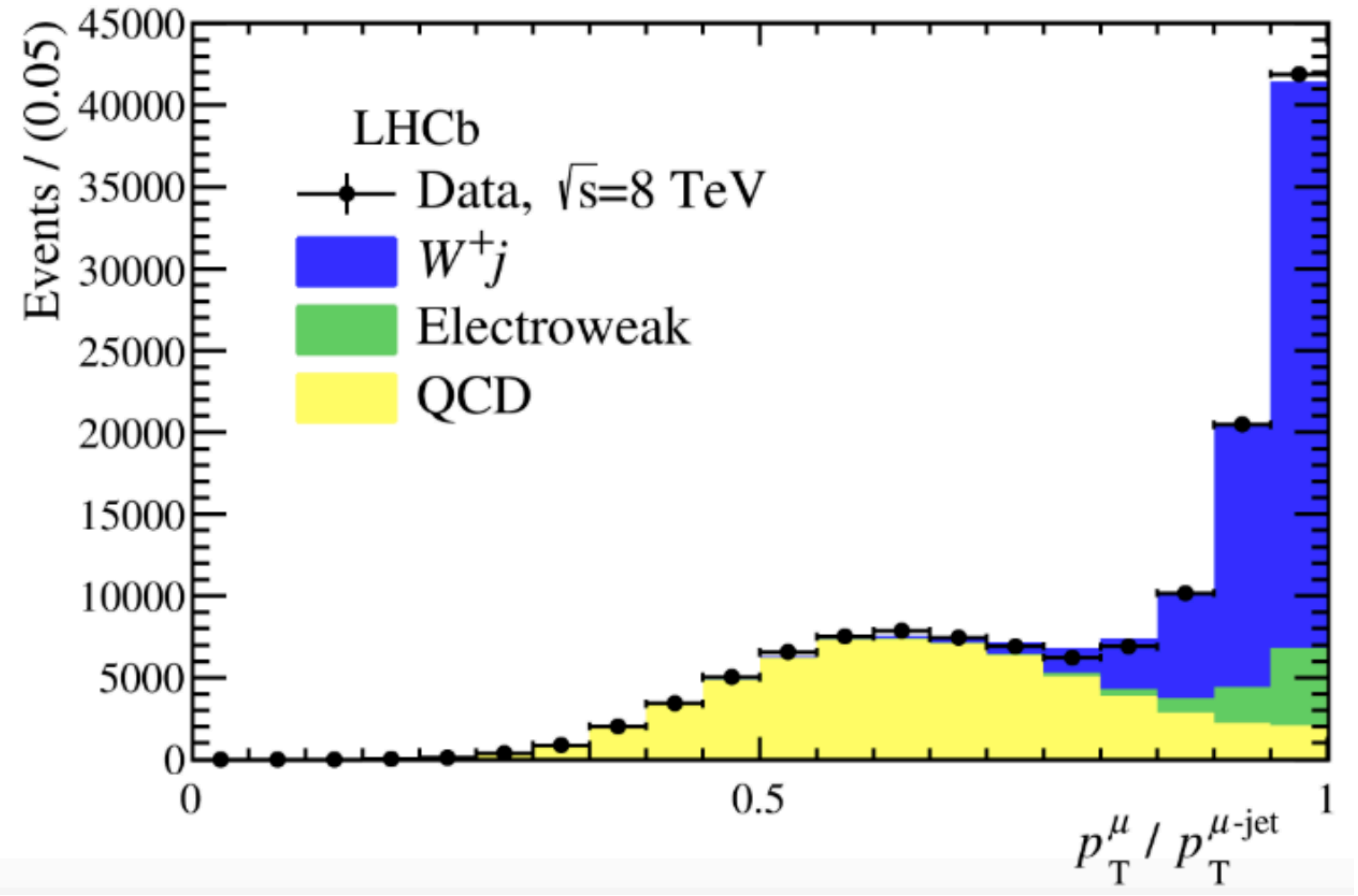


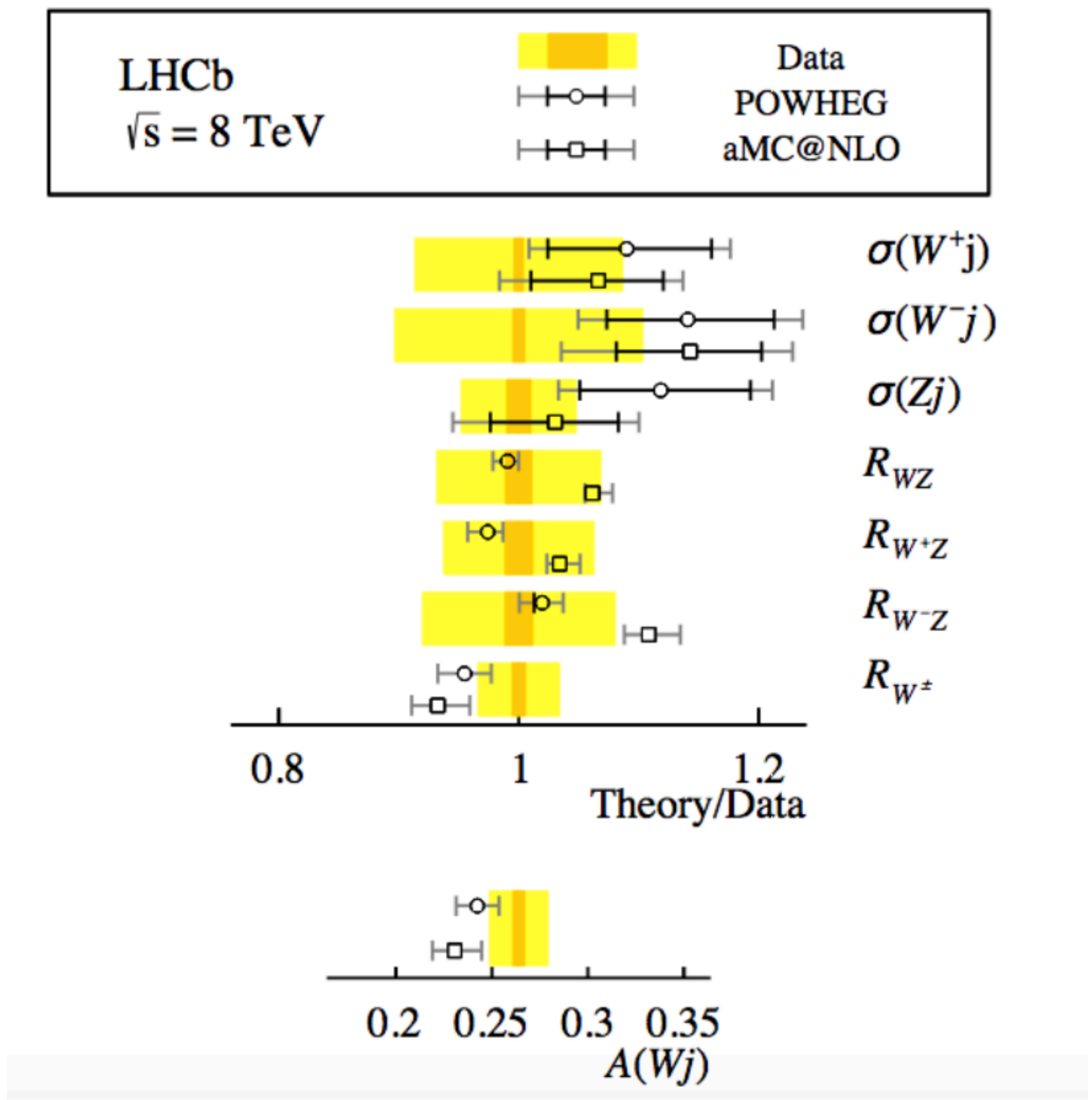
W/Z+jet

Run I analysis at $\sqrt{s} = 8$ TeV

- $W \to \mu\nu$ and $Z \to \mu\mu$ decay channels
- Fiducial region: $p_T(\mu) > 20$ GeV, $2.0 < \eta(\mu) < 4.5$, $p_T(\text{jet}) > 20$ GeV, $2.2 < \eta(\text{jet}) < 4.2$, $\Delta R(\text{jet}, \mu) > 0.5$
- Fit to the muon isolation to extract the W/Z+jet yield
- W/Z ratios and W^+/W^- asymmetry are also determined
- Measurements are in good agreement with theory predictions

JHEP 05 (2016) 1-23





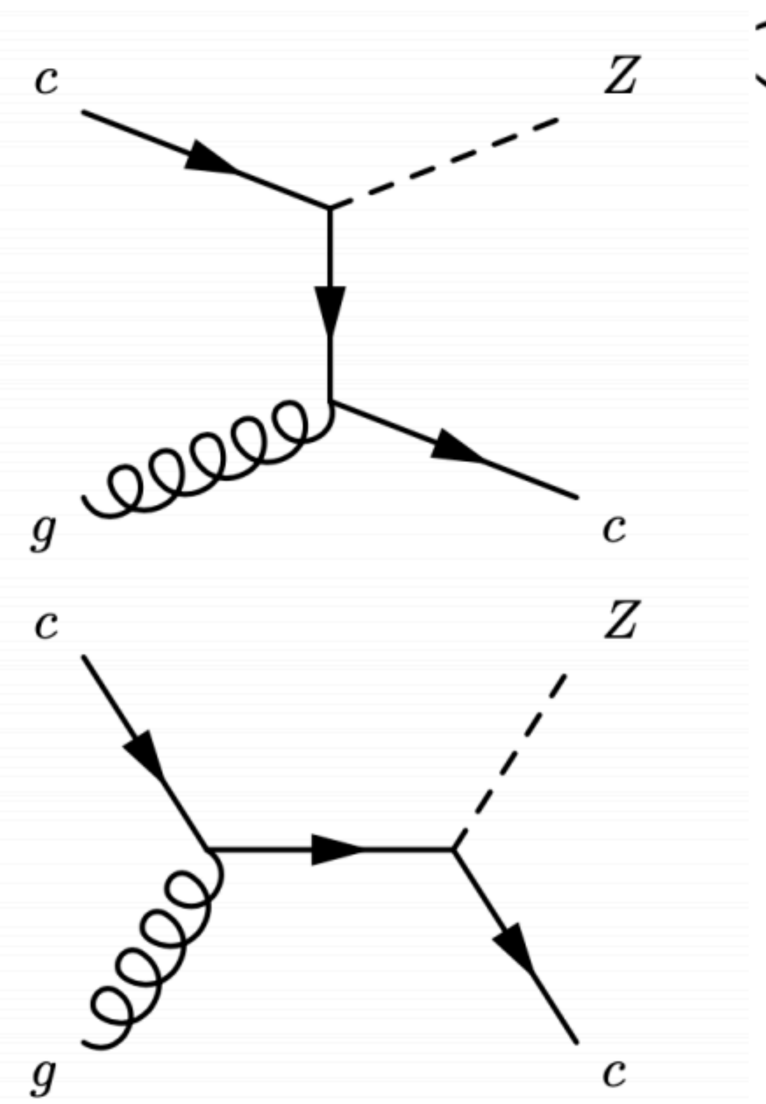
NEW

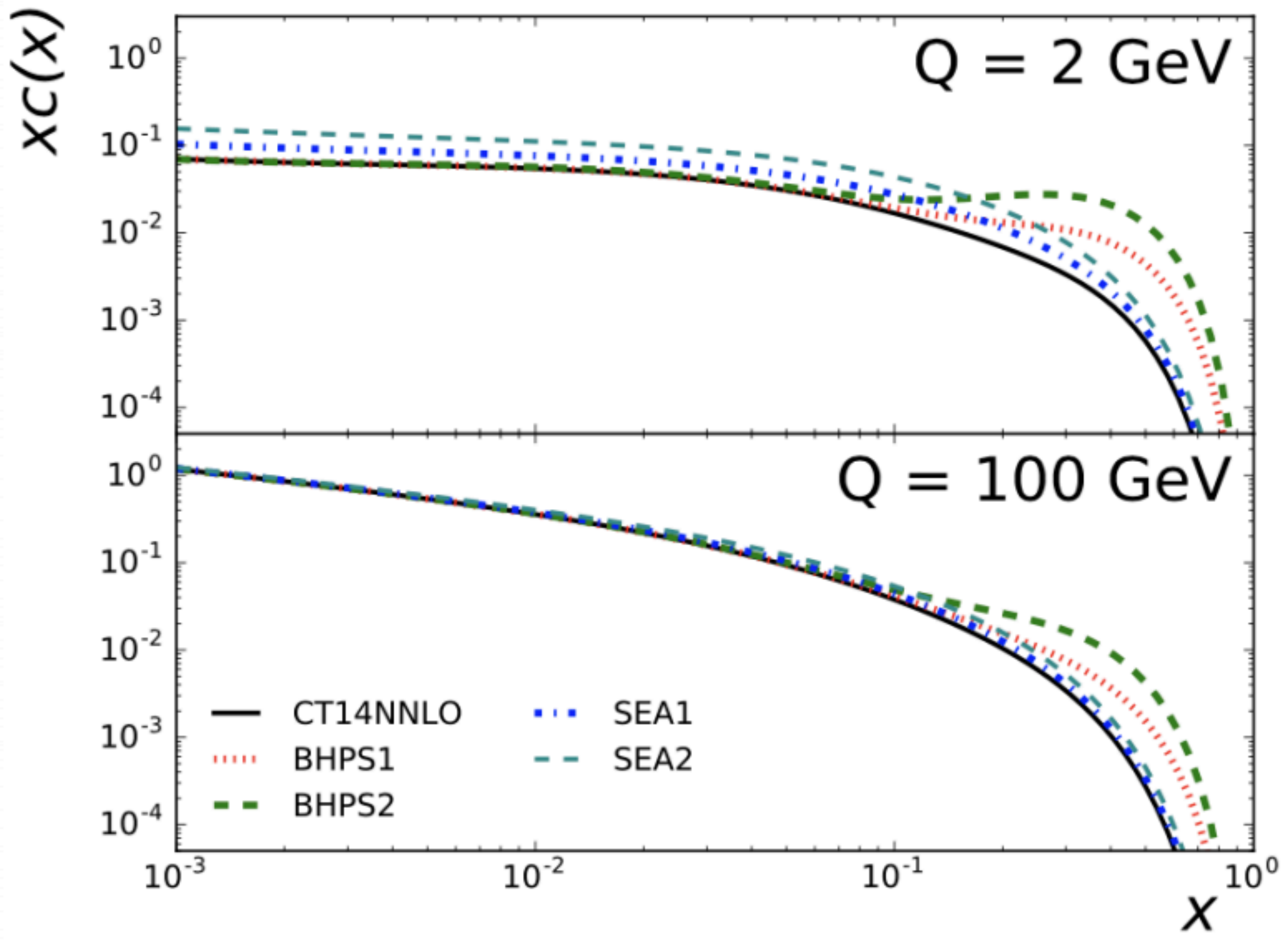
$Z + c$-jet production

Intrinsic charm

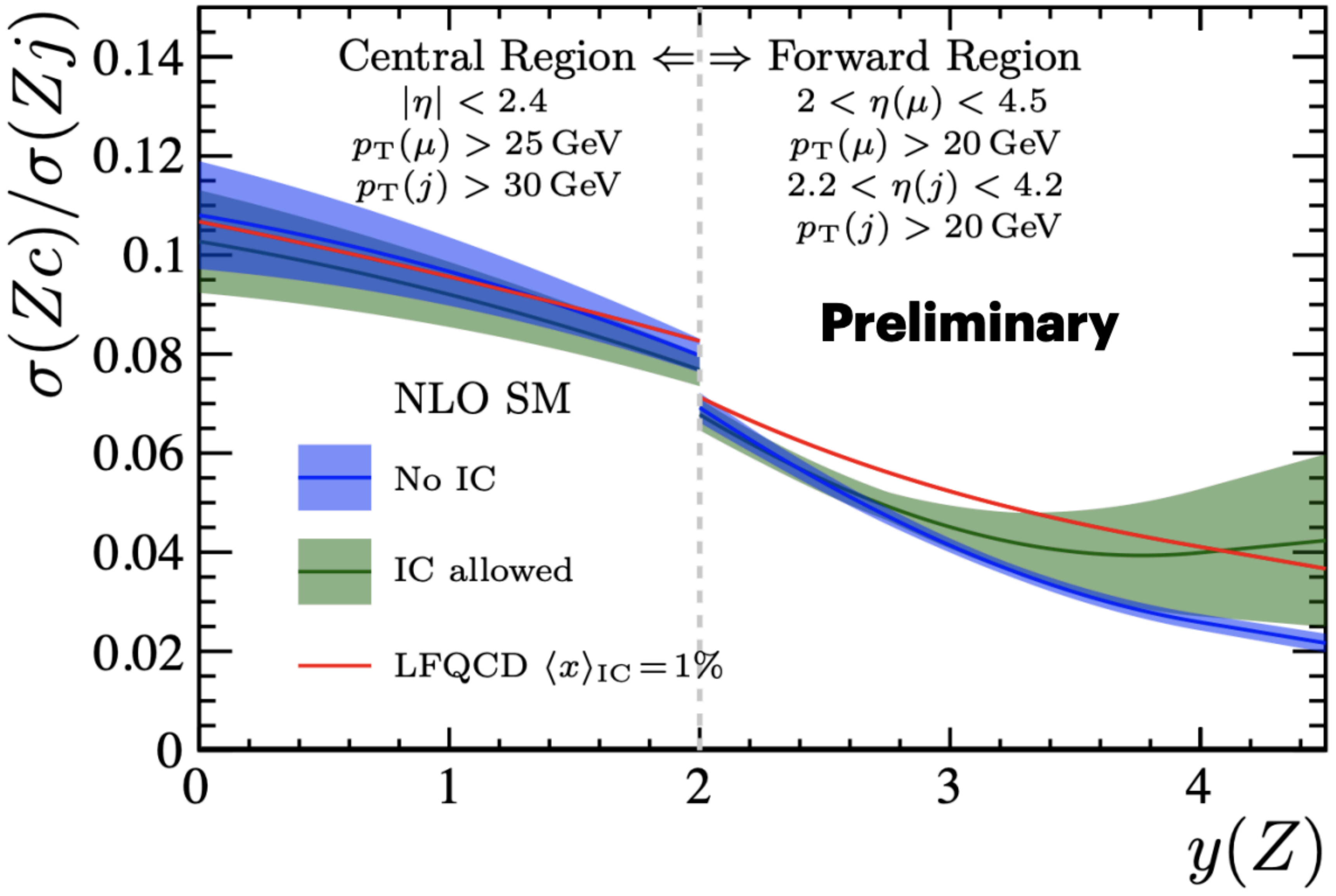
LHCb-PAPER-2021-029 in prep.

- In proton content charm can be extrinsic (produced by gluon splitting) or intrinsic (bound to valence quarks)
- Intrinsic charm PDF can be valence-quark-like or sea-quark-like, clear signature at $x > 0.1$
- Valence-like intrinsic charm is predicted by Light Front QCD (LFQCD, not-perturbative)





Phys. Rev. D 93, 074008



- Current limits do not rule out the intrinsic charm content at % level
- The Z+c-jet production in the forward region is sensitive to the high x and high Q^2 intrinsic charm component

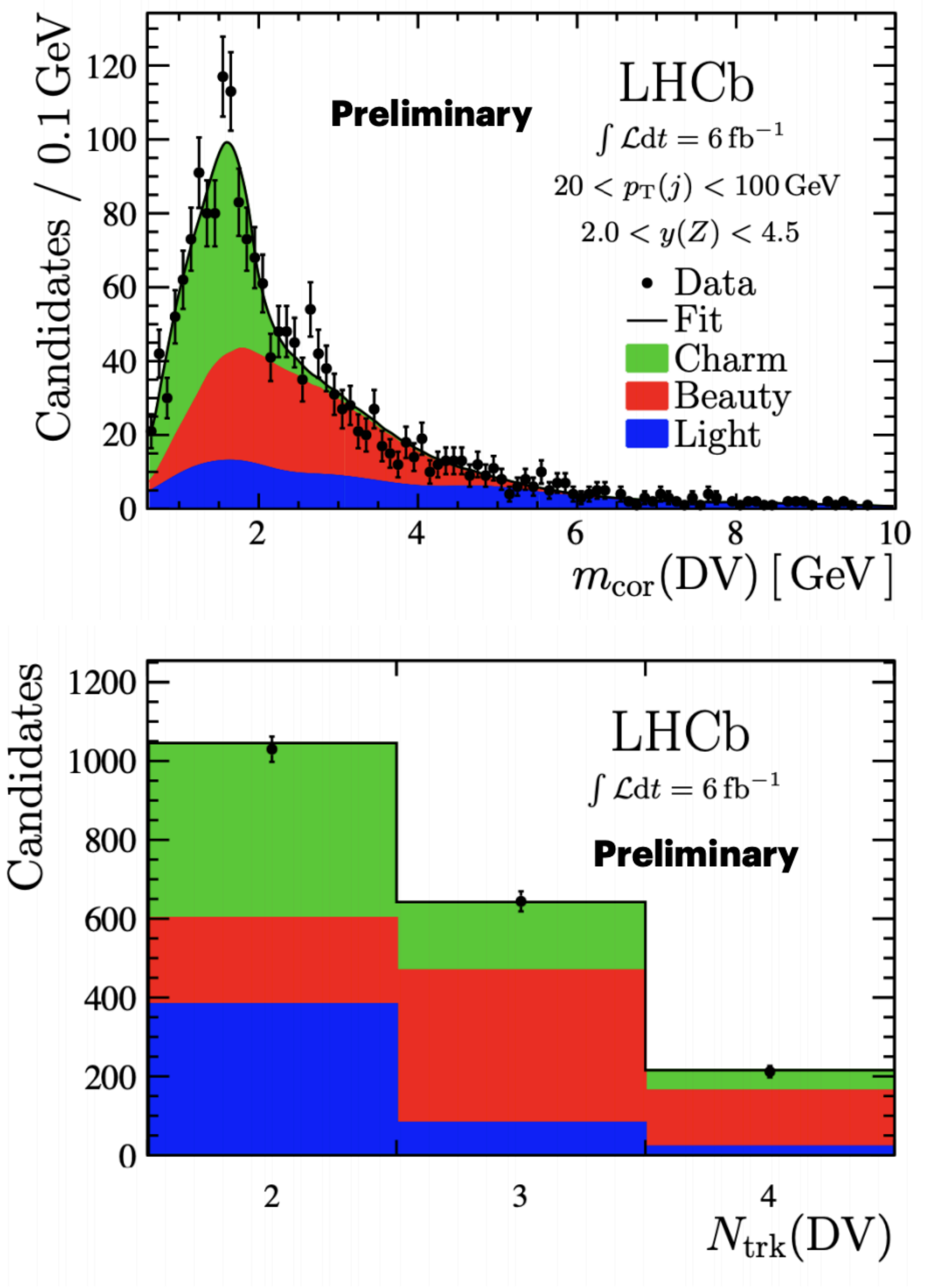
NEW

$Z + c$-jet production

Analysis in the forward region

- The 13 TeV dataset is used, for a total integrated luminosity of $6\ \text{fb}^{-1}$ (Run II condition)
- Z boson is reconstructed in the di-muon final state → high purity sample
- Heavy flavour jets are tagged with a Displaced Vertex (DV) technique
- The corrected DV-mass and the number of tracks in the DV are fitted to obtain the flavour components
- Templates are obtained from calibration samples (heavy flavour enriched di-jets)

LHCb-PAPER-2021-029 in prep.



NEW

$Z + c$-jet production
Analysis in the forward region

- Systematic uncertainty dominated by the c-tagging efficiency systematic, obtained from calibration samples
- Hint of the intrinsic charm component in the high rapidity interval $(3.5 < y(Z) < 4.5)$
- Result is statistically limited → more data is needed!

Source	Relative Uncertainty
c tagging	6–7%
DV-fit templates	3–4%
Jet reconstruction	1%
Jet p_{T} scale & resolution	1%
Total	8%

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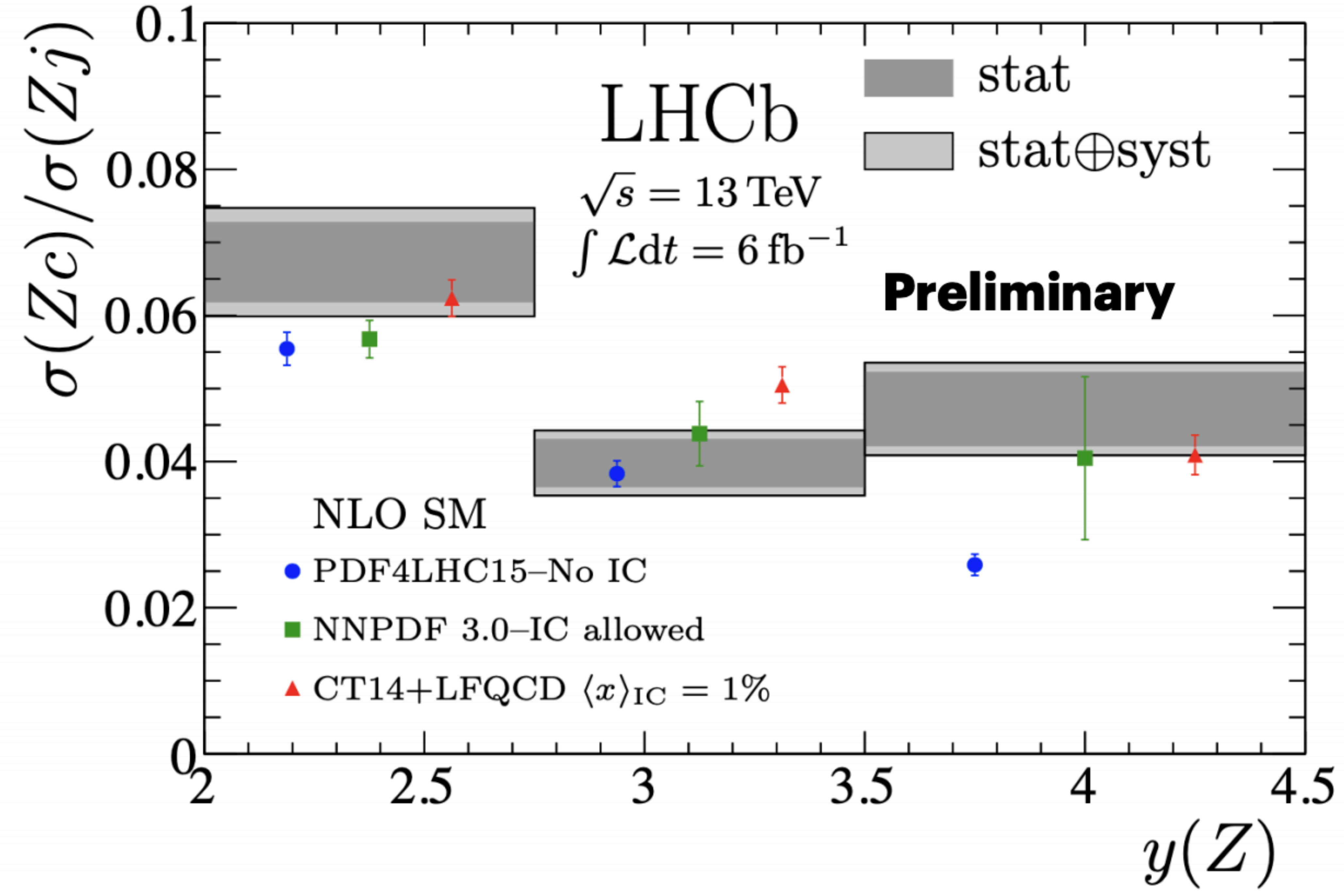


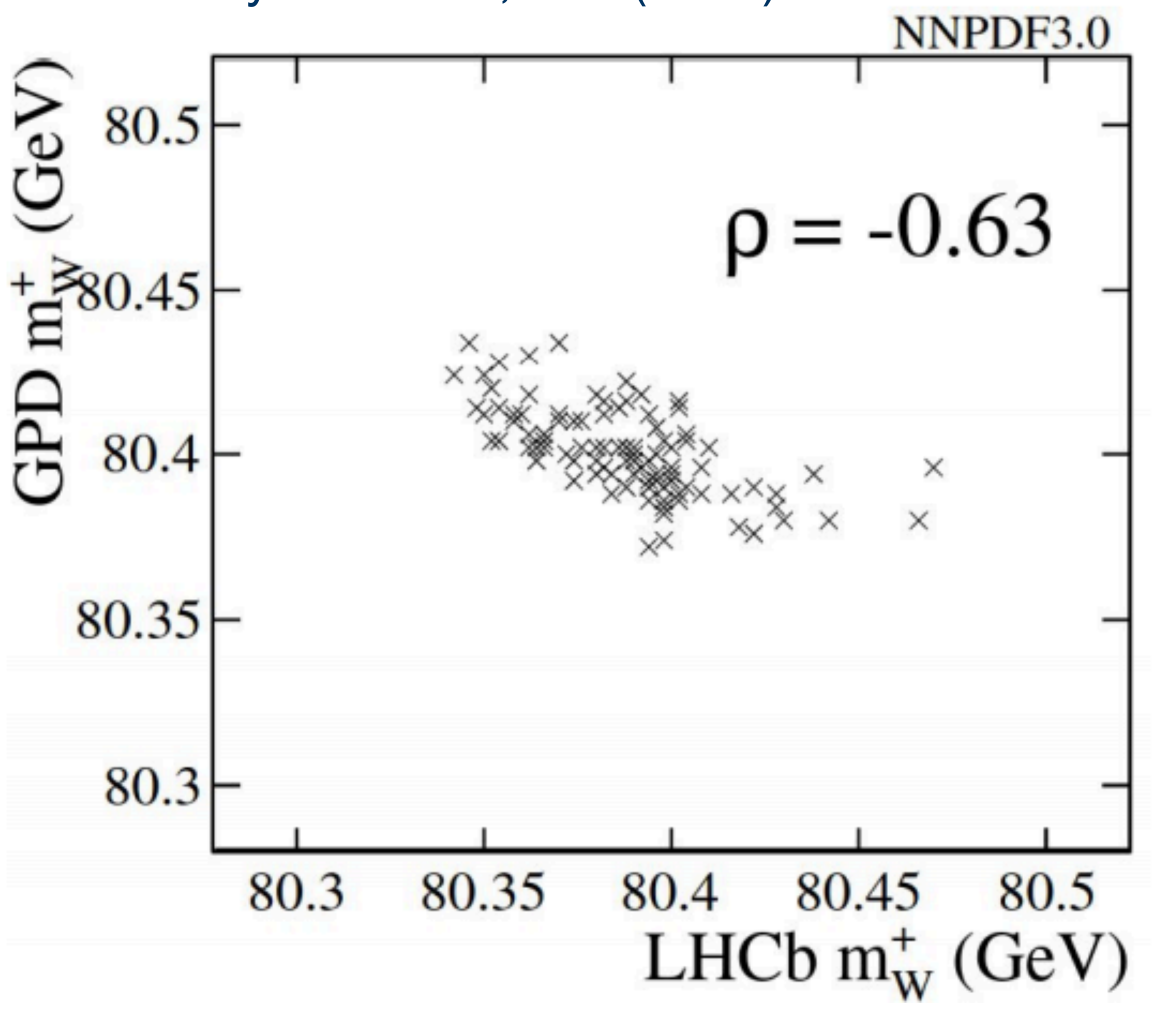
NEW

W mass measurement

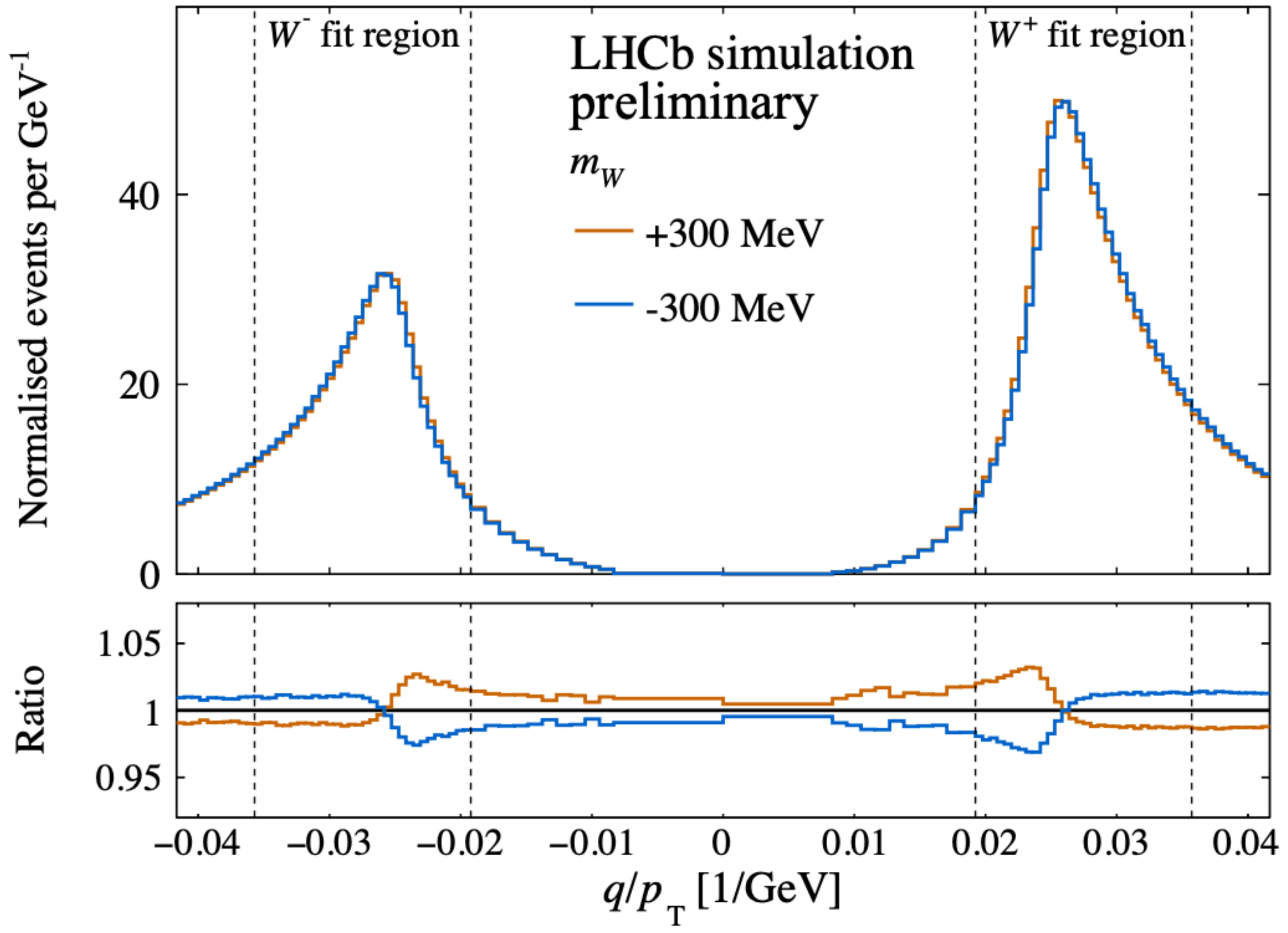
At LHCb vs. GPD

- High precision measurement of the W mass is possible at LHCb
- PDF uncertainties are anti-correlated with respect to ATLAS and CMS
- First "proof-of-principle" measurement with 2016 data
  - Reaching a ~ 20 MeV precision
- Sensitivity to the W mass by carefully measuring the muon q/p_T distribution

Eur. Phys. J. C 75, 601 (2015)



LHCb-PAPER-2021-024 in prep.



$$\frac{d\sigma}{dp_T^W\, dy\, dM\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol}}}{dp_T^V\, dy\, dM}$$

Unpolarised cross-section

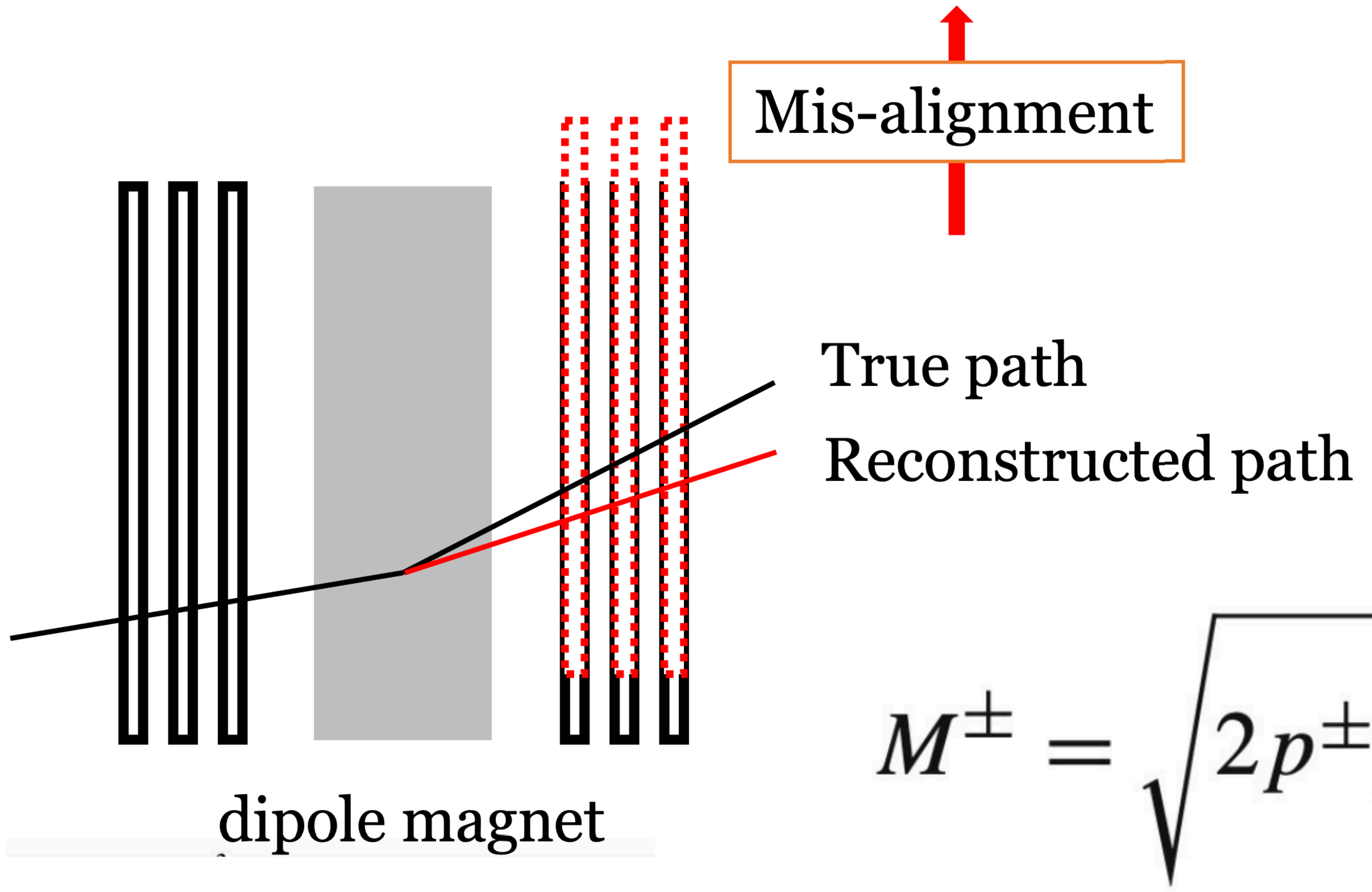
$$\{(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi$$
$$+ A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta$$
$$+ A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\}$$

Angular terms (A_i = angular coefficients)

W mass measurement

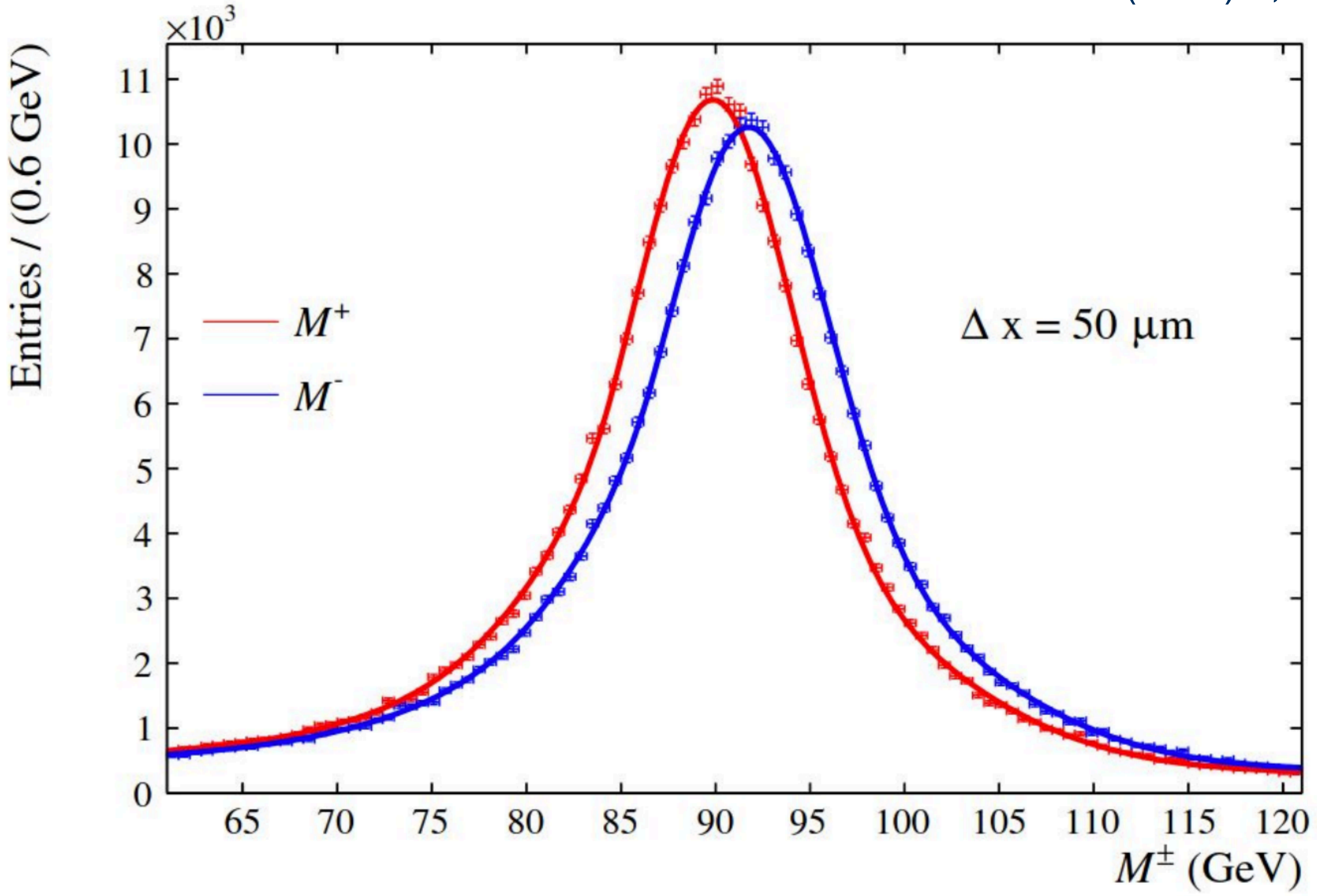
Detector alignment

- To measure W mass detector alignment is necessary
  - Misalignment of $\mathcal{O}(10)\mu$m translates into a $\mathcal{O}(50)$MeV shift in W mass
- Default LHCb alignment and calibration are not suitable → custom alignment for high p_T muons
- "Pseudo-mass" method included for finer analysis
- Correction applied independently to both charges
- Differences in fitted $M^{\pm}$ → curved bias correction



$$M^{\pm} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1-\cos\theta)}$$

EPJC 81 (2021) 3, 251



NEW

W mass measurement

Uncertainties

LHCb-PAPER-2021-024 in prep.

Source Preliminary	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

- Total uncertainty is 32 MeV
- Only 2016 data have been used so far (almost $1/3$ of total Run II data)
- Remarkable results:
  - 9 MeV for PDFs
  - 10 MeV for experimental uncertainty

NEW

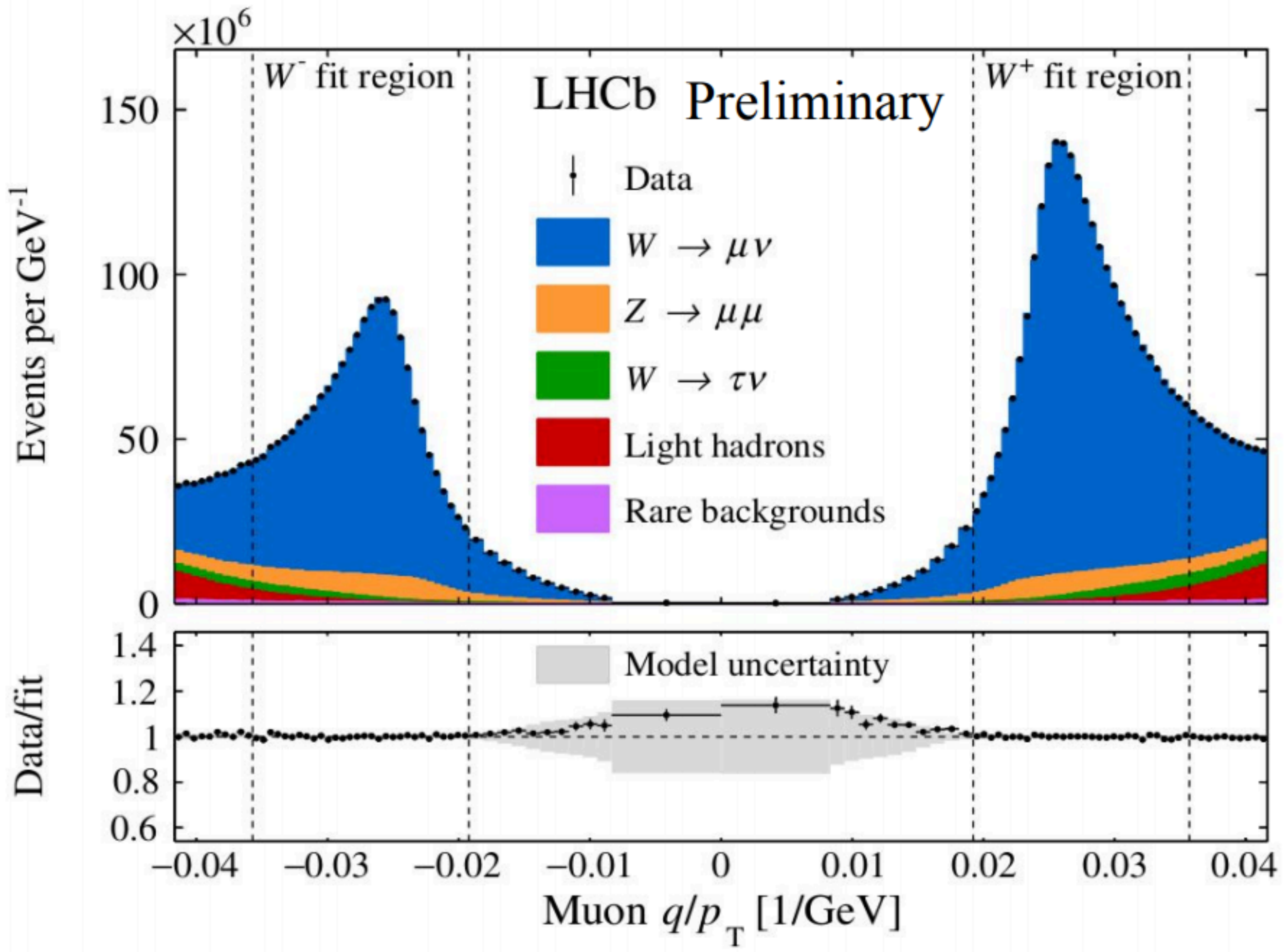
W mass measurement

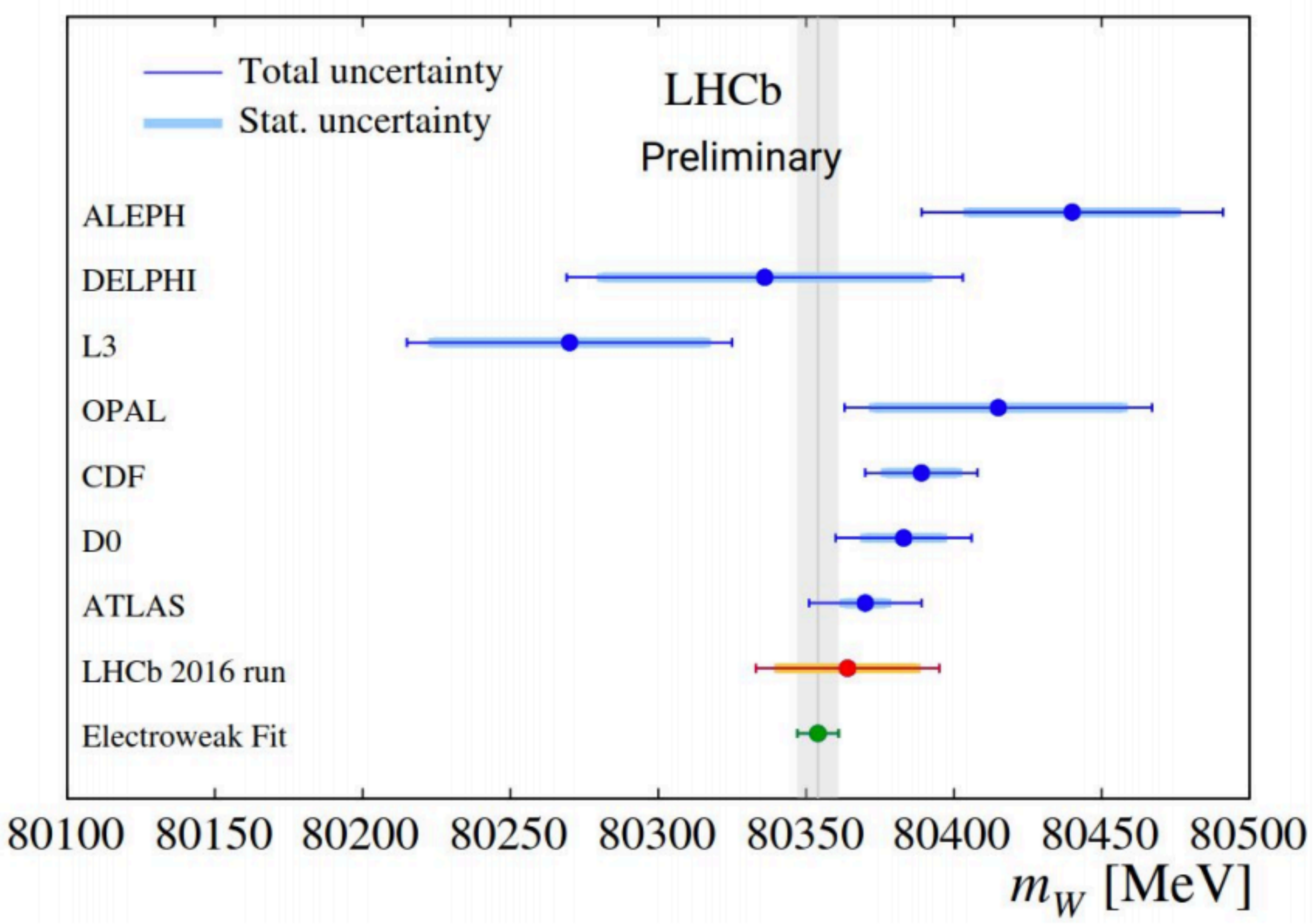
First result at LHCb!

- Result obtained from a simultaneous fit to the muon spectrum and φ^* of the Z
- EW and rare backgrounds determined from simulation
- QCD background parametrized from data

$$\varphi^* = \frac{\tan(\phi_{acop}/2)}{\cosh(\Delta\eta/2)} \sim \frac{p_T}{M}$$

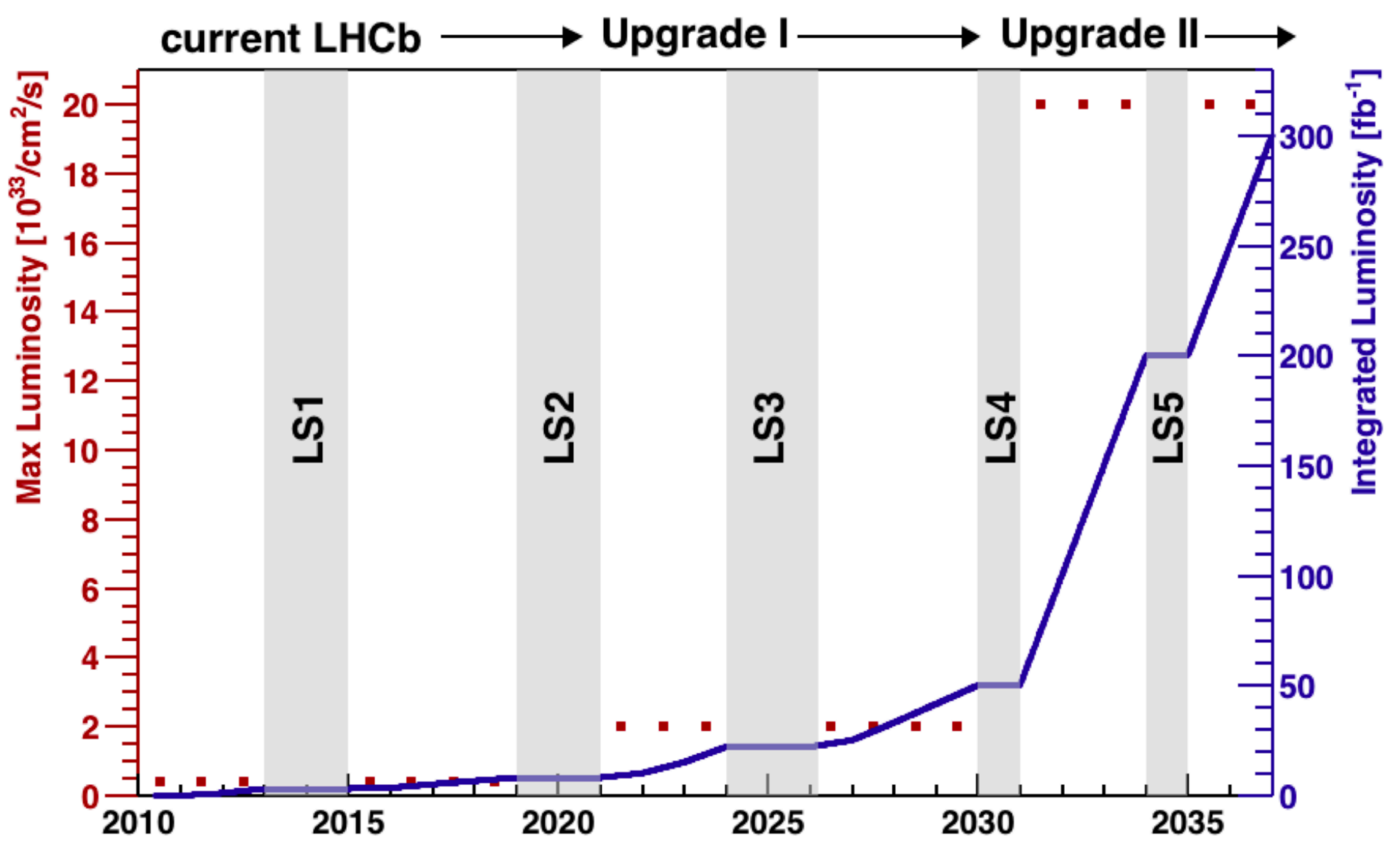
LHCb-PAPER-2021-024 in prep.





$$m_W = 80364 \pm 23_{\text{stat}} \pm 11_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

CERN-LHCC-2018-027

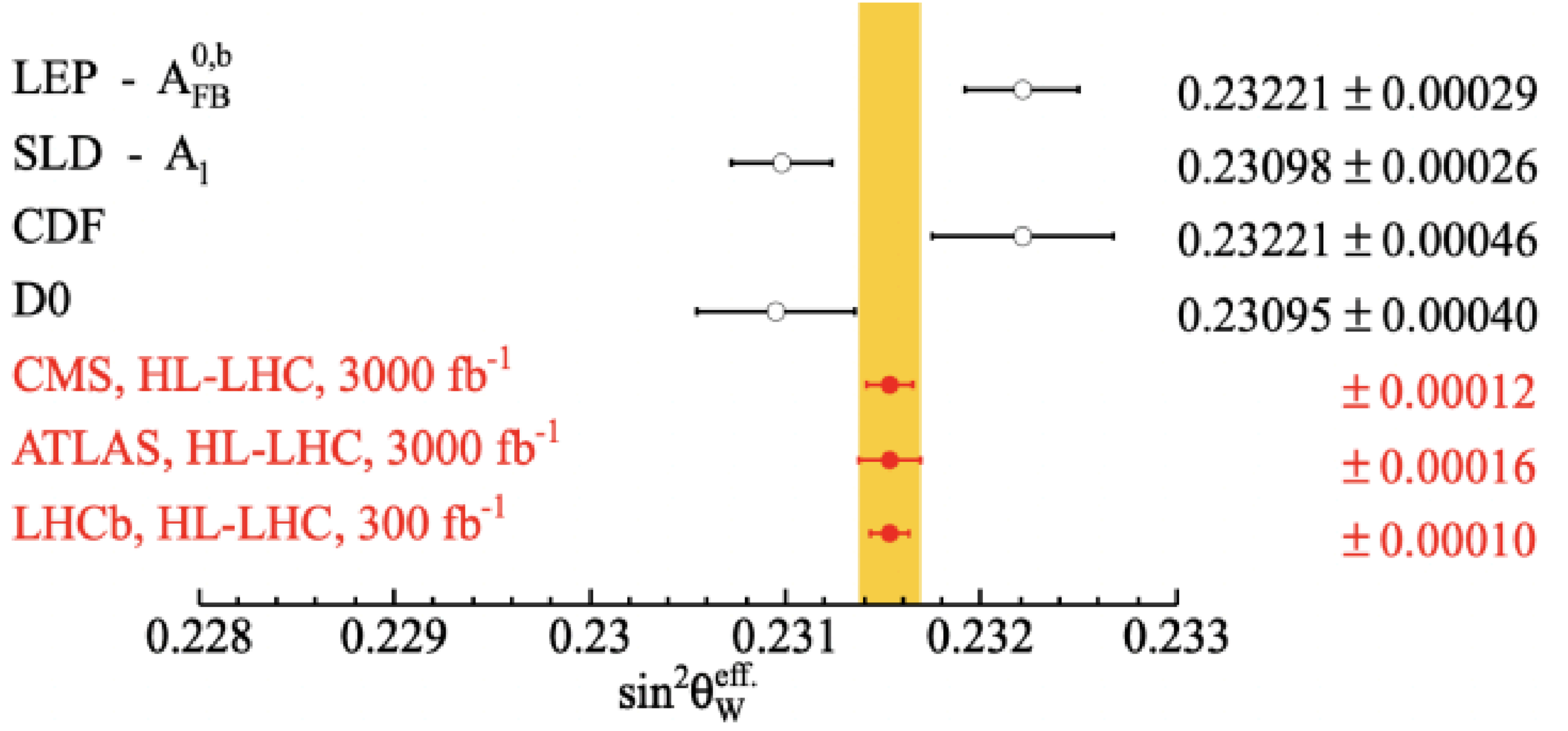


Future prospects at LHCb

Going to HL-LHC

- LHCb will go through an intense upgrade in the following years
- Several EW measurements where LHCb could play an interesting role:
  - Weak mixing angle $\sin^2\theta_W^{eff}$, improving both statistics and systematic uncertainties
  - W mass measurement using $W \to e\nu$ decay, given a new upgraded ECAL
  - …
- Not only EW physics, also top and Higgs!

LHC Yellow Report [CERN-LPCC-2018-03]



Conclusions

Wrap it up

- Not only flavour physics: LHCb is now considered a general purpose forward experiment
- LHCb performed measurements of EW physics in the forward region of pp collisions, unexplored by other experiments
    - All results are in agreement with SM predictions
- The first measurement of the W boson mass at LHCb is a big achievement, towards a similar sensitivity to the global electroweak fit
- With the future upgrades LHCb could play an interesting role in measuring EW quantities

Stay tuned!

Thank you for your attention

Any questions?

Backup slides

For further details...