Recent EW and QCD results from LHCb

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The 8th China LHC Physics Workshop
November 24, 2022

Outlines

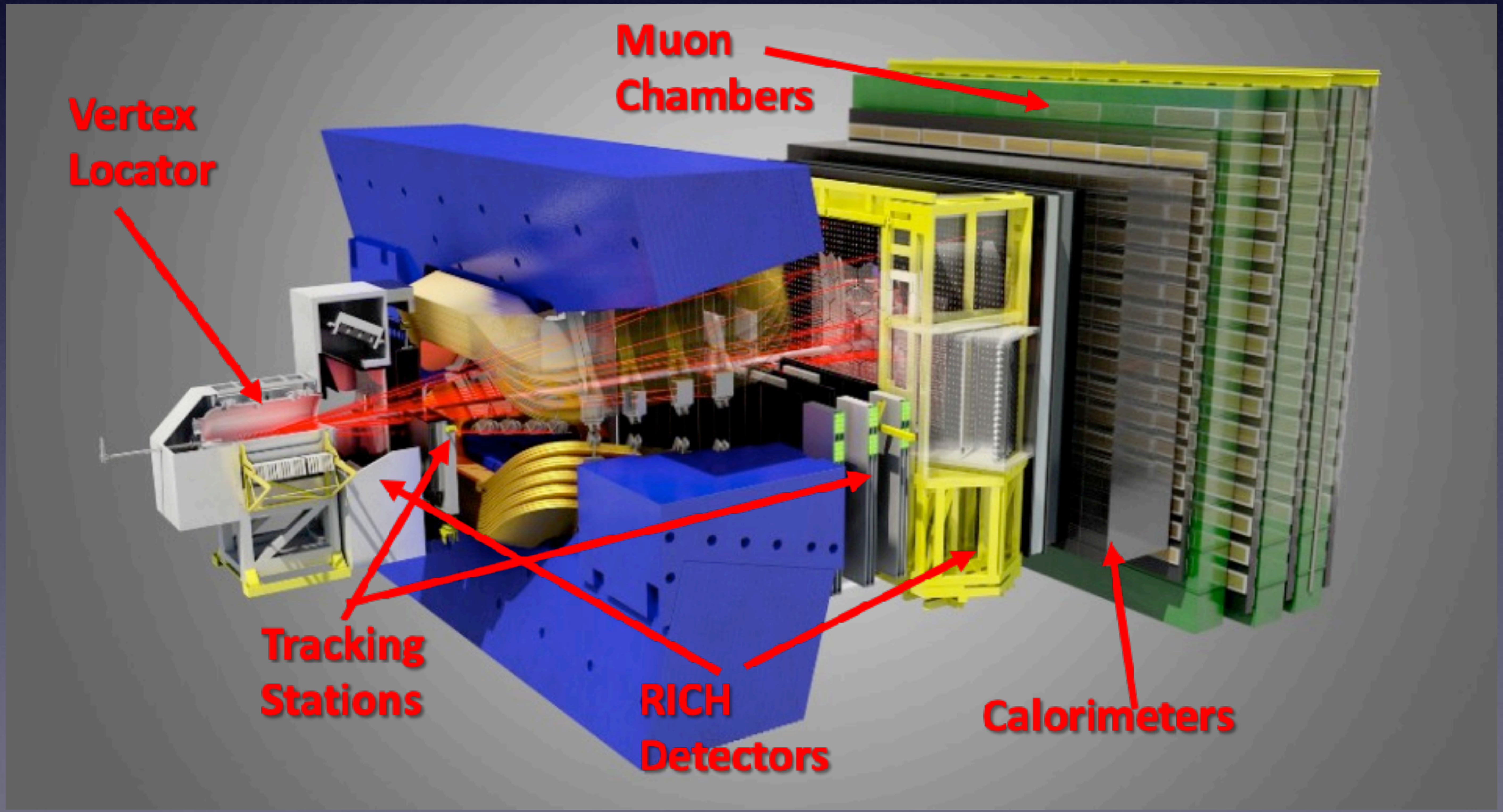
- Introduction
- Selected results from LHCb published W and Z boson measurements
  - Z boson production cross section — JHEP 07 (2022) 26
  - Z angular coefficient measurement — PRL 129 (2022) 091801
  - $Z+c$ measurement — PRL 128 (2022) 082001
  - W boson mass measurement — JHEP 01 (2022) 036
- Conclusions

More details can be found in Jianqiao Deng's talk: Link to the talk (this afternoon)

LHCb detector

JINST 3 (2008) S08005
Int. J. Mod. Phys. A30 (2015) 1530022

- Designed for the heavy flavour physics, with $2 < \eta < 5$
- Extended to EW measurements: excellent performance of tracking and muon detector

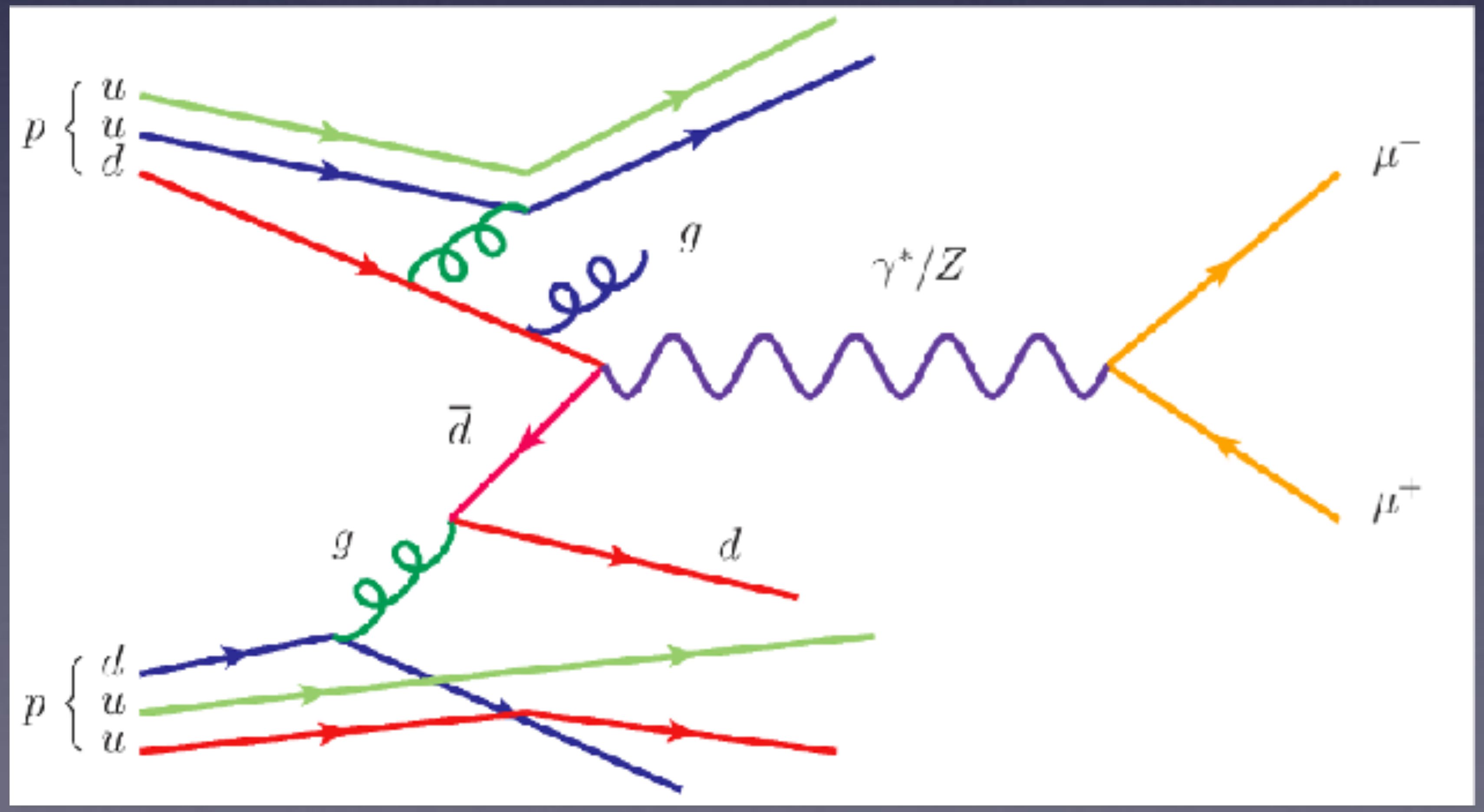


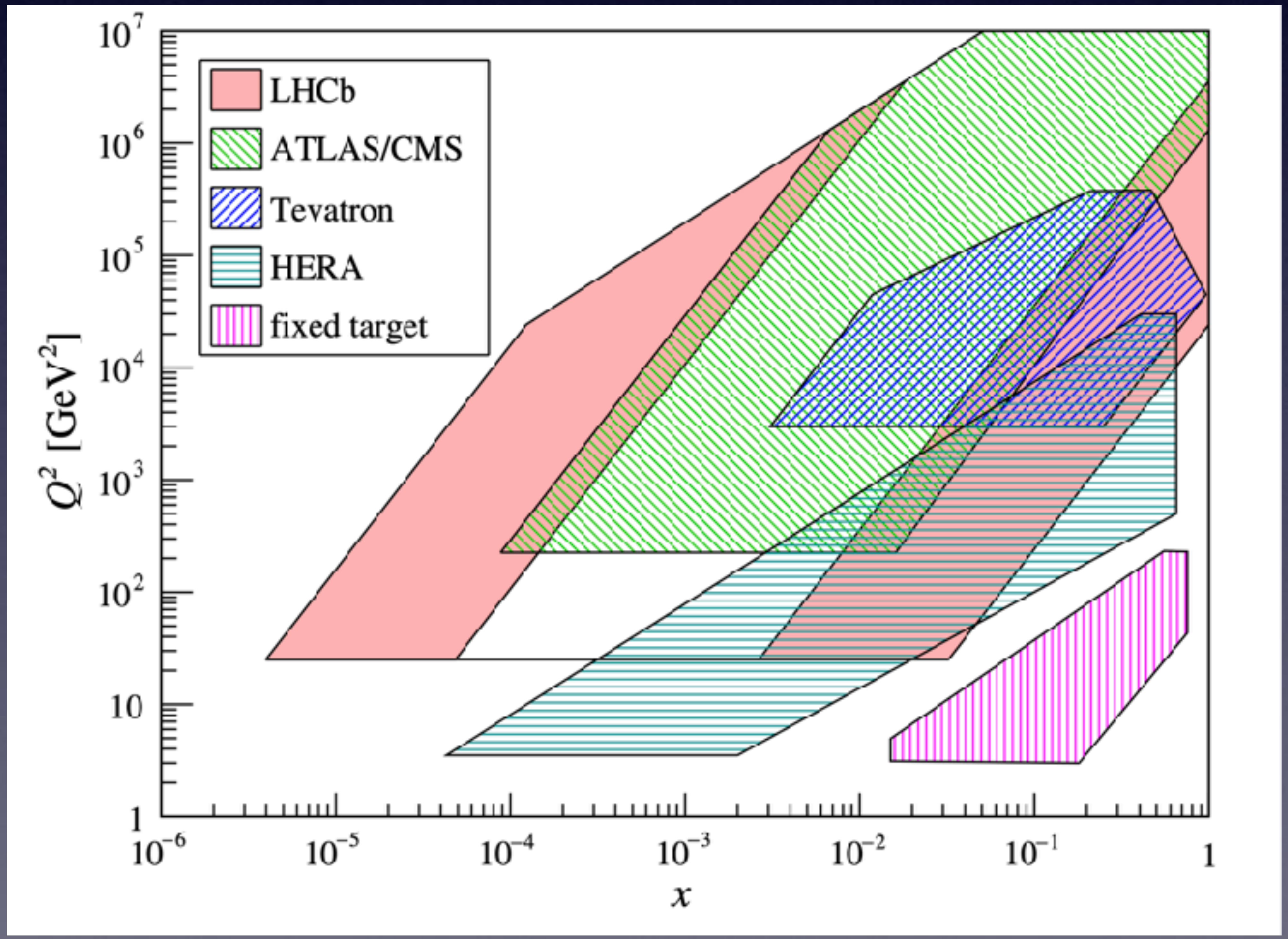
EW production @LHCb

- The Bjorken-x value of interacting parton are correlated with EW boson production

Rapidity: $y = \frac{1}{2} \ln \frac{x_1}{x_2}$

Large rapidity: either very large or very small $x_{1,2}$





Phys. Rev. D93, 074008 (2016)

JHEP 07 (2022) 26

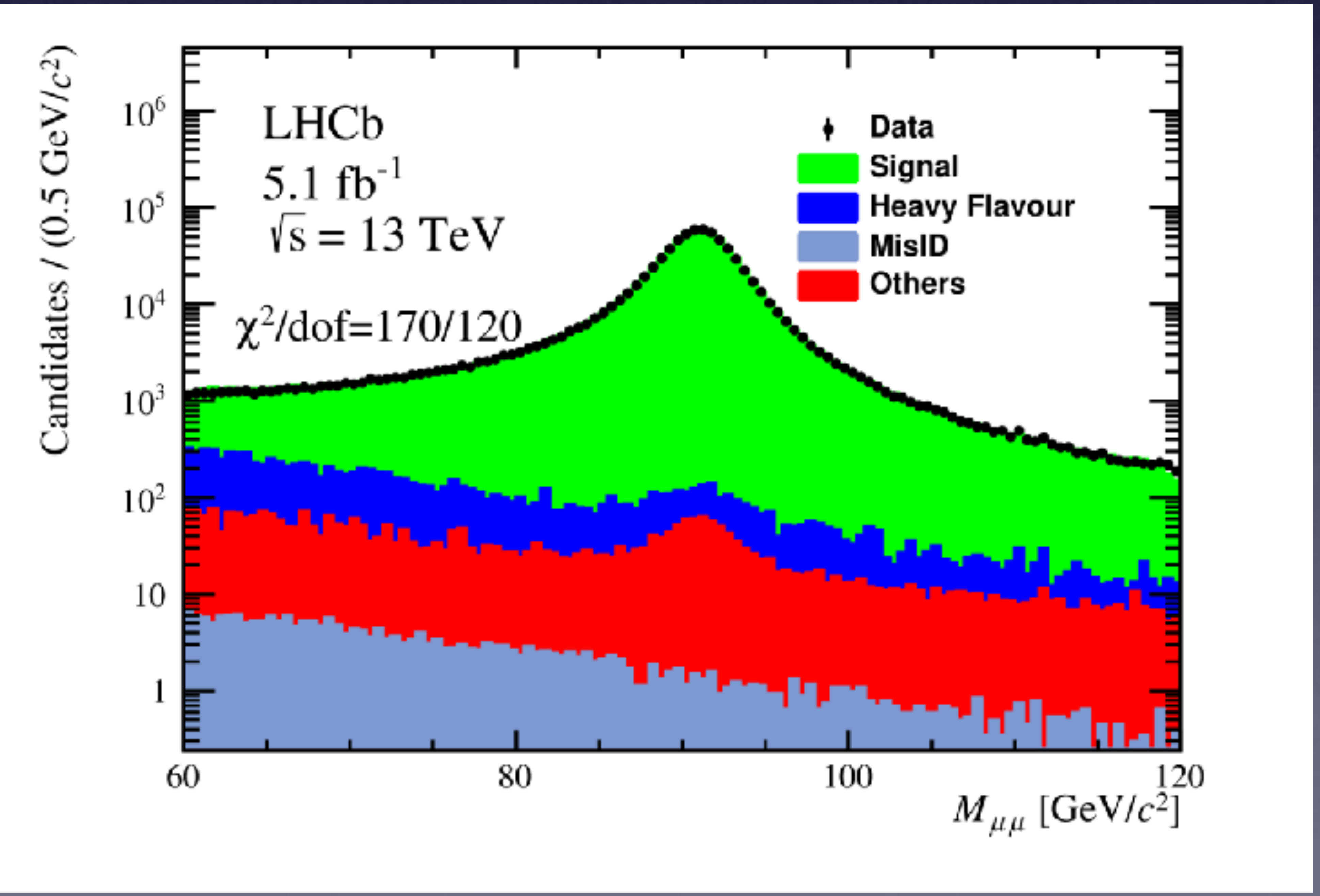
Z boson production cross-section measurement

- Dataset: 2016-2018, pp collision data @ 13 TeV, 5.1 fb^{-1}
- $Z \to \mu^+\mu^-$ events:
  - Trigger: at least one μ must fire single muon trigger decision stages
  - Event selection: 796k candidates

μ	Z
$p_{\mathrm{T}} > 20\,\mathrm{GeV}/c$	$60 < M_{\mu^+\mu^-} < 120\,\mathrm{GeV}/c^2$
$2 < \eta < 4.5$	
$\sigma_P/P < 10\%$	

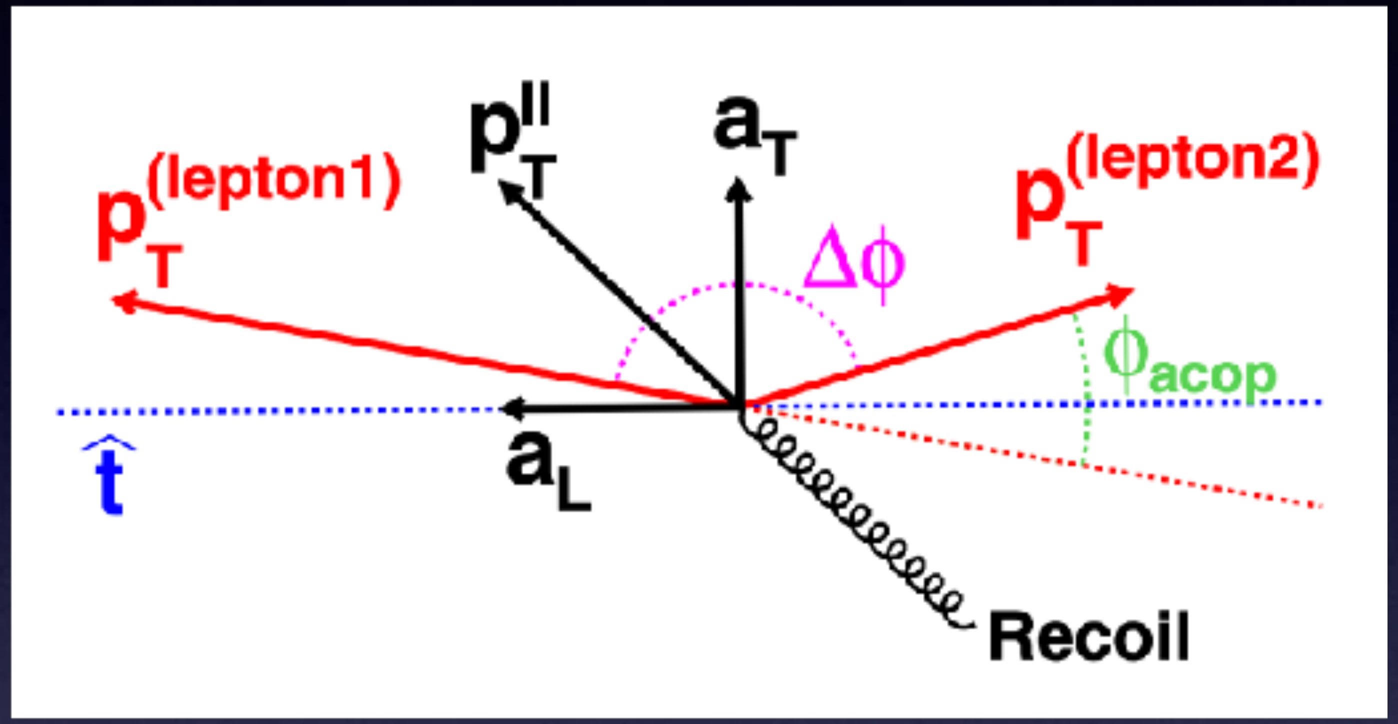
Z boson production cross-section measurement

- Background contributions: 1.5%
  - Heavy flavor: semileptonic decay, $(1.0 \pm 0.1)\ \%$
    - Data driven method: reverse isolation and vertex fit quality cuts to get background dominated samples
  - Misidentified hadron:
    - Remove overlap with Heavy flavor
  - Other physics process:
    - $Z \to \tau^+\tau^-, W^+W^-, W^\pm Z, t\bar{t}$



Analysis strategy

- LHCb Fiducial region:
  - Muons within $2 < \eta < 4.5$, $p_T > 20$ GeV/c
  - $60 < M_{\mu\mu} < 120$ GeV/c^2



- Cross-section measured in bin of Z boson rapidity, p_T, and ϕ^*

$$\frac{d\sigma_{Z\to\mu^+\mu^-}}{dy}(i) = \frac{N_Z(i)\cdot f^Z_{FSR}(i)}{\mathcal{L}\cdot\varepsilon^Z_{REC}(i)\cdot\Delta y(i)}$$

- Corrected to the Born level in QED: direct comparison of the results and different predictions

Systematic uncertainties

- Luminosity determination: 2%
- Tracking reconstruction: for each muon is determined to be 0.47%

Integrated cross-section

Source	$\Delta\sigma/\sigma$ [%]
Statistical	0.11
Background	0.03
Alignment & calibration	-
Efficiency	0.77
Closure	0.06
FSR	0.04
Total Systematic (excl. lumi.)	0.77
Luminosity	2.00
Total	2.15

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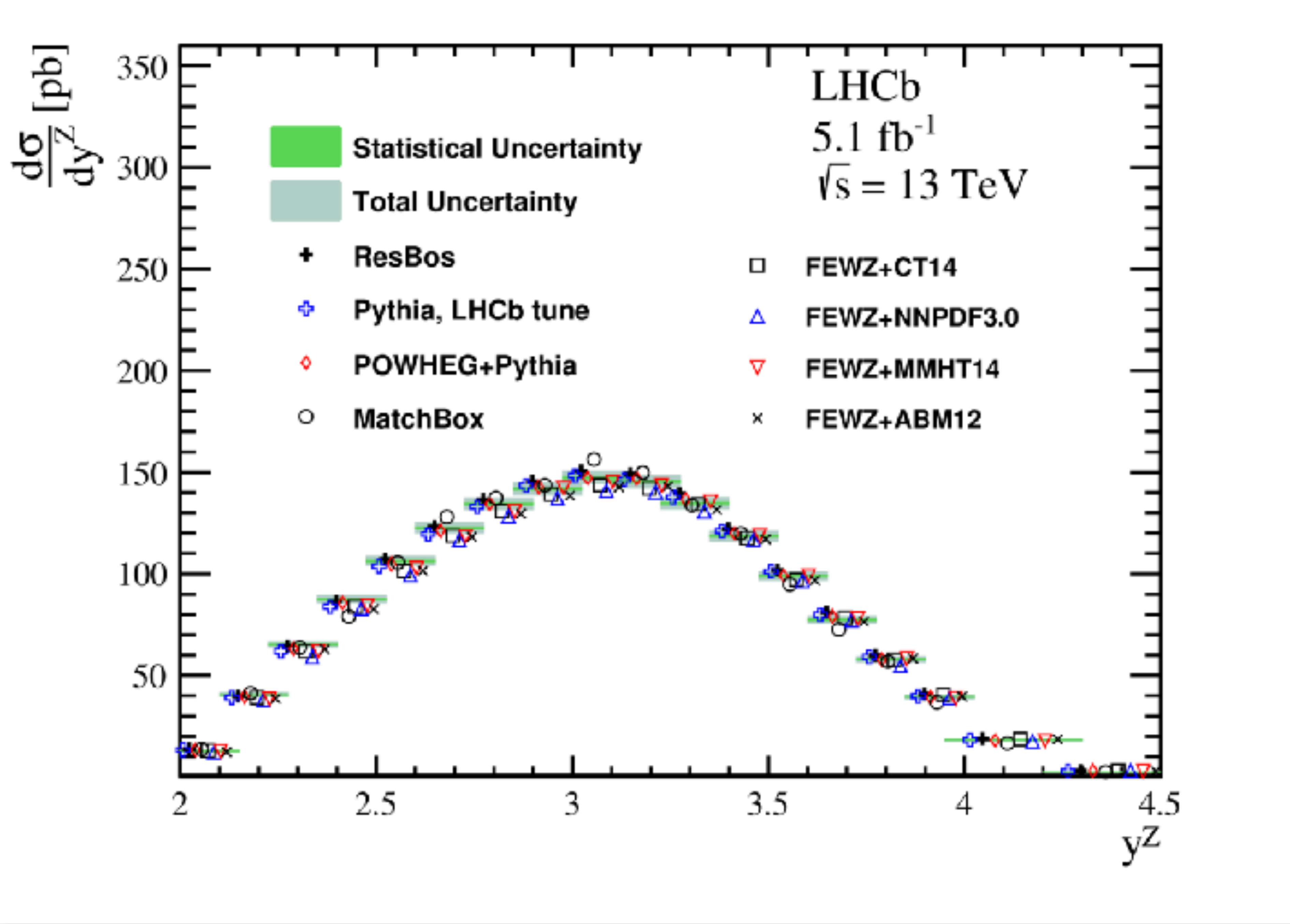
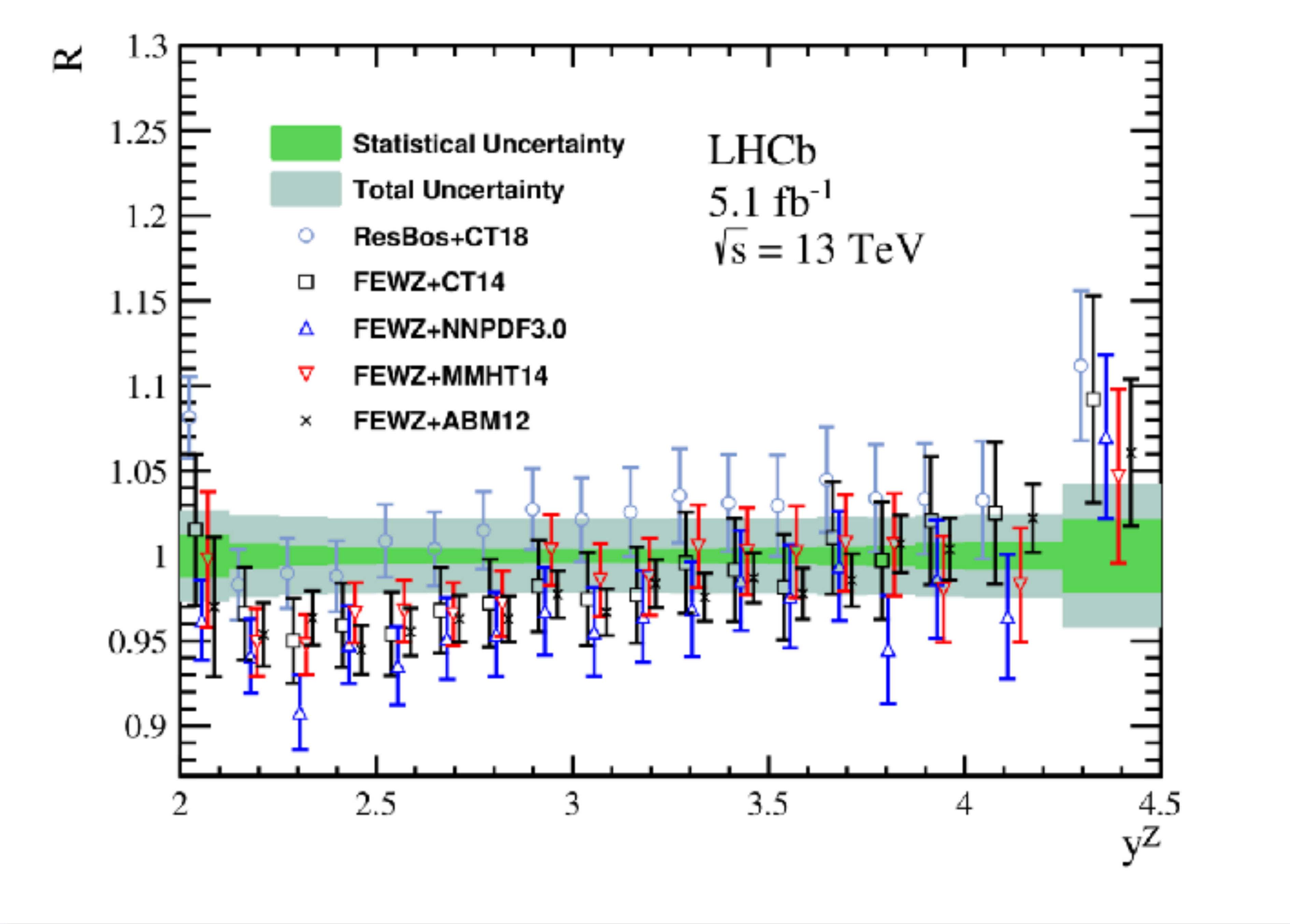
Differential cross-section: 1-D

- Reasonable agreements between data and predictions
- Predictions are systematically smaller than the measured results in the lower rapidity region
    - Same behaviours are seen in 2015 LHCb data-set





$$R = \frac{\text{Predictions}}{\text{Data}}$$

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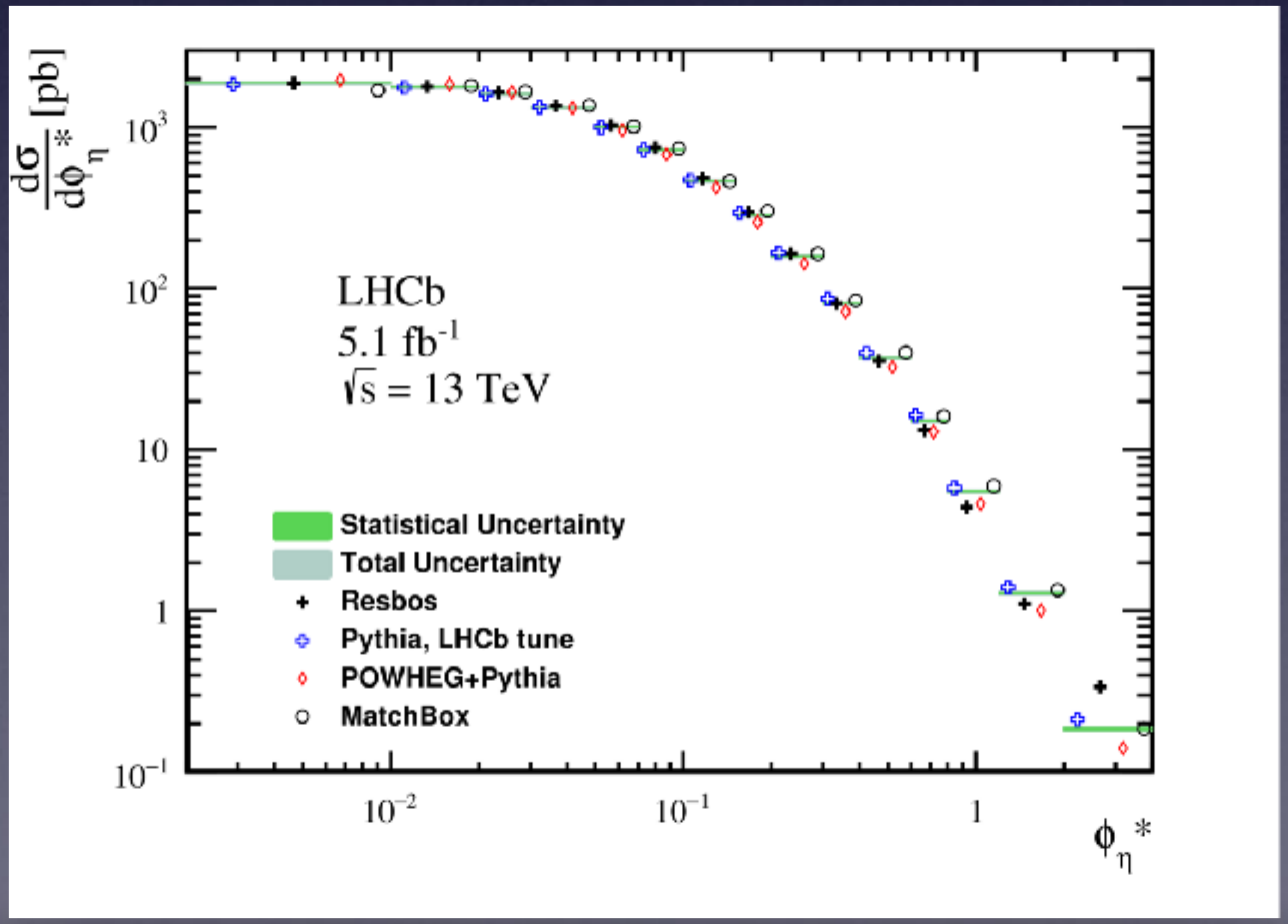
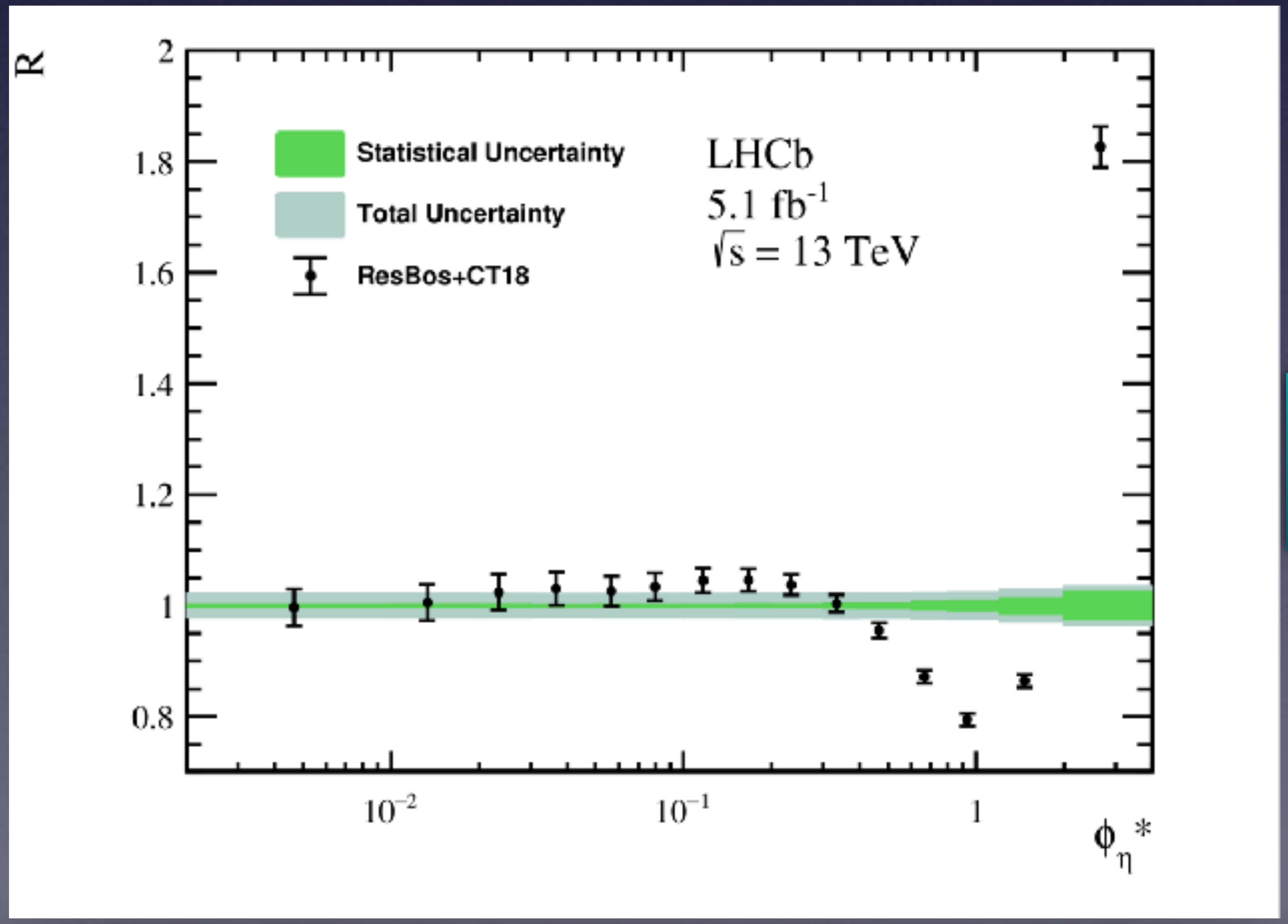
Differential cross-section: 1-D

- Measured cross section in different intervals of Z boson ϕ^*
- ResBos describes the low ϕ^* data, but tensions are seen in the large ϕ^* region





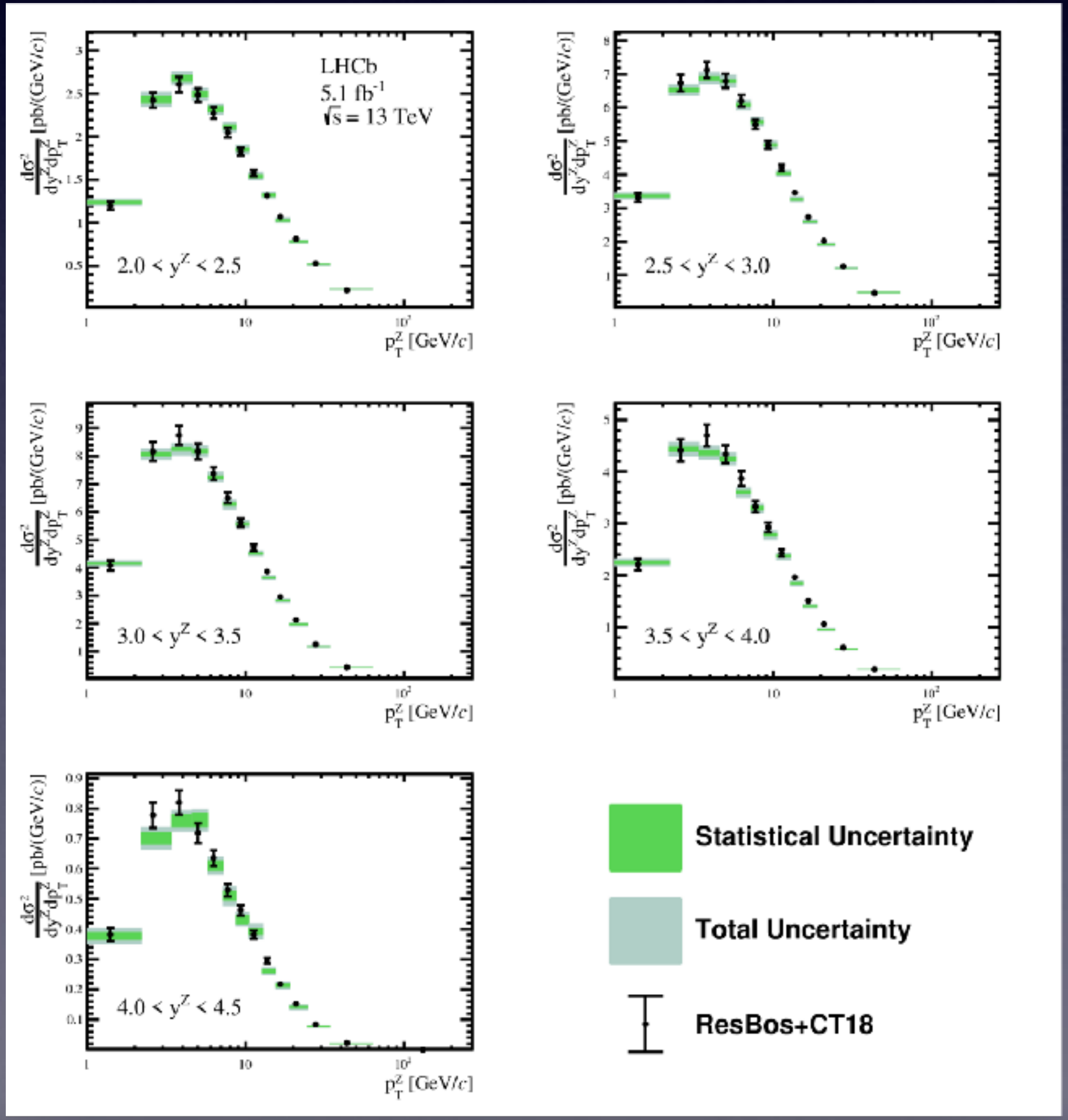
$$R = \frac{\text{Predictions}}{\text{Data}}$$

JHEP 07 (2022) 26

Double differential cross-section

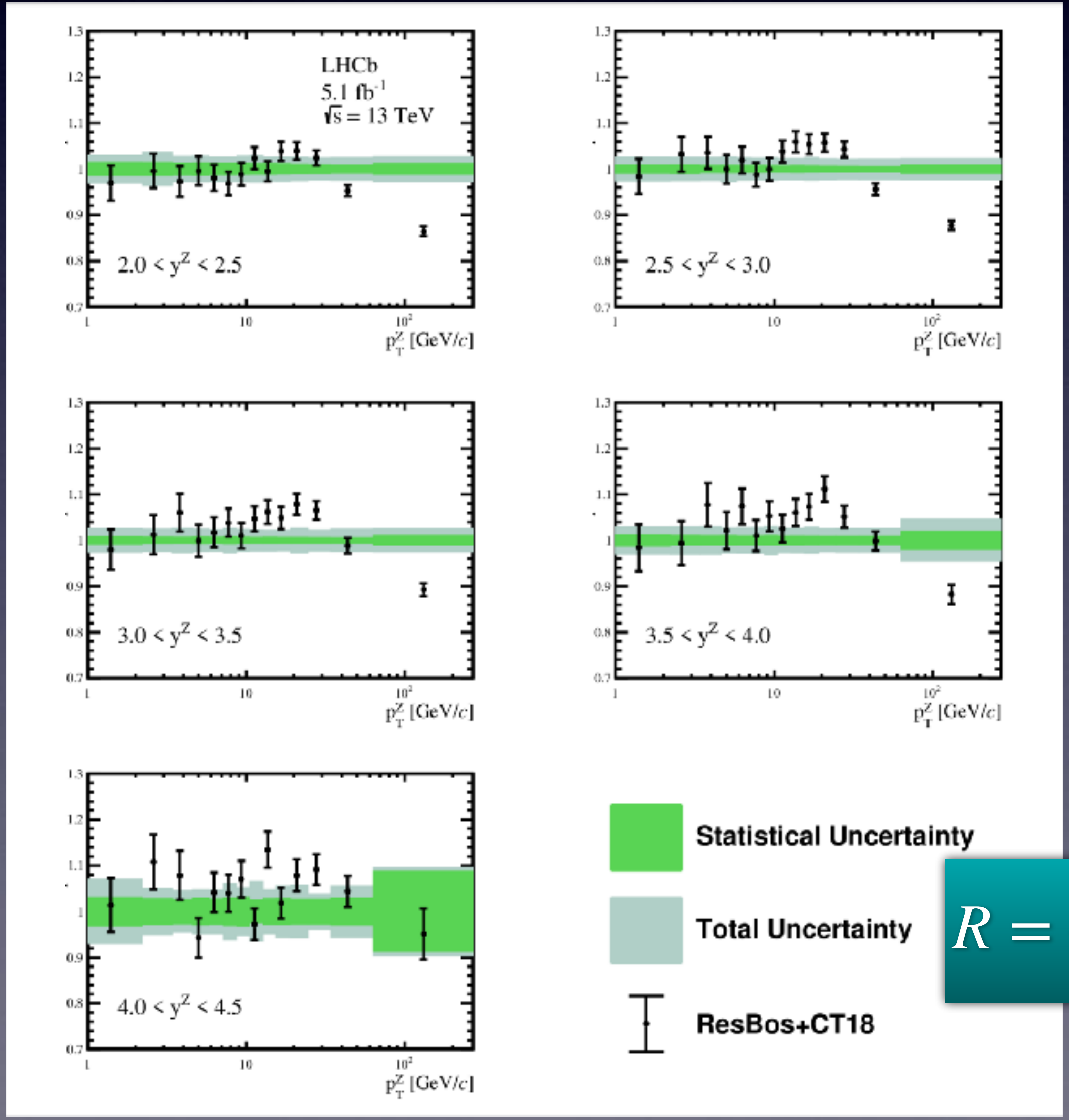
First double differential cross-section measurement in the forward region

Reasonable agreement with RESBOS predictions



p_T^Z

In the high p_T region, ResBos is only up to NLO



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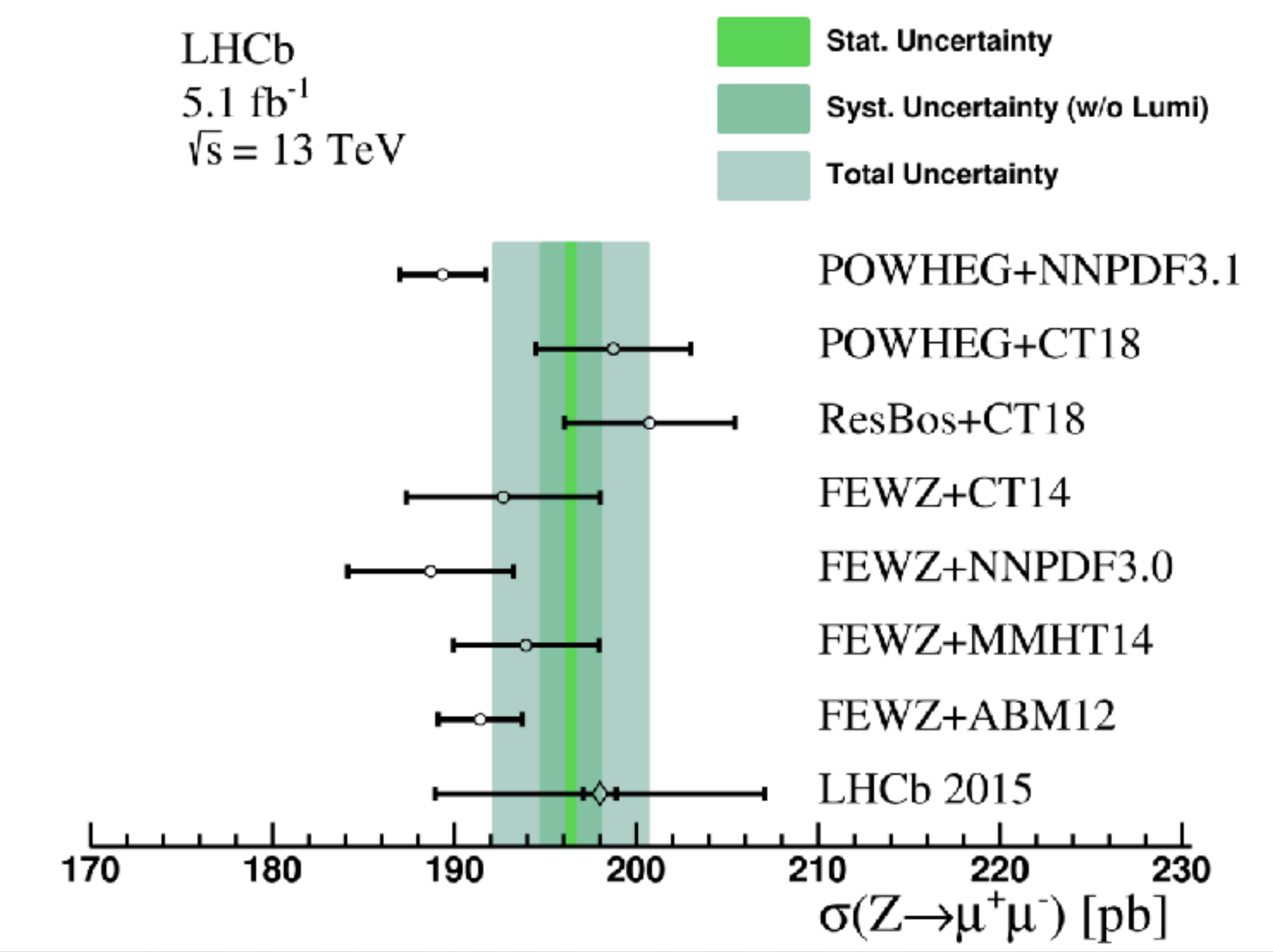
Integrated cross-section

Integrated cross-section



Good agreements between data and predictions are seen

$$\sigma(Z \to \mu^+\mu^-) = 196.4 \pm 0.2(\text{stat.}) \pm 1.6(\text{syst.}) \pm 3.9(\text{lumi})\ \text{pb}$$

Angular coefficient measurement of Z boson

- To further encode the Z production mechanism, angular coefficients of Z boson are measured
- A_2 is sensitive to the transverse momentum dependent PDFs (TMD)
  - Measured A_2 in the low p_T region, using events in different mass regions

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

A_4 sensitive to $\sin^2\theta_W$
In pQCD, A_5 to A_7 near to 0

Analysis strategy

- Event selection:
    - Same data-sets as Z boson cross-section measurement
    - Similar event selections as Z production cross-section measurement
    - Additional cuts to further suppress background contributions
        - Muon isolation requirement
        - Originate from a common primary pp interaction vertex

Analysis strategy

- Background contribution: ~0.2%
  - Removed with negative weights in the fit
- An iterative method: stable after four iterations
  - Normalization weights method
    - Introduced and used by the Babar collaboration
    - Extensively used in the heavy-flavour studies
- Several closure tests

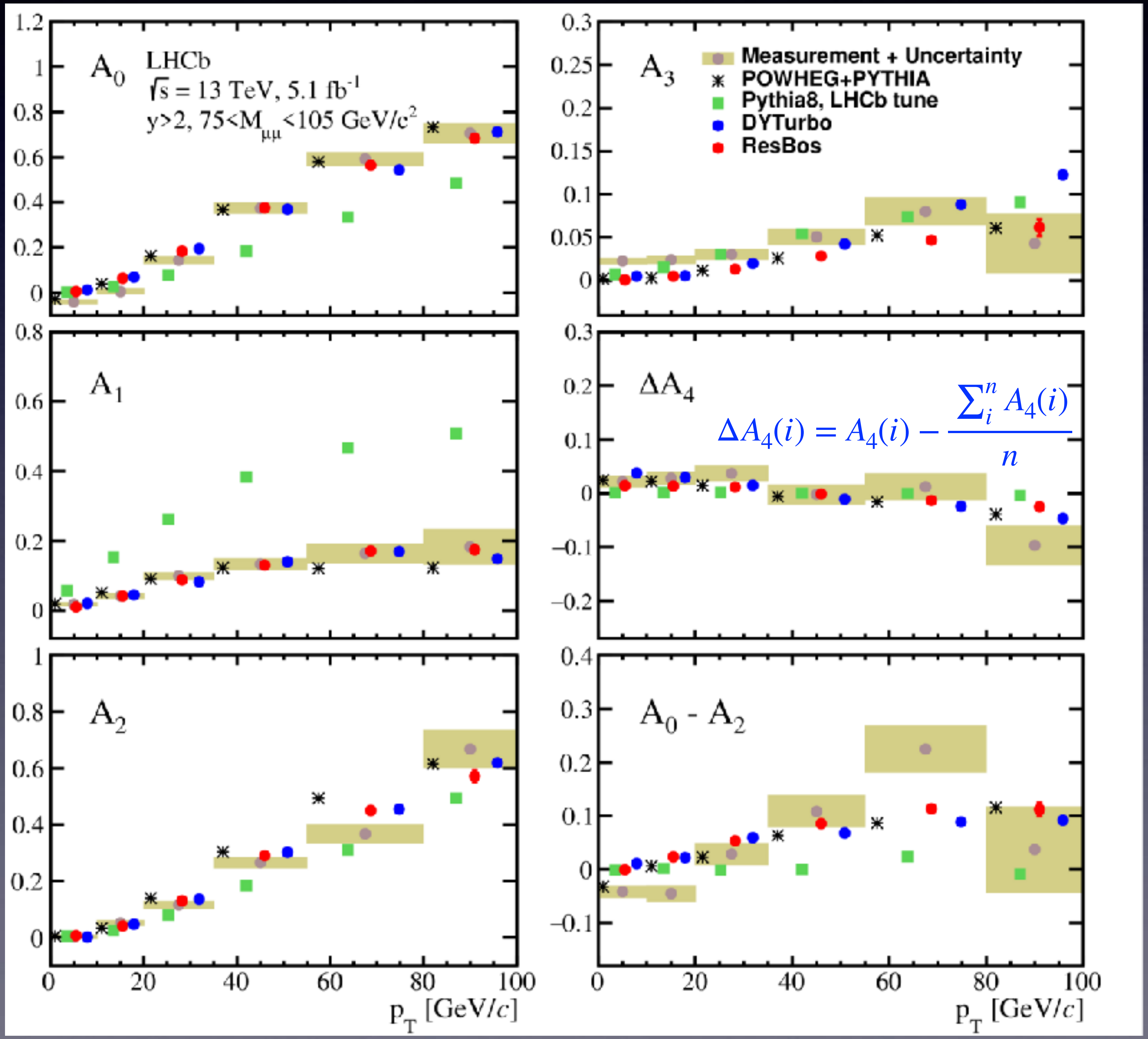
Phys. Rev. Lett. 87 (2001) 241801

Phys. Rev. D 71 (2005) 032005

PRL 129 (2022) 091801

Z boson p_T dependent results

- Measured results are at Born level in QED
- Dominated uncertainty: statistical uncertainty
- Compared with various predictions
  - POWHEG+PYTHIA
  - DYTurbo
  - RESBOS
  - PYTHIA8+LHCb tune

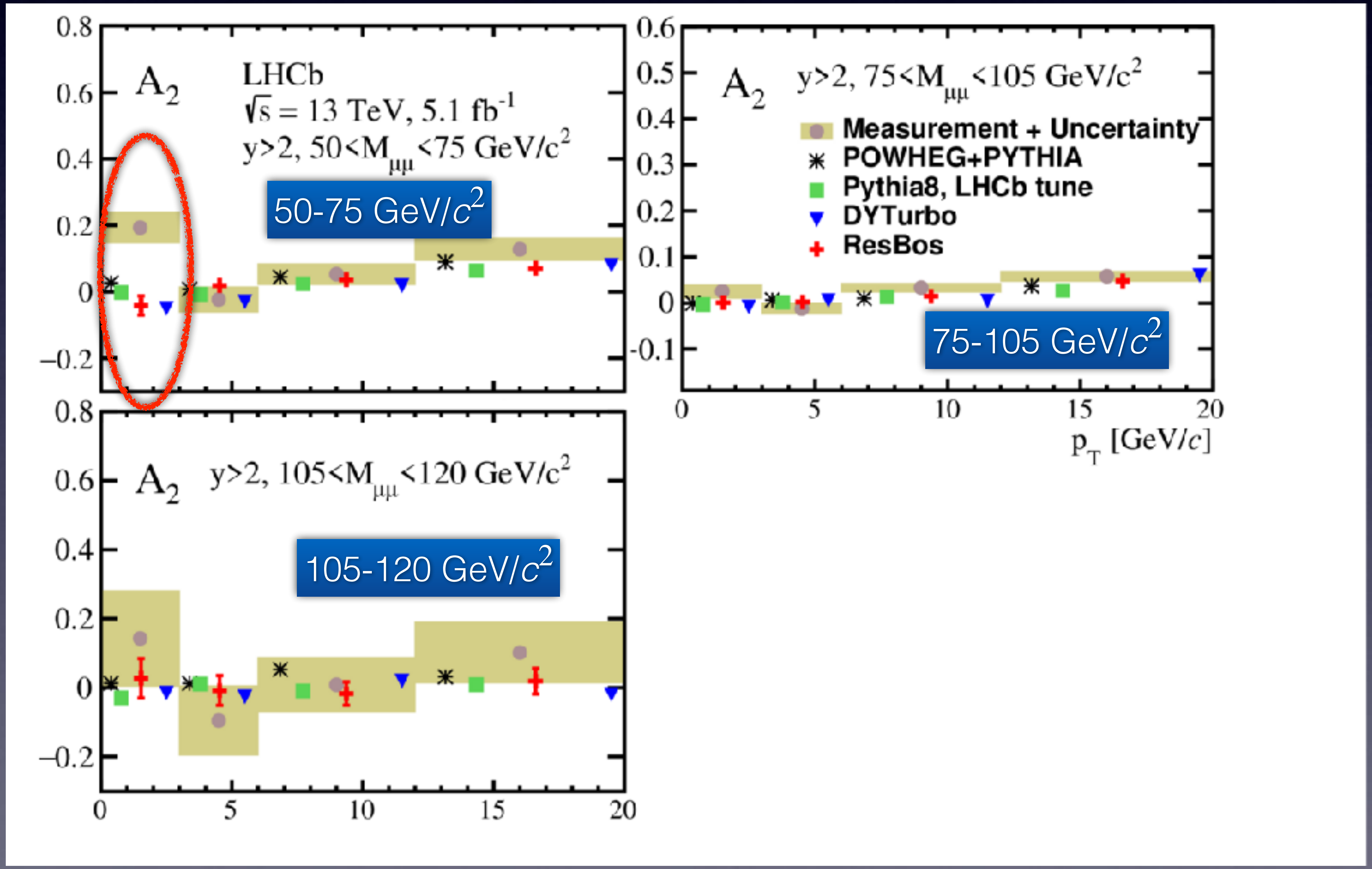


$$\frac{d\sigma}{d\cos\theta\, d\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi + A_4\cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi,$$

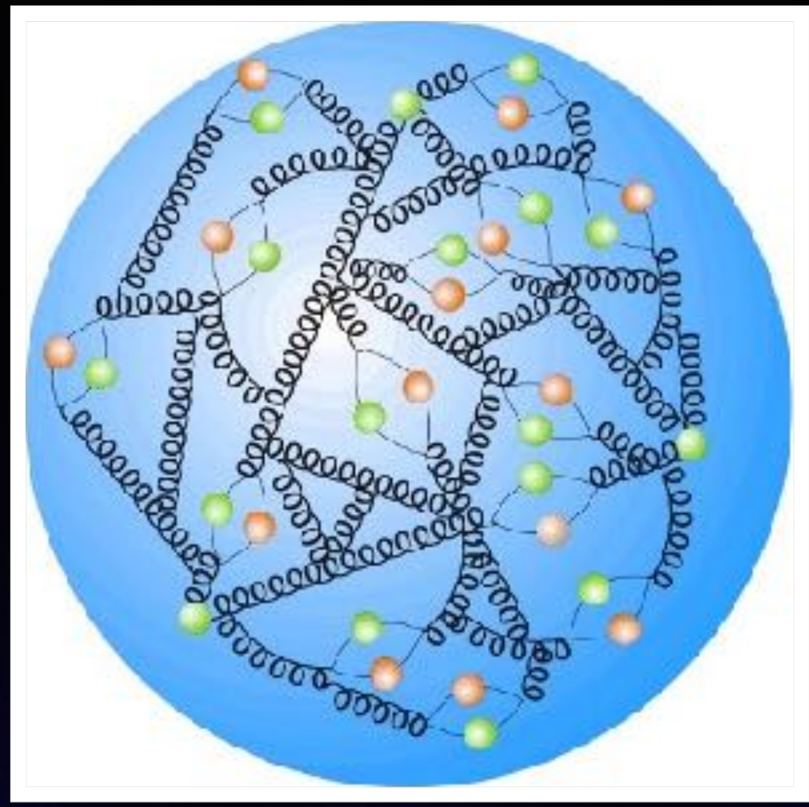
PRL 129 (2022) 091801

Results in low $Z\ p_T$ region

- Use measured A_2 to probe Boer-Mulders TMD PDFs
- In different mass regions: 50-75 GeV/c^2, 75-105 GeV/c^2, 105-120 GeV/c^2
- None of predictions include non-perturbative spin-momentum correlations



Intrinsic Charm

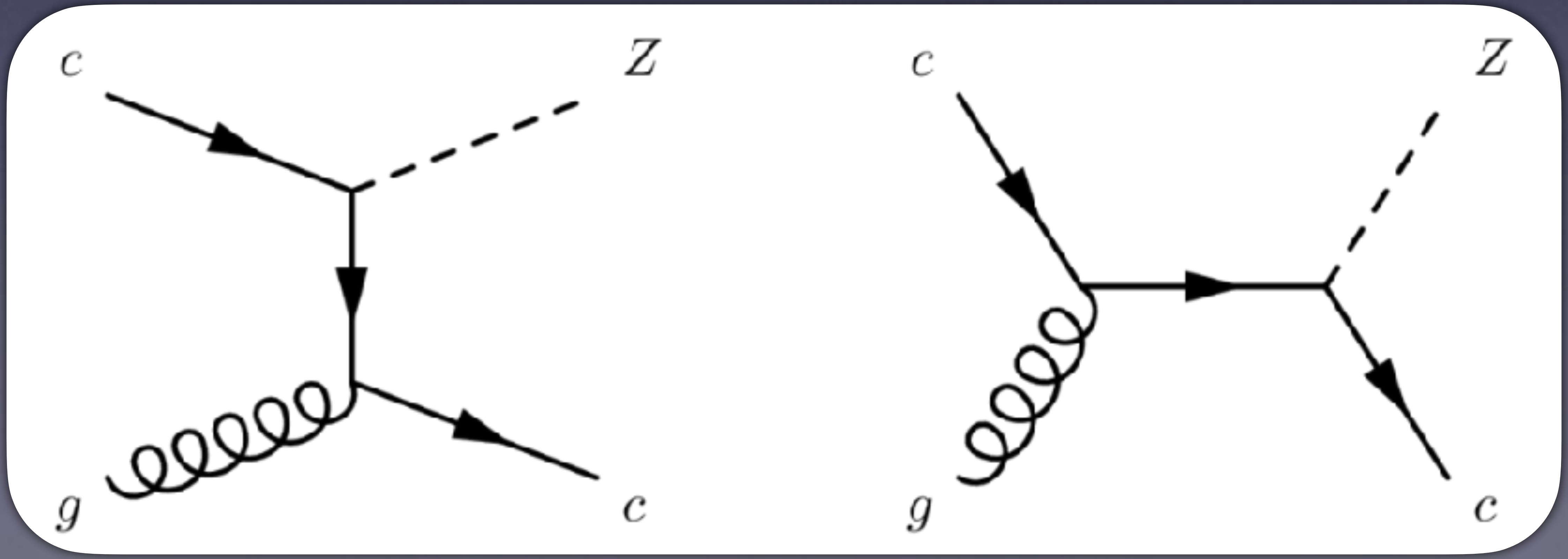


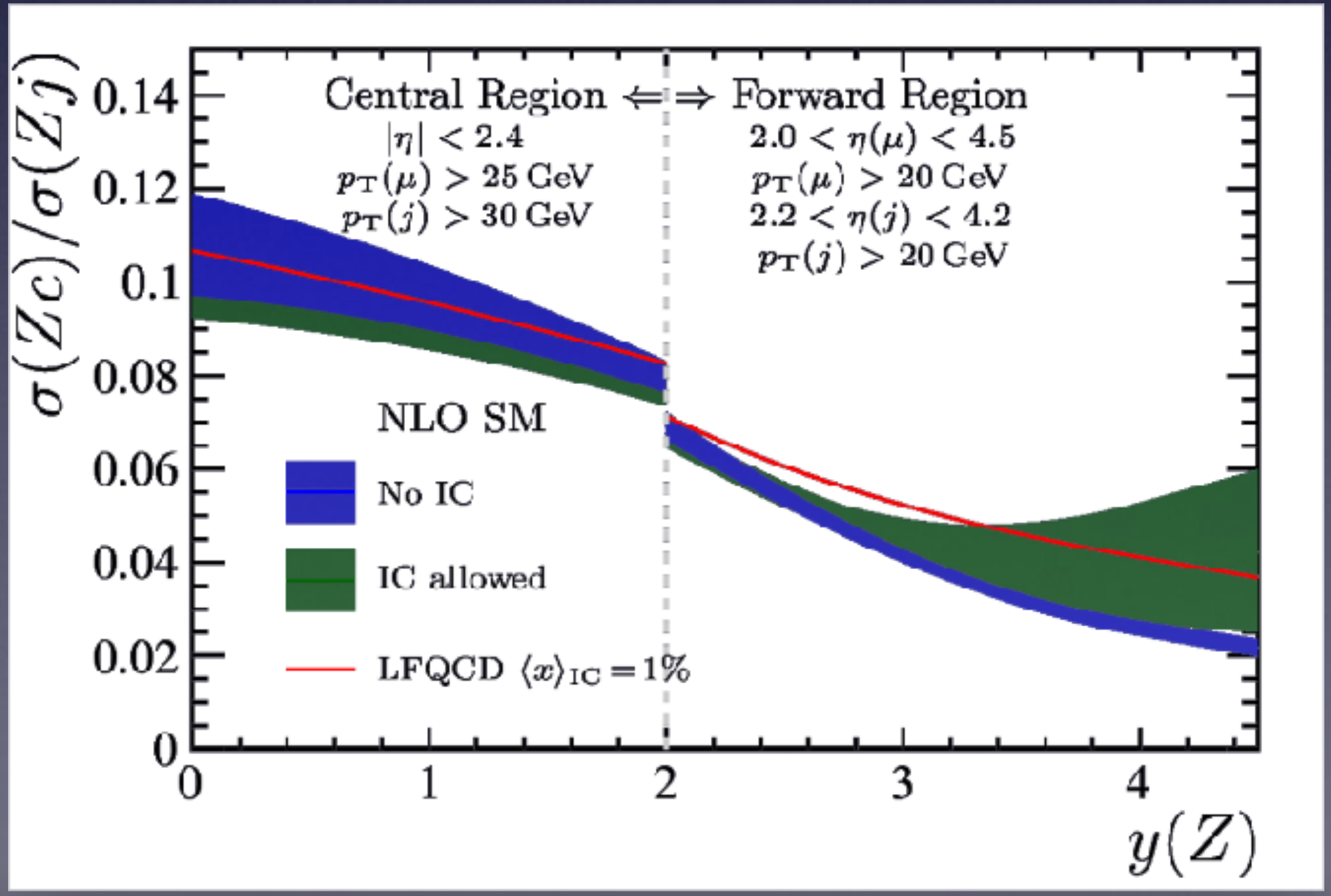
- Two types of parton contributions
- The extrinsic quarks/gluons:
  - Generated on a short time scale in association with a large transverse-momentum reaction
- The intrinsic quarks/gluons:
  - Exist over a time scale independent of any probe momentum, they are associated with the found state hadron dynamics
- Intrinsic charm:
  - Long-lived charm component: longer than the interaction time of the probe
  - BHPS model: non-negligible $uudc\bar{c}$ component (independent of PDFs)

PRL 128 (2022) 082001

Probe intrinsic charm at LHCb

- Ratio measurement: $Z_j^c = \sigma(Zc)/\sigma(Zj) = \dfrac{N_c^{tag}}{N_j \times \varepsilon_c^{tag}}$
- IC may enhance c-jet production at high $y(Z)$
- Challenges: c-jet tagging and its efficiency



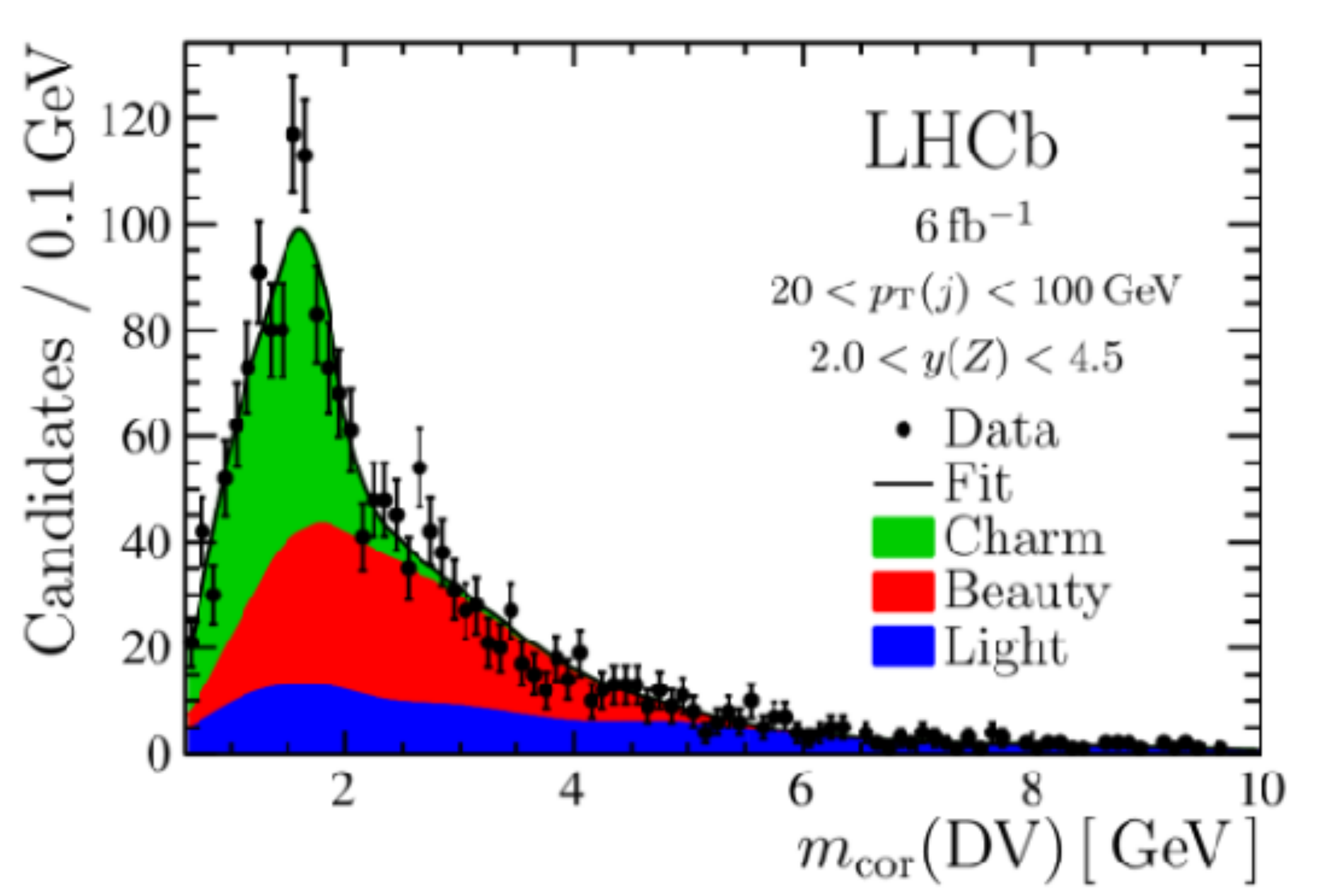


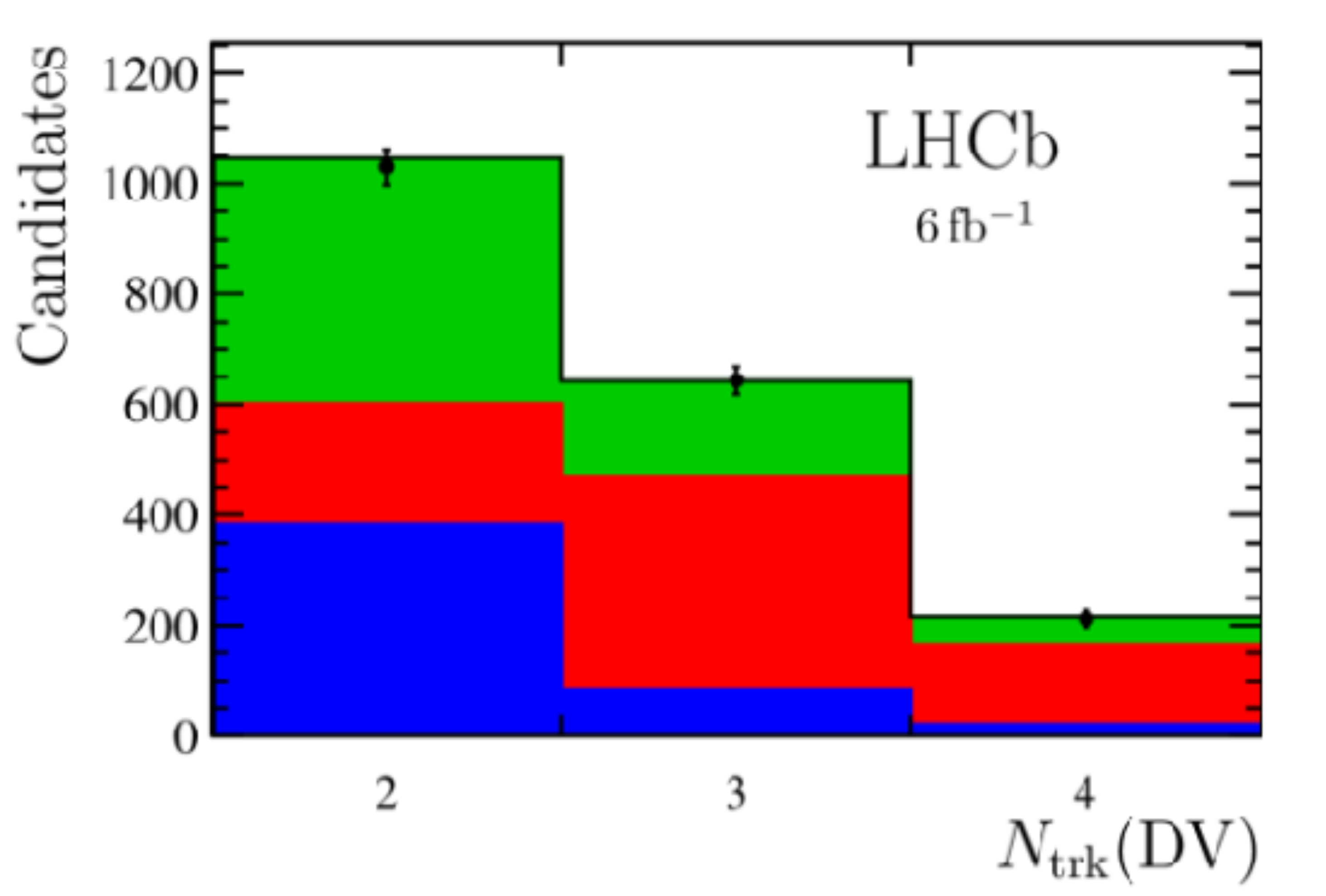
PRL 128 (2022) 082001

Jet and c-jet

- Jet reconstruction: particle-flow algorithm using the anti-κ_T clustering algorithm (FastJet)
- Displaced-vertex (DV) tagger: to separate c-jet from b-jet and light jets
    - Inputs: mass, momentum, position, direction
    - ≤ 4 tracks: to reject b-hadron decays

Simultaneously fit of m_{cor} and N_{trk}





PRL 128 (2022) 082001

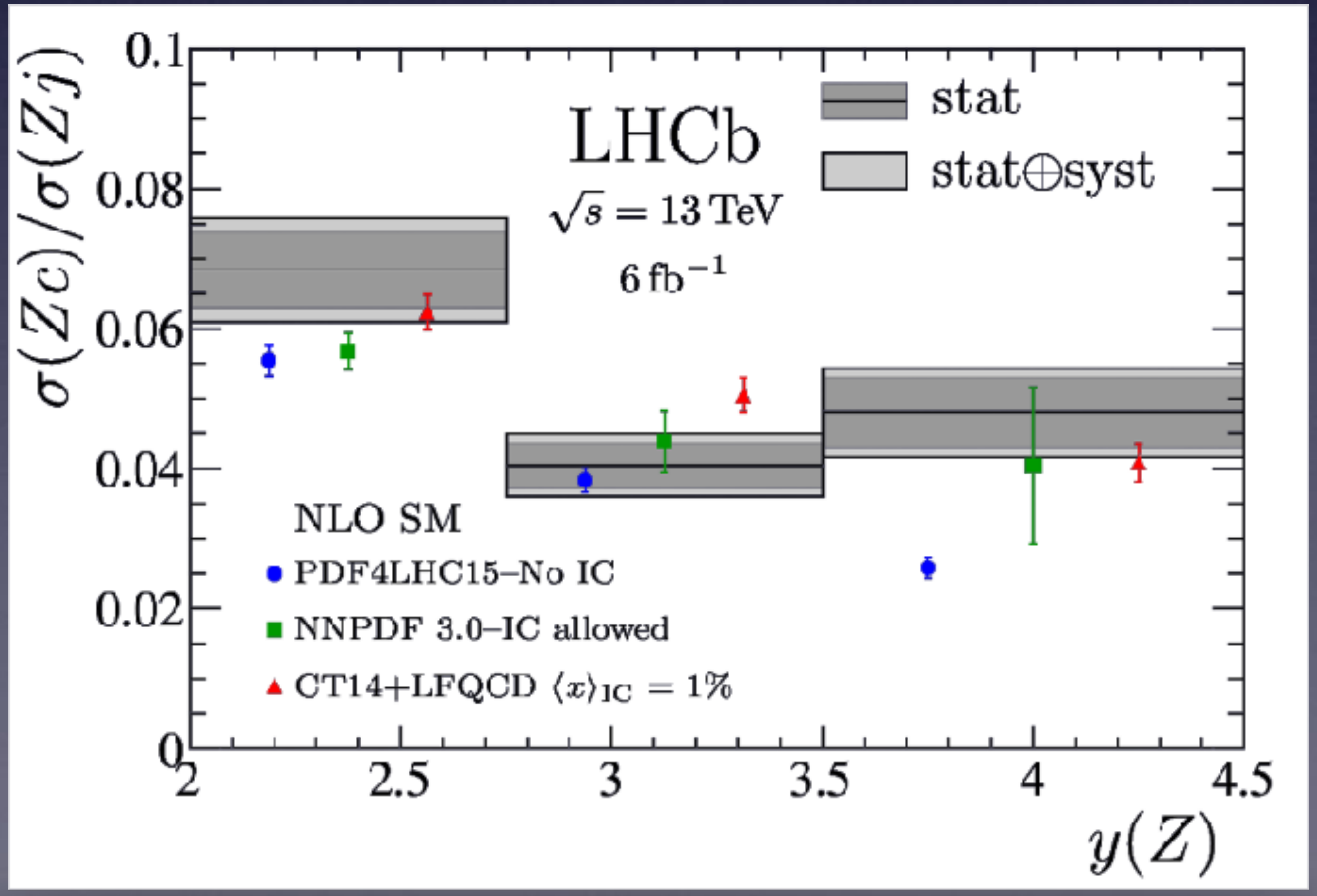
Uncertainties

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

PRL 128 (2022) 082001

$Z + c$ results

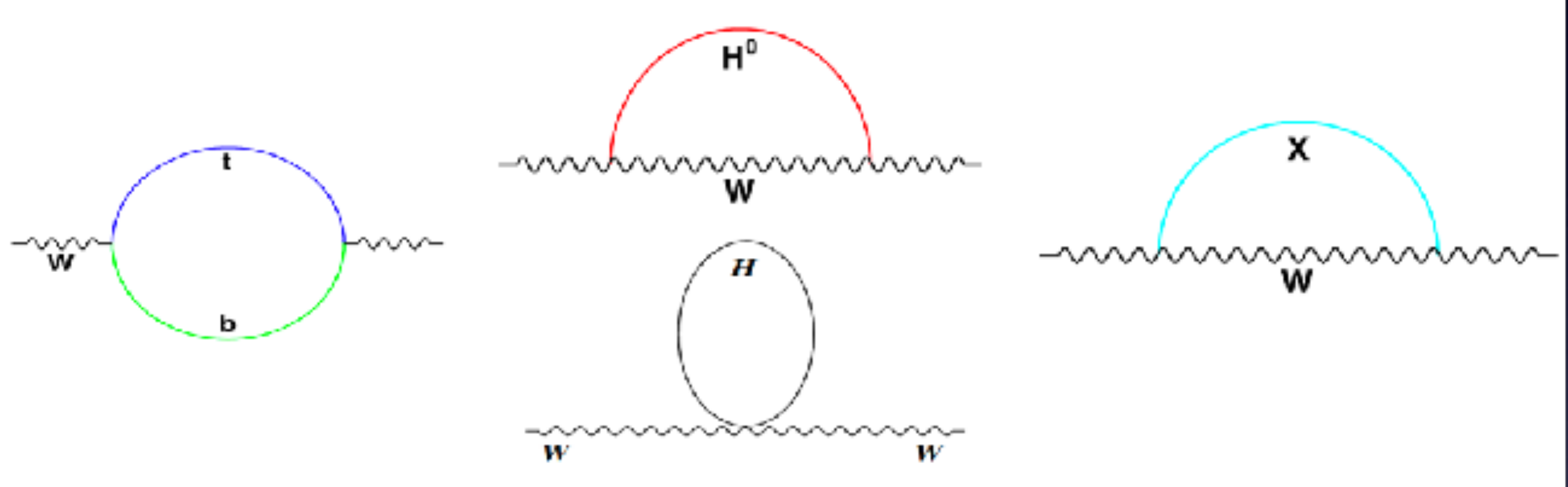
- The measured result has a sizable enhancement at forward Z rapidity region
- Consistent with LFQCD + IC
- Indicate a valence-like IC component in the proton wave function



Measurement of the W boson mass

- m_W is related to other fundamental parameters in SM EW sector

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$



- Radiative corrections (Δ) dominated by top quark and Higgs loop, also can be affected by new physics contributions

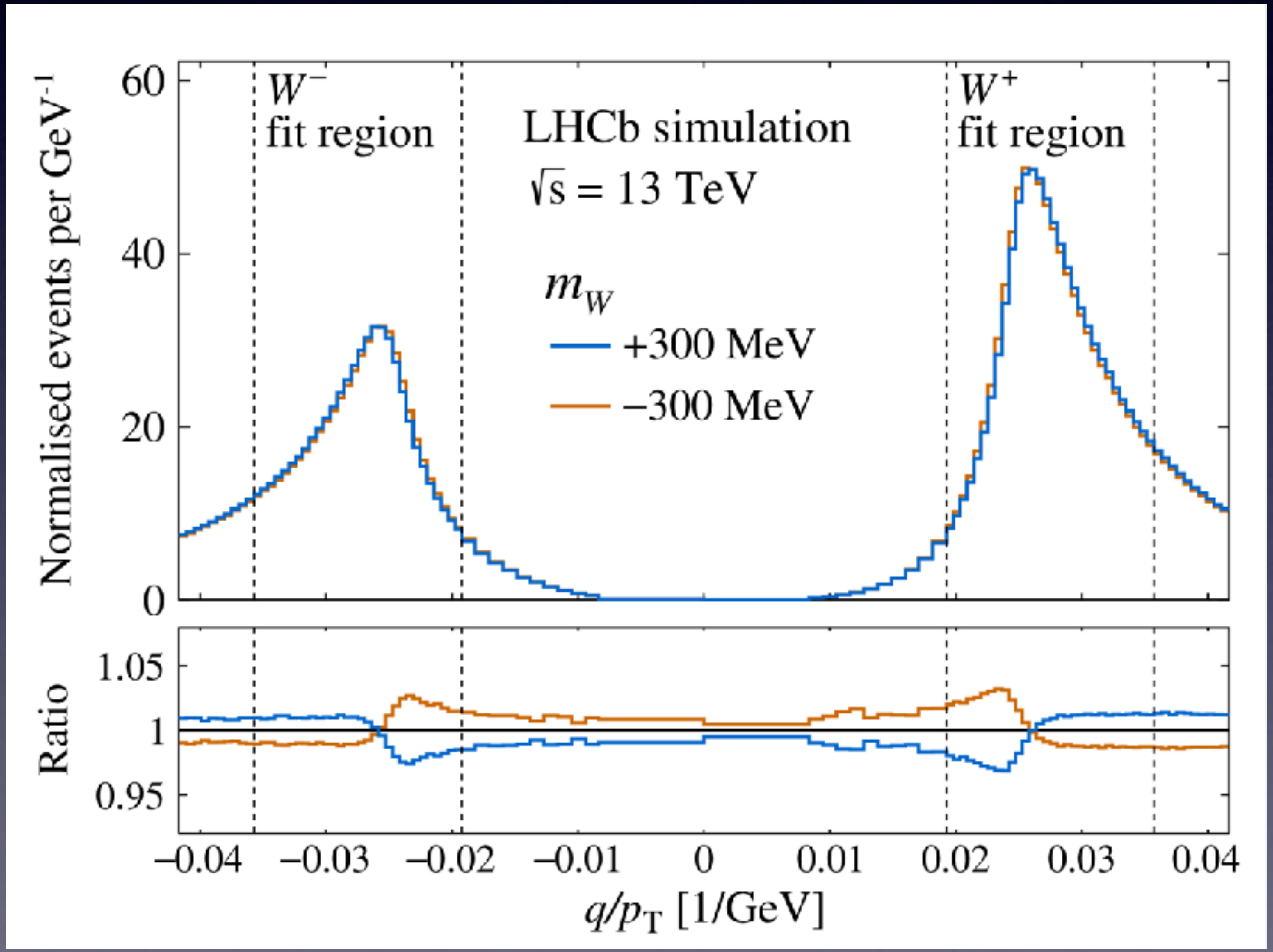
- The LHCb measurement is complementary to the ATLAS and CMS results
  - PDFs uncertainty could partially cancel in the combination of LHC measurements

Eur. Phys. J. C75 (2015) 601

JHEP 01 (2022) 036

Analysis strategy

- 2016 data-set: $W \to \mu\nu$ decays
- Muon q/p_T distribution is used to measure m_W
  - Detector response
    - Muon momentum measurement
    - Muon reconstruction and selection efficiency
    - Backgrounds
  - EW boson production
    - $W\,p_T$ modelling, PDFs, boson polarisation, electroweak corrections
- Simultaneously fitting the W and Z data: Z boson ϕ^*



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Systematic uncertainties

Source	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

PDFs: Average of NNPDF31, CT18 and MSHT20

p_T model: Envelope from five different models

A_i: scale variation

QED: Envelope of the QED FSR from PYTHIA8, Photos, and Herweig7

Efficiencies: statistical uncertainties, details of method (e.g. binning, smoothing)

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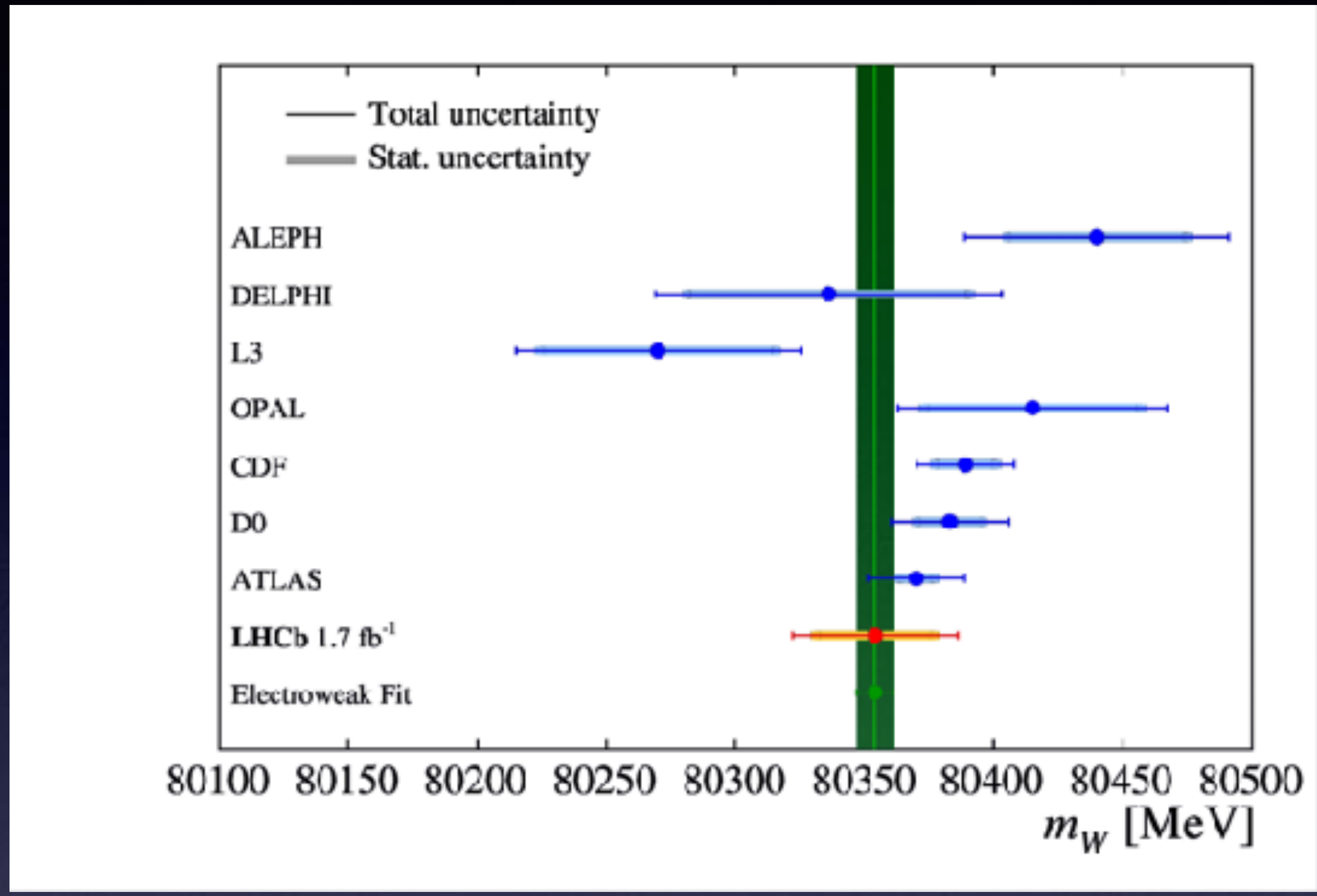
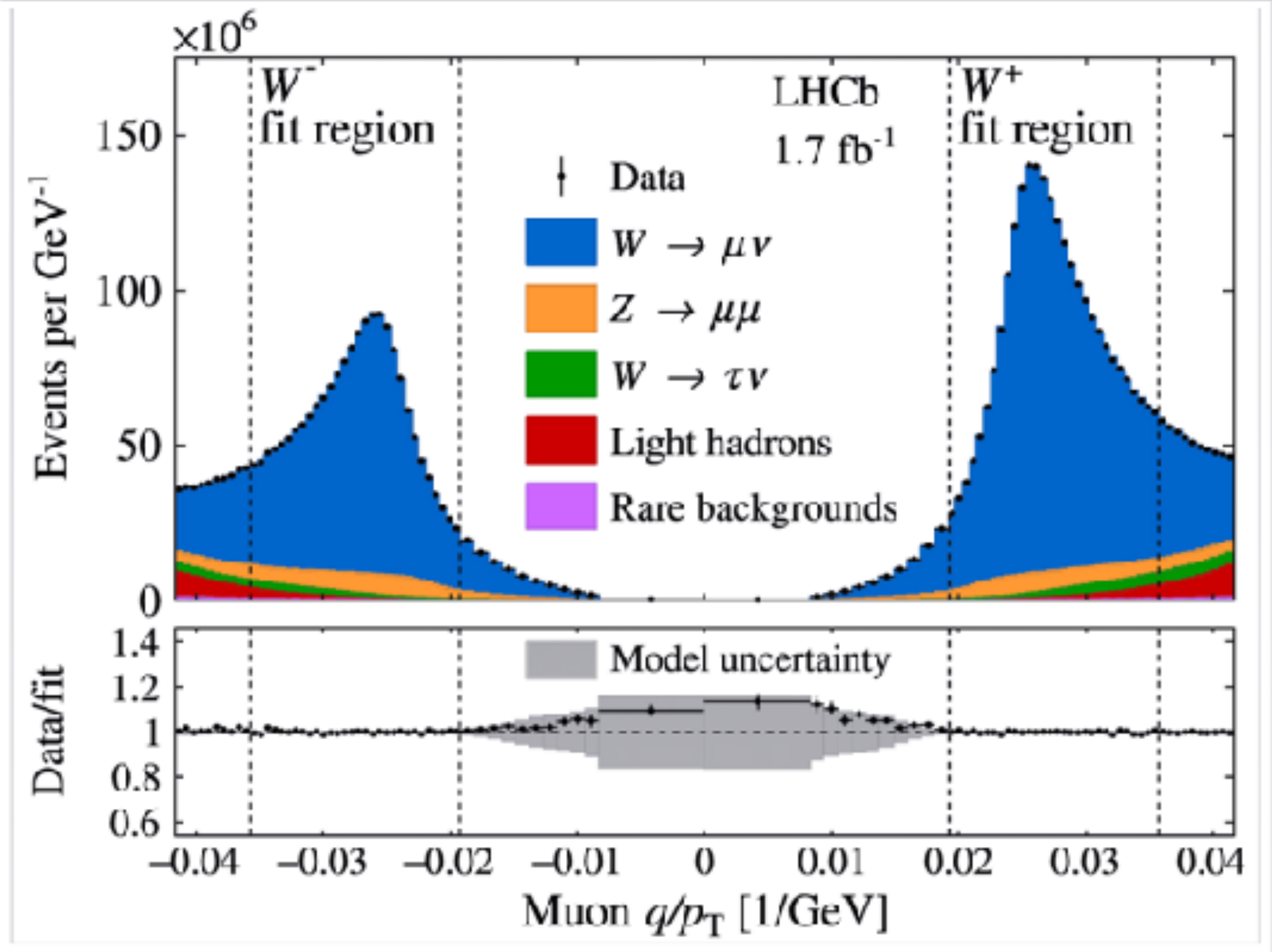
Results

- The determined m_W with the NNPDF31_nlo_as_0118 PDFs set
  - $\chi^2/dof = 105/102$
- Combined results obtained with NNPDF3.1, CT18, and MSHT20 PDFs sets:
  - $m_W = 80354 \pm 23(\textbf{stat.}) \pm 10(\textbf{exp.}) \pm 17(\textbf{theory}) \pm 9(\textbf{PDF})$
  - Analysis with full data-sets is ongoing





Parameter	Value
Fraction of $W^+ \to \mu^+\nu$	0.5288 ± 0.0006
Fraction of $W^- \to \mu^-\nu$	0.3508 ± 0.0005
Fraction of hadron background	0.0146 ± 0.0007
α_s^Z	0.1243 ± 0.0004
α_s^W	0.1263 ± 0.0003
k_T^{intr}	1.57 ± 0.14 GeV
A_3 scaling	0.975 ± 0.026
m_W	80362 ± 23 MeV

Conclusions

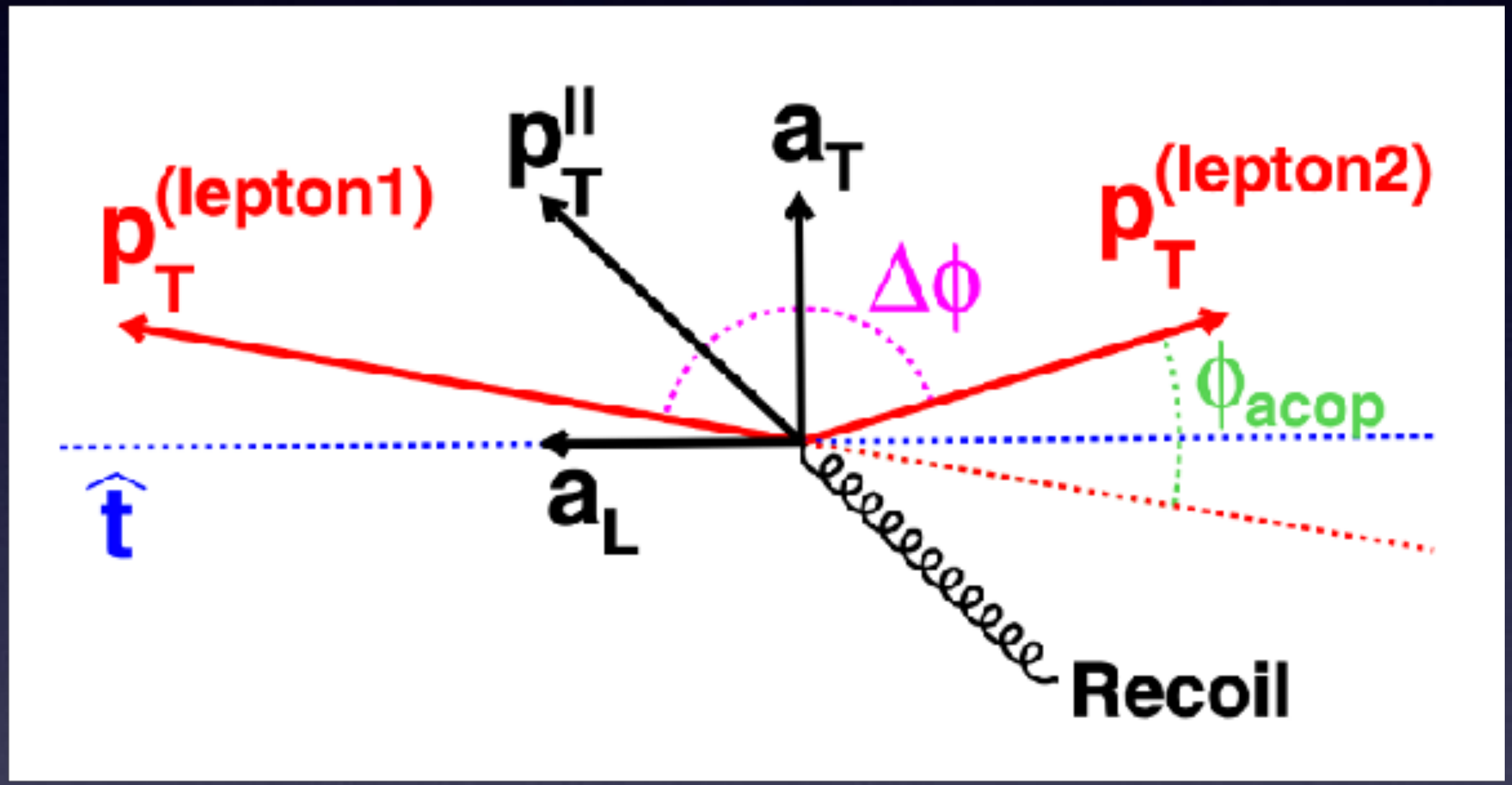
- LHCb has an extensive program on W/Z boson production and properties
  - Z boson production cross-check measurement
  - Intrinsic charm study
  - Measurement of Z boson angular coefficients
  - Precise measurement of the W boson mass
- The LHCb results could provide unique information for the PDF global fitting
  - The W/Z results are complementary to that of ATLAS and CMS
  - Sensitive to large and small Bjorken-x

Stay tuned for new results!

Backup

ϕ^*_η angle

- Probe same physics as Z boson p_T, but smaller uncertainty

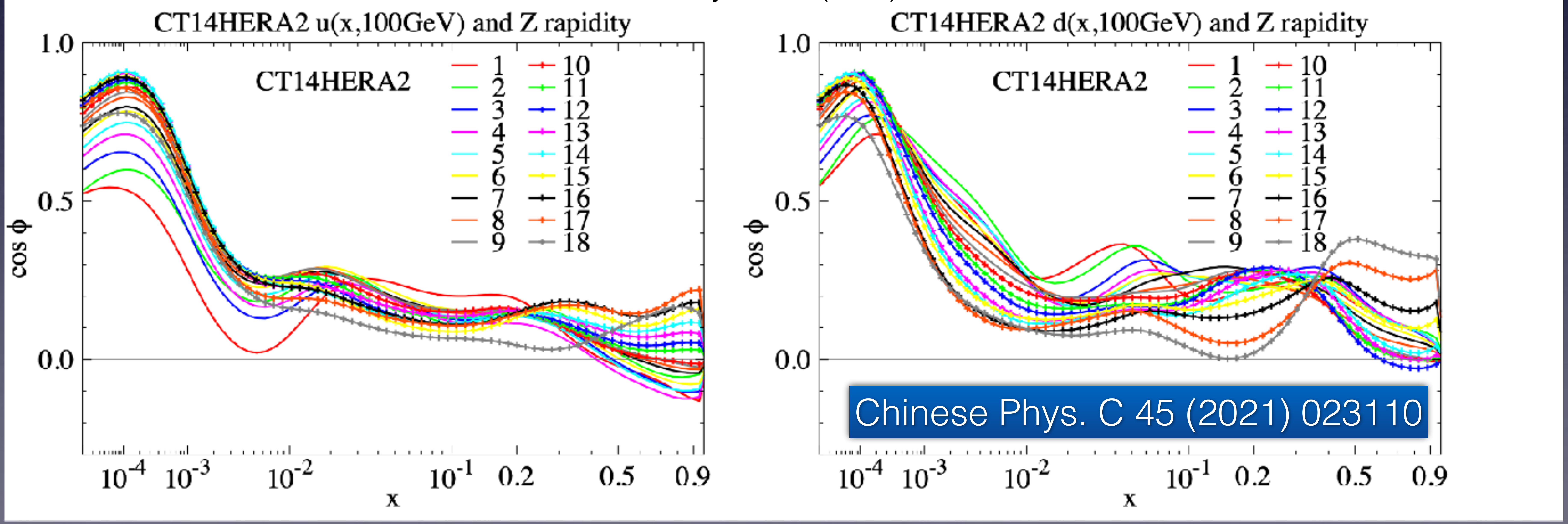


- $\phi^*_\eta = \tan\left(\phi_{acop}/2\right)\sin\theta^*_\eta$
  - ϕ_{acop}: acoplanarity angle, $\pi - \Delta\phi_{ll}$
  - $\Delta\phi_{ll}$: the difference in azimuthal angle, ϕ, between two lepton candidates
  - θ^*_η: scattering angle of leptons with respect to the proton beam in the rest frame of dilepton system
    - $\cos\theta^*_\eta = \tanh[(\eta^- - \eta^+)/2]$

LHCb W/Z data and PDFs

- Strong correlations between Z boson rapidity results measured by LHCb and PDFs in the small x region
    - For both u and d quarks

Chinese Phys. C 45 (2021) 023110



A confirmation from LHCb?

With 300 fb^{-1} LHCb pp collision data in future

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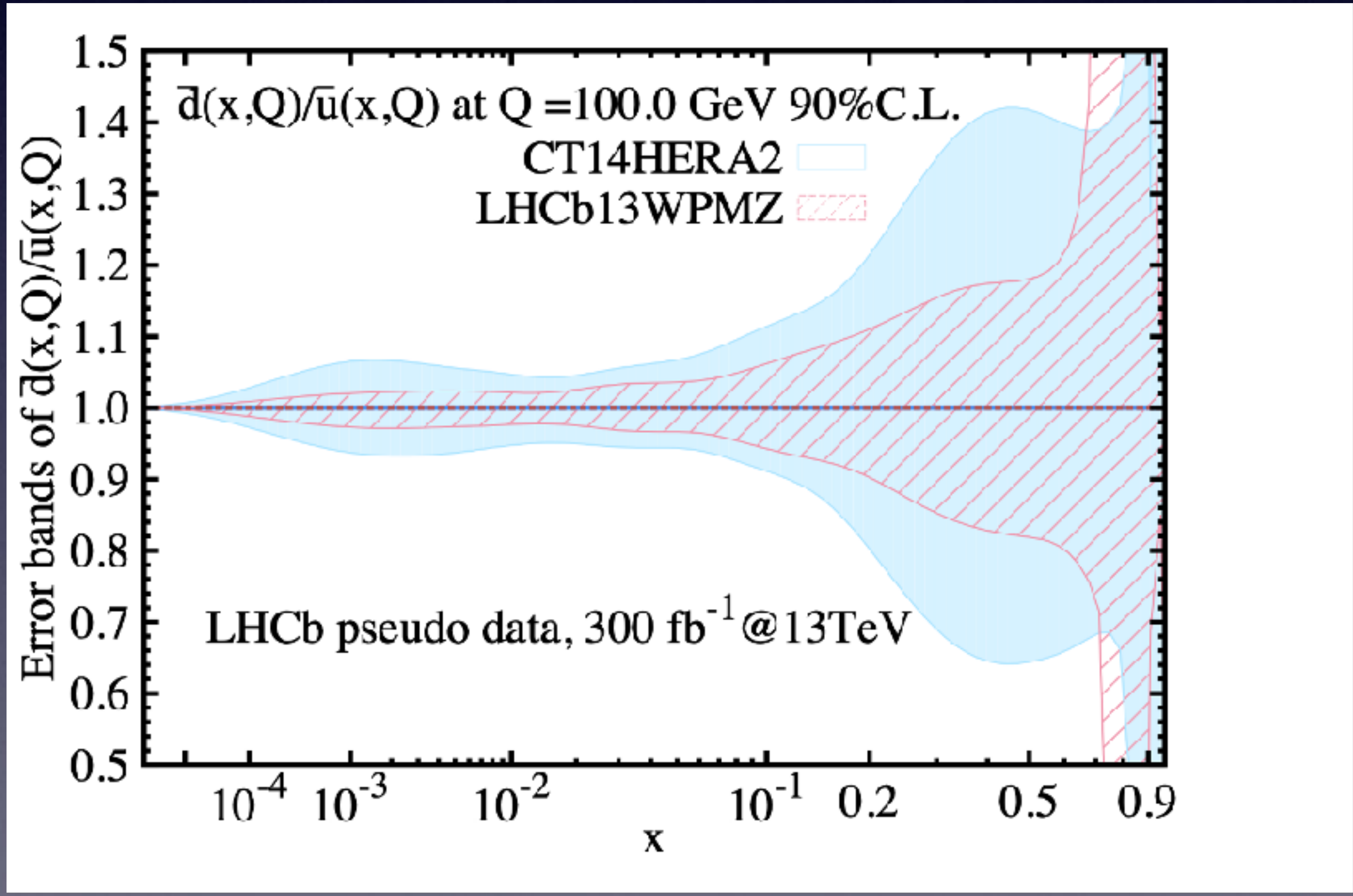
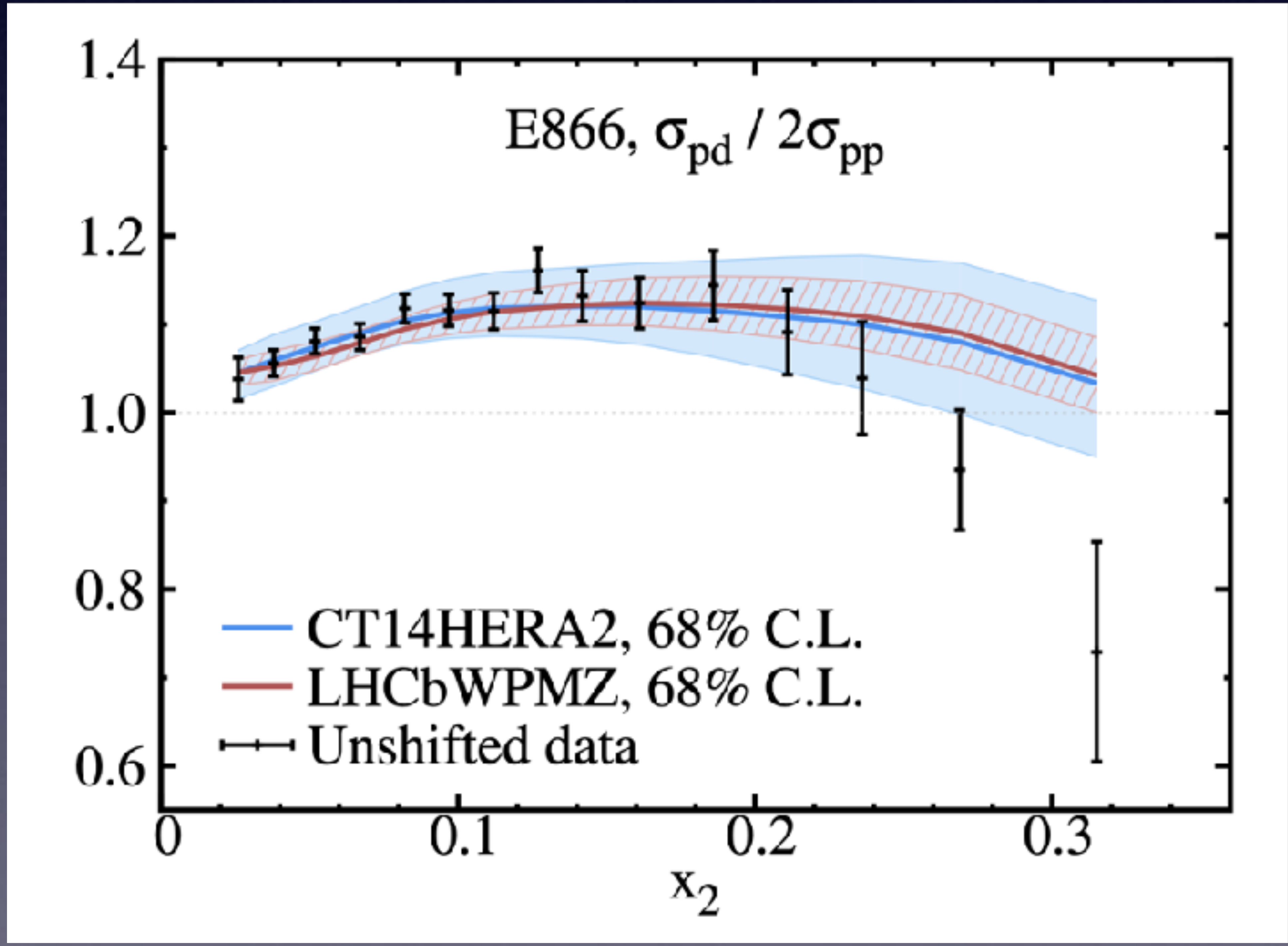
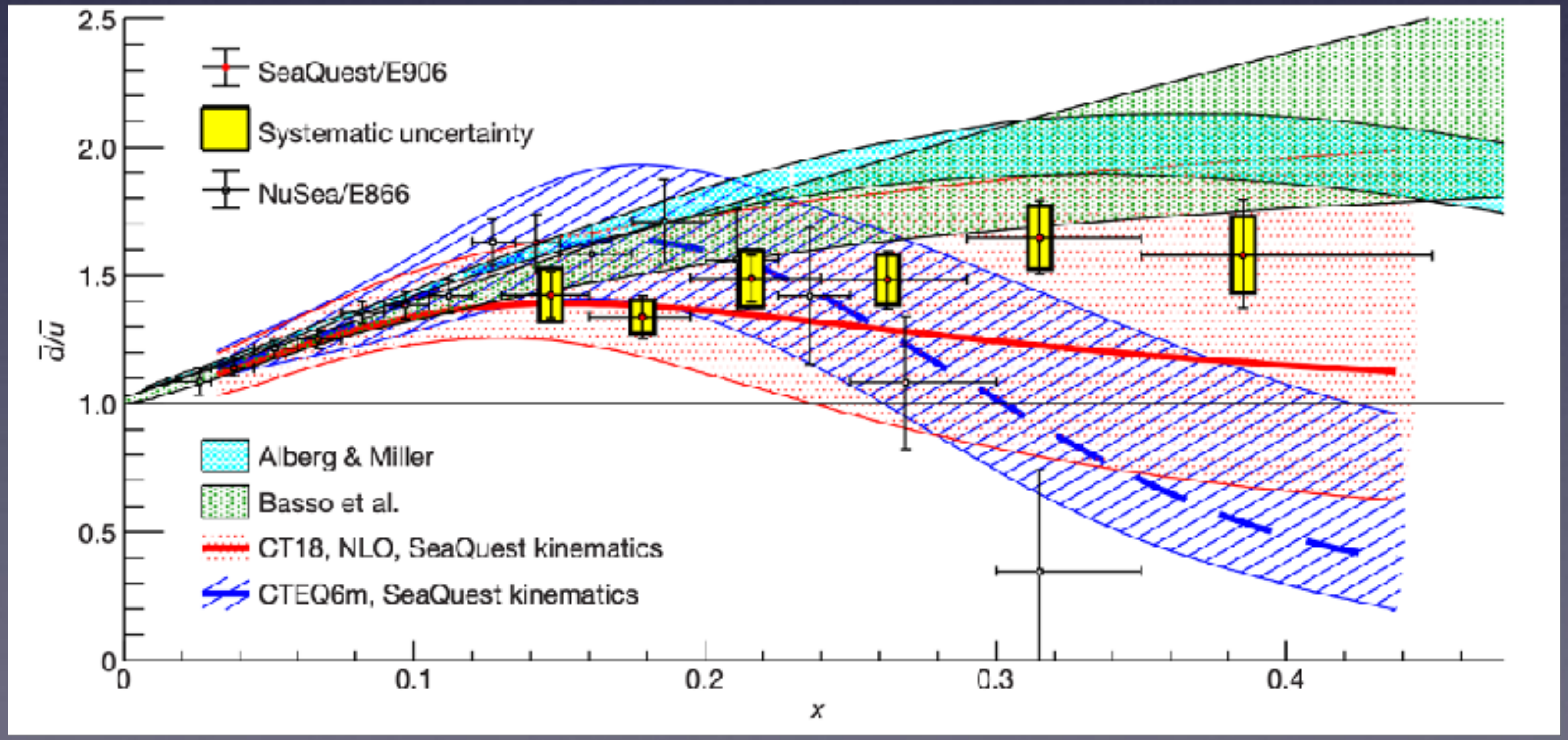


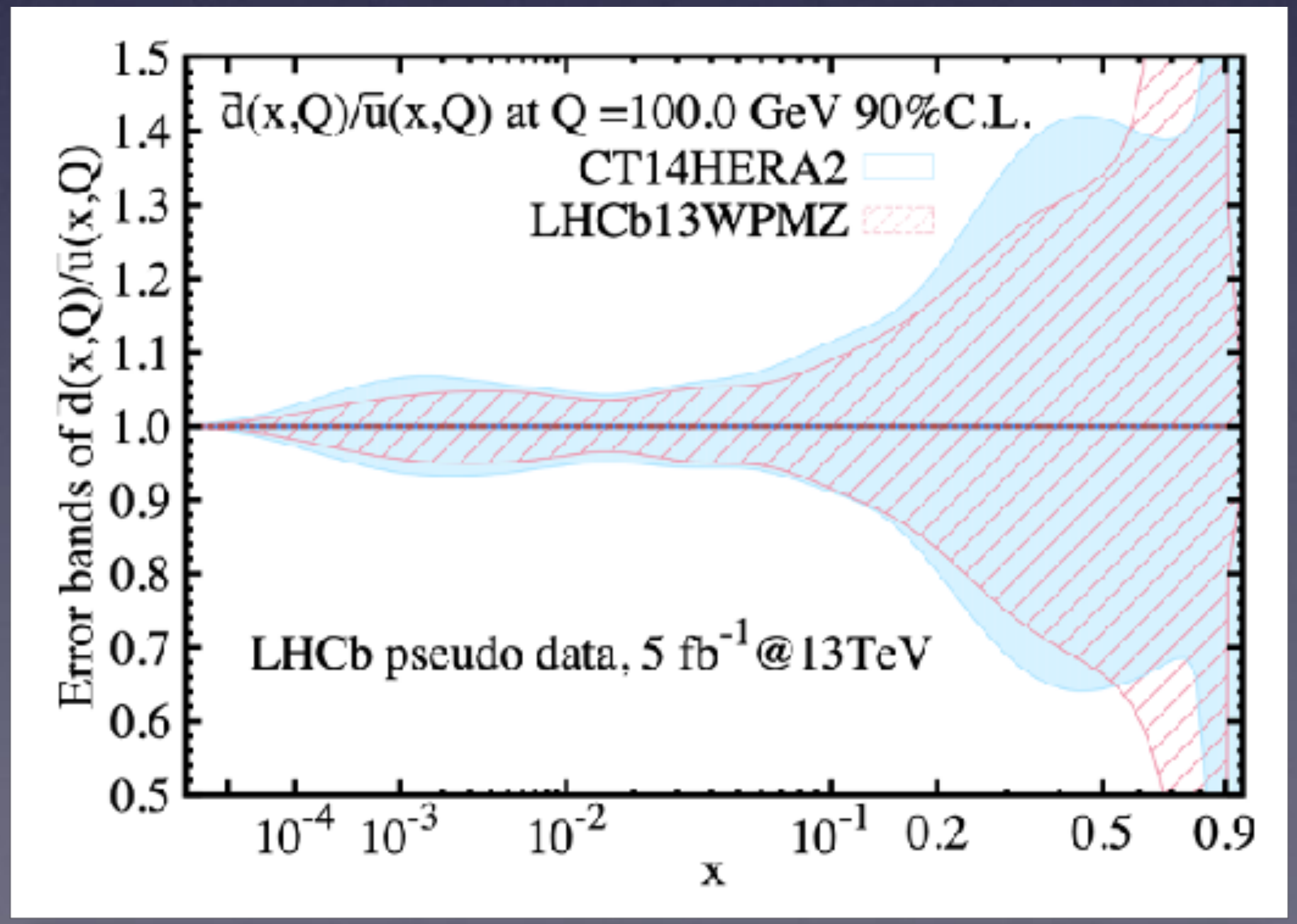


Sea quark PDFs

- Recently, the SeaQuest experiment reported new results on the $\bar{d}/\bar{u}$ PDFs ratio
  - Tensions between SeaQuest result and NuSea result are seen
- The LHCb data will be an ideal input: no uncertainty from nuclear effects



Nature 590, 561 (2021)



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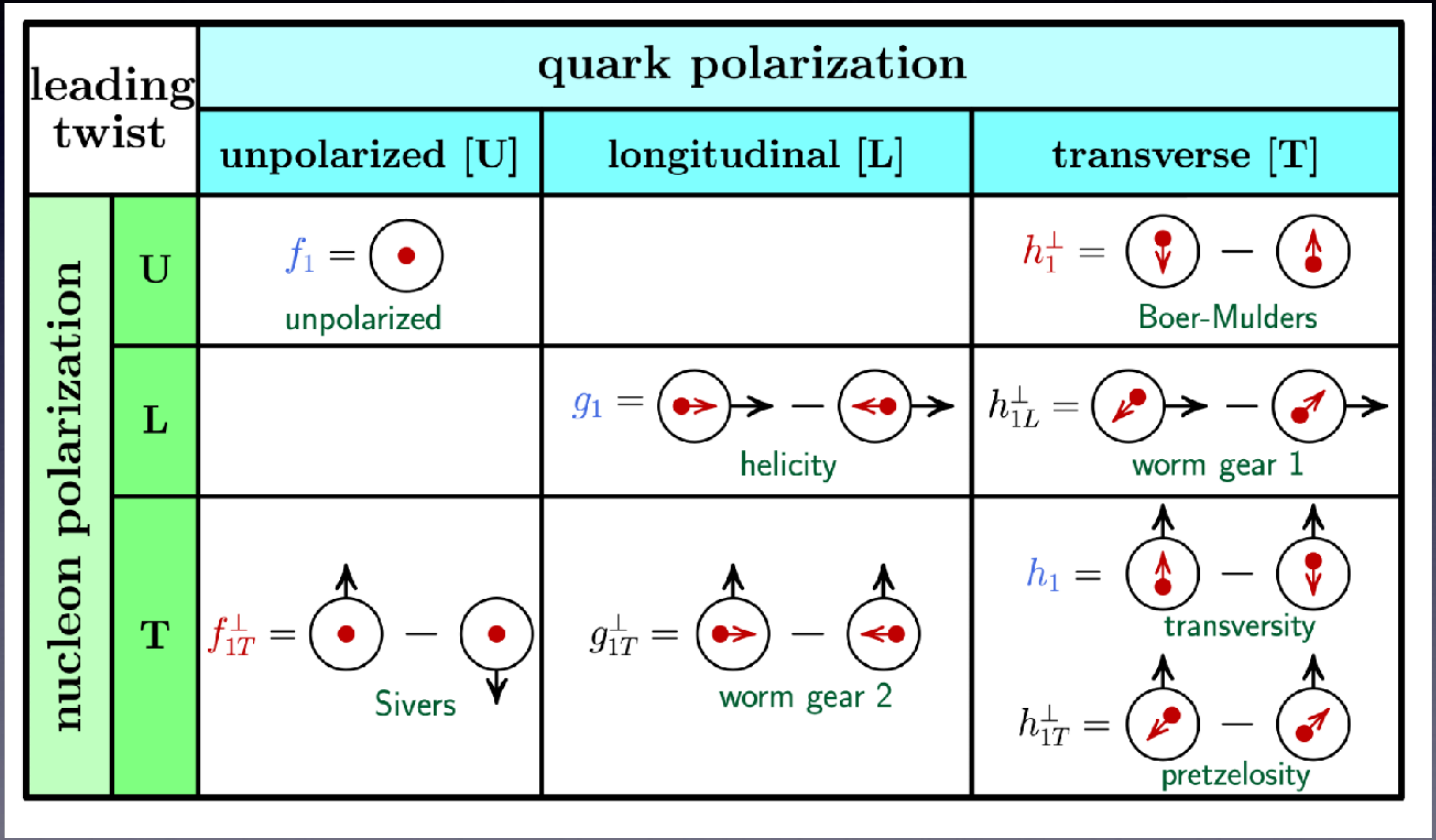
TMD

- General PDFs describes the Parton inside a proton
  - One longitudinal freedom: x
  - Quarks are perfectly collinear
- Transverse moment dependent PDFs
  - Admit a finite quark transverse momentum k_T
  - Provides 3D image of proton in momentum space
  - Correlation between parton momentum and hadron spin

Nucleon/quark polarization



Boer-Mulders function

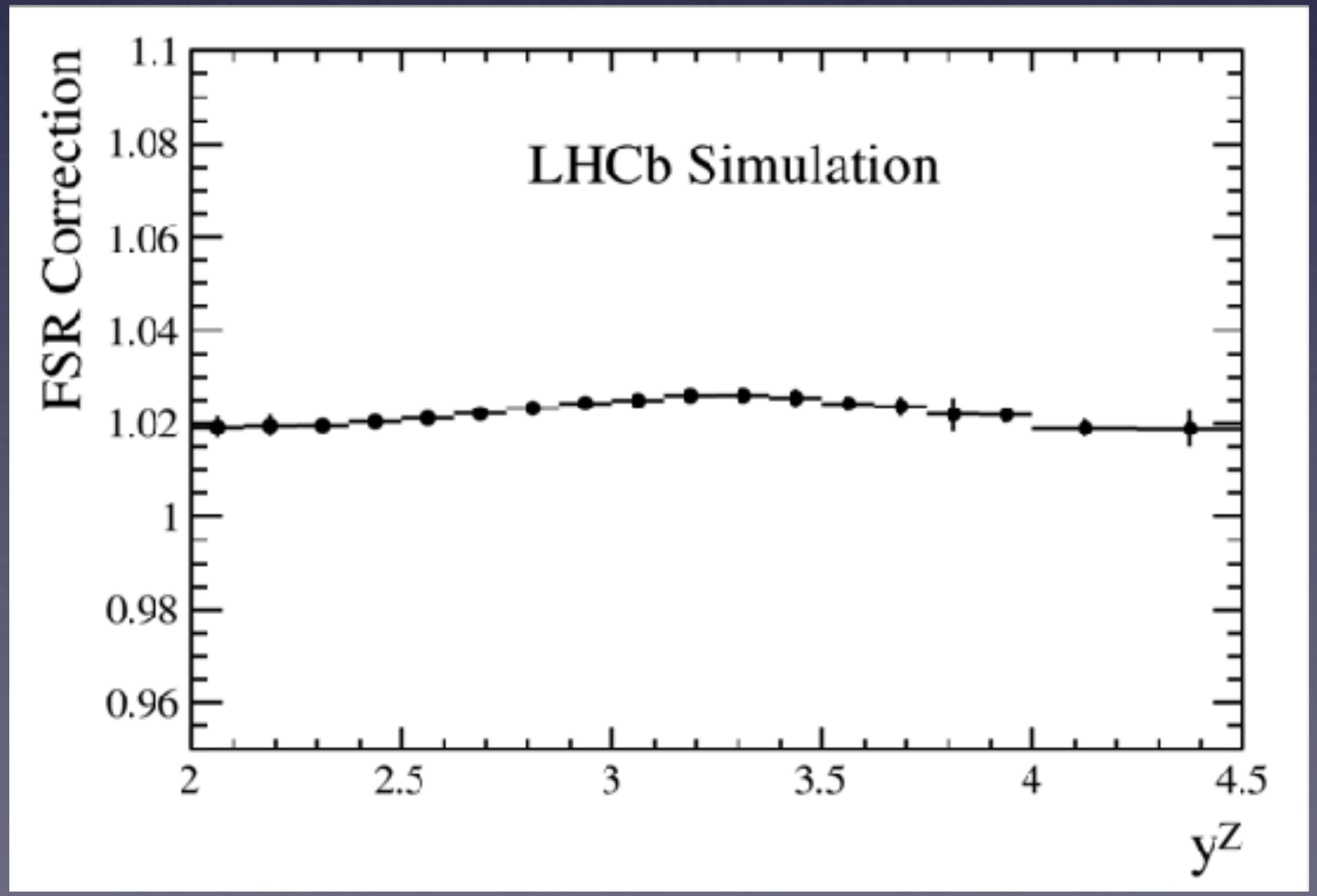
- D. Boer, P. J. Mulders: Phys. Rev. D 57 (1998) 5780

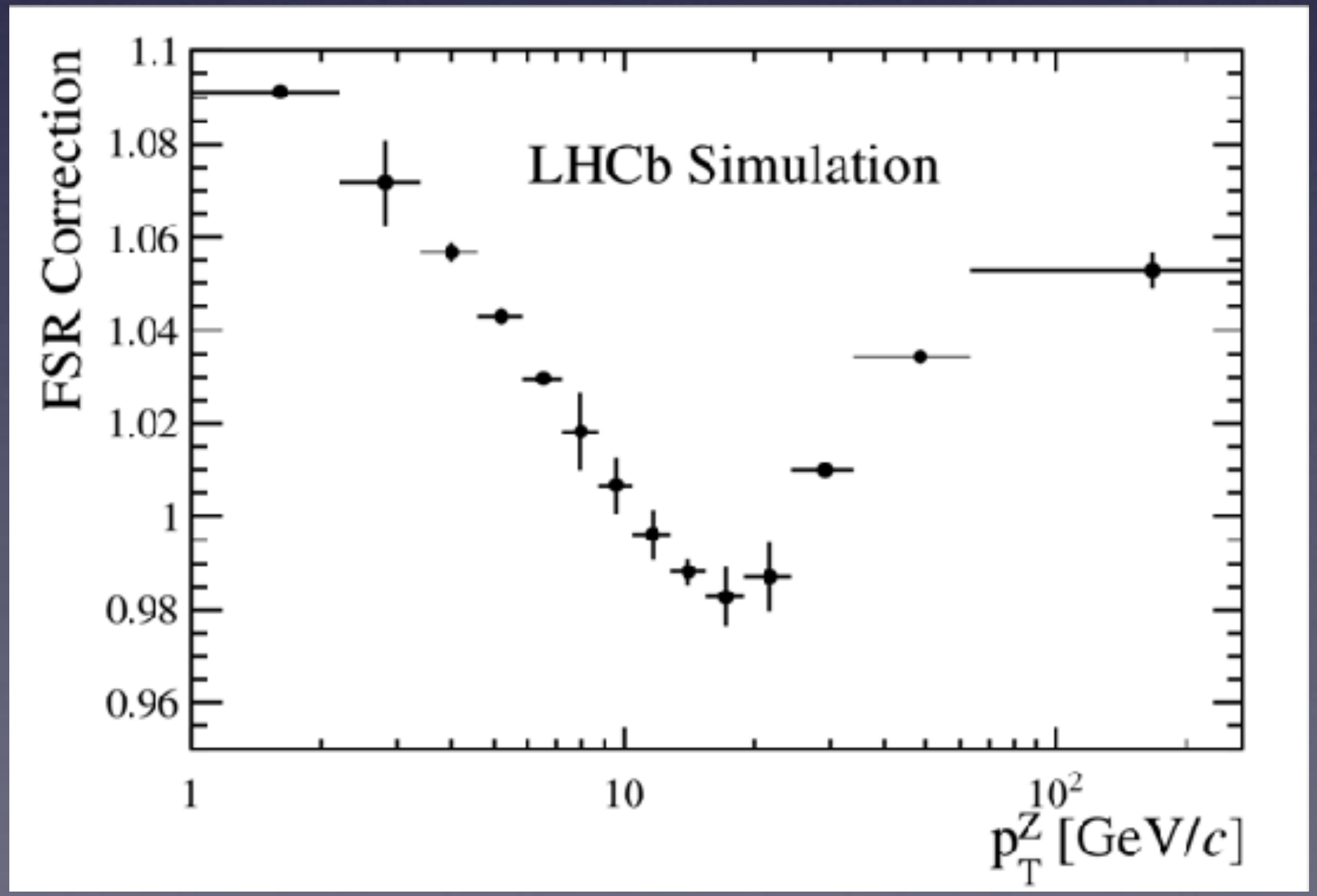
$$h_1^{\perp[\mathcal{C}]}(x, k_T^2)\, \epsilon_T^{ij} k_{Tj} = \frac{M}{2}\,\mathrm{F.T.}\,\langle P|\, \overline{\psi}(0)\, \mathcal{L}_{\mathcal{C}}(0,\xi) \gamma^i \gamma^+ \gamma_5 \psi(\xi)\, |P\rangle\big|_{\xi^+=0}$$

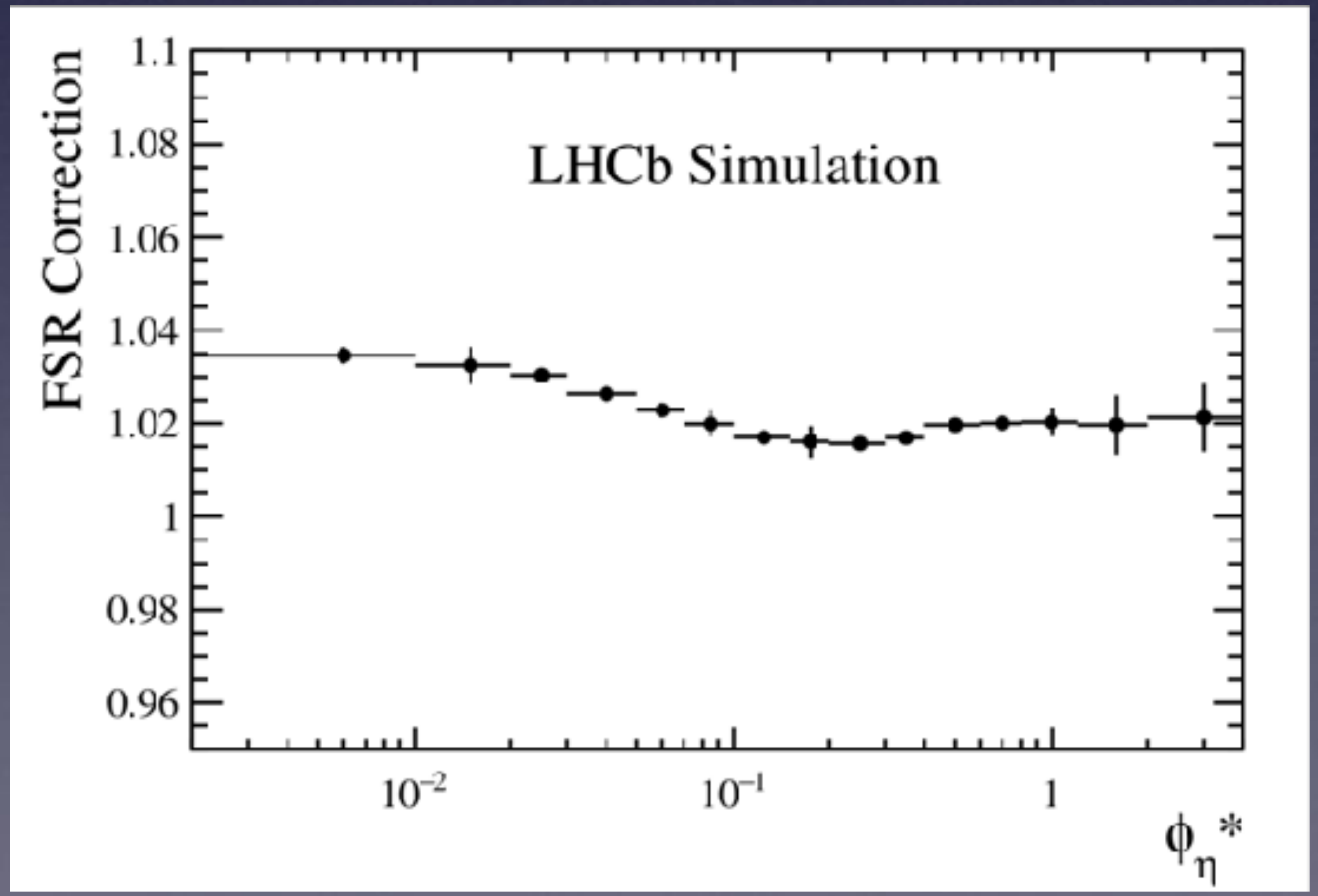
- Represents the correlation between quark k_T and transverse spin in an unpolarized hadron
  - A time-reversal odd, chiral-odd TMD PDFs
  - Lead to an azimuthal $\cos(2\phi)$ dependence in Drell-Yan

FSR correction

- ResBos with/without PHOTOS
- POWHEG with/without PYTHIA : to estimate uncertainty from FSR

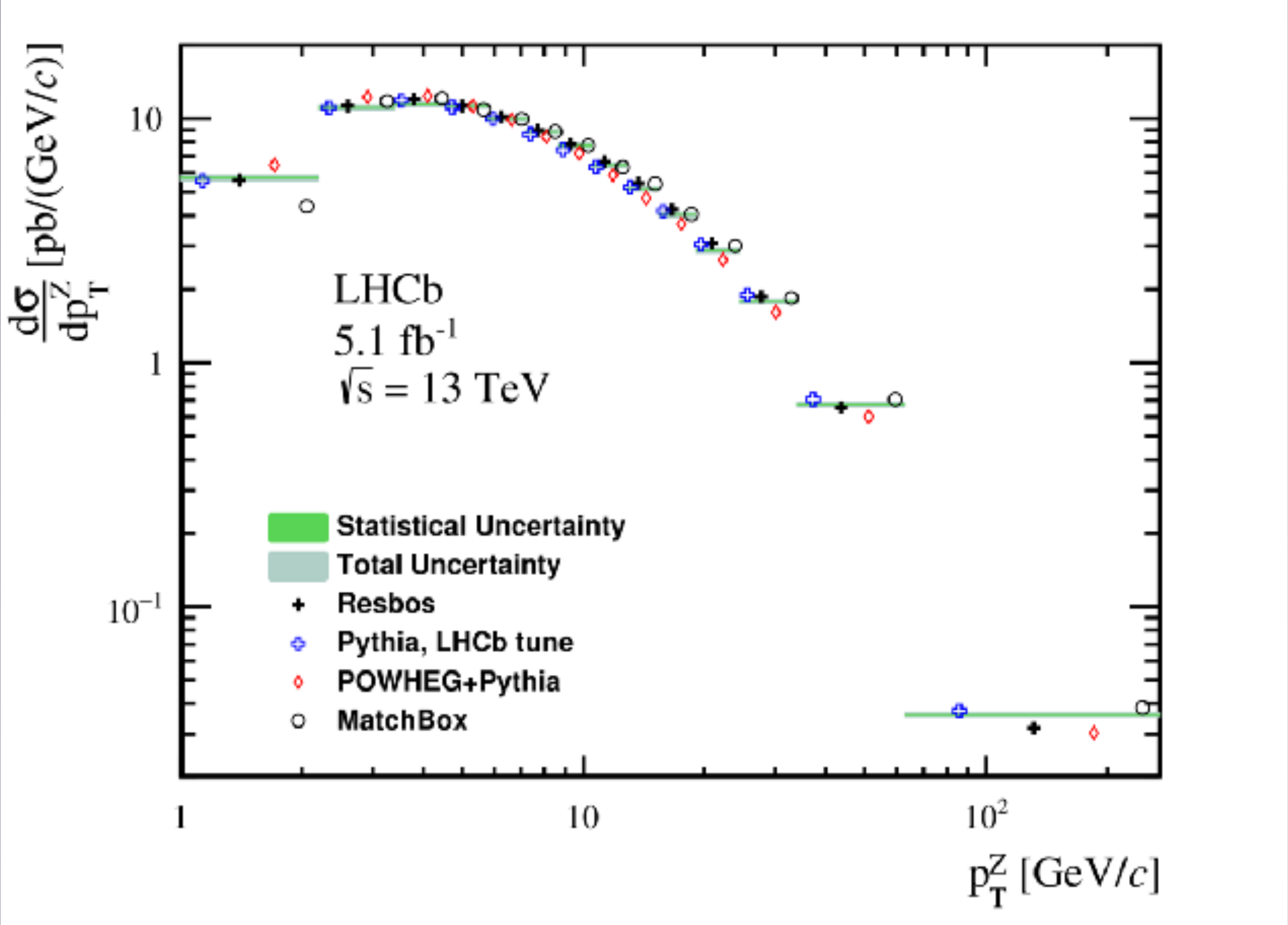


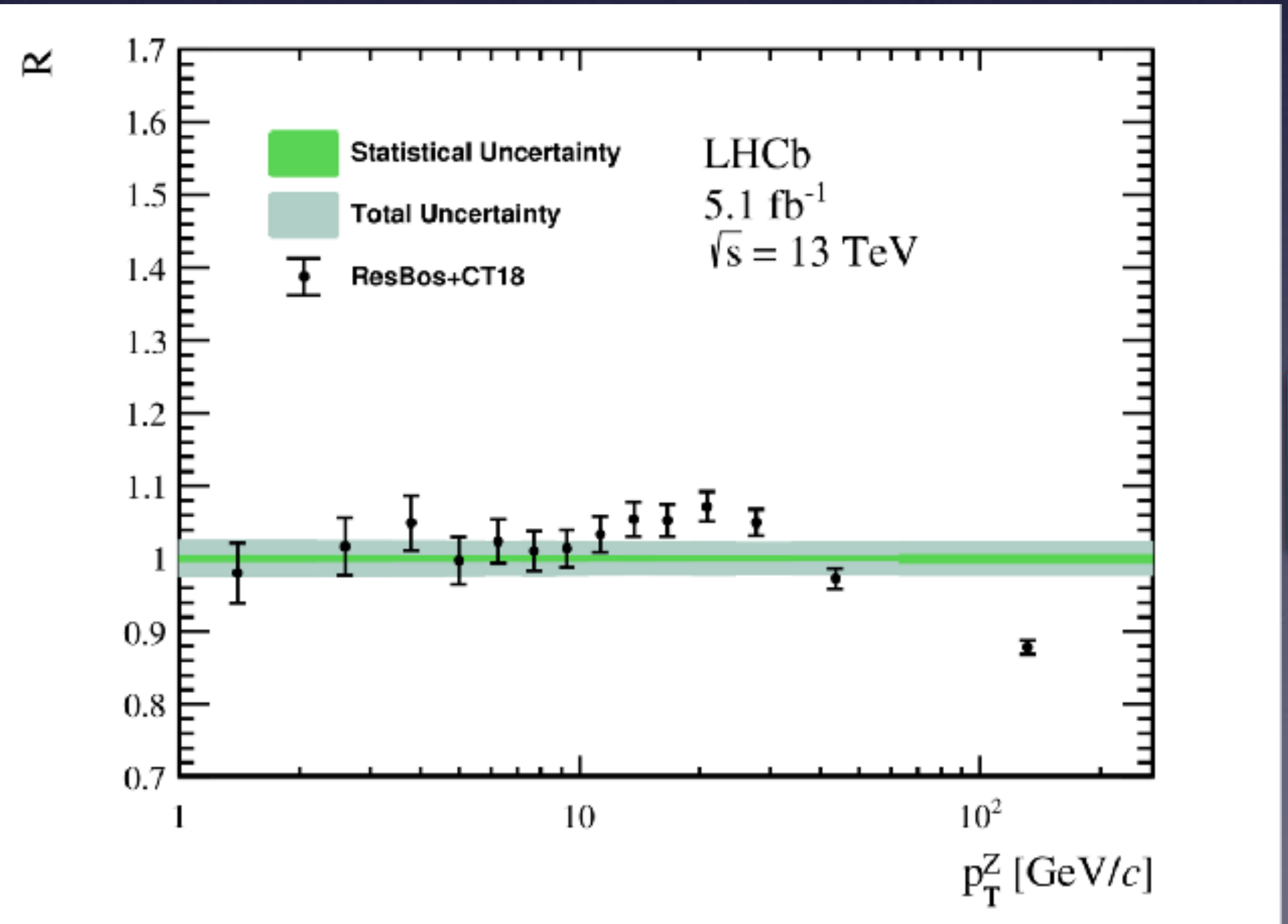




Differential cross-section: 1-D

- Measured cross section in different intervals of Z boson p_T
- ResBos describes the low p_T^Z data, but tensions are seen in the middle and large p_T regions





$$R = \frac{\text{Predictions}}{\text{Data}}$$

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Double differential cross-section

First double differential cross-section measurement in the forward region

ϕ^*

Tensions in the large ϕ^* region are seen