Electroweak physics and *W* mass measurement at LHCb

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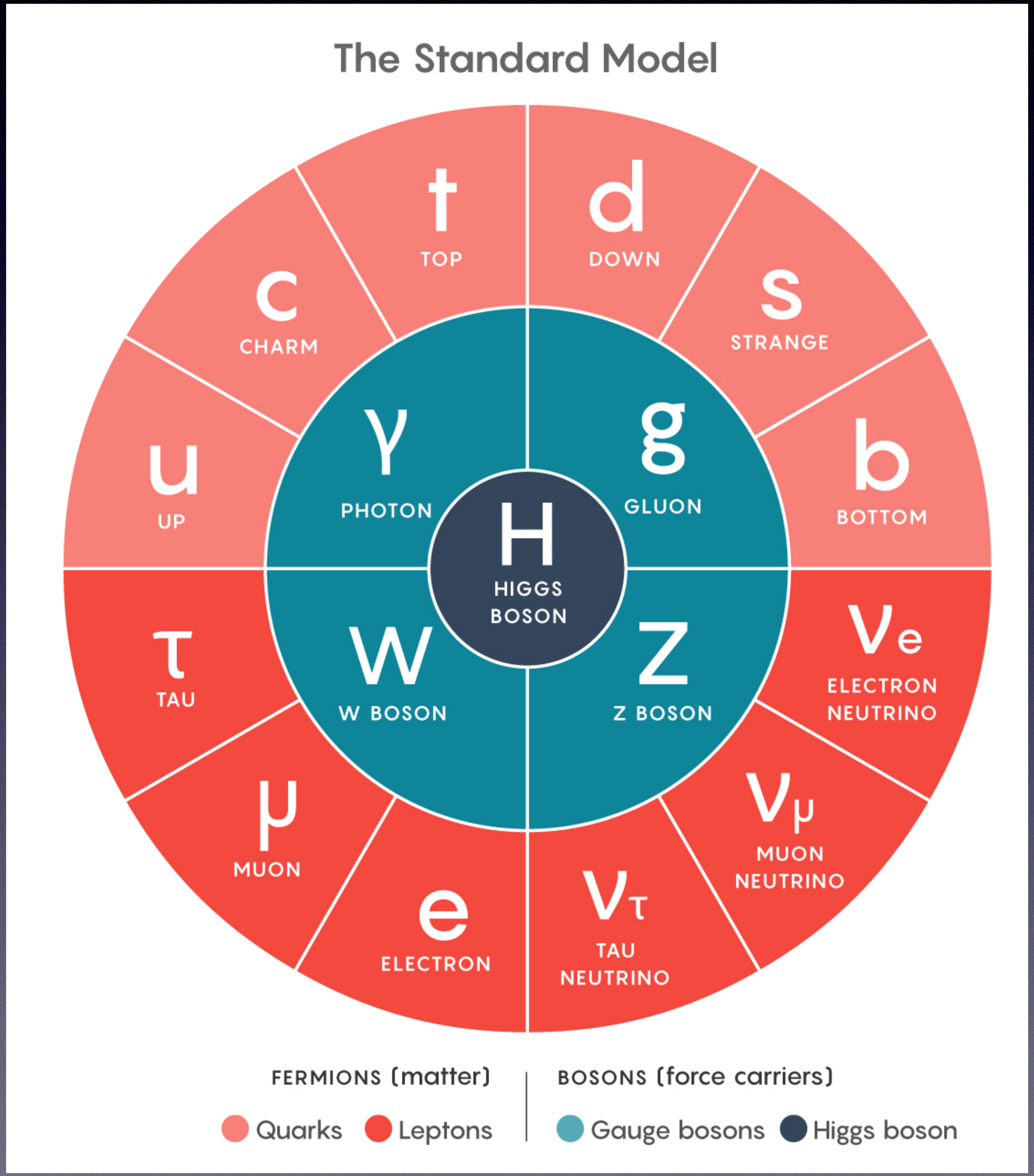
Outlines

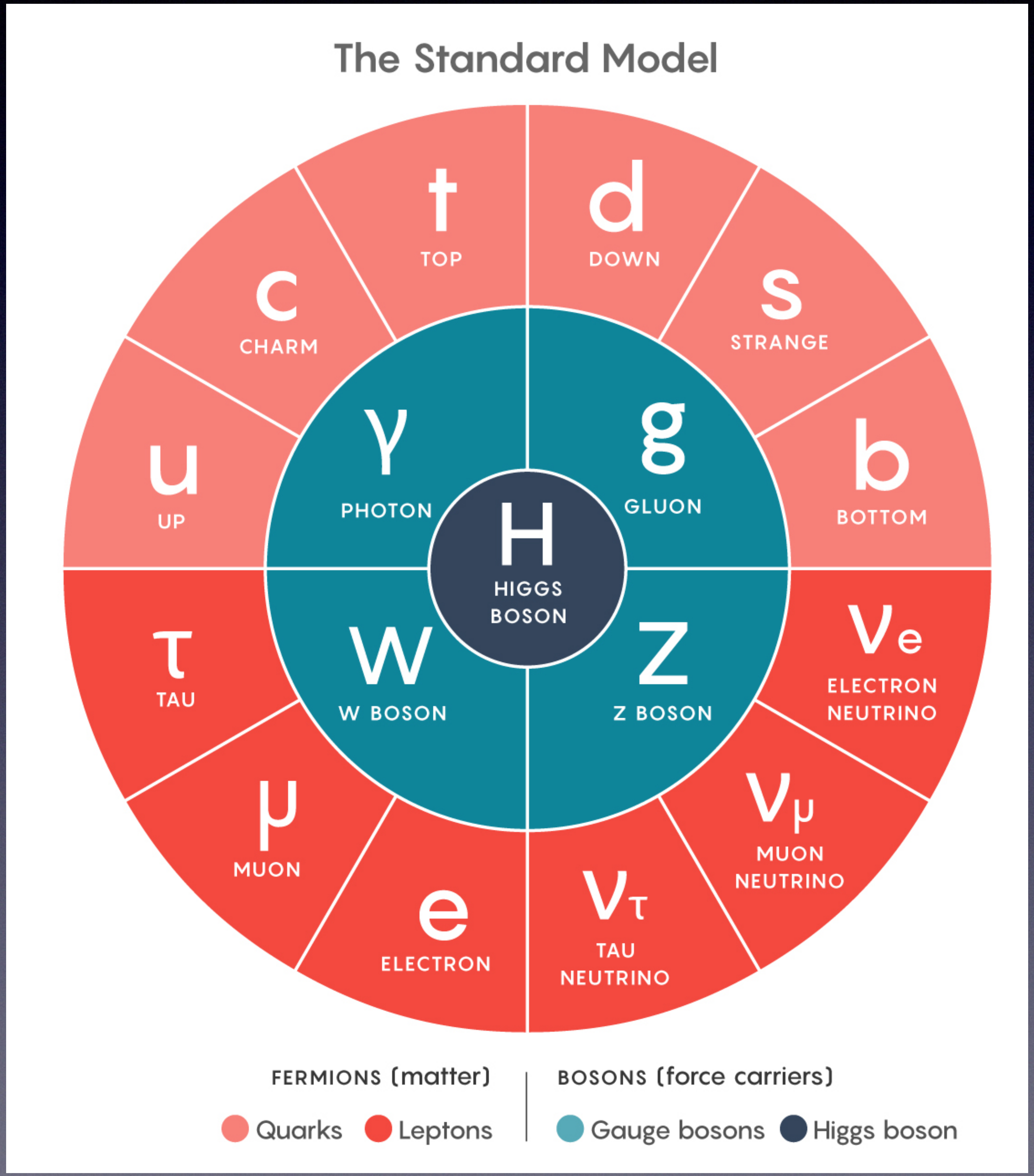
- Introduction
- Selected results from LHCb W and Z boson measurements
  - W boson mass measurement — JHEP 01 (2022) 036
  - Z boson production cross section — arXiv: 2112.07458
  - Z angular coefficient measurement — arXiv: 2203.01602
- Conclusions

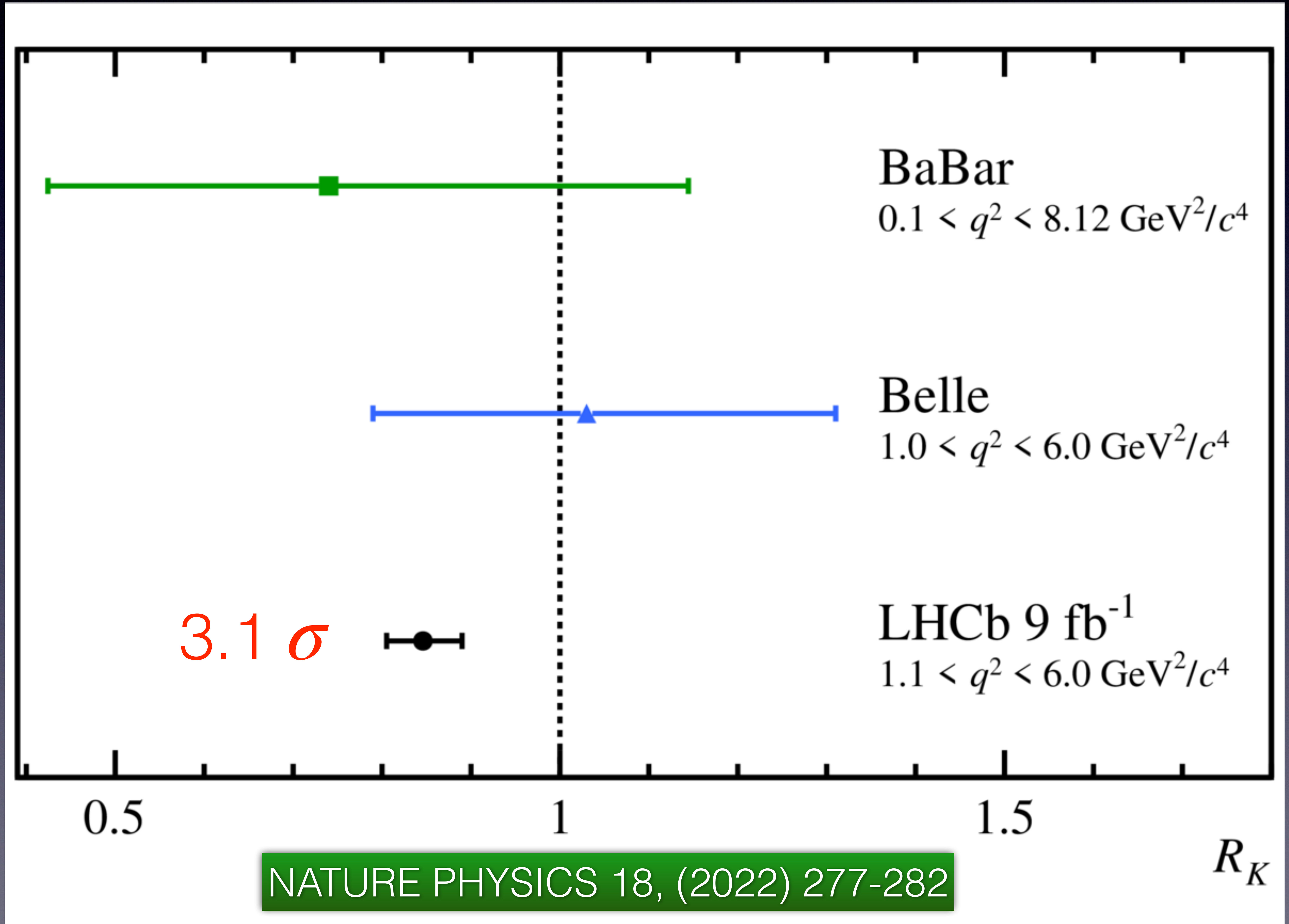
The Standard Model and New physics



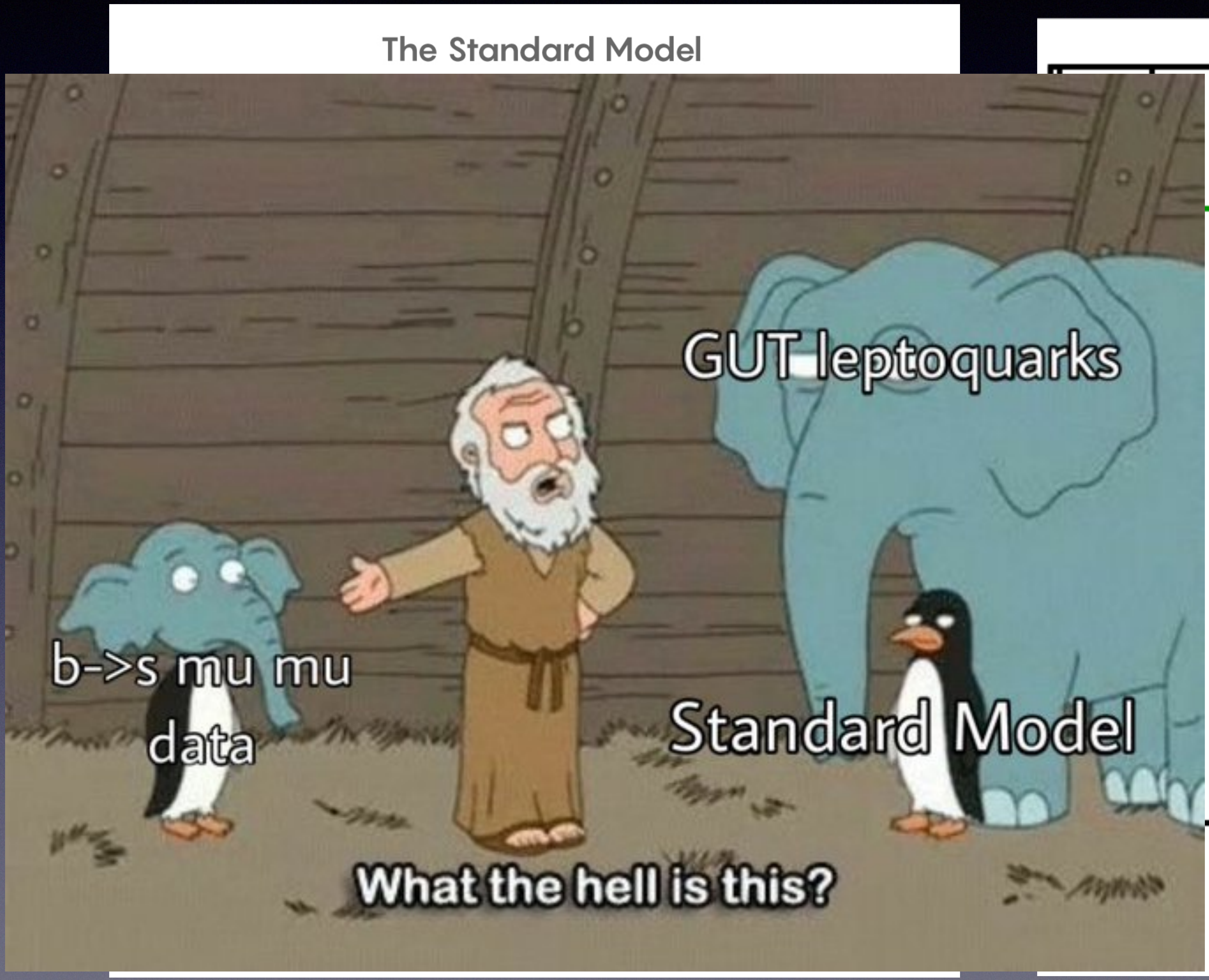
- Describes elementary particles and their interactions
- A huge success, but must be an effective theory valid up to some scale

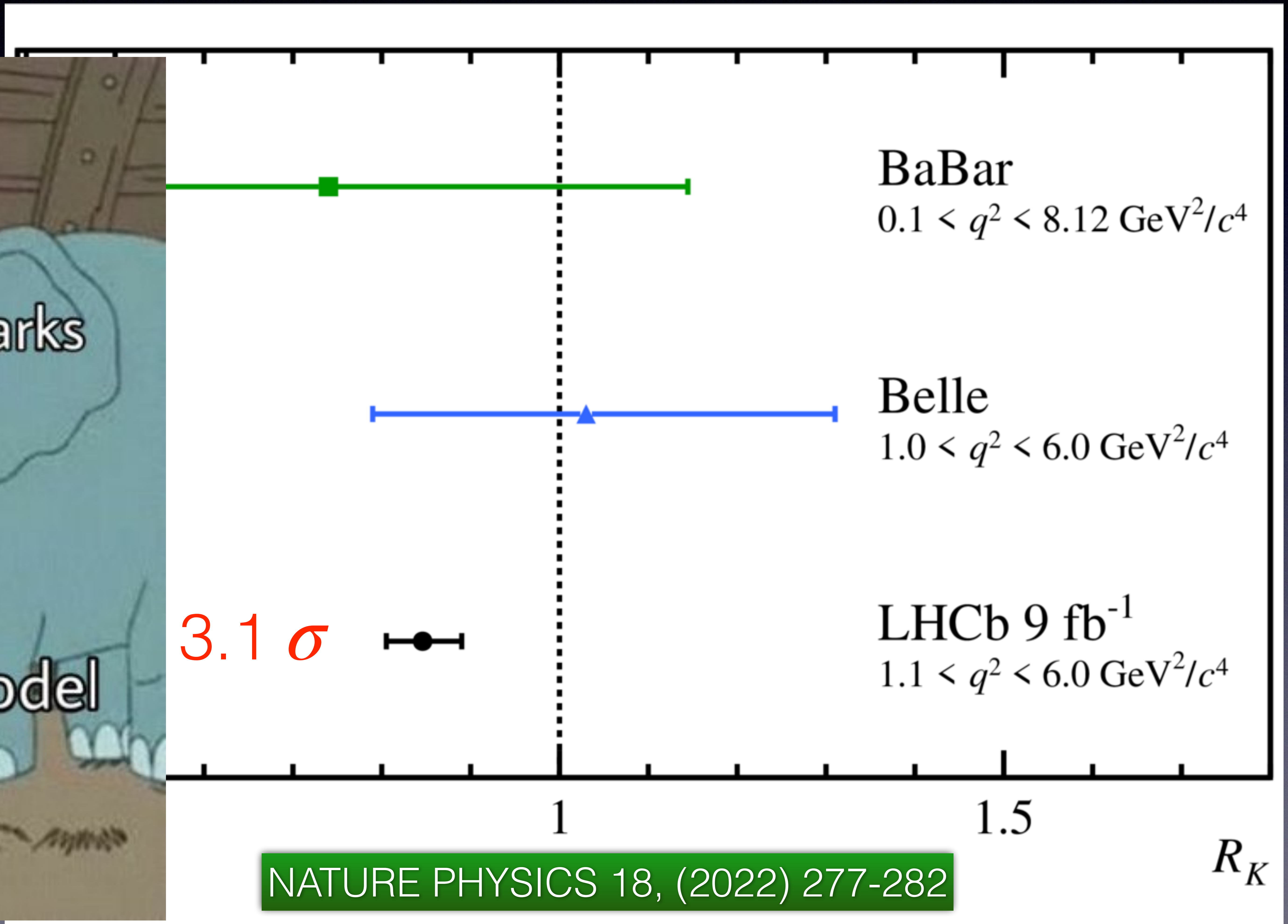
The Standard Model and New physics





The Standard Model and New physics

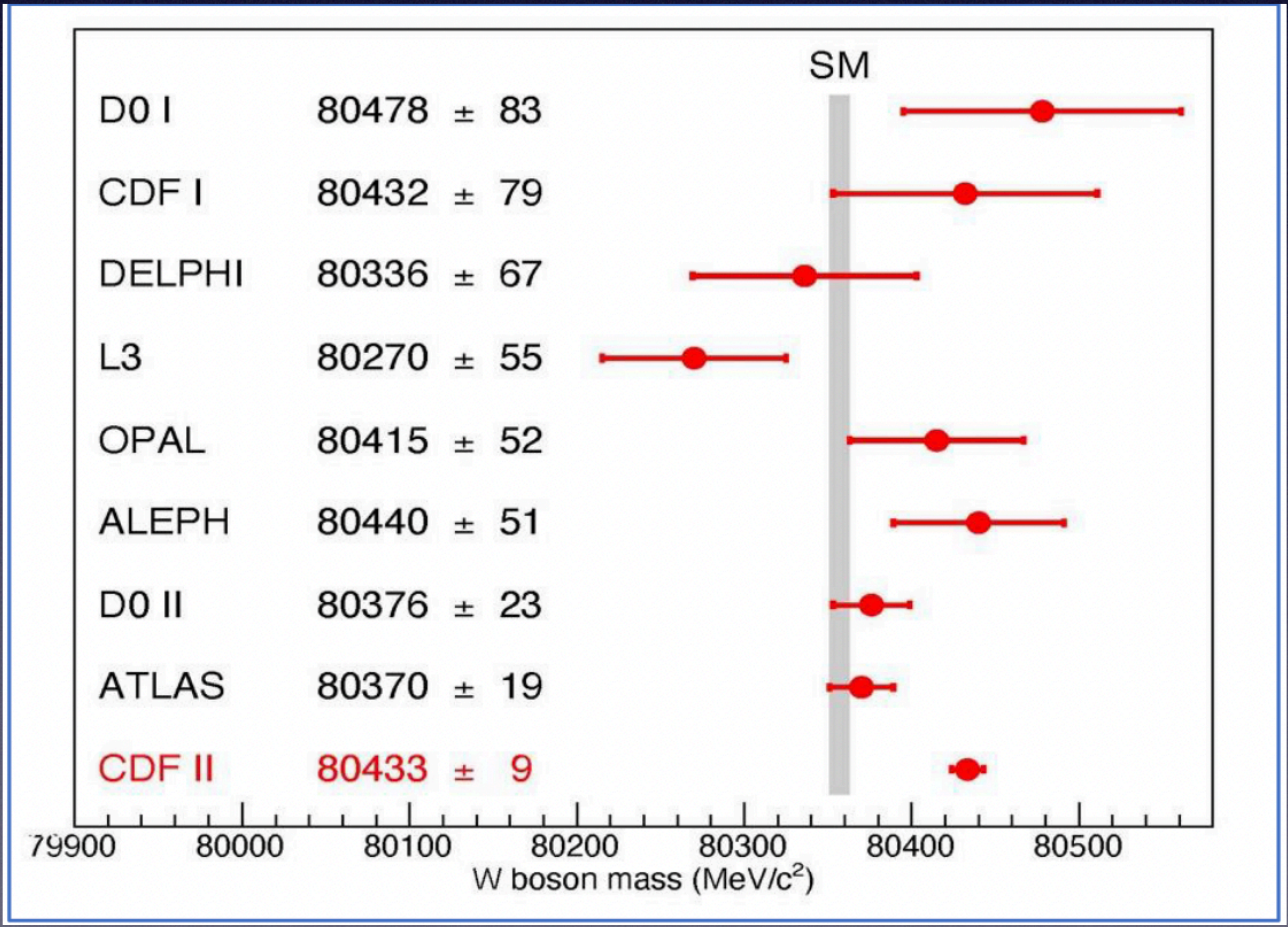


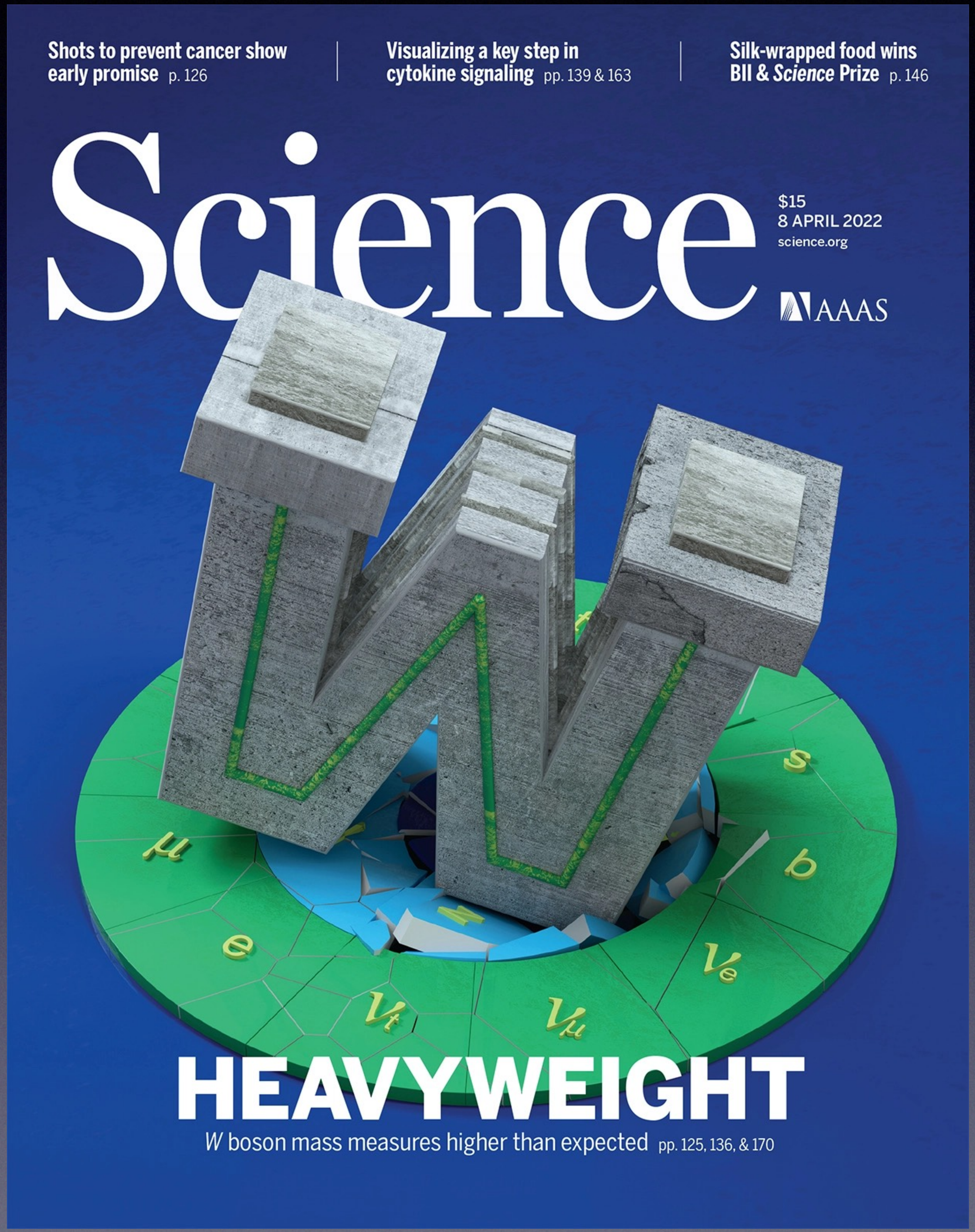


Science 376 (2022) 6589, 170-176

New results from CDF

- Precision W mass measurement from CDF experiment
- Significant tension (7.0σ) with the SM expectation (global fit)





Extraordinary claims require extraordinary evidence — Carl Sagan (1999)

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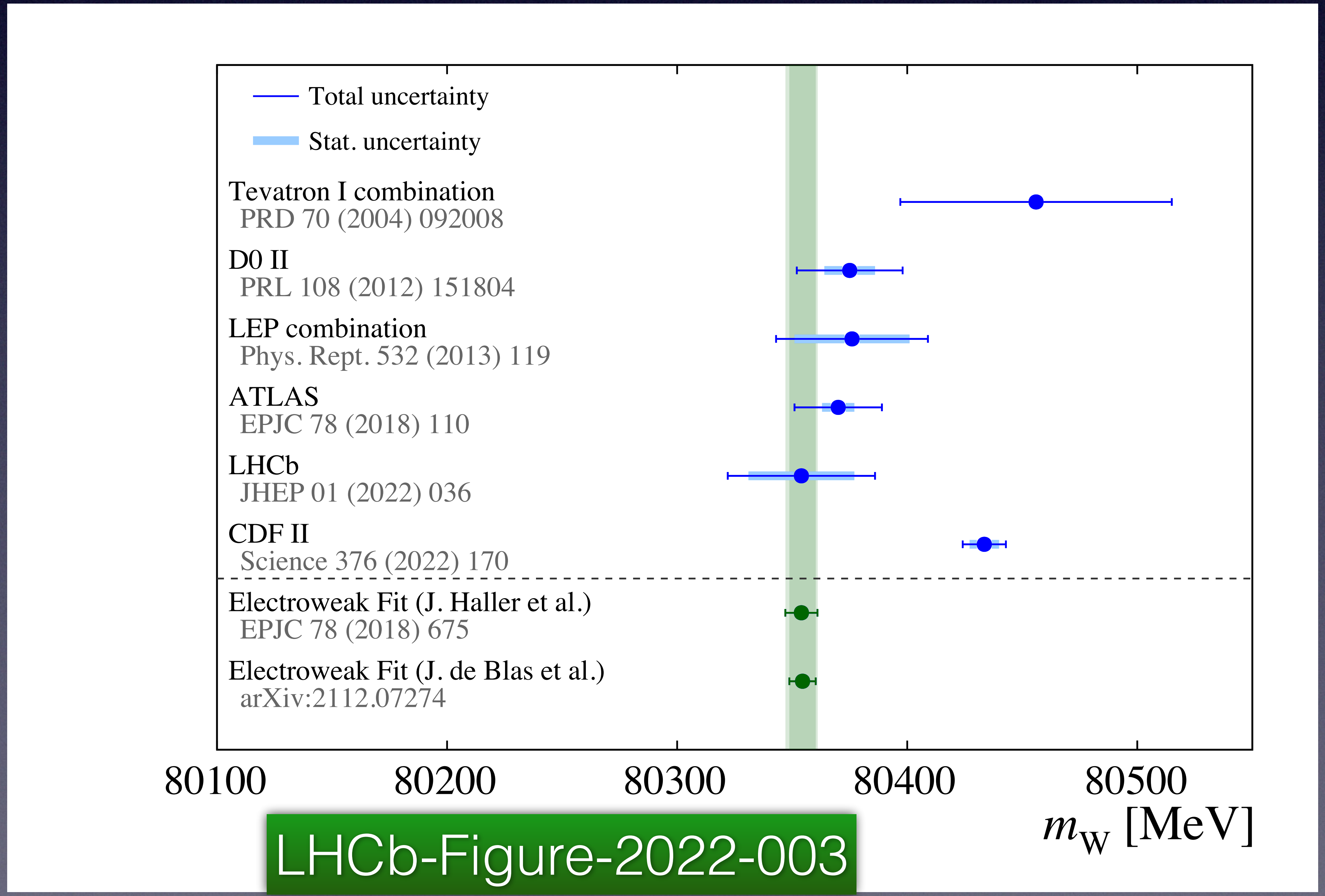
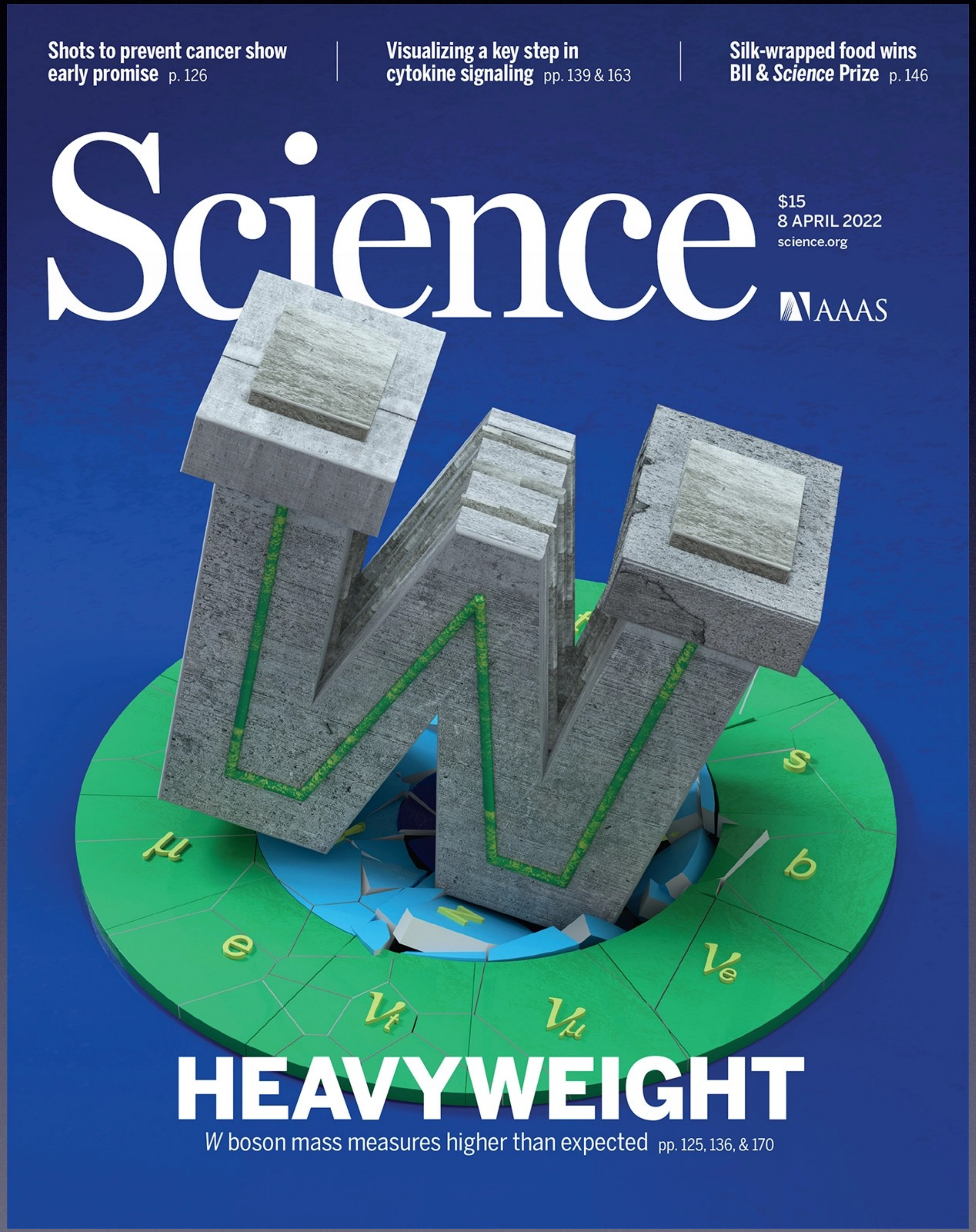
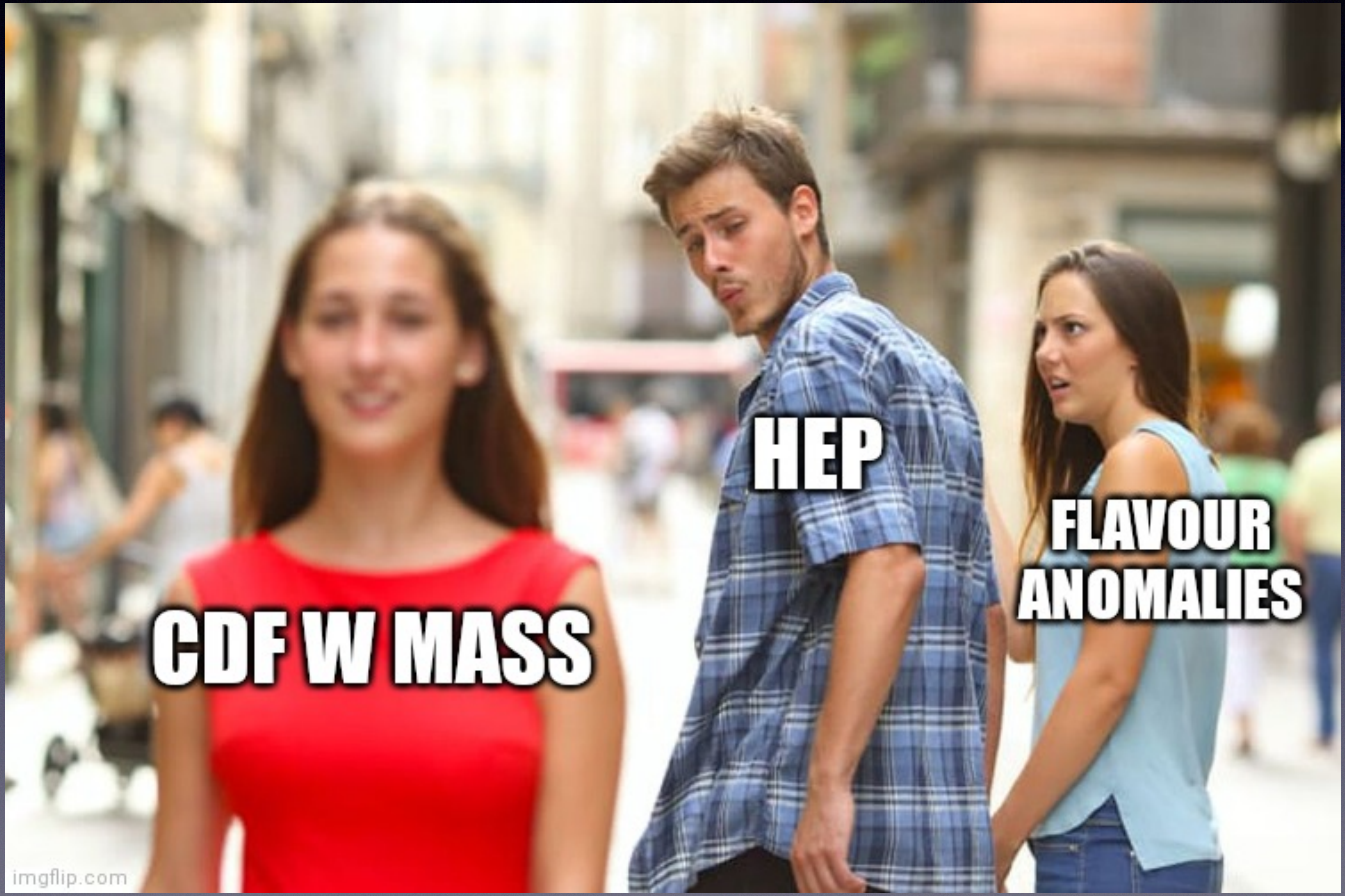


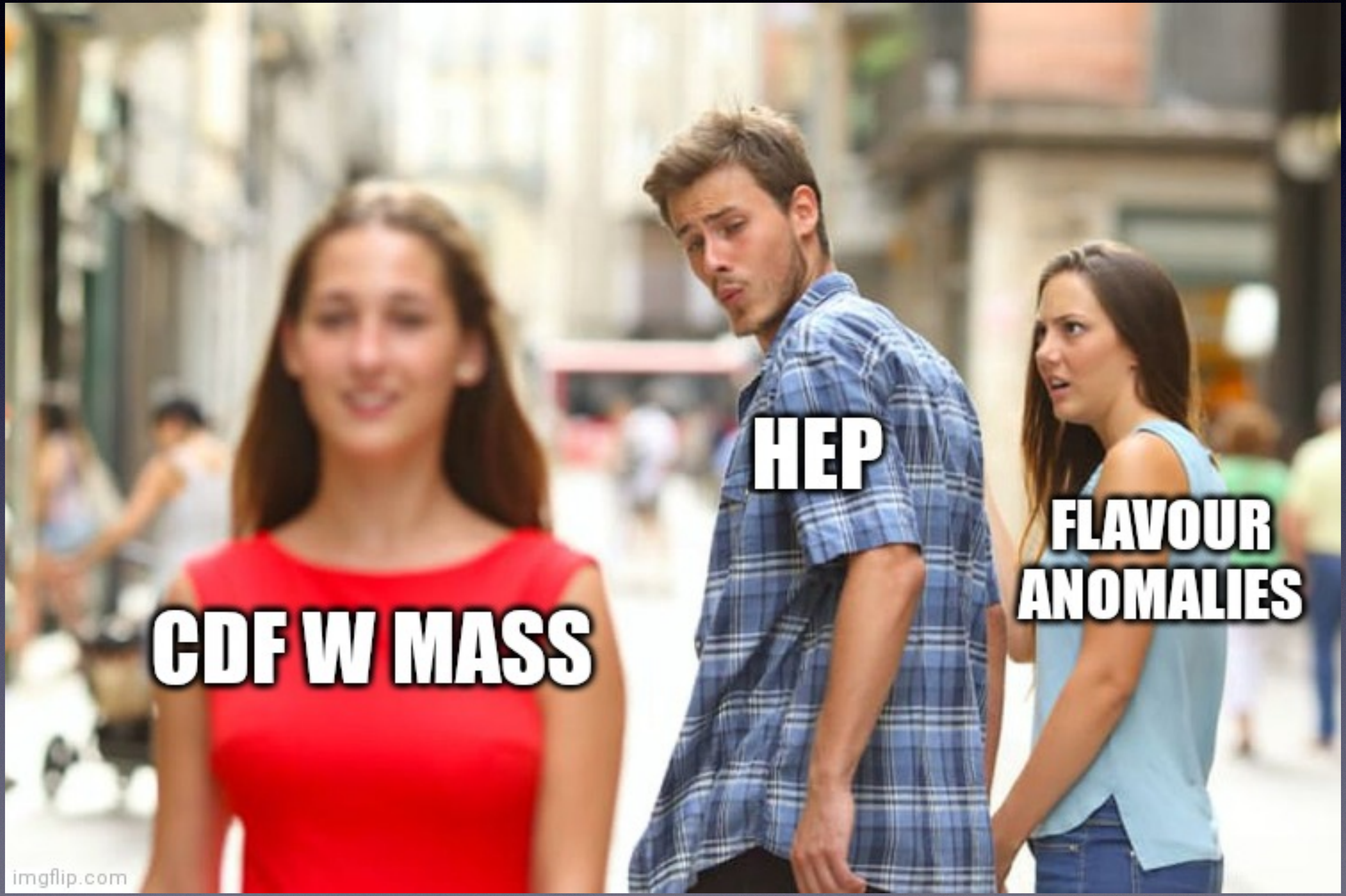


Extraordinary claims require extraordinary evidence — Carl Sagan (1999)

Impacts to the HEP



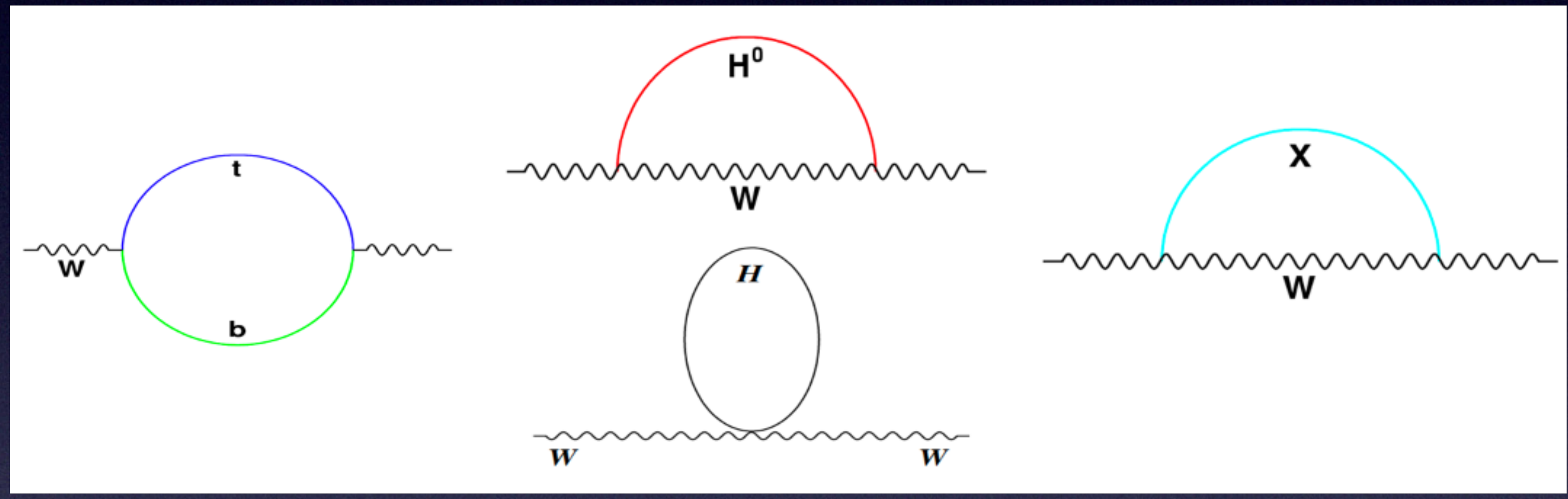
Impacts to the HEP



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

LHCb W mass measurement

- ATLAS and CMS experiments have the high pileup environment
- $W \to \mu\nu$ sample with high purity can be selected using the LHCb data, without requirement on the missing E_t
- Anti-correlation of PDFs uncertainty: 10.5 MeV to 7.7 MeV

$$\delta_{\mathrm{PDF}} = \begin{pmatrix} \mathbf{G}^+ & 24.8 \\ \mathbf{G}^- & 13.2 \\ \mathbf{L}^+ & 27.0 \\ \mathbf{L}^- & 49.3 \end{pmatrix},$$

Estimated PDFs uncertainties
G: General purpose detector
L: LHCb
±: charge of W boson

$$\rho = \begin{pmatrix} & \mathbf{G}^+ & \mathbf{G}^- & \mathbf{L}^+ & \mathbf{L}^- \\ \mathbf{G}^+ & 1 & & & \\ \mathbf{G}^- & -0.22 & 1 & & \\ \mathbf{L}^+ & -0.63 & 0.11 & 1 & \\ \mathbf{L}^- & -0.02 & -0.30 & 0.21 & 1 \end{pmatrix}$$

Correlation matrix

$$\alpha = \begin{pmatrix} \mathbf{G}+ & 0.30 \\ \mathbf{G}- & 0.45 \\ \mathbf{L}+ & 0.21 \\ \mathbf{L}- & 0.04 \end{pmatrix}$$

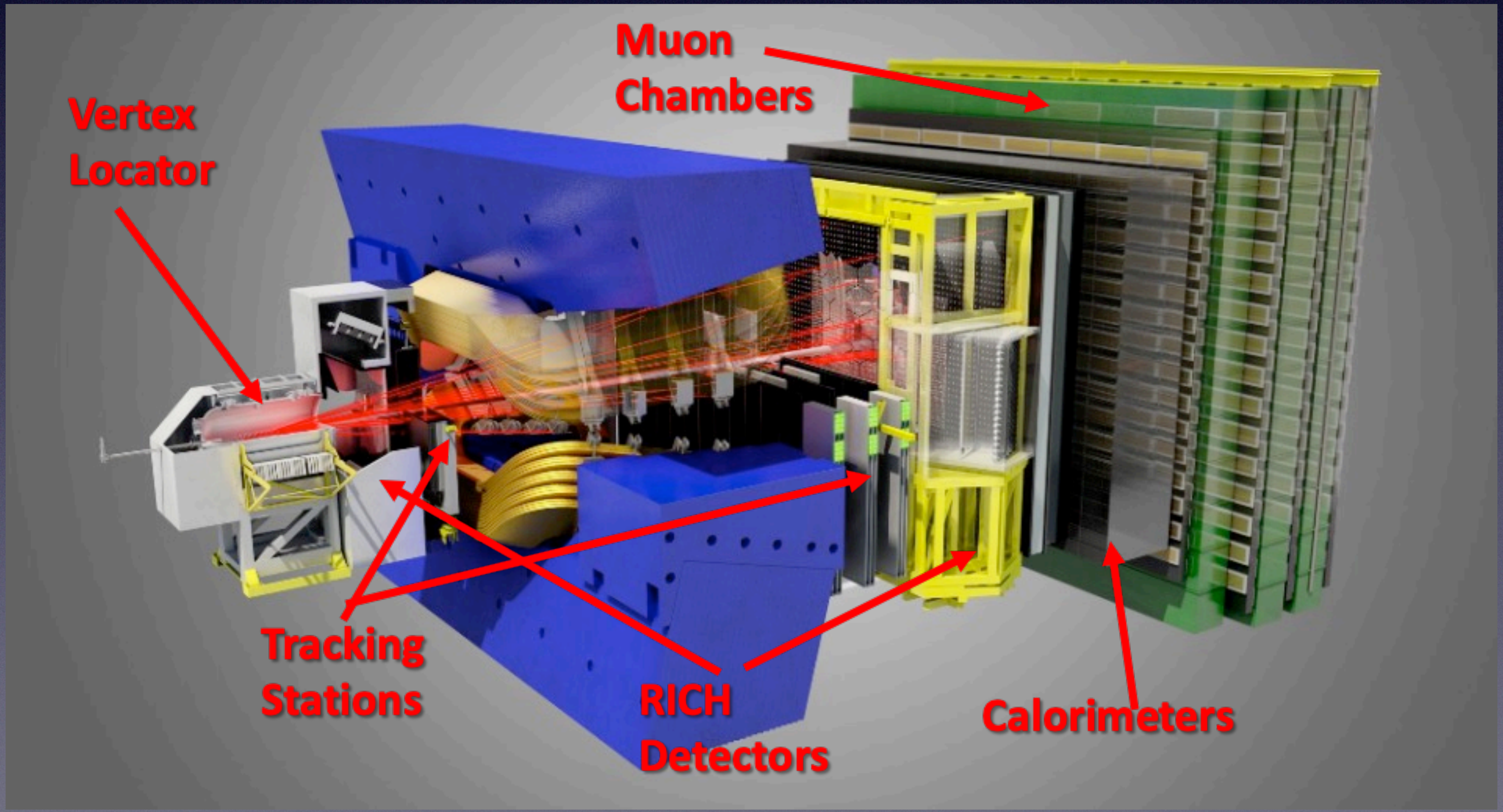
Weights

Statistical uncertainty with LHCb Run-2 data-set would be better than 10 MeV

LHCb detector

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

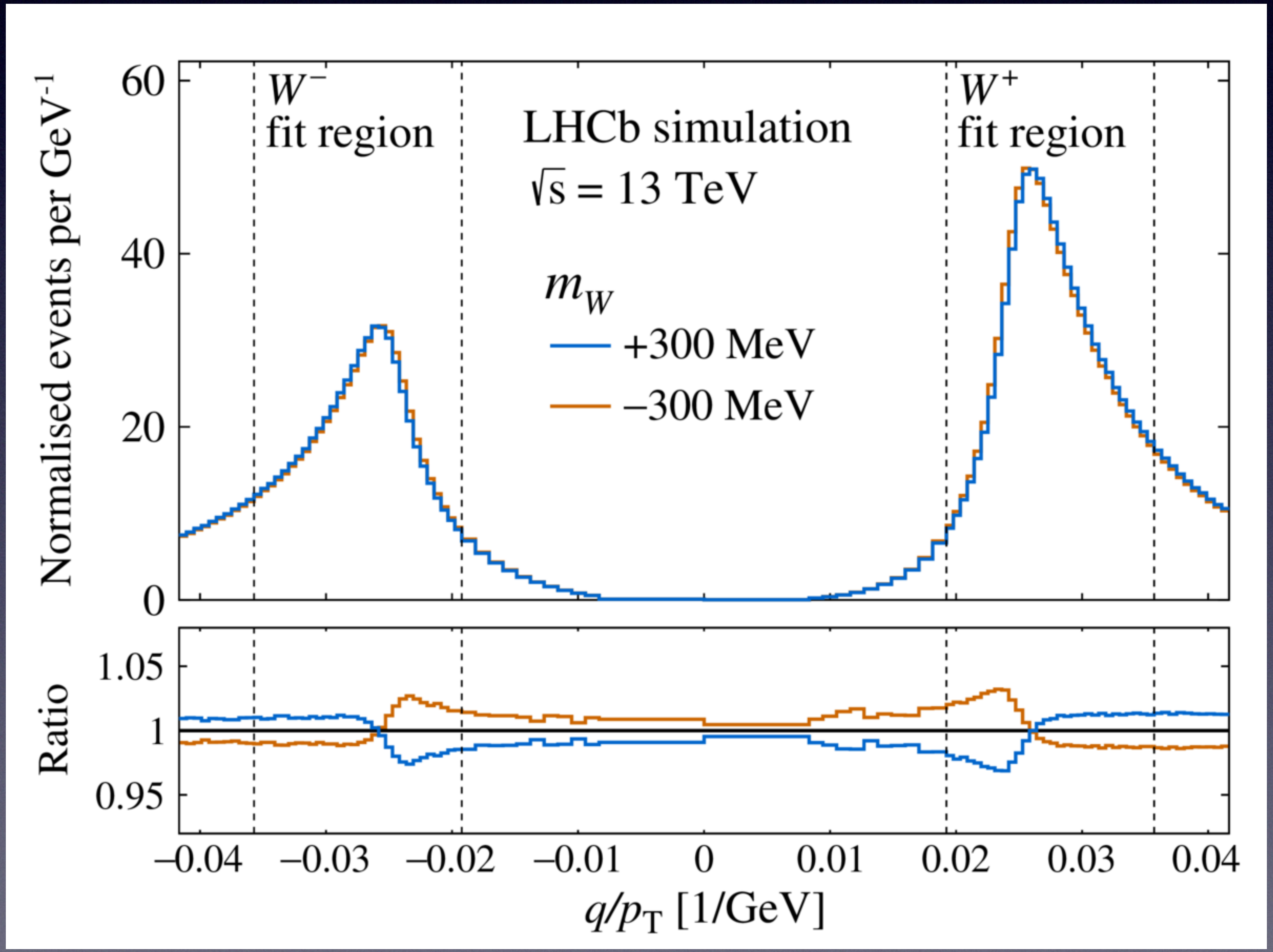
- Designed for the heavy flavour physics, with $2 < \eta < 5$
- Extended to EW measurements: excellent performance of tracking and muon detector



JHEP **01** (2022) 036

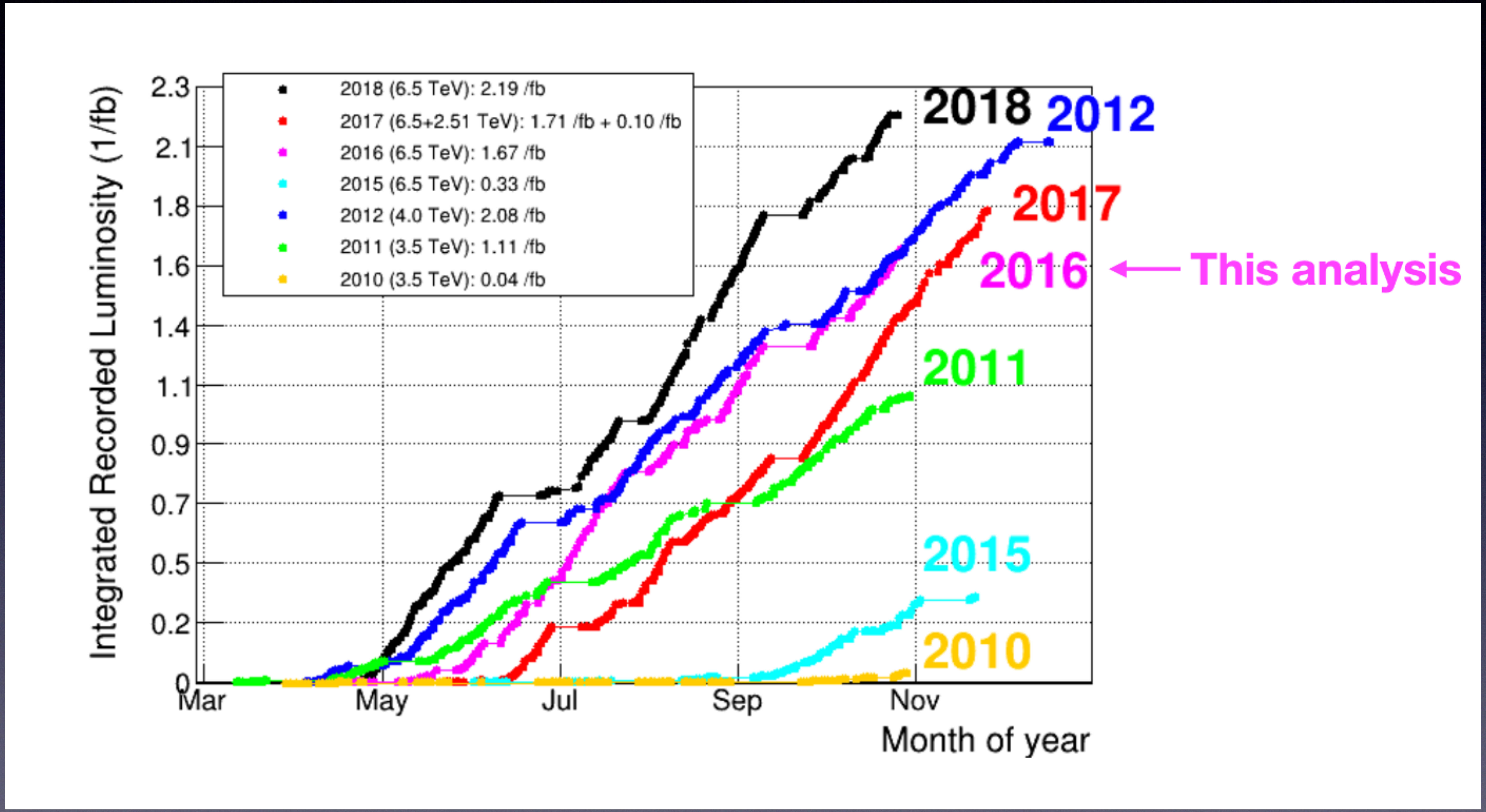
Analysis strategy

- Leptonic decay of W boson, $W \to \mu\nu$
    - Limited detector coverage: cannot get MET information, same for m_T
    - 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^*

Datasets



As a pathfinder measurement, only use 2016 data-set

PYTHIA is used with full simulation: missing higher effects, reweightings are needed

Event selection

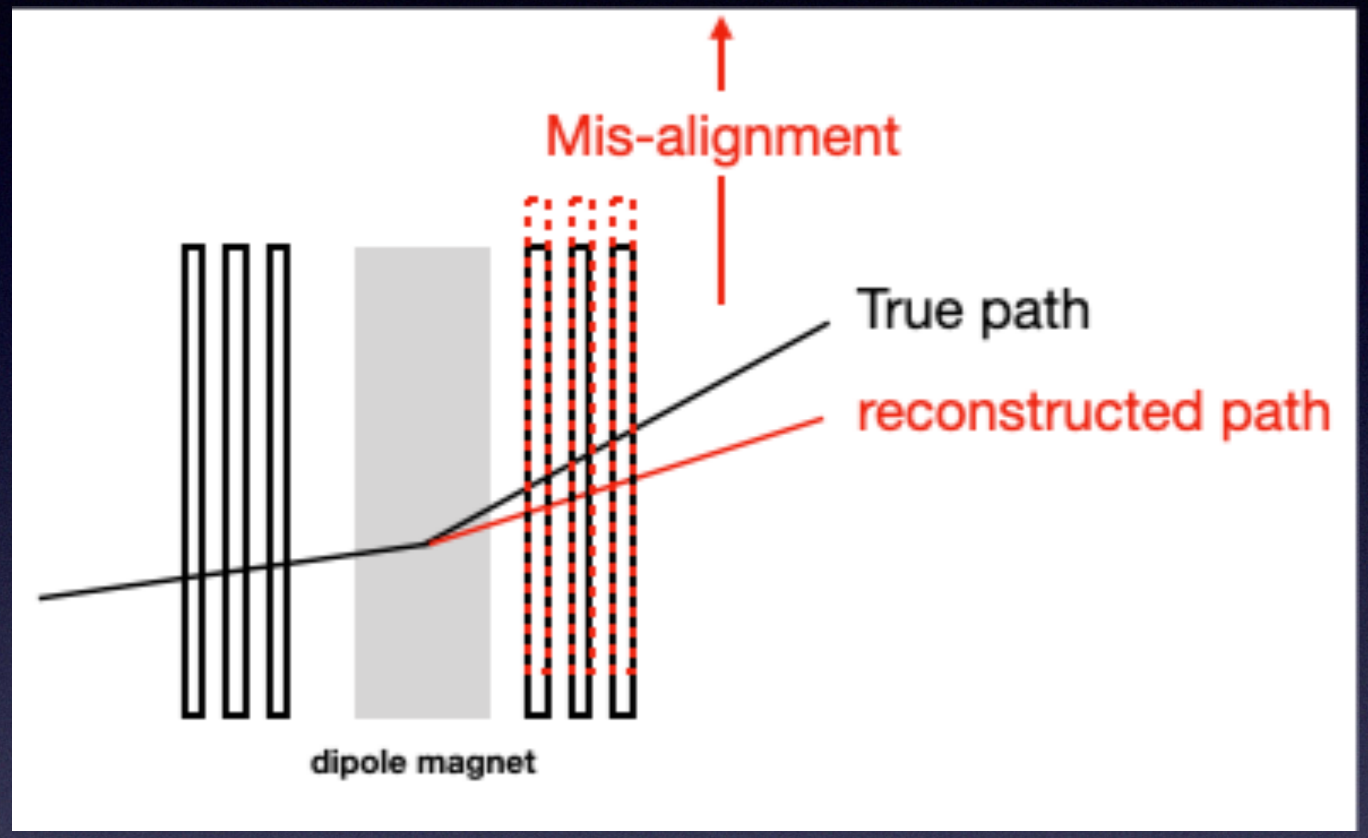
- Identified muon candidate matched to single muon trigger (threshold 20 GeV)
  - Relative momentum uncertainty: $\delta p/p < 6\,\%$
  - $\chi^2_{IP} < 9$: difference in the vertex fit χ^2 of the PV, with and without the muon
- Hadronic backgrounds are suppressed to the precent level by an isolation requirement
  - $\sum_i p_T(i) < 4$ GeV in cone size of 0.4
- Second muon veto: to suppress $Z \to \mu\mu$ background by a factor of 2
- In the region $28 < p_T < 52$ GeV, and $2.2 < \eta < 4.4$
  - Roughly 2.4 million events

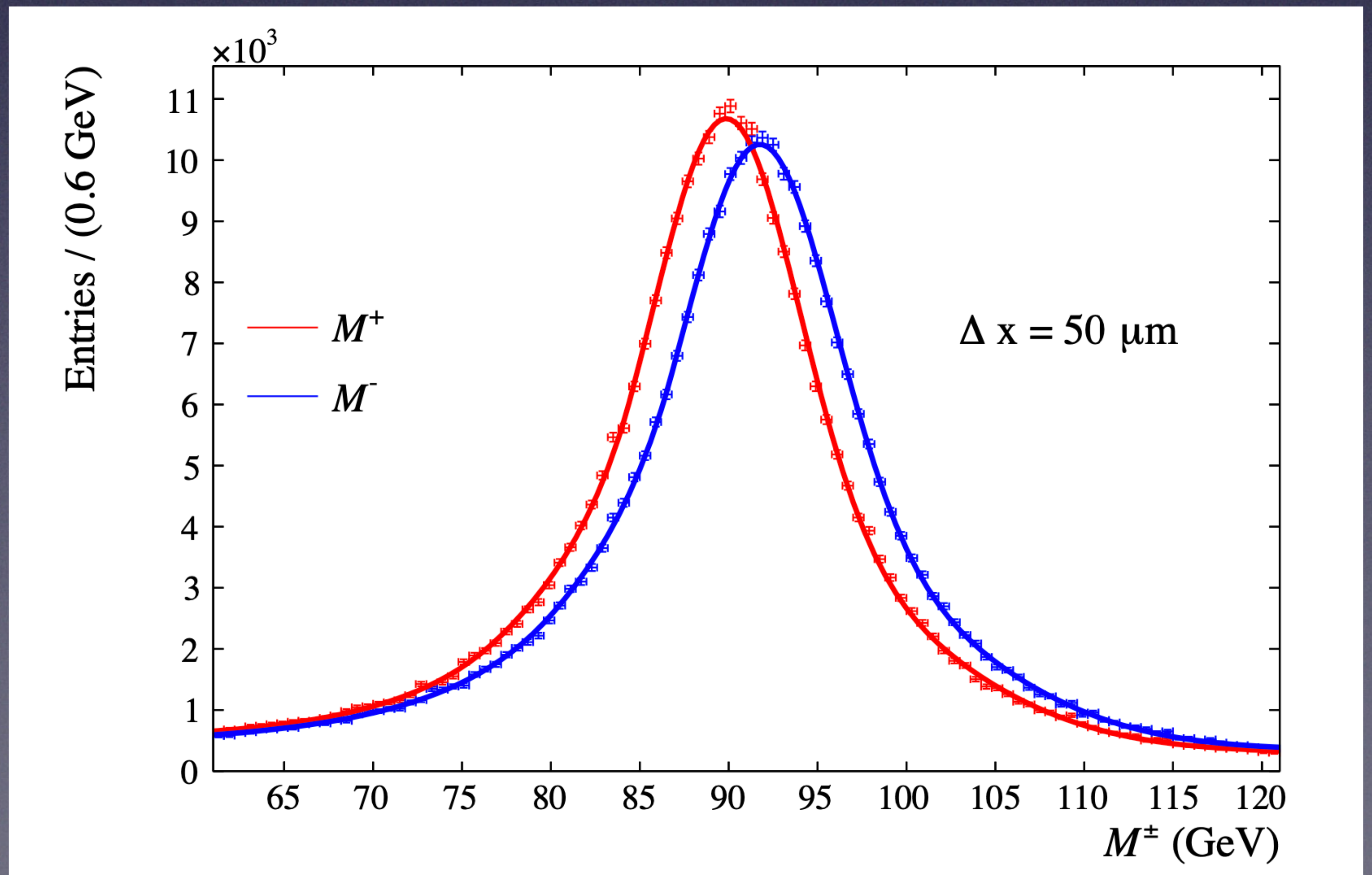
Eur. Phys. J. **C81** (2021) 251

Charge dependent curvature biases

- Real-time detector alignment/calibration in the LHCb Run-2
- However, the alignment is optimized for the heavy flavour physics
  - Use D^0, $D^{\pm}$,J/ψ events
  - Does not work well for W/Z events
- Detector level alignment and a custom alignment
  - Corrections developed using pseudo-mass (for + and - charged muons):

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





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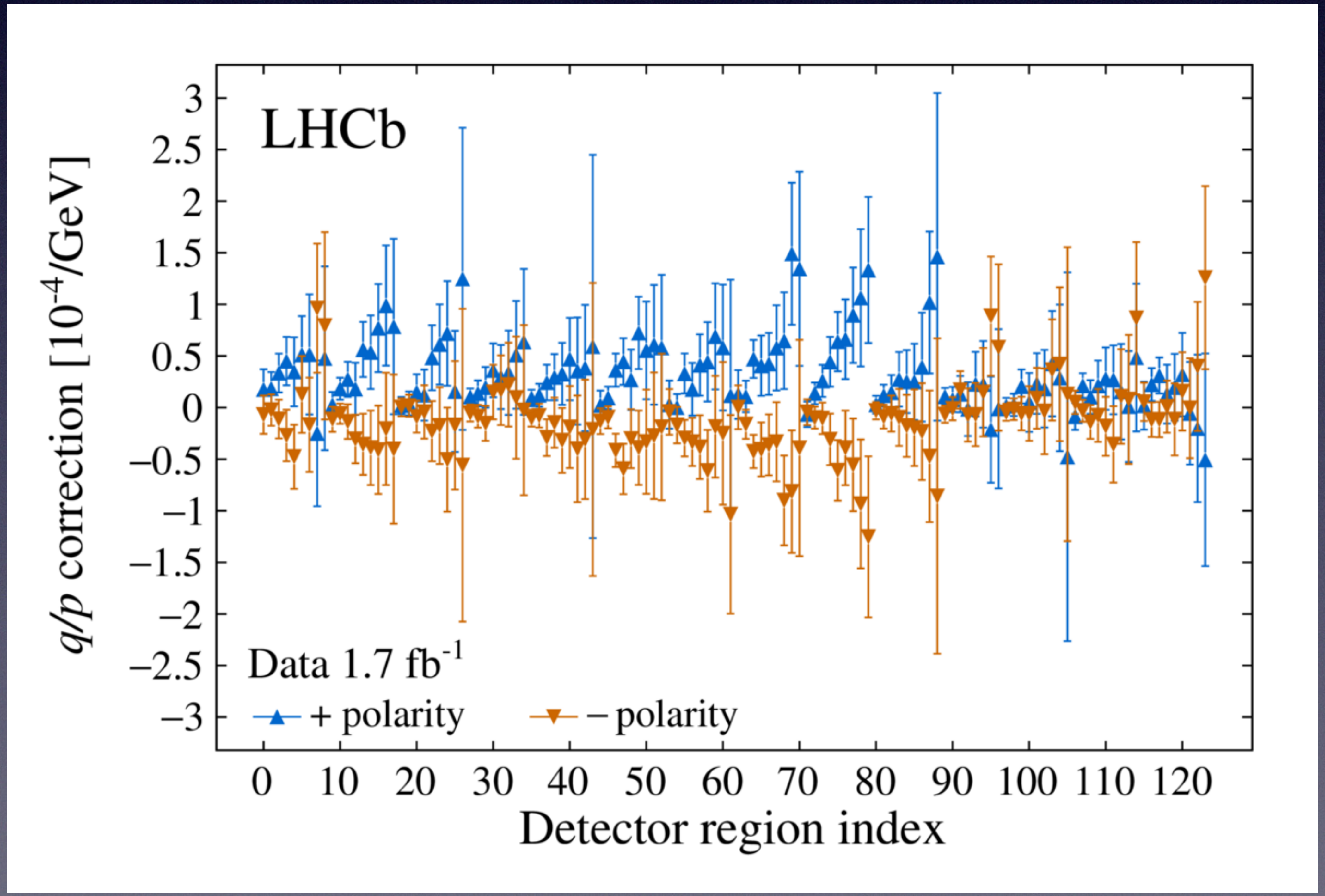
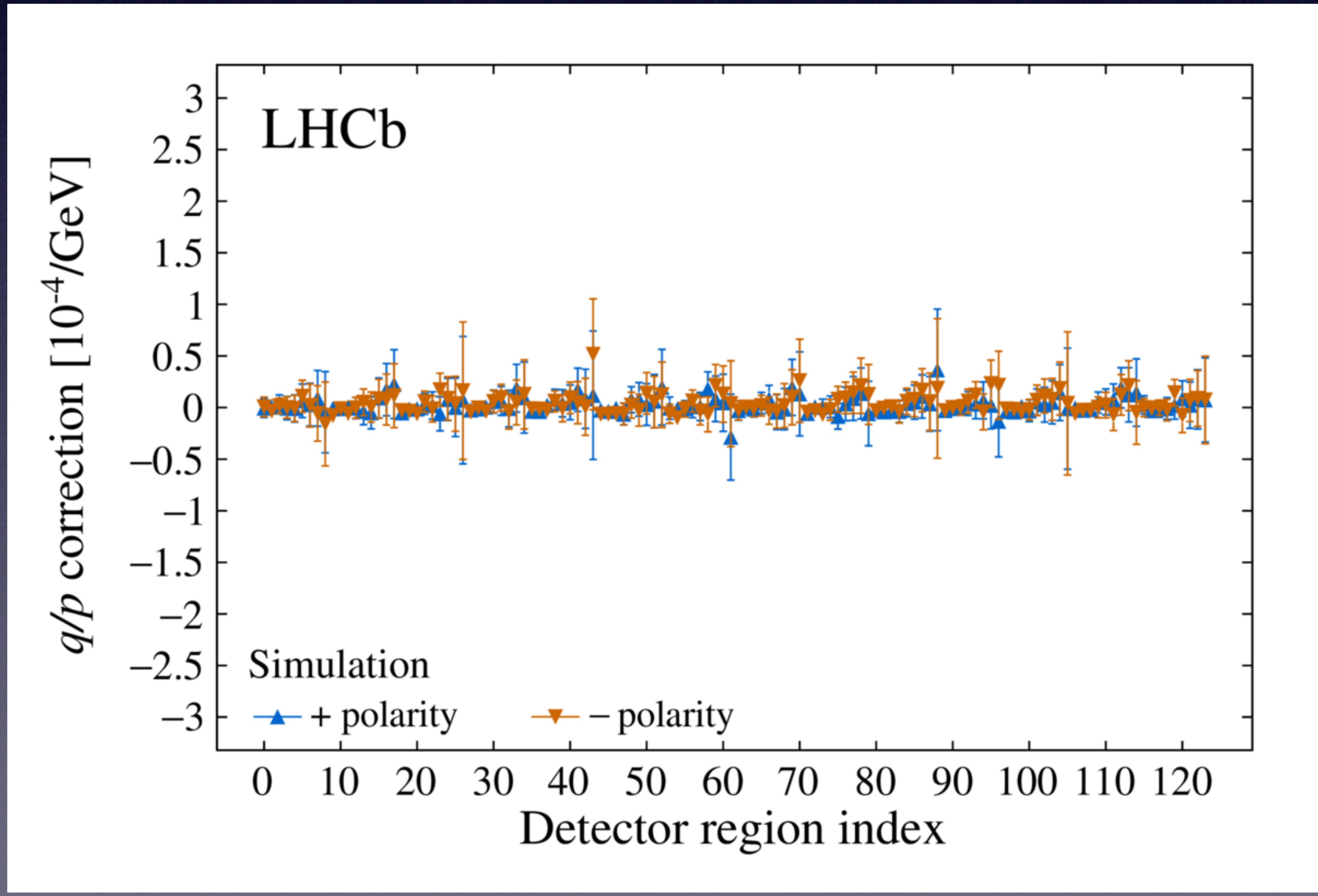
Charge dependent curvature biases

- An example of curvature corrections





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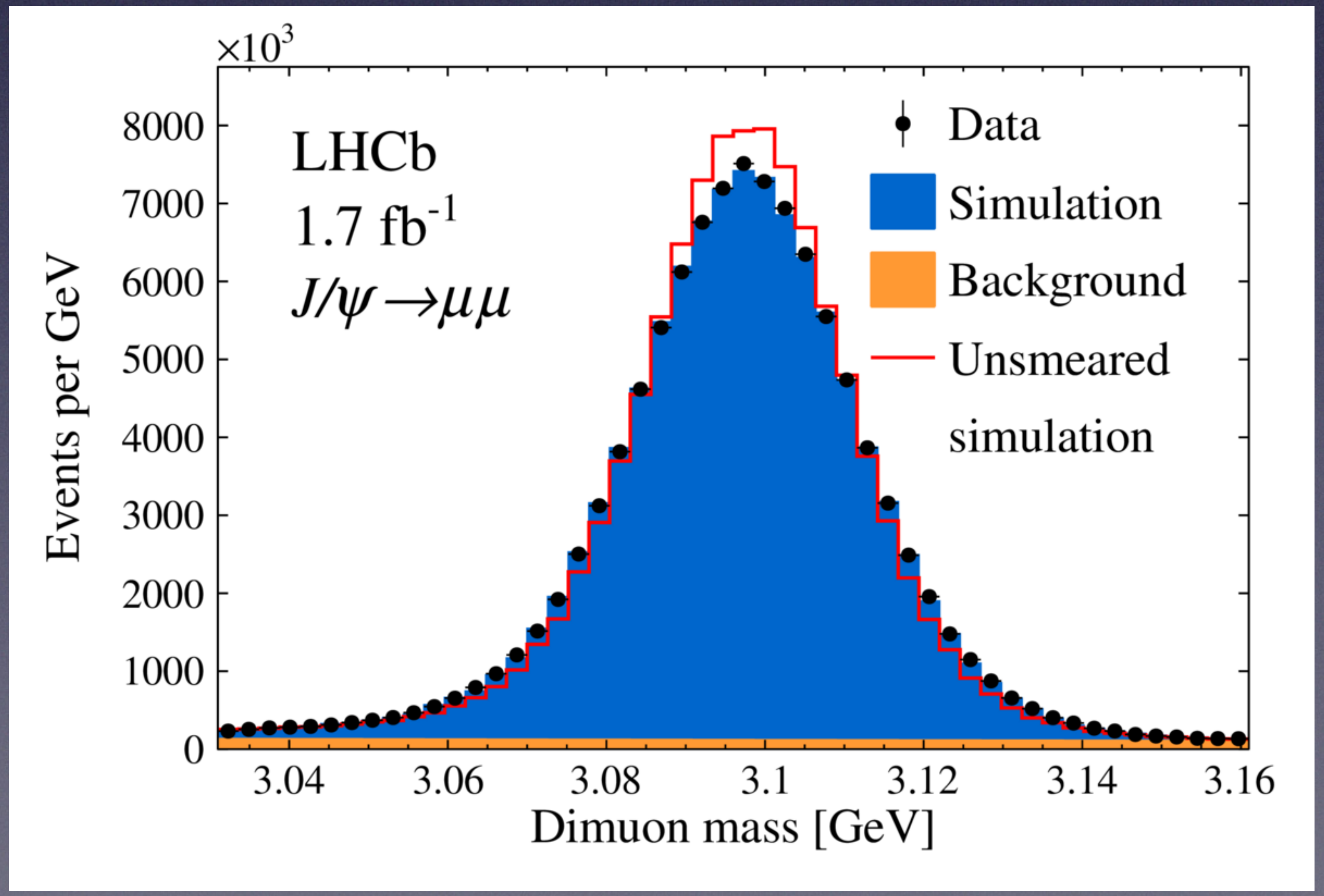
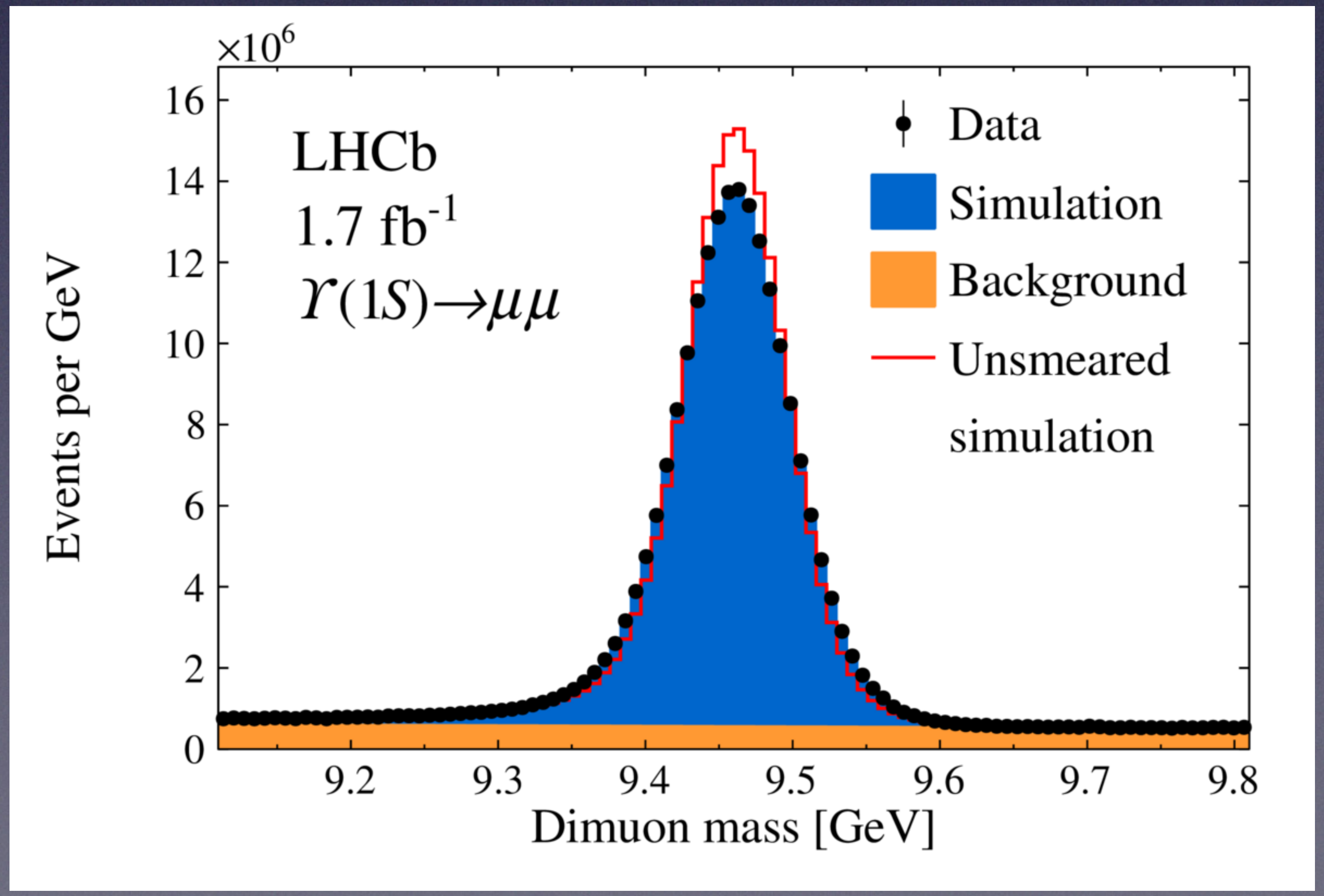
Momentum smearing fit

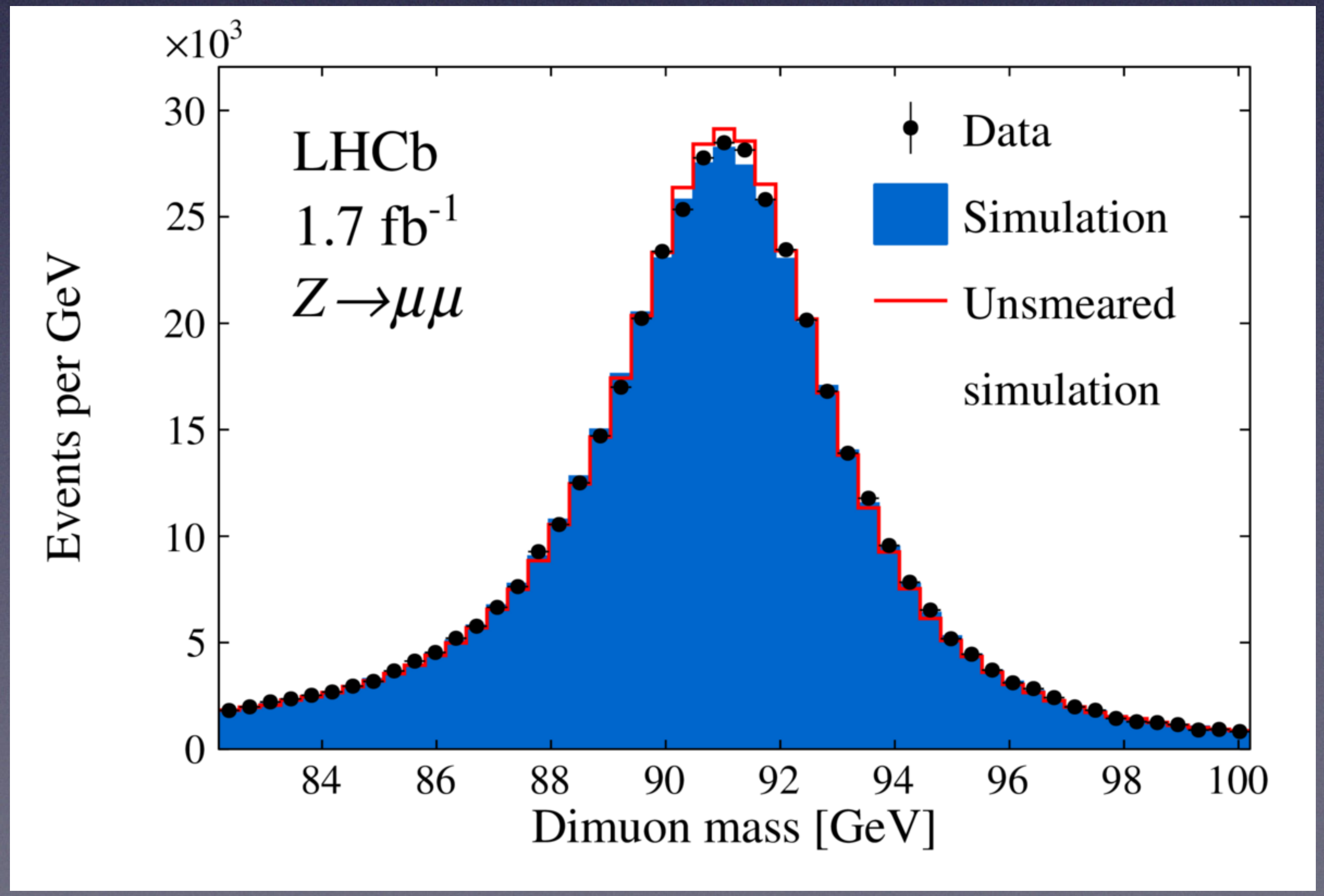
$$\frac{q}{p} \to \frac{q}{p \cdot \mathcal{N}(1+\alpha, \sigma_{MS})} + \mathcal{N}\left(\sigma, \frac{\sigma_\delta}{\cosh \eta}\right)$$

- Simultaneous fit of $J/\psi, \Upsilon(1S), Z$ mass distribution: $\chi^2/dof = 1862/2082$

- Simulation to describe data







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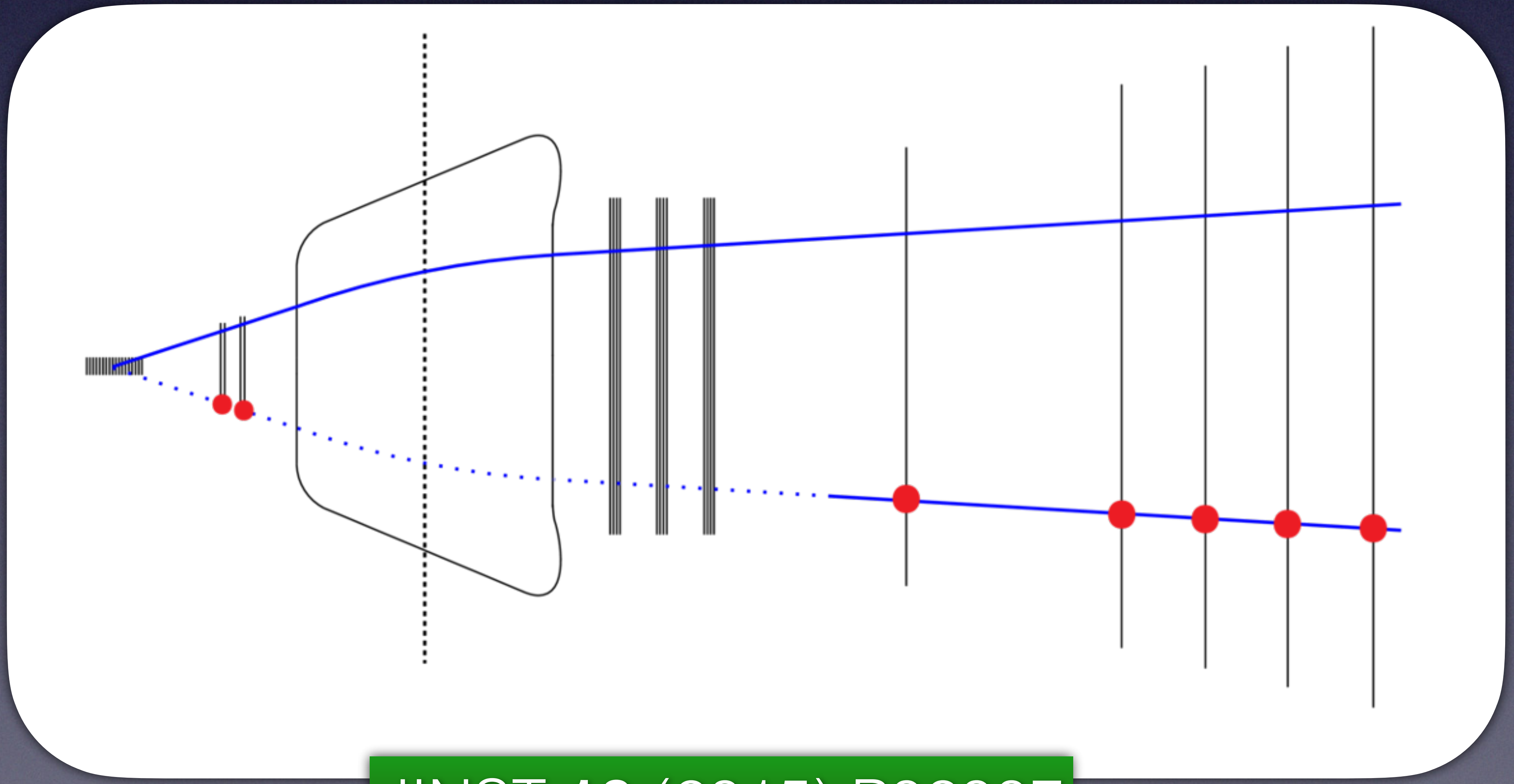
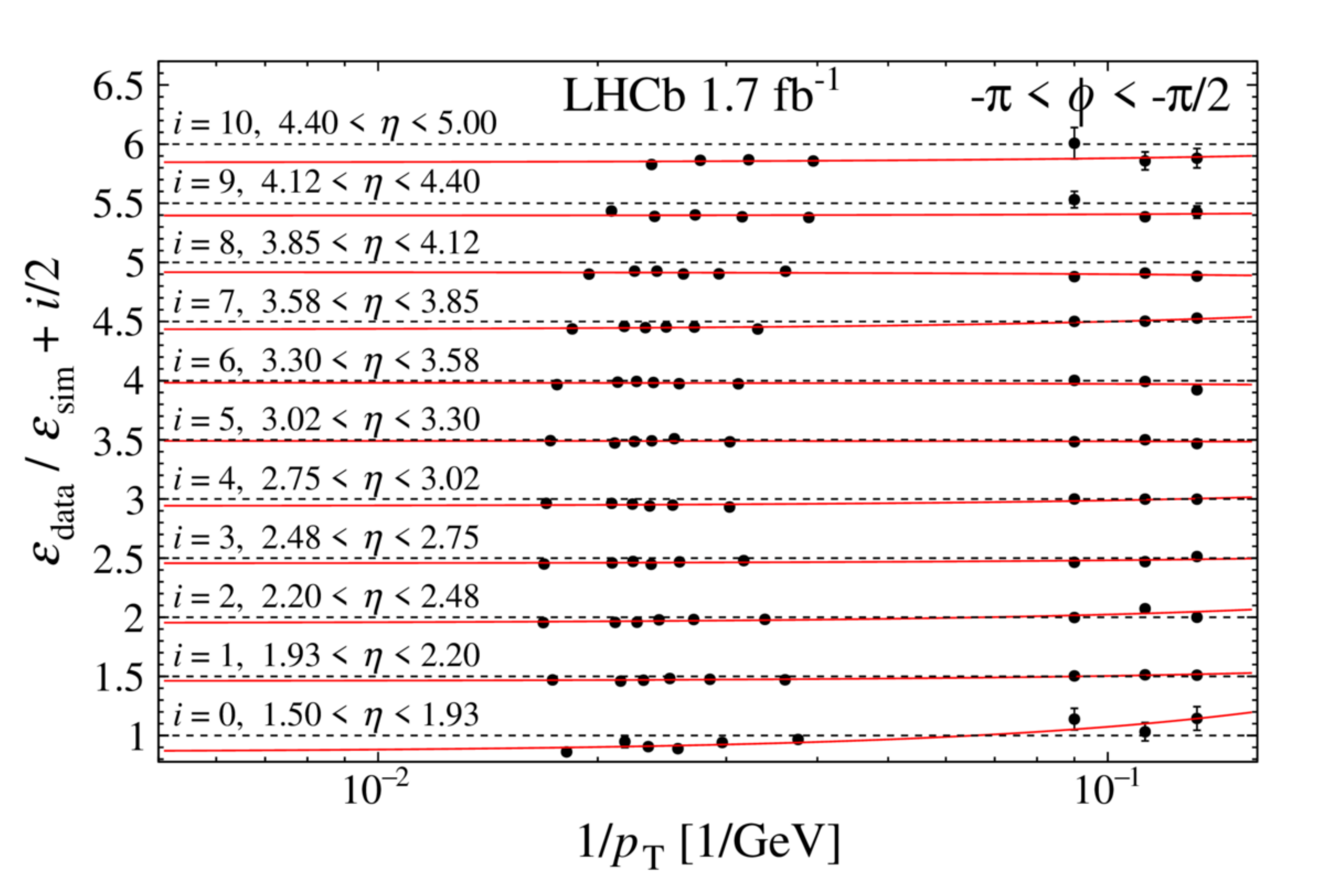
Efficiency corrections

- Traditional tag-and-probe method: $Z \to \mu^+\mu^-$, $\Upsilon(1S) \to \mu^+\mu^-$events
- The simulated events are corrected with event-by-event weight



JINST **10** (2015) P02007

Tracking efficiency determination



Trigger efficiency

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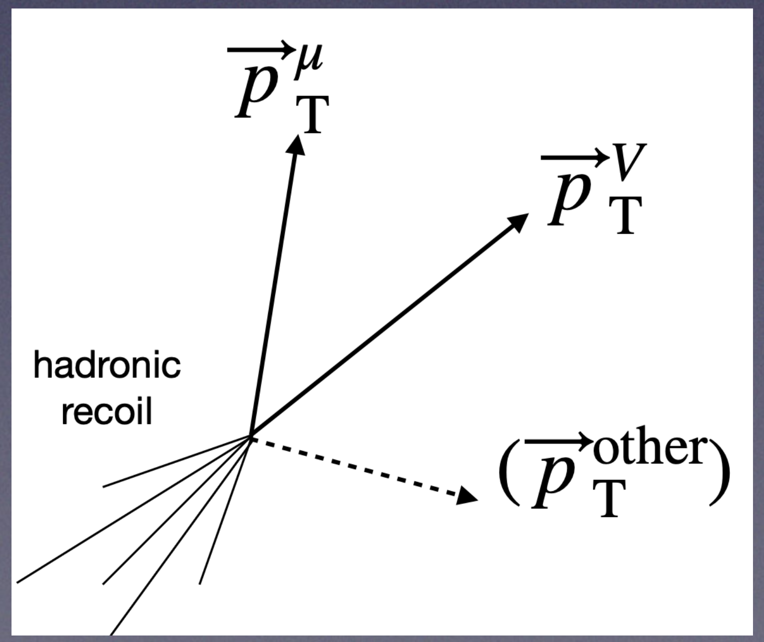
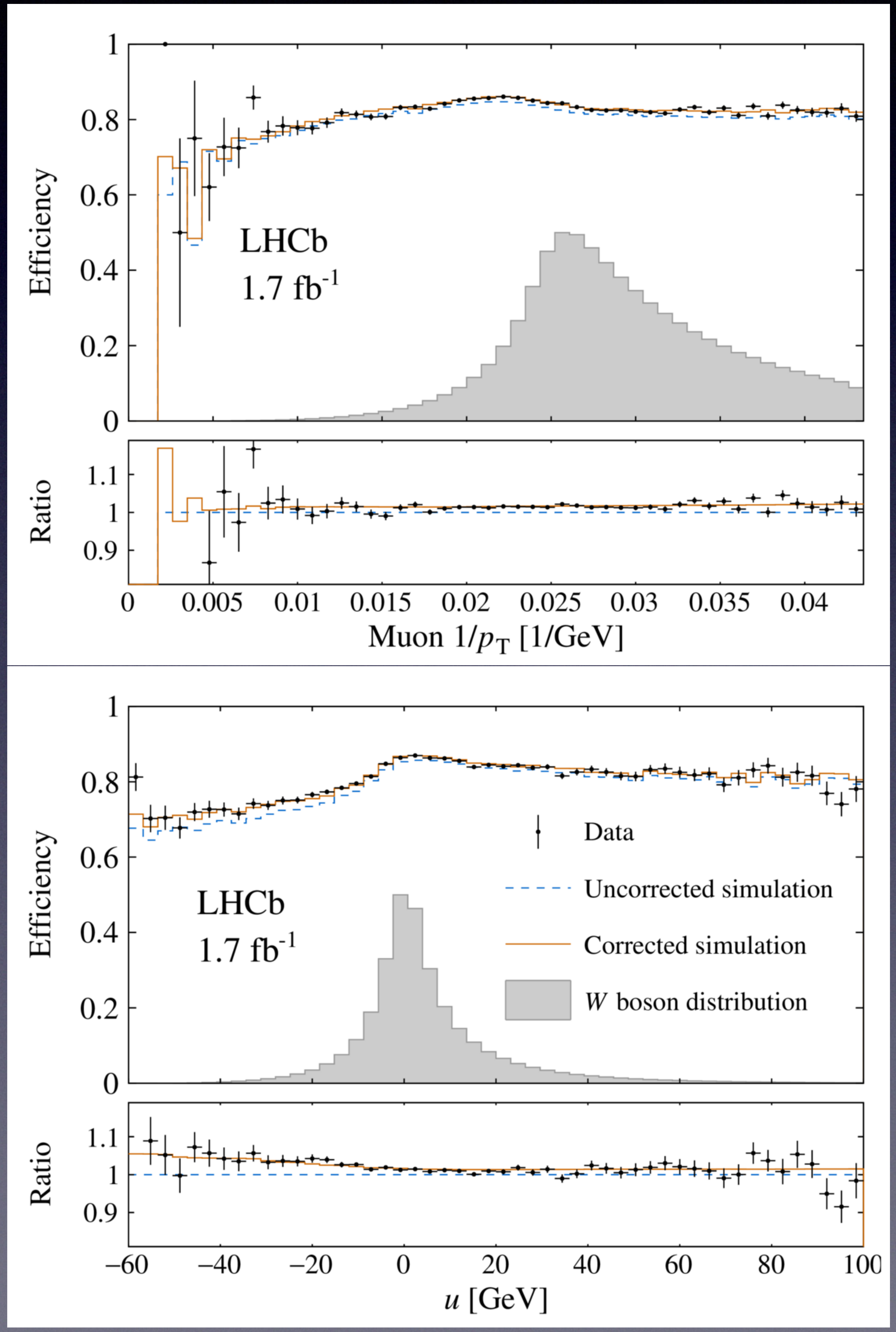
Muon isolation efficiency

- The muon isolation cut is used to suppress heavy flavour background
- Sizable contributions from pile-up, underlying event and the recoil component of the hard process
- Study isolation efficiency as a function of u, with $Z \to \mu\mu$ events:

$$u = \frac{\overrightarrow{p}_T^V \cdot \overrightarrow{p}_T^\mu}{p_T^\mu}$$





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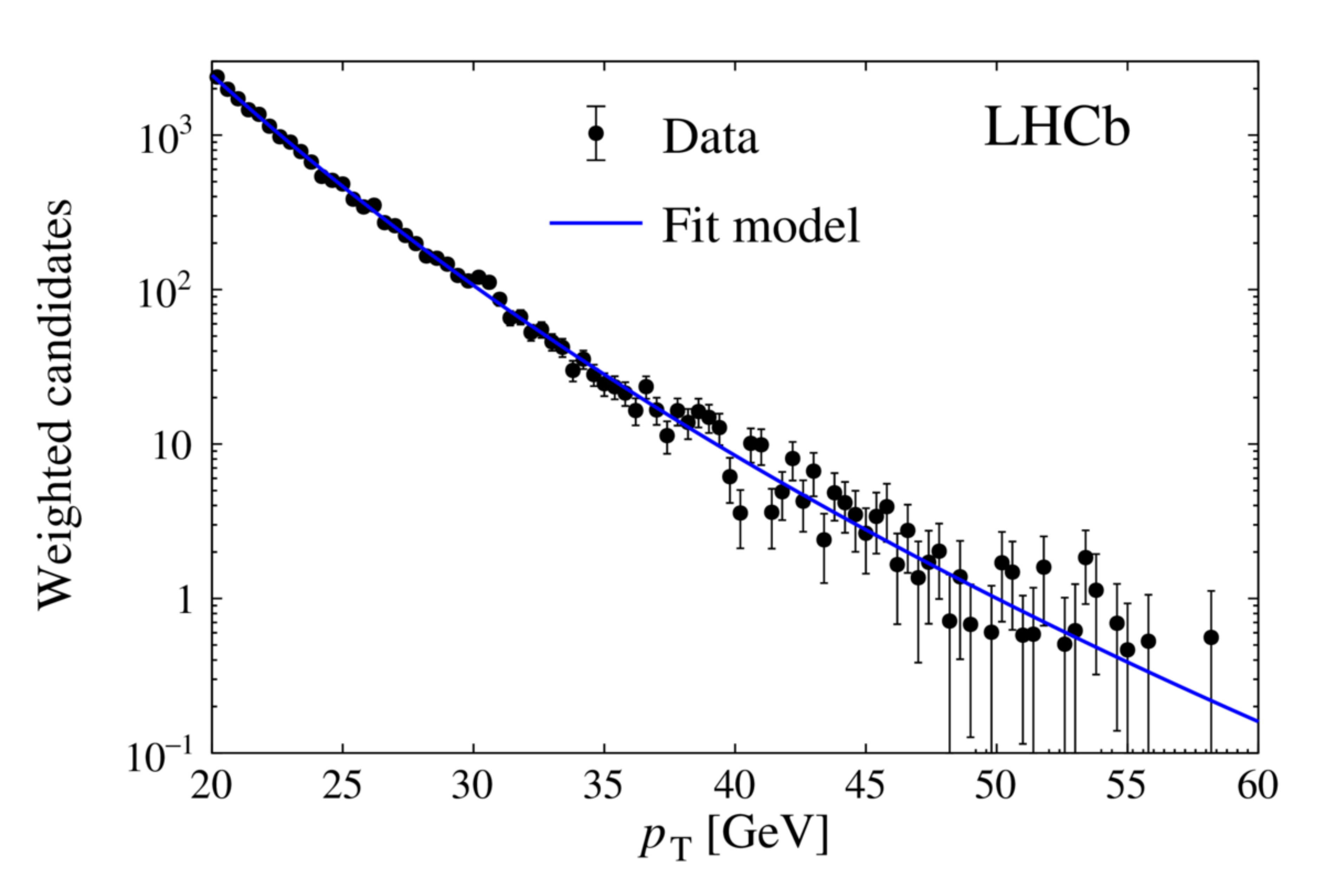
Background modeling

- Electroweak backgrounds and heavy flavour hadrons are modeled with simulation
- Hadronic background: the decay-in-flight of pions and kaons
  - Cannot get from simulation
  - Special triggered events without muon ID requirement
  - Majority occur outside the magnetic field region



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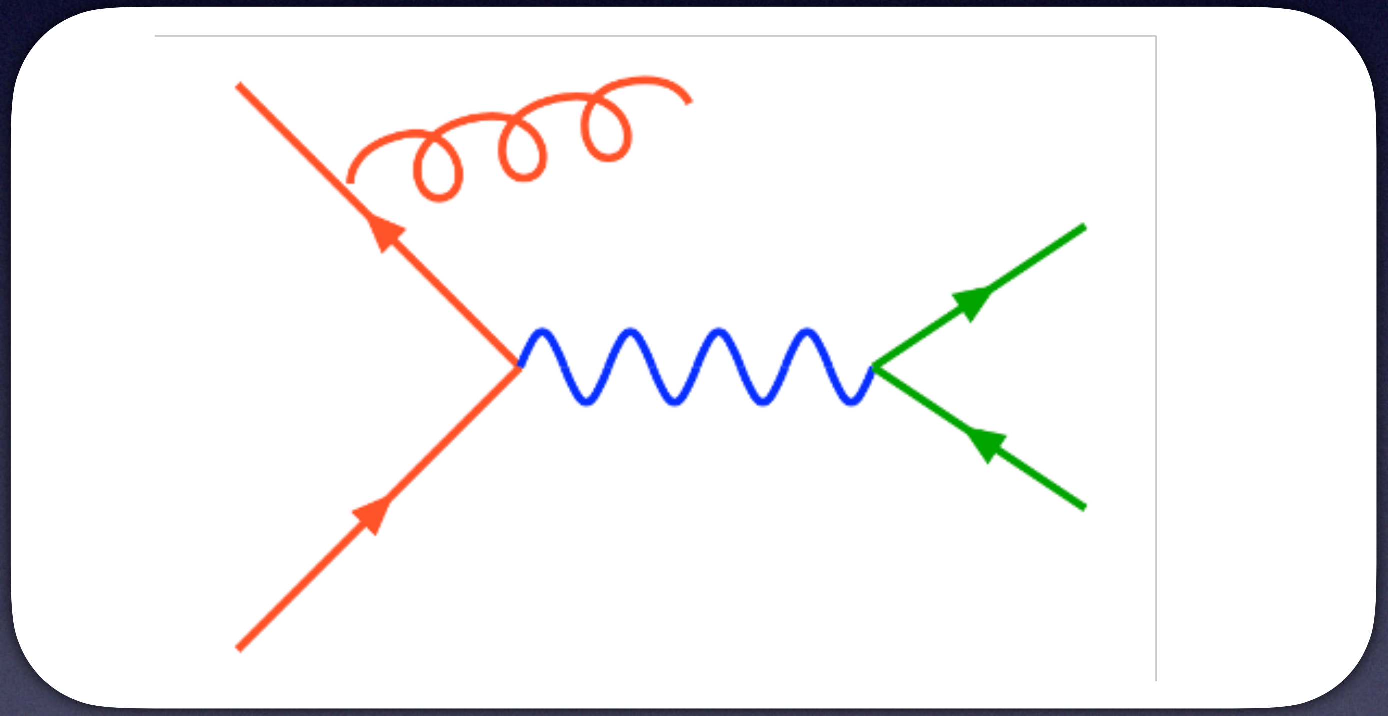
QCD corrections: polarisation

- Born-level form of $W \to \mu\nu$

$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{W}\,\mathrm{d}y\,\mathrm{d}M\,\mathrm{d}\cos\vartheta\,\mathrm{d}\varphi} = \frac{3}{16\pi}\frac{\mathrm{d}\sigma^{\mathrm{unpol.}}}{\mathrm{d}p_{\mathrm{T}}^{W}\,\mathrm{d}y\,\mathrm{d}M} \\
&\Big\{(1+\cos^2\vartheta) + A_0\frac{1}{2}(1-3\cos^2\vartheta) + A_1\sin 2\vartheta\cos\varphi \\
&+ A_2\frac{1}{2}\sin^2\vartheta\cos 2\varphi + A_3\sin\vartheta\cos\varphi + A_4\cos\vartheta \\
&+ A_5\sin^2\vartheta\sin 2\varphi + A_6\sin 2\vartheta\sin\varphi + A_7\sin\vartheta\sin\varphi\Big\},
\end{aligned}
$$



- An equivalent expression of $Z \to \mu\mu$ production
- A_3 is particularly important for the muon p_T distribution

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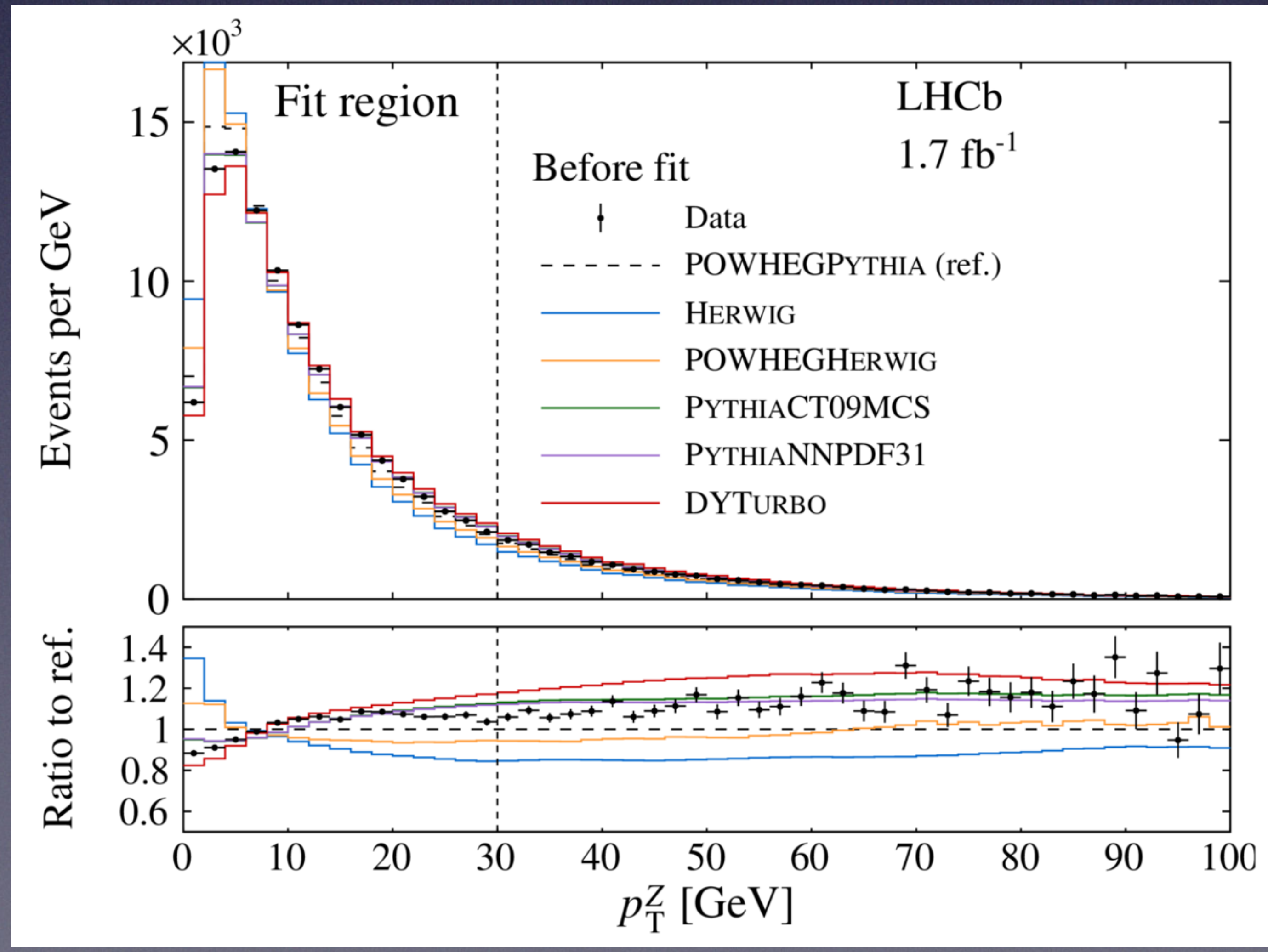
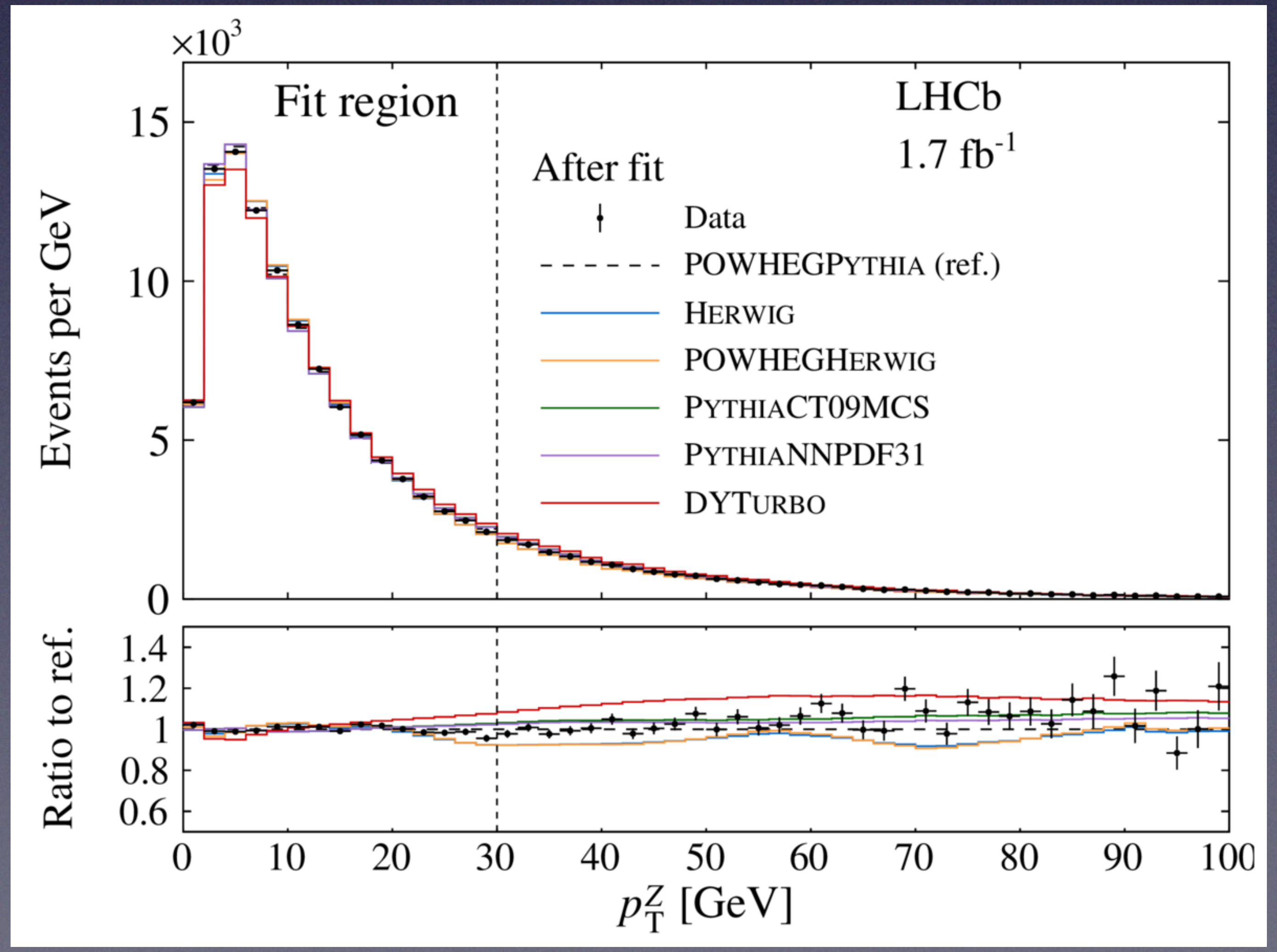
QCD Corrections: W boson p_T

- The p_T of a muon has a strong dependence on the W boson p_T (extremely important for this analysis)
  - W p_T measurement from ATLAS/CMS/D0: limited by p_T resolution
  - POWHEG+PYTHIA: tuning of α_s and k_T^{intr}
  - $Z \to \mu\mu$ events are used to validate

QCD reweighting
p_T: POWHEGPYTHIA
A_i: DYTURBO





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QCD Corrections: Higher p_T region

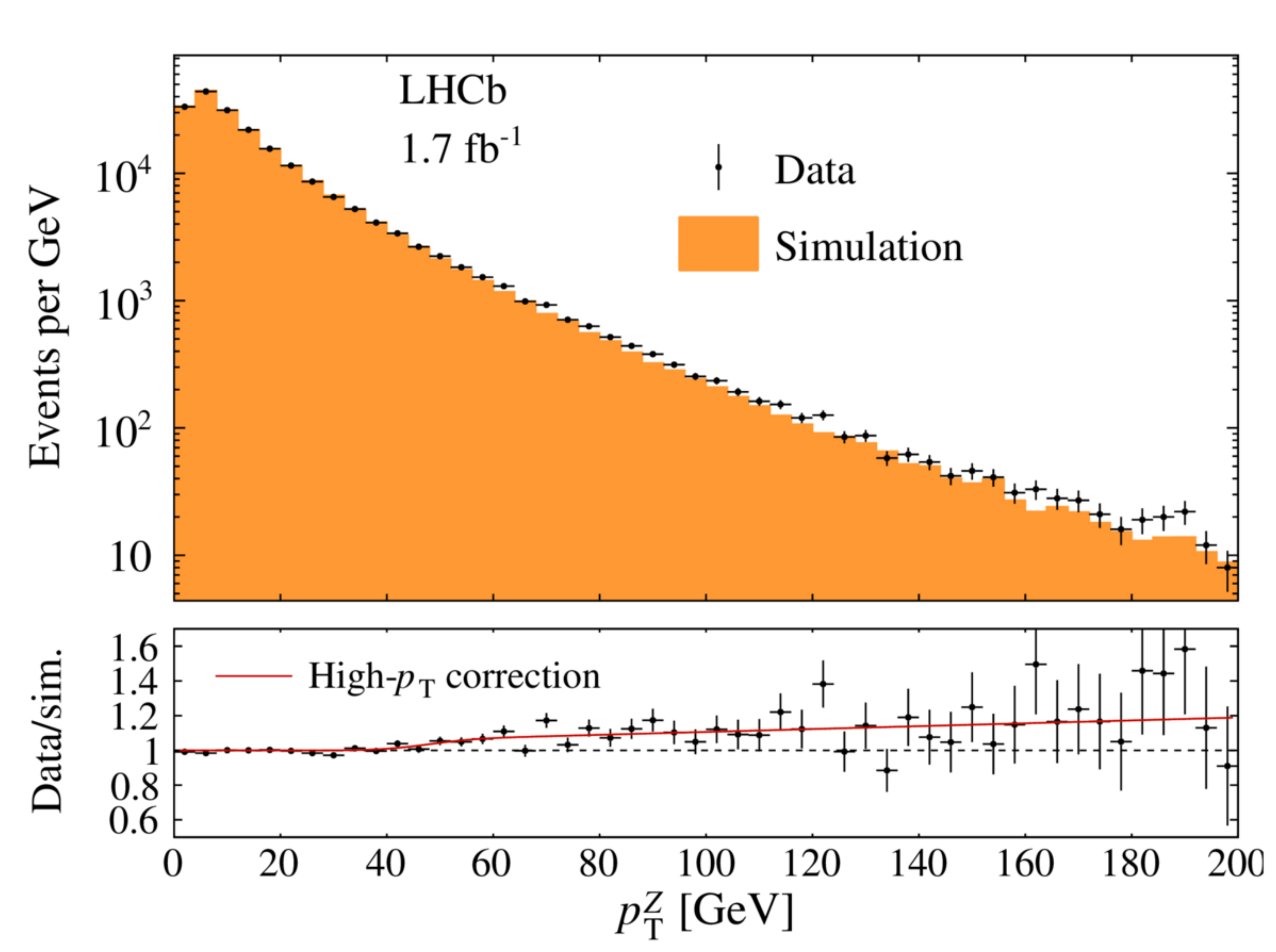
- However, in the high boson p_T region
- Significant difference between data ($Z \to \mu\mu$) and POWHEG+PYTHIA prediction
  - Missing matrix elements for the production of a weak boson and more than one jet

Up to 10% at PTZ ~ 100 GeV

$$(1 + p_0 + p_0 \mathrm{Erf}(p_1(p_{\mathrm{T}}^V - p_2))) \times (1 + p_3 p_{\mathrm{T}}^V).$$

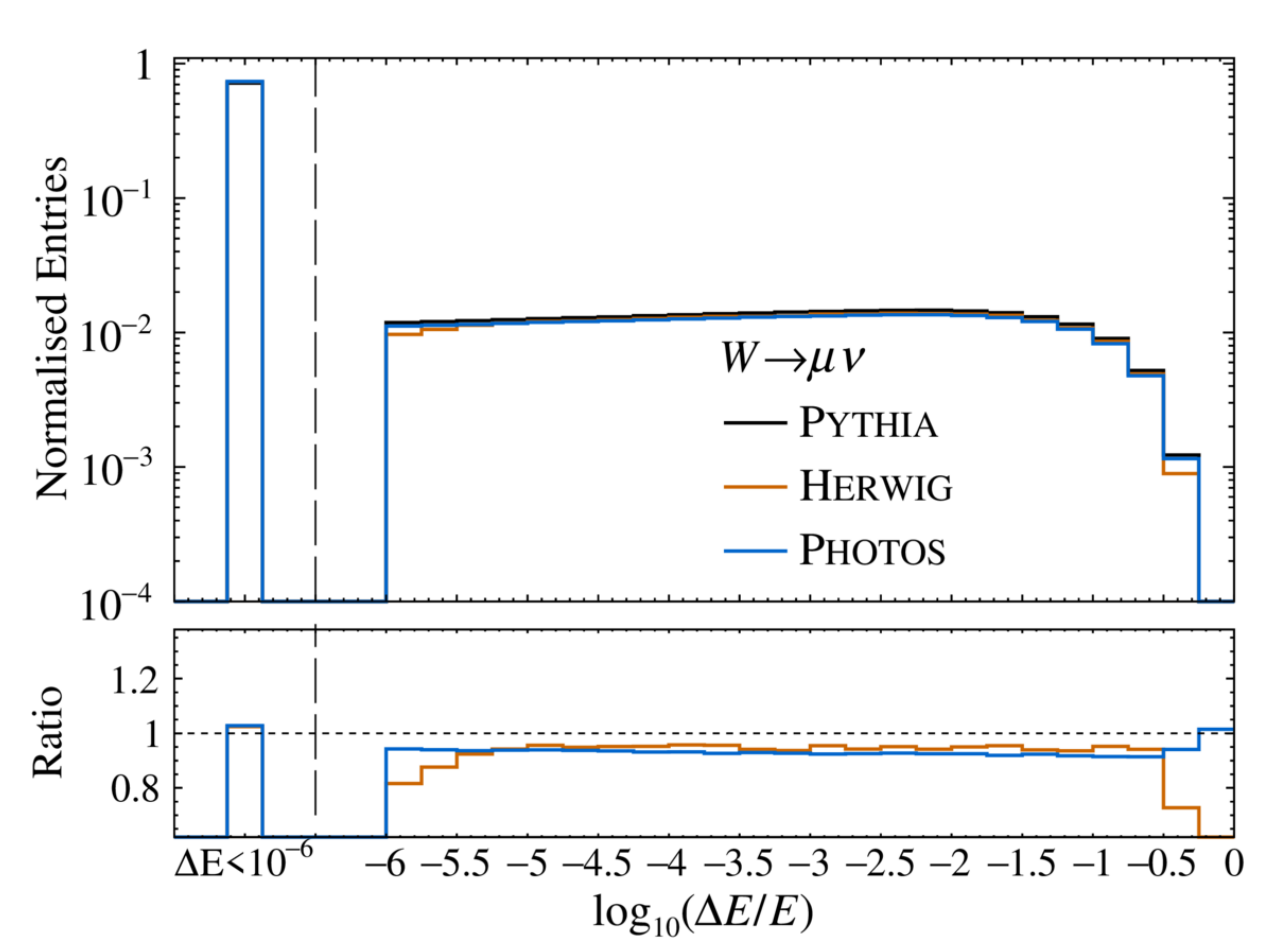
100% of this correction: < 1 MeV uncertainty

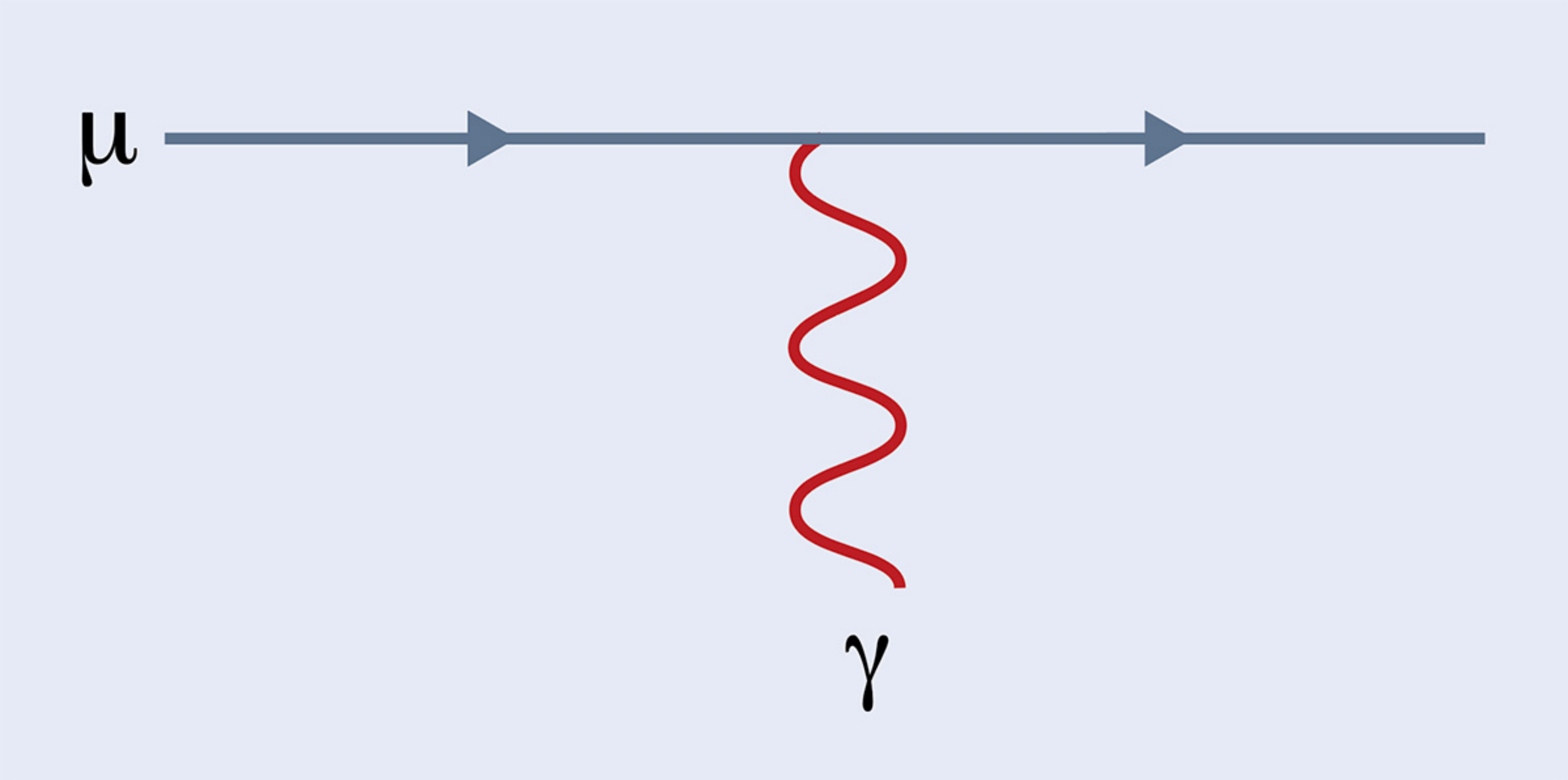
QCD reweighting
p_T: POWHEGPYTHIA
A_i: DYTURBO
High p_T: data/Prediction



QED corrections

- Effects from final-state radiation (FSR): larger effects on the muon channel
  - Showing algorithms: PHOTOS, HERWIG, PYTHIA





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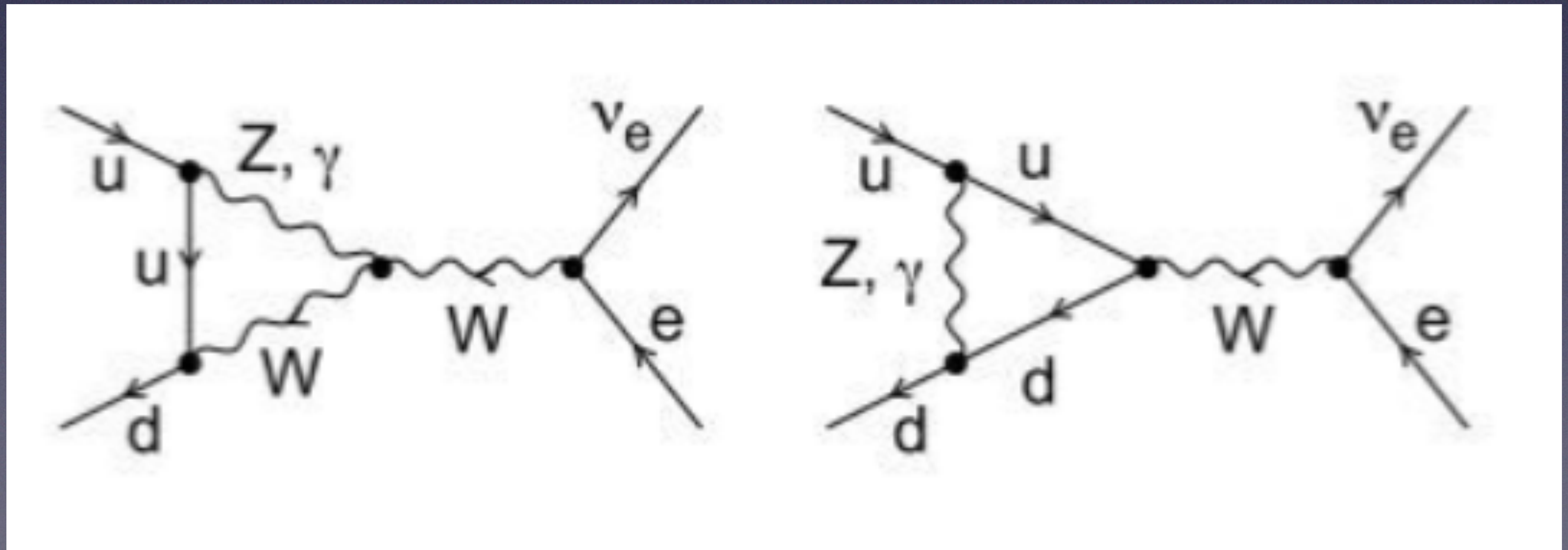
Electroweak correction

- The higher order EW corrections are not included in the model
- 5 MeV uncertainty is assigned: compare POWHEGBOXV2 prediction with and without electroweak corrections



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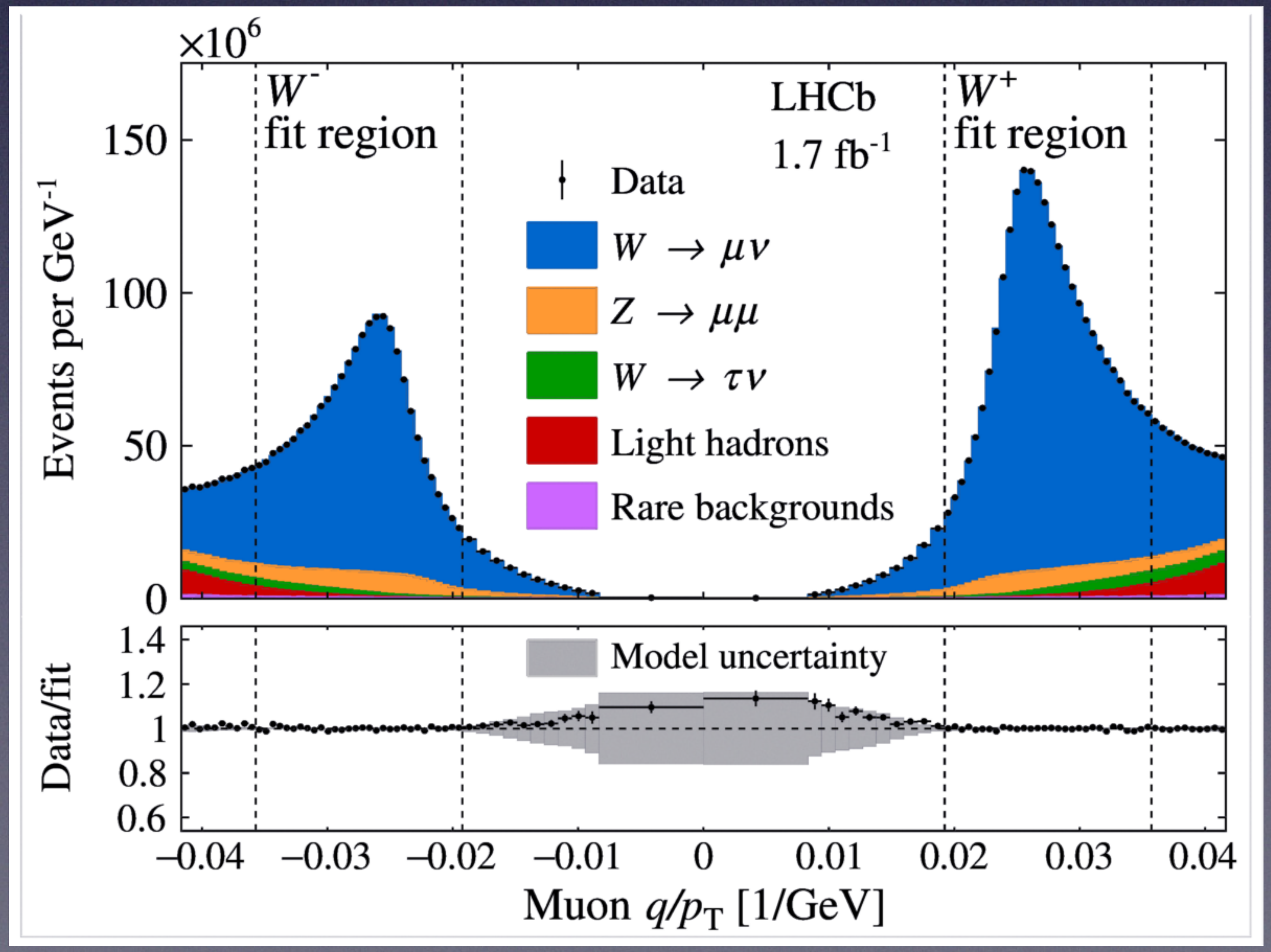
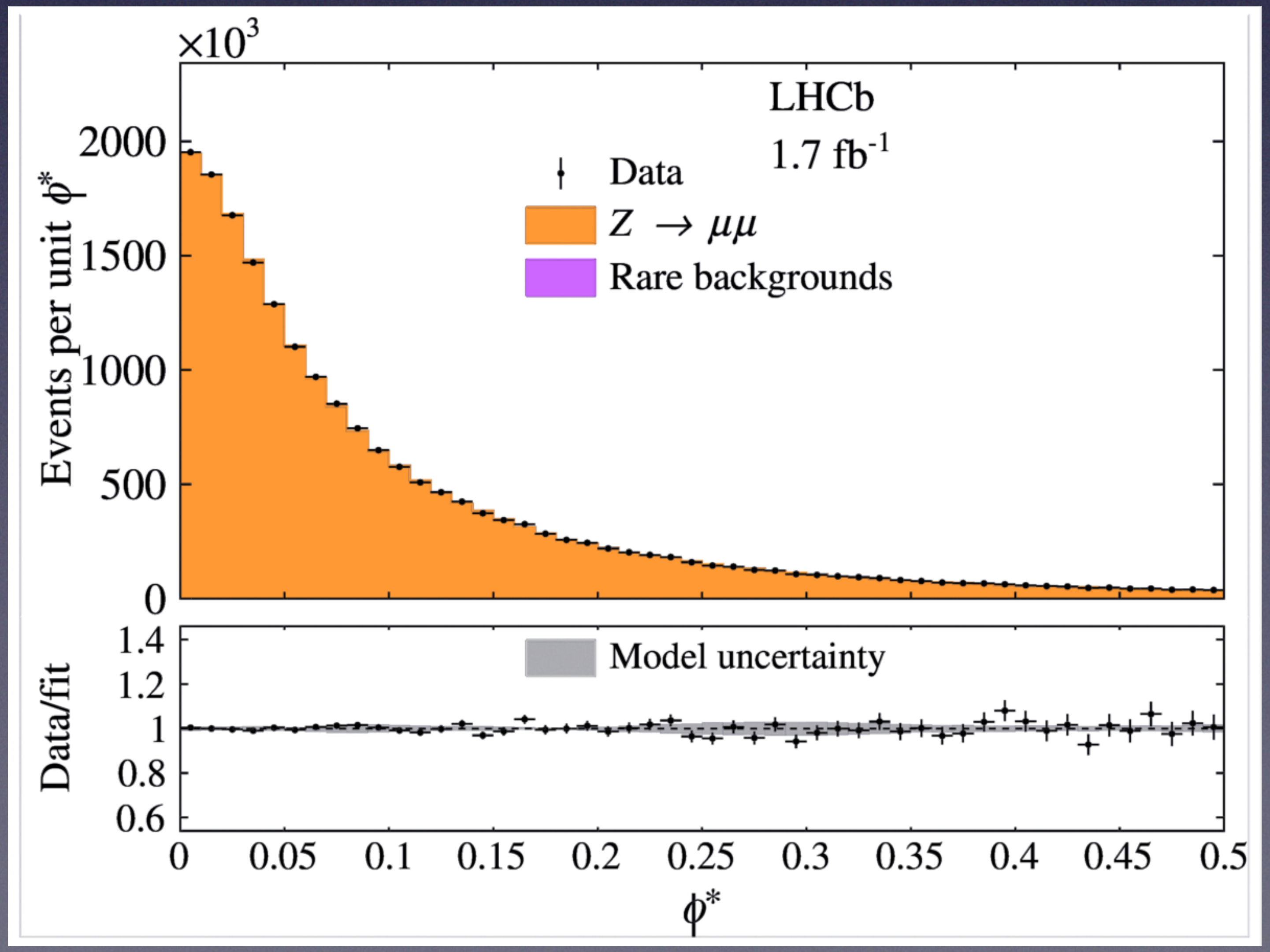
Fit results

- 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





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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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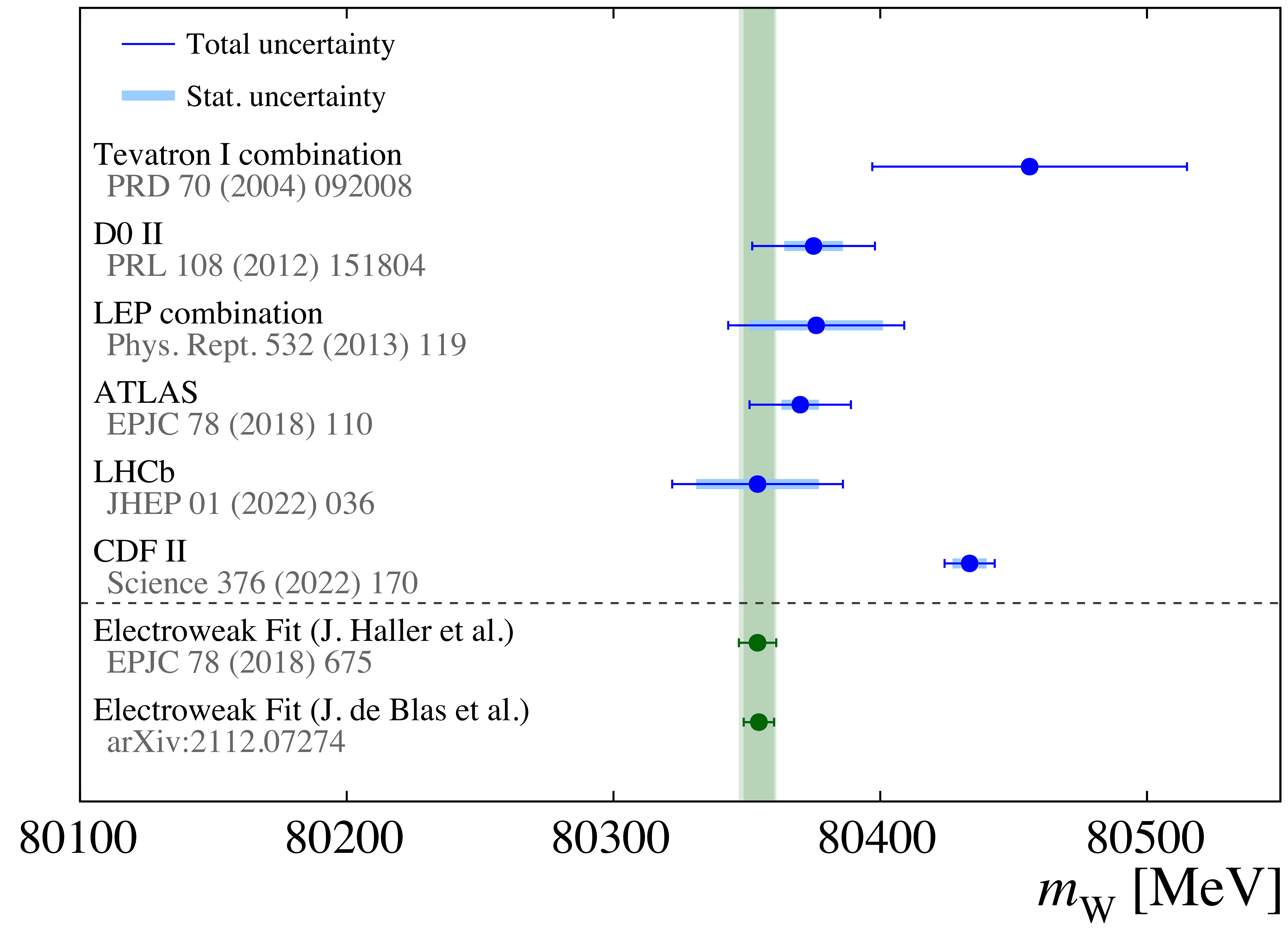
LHCb measured result



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Full Run-2 data-sets

- First measurement of m_W from LHCb: 32 MeV
- Consistent with previous measurements and with the prediction
  - A total uncertainty of $\lesssim 20$ MeV
  - Upgrade to a double differential fit

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$$m_W = 80354 \pm 23(\textbf{stat.}) \pm 10(\textbf{exp.}) \pm 17(\textbf{theory}) \pm 9(\textbf{PDF})$$

Z boson production cross section measurement

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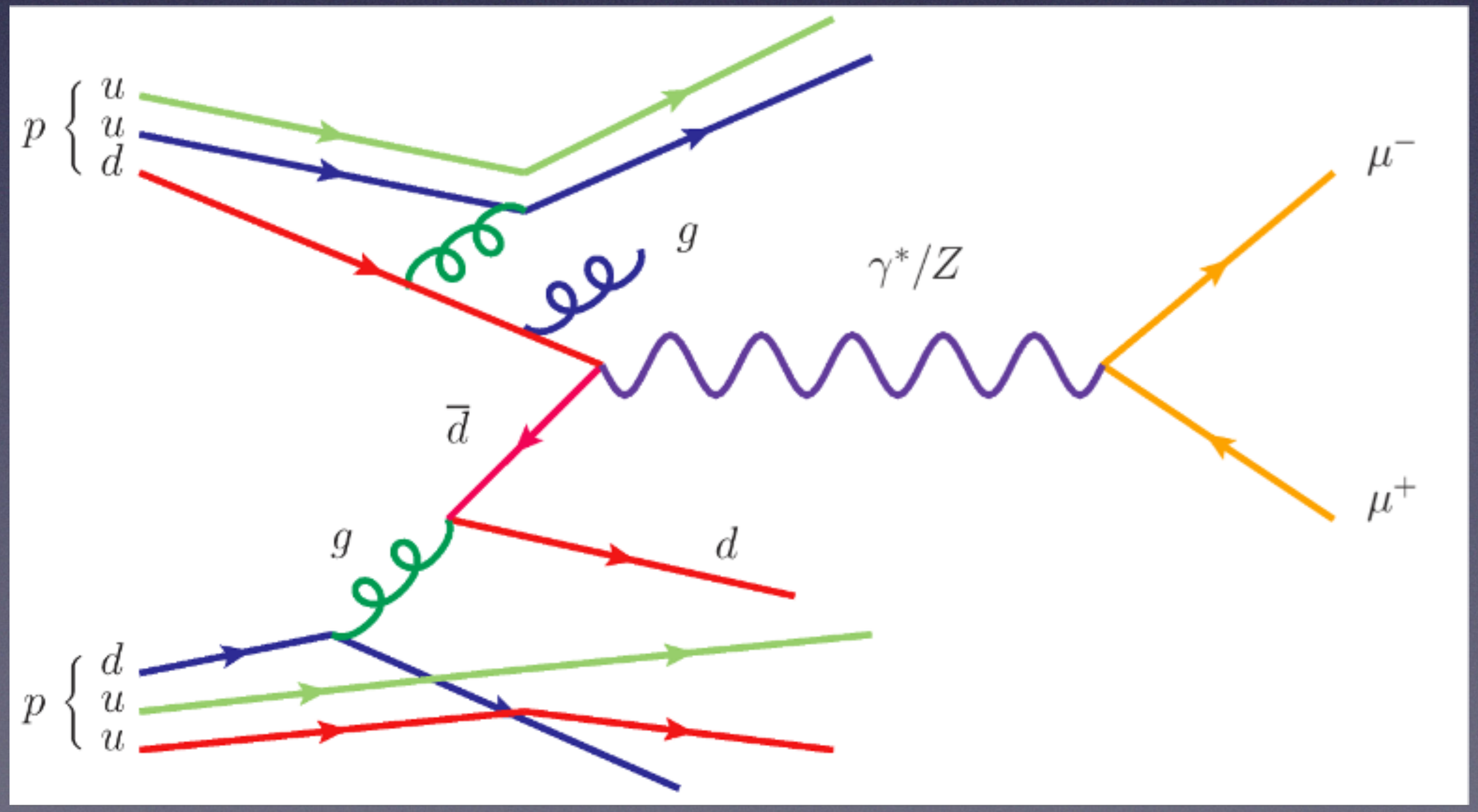
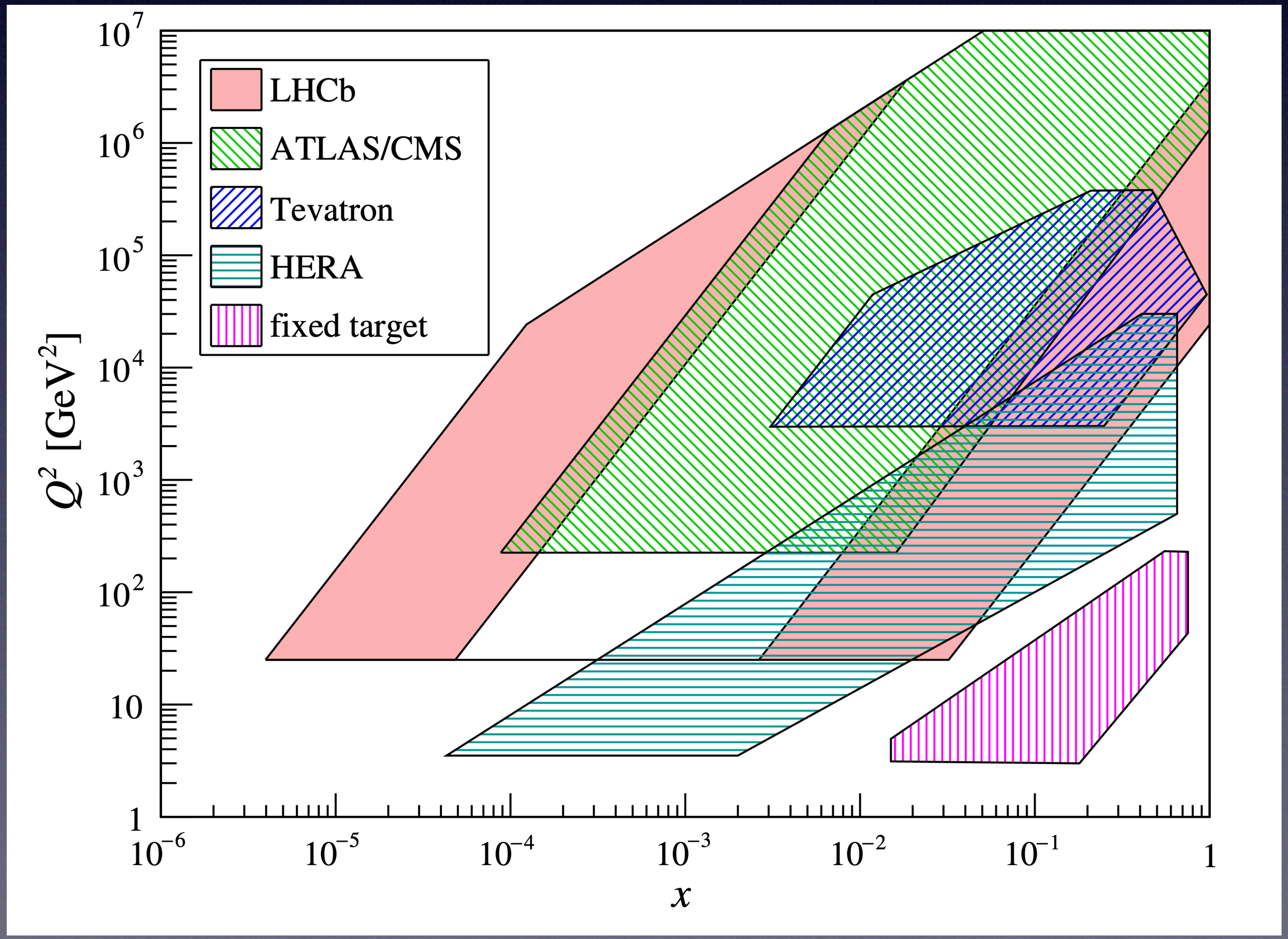
EW production @LHCb

- 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)

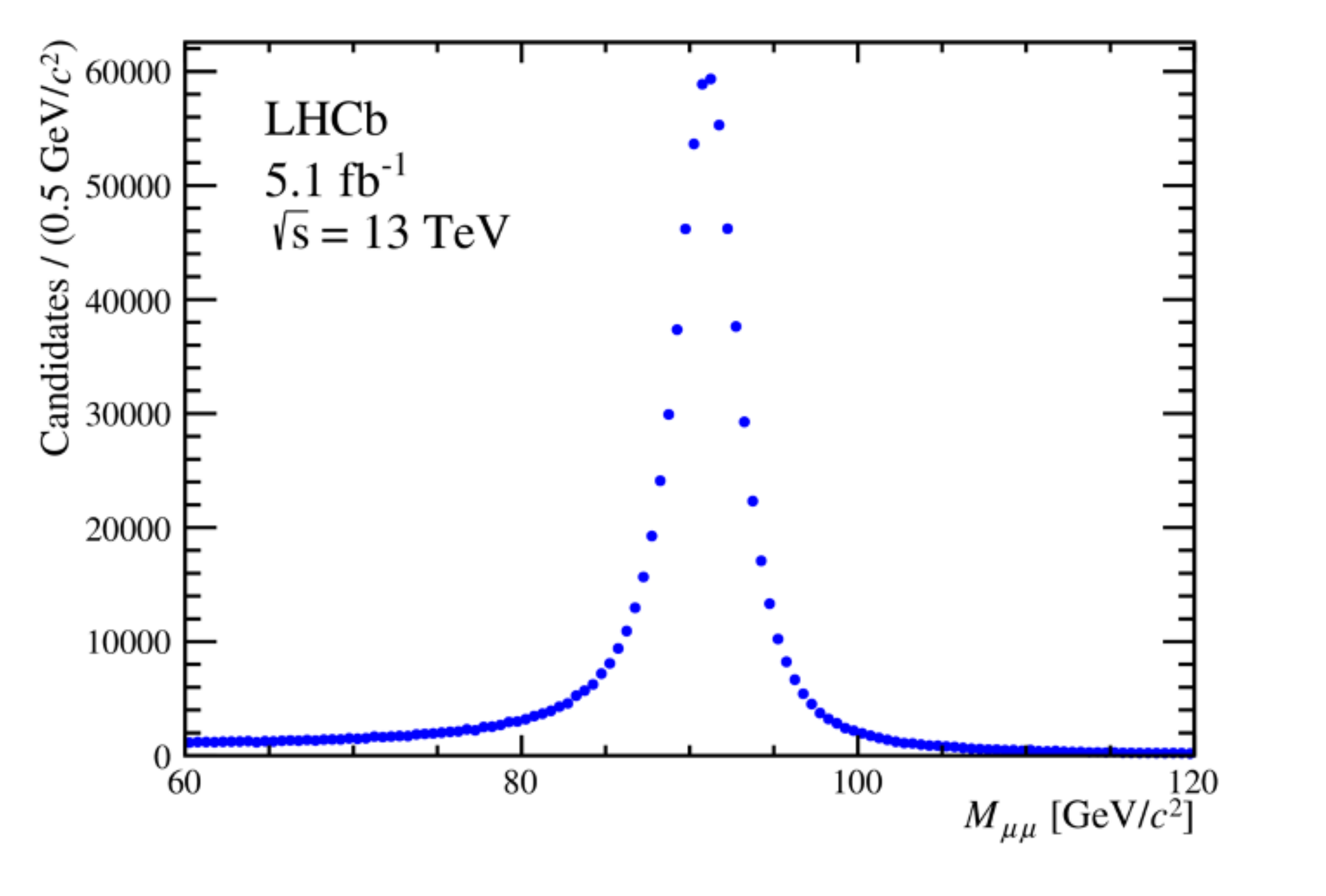
arXiv: 2112.07458
Submitted to JHEP

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:

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

- Background contribution: 2%



Analysis strategy

- 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^*

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

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

arXiv: 2112.07458
Submitted to JHEP

Systematic uncertainties

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

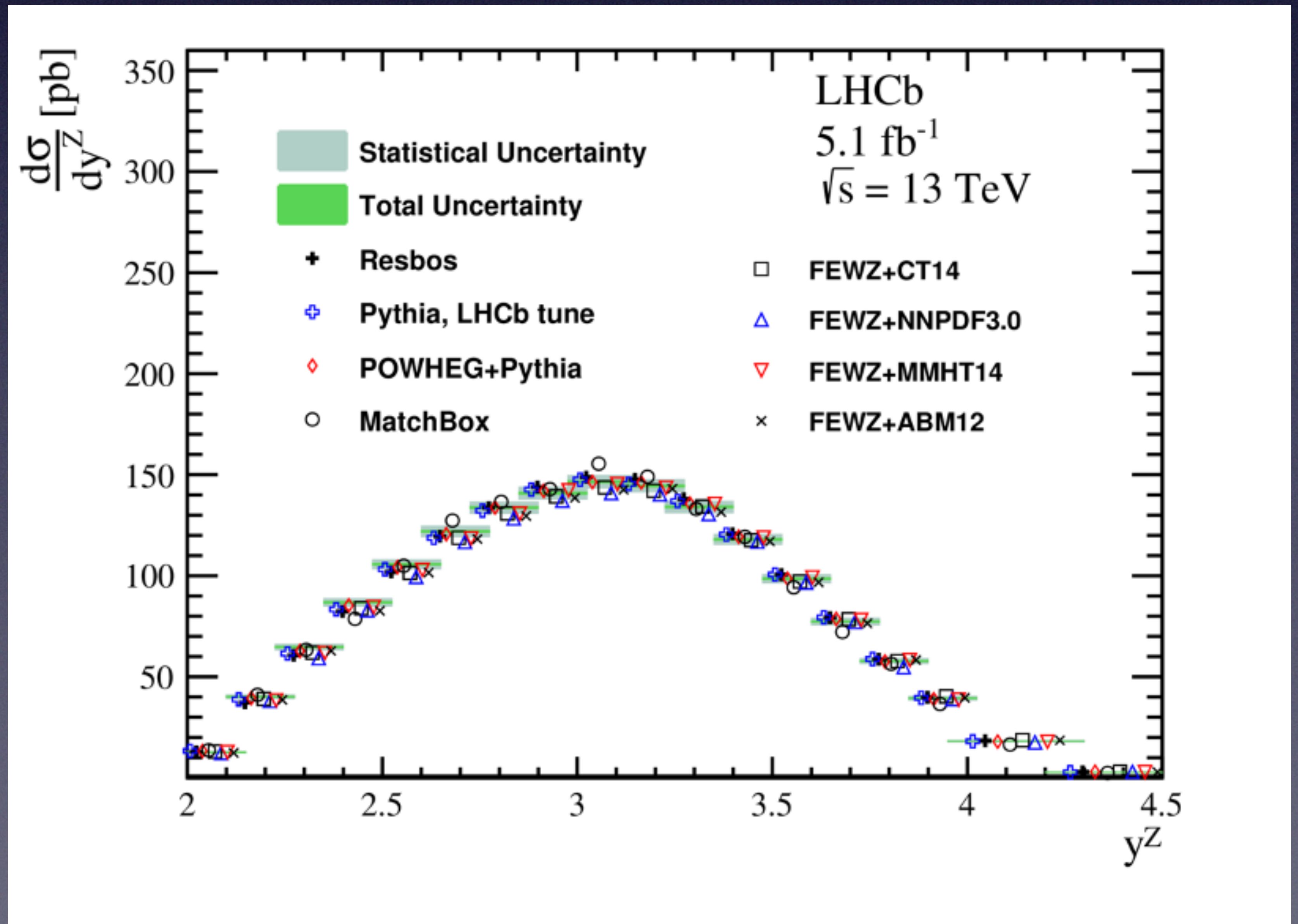
Integrated cross-section

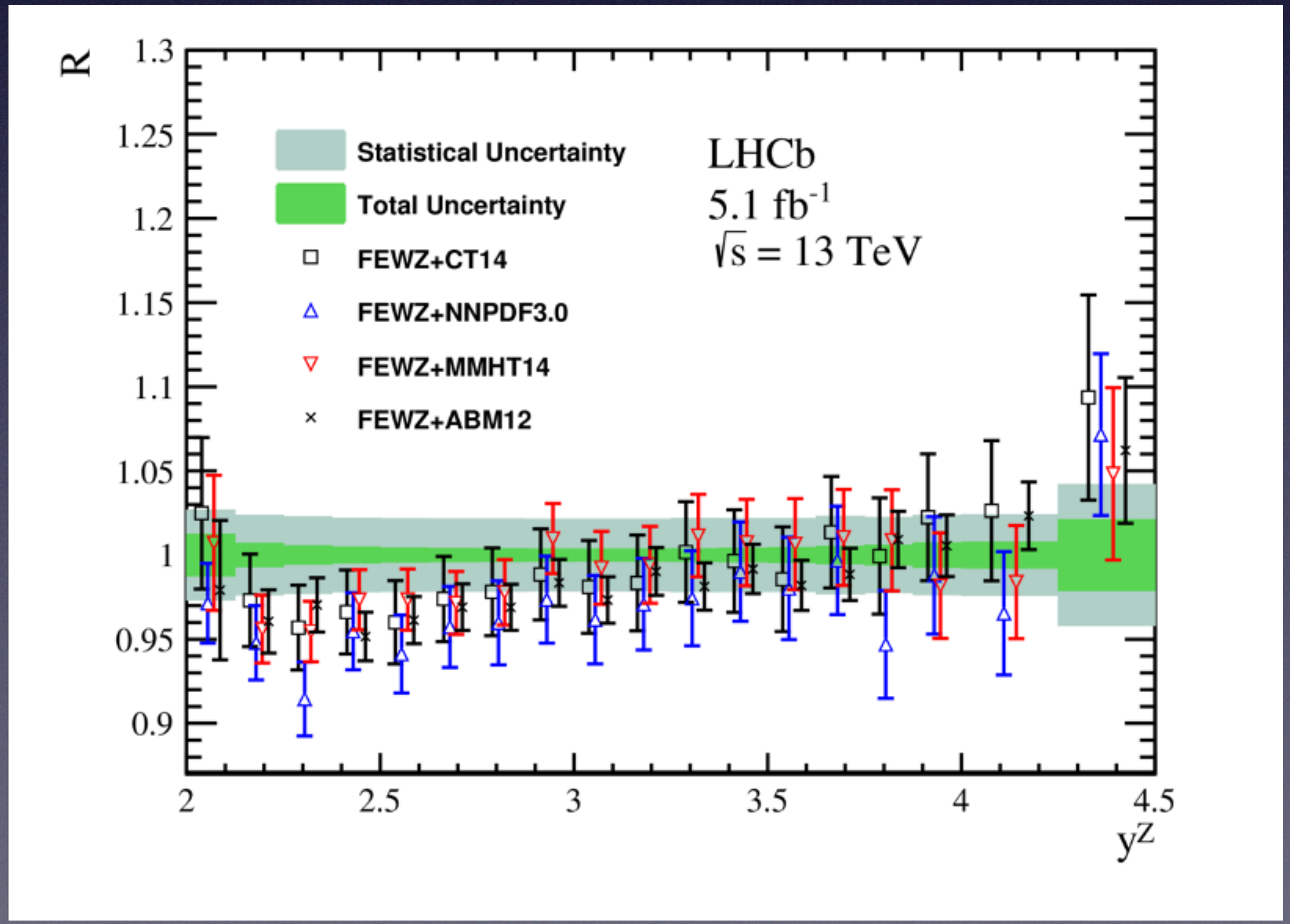
Source	$\Delta\sigma/\sigma$ [%]
Statistical	0.11
Background	0.03
Alignment & calibration	-
Efficiency	0.77
Closure	0.06
FSR	0.04
Total Systematic (excl. lumi.)	0.77
Luminosity	2.00
Total	2.15

arXiv: 2112.07458
Submitted to JHEP

Differential cross-section: 1-D

- Reasonable agreements between data and predictions
- Predictions are systematically smaller than the measured results in the lower rapidity region



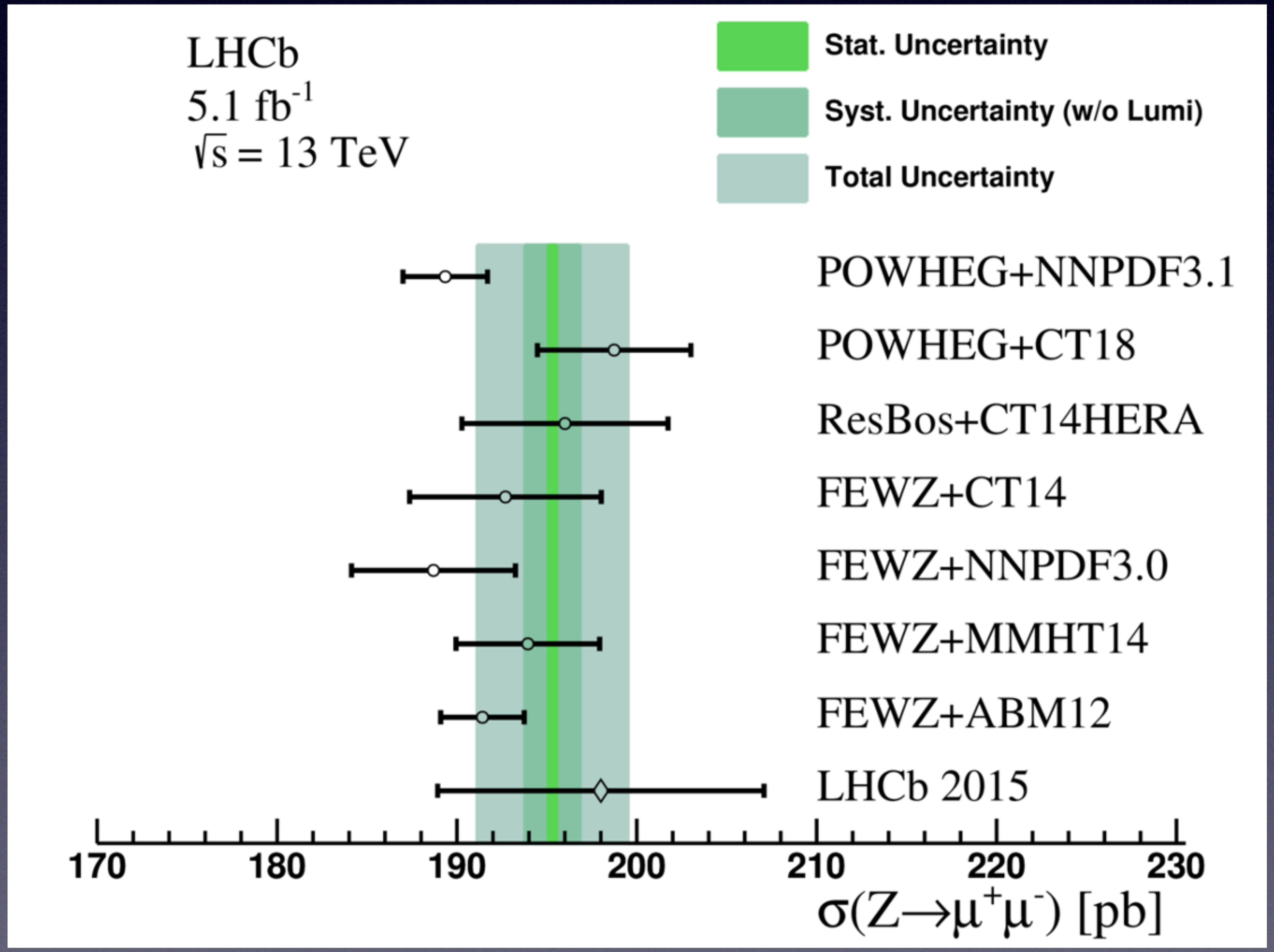


$$R = \frac{\text{Predictions}}{\text{Data}}$$

arXiv: 2112.07458
Submitted to JHEP

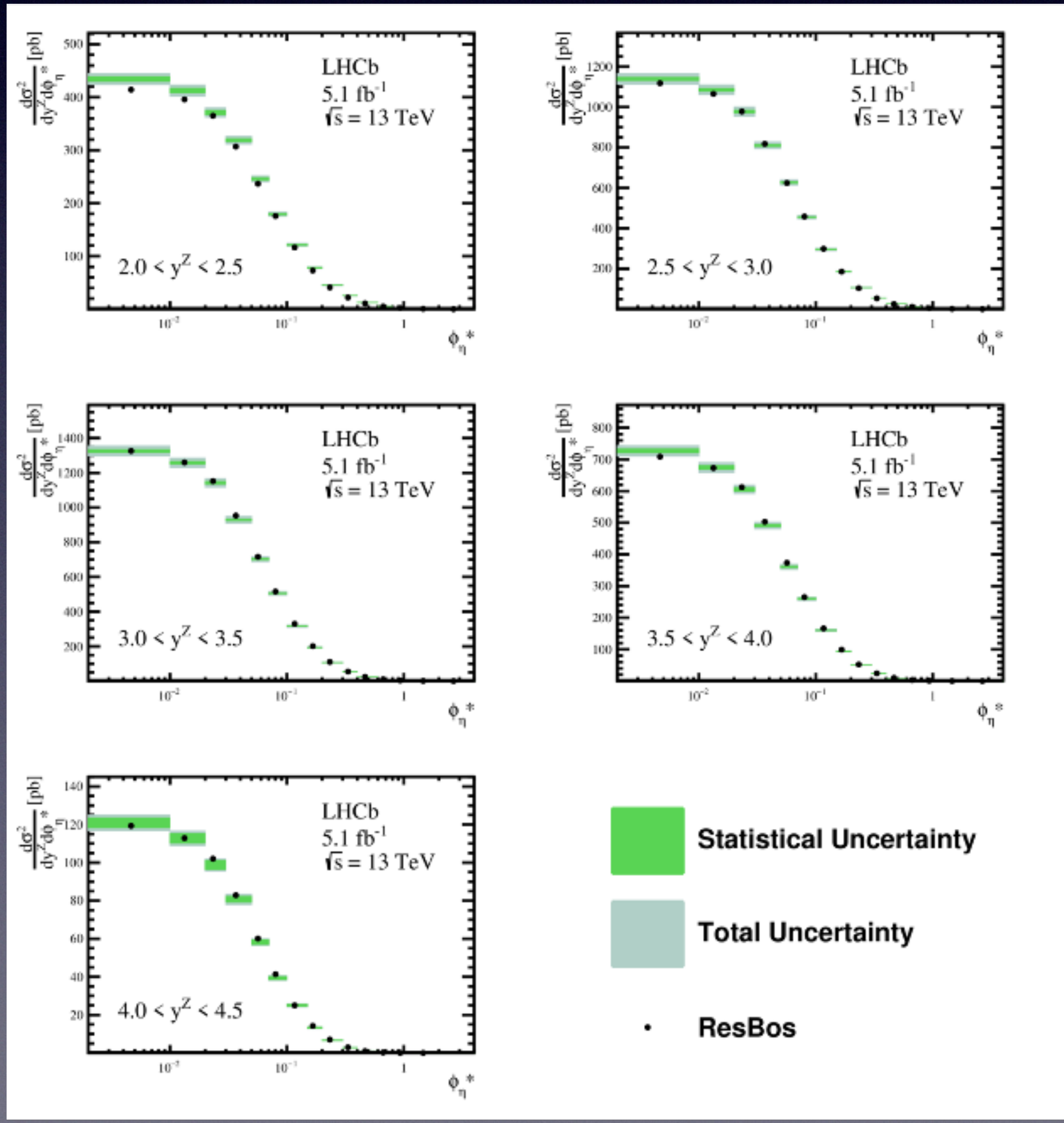
Integrated and double differential cross-section

Integrated cross-section



$\sigma(Z \rightarrow \mu^+\mu^-) = 195.3 \pm 0.2(\text{stat.}) \pm 1.5(\text{syst.}) \pm 3.9(\text{lumi})$ pb

First double differential cross-section measurement in the forward region



Z boson angular coefficient measurement

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

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

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

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

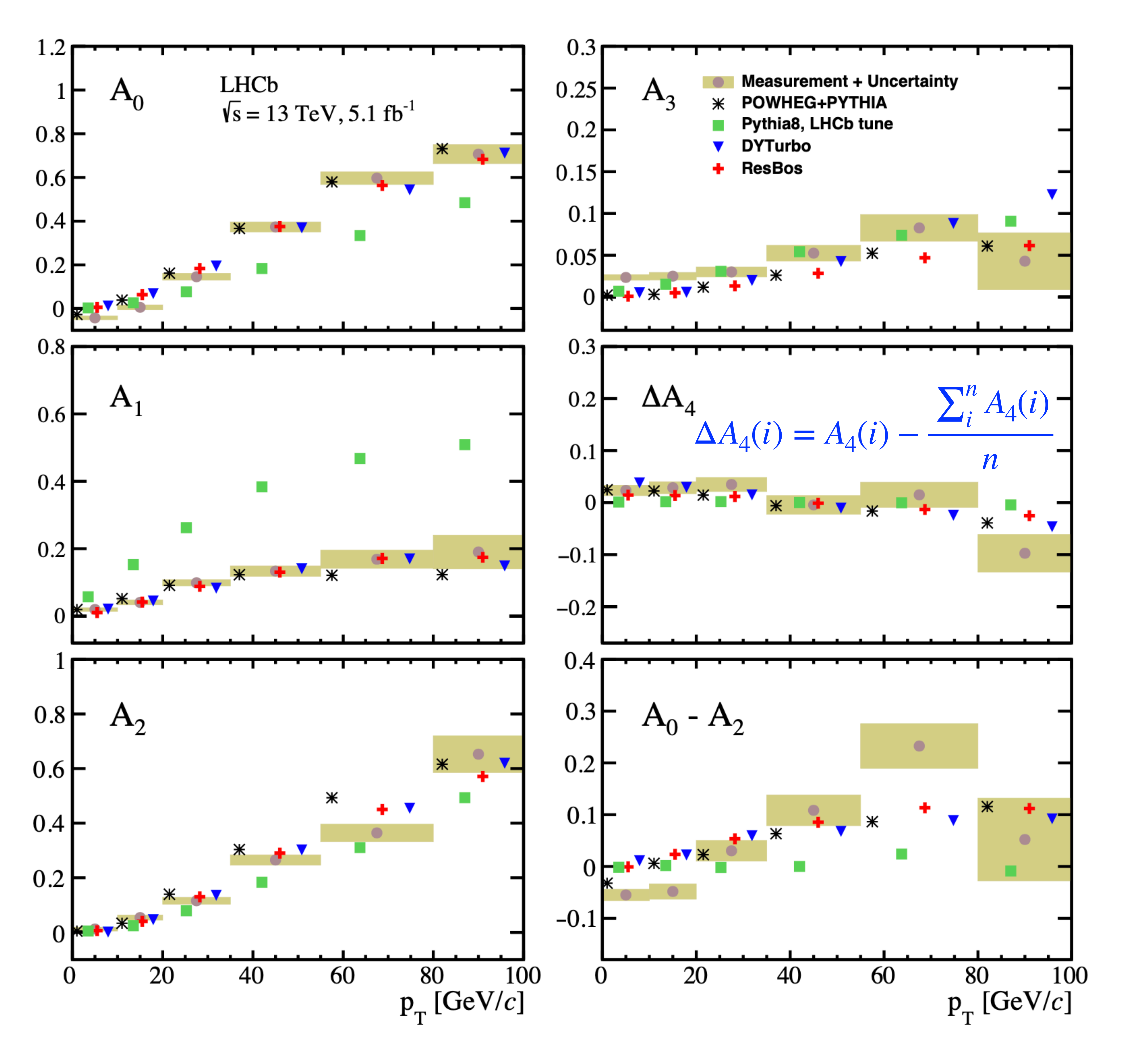
- Background contribution: ~0.2%
  - Removed with negative weights in the fit
- An iterative method: stable after four iterations
  - Normalization weights method
    - Introduced and used by the Babar collaboration
    - Extensively used in the heavy-flavour studies
- Several closure tests

Phys. Rev. Lett. 87 (2001) 241801
Phys. Rev. D 71 (2005) 032005

arXiv: 2203.01602
Submitted to PRL

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

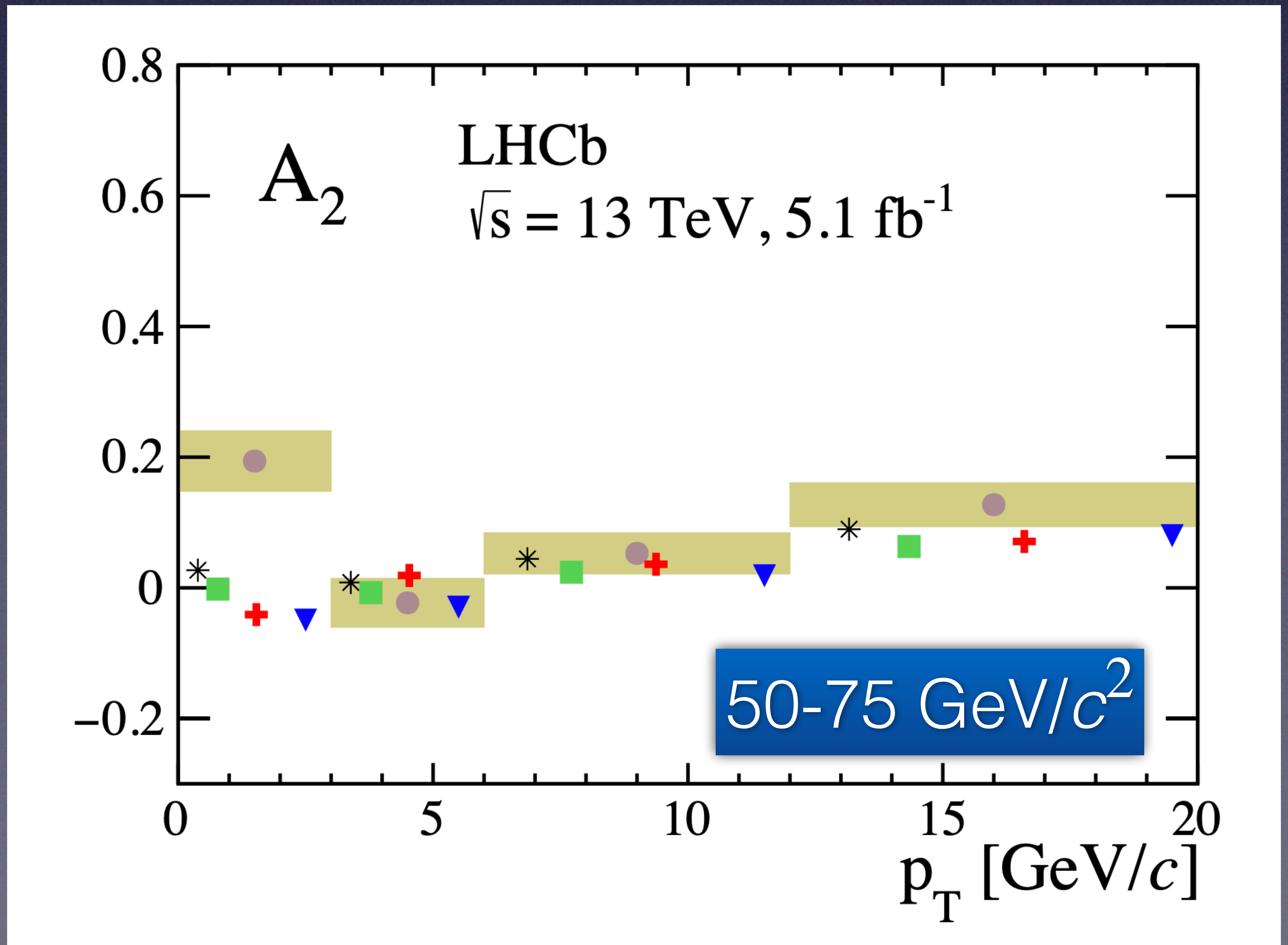


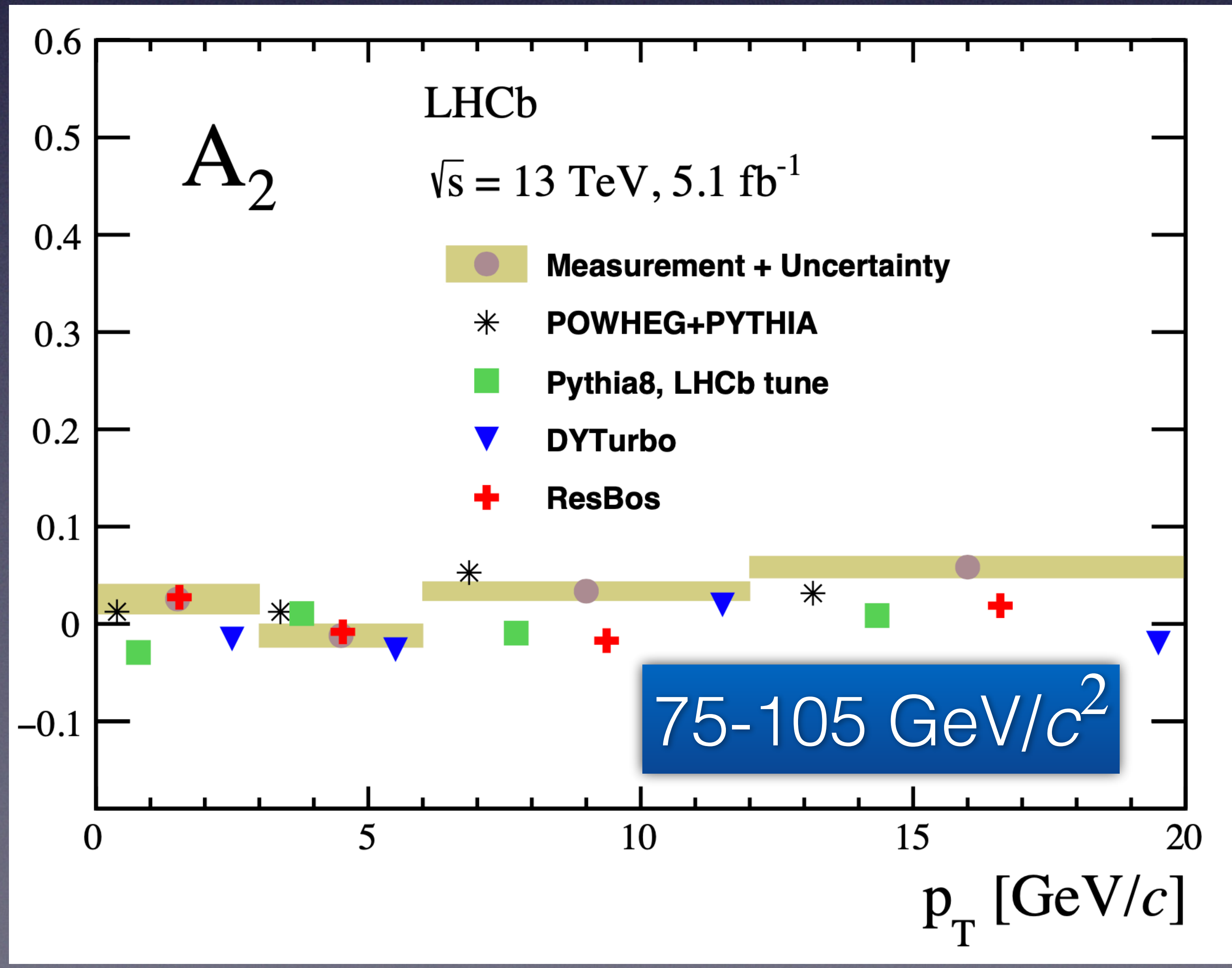
$$\frac{d\sigma}{d\cos\theta d\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi$$
$$+ A_3 \sin\theta\cos\phi + A_4\cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi,$$

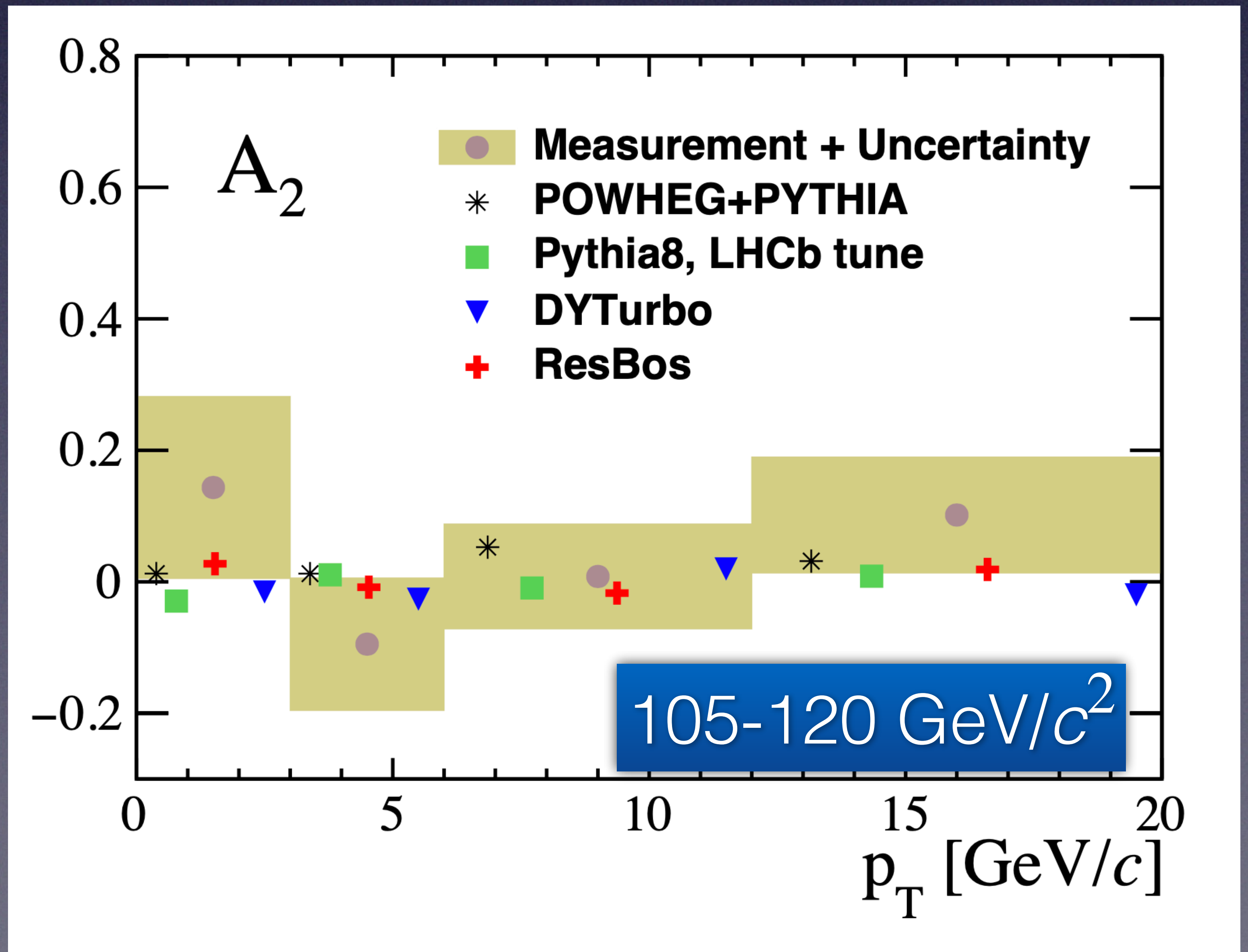
arXiv: 2203.01602
Submitted to PRL

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





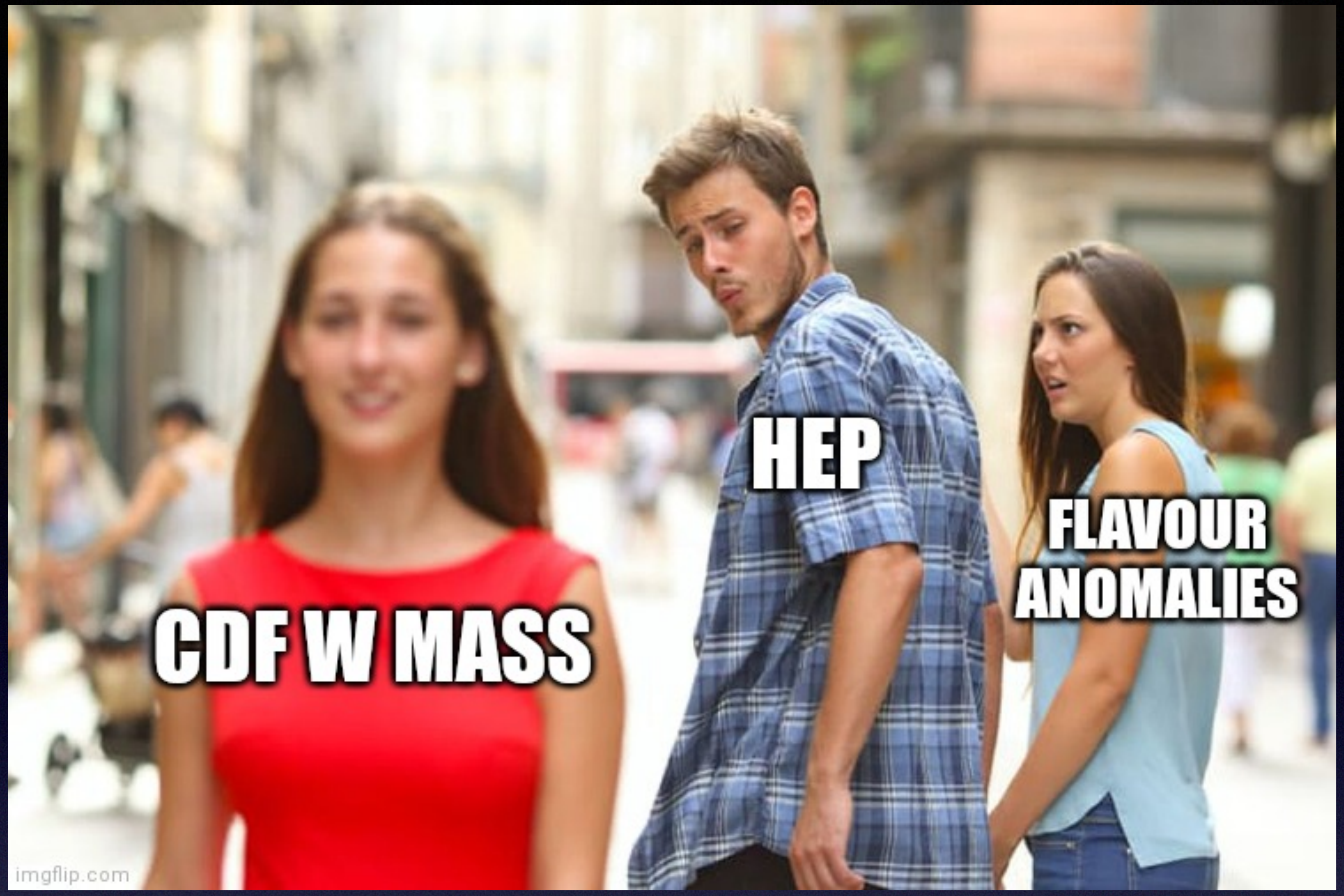


Conclusions

- LHCb has an extensive program on W/Z boson production and properties
  - Precise measurement of the W boson mass: consistent with SM expectation
  - Z boson production cross-check measurement
  - Measurement of Z boson angular coefficients
- With detector instrumented in the forward region, the LHCb results could provide unique information for the PDF global fitting and boson production mechanism
  - Future measurements: systematic uncertainty dominated (challenging and exciting)

Stay tuned for new results!

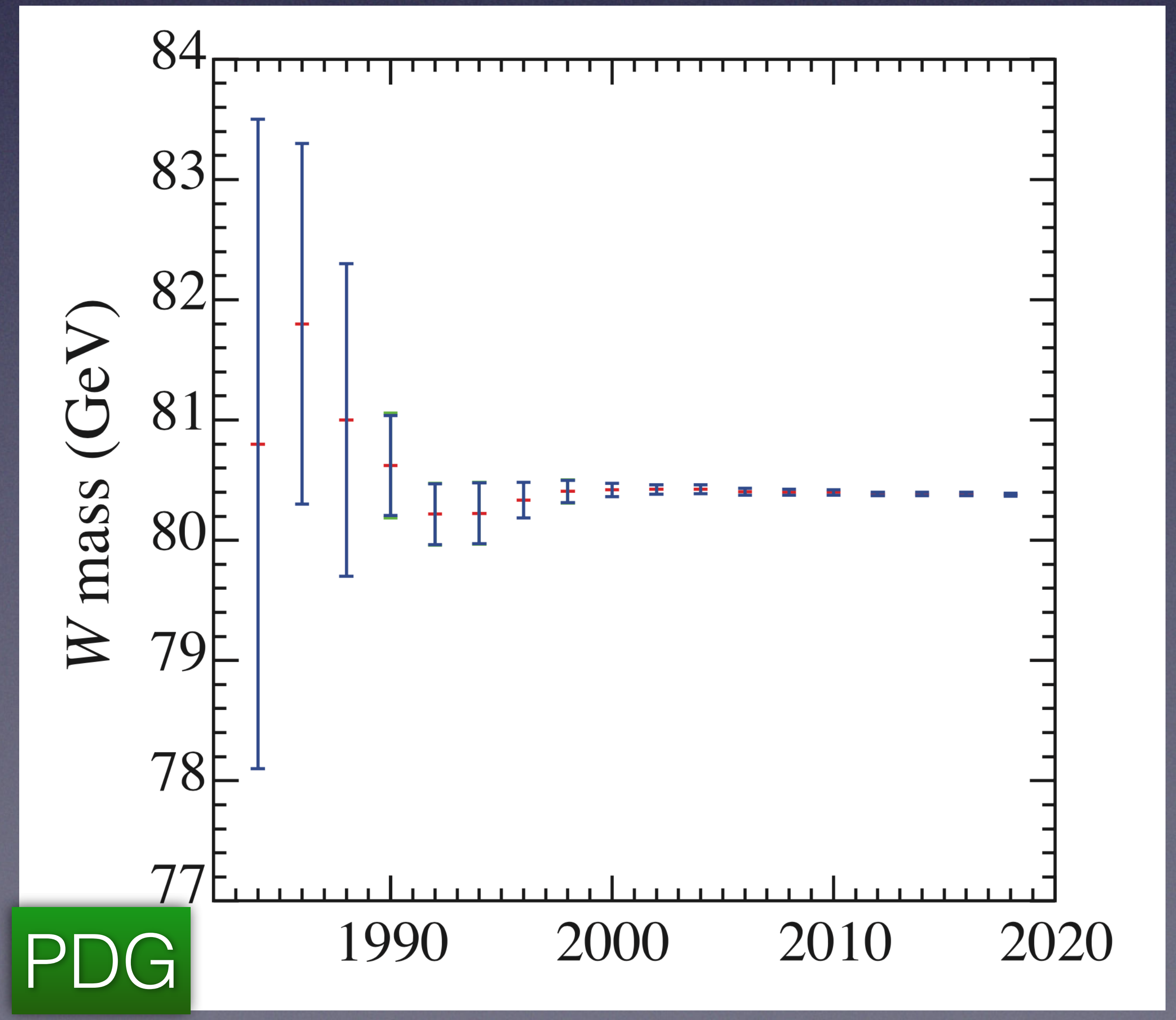
Backup


HEP
FLAVOUR ANOMALIES
CDF W MASS
imgflip.com



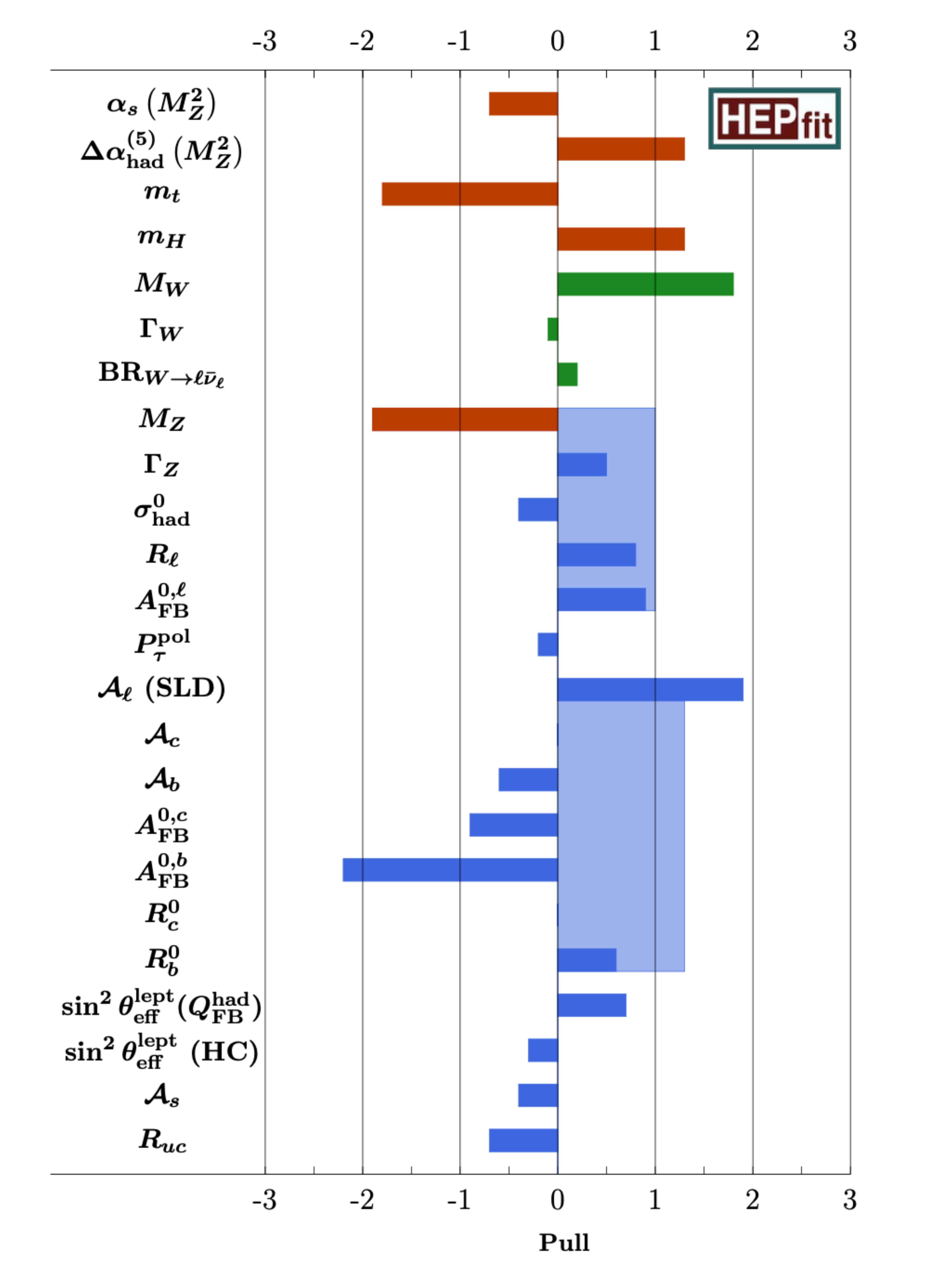
It is a long journey …

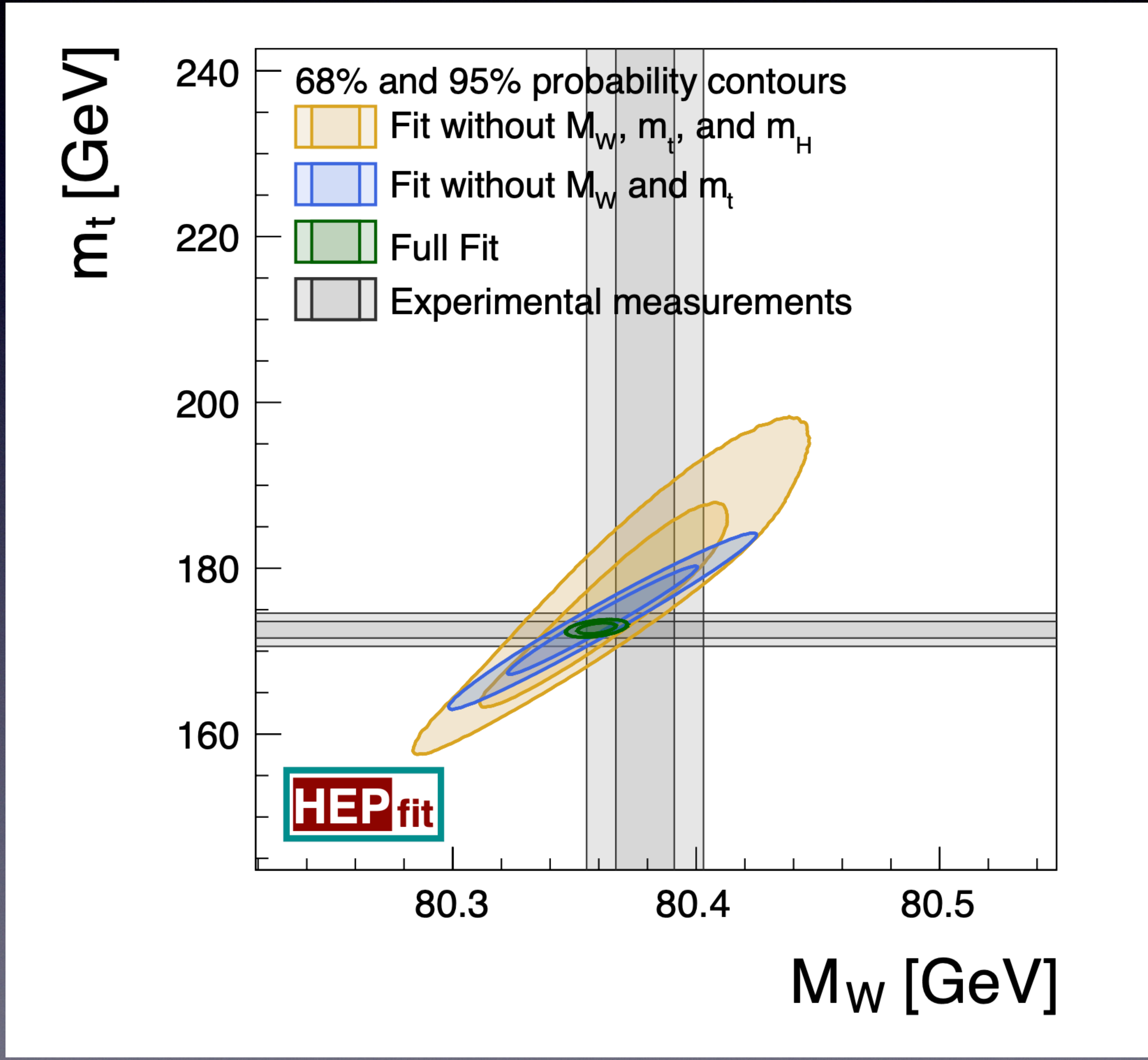
- 1967: $SU(2) \times U(1)$ theory, weak force mediated by the W and Z bosons
- 1983: W boson was discovered UA1, UA2 @SppS ($\sqrt{s} = 546$ GeV): $m_W = 81 \pm 5$ GeV
- 1990: First W mass with precision (< 1 GeV) (UA2, $\sqrt{s} = 630$ GeV)
- 1992-1995: Tevatron Run-1 measurement (CDF & D0): Combined precision 59 MeV
- 1996-2000: LEP experiments ($\sqrt{s} = 2M_W$): 80375 ± 33 MeV
- 2001-2012: Tevatron Run II, combined precision 16 MeV
- 2012-2022: ATLAS and LHCb 19 MeV/32 MeV
- **2022: CDF 9 MeV**

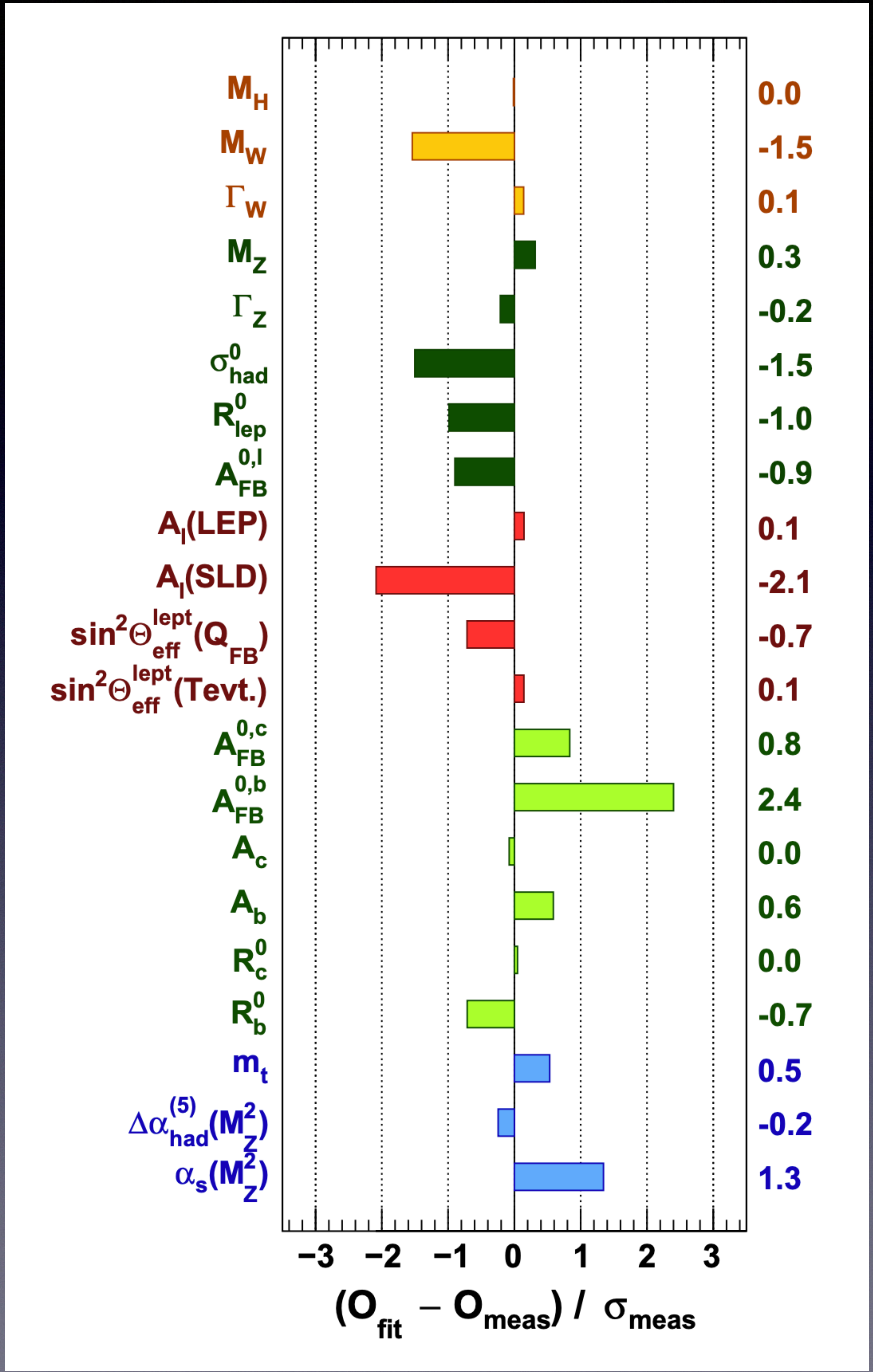


arXiv:2112.07274

Electroweak Global fit

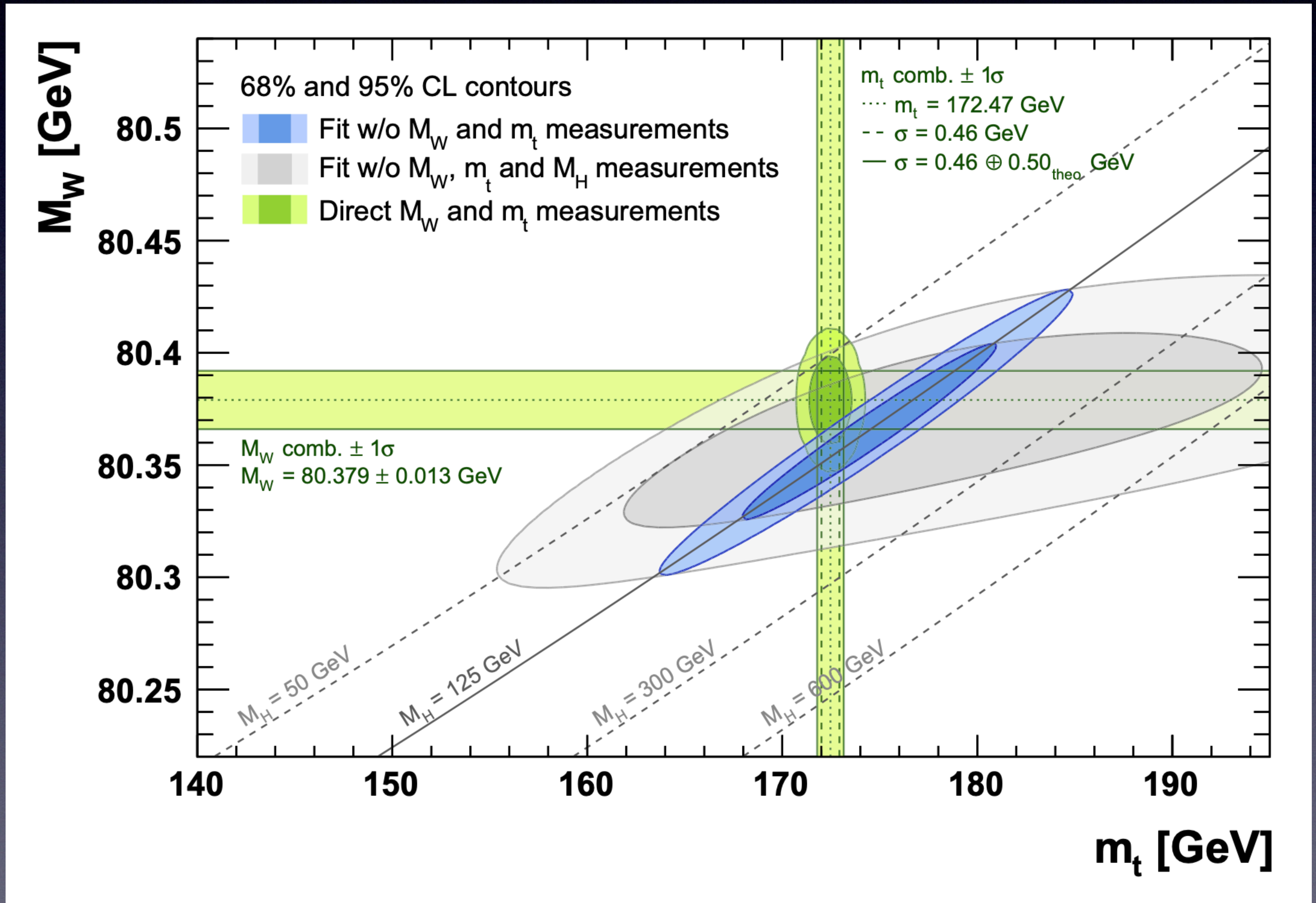




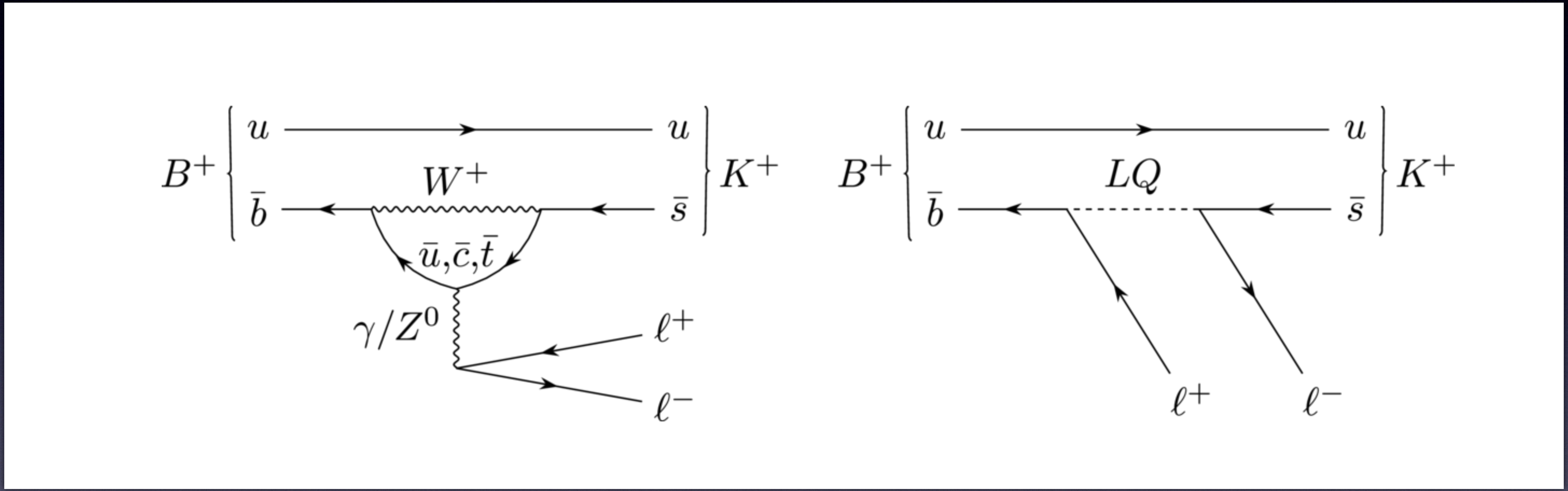


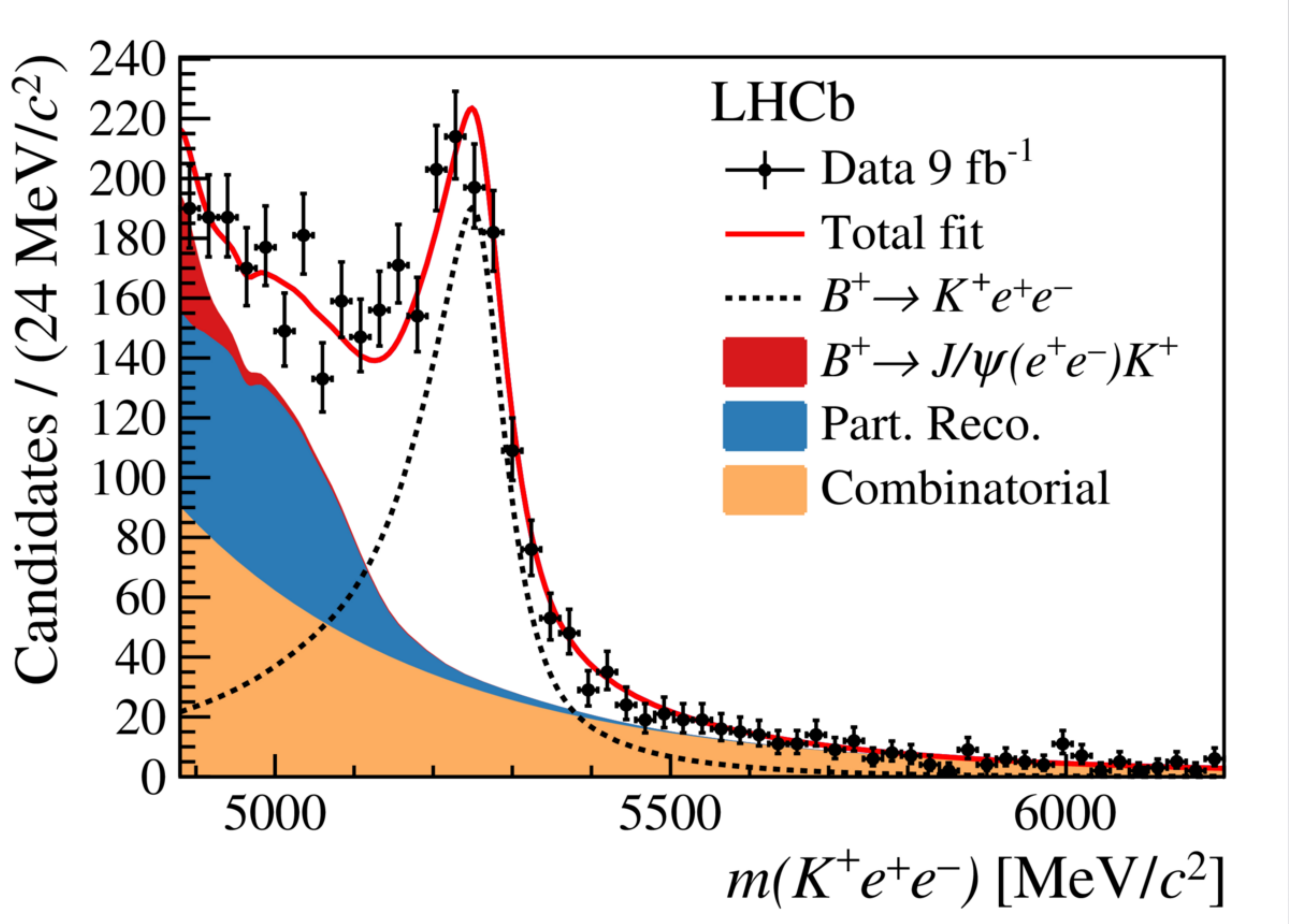
GFitter

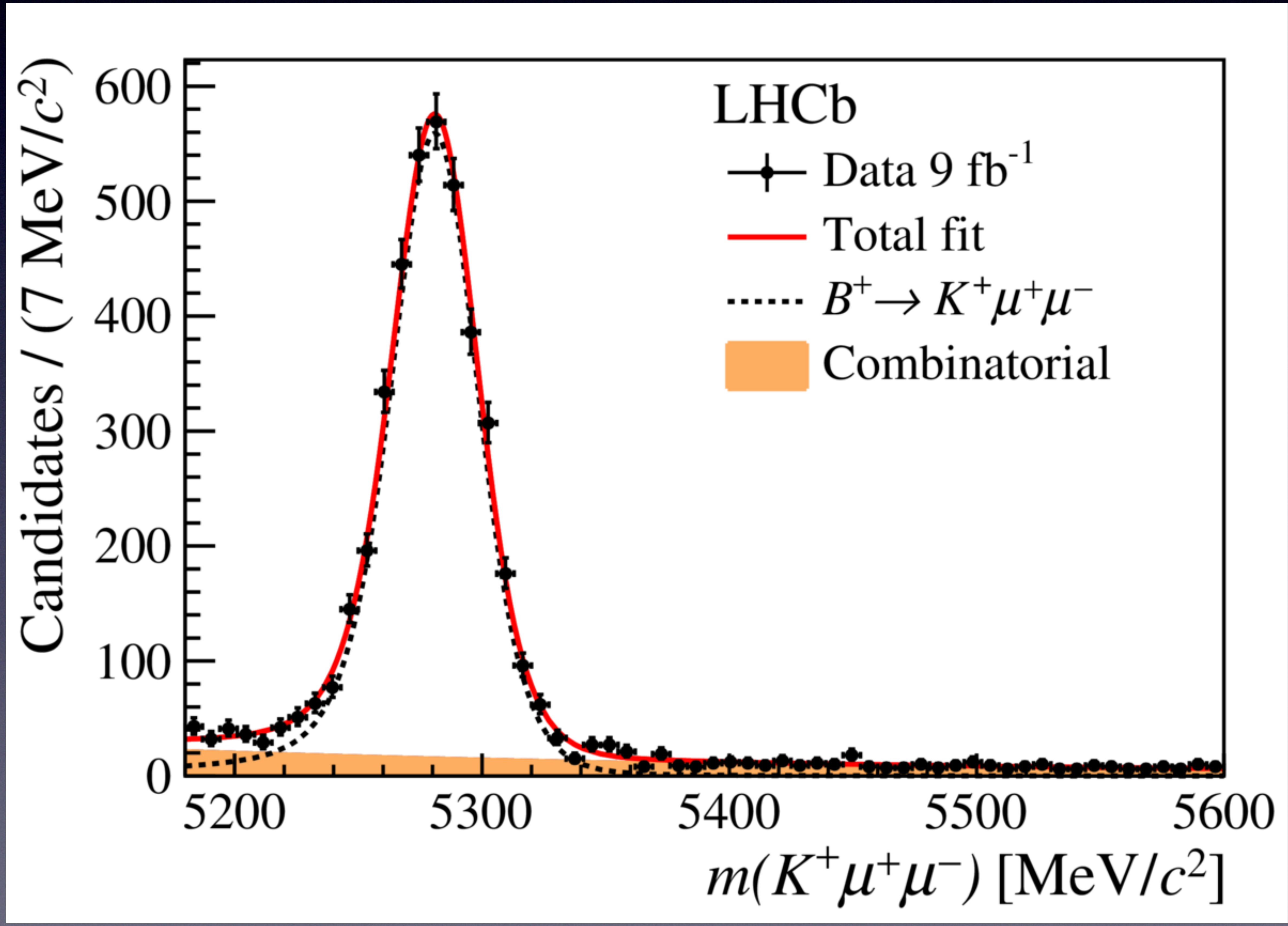
Eur. Phys. J. C78 (2018) 675



Parameter	Input value	Free in fit	Fit result	Fit w/o exp. input in line	Fit w/o exp. input in line, no theo. unc.
M_H [GeV]	125.1 ± 0.2	Yes	125.1 ± 0.2	90^{+21}_{-18}	89^{+20}_{-17}
M_W [GeV]	80.379 ± 0.013	–	80.359 ± 0.006	80.354 ± 0.007	80.354 ± 0.005
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	Yes	91.1882 ± 0.0020	91.2013 ± 0.0095	91.2017 ± 0.0089
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4947 ± 0.0014	2.4941 ± 0.0016	2.4940 ± 0.0016
σ^0_{had} [nb]	41.540 ± 0.037	–	41.484 ± 0.015	41.475 ± 0.016	41.475 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.742 ± 0.017	20.721 ± 0.026	20.719 ± 0.025
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	–	0.01620 ± 0.0001	0.01619 ± 0.0001	0.01619 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1470 ± 0.0005	0.1470 ± 0.0005	0.1469 ± 0.0003
$\sin^2\theta^\ell_{\mathrm{eff}}(Q_{\mathrm{FB}})$	0.2324 ± 0.0012	–	0.23153 ± 0.00006	0.23153 ± 0.00006	0.23153 ± 0.00004
$\sin^2\theta^\ell_{\mathrm{eff}}(\mathrm{Tevt.})$	0.23148 ± 0.00033	–	0.23153 ± 0.00006	0.23153 ± 0.00006	0.23153 ± 0.00004
A_c	0.670 ± 0.027	–	0.6679 ± 0.00021	0.6679 ± 0.00021	0.6679 ± 0.00014
A_b	0.923 ± 0.020	–	0.93475 ± 0.00004	0.93475 ± 0.00004	0.93475 ± 0.00002
$A^{0,c}_{\mathrm{FB}}$	0.0707 ± 0.0035	–	0.0736 ± 0.0003	0.0736 ± 0.0003	0.0736 ± 0.0002
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016	–	0.1030 ± 0.0003	0.1032 ± 0.0003	0.1031 ± 0.0002
R^0_c	0.1721 ± 0.0030	–	0.17224 ± 0.00008	0.17224 ± 0.00008	0.17224 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21582 ± 0.00011	0.21581 ± 0.00011	0.21581 ± 0.00004
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	Yes	$1.27^{+0.07}_{-0.11}$	–	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	Yes	$4.20^{+0.17}_{-0.07}$	–	–
m_t [GeV]$^{(\triangledown)}$	172.47 ± 0.68	Yes	172.83 ± 0.65	176.4 ± 2.1	176.4 ± 2.0
$\Delta\alpha^{(5)}_{\mathrm{had}}(M^2_Z)$ $^{(\dagger\triangle)}$	2760 ± 9	Yes	2758 ± 9	2716 ± 39	2715 ± 37
$\alpha_s(M^2_Z)$	–	Yes	0.1194 ± 0.0029	0.1194 ± 0.0029	0.1194 ± 0.0028


B^+
u
u
K^+
W^+
$\bar{b}$
$\bar{s}$
$\bar{u},\bar{c},\bar{t}$
γ/Z^0
ℓ^+
ℓ^-
B^+
u
u
K^+
LQ
$\bar{b}$
$\bar{s}$
ℓ^+
ℓ^-


LHCb
Data 9 fb^{-1}
Total fit
$B^+\to K^+e^+e^-$
$B^+\to J/\psi(e^+e^-)K^+$
Part. Reco.
Combinatorial
Candidates / (24 MeV/c^2)
$m(K^+e^+e^-)$ [MeV/c^2]


LHCb
Data 9 fb^{-1}
Total fit
$B^+\to K^+\mu^+\mu^-$
Combinatorial
Candidates / (7 MeV/c^2)
$m(K^+\mu^+\mu^-)$ [MeV/c^2]

$Z \to \mu\mu$ selection in the W mass measurement

- Two oppositely charged identified muons, associated to the same PV
- Invariant mass: ± 14 GeV of the known Z boson mass
- At least one muon must be triggered by single muon trigger
- Muon $p_T > 20$ GeV, isolated (isolation < 10 GeV)
- $IP - significance < 10$

~190k selected candidates

$J/\psi \to \mu\mu$ and $\Upsilon(1S) \to \mu\mu$ selection

- Calibrate the modeling of the momentum measurement
- A pair of oppositely charged identified muons
- Muon $p_T > 3$ GeV, tight muon identification selection
- J/ψ from b hadron decays: displaced from the nearest PV with a significance of at least three standard deviations

~ 1.0M $\Upsilon(1S) \to \mu\mu$
~ 220k $J/\psi \to \mu\mu$

Systematic uncertainty: smearing

$$\frac{q}{p} \rightarrow \frac{q}{p \cdot \mathcal{N}(1+\alpha, \sigma_{MS})} + \mathcal{N}\left(\sigma, \frac{\sigma_\delta}{\cosh \eta}\right)$$

- Statistical uncertainties: 3 MeV
- $\Upsilon(1S)$ mass: 2 MeV
- J/ψ mass: negligile
- Detector material: varied by 10%, 3 MeV
- Smearing modeling method: 5 MeV
  - An alternative form of $\frac{1}{\cosh \eta}$ and variations of σ_{MS}
- Radiative tails of J/ψ and $\Upsilon(1S)$: 2 MeV

Parameter	Fit value
α $(\eta < 2.2)$	$(0.58 \pm 0.10) \times 10^{-3}$
α $(2.2 < \eta < 4.4)$	$(-0.0054 \pm 0.0025) \times 10^{-3}$
δ	$(-0.48 \pm 0.37) \times 10^{-6}$ GeV^{-1}
σ_δ $(\eta < 2.2)$	(17.7 ± 1.2) keV^{-1}
σ_δ $(2.2 < \eta < 4.4)$	(14.9 ± 0.9) keV^{-1}
σ_{MS}	$(2.015 \pm 0.019) \times 10^{-3}$

Total: 7 MeV

Systematic uncertainty: muon efficiency

- Statistical uncertainties in the trigger, tracking and identification efficiency corrections
- Binning schemes of efficiencies
- Tag muon requirements, mass window cut
- Probe muon has worse resolution (MuonTT track): smearing

Total: 6 MeV

Systematic uncertainty: isolation efficiency

- Statistical uncertainty
- Binning schemes
- A smoothing procedure: enhance the effective statistical precision of the correction map

Total: 4 MeV

Systematic uncertainty: background

- For the hadronic background
- The data sample is treated as containing a single hadron species
    - 60% of pion, 30% of kaon and 10% of proton
- Inverted muon identification requirements
- Dependence on the range of p_T values used in the fits

$$\left(1 + \frac{p_T}{\alpha}\right)^{-n}$$

Total: 2 MeV

Systematic uncertainty: EW correction

- Higher order electroweak correction
- Not included in the model
- POWHEGBOXV2: with and without electroweak corrections

JHEP **04** (2012) 037
Eur. Phys. J. **C73** (2013) 2474
Phys. Rev. **D96** (2017) 093005

Total: 5 MeV

Systematic uncertainty: boson p_T modeling

JHEP 11 (2017) 003

- Renormalisation and factorisation scales
  - Fully correlating the scale variations between angular coefficient numerator and denominator: inadequate uncertainty
  - Recommendation: vary four scales independently by factors of 1/2 and 2, with constraint that all ratios that constructed from the four scales are between 1/2 and 2
- POWHEG+PYTHIA is used as default input
  - PYTHIA+CT09MCS LO PDFs
  - PYTHIA+NNPDF31 LO PDFs
  - HERWIG/POWHEG+HERWIG + NNPDF31 NLO PDFs

Total: 11 MeV

Systematic uncertainty: PDFs

- NNPDF31 LO vs. NLO PDFs: 1 MeV
- NNPDF31, CT18, MSHT 20, α_s: fully correlated
-

Set	$\sigma_{\mathrm{PDF,base}}$ [MeV]	$\sigma_{\mathrm{PDF},\alpha_s}$ [MeV]	σ_{PDF} [MeV]
NNPDF3.1	8.3	2.4	8.6
CT18	11.5	1.4	11.6
MSHT20	6.5	2.1	6.8

Systematic uncertainty: angular scale factor

- As ATLAS data are reasonably well described by $O(\alpha_s^2)$ prediction from DYNNLO (DYTURBO)
- In this measurement, use DYTURBO prediction as inputs
- Uncertainty from DYTURBO is $O(30)$ MeV
- Only vary A_3: 10 MeV

Systematic uncertainty: high p_T

- A data/prediction correction is applied to the simulation
- Vary the correction 100% : 1 MeV

Systematic uncertainty: QED

- Final state radiation: PHOTOS, HERWIG, PYTHIA
- Arithmetic average of these predictions
- 7 MeV

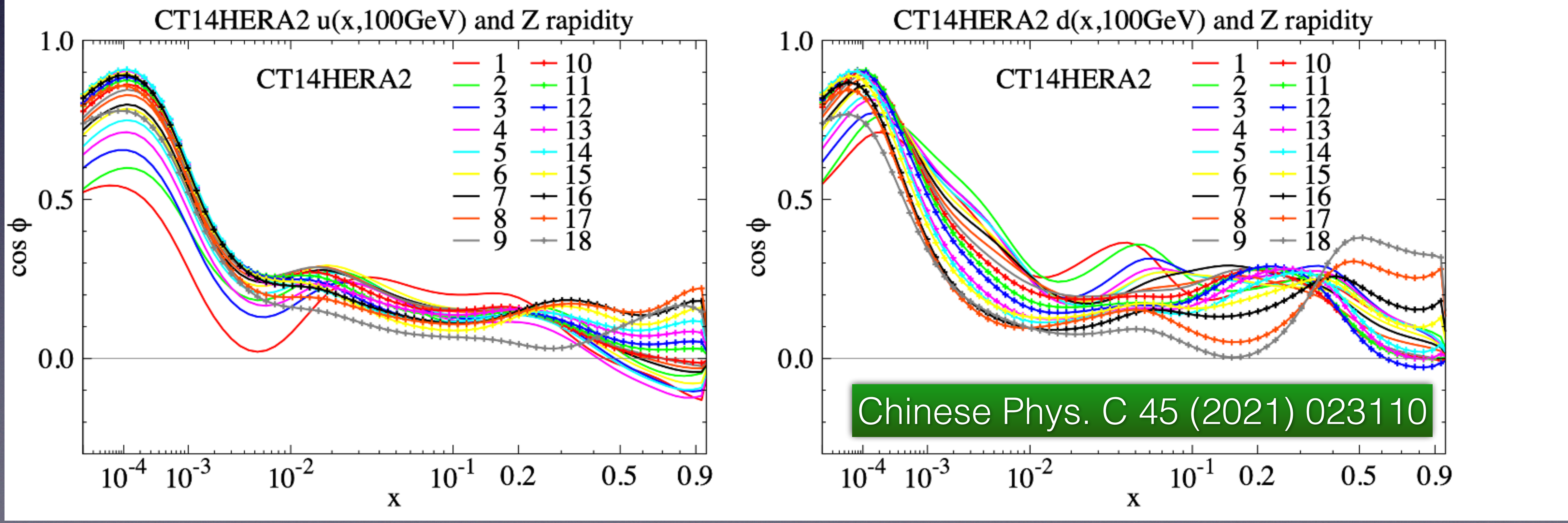
Cross checks

- Orthogonal splits (5): polarity, charge X polarity, within 2σ
- Fit range: variations in the upper/lower limits
- Fit freedom: 3 α_s or 1 α_s
- W-like fit of the Z mass: consistent with PDG value with uncertainty
- δm_W fit: check differences between W^+ and W^-
- Additional test: NNLO PDFs instead of NLO PDFs, smaller than 1 MeV

LHCb W/Z data and PDFs

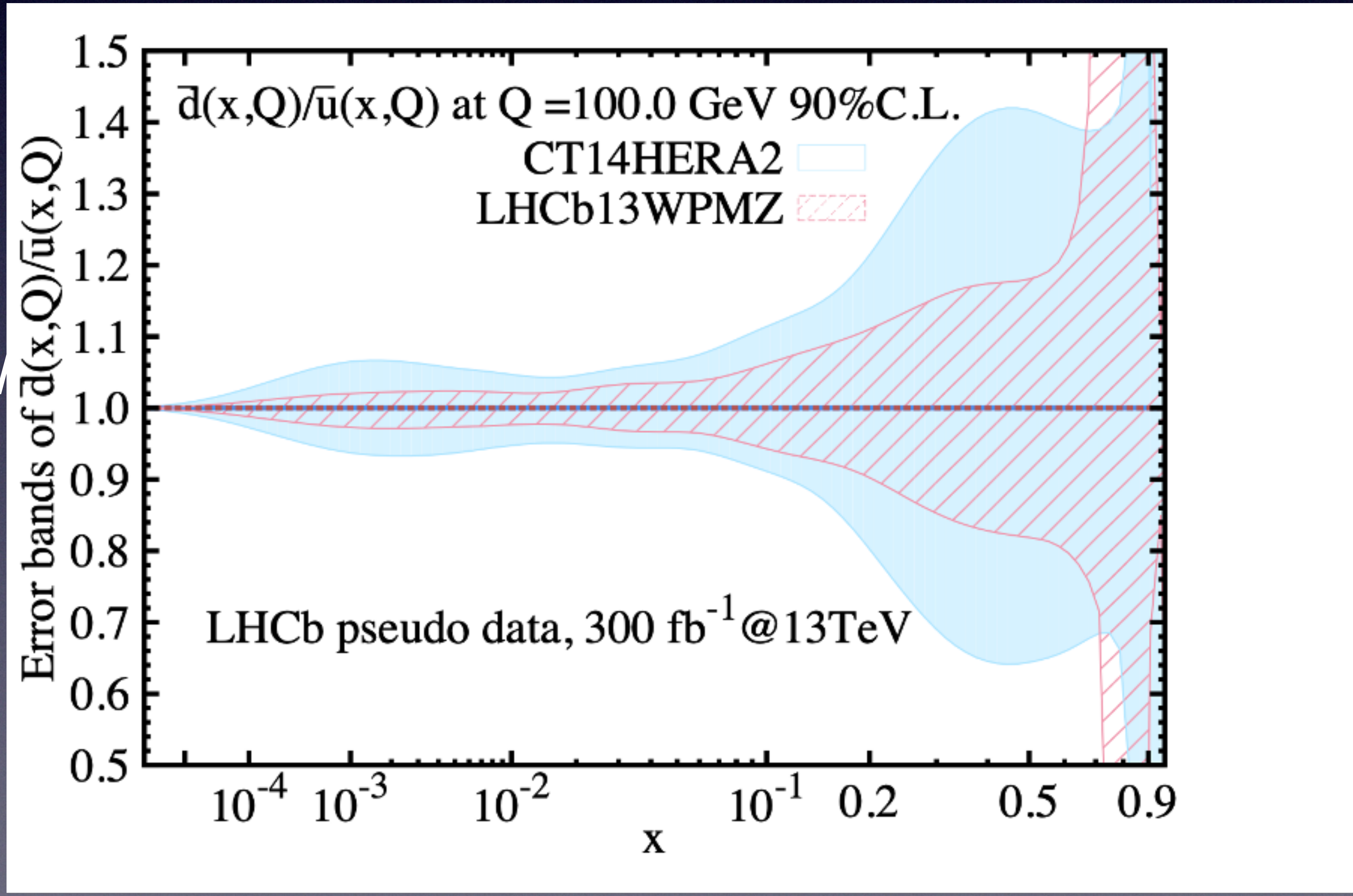
- Strong correlations between Z boson rapidity results measured by LHCb and PDFs in the small x region
  - For both u and d quarks

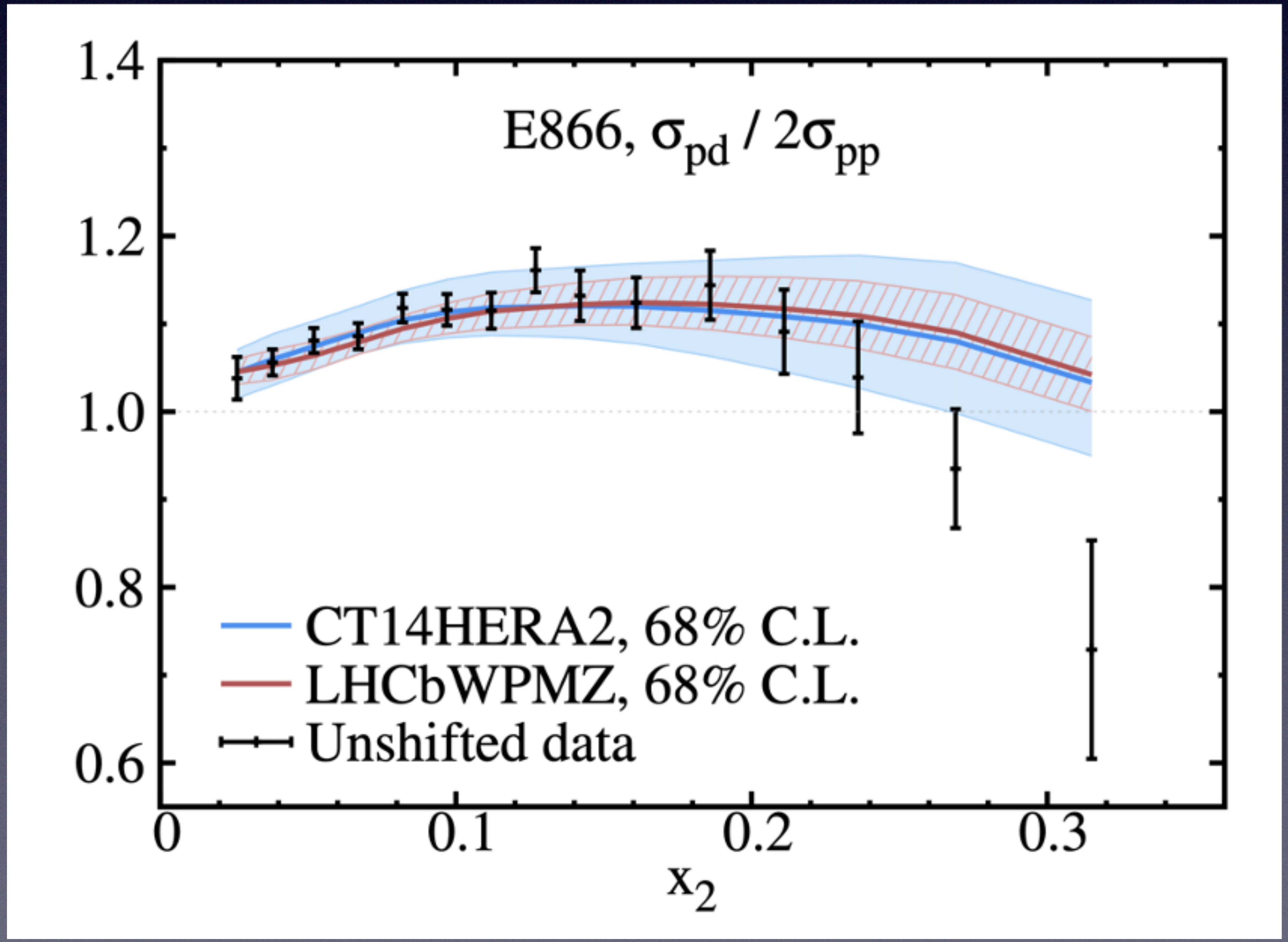
Chinese Phys. C 45 (2021) 023110



A confirmation from LHCb?

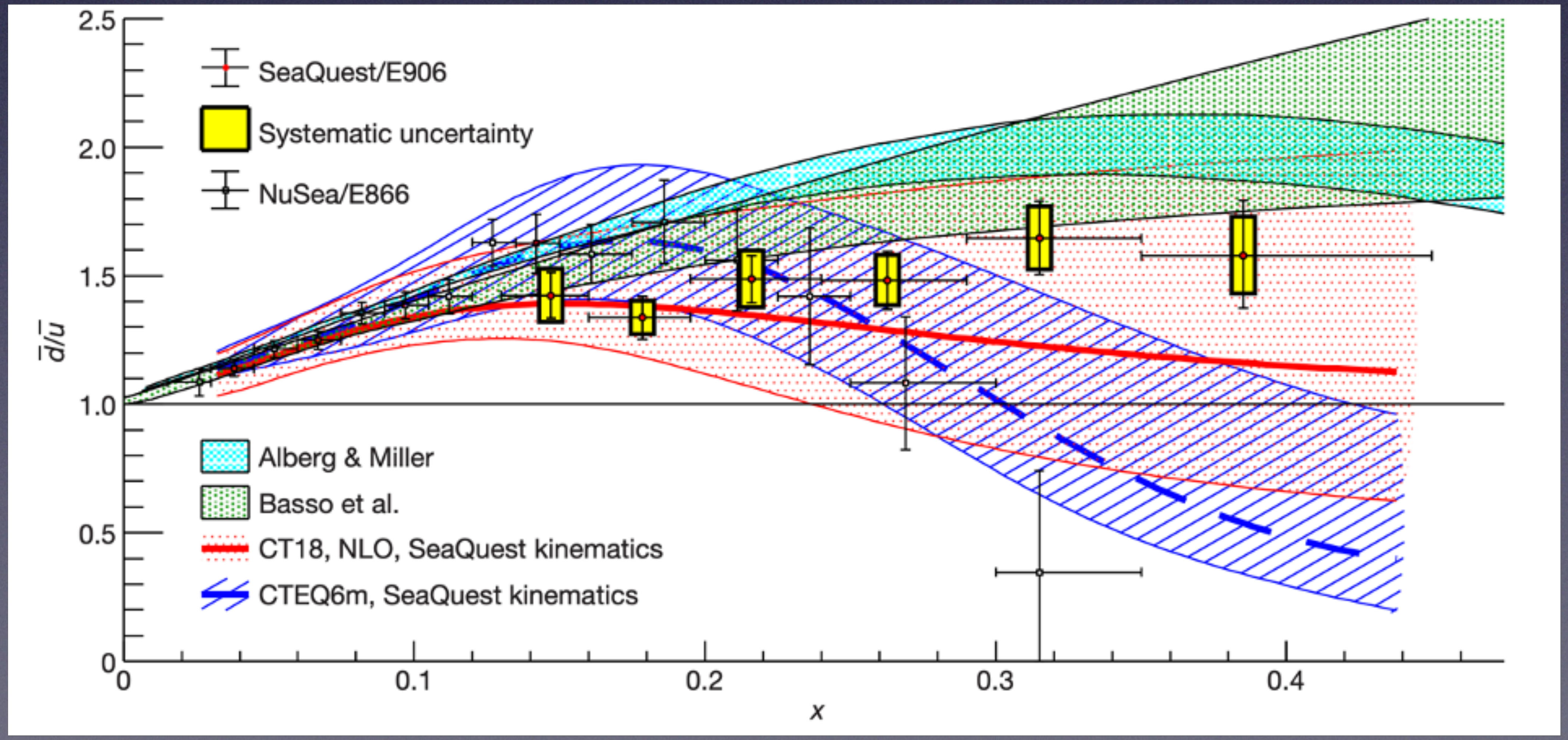
Chinese Phys. C 45 (2021) 023110



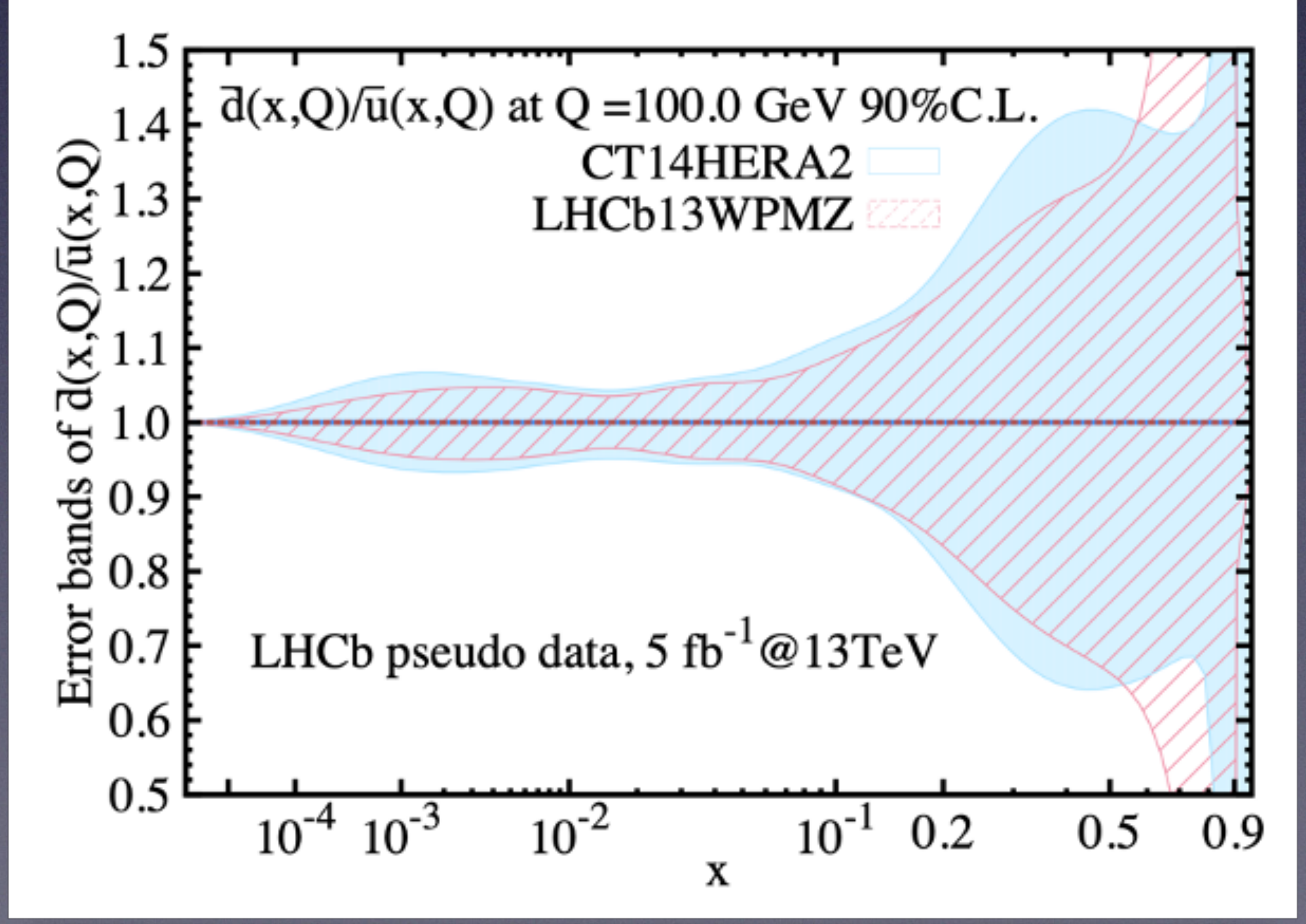


Sea quark PDFs

- 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)

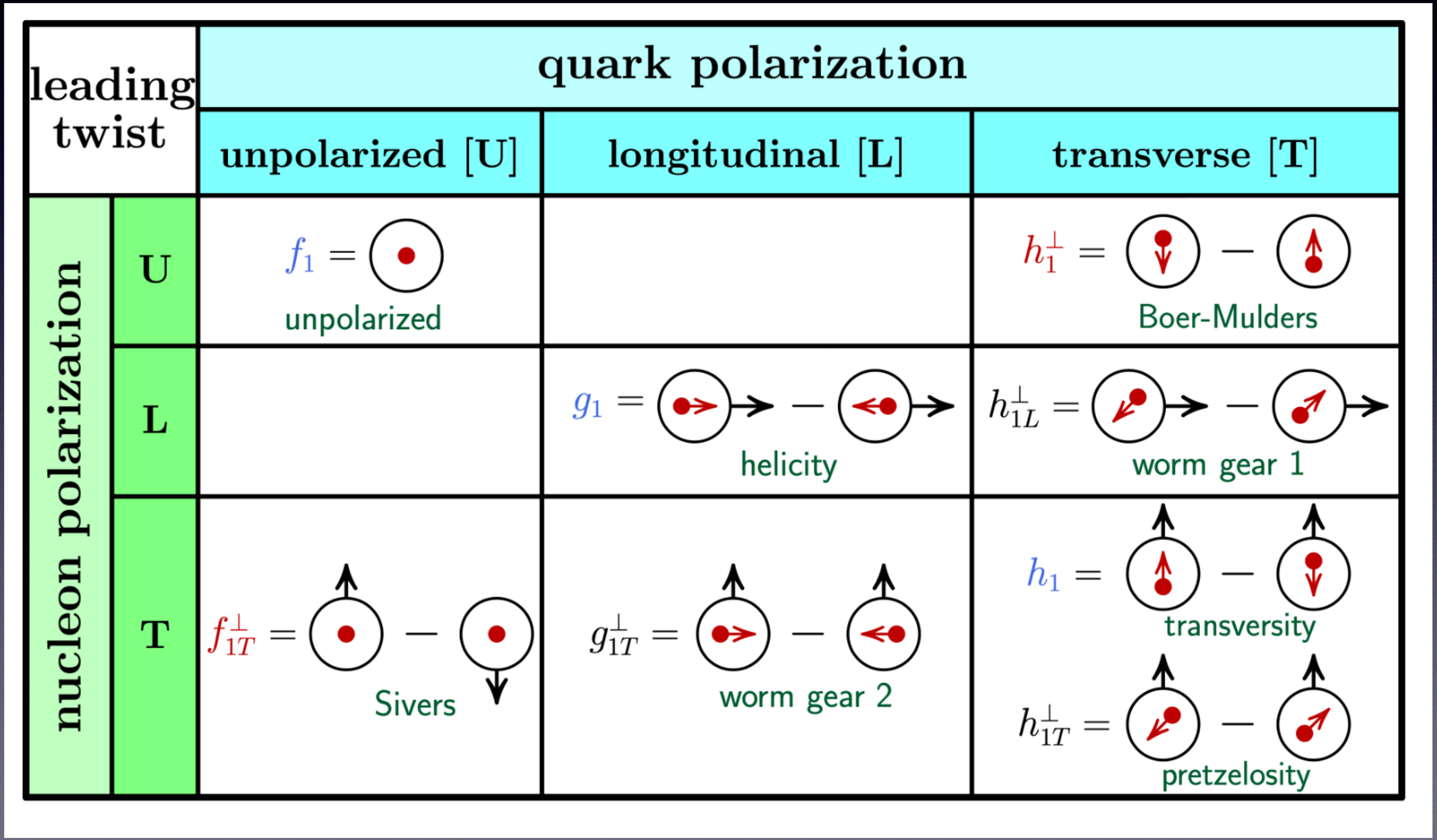


Chinese Phys. C 45 (2021) 023110

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

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

- 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