W mass measurement at LHCb

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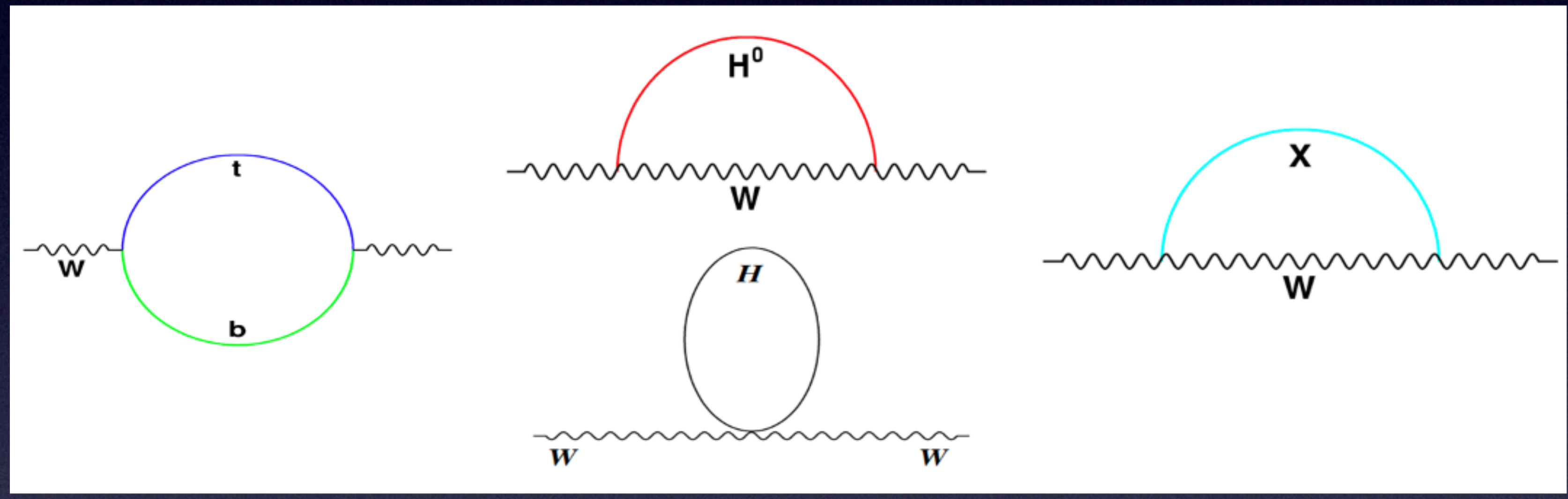
Measurement of the W boson mass

- 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

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

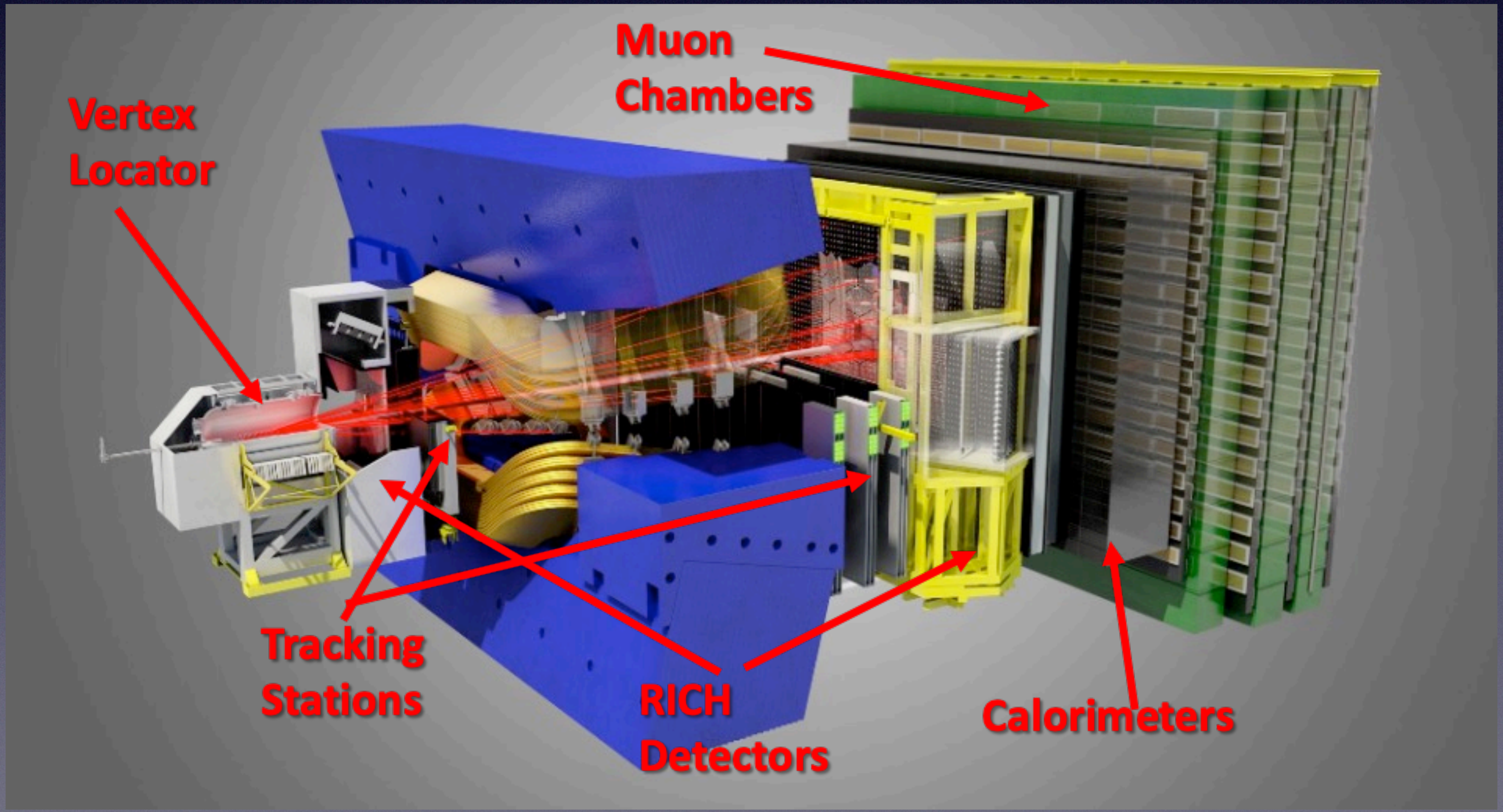
Weights

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

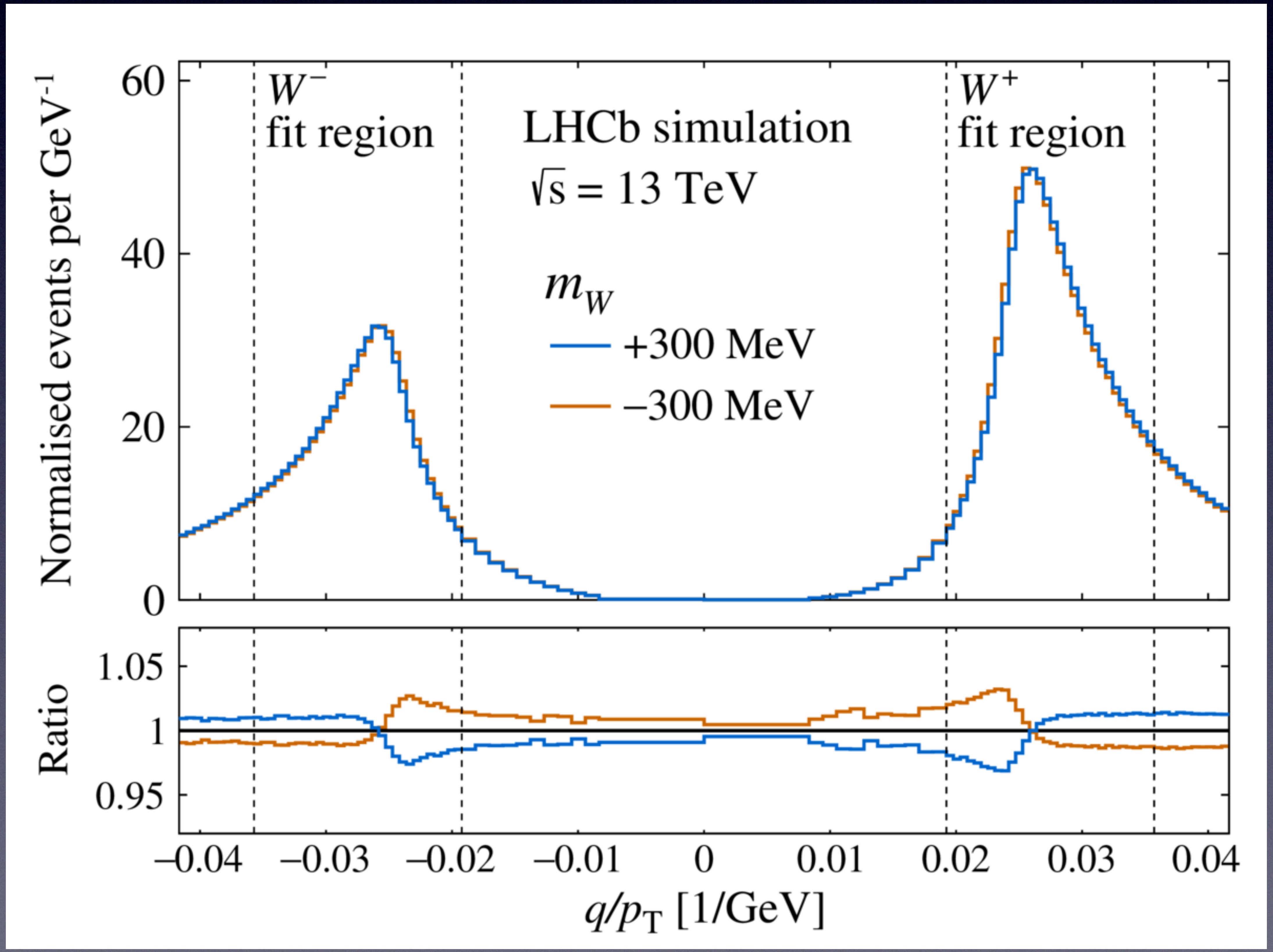
- Designed for the heavy flavour physics, with $2 < \eta < 5$
- Extended to EW measurements: excellent performance of tracking and muon detector



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^*

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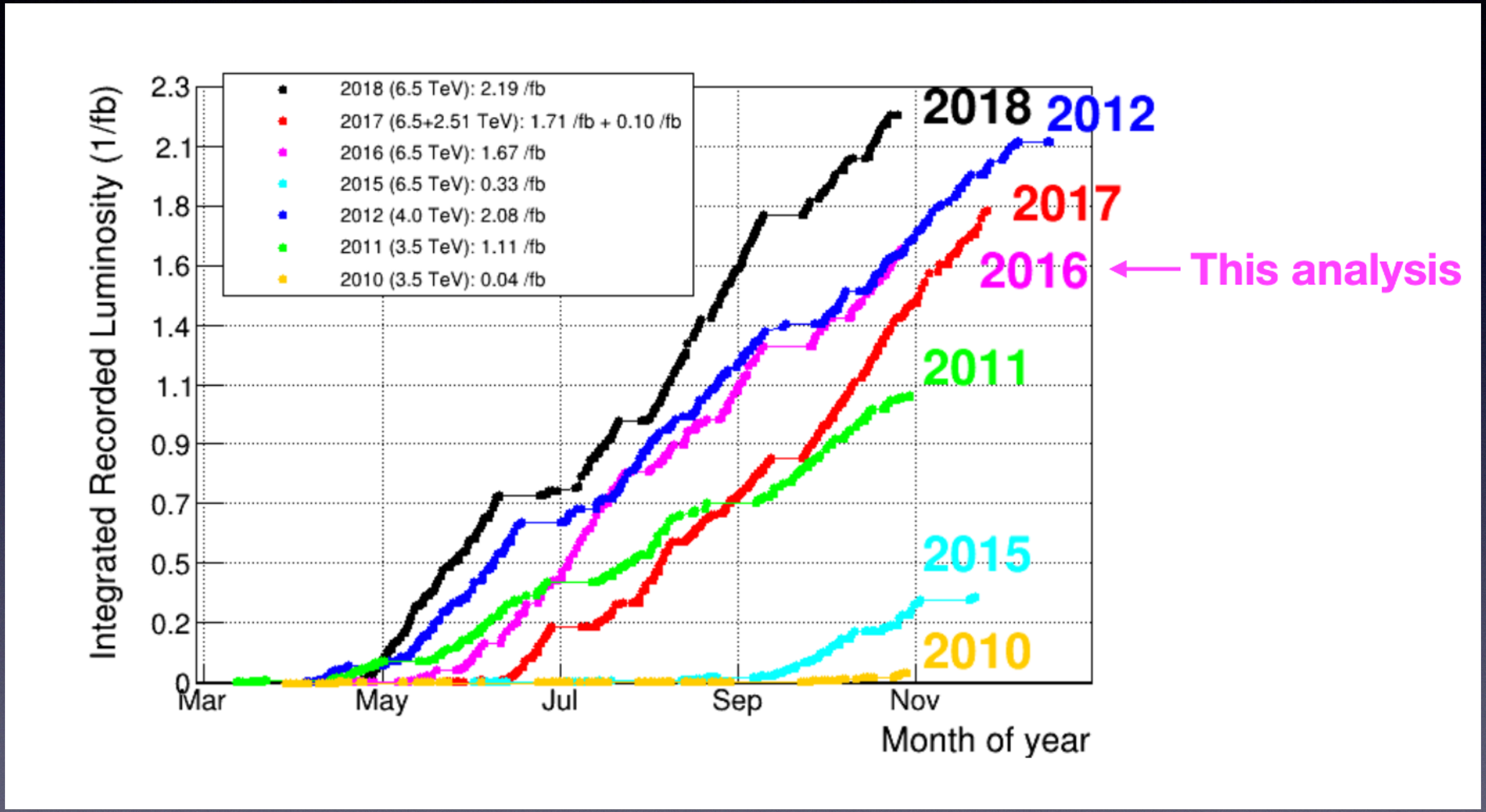
Datasets



As a pathfinder measurement, only use 2016 data-set

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

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Event selection

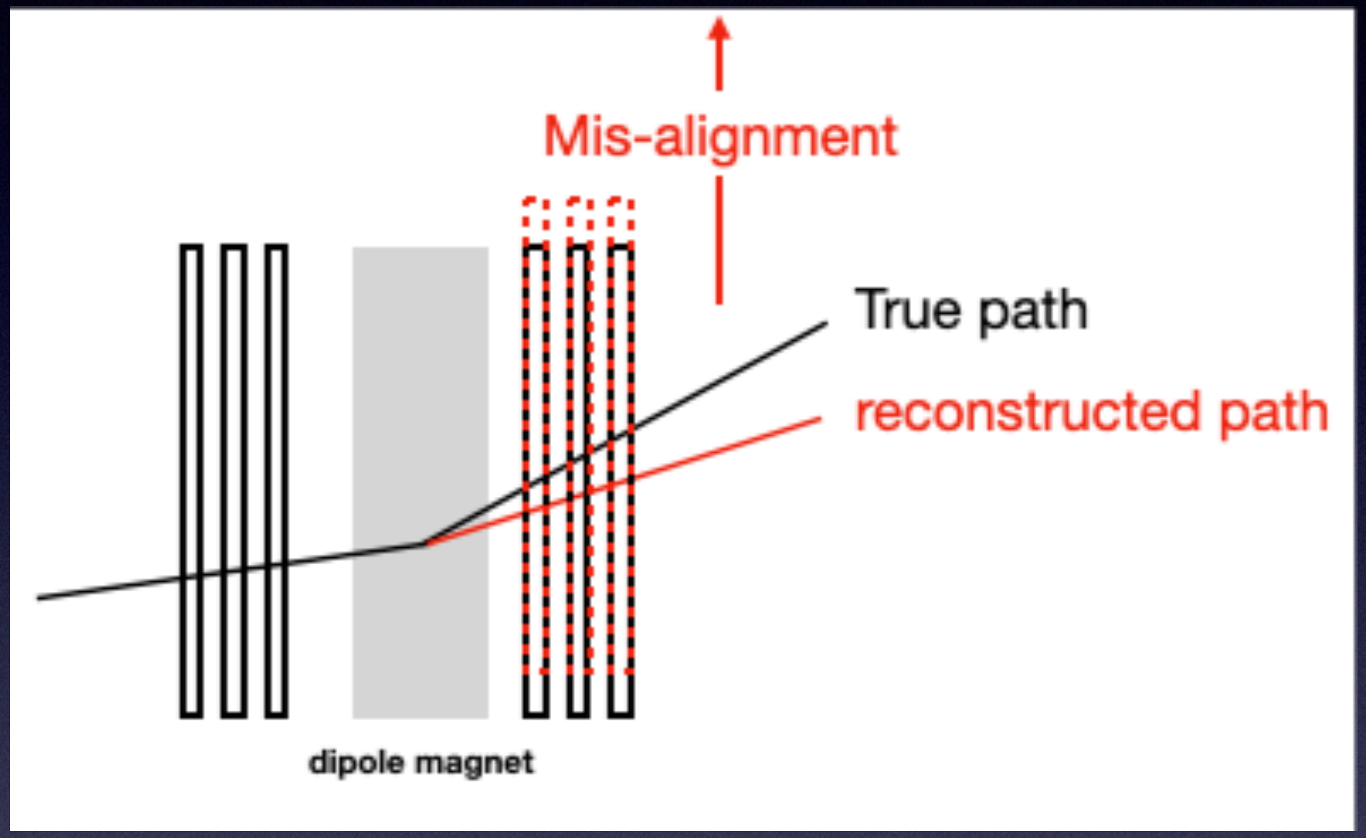
- Identified muon candidate matched to single muon trigger (threshold 20 GeV)
  - Relative momentum uncertainty: $\delta p/p < 6\,\%$
  - $\chi^2_{IP} < 9$: difference in the vertex fit χ^2 of the PV, with and without the muon
- Hadronic backgrounds are suppressed to the precent level by an isolation 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

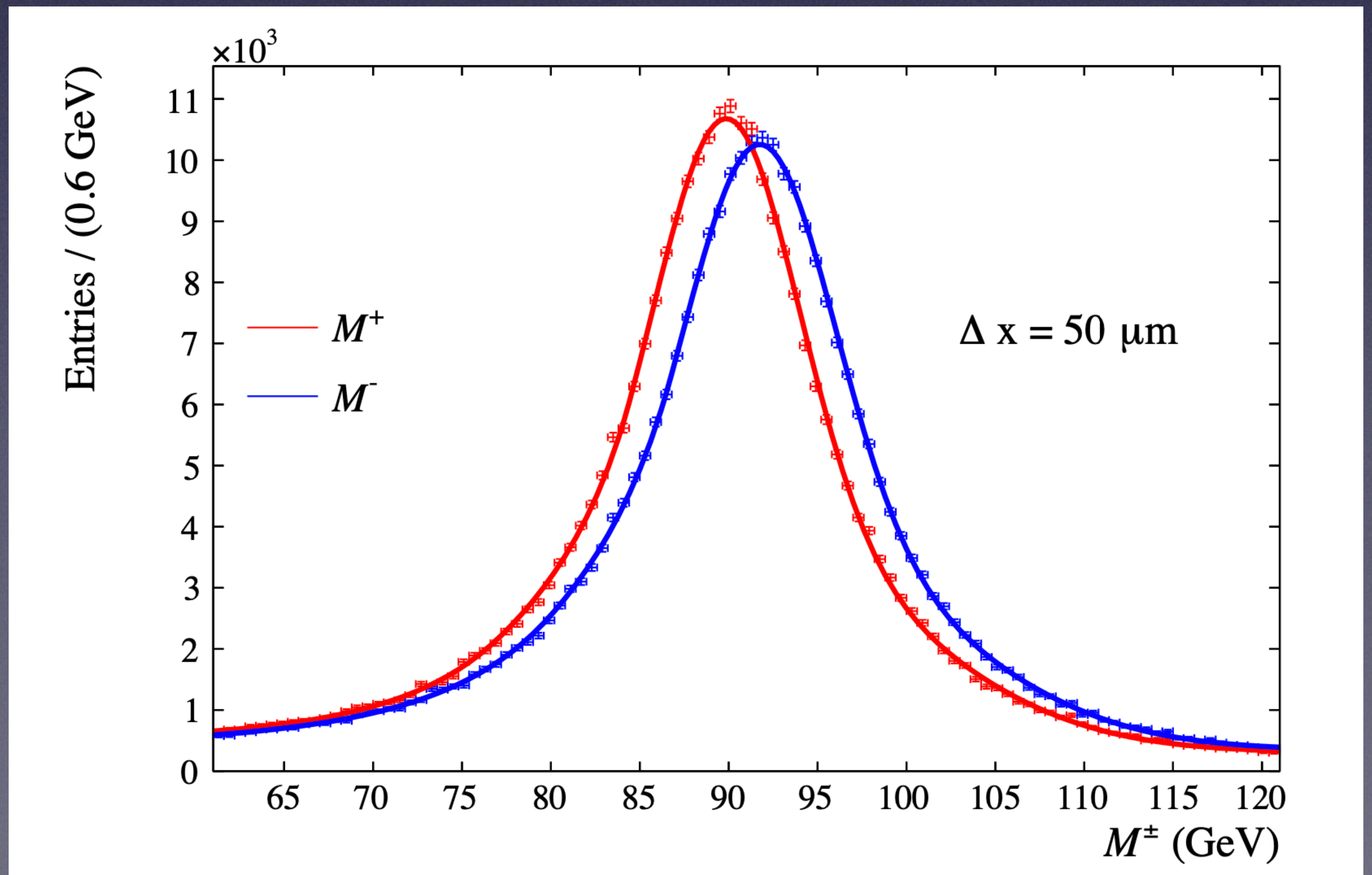
Eur. Phys. J. **C81** (2021) 251

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):

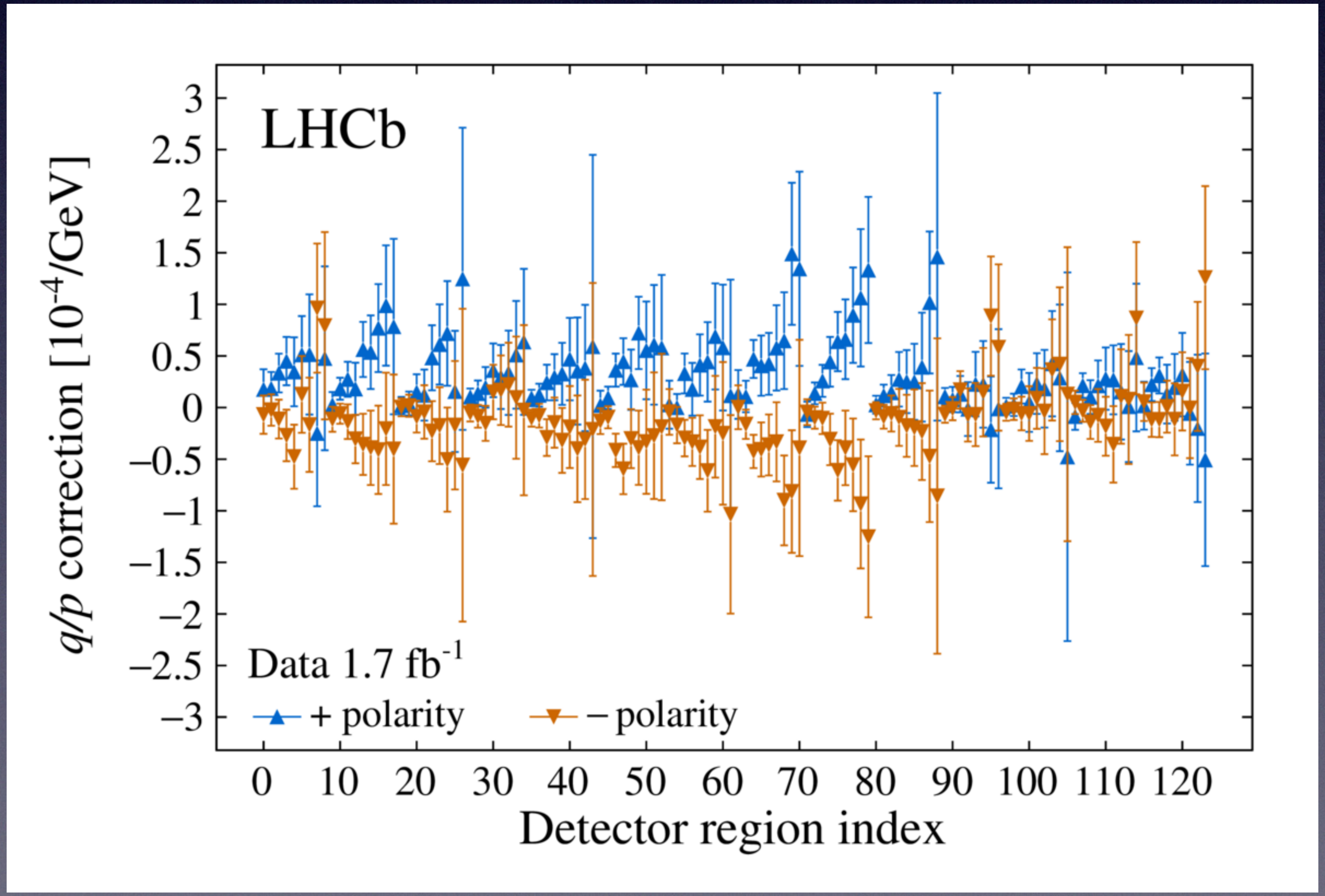
$$M^{\pm} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1 - cos\theta)}$$

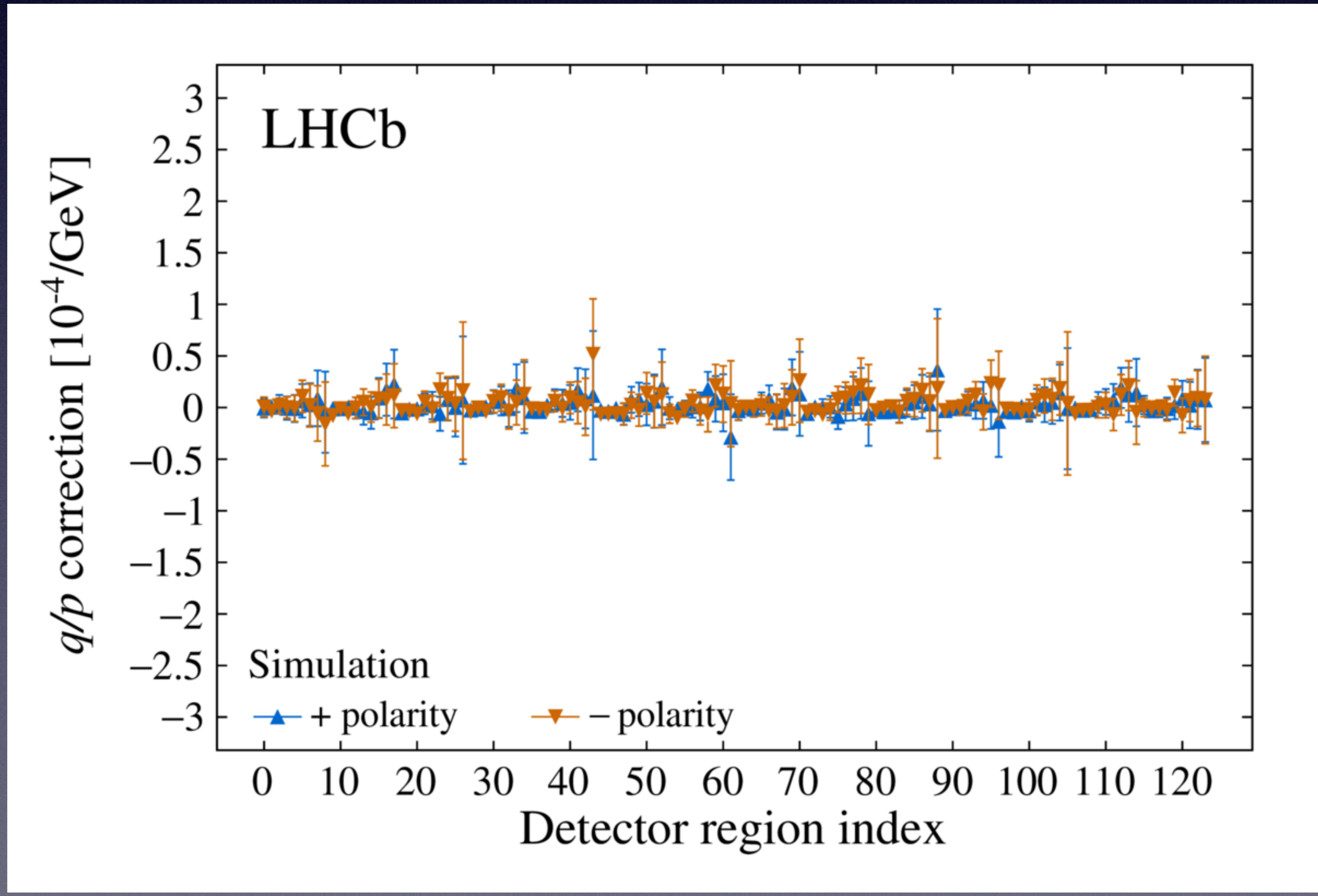




Charge dependent curvature biases

- An example of curvature corrections





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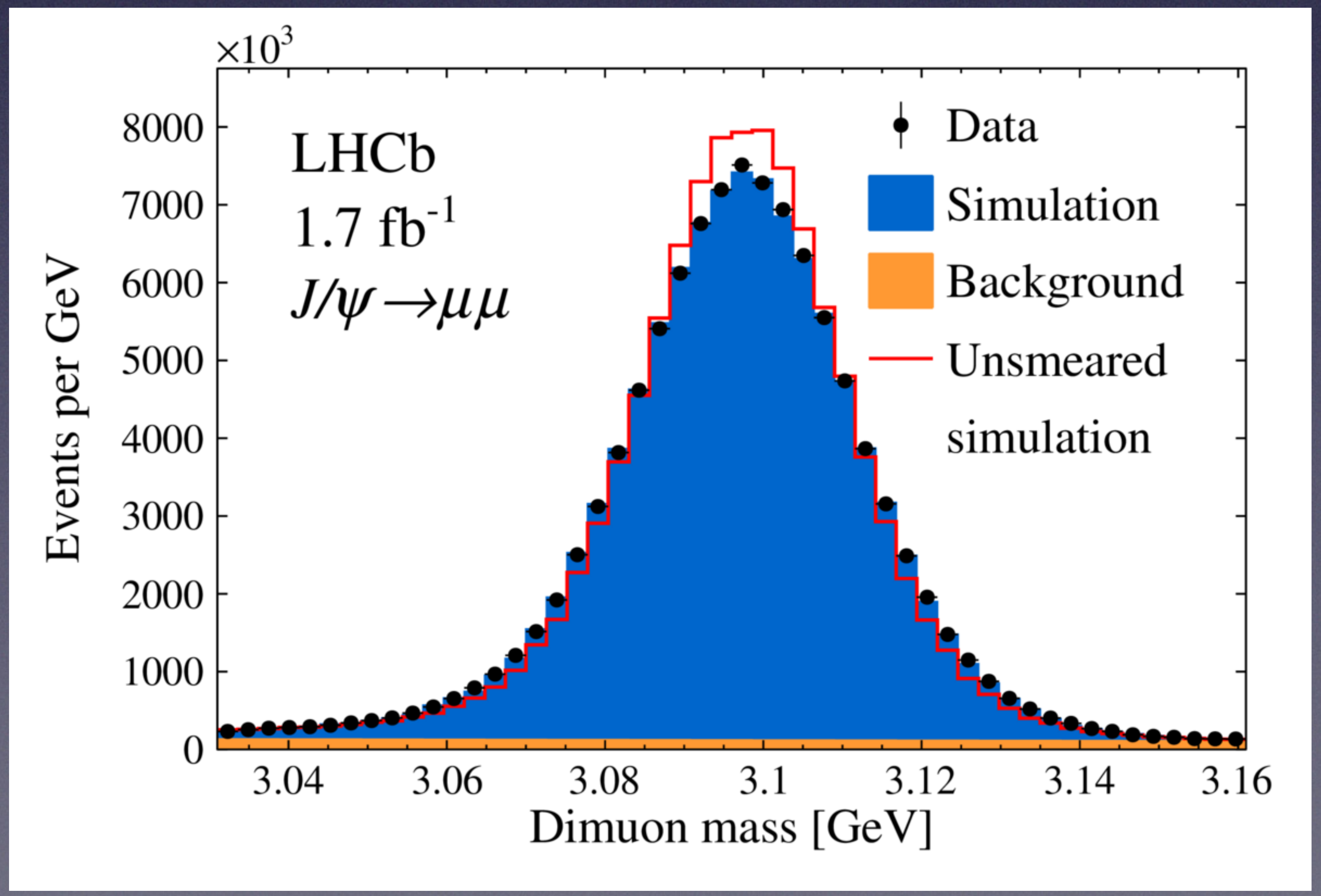
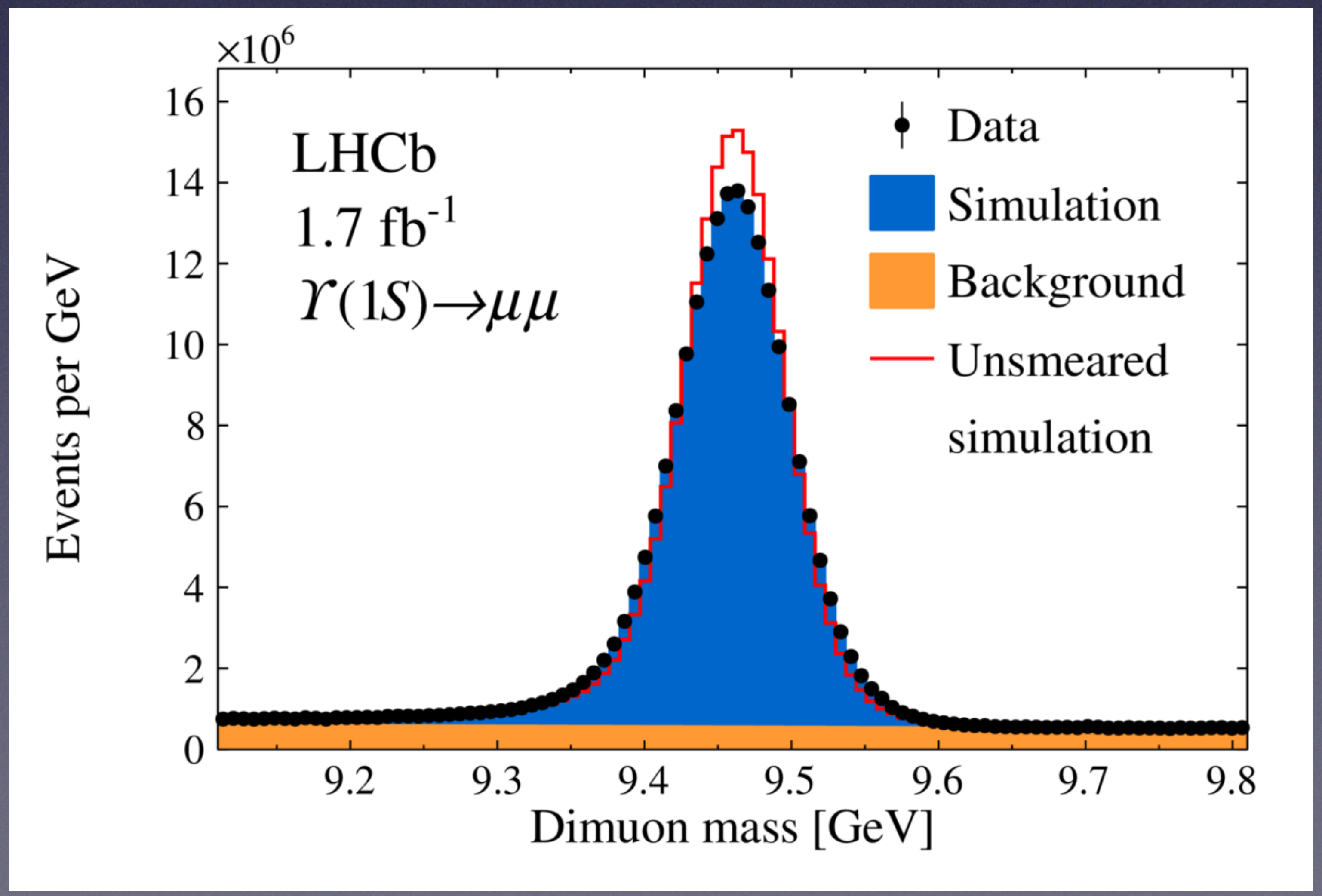
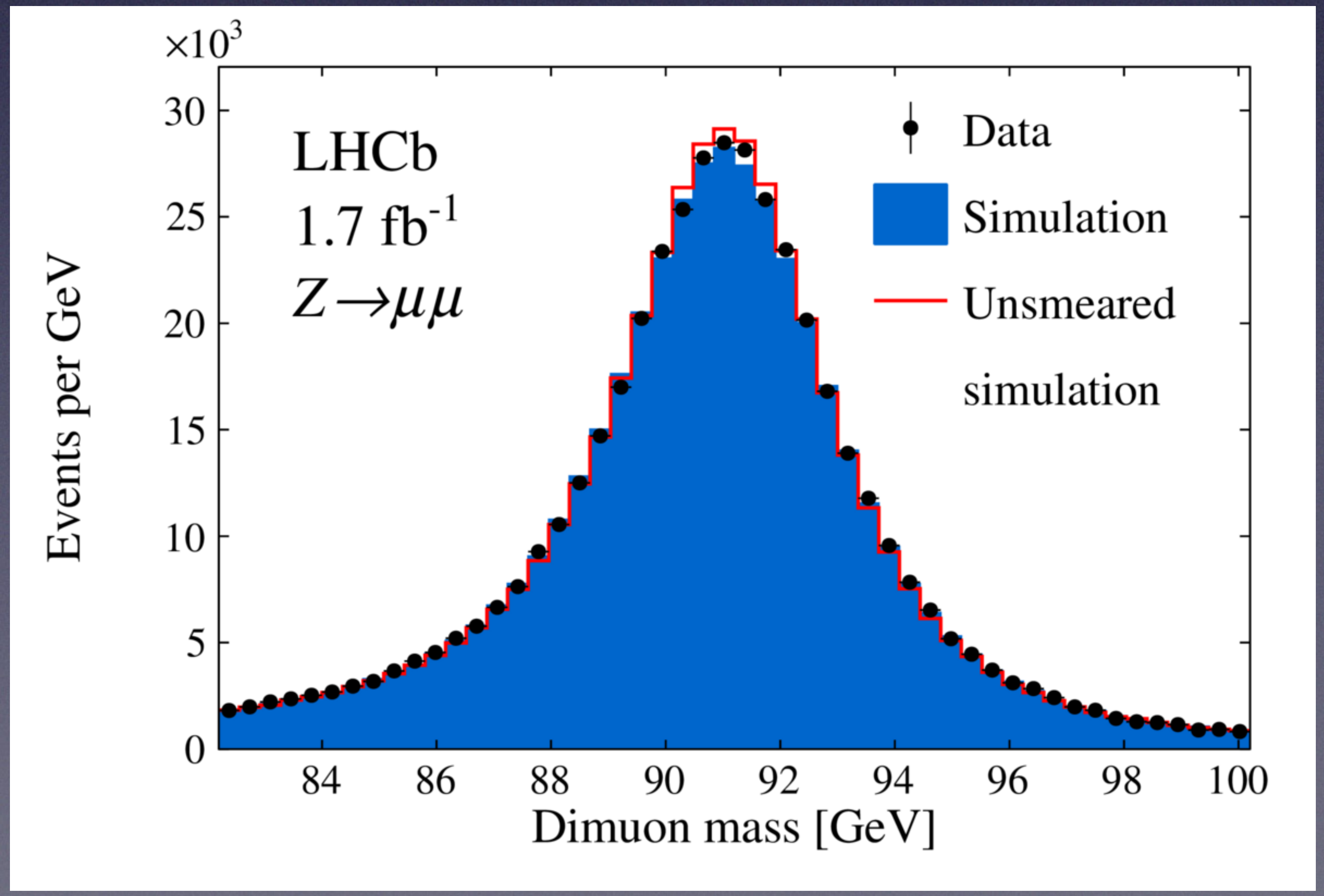
Momentum smearing fit

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

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







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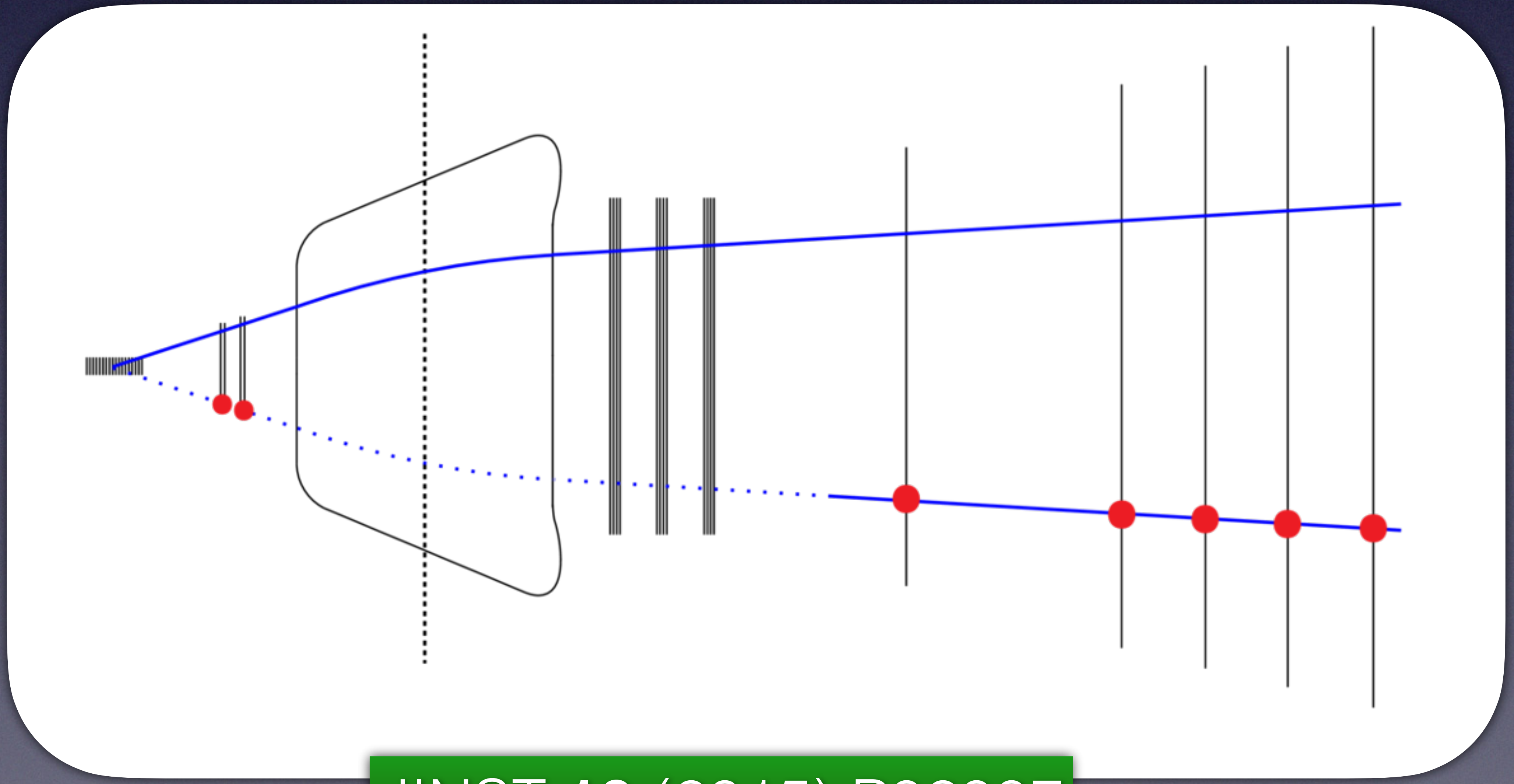
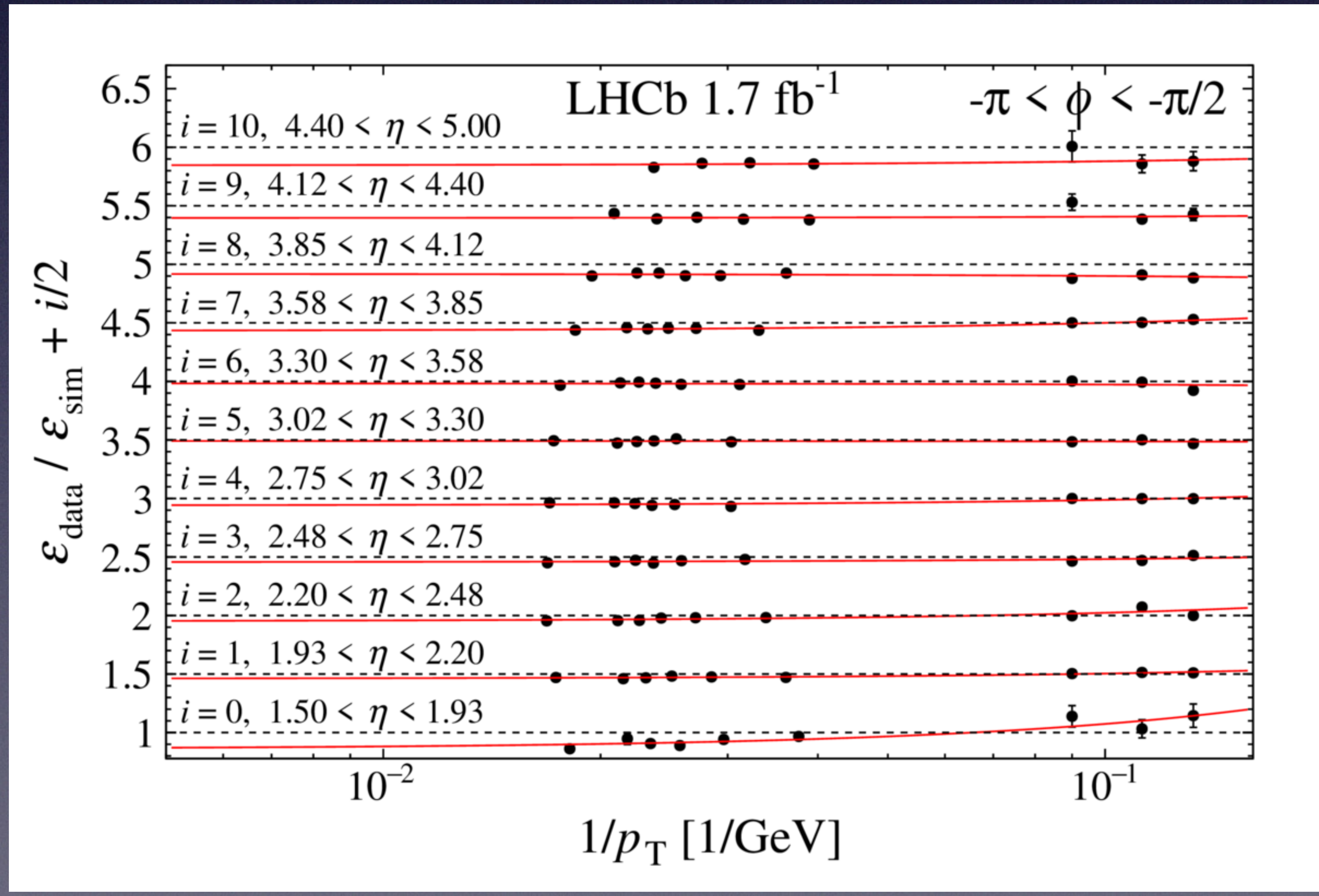
Efficiency corrections

- 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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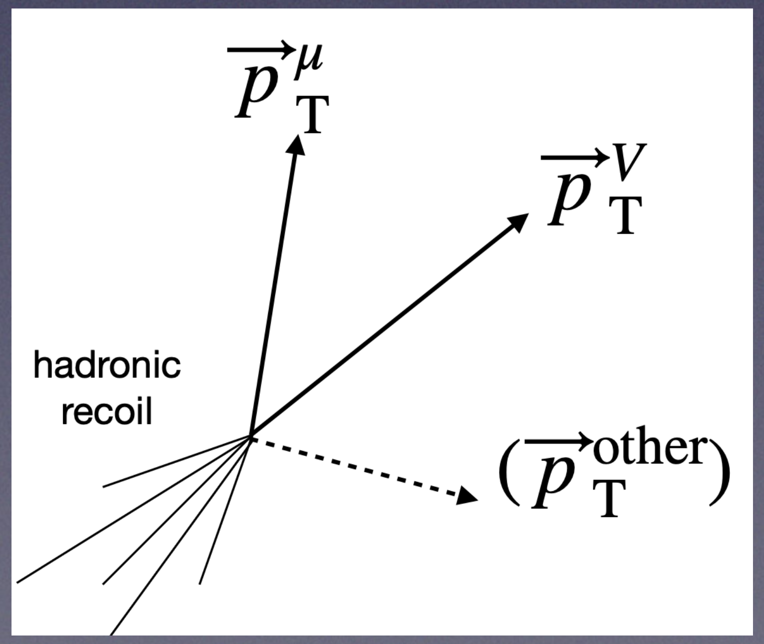
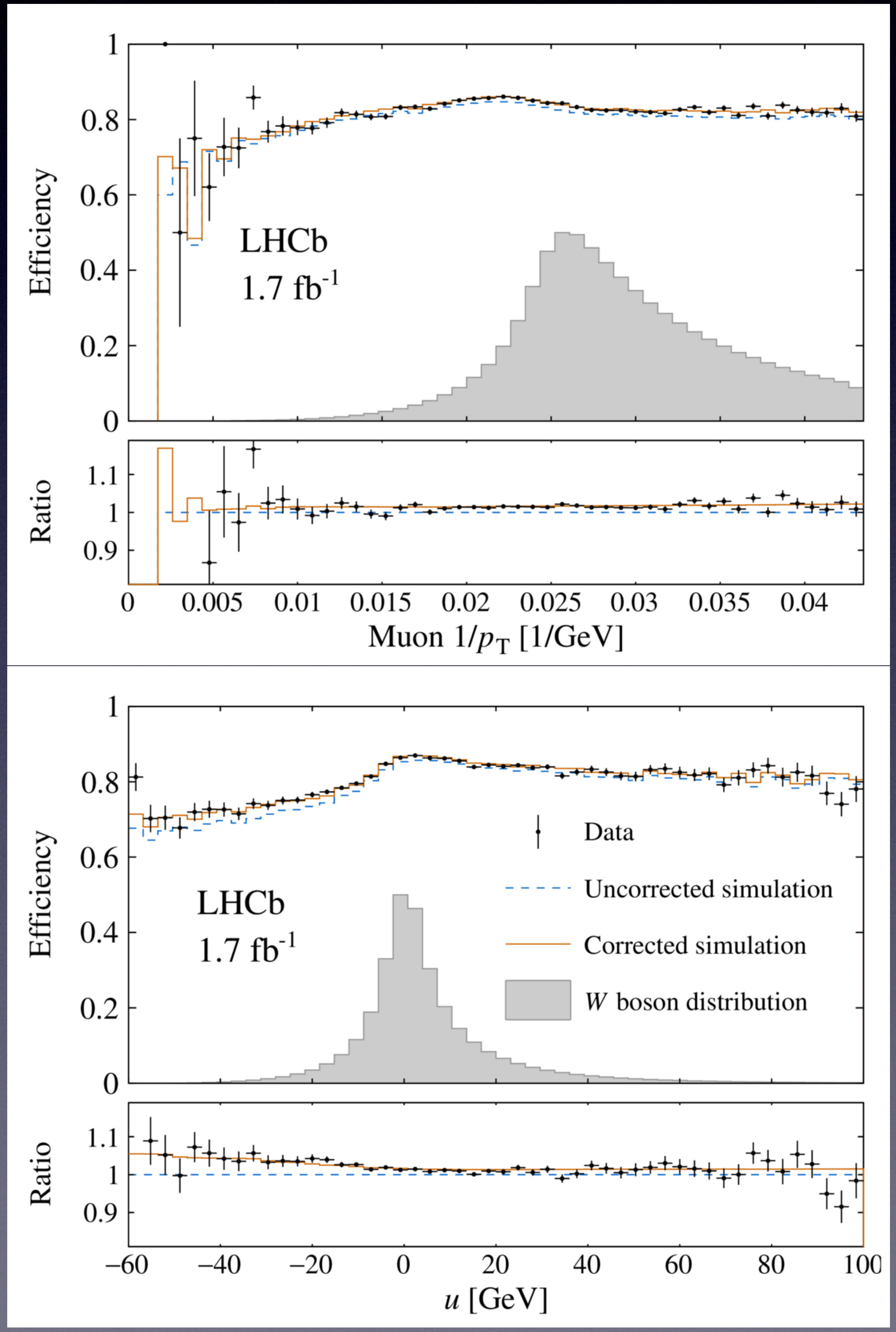
Muon isolation efficiency

- 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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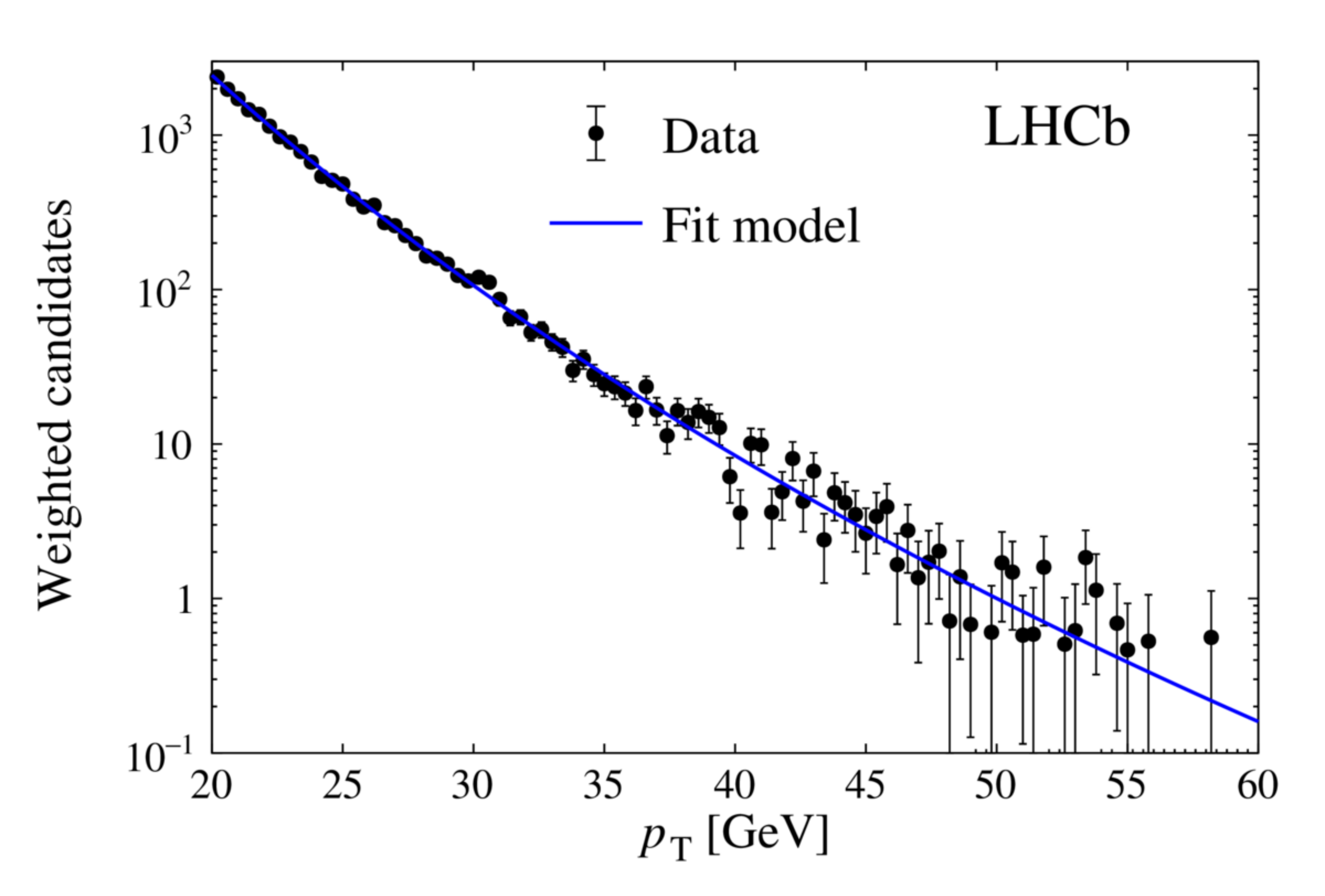
Background modeling

- 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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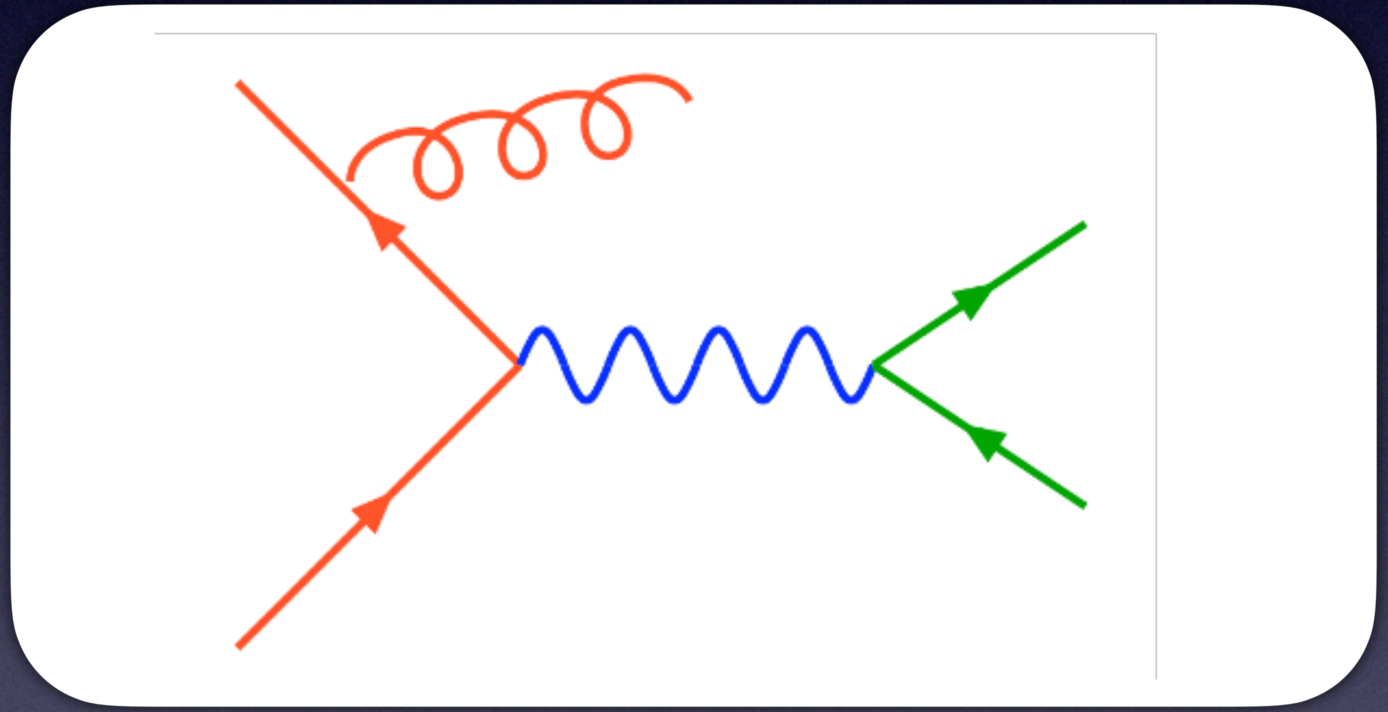
QCD corrections: polarisation

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

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



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

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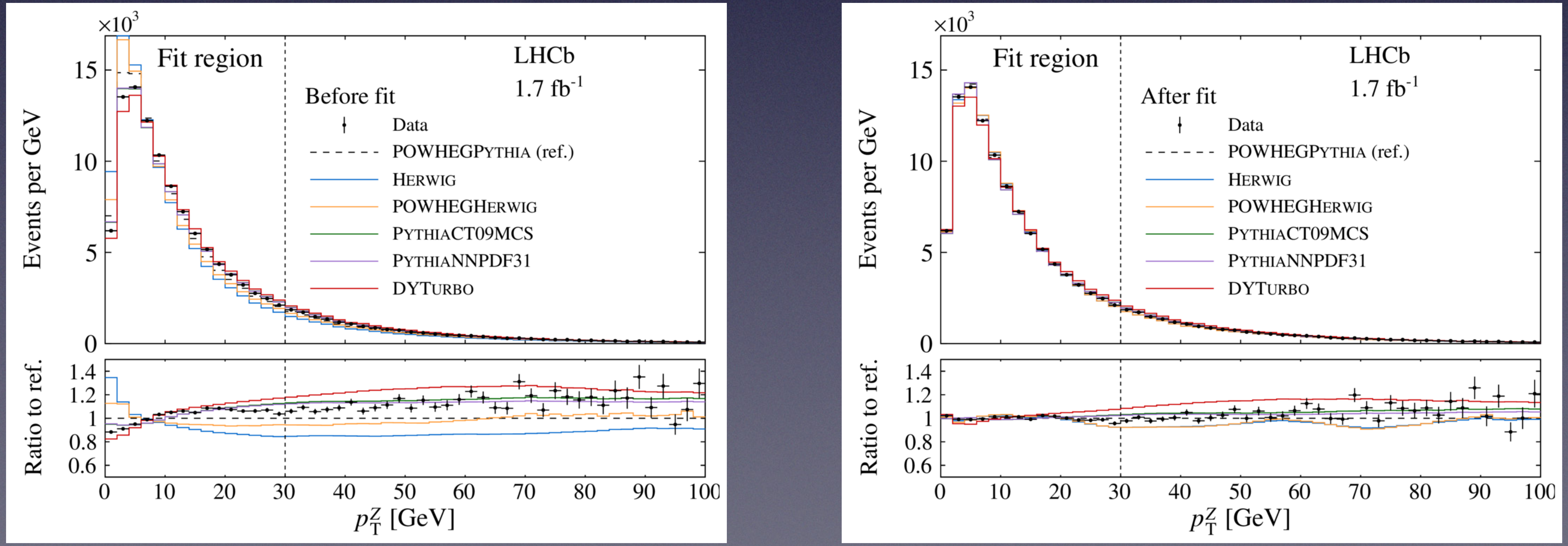
QCD Corrections: W boson p_T

- 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}
  - $Z \rightarrow \mu\mu$ events are used to validate

QCD reweighting
p_T: POWHEGPYTHIA
A_i: DYTURBO



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QCD Corrections: Higher p_T region

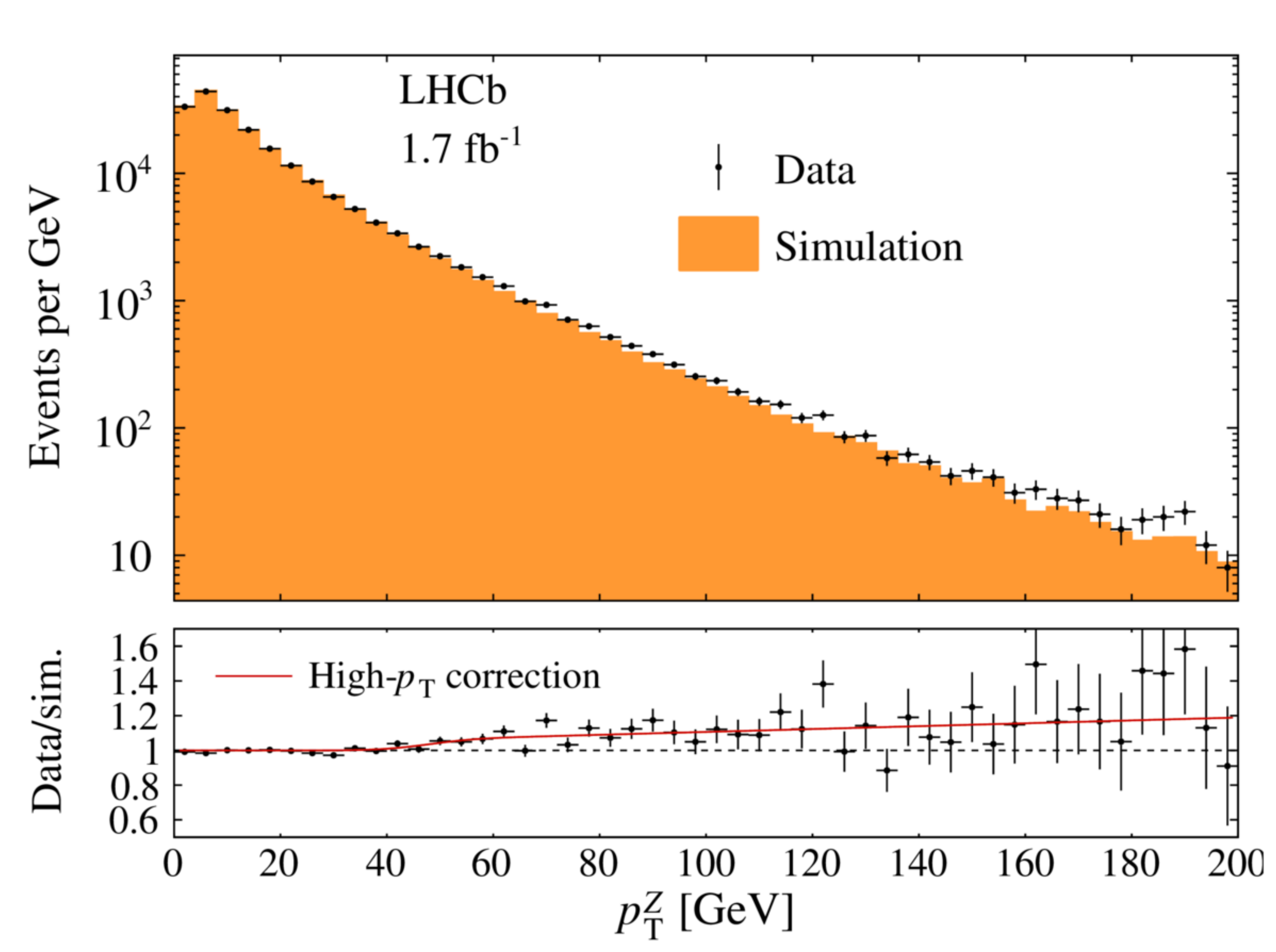
- However, in the high boson p_T region
- Significant difference between data ($Z \to \mu\mu$) and POWHEG+PYTHIA prediction
  - Missing matrix elements for the production of a weak boson and more than one jet

Up to 10% at PTZ ~ 100 GeV

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

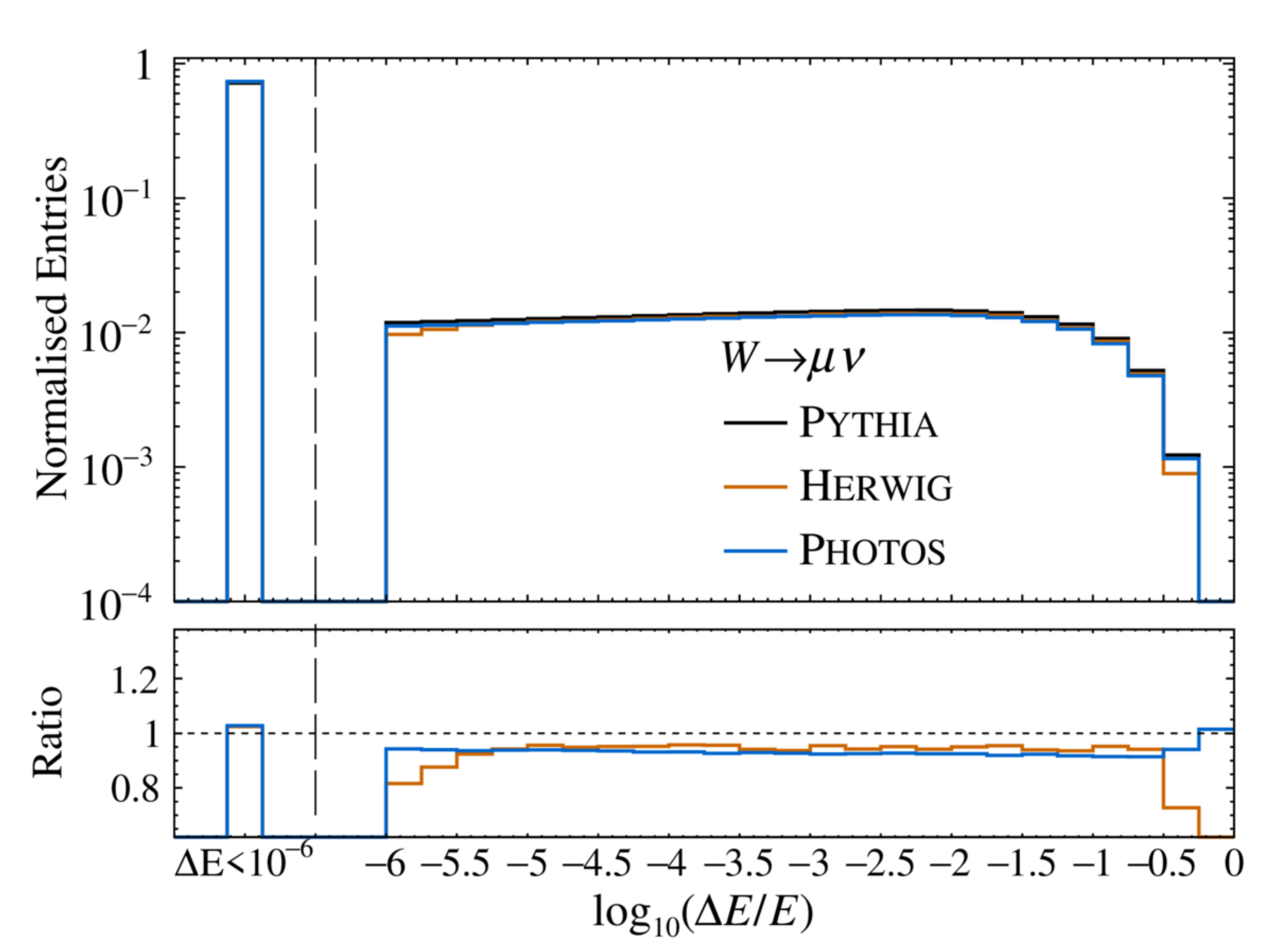
100% of this correction: < 1 MeV uncertainty

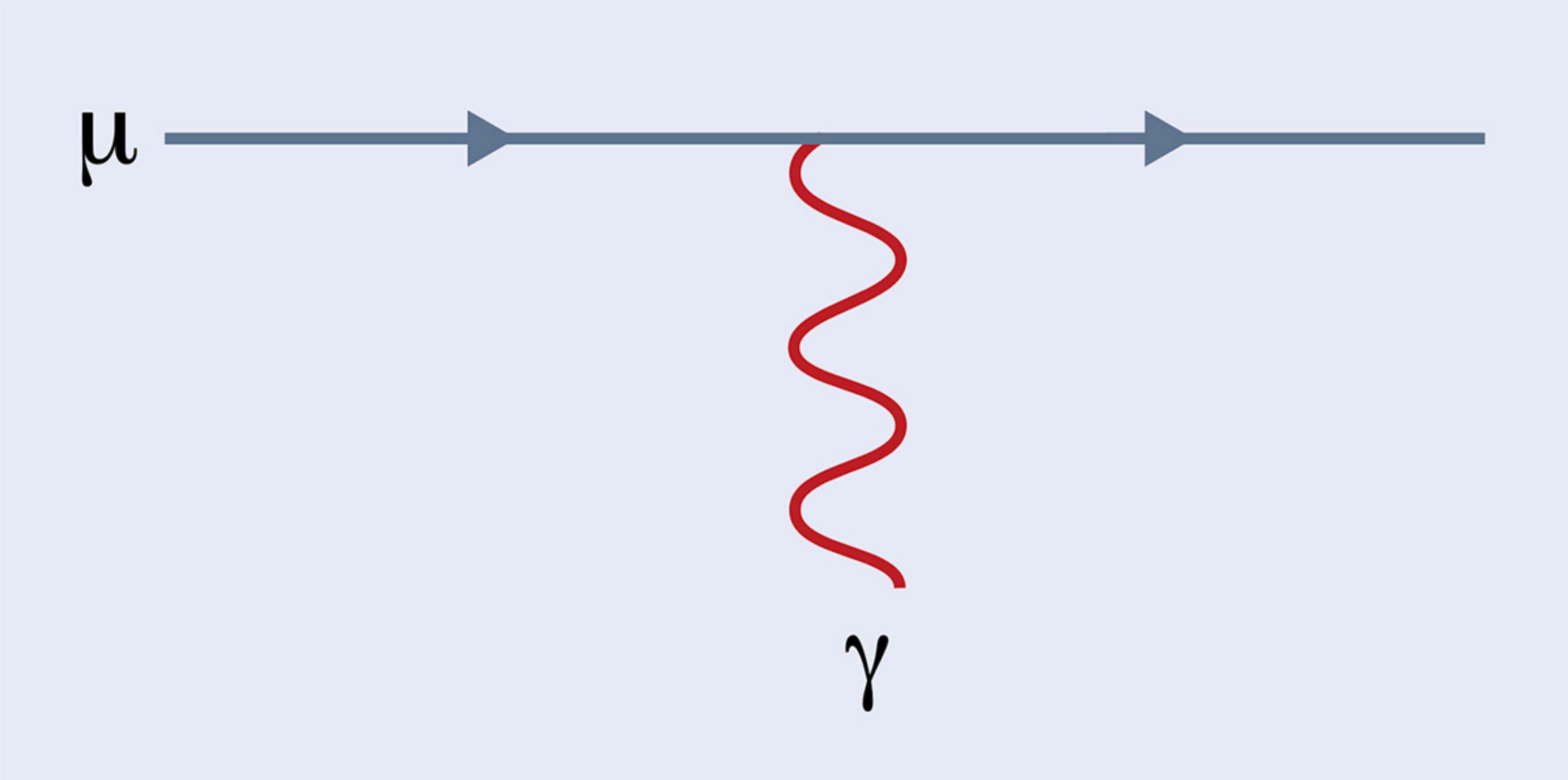
QCD reweighting
p_T: POWHEGPYTHIA
A_i: DYTURBO
High p_T: data/Prediction



QED corrections

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





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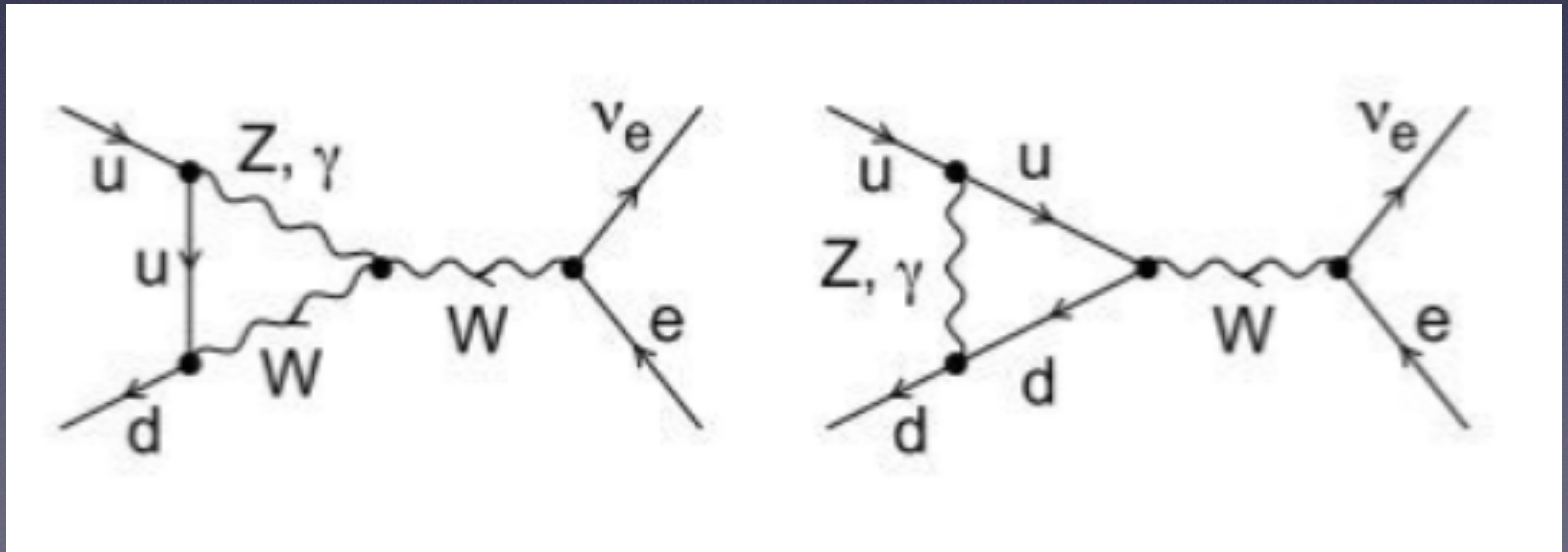
Electroweak correction

- 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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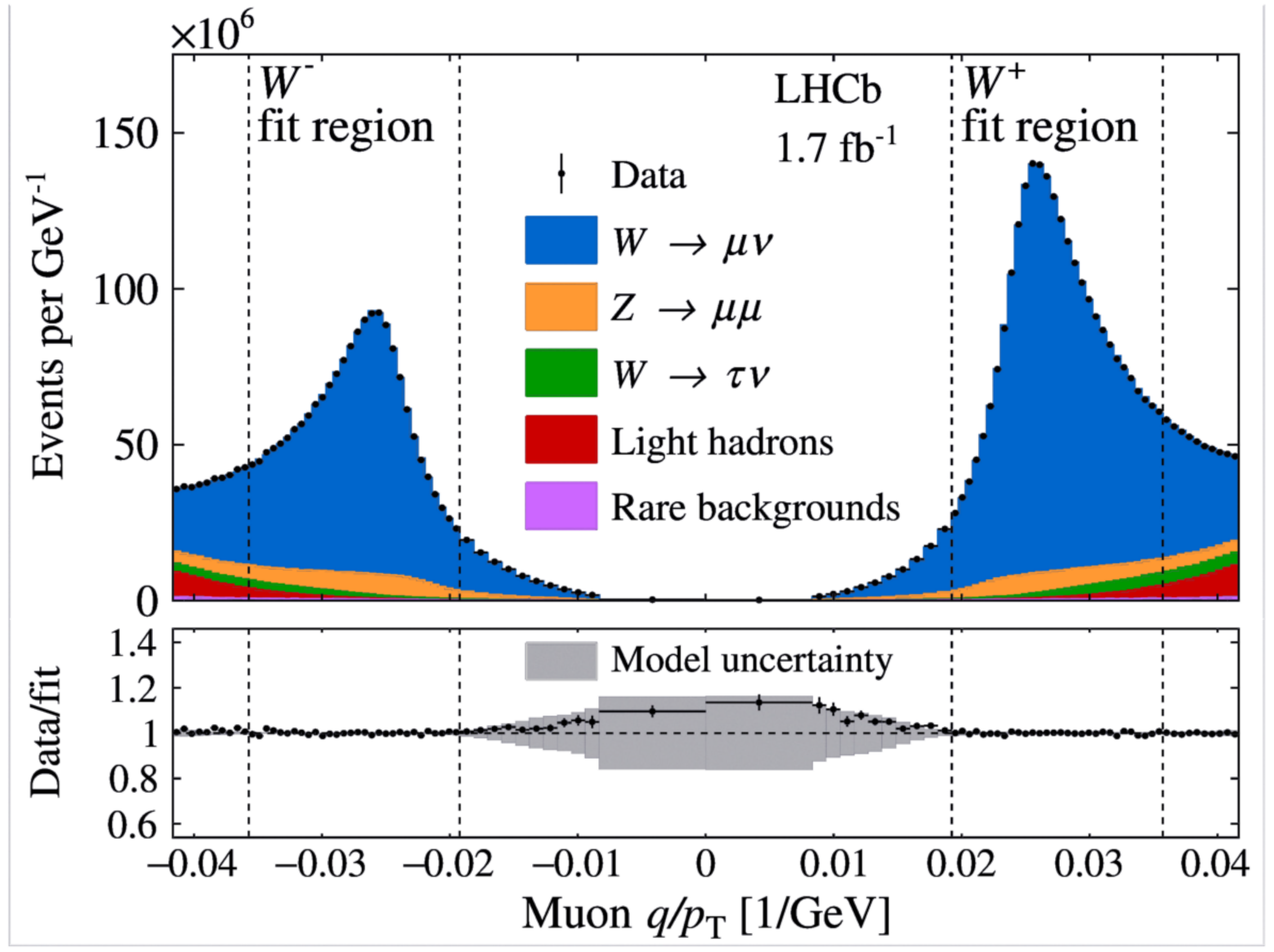
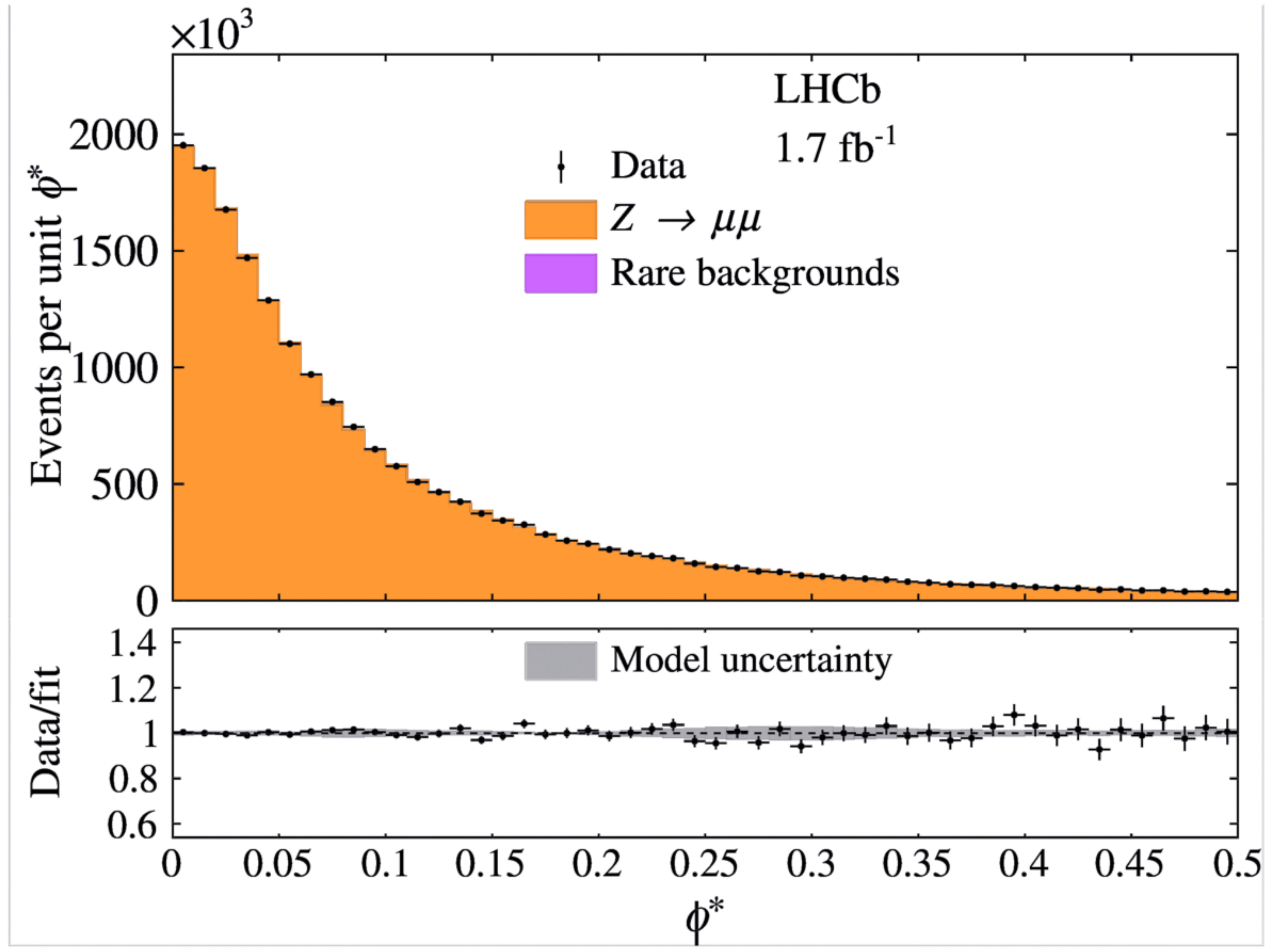
Fit results

- 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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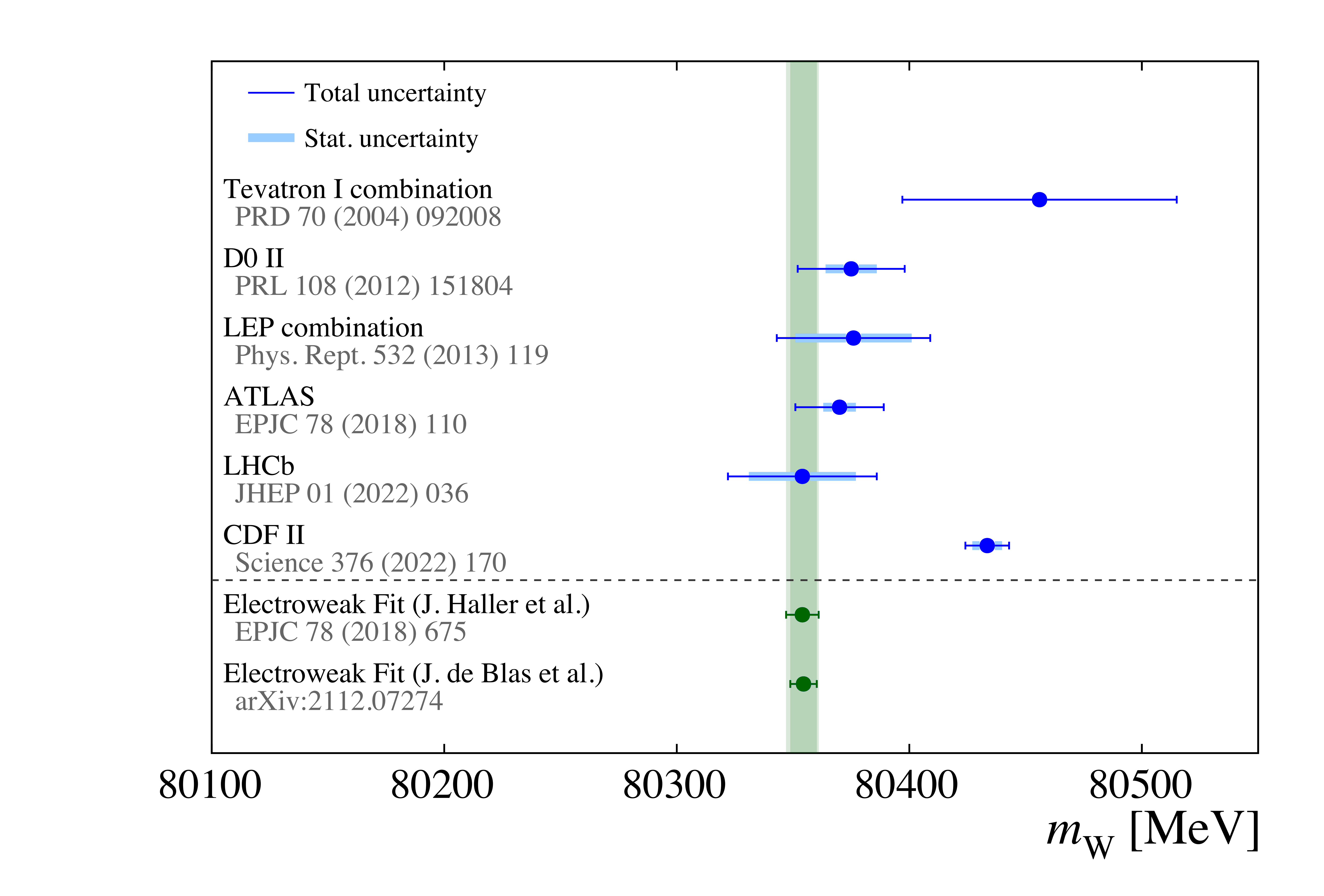
LHCb measured result



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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 ≤ 20 MeV
  - Upgrade to a double differential fit

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Total	32

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

Conclusion

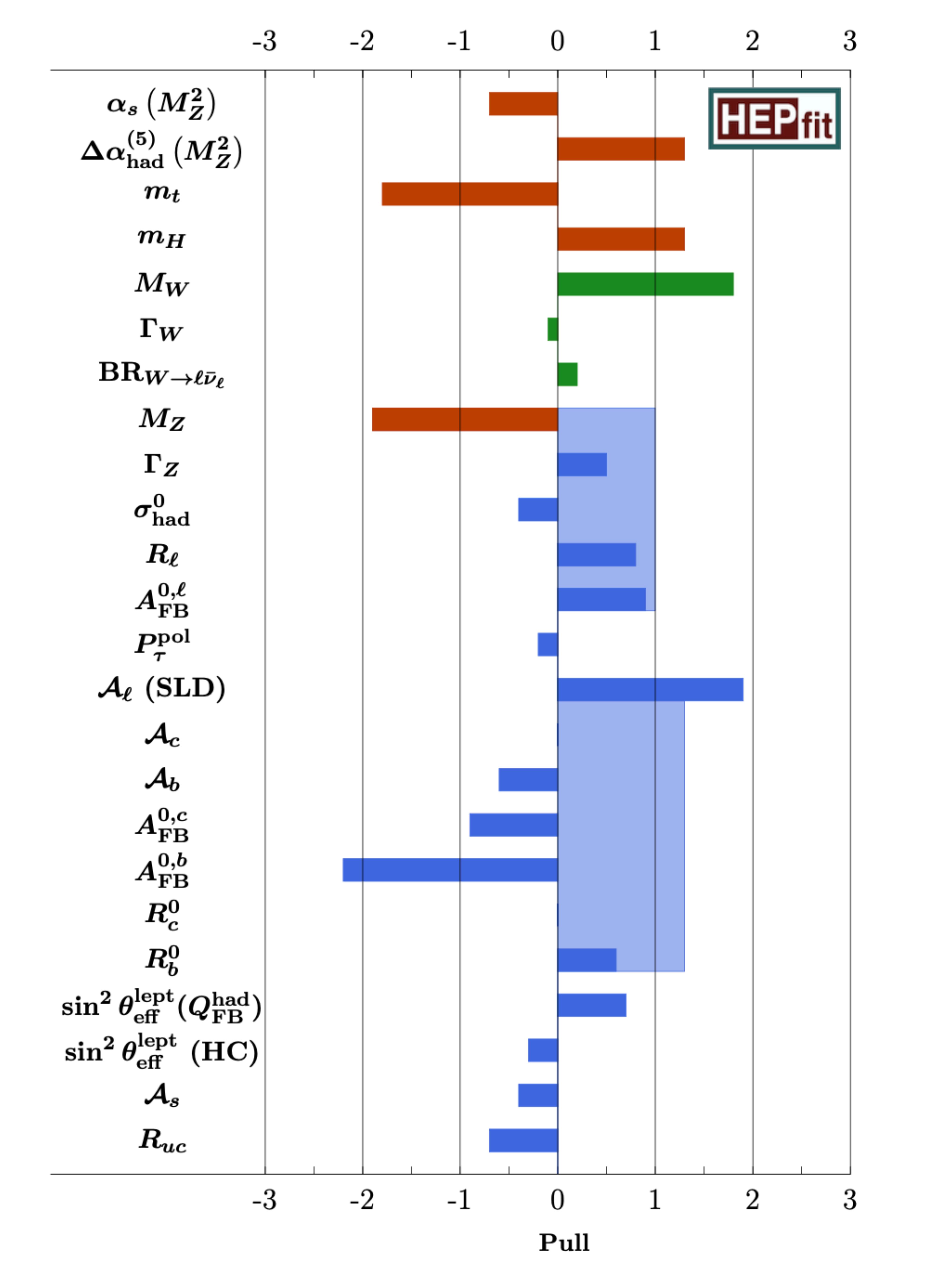
- LHCb has an extensive program on W/Z boson production and properties
  - Precise measurement of the W boson mass: consistent with SM expectation
- With detector instrumented in the forward region, the LHCb results could provide unique information in the LHC combination
- Future measurement: systematic uncertainty dominated (challenging and exciting)

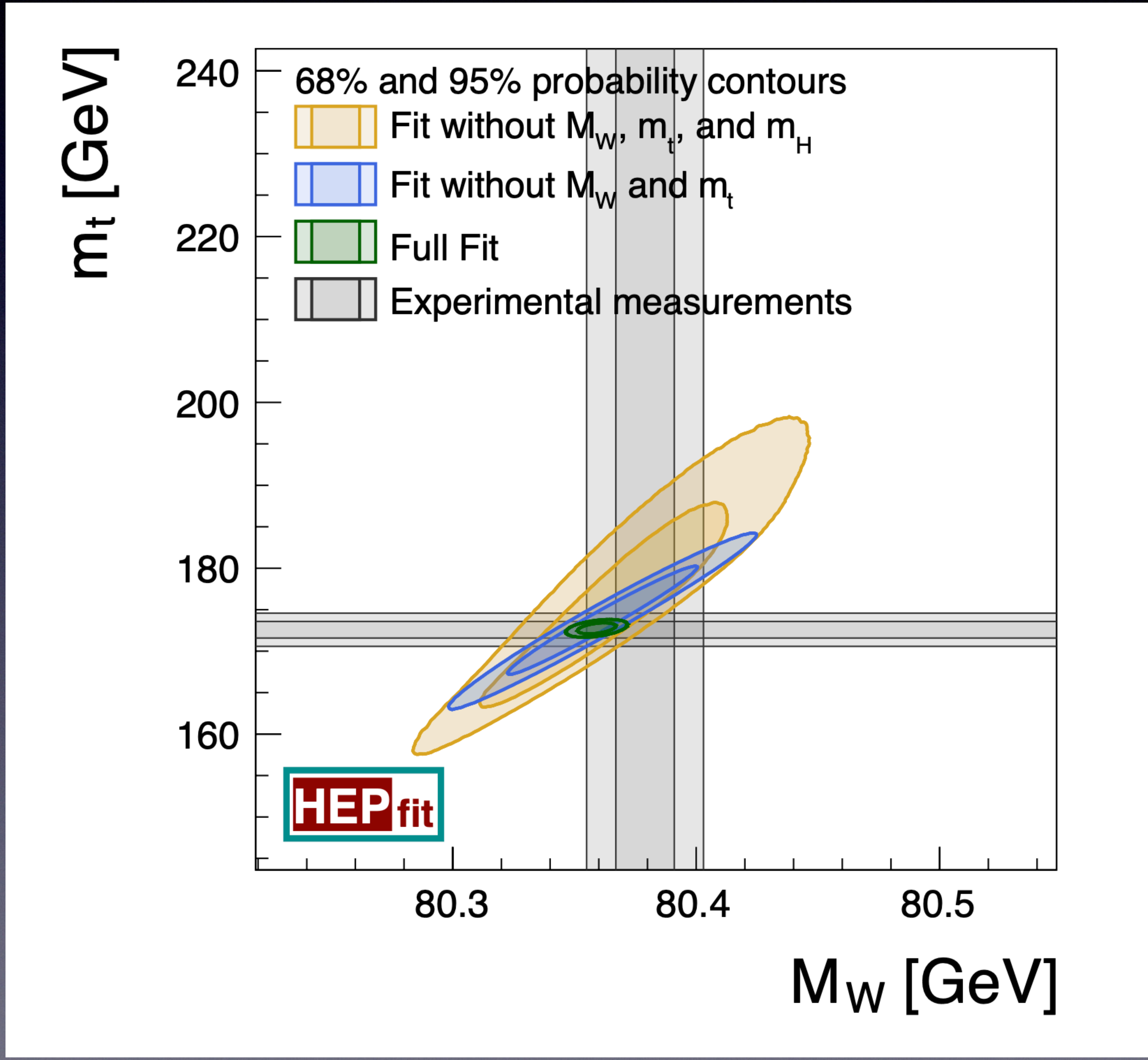
Stay tuned for new results!

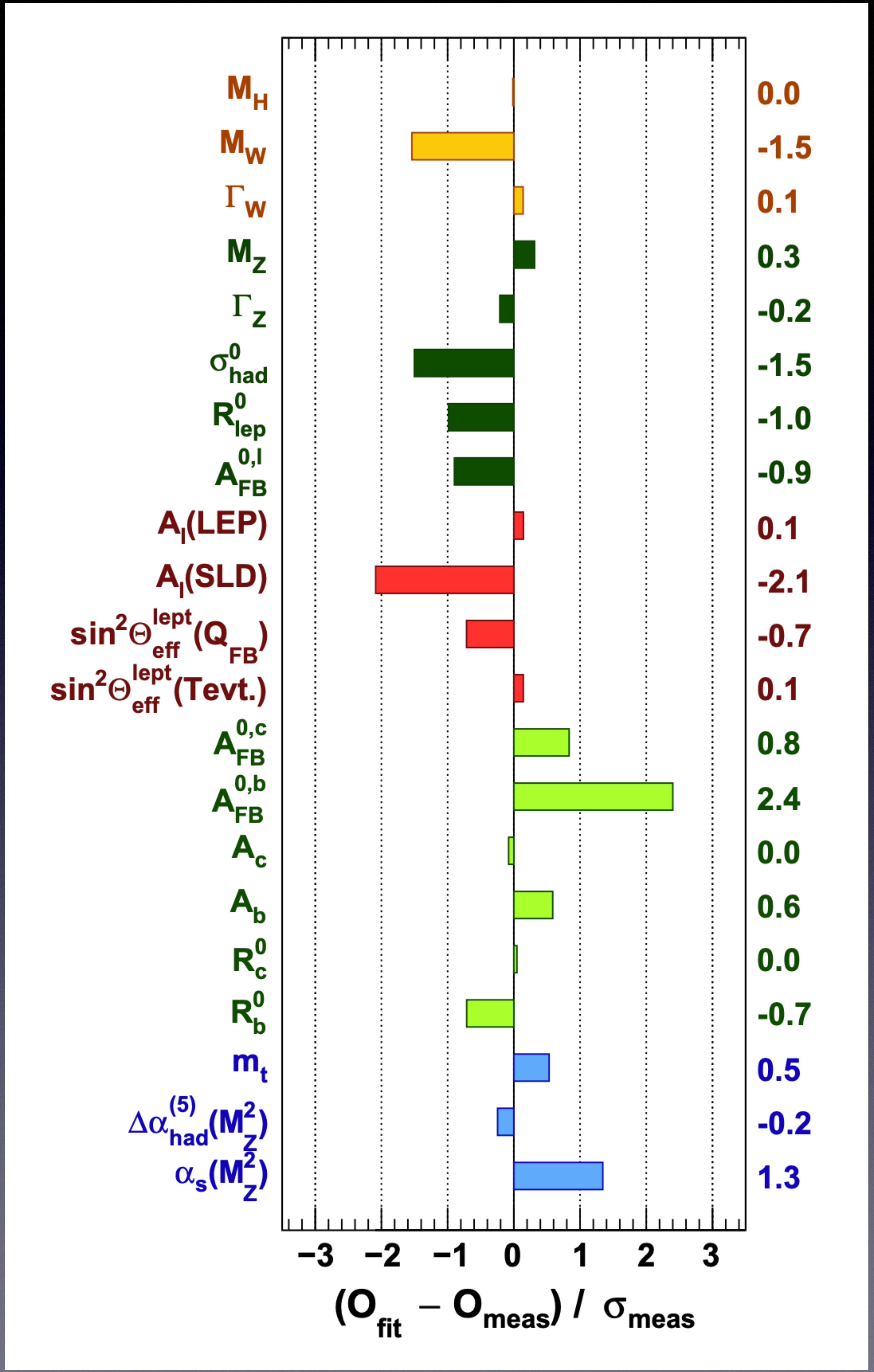
Backup

arXiv:2112.07274

Electroweak Global fit







GFitter

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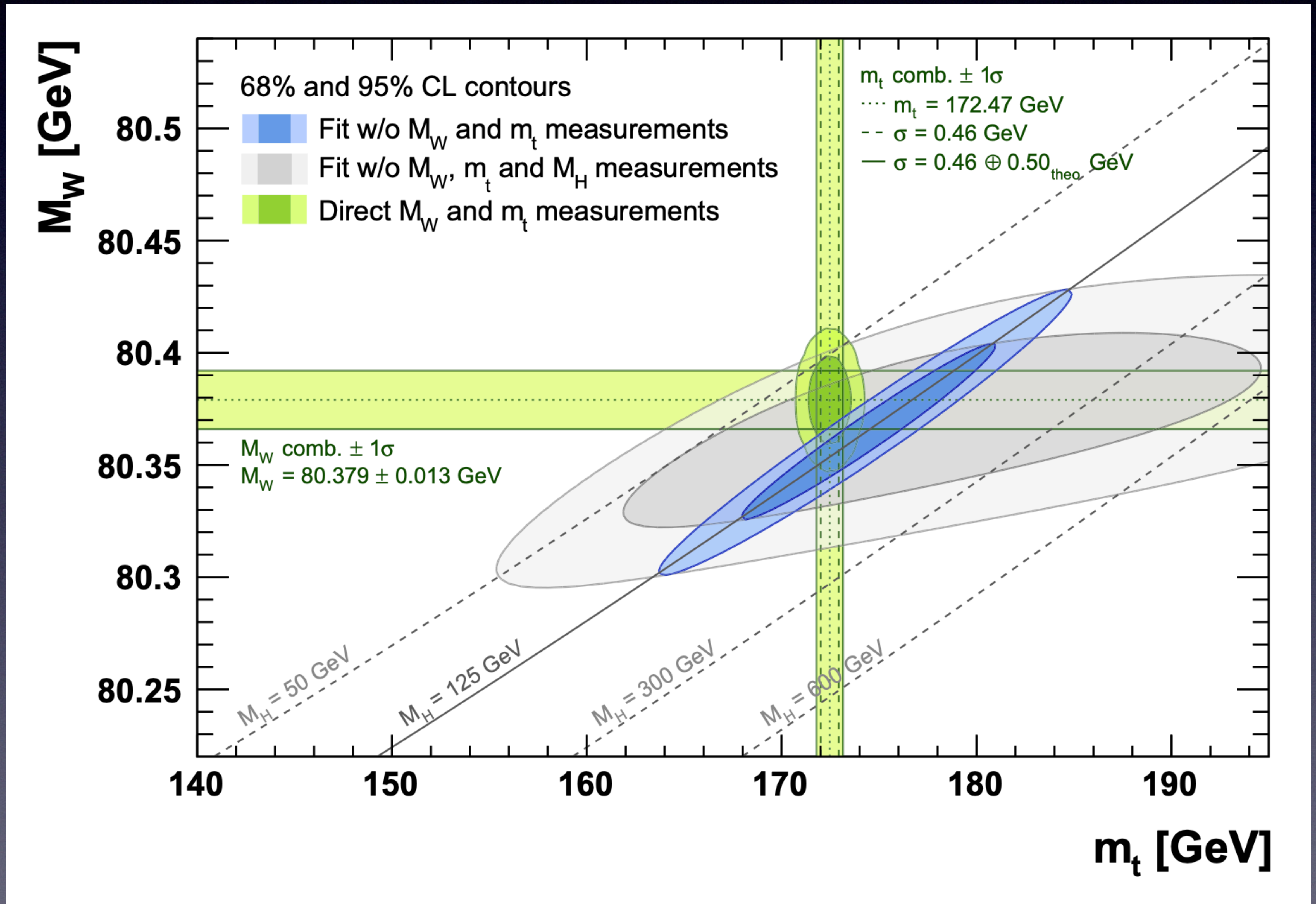

Parameter	Input value	Free in fit	Fit result	Fit w/o exp. input in line	Fit w/o exp. input in line, no theo. unc.
M_H [GeV]	125.1 ± 0.2	Yes	125.1 ± 0.2	90^{+21}_{-18}	89^{+20}_{-17}
M_W [GeV]	80.379 ± 0.013	–	80.359 ± 0.006	80.354 ± 0.007	80.354 ± 0.005
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 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
$A^{0,\ell}_{\text{FB}}$	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
$\sin^2\theta^\ell_{\text{eff}}(Q_{\text{FB}})$	0.2324 ± 0.0012	–	0.23153 ± 0.00006	0.23153 ± 0.00006	0.23153 ± 0.00004
$\sin^2\theta^\ell_{\text{eff}}(\text{Tevt.})$	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
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	–	0.0736 ± 0.0003	0.0736 ± 0.0003	0.0736 ± 0.0002
$A^{0,b}_{\text{FB}}$	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
$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$ $^{(\dagger\triangle)}$	2760 ± 9	Yes	2758 ± 9	2716 ± 39	2715 ± 37
$\alpha_s(M_Z^2)$	–	Yes	0.1194 ± 0.0029	0.1194 ± 0.0029	0.1194 ± 0.0028

$Z \to \mu\mu$ 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

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Eur. Phys. J. **C73** (2013) 2474
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Total: 5 MeV

Systematic uncertainty: boson p_T modeling

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- 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

W width

- Fixed to the SM value
- However, it could be better use the SM prediction
- $$\Gamma_W = (3 + 2 f_{QCD}) \frac{G_F M_W^3}{6\sqrt{2}\pi}(1 + \delta),$$