W mass measurement at LHCb

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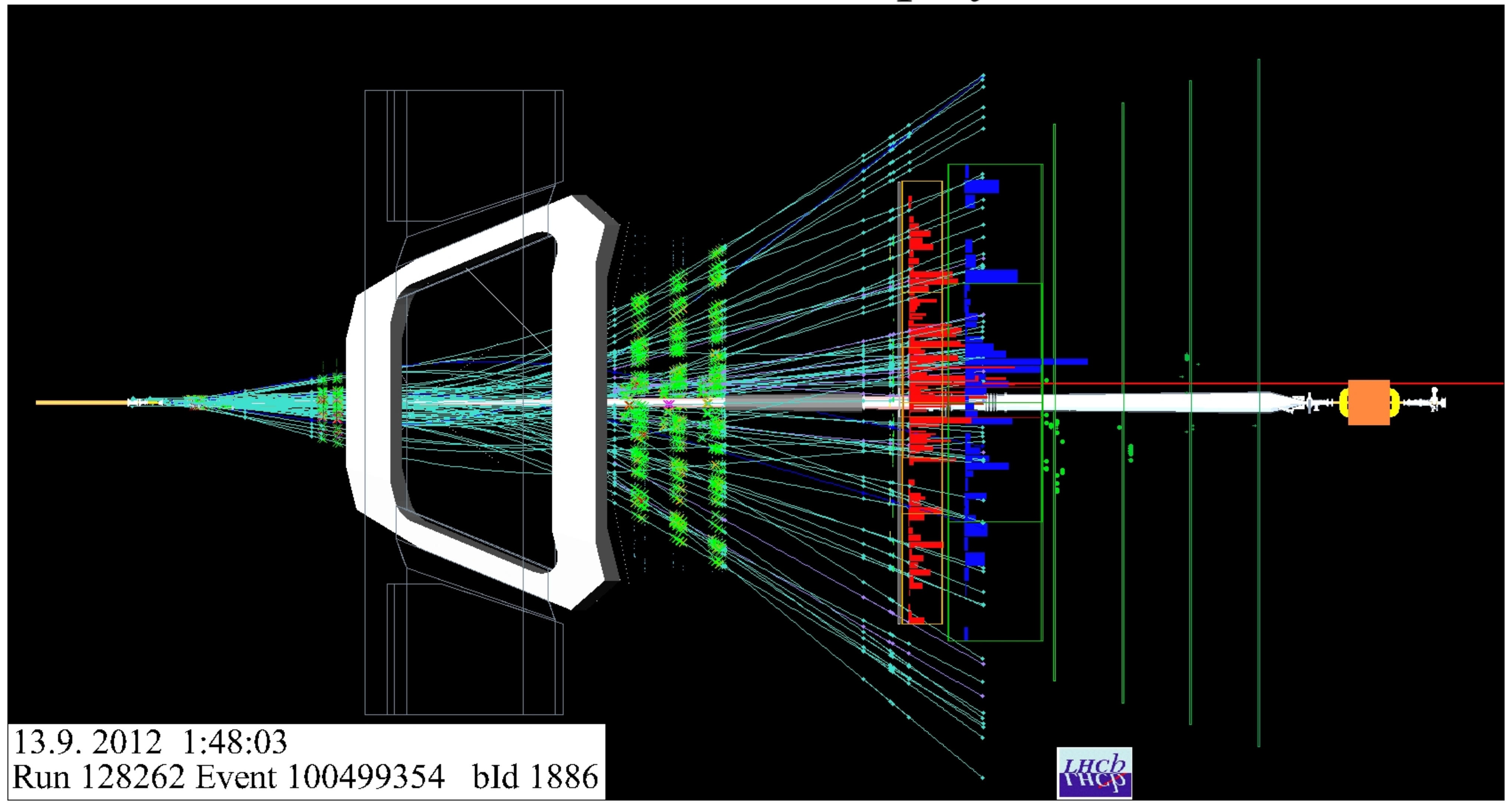
Introduction

- The environment of proton-proton colliders is probably the **most challenging** for the W boson mass measurement
- Experimental conditions are not as clean as at lepton colliders
- The W boson production modeling is more under control at proton-anti-proton colliders
- **LHCb** has been designed as a flavour physics experiment, but it has developed a wide and rich **electroweak program**
- At LHCb millions of W bosons can be analyzed to extract the W boson mass measurements, **the challenge has been accepted!**

LHCb Event Display



LHCb

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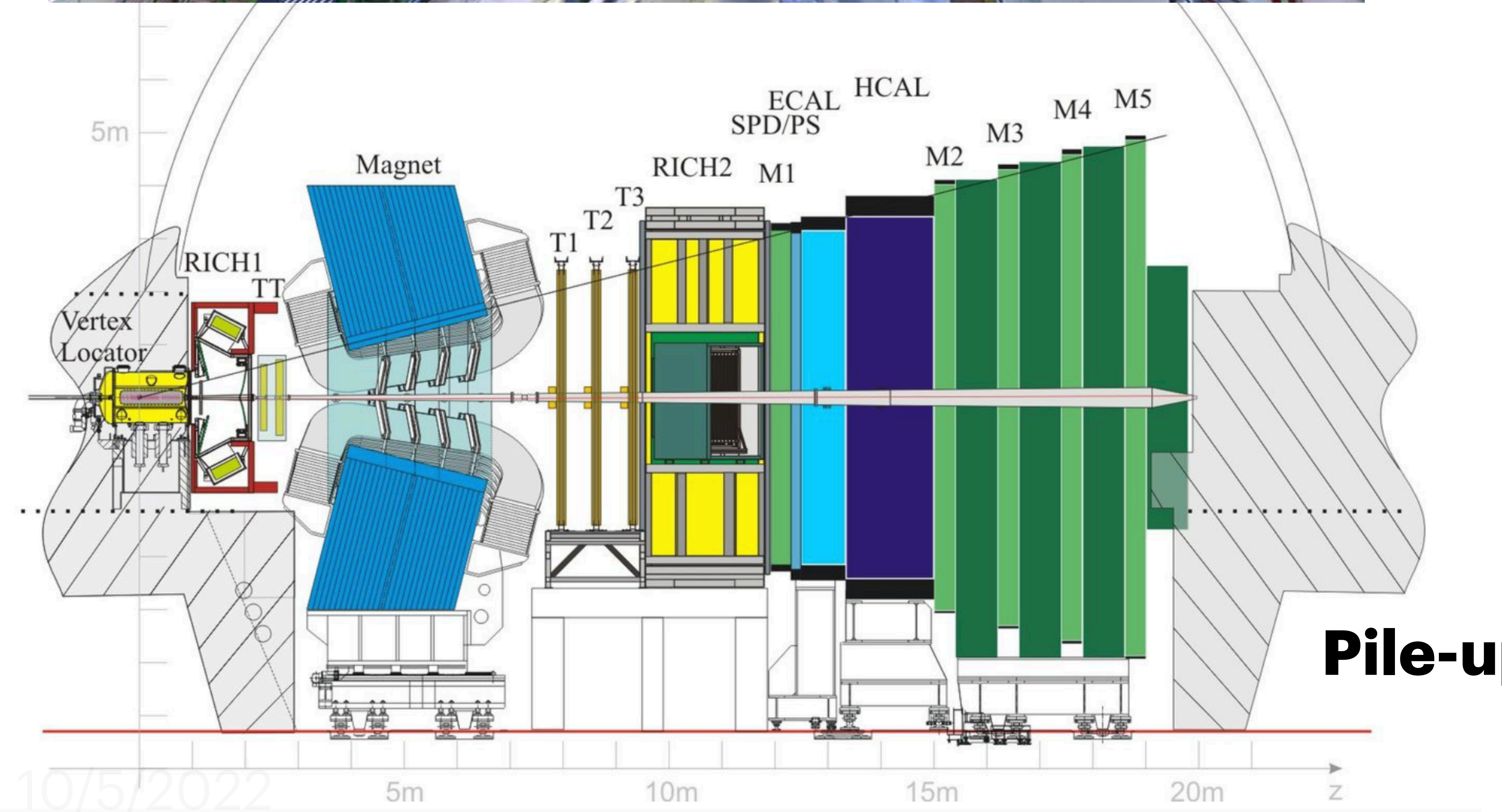
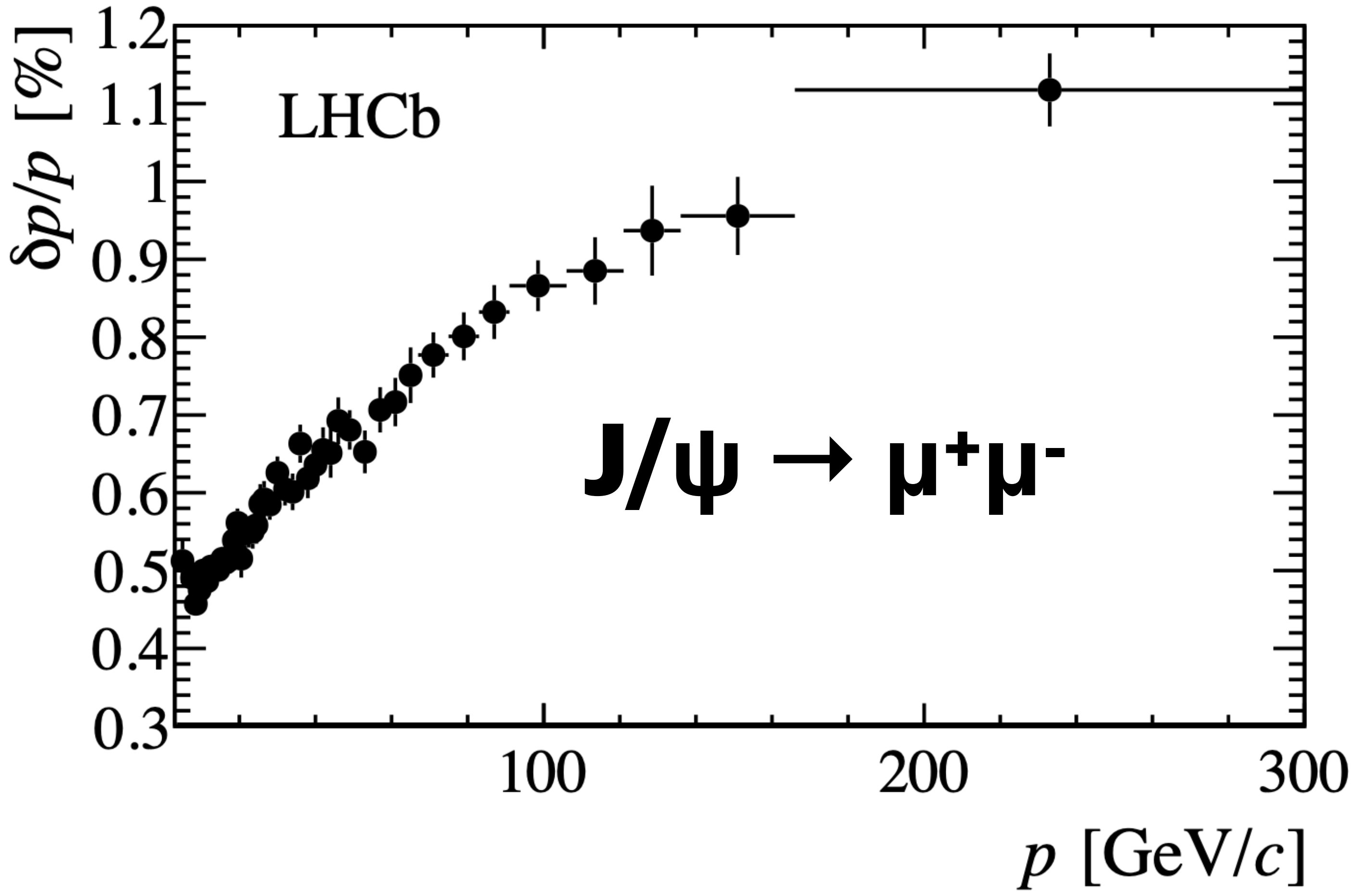
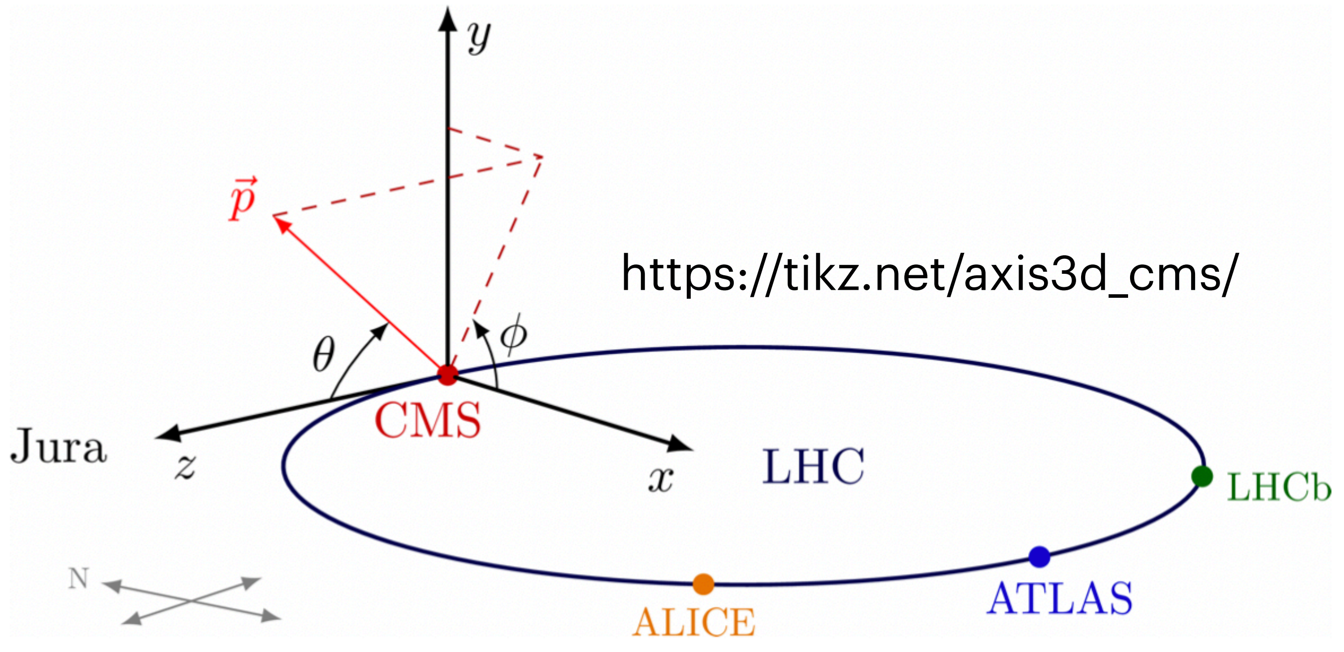
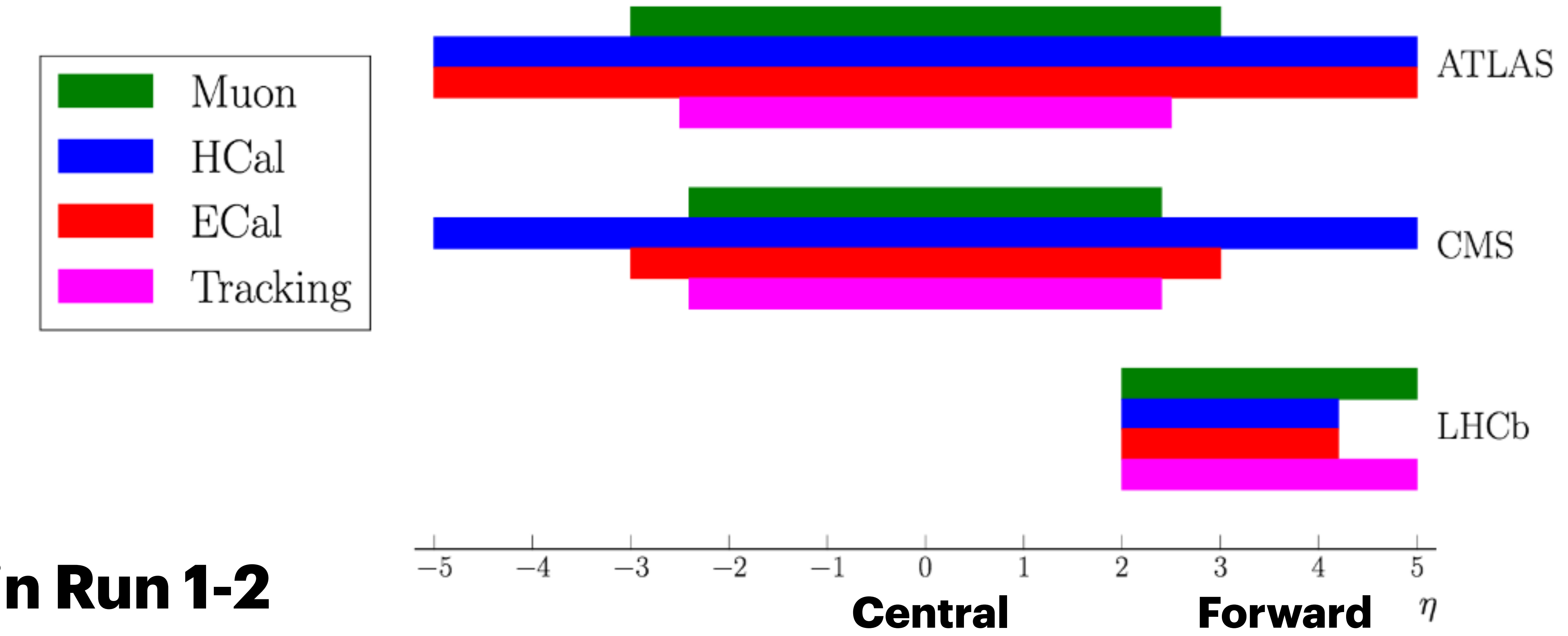
General purpose detector in the forward region







$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



Pile-up ~1 in Run 1-2

Complementarity

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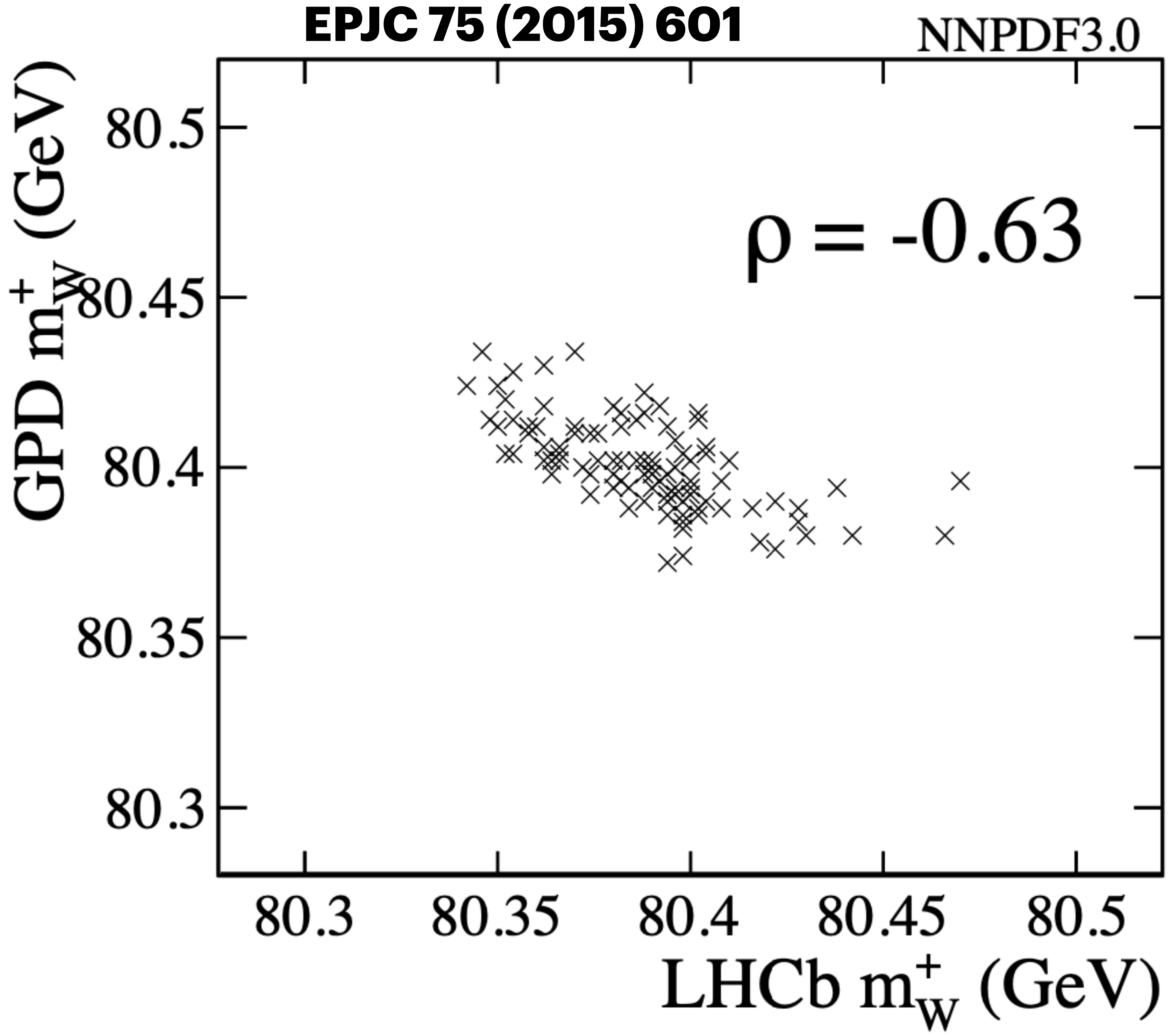
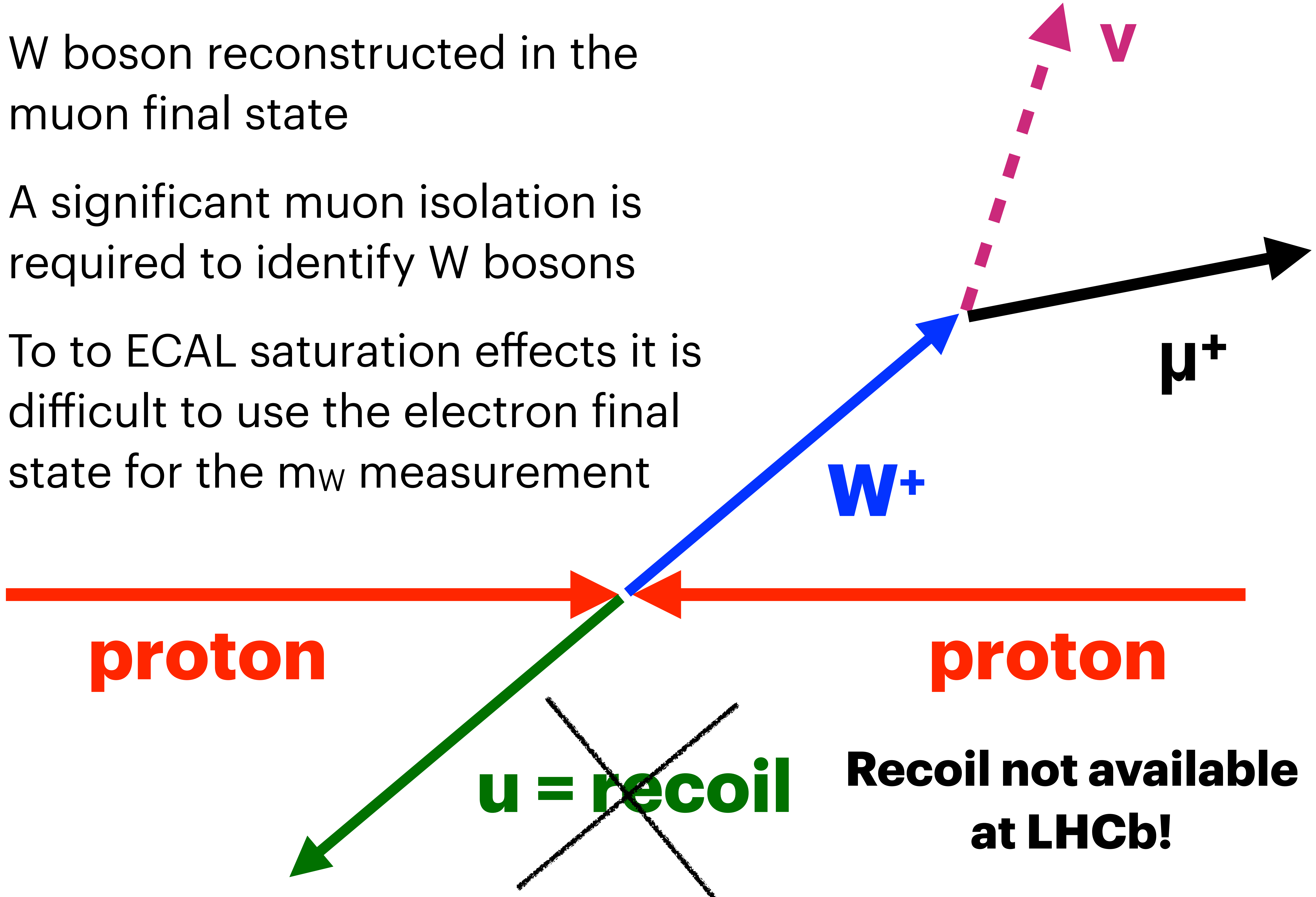


GPD = General Purpose Detectors = ATLAS/CMS

- PDFs uncertainties in the W mass measurement are anti-correlated between the central and forward region
- Combining ATLAS/CMS+LHCb can reduce the PDFs uncertainty
- All the three experiments can significantly contribute in a LHC-wide average
- **The overall average is ultimately the quantity that matters**

W boson identification at LHCb

- W boson reconstructed in the muon final state
- A significant muon isolation is required to identify W bosons
- To to ECAL saturation effects it is difficult to use the electron final state for the m_W measurement



Recoil not available at LHCb!

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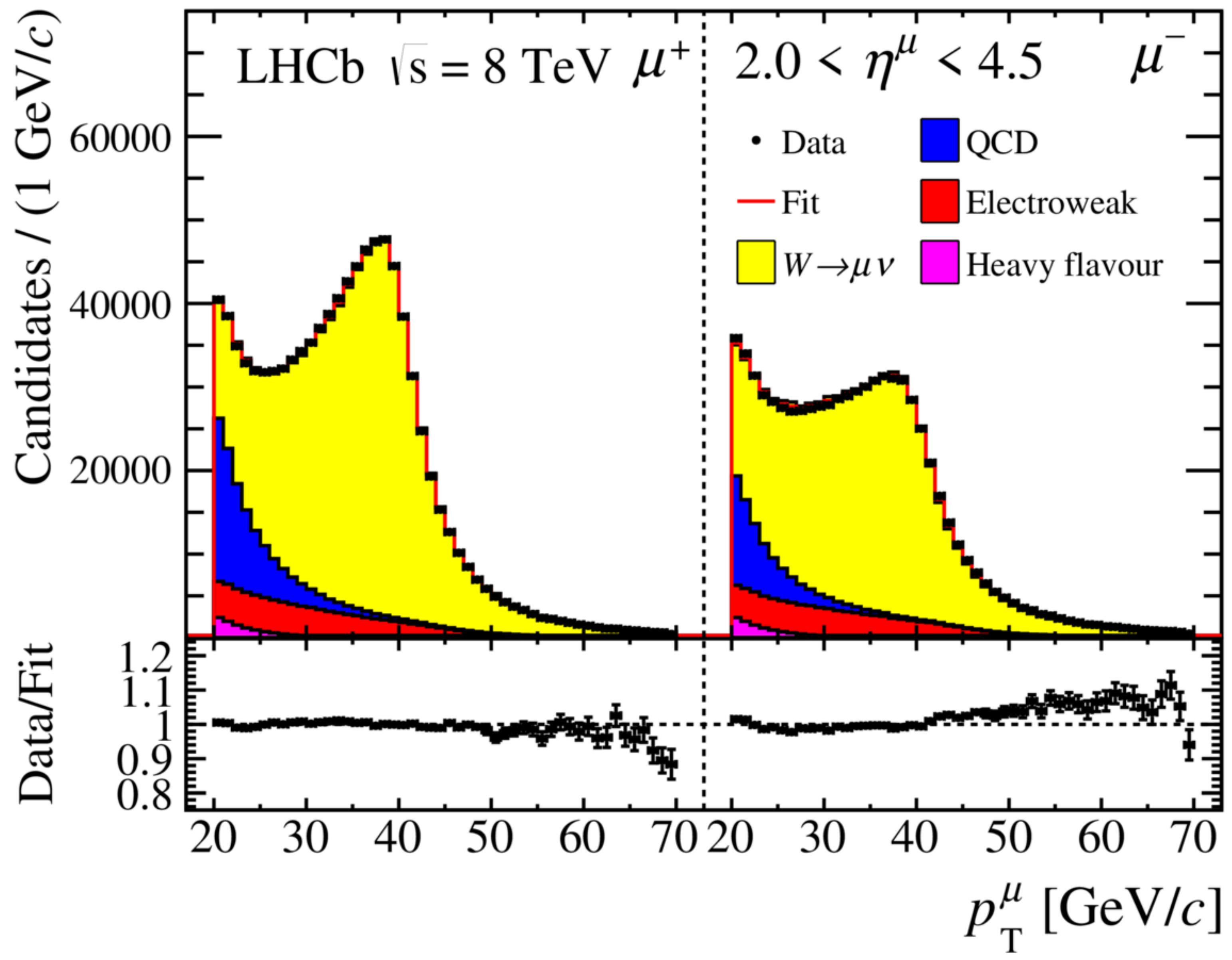

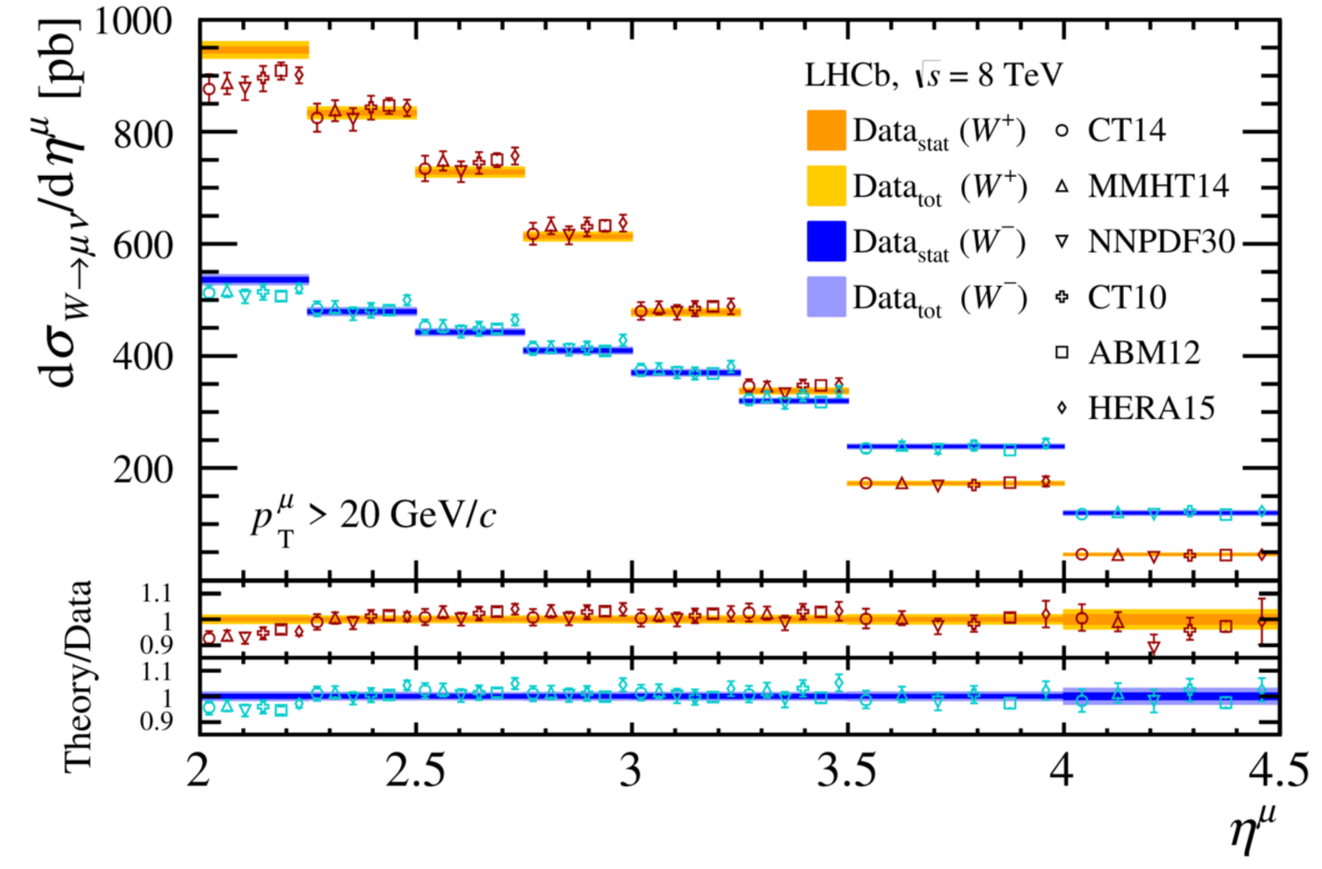

W mass measurement at LHCb

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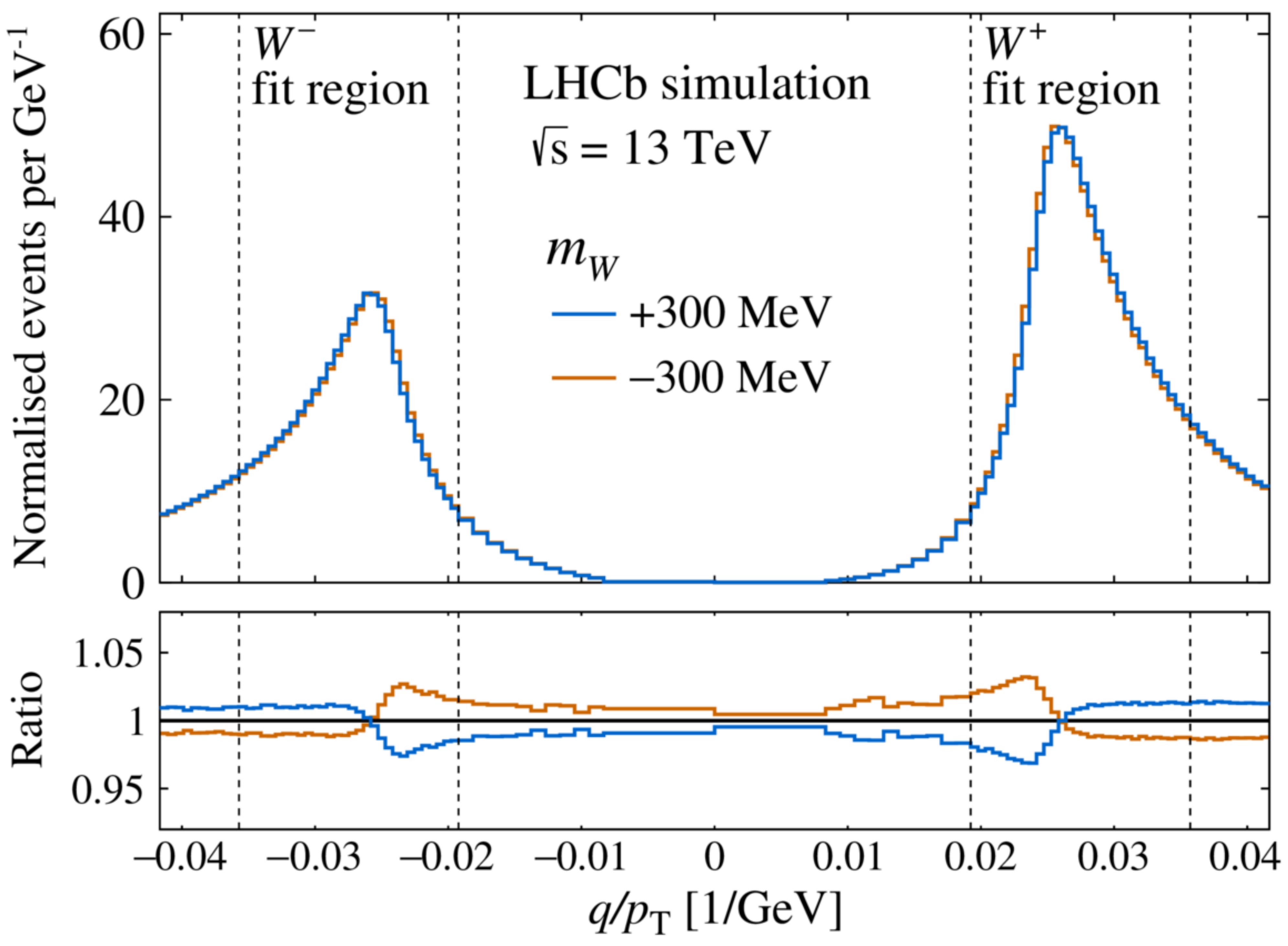
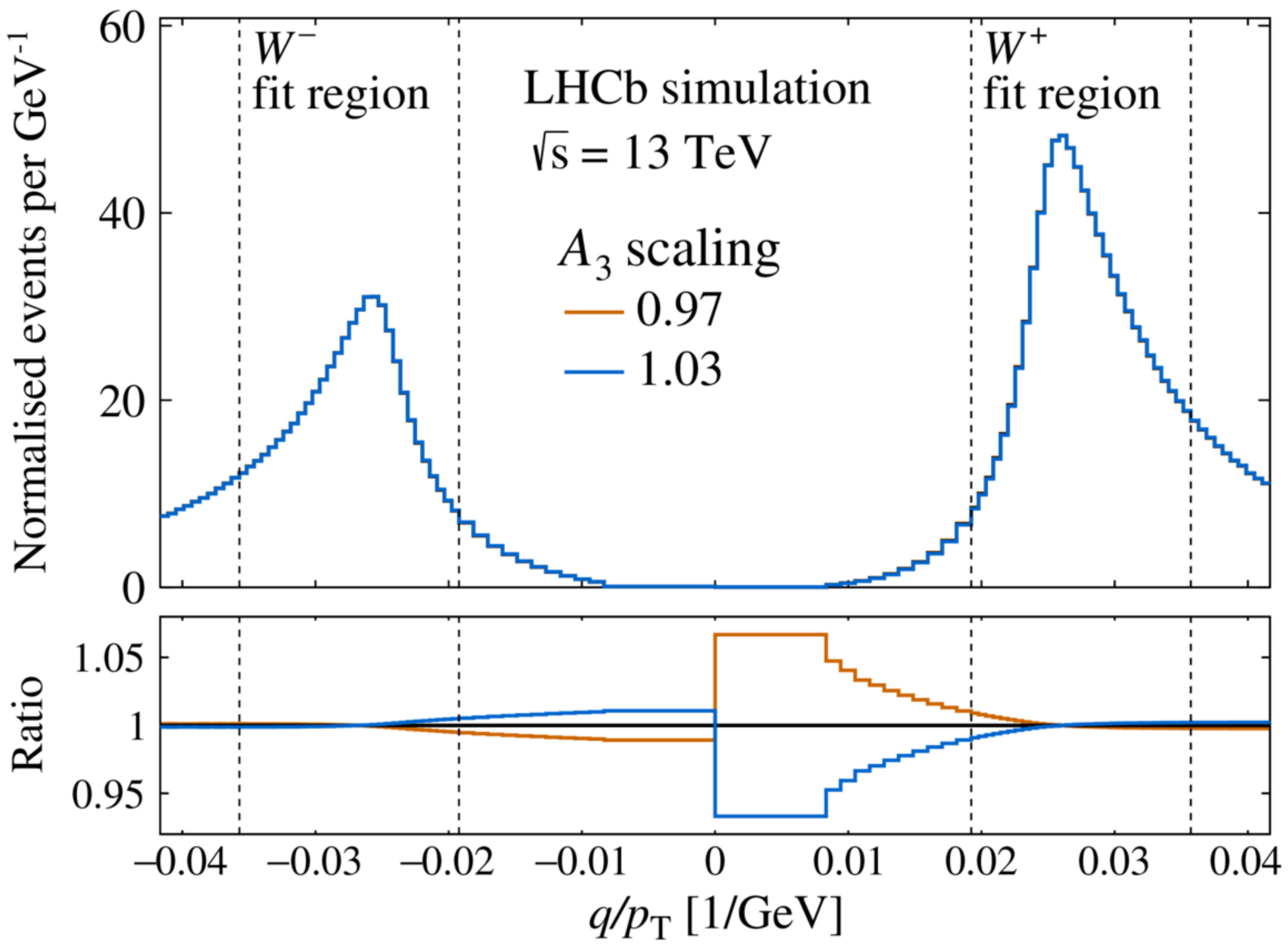
- Measurement with muon final state, just a part of the Run 2 dataset has been used (1.7 fb^{-1})
- **Simultaneous fit to W boson q/p_T and Z^0 boson ϕ^***

$$\phi^* = \frac{\tan((\pi - \Delta\phi)/2)}{\cosh(\Delta\eta/2)} \sim \frac{p_T^Z}{M}$$

- 28 < $p_T(\mu)$ < 52 GeV is the optimal range for the fit: **2.4M W candidates**





Modeling

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

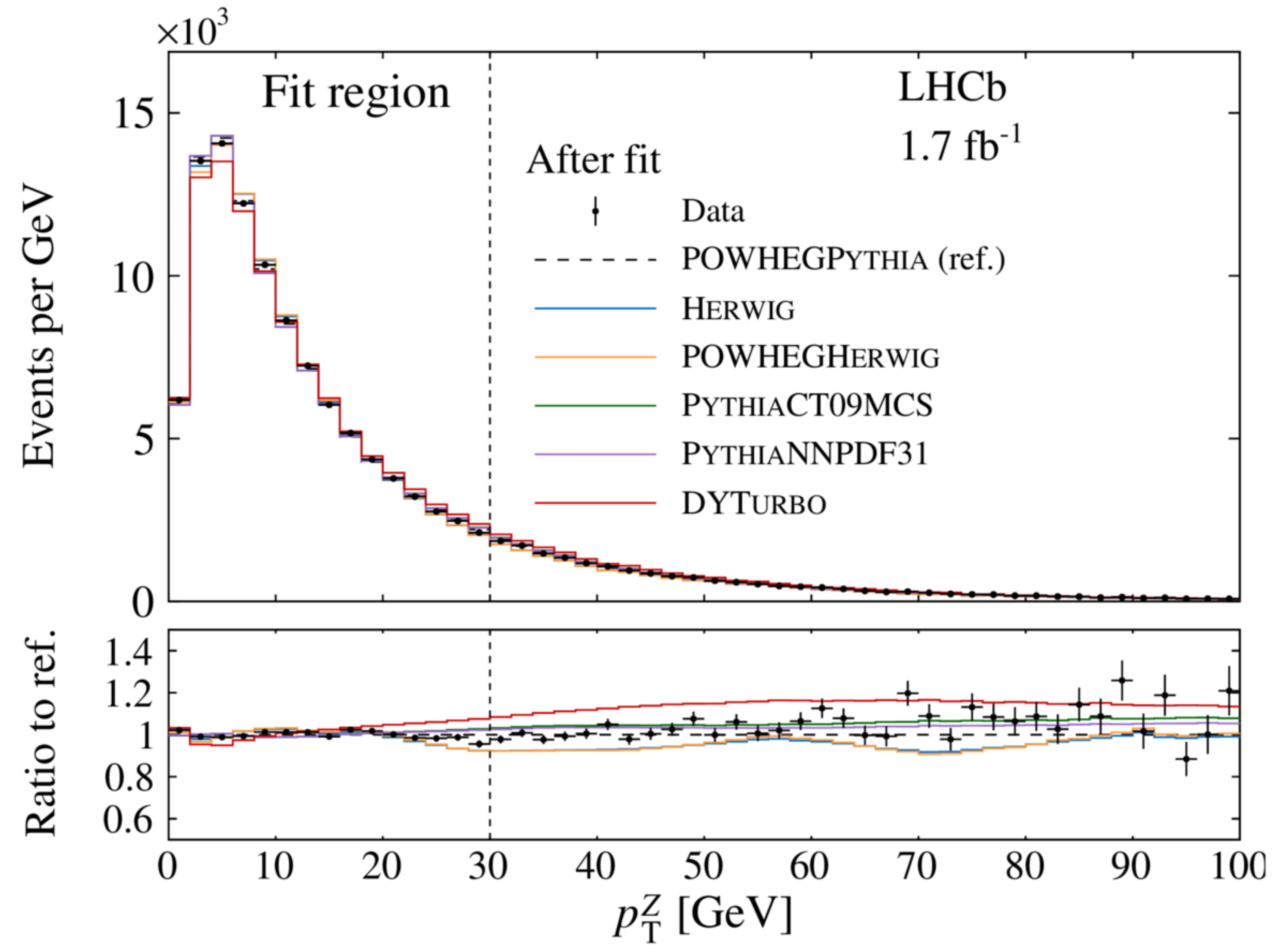
Inv. mass: Breit Wigner

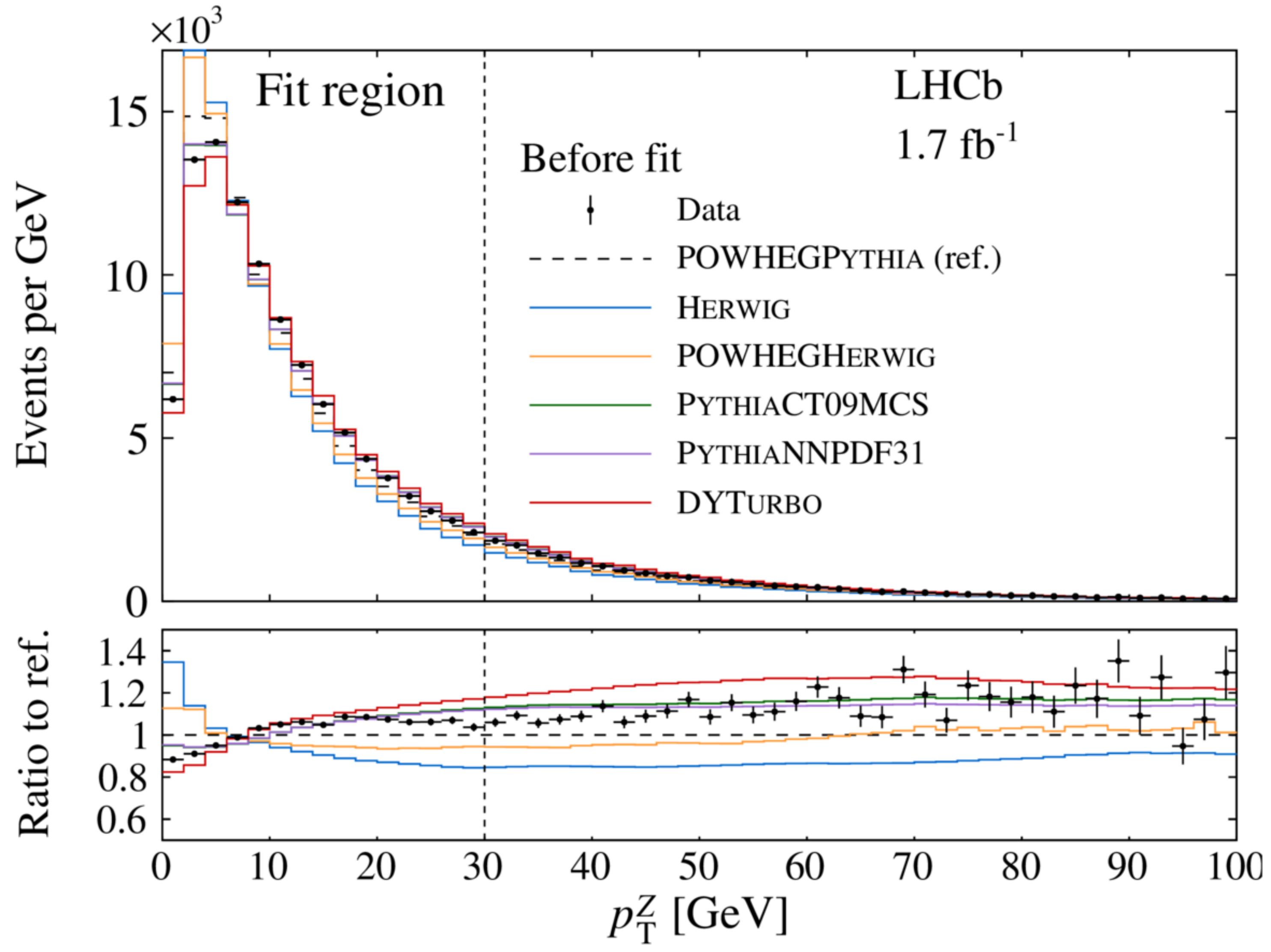
Rapidity: fixed order pQCD

p_T: parton shower

Angular coefficients: fixed order pQCD

- As for ATLAS, Powheg+Pythia is used as baseline simulation
- Pythia QCD parameters are fitted to match $p_T(Z^0 \rightarrow \mu^+\mu^-)$ distribution
- Templates reweighted also to match DYTurbo
- Pythia, Photos, Herwig for QED description
- Three different PDFs sets: NNPDF3.1, CT18, MSHT20





Muon curvature biases

- ATLAS determined the curvature bias (δ) in E/p calibration for electrons: usable only if muon and electron reconstruction has a comparable performance
- Due to saturation effects in ECAL, at LHCb electrons are not usable for this purpose
- **Pseudo-mass method applied to $Z^0 \to \mu^+\mu^-$:** does not depend from the magnitude of the momentum

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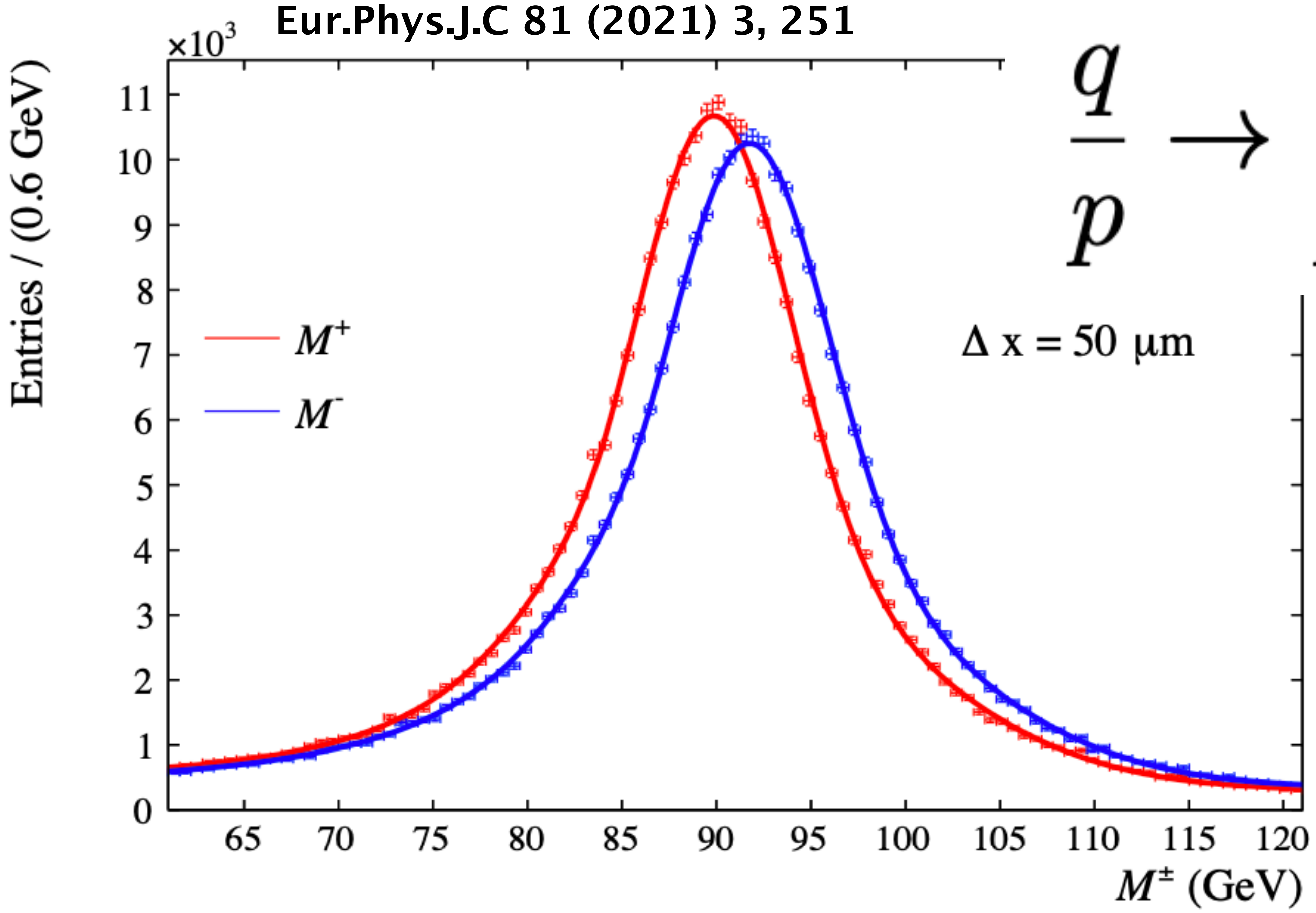
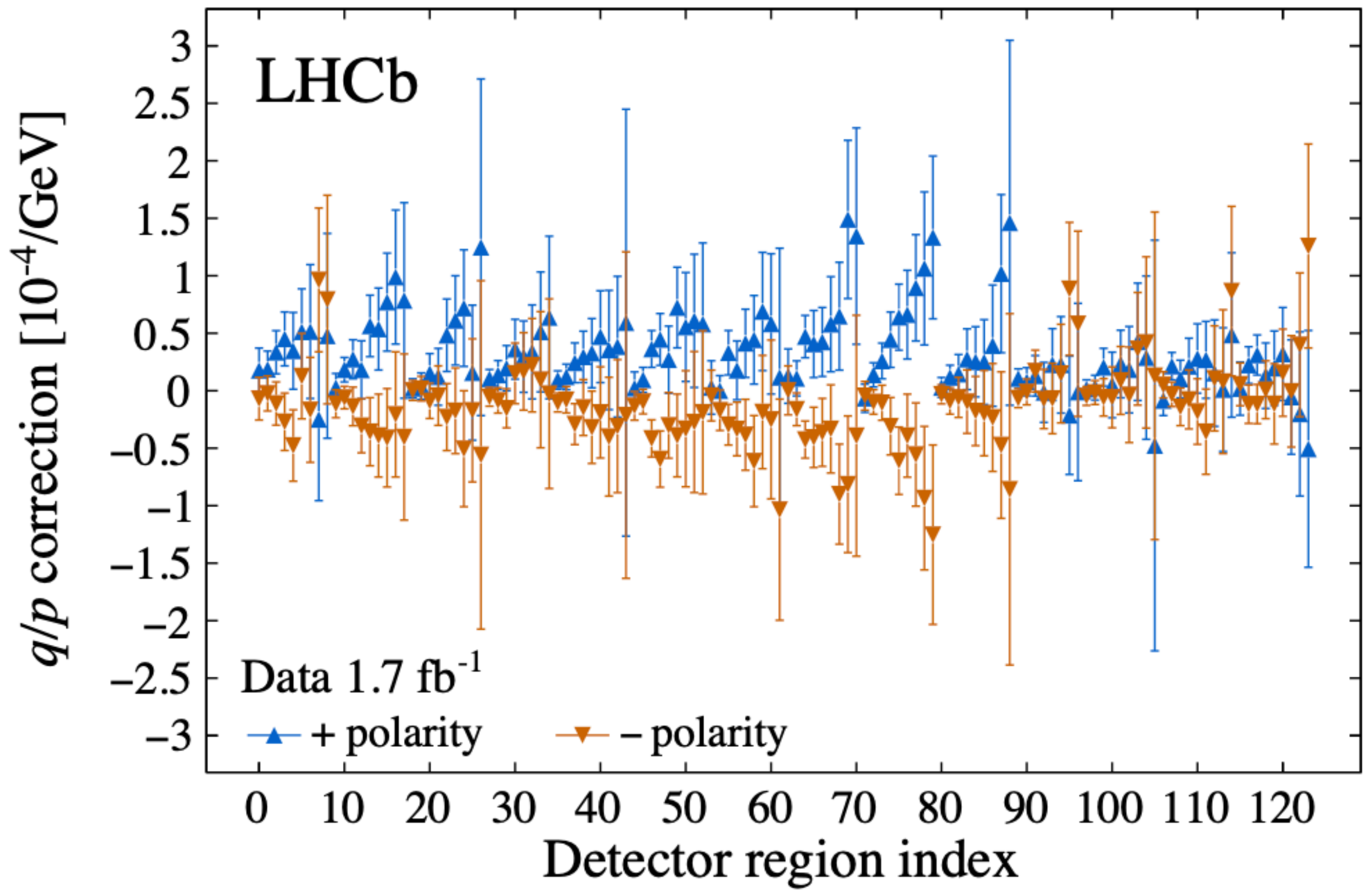


$$\frac{q}{p} \to \frac{q}{p} + \delta$$

$$\mathcal{M}^{\pm} = \sqrt{2p^{\pm}p_{\mathrm{T}}^{\pm}\frac{p^{\mp}}{p_{\mathrm{T}}^{\mp}}(1-\cos\theta)}$$

$$\delta \approx A\frac{<\frac{1}{p^{+}}> + <\frac{1}{p^{-}}>}{2}$$

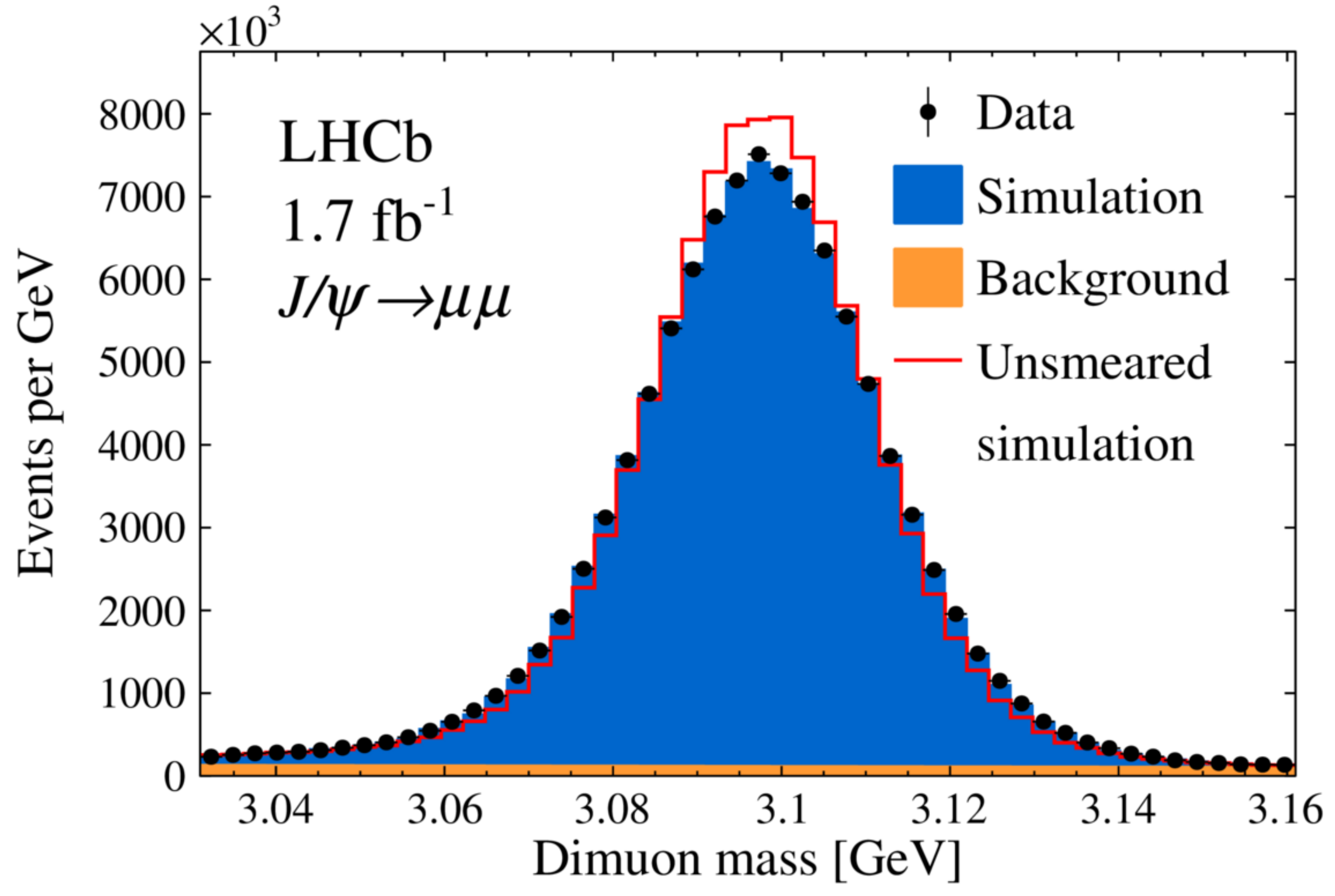


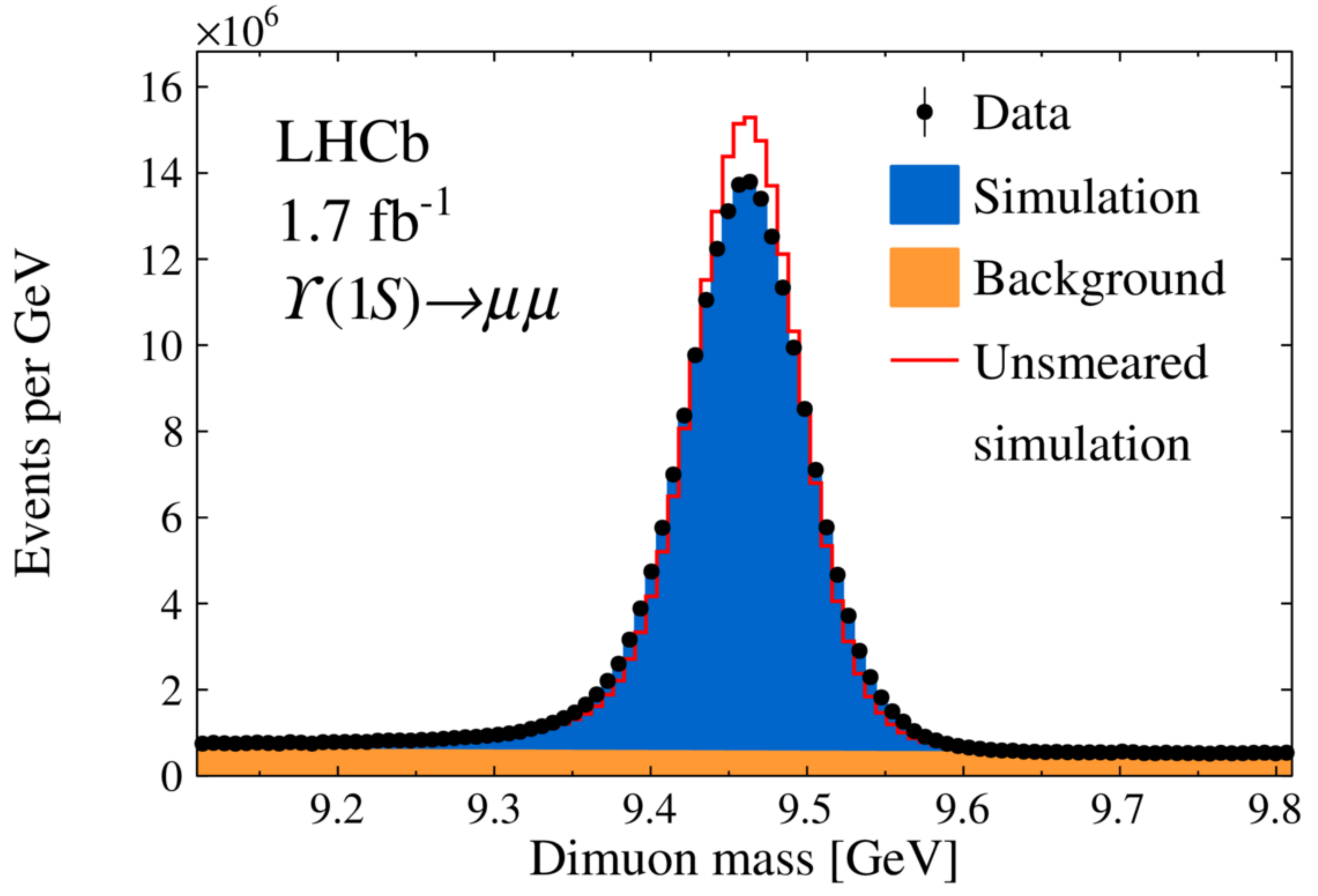
Muon calibration

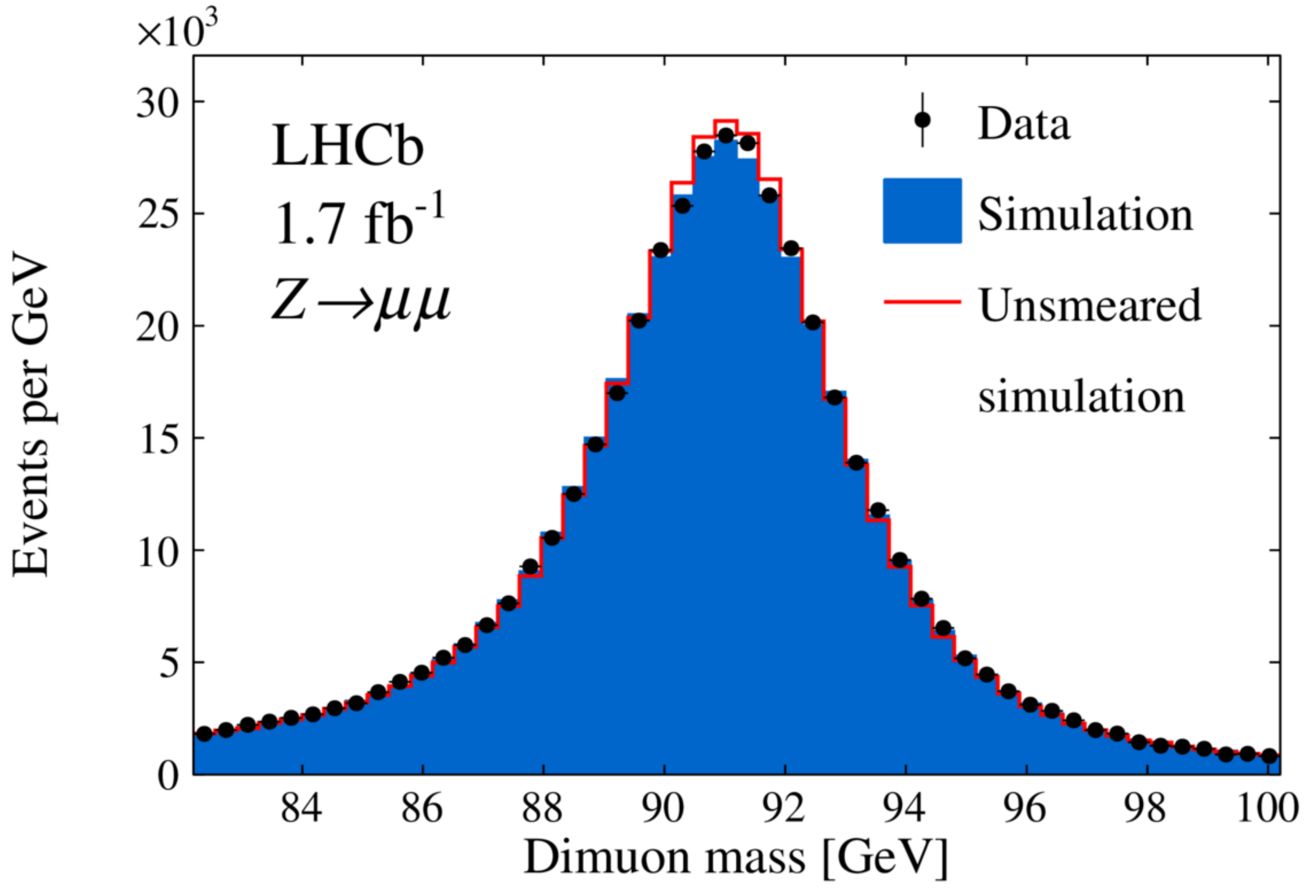
- Muon momentum scale and resolution obtained with several dimuon resonances samples
- Reconstruction efficiencies with tag & probe $\mathbf{Z^0 \rightarrow \mu^+\mu^-}$

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

scale (α) **smearing** (σ_{MS}) **bias** ($\mathcal{N}(\delta, \sigma_\delta/\cosh\eta)$)

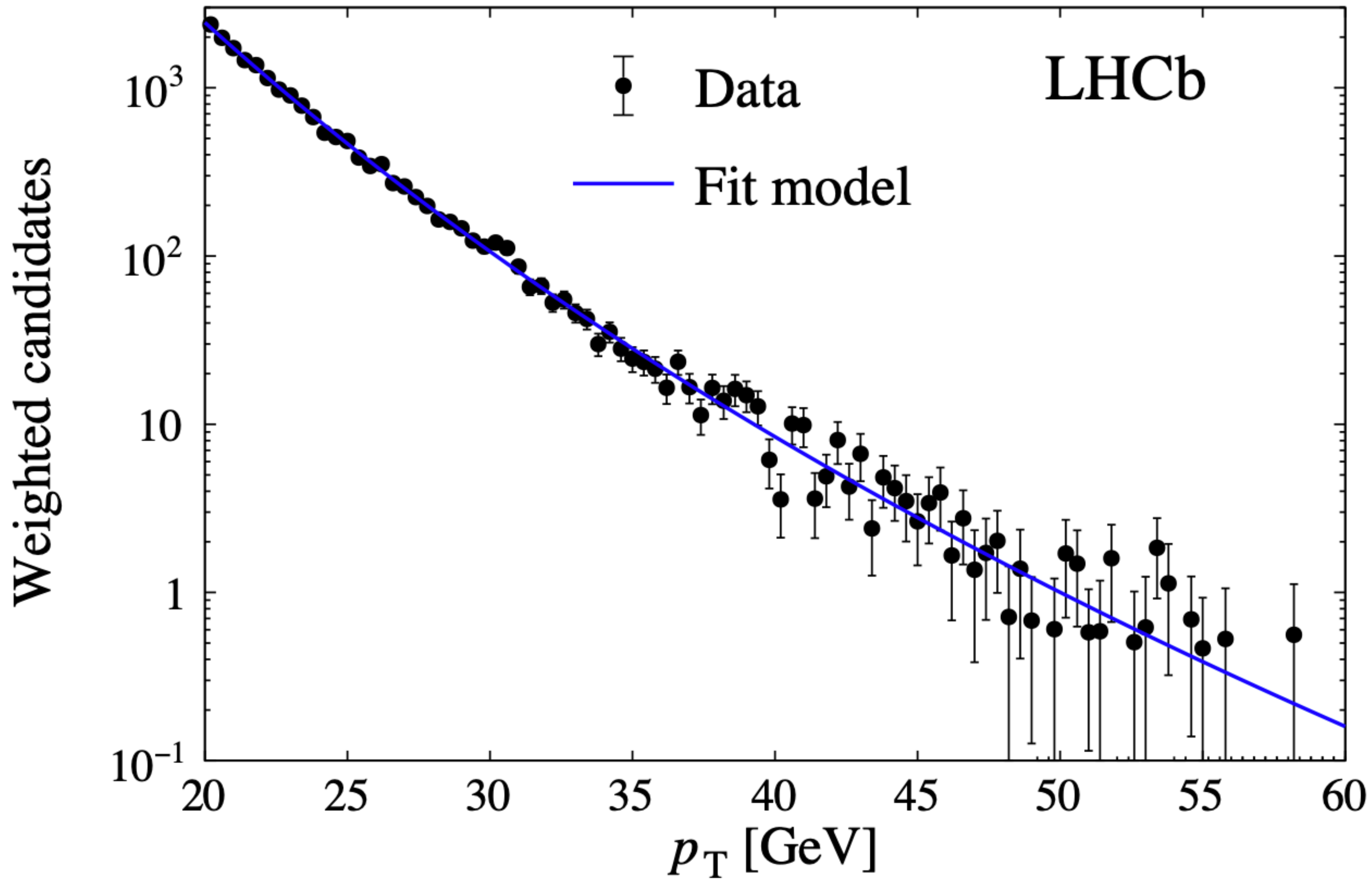






Background

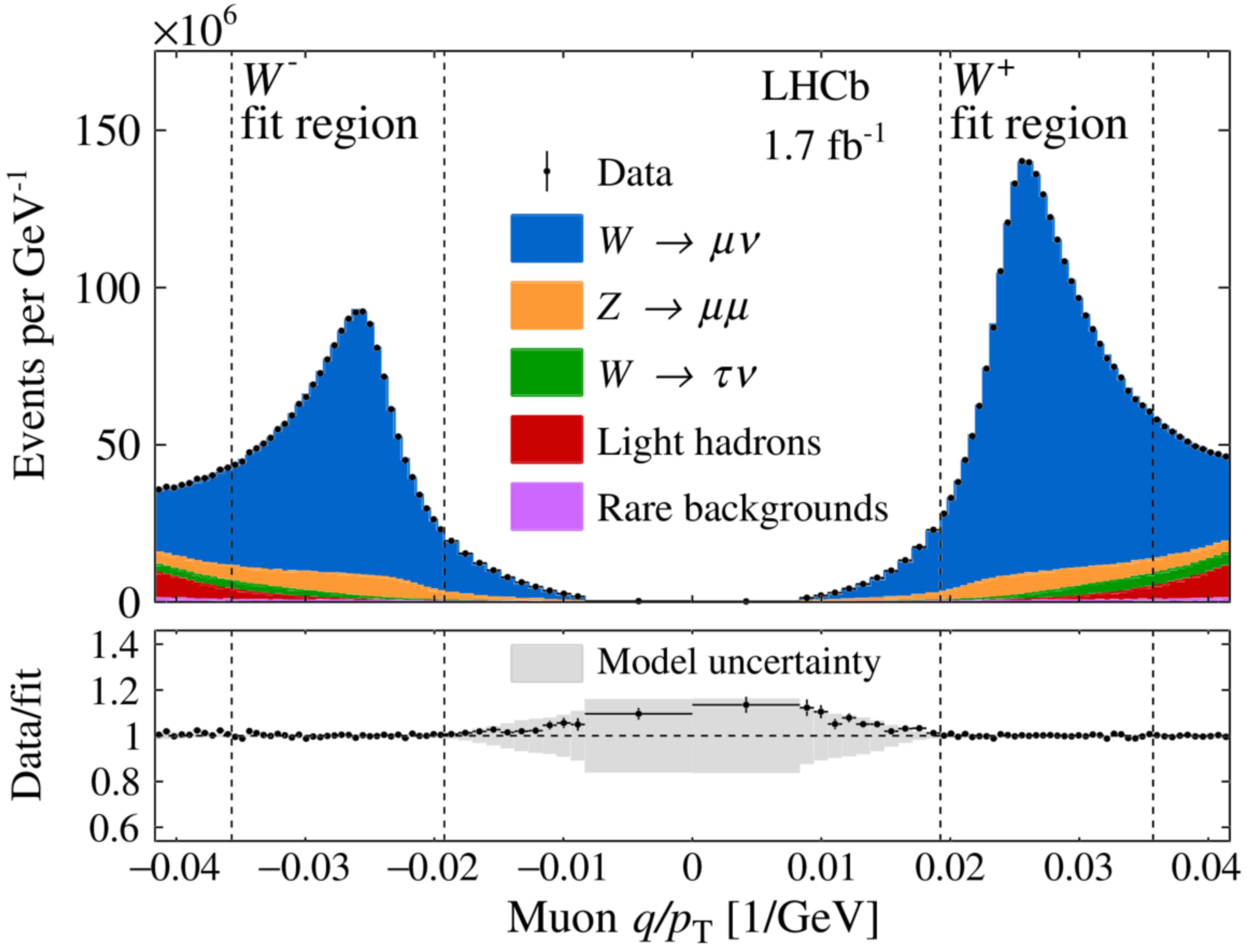
- Most of backgrounds are modeled with simulated samples: single-top, quark/anti-quark (t, b, c), Z/W decays, Drell-Yan
- QCD background (decays-in-flight) has been obtained with a data-driven technique, by inverting the muon identification cuts (i.e. impact parameter/isolation)
- This model (Hagedorn distribution) accurately describes the region of the Jacobian peak

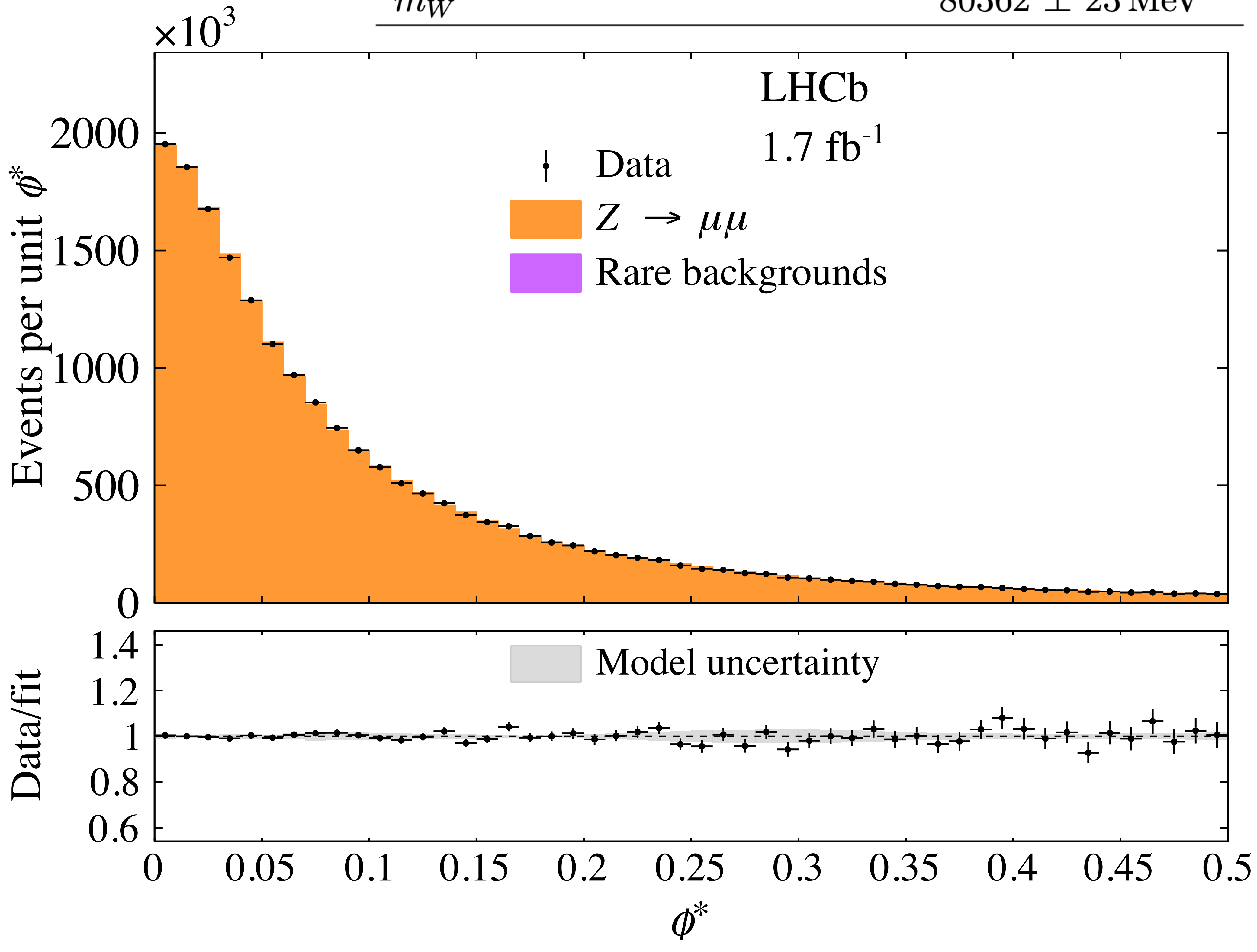


W mass fit result

- Several QCD parameters and A_3 scaling are also extracted from the m_W template fit

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





Systematics and cross-checks

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

Statistical uncertainty still large: with the full Run 2 dataset a total uncertainty < 20 MeV is already possible

Cross checks:

- W-like measurement of Z^0 boson mass
- Consistency of orthogonal subsets: muon charge, magnet polarities, ϕ, η
- Fit p_T range
- Fit model freedom
- NNLO vs NLO PDFs

$m_W = 80362 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ MeV, **NNPDF3.1**

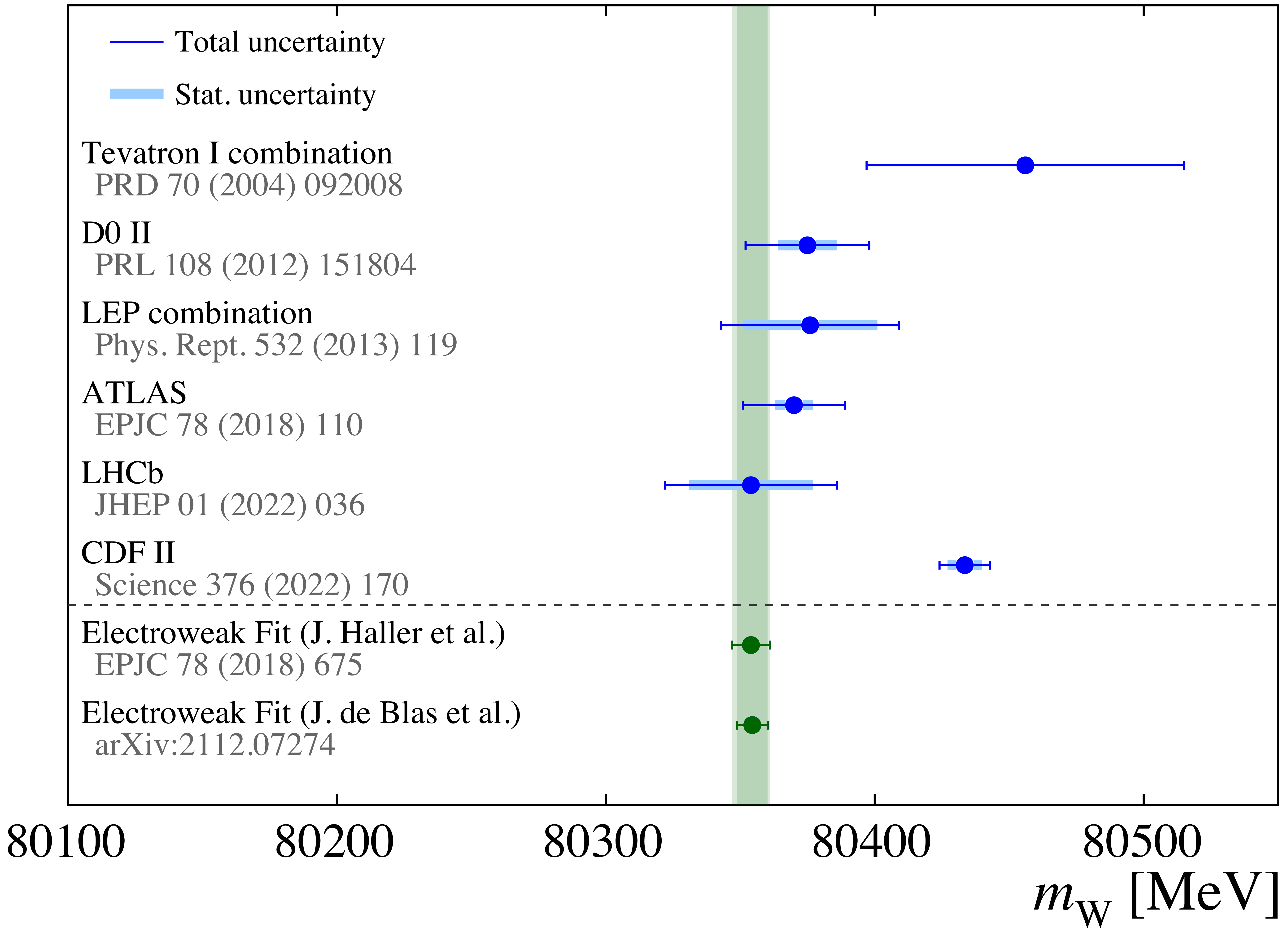
$m_W = 80350 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 12_{\text{PDF}}$ MeV, **CT18**

$m_W = 80351 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 7_{\text{PDF}}$ MeV, **MSHT20**

Final result:

$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

Comparison with CDF



- Significant displacement between new CDF II measurement and other most precise measurements
- LHC measurements are closer to the Electroweak Fit prediction with respect to CDF II
- However precision of CDF II measurement is much better

Comparison with CDF

Uncertainties (in MeV)

	CDF	ATLAS	LHCb
Statistical	6.4	6.8	23
Lepton energy/ momentum scale	2 (μ) + 6 (e)	7* (μ) + 7* (e)	7 (μ)
PDFs	4	7*	9
Model (excl. PDFs)	3.5	8*	17
Total	9.4	18.5	31.4

Modeling

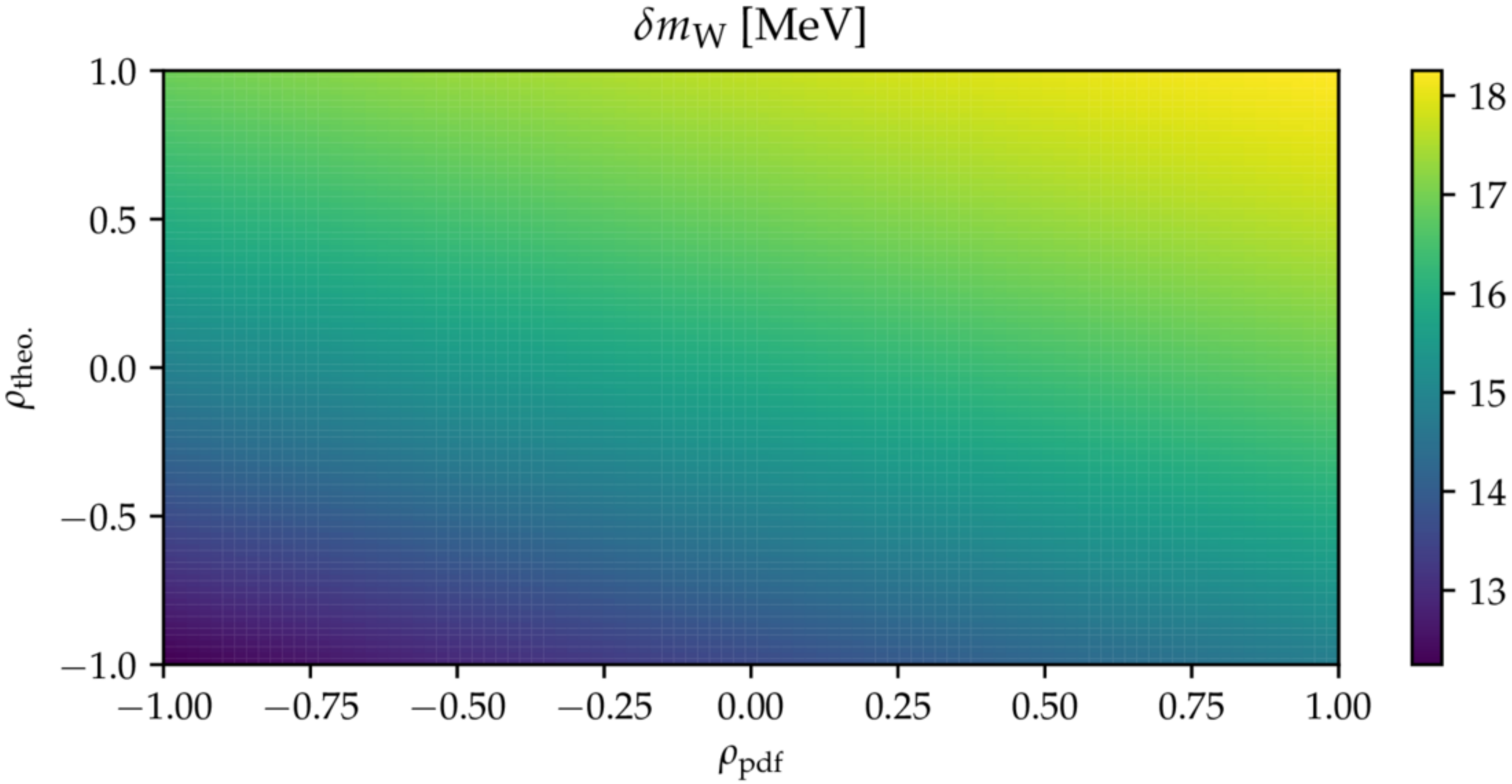
	CDF	ATLAS	LHCb
Baseline	RESBOS	Powheg+Pythia	Powheg+Pythia
Reweight	-	DYNNLO	DYTURBO
Parton shower	data-driven	data-driven	data-driven
QED	PHOTOS+HORACE	PHOTOS	Pythia+PHOTOS+Herwig

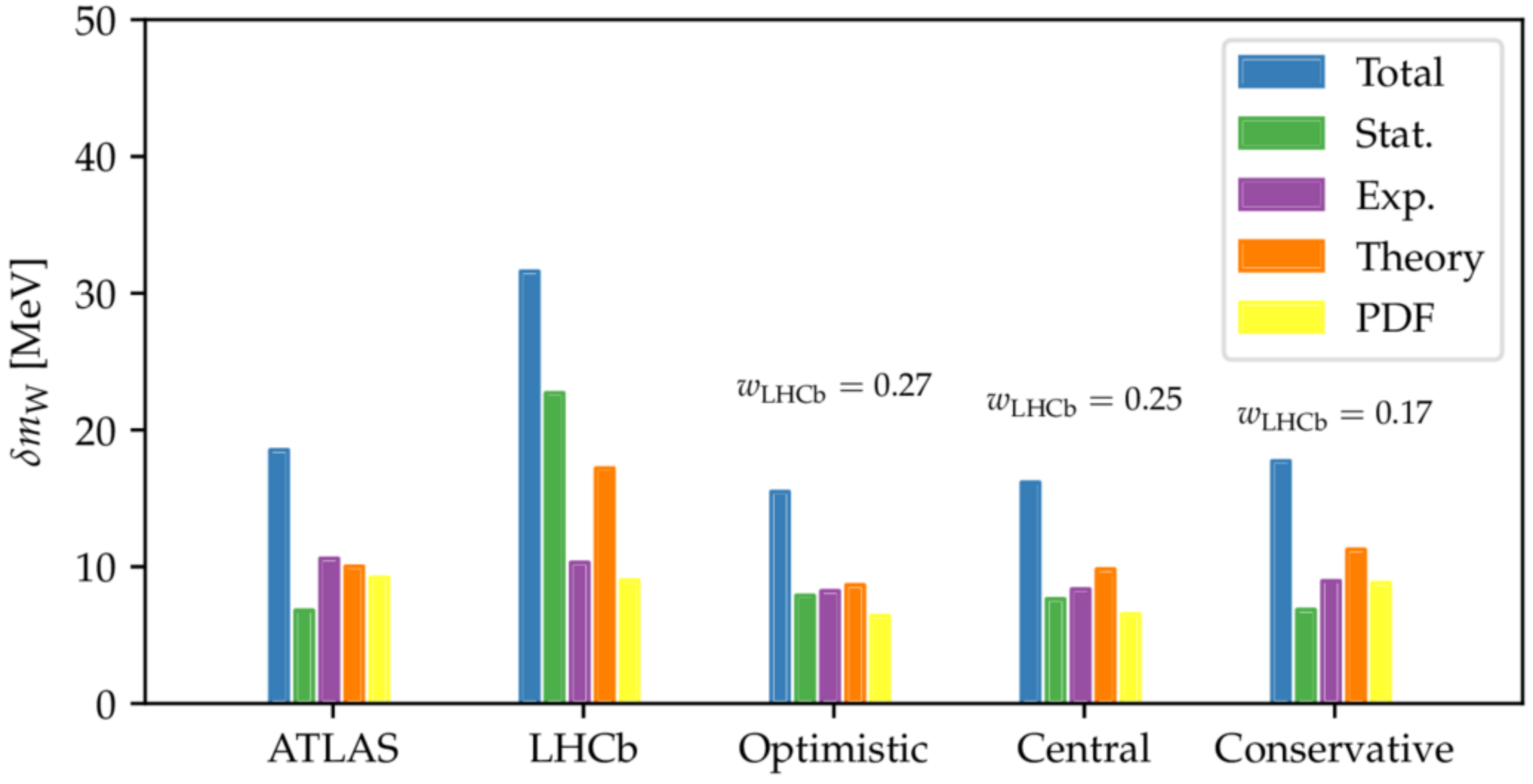
*given separately for p_T and m_T fits, combined assuming 50% correlation

Notice: CDF measurement took profit of the PDFs determination at LHC

LHC combination

- LHC measurements combination is not trivial, it depends on several correlations
- A naive expectation on **ATLAS+LHCb combination** is given





PDFs uncertainty correlation is expected to be negative

Future prospects at LHC

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Scenario	Experiments	δm_W (MeV) Tot	Exp	PDF
Default	2×GPD + LHCb	9.0	4.7	7.7
Default	1×GPD + LHCb	10.1	6.5	7.7
Default	2×GPD	12.0	5.8	10.5
PDF4LHC(3-sets)	2×GPD + LHCb	13.6	4.8	12.7
PDF4LHC(3-sets)	1×GPD + LHCb	14.6	7.3	12.7
PDF4LHC(3-sets)	2×GPD	17.7	5.5	16.9
$\delta^{\text{LHCb}}_{\text{exp}} = 0$	2×GPD + LHCb	8.7	4.0	7.7
$\delta^{\text{LHCb}}_{\text{exp}} = 0$	1×GPD + LHCb	9.8	5.9	7.9
$\delta^{\text{LHCb}}_{\text{exp}} = 0$	2×GPD	12.0	5.8	10.5
$\delta^{\text{GPD}}_{\text{exp}} = 0$	2×GPD + LHCb	7.9	1.9	7.7
$\delta^{\text{GPD}}_{\text{exp}} = 0$	1×GPD + LHCb	7.9	1.9	7.7
$\delta^{\text{GPD}}_{\text{exp}} = 0$	2×GPD	10.5	0.1	10.5
$\delta_{\text{PDF}} = 0$	2×GPD + LHCb	4.6	4.6	0.0
$\delta_{\text{PDF}} = 0$	1×GPD + LHCb	5.8	5.8	0.0
$\delta_{\text{PDF}} = 0$	2×GPD	5.5	5.5	0.0

GPD = General Purpose Detector = ATLAS/CMS

- Not a precise extrapolation, just a way to visualize the contribution of the three experiments to the m_W combination
- Only the PDF uncertainty is considered for the model
- Statistical uncertainty not included

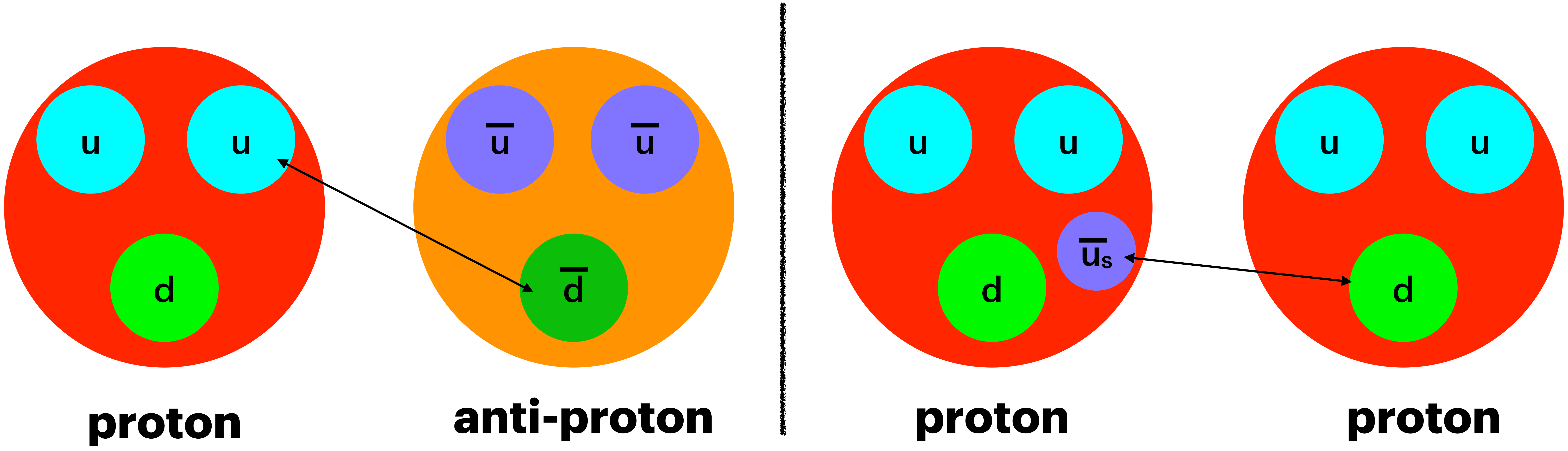
Conclusions

- LHCb have already performed a W mass boson measurement, just with a part of Run 2 data
- A measurement with a precision <20 MeV is possible with the available dataset, the work is currently on-going
- LHCb Upgrade-II for the HL-LHC (https://arxiv.org/abs/1808.08865) will allow 100x higher statistics (x50 from luminosity and x2 from having an ECAL with sufficient dynamic range for $Z \rightarrow ee$)
- There are several ideas to improve the modeling systematic uncertainty
- **The combination of the measurements from the three experiments is fundamental to obtain the final precision at LHC**
- **We have many years before the next lepton collider, LHC could be the the only way to confirm CDF result in the short period**

Thanks for your attention!

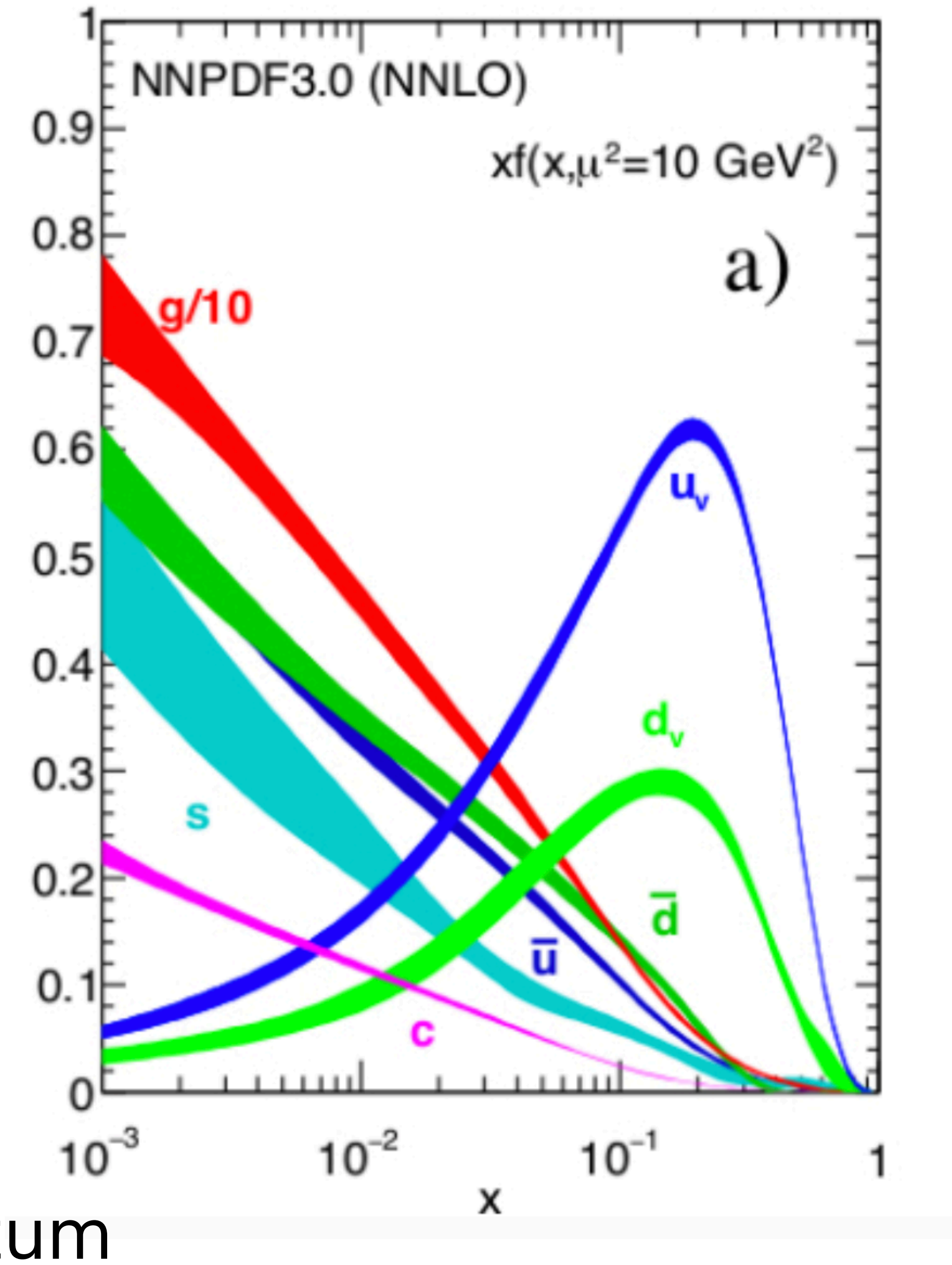
Backup

Proton-anti-proton vs proton-proton



- At Tevatron W boson is mainly produced via valence quark interactions
- At LHC mainly through valence-sea quarks interaction

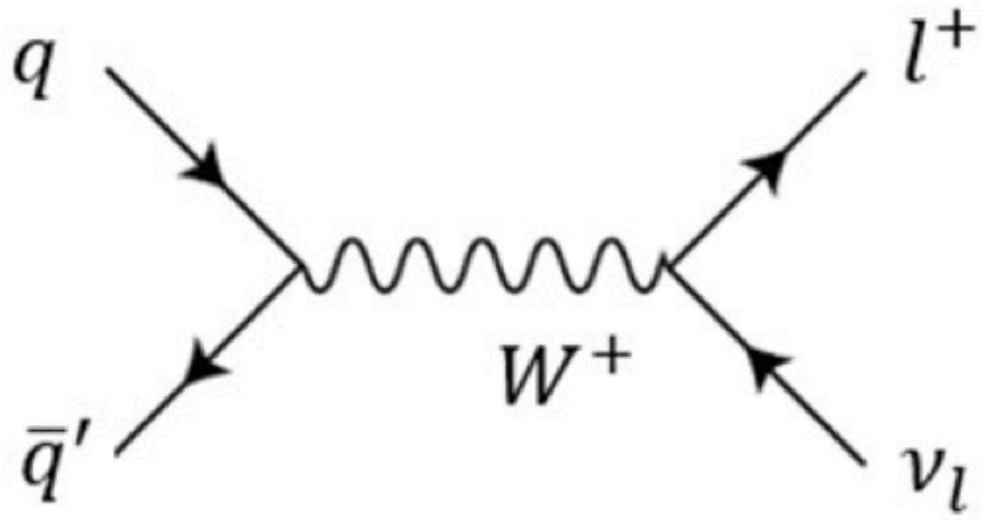
Knowledge of Parton Distribution Functions is fundamental for modeling the W boson production



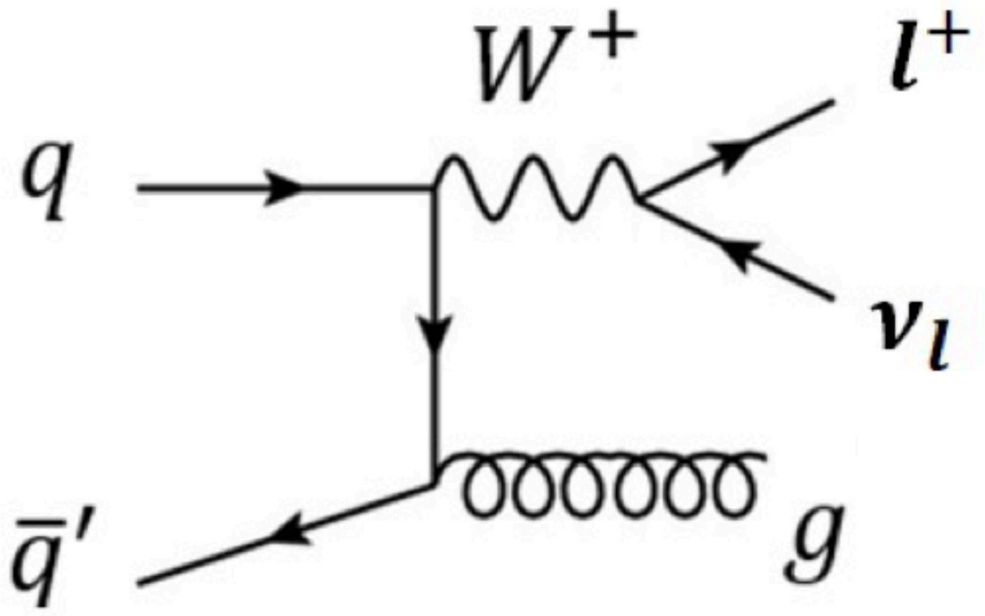
x = fraction of proton momentum taken by the parton

W boson cross section

leading diagrams



$P_T(W)=0$



$P_T(W)>0$

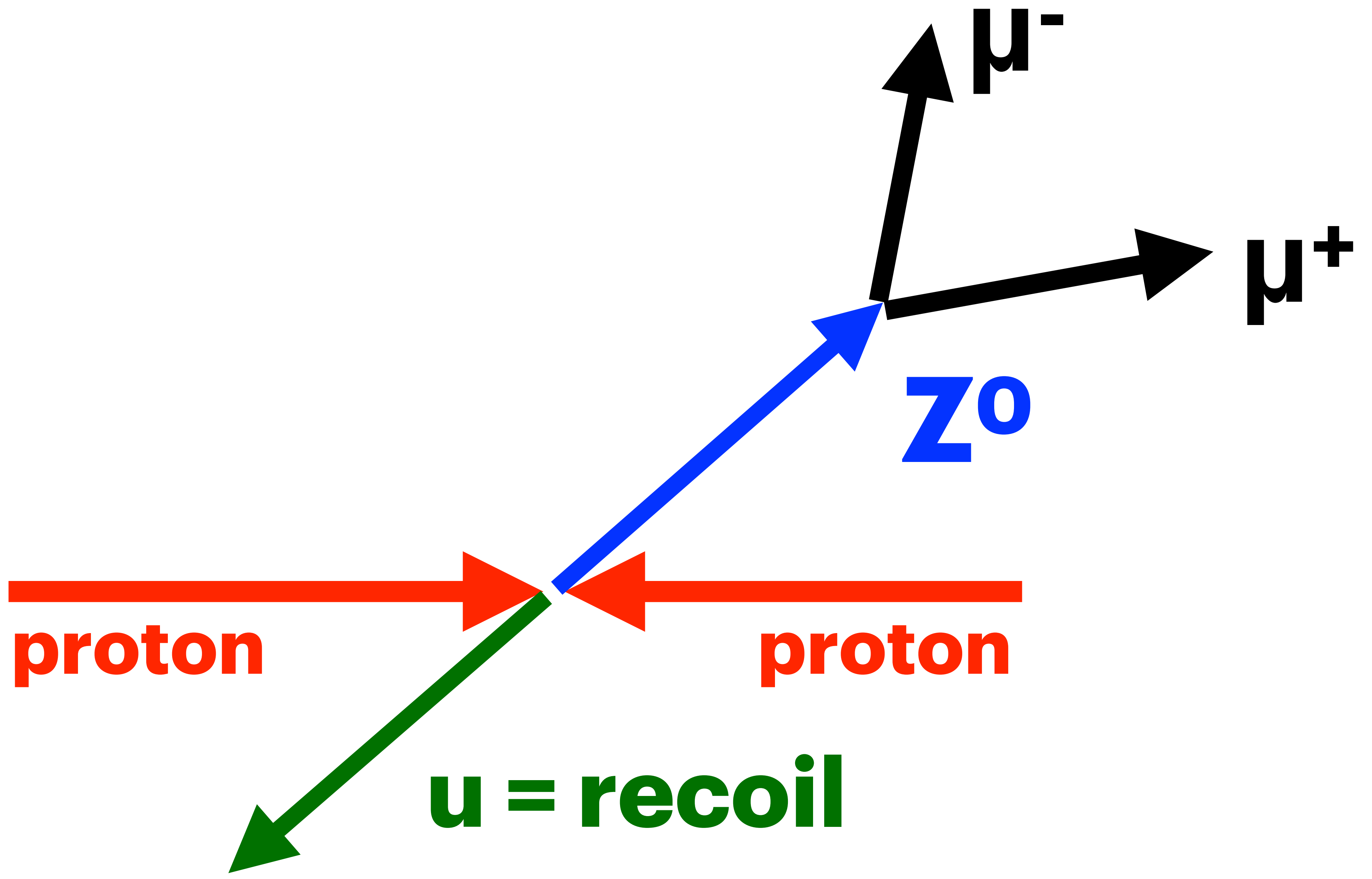
A_i = angular coefficients: ratio between helicity dependent and unpolarized cross-sections

Angular-integrated cross-section

$$\frac{d\sigma}{dp_T^2\,dy\,dm\,d\cos\theta\,d\phi} = \frac{3}{16\pi}\frac{d\sigma}{dp_T^2\,dy\,dm} \times [(1+\cos^2\theta) + A_0\,\frac{1}{2}(1-3\cos^2\theta)$$
$$+\; A_1\,\sin 2\theta\cos\phi + A_2\,\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\,\sin\theta\cos\phi + A_4\,\cos\theta$$
$$+\; A_5\,\sin^2\theta\sin 2\phi + A_6\,\sin 2\theta\sin\phi + A_7\,\sin\theta\sin\phi].$$

Experimental techniques

- Large sample of $Z^0 \to \mu^+\mu^-$ for tuning and validation
- Z^0 fully reconstructed
- energy scale and resolution can be determined by comparing Z^0 data and simulation
- Tag & Probe technique to measure lepton efficiencies in data



- Templates depend from the W boson production model, should be corrected for data/simulation differences

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_1\,\mathrm{d}p_2} = \left[\frac{\mathrm{d}\sigma(m)}{\mathrm{d}m}\right]\left[\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right]\left[\frac{\mathrm{d}\sigma(p_\mathrm{T},y)}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}y}\left(\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_\mathrm{T},y)P_i(\cos\theta,\phi)\right]$$

Inv. mass: Breit Wigner

Rapidity: fixed order pQCD

p_T: parton shower

Angular coefficients: fixed order pQCD

Uncertainties

Experimental uncertainties

- Muon momentum calibration and scale
- Background processes
- Differences between data and simulation for lepton efficiencies

Theoretical uncertainties

- Parton Distribution Functions
- Modeling of $p_T(W)$
- Modeling of angular coefficients A_i
- Modeling of QED radiation

LHCb performance

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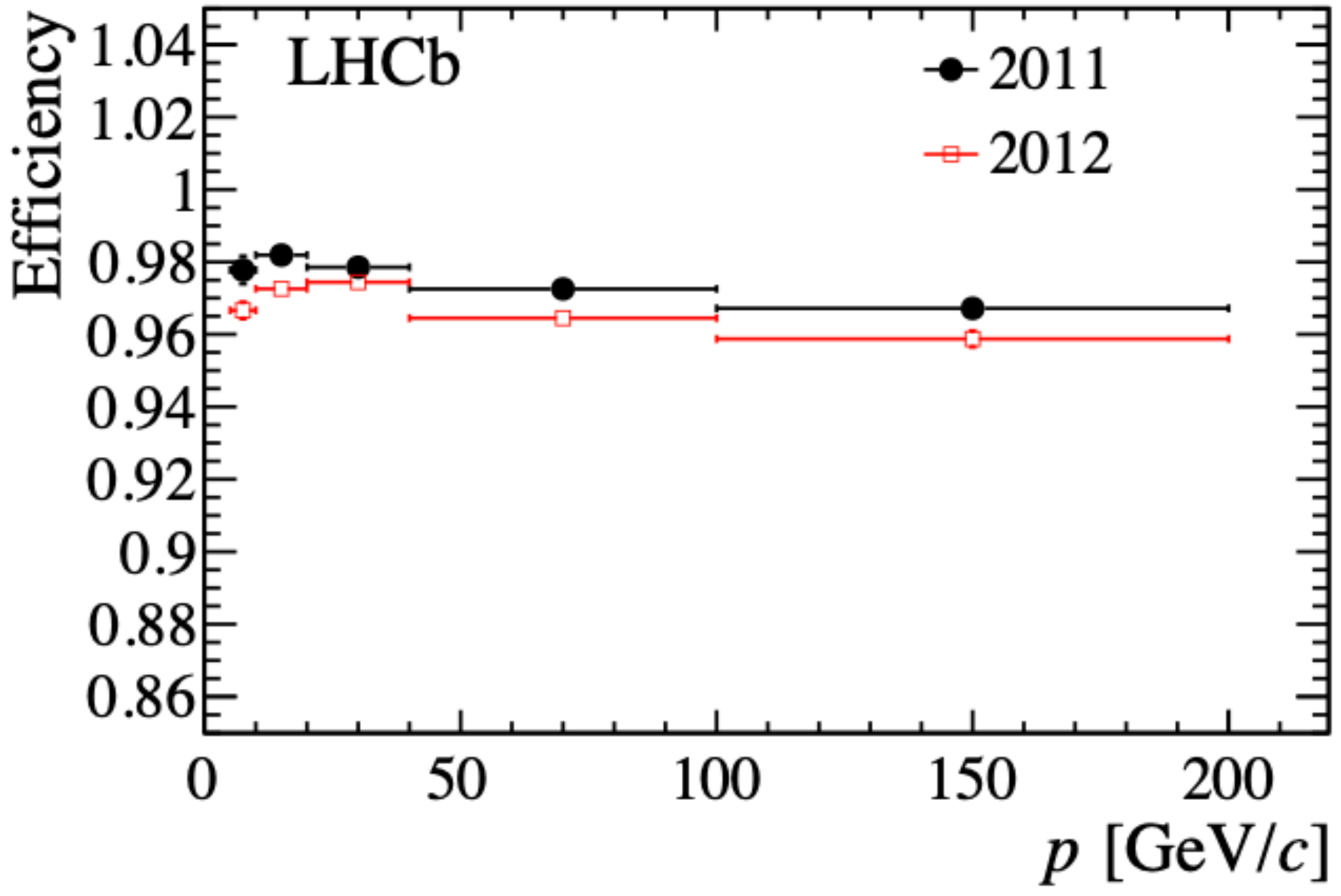


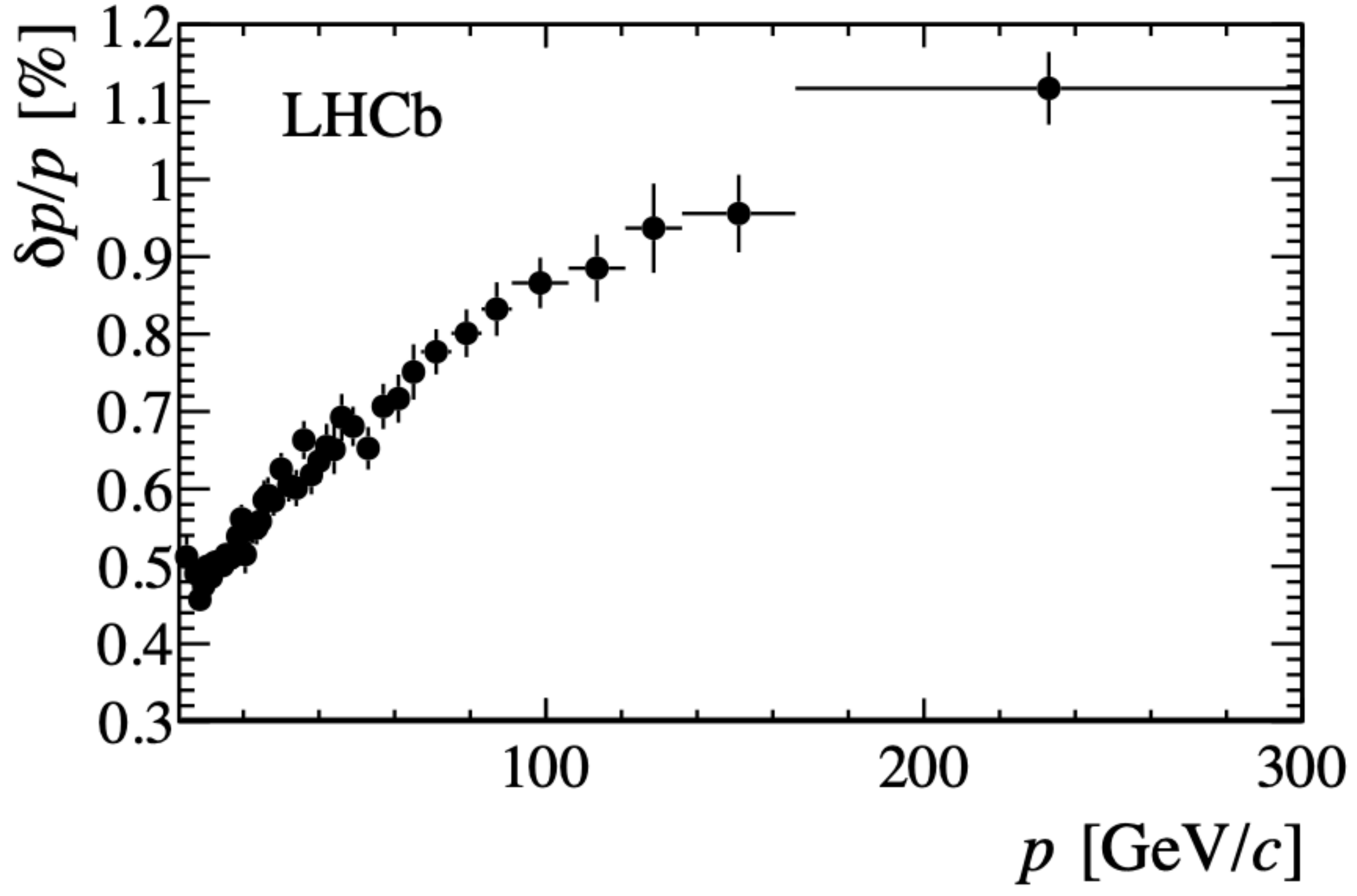
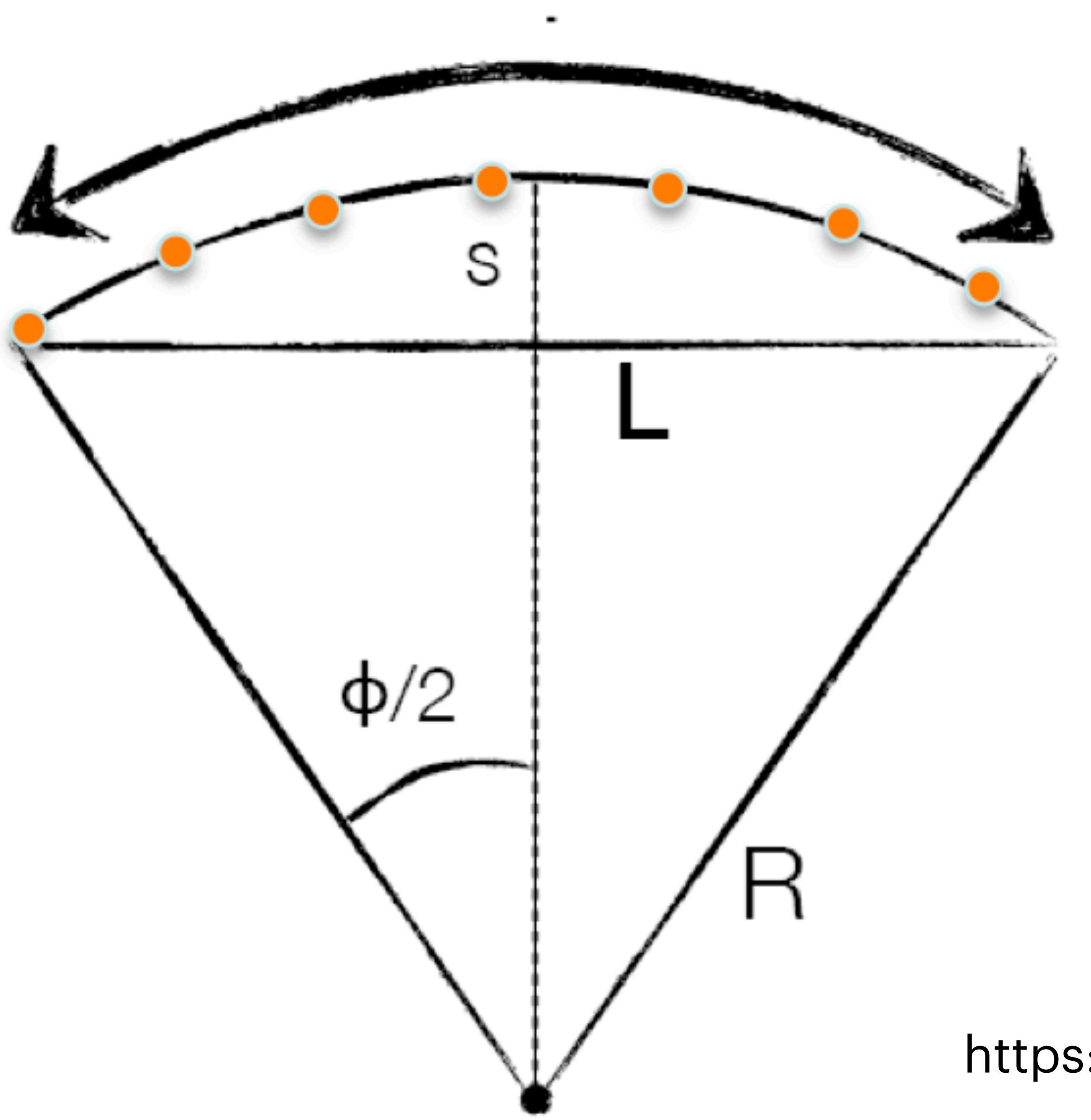


Figure 17: Relative momentum resolution versus momentum for long tracks in data obtained using J/ψ decays.

Tracking



$$p\left[\frac{GeV}{c}\right] = 0.3\ \mathrm{B[T]\ R[m]}$$

$$R = \frac{L^2}{8s}$$

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

scale (α) **smearing** (σ_{MS}) **bias** ($\mathcal{N}\left(\delta, \frac{\sigma_\delta}{\cosh\eta}\right)$)

https://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/L9_Tracking.pdf