Precision measurement of the W boson mass @LHCb

Henrikas Svidras, on behalf of the Group F

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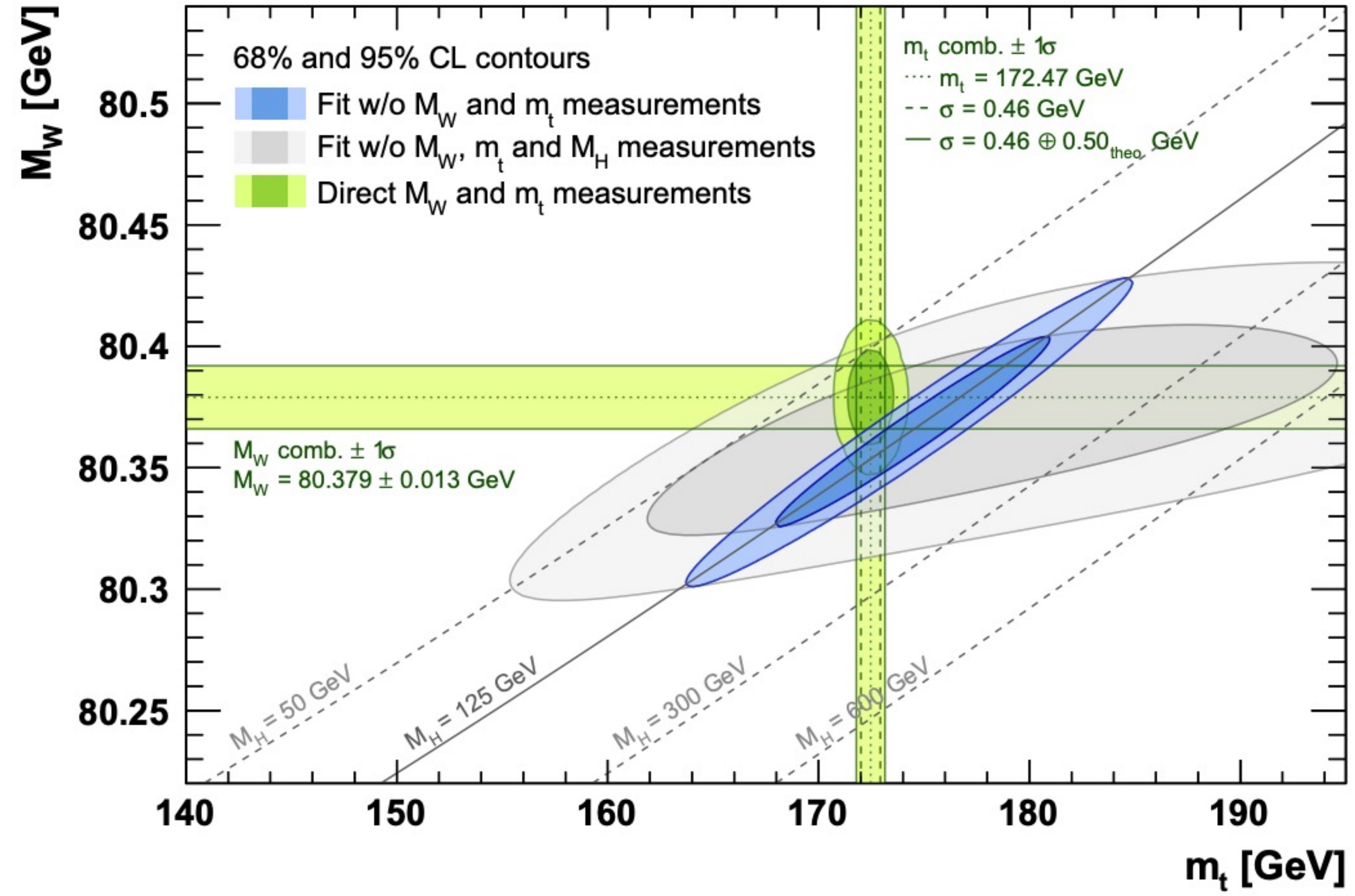
Pyeongchang AEPSHEP - Students project

Introduction

- The **W boson mass** is one of the most **important parameters of the SM**
  - Constrains many other parameters
  - Great probe for new physics
- **LHCb** measurement **complementary to ATLAS/CMS**
  - PDF uncertainties expected to be anti-correlated

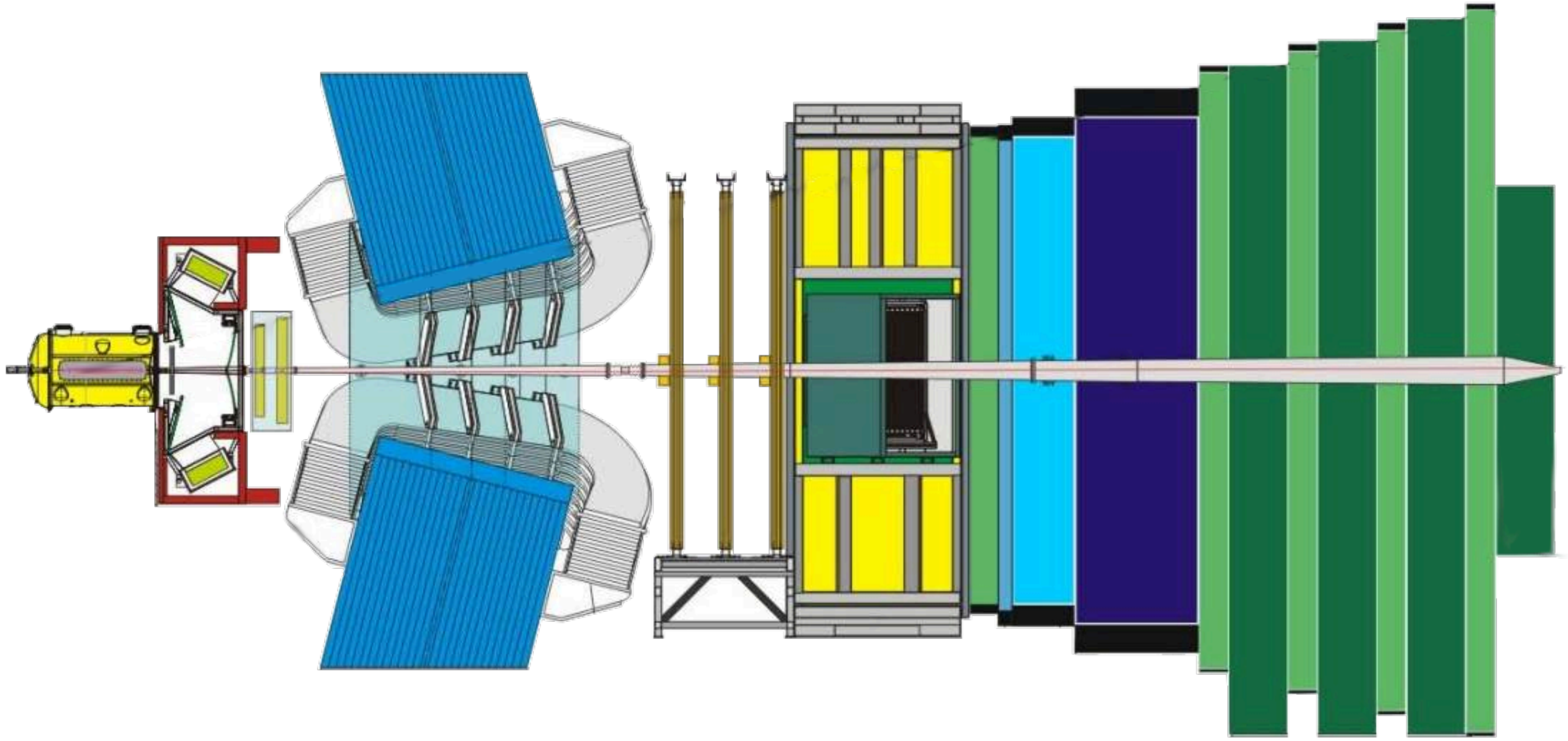
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$

	SM prediction	PDG average
M_W	80354 ± 7 MeV	80379 ± 12 MeV



LHCb detector

- Single-arm **forward spectrometer** designed for **high-precision** physics
- Unique option to perform measurements in the forward region $2 < \eta < 5$
  - Complementary to ATLAS/CMS!



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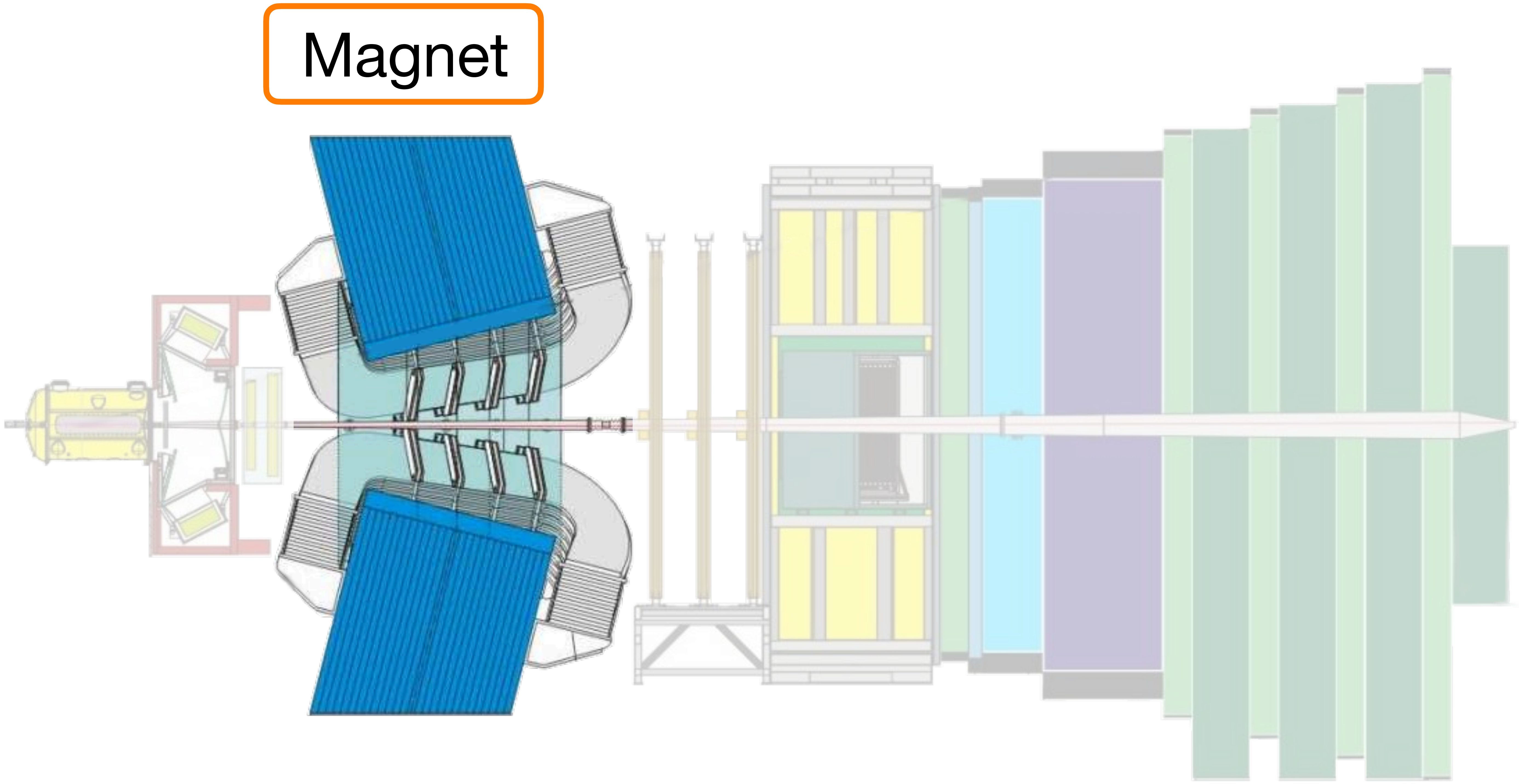

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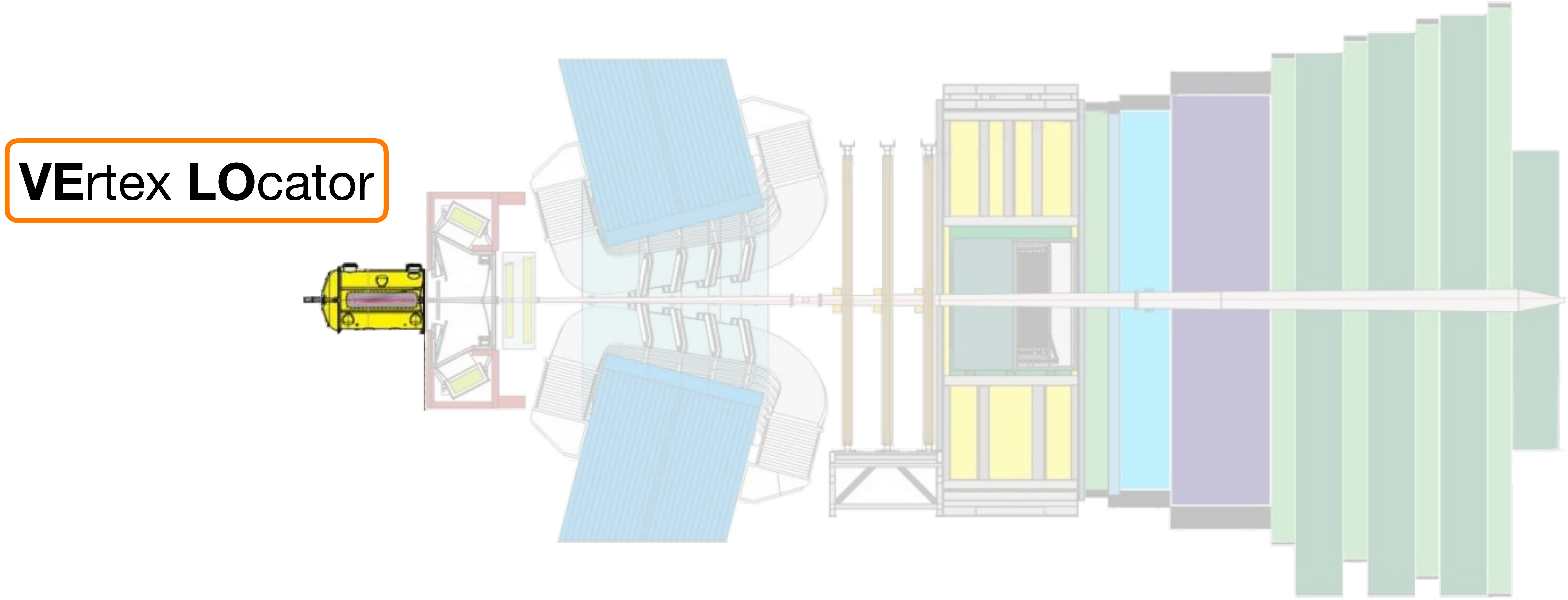

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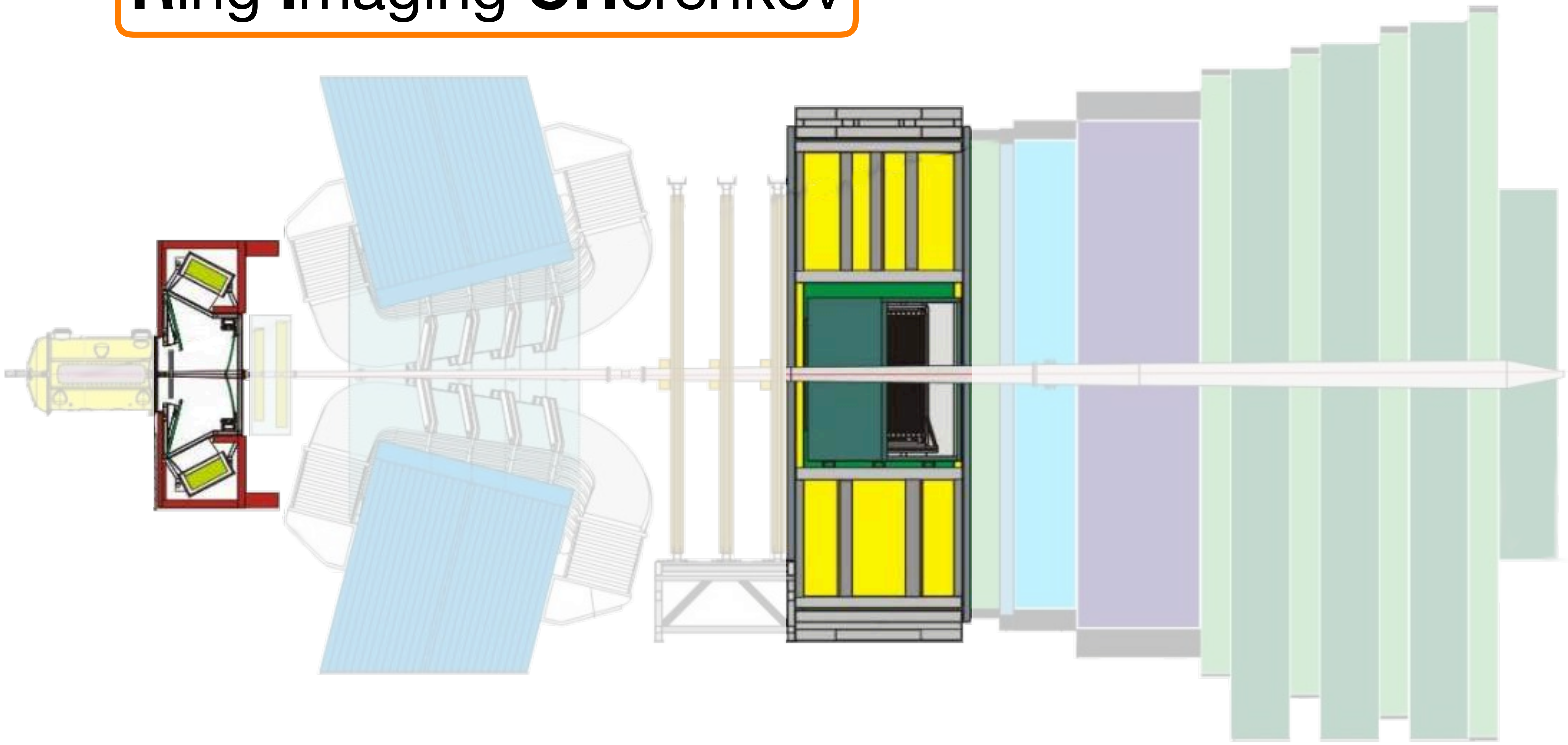
Ring **I**maging **CH**erenkov



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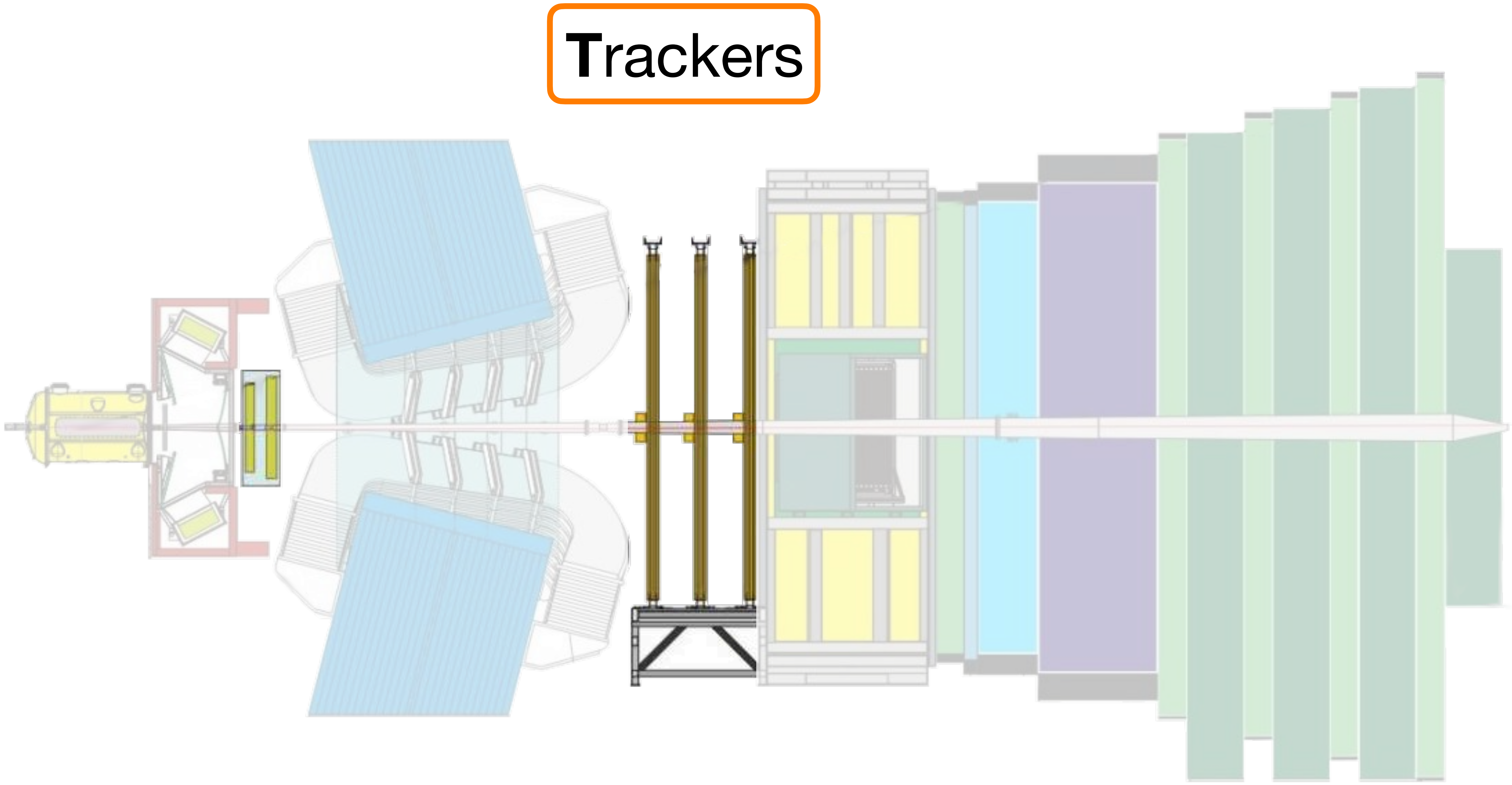

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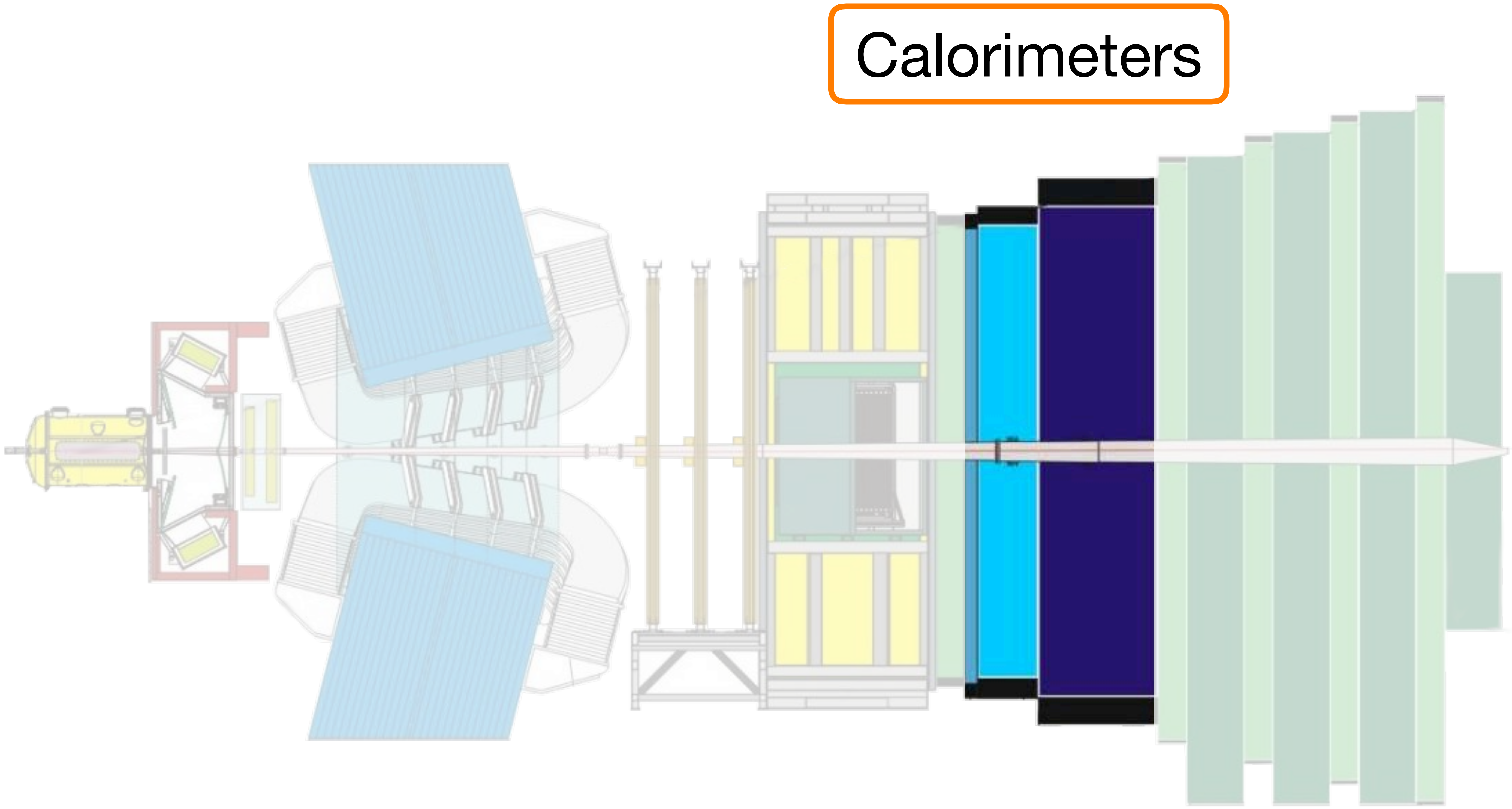

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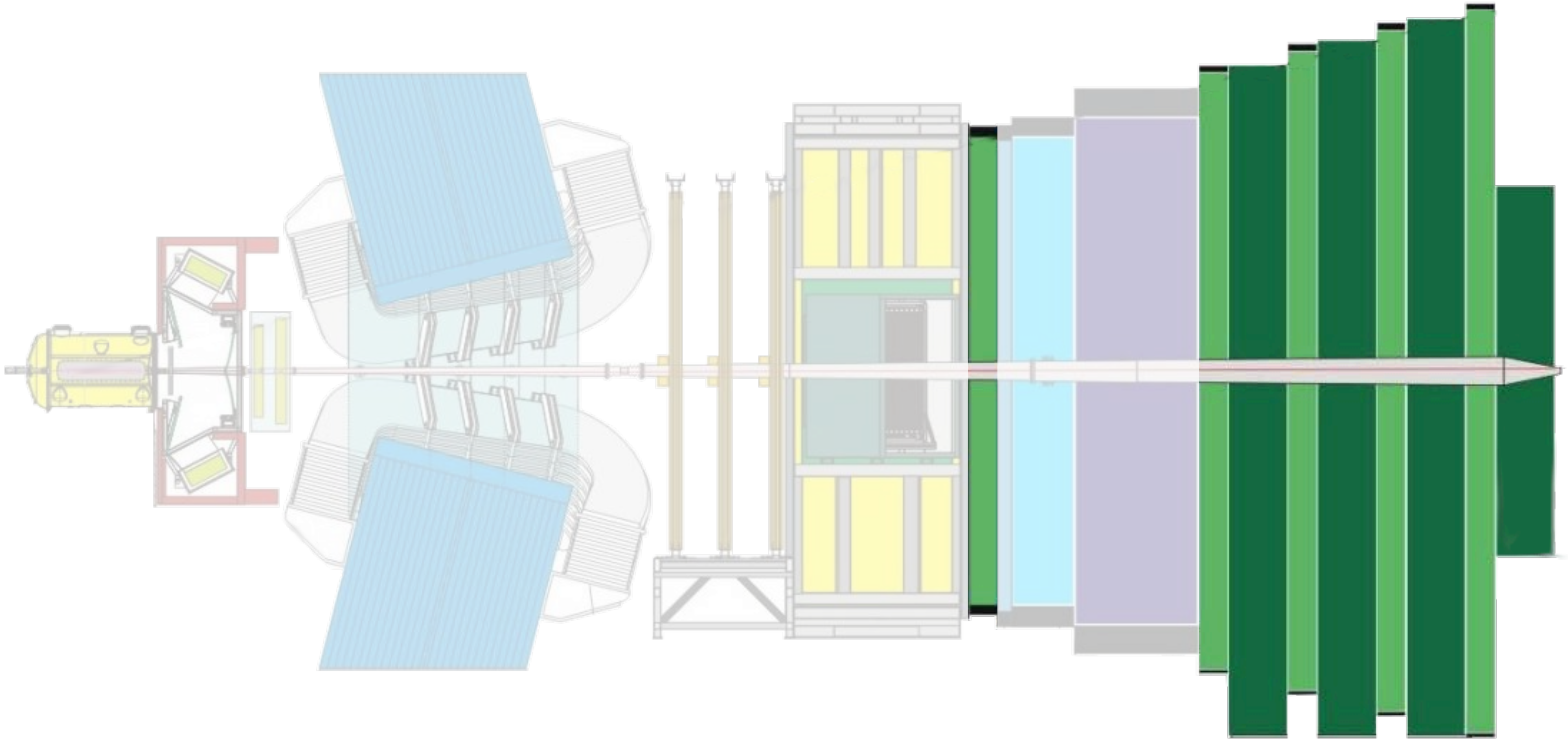
Muon systems



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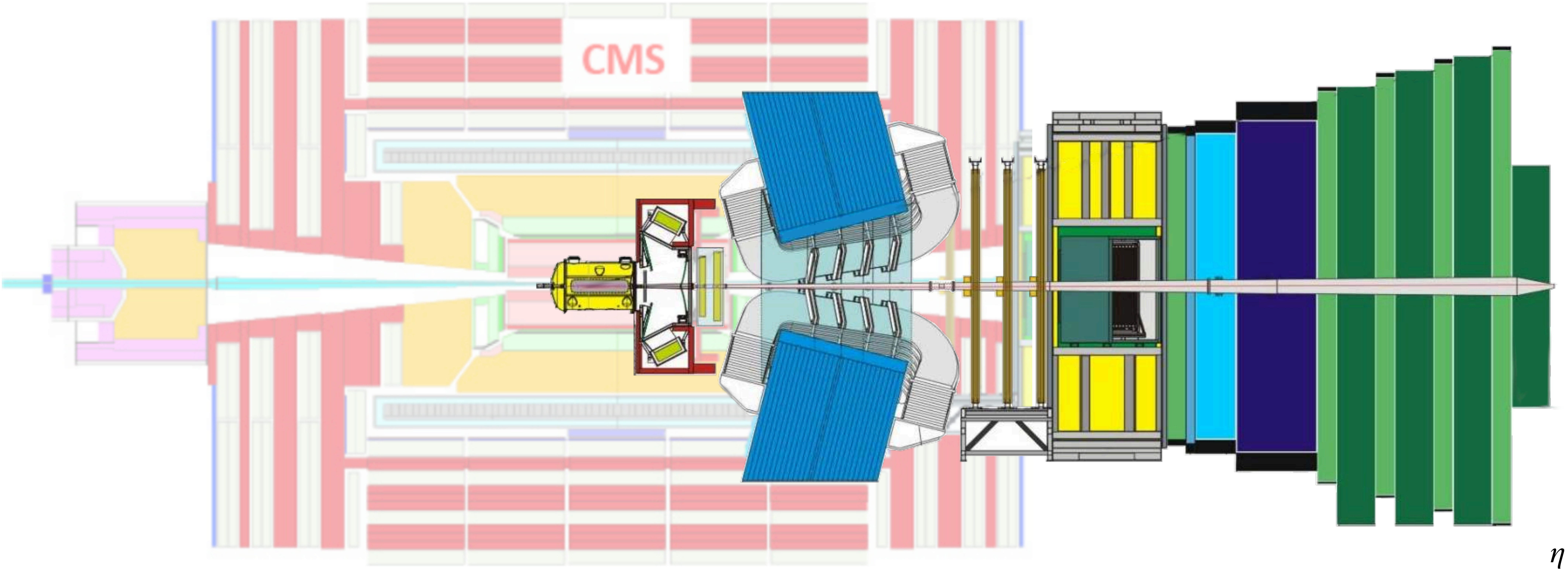

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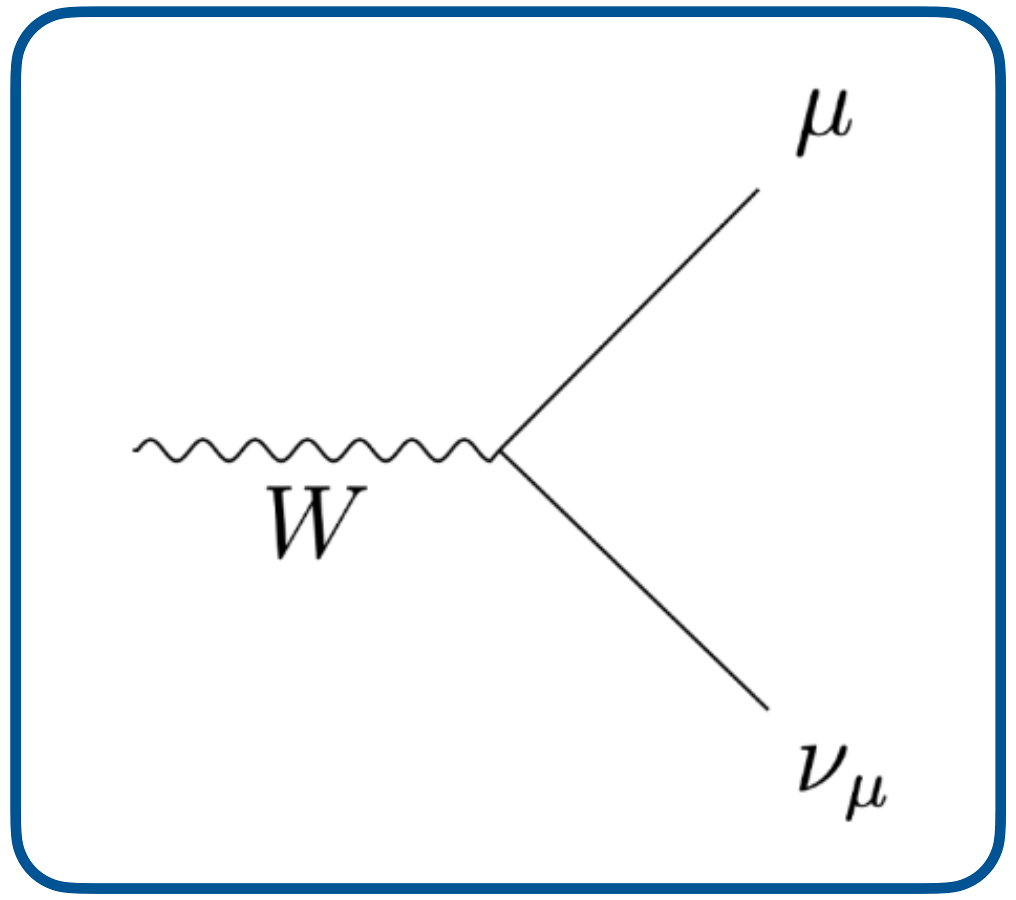
Analysis strategy

- Analysis of **leptonic decay** $W \to \mu\nu$ (impossible to reconstruct mass $m_{\mu\nu}$)
- **Variable of interest** is $\mathbf{q/p_T}$ of the muon → peaks at ~ $2/m_W$ at LO
- Data of pp collision at $\sqrt{s} = 13$ TeV, $L_{\text{int}} = 1.7\ \text{fb}^{-1}$ (2016 data)
- Processes:
  - $W \to \mu\nu\ (q/p_T)$



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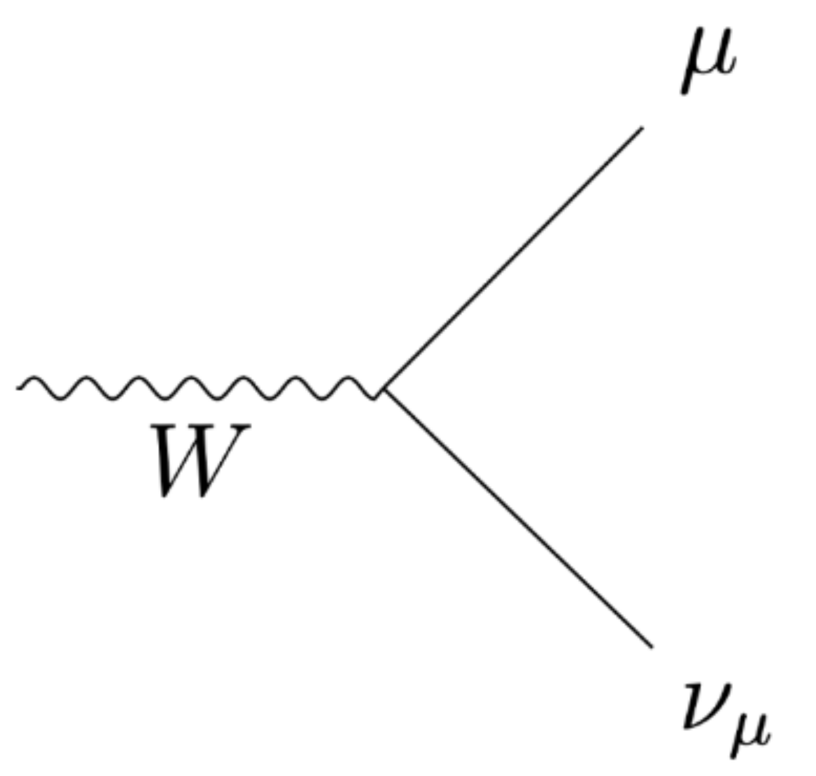
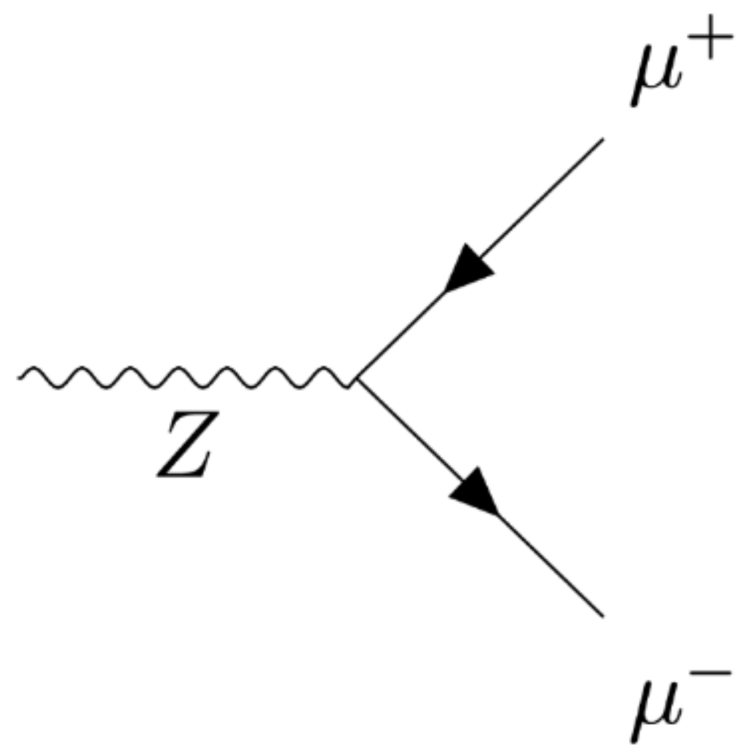
Enter the fit





$\mathbf{q/p_T}$

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

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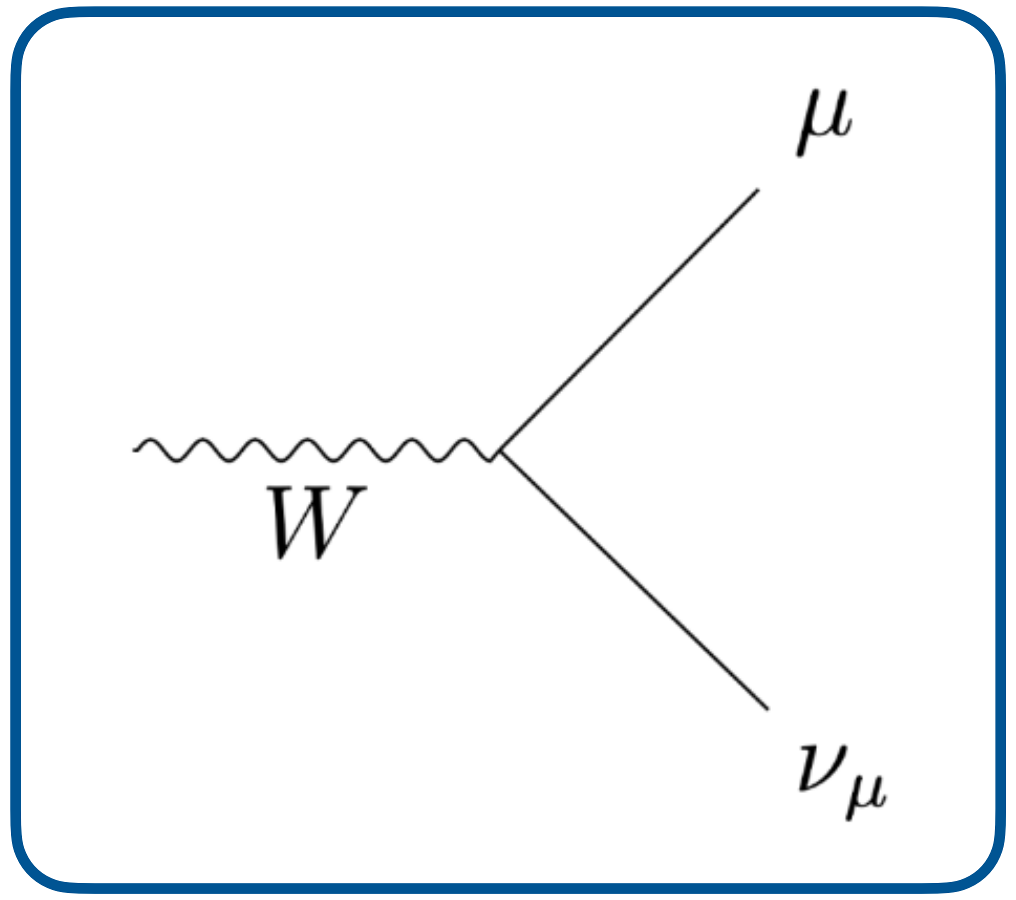
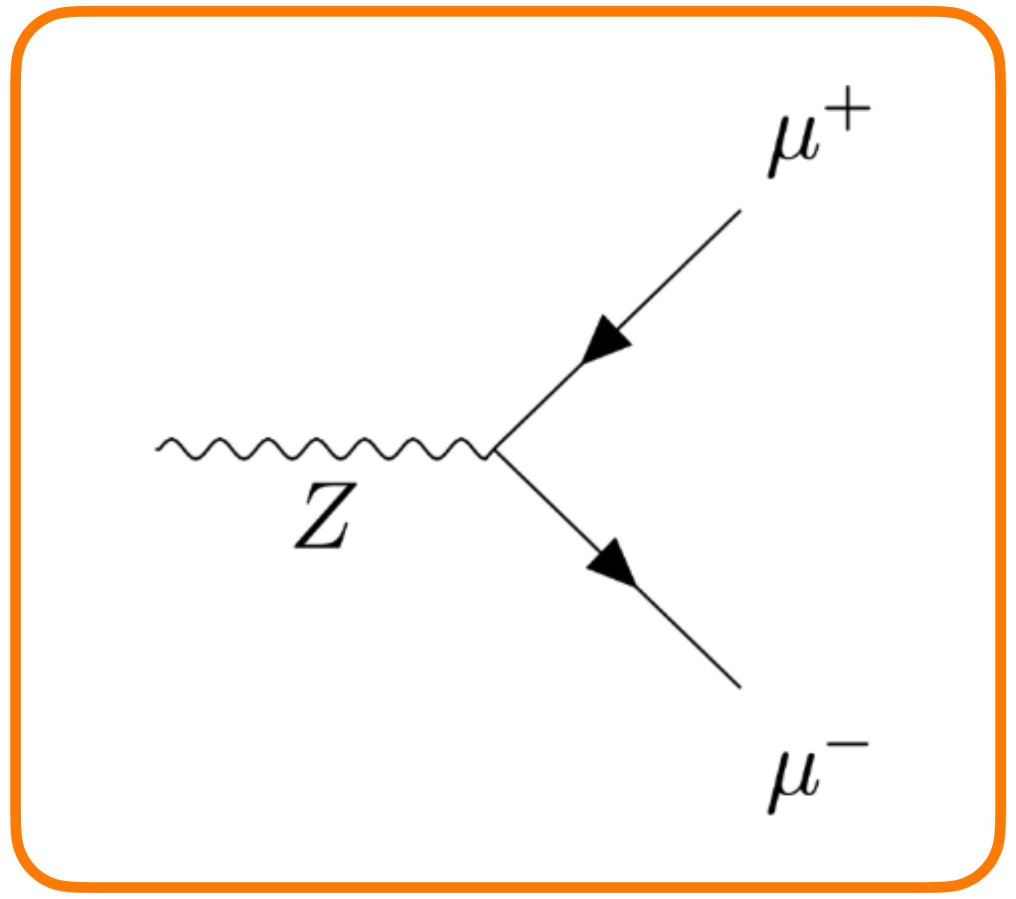
W and Z → Enter the fit

Z, $\Upsilon(1S)$ and J/Ψ → Corrections





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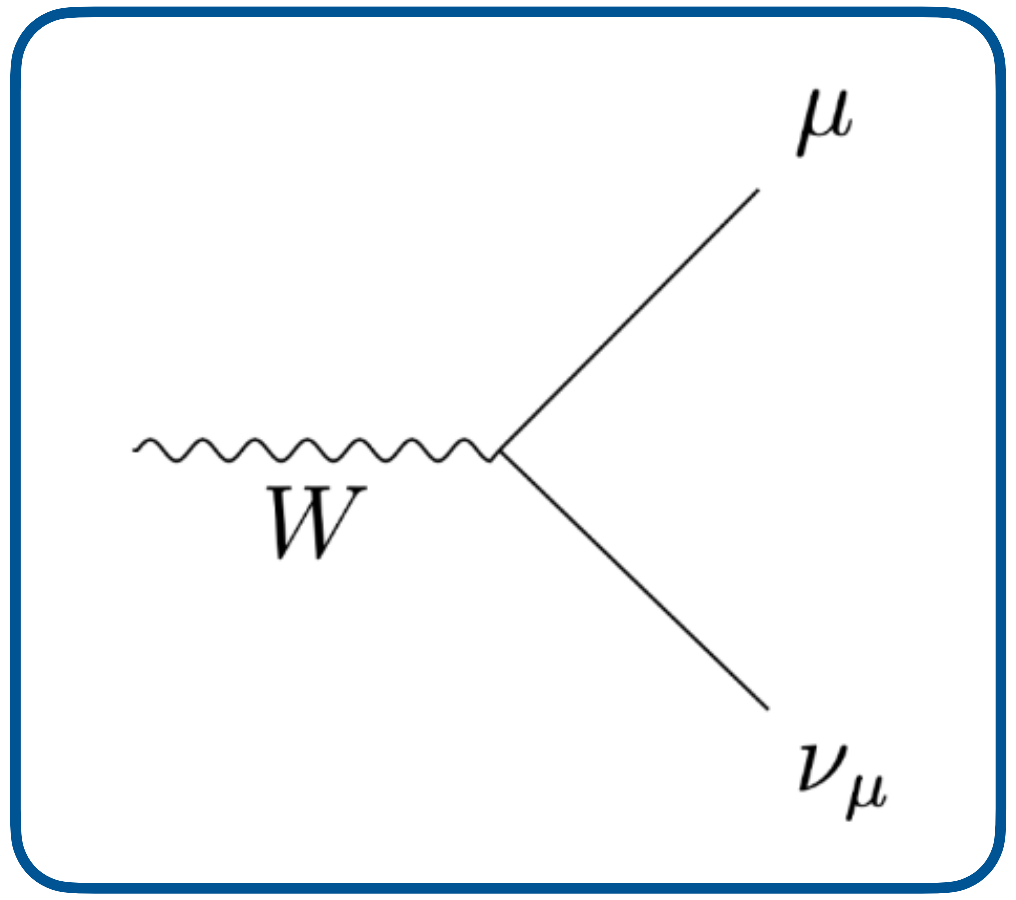
  $W \to \mu\nu$ and $Z \to \mu\mu$ → Enter the fit

  $Z \to \mu\mu$, $\Upsilon(1S) \to \mu\mu$ and $J/\Psi \to \mu\mu$ → Corrections
- Selection:
  - Require 1(2) muons per event
  - Muons must be isolated



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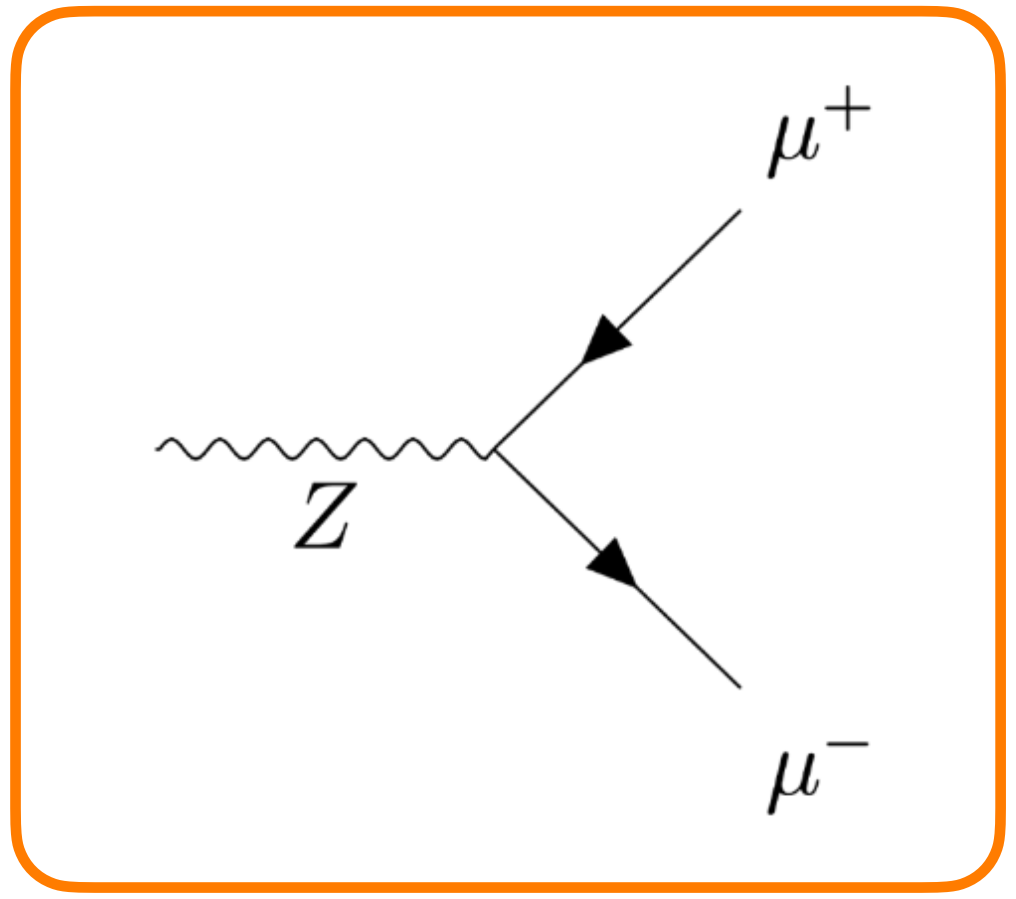

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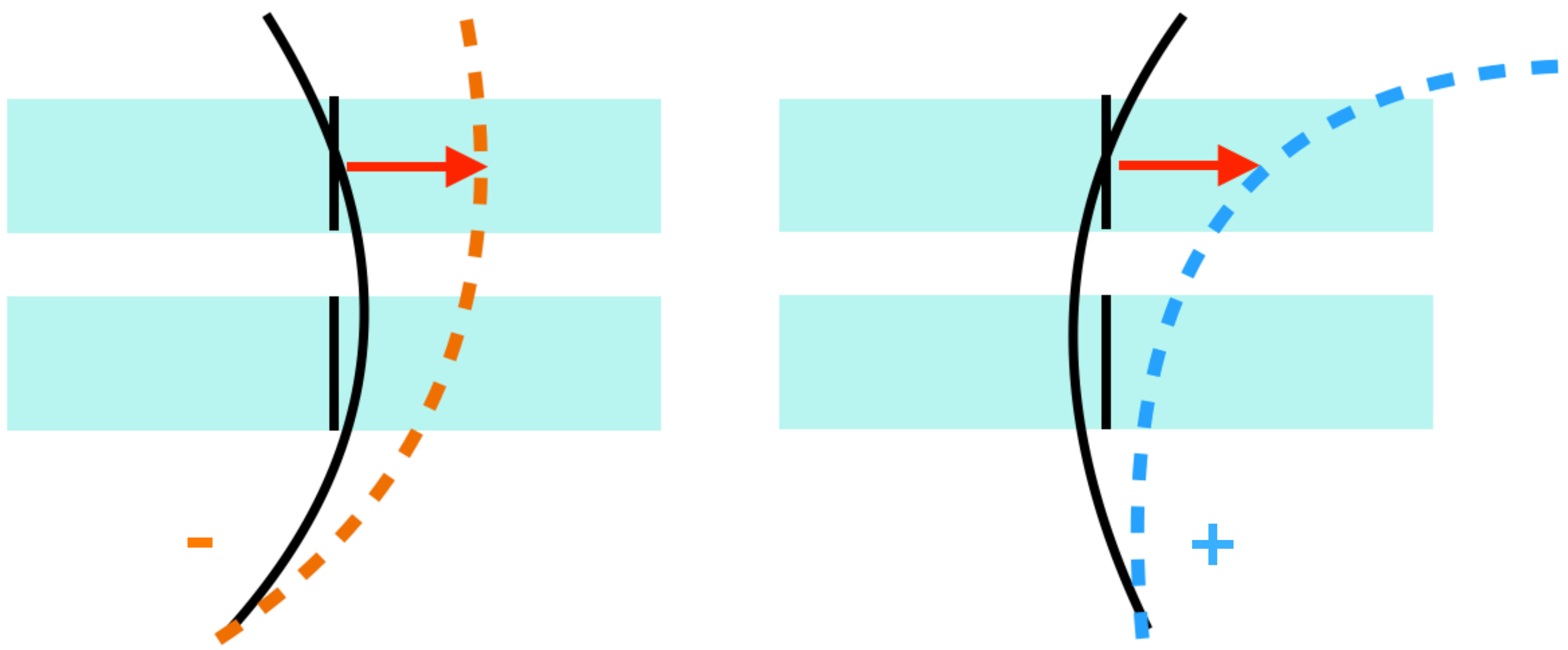
Correction of curvature biases

- Possible **misalignments** in the tracking detectors

$$\frac{q}{p_T} \rightarrow \frac{q}{p_T} + \delta$$

Charge-dependent bias



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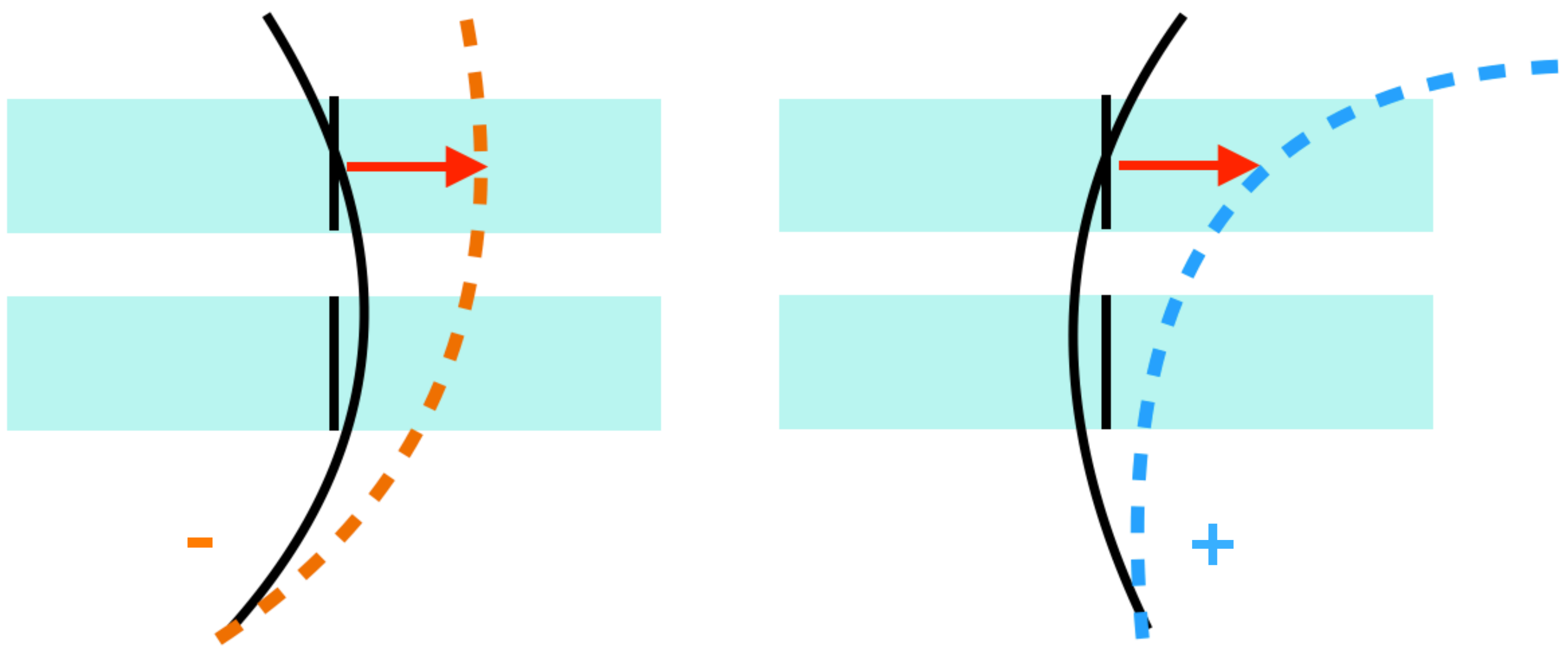

- **Correction** calculated in $Z \to \mu\mu$ events is applied
  - Calculate **pseudo-mass** variables

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

    - not simultaneously dependent on $|p^+|$ and $|p^-|$
  - $\mathscr{M}^{\pm}$ shifted in opposite directions by curvature bias
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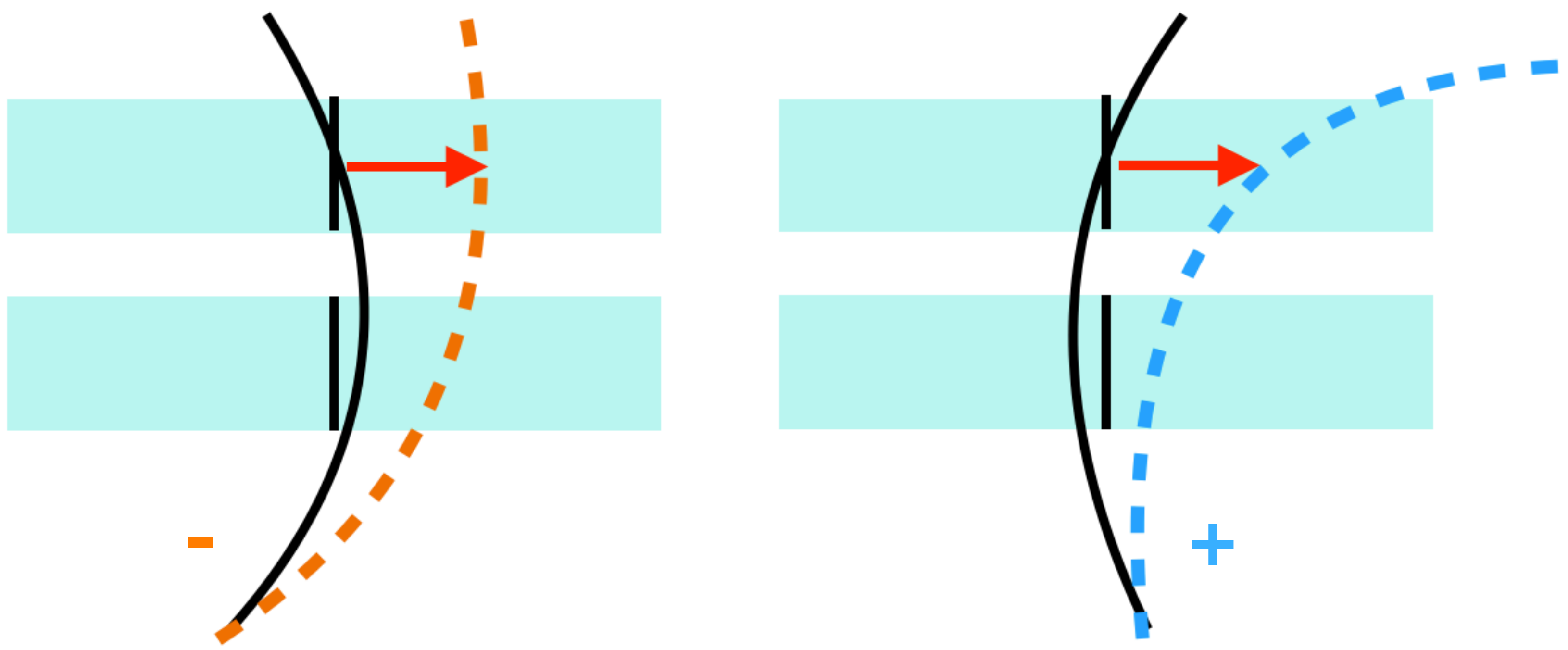
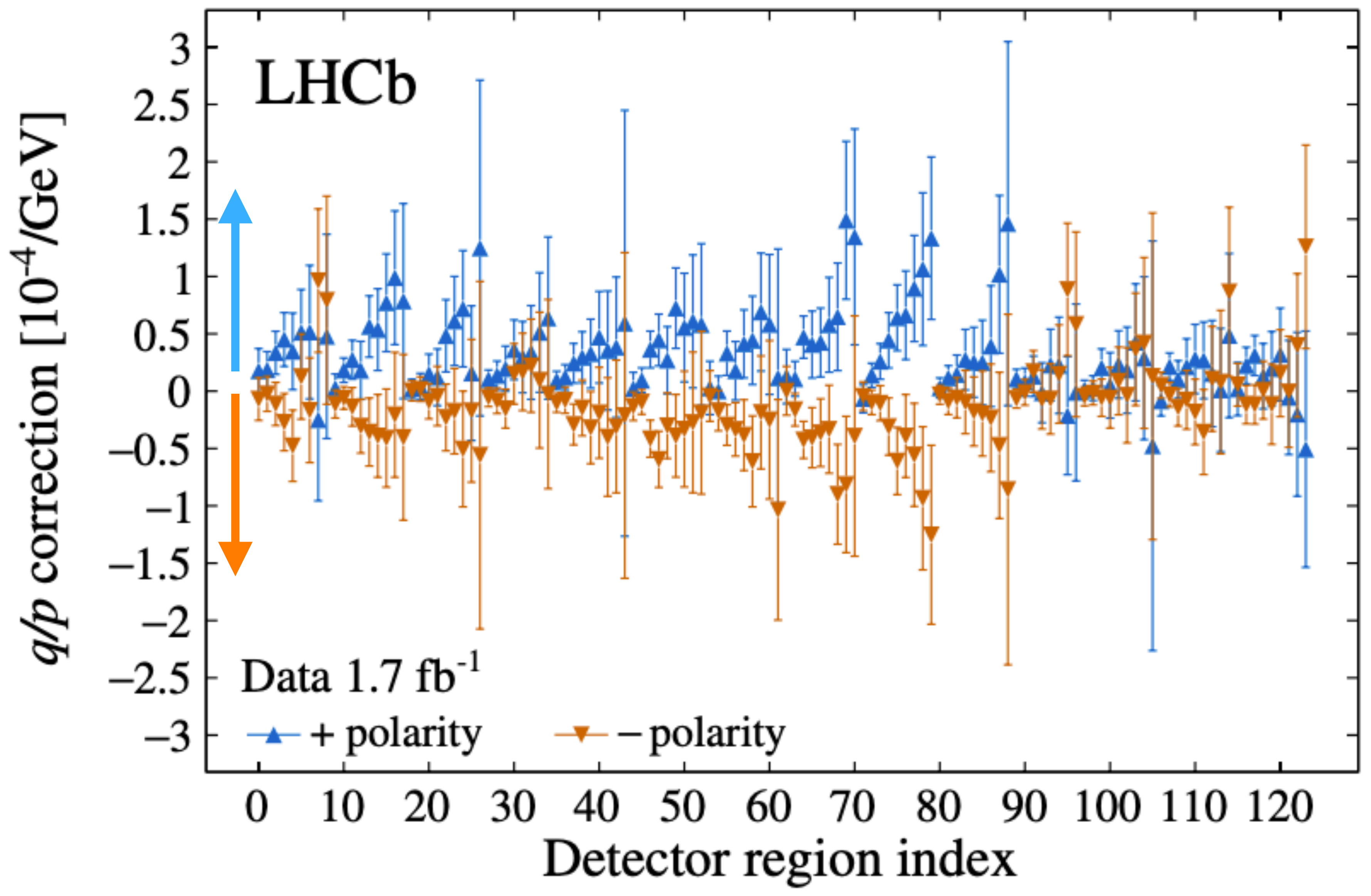
  - **Extract bias corrections from $\mathscr{M}^{\pm}$ fits**



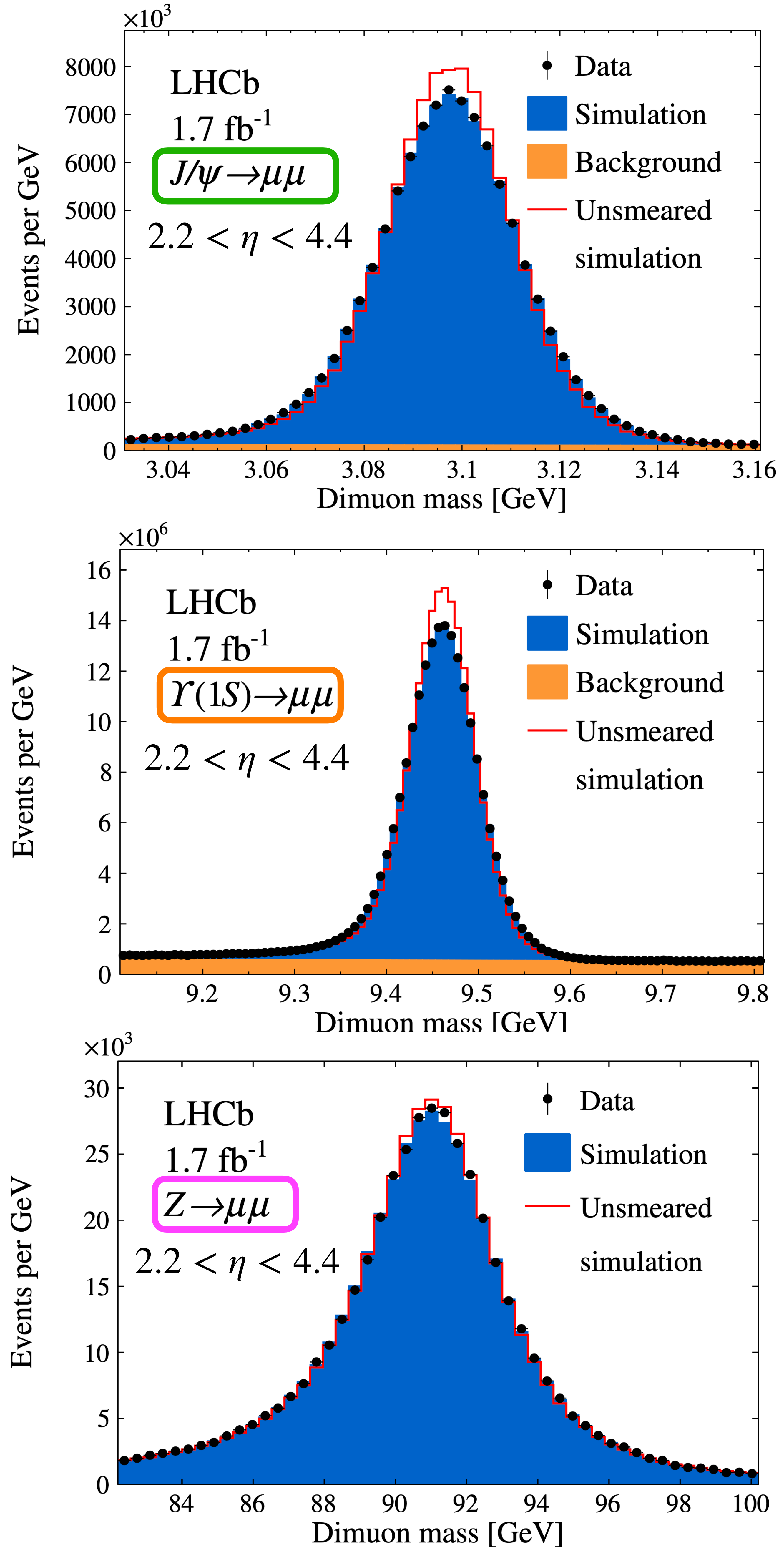


Momentum smearing

- **Simulation** of detector is **not perfect**
- **Smear** the simulation results

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

  - where $\mathcal{N}(a,b)$ is a random Gaussian number
- Fit to data to obtain **6 smearing parameters**



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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}
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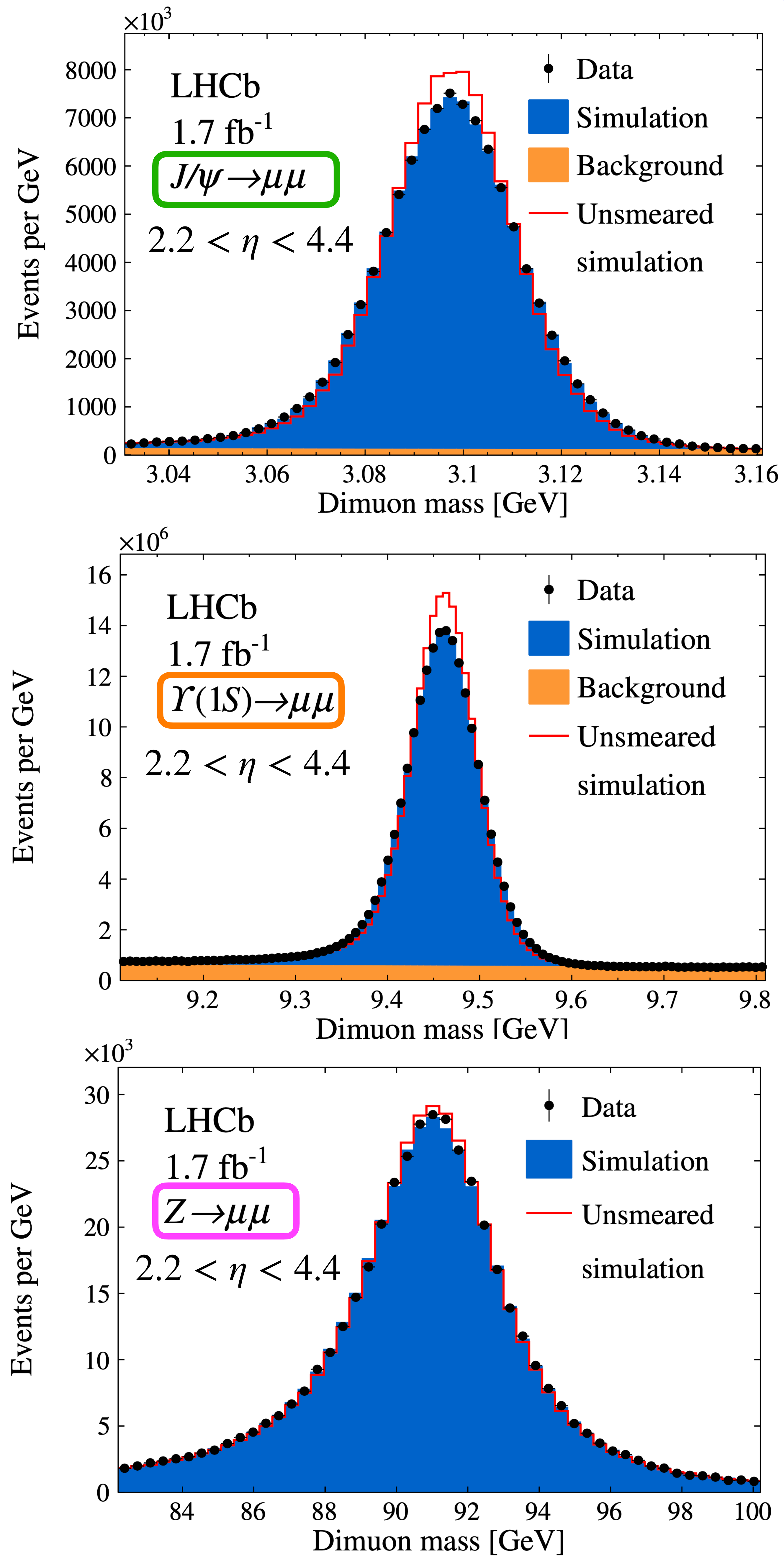

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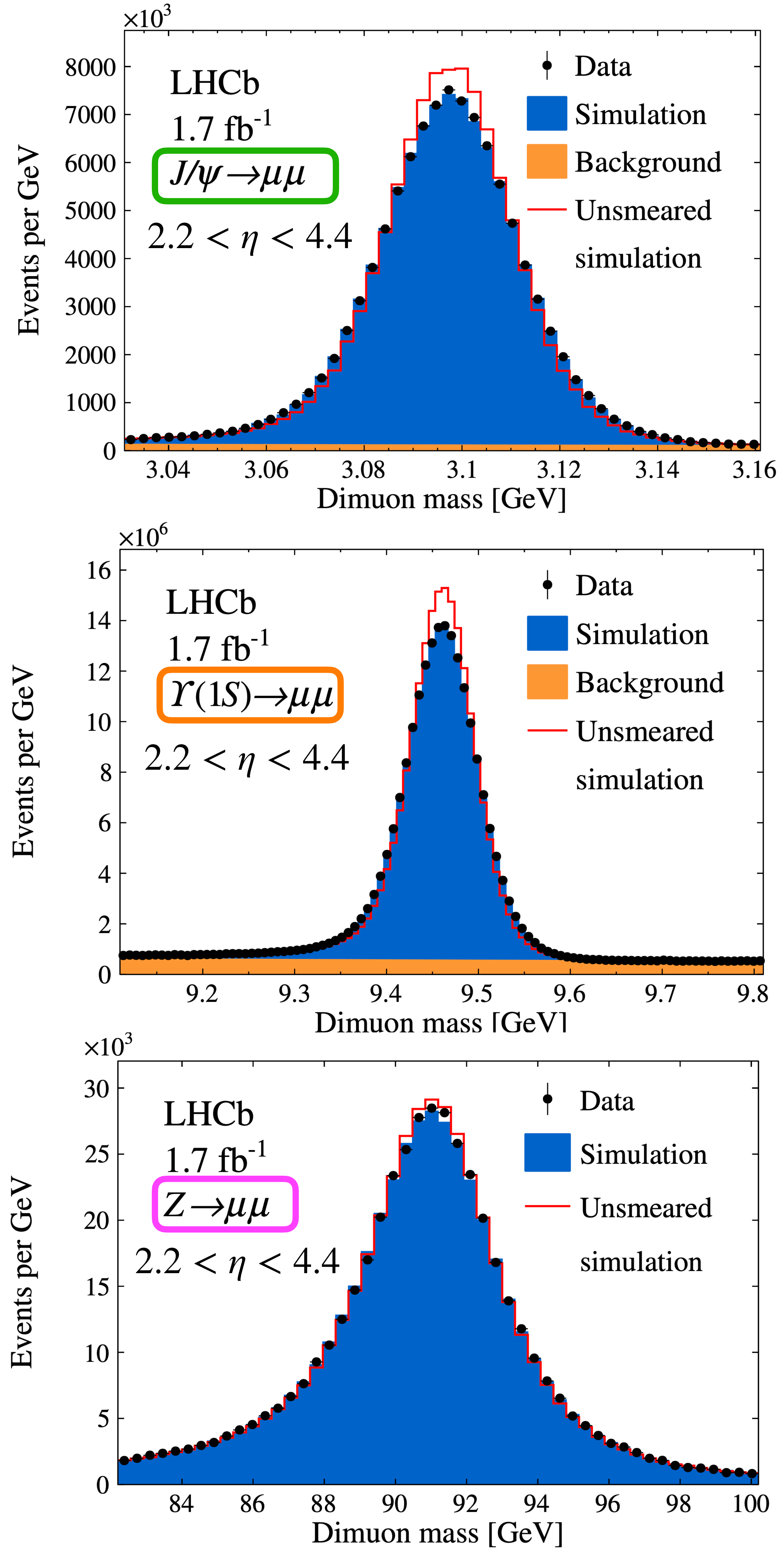
Almost zero due to curvature correction



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Trigger | Identification | Track reconstruction | Isolation

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  - **Tagged** muon: well identified, triggered muon (tight selection criteria)
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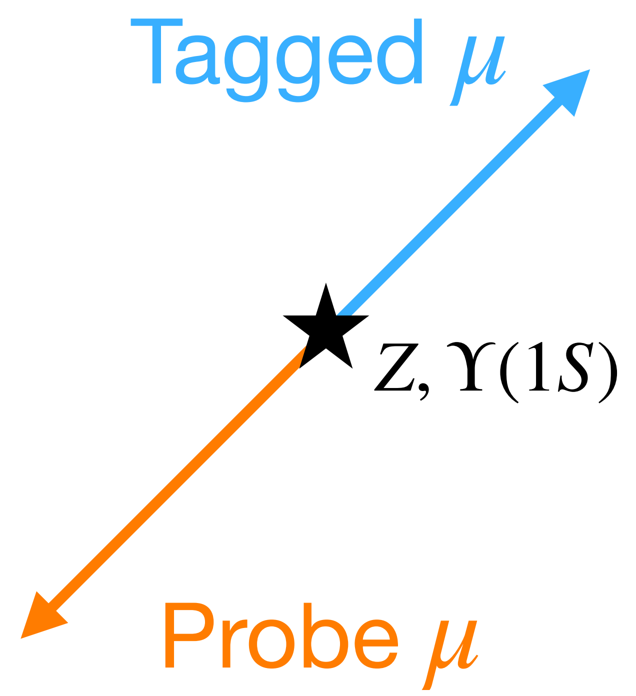

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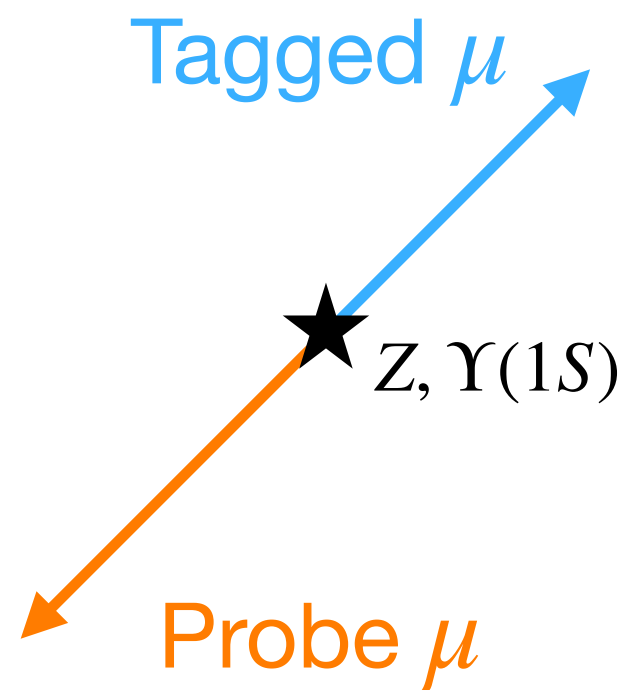
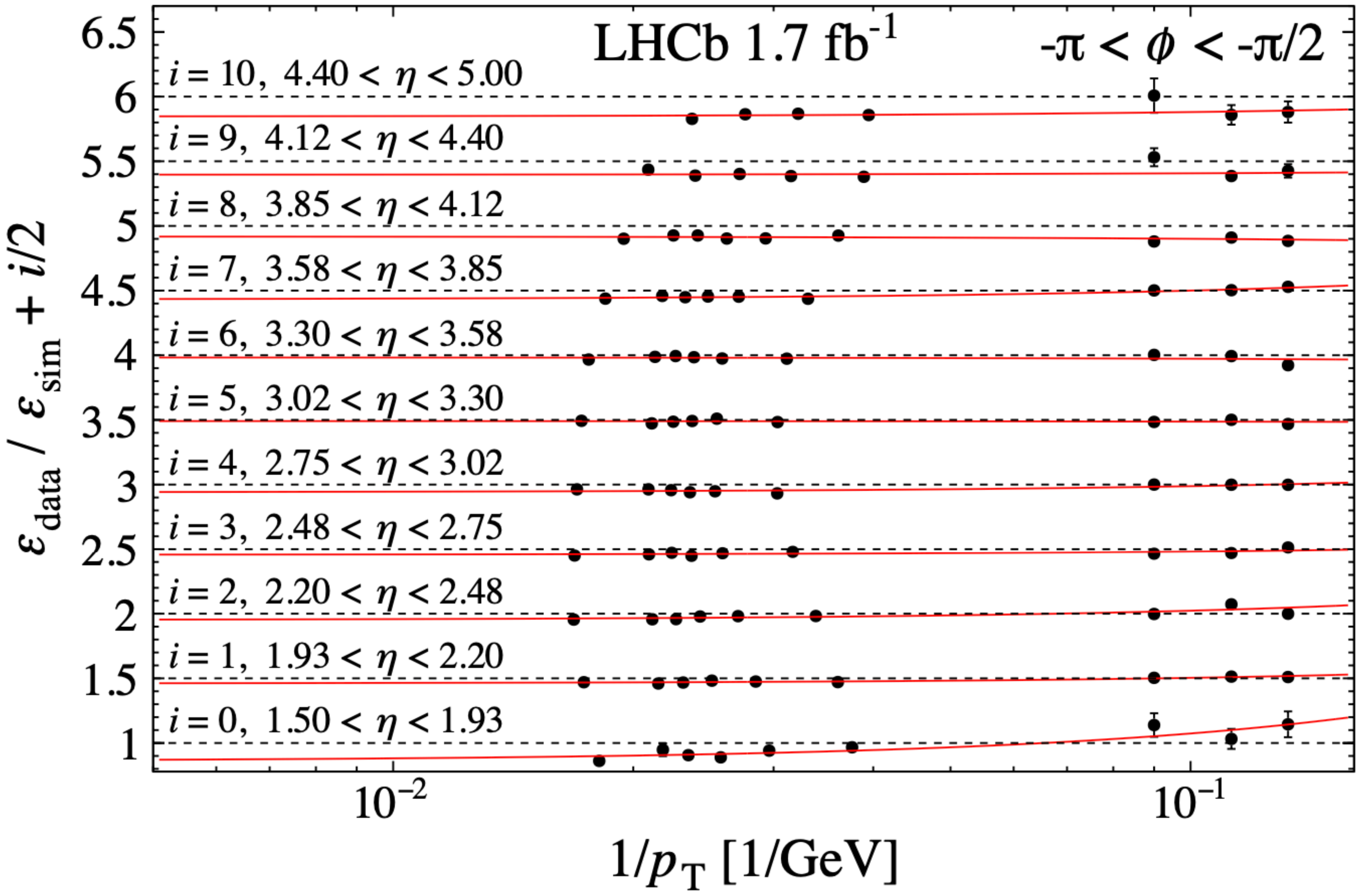


Trigger efficiency ratio



QCD background model

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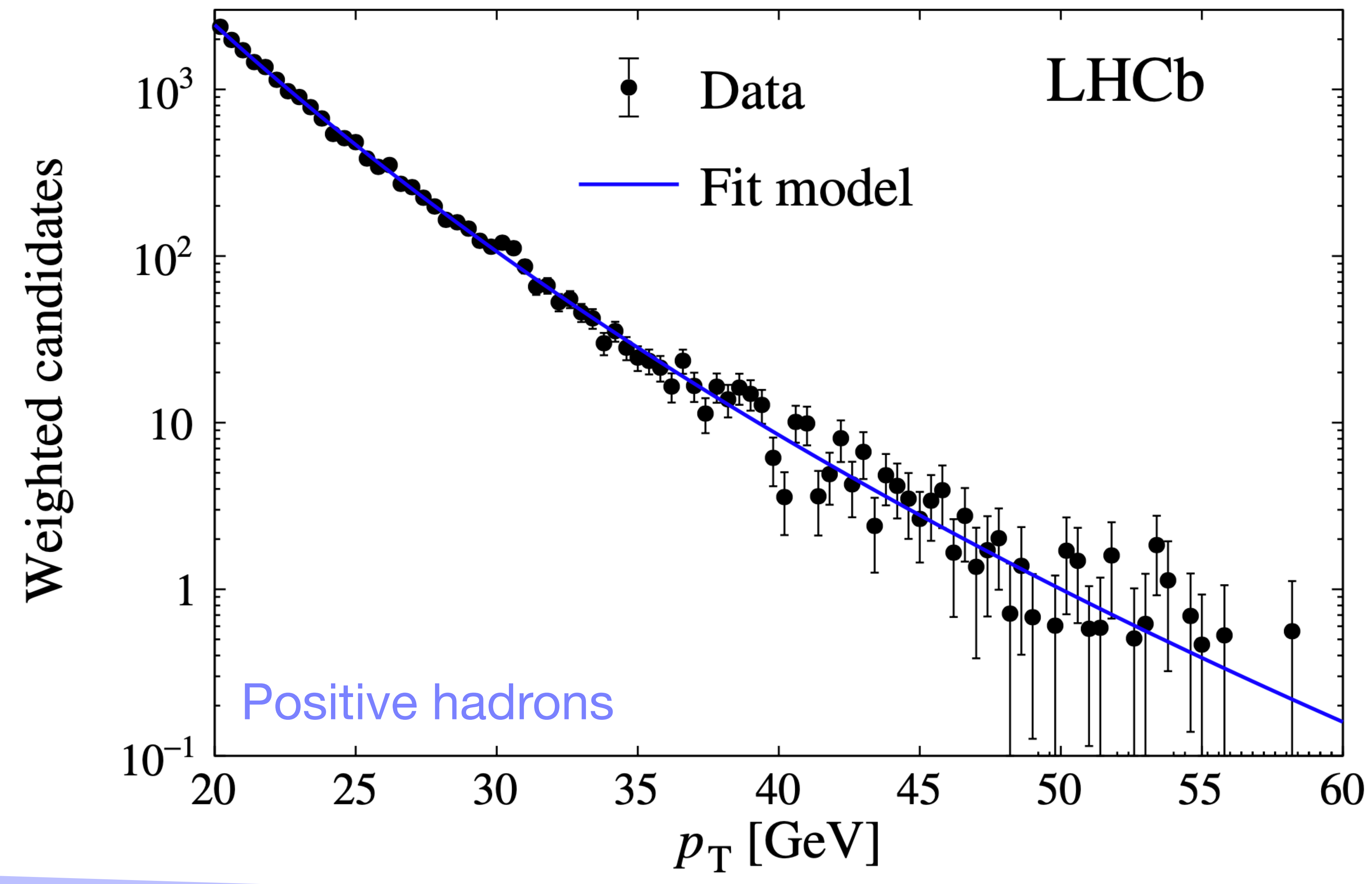
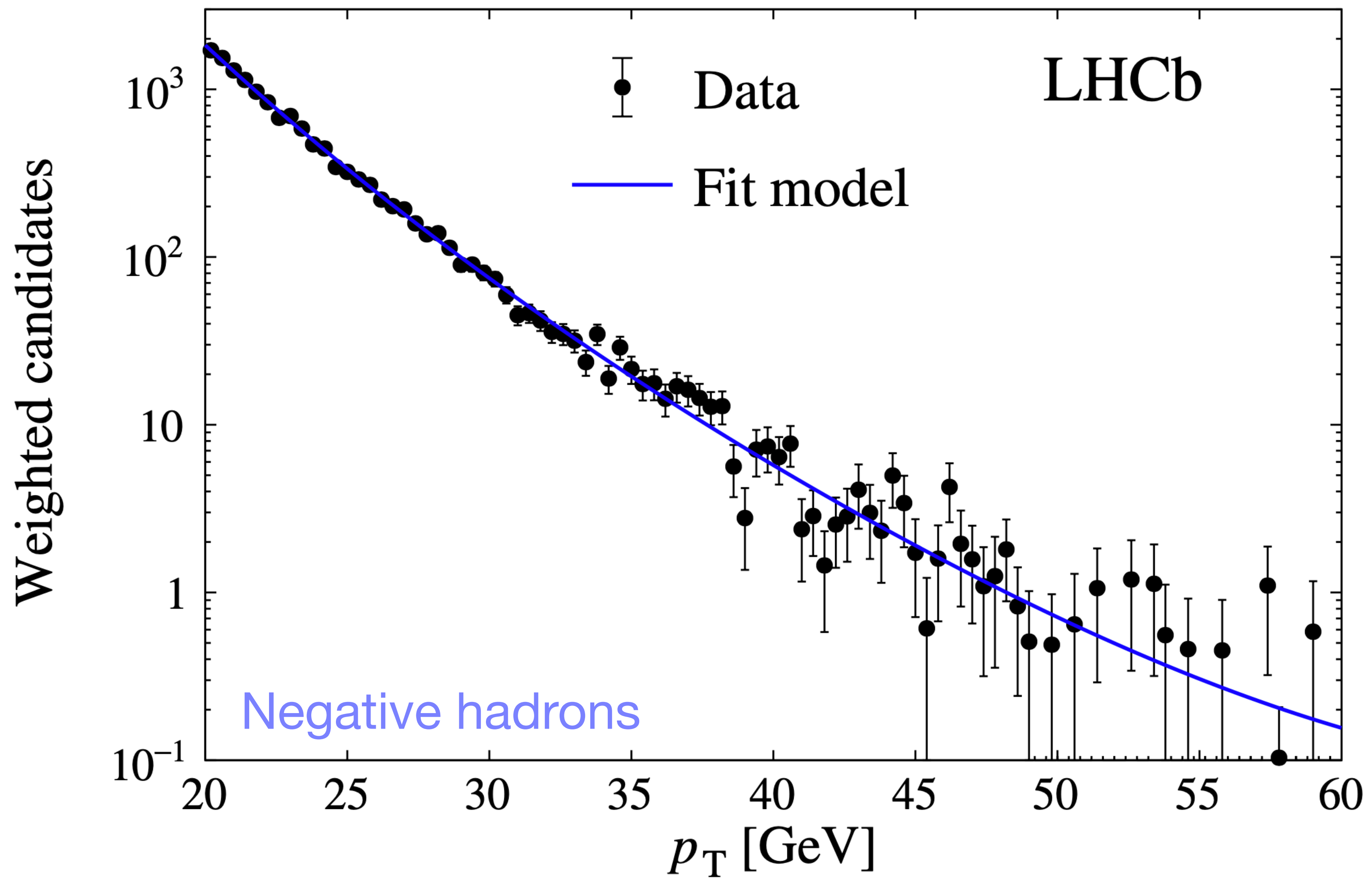
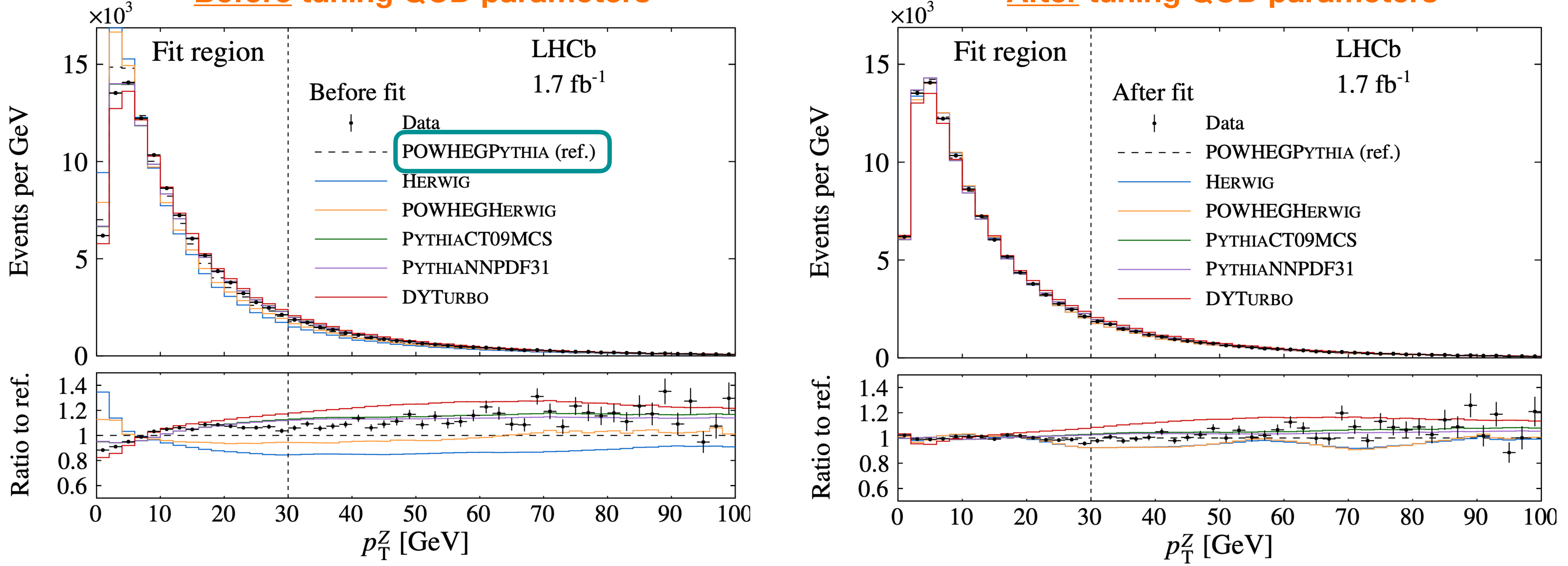




Signal modeling

- **Different generators** are tested to find the best one by fitting the $Z \to \mu\mu$ events data
  - POWHEGPYTHIA is found to be the most reliable after tuning QCD parameters
- Generator **QCD parameters** α_S and k_T^{intr} are therefore included in the fit

Before tuning QCD parameters | **After tuning QCD parameters**



Fitting procedure

- M_W is extracted by fitting background and signal templates **simultaneously** :
  - q/p_T of the muon in $W^{\pm}$ decay
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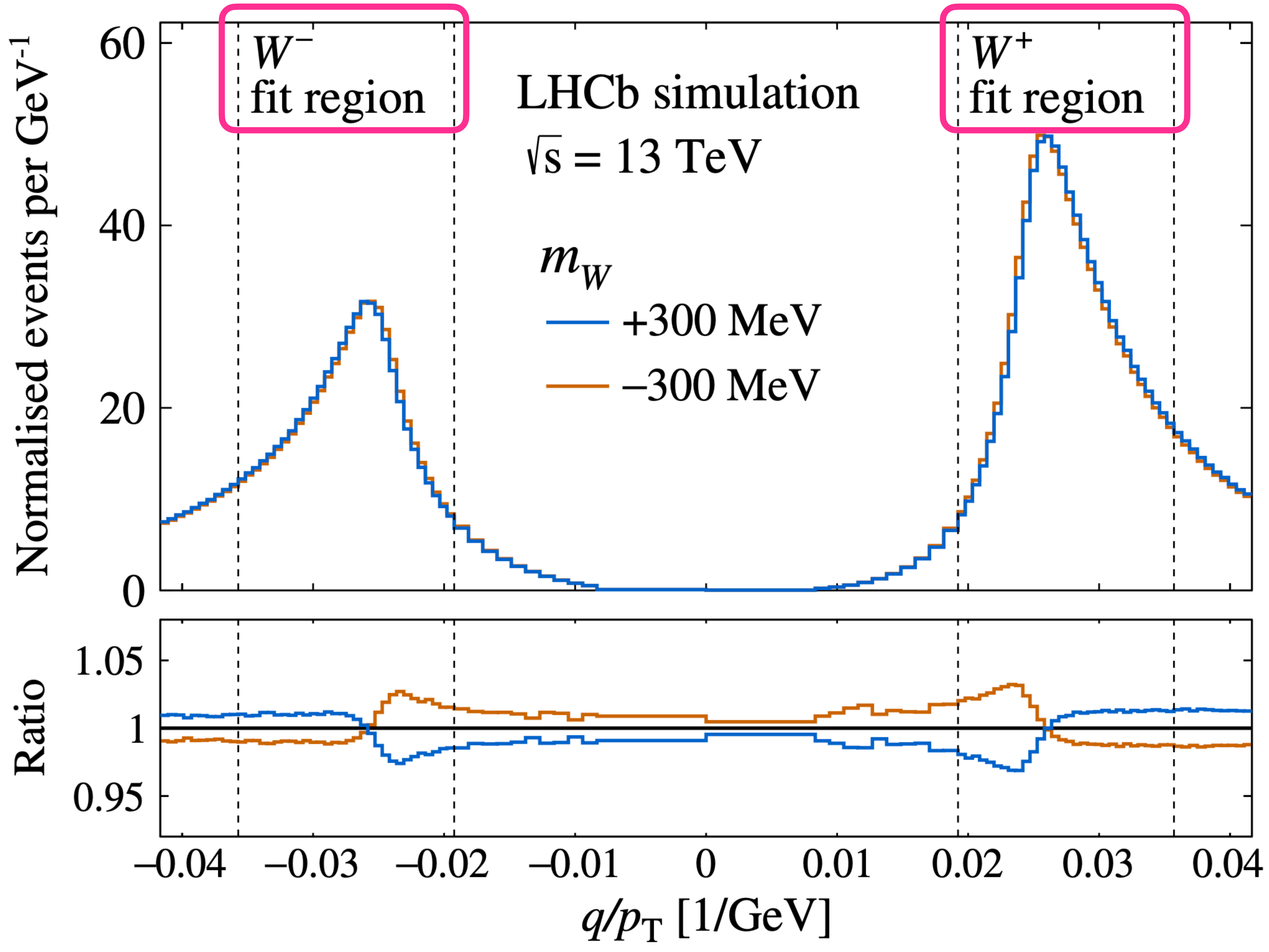

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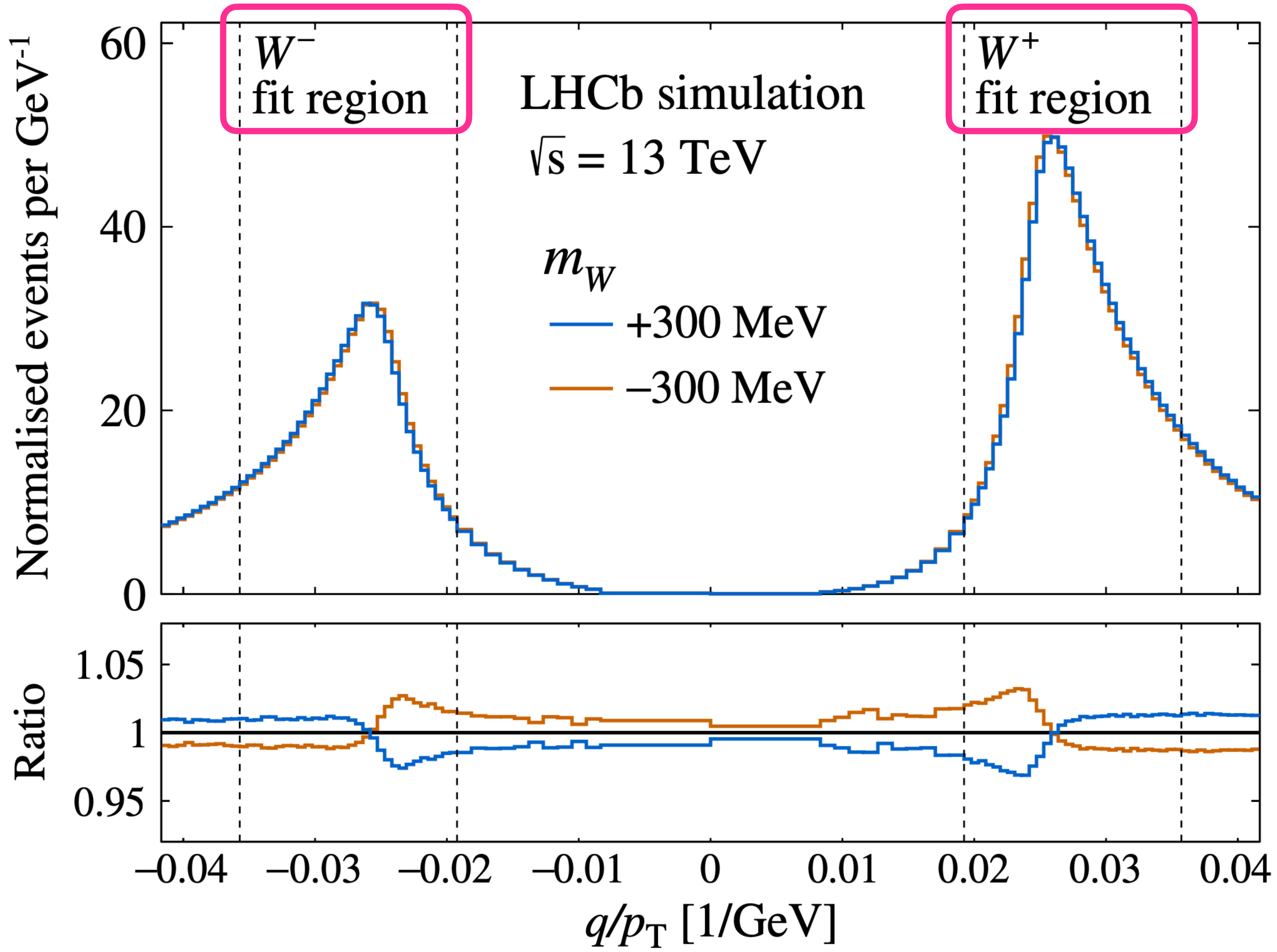
- **8 free parameters** to be extracted
  - M_W
  - $W^{\pm}$ fractions and QCD background
  - α_S for the Z boson process
  - α_S for the W boson process
  - intrinsic p_T of the initial state partons (k_T^{intr})
  - scaling of angular coefficient A_3



Fit validation and cross check

- **Pseudo data validation**:
  - Pseudo data are generated with alternative model predictions and fitted
  - Variations of M_W not large and differences in shape absorbed by α_S and k_T^{intr}
- **Cross checks** on orthogonal subset
  - Fit range variation
  - More or less α_S freedom
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  - Different M_W for W^+ and W^-
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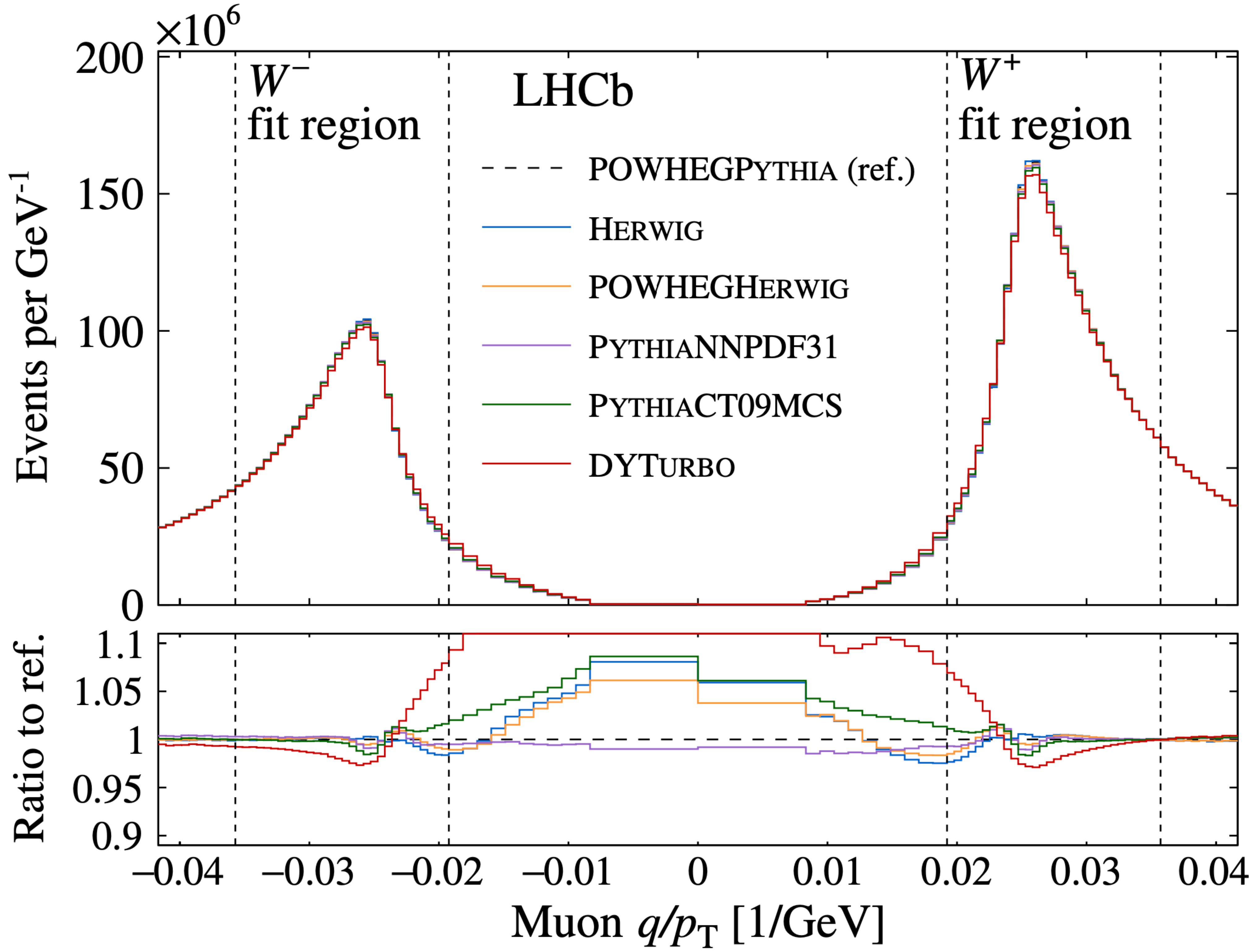

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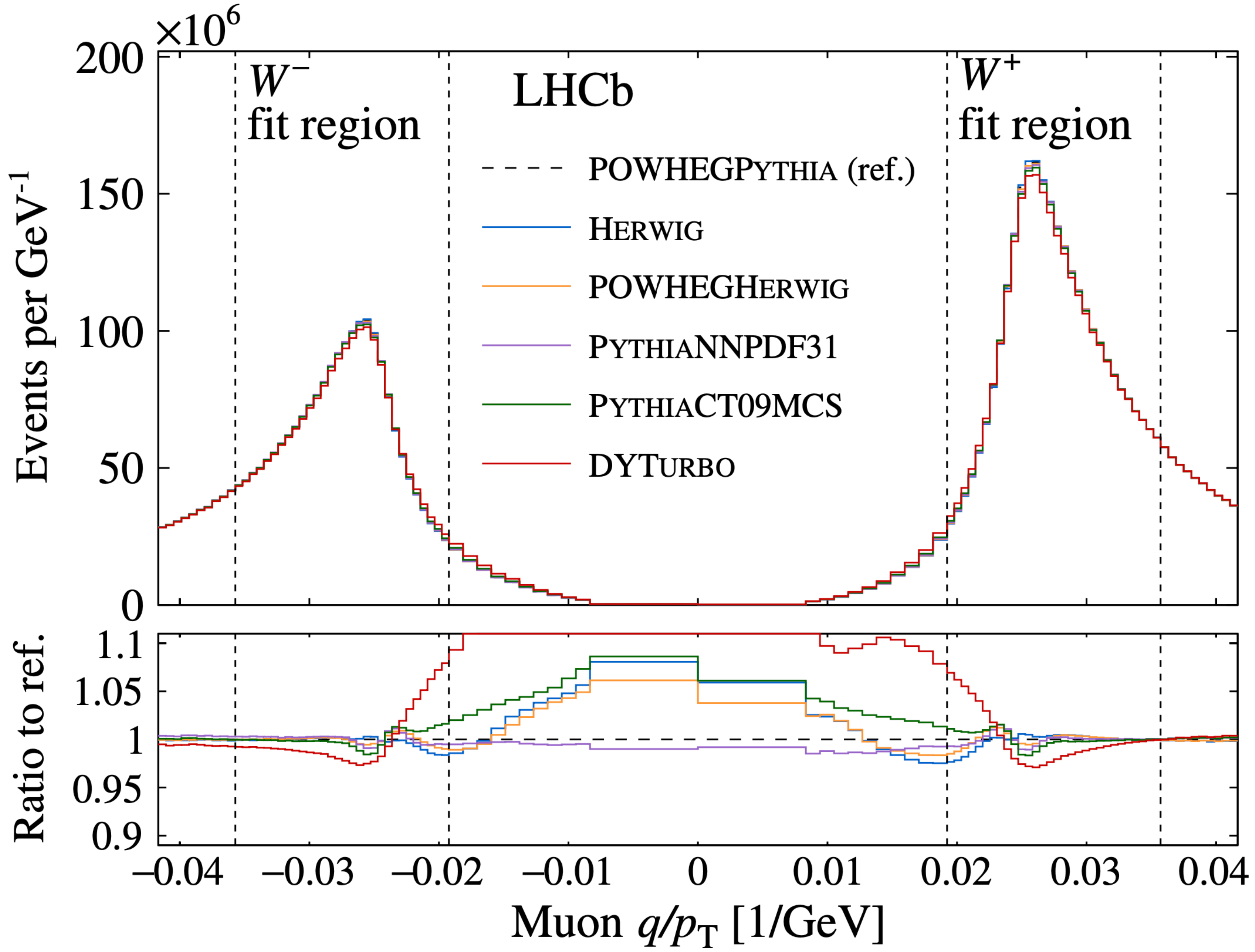
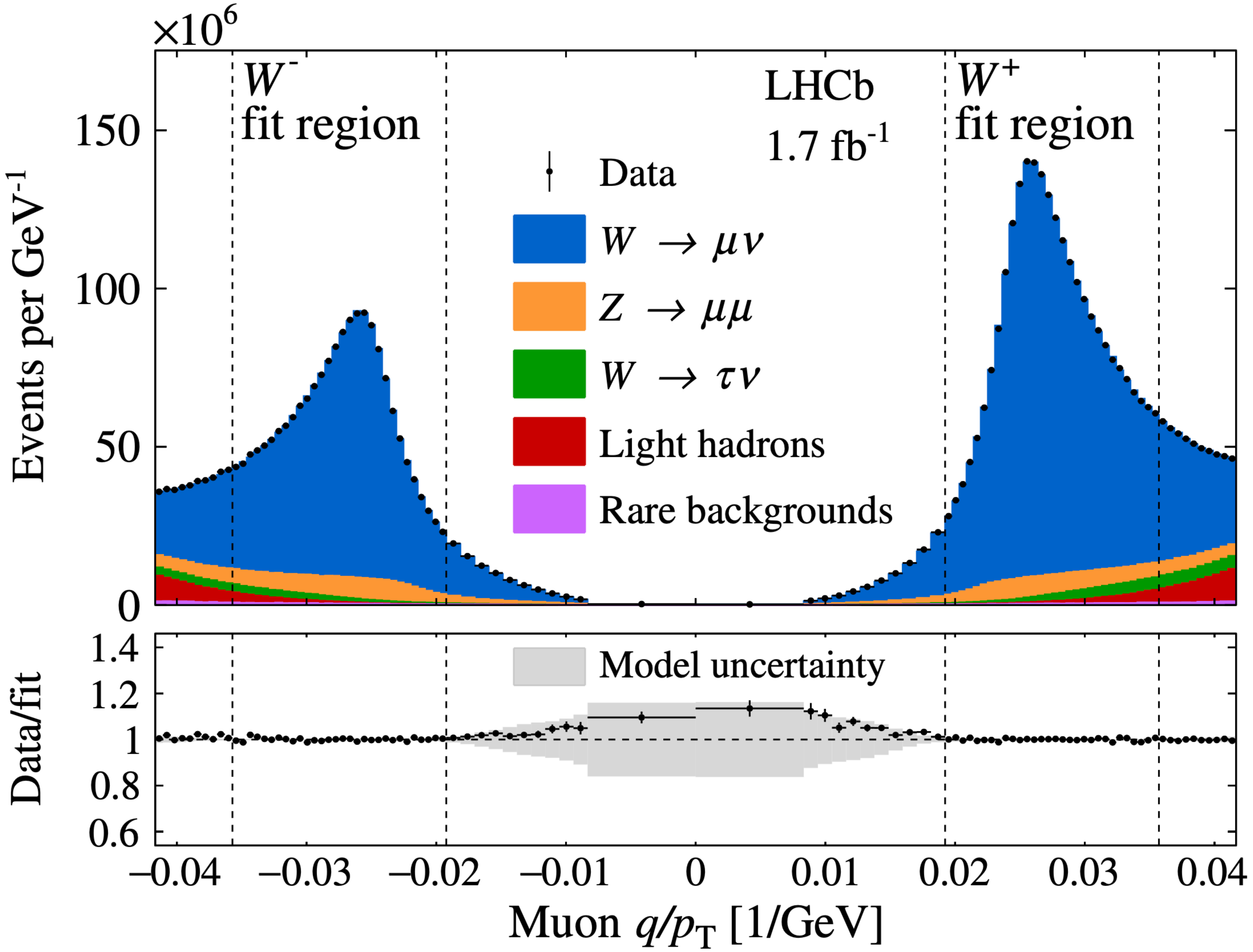


No significant variations in M_W value !

Fit results



Best fit parameters

Parameter	Value
Fraction of $W^+ \rightarrow \mu^+\nu$	0.5288 ± 0.0006
Fraction of $W^- \rightarrow \mu^-\nu$	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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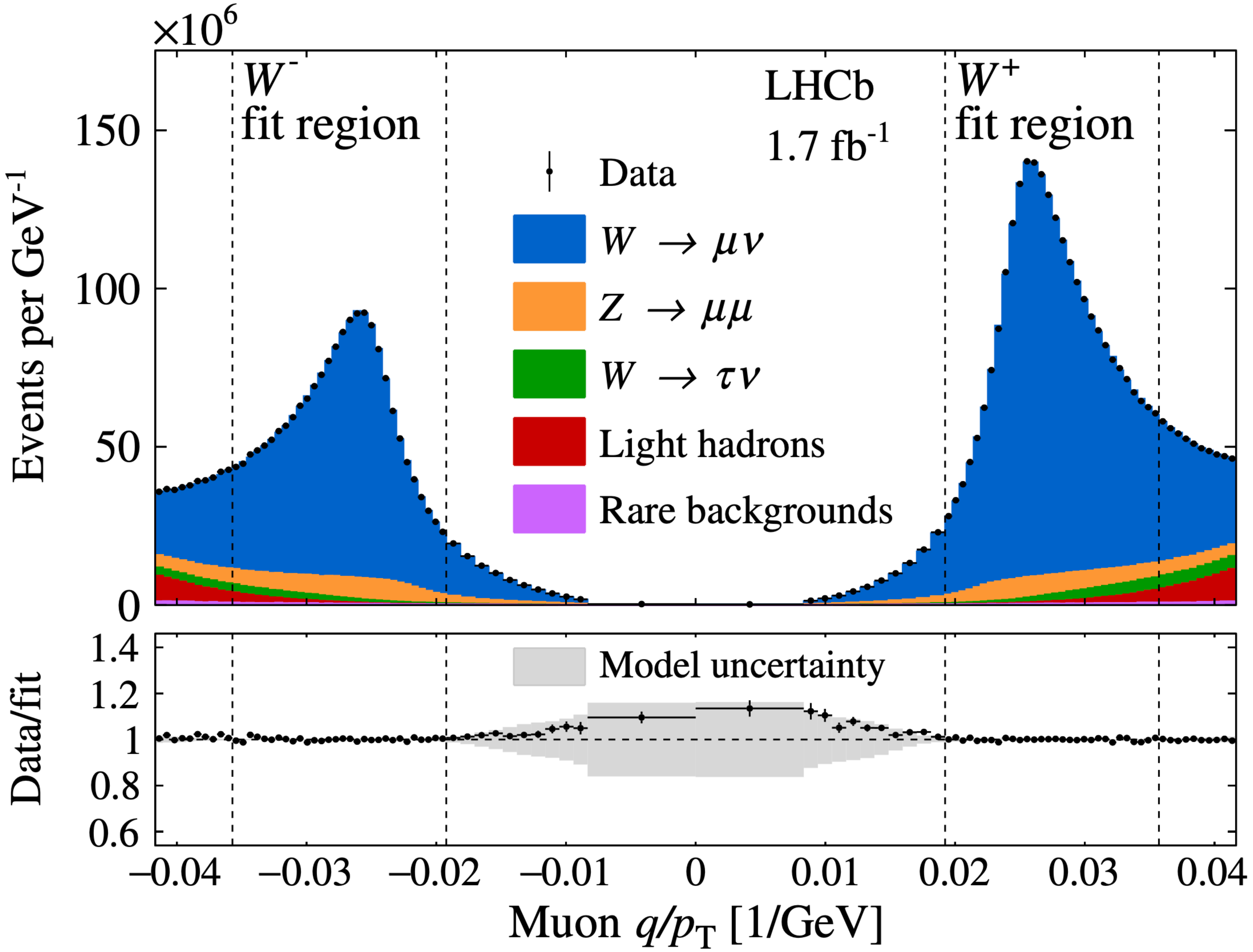

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x3 PDF models

$$m_W = 80362 \pm 23_{stat} \pm 10_{exp} \pm 17_{theory} \pm 9_{PDF} \text{ MeV},$$
$$m_W = 80350 \pm 23_{stat} \pm 10_{exp} \pm 17_{theory} \pm 12_{PDF} \text{ MeV},$$
$$m_W = 80351 \pm 23_{stat} \pm 10_{exp} \pm 17_{theory} \pm 7_{PDF} \text{ MeV},$$

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 modeling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
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PDFs (9) → Average of PDF models used for fitting

Transverse momentum model (11) → M_W description from alternative generators

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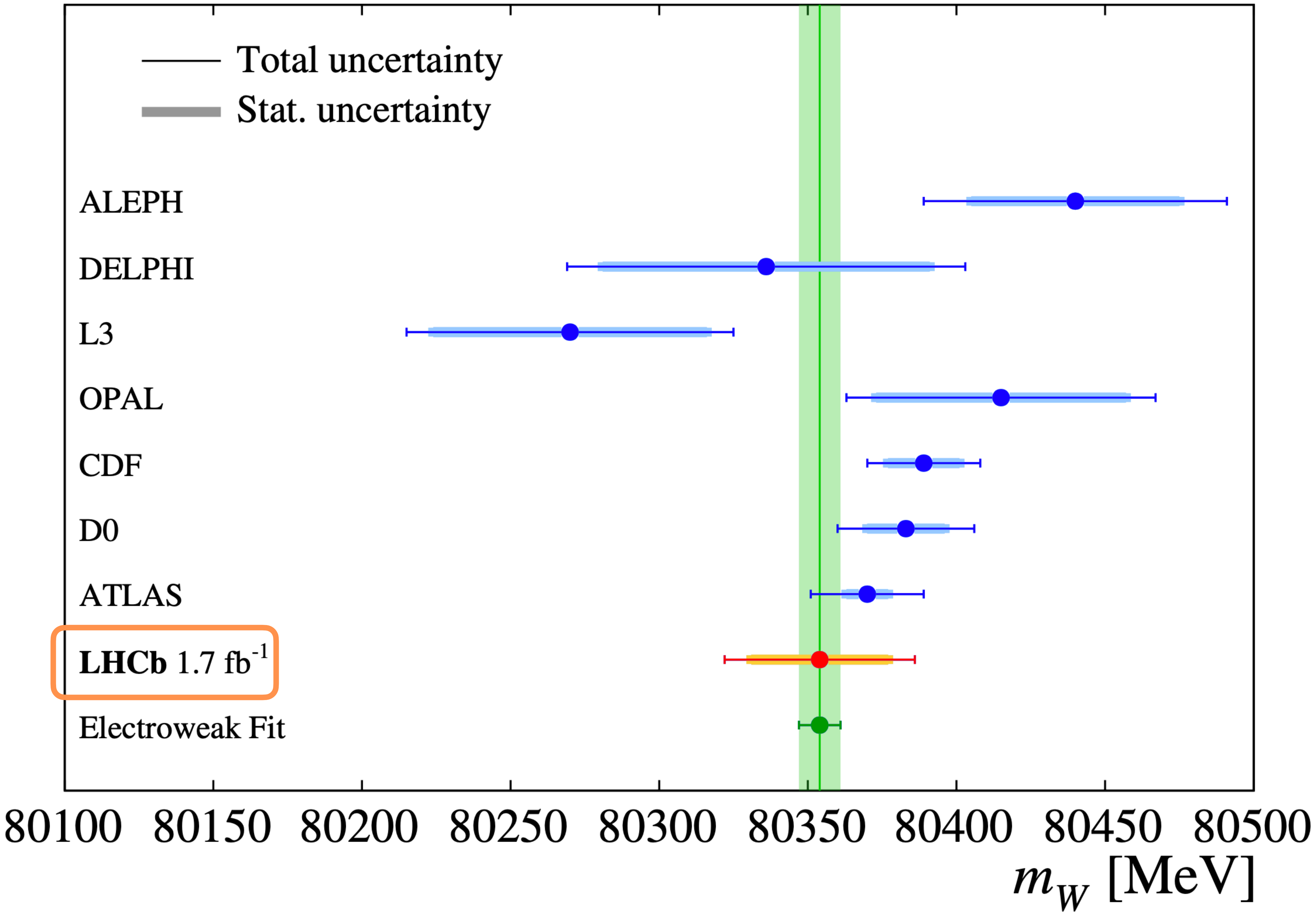
Average of PDF models used for fitting

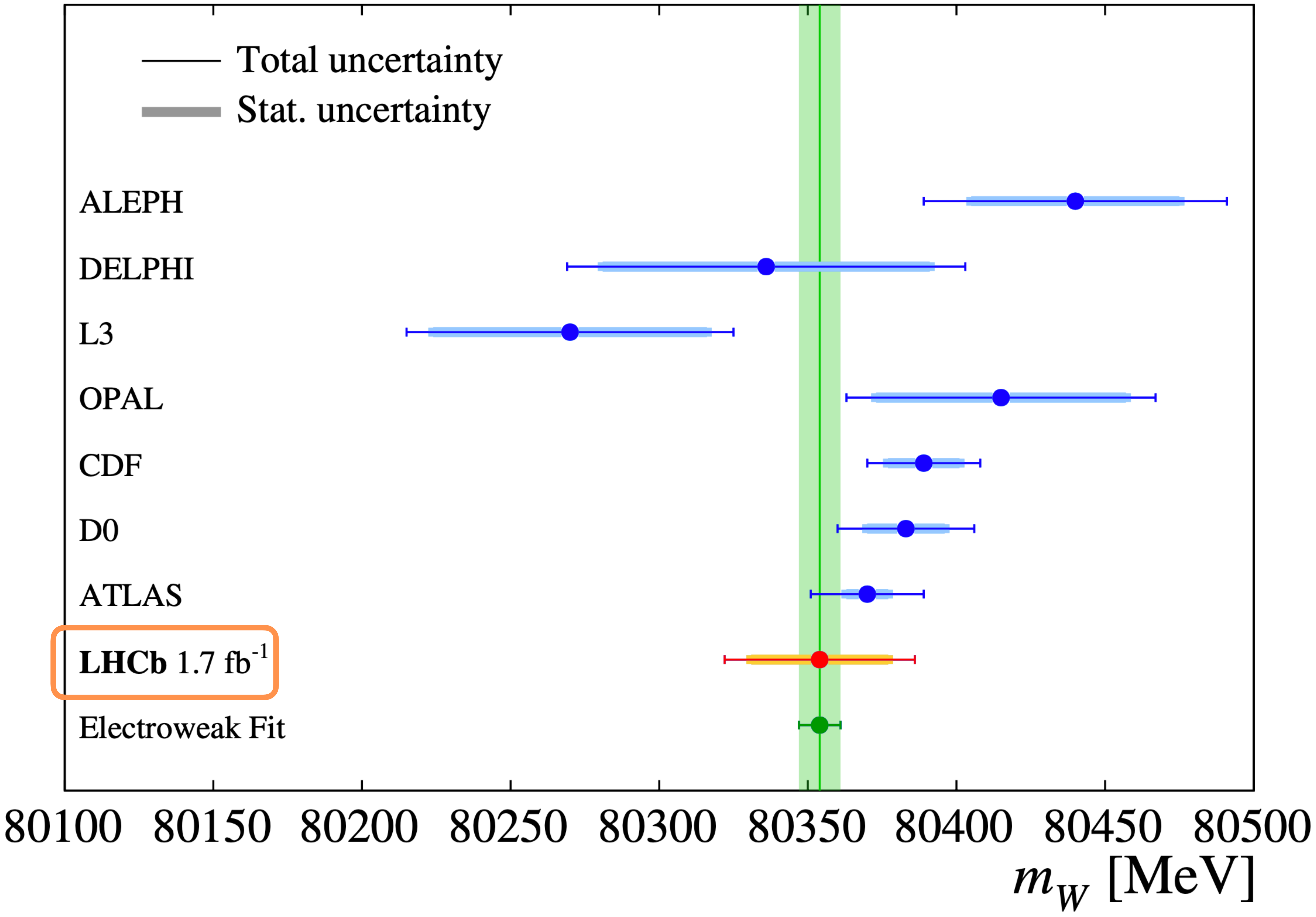
M_W description from alternative generators

Evaluated using control samples of Z, Υ and J/ψ

Comparison with other measurements



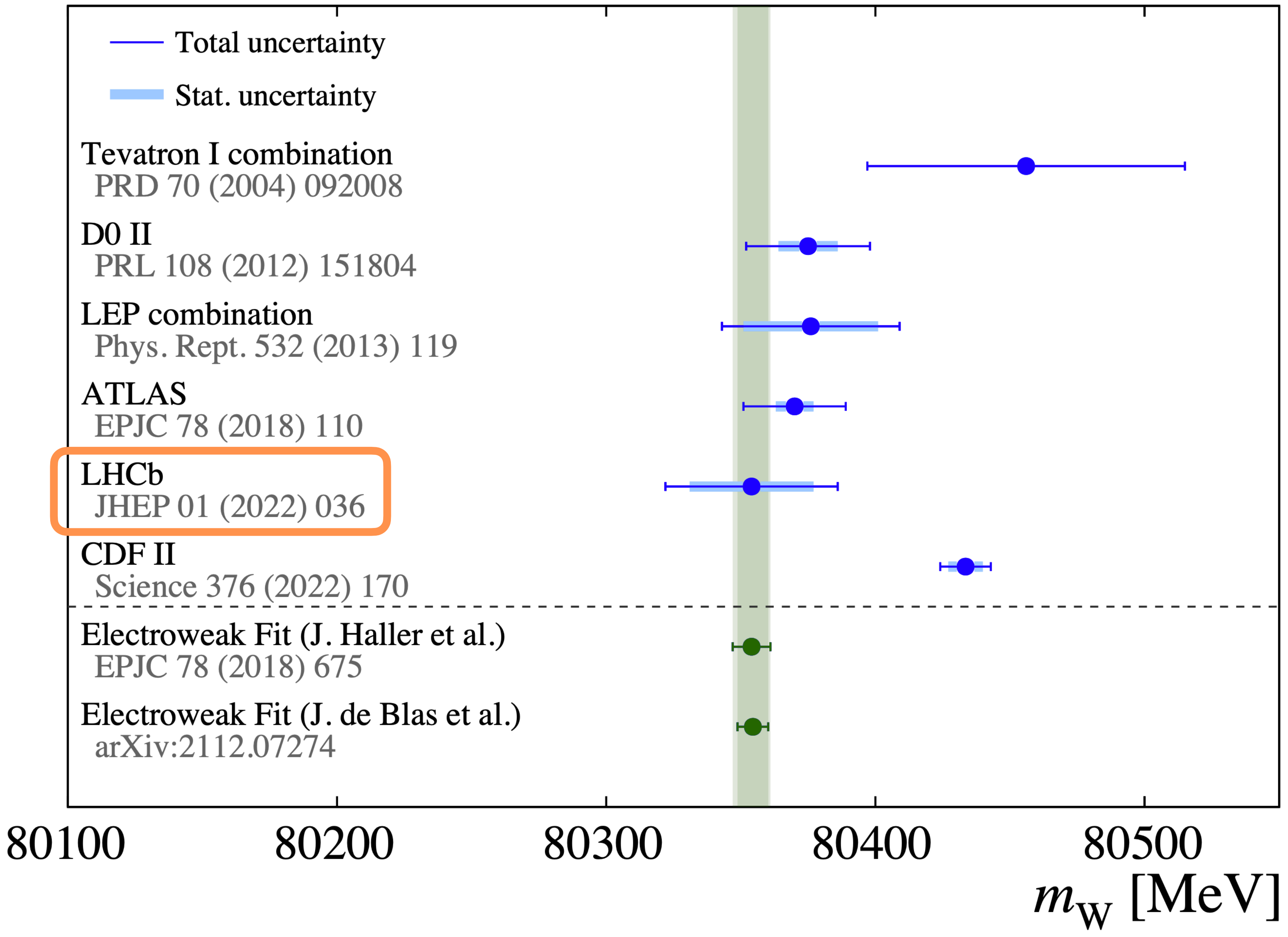
Comparison with other measurements



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

Summary & Outlook

- **First M_W measurement** performed at LHCb
- The measurement will complement results from ATLAS and CMS
- Resulting value **consistent** with SM expectations
- However, recent CDF measurement is in tension with the SM predictions



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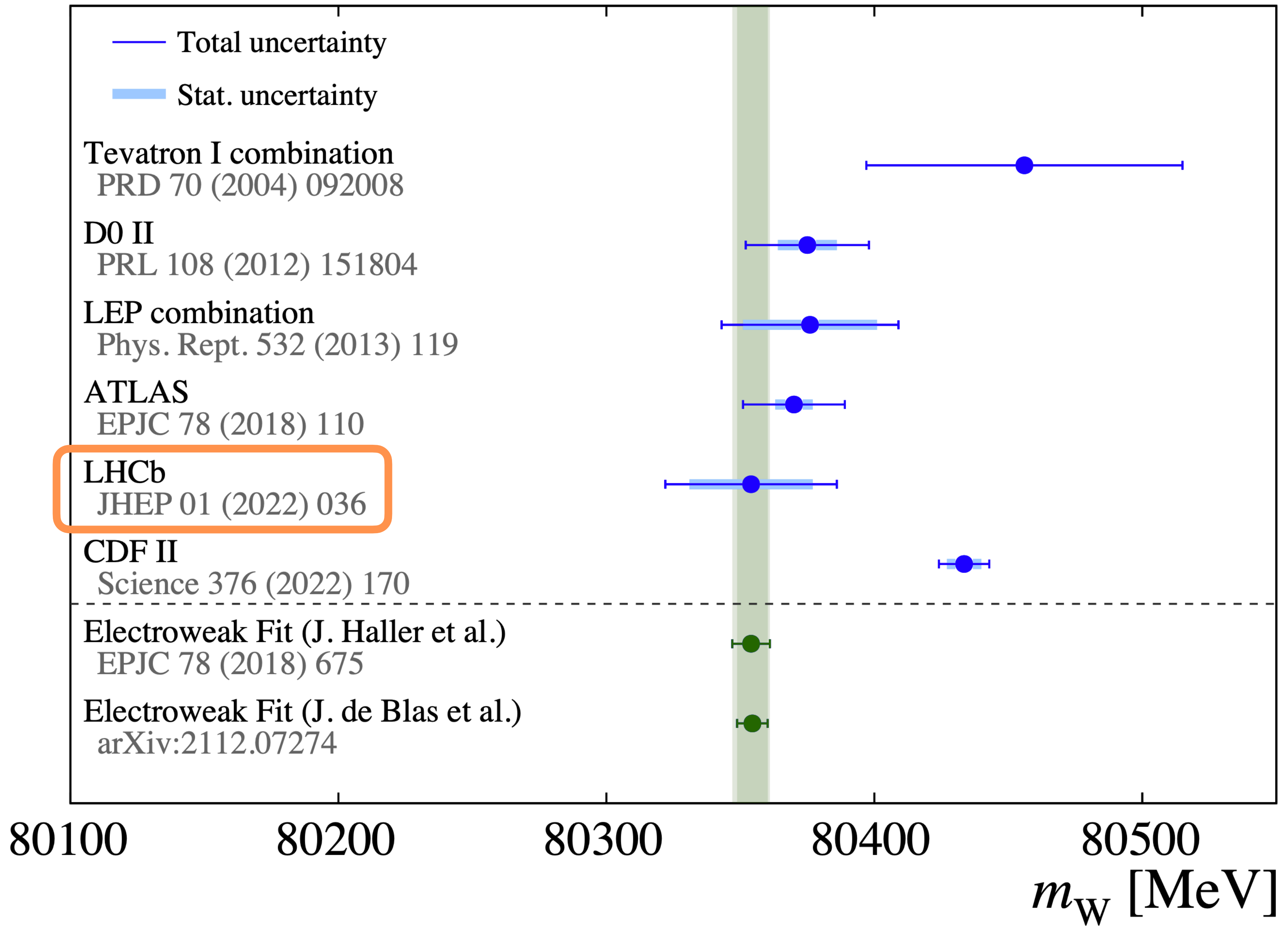
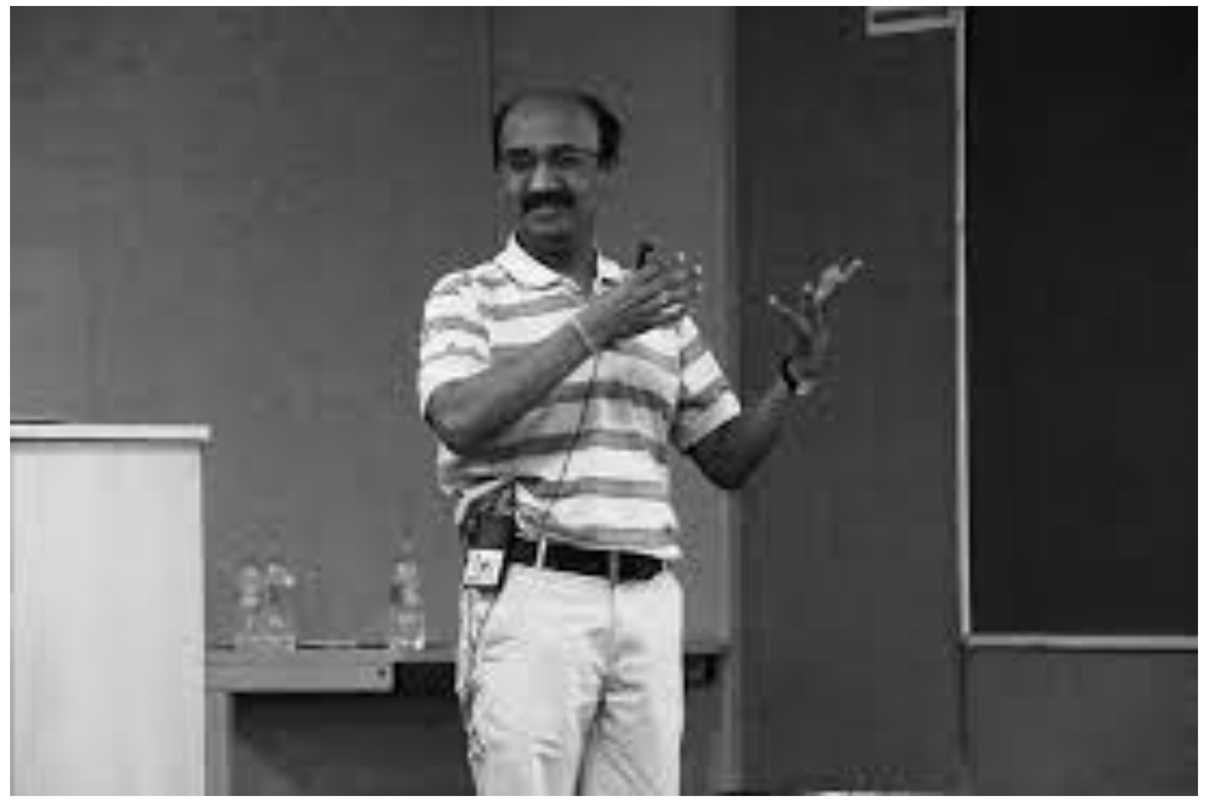




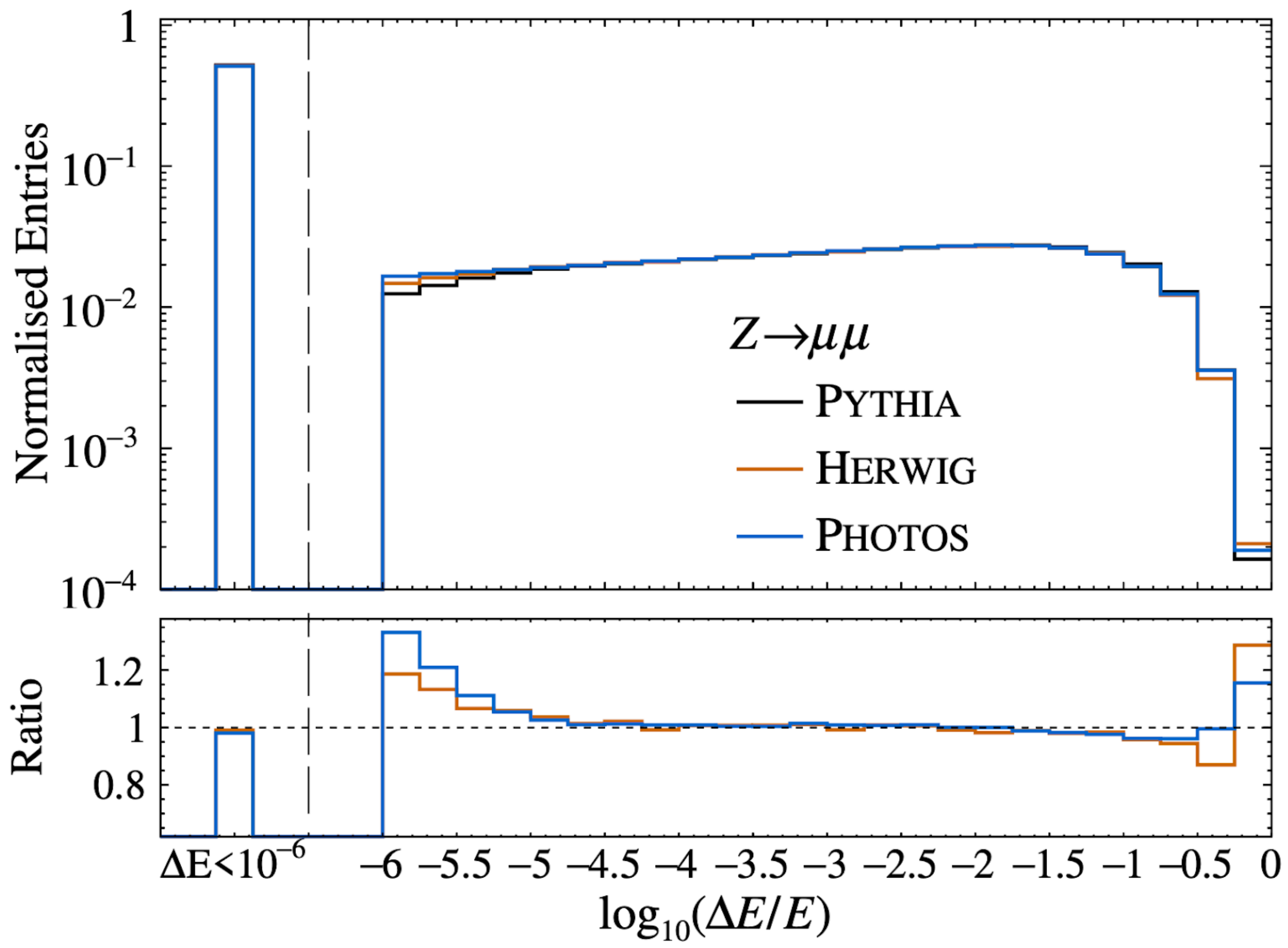
“The truth is in the details …”

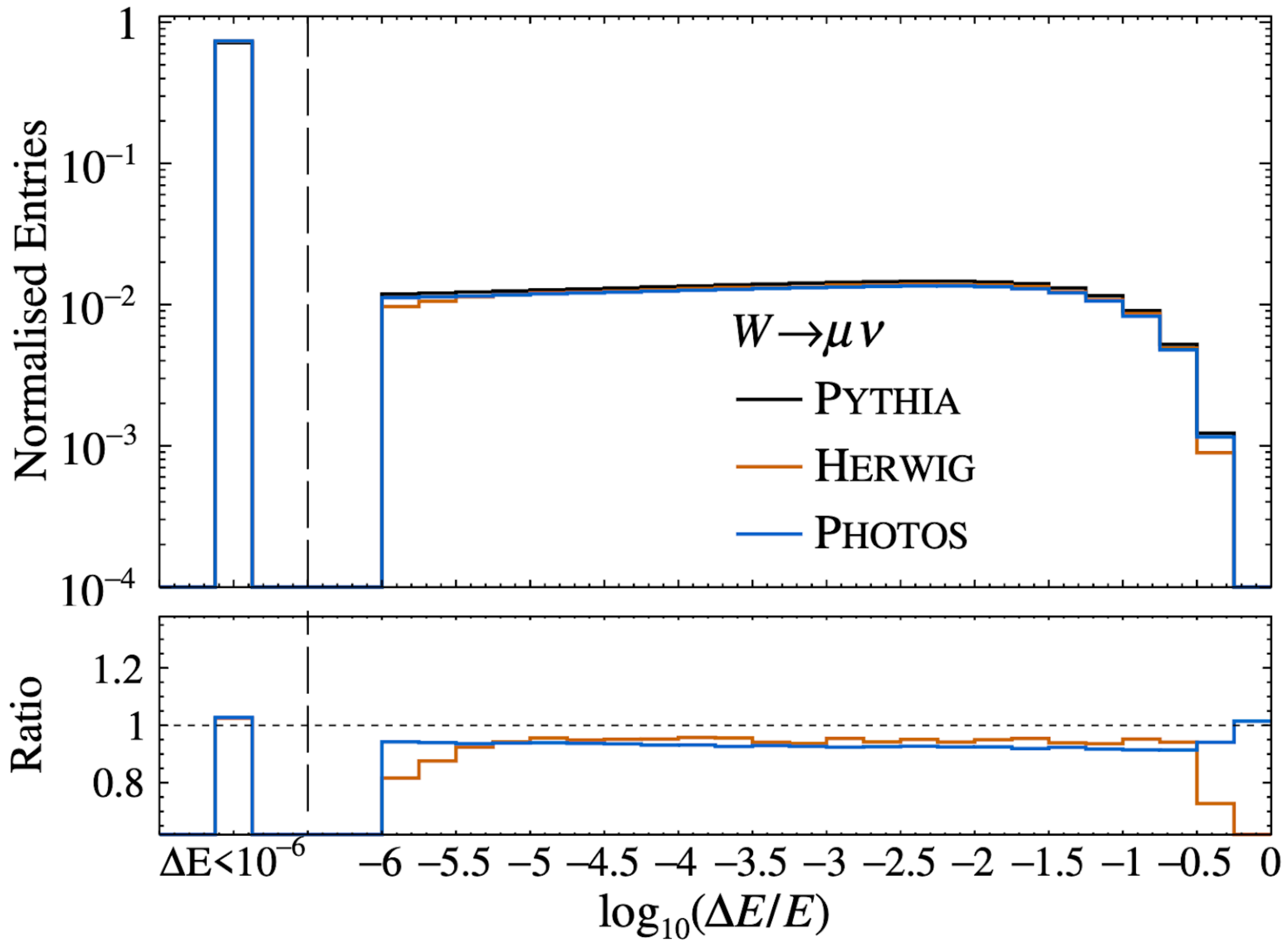
Vajravelu Ravindran, 2022 AEPSHEP Pyeongchang

Backup slides

QED corrections

- Muons can lose part of their energy ΔE due to final-state radiation.
- Three different LO QED models are combined to extract the energy loss distribution.
- Higher order electroweak corrections are not considered.





Angular coefficients

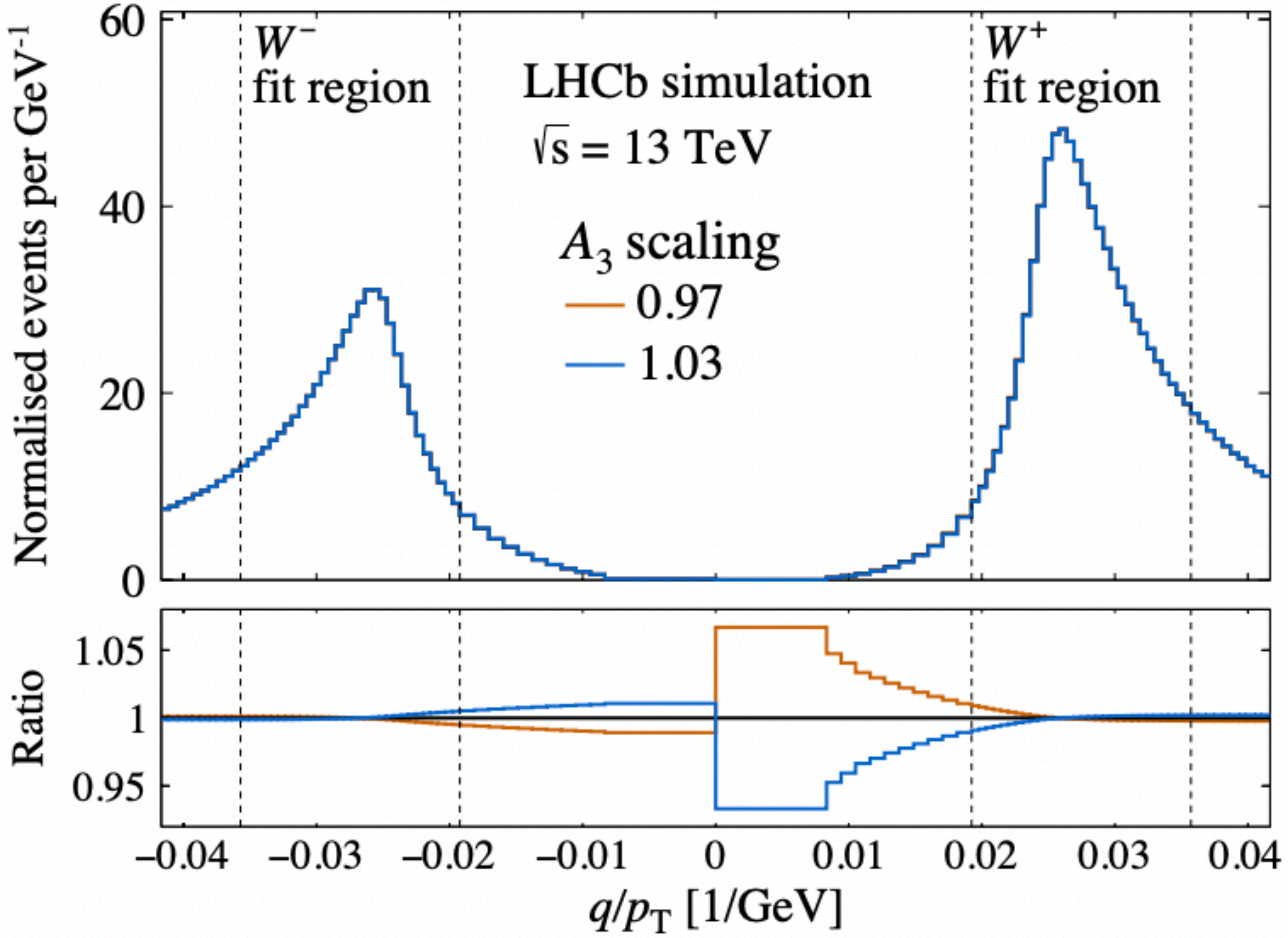
$$\frac{d\sigma}{dp_T^W\,dy\,dM\,d\cos\theta\,d\phi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol}}}{dp_T^V\,dy\,dM}$$

Unpolarised cross-section

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

Angular terms (A_i = angular coefficients)

- A_i Predictions from DYTurbo at O(α_3^2)
- Float a single A_3 scale factor in the fit to absorb the uncertainty on the prediction of A_3



Fit results

- The data and simulation samples are split into orthogonal subsets

Subset	$\chi^2_{\text{tot}}/\text{ndf}$	δm_W [MeV]
Polarity $= -1$	$92.5/102$	–
Polarity $= +1$	$97.3/102$	-57.5 ± 45.4
$\eta > 3.3$	$115.4/102$	–
$\eta < 3.3$	$85.9/102$	$+56.9 \pm 45.5$
Polarity $\times\, q = +1$	$95.9/102$	–
Polarity $\times\, q = -1$	$98.2/102$	$+16.1 \pm 45.4$
$\lvert\phi\rvert > \pi/2$	$98.8/102$	–
$\lvert\phi\rvert < \pi/2$	$115.0/102$	$+66.7 \pm 45.5$
$\phi < 0$	$91.8/102$	–
$\phi > 0$	$103.0/102$	-100.5 ± 45.3

Fit results

- Variations the p_T^{min} and p_T^{max} of the fit range in the q/p_T distribution

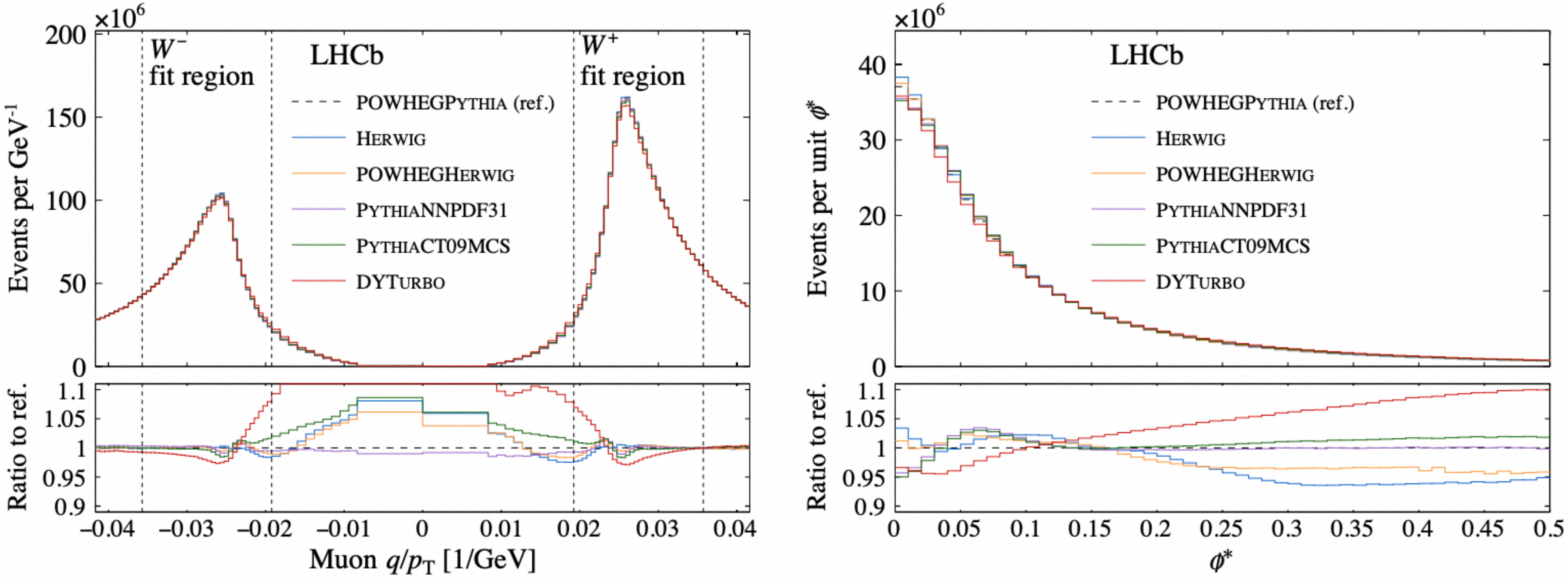
Change to fit range	$\chi^2_{\text{tot}}/\text{ndf}$	δm_W [MeV]	$\sigma(m_W)$ [MeV]
$p_\text{T}^\text{min} = 24$ GeV	96.5/102	+6.8	19.7
$p_\text{T}^\text{min} = 26$ GeV	97.7/102	+9.6	20.9
$p_\text{T}^\text{min} = 30$ GeV	102.7/102	+3.0	25.7
$p_\text{T}^\text{min} = 32$ GeV	84.9/102	−21.6	30.8
$p_\text{T}^\text{max} = 48$ GeV	105.3/102	−3.8	23.2
$p_\text{T}^\text{max} = 50$ GeV	103.0/102	−2.1	23.0
$p_\text{T}^\text{max} = 54$ GeV	96.3/102	−8.6	22.6
$p_\text{T}^\text{max} = 56$ GeV	103.7/102	−14.3	22.4

Fit results

- Variations in the parameters determined in the fit (Fit model freedom)

Configuration change	$\chi^2_{\mathrm{tot}}/\mathrm{ndf}$	δm_W [MeV]	$\sigma(m_W)$ [MeV]
$2 \to 3$ α_s parameters	103.4/101	−6.0	±23.1
$2 \to 1$ α_s and $1 \to 2$ $k_{\mathrm{T}}^{\mathrm{intr}}$ parameters	116.1/102	+13.9	±22.4
$1 \to 2$ $k_{\mathrm{T}}^{\mathrm{intr}}$ parameters	104.0/101	+0.4	±22.7
$1 \to 3$ $k_{\mathrm{T}}^{\mathrm{intr}}$ parameters	102.8/100	−2.7	±22.9
No A_3 scaling	106.0/103	+4.4	±22.2
Varying QCD background asymmetry	103.8/101	−0.7	±22.7

(Pseudo) data challenges



- Using the central model to fit pseudo data generated from different models gives a similar spread as using those different models to fit the real data

Data config.	χ^2_W	χ^2_Z	δm_W [MeV]	α_s^Z	α_s^W	A_3 scaling
POWHEGPYTHIA	64.8	34.2	–	0.1246 ± 0.0002	0.1245 ± 0.0003	0.979 ± 0.029
HERWIG	71.9	600.4	1.6	0.1206 ± 0.0002	0.1218 ± 0.0003	1.001 ± 0.029
POWHEGHERWIG	64.0	118.6	2.7	0.1206 ± 0.0002	0.1226 ± 0.0003	0.991 ± 0.029
PYTHIA, CT09MCS	71.0	215.8	−2.4	0.1239 ± 0.0002	0.1243 ± 0.0003	0.983 ± 0.029
PYTHIA, NNPDF31	66.9	156.2	−10.4	0.1225 ± 0.0002	0.1223 ± 0.0003	0.967 ± 0.029
DYTURBO	83.0	428.5	4.3	0.1305 ± 0.0001	0.1321 ± 0.0003	0.982 ± 0.028