Measurement of the Z boson mass with the LHCb detector

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European Research Council

Established by the European Commission

WARWICK

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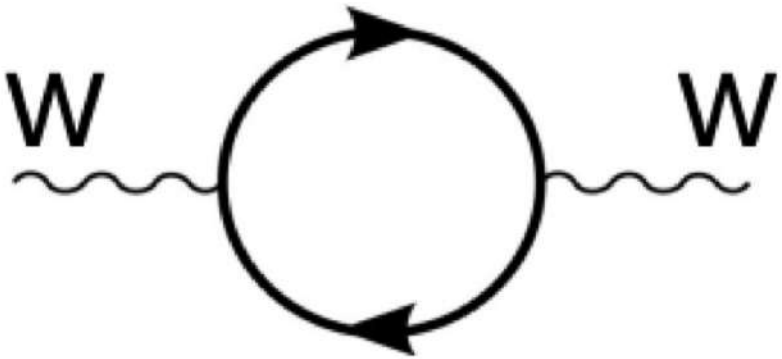
Introduction

- m_z is an important fundamental parameter in the Standard Model
- Known at tree level:

$$m_z = \frac{v\sqrt{g^2 + g'^2}}{2}$$

- Predictions at higher precision require loop corrections
  - Depends on top mass, Higgs mass, etc..



Indirect m_z = 91204.7 ± **8.8** MeV

Phys. Rev. D 106 (2022) 033003

Direct Z boson mass measurements

LEP

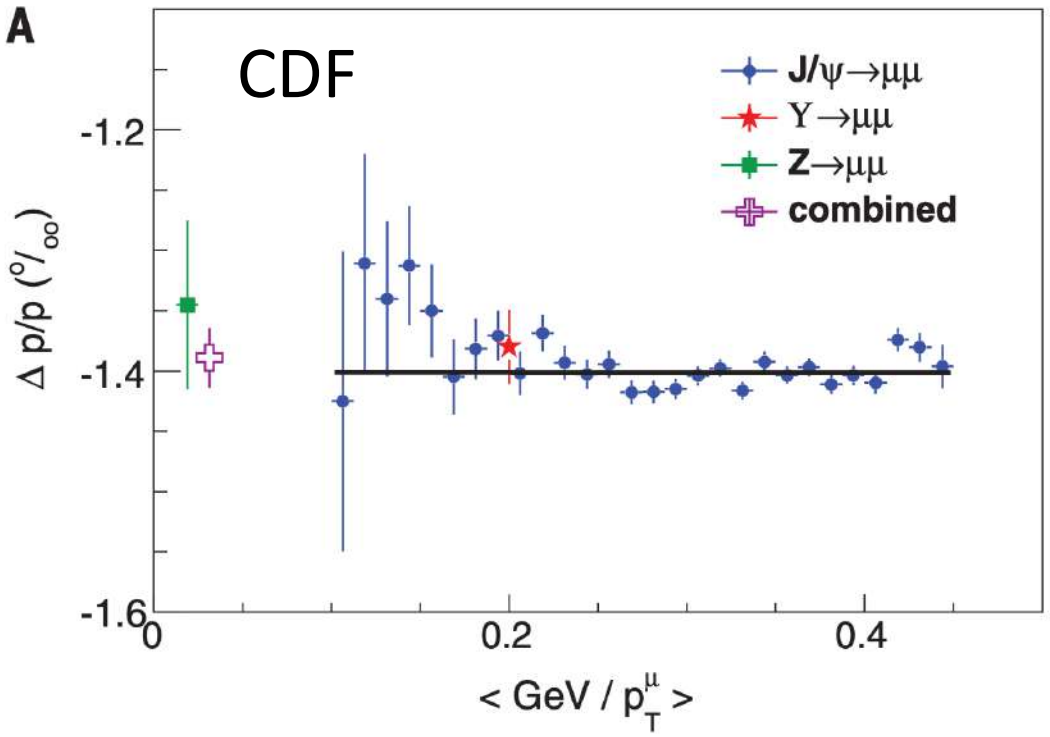
- Measure m_Z with beam-energy scan of total cross-section
- **Beam-energy calibration.**
  m_Z = 91187.6 ± **2.1** MeV

LHC

- Measure m_Z with from final-state kinematics
- **Detector calibration.**

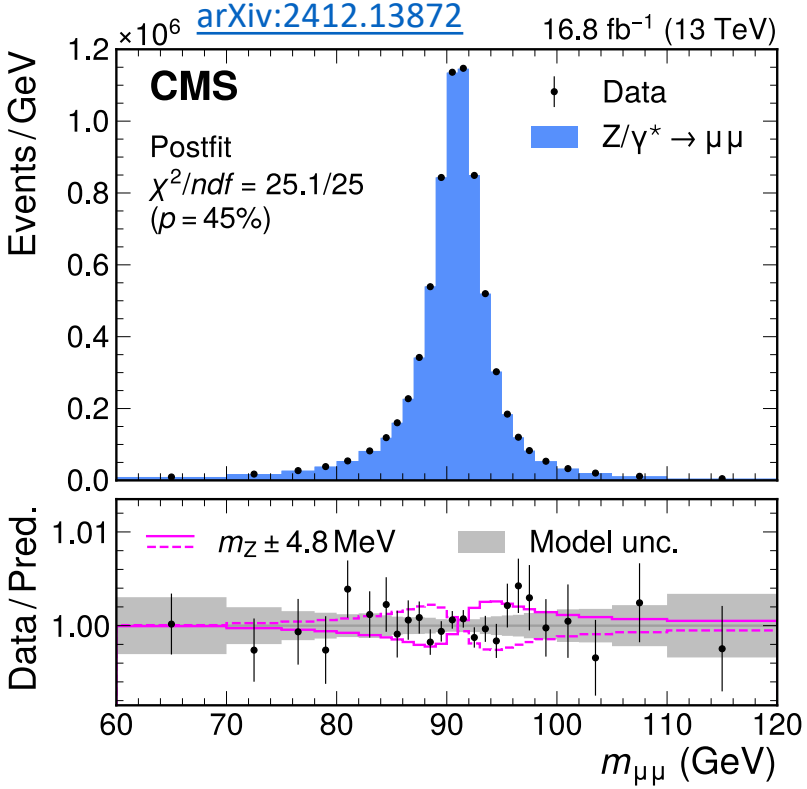
Prospects of Z measurements at LHC

Science 374 (2021) 6568



$m_Z = 91192.3 \pm 7.1$ MeV

arXiv:2412.13872



$m_Z - m_{PDG} = -2.2 \pm 4.8$ MeV

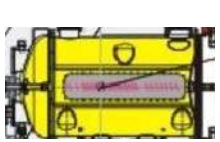
"Since J/ψ vs Z closure was used to tune calibration and enters the uncertainty model, not (yet) a fully independent measurement for inclusion in world average"

LHCb's Run II detector

Int J Mod Phys A 30 (2015), 1530022

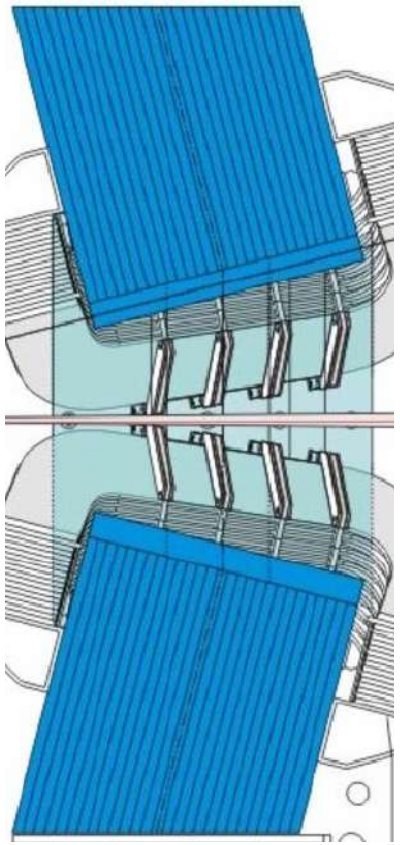
TT

Silicon microstrip tracker



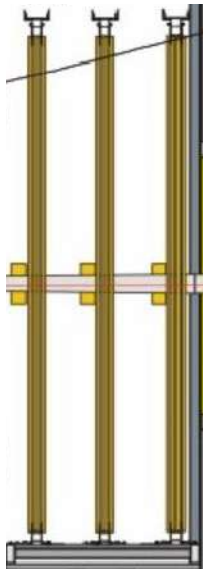
Silicon strip vertex detector

VELO



T Stations

Inner tracker: silicon strips
Outer trackers: straw drift tubes



Muon stations

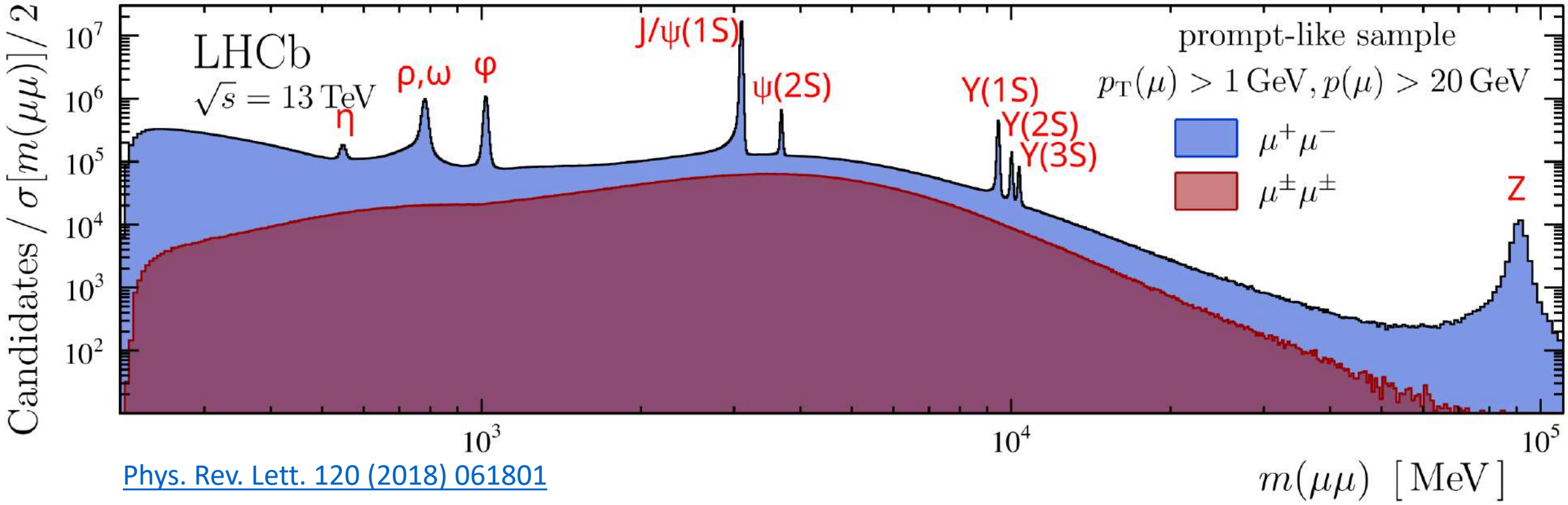
MWPCs + GEMs
Excellent Muon ID

Dipole magnet

4 Tm (vertical)
Polarity switchable

Tracking ranges
ATLAS / CMS: $|\eta| < 2.5$
LHCb: $2 < \eta < 5$

Dimuon mass spectrum



Phys. Rev. Lett. 120 (2018) 061801

Z mass measurement at LHCb

Sensitive via the dimuon mass distribution

JHEP 01 (2022) 036 JHEP 12 (2024) 026

- Fit compares full simulation with the data
- m_z hypothesis varied by reweighting full simulation with generator level events
- Build off previous m_W and weak mixing measurement tools
- Difference between data and simulation needs to be well under control

Dataset and selections

- Signal selection of:
  - $Z \to \mu\mu$
  - Muon η : 2.2 < η < 4.4
  - Muon p_T > 20 GeV
  - Identified muon candidate matched to single muon trigger path.

- Quarkonia selection of:
  - $\Upsilon(1S) \to \mu\mu$ (calibration)
  - $\mathrm{J}/\psi \to \mu\mu$ (cross check)
  - Muon η : 2.2 < η < 4.4
  - Muon p_T > 5 GeV

Use 2016 dataset @ $\sqrt{s} = 13$ TeV, 1.7 fb^{-1}

Sample	Data events
$Z \to \mu\mu$	170,000
$\Upsilon(1S) \to \mu\mu$	190,000
$\mathrm{J}/\psi \to \mu\mu$	48,000

- Naïve statistical uncertainty

$$\frac{3\ \mathrm{GeV}}{\sqrt{170{,}000}} \approx 8\ \mathrm{MeV}$$

The Simulation

The completed events and detector interactions are initially simulated with Pythia and GEANT4, respectively

A variety of models are used to fully reweight the events to next to leading order accuracy (we'll get to that later)

Pythia

Comput. Phys. Commun. 178 (2008) 852

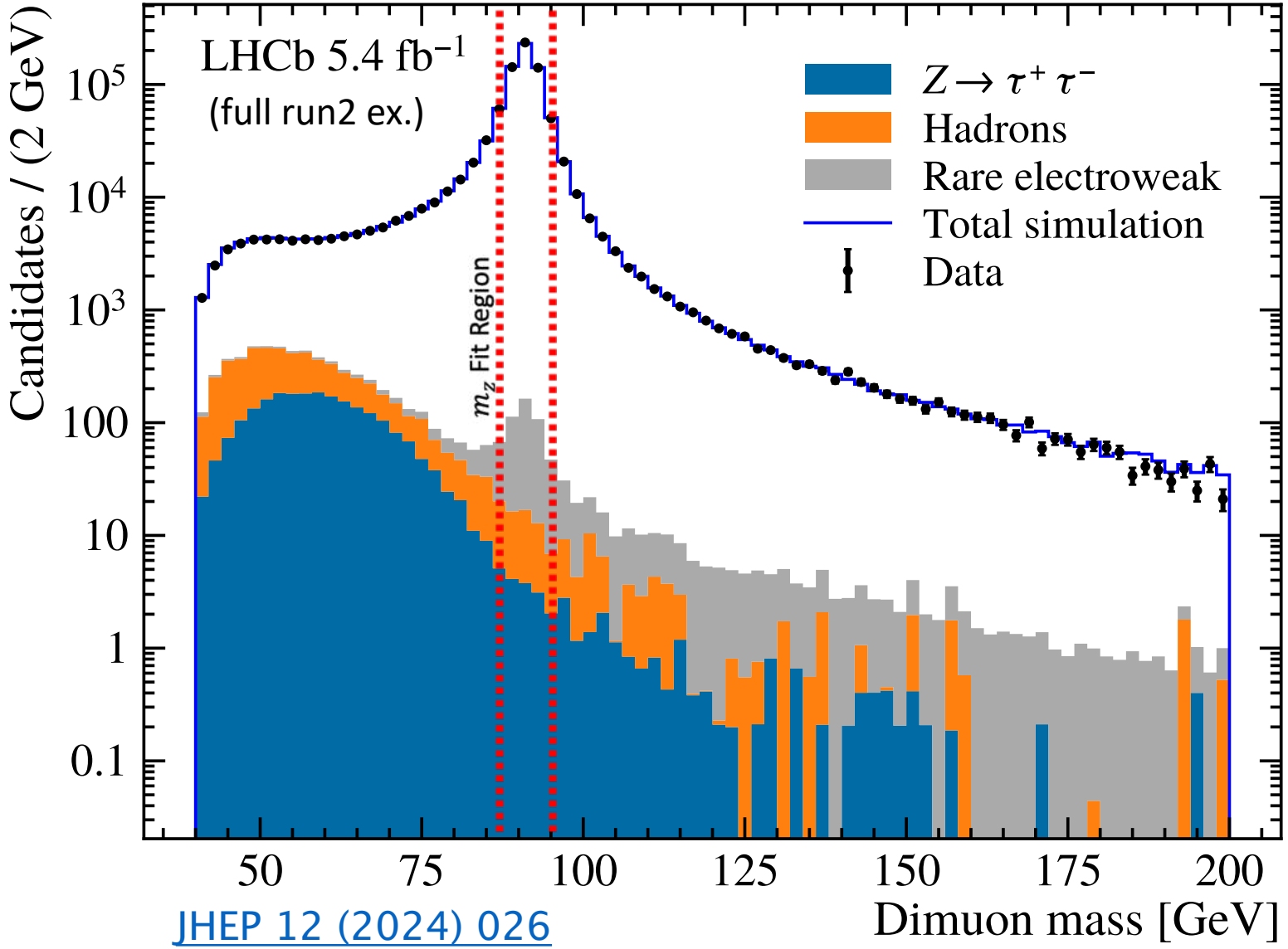
JHEP 05 (2006) 026, 517

GEANT4

Nucl. Instrum. Meth. A506 (2003) 250

IEEE Trans. Nucl. Sci. 53 (2006) 270

Backgrounds



JHEP 12 (2024) 026

The momentum response

$\mathcal{R} \sim \mathcal{N}(0,1)$

$$p^{\pm} \rightarrow (\,1 + \alpha + \frac{\beta}{p^{\pm}} \mp \delta p^{\pm})(1 + a\mathcal{R}_1\sigma_1)(1 + b\mathcal{R}_2\sigma_2 p^{\pm})p^{\pm}$$

Differences between data and simulation are of the form above

The momentum response

$\mathcal{R} \sim \mathcal{N}(0,1)$

$$p^{\pm} \rightarrow (\,1 + \alpha + \frac{\beta}{p^{\pm}} \mp \delta p^{\pm})(1 + a\mathcal{R}_1\sigma_1)(1 + b\mathcal{R}_2\sigma_2 p^{\pm})p^{\pm}$$

Bias terms

Large effect on mass bias
Small effect on mass resolution

Smearing terms

Small effect on mass bias
Large effect on mass resolution

The momentum response

$\mathcal{R} \sim \mathcal{N}(0,1)$

$$p^{\pm} \rightarrow \left(1 + \alpha + \frac{\beta}{p^{\pm}} \mp \delta p^{\pm}\right)\left(1 + a\mathcal{R}_1\sigma_1\right)\left(1 + b\mathcal{R}_2\sigma_2 p^{\pm}\right)p^{\pm}$$

Bias terms

Smearing terms

Momentum Scale
(time/direction dependent)

Detector Misalignment

Detector resolution

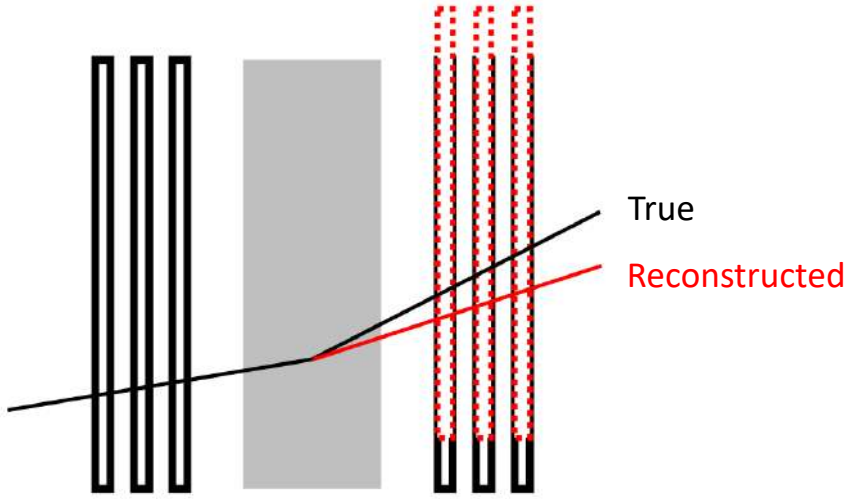
Energy Loss

Material scattering

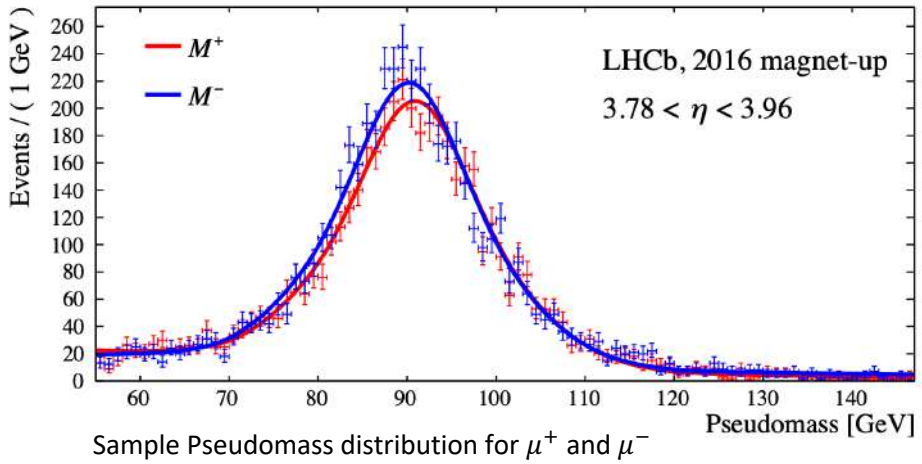
$$a(\eta) = \begin{cases} 1, & \eta < 3.3 \\ 1.5, & \eta \geq 3.3 \end{cases} \qquad b(\eta) = \frac{1}{\cosh \eta}$$

Correct in a four step procedure

1. Charge-dependent Curvature Bias



JINST 19 (2024) P03010



Sample Pseudomass distribution for μ^+ and μ^-

- Caused by tracker misalignments
- Corrected via the *pseudomass* method
- Fit $\mathcal{M}^{\pm}$ from muons of $Z \rightarrow \mu\mu$

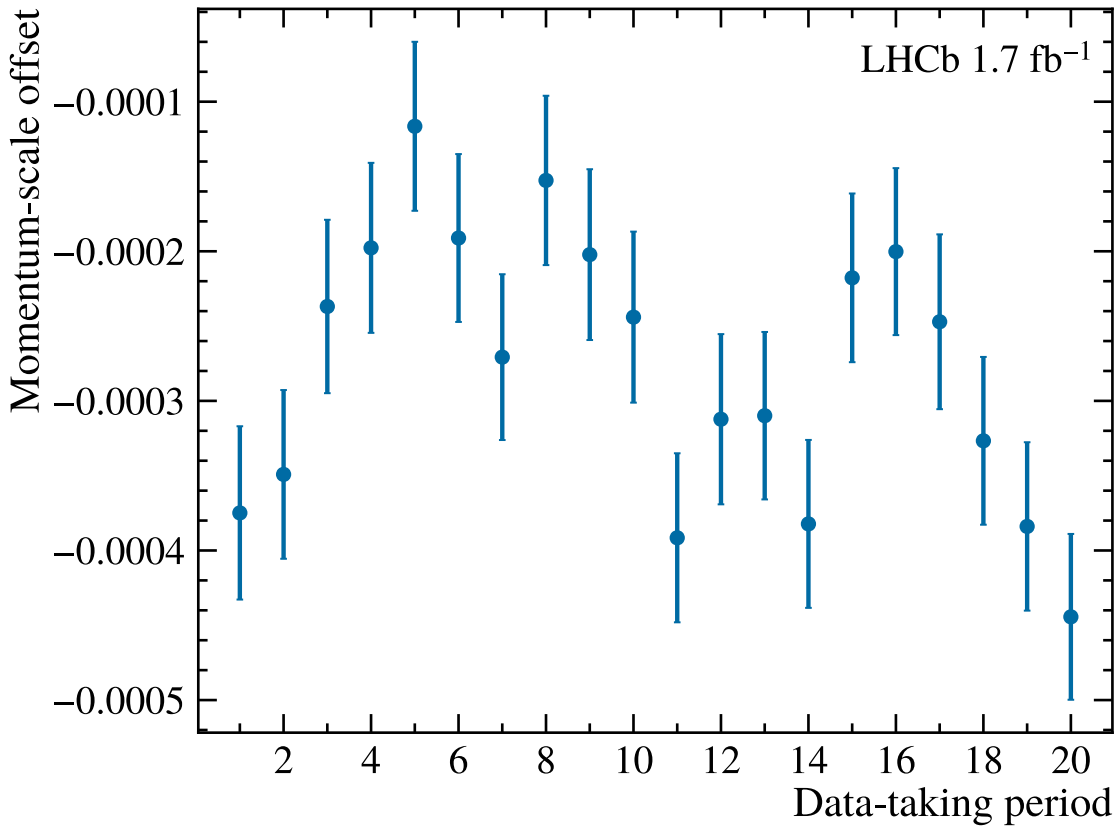
$$\mathcal{M}^{\pm} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\pm}}(1 - cos\theta)}$$

- Correct <u>data</u> from data-sim differences
- Method is **unbiased**
- does not rely on any assumptions on the Z mass

$$p^{\pm} \rightarrow (1 + \alpha + \frac{\beta}{p^{\pm}} \mp \delta p^{\pm})(1 + a\mathcal{R}_1\sigma_1)(1 + b\mathcal{R}_2\sigma_2 p^{\pm})p^{\pm}$$

2. Time varying momentum scale

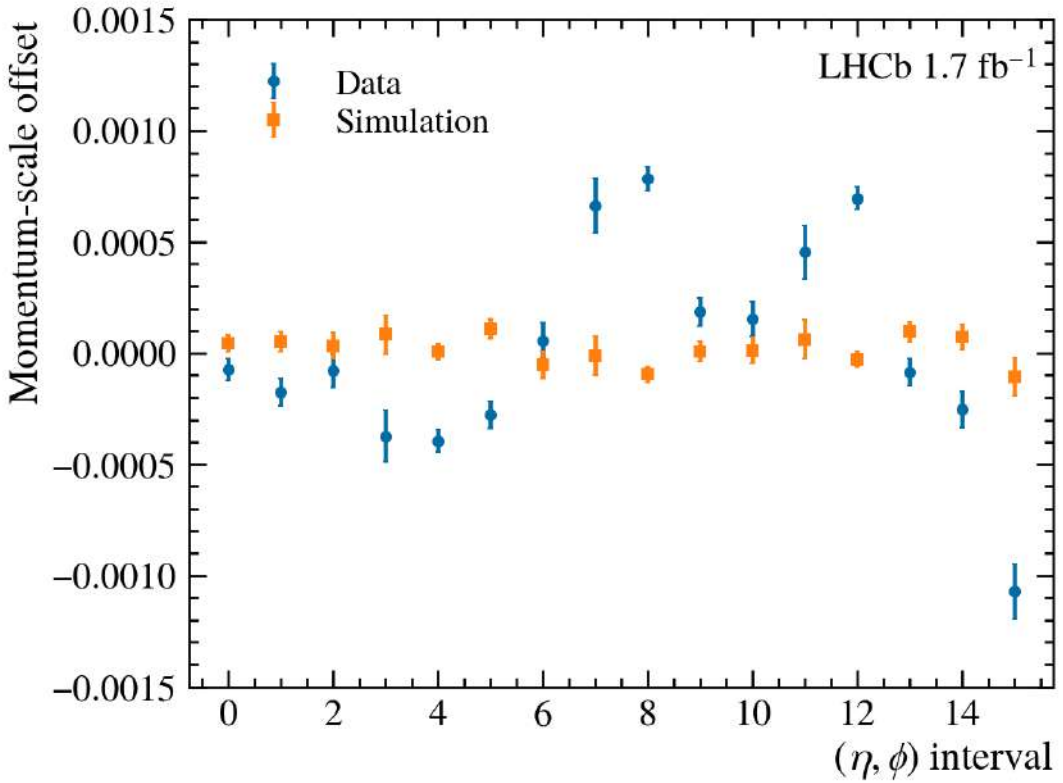
- Detector movement over time cause variations
- Extract the $\Upsilon(1S)$ line shape parameters in bins of the 2016 data-taking period [2024 JINST 19 P02008]
- Correct mass scales by comparing with PDG values
- Corrected in data



$$p^{\pm} \to (1 + \alpha + \frac{\beta}{p^{\pm}} \mp \delta p^{\pm})(1 + a\mathcal{R}_1\sigma_1)(1 + b\mathcal{R}_2\sigma_2 p^{\pm})p^{\pm}$$

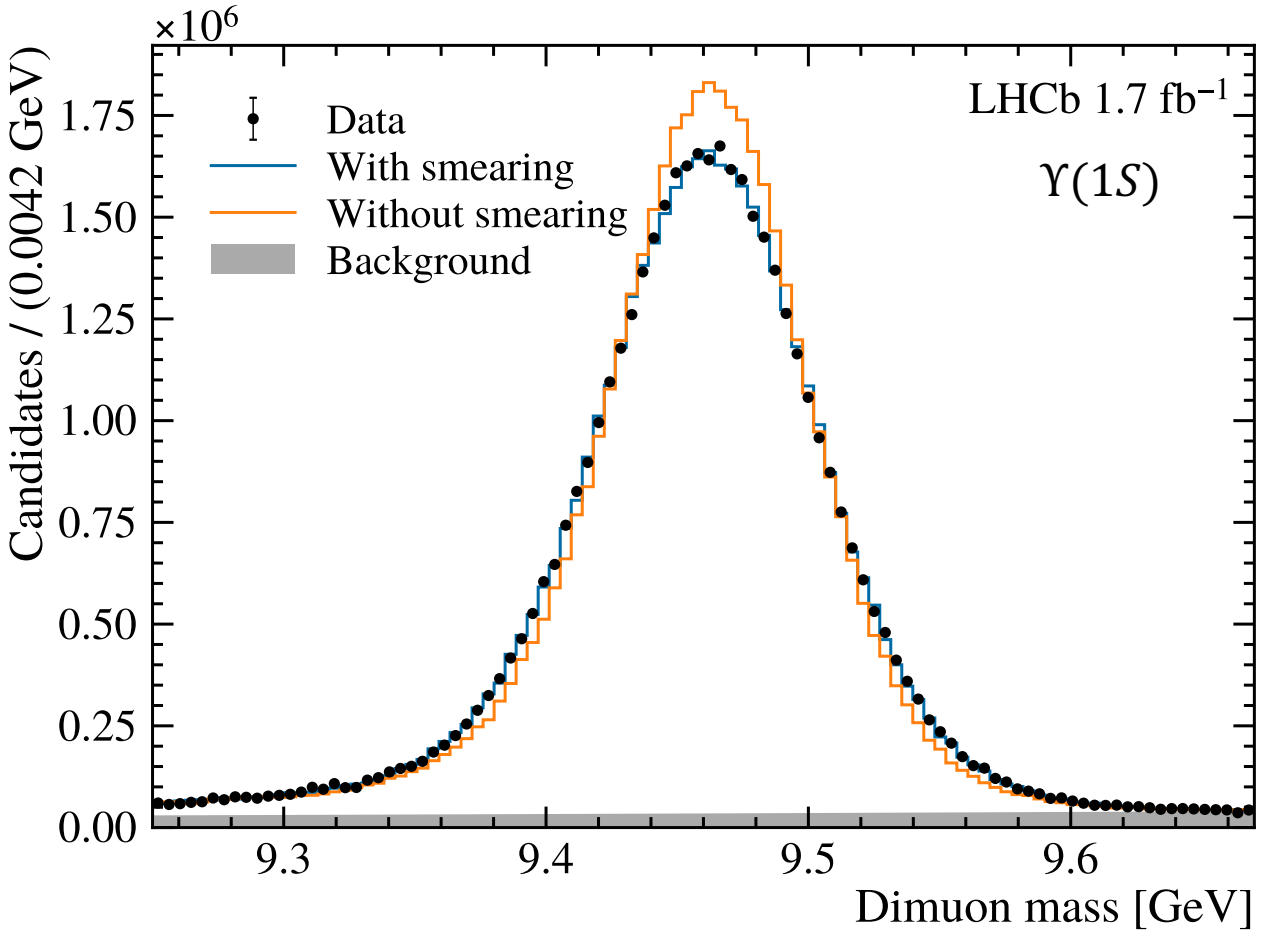
3. Direction dependent momentum scale

- Magnetic field map not perfect
- Corrections in 16 bins of η / ϕ
- Extract $\Upsilon(1S)$ lineshape parameters from each bin for data and simulation
- Correct simulation to match data



$$p^{\pm} \rightarrow (1 + \alpha + \frac{\beta}{p^{\pm}} \mp \delta p^{\pm})(1 + a\mathcal{R}_1\sigma_1)(1 + b\mathcal{R}_2\sigma_2 p^{\pm})p^{\pm}$$

4. Final scale and resolution calibration



Parameter	Value
α	(-0.65 ± 0.16) x 10^{-4}
σ_1	(1.98 ± 0.07) x 10^{-3}
σ_2	(0.147 ± 0.009) TeV^{-1}

- Smearing parameters are somewhat anticorrelated
- σ_2 allowed to float with some multiplicative factor in the final Z mass fit
- Z width not possible in this analysis

$$p^{\pm} \to (1 + \alpha + \frac{\beta}{p^{\pm}} \mp \delta p^{\pm})(1 + a\mathcal{R}_1\sigma_1)(1 + b\mathcal{R}_2\sigma_2 p^{\pm})p^{\pm}$$

Momentum Uncertainties

Source	Size [MeV]
Detector material description	2.6
Smearing fit	1.8
Mass of the $\Upsilon(1S)$	1.5
Curvature Biases	0.7
QED corrections for $\Upsilon(1S)$	0.6
Momentum calibration uncertainty	**3.6**

$$p^{\pm} \rightarrow (\,1 + \alpha + \frac{\beta}{p^{\pm}} \mp \delta p^{\pm})(1 + a\mathcal{R}_1\sigma_1)(1 + b\mathcal{R}_2\sigma_2 p^{\pm})p^{\pm}$$

Muon reconstruction efficiencies

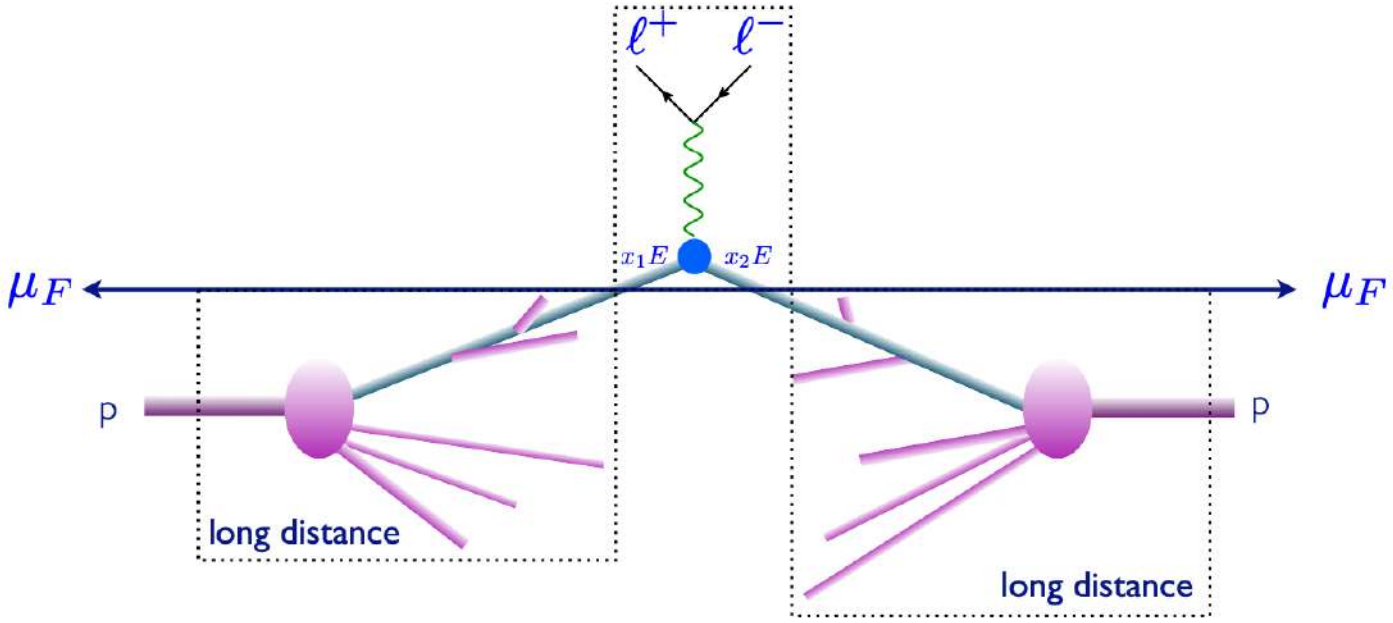
Muon trigger, ID, and tracking efficiencies measured in data and simulation with the tag-and-probe method

Similar to the W mass and the weak mixing analyses

Simulation corrected with event-by-event weights

Contributes 0.1 MeV to the uncertainty

Signal modelling



Reminder:
Pythia (LO + LL) was used to generate the simulation

Want to

- Vary m_Z
- Treat Z/γ interference
- Increase accuracy of predictions
- Propagate uncertainties

Solution: reweight events

$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{\mathrm{FS}}\, f_a(x_1,\mu_F) f_b(x_2,\mu_F)\, \hat{\sigma}_{ab\to X}(\hat{s},\mu_F,\mu_R)$$

Phase-space integral — Parton density functions — Parton-level cross section

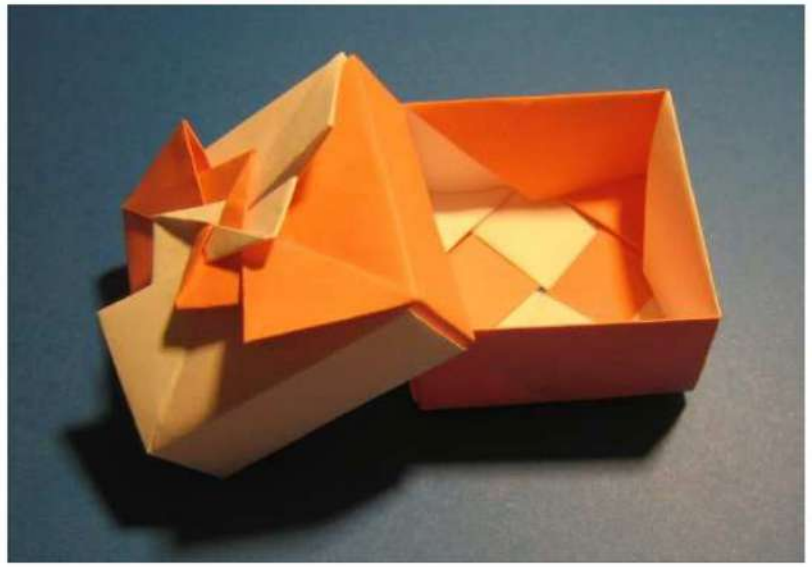
Dimuon mass templates

- Generated from a special version of POWHEG-BOX [Eur. Phys. J. C 73 (2013) 6]
- Includes QED Predictions at NLO
- EW theory input scheme: (G_F, m_W, m_Z)
- Samples generated with varying m_Z
- Z mass was blinded during analysis development

The POWHEG BOX

Project

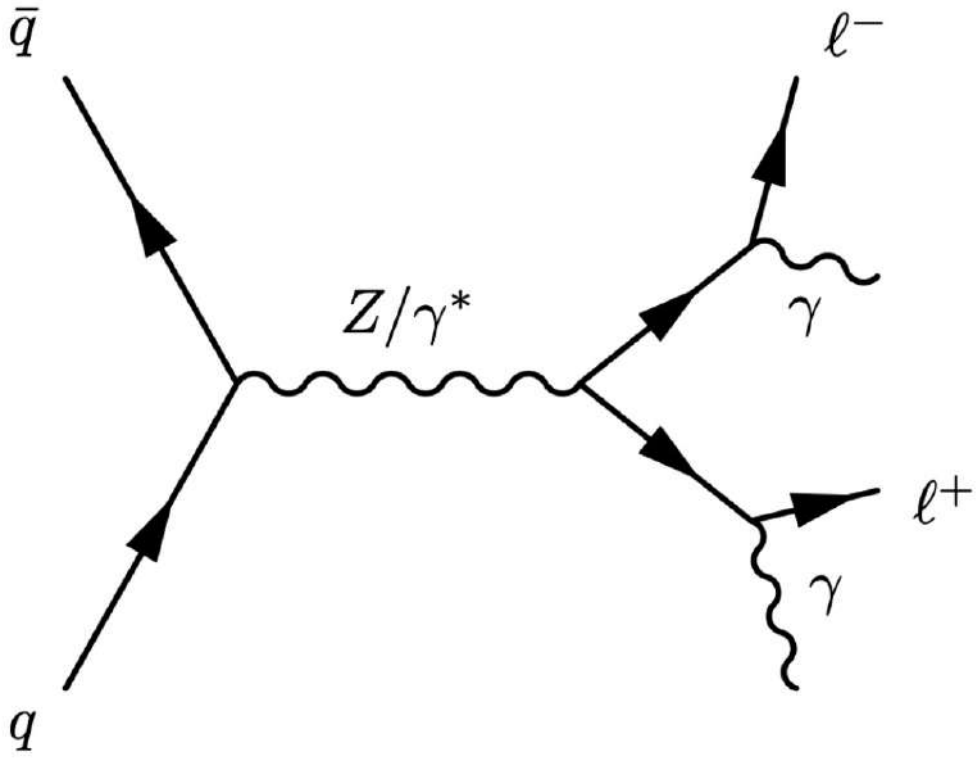
The POWHEG BOX is a general computer framework for implementing NLO calculations in shower Monte Carlo programs according to the POWHEG method. It is also a library, where previously included processes are made available to the users. It can be interfaced with all modern shower Monte Carlo programs that support the Les Houches Interface for User Generated Processes.



→ we get multiple Z mass hypothesis with correct NLO corrections

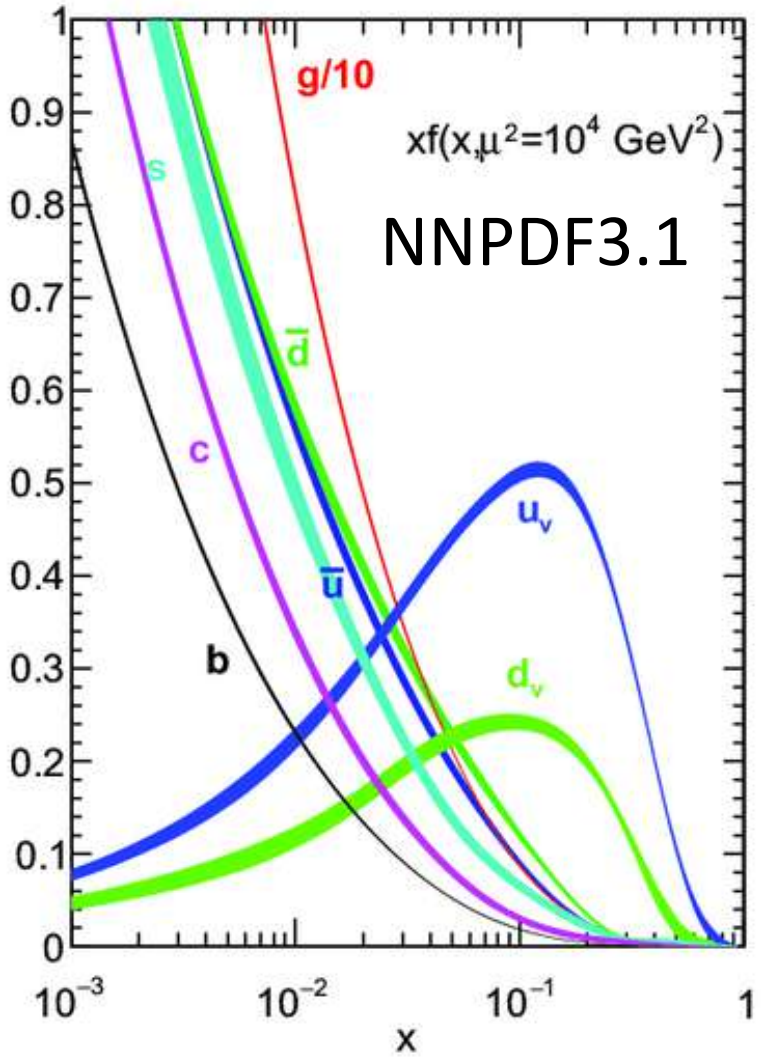
Dimuon mass templates

- The first photon emission is computed exactly by POWHEG.
  - Including radiation from initial- and final-state, and their interference.
- Additional final-state photon emissions handled by PHOTOS.
  - Resummation of log-enhanced terms.
- Uncertainty on m_Z of 0.8 MeV from alternative prescription with PYTHA.

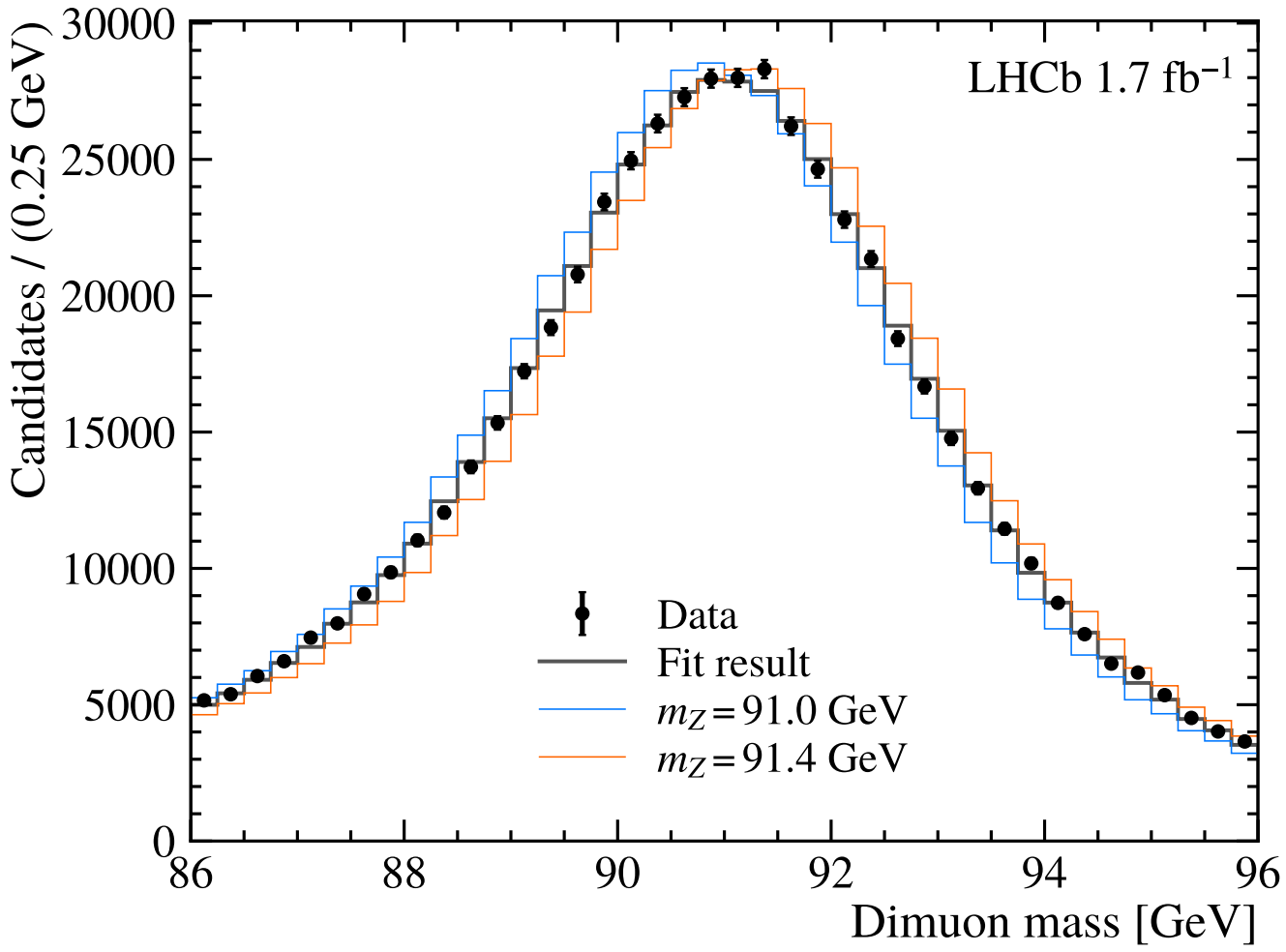


Parton density functions

- Central fit result from NNPDF3.1 NLO Eur. Phys. J.C 77 (2017) 663
- Choice of
  - MSHT20NLO Phys. Rev. D 103 (2021) 014013
  - CT18NLO Eur. Phys. J. C 81 (2021) 341
- Uncertainty of 0.7 MeV is assigned
- Given by the envelope between the three PDF sets



Fitting m_Z



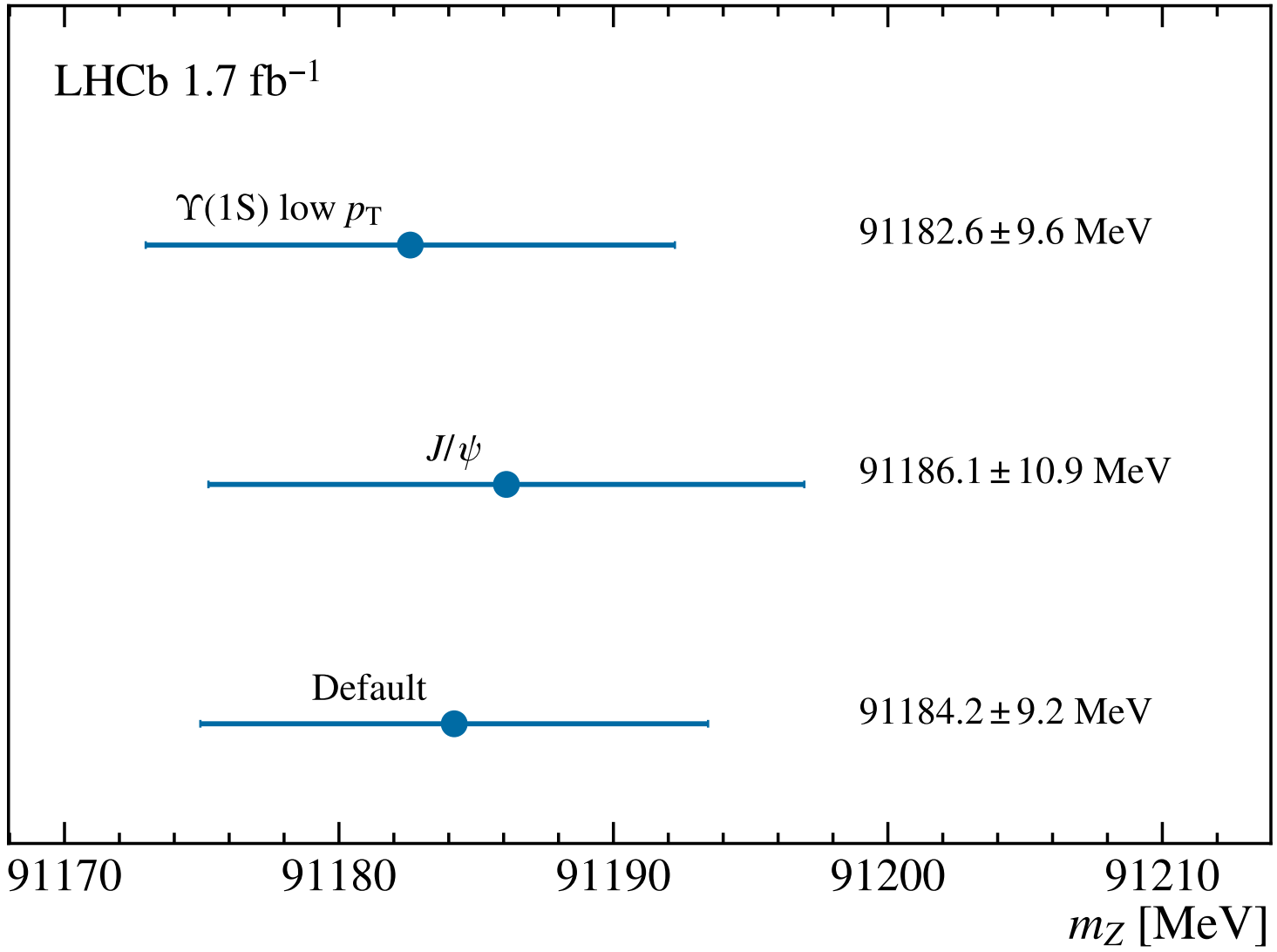
Chi squared	44.2/37
Z mass m_Z	91xxx ± 8.5 MeV
q/p smearing factor	1.25 ± 0.06
correlation	0.015

Uncertainties

Source	Size [MeV]
Momentum calibration	3.6
Signal QED corrections	0.8
Parton distribution functions	0.7
Detection Efficiency	0.1
Statistical uncertainty	8.5
Total	**9.3**

- Measurement unbiased with m_Z
  - Momentum calibration with $\Upsilon(1S)$
  - Pseudomass does not depend on m_Z

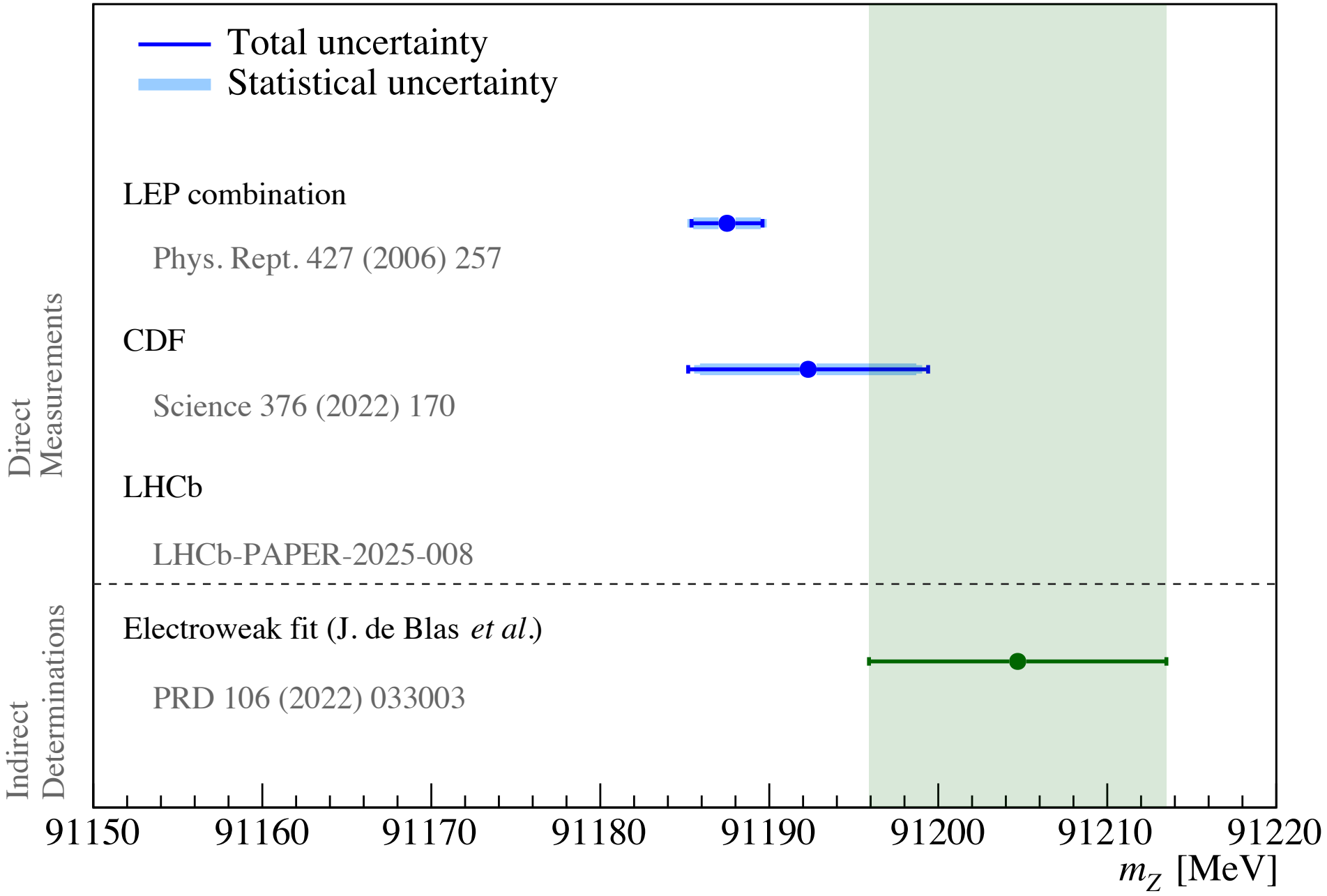
Consistency of calibration samples



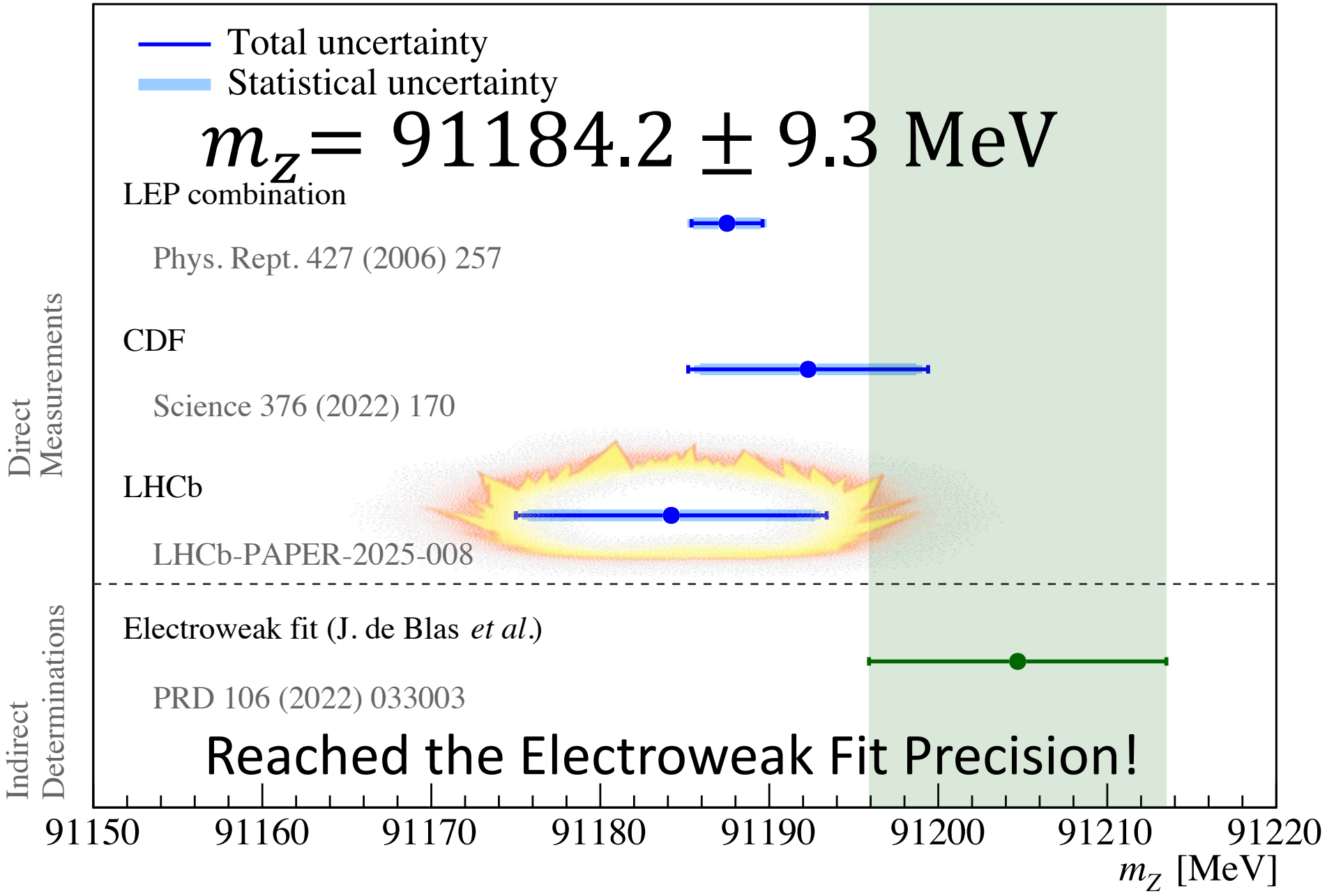
Other checks

- Varying the analysis in various ways yields < 1 MeV changes
  - Varying number of bins used in the various fitters
  - Varying the ranges used in various fitters
  - …
- Closure checks all pass
  - Both momentum scale corrections
  - Momentum smearing with all samples
  - Final Z mass fit

Result


Total uncertainty
Statistical uncertainty
LEP combination
Phys. Rept. 427 (2006) 257
CDF
Science 376 (2022) 170
LHCb
LHCb-PAPER-2025-008
Direct Measurements
Electroweak fit (J. de Blas et al.)
PRD 106 (2022) 033003
Indirect Determinations
91150
91160
91170
91180
91190
91200
91210
91220
m_Z [MeV]

Result


Total uncertainty
Statistical uncertainty
$m_Z = 91184.2 \pm 9.3$ MeV
LEP combination
Phys. Rept. 427 (2006) 257
CDF
Science 376 (2022) 170
LHCb
LHCb-PAPER-2025-008
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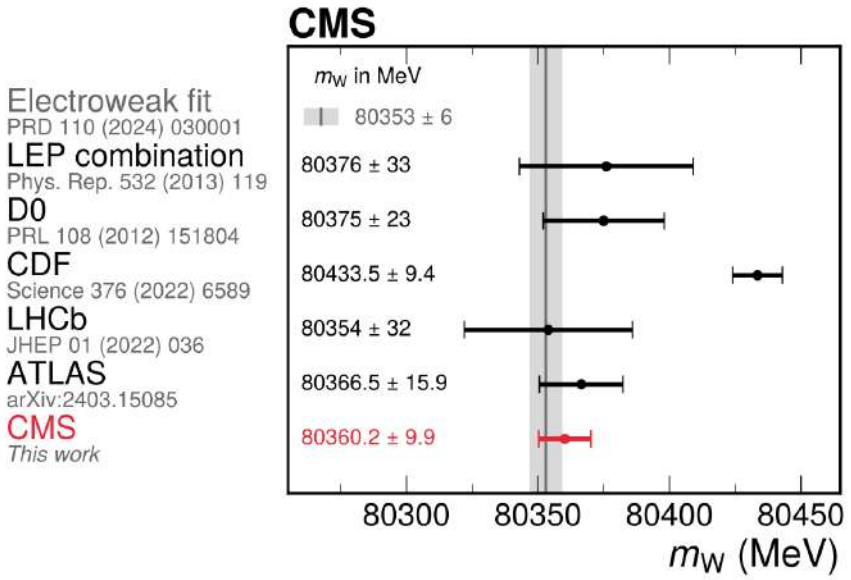
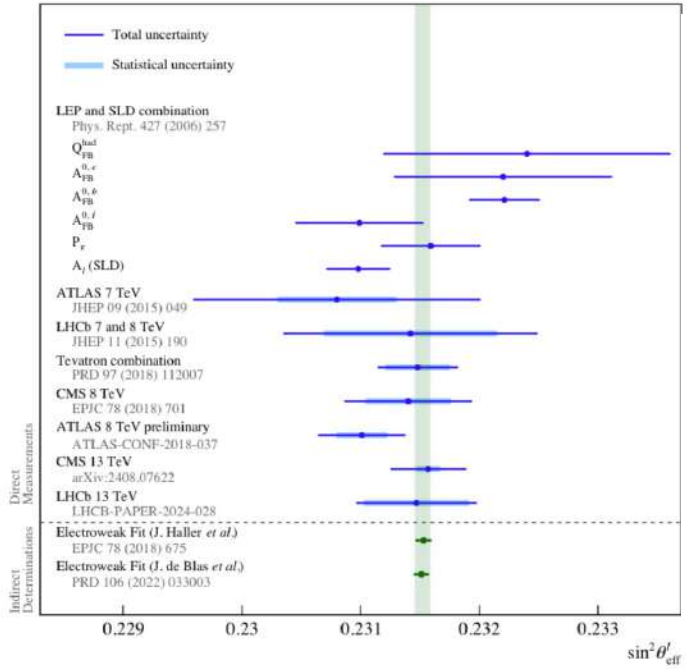
PRD 106 (2022) 033003
Indirect Determinations
Reached the Electroweak Fit Precision!
91150
91160
91170
91180
91190
91200
91210
91220
m_Z [MeV]

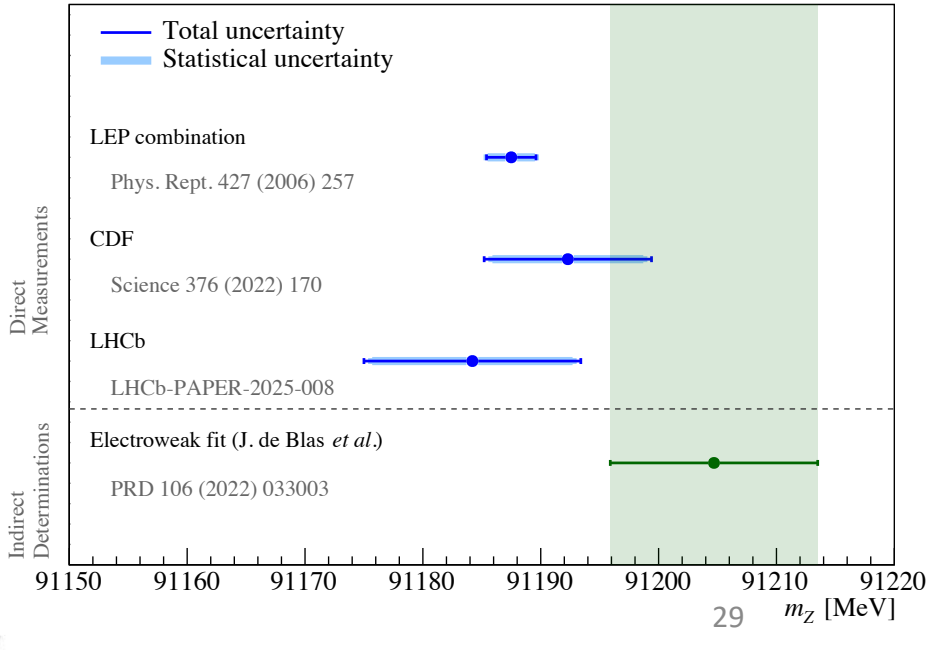
Future prospects

- **LHCb** measurements of (2022) m_W, (2024) weak-mixing angle, and (2025) m_Z
- Analyses of m_W and m_Z with full Run-2 dataset ongoing
  - ~(5)20 MeV for $m_{Z(W)}$
- Program also well underway with Run-3 data

- Encouraging prospects for m_Z at the **LHC**
  - Eagerly anticipate dedicated m_Z results from ATLAS and CMS
  - Detector calibration uncertainties mostly uncorrelated between experiments.
  - An LHC average could challenge LEP soon!







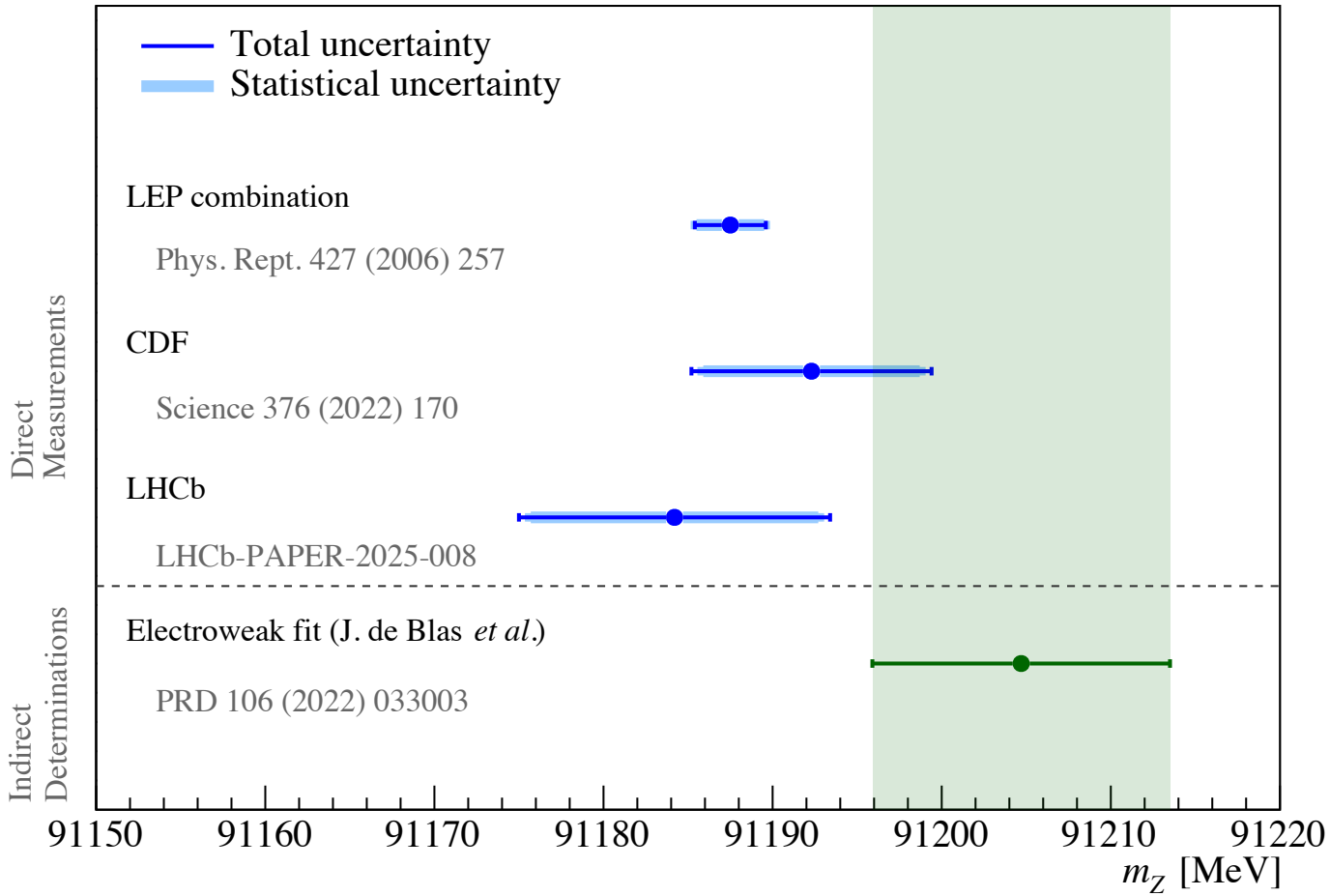
Summary

- m_Z measurable at ***LHCb***!

$m_Z = 91184.2 \pm 9.3$ MeV

- Results consistent with SM and previous measurements

- First dedicated measurement at the LHC



Backups

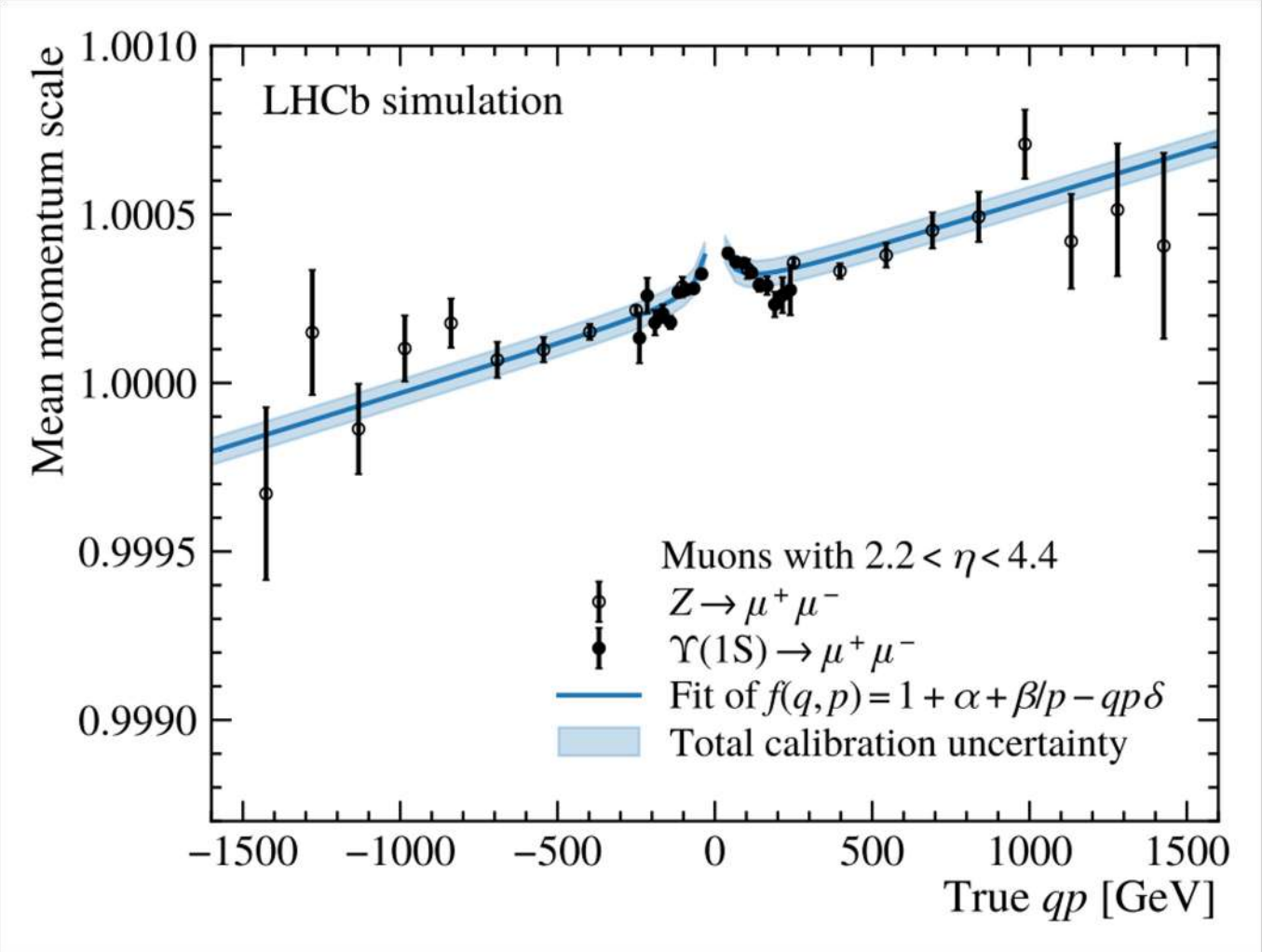
LHCb EW Program

Analysis	Reference
$W \rightarrow \mu\nu$ @ 8 TeV	JHEP 01 (2016) 155
$Z \rightarrow \mu\mu$ @ 13 TeV	JHEP 07 (2022) 026
W mass	JHEP 01 (2022) 036
Leptonic weak mixing angle	JHEP 12 (2024) 026
…	…

For the most up to date results of the LHCb EW program, see https://lbfence.cern.ch/alcm/public/analysis and filter by QCD, Electroweak and Exotica

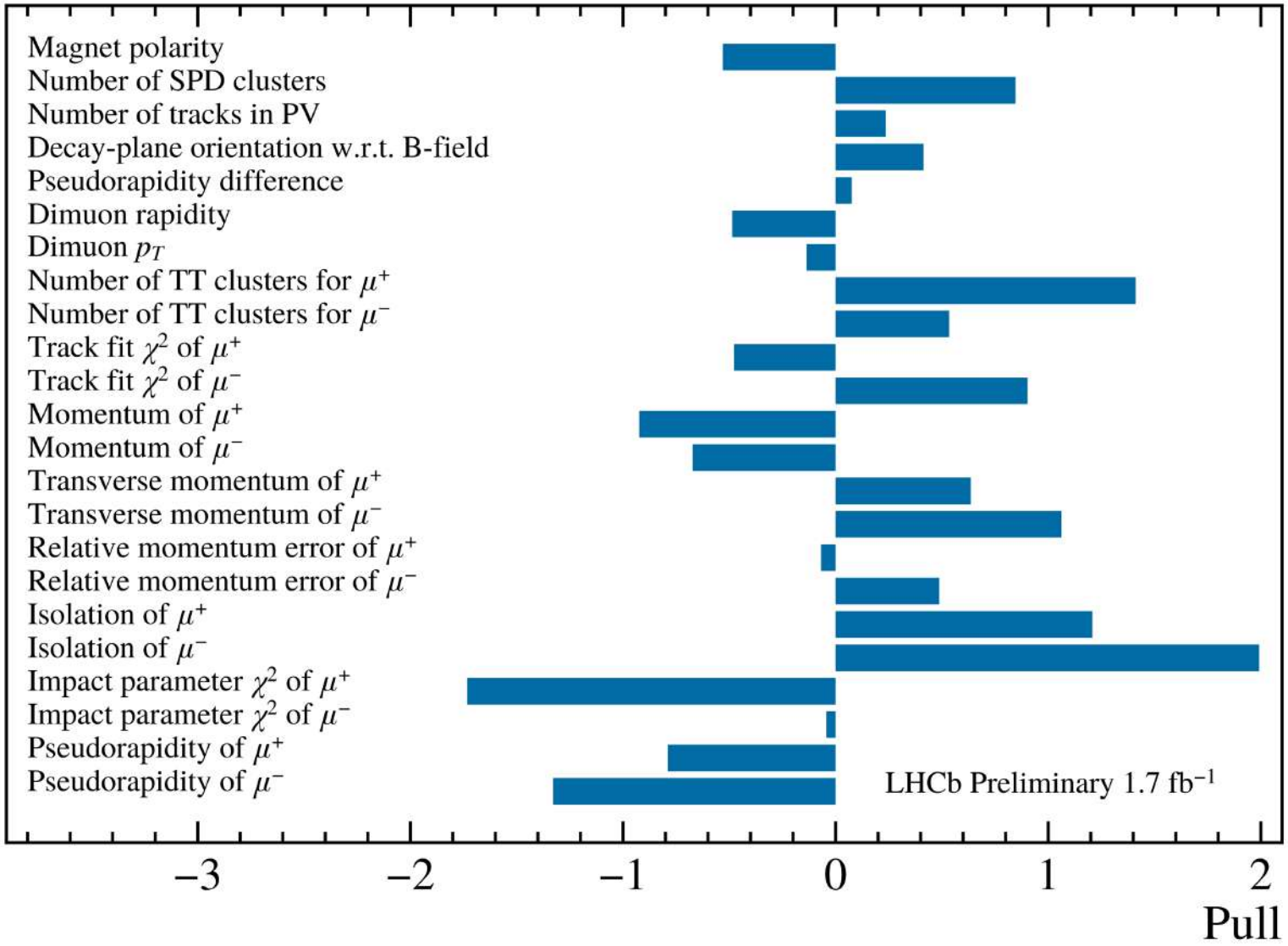
Alternatively, click here!

Validity of the model

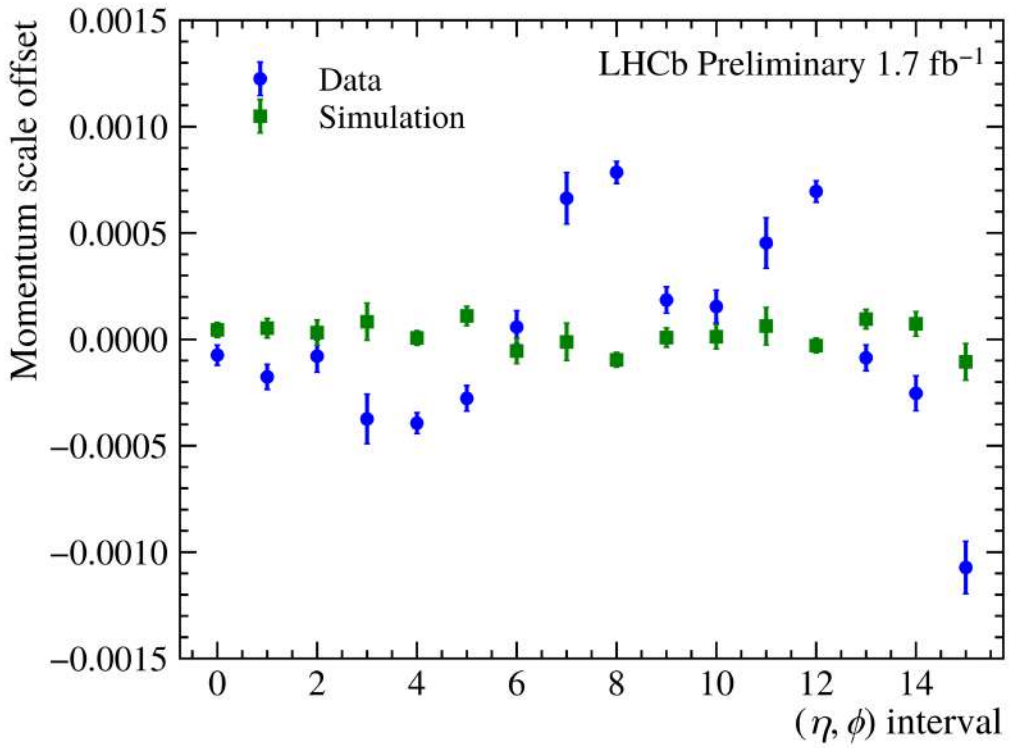


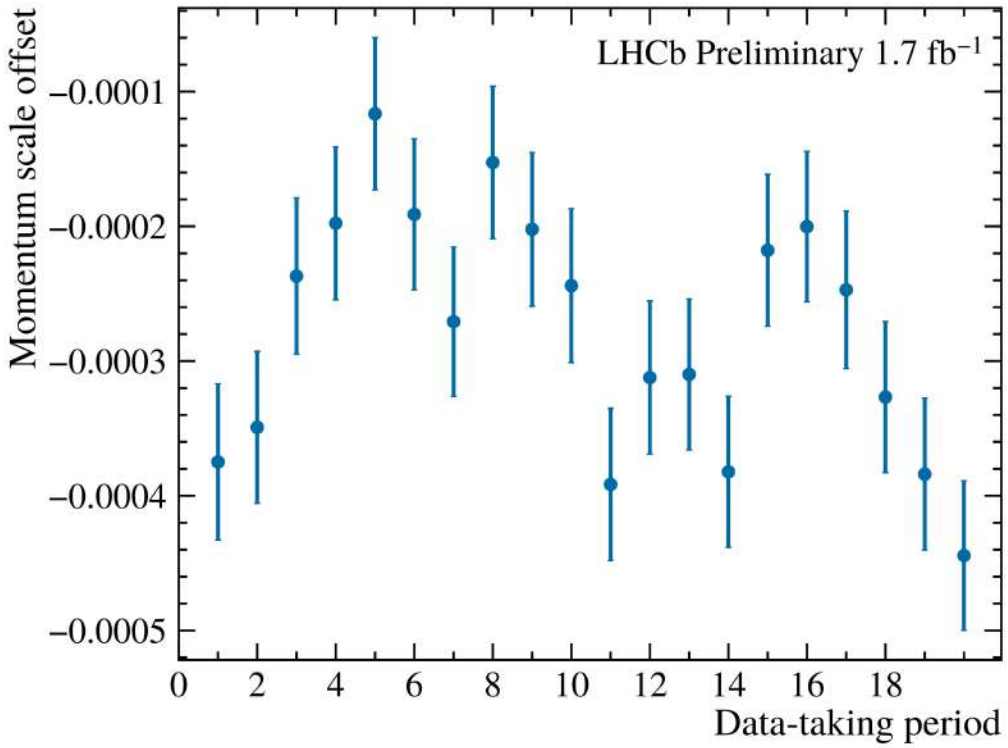
- Note: new plot compared to preliminary results by popular demand

Consistency of sub samples

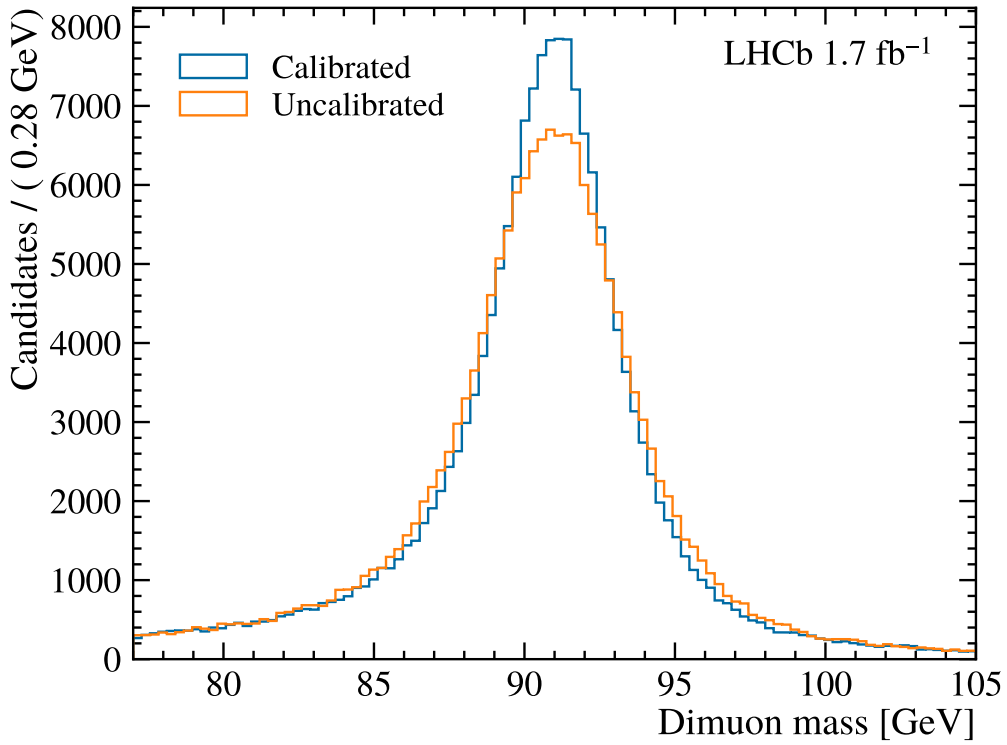


Supplementary plots

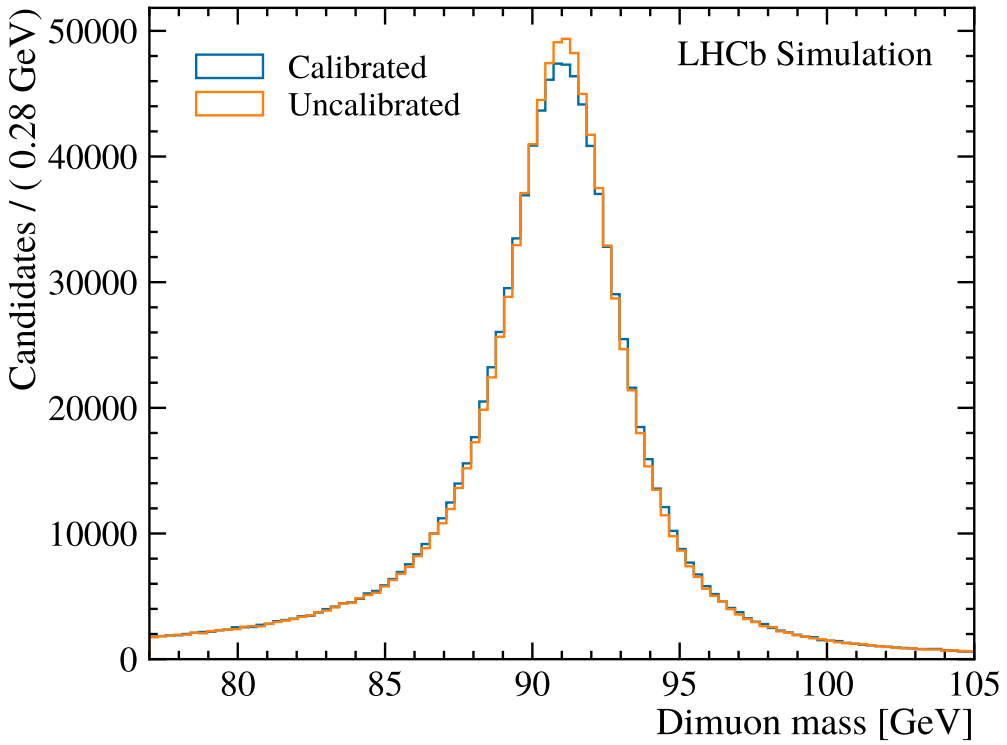




Supplementary plots

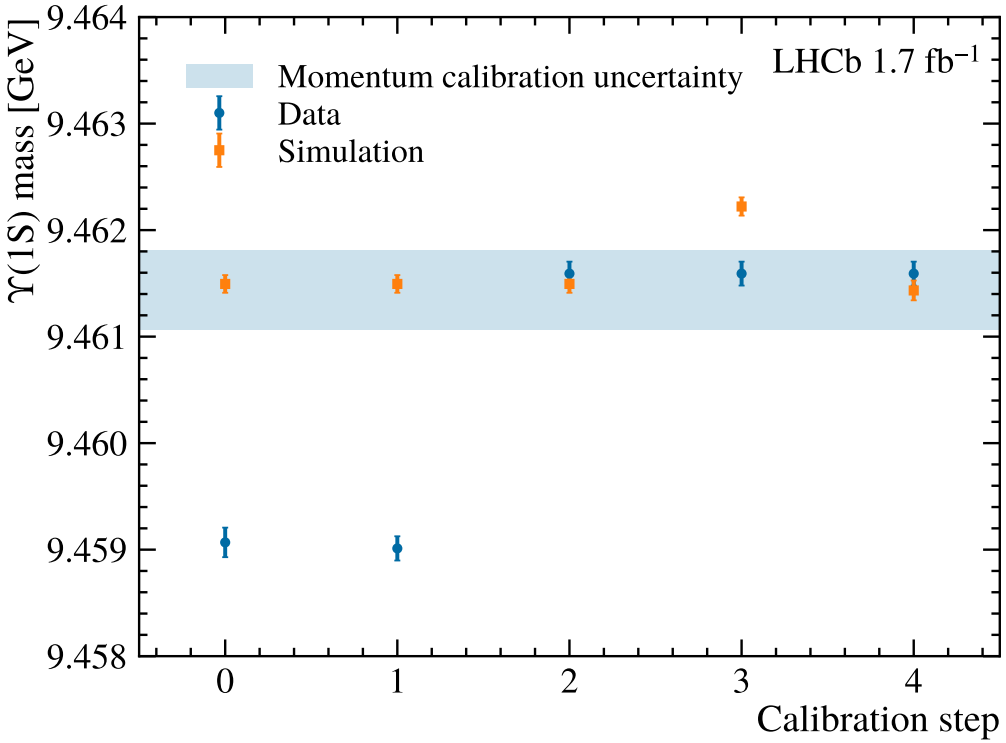


Dimuon mass distribution of Z candidates before and after calibration in *data*

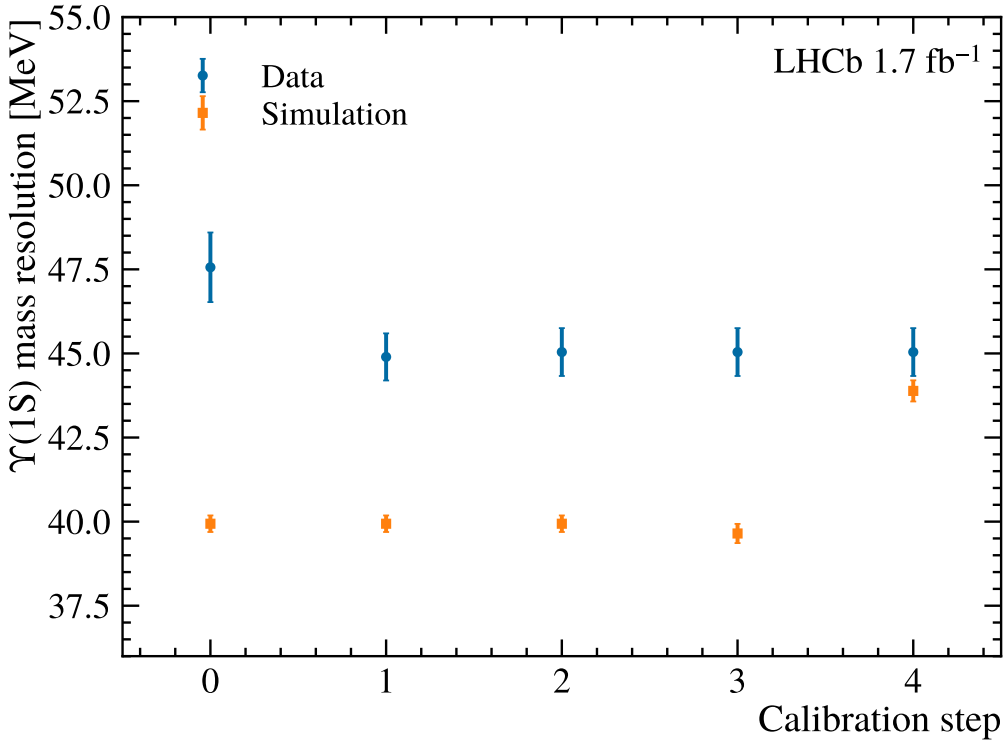


Dimuon mass distribution of Z candidates before and after calibration in *sim*

Supplementary plots

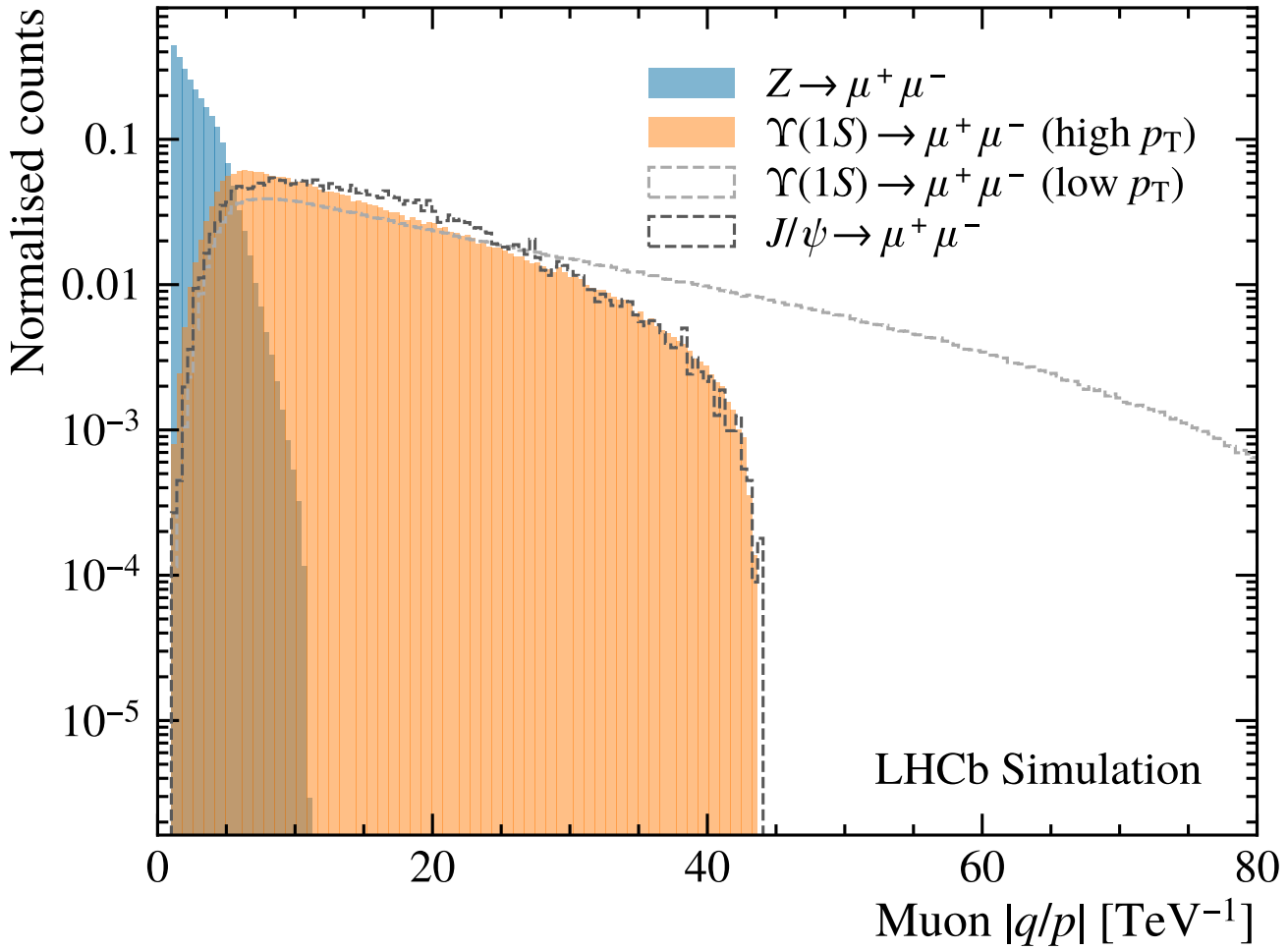


Average $\Upsilon(1S)$ mass as calibrations are applied, in data



Average $\Upsilon(1S)$ resolution as calibrations are applied, in data

Supplementary plots



Magnetic Field Map

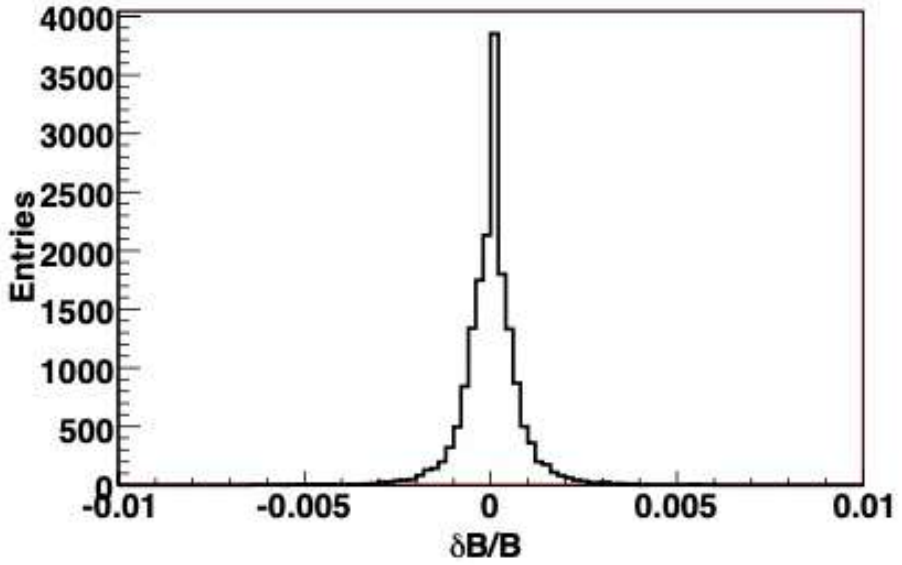


Figure 4.2: Relative difference between the measurements of B using different Hall probes at the same position in the magnet. The resolution is completely dominated by the precision of the calibration of the Hall probes.