Z Mass Measurement at LHCb

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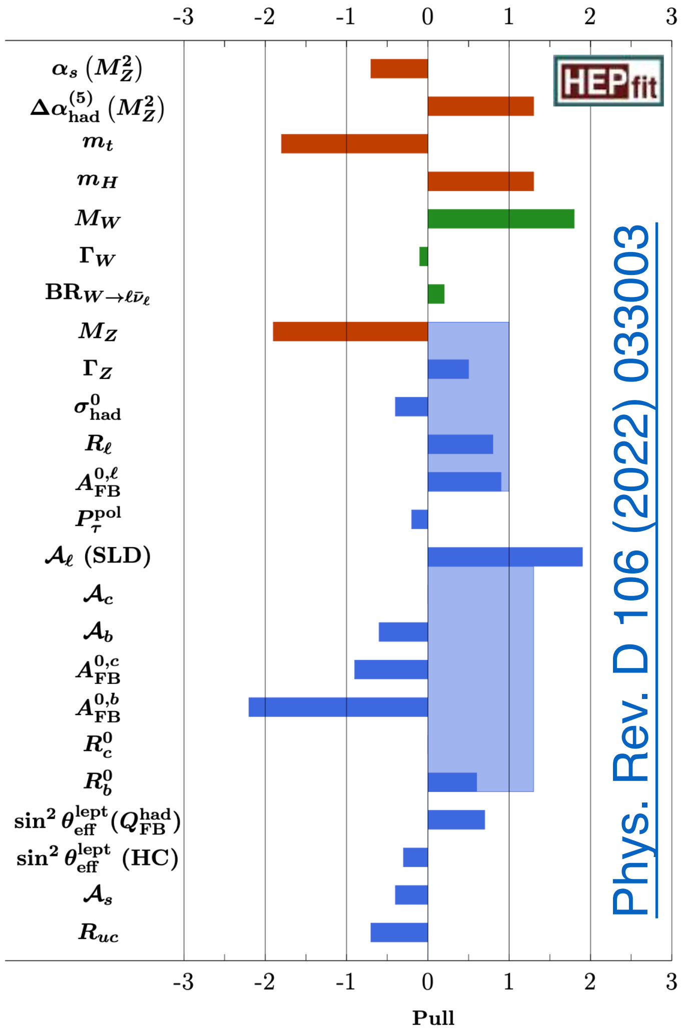
Theory prediction

$$m_W = \frac{gv}{2},\ m_Z = \frac{v\sqrt{g^2+g'^2}}{2},$$

$$cos\theta_W = \frac{g}{\sqrt{g^2+g'^2}} = \frac{m_W}{m_Z}$$

Tree level prediction: $m_Z > 80$ GeV,

Higher precision requires loop corrections



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Indirect m_Z = 91204.7 $\pm$ **8.8** MeV

The LEP legacy

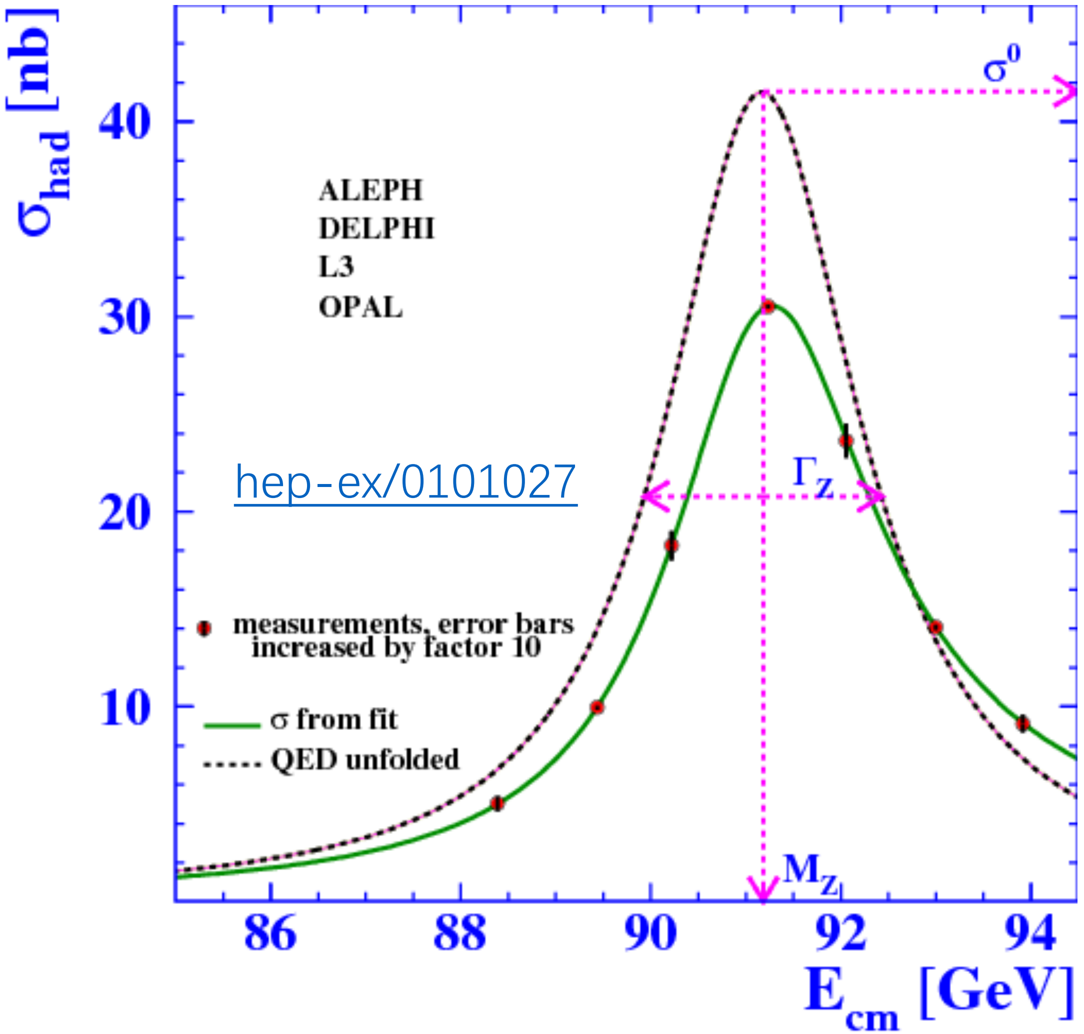
- Large Electron Positron collider 1989 – 2000 @ CERN

- e^+e^- collider, tuned to Z resonance

- ~ 17 million Z bosons

- Access via energy scan

LEP m_Z = 91187.6 ± **2.1** MeV



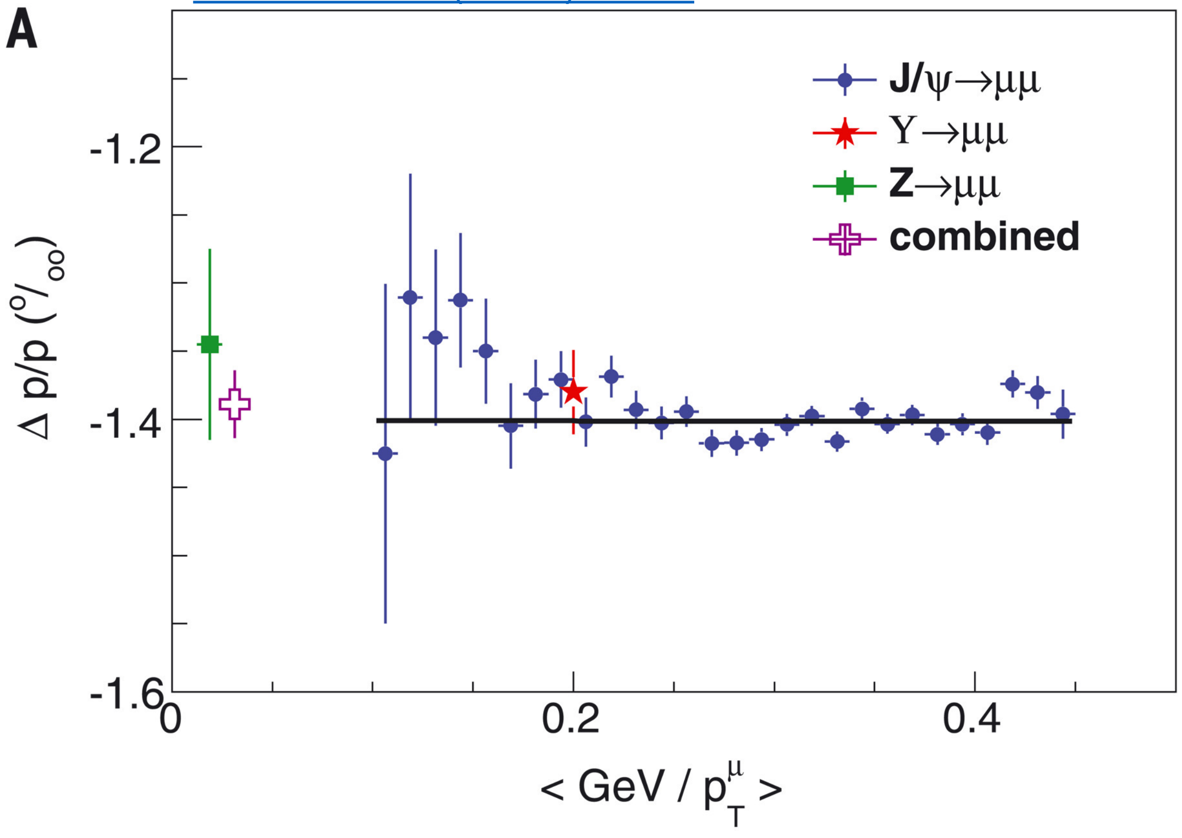
Prospects of $\boldsymbol{Z}$ measurements at LHC

Designed to be a discovery machine. Is precision EW possible?

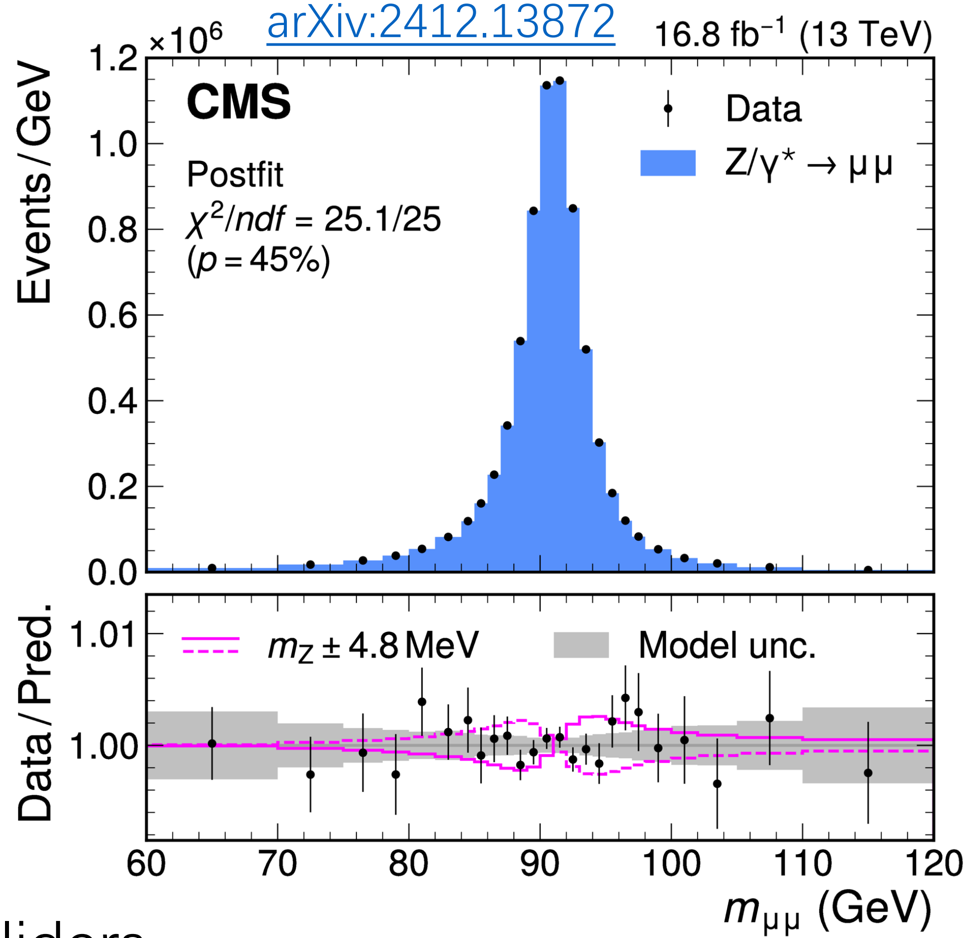
	LEP	LHC
Production model	ee	PDF
Observables	through beam energy	through final states
Calibration	Beam energy	Detector

Prospects of $\boldsymbol{Z}$ measurements at LHC

Science 374 (2022) 6568



arXiv:2412.13872

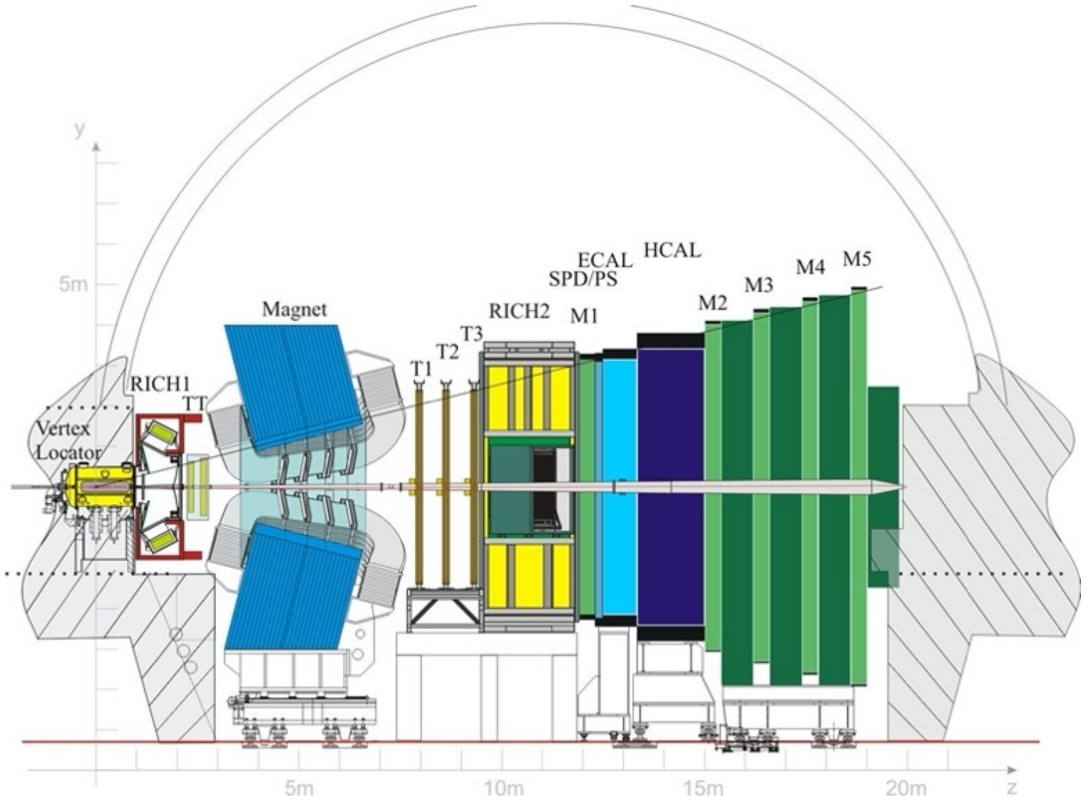


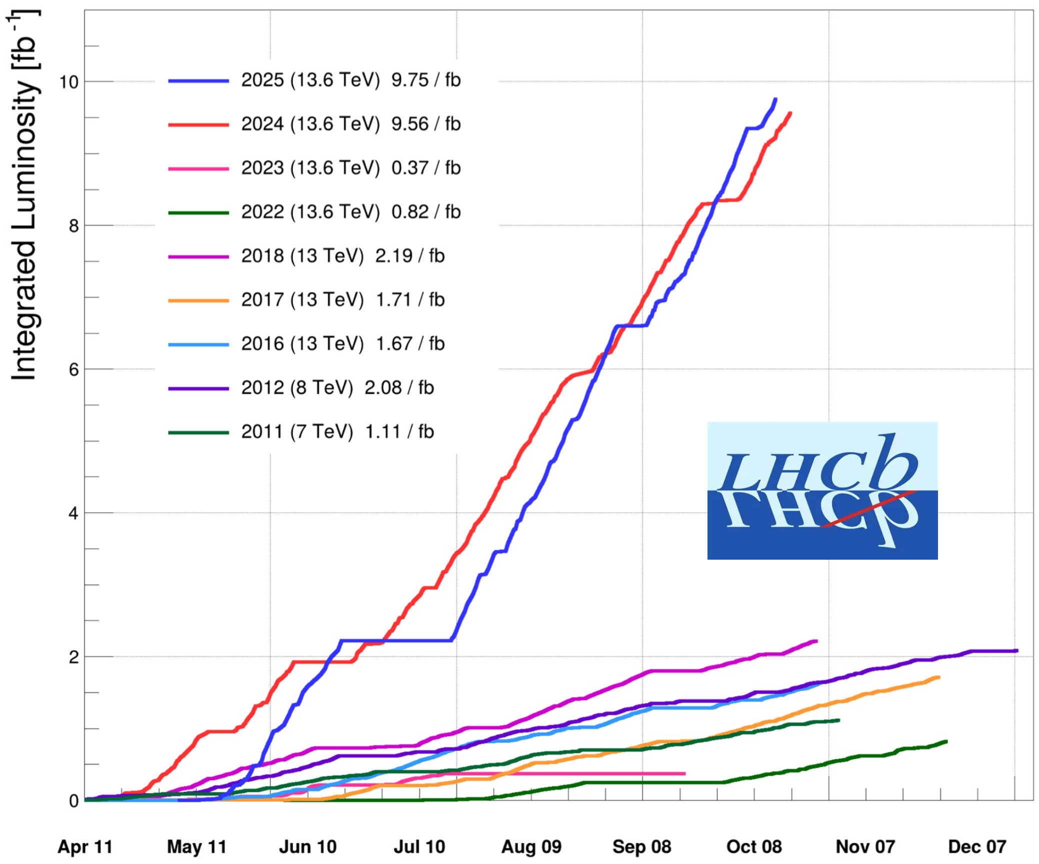
m_W main interest in hadron colliders

m_Z used for validation of that measurement

m_Z hadron collider combinations can challenge LEP

LHCb @ CERN





Tracking ranges

ATLAS / CMS: $|\eta| < 2.5$

LHCb: $2 < \eta < 5$

- Originally for b/c physics
- General Purpose!

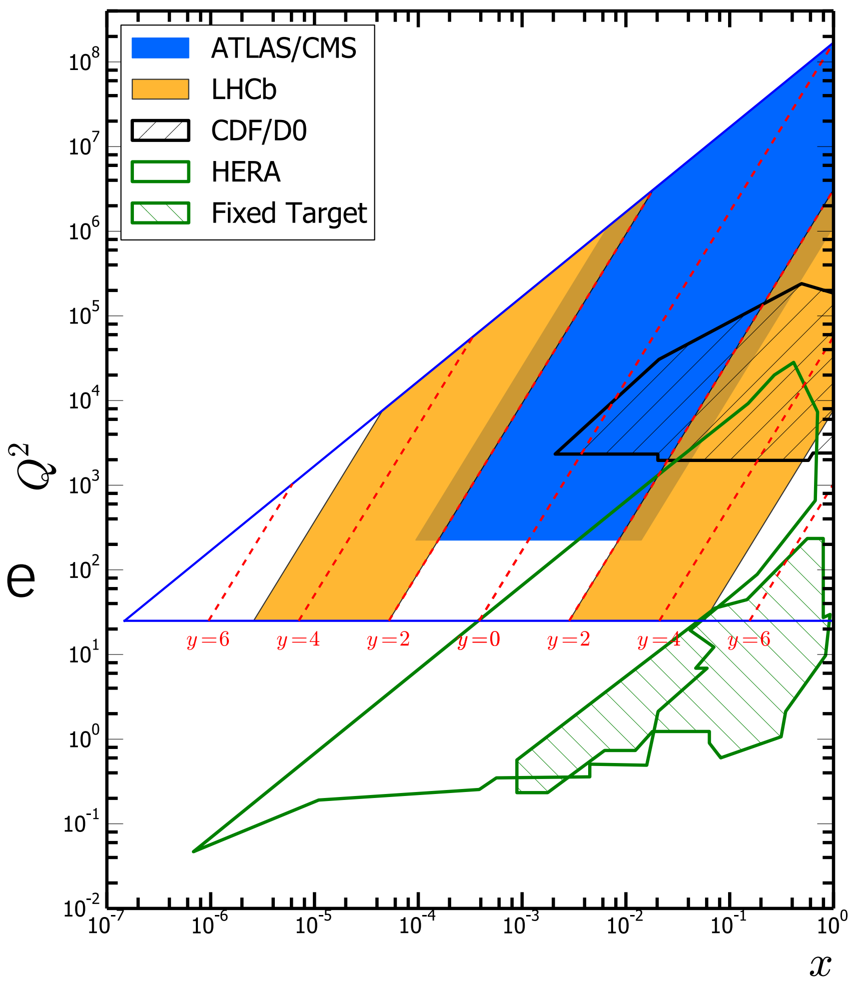
LHCb EW program

Complementary regions with other experiment

- Cross sections
- $W \rightarrow \mu\nu$ @ 8 TeV
- $Z \rightarrow \mu\mu$ @ 13 TeV

- Precision EW
- W mass
- Leptonic weak mixing angle
- .. Z mass?

LHC 13 TeV Kinematics



Z measurements at LHCb

Sensitive via the dimuon mass distribution

- m_Z hypothesis varied by reweighting full simulation with templates
- Build off previous EW precision measurement tools
- Difference between data and simulation needs to be well under control

Dataset and selections

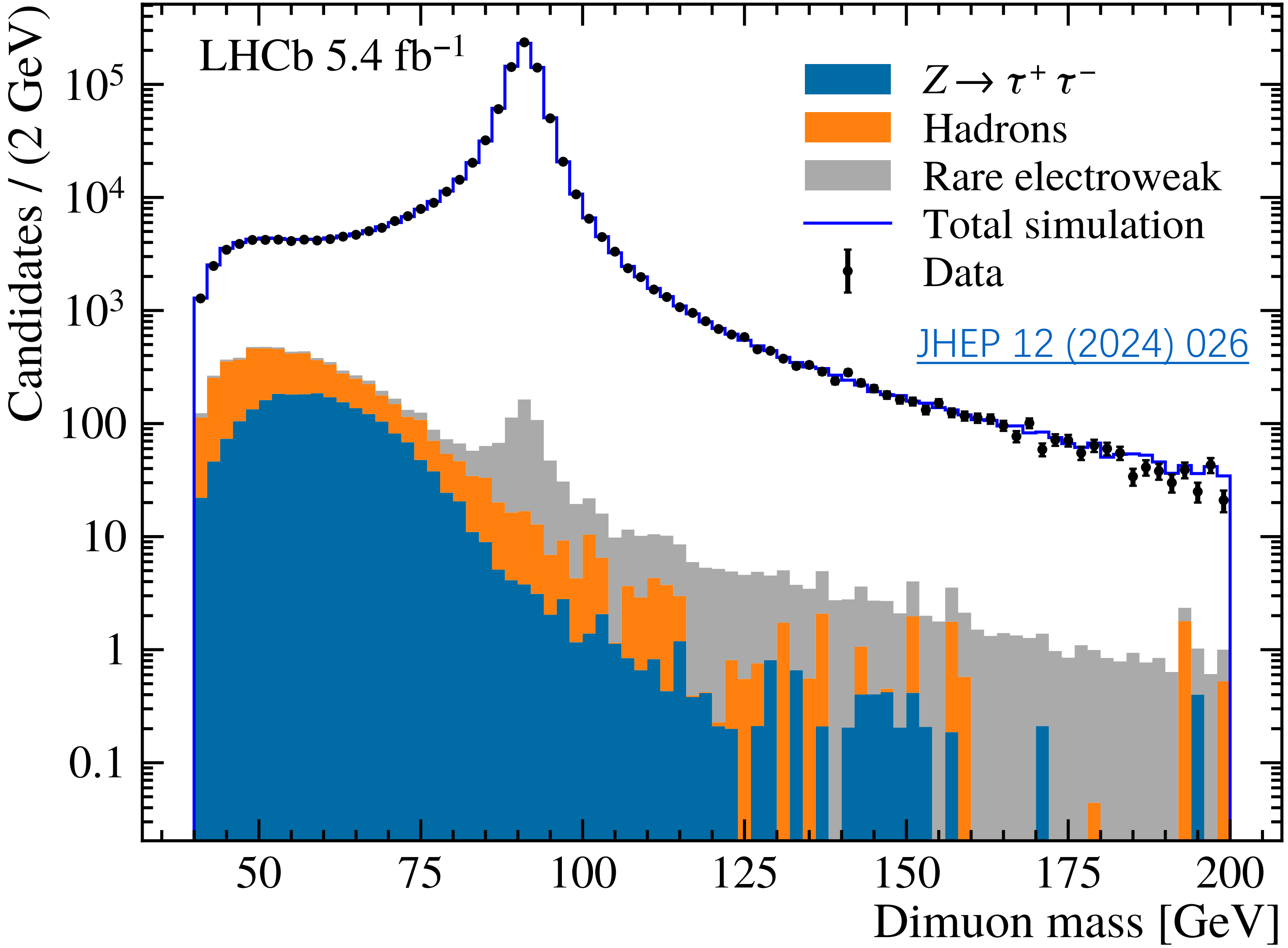
Strategic choice to use 2016 dataset
$\sqrt{s}$ = 13 TeV

- Signal selection of:
- $Z \rightarrow \mu\mu$
- Muon η : $2.2 < \eta < 4.4$
- Muon P_T > 20 GeV
- Identified muon candidate matched to single muon trigger path.
- $86 < M_{\mu\mu} < 96$ GeV

- Quarkonia selection of:
- $\Upsilon(1S) \longrightarrow \mu\mu$(calibration)
- $J/\psi \longrightarrow \mu\mu$(cross check)
- Muon η : $2.2 < \eta < 4.4$
- Muon P_T > 5 GeV

Sample	Events
$Z \rightarrow \mu\mu$	170k
$\Upsilon(1S) \rightarrow \mu\mu$	190k
$J/\psi \rightarrow \mu\mu$	48k

Backgrounds



The momentum response

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

$$\mathcal{R}\sim\mathcal{N}(0,1),\ a = f(\eta),\ b = p^{\pm}/cosh(\eta)$$

α: momentum scale

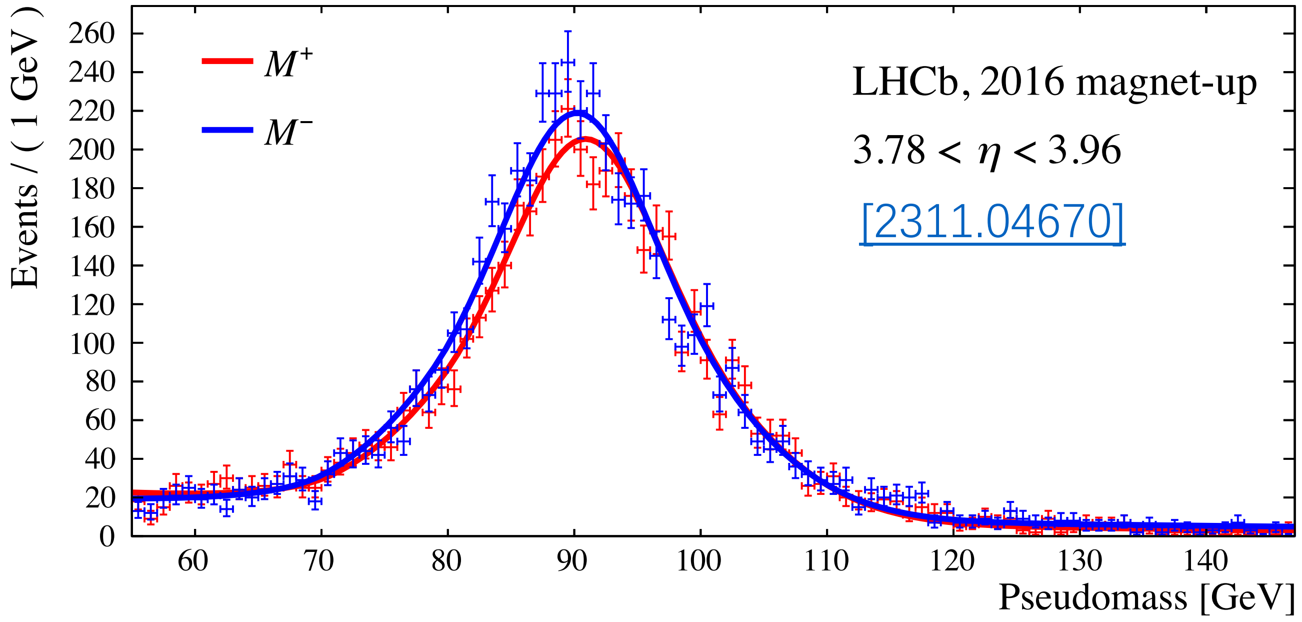
β: $Energy\ loss$

δ: $detector\ misalignment$

σ_1: Material scattering

σ_2: $Detector\ resolution$

1.Charge-dependent curvature bias



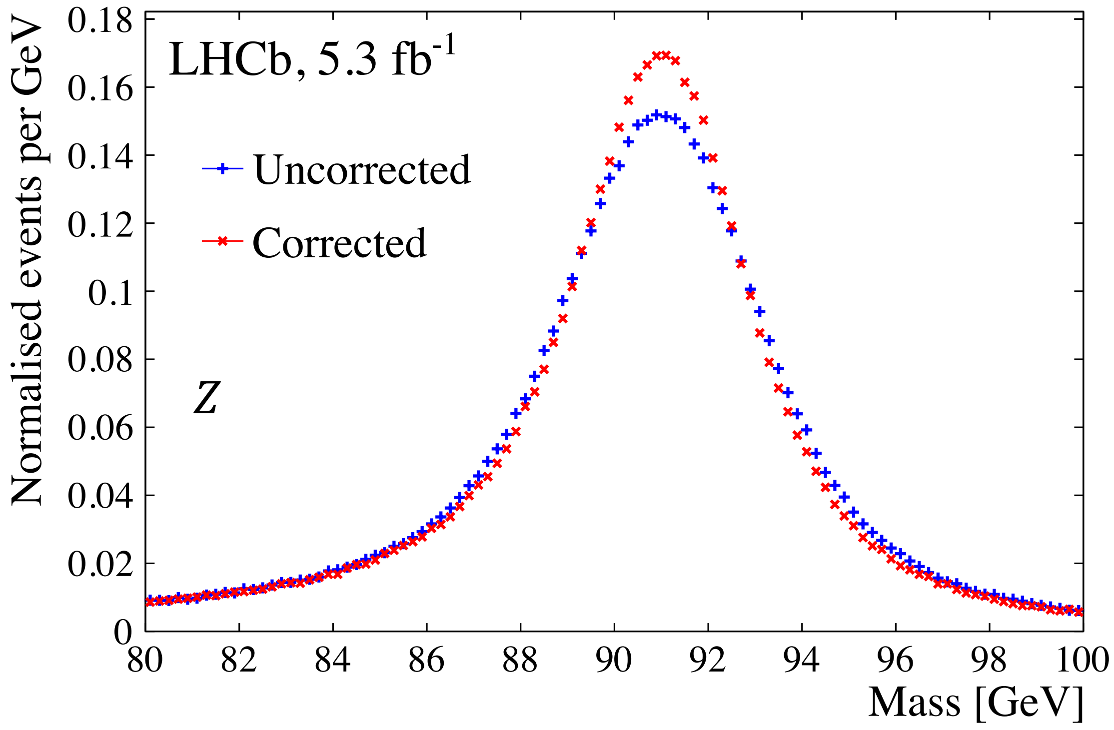
Pseudomass $M^{\pm}$ with $Z \rightarrow \mu\mu$

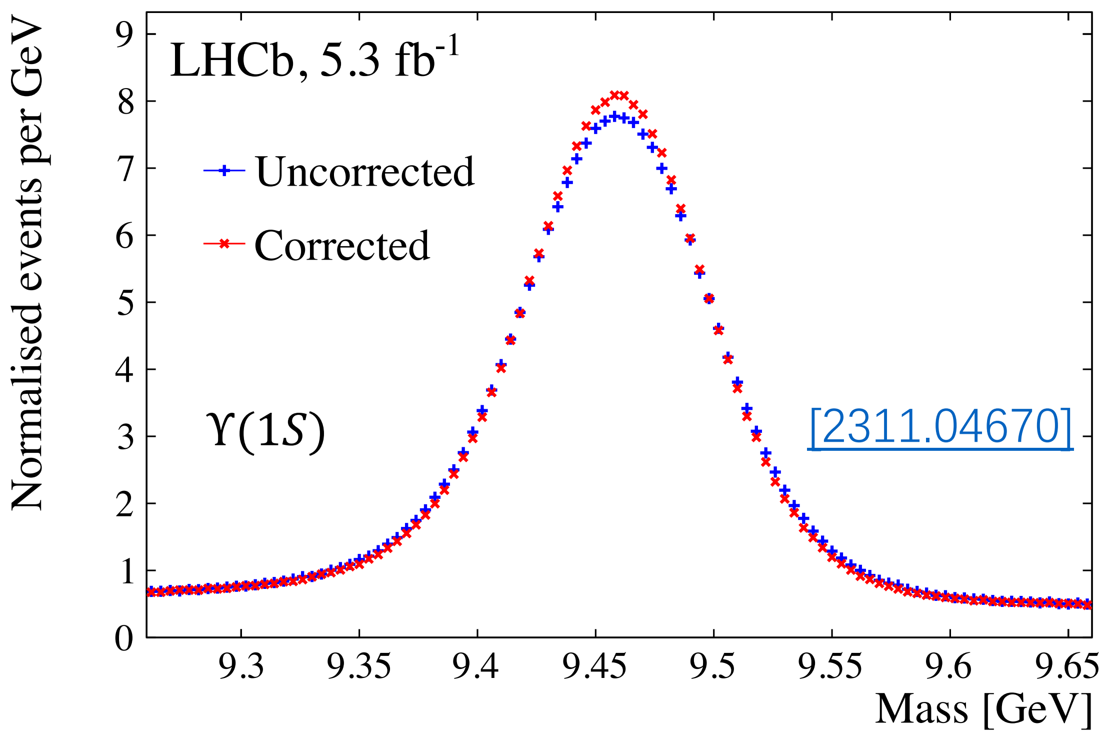
$$M^{\pm} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1 - cos\theta)}$$

Misalignments lead to curvature bias δ largely can be estimated by the difference between M^+ and M^-

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

1.Charge-dependent curvature bias

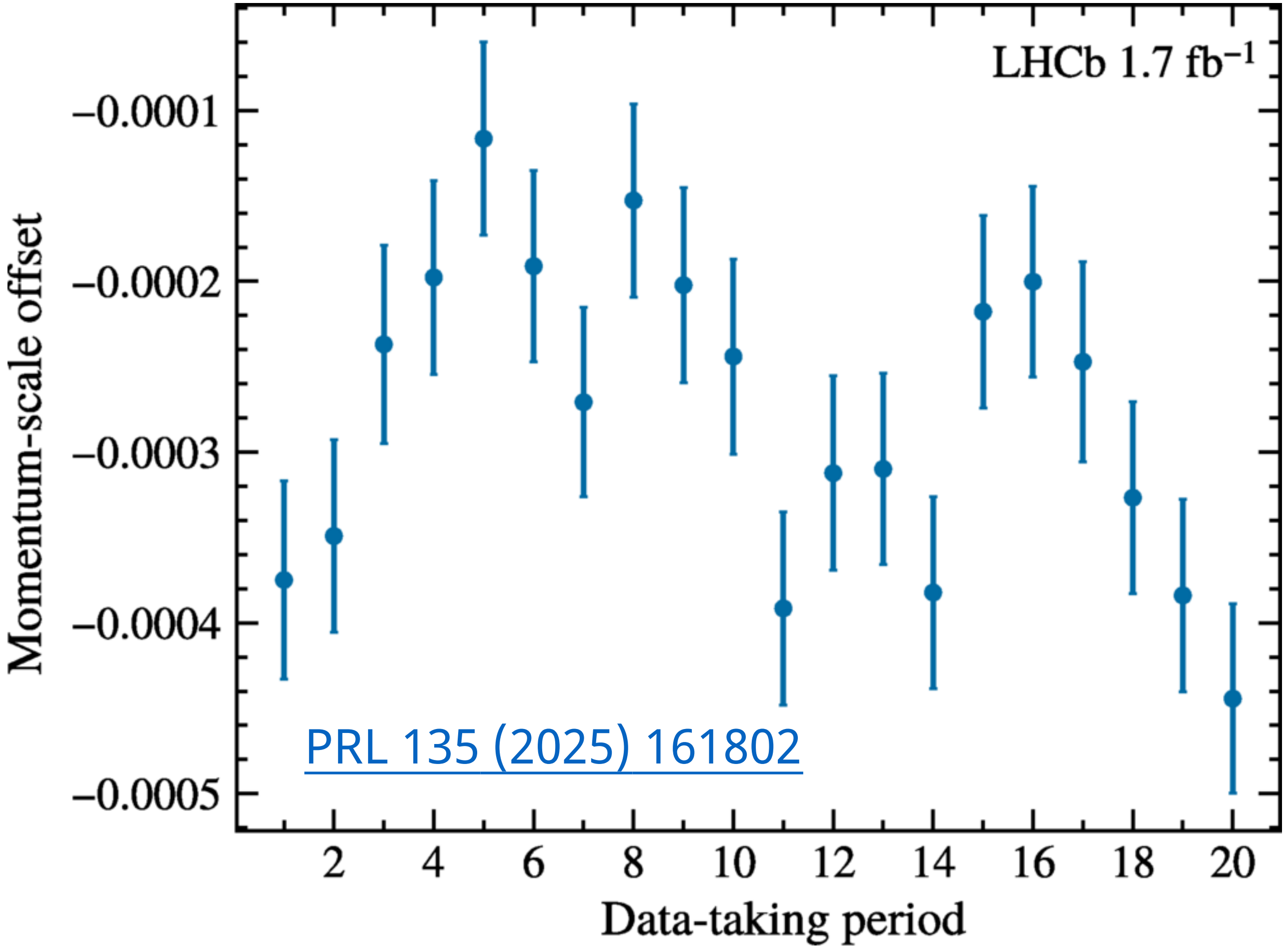




$$p^{\pm} \rightarrow (1 + \alpha + \frac{\beta}{p^{\pm}} \mp \delta p^{\pm})(1 + a\mathcal{R}_1\sigma_1)(1 + b\mathcal{R}_2\sigma_2 p^{\pm})p^{\pm}$$

2. Time varying momentum scale

- Time dependent mass scale in LHCb
- 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

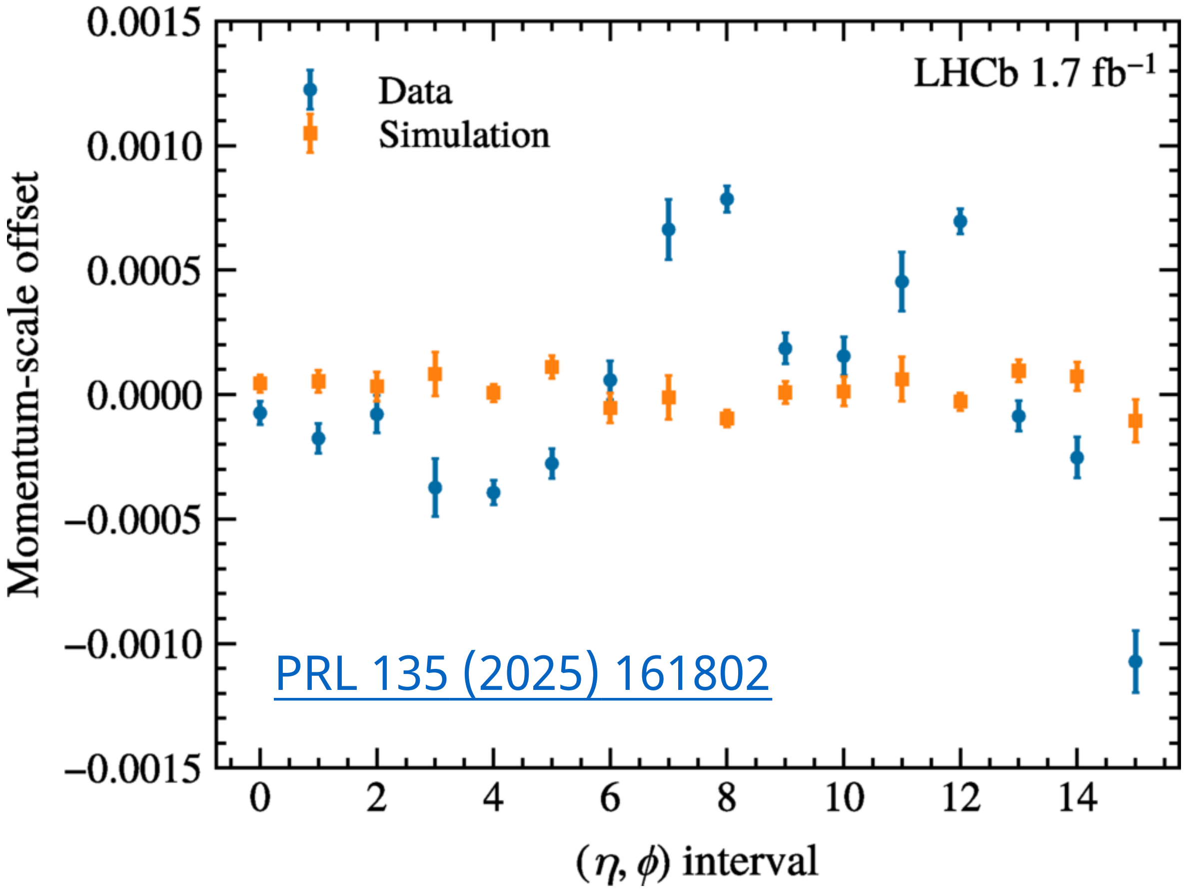


[PRL 135 (2025) 161802]

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

3. Phase space momentum scale

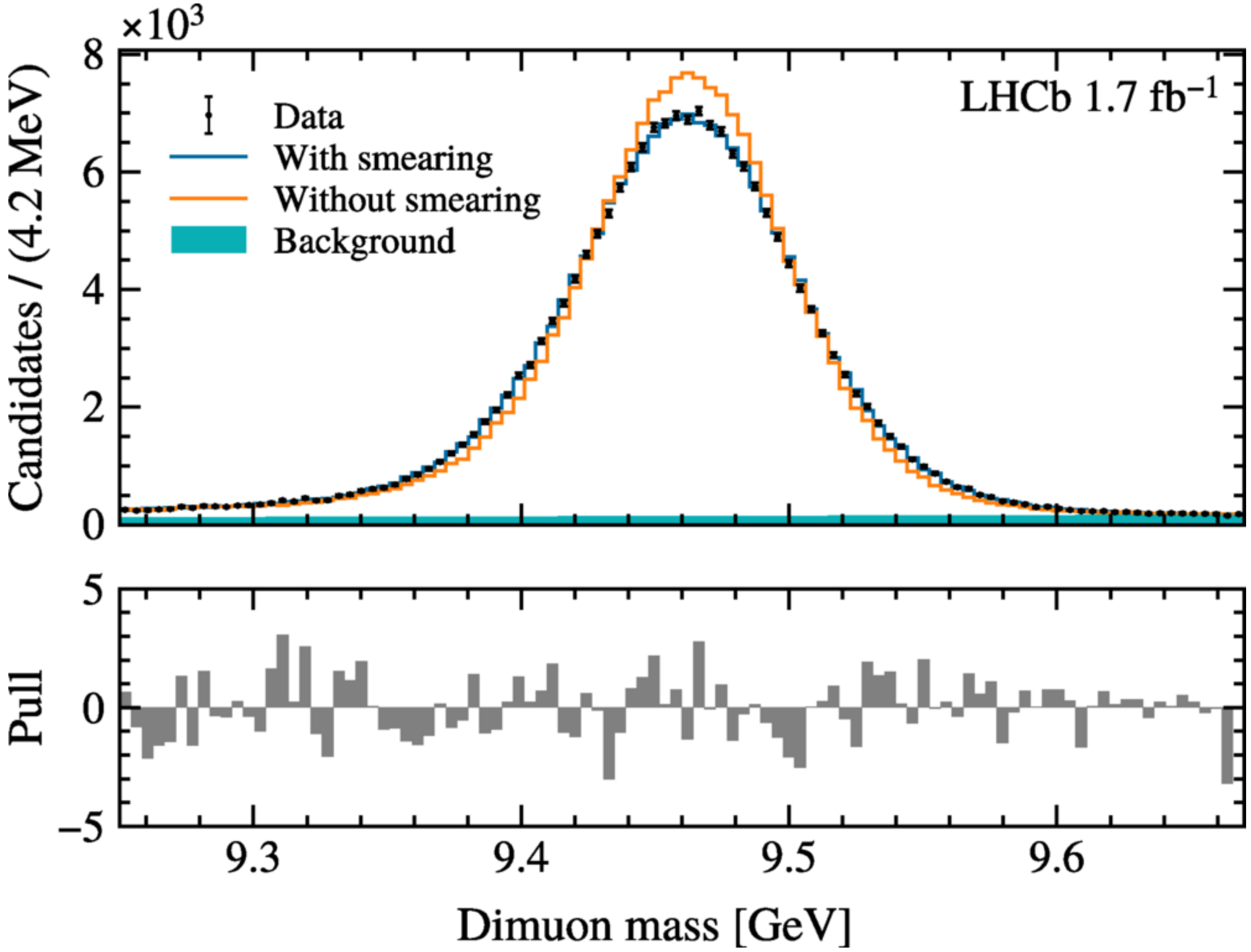
- Localised biases across the detector
- Corrections in 16 bins of η / ϕ
- Extract $\Upsilon(1S)$ lineshape parameters from each bin for data and simulation
- Correct simulation to match data



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

4. Momentum smearing

PRL 135 (2025) 161802



Smearing parameters are somewhat anticorrelated

Parameter	Value
α	$(-0.65 \pm 0.16) \times 10^{-4}$
σ_1	$(1.98 \pm 0.07) \times 10^{-3}$
σ_2	$0.147 \pm 0.009\ \mathrm{TeV}^{-1}$

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

Muon reconstruction efficiencies

- Muon trigger, ID, and tracking efficiencies measured in data and simulation with the tag-and-probe method
- Contributes 0.1 MeV to the uncertainty

Signal templates

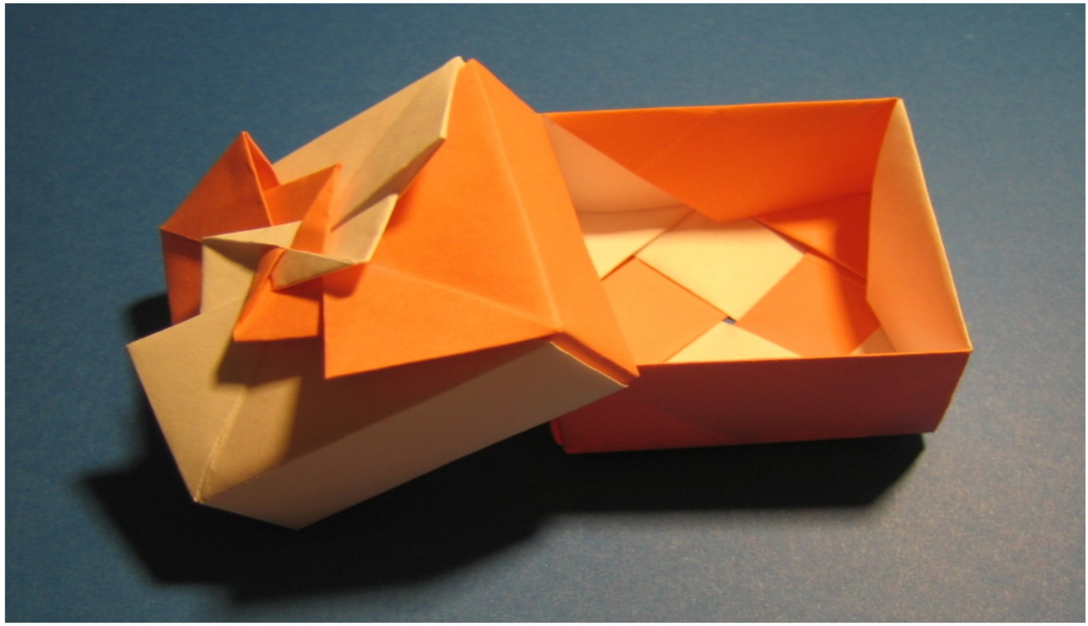
Pythia (LO + LL) was used to generate the simulation. Want to:

- Vary m_Z
- Increase accuracy of predictions

Signal templates generated from POWHEG(NLO), Includes QED Predictions at NLO

Samples generated by varying m_Z

The POWHEG BOX

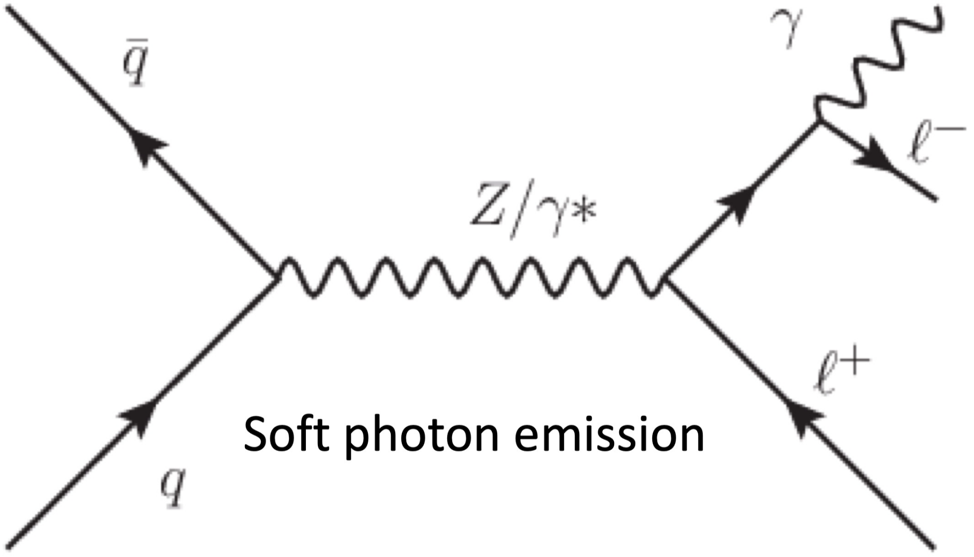


FSR correction and PDF sets

Final state radiation correction:

- QED radiative corrections for sub-leading FSR (eg: soft/collinear emissions)

- Specific tools to model QED FSR exists (photos / pythia)



PDF sets:

NNPDF3.1 NLO (default), MSHT20NLO and CT18NLO

Fitting m_Z

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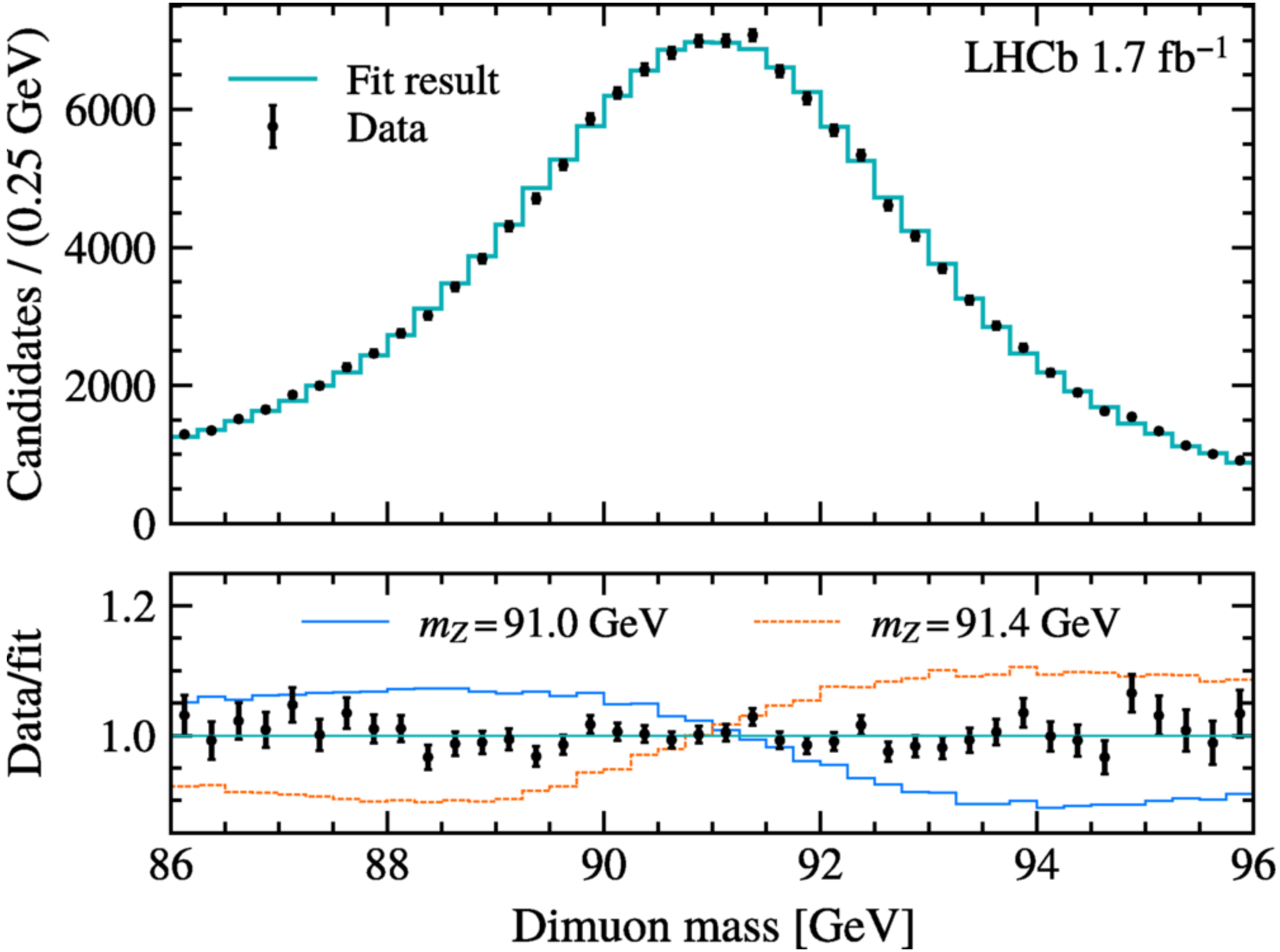


Parameter	Value
χ^2/ndf	43.4/37
Statistical uncertainty	8.3 MeV
σ_2 multiplicative factor	1.2 ± 0.1
m_Z: σ_2 factor correlation	0.015

Systematic uncertainties

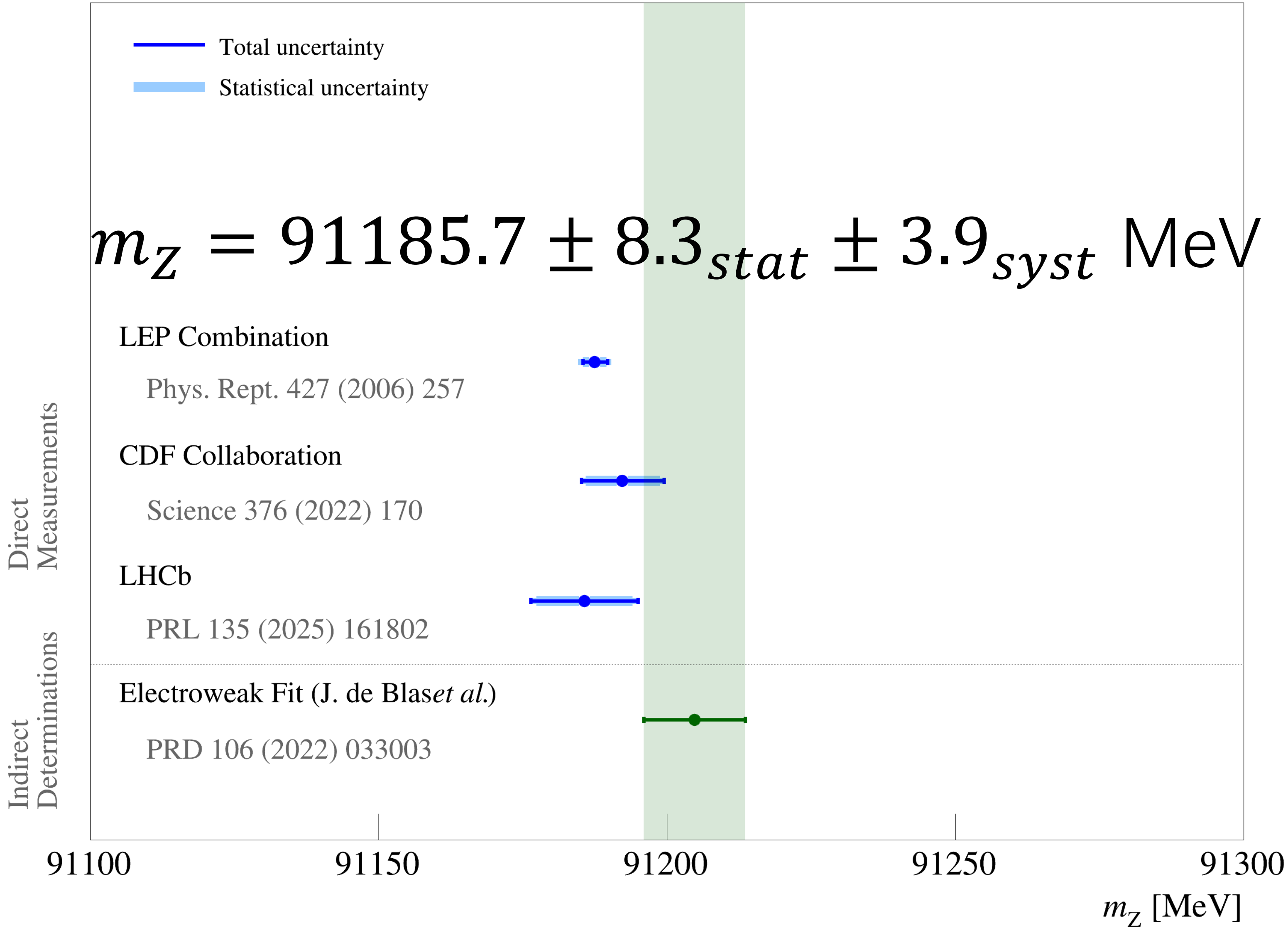
TABLE I. Systematic uncertainties on the m_Z measurement.

Source	Uncertainty [MeV]
Momentum calibration	3.6
Theory template statistics	1.0
Signal final-state radiation	1.0
Parton distribution functions	0.7
Detection efficiency	0.1
Total systematic uncertainty	3.9

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	**3.6**

Result

$$m_Z = 91185.7 \pm 8.3_{stat} \pm 3.9_{syst}\ \text{MeV}$$



Summary and Future prospects

- m_Z measurable at LHCb!

  $$m_Z = 91185.7 \pm 9.2 \text{ MeV}$$
- Results consistent with SM and previous measurements
- First dedicated measurement at the LHC

- For LHCb
- Massive success with m_Z , m_W
- Full Run 2 measurements are ongoing

  ~ 5 MeV m_Z ?

  ~ 20 MeV m_W ?

- For the LHC
- Looking positive for CMS and ATLAS
- Momentum uncertainties uncorrelated between experiments
- Can challenge LEP together!

Backup

[2311.04670]