Measurement of the Z boson mass with the LHCb detector

Emir Muhammad, on behalf of the LHCb Collaboration

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LHCb

A MODEL OF LEPTONS*

Phys. Rev. Lett. 19, 1264

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate

and on a right-handed singlet

$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e. \qquad (2)$$

The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu \partial_\mu L - \bar{R}\gamma^\mu \partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q = T_3 - N_R - \frac{1}{2}N_L$, and the electron number $N = N_R + N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,[4] and there is no massless particle coupled to N,[5] so we must form our gauge group out of the electronic isospin $\vec{T}$ and the electronic hyperchange $Y \equiv N_R + \frac{1}{2}N_L$.

At tree level…

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

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

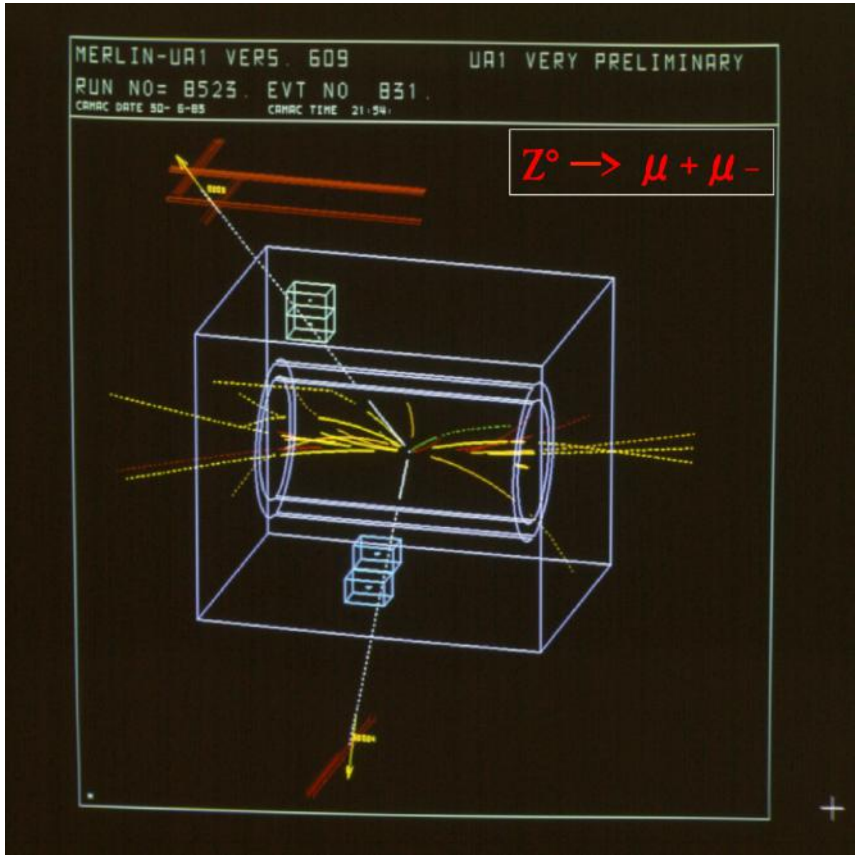
In 1967:

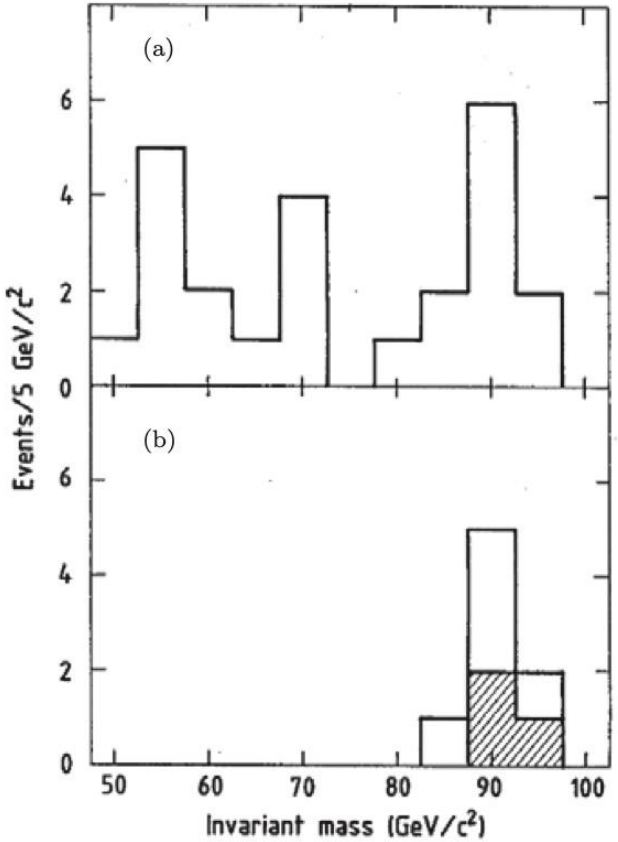
$$m_W > 40 \text{ GeV}, m_z > 80 \text{ GeV}$$

By ~1980:

$$m_z \sim 90 \text{ GeV}$$

The Z discovery





UA1 m_Z = 91.2 ± 3.2 GeV

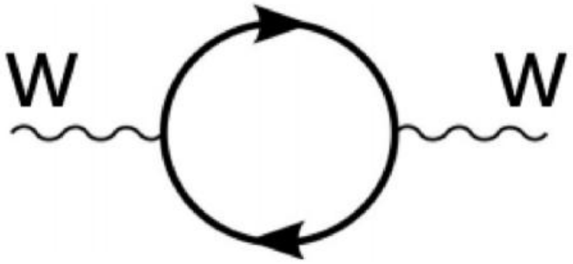
Z.Phys.C 44 (1989) 15-61

UA2 m_Z = 91.74 ± 0.97 GeV

Phys.Lett.B 276 (1992) 354-364

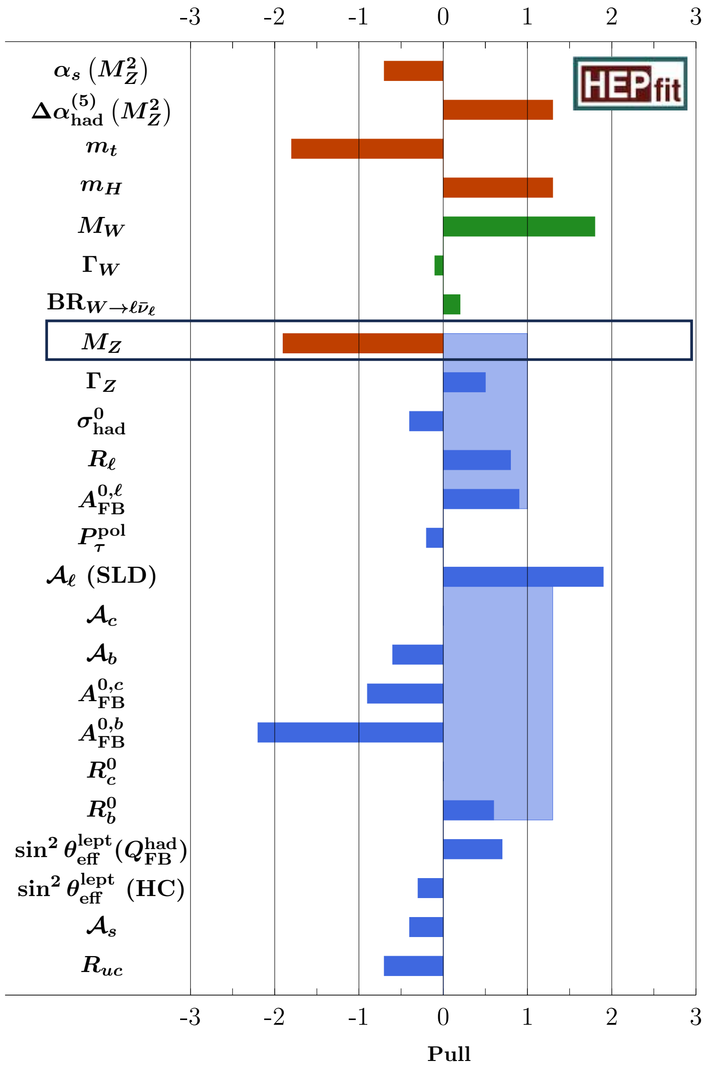
PDG 2024

To higher precision



- Higher precision requires loop corrections

- Now depends on top mass etc..



Phys. Rev. D 106 (2022) 033003

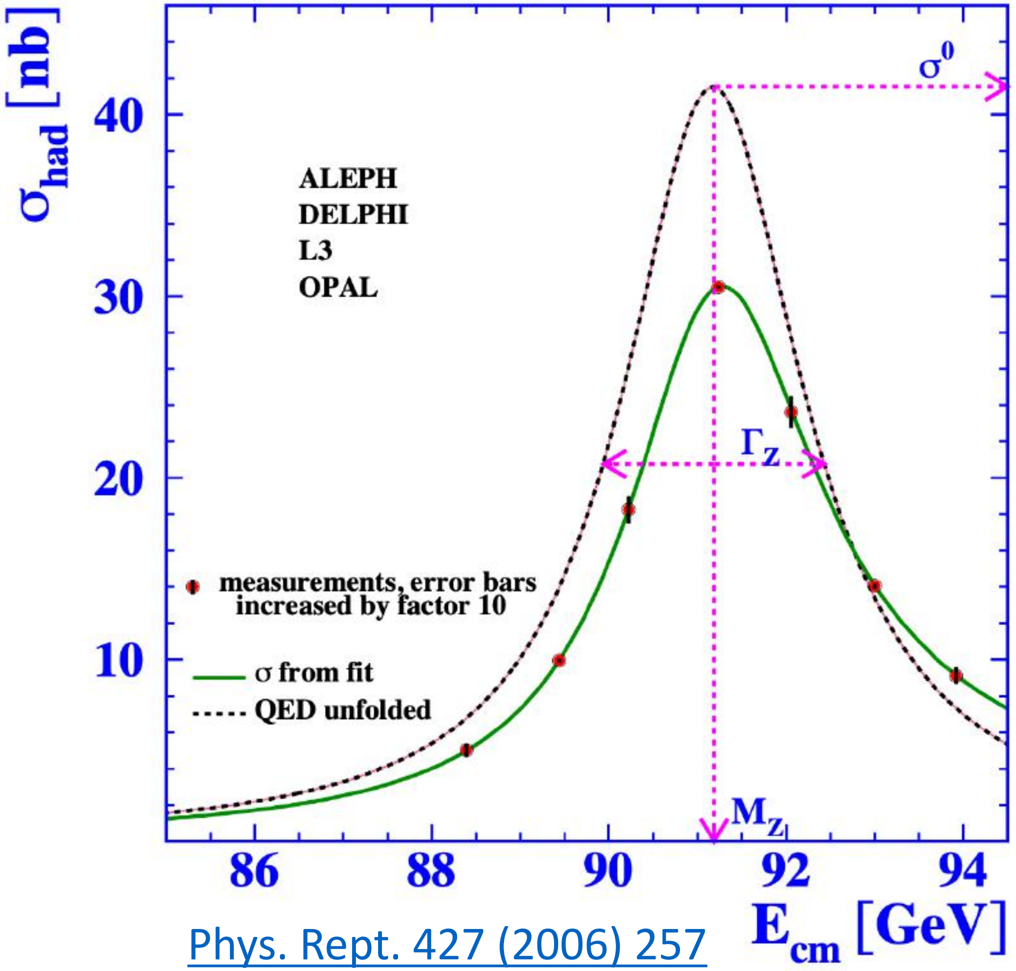
Indirect m_Z = 91204.7 ± **8.8** MeV

The LEP legacy

- Large Electron Positron collider
- 1989 – 2000 @ CERN

- e^+e^- collider, tuned to Z resonance
- $\sim$ 17 *million* Z bosons

- Access via *energy scan*

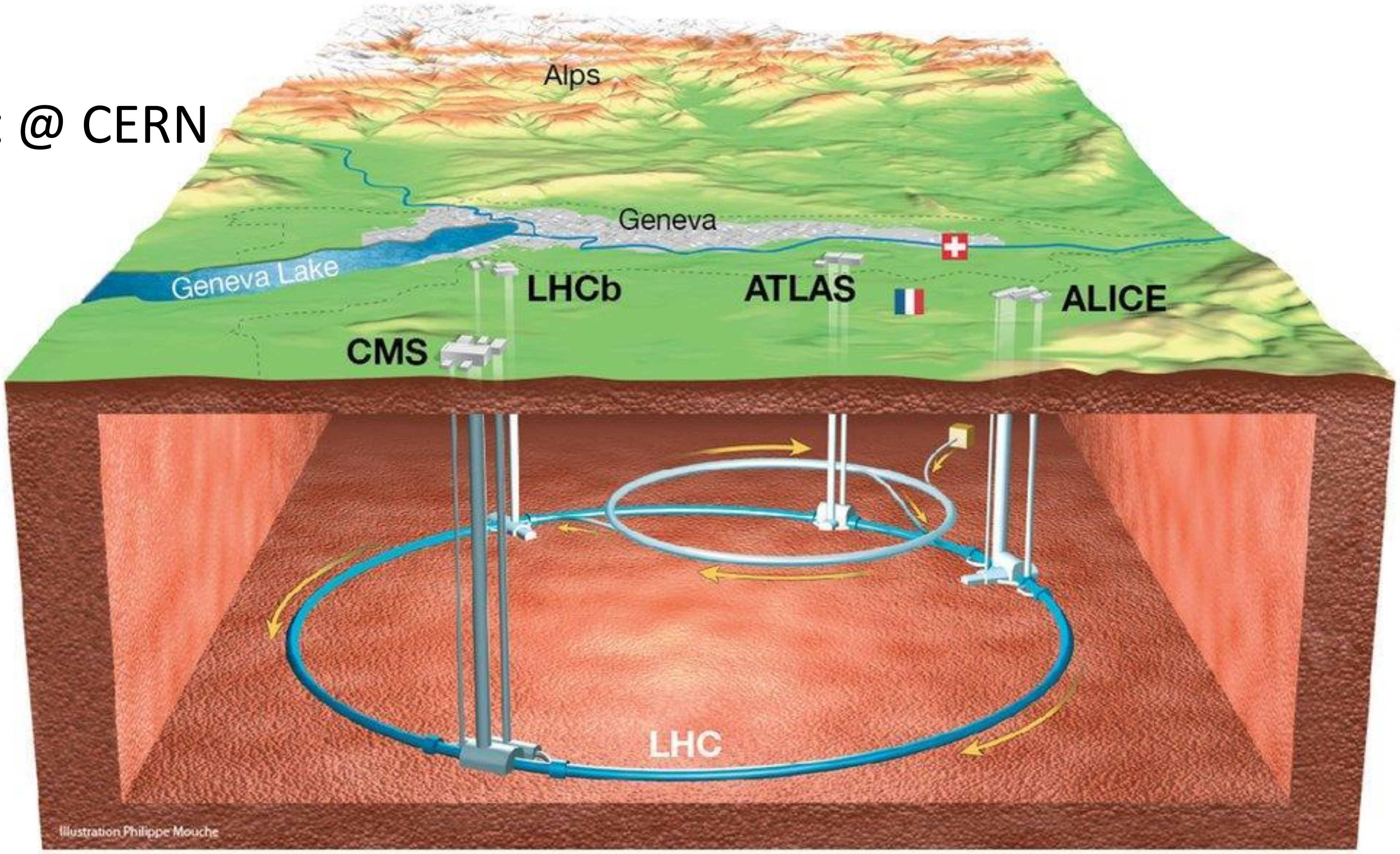


Phys. Rept. 427 (2006) 257

LEP m_Z = 91187.6 ± **2.1** MeV

The LHC

- pp collider
- 2008 – present @ CERN



Prospects of Z measurements at LHC

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

LEP

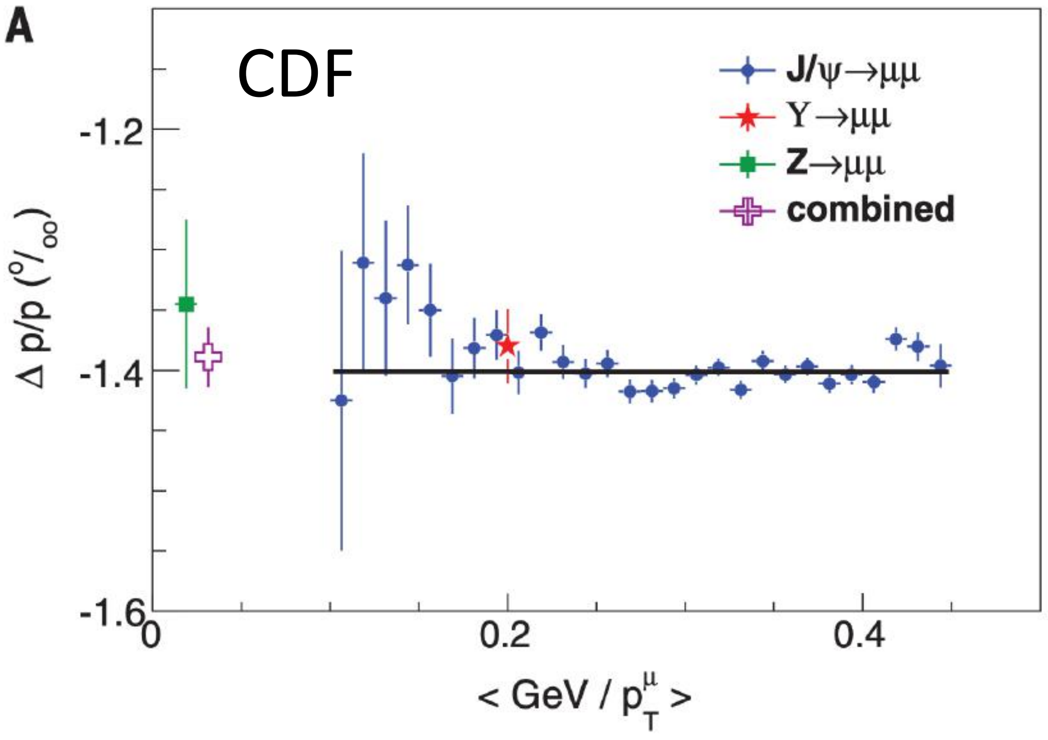
- Measure m_Z with beam-energy scan.
- **Beam-energy calibration.**

LHC

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

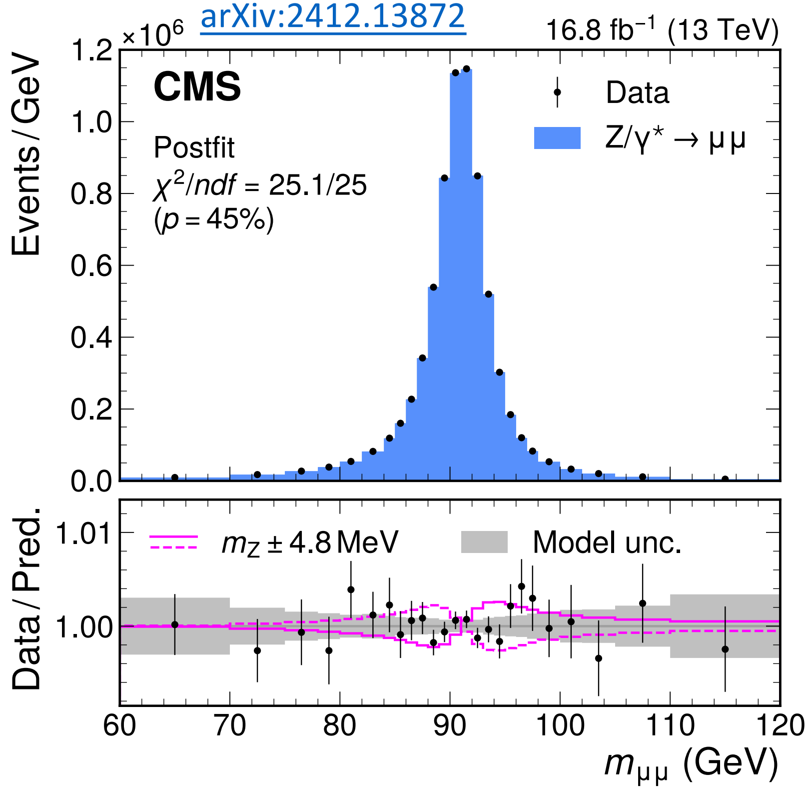
Prospects of Z measurements at LHC

Science 374 (2021) 6568



$m_Z = 91192.3 \pm 7.1$ MeV

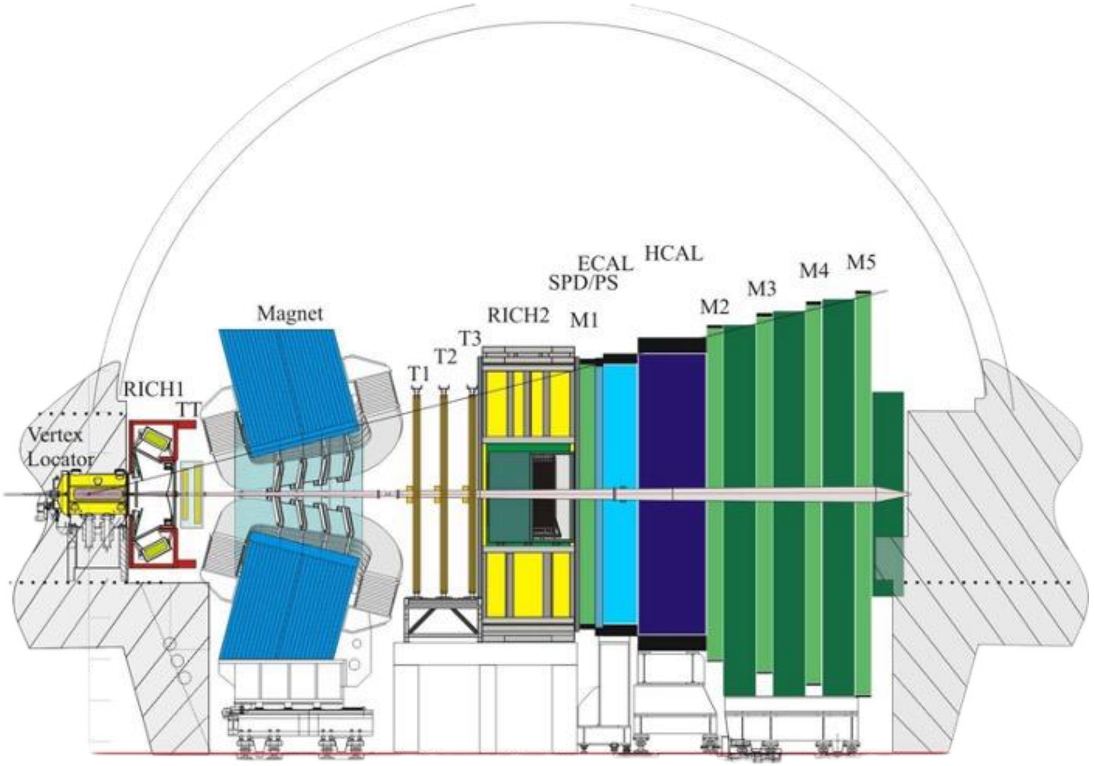
arXiv:2412.13872

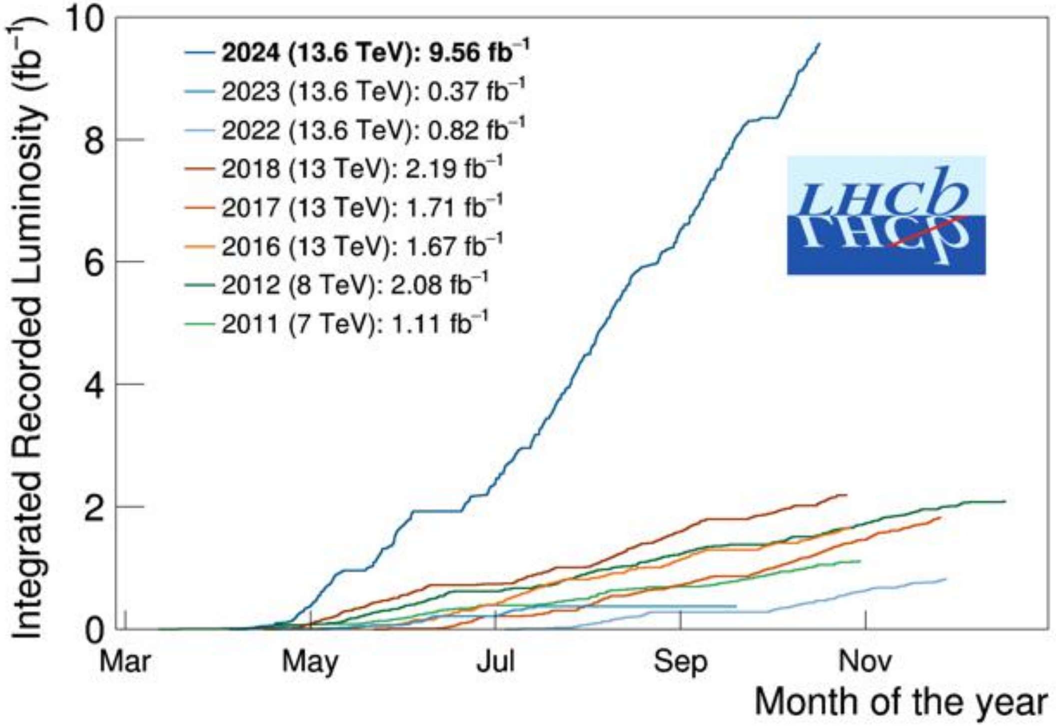


$m_Z - m_{PDG} = -2.2 \pm 4.8$ MeV

"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 @ CERN



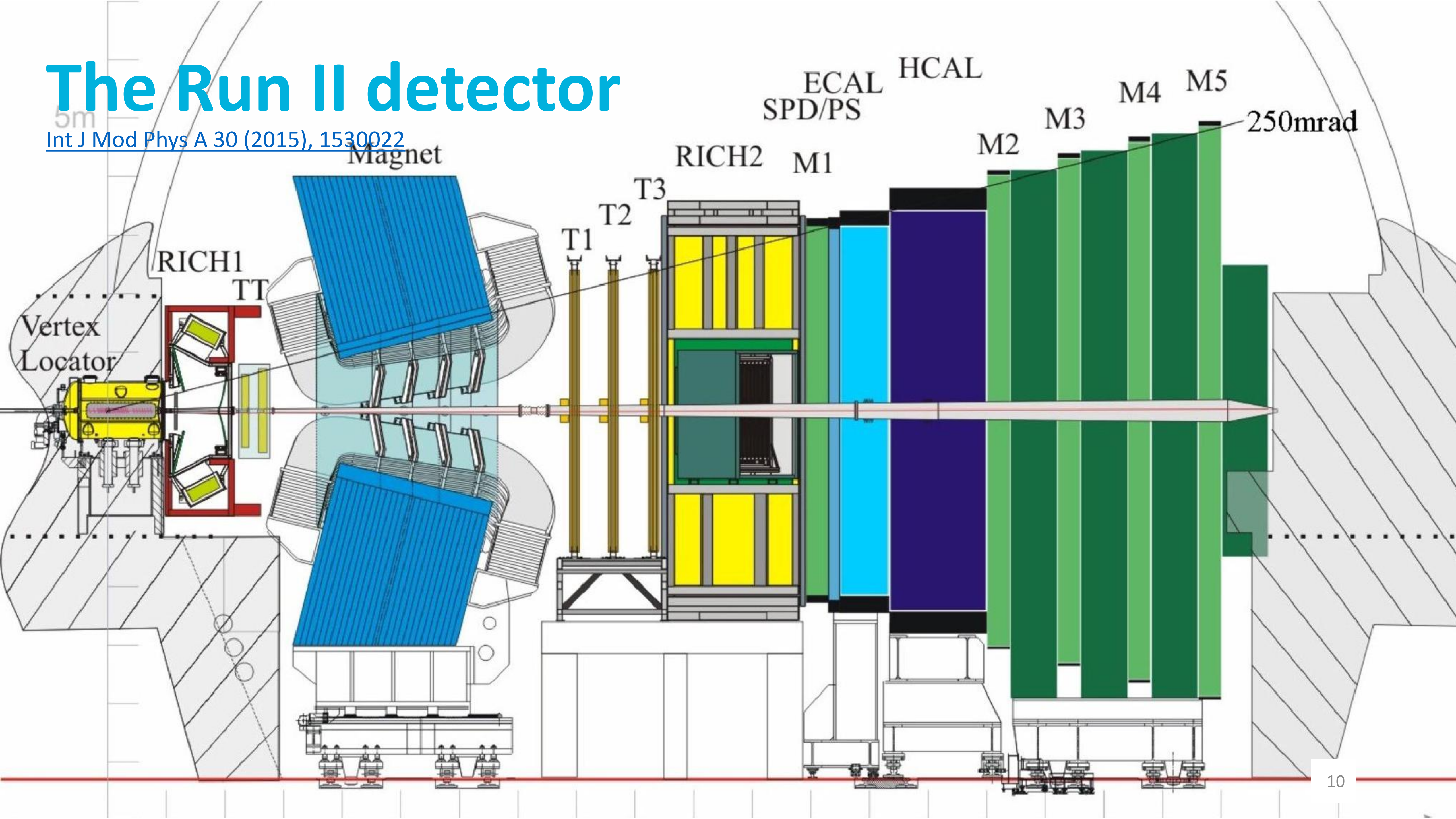


Tracking ranges
ATLAS / CMS: $|\eta| < 2.5$
LHCb: $2 < \eta < 5$

- Originally for b/c physics
- General Purpose!

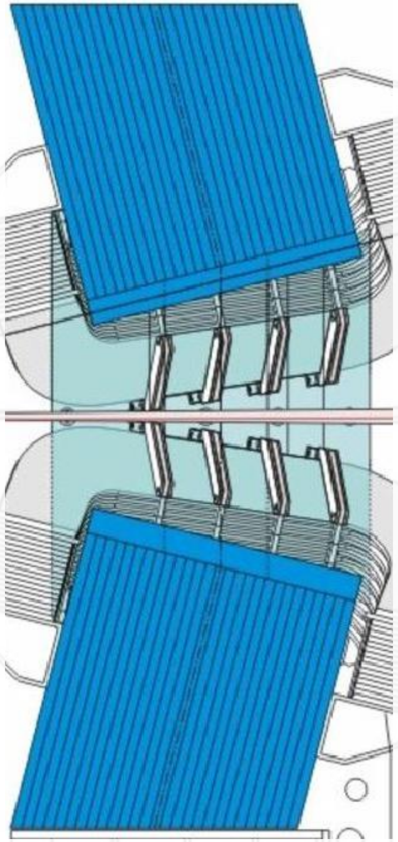
The Run II detector

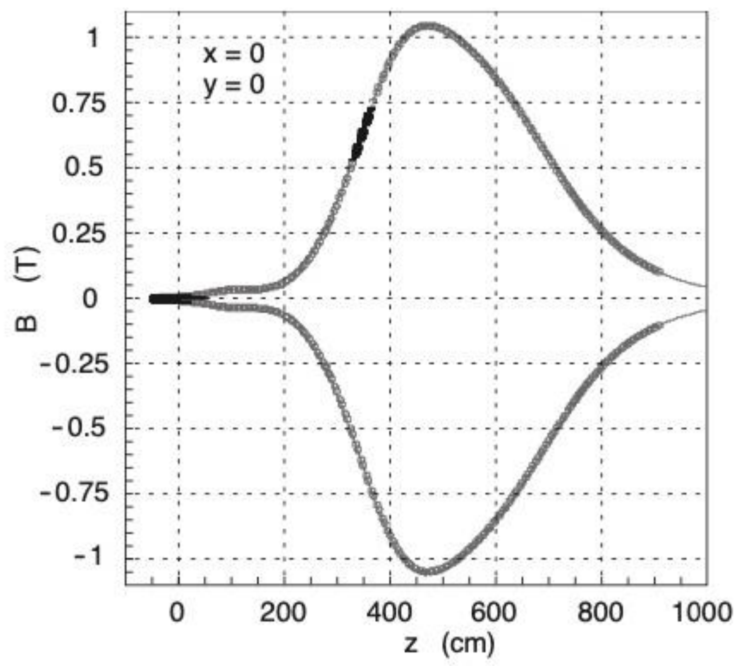
[Int J Mod Phys A 30 (2015), 1530022]



The Run II detector

Int J Mod Phys A 30 (2015), 1530022



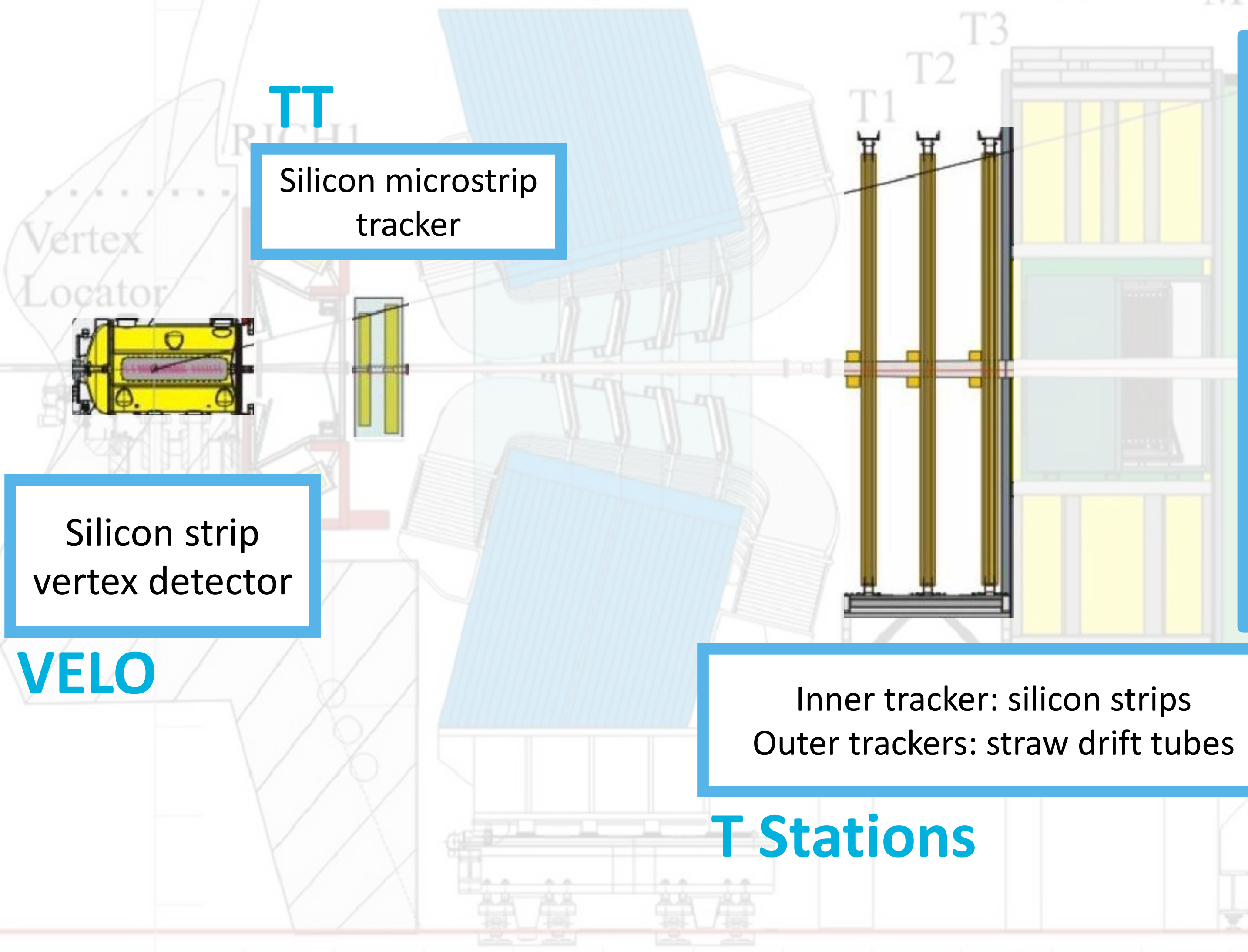


Dipole magnet

4 Tm (vertical)
Polarity switchable

The Run II detector

[Int J Mod Phys A 30 (2015), 1530022]



TT

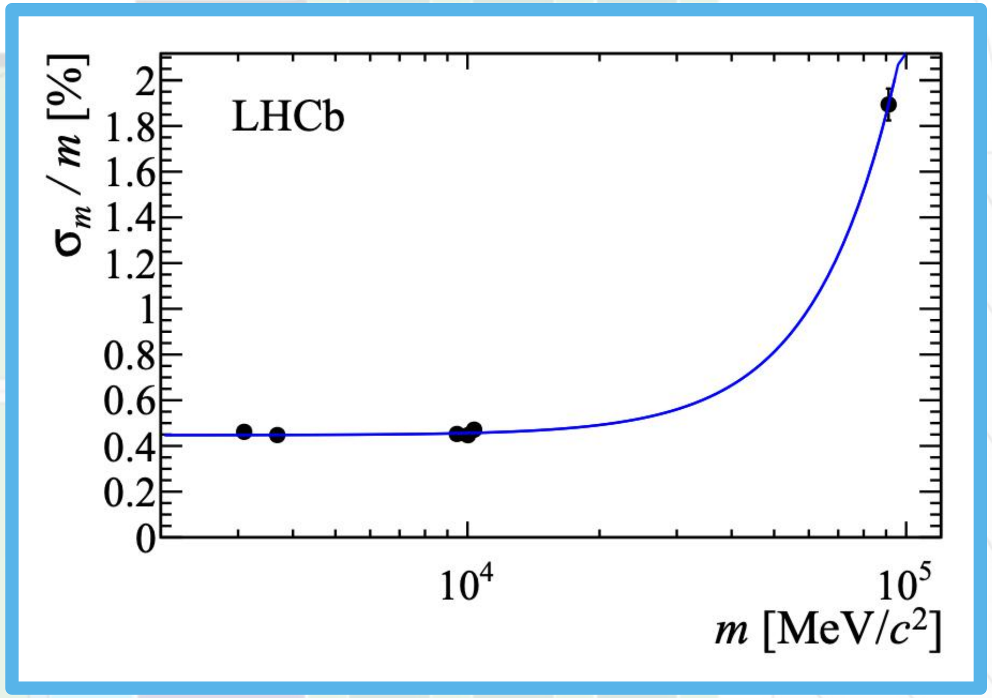
Silicon microstrip tracker

VELO

Silicon strip vertex detector

T Stations

Inner tracker: silicon strips
Outer trackers: straw drift tubes



The Run II detector

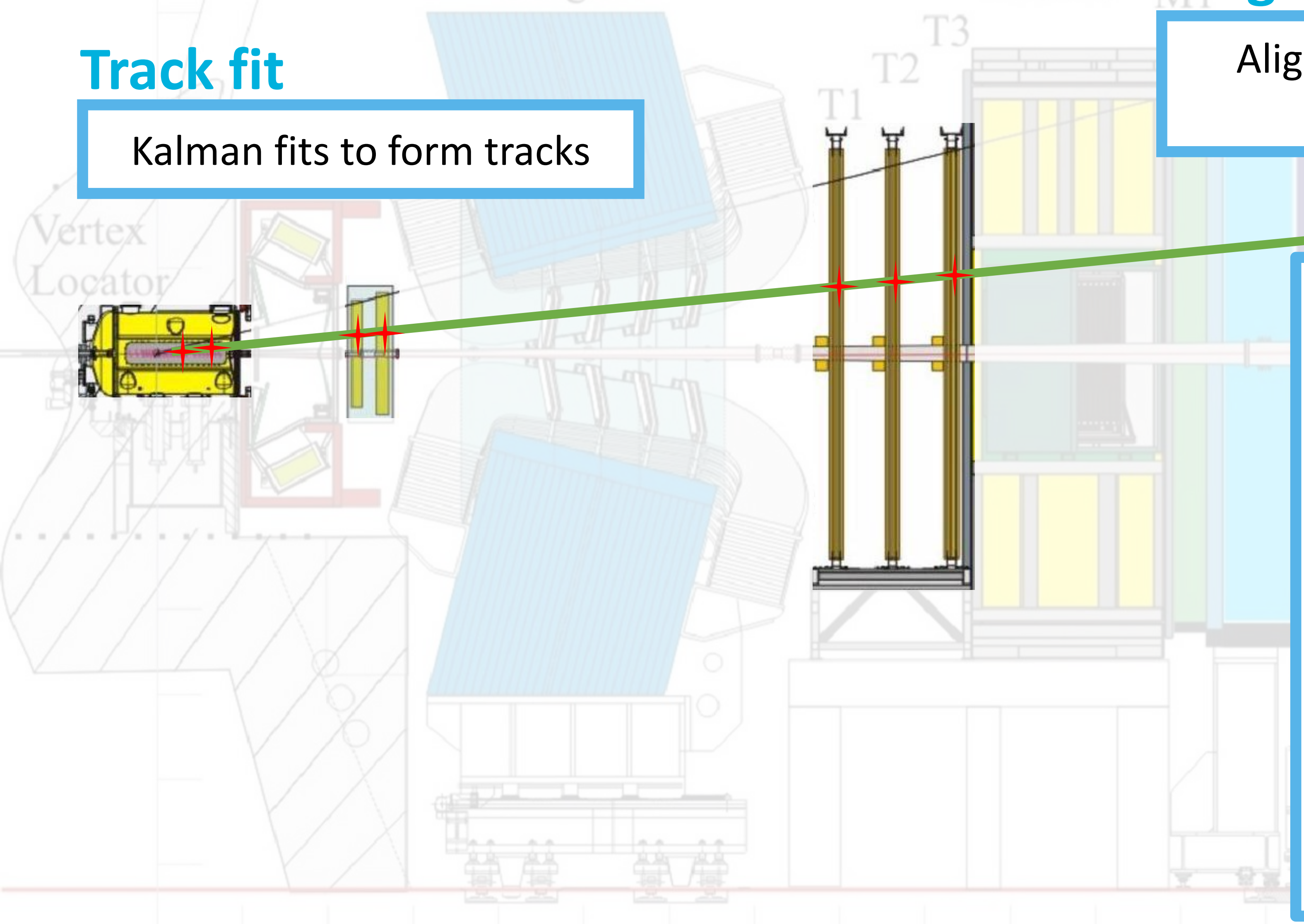
[Int J Mod Phys A 30 (2015), 1530022]

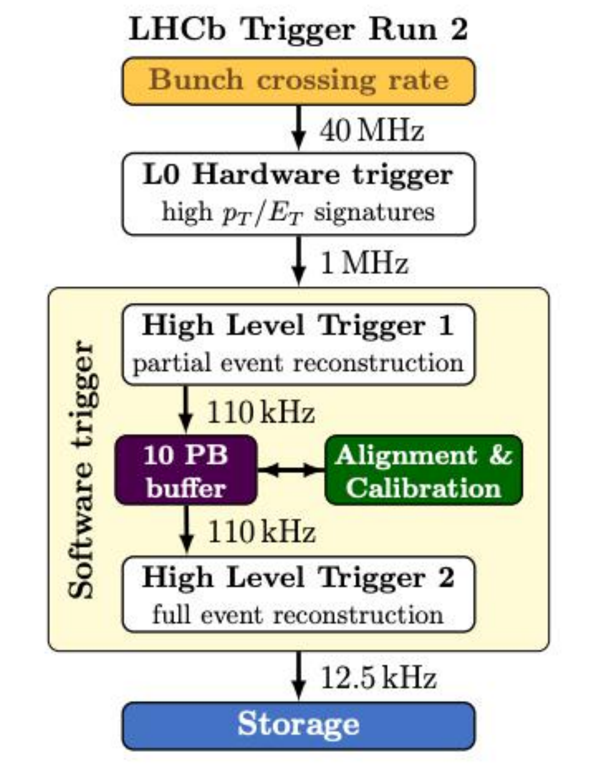
Track fit

Kalman fits to form tracks

Alignment

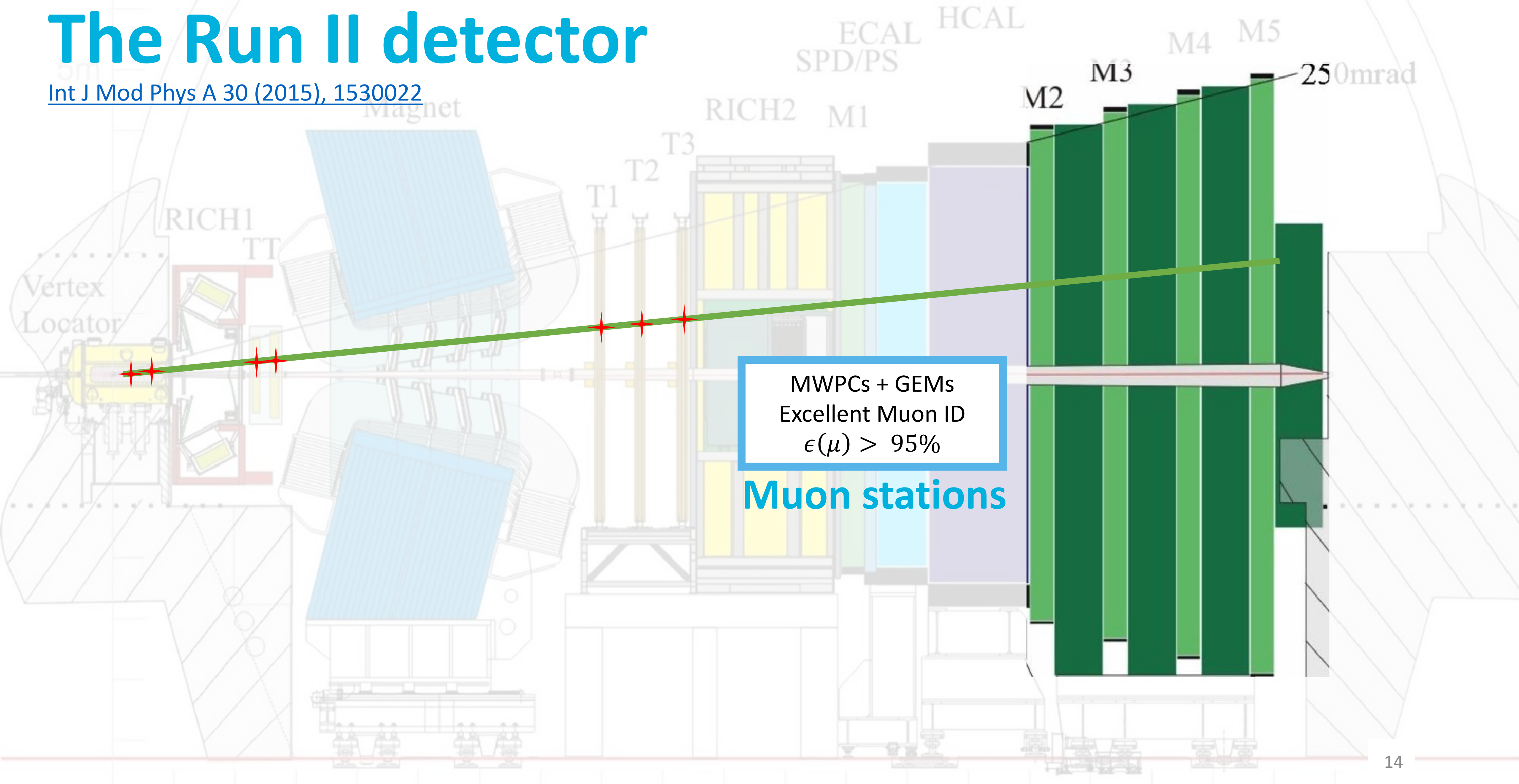
Alignment by reducing track residuals





The Run II detector

Int J Mod Phys A 30 (2015), 1530022

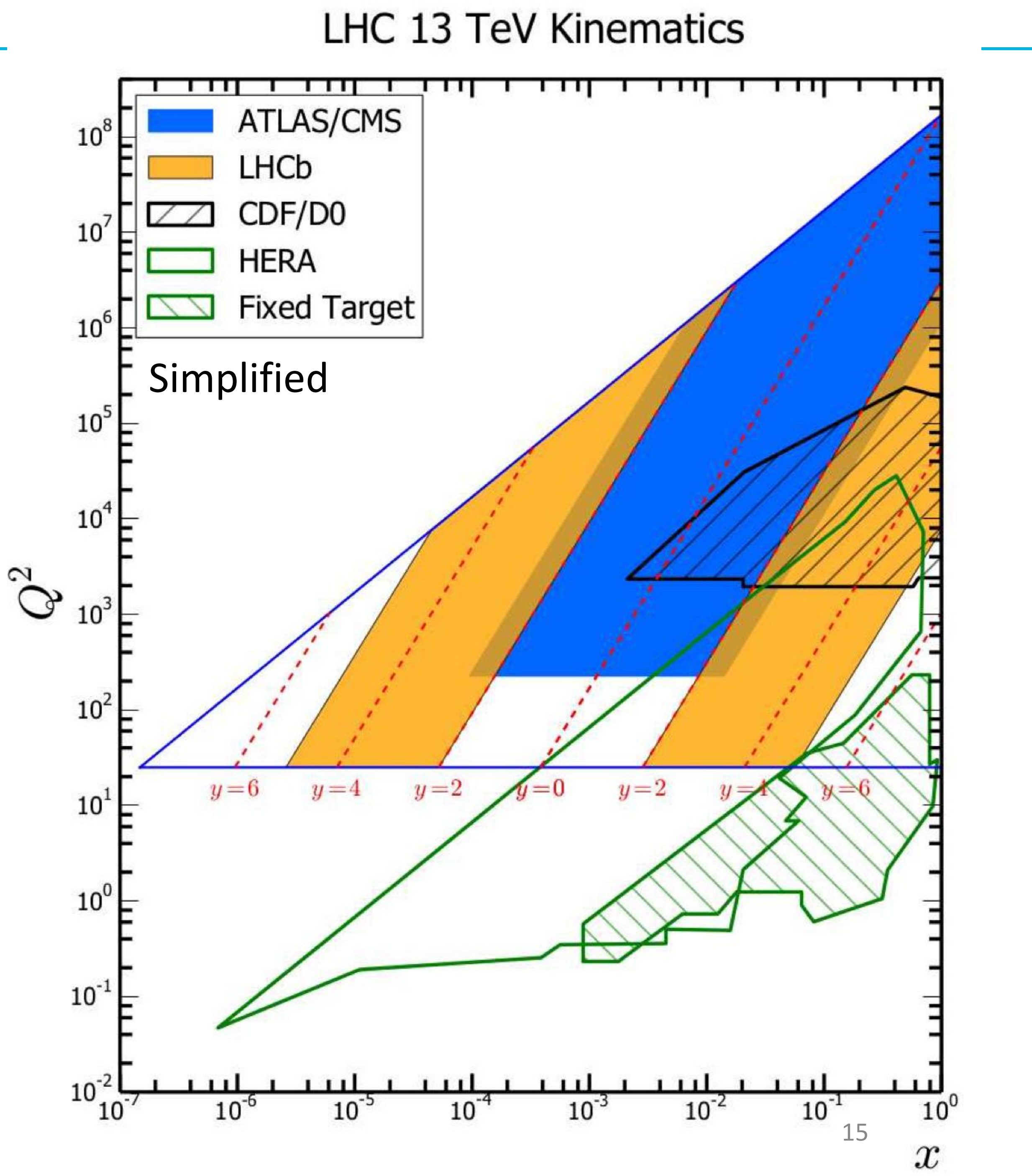


LHCb EW program

- Complementary regions with other experiment

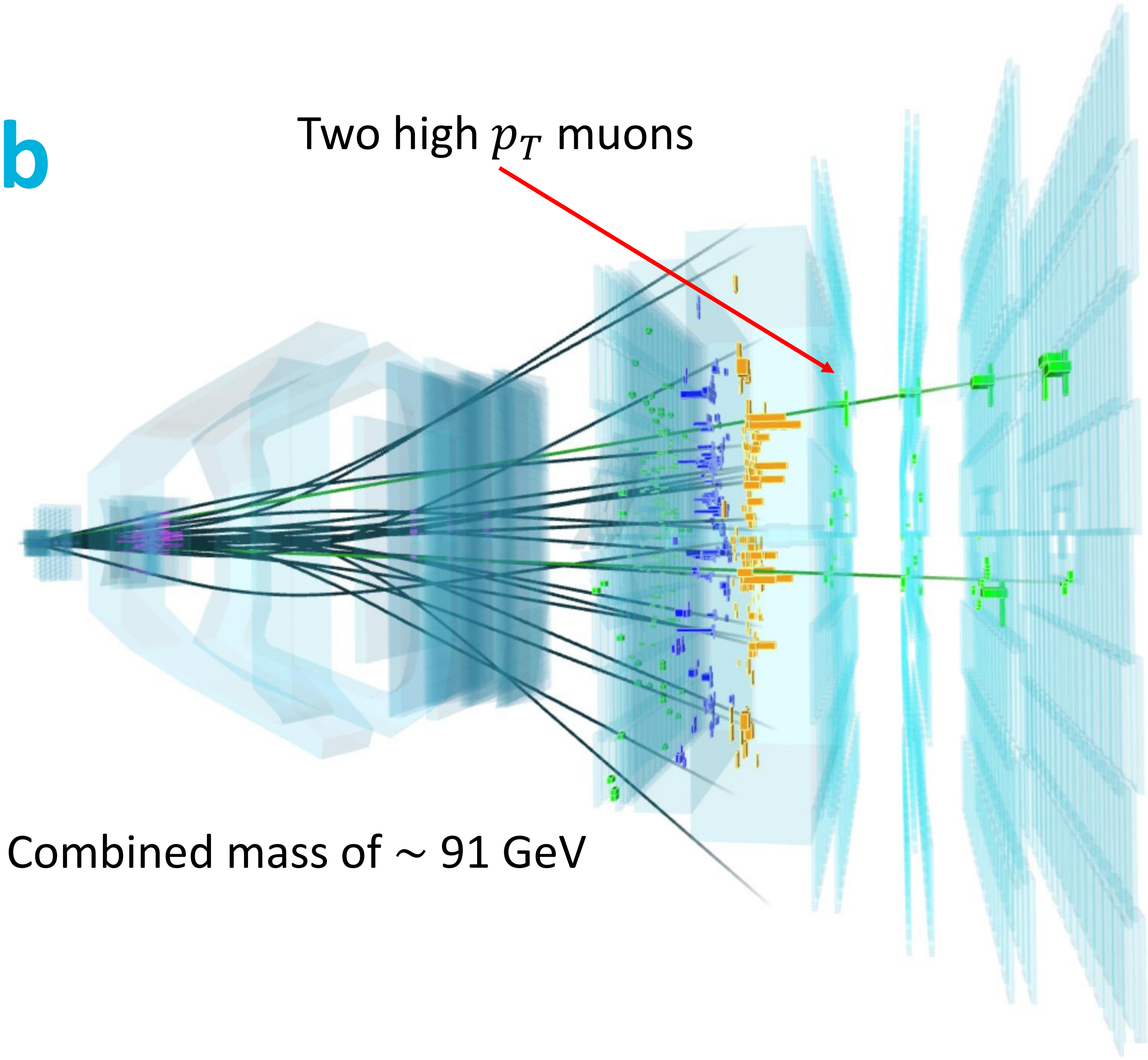
- Cross sections
  - $W \rightarrow \mu\nu$ @ 8 TeV
  - $Z \rightarrow \mu\mu$ @ 13 TeV
  - …
- Precision EW
  - W mass
  - Leptonic weak mixing angle
  - .. Z mass?

Collection of results in the backup



Z decay at LHCb

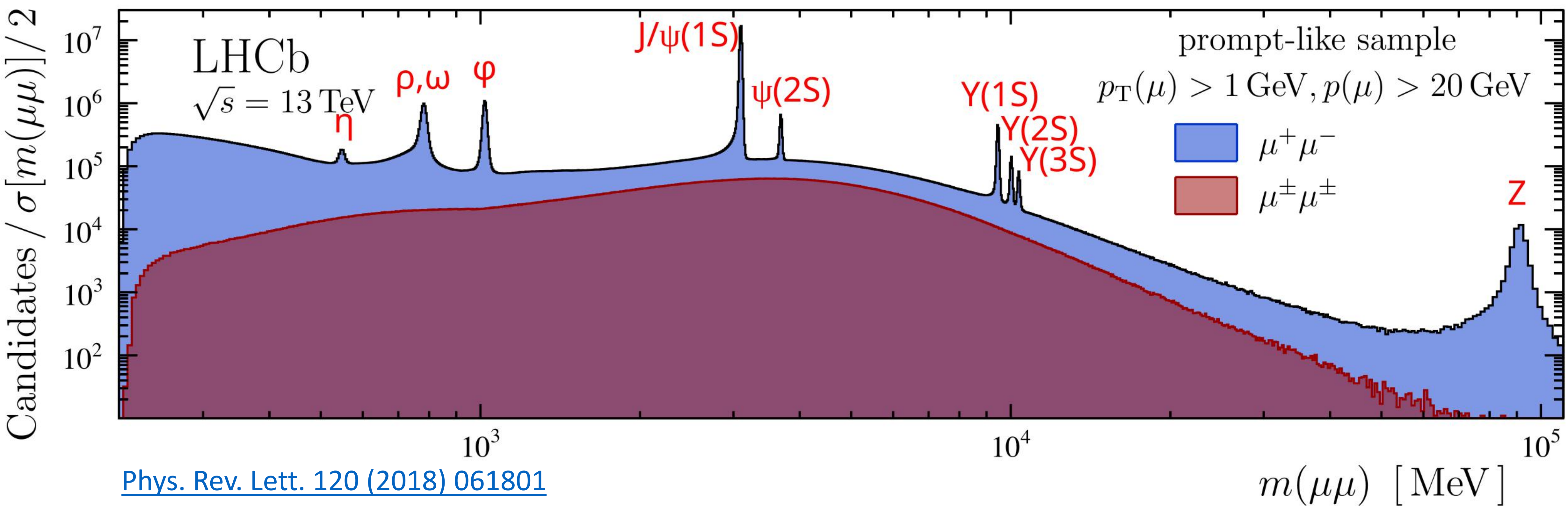
Most sensitive to $Z \rightarrow \mu\mu$



Event 285193784
Run 157633
Sat, 11 Jul 2015 14:03:29

LHCb

Dimuon mass spectrum



Phys. Rev. Lett. 120 (2018) 061801

Z mass measurement at LHCb

Sensitive via the dimuon mass distribution

- Fit compares full simulation with the data
- m_Z hypothesis varied by reweighting full simulation with generator level events

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

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

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

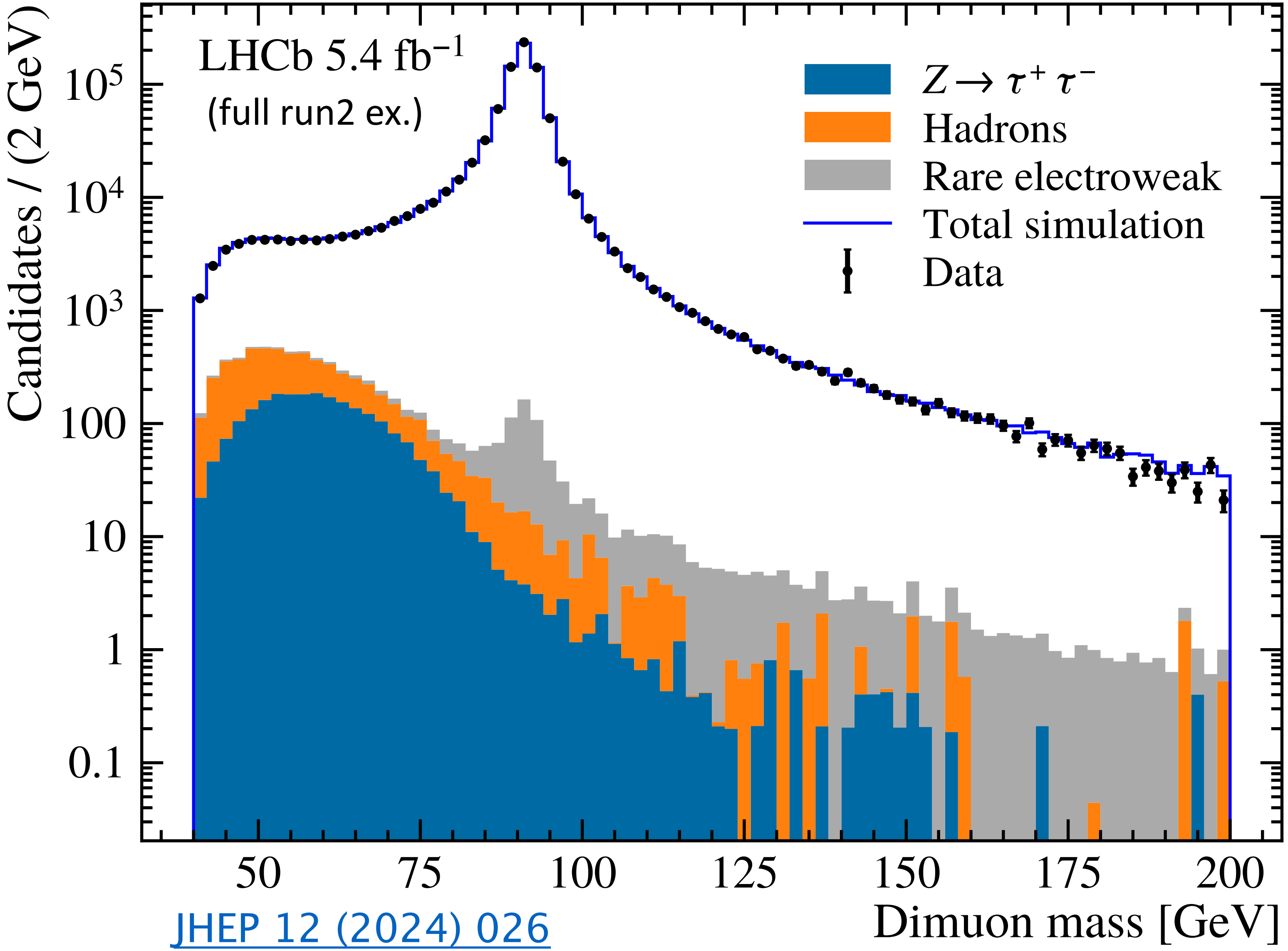
JHEP 05 (2006) 026, 517

GEANT4

Nucl. Instrum. Meth. A506 (2003) 250

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

Backgrounds



JHEP 12 (2024) 026

The momentum response

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

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

Differences between data and simulation are of the form above

The momentum response

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

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

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

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

The momentum response

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

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

Correct in a 4 step procedure

1. Curvature bias via pseudomass and Z

The momentum response

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

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

Correct in a 4 step procedure

1. Curvature bias via pseudomass and Z
2. Time dependent correction with $\Upsilon(1S)$

The momentum response

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

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

Correct in a 4 step procedure

1. Curvature bias via pseudomass and Z
2. Time dependent correction with $\Upsilon(1S)$
3. Direction dependent correction with $\Upsilon(1S)$

The momentum response

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

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

Correct in a 4 step procedure

1. Curvature bias via pseudomass and Z
2. Time dependent correction with $\Upsilon(1S)$
3. Direction dependent correction with $\Upsilon(1S)$
4. **Generalised momentum smearing for $\boldsymbol{\alpha}$, $\boldsymbol{\sigma_1}$, $\boldsymbol{\sigma_2}$**

1. Charge-dependent curvature bias

Misalignments lead to curvature bias

$$m^2 = 2p^+p^-(1 - \cos\theta)$$

δ largely cancels out in the above

Needs an estimator that doesn't..

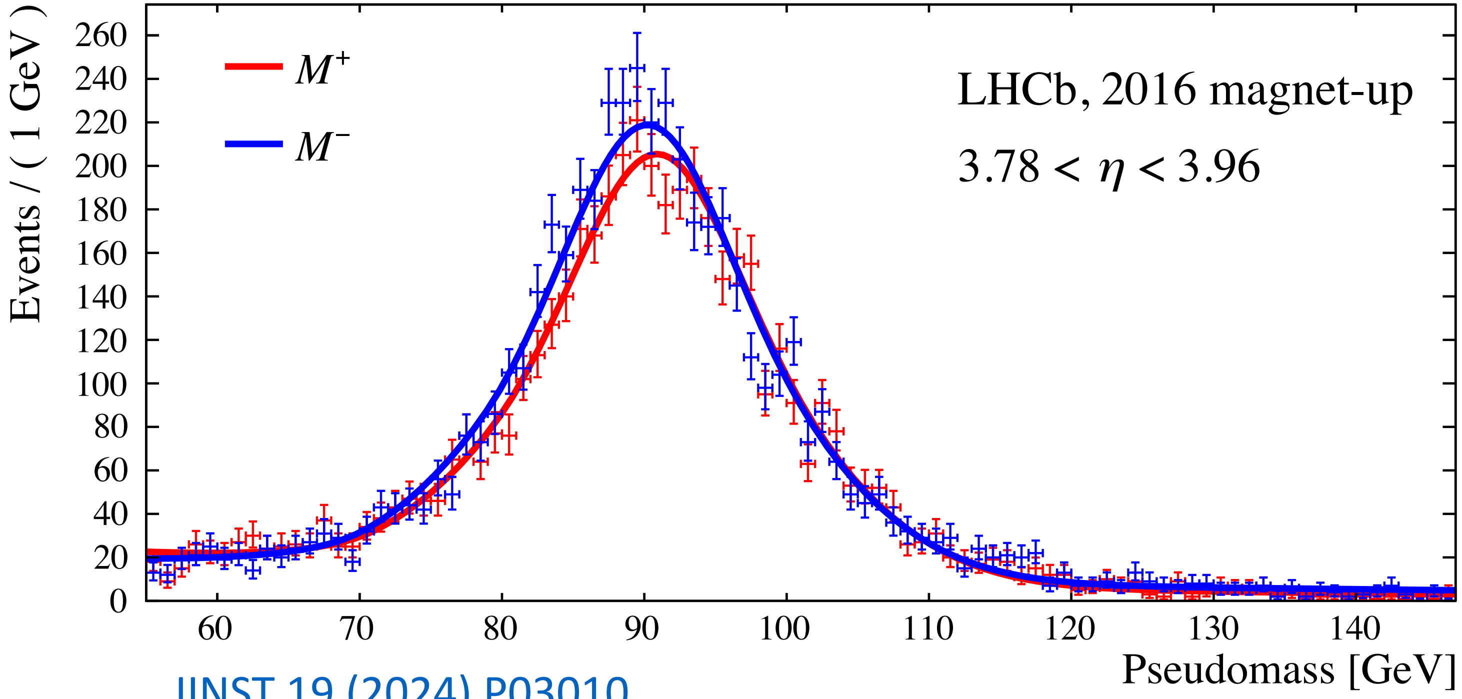
Pseudomass $M^{\pm}$ with $Z \rightarrow \mu\mu$

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

PRD 91 (2015) 072002

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

1. Charge-dependent curvature bias



JINST 19 (2024) P03010

Correct the pseudomass *asymmetry*

-> Use this to correct *data*

Corrects asymmetry from the difference between data and simulation to account for small biases

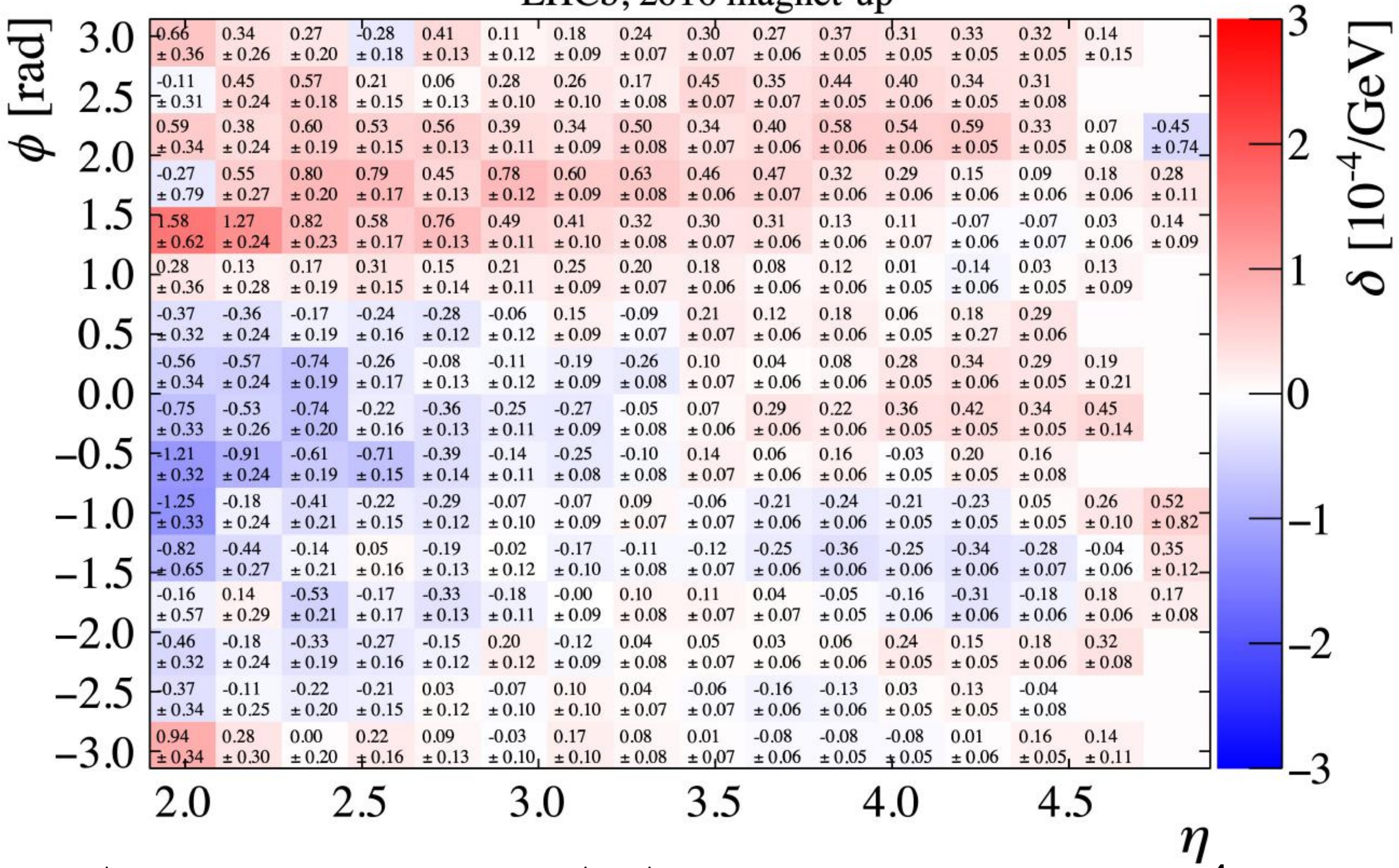
Unbiased with m_Z

Changing m_Z in simulation by ± 100 MeV has 300 keV effect in final measurement

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

1. Charge-dependent curvature bias

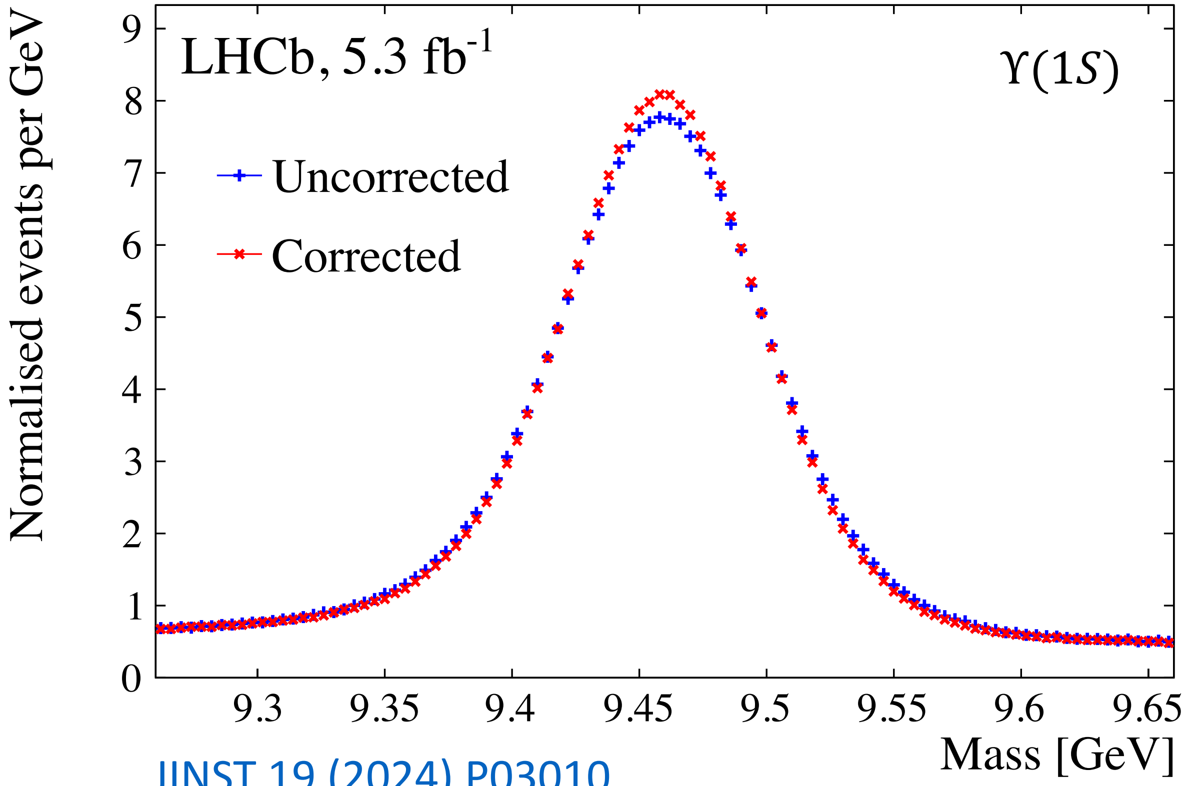
[JINST 19 (2024) P03010]

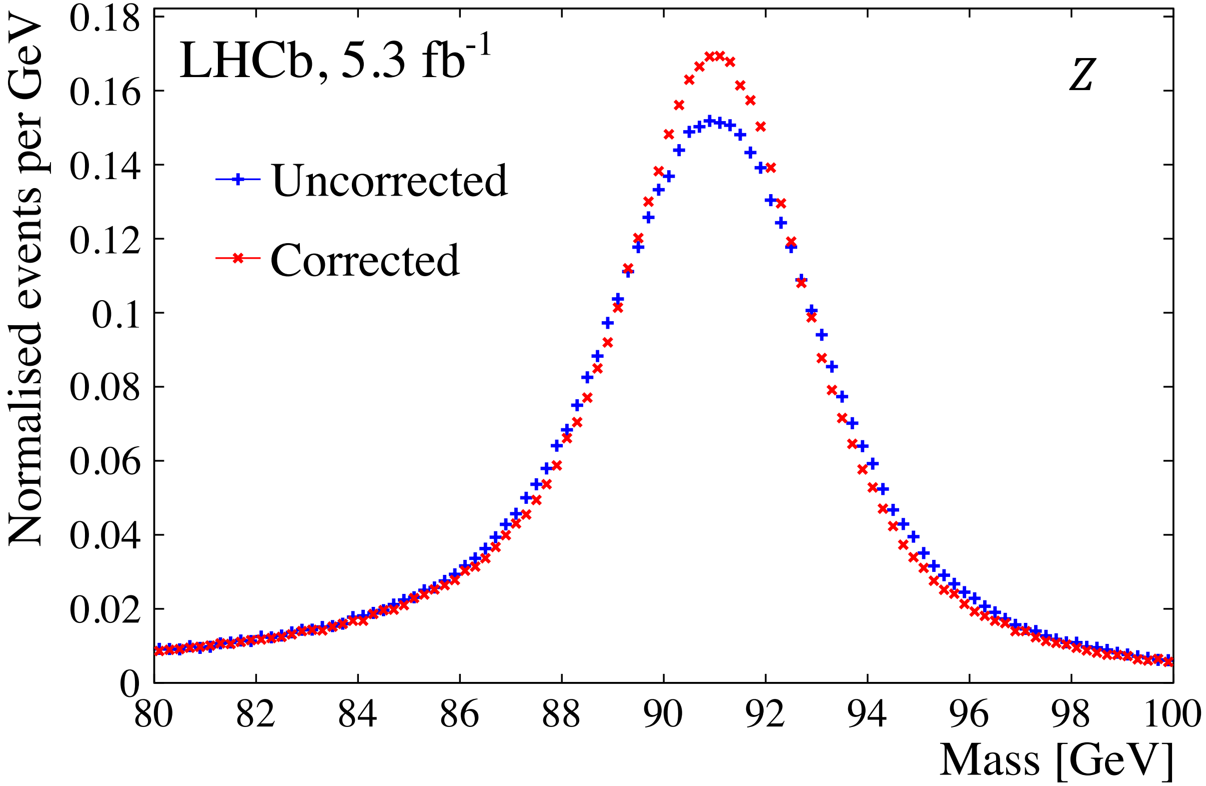


$$p^{\pm} \rightarrow \left(1 + \alpha + \frac{\beta}{p^{\pm}} \mp \delta p^{\pm}\right)(1 + a\mathcal{R}_1\sigma_1)(1 + b\mathcal{R}_2\sigma_2 p^{\pm})p^{\pm}$$

Corrections $\sim 10^{-4}$

1. Charge-dependent curvature bias





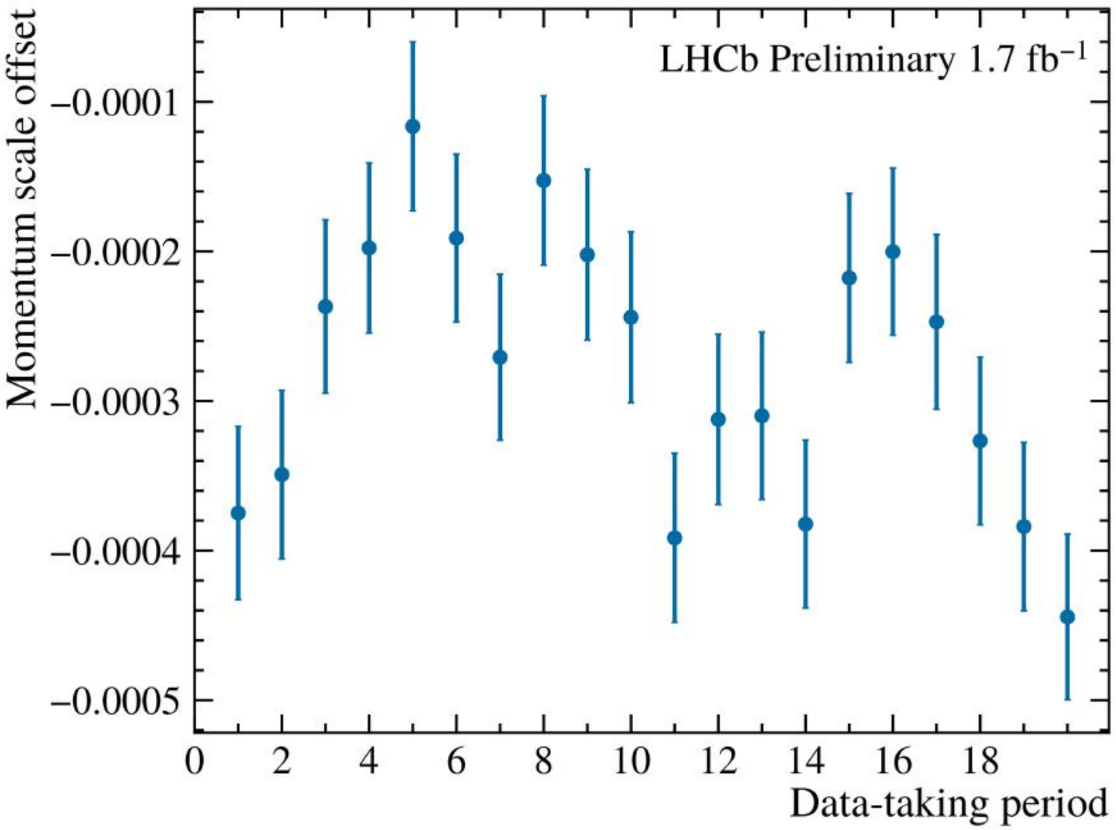
JINST 19 (2024) P03010

Contributes 0.8 MeV to uncertainty

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

2. Time varying momentum scale

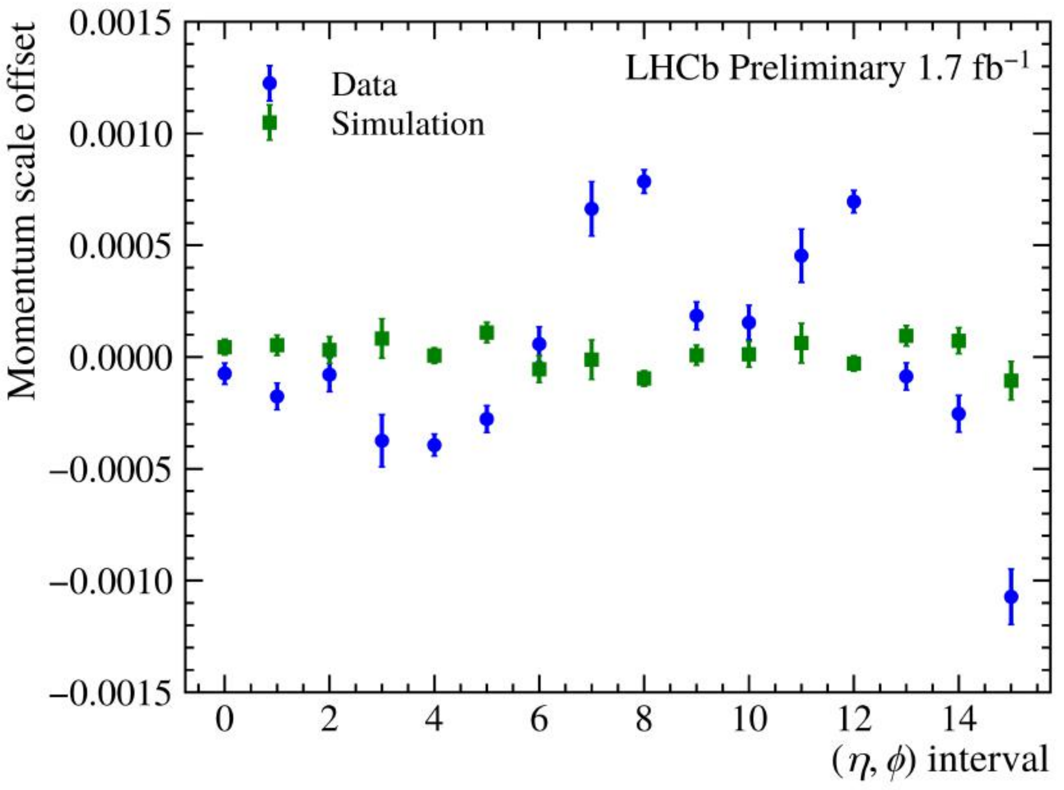
- Time dependent mass scale in LHCb
- Extract the $\Upsilon(1S)$ line shape parameters in bins of the 2016 data-taking period [2024 JINST 19 P02008]
- Correct mass scales by comparing with PDG values
- Corrected in data



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

3. Direction dependent momentum scale

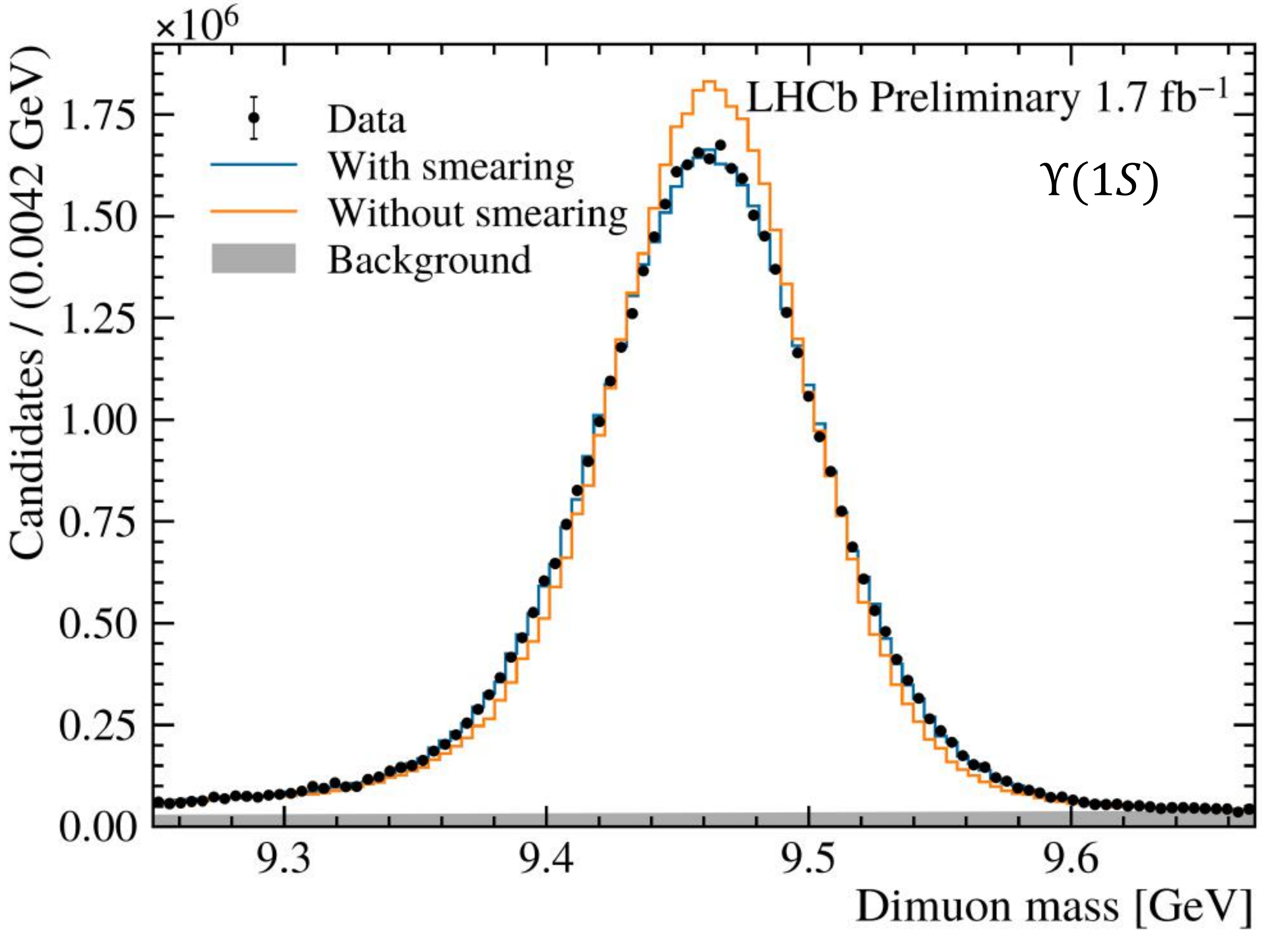
- Localised biases across the detector
- Corrections in 16 bins of η / ϕ
- Extract $\Upsilon(1S)$ lineshape parameters from each bin for data and simulation



- Correct simulation to match data

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

4. Momentum smearing



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 ± 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

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

4. Momentum smearing

Source	Size [MeV]
Detector material description	2.6
Calibration samples	2.0
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	**4.1**

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

Muon reconstruction efficiencies

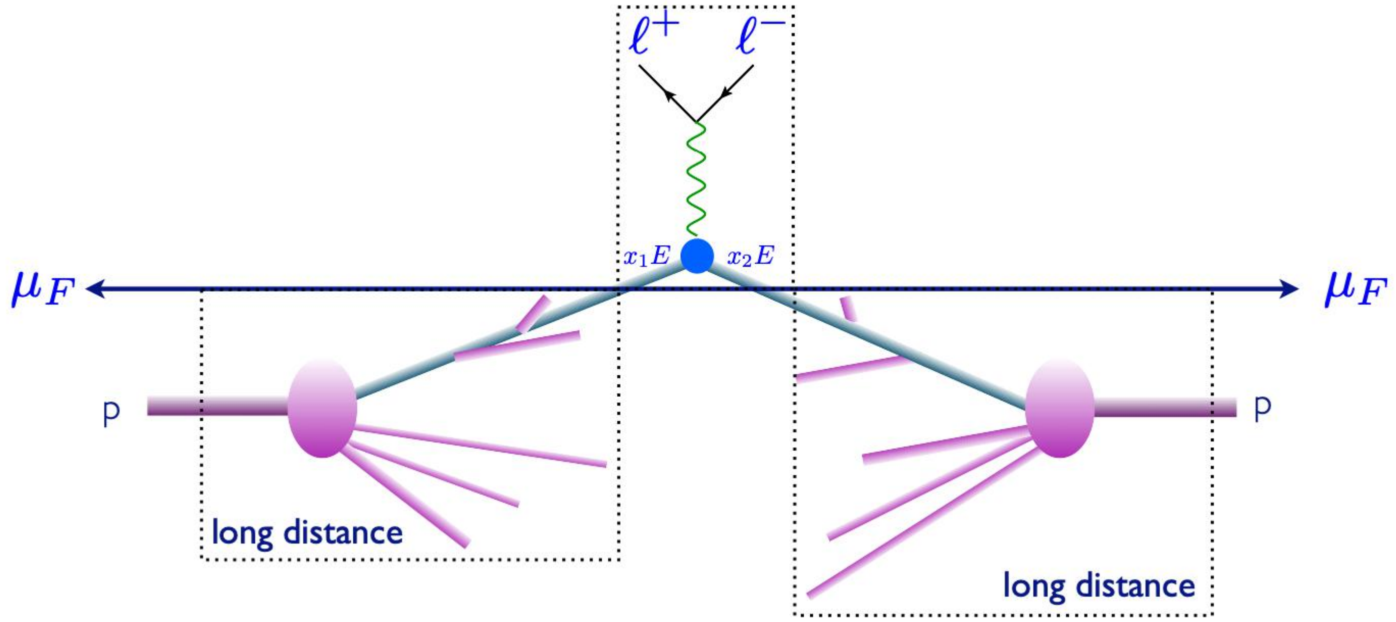
Muon trigger, ID, and tracking efficiencies measured in data and simulation with the tag-and-probe method

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

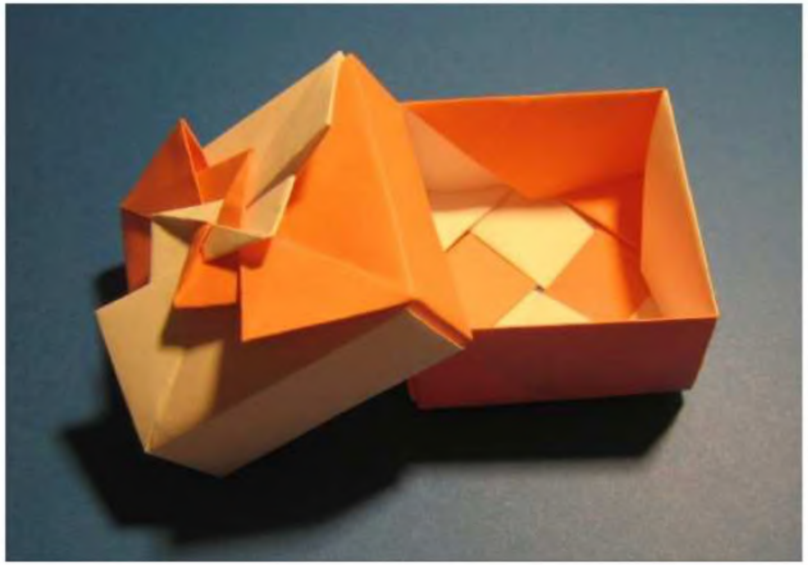
Dimuon mass templates

- 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

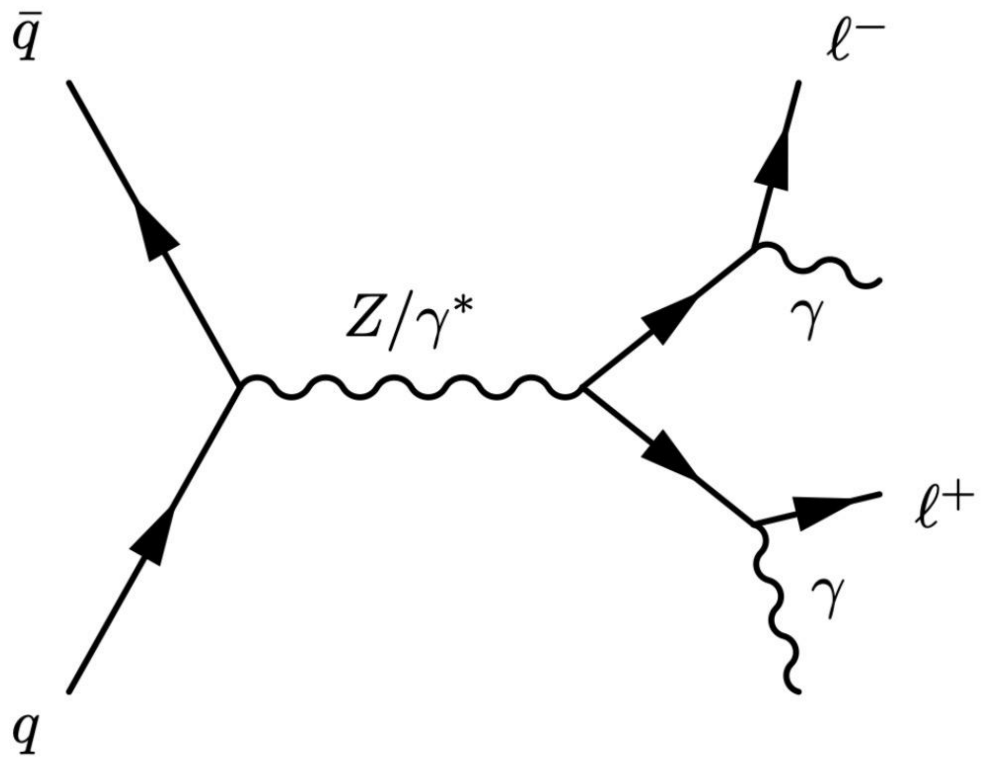
The POWHEG BOX is a general computer framework for implementing NLO calculations in shower Monte Carlo programs according to the POWHEG method. It is also a library, where previously included processes are made available to the users. It can be interfaced with all modern shower Monte Carlo programs that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



→ we get multiple Z mass hypothesis with correct NLO corrections

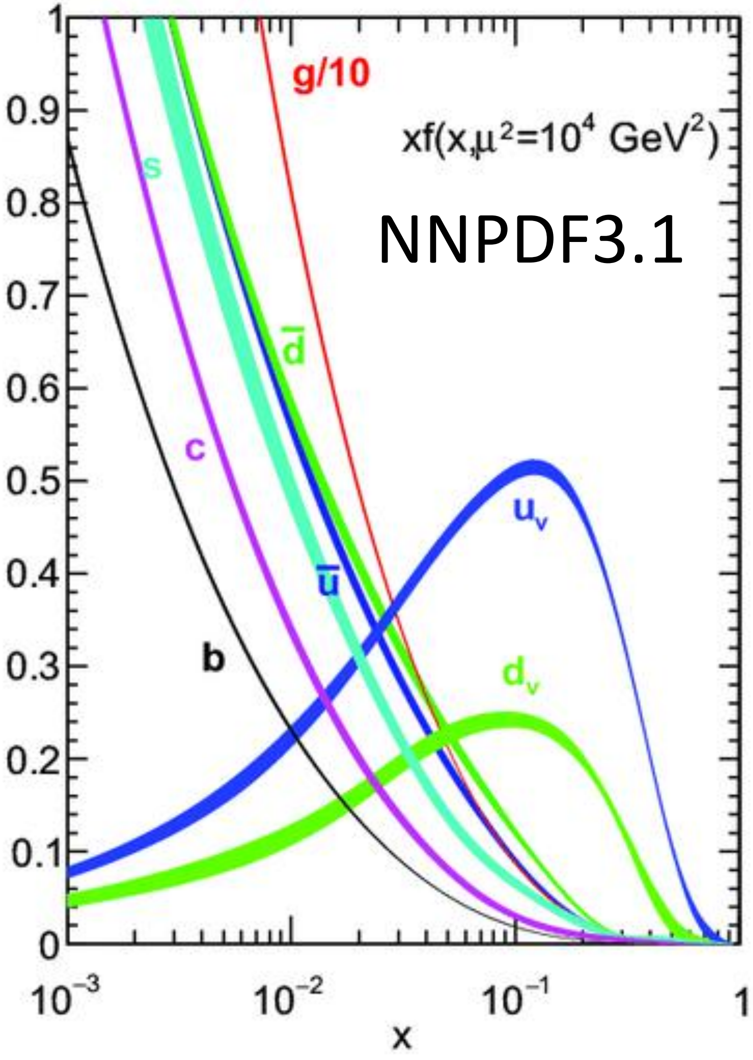
Dimuon mass templates

- 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.

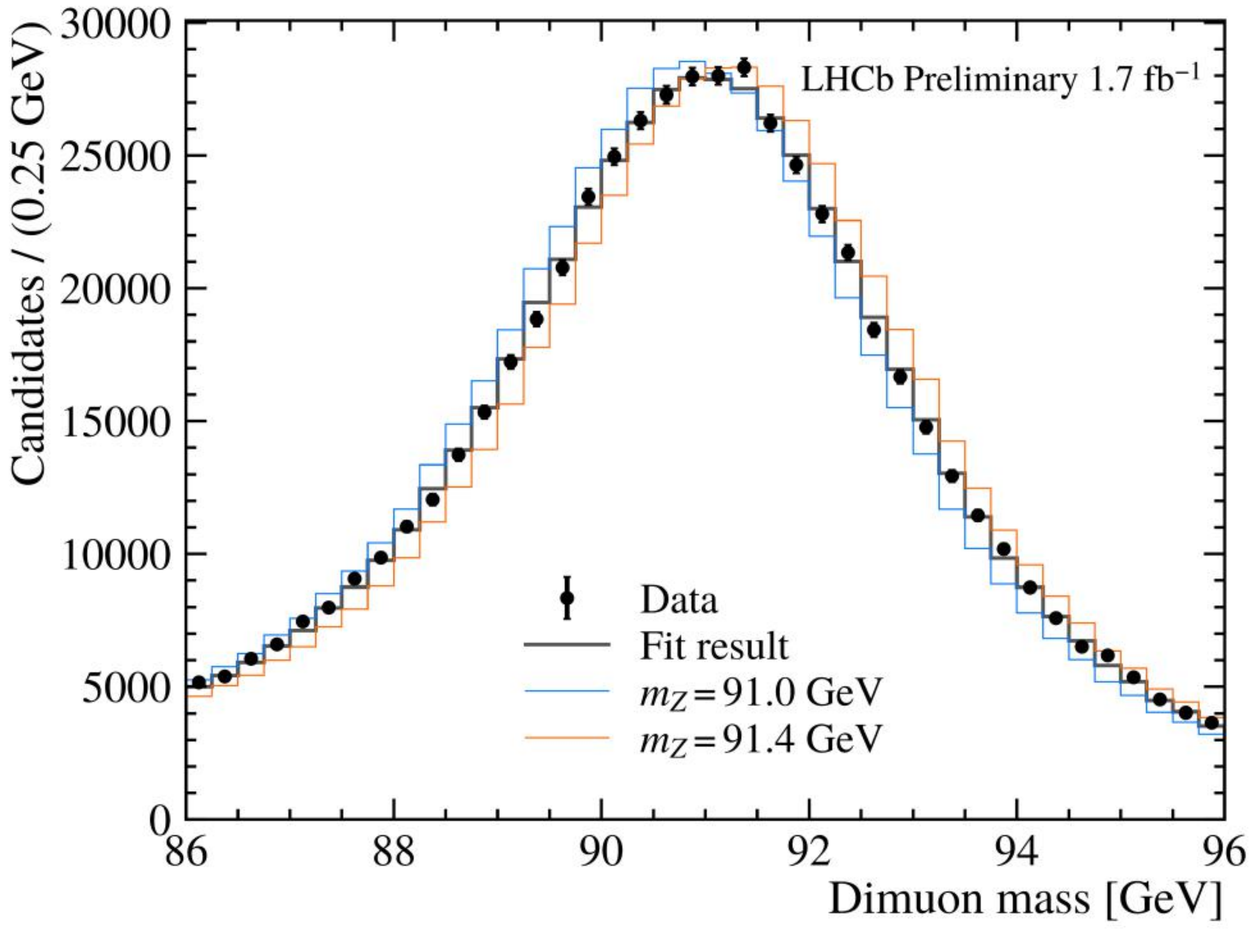


Parton density functions

- 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	4.1
Signal QED corrections	0.8
Parton distribution functions	0.7
Detection Efficiency	0.1
Statistical uncertainty	8.5
Total	**9.5**

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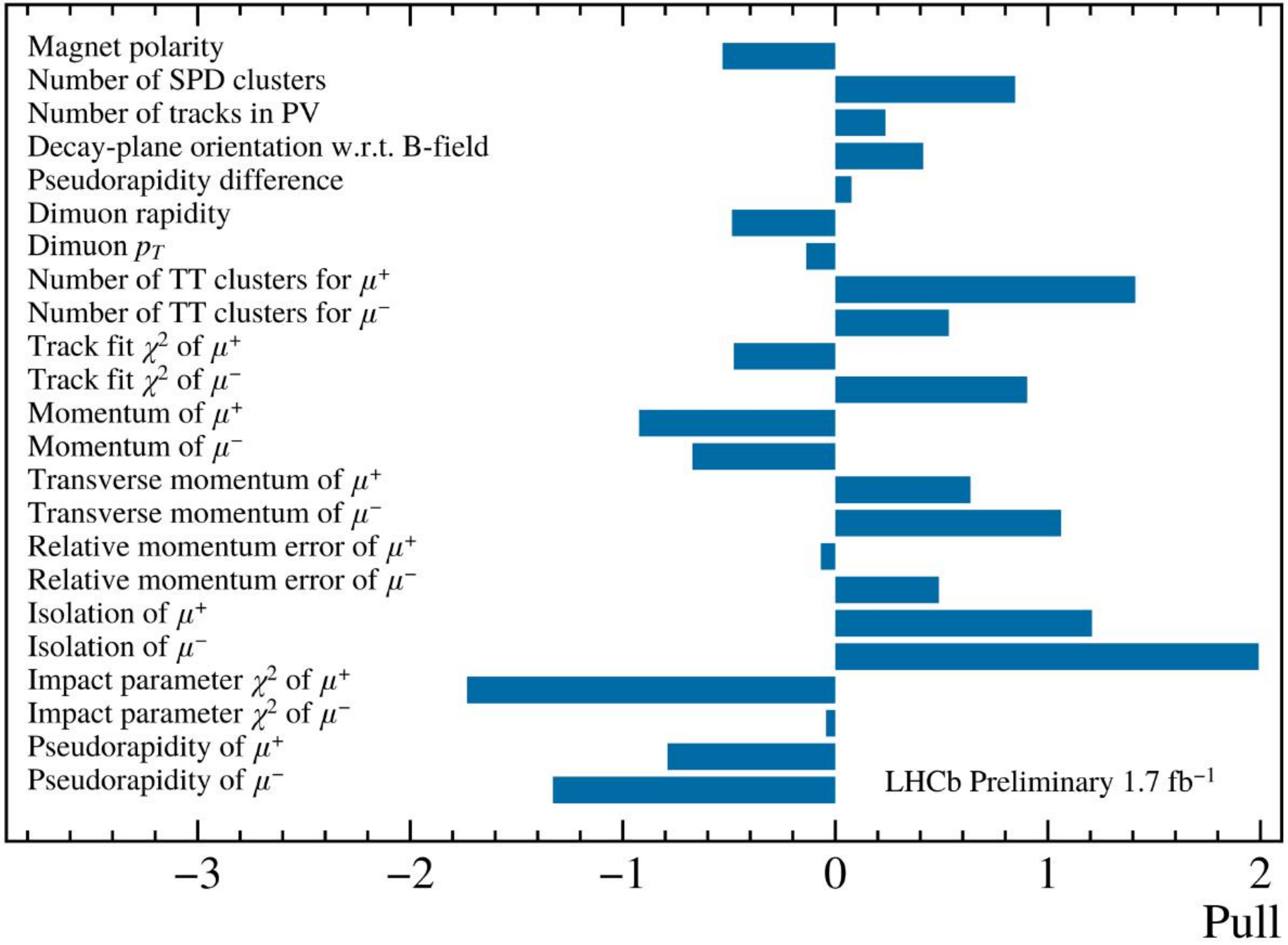
Momentum calibration	4.1
Signal QED corrections	0.8
Parton distribution functions	0.7
Detection Efficiency	0.1
Statistical uncertainty	8.5
Total	**9.5**

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

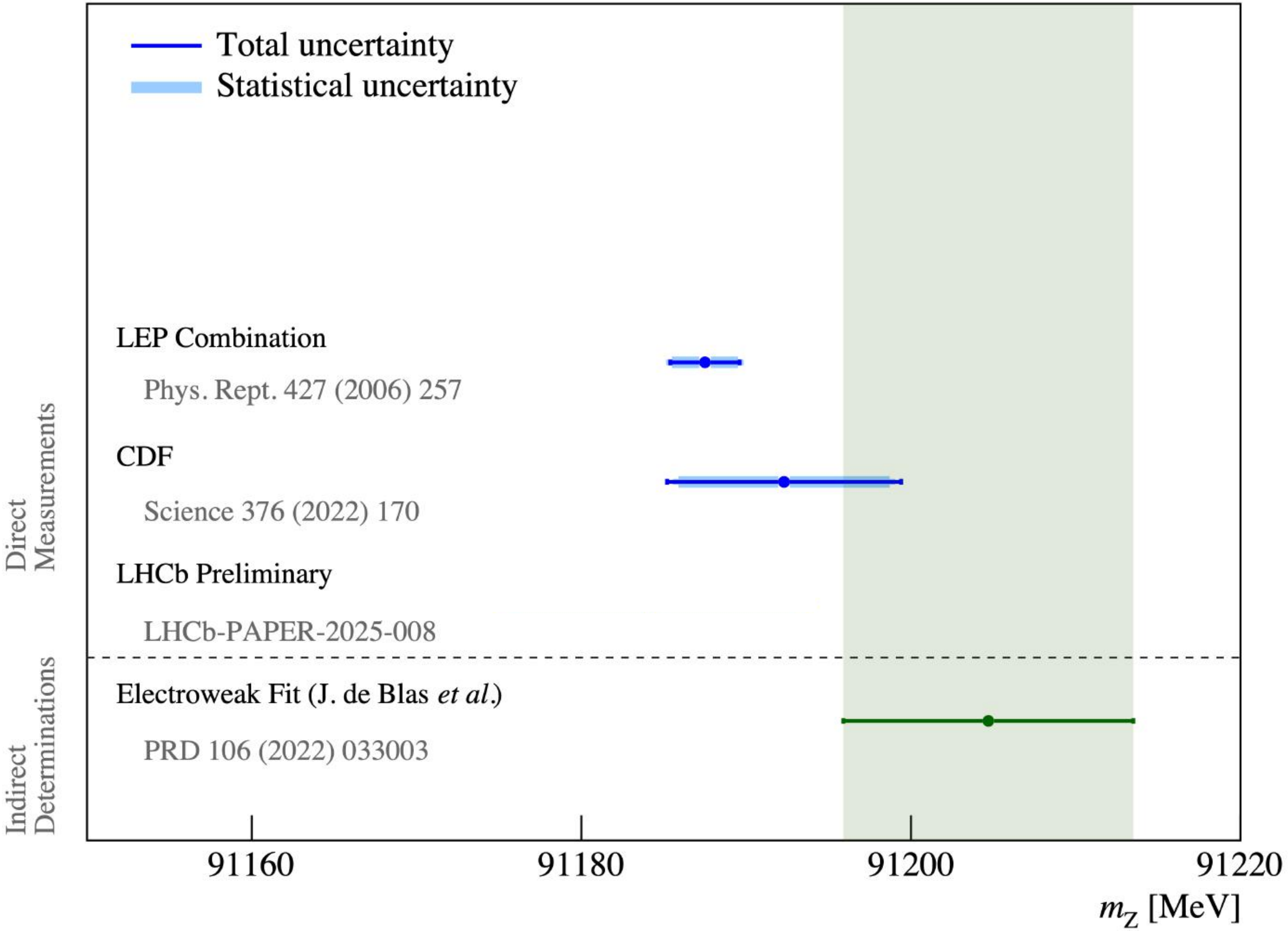
Consistency of sub samples



Other checks

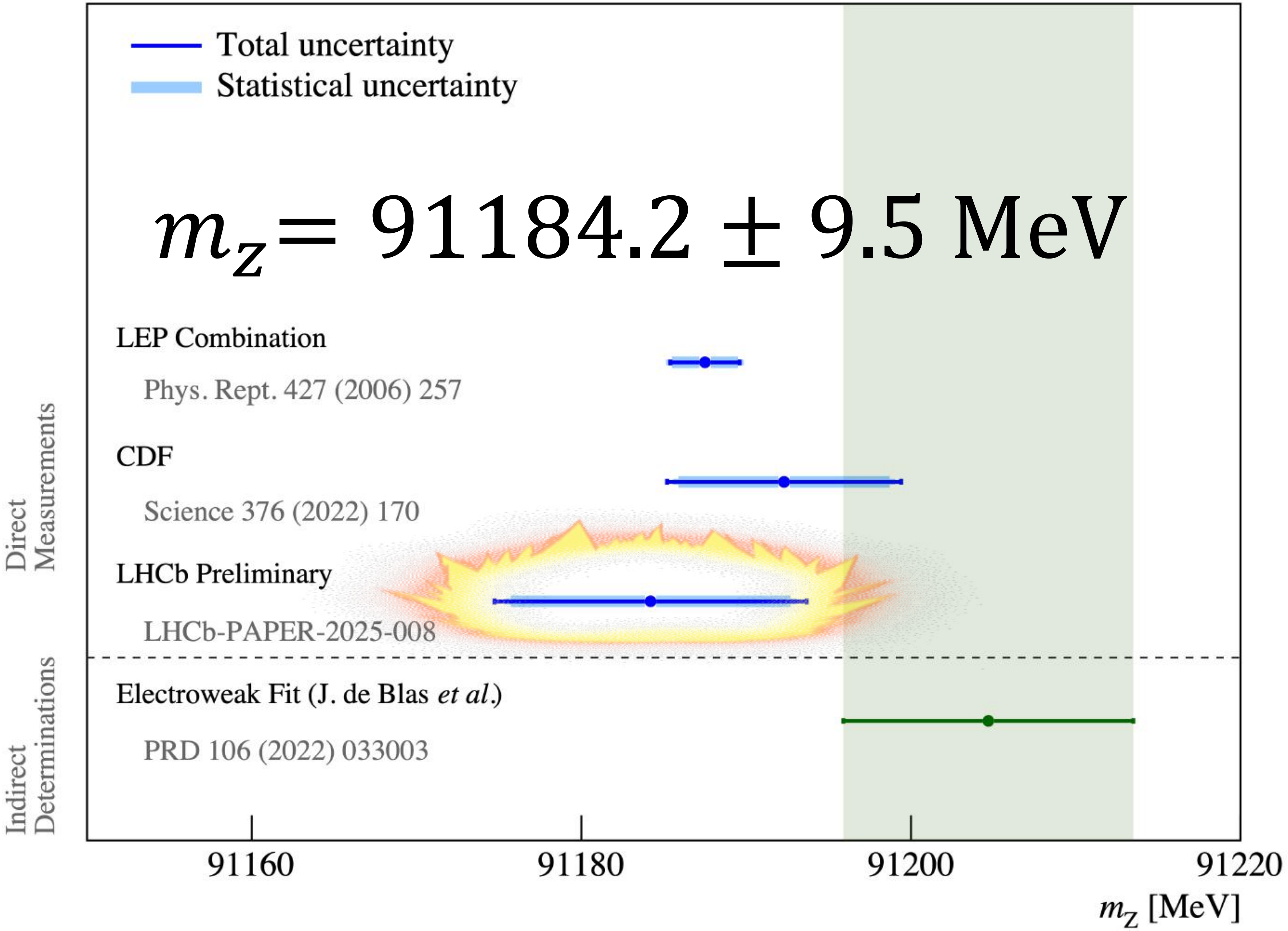
- Varying the analysis in various ways yields < 1 MeV changes
  - Varying number of bins used in the various fitters
  - Varying the ranges used in various fitters
  - …
- Closure checks all pass
  - Both momentum scale corrections
  - Momentum smearing with all samples
  - Final Z mass fit

Result



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

Result


Total uncertainty
Statistical uncertainty
$m_z = 91184.2 \pm 9.5$ MeV
LEP Combination
Phys. Rept. 427 (2006) 257
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91160
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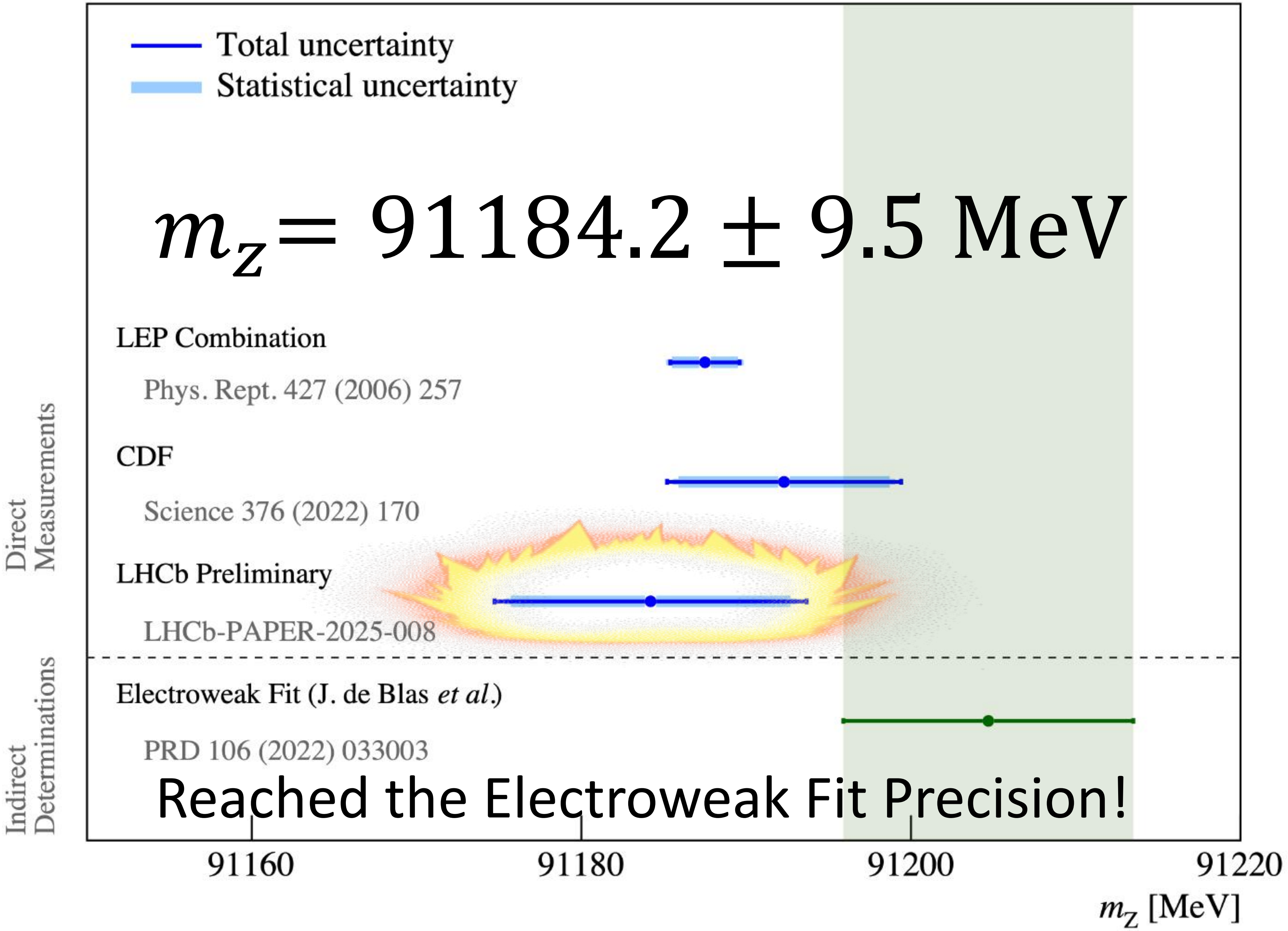
Result



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Phys. Rept. 427 (2006) 257
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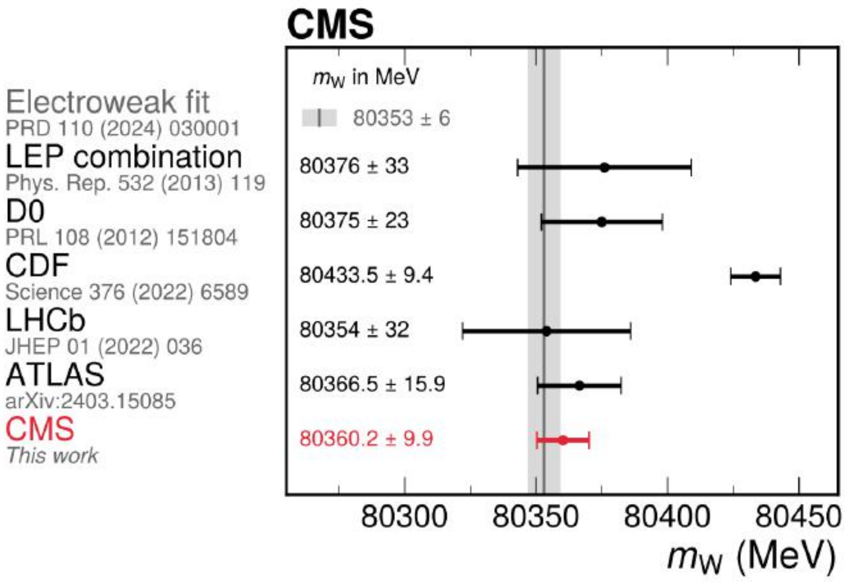
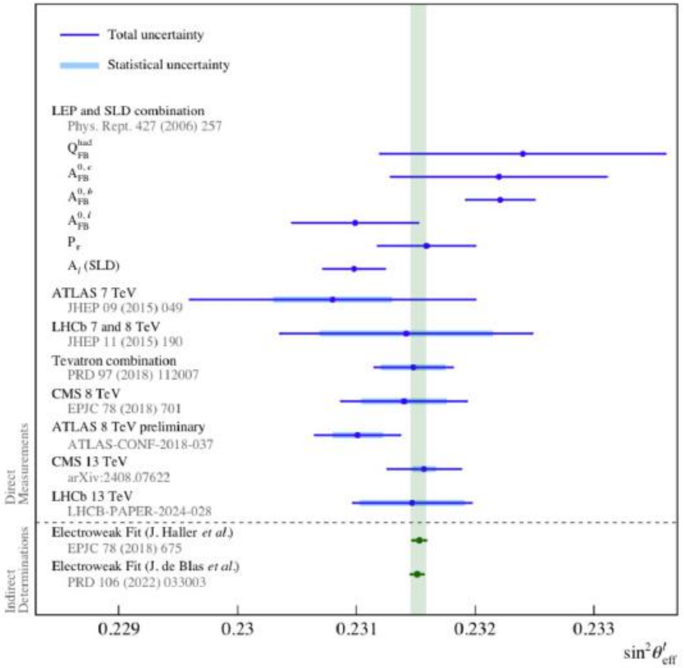
Science 376 (2022) 170
LHCb Preliminary
LHCb-PAPER-2025-008
Direct Measurements
Electroweak Fit (J. de Blas *et al.*)
PRD 106 (2022) 033003
Indirect Determinations
Reached the Electroweak Fit Precision!
91160
91180
91200
91220
m_Z [MeV]

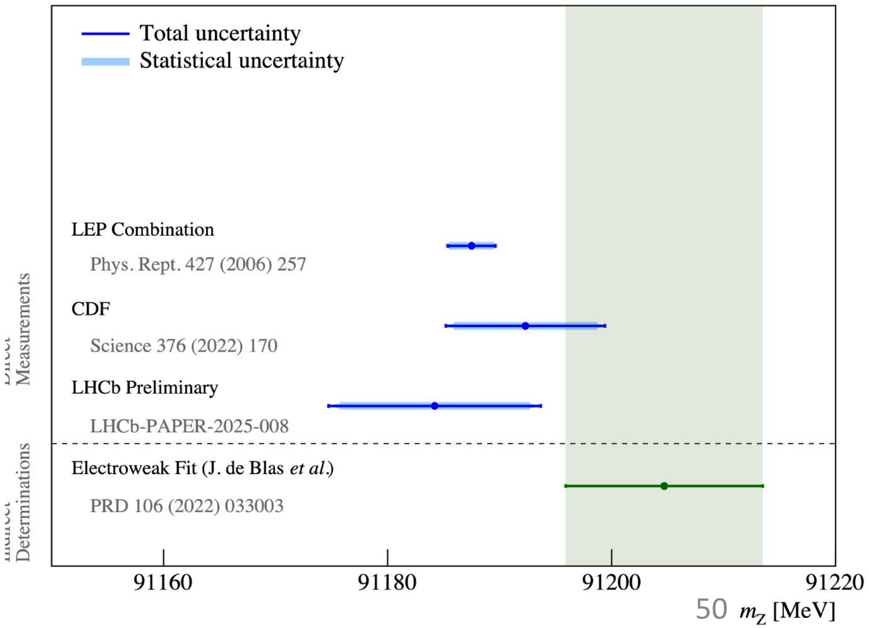
Future prospects

- **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!







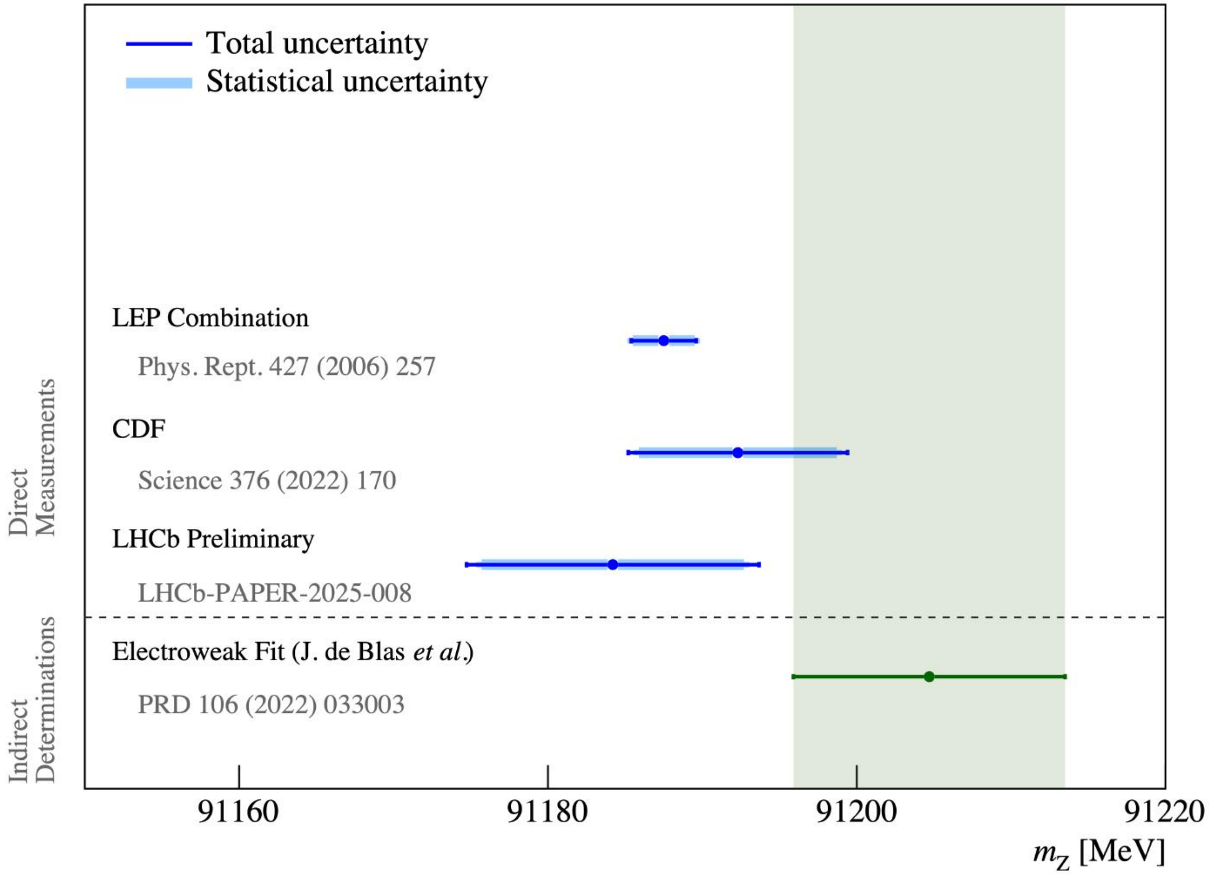
Summary

- m_z measurable at ***LHCb***!

  $m_z = 91184.2 \pm 9.5$ MeV

- Results consistent with SM and previous measurements

- First dedicated measurement at the LHC



Backup

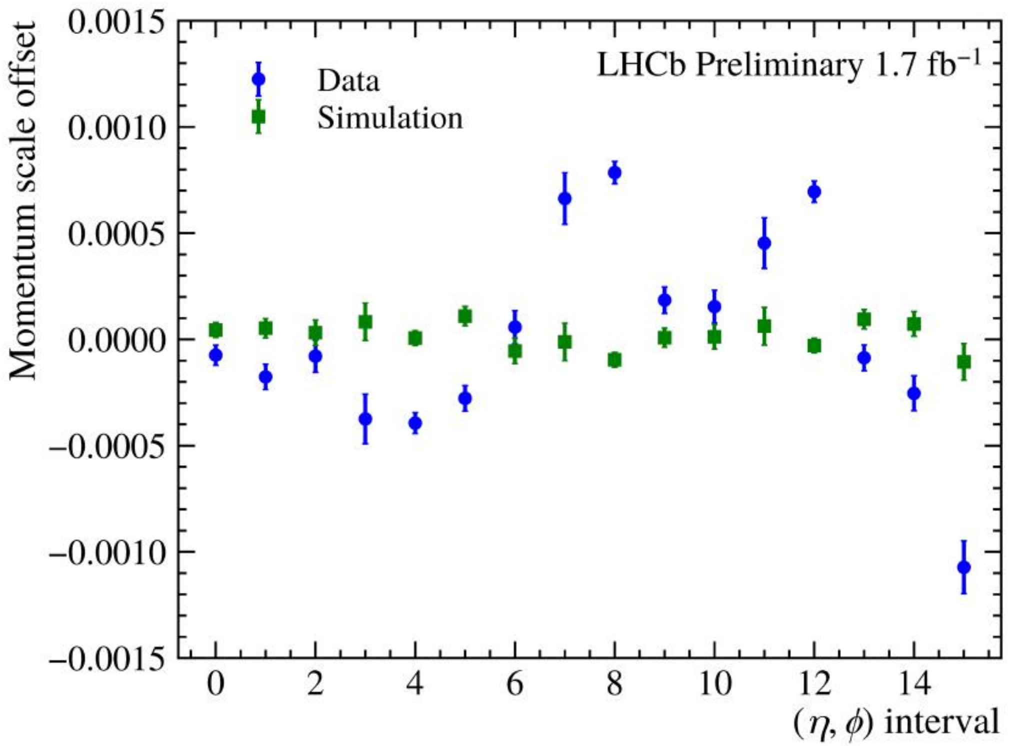
LHCb EW Program

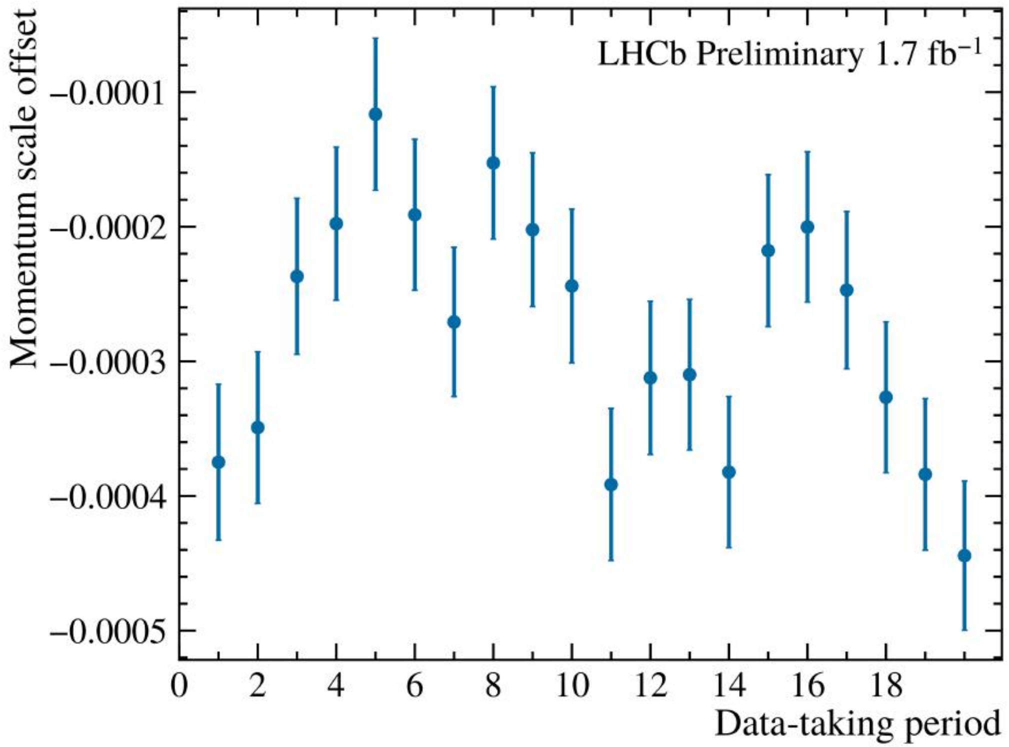
Analysis	Reference
$W \to \mu\nu$ @ 8 TeV	JHEP 01 (2016) 155
$Z \to \mu\mu$ @ 13 TeV	JHEP 07 (2022) 026
W mass	JHEP 01 (2022) 036
Leptonic weak mixing angle	JHEP 12 (2024) 026
…	…

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

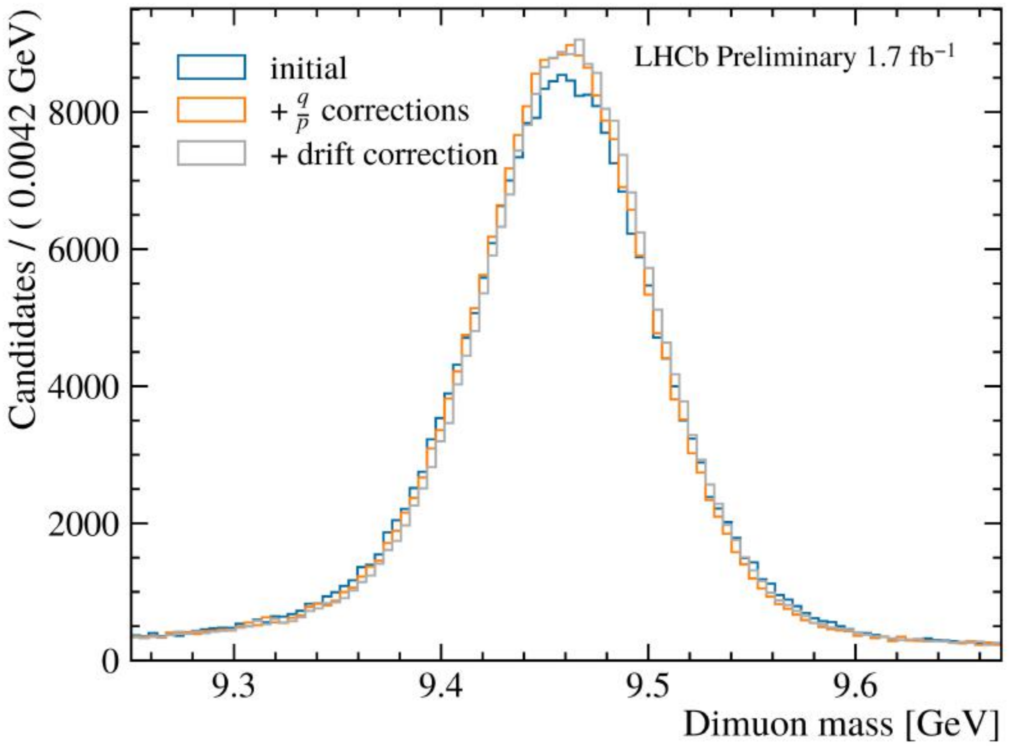
Alternatively, click here!

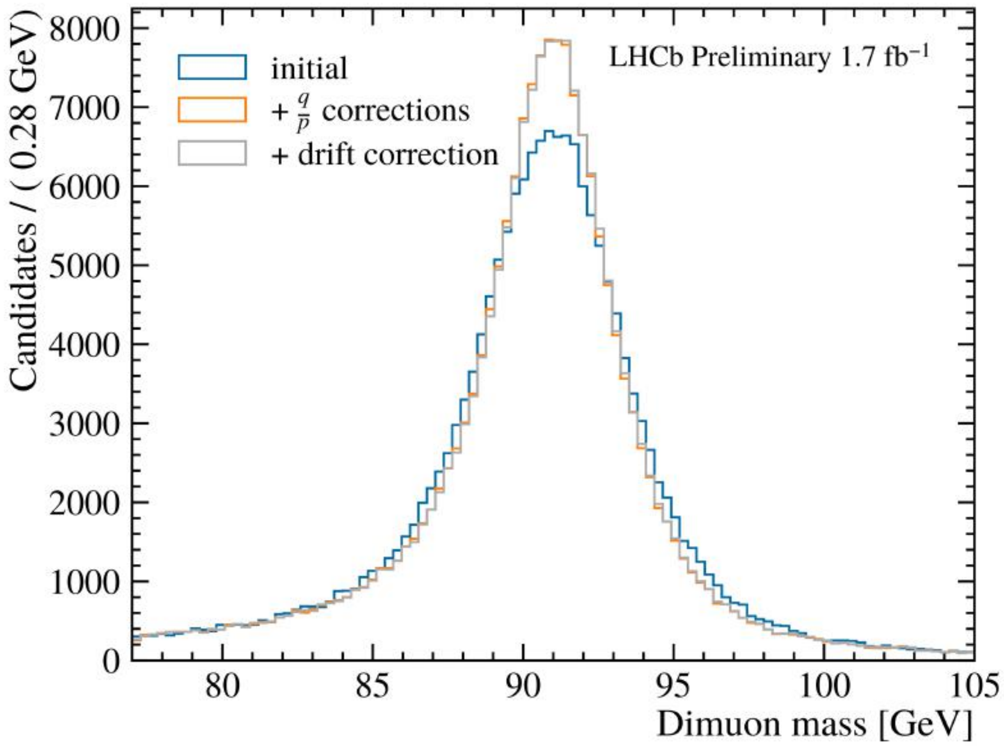
Supplementary plots



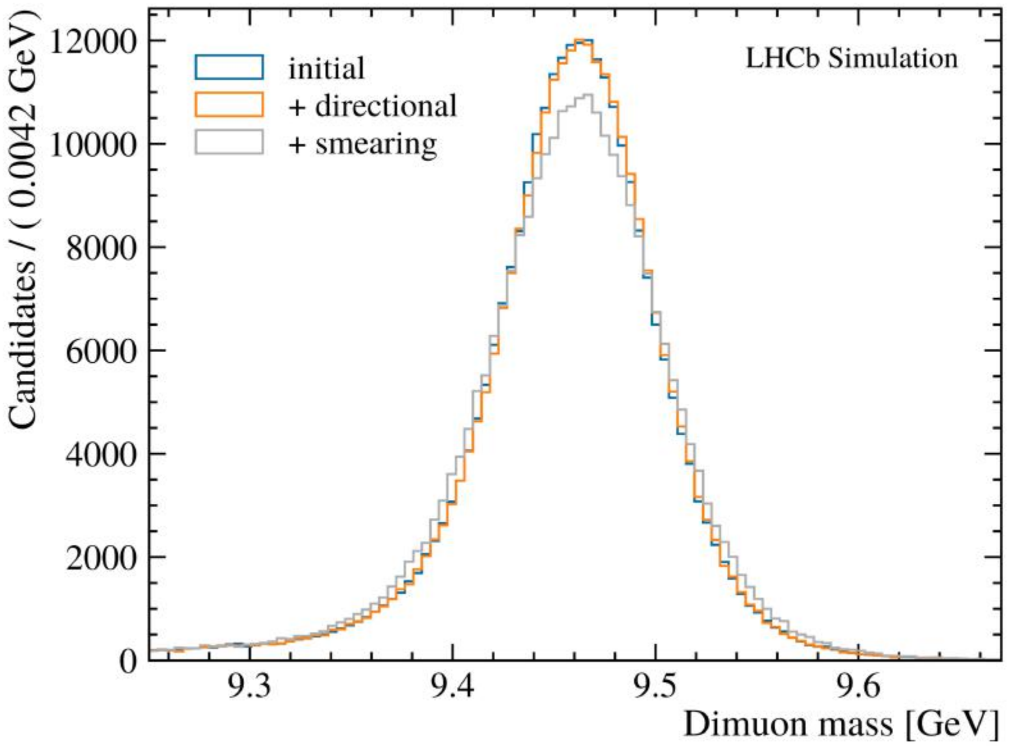


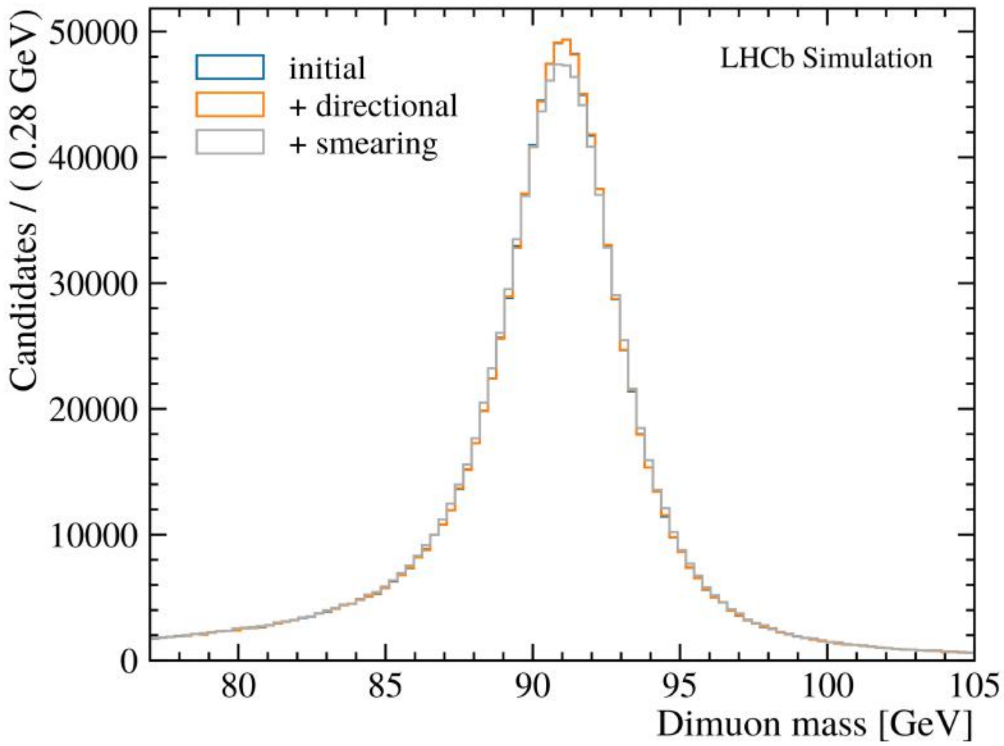
Supplementary plots



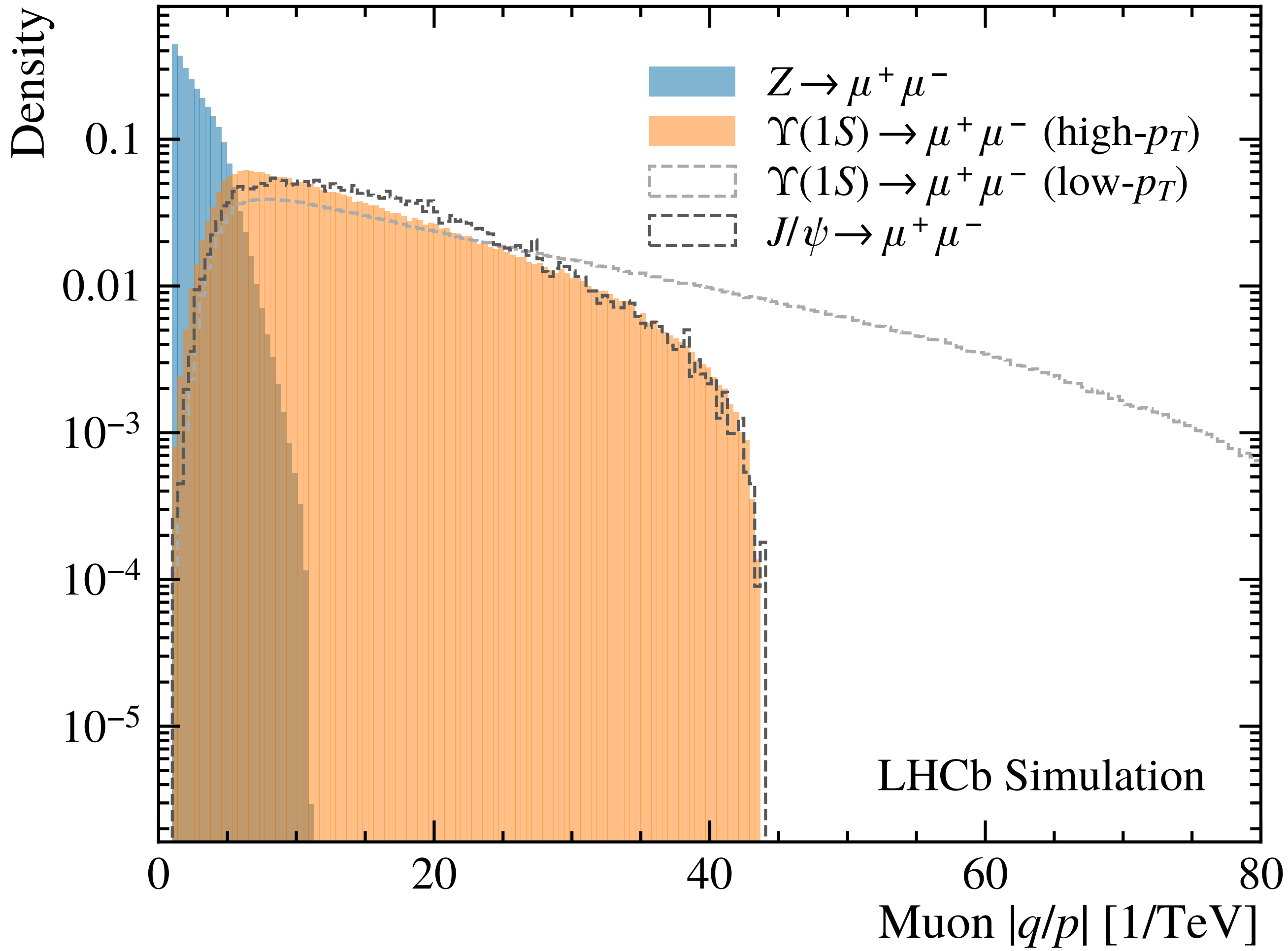


Supplementary plots





Supplementary plots



Magnetic Field Map

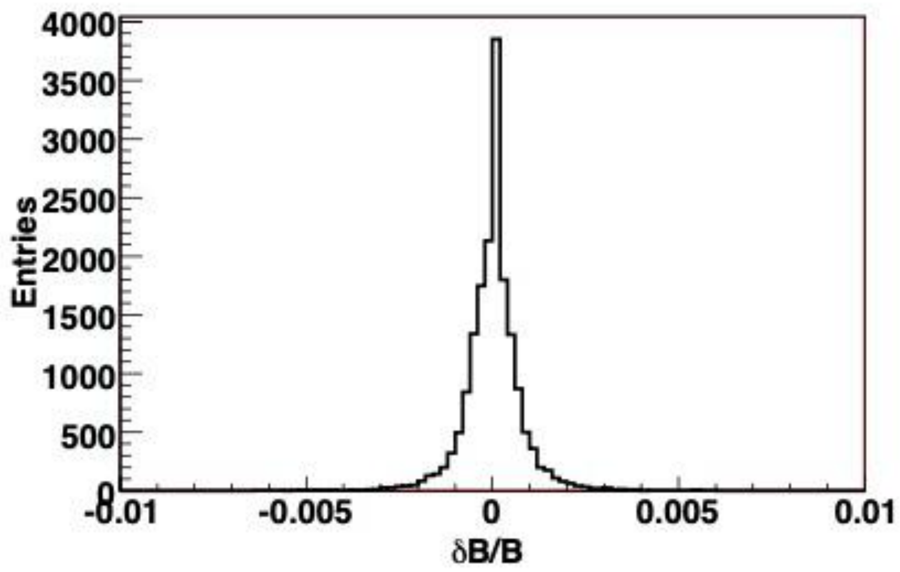


Figure 4.2: Relative difference between the measurements of B using different Hall probes at the same position in the magnet. The resolution is completely dominated by the precision of the calibration of the Hall probes.