# Z Mass Measurement at 13 TeV with LHCb

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With thanks to the rest of the team working on EW-Analyses

10 April 2024 / IOP Joint APP, HEPP, and NP Conference

# Introduction and Motivation

- $m_z$ an important fundamental parameter in SM
- At tree level:

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

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

- ***LHCb*** has measured $m_W$, and $\sin^2\theta_W$..., can we measure $m_Z$?

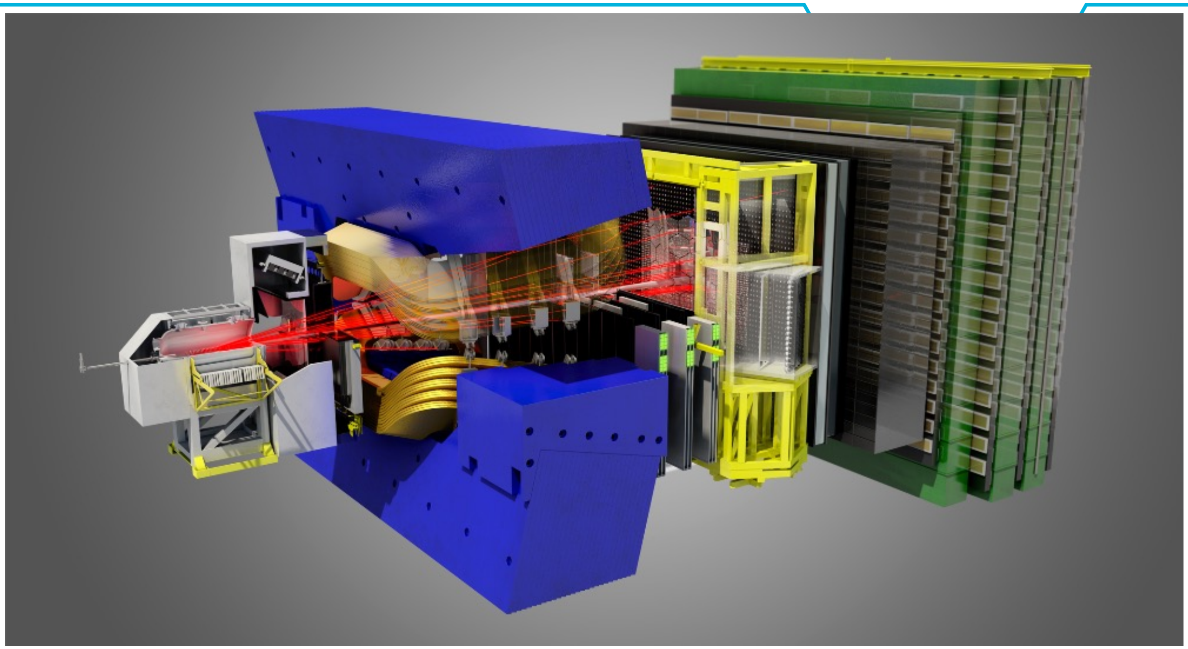
# Current Landscape as seen in PDG

| VALUE (GeV) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **91.1876 ± 0.0021** **OUR FIT** | | | | | |
| 91.1852 ±0.0030 | 4.57M | [1] ABBIENDI | 2001A | OPAL | $E^{ee}_{cm}$= 88 — 94 GeV |
| 91.1863 ±0.0028 | 4.08M | [2] ABREU | 2000F | DLPH | $E^{ee}_{cm}$= 88 — 94 GeV |
| 91.1898 ±0.0031 | 3.96M | [3] ACCIARRI | 2000C | L3 | $E^{ee}_{cm}$= 88 — 94 GeV |
| 91.1885 ±0.0031 | 4.57M | [4] BARATE | 2000C | ALEP | $E^{ee}_{cm}$= 88 — 94 GeV |
| • • We do not use the following data for averages, fits, limits, etc. • • | | | | | |
| 91.084 ±0.107 | | [5] ANDREEV | 2018A | H1 | $e^{\pm}p$ |
| 91.1872 ±0.0033 | | [6] ABBIENDI | 2004G | OPAL | $E^{ee}_{cm}$= LEP1 + 130 — 209 GeV |
| 91.272 ±0.032 ±0.033 | | [7] ACHARD | 2004C | L3 | $E^{ee}_{cm}$= 183 — 209 GeV |
| 91.1875 ±0.0039 | 3.97M | [8] ACCIARRI | 2000Q | L3 | $E^{ee}_{cm}$= LEP1 + 130 — 189 GeV |
| 91.151 ±0.008 | | [9] MIYABAYASHI | 1995 | TOPZ | $E^{ee}_{cm}$= 57.8 GeV |
| 91.74 ±0.28 ±0.93 | 156 | [10] ALITTI | 1992B | UA2 | $E^{p\bar{p}}_{cm}$= 630 GeV |
| 90.9 ±0.3 ±0.2 | 188 | [11] ABE | 1989C | CDF | $E^{p\bar{p}}_{cm}$= 1.8 TeV |
| 91.14 ±0.12 | 480 | [12] ABRAMS | 1989B | MRK2 | $E^{ee}_{cm}$= 89 — 93 GeV |
| 93.1 ±1.0 ±3.0 | 24 | [13] ALBAJAR | 1989 | UA1 | $E^{p\bar{p}}_{cm}$= 546,630 GeV |

Potentially first measurement in pp collider!

PDGLive

# $m_Z$ at $LHCb$



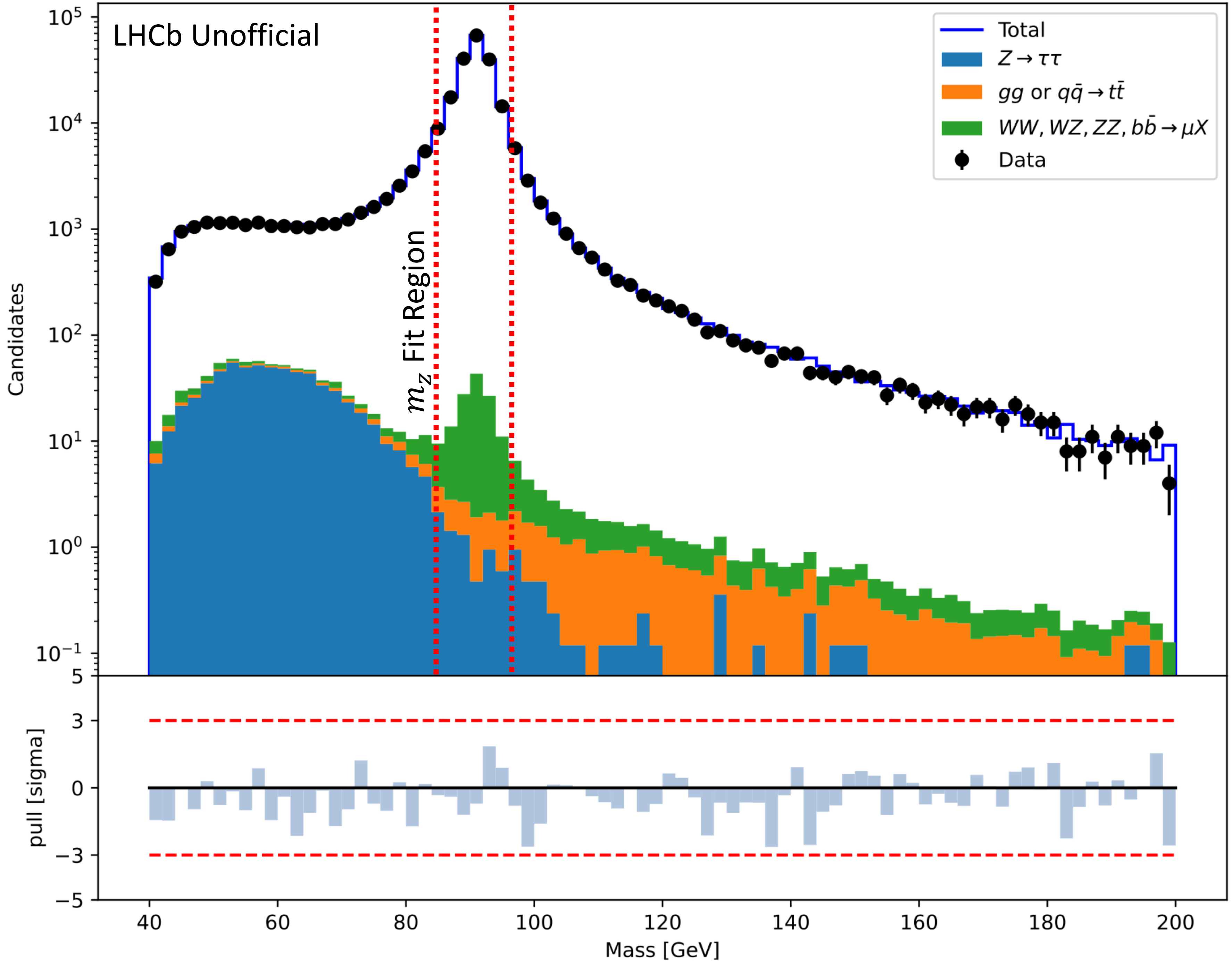
- Most sensitive with $Z \rightarrow \mu\mu$
- 2016 dataset sufficient to study the feasibility of the analysis
  - Statistical precision of 7 MeV
  - Run2+3 can then challenge LEP result
- How low can we get the systematics?

# Dataset and selections

- Selection of:
  - $Z \to \mu\mu$
  - Muon $\eta$ : $2 < \eta < 4.5$
  - Muon $p_T > 20$ GeV

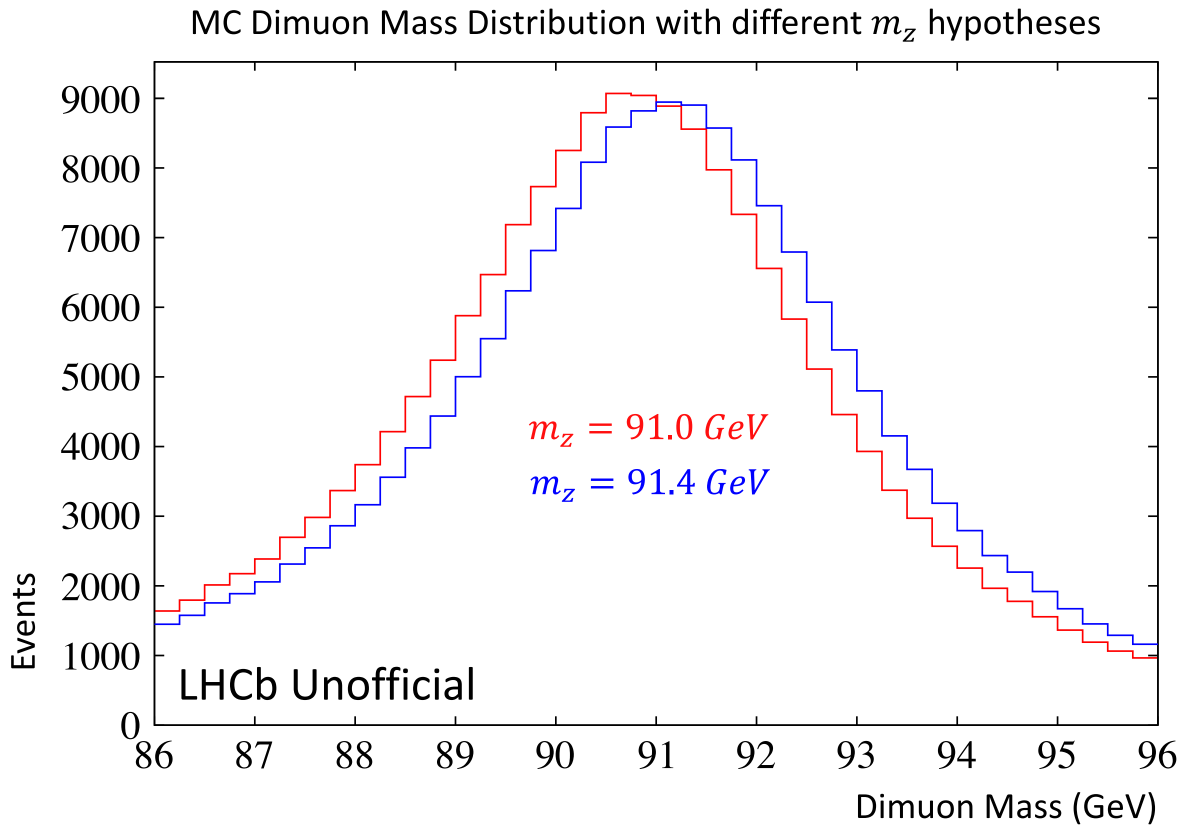
  - Typical trigger requirements
  - Loose track and Impact Parameter requirements
- ~300 k data events after selections in 2016

# Backgrounds



# Measurement Strategy

- Fit compares full simulation with the data
- $m_z$ hypothesis varied by reweighting full simulation with templates
- Using a special version of POWHEG which provides predictions in QED at NLO
- Using a scheme where $m_z$ is an input
- Blinded by a random offset



# Theoretical Uncertainties

- Final State Radiation
  - Default description uses Pythia
  - Can be switched to Herwig & Photos
- Parton Distribution Functions
  - Using NNPDF default
  - Can be switched to MSHT20 or CT18

| Source | Size [MeV] |
|---|---|
| Z QED Final State Radiation | 3.2 |
| Parton Distribution Functions | 1.7 |

Other sources under consideration but expected to be small

# Data and Simulation Corrections

- Data Corrections
  - Run-number dependence in momentum scale
  - Curvature bias with a novel method* [2311.04670]
- Simulation Corrections
  - Muon Trigger/ID/Tracking Eff.
  - Isolation Efficiencies

| Source | Size [MeV] |
|---|---|
| Curvature Bias | 0.8 |
| ID, Trigger, Tracking | 0.1 |
| Isolation Efficiencies (WIP) | <0.1 |

*Pseudomass method, see backup ☺

# Momentum Smearing

Momentum scale offset

Curvature Smearing

$$p_\mu \rightarrow (1+\alpha)(1+\mathcal{R}_1\sigma_1)(1+p\mathcal{R}_2\sigma_2)(p+\beta)$$

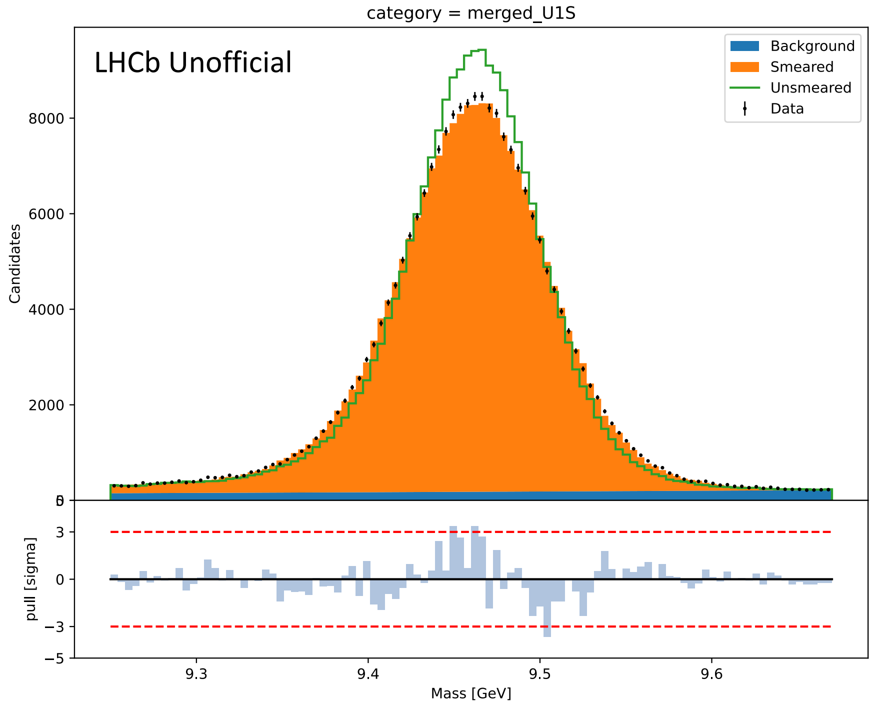
Momentum Smearing

"Energy Offset"

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

# Momentum Smearing

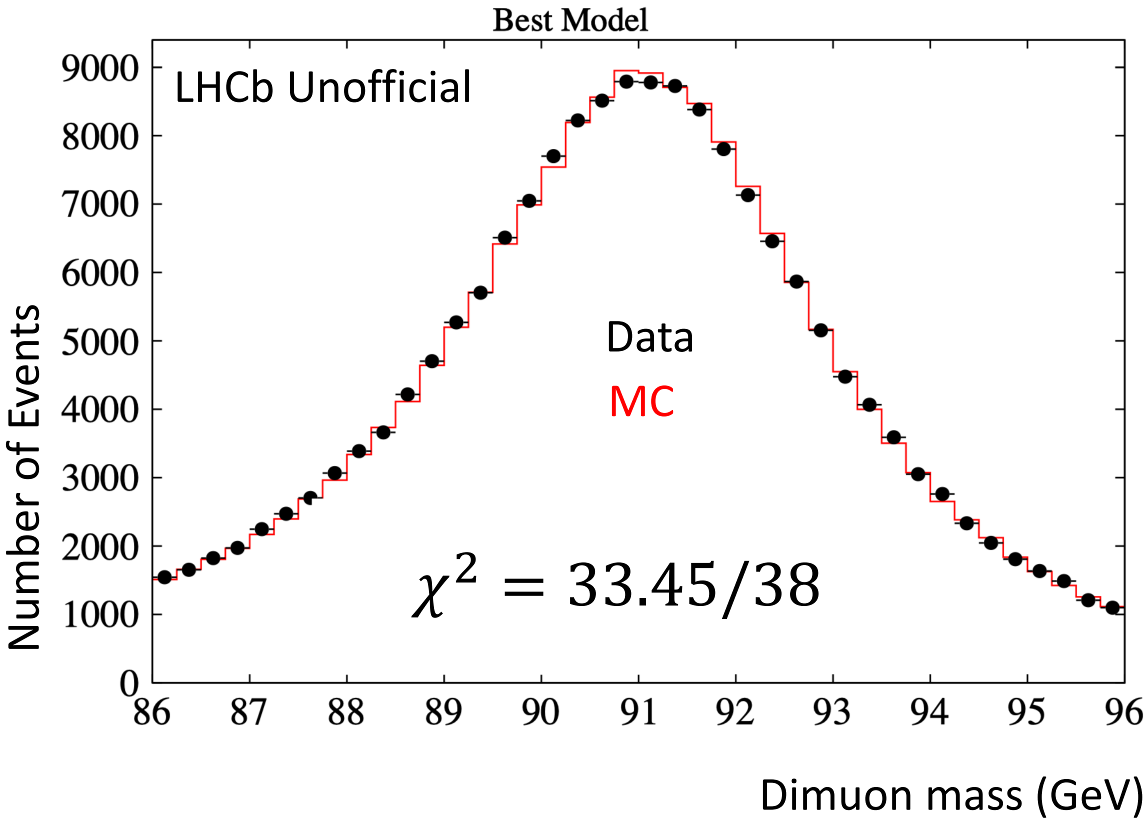
- Simultaneous fit using $J/\psi, \Upsilon(1S)$
- No $Z$!
- Fix Energy Offset (too highly correlated wrt others)
  - Vary by fixed amounts to assess syst.




| Parameter | Value | Error |
|---|---|---|
| Momentum Bias | -0.05 | 0.01 |
| Momentum Smear eta 0 | 2.66 | 0.04 |
| Momentum Smear eta 1 | 2.15 | 0.06 |
| Curvature Smear Flat eta 0 | 0.46 | 0.09 |
| Curvature Smear Flat eta 1 | 1.64 | 0.02 |
| Energy Offset (fixed) | 0 | 0 |

- Challenges:
  - Energy offset needs to be better understood
  - Fit unstable at larger number of bins

# Results




| Source | Size [MeV] |
|---|---|
| **Theory Uncertainty total** | **3.6** |
| Z QED Final State Radiation | 3.2 |
| Parton Distribution Functions | 1.7 |
| **Experimental total** | **8.1** |
| Energy Offset | 5.5 |
| $\Upsilon(1S)$ Mass | 3.8 |
| Quarkonia FSR | 2.3 |
| Curvature Biases | 0.8 |
| Momentum Smearing | 1.4 |
| ID, Trigger, Tracking | 0.1 |
| $J/\psi$ Mass | < 0.1 |
| Backgrounds (WIP) | < 0.1 |
| Isolation (WIP) | < 0.1 |
| **Statistical total** | **7.4** |
| **Total** | **11.6** |

Table still incomplete, will update as more studies progress

# Summary

- $m_z$ measurable at $\boldsymbol{LHCb}$!
- 8 MeV systematic achievable with 2016
- Try to finalise as a proof of principle measurement
- Need to
  - Improve momentum calibration understanding
  - Cross checks
  - …

| Source | Size [MeV] |
|---|---|
| **Theory Uncertainty total** | **3.6** |
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| ID, Trigger, Tracking | 0.1 |
| $J/\psi$ Mass | < 0.1 |
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| **Statistical total** | **7.4** |
| **Total** | **11.6** |

# Backups

Using old results, take numbers/plots with a grain of salt

# Curvature Bias With Pseudomass

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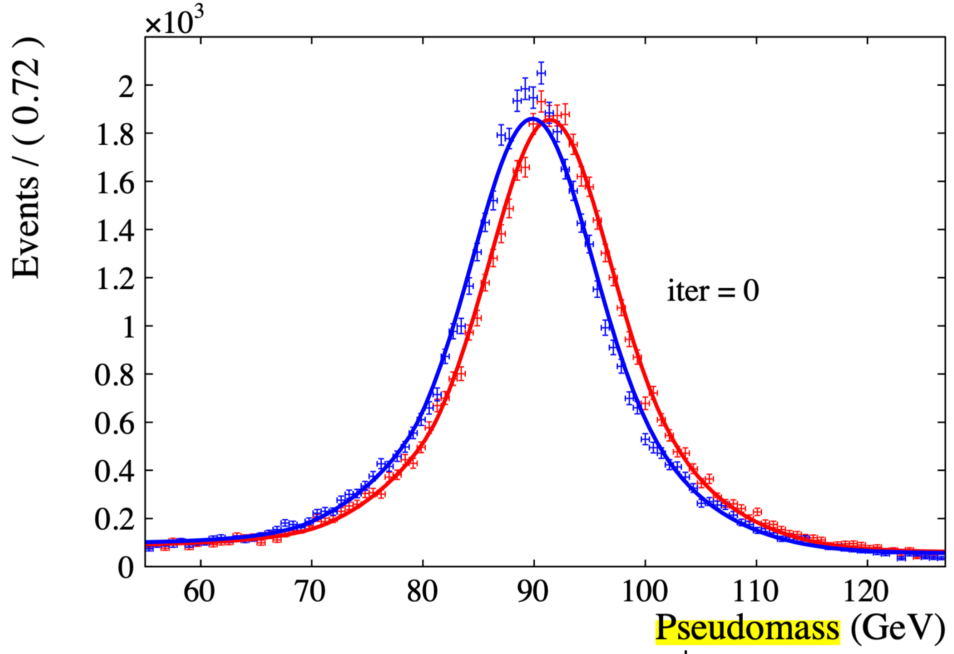
- Applied to data/mc to correct curvature bias

- Use Pseudomass method like in other EW analyses

- Performed by fitting pseudomass distribution of $\mu^+$ and $\mu^-$




Pseudomass distribution for $\mu^+$ and $\mu^-$

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

# Cross Checks

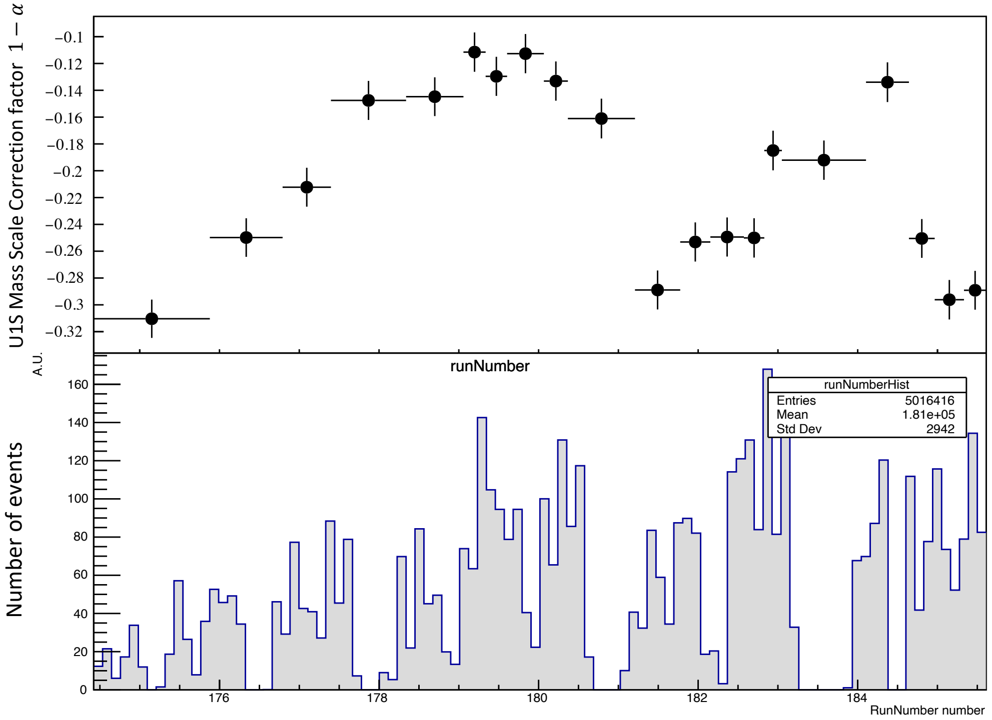
- Brief look, still plenty to check
- Check against magnet polarity and $\phi_d$
  - $\phi_d$ = angle between normal of $Z \rightarrow \mu\mu$ decay plane and the magnetic field

| Name | Central value | Stat. unc. | $\chi^2$ | Variation |
|---|---|---|---|---|
| up | 91288.20 | 10.56 | 32.19 | 0.00 |
| down | 91291.82 | 10.26 | 40.39 | 3.62 |

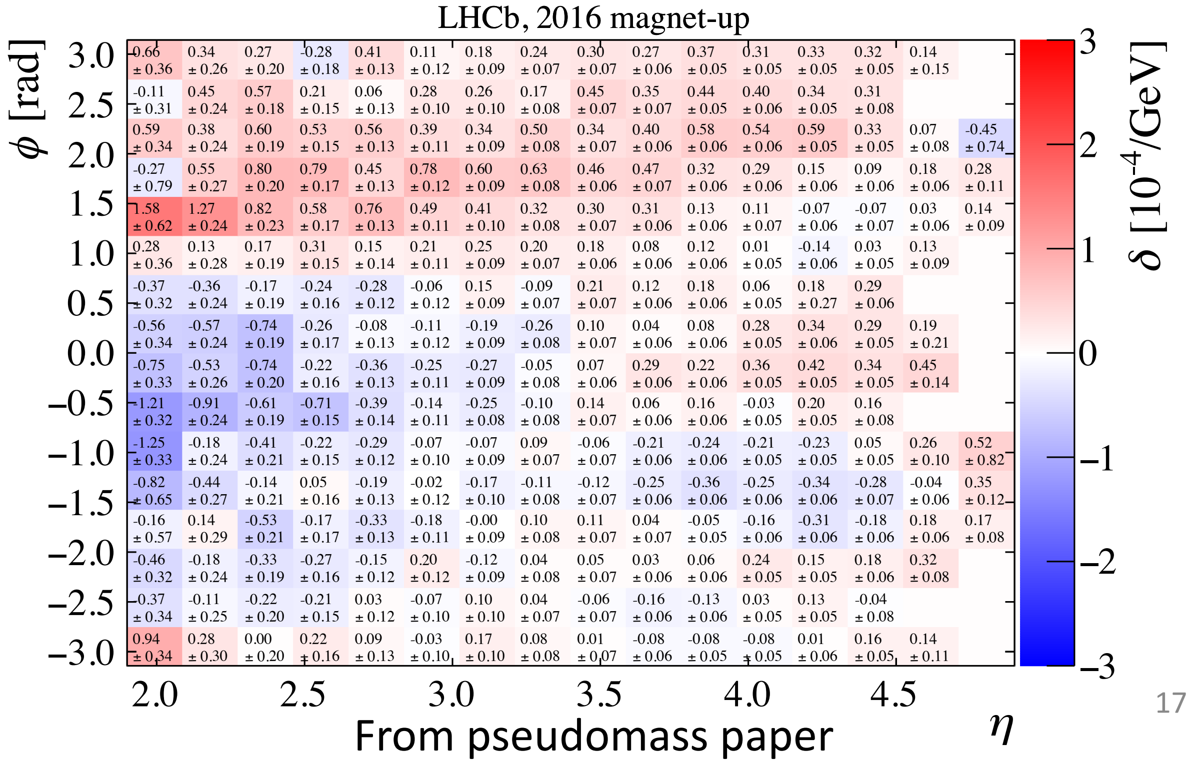
| Name | Central value | Stat. unc. | $\chi^2$ | Variation |
|---|---|---|---|---|
| $\phi_d < \frac{\pi}{2}$ | 91303.18 | 10.39 | 48.09 | 0.00 |
| $\phi_d \geq \frac{\pi}{2}$ | 91276.46 | 10.42 | 45.95 | -26.71 |

# Data Corrections

- Momentum scale corrected downwards by ~ $10^{-4}$, additional run-number dependence at a similar level




- Curvature bias corrected by the *Pseudomass* method
  [arXiv:2311.04670](https://arxiv.org/abs/2311.04670)




From pseudomass paper

# Momentum Scale Theory

- Have N bins in eta/phi $b_i$, with each bin having an associated scaling parameter $\delta_i$. Bin U1S in eta / phi for positive *and* negative muons $b_{i+}b_{j-}$
- Measure dimuon mass $d_{ij}$ and error $\sigma_{d,ij}$ in each $b_{i+}b_{j-}$ bin
- Scaling parameters $\delta_i$ defined by (massless muons)

$$M_s = \sqrt{\delta_i p_i \delta_j p_j (1 - \cos\theta)} = \sqrt{\delta_i \delta_j}\, M_{pdg}$$

- Extract scaling parameters $\delta_i$ by minimizing

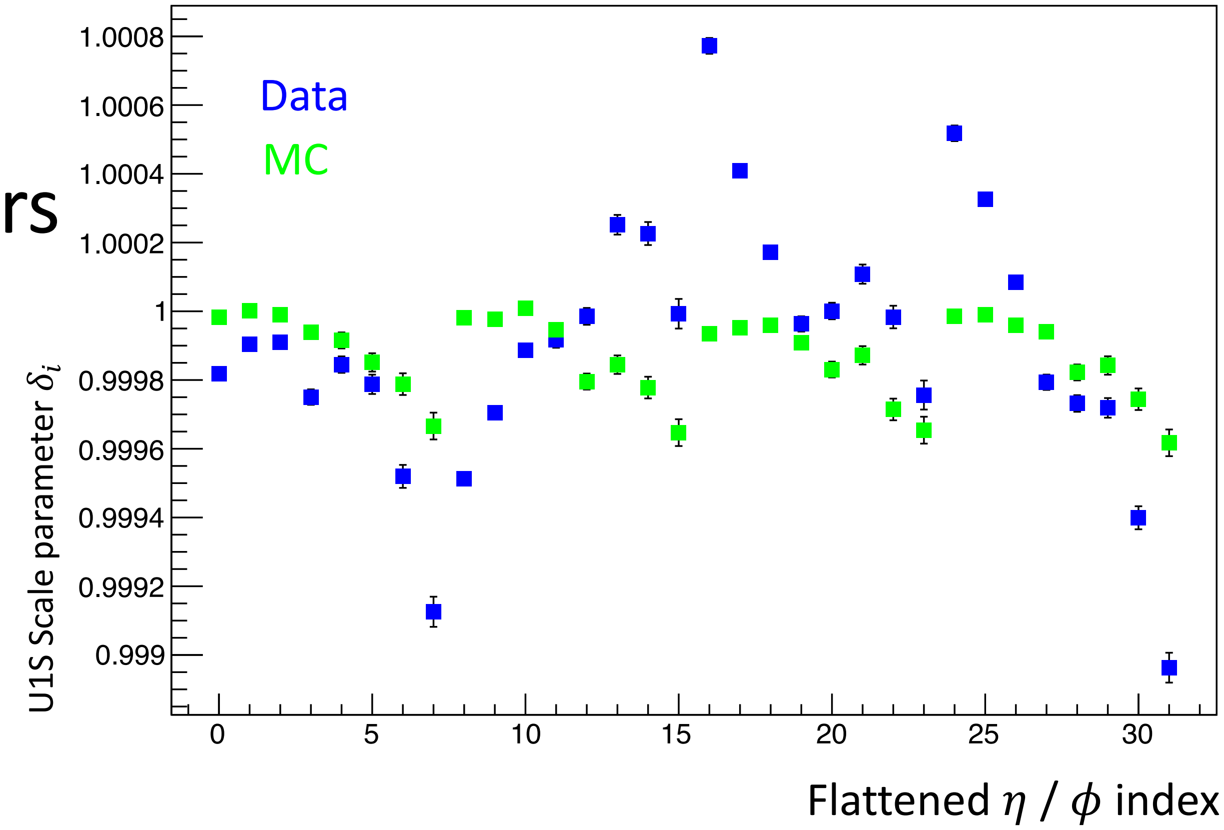
$$\chi^2 = \sum_{i,j \in b} \left( \frac{d_{ij} - \sqrt{\delta_i \delta_j}\, M_{pdg}}{\sigma_{d,ij}} \right)$$

# Momentum Scale

WIP!

- Momentum smearer limited in the amount of $\eta$ bins usable
- Extract $\Upsilon(1S)$ scaling parameters for both data and simulation
- Used to **correct** simulation
- -5 MeV shift on $m_Z$

$$\chi^2 = \sum_{i,j \in b} \left( \frac{d_{ij} - \sqrt{\delta_i \delta_j}\, M_{pdg}}{\sigma_{d,ij}} \right)^2$$



# Selections

```
"nCandidate":"(nCandidate==0)",
"M": "(V_M > 86 && V_M < 96)",
"PT_mum" : "(mum_pt > 20)",
"PT_mup" : "(mup_pt > 20)",
"ETA_mum" : "(mum_eta > 2.0 && mum_eta < 4.5)",
"ETA_mup" : "(mup_eta > 2.0 && mup_eta < 4.5)",
"Psanity": "( mup_P < 2000 && mum_P < 2000 )",
"Trigger": "((mup_L0MuonEWTOS && mup_Hlt1TOS && mup_Hlt2TOS) ||
(mum_L0MuonEWTOS && mum_Hlt1TOS && mum_Hlt2TOS))",
"ISO": "(mup_ISO_PF < 10.0 && mum_ISO_PF < 10.0)",
"IPCHI2": "(mup_IPCHI2 < 100 && mum_IPCHI2 < 100)",
"TRCHI2": "(mup_TRCHI2 < 1.8 && mum_TRCHI2 < 1.8)",
"MomErr":"(mup_RelMomErr < 0.06 && mum_RelMomErr < 0.06)"
```