Probing the Standard Model with Electroweak bosons at LHCb

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Introduction

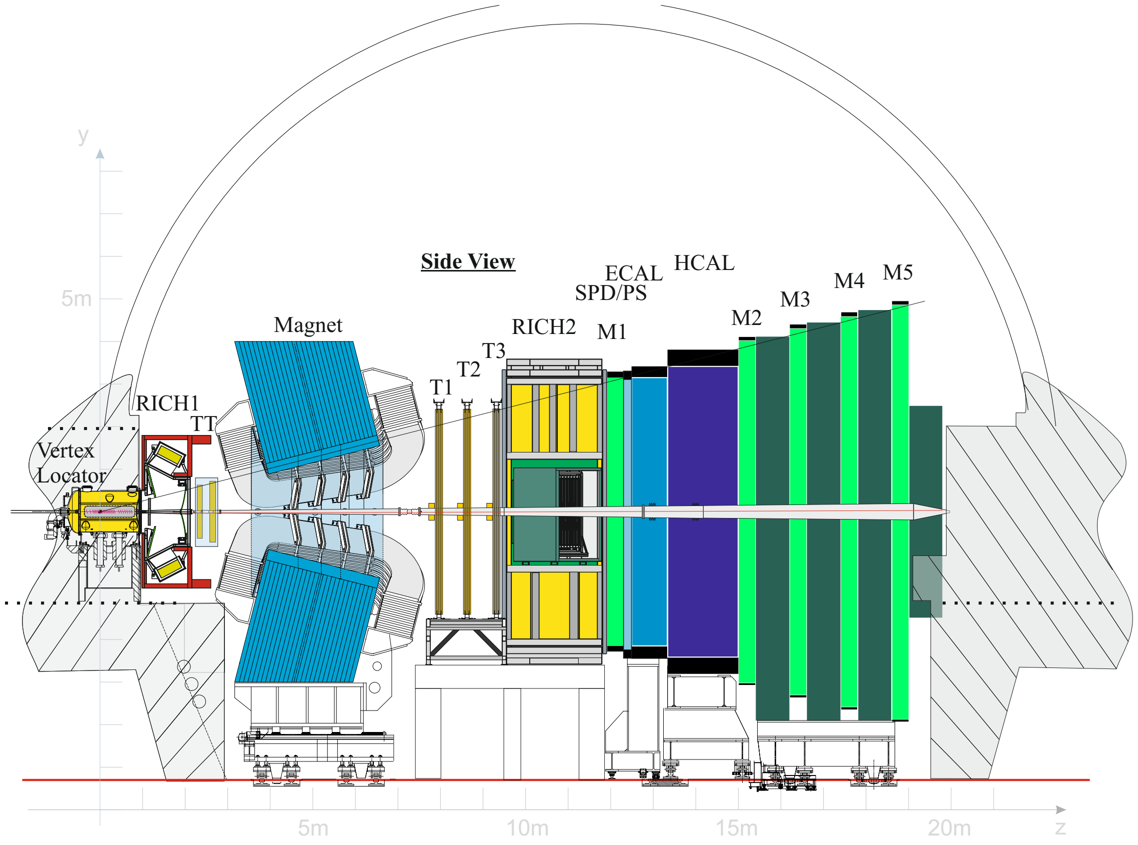
- Precision measurements of electroweak physics provide compelling tests of the Standard Model theory

- LHCb's forward coverage provides unique perspective on such measurements

- Requires a good understanding of QCD, the LHC collision environment and the detector itself

    - Alignment conditions: curvature bias corrections

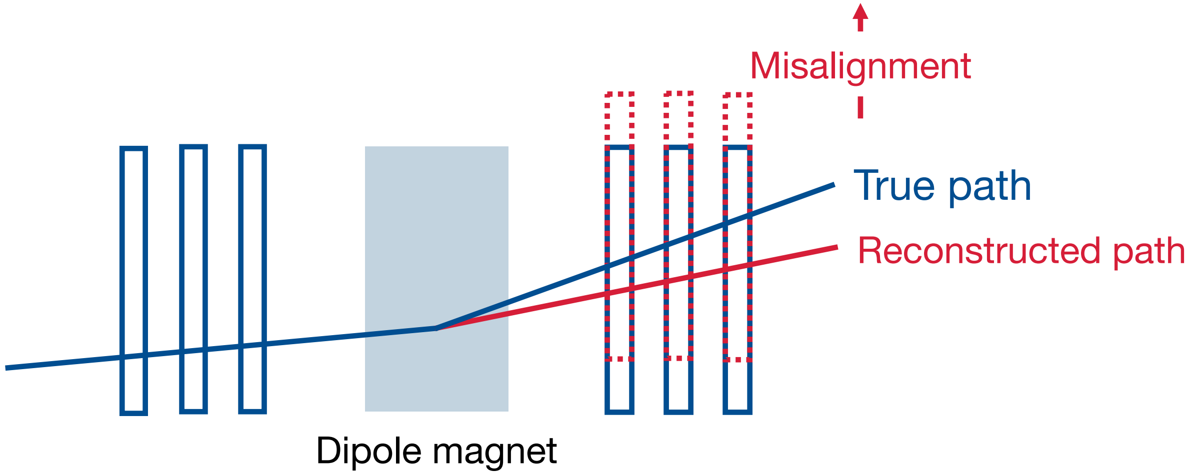
    - QCD & collision environment: $Z + D$ analysis



Curvature-bias corrections

Curvature-bias corrections

JINST 19 (2024) P03010



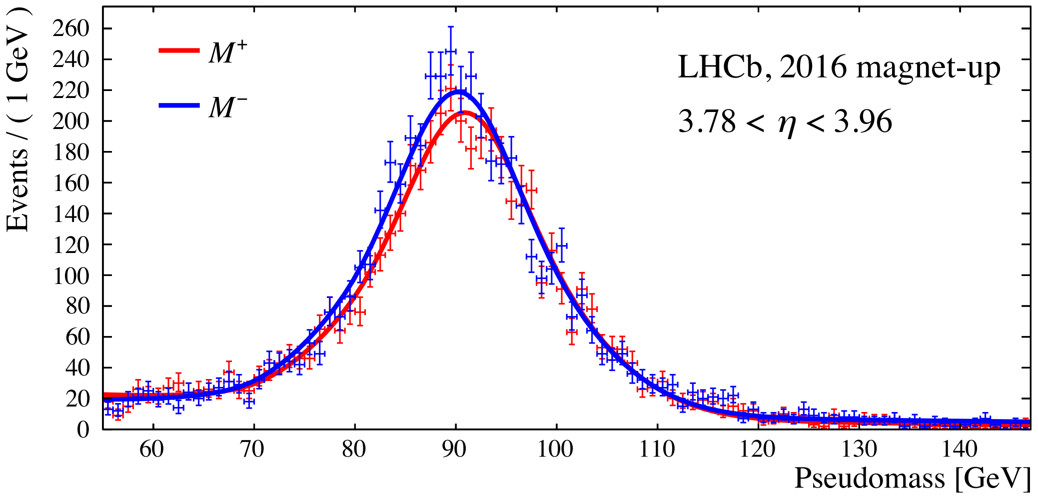
- Good understanding of detector alignment critical for accurately measuring muon p_{T}
  - $5\mu\mathrm{m}$ misalignment can lead to $O(50)$ MeV bias in m_W
- Misalignments cause curvature-biases of the form

$$\frac{q}{p} \to \frac{q}{p'} = \frac{q}{p} + \delta$$

- Such biases are the leading experimental systematic in the measurement of m_W

- Corrected for using the pseudomass ($M^{\pm}$) method with $Z \to \mu^+\mu^-$ decays

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



- δ proportional to asymmetry in peak position of M^+ and M^-

Curvature-bias corrections

- Pseudomass method used in measurement of m_W using 2016 dataset

- Implementation has since been updated:

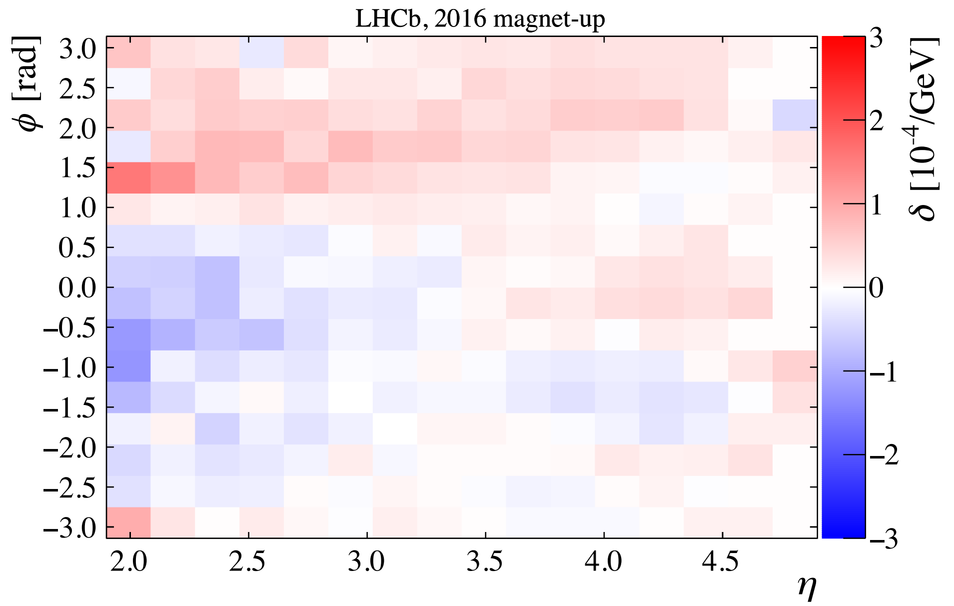
  - Assumption that $\langle p_T^+ \rangle = \langle p_T^- \rangle$ not perfect ⇒ some of asymmetry in peak positions due to vector – axial-vector coupling of Z boson

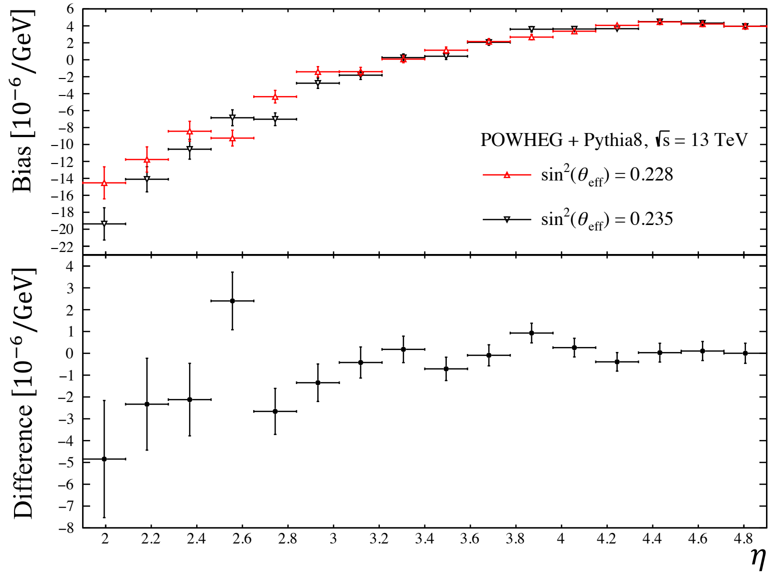
  - To avoid correcting this physics bias out of the data, calculate δ as

$$\delta = \delta_{\mathrm{DATA}} - \delta_{\mathrm{MC}}$$

  - δ_{MC} 1 – 2 orders of magnitude smaller than δ_{DATA}

- Verified that corrections do not depend on physics modelling using generator level simulation with varied values for the weak mixing angle





Curvature-bias corrections

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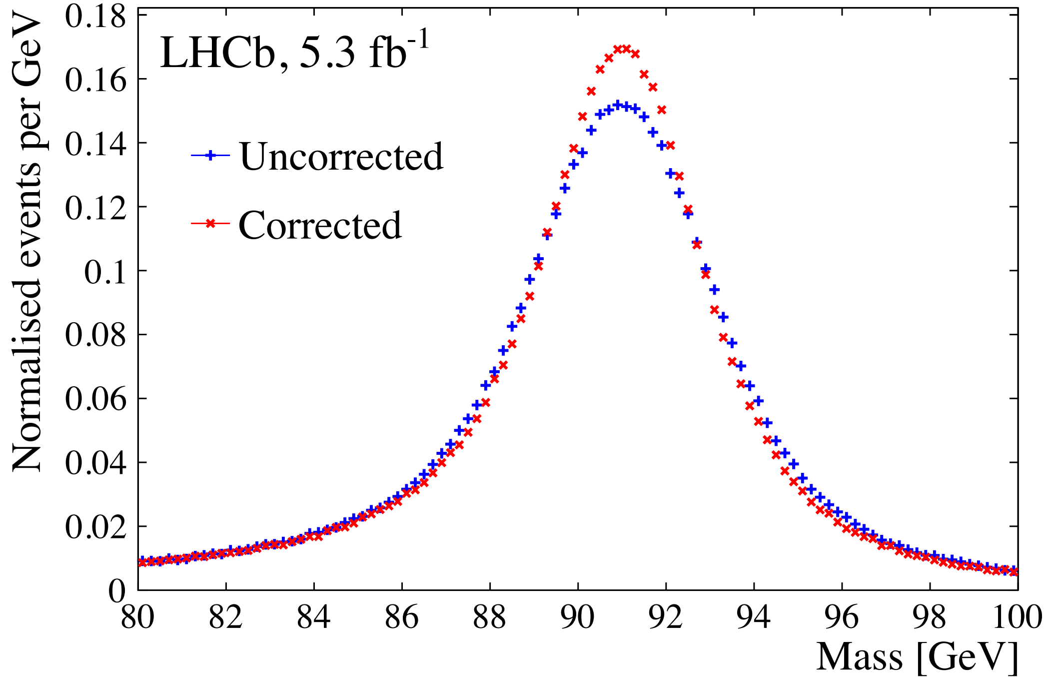
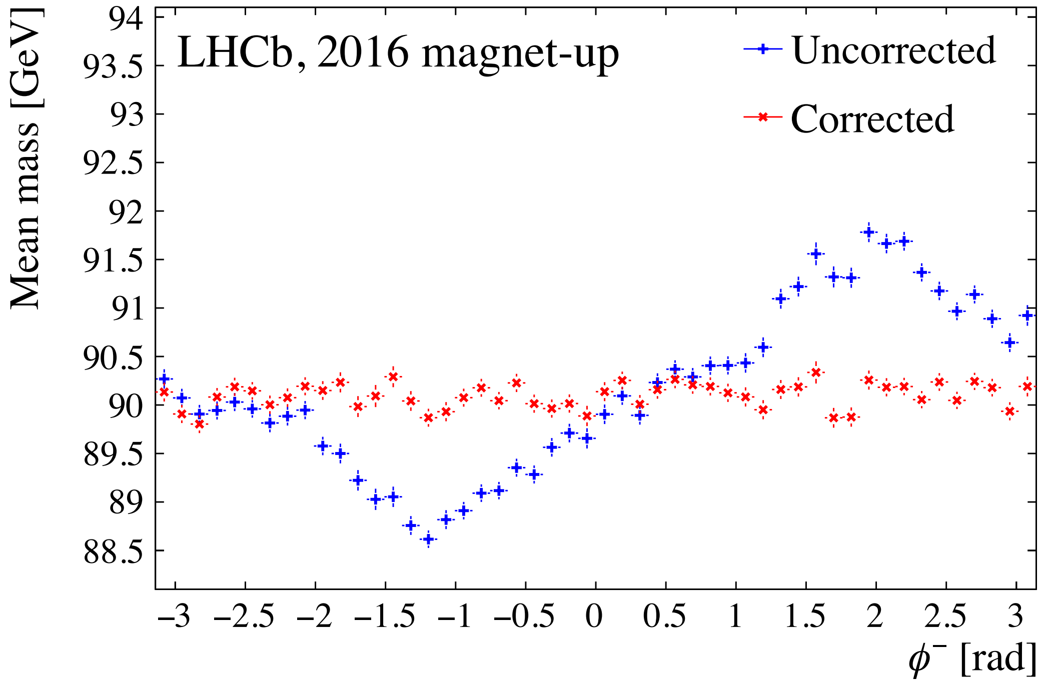
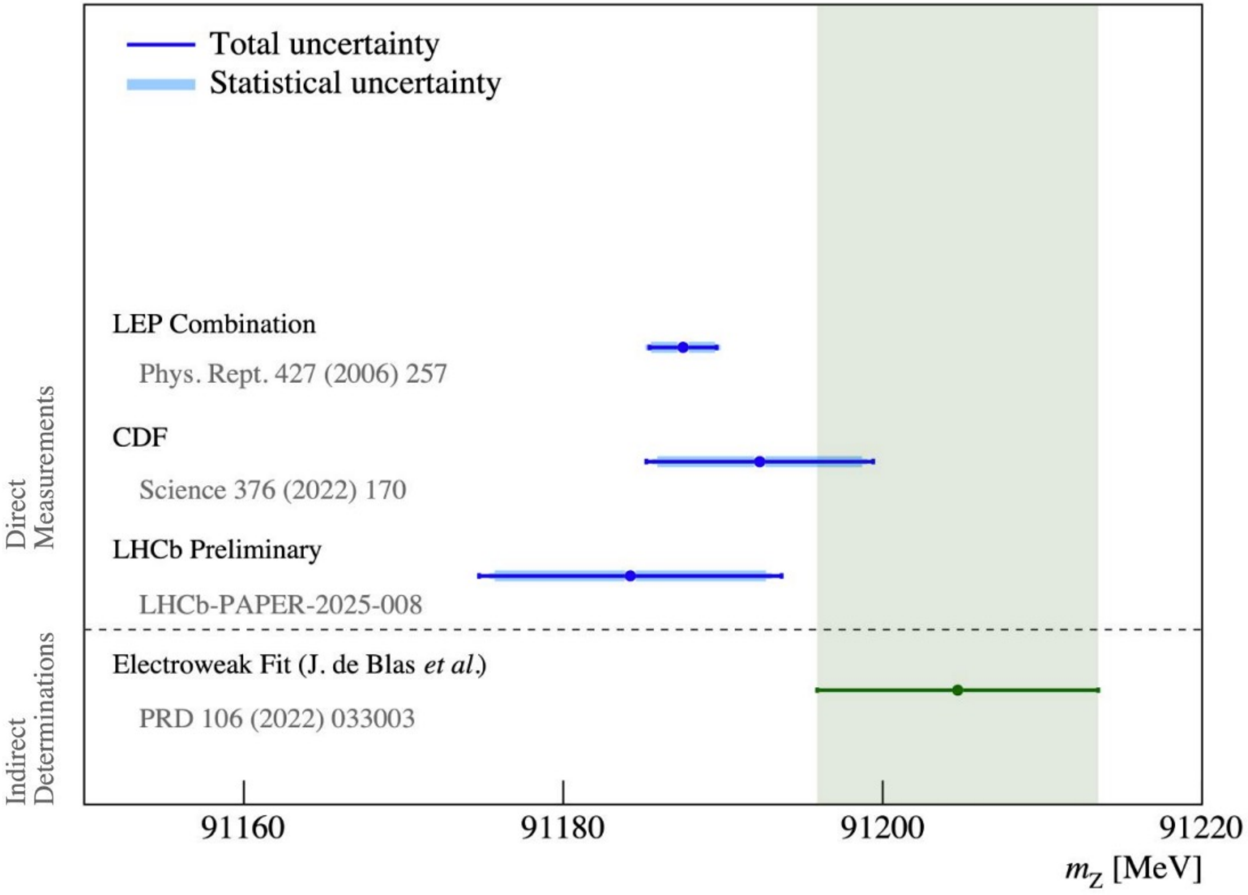
- $\mathcal{O}(20\%)$ improvement in resolution of width of Z mass peak



- Non-physical trends in $m_{\mu\mu}$ as a function of ϕ removed



Measurement of m_Z



- Measurement of the Z boson mass using LHCb data collected during 2016 was recently presented at the LHC Seminar

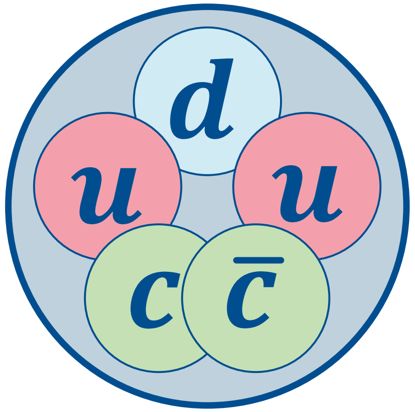
Uncertainty source	Size (MeV)
Momentum calibration	4.1
Signal QED corrections	0.8
Parton distribution functions	0.7
Detection efficiency	0.1
Statistical uncertainty	8.5
Total	**9.5**

- Curvature bias corrections contribute 0.7 MeV to the momentum calibration uncertainty

$Z + D$ analysis

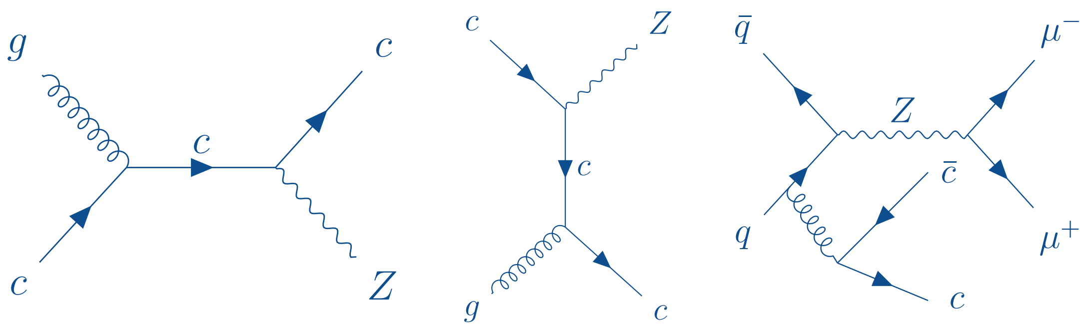
Motivation

- Previous LHCb studies of $Z + c$-jets yield results that could be explained by the proton having an intrinsic charm content [Phys. Rev. Lett. 128 (2022)]



- Occurs at large values of Bjorken-x → region of proton probed through $Z + D$ events [Phys. Rev. D 109 (2024)]

- Existence of intrinsic charm still disputed [Eur. Phys. J. C 83 (2023)]



(a) (b) (c)

- $Z + D$ events can occur via either single parton scattering (SPS) or double parton scattering (DPS)

$$\sigma_{\mathrm{DPS}}^{Z+D} = \frac{\sigma^Z \sigma^D}{\sigma_{\mathrm{eff}}}$$

- Investigate what fraction of $Z + D$ events occur via SPS compared to DPS

Datasets & event selection

- Follows on from previous observation of $Z + D^0$ and $Z + D^+$ events using $\sqrt{s} = 7\ \mathrm{TeV}$ dataset [JHEP 091 (2014)]

- Using $\sqrt{s} = 13\ \mathrm{TeV}$ data collected between 2016 and 2018

$Z \to \mu^+\mu^-$	$D^0 \to K^-\pi^+$
	$D^+ \to K^-\pi^+\pi^+$
	$D_s^+ \to K^+K^-\pi^+$

- Trigger on Z boson only → unbiases selection

Event selection

- Selection of Z candidates follows those of the 2016 m_W analysis [JHEP 01 (2022) 036]

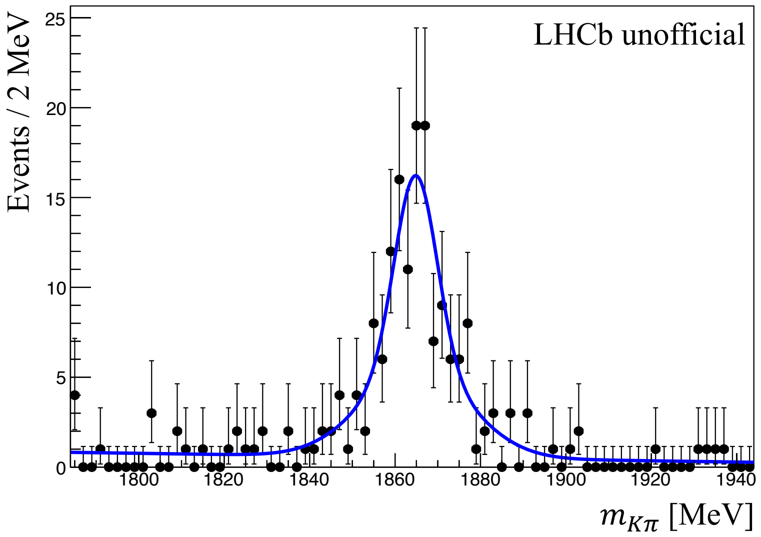
- D meson candidates selected using modified version of trigger requirements from charm production cross-sections analysis [JHEP 05 (2017) 074]
  - Modifications target and improve the selection efficiency for high-p D mesons

D meson mass fits

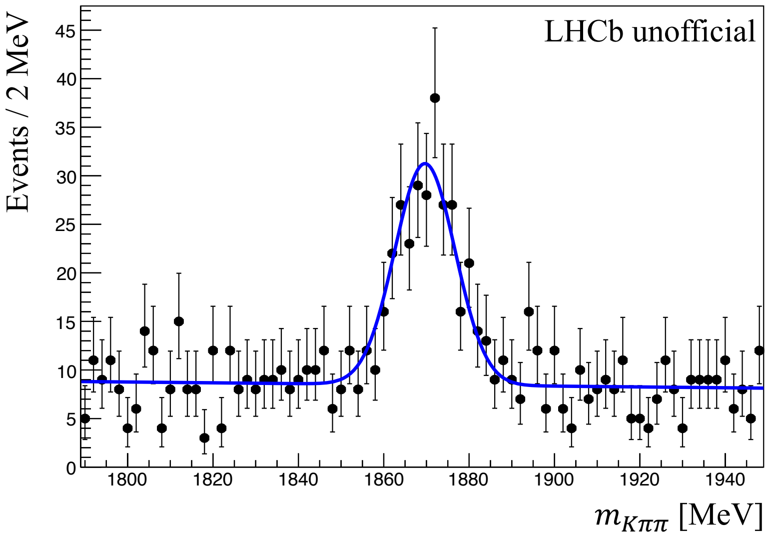
- Signal PDF: double Gaussian
  - Mean of each Gaussian fixed to known m_D
  - Widths of each Gaussian allowed to vary freely
- Background PDF: first-order polynomial

- Functional form of fits found to be unbiased:
  - 50 independent samples of
    - $\sim$ 200 MC signal events events
    - $\sim$ 100 uniformly distributed background events

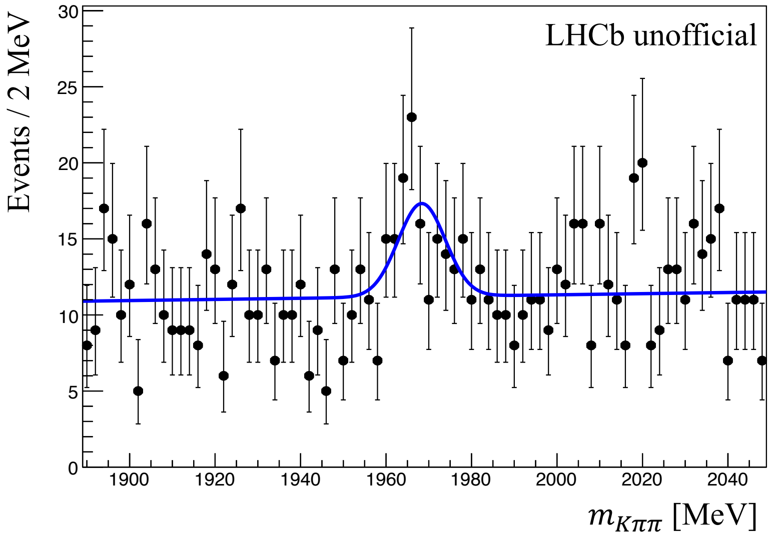
$D^0 \to K^-\pi^+$



$D^+ \to K^-\pi^+\pi^+$

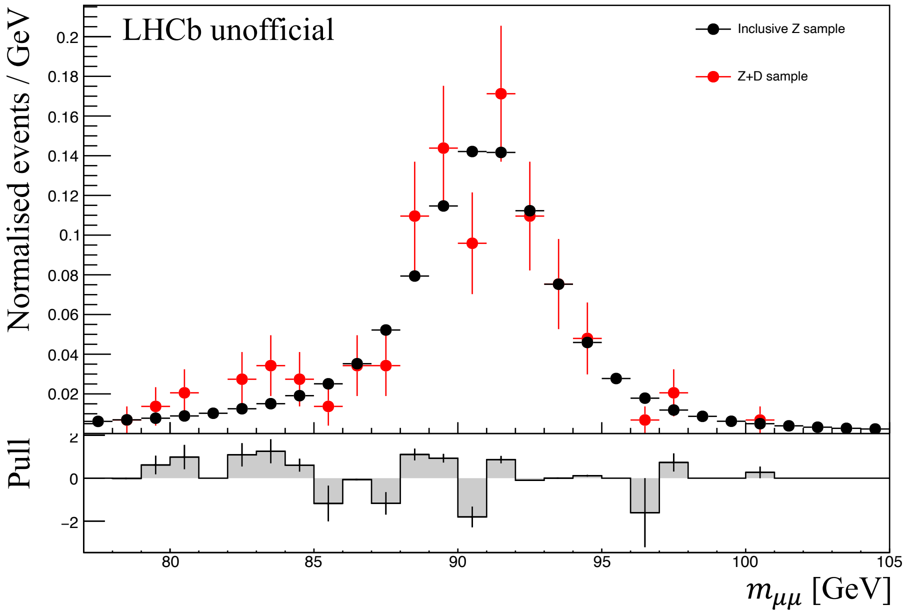


$D_s^+ \to K^-K^+\pi^+$



Signal yields

$Z + D^0$



- Inclusive Z sample found to be $> 99\%$ pure ⇒ signal yields obtained from D meson mass fits

- Efficiencies determined using simulation, with corrections to account for differences between data and MC applied

$$\epsilon = \epsilon^{Z}_{\text{rec\&sel}} \times \epsilon^{D}_{\text{rec\&sel}} \times \epsilon^{Z+D}_{\text{sel}} \times \epsilon^{D}_{\text{PID}} \times \epsilon^{Z}_{\text{trg}}$$

- Fraction of Z events which also contain a D meson:

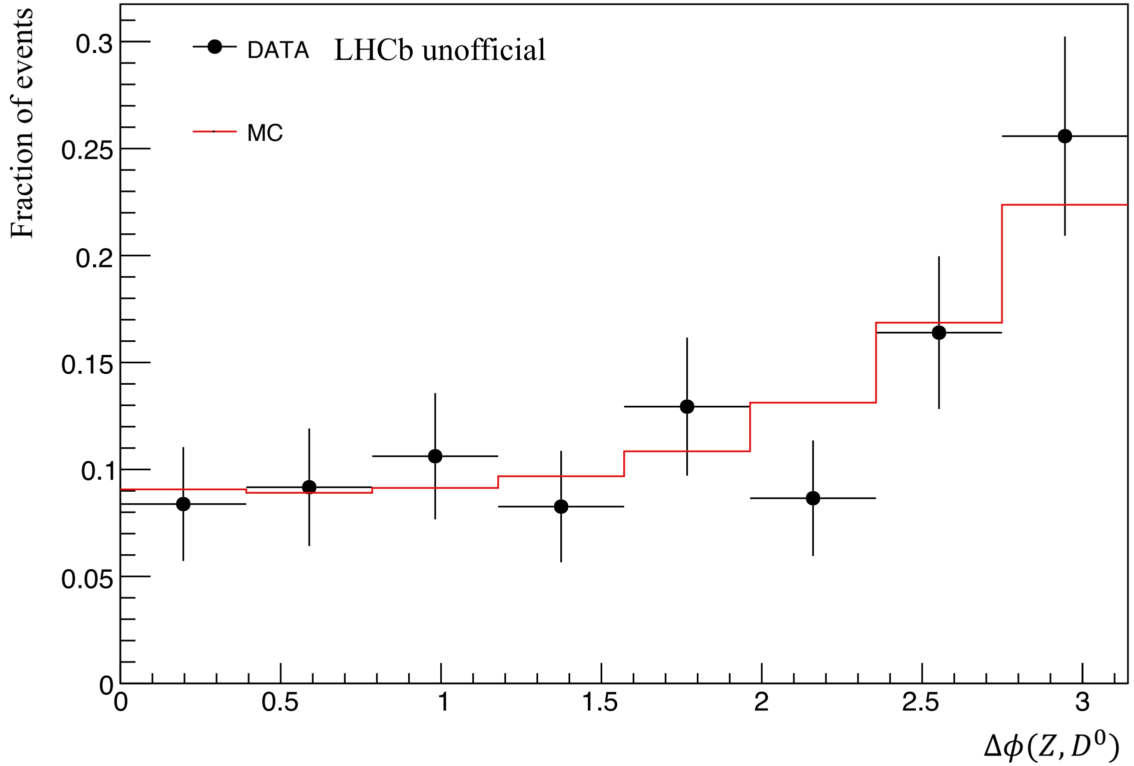
$$\frac{N(Z+D)}{N(Z)} \times \frac{1}{\epsilon^{D}_{\text{rec\&sel}} \times \epsilon^{Z+D}_{\text{sel}} \times \epsilon^{D}_{\text{PID}}}$$

- Determine $N(Z+D)/N(Z)$ as a function of $y(Z)$
  - Do we observe an enhancement for large $y(z)$ and large $p_{\text{T}}(D)$?
    → Intrinsic charm

Azimuthal opening angle

$$\Delta\phi = |\phi(Z) - \phi(D)|$$

- **Flat component throughout $[\mathbf{0}, \boldsymbol{\pi}]$:** uncorrelated contribution from DPS events
- **Peaking component at $\boldsymbol{\pi}$:** contribution from "back-to-back" $Z + D$ events produced via SPS



Summary

- Updates to the implementation of the pseudomass method allow a deep understanding of detector alignment conditions, facilitating precision electroweak measurements
- Studying $Z + D$ production at LHCb provides access to the intrinsic charm content of the proton
- $Z + D^0$ and $Z + D^+$ events were observed during Run 1
- Updated analysis with larger Run 2 dataset allows production mechanisms and kinematic properties of the events to be studied
- Further studies with Run 3 dataset necessary to determine full picture