Measurement of single W and Z boson properties in the Forward Region

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On behalf of the LHCb Collaboration
ICHEP 2024 – Prague, Czech Republic
18 July 2024

Topics

- The LHCb detector
- Rare W and Z decays [Chin. Phys. C **47** 093002]
- Z cross-section at $\sqrt{s} = 5.02$ TeV [JHEP 02 (2024) 070]
- $Z \to \mu^+\mu^-$ angular coefficients at $\sqrt{s} = 13$ TeV [Phys. Rev. Lett. 129 (2022) 091801]
- Measurement of the effective leptonic weak mixing angle **NEW!**

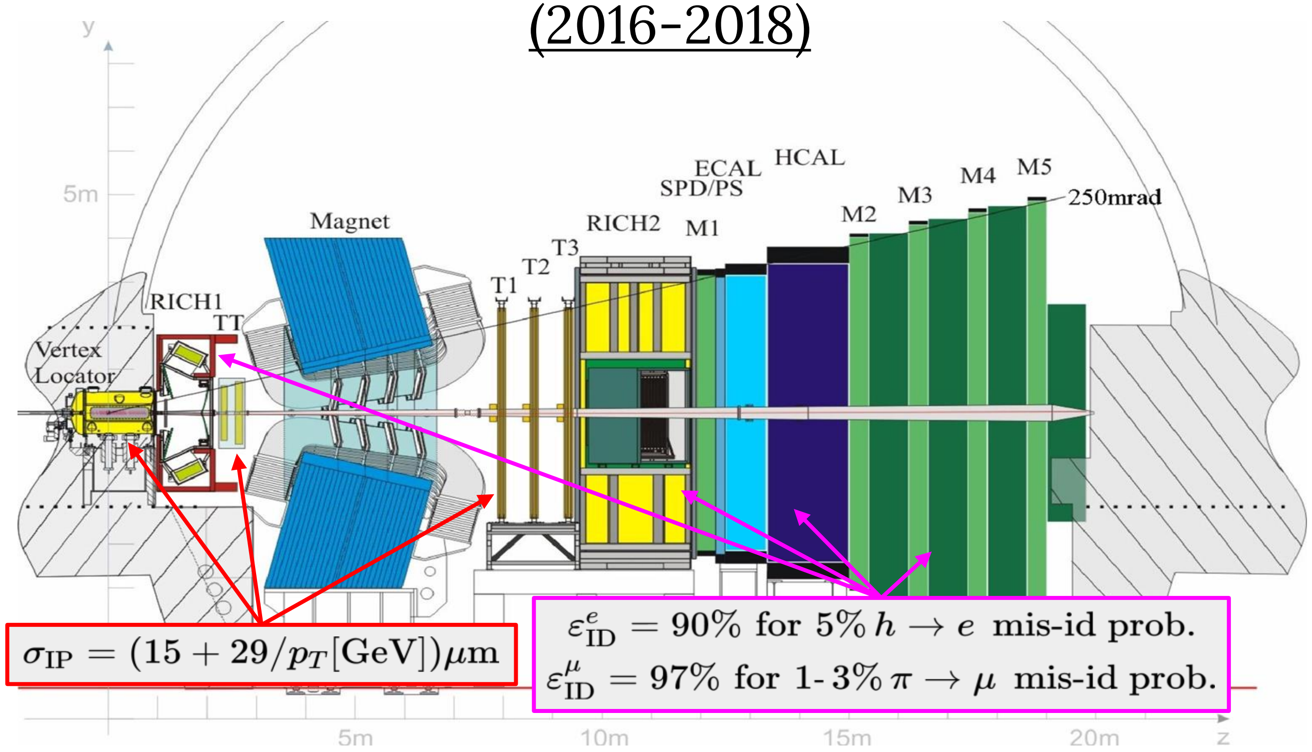
LHCb detector (Run-II)

- Single-arm forward spectrometer
- Designed for heavy flavor physics (b and c hadrons)

Key features:

- Forward geometry (covering pseudorapidty range $2 < \eta < 5$)
- Excellent vertex resolution and particle identification
- High-precision momentum measurement
- Efficient trigger system for selecting rare decay processes

Detector used in Run-II (2016-2018)

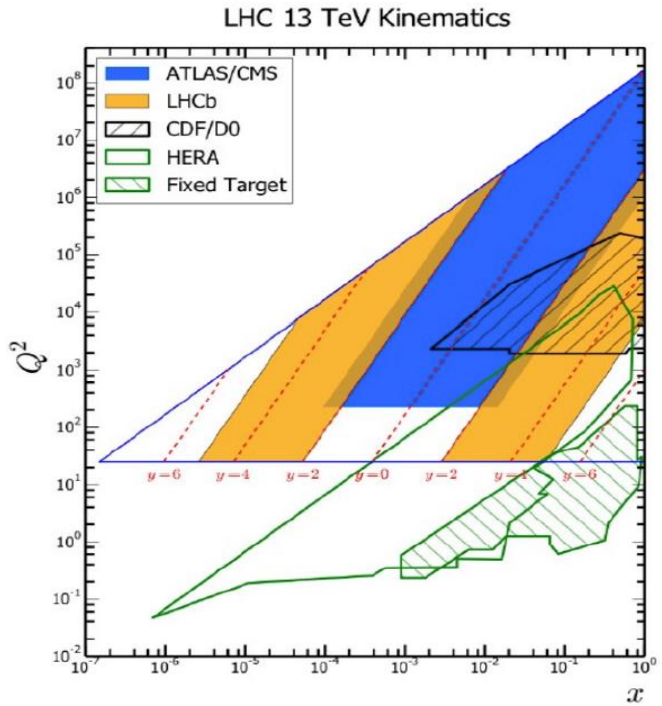


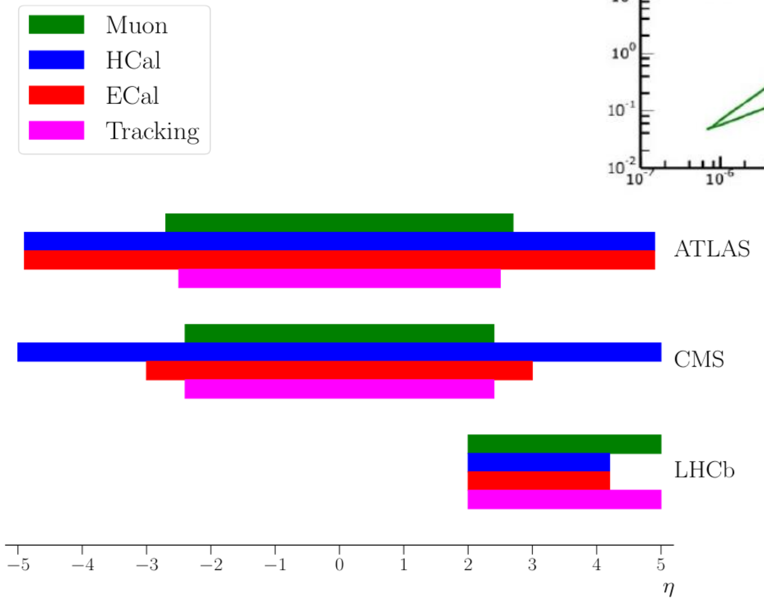
[JINST 3 (2008) S08005]

Electroweak Physics at LHCb

- Cannot measure missing energy
- Low luminosity with respect to ATLAS and CMS

+ Low pile-up environment
+ Low momentum triggers
+ Complementary coverage to ATLAS and CMS (with some overlapping at low pseudorapidity)
+ Excellent performance of tracking and muon detector





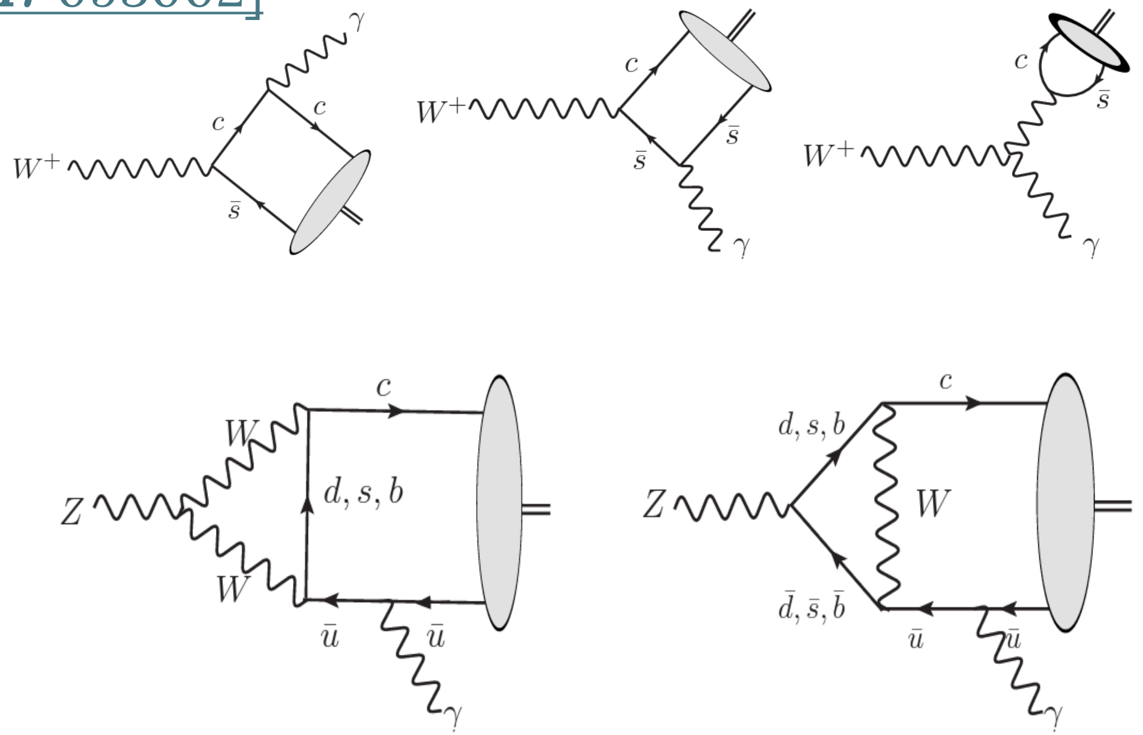
➢ Boson Production and asymmetries (e.g. W and Z cross-sections, PDF functions)

➢ Rare decays (e.g. radiative decays, LFU tests)

Rare W and Z decays

[Chin. Phys. C **47** 093002]

- Focus on radiative decays of W and Z bosons
- Update on search for $W^+ \to D_s^+\gamma(\to \mathrm{K^+K^-}\pi^-)$
- First reported search for $Z \to D^0\gamma(\to K^-\pi^+)$
- 2018 data @ $\sqrt{s} = 13$ TeV → **2.0 fb^{-1}**

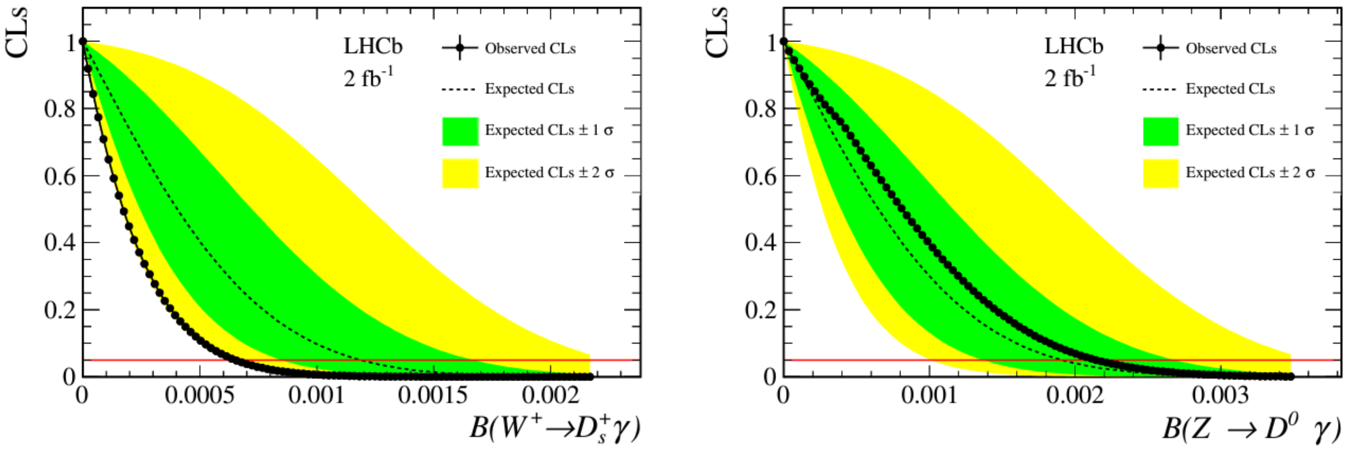


Rare W and Z decays

- No significant signal is observed above background
- For the $W^+ \to D_s^+\gamma$ decay, the absolute BR upper limit is determined to be $\mathbf{6.5 \times 10^{-4}}$ at 95% C.L
- For the $Z \to D^0\gamma$ decay, the absolute BR upper limit is determined to be $\mathbf{2.1 \times 10^{-3}}$ at 95% C.L

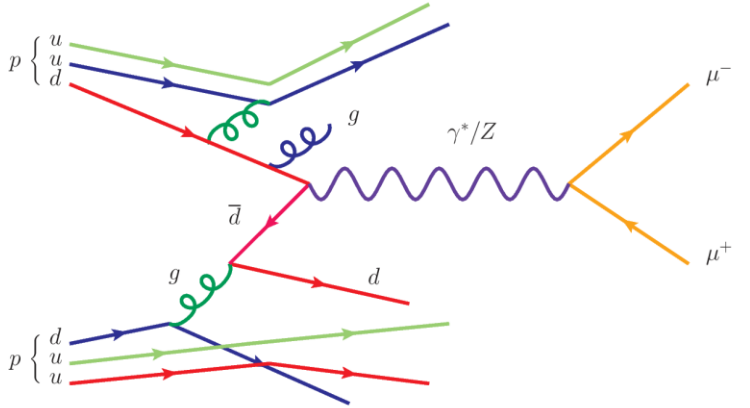
[Chin. Phys. C **47** 093002]

Decay	Observed	Expected
$Z \to D^0\gamma$	2.14×10^{-3}	1.91×10^{-3}
$W^+ \to D_s^+\gamma$	1.03×10^{-3}	1.46×10^{-3}
$W^- \to D_s^-\gamma$	1.38×10^{-3}	1.88×10^{-3}
$W^\pm \to D_s^\pm\gamma$	6.52×10^{-4}	1.19×10^{-3}

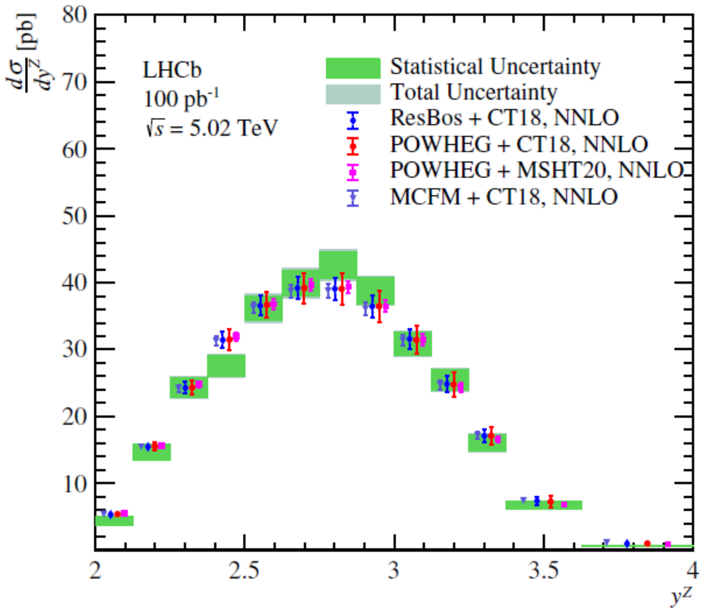


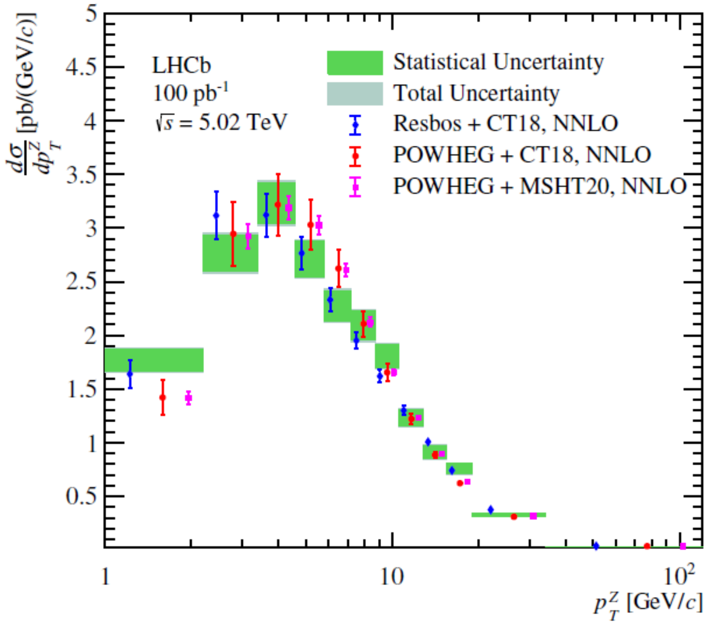
Z cross-section at $\sqrt{s} = 5.02$ TeV

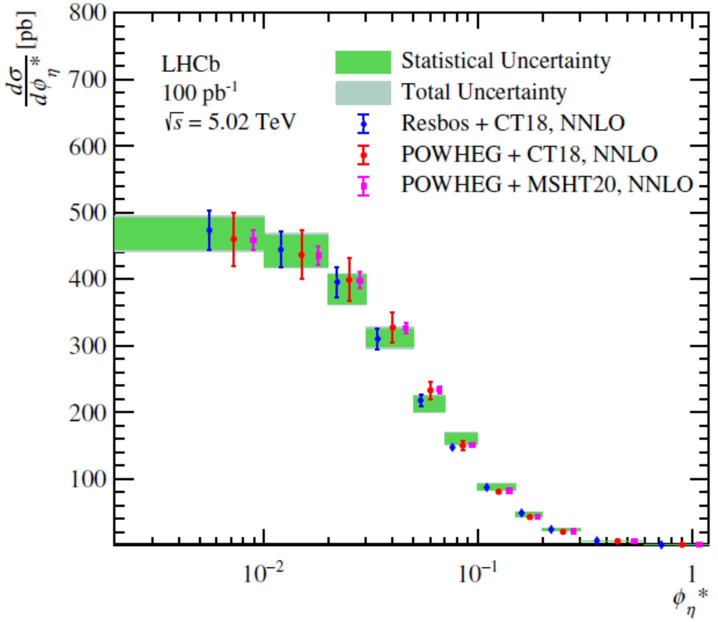
- Particularly important for constraining $\boldsymbol{u}$-, $\boldsymbol{d}$-quark PDFs at high $\boldsymbol{x}$ region
- **High purity**: $\frac{N_{bkg}}{N_{sig}} \sim 2\%$
- ϕ_η^*: the scattering angle of the muons with respect to the proton beam direction in the rest frame of the dimuon system



[JHEP 02 (2024) 070]

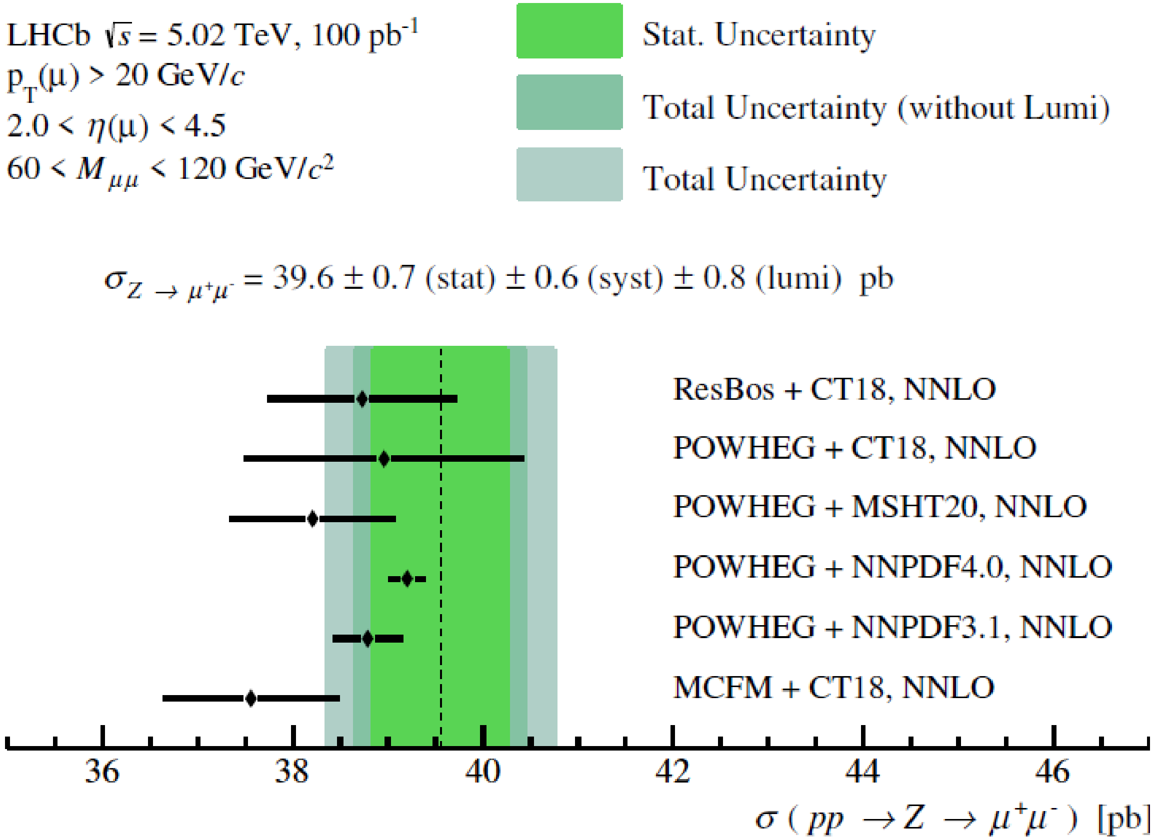






Z cross-section at $\sqrt{s} = 5.02$ TeV

[JHEP 02 (2024) 070]

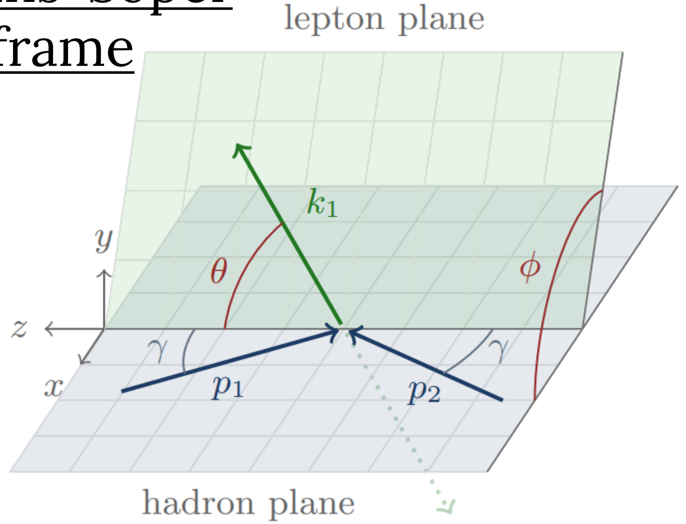


Source	$\Delta\sigma$ [pb]	$\Delta\sigma/\sigma$ [%]
Luminosity	0.79	2.00
Statistical	0.70	1.77
Tracking	0.40	1.01
Efficiency Closure	0.24	0.61
Trigger	0.21	0.54
Background	0.19	0.48
Identification	0.10	0.25
FSR	0.07	0.18
Calibration	$< 4.0 \times 10^{-3}$	< 0.01
Total Systematic (excl. lumi.)	0.56	1.42

$Z \to \mu^+\mu^-$ angular coefficients at $\sqrt{s} = 13$ TeV

- Kinematic distributions of final-state leptons offers insight into:
  - Electroweak parameters (weak mixing angles and gauge boson masses)
  - Polarization of intermediate gauge bosons
  - Proton structure and underlying strong-interaction dynamics as theorised by QCD

Collins-Soper frame

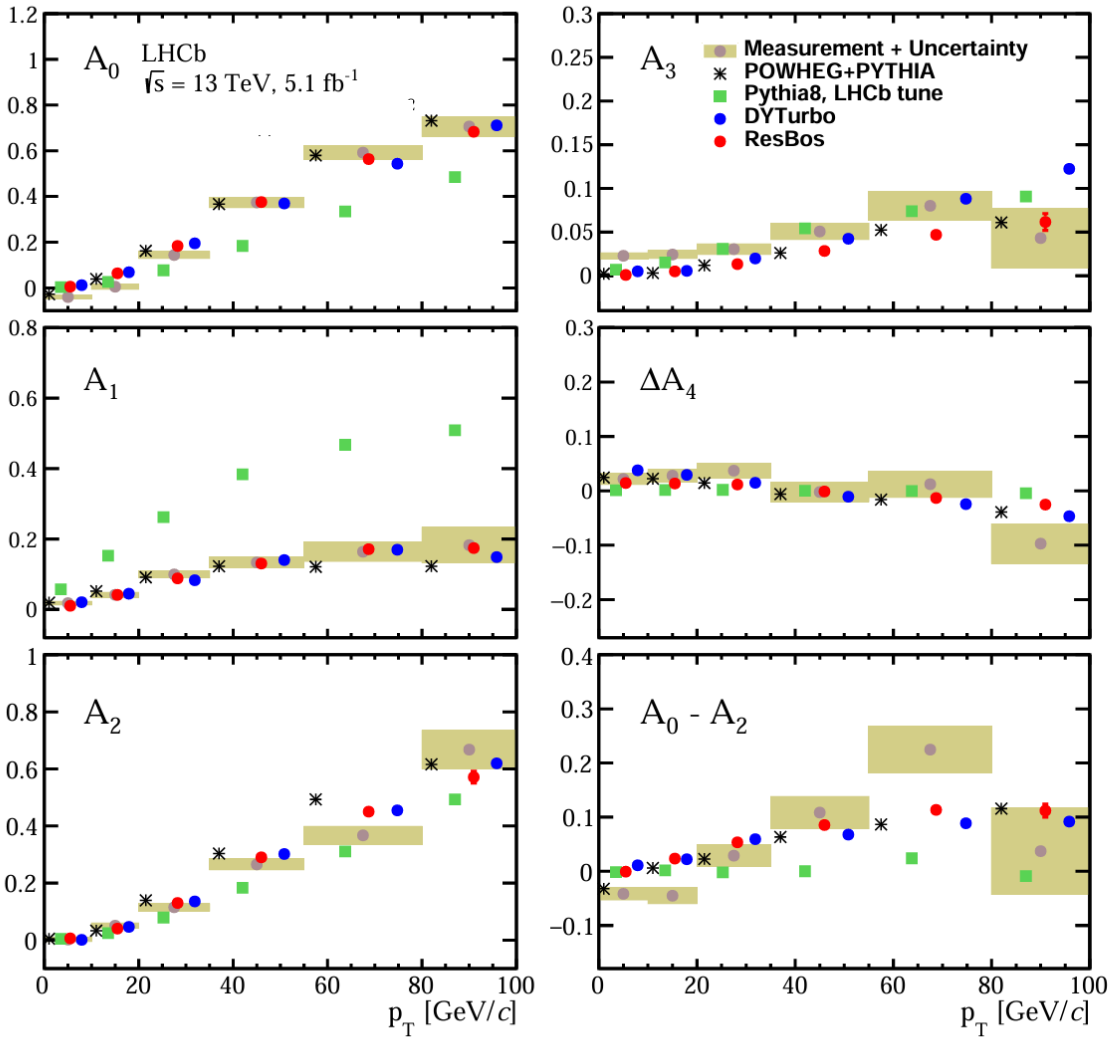


$$\frac{d\sigma}{d\cos\theta d\phi} \propto \boxed{(1+\cos^2\theta)} + \frac{1}{2}A_0(1-3\cos^2\theta)$$
$$+ A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi$$
$$+ A_3 \sin\theta\cos\phi + \boxed{A_4\cos\theta} + A_5\sin^2\theta\sin 2\phi$$
$$+ A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi,$$

LO term

[JHEP11(2017)003]
[Phys. Rev. Lett. 129 (2022) 091801]

$Z \to \mu^+\mu^-$ angular coefficients at $\sqrt{s} = 13$ TeV

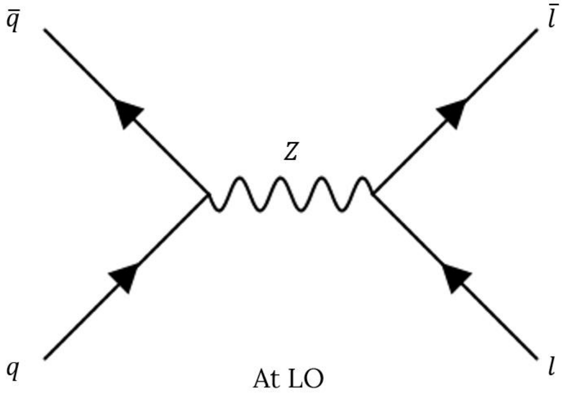


[Phys. Rev. Lett. 129 (2022) 091801]

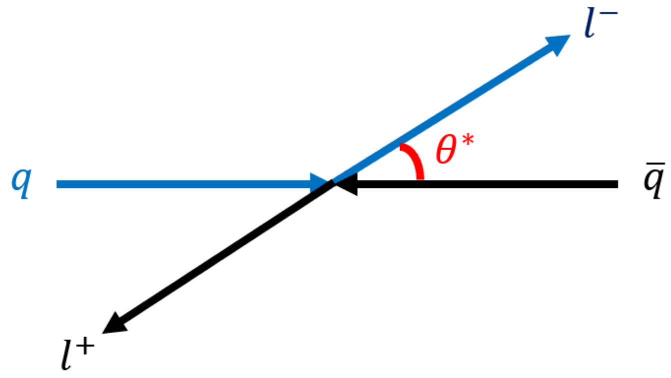
- Run-II data (2016 – 2018) → $\mathbf{5.1\ fb^{-1}}$
- $y_Z > 2$
- $75 < M_{\mu\mu} < 105\ \mathrm{GeV}/c^2$
- Measured at Born level
- Total uncertainty dominated by **statistical uncertainty**

Measurement of the Weak Mixing angle

Presence of vector and axial-vector couplings that depend on θ_W introduces a **forward-backward asymmetry** of angular distribution of lepton pairs in DY events



$$\propto 1 + \cos^2\theta^* + A_4 \cos\theta^*$$



$$A_{FB} = \frac{3}{8} A_4$$

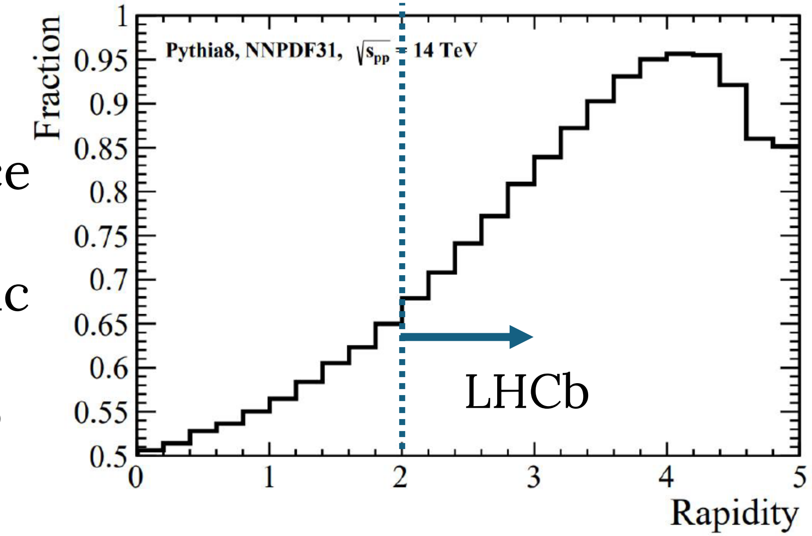
$$A_{FB} = \frac{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}{N(\cos\theta^* > 0) + N(\cos\theta^* < 0)} = \frac{N_F - N_B}{N_F + N_B}$$

- At the **tree level**, $\cos\theta_W = \frac{m_W}{m_Z} \Rightarrow \sin^2\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right)$
- $\sin^2\theta_{\text{eff}}^{\text{lept}}$ accounts for higher-order corrections

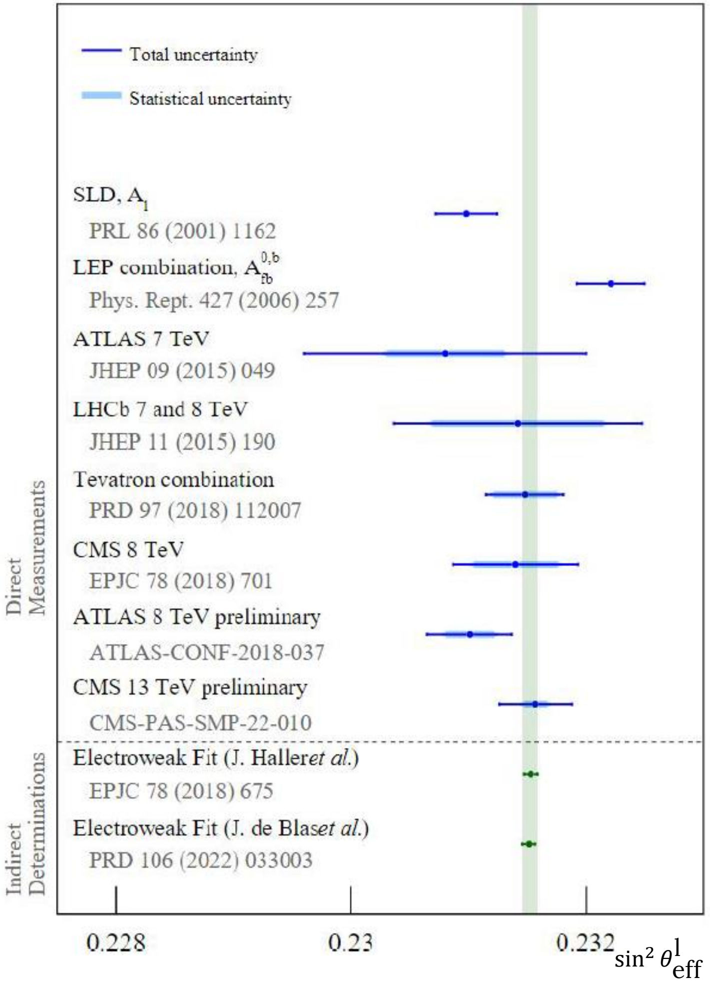
Measurement of the Weak Mixing angle

- Key parameter in SM
- A 3.2 σ difference exists between the two most precise individual measurements (SLD and LEP)
- Potential BSM process dependence
- At large rapidities have asymmetric initial state:
  - One parton at high $\boldsymbol{x}$ tends to be a valence quark
  - Other at low $\boldsymbol{x}$ tends to be an anti-quark
- PDF uncertainty is smallest in the forward region

Fraction of events where the Z boson travels in direction of initial state quark



[LHCb-PUB-2018-013]



Measurement of the Weak Mixing angle

- Run-II pp collision dataset (2016-2018) @ $\sqrt{s}$ = 13 TeV → $\mathbf{5.3\ fb^{-1}}$

- Fiducial region:
  - $2.0 < \eta_\mu < 4.5$
  - $p_T^\mu > 20\ \mathrm{GeV/c}$
  - $66 < M_{\mu\mu} < 116\ \mathrm{GeV/c^2}$

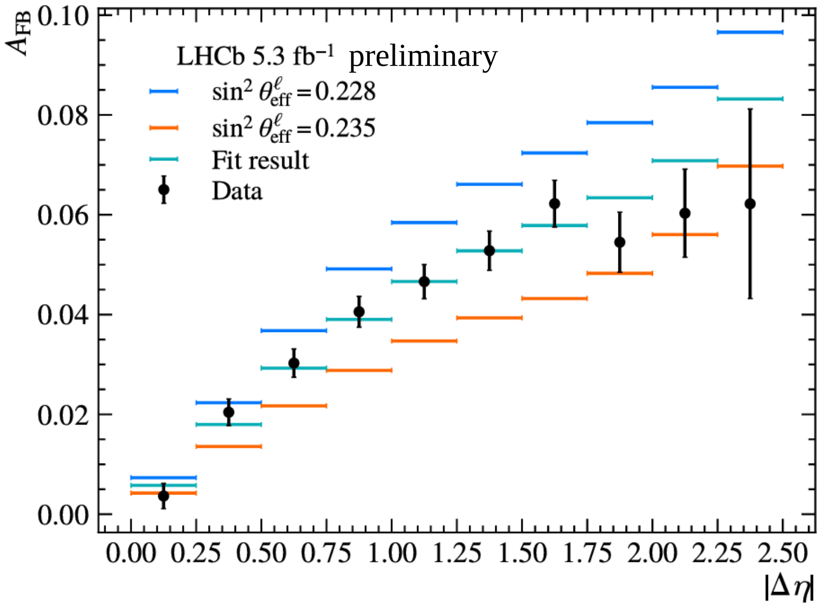
- Hadronic and heavy-flavour backgrounds are suppressed to the **percent level** by isolation, muon track fit, and muon impact parameter requirements.

- Total background fraction, within the fiducial kinematic region for the measurement is just $\mathbf{2 \times 10^{-3}}$

- All backgrounds are estimated through simulation and then scaled to the data →background subtraction

Measurement of the Weak Mixing angle

- Fit A_{FB} in (10) intervals of $|\Delta\eta|$ ($\cos\theta^* \sim \tanh\frac{\Delta\eta}{2}$)
- In simulation this binning improves sensitivity to the weak mixing angle by 14%
- $\sin^2\theta_{\text{eff}}^{\text{lept}}$ is extracted using predictions at NLO in the strong and EW couplings using POWHEG-BOX
- Compare data with predictions to extract the value of $\sin^2\theta_{\text{eff}}^{\text{lept}}$ that best corresponds to the data
- Experimental uncertainty is much smaller than the statistical uncertainty



Interval number	Interval	A_{fb}
0	$0.00 < \lvert\Delta\eta\rvert \leq 0.25$	$0.0036 \pm 0.0025 \pm 0.0001$
1	$0.25 < \lvert\Delta\eta\rvert \leq 0.50$	$0.0204 \pm 0.0027 \pm 0.0002$
2	$0.50 < \lvert\Delta\eta\rvert \leq 0.75$	$0.0303 \pm 0.0028 \pm 0.0002$
3	$0.75 < \lvert\Delta\eta\rvert \leq 1.00$	$0.0406 \pm 0.0031 \pm 0.0003$
4	$1.00 < \lvert\Delta\eta\rvert \leq 1.25$	$0.0466 \pm 0.0034 \pm 0.0002$
5	$1.25 < \lvert\Delta\eta\rvert \leq 1.50$	$0.0528 \pm 0.0039 \pm 0.0004$
6	$1.50 < \lvert\Delta\eta\rvert \leq 1.75$	$0.0622 \pm 0.0047 \pm 0.0003$
7	$1.75 < \lvert\Delta\eta\rvert \leq 2.00$	$0.0545 \pm 0.0060 \pm 0.0004$
8	$2.00 < \lvert\Delta\eta\rvert \leq 2.25$	$0.0603 \pm 0.0088 \pm 0.0010$
9	$2.25 < \lvert\Delta\eta\rvert \leq 2.50$	$0.0622 \pm 0.0190 \pm 0.0008$

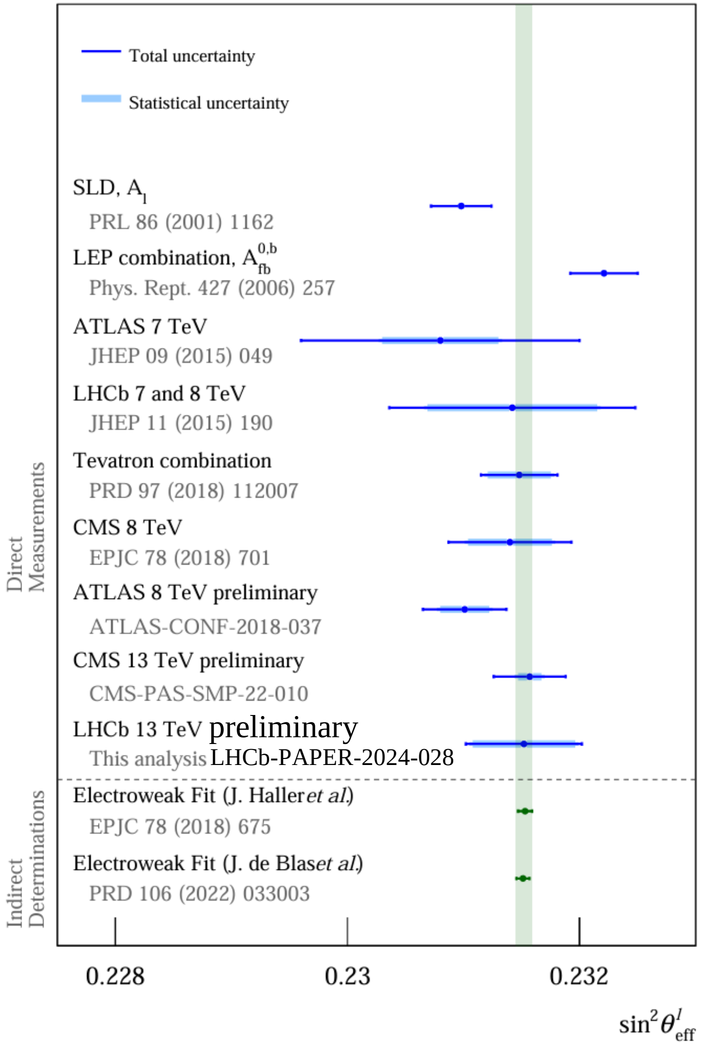
Measurement of the Weak Mixing angle

- Final result:

$$\sin^2\theta^{\text{lept}}_{\text{eff}} = 0.23152 \pm 0.00044(stat.) \pm 0.00005(exp.) \pm 0.00022(theory)$$

- Consistent with previous measurements and indirect determinations from global electroweak fit

- Aim to improve statistical uncertainty with LHCb Upgrade I, which includes a **fivefold** increase in instantaneous luminosity



Summary

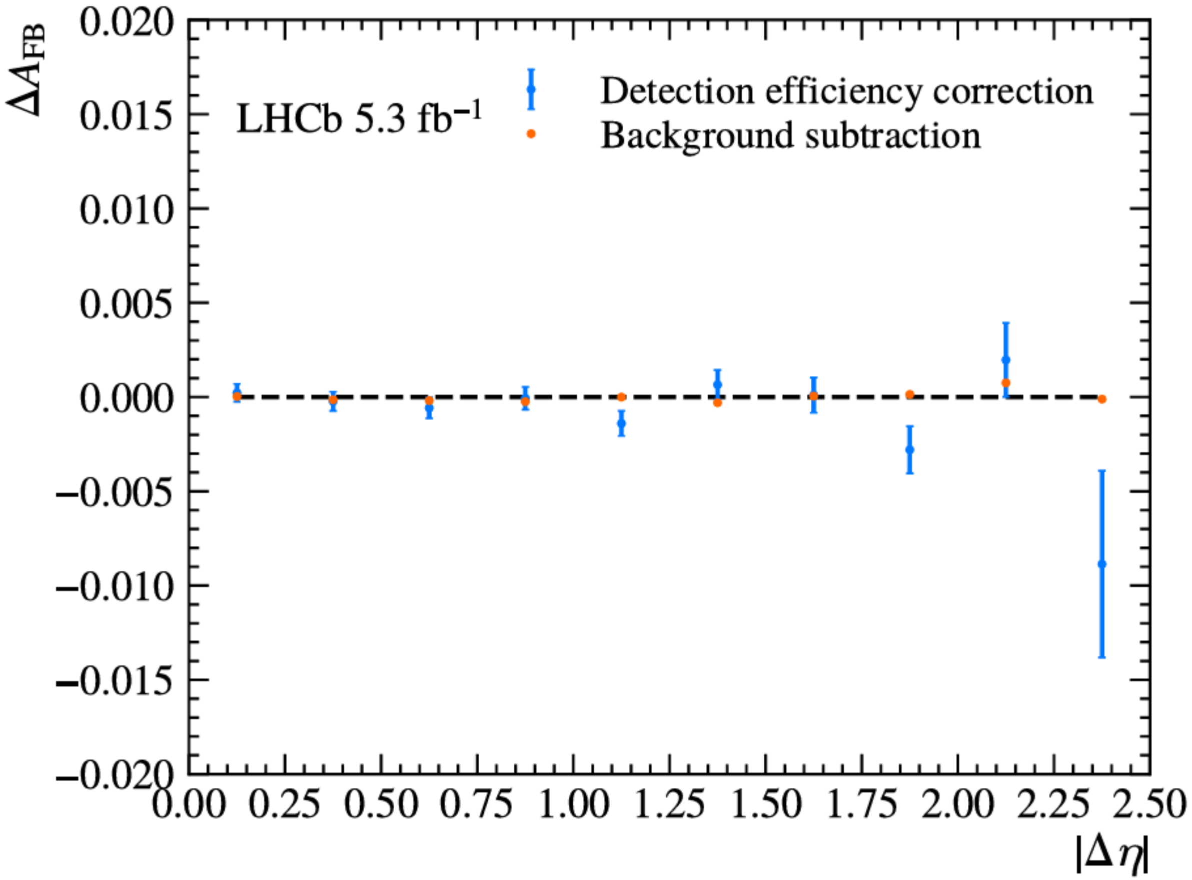
- LHCb with its unique coverage is an important player when it comes to electroweak physics
- Upper limits on rare W and Z decays using 2018 data
- High purity Z cross-section measurement at $\sqrt{s} = 5.02$ TeV
- Study of $Z \to \mu^+\mu^-$ angular coefficients at $\sqrt{s} = 13$ TeV (Born level, ongoing need for more statistics)
- Precise weak mixing angle measurement (also need more statistics)
- Anticipate significant statistical improvements in Run 3 with five times the instantaneous luminosity!

Stay tuned!

Backup Slides

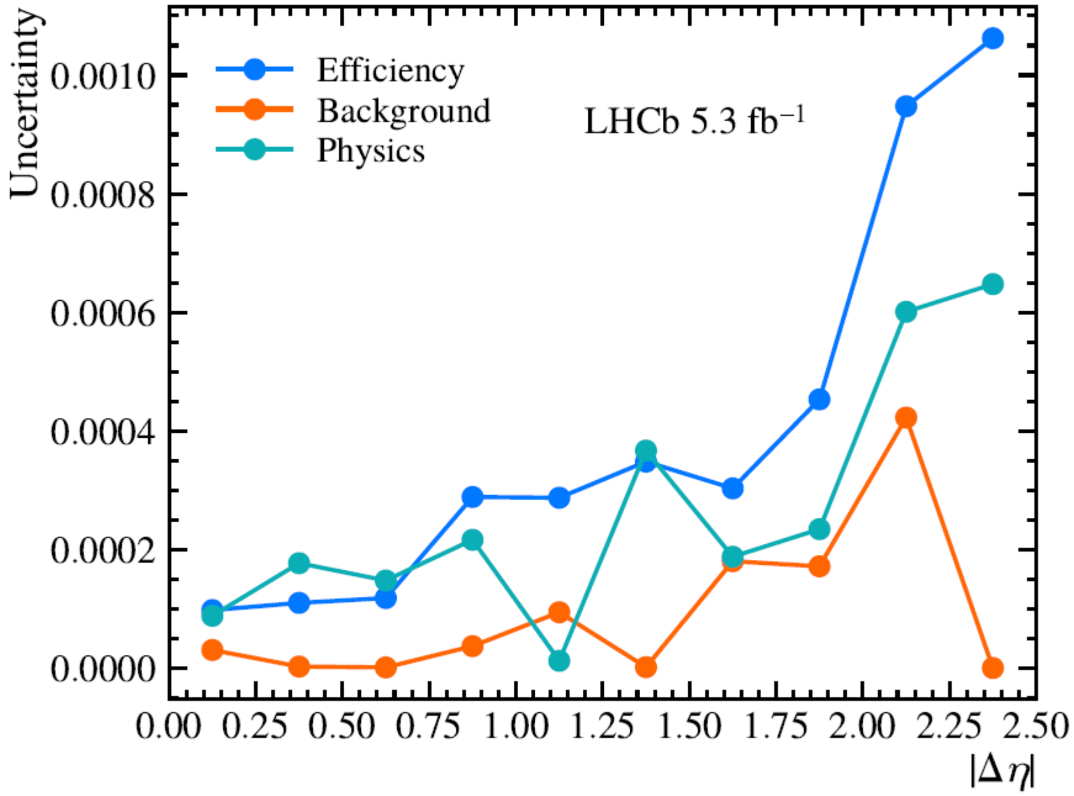
A_{FB} efficiencies/bkg subtraction

- Effect of detection efficiency and background subtraction on the measured A_{FB}
- Tiny effect



A_{FB} systematics

- Efficiency:
  - ➢ Randomly vary estimated efficiencies (trigger, muon identification, and tracking)
- Background:
  - ➢ Assumed cross-sections varied up and down by 50%
- Physics:
  - ➢ Simulated signal events are weighted to match the kinematic distributions predicted by the DYTurbo program



→ Tiny effect compared to statistical uncertainties

A_{FB} templates EW normalisation scheme

- SM templates can be derived from 3 electroweak parameters: two masses and one coupling
- Different schemes take different input parameters
- G_f scheme: G_μ, m_W, m_Z
  - Not stable wrt higher order effects
  - Not used in the default measurement
- xW scheme: $G_\mu, m_Z, \sin^2\theta_{\text{eff}}^{\text{lept}}$
  - Defines $\sin^2\theta_{\text{eff}}^{\text{lept}}$ clearly in theory context
  - Recommended for use by LHC-wide Electroweak Working Group experts