Precision measurements of Z boson production (with a focus on the Weak Mixing Angle)

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On behalf of the ATLAS, CMS and LHCb collaborations

SM @ LHC 2025

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Topics

Introduction

ATLAS measurement

CMS measurement

LHCb measurement + bonus!

Summary and prospects

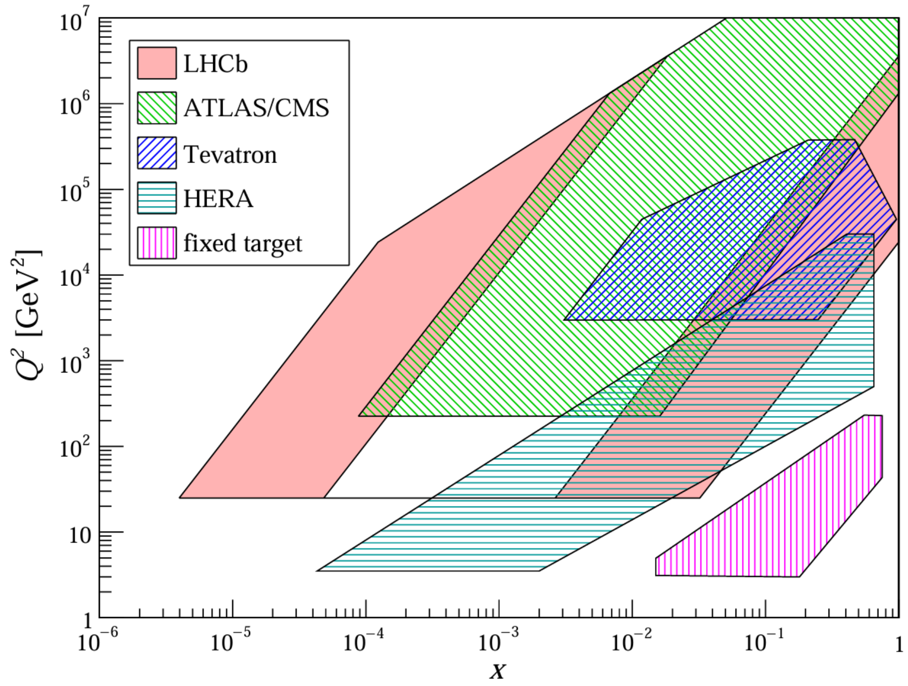
Introduction

ATLAS, CMS, and LHCb

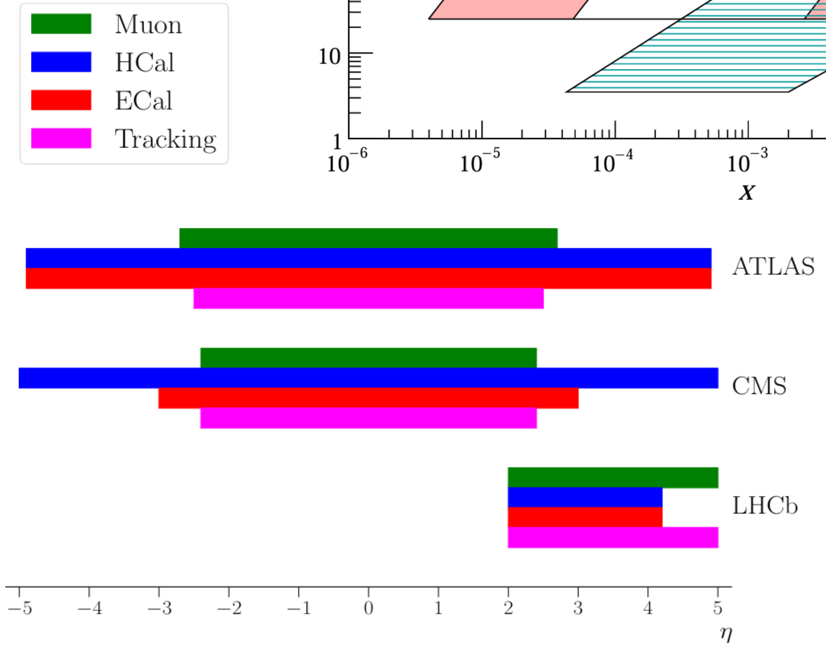
- Both ATLAS and CMS cover the central pseudorapidity region
  - ❖ ECAL used to study electron modes in more detail

- LHCb covers the forward region, with access to low and high Bjorken-x regions of the phase-space
  - ❖ Focuses on muons with excellent tracking and detection

- Having 3 experiments with complementary coverage has big implications on modelling – especially with PDFs



[arXiv: 1512.06666]



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

Weak mixing angle

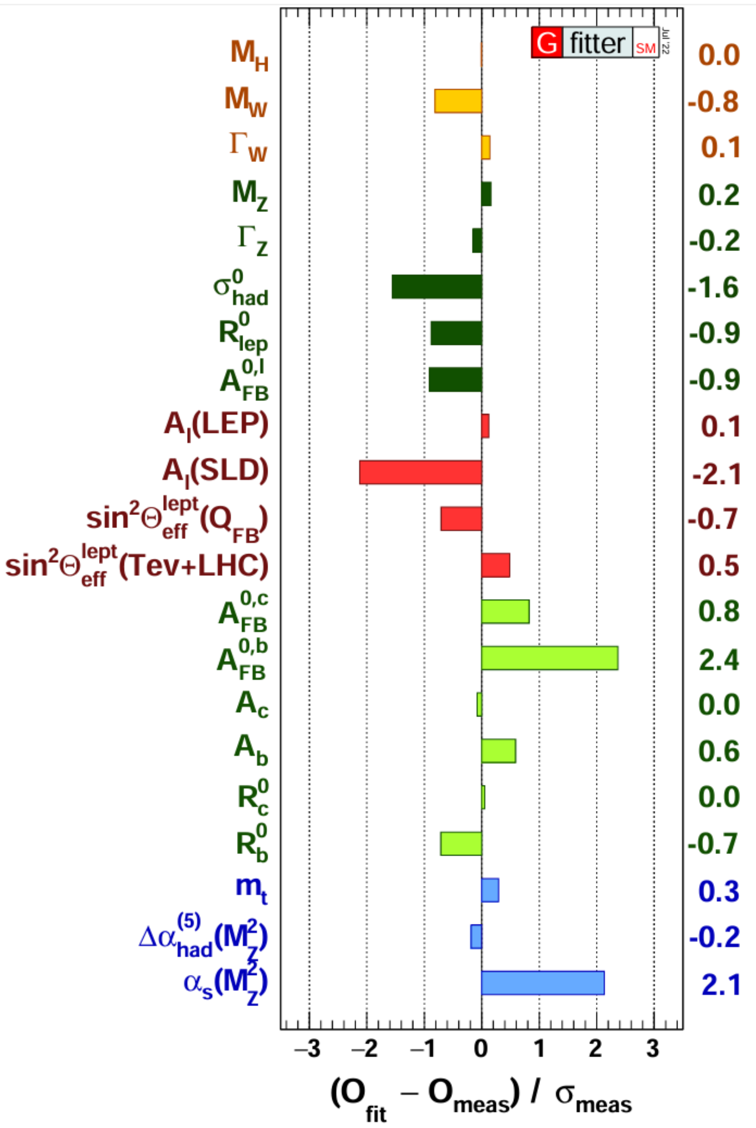
- Key parameter in SM
- At the **tree level**:

$$\cos\theta_W = \frac{m_W}{m_Z} \Rightarrow \sin^2\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right)$$

- $\sin^2\theta_{\text{eff}}^{\text{lept}}$ accounts for higher-order corrections:

$$\sin^2\theta_{eff}^{lept} = k_f \sin^2\theta_W$$

  - ❖ k_f is a flavour-dependent effective scaling factor absorbing higher order corrections ($k_f = 1$ at LO)



[arXiv:2211.07665]

Angular coefficients

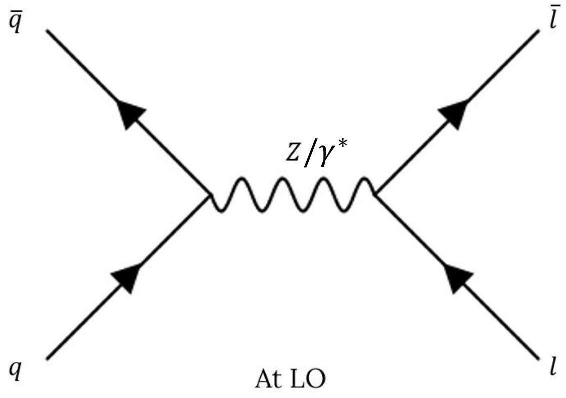
$$\frac{d\sigma}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}}$$

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

- At leading order in EW theory, the 5D differential cross-section for pp $\rightarrow Z/\gamma^* \rightarrow ll$ can be expressed as a sum of 9 harmonic polynomials
- Factorise out the unpolarised cross-section
- The helicity cross-sections depend on Z boson p_T, rapidity (y^{ll}), and mass (m^{ll})
- End up with 9 harmonic polynomials and 8 dimensionless angular coefficients ($A_0 - A_7$)
- Each polynomial is multiplied by a helicity cross-section
- A_4 deserves special attention as it includes info about the vector and axial-vector couplings of the Z boson

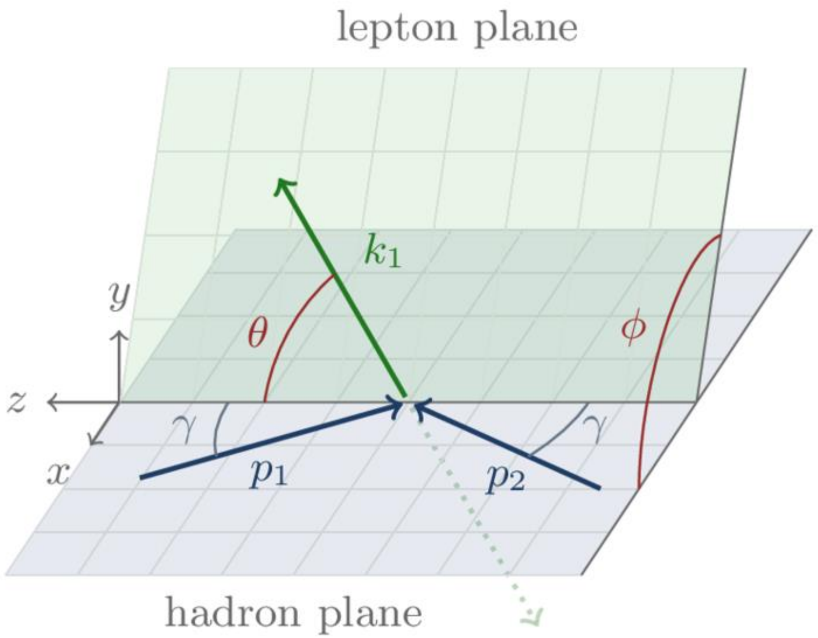
Forward-backward asymmetry

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



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

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



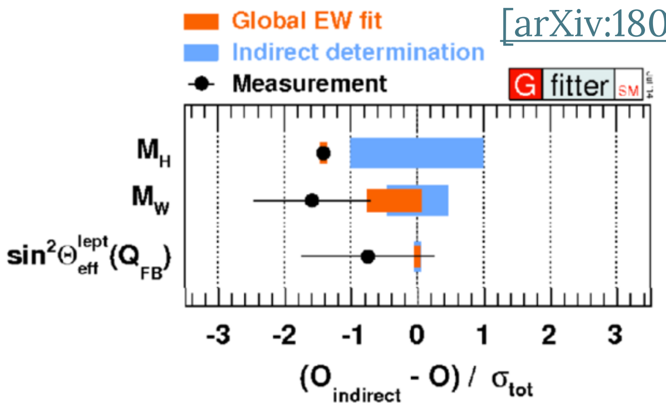
Collins-Soper frame

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

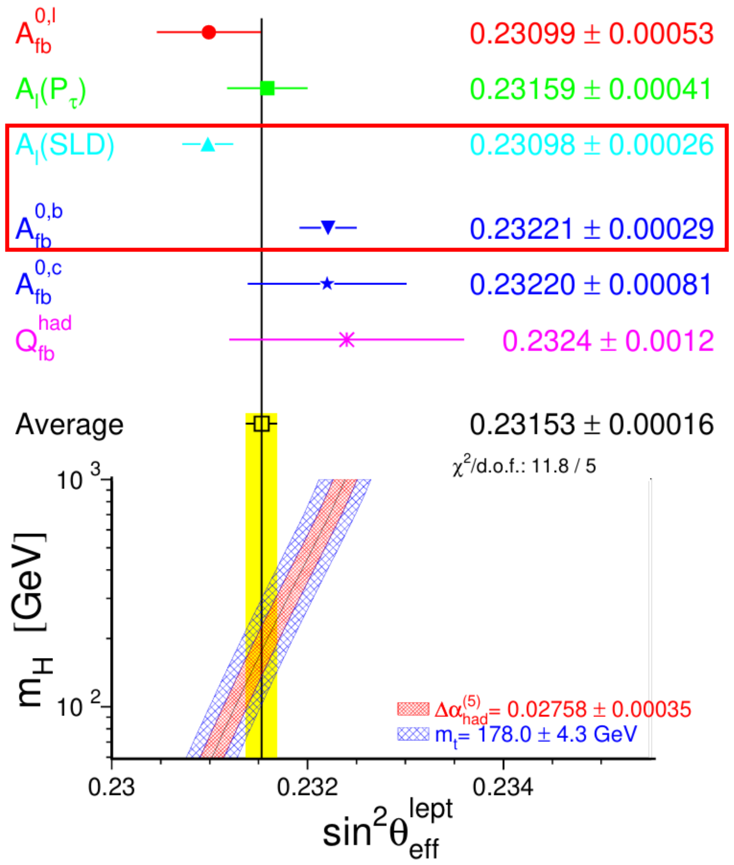
Motivation

- A 3.2 σ difference exists between the two most precise individual measurements (SLD and LEP)
- Potential BSM process dependence
- Indirect determinations of $\sin^2\theta_{\text{eff}}^{\text{lept}}$ are more precise than current experimental measurements
- Further studies needed – now performed by LHC experiments
- Can we reach Global EW fit precision with LHC?

[arXiv:1803.01853]



[arXiv:hep-ex/0509008]



Dilution

- Measured A_{FB} is diluted because it relies on PDFs to infer the initial state quark direction

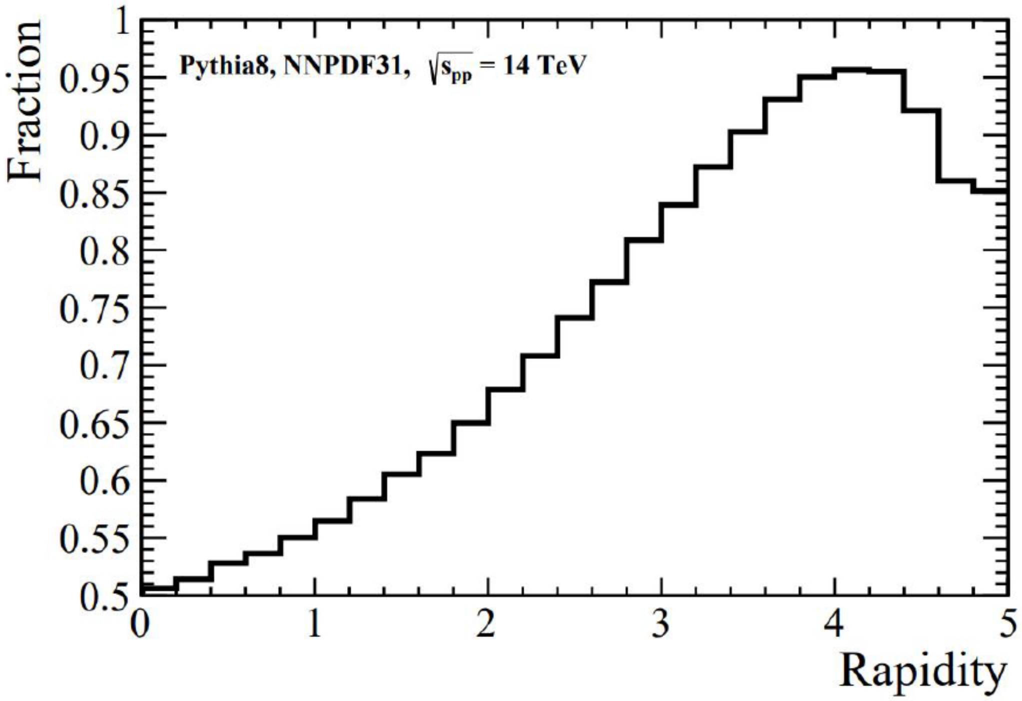
- At large rapidities have asymmetric initial state:
  - ❖ One parton at high $\boldsymbol{x}$ tends to be a valence quark
  - ❖ Other at low $\boldsymbol{x}$ tends to be an anti-quark

- **PDF uncertainty** is smaller in the forward region

- LHCb (with forward-region detector) seems to have an advantage here where the dilution between proton and parton level is reduced

- Can also decrease uncertainty with PDF profiling

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



[arXiv:1902.04070]

General Analysis Strategy

1. All backgrounds are estimated through simulation and then scaled to the data

2. Template fit for A_{FB}/A_4 distribution

3. Create MC predictions of the A_{FB}/A_4 distribution with different values of $\sin^2\theta_{eff}^{lept}$

4. Compare predictions with data to extract the value of $\sin^2\theta_{eff}^{lept}$ that best matches the data

ATLAS measurement

Setup

- Latest result from ATLAS-CONF-2018-037 with 2012 dataset @ $\sqrt{s}$ = 8 TeV → 20.2 fb^{-1}. Same dataset used in measuring angular coefficients

- 3 analysis channels:
  - $e - e$ in central region (ee_{CC})→ 6 million events
  - $\mu - \mu$ in central region ($\mu\mu_{CC}$) → 7.5 million events
  - $e - e$ in central and forward region (ee_{CF}) → 1.5 million events

  ➡ Significant enhancement compared to measurement using the central-central channels alone

Central: ($|\eta| < 2.4$)

Forward: ($2.5 < |\eta| < 4.9$)

- The background contamination for the ee_{CC} and $\mu\mu_{CC}$ channels amount to ~0.5%, whereas in the ee_{CF} it is about 3% in the Z pole region

Strategy

- Binned templates in dilepton mass and absolute rapidity → constrain PDF uncertainties
- Extract A_4 by fitting P_i polynomial templates to the angular distributions ($cos\theta, \phi$) of the leptons in the rest frame of the Z boson (Collins-Soper frame)
- Compare extracted angular coefficients to previous measurements, then focusing on A_4
- Use DYTurbo predictions for $A_4(\sin^2\theta^{\text{lept}}_{\text{eff}})$ at LO in EW and NLO in QCD, with $\alpha(0)$ scheme: $G_\mu, m_Z, \alpha(0)$
- Predictions are compared to measured data

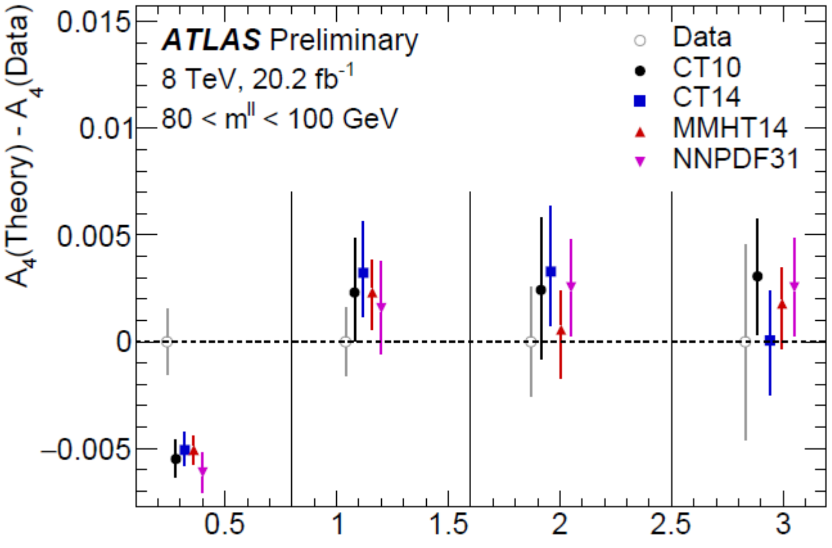
Results

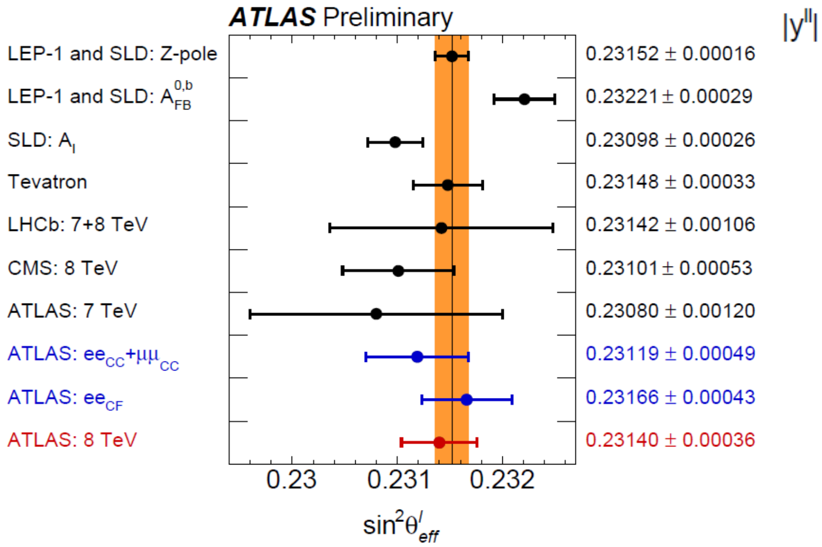
- Final result:

  $$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23140 \pm 0.00021_{stat} \pm 0.00016_{syst} \pm 0.00024_{PDF}$$

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

- PDFs are the biggest source of uncertainty
  - ❖ Uncertainty is estimated by assessing variations given each PDF set replica and profiling
  - ❖ Used MMHT14 PDF set as default





ATLAS-CONF-2018-037

CMS measurement

Setup

- Latest result from CERN-EP-2024-208 with full Run-2 pp collision dataset (2016-2018) @ $\sqrt{s}$ = 13 TeV → 138 fb^{-1}

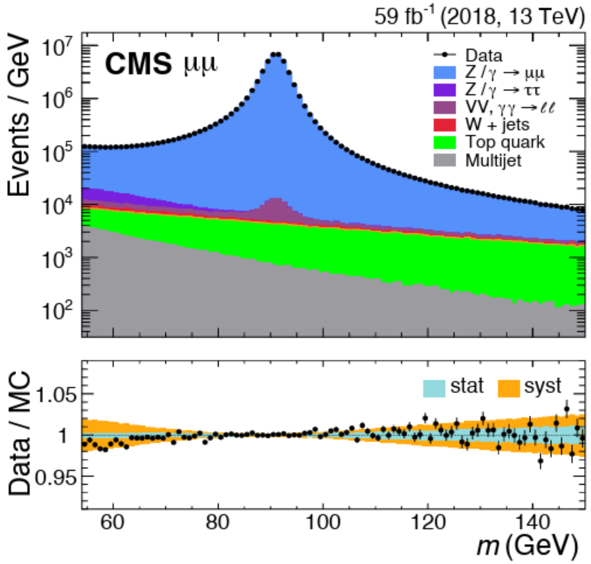
- Uses forward calorimeters to gather more electron events

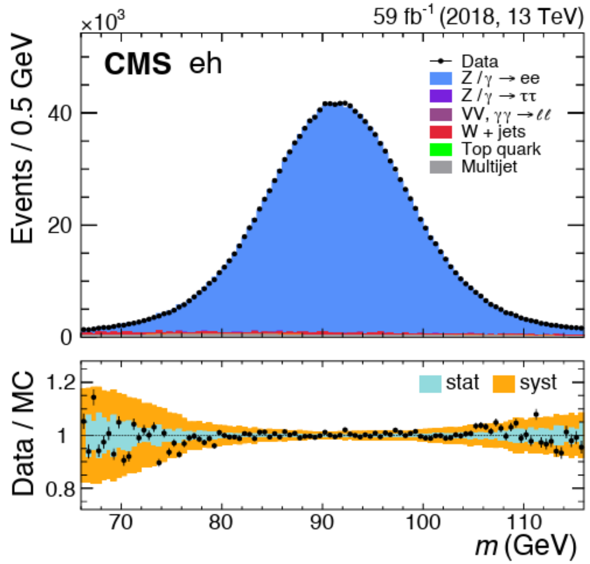
- 4 dilepton analysis channels:
  - $\mu\mu \rightarrow$ 111 million
  - $ee \rightarrow$ 59 million
  - $eg \rightarrow$ 5 million
  - $eh \rightarrow$ 3.3 million

- g – forward ECAL electron
- h – forward HCAL electron

	$\lvert\eta\rvert$	$p_{\mathrm{T,min}}^{\mathrm{leading}}$	$p_{\mathrm{T,min}}^{\mathrm{trailing}}$
$\mu\mu$	0.00–2.40	20 GeV	10 GeV
ee	0.00–2.50	25 GeV	15 GeV

	$\lvert\eta_{\mathrm{e}}\rvert$	$\lvert\eta_{\mathrm{g,h}}\rvert$	$p_{\mathrm{T,min}}^{\mathrm{e}}$	$p_{\mathrm{T,min}}^{\mathrm{g,h}}$
eg	0.00–2.50	2.50–2.87	30 GeV	20 GeV
eh	1.57–2.50	3.14–4.36	30 GeV	20 GeV

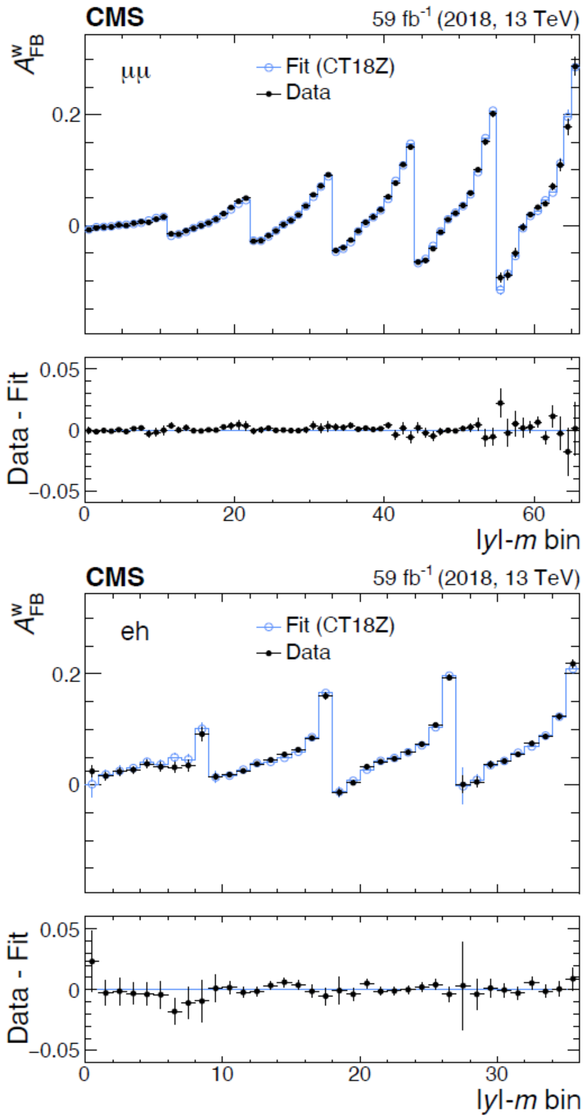




[CERN-EP-2024-208]

Strategy

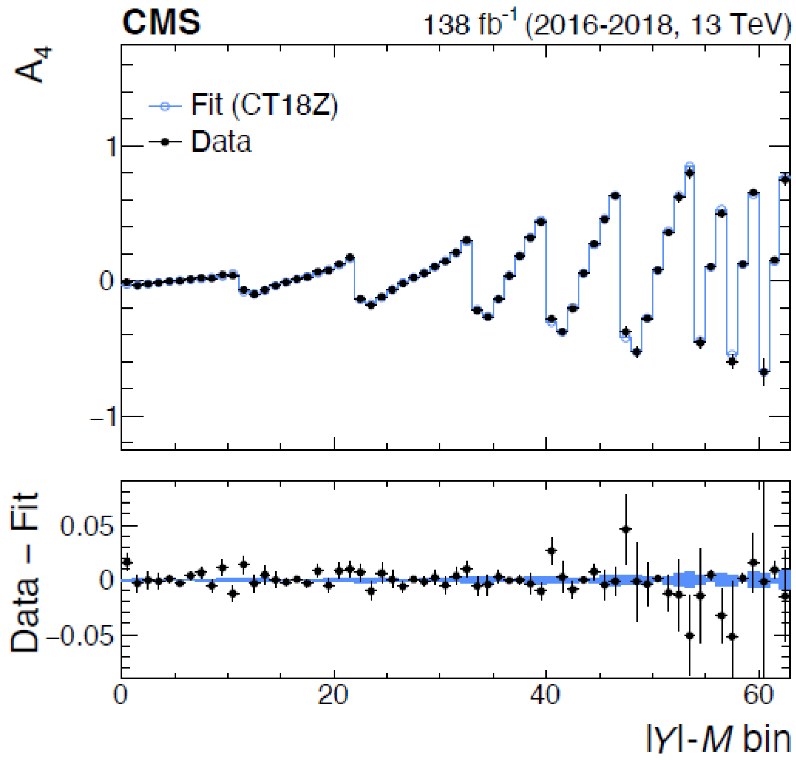
- Template fits of weighted **detector-level A_{FB}** in bins of mass and absolute rapidity
- 9 bins of dilepton rapidity, with $y^{ll} < 3.4$ and in 11 bins of dilepton mass, with $54 < m^{ll} < 150$ GeV
- Signal MC sample generated using the Zj-MiNNLOPS program in POWHEG-BOX at NNLO QCD
- EW corrections calculated at NLO with Powheg Z_EW-BMNNPV program using xW scheme: $G_\mu, \sin^2\theta^{lept}_{eff}, m_Z$
- Use **PDF profiling** to improve PDF uncertainties and reduce differences between final results that use different PDF sets



[CERN-EP-2024-208]

Strategy 2

- Template fits **unfolded A_4** in full phase space in bins of mass and absolute rapidity at Born level, pre-FSR
- Also use PDF profiling - float and extract $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ and PDF nuisance parameters simultaneously
- Result from unfolded A_4 can be used for reinterpretations and combinations
- Result compatible with first strategy



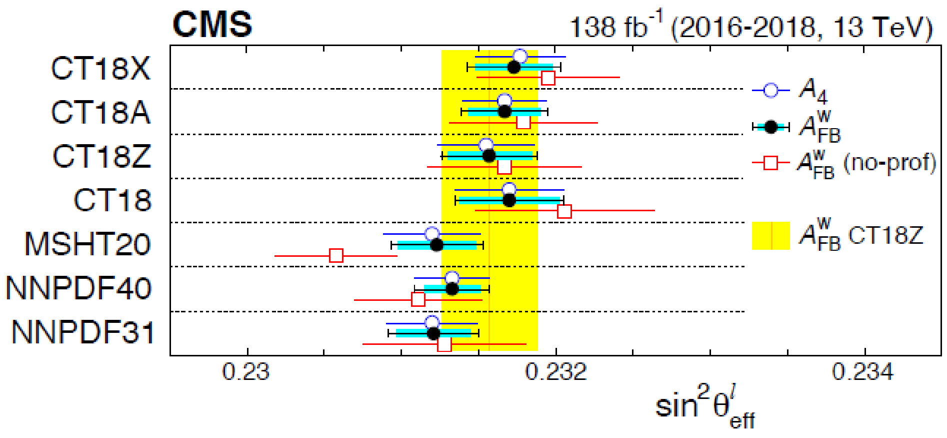
[CERN-EP-2024-208]

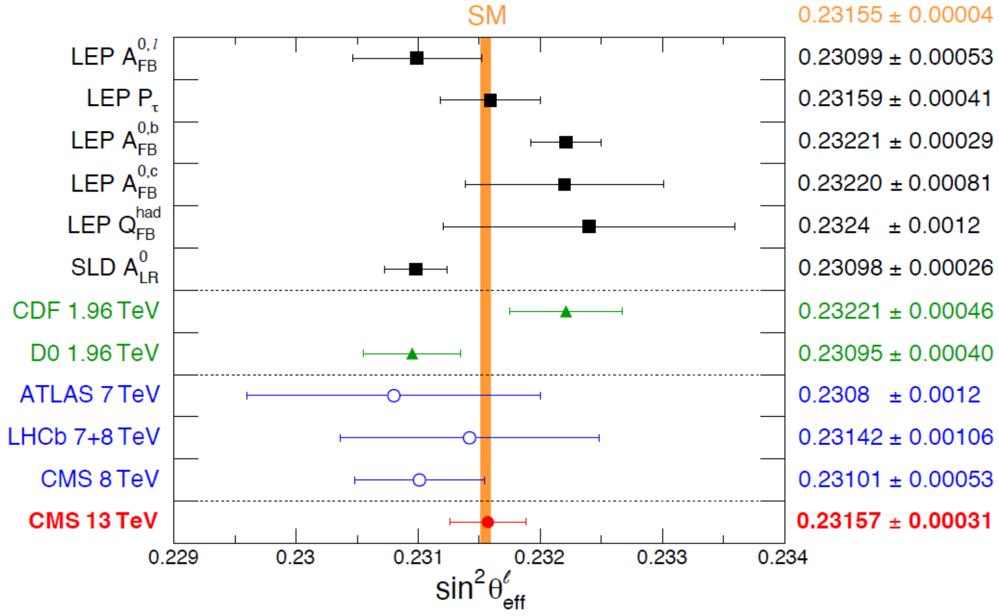
Results

- Final result:
  $\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23157 \pm 0.00010_{stat} \pm 0.00015_{exp} \pm 0.00009_{theo} \pm 0.00027_{PDF}$

- $\sin^2\theta_{\text{eff}}^{\text{lept}}$ result extracted from A_{FB} is the baseline result because systematics cancel out to a large extent

- PDFs are the biggest source of uncertainty
  - ❖ Used CT18Z PDF as default – covers the central values obtained by other sets





[CERN-EP-2024-208]

LHCb measurement

Setup

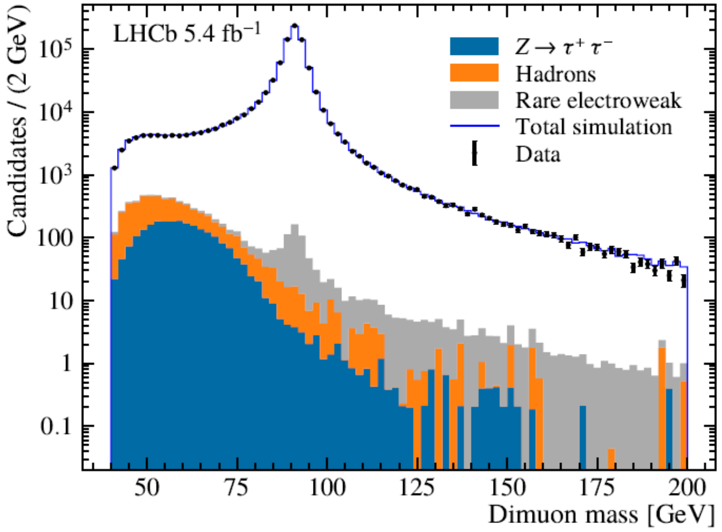
- Latest result from JHEP12(2024)026 with full Run-2 pp collision dataset (2016-2018) @ $\sqrt{s} = 13$ TeV → 5.3 fb^{-1} (× 26 smaller)

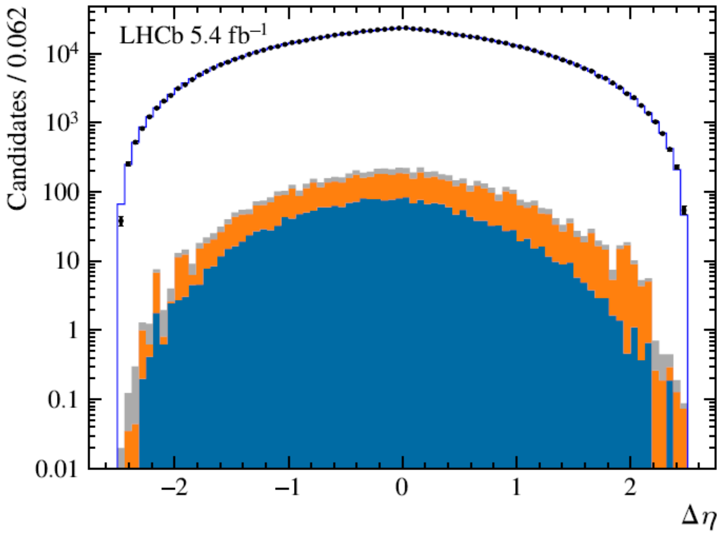
- Fiducial region:
  - ❖ $2.0 < \eta_\mu < 4.5$
  - ❖ $p_T^\mu > 20$ GeV/c
  - ❖ $66 < M_{\mu\mu} < 116$ GeV/c^2

- 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 **2×10^{-3}**

- Roughly 860,000 events selected for this measurement





[JHEP12(2024)026]

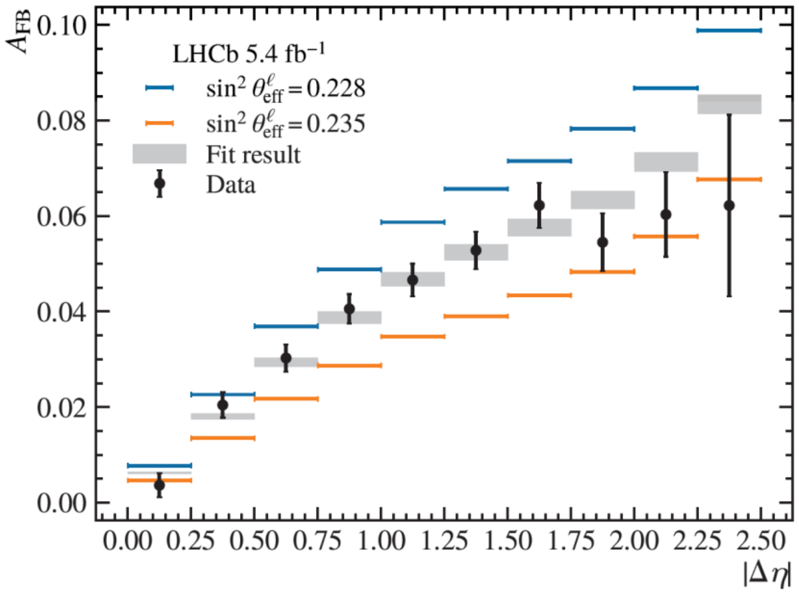
Strategy

- Fit A_{FB} in (10) intervals of $|\Delta\eta|$ with a single mass bin ($\cos\theta^* \sim \tanh\frac{\Delta\eta}{2}$) - improves sensitivity to the weak mixing angle by 14% in simulation

- Unfold using simulation to get generator-level A_{FB}

- $\sin^2\theta_{\text{eff}}^{\text{lept}}$ is extracted using predictions of $A_{FB}(\sin^2\theta_{\text{eff}}^{\text{lept}})$ at **NLO** in the strong and EW couplings using **POWHEG-BOX -** uses xW scheme: $G_\mu, \sin^2\theta_{eff}^{lept}, m_Z$

- Compare data with predictions to extract the value of $\sin^2\theta_{\text{eff}}^{\text{lept}}$ that best corresponds to the data

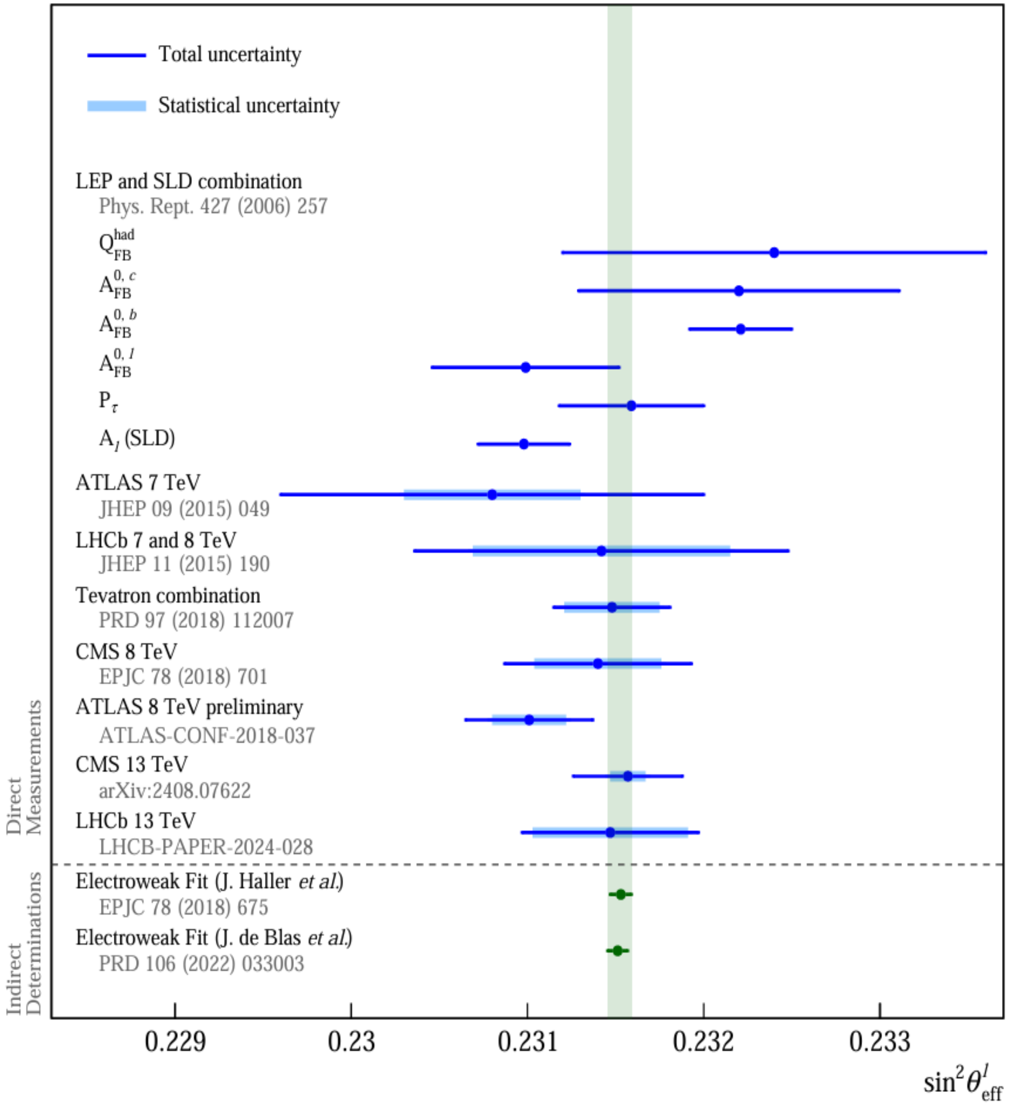


Interval number	Interval	A_{fb}
0	$0.00 < \|\Delta\eta\| \leq 0.25$	$0.0036 \pm 0.0025 \pm 0.0001$
1	$0.25 < \|\Delta\eta\| \leq 0.50$	$0.0204 \pm 0.0027 \pm 0.0002$
2	$0.50 < \|\Delta\eta\| \leq 0.75$	$0.0303 \pm 0.0028 \pm 0.0002$
3	$0.75 < \|\Delta\eta\| \leq 1.00$	$0.0406 \pm 0.0031 \pm 0.0003$
4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

[JHEP12(2024)026]

Results

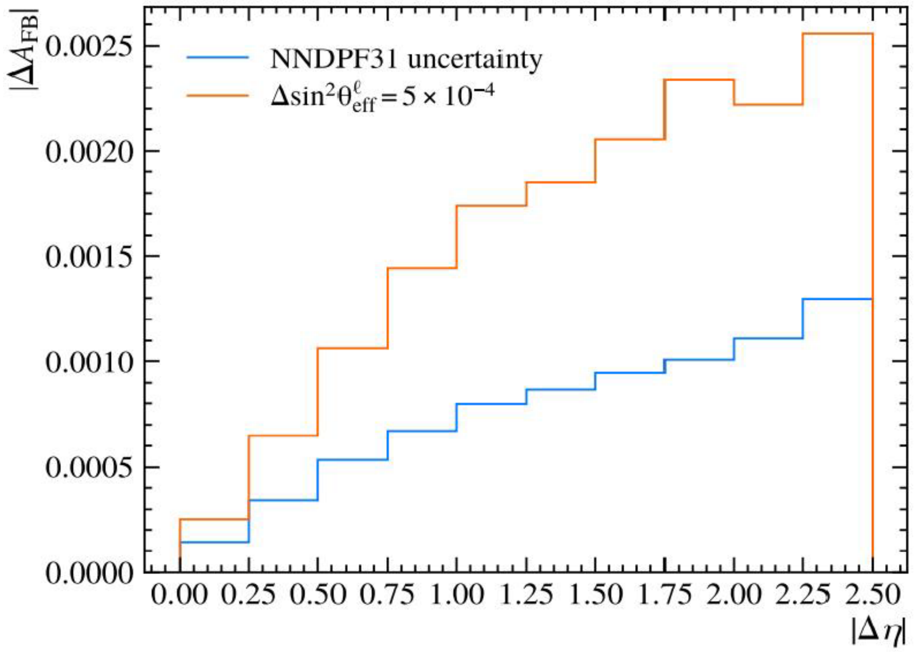
- Final result:
  $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}} = 0.23152 \pm 0.00044_{stat} \pm 0.00005_{syst} \pm 0.00022_{theo}$
- Experimental uncertainty is **much smaller** than the statistical uncertainty
- Consistent with previous measurements and indirect determinations from Global EW fit
- Aim to improve statistical uncertainty with LHCb Upgrade I, which includes a **fivefold** increase in instantaneous luminosity



[JHEP12(2024)026]

PDF uncertainty

- PDF uncertainty is estimated by assessing variations given each PDF set replica
- Use NNPDF31 PDF set as default
- **PDF uncertainty << statistical uncertainty** because of the unique LHCb acceptance
- Profiling was not used to reduce PDF uncertainty
- Advantage LHCb offers so far is that by not profiling we are able to examine if the profiled results are robust



[JHEP12(2024)026]

NEW

Z boson mass

Intro

- LEP experiments measured the Z boson mass with 2 MeV precision
- With LHC, Z boson mass have been primarily in the context of calibrations for the W mass analyses
- Can LHC collectively challenge LEP?

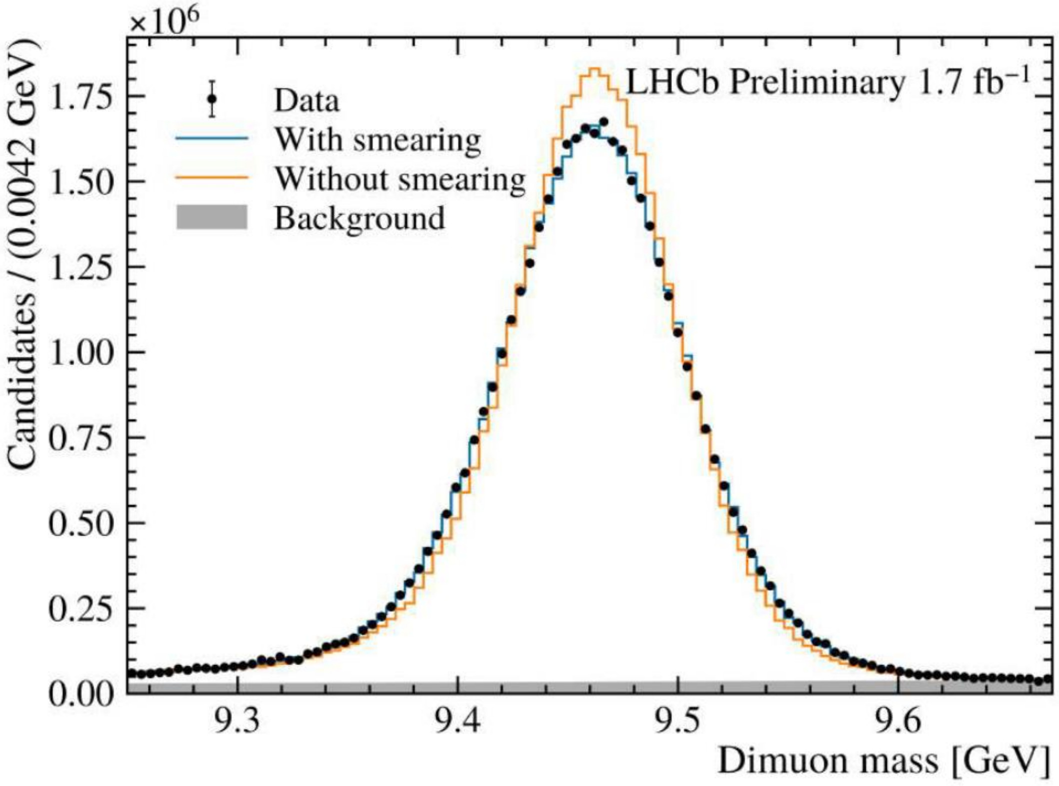
[PDG]

VALUE (GeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
91.1876±0.0021 OUR FIT					
91.1852±0.0030	4.57M	[1] ABBIENDI	01A	OPAL	E^{ee}_{cm}= 88–94 GeV
91.1863±0.0028	4.08M	[2] ABREU	00F	DLPH	E^{ee}_{cm}= 88–94 GeV
91.1898±0.0031	3.96M	[3] ACCIARRI	00C	L3	E^{ee}_{cm}= 88–94 GeV
91.1885±0.0031	4.57M	[4] BARATE	00C	ALEP	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
91.1872±0.0033		[5] ABBIENDI	04G	OPAL	E^{ee}_{cm}= LEP1 + 130–209 GeV
91.272 ±0.032 ±0.033		[6] ACHARD	04C	L3	E^{ee}_{cm}= 183–209 GeV
91.1875±0.0039	3.97M	[7] ACCIARRI	00Q	L3	E^{ee}_{cm}= LEP1 + 130–189 GeV
91.151 ±0.008		[8] MIYABAYASHI	95	TOPZ	E^{ee}_{cm}= 57.8 GeV
91.74 ±0.28 ±0.93	156	[9] ALITTI	92B	UA2	$E^{p\overline{p}}_{cm}$= 630 GeV
90.9 ±0.3 ±0.2	188	[10] ABE	89C	CDF	$E^{p\overline{p}}_{cm}$= 1.8 TeV
91.14 ±0.12	480	[11] ABRAMS	89B	MRK2	E^{ee}_{cm}= 89–93 GeV
93.1 ±1.0 ±3.0	24	[12] ALBAJAR	89	UA1	$E^{p\overline{p}}_{cm}$= 546,630 GeV

Analysis strategy

- $Z \to \mu\mu$; **2016 data**; 1.7 fb^{-1} - feasibility study
- Uses Weak Mixing analysis tools
- Use $\Upsilon(1S) \to \mu\mu$ for momentum calibration, $J/\psi \to \mu\mu$ as cross-check
- Dimuon mass fit comparing full simulation with the data
- Reweight the events to NLO accuracy
- Uses POWHEG box with EW scheme: G_μ, m_W, m_Z

[LHCb-PAPER-2025-008]



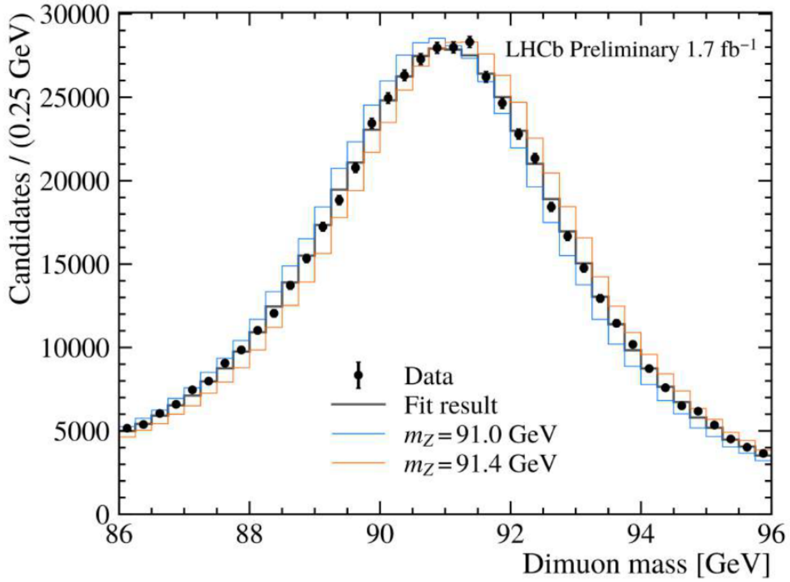
$$p^\pm \to \left(1 + \alpha + \frac{\beta}{p^\pm} \mp \delta p^\pm\right)(1 + a\mathcal{R}_1\sigma_1)(1 + b\mathcal{R}_2\sigma_2 p^\pm)p^\pm$$

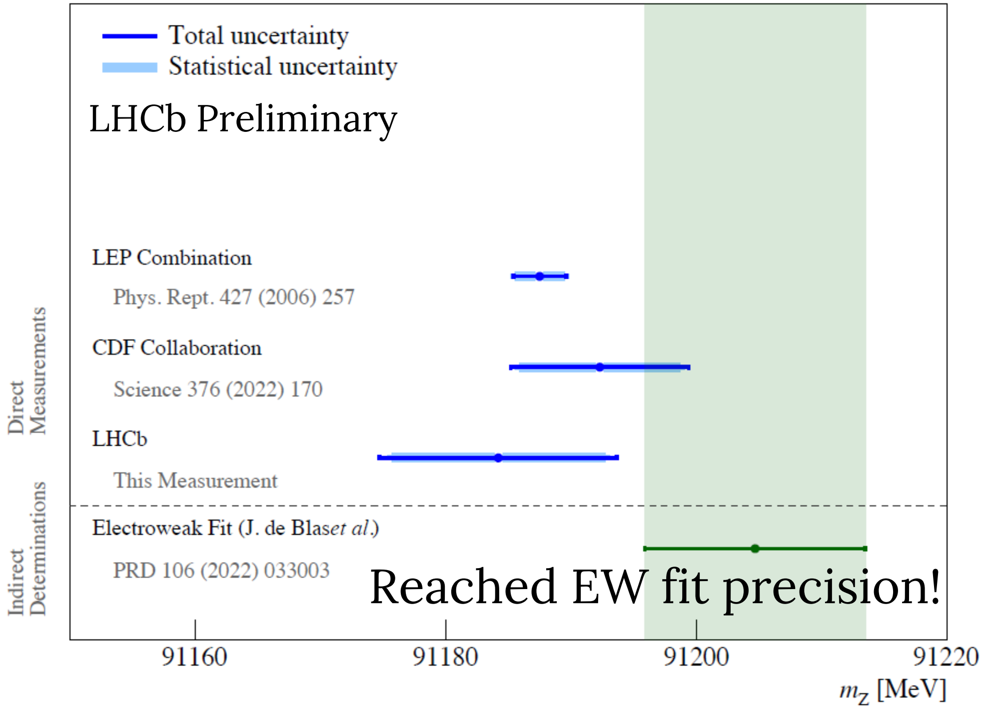
Results and status

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**

LHCb-PAPER-2025-008 targeting Phys. Rev. Lett.

Latest CERN seminar talk





$$m_Z = 91184.2 \pm 9.5 \text{ MeV (8.5 MeV statistical)}$$

Summary and prospects

Summary – Weak mixing angle

Experiment	$\sqrt{s}$ [TeV]	Luminosity $[\mathrm{fb}^{-1}]$	$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$	Statistical uncertainty	Systematic uncertainty	Theory uncertainty (including PDF)	**Total uncertainty**
ATLAS	8	20.2	0.23140	0.00021	0.00016	0.00024	0.00036
CMS	13	138	0.23157	0.00010	0.00015	0.00028	0.00031
LHCb	13	5.3	0.23152	0.00044	0.00005	0.00022	0.00049

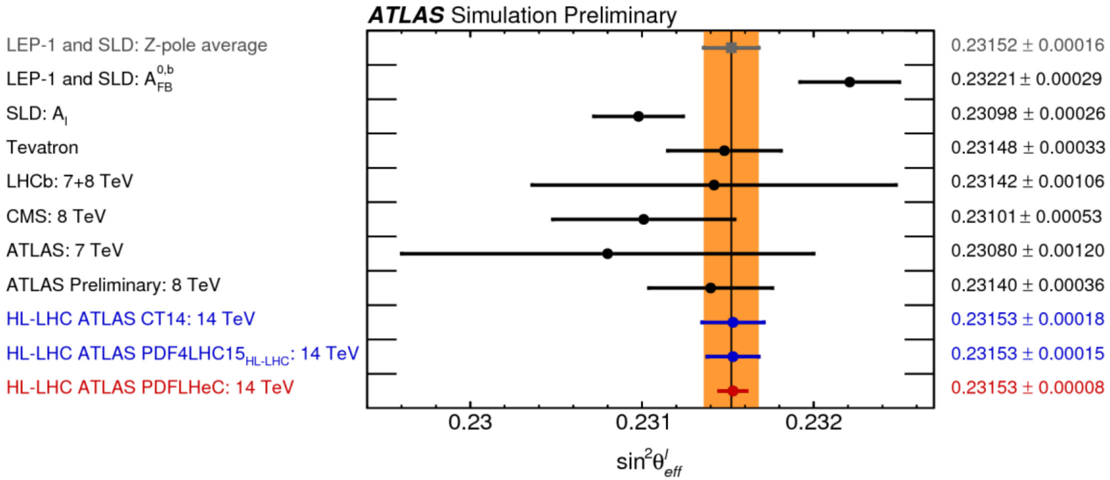
- LHCb suffers from statistics
- ATLAS EXPERIMENT and CMS suffer from PDFs

Experiment	Strategy	Pseudorapidity region	Default PDF set	PDF profiling
ATLAS	A_4	$\eta < 3.6$	MMHT14	Yes
CMS	A_{FB} (+unfolded A_4)	$\eta < 3.4$	CT18Z	Yes
LHCb	A_{FB}	$\eta < 4.5$	NNPDF31	No

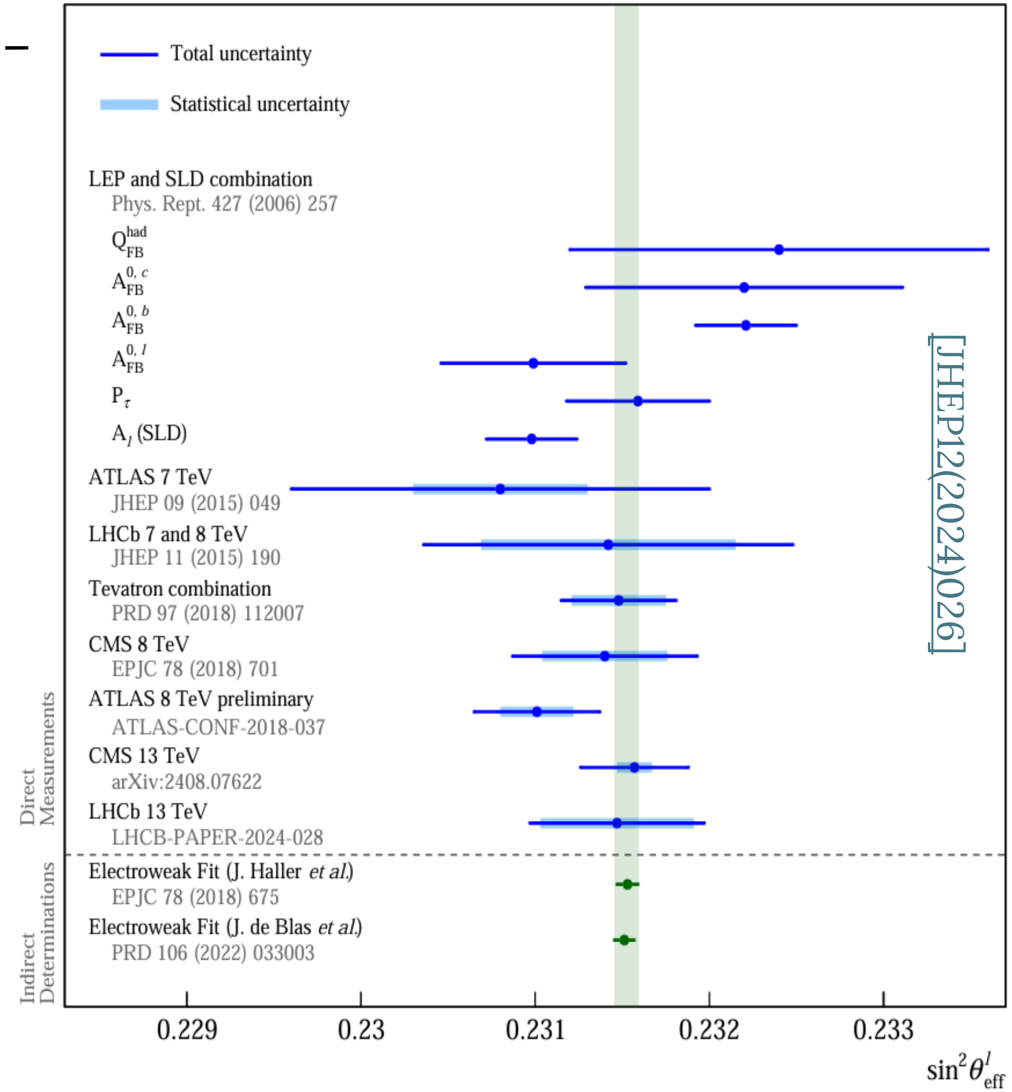
Summary and prospects

- Run 2 @ $\sqrt{s} = 13$ TeV measurements from CMS and LHCb – still waiting for ATLAS
- Precision and accuracy of measurement limited by PDFs
- Already looking forward to Run 3 results
- Aim to beat LEP/SLD ($26 - 29 \times 10^{-5}$)

- m_Z with LHCb full Run 2 data → ~5 MeV precision
- LHC average could challenge LEP soon!



[arXiv:1902.04070]



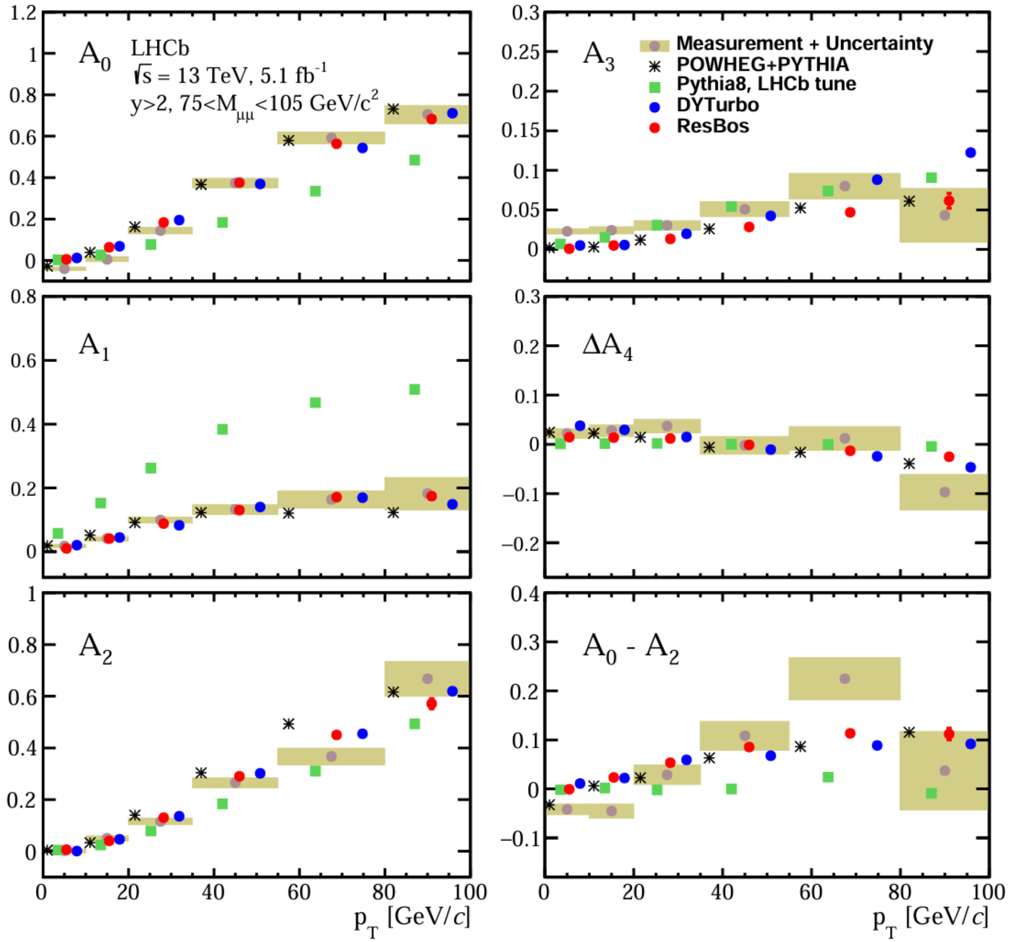
[JHEP12(2024)026]

Backup Slides

Angular coefficients - LHCb

$$\frac{d\sigma}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}}$$

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



PDF profiling

- Compare experimental data to PDF predictions to find best matches
- Reweight or rescale PDF replicas based on their agreement with the data to create a profiled PDF set that reflects the new constraints
- Use the profiled PDFs to reduce uncertainties
- Hessian sets quantify PDF uncertainties, showing error bands and variations in the PDFs