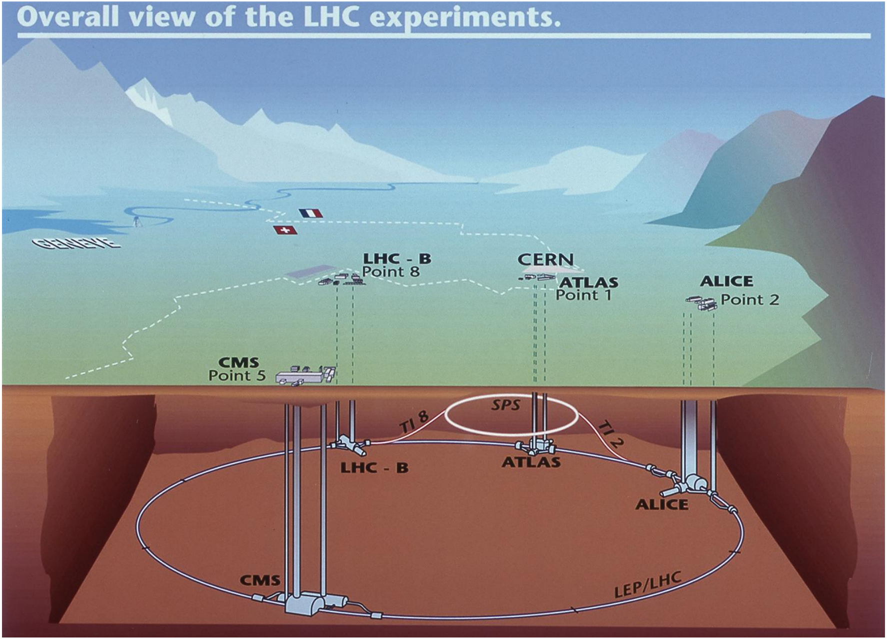
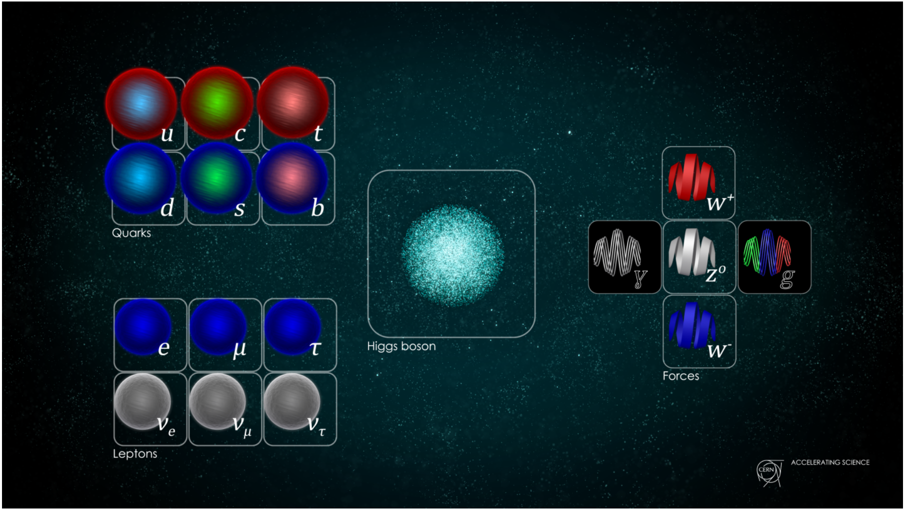
Recent LHCb results in precision electroweak physics, and outlook for the upcoming Run 3 data set

Nathan Grieser

August 26, 2025


Overall view of the LHC experiments.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

Credit: CERN


u
c
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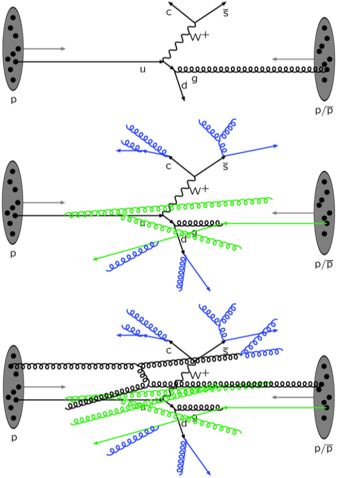
Leptons
Higgs boson
W+
γ
Z0
g
W-
Forces
CERN
ACCELERATING SCIENCE



Proton bunches collide at rates of 40K times per second

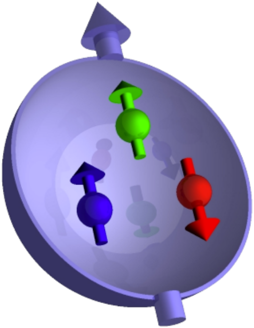
Hadron collisions provide a very high energy environment

- But very noisy!

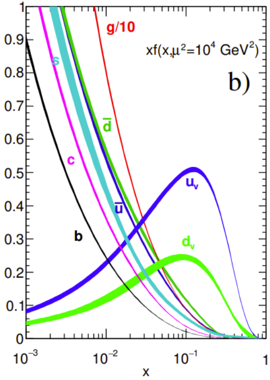
Interactions rarely create **electroweak bosons (*W* and *Z*)** which rapidly decay into particles that are detectable (electrons, muons, hadrons)

Understanding the Proton – A probabilistic system

Protons at the LHC carry a known energy, but the collisions do not!



Credit: A. Accardi



Credit: PDG

Each parton carries a probabilistic amount of the proton energy

→ Numerous collaborations calculate these "Parton Distribution Functions"

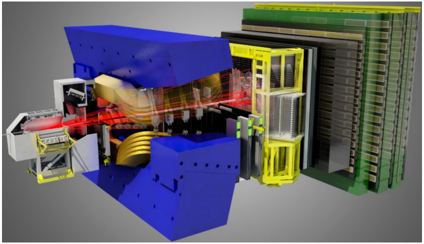
→ Forward experiments like LHCb cover a unique *x*-space

LHCb Detector Overview

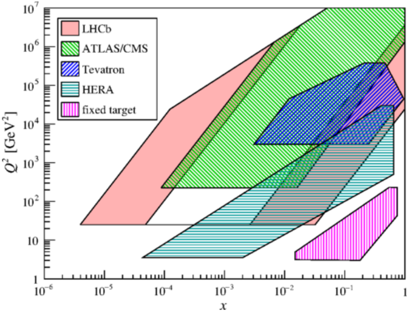
JINST 3 (2008) S08005

→ LHCb Strengths of Design:

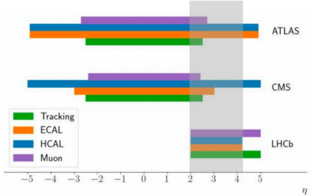
- Long tracking distances for improved momentum calibrations
- Ring-Imaging Cherenkov (RICH) detectors for particle identification (PID)



- Forward design allows for LHC-unique coverage of low- and high-x partons

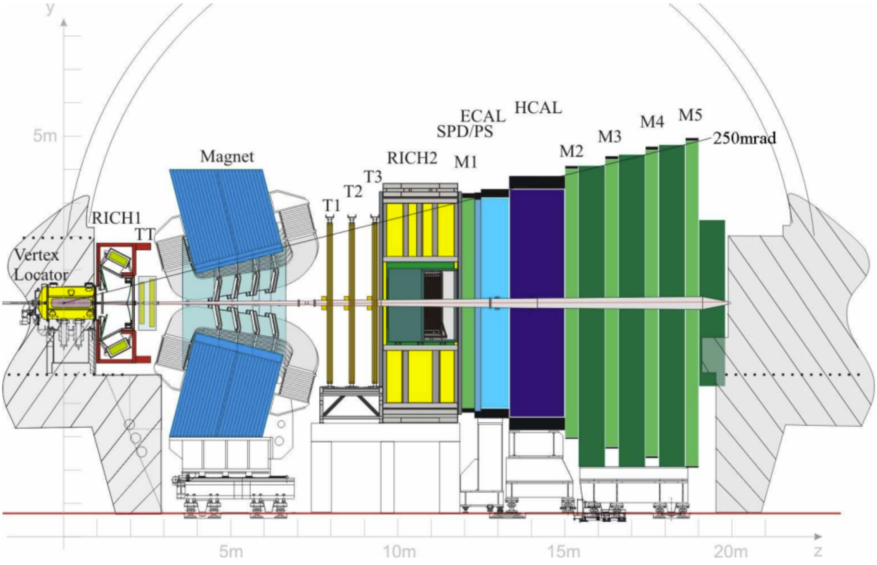


PRD 93, 074008 (2016)

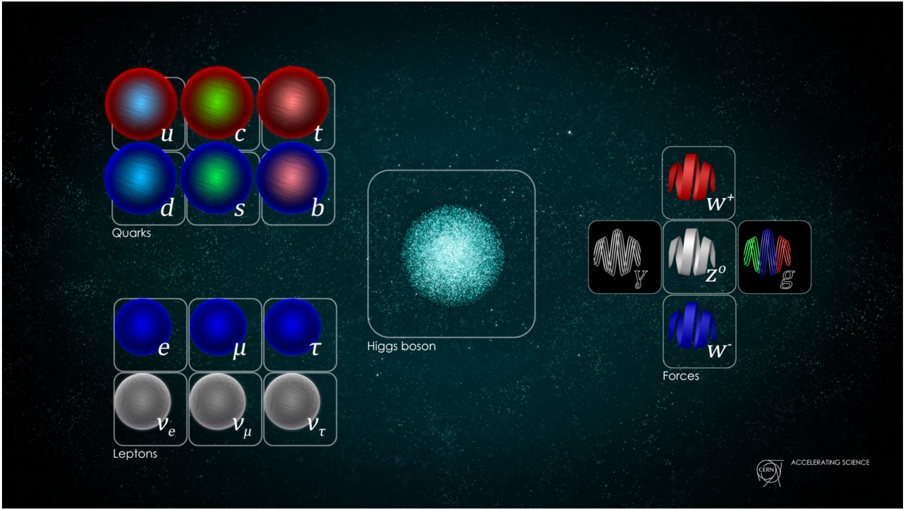


LHCb Detector Overview

JINST 3 (2008) S08005



Understanding the Fundamental Building Blocks



Understanding the Fundamental Building Blocks

Precisely Measuring Electro-Weak Theory: A probe of New Physics

Choice of three free parameters of electroweak theory:

$$m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_\mu}(1 + \Delta r)$$

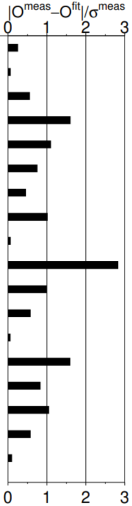
A lot of recent activity on this front with numerous collaborations producing interesting measurements of dependent values

$\rightarrow$ Measured values deviating from prediction can give evidence of new physics in the higher order corrections (Δr)

State of the Field Post-LEP

arXiv.hep-ex/0509008

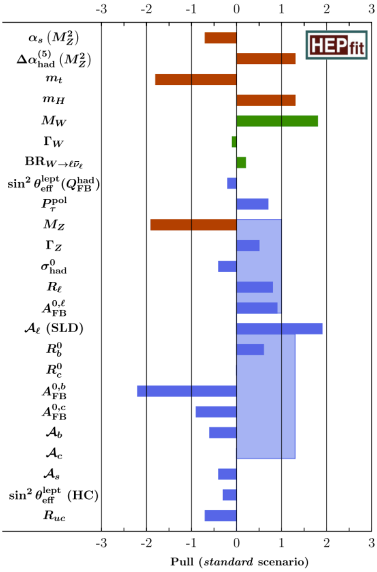
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5

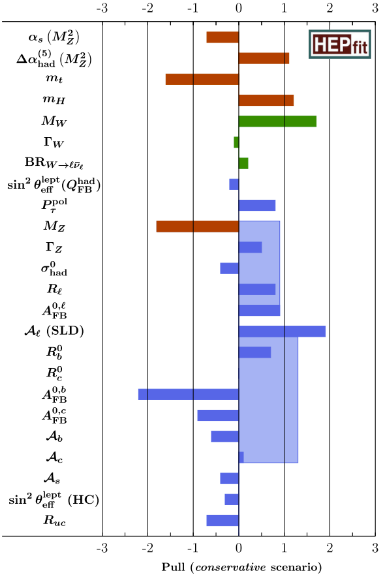


State of the Art 2005

State of the Field

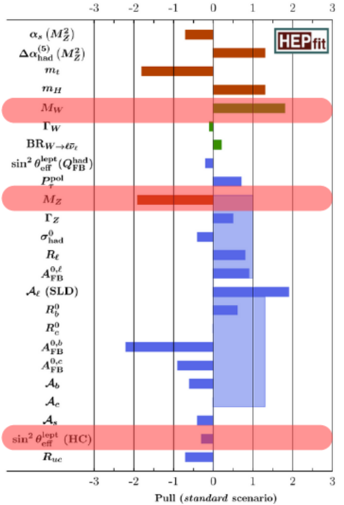
Phys. Rev. D. 106 (2022) 033003





State of the Field

Phys. Rev. D. 106 (2022) 033003

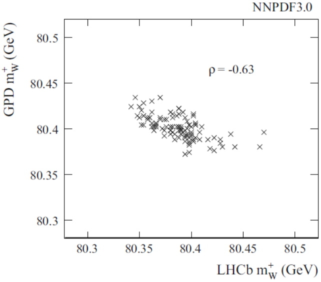


LHCb has produced results of the following in the past year:

1. m_W
2. $\sin^2\theta_{\mathrm{eff}^\ell}$
3. m_Z

Why LHCb? Global Contributor!

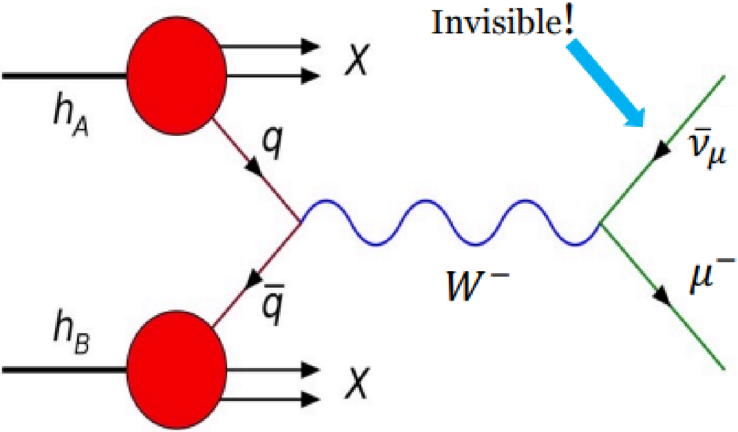
Eur. Phys. J. C 75, 601 (2015)



The unique forward coverage of LHCb contributes to an **anti-correlation effect** on the global PDF uncertainty of m_W measurements

PDFs	Experiments	δ_{PDF} (MeV)	α
PDF4LHC(2-sets)	2 × GPD	10.5	(0.26, 0.74, 0, 0)
PDF4LHC(2-sets)	2 × GPD + LHCb	7.7	(0.30, 0.45, 0.21, 0.04)
PDF4LHC(3-sets)	2 × GPD	16.9	(0.50, 0.50, 0, 0)
PDF4LHC(3-sets)	2 × GPD + LHCb	12.7	(0.43, 0.41, 0.11, 0.04)
NNPDF30	2 × GPD	5.2	(0.50, 0.50, 0, 0)
NNPDF30	2 × GPD + LHCb	3.6	(0.35, 0.47, 0.16, 0.02)
MMHT2014	2 × GPD	9.2	(0.45, 0.55, 0, 0)
MMHT2014	2 × GPD + LHCb	4.6	(0.39, 0.14, 0.46, 0)
CT10	2 × GPD	11.6	(0.33, 0.67, 0, 0)
CT10	2 × GPD + LHCb	6.3	(0.38, 0.20, 0.40, 0.03)

Measuring the W Boson Mass at the LHC



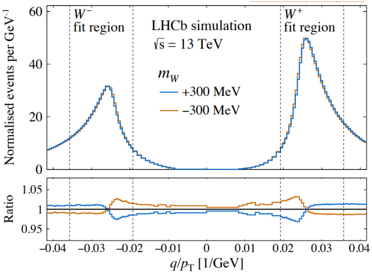
Cannot fully-reconstruct the W!

$\rightarrow$ Need a very precise muon momentum extraction!

Measuring the W Boson Mass at LHCb

JHEP 01 (2022) 036

- $W^{\pm} \to \mu^{\pm}\nu_{\mu}$ produces a single, well-isolated muon
- m_W sensitivity available from the p_T^{μ} distribution $\rightarrow$
- Need precise understanding of factors that impact p_T^{μ} shape $\downarrow$



Experimental modelling:

Muon momentum calibration, detector misalignment, reconstruction and selection efficiences

Theoretical modelling:

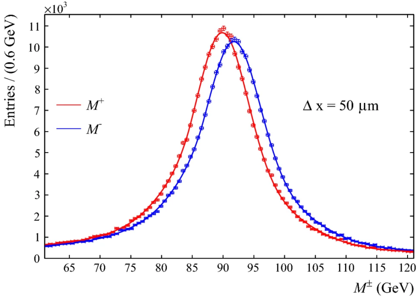
W cross-section predictions, QED FSR, PDFs

m_W Momentum Calibration

JHEP 01 (2022) 036

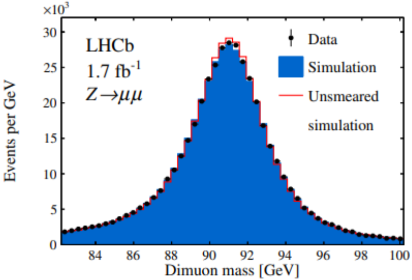
Curvature biases introduced from imperfect detector alignment are corrected using the pseudo-mass method:

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



A stochastic smearing method is applied to the simulation, extracted simultaneously from samples of J/Ψ, ϒ, and Z bosons decaying to a pair of muons:

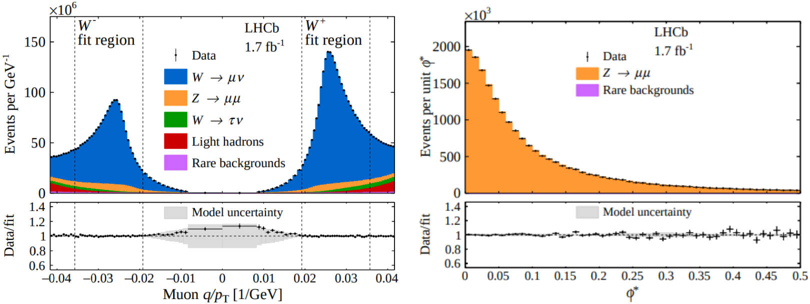
$$\frac{q}{p} \to \frac{q}{p \cdot \mathcal{N}(1+\alpha, \sigma_{\mathrm{MS}})} + \mathcal{N}(\delta, \frac{\sigma_\delta}{\cosh\eta})$$



Measuring the W Boson Mass at LHCb

JHEP 01 (2022) 036

Final m_W result extracted with a simultaneous fit:

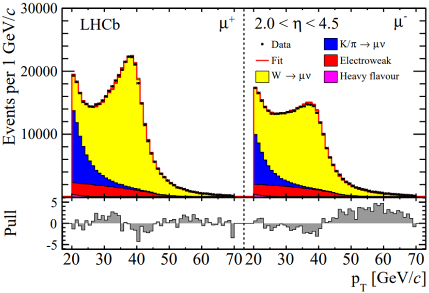


- Overall uncertainty of 32 MeV (23 MeV stat.)
  $\rightarrow$ Factor 3 off world-leading CMS result
- Turning the crank on full Run 2 cuts stat uncertainty in half
  $\rightarrow$ Need to add intuition!

Measuring the W Boson Mass at LHCb – A side-effect

Previous m_W measurements fit $\frac{d\sigma}{dp_T^{\mu}}$ at the reconstructed level

- Requires a fully-calibrated simulation to fit
- Theoretical model deeply baked into the analysis
- Theorists must provide new model and ask us to re-run analysis



JHEP 12 (2014) 079

Instead: Measure $\frac{d\sigma}{dp_T^{\mu}}$ directly, then extract m_W ↑

Measuring the W Boson Mass at LHCb

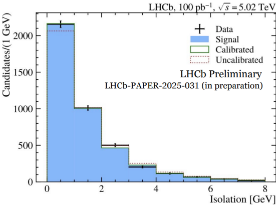
LHCb-PAPER-2025-031 (In Preparation)

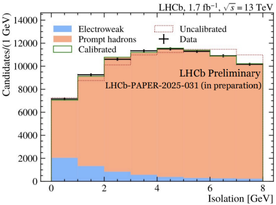
Perform a $\frac{d\sigma}{dp_T^\mu}$ measurement on 2017 5 TeV pp run as proof of principle:

- Perform background-subtraction (and the usual calibrations! ↓) in a dimension which is less theory-dependent:

  Muon Isolation[1]!

- Fit I^μ in bins of p_T^μ to translate to $\frac{d\sigma}{dp_T^\mu}$
- Compare integrated cross sections to various predictions and PDFs
- Fit $\frac{d\sigma}{dp_T^\mu}$ with a semi-arbitrary model to extract m_W



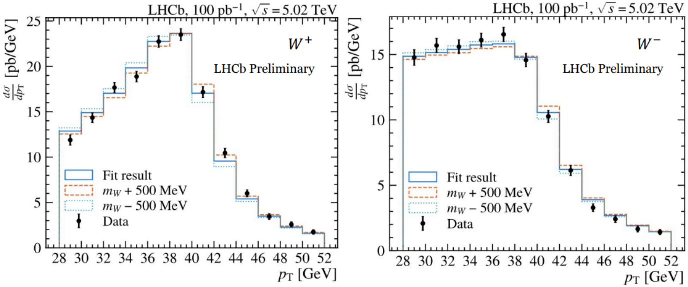


[1] Sum of transverse momentum of charged and neutral particles surrounding the muon

Measuring the W Boson Mass at LHCb

LHCb-PAPER-2025-031 (In Preparation)

Extract m_W from a fit to $\frac{d\sigma}{dp_T^\mu}$:



$\rightarrow$ Scaling method to full Run 2 data set gives 12 MeV stat uncertainty

Provides first proof-of-principle $\frac{d\sigma^W}{dp_T^\mu}$ measurement

to extract m_W at the LHC!

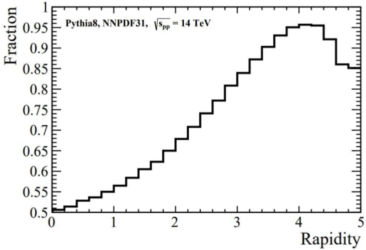
Measurement of the Effective Leptonic Weak Mixing Angle — JHEP 12(2024)026

Significant probe of EW theory; relation of U(1) and SU(2) gauge couplings

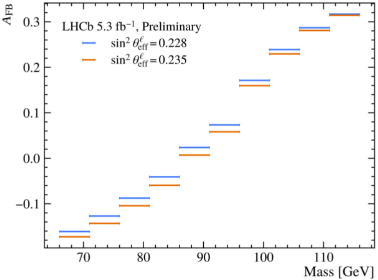
$$\sin^2\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right) \; ; \; \sin^2\theta_W = \frac{1}{\kappa_\ell}\sin^2\theta^\ell_{\mathrm{eff}}$$

q–$\bar{q}$ differences at high-x and low-x has significant sculpting of Z relations to initial-state partons

Fraction of events with Z in line with initial-state quark ↓



LHCB-PUB-2018-013

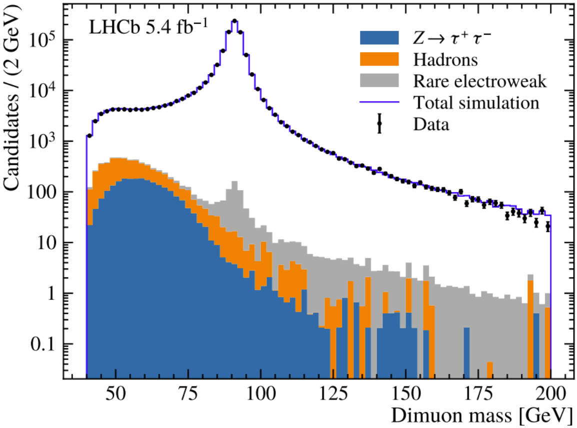


↑ Extract $\sin\theta_W$ using A_{FB}:

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

Mass dependent $\sin^2\theta_W$ no sensitivity

Measurement of the Effective Leptonic Weak Mixing Angle JHEP 12(2024)026



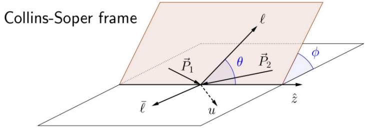
↑ Can use single, large window mass bin due to very pure signal selection

$$66\mathrm{GeV} \leq M_Z \leq 116\mathrm{GeV}$$

Measurement of the Effective Leptonic Weak Mixing Angle — JHEP 12(2024)026

Separate events at large and small $\cos\theta^*$ to increase sensitivity

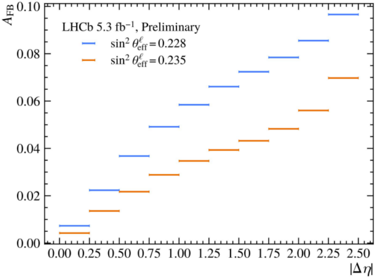
$$\frac{d\sigma}{d\cos\theta^*} \propto 1 + \cos^2\theta^* + \frac{8}{3} A_{FB} \cos\theta^*$$



Definition of **forward** and **backward** is more complicated at LHC than at lepton colliders due to differences in quark vs. proton information:

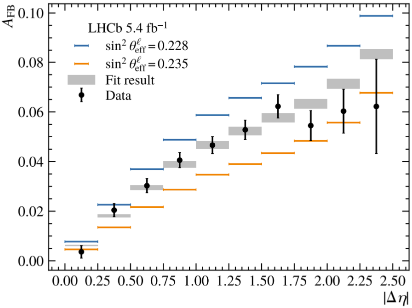
$$\text{At LEP: } \vec{P}_i \equiv \vec{p}_{e^\pm}$$
$$\text{At LHC: } \vec{P}_i \equiv \vec{p}_{q/\bar{q}} \sim \vec{p}_p$$

Bin the measurement of A_{FB} in $\Delta\eta$ of the muons shows significant sensitivity to $\sin^2\theta_W$ ↓



Measurement of the Effective Leptonic Weak Mixing Angle — JHEP 12(2024)026

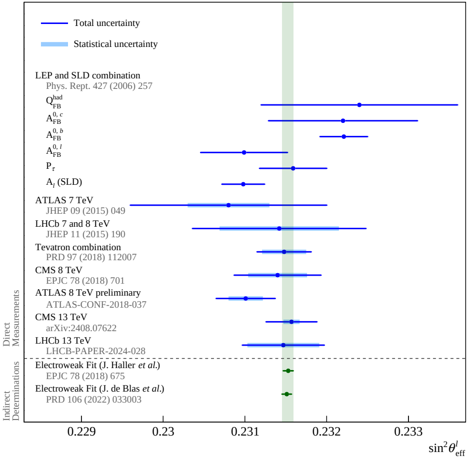
Results: $\sin^2\theta^{\ell}_{\text{eff}} = 0.23152 \pm 0.00044\ (\text{stat.}) \pm 0.00005\ (\text{syst.}) \pm 0.00022\ (\text{theory})$



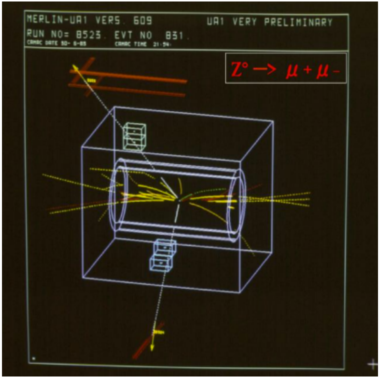
Stats are significant limitation in the most sensitive bins

→ Look out for Run 3!

No deviation from SM observed



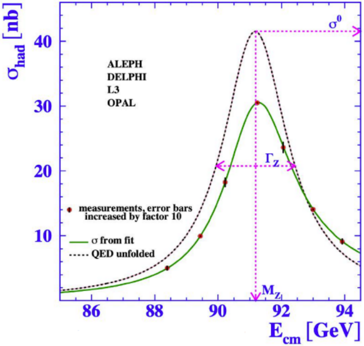
Measuring the Z Boson Mass – A brief (recent) history



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

Discovery of Z boson and first m_Z measurement at UA1 using $p\bar{p}$ collisions
Refinement made with UA2, but still GeV scale uncertainties

Large Electron–Positron (LEP) collider enters the game:

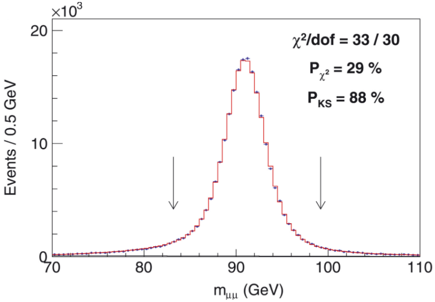


Phys. Rept. 427 (2006) 257

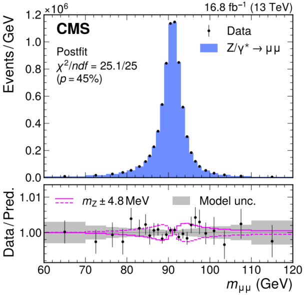
Experiment tuned to Z resonance allows m_Z access through energy scans
$\rightarrow$ 2 MeV precision in final combination!

Measuring m_Z At Hadron Colliders

Question: Can hadron collider experiments compete with LEP m_Z precision?



Science 374 (2021) 6568



arXiv.2412.13872

CDF: $m_Z = 911923 \pm 7.1$ MeV **CMS:** $m_Z - m_{PDG} = \text{-}2.2 \pm 4.8$ MeV

The right scale, but some work to do!

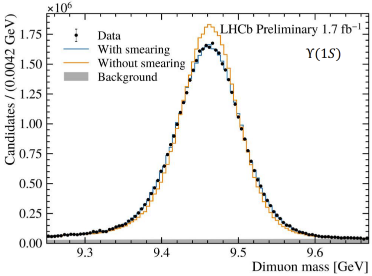
Measurement of Z Boson Mass

arXiv.2505.15582

Goal: Further probe of EW theory by measuring m_Z with a dimuon mass distribution

Clean signal selection $\rightarrow$ Precision to come from calibrations!

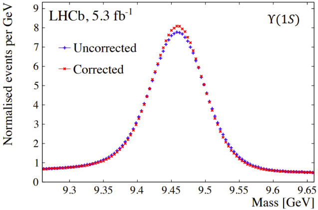
$\Upsilon(1S) \rightarrow \mu^+\mu^-$ as calibration channel for both data $\rightarrow$ and MC $\downarrow$

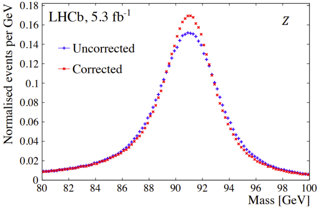


$\rightarrow$ Full detector response is dominant systematic

JINST 19 P03010

Data correction with pseudo-mass method

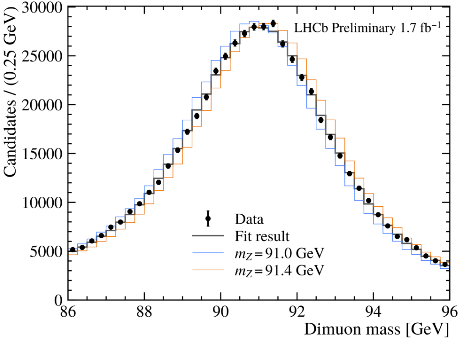




Measurement of Z Boson Mass

arXiv.2505.15582

Mass Extraction: Simple fit to the dimuon mass spectrum following all calibrations



Analysis using 2016 dataset

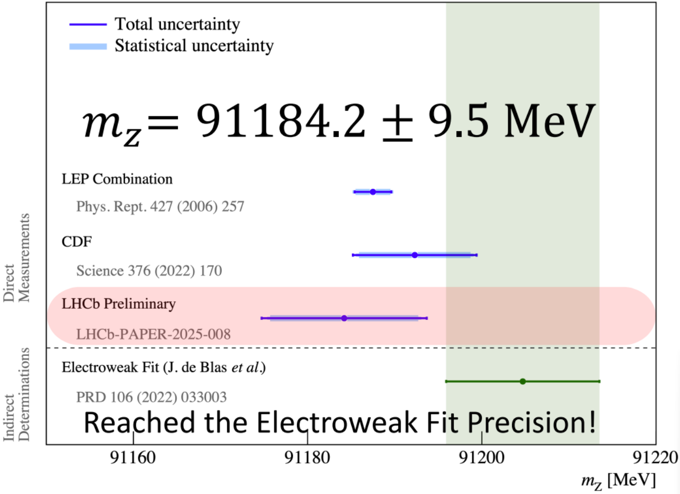
- Binned χ^2 fit used to extract mass value
- Simulation taken from PowHeg with NLO-QED predictions
- Analysis statistically limited
  - Full Run 2 to follow

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**

Measurement of Z Boson Mass

arXiv.2505.15582

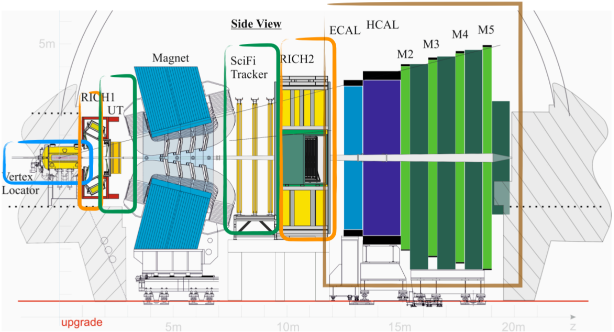
Results: **First dedicated measurement of m_Z at the LHC**



LHCb Upgrade I

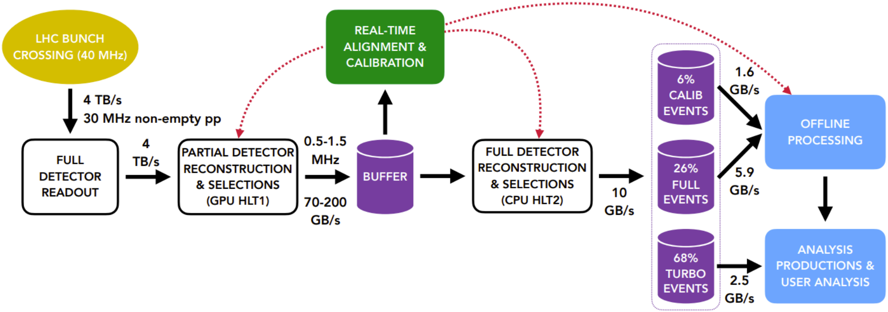
arXiv:2305.10515

Significant upgrades to the LHCb detector were made during the recent LHC LS2



- New Vertexing Detector → Closer to beam; Silicon pixels improve IP resolution
- New PID detector → New photon detectors and improved readout
- New tracking system → Silicon strip UT for improved tracking granularity; Fibre tracking for high particle density momentum resolution
- New Readout Systems
- *BONUS* : New GPU-based trigger

LHCb Run 3 Dataflow



$\rightarrow$ LHCb utilizes a purely software-based trigger system

All stages (HLT1, HLT2, Offline) built on top of the same software stack and selections made by analysts

Offline data processed in real time $\rightarrow$ Analysis flows already running!

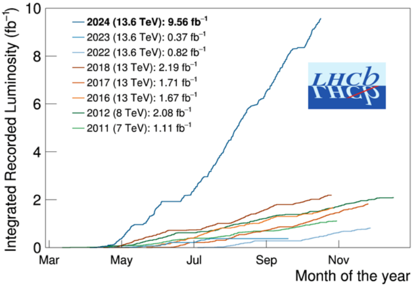
Getting the Most Out of Run 3 Dataset

→ LHCb Run 3 will offer a unique environment for EW physics at the LHC and is already underway

- Forward fiducial region with relatively low pile-up
- Expected luminosity above 30 fb^{-1} → More opportunities!
- Malleable fully software-based trigger
- ML efforts to leverage electron modes

Caveat: EW-scale analysis activity is a small group with a huge phase-space to cover

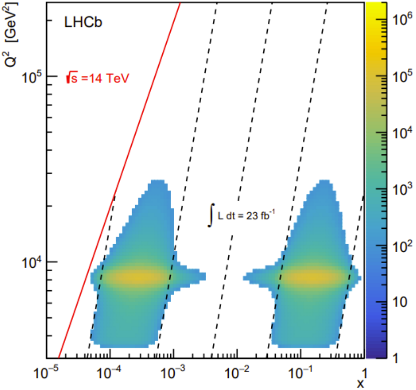
→ Electroweak group closely collaborating with theorists to best-leverage the data set



Vector Boson Measurements in Run 3

Full Run 2 data set measurements of m_W and m_Z are still in progress

Cross section measurements of W and Z production pipelines are running in real time as data becomes available



Statistical uncertainty expectation of boson masses in Run 3:

- $m_W \sim 5$ MeV
- $m_Z \sim 2$ MeV

Both now competitive with world-leading results

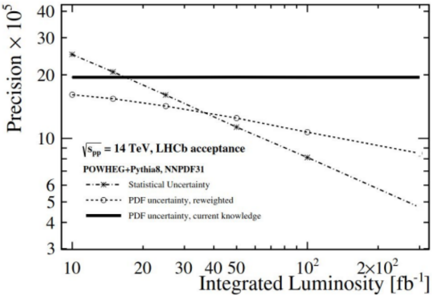
$\rightarrow$ **Systematic challenge begins!**

Weak Mixing Angle in Run 3

Experiment	Energy [TeV]	Luminosity [fb-1]	$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$	Stat. unc.	Syst. unc.	Theo. unc.	Total unc.
ATLAS	8	20	0.23140	0.00021	0.00016*	0.00024**	0.00036
CMS (Run 1)	8	19	0.23101	0.00036	0.00018	0.00035	0.00053
CMS (Run 2)	13	138	0.23157	**0.00010**	0.00015	0.00028	**0.00031**
LHCb (Run 1)	7 + 8	1 + 2	0.23142	0.00073	0.00052	0.00056	0.00106
LHCb (Run 2)	13	5.3	0.23147	0.00044	**0.00005**	**0.00023**	0.00049

↑ Each experiment brings strengths to the calculation of $\sin^2\theta_W$ at the LHC

Competing with LEP ($29\text{x}10^{-5}$) precision remains in play →



Pack Your Bags and Go – With This

Electroweak physics is alive and thriving at the LHC

- LHCb contributes significant measurements on the fundamental quantities of electroweak theory
- In a global LHC setting, the unique forward acceptance provides complementary physics results to the LHC community
- Entering Run 3 LHCb is poised to move from a **stats-limited** to **systematics-limited** precision electroweak program

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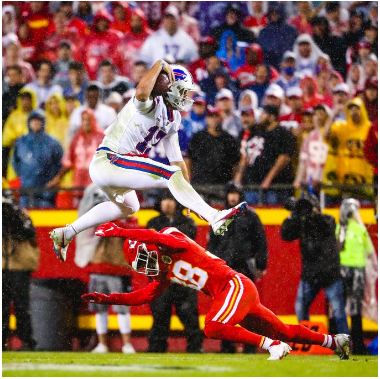
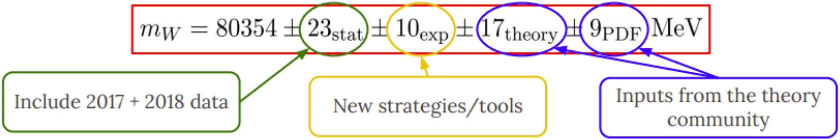


Be good, do good, and Go Bills

BACKUP

Measurement of the W Boson Mass – Making Progress



1. Cross checks between years, polarities, etc.; Selection validation and improvements
2. More robust application of pseudo-mass method for curvature bias corrections JINST 19 (2024) P03010
3. Full detector simulation for misidentified hadron background
4. State-of-the-art modelling of boson production (PowPy $\rightarrow$ DYTurbo up to N2LL)
5. New PDF sets (NNPDF4.0) $\rightarrow$ Have feedback?

Measurement of the W Boson Mass – Making Progress

$$\boxed{m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\,\text{MeV}}$$

Include 2017 + 2018 data

New strategies/tools

Inputs from the theory community

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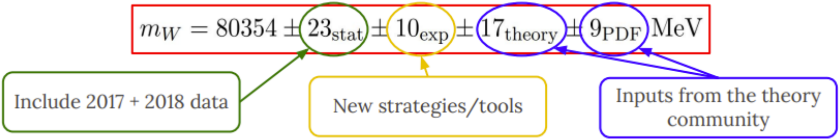

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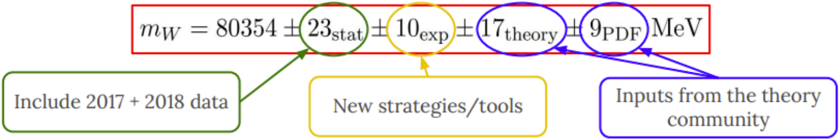

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Goal: 20 MeV Sensitivity