EW Physics and LLPs at LHCb

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On behalf of the LHCb Collaboration

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59th Recontres de Moriond 2025

Electroweak Intractions & Unified Theories

Outlines

- **Introduction**

- **Latest Electroweak/LLPs results at LHCb**
  - Weak mixing angle — JHEP 13 (2024) 026
  - Z boson mass — LHCb-paper-2025-008[1]
  - Status of LLPs searches

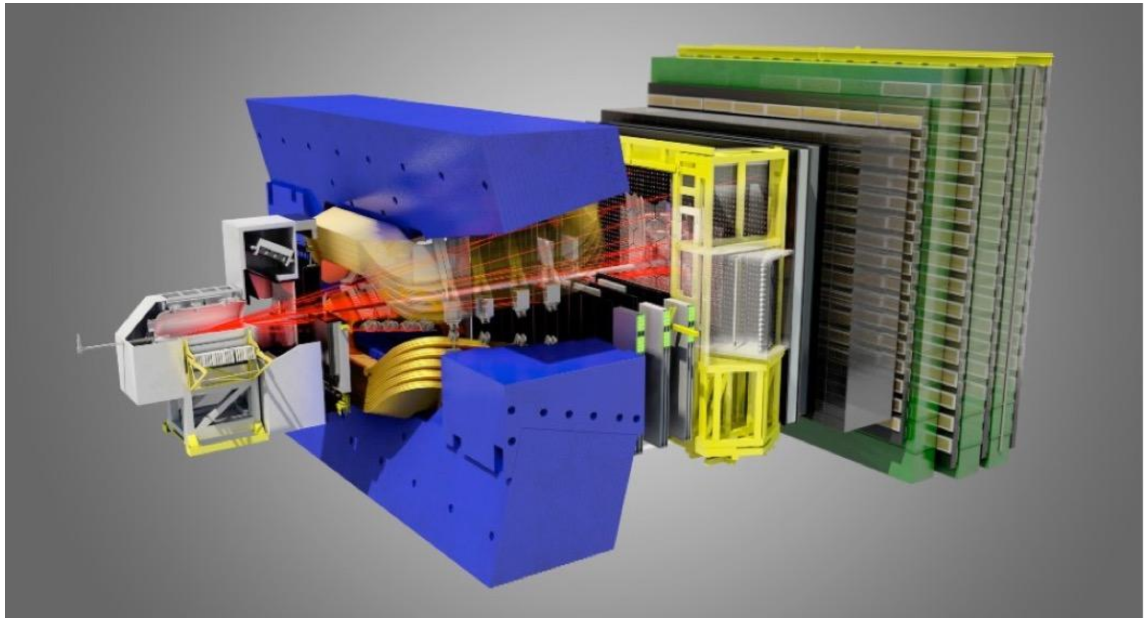
- **Summary**

1. Also covered by Emir Muhammad's talk at the 'Young Scientists Forum' (Saturday)

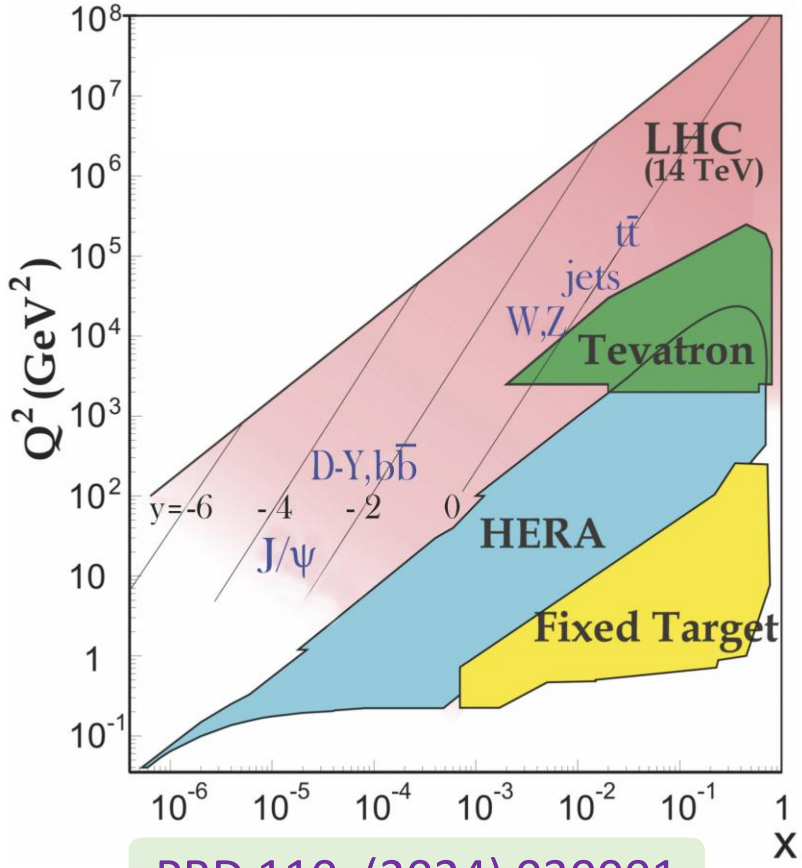
Unique acceptance of LHCb

The x value of interacting partons is correlated with the boson rapidity

- Rapidity (y): $y = \frac{1}{2} ln \frac{x_1}{x_2}$
- Large rapidity: either very large x (up to 0.8) or very small x (5×10^{-5})



JINST 3 (2008) S08005



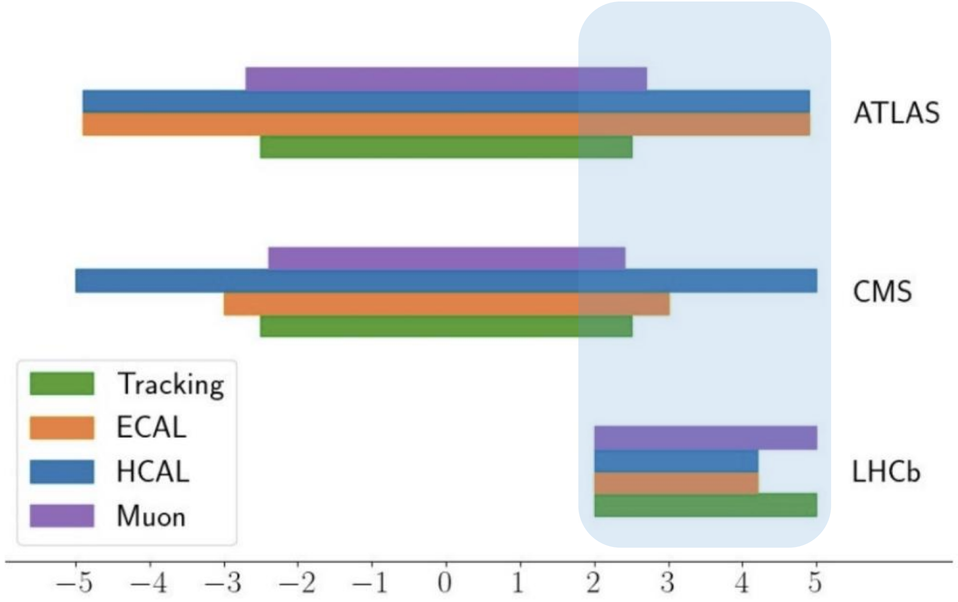
PRD 110, (2024) 030001

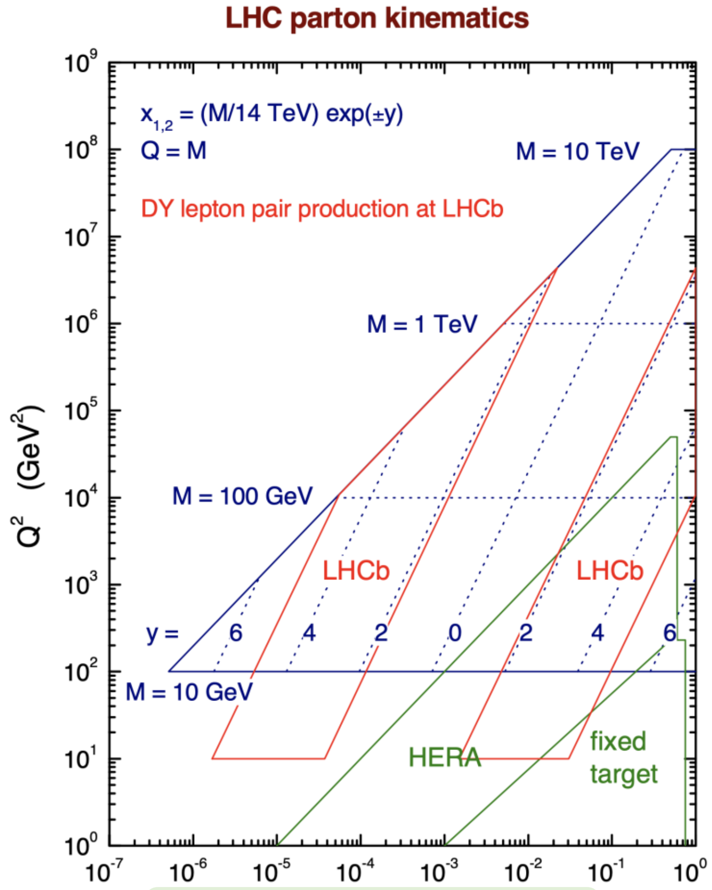
Unique acceptance of LHCb

Forward acceptance!

The x value of interacting partons is correlated with the boson rapidity

- Rapidity (y): $y = \frac{1}{2} ln \frac{x_1}{x_2}$
- Large rapidity: either very large x (up to 0.8) or very small x (5×10^{-5})
- ATLAS/CMS and LHCb: **complementary to each other**



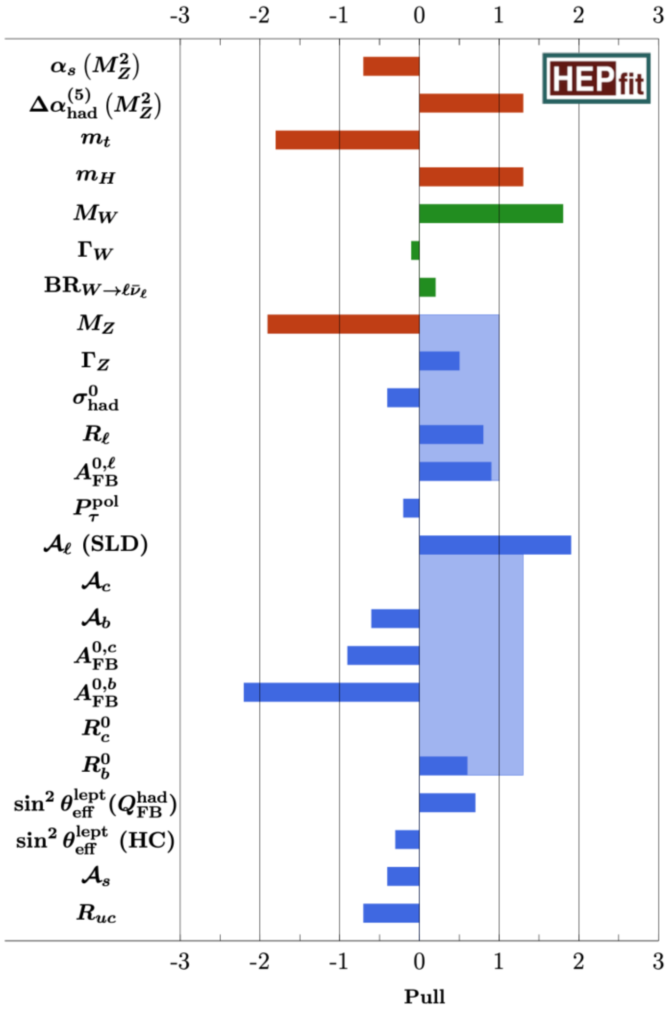


arXiv:0808.1847

Weak mixing angle

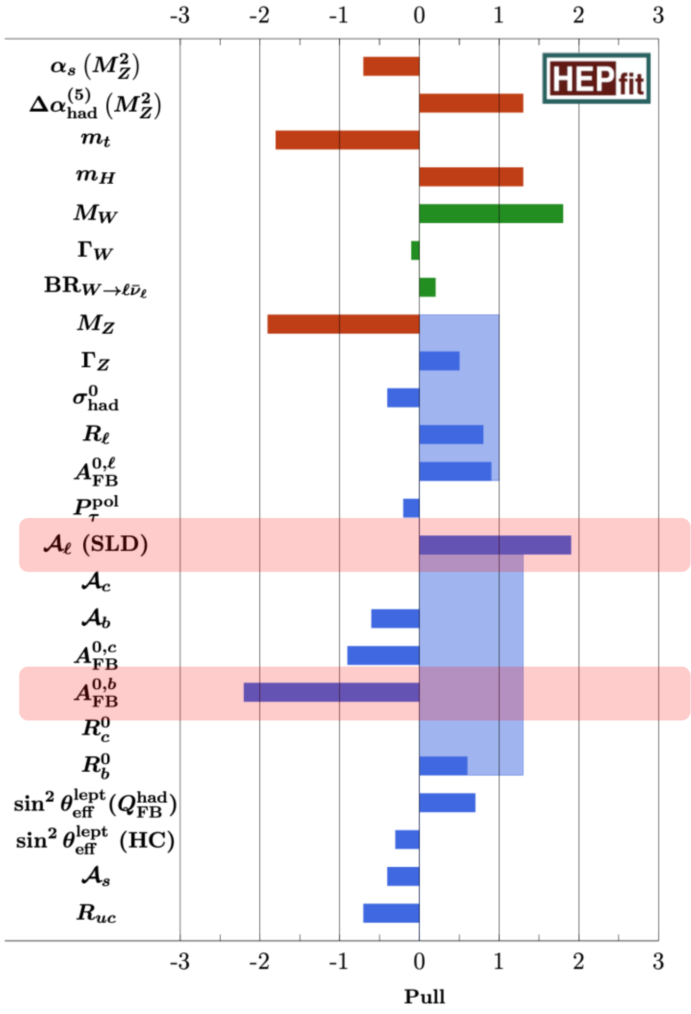
- **Fundamental parameters of SM electroweak sector**
- **Couplings between fermions and Z boson: $(V - A)$**
  - Vector couplings: $V = I_3 - 2Q sin^2\theta_W$
  - Axial-vector coupling: $A = I_3$
- **At tree level,** $sin^2\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right)$
- **At higher order:** $sin^2\theta_W^{\ell} = \kappa_f sin^2\theta_W$
  - κ_f: a flavour dependent effetive scaling factor absorbing higher order corrections

Well-known deviation



PRD 106 (2022) 3, 033003

Well-known deviation

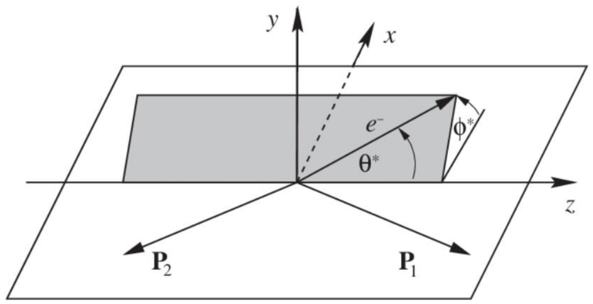


PRD 106 (2022) 3, 033003

- **Excellent agreement between individual measurement and global fit**
- **Tension between A_{FB}^b and $A_l(SLD)$: $\sim 3.2\ \sigma$**
  - Precision weak mixing angle measurements from LEP and SLD
- **Other EW observables are within 2σ band**

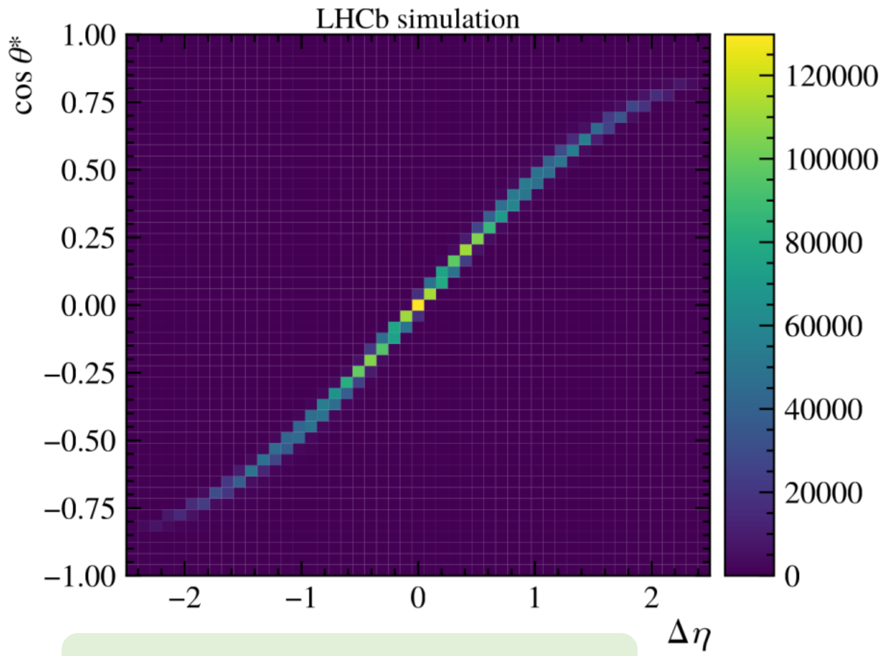
Extraction of $sin^2\theta_W^\ell$

- $\frac{d\sigma}{dcos\theta^*} \propto 1 + cos^2\theta^* + \frac{8}{3}A_{fb}^{4\pi}cos\theta^*$
  - θ^* is the angle in Collins-Soper frame
  - $A_{fb} = \frac{\sigma_F-\sigma_B}{\sigma_F+\sigma_B}$, as a function of mass
  - large $|\cos\theta^*|$ are more influenced by changes in $\sin^2\theta_{\rm eff}^\ell$
  - small $|\cos\theta^*|$ mostly dilute the measurement



- Forward range, $\cos\theta^* > 0$
- Backward range, $\cos\theta^* < 0$

- $\cos\theta^* \sim \tanh(|\Delta\eta|/2)$, $\Delta\eta = \eta^- - \eta^+$



JHEP 13 (2024) 026

Extraction of $sin^2\theta_W^\ell$

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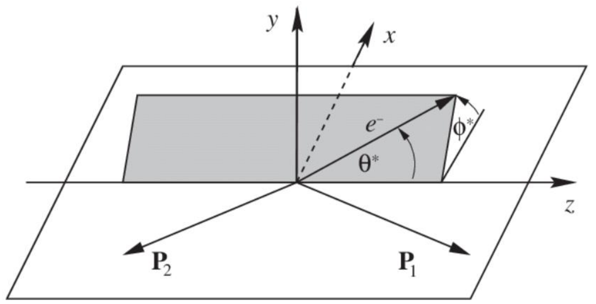

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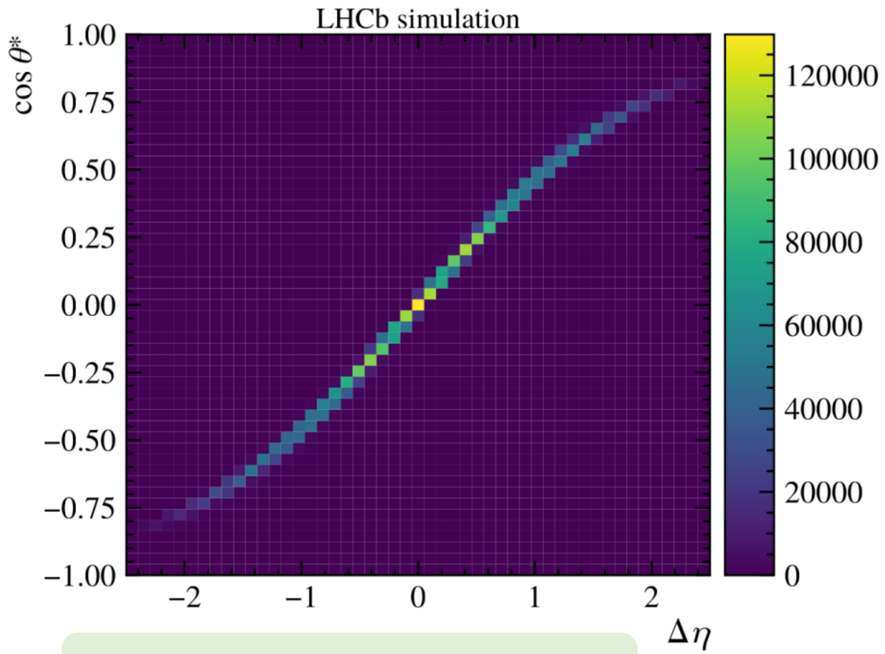
- Backward range, $cos\theta^* < 0$

- $cos\theta^* \sim \tanh(|\Delta\eta|/2)$, $\Delta\eta = \eta^- - \eta^+$

- **Improves the precision of the $sin^2\theta_{eff}^\ell$ measurement by 14% in simulation**

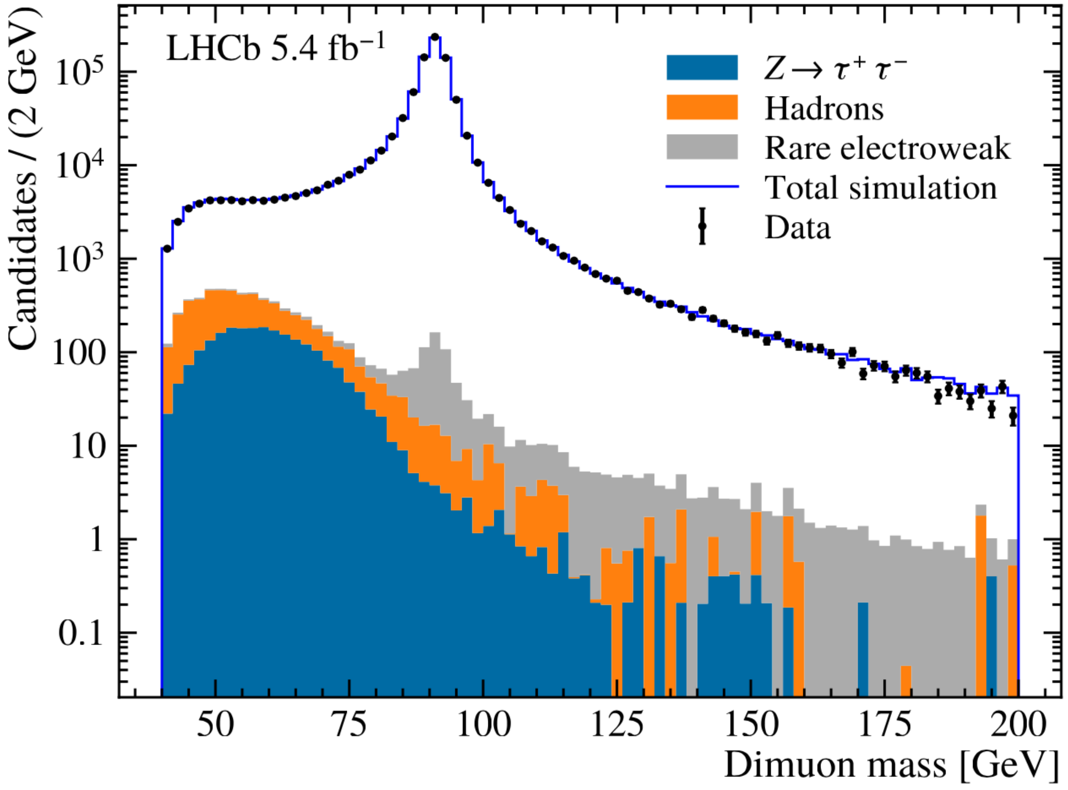


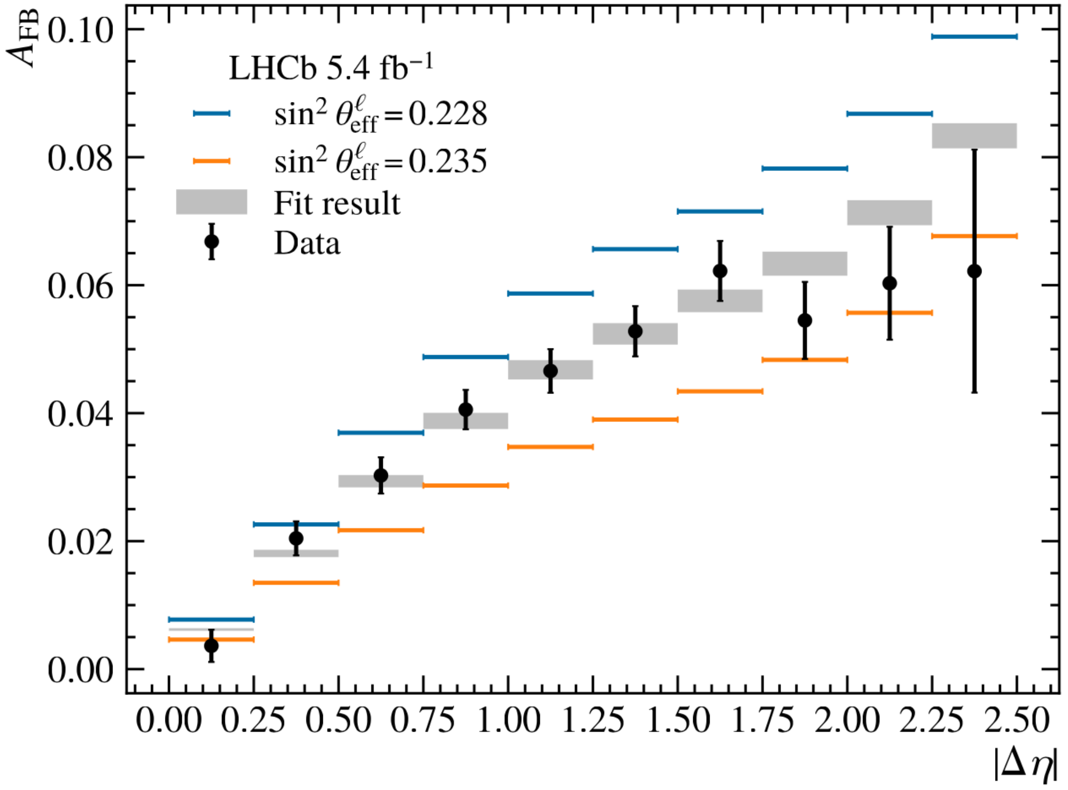
JHEP 13 (2024) 026

Selected events

- **Dataset: 2016+2017+2018 pp collision data at $\sqrt{s} = 13$TeV, $\mathcal{L} = 5.3\ \text{fb}^{-1}$**
- **Identified single muon trigger, in a fiducial region**
  - $2.0 < \eta_\mu < 4.5, p_\text{T}^\mu > 20$ GeV and $66 < M_{\mu\mu} < 116$ GeV
- **Background contributions:**
  - Heavy-flavour: suppressed to the percent level using the muon impact parameter requirement
  - Hadronic background: suppressed to the percent level using an isolation requirement and a muon track fit requirement
- **Roughly 860k events are selected for the measurement**

Mass and $sin^2\theta^{\ell}_{eff}$ fit



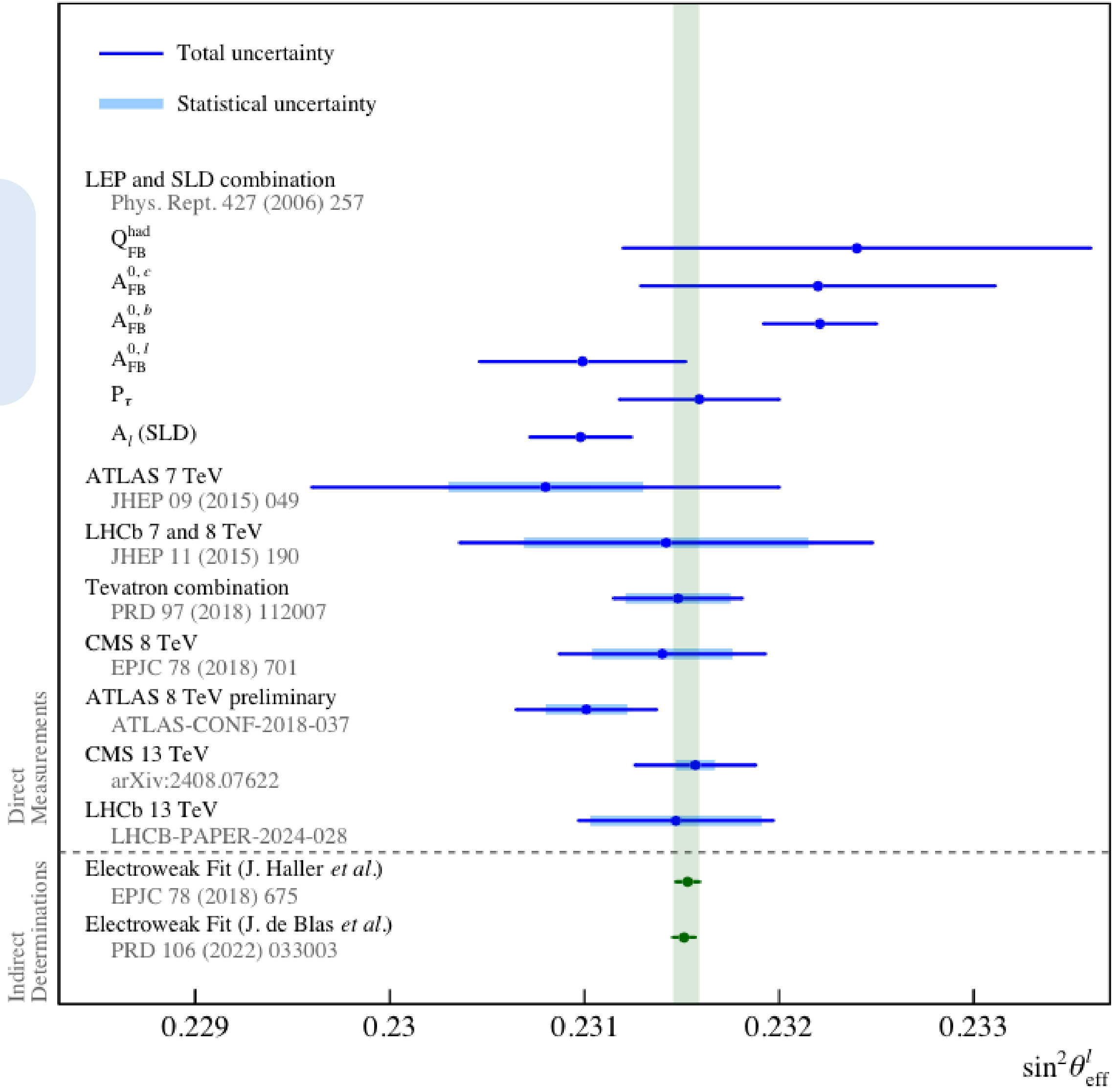


Templates fit method to extract the $sin^2\theta^{\ell}_{eff}$

Measured result

$$0.23147 \pm 0.00044\,(\text{stat.}) \pm 0.00005\,(\text{syst.}) \pm 0.00023\,(\text{theory})$$

- Theory uncertainty includes PDF uncertainty, QCD and EW uncertainty



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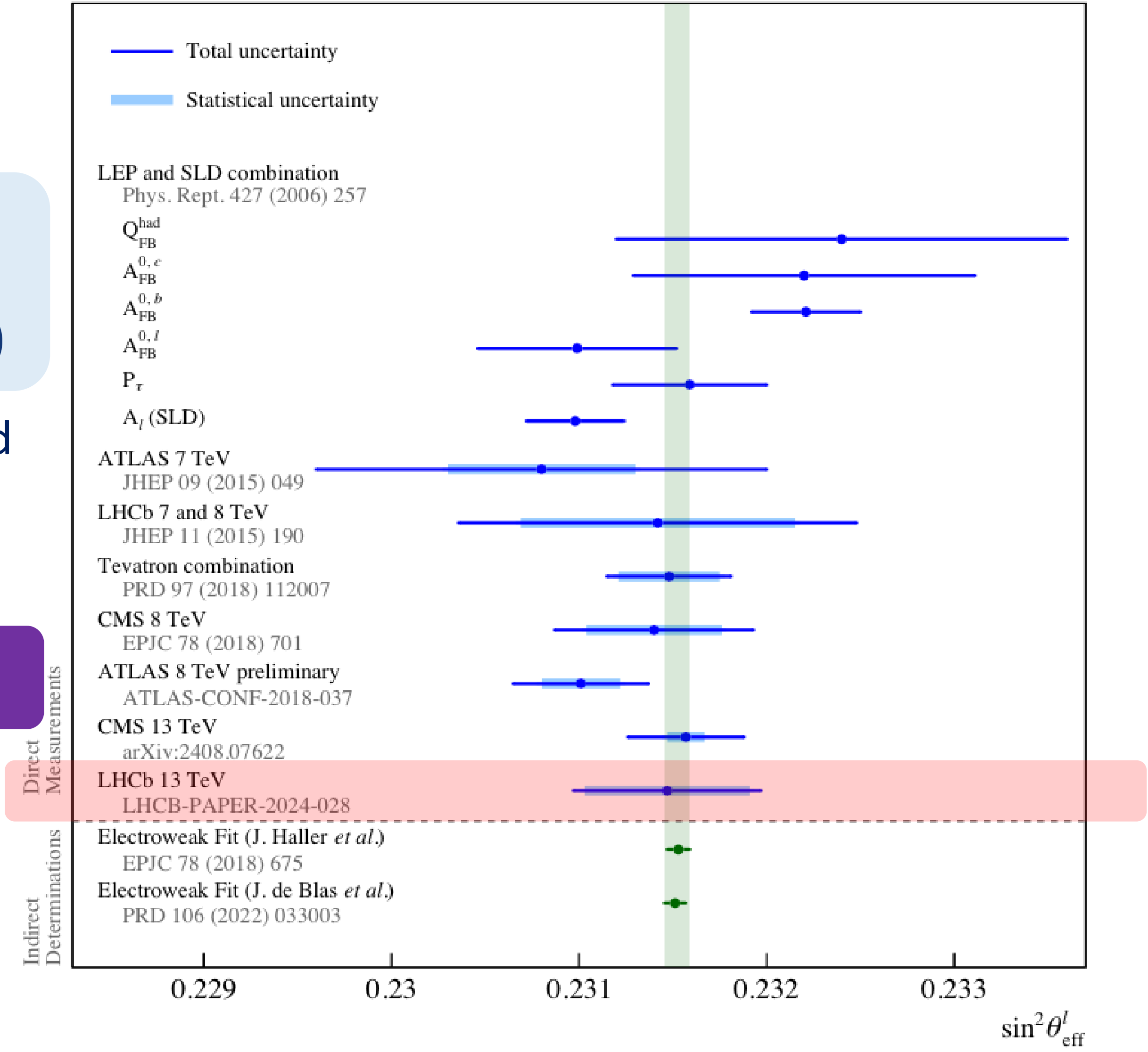
Dominated by the statistical uncertainty!



JHEP 13 (2024) 026

Z mass measurement

- Fundamental parameters of SM electroweak sector
- Couplings between fermions and Z boson: $(V - A)$
  - Vector couplings: $V = I_3 - 2Q sin^2\theta_W$
  - Axial-vector coupling: $A = I_3$
- In the tree level, $sin^2\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right)$
  - $cos\theta_W = \frac{m_W}{m_Z}$

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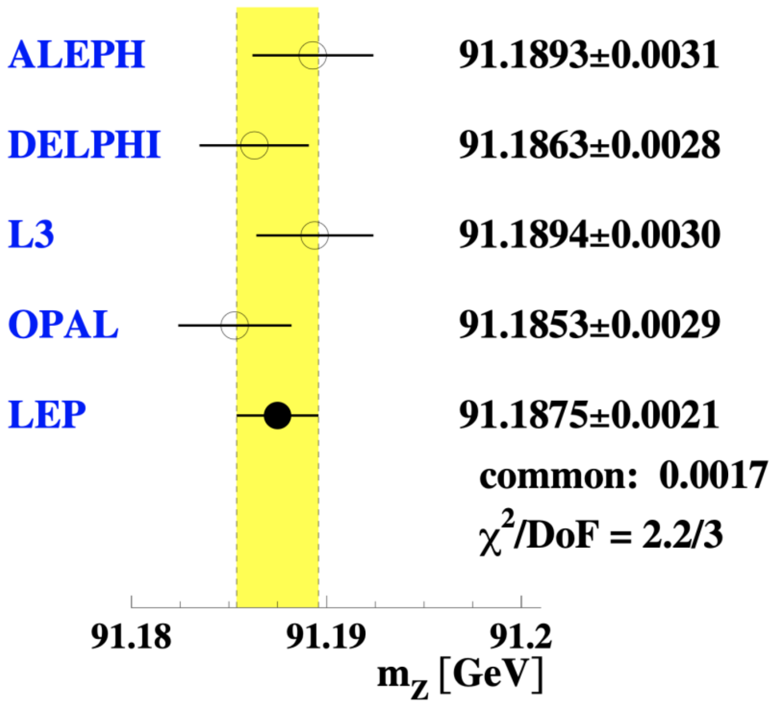
- **In the tree level, $sin^2\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right)$**
  - $cos\theta_W = \frac{m_W}{m_Z}$
  - How about a m_Z measurement at LHCb?
    - → The measurements of m_W and $sin^2\theta_W$ are published



Legacy measurement from LEP:
Phys. Rept. 427 (2006) 257-454

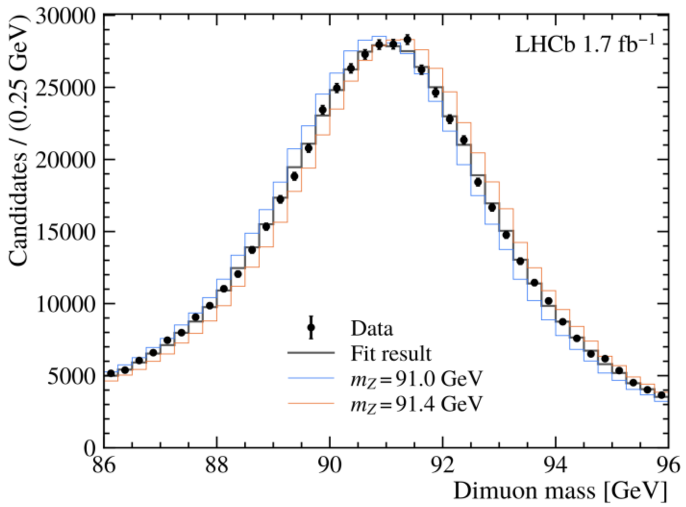
The m_Z measurement at LHCb

- Only using part of Run-2 dataset (2016)
  - Feasibility study
  - Same dataset used for m_W measurement
- Using $Z \to \mu^+\mu^-$ events
  - Narrow cut on η_μ: 2.2 – 4.4
  - Selection cuts: similar cuts to weak mixing angle
  - 173k selected data
- Same analysis framework as $m_W, \sin^2\theta_W^\ell$

A challenging measurement at hadron collider

- Pseudomass method to correct charge-dependent curvature biases in the data
  - Improves the Z mass resolution by $\mathcal{O}(20\%)$
- Time varying momentum scale applied to data
  - Use $\Upsilon(1S)$ to calibrate the momentum scale drift of $\mathcal{O}(10^{-4})$
- Direction dependent momentum scale applied to MC
  - Use $\Upsilon(1S)$ data and MC
- Momentum smearing to MC

LHCb-PAPER-2025-008

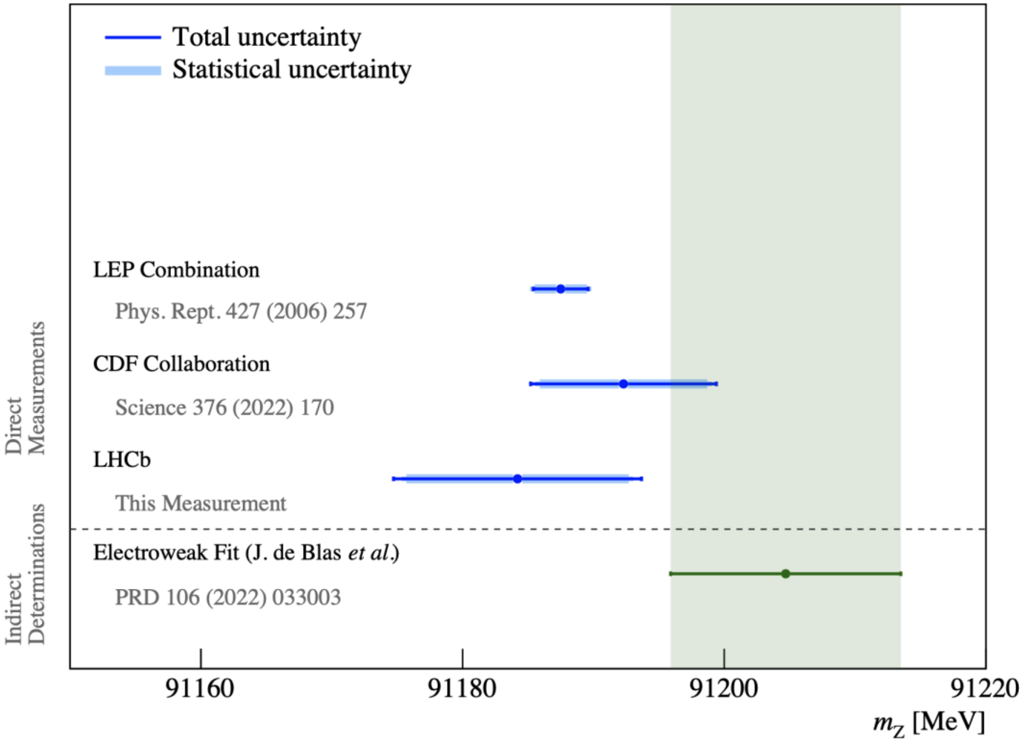


Results

LHCb-PAPER-2025-008

Source	Uncertainty [MeV]
Momentum calibration	4.1
Signal QED corrections	0.8
Parton distribution functions	0.7
Detection efficiency	0.1
Total systematic uncertainty	4.3

- First dedicated measurement of m_Z @LHC
- Reached the EW fit precision!



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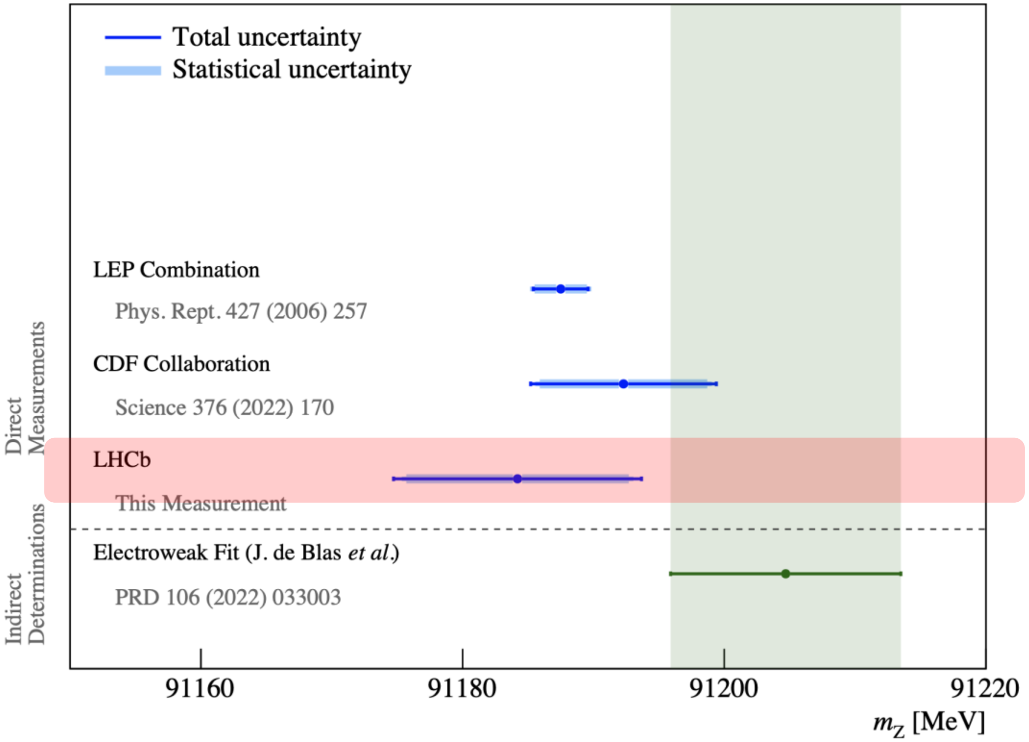
$m_Z = 91184.2 \pm 8.5 \pm 4.3$ MeV

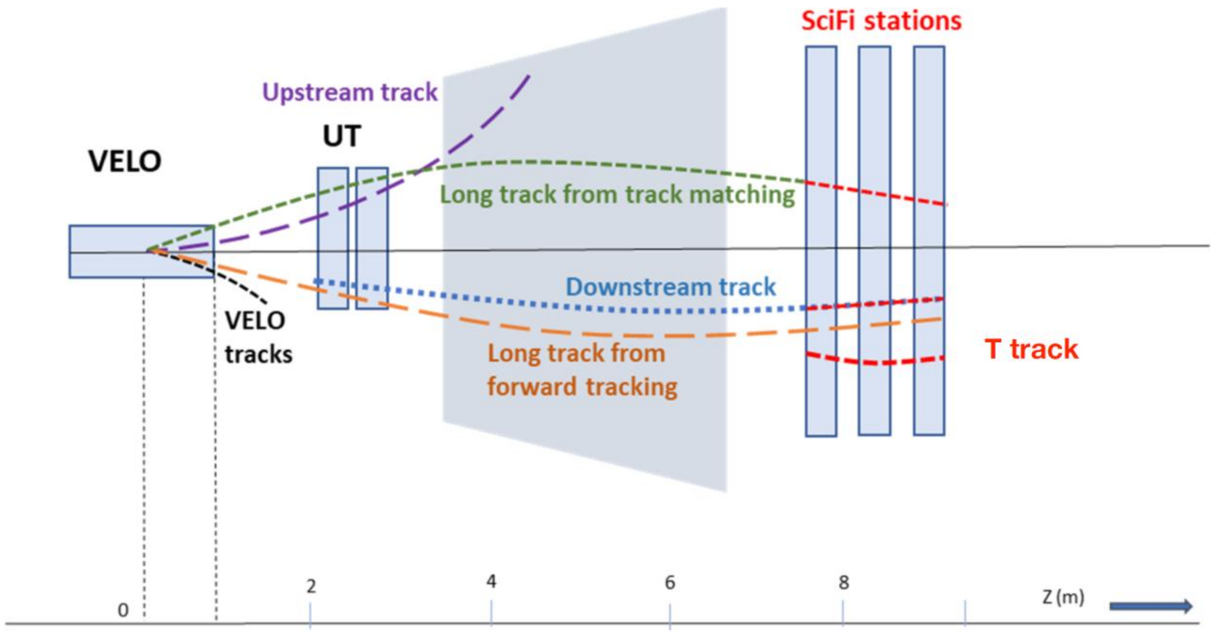


LLPs searches

- **Displaced leptons**
  - Dark photon — PRL 120 (2018) 061801, PRL 124 (2020) 041801
  - Low-mass dimuon resonances — JHEP 10 (2020) 156
  - (Heavy) LLPs decaying to $e^{\pm}\mu^{\pm}\nu$ — EPJC 81 (2021) 261
  - Majorana neutrino — PRL 112 (2014) 131802
  - Light boson from $b \to s$ decays — PRL 115 (2015) 161802, PRD 95 (2017) 071101
- **Displaced jets**
  - HNL in $W^{\pm} \to \mu^{+}\mu^{\pm}$jet — EPJC 81 (2021) 248
  - LLP → jet jet — EPJC 77 (2017) 812
  - LLP → μ + jets — EPJC 77 (2017) 224

Run-3 prospects

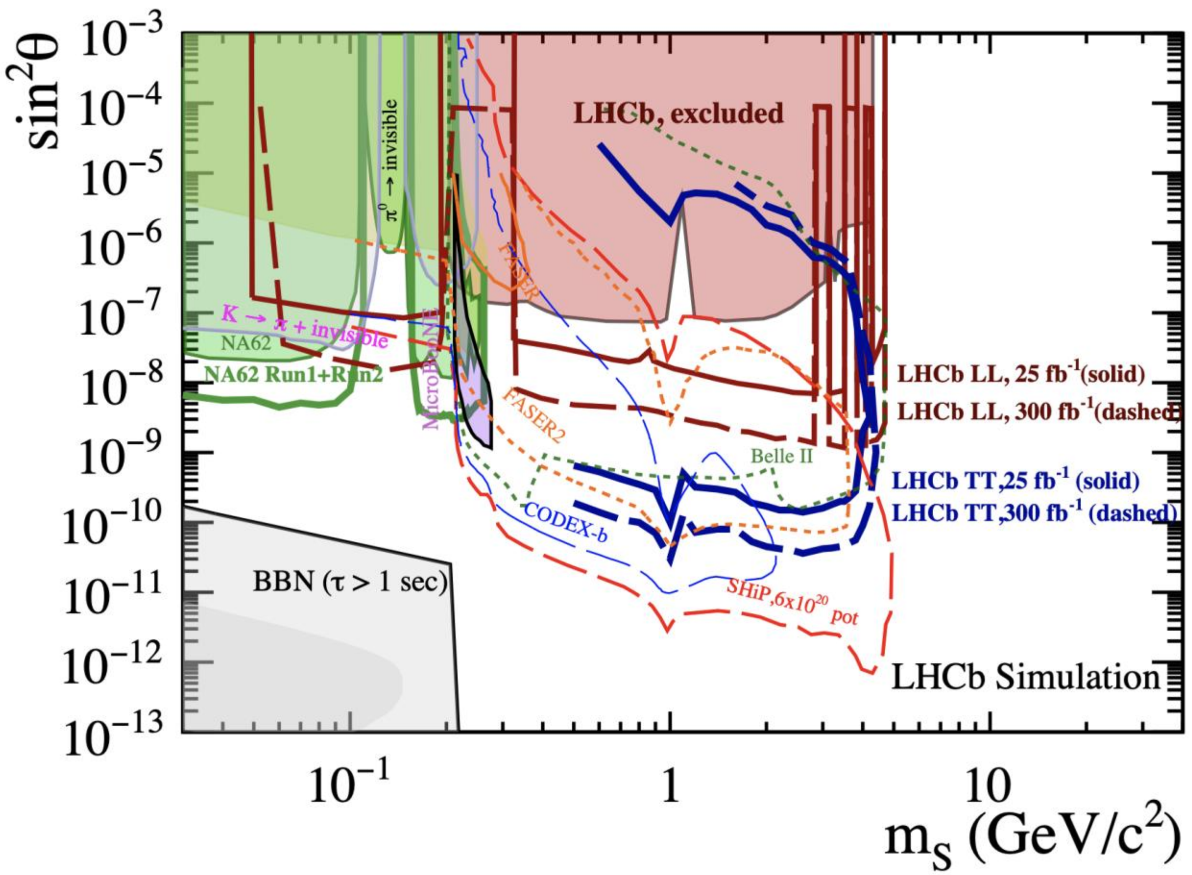
- Physics track types supported in online selection:
  - Long: lepton ID in HLT1 (both electron and muon)
  - Downstream (new in Run-3)
  - Special cases for T-tracks (new in Run-3)



Run-3 prospects

LHCb-Figure-2025-001

- **Expectations:**
  - Access to particles with lifetimes up to 10 ns
  - New sensitivity for New physics
  - Competitive with dedicated LLP experiments



Summary

- **LHCb has an extensive program on electroweak measurements**
  - Provide essential inputs for PDFs global fitting: **unique acceptance**
  - Precision measurements: weak mixing angle, m_Z, m_W …
- **LHCb also performed plenty of searches for LLPs**
  - Ongoing Run-3 data taking
  - A new GPU-based trigger system
  - Probes very long-lived particles

Backup

Generator used in $sin^2\theta_W^\ell$ measurement

Eur. Phys. J. C 73 (2013) 6
Phys. Rev. D 100 (2019) 071302

- **POWHEG-EWNLO**
  - Includes QED predictions at NLO
  - EW theory inputs scheme, xW scheme: $(G_F, sin^2\theta_W^\ell, m_Z)$
  - well defined in theory, encouraged to use by LHC-wide EW WG
- **PDFs:**
  - NNPDF 3.1, CT 18, MSHT20

	QCD	EW	QED	rest of the events
POWHEG-ewnlo [1] (**default prediction**)	NLO	NLO	PHOTOS	PYTHIA8
POWHEG-ewlo	NLO	LO	PHOTOS	PYTHIA8
POWHEG-plain	NLO	LO	PYTHIA8	PYTHIA8

Generator used in m_Z measurement

Eur. Phys. J. C 73 (2013) 6

- **POWHEG-EWNLO**
  - Includes QED predictions at NLO
  - EW theory inputs scheme: (G_F, m_W, m_Z)
  - Samples generated with varying m_Z
- **FSR:**
  - The first photon emission is computed by POWHEG: ISR, FSR and their interference
  - Additional FSR emission handled by PHOTOS: resummation of log-enhanced ter ms
  - Uncertainty on m_Z 0.8 MeV: alternative prescription with PYTHIA
- **PDFs:**
  - Central fit from NNPDF3.1 NLO
  - Choice of MSHT20NLO and CT19NLO: 0.7 MeV uncertainty is assigned

Prospects

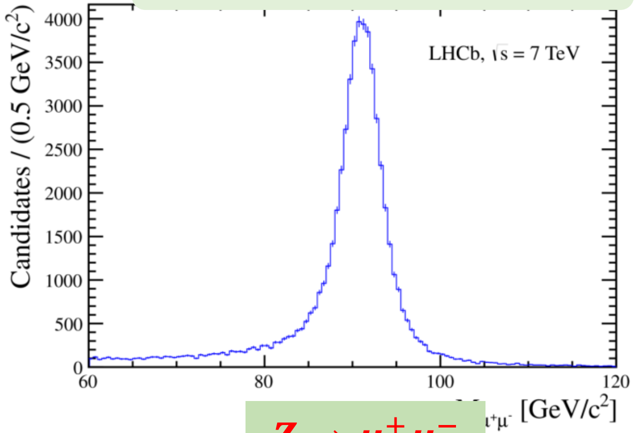
- **Cross-section measurements:**
  - W Xsec (5.02 TeV, 13 TeV, 13.6 TeV), leptnoic WW, ZZ Xsec, DPS measurement
- **Properties of EW boson:**
  - Mass of W/Z boson, W helicity, Z angular coefficient (Run-1/Run-3)
- **Higgs/Jet measurements:**
  - $H \to \mathrm{bb}/cc$, W+Jet Xsec, semi-leptonic WW Xsec
- **Top physics**

Prospects: m_W measurement

- Including 2017+2018 data
  - Cross-check between years, polarities …
- Goal: 20 MeV
  - Predicted statistical precision of 14 MeV
- Improvements on theoretical predictions
  - From POWHEG -> DYTurbo
  - New PDF sets
- Calibrations, momentu scale and efficiencies optimised
  - Pseudo mass method to curvature bias correction

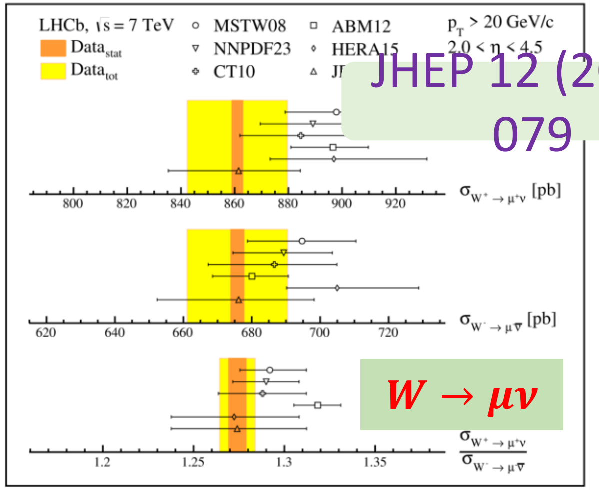
LHCb EW Highlights

JHEP 08 (2015) 039



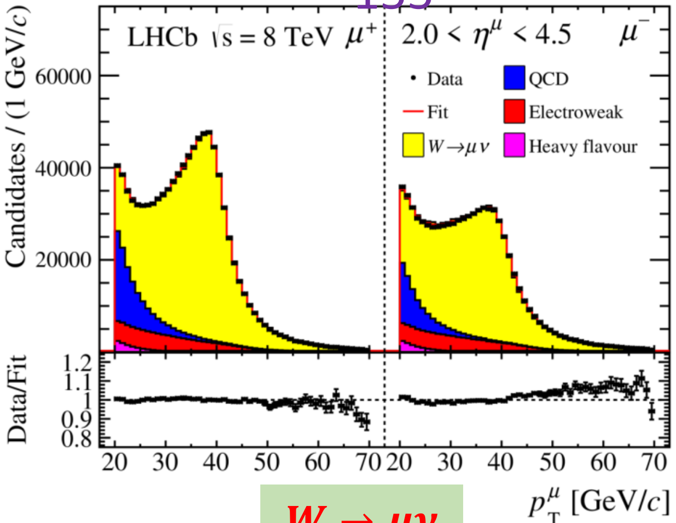
$Z \to \mu^+\mu^-$

JHEP 12 (2014) 079



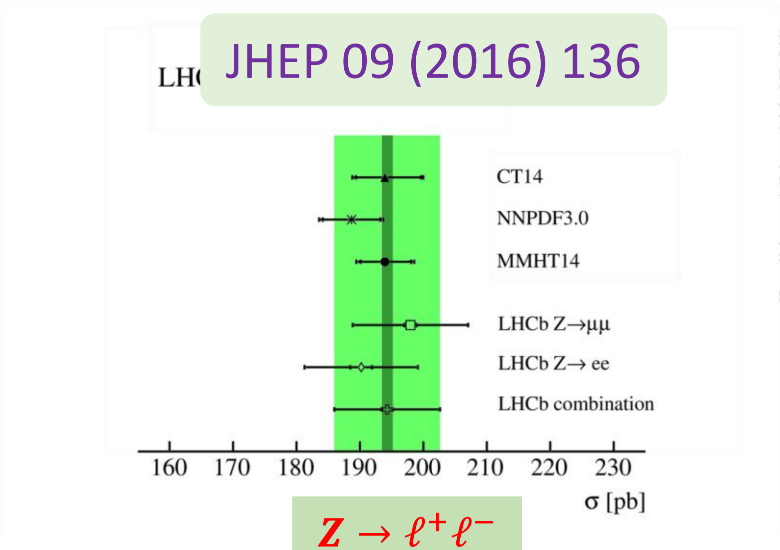
$W \to \mu\nu$

JHEP 01 (2016) 155



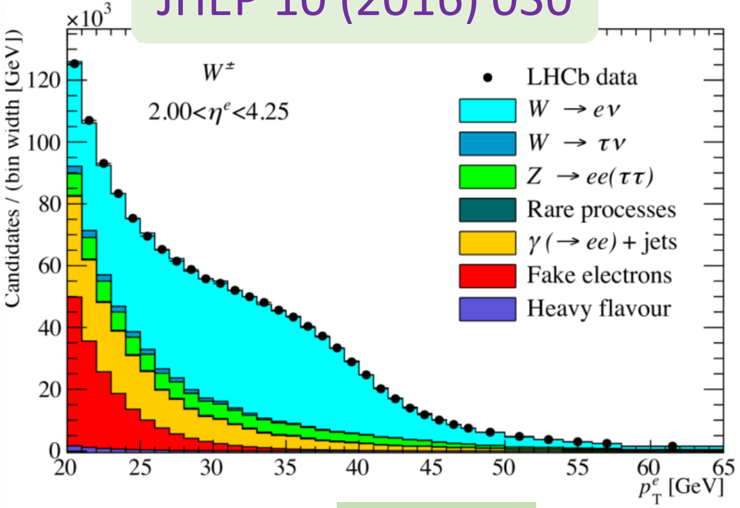
$W \to \mu\nu$

JHEP 09 (2016) 136



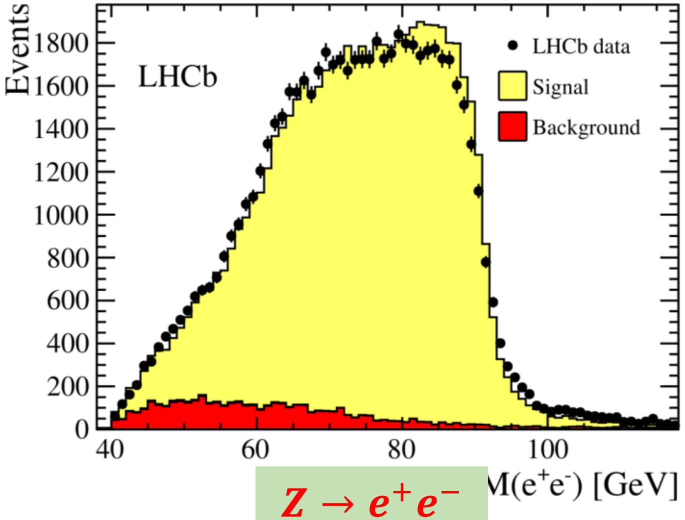
$Z \to \ell^+\ell^-$

JHEP 10 (2016) 030



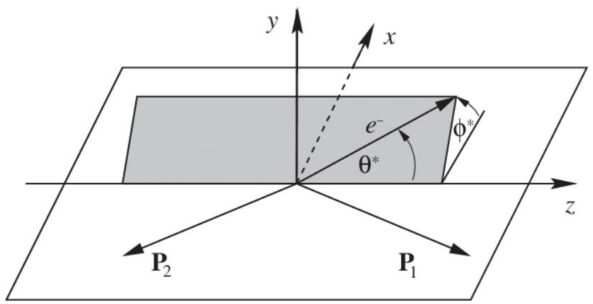
$W \to e\nu$

JHEP 05 (2015) 109



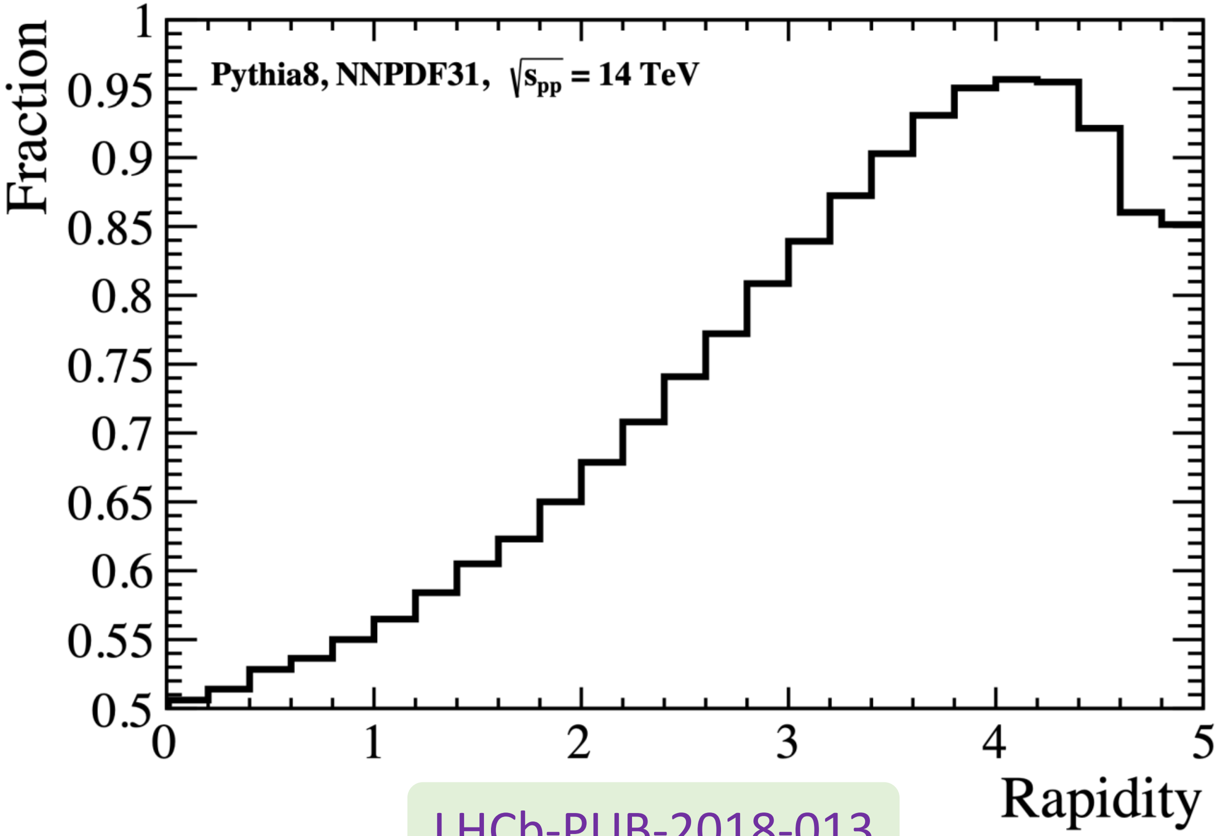
$Z \to e^+e^-$

Dilution effects



At the LHC, the direction of the quark and anti-quark in each collision is unknow: use the p_z of Z boson

- **LHCb: larger rapidity region**
  - one larger x + one small x
  - valence quark intends to have large x



LHCb-PUB-2018-013

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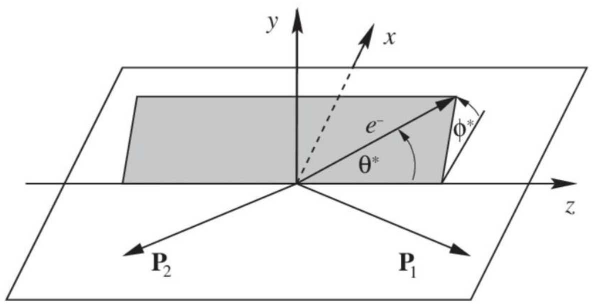

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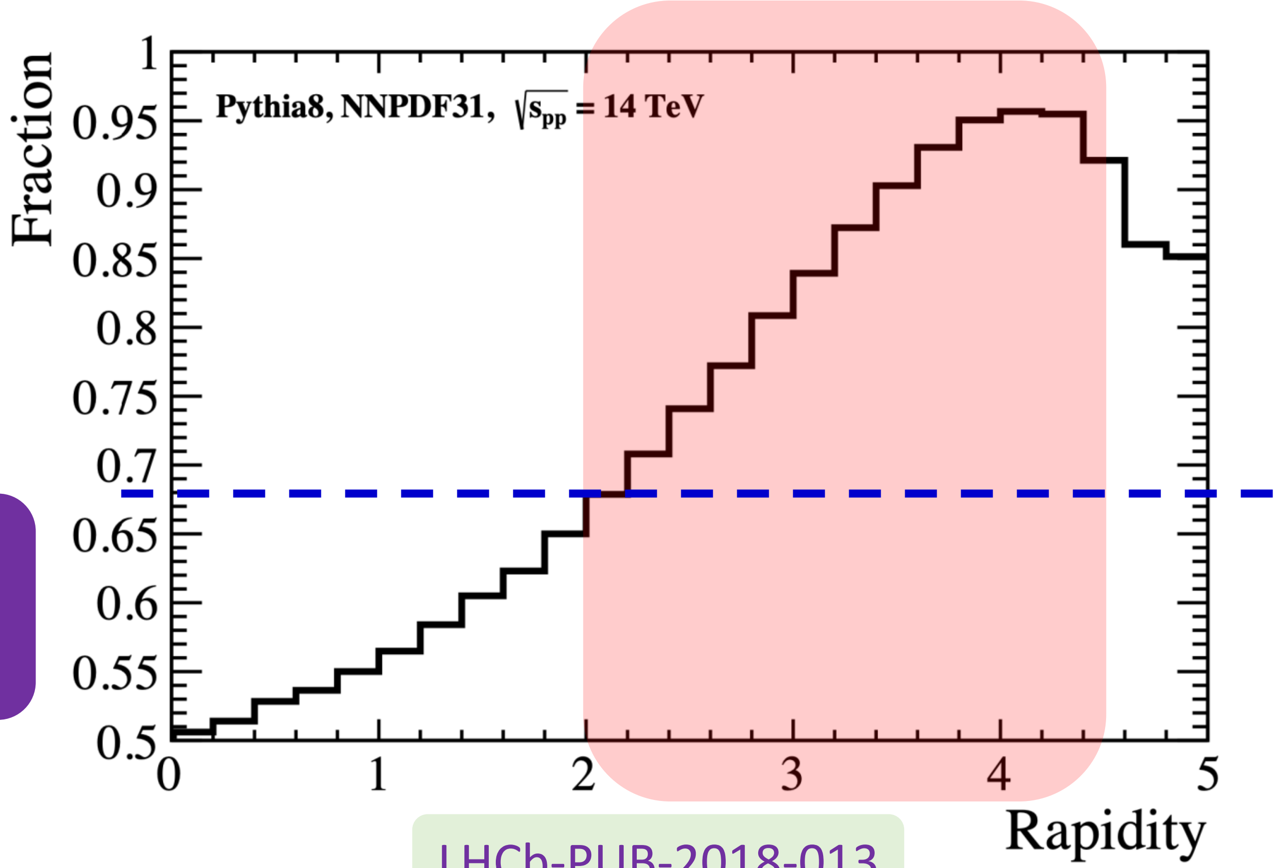
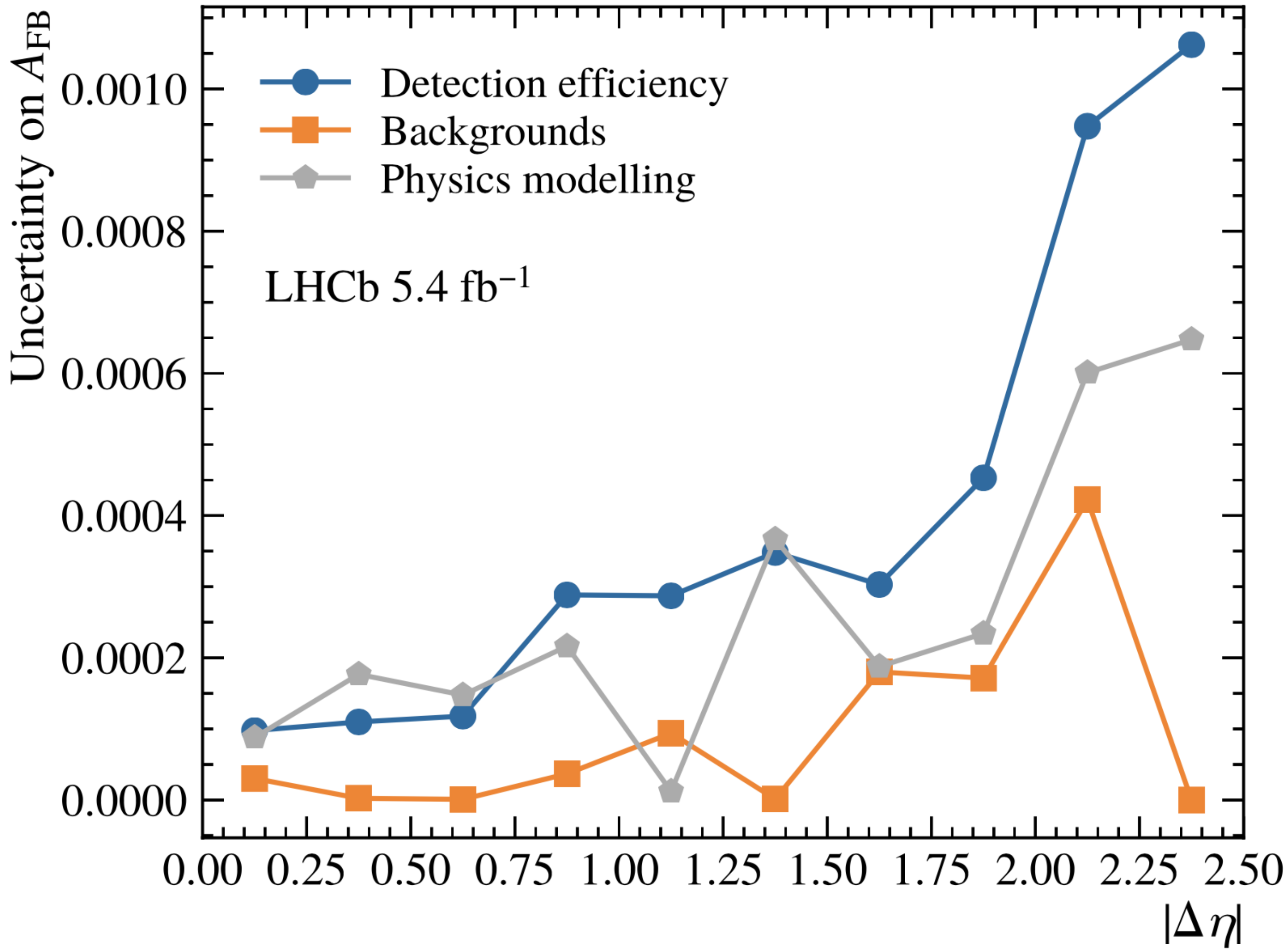
Smaller statistics ($\sim 1/65$), but similar sensitivity as ATLAS/CMS!



LHCb-PUB-2018-013

A_{FB} uncertainties



JHEP 13 (2024) 026

Weak mixing angle: different PDFs

PDF set	$\sin^2\theta^{\ell}_{\rm eff}$	PDF uncertainty	Shift	Fit χ^2/ndof
NNPDF31_nlo_as0118	0.23155	0.00023	—	8.4/9
CT18NLO	0.23165	0.00022	+0.00009	8.4/9
MSHT20nlo_as118	0.23137	0.00017	−0.00018	8.2/9
Arithmetic average	—	0.00021	−0.00003	–

PDF set	$\sin^2\theta^{\ell}_{\rm eff}$	PDF uncertainty	Shift	Fit χ^2/ndof
CT18ZNLO	0.23147	0.00019	−0.00008	8.4/9
NNPDF40_nlo_as_01180	0.23142	0.00022	−0.00014	8.6/9

JHEP 13 (2024) 026

Weak mixing angle: cross-checks

Subset	$\sin^2\theta^\ell_{\text{eff}}$	Fit χ^2/ndof	Pull
2016	0.23014 ± 0.00082	$2.0/9$	—
2017	0.23155 ± 0.00085	$13.4/9$	$+1.2\ \sigma$
2018	0.23242 ± 0.00077	$10.5/9$	$+2.0\ \sigma$
Down polarity	0.23087 ± 0.00065	$8.2/9$	—
Up polarity	0.23211 ± 0.00065	$12.1/9$	$1.4\ \sigma$
$0 \leq \phi_d < \frac{\pi}{2}$	0.23136 ± 0.00065	$10.1/9$	—
$\frac{\pi}{2} \leq \phi_d < \pi$	0.23161 ± 0.00065	$6.5/9$	$+0.3\ \sigma$

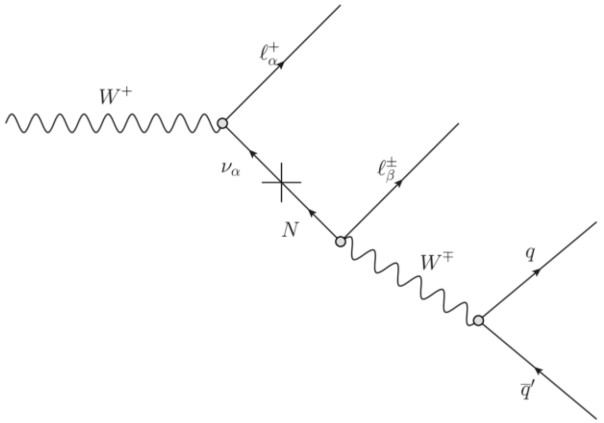
Number of intervals	$\sin^2\theta^\ell_{\text{eff}}$	Shift	Fit χ^2/ndof
1	0.23151 ± 0.00050	—	—
4	0.23167 ± 0.00045	$+0.00016$	$3.1/3$
6	0.23145 ± 0.00044	-0.00004	$3.2/5$
8	0.23146 ± 0.00044	-0.00003	$11.7/7$
10	0.23148 ± 0.00044	-0.00003	$8.1/9$

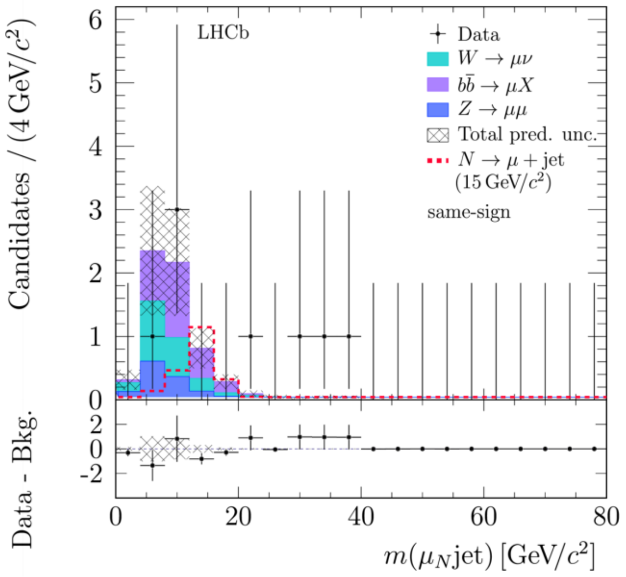
JHEP 13 (2024) 026

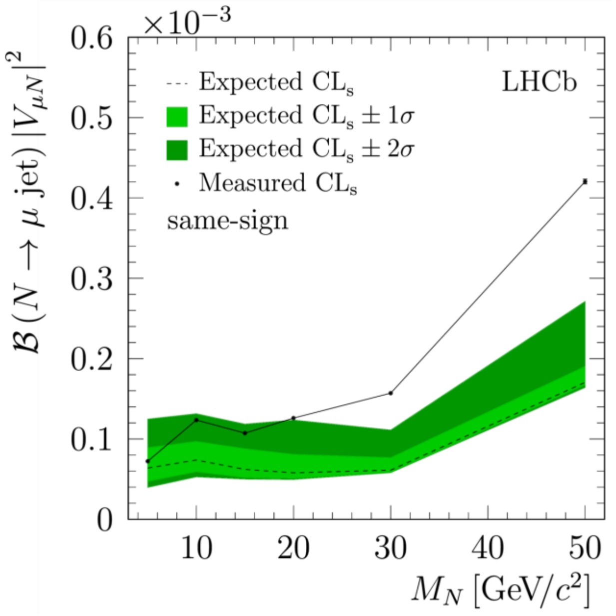
HNL in $W^{\pm} \to \mu^{+}\mu^{\pm} jet$

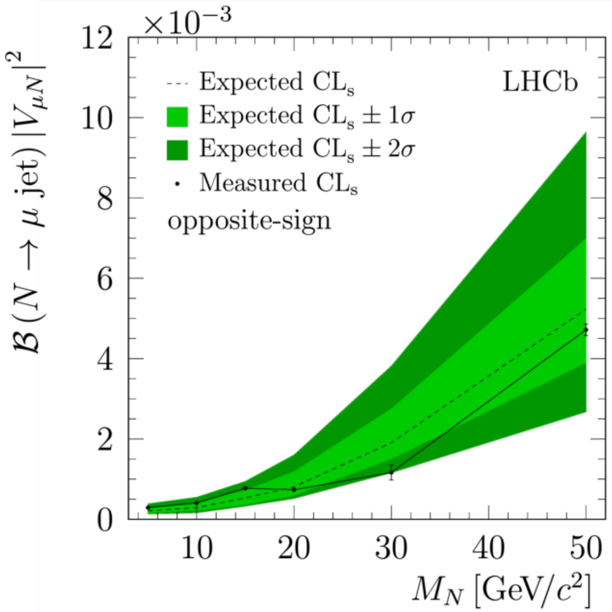
EPJC 81 (2021) 248

- **Search for neutral leptons via W decays**
- **Upper limit for both same- and opposite-sign muons using Run-1 dataset**
  - not competitive with ATLAS, CMS and DELPHI results





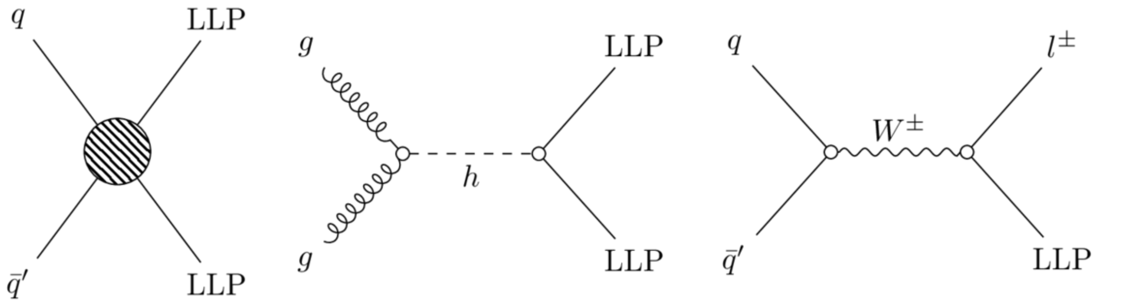




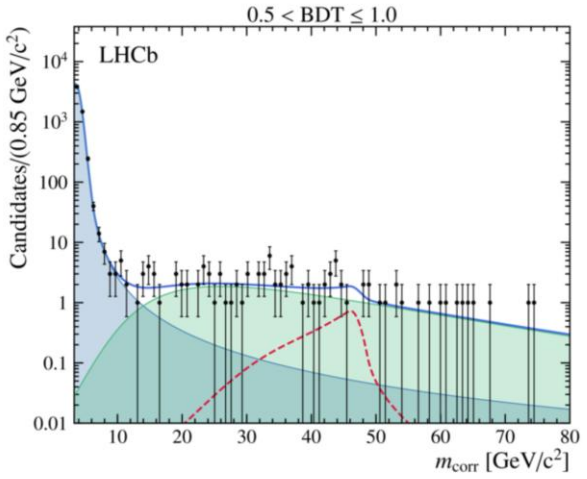
LLP decaying to $e^{\pm}\mu^{\mp}\nu$

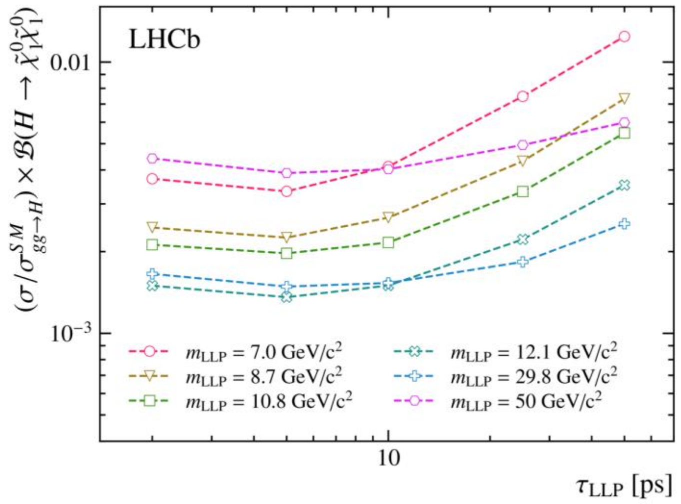
EPJC 81 (2021) 261

- **With full Run-2 dataset**
- **LLP masses down to 7 GeV**
- **Correcting mass to flight direction:**
  - A proof-of-concept analysis
- **Simultaneous fit to corrected mass and lifetime**



$$m_{\text{corr}} = \sqrt{m(e\mu)^2 + p(e\mu)^2 \sin^2\theta} + p(e\mu)\sin\theta$$

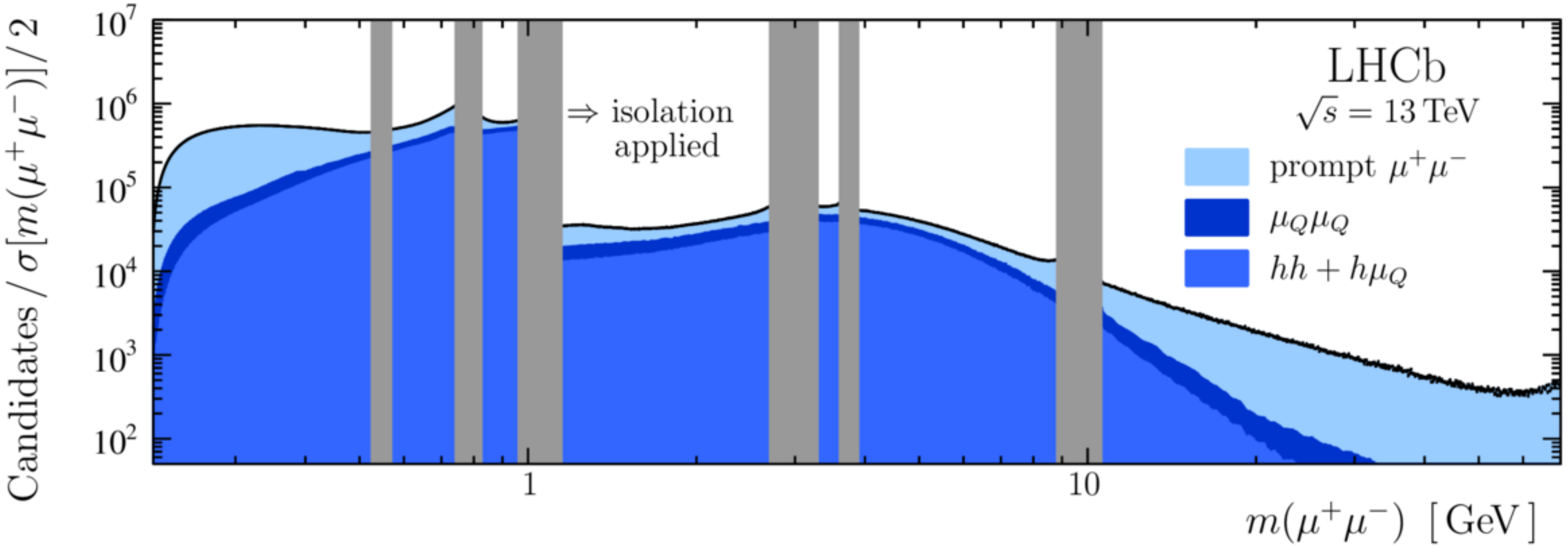




Dark photons in di-muon spectrum

PRL 124 (2020) 041801

- **Light dark photon can appear in a mixing with off-shell photon**
  - Large fraction in forward region, low p_T
- **Normalized to off-shell photons**
  - No need for efficiencies (for prompt search)
- **Search for both prompt and displaced signatures using Run-2 data**



Dark photons in di-muon spectrum

PRL 124 (2020) 041801

- World best upper limits for invariant mass range of 200-700 MeV (prompt)
- First displacement search: not from beam-dump experiments (214-350 MeV)
- Very low masses: di-electron search in hadrons decays