Electroweak Physics at LHCb

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华中师范大学

第十届中国LHC物理会议
山东青岛
2024年11月14日

Outlines

- Introduction

- Recent LHC Electroweak results
  - Weak mixing angle measurement
  - Z boson property measurements
  - W/Z rare decay search
  - Prospects

- Summary

Physics @LHC

Better understanding of the SM

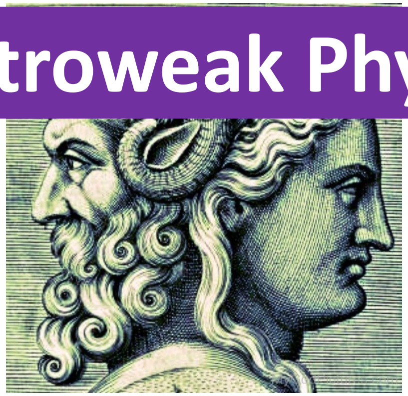
Challenging the SM

QCD

QED and Weak

Physics @LHC

Electroweak Physics



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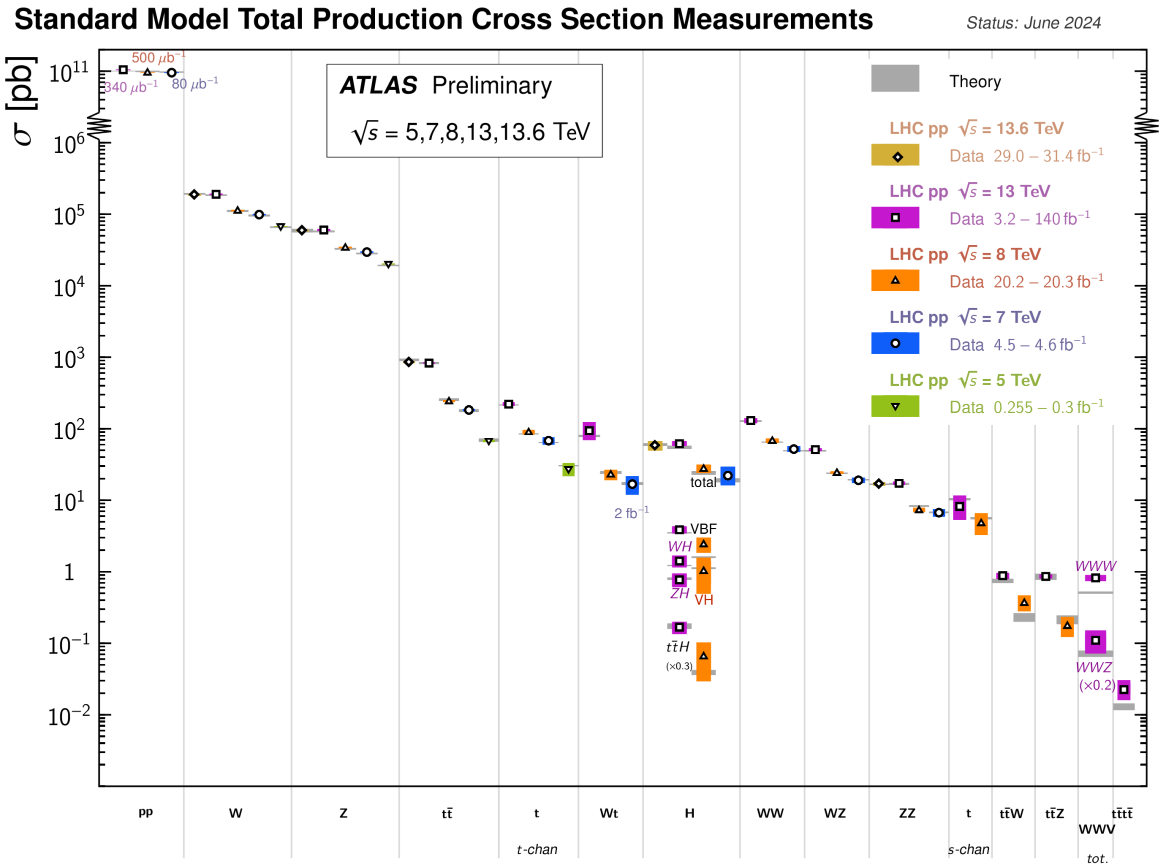
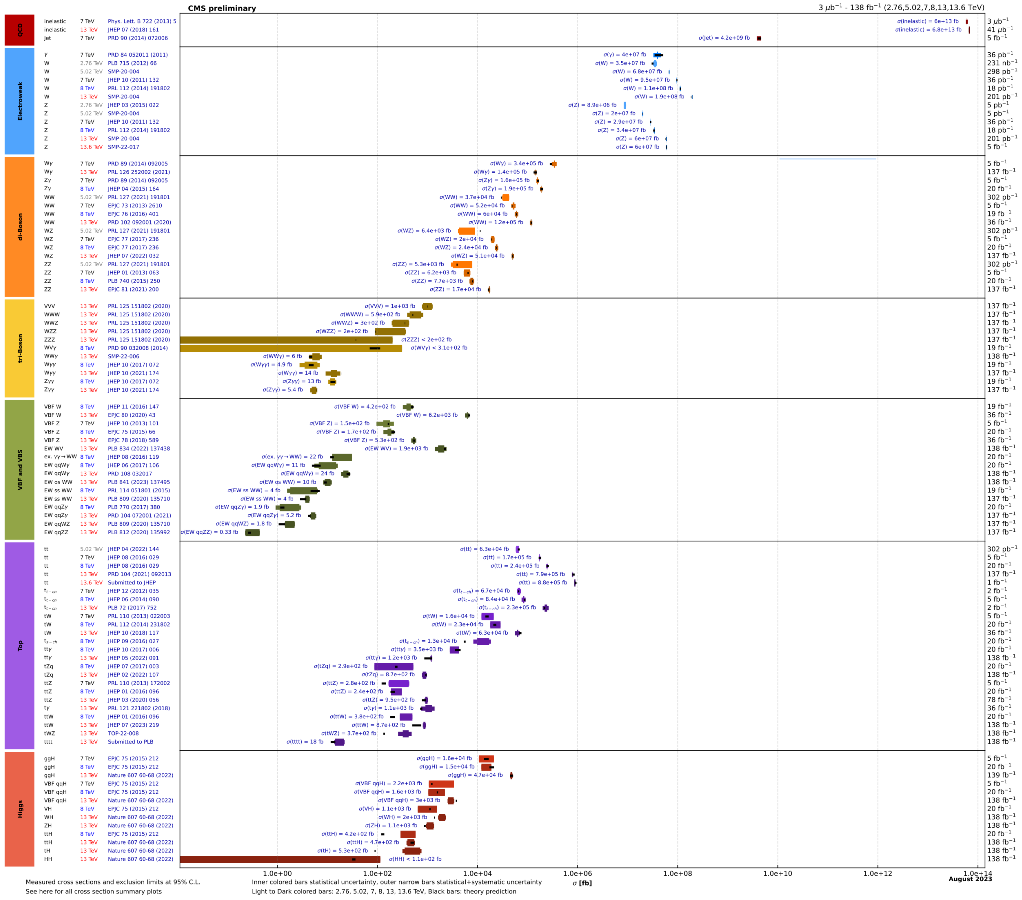
Electroweak physics @LHC

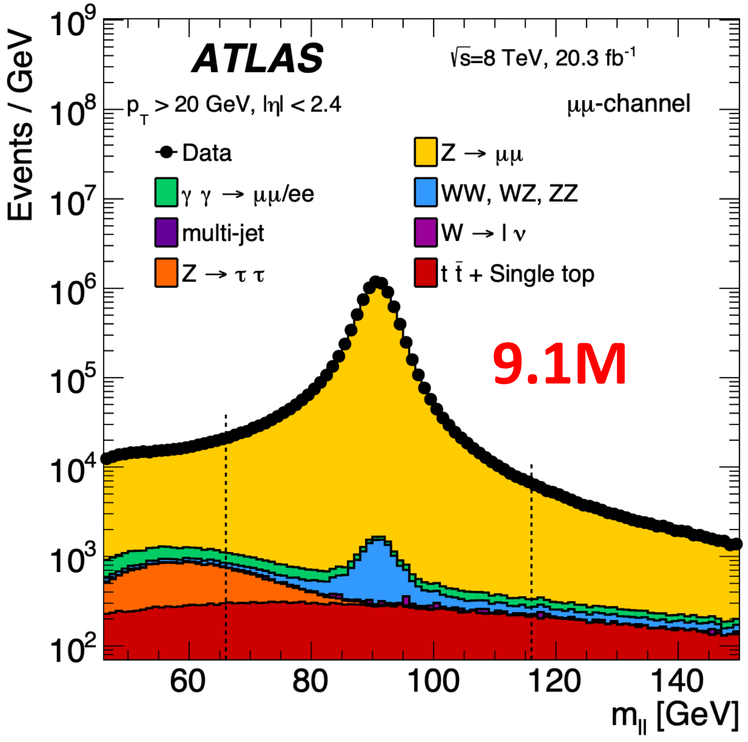


Overview of CMS cross section results

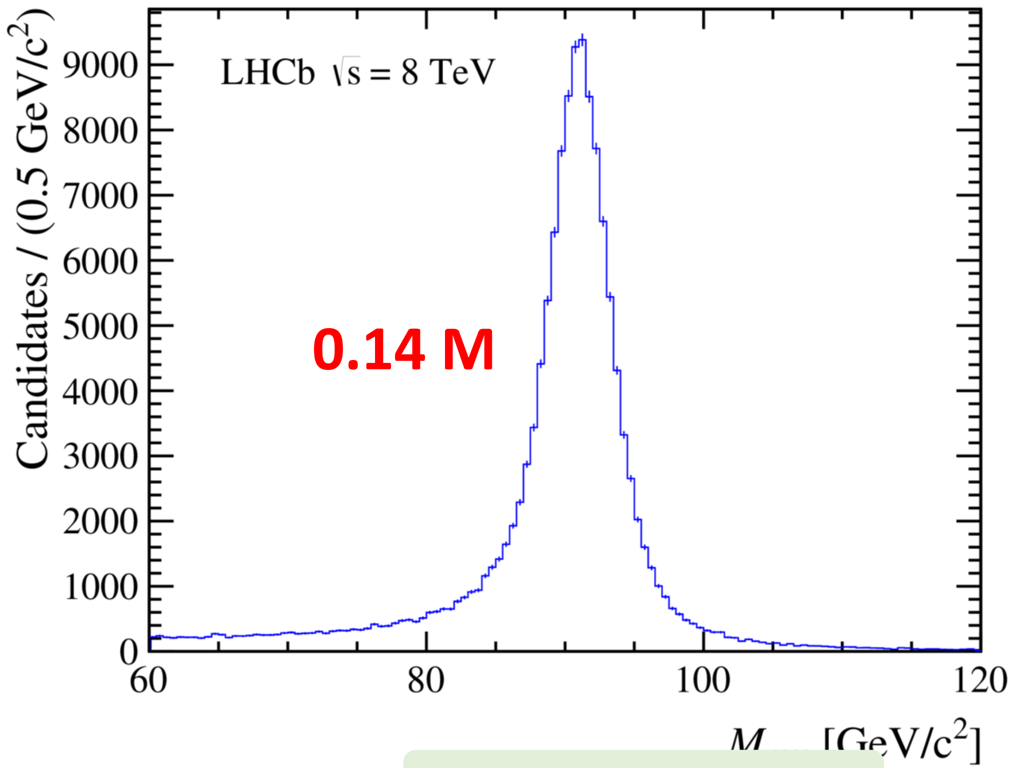


Stringent tests on the SM!

Electroweak physics @LHCb: why?



Eur. Phys. J. C 76 (2016) 291



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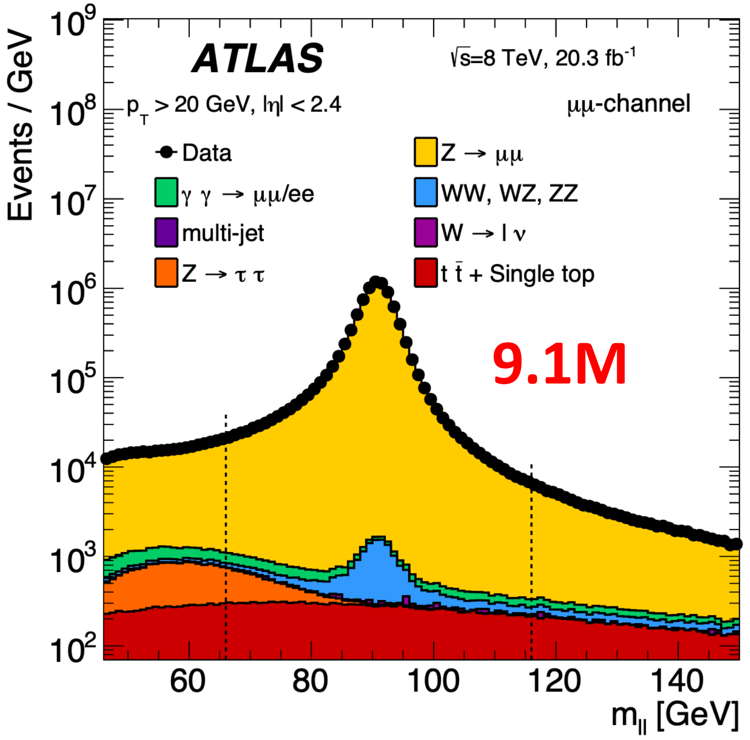
Electroweak physics @LHCb: why?

Data collected in same period: ATLAS $Z \to \mu^+\mu^-$ signal yeild is 65 times larger than that of LHCb



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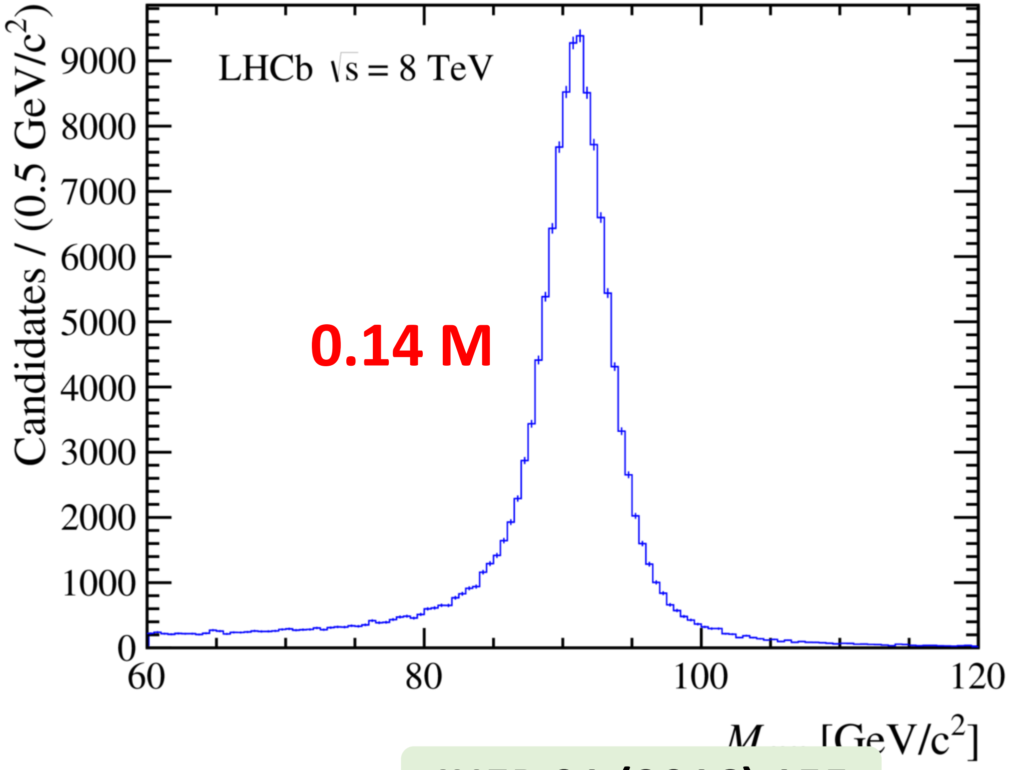

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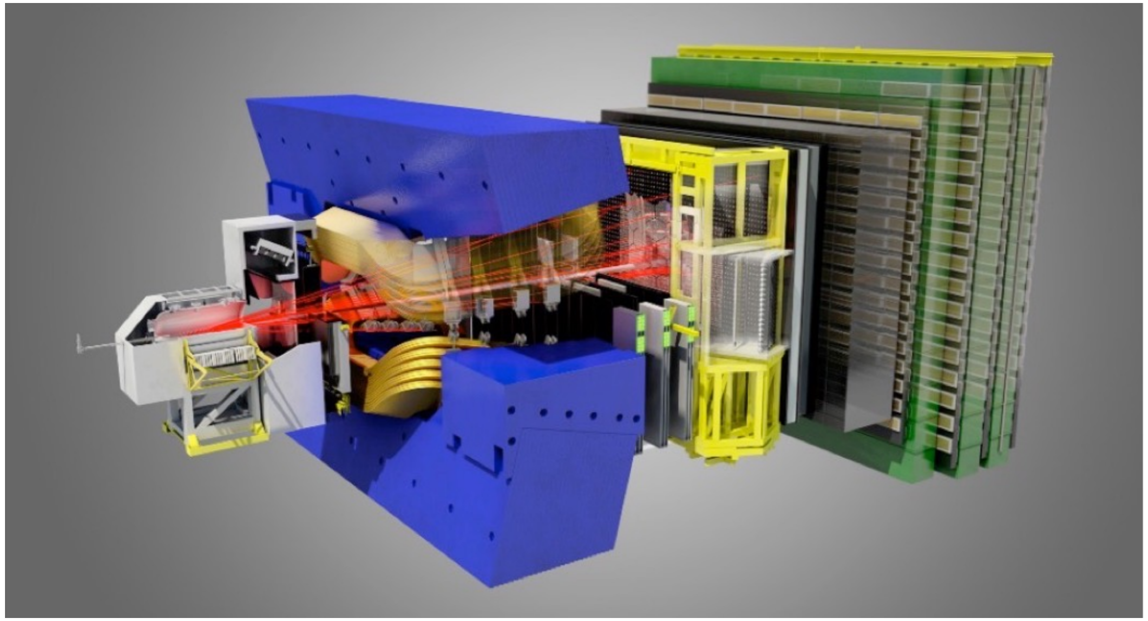
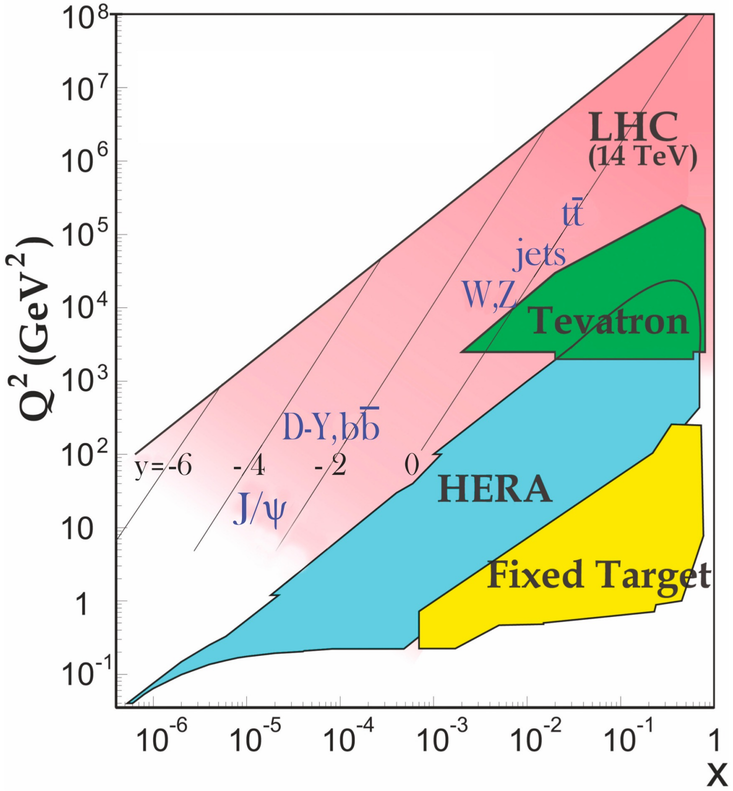
Unique acceptance of LHCb

The x value of interacting partons are correlated with the boson production

- Rapidity (y): $y = \frac{1}{2} ln \frac{x_1}{x_2}$
- Large rapidity: either very large x or very small x





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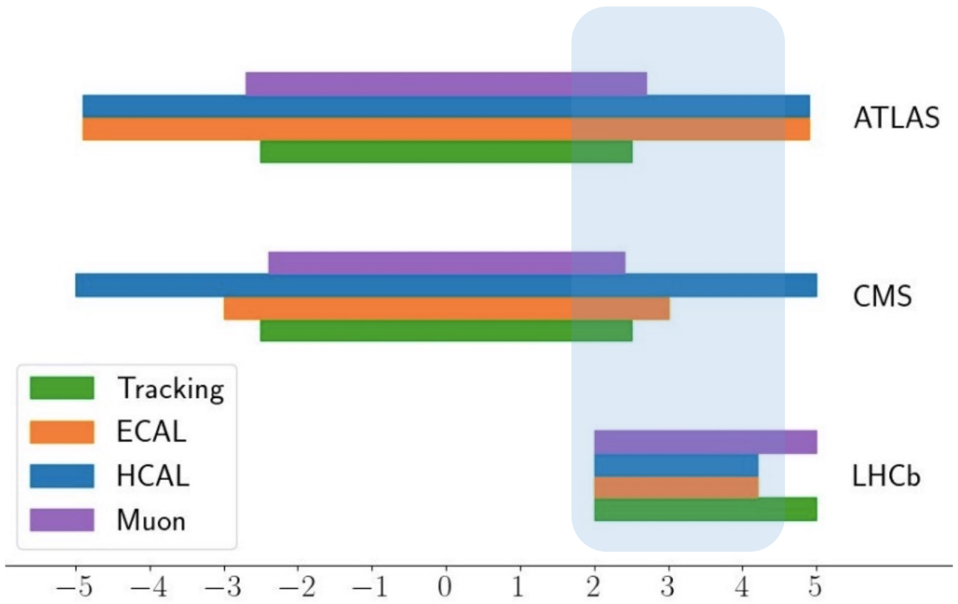

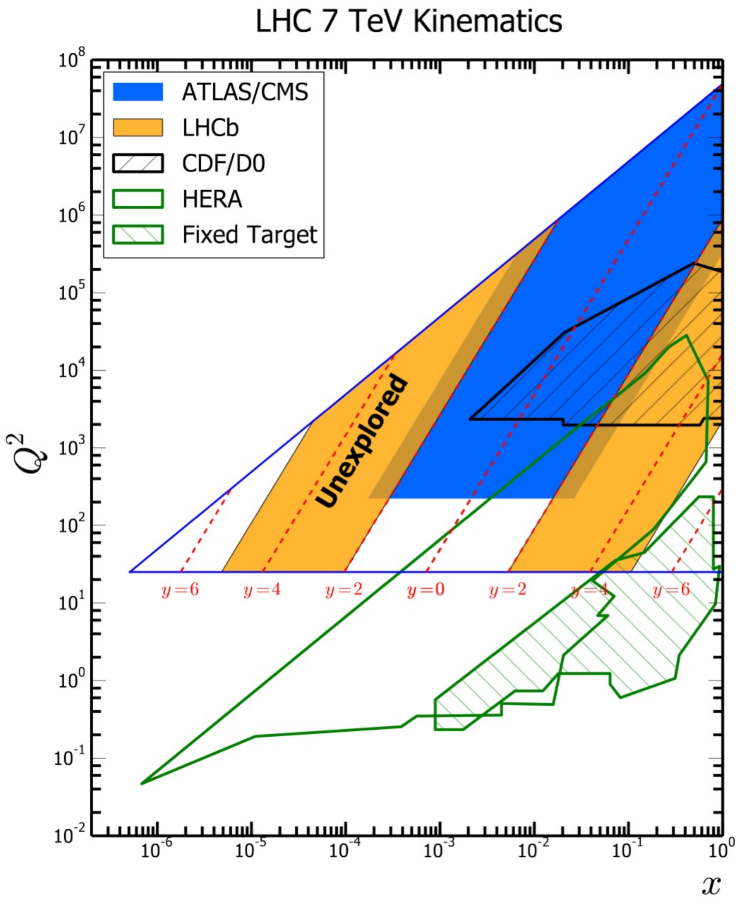

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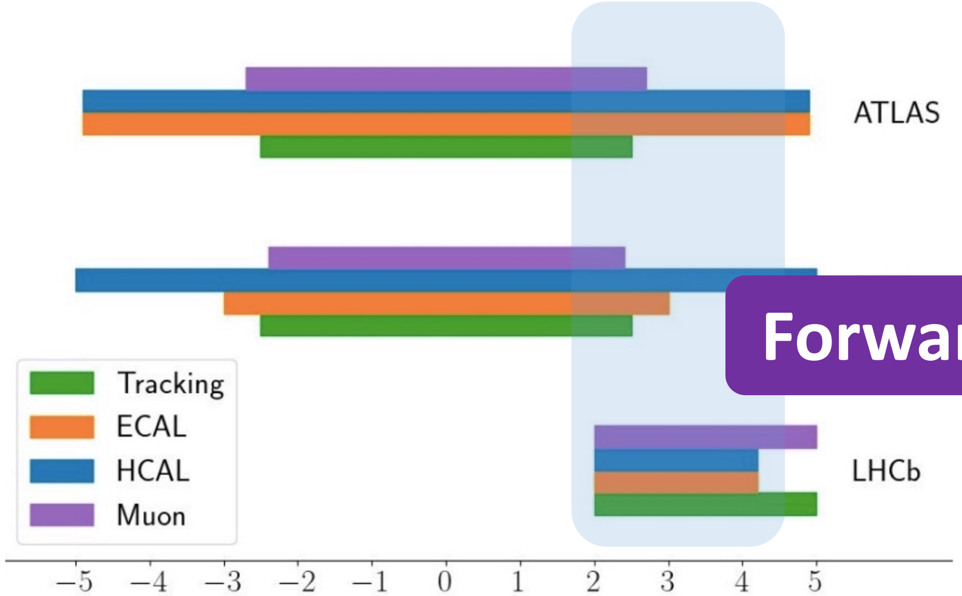
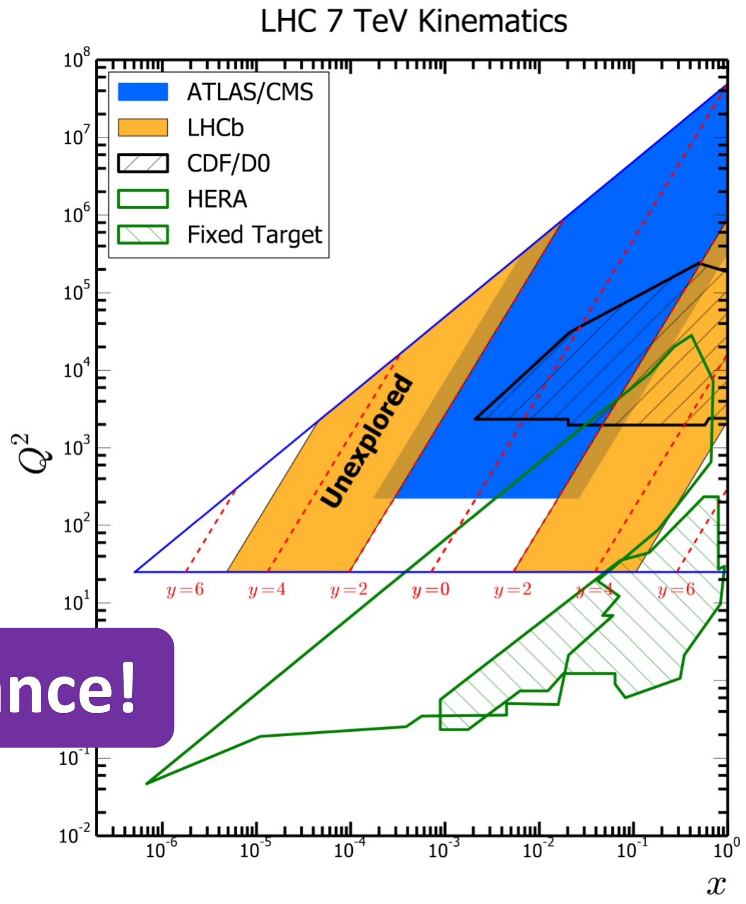


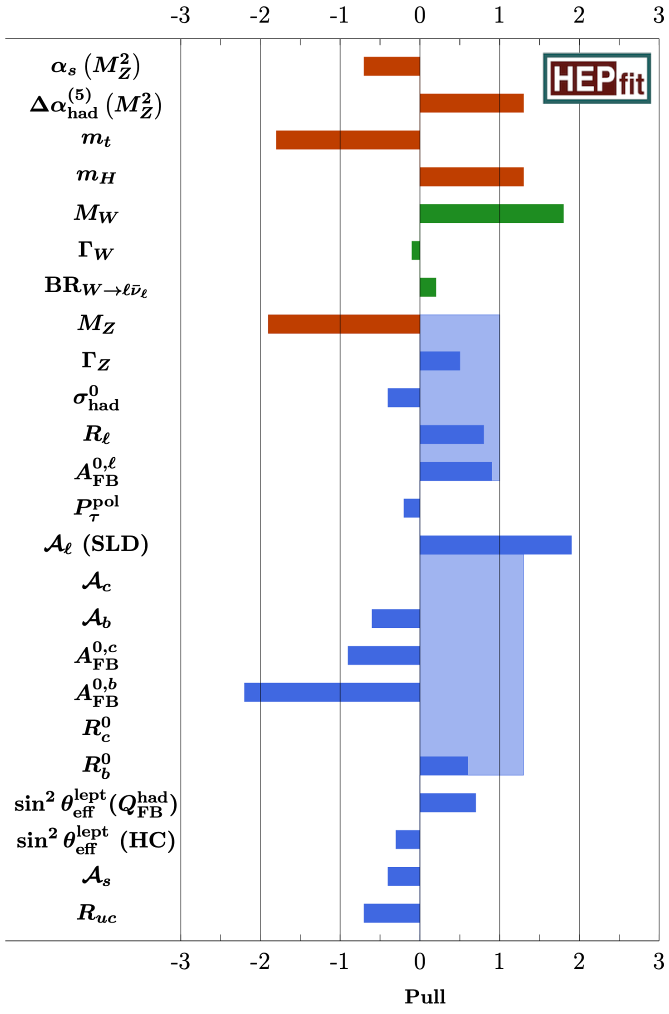
Forward acceptance!



Weak mixing angle

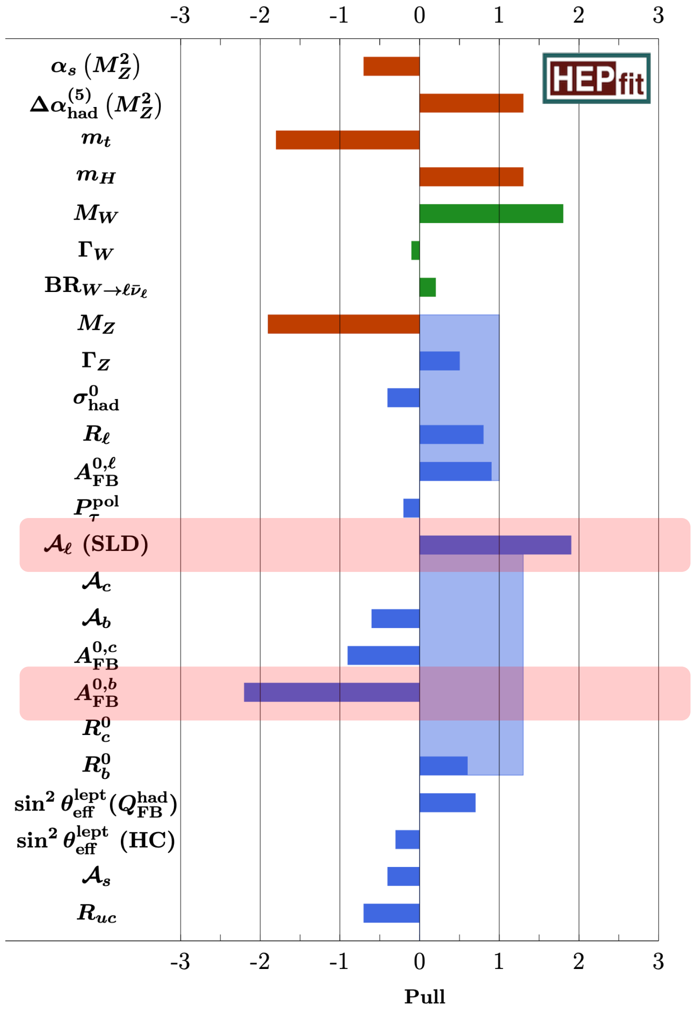
- **Fundamental parameters of SM electroweak sector**
- **Couplings between fermions and Z boson: $(V - A)$**
  - Vector couplings: $V = I_3 - 2Q sin^2\theta_W$
  - Axial-vector coupling: $A = I_3$
- **In the tree level,** $sin^2\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right)$
- **At higher order:**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

Well-known deviation



PRD 106 (2022) 3, 033003

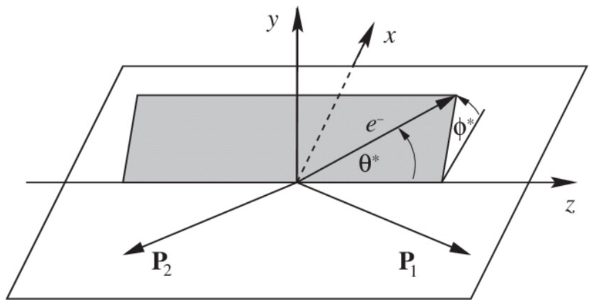
Well-known deviation



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**

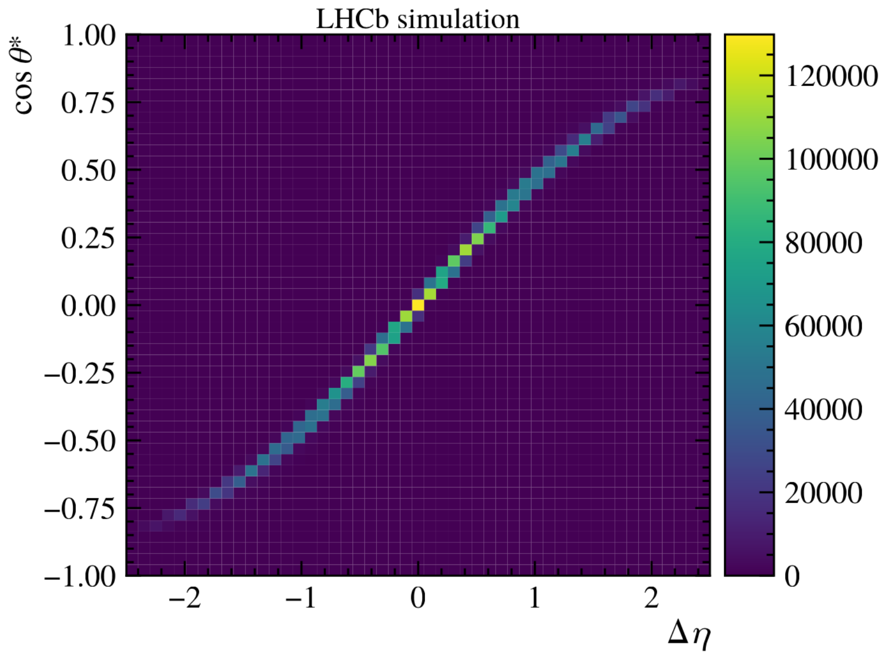
Extraction of $sin^2\theta_W^{lept}$



- $\frac{d\sigma}{dcos\theta^*} \propto 1 + cos^2\theta^* + \frac{8}{3}A_{fb}^{4\pi}cos\theta^*$
  - 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 $\sin^2\theta_{eff}^{lept}$
  - small $|\cos\theta^*|$ mostly dilute the measurement

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

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



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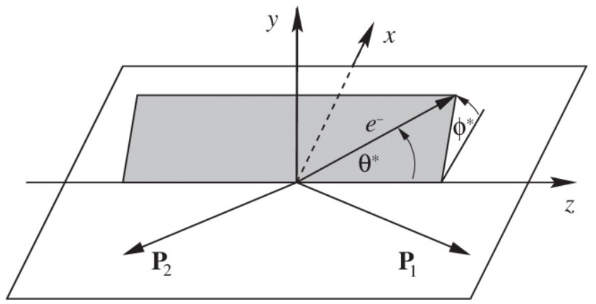

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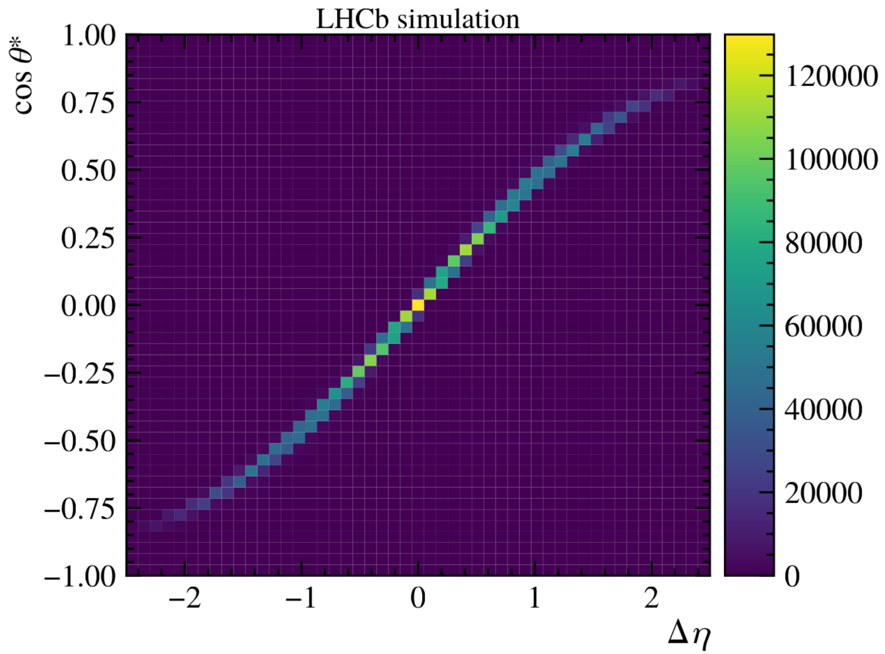
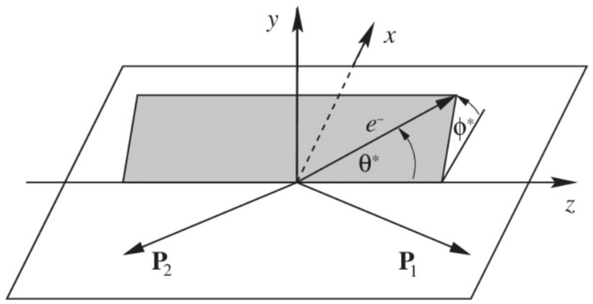
- **Improve the precision on $\sin^2\theta_{eff}^{lept}$ measurement by 14% in simulation**

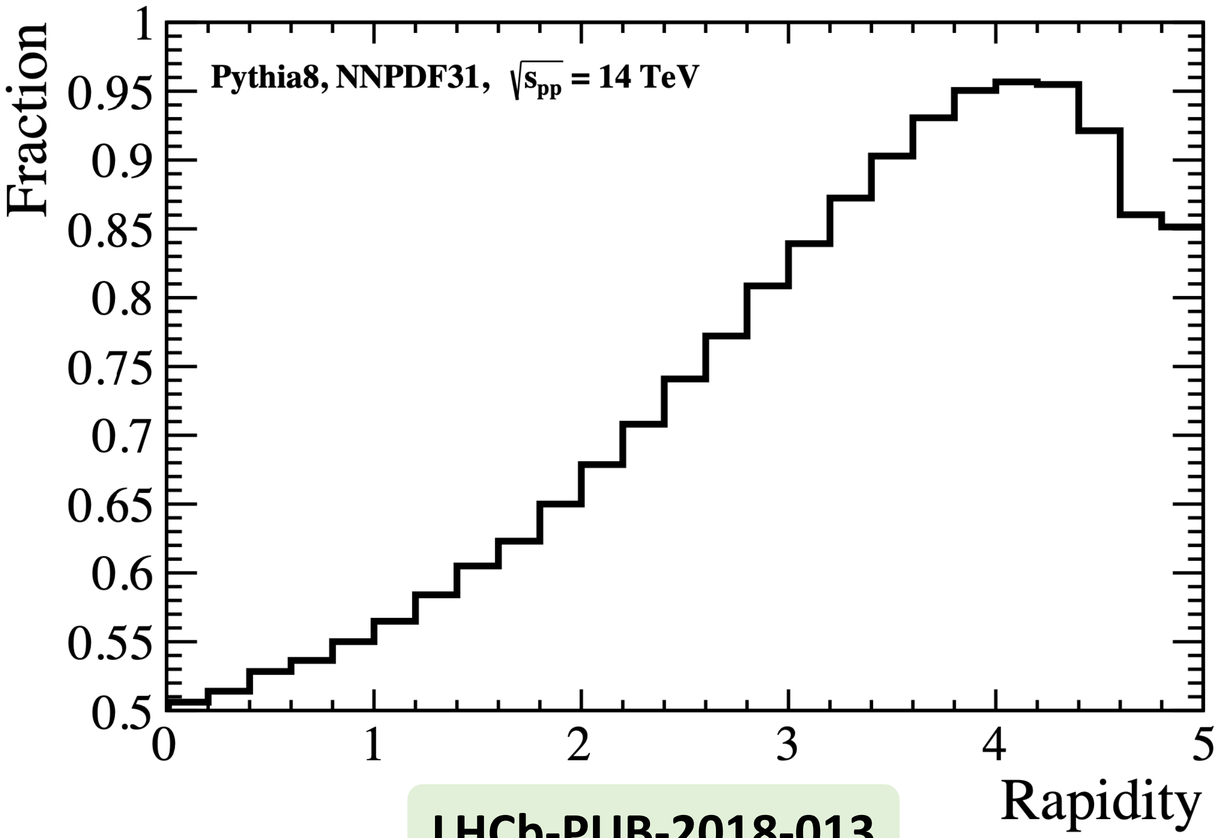


Dilution effects



At the LHC, the direction of 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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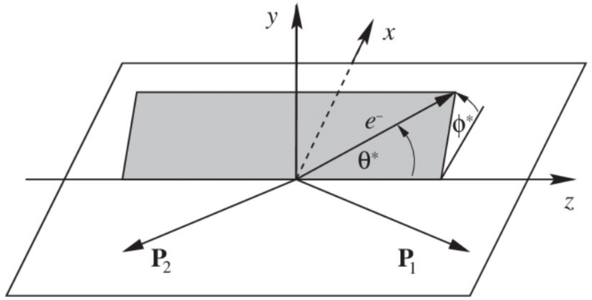

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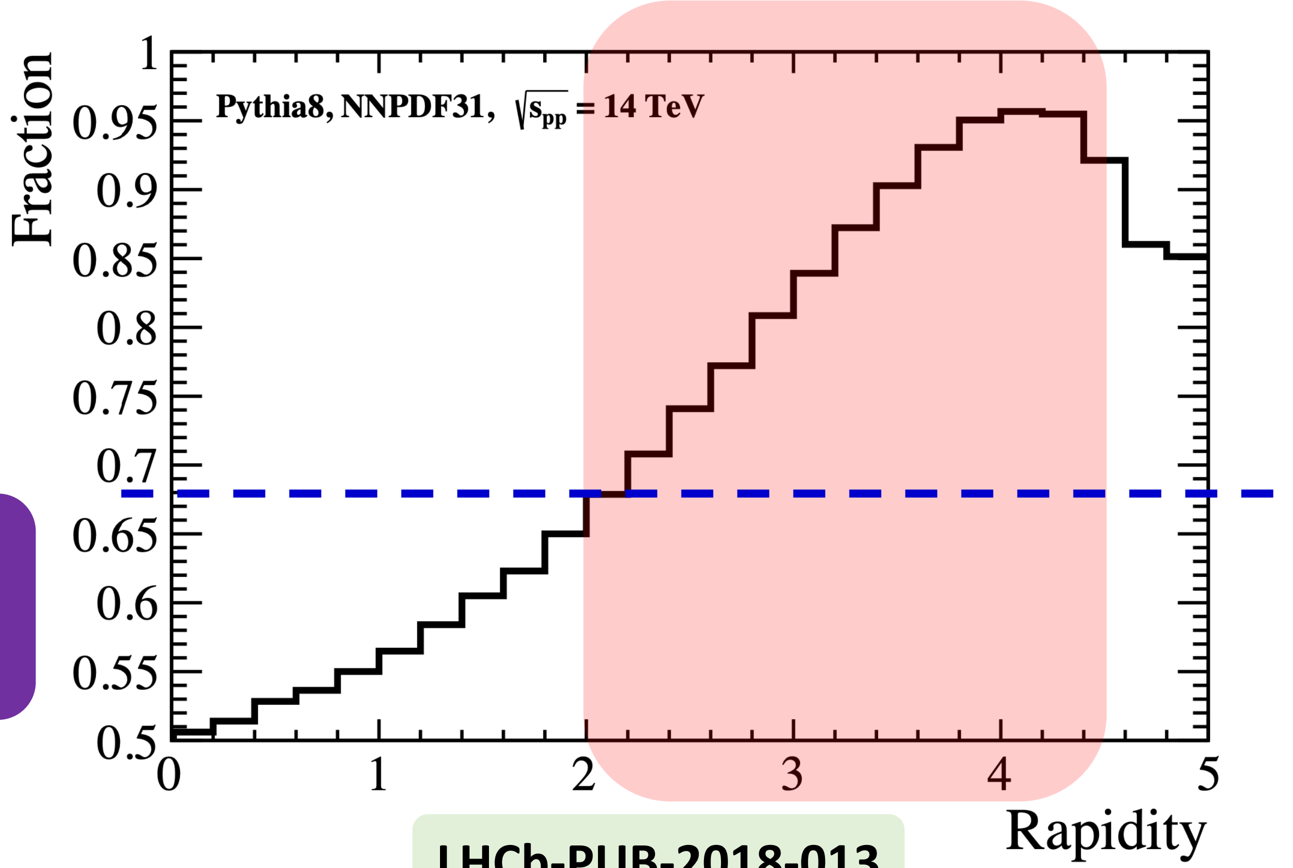
Smaller statistics ($\sim 1/65$), but similar sensitivity as ATLAS/CMS!



LHCb-PUB-2018-013

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, the muon impact parameter requirement
  - Hadronic background: suppressed to the percent level, an isolation requirement and muon track fit requirement
- Roughly 860k events are selected for the measurement

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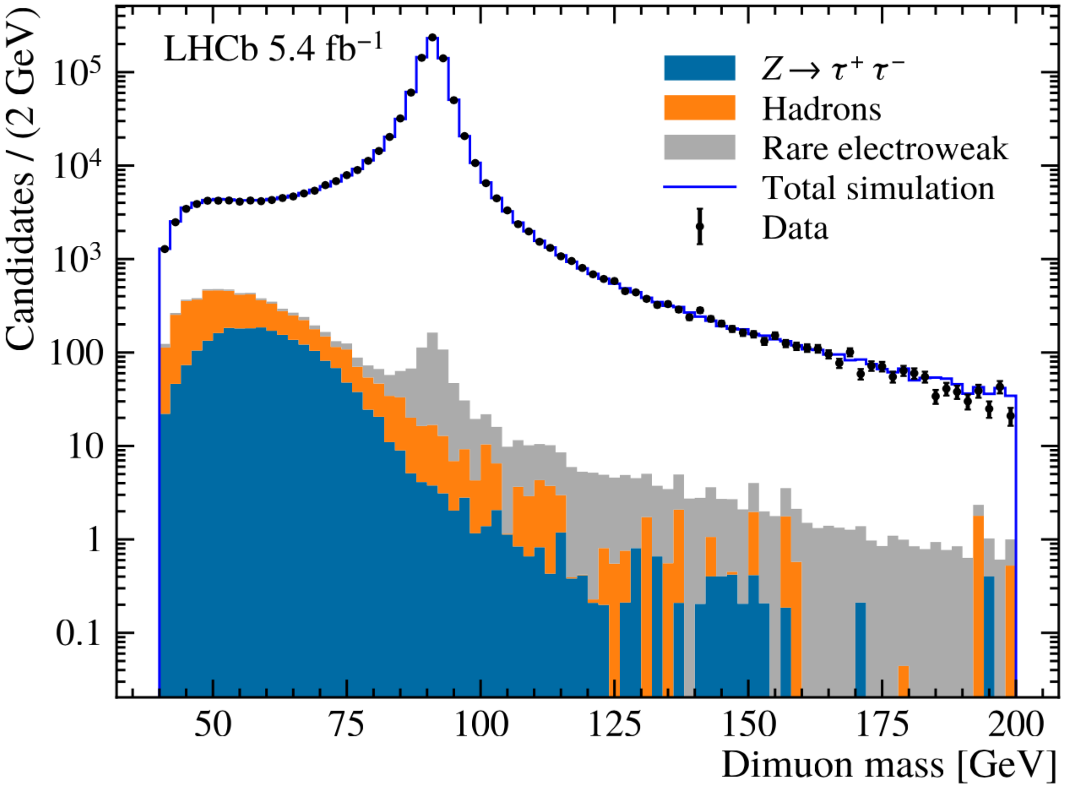
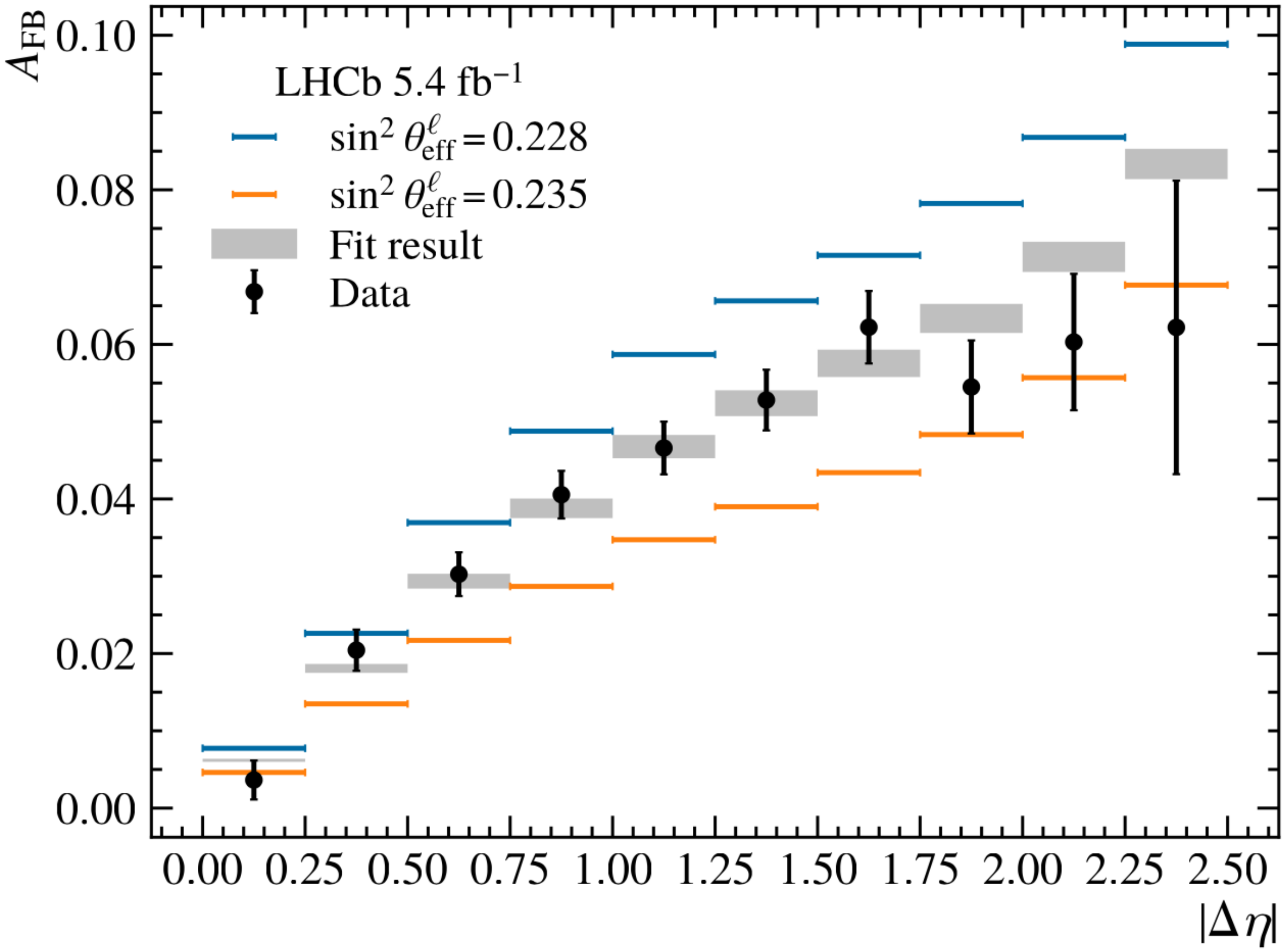


Bset fit point

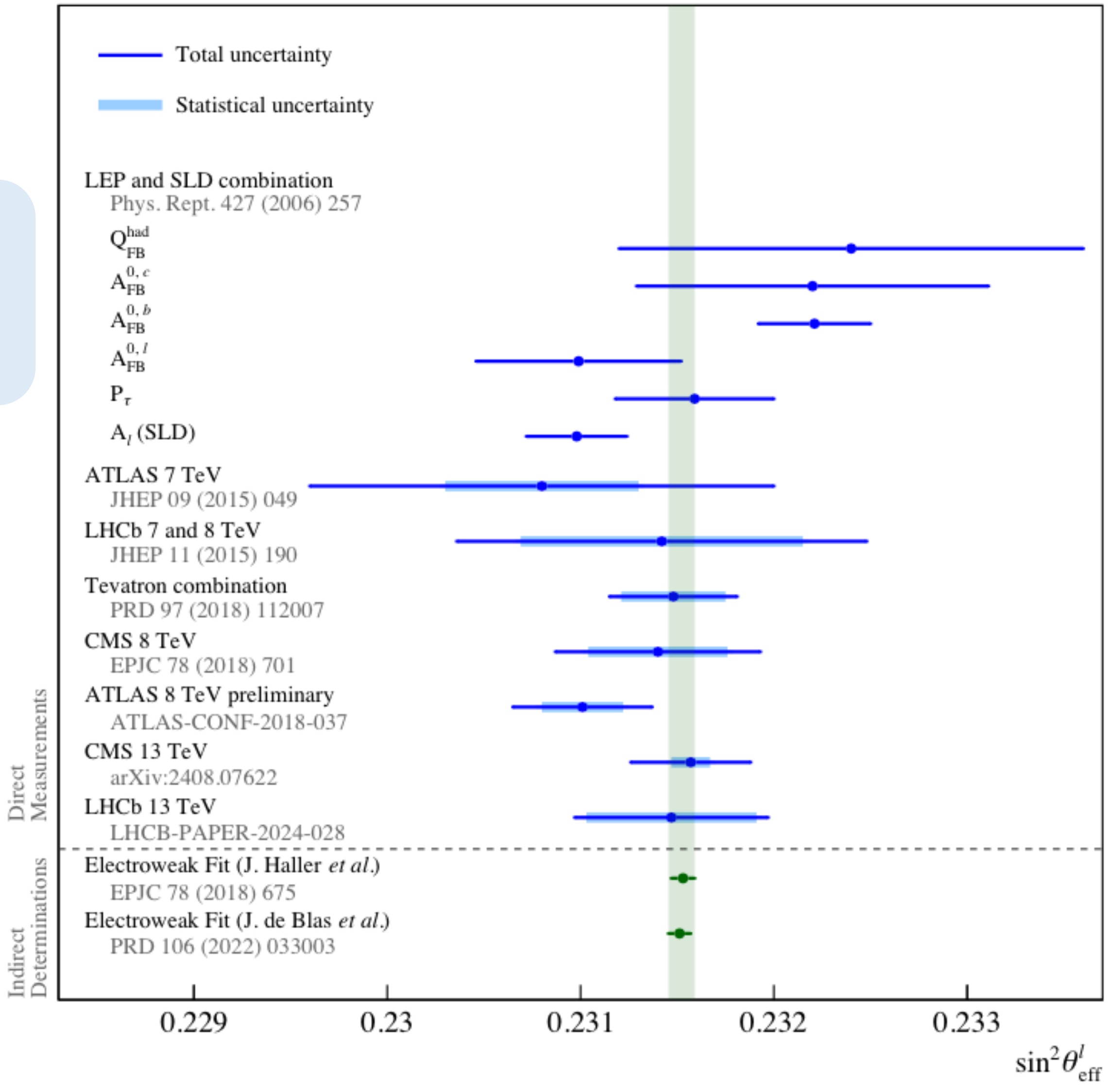


Measured result

$$0.23152 \pm 0.00044\ (\text{stat.}) \pm 0.00005\ (\text{syst.}) \pm 0.00022\ (\text{theory})$$

- Theory uncertainty include PDF uncertainty, QCD and EW uncertainty

arXiv:2410.02502, accepted by JHEP



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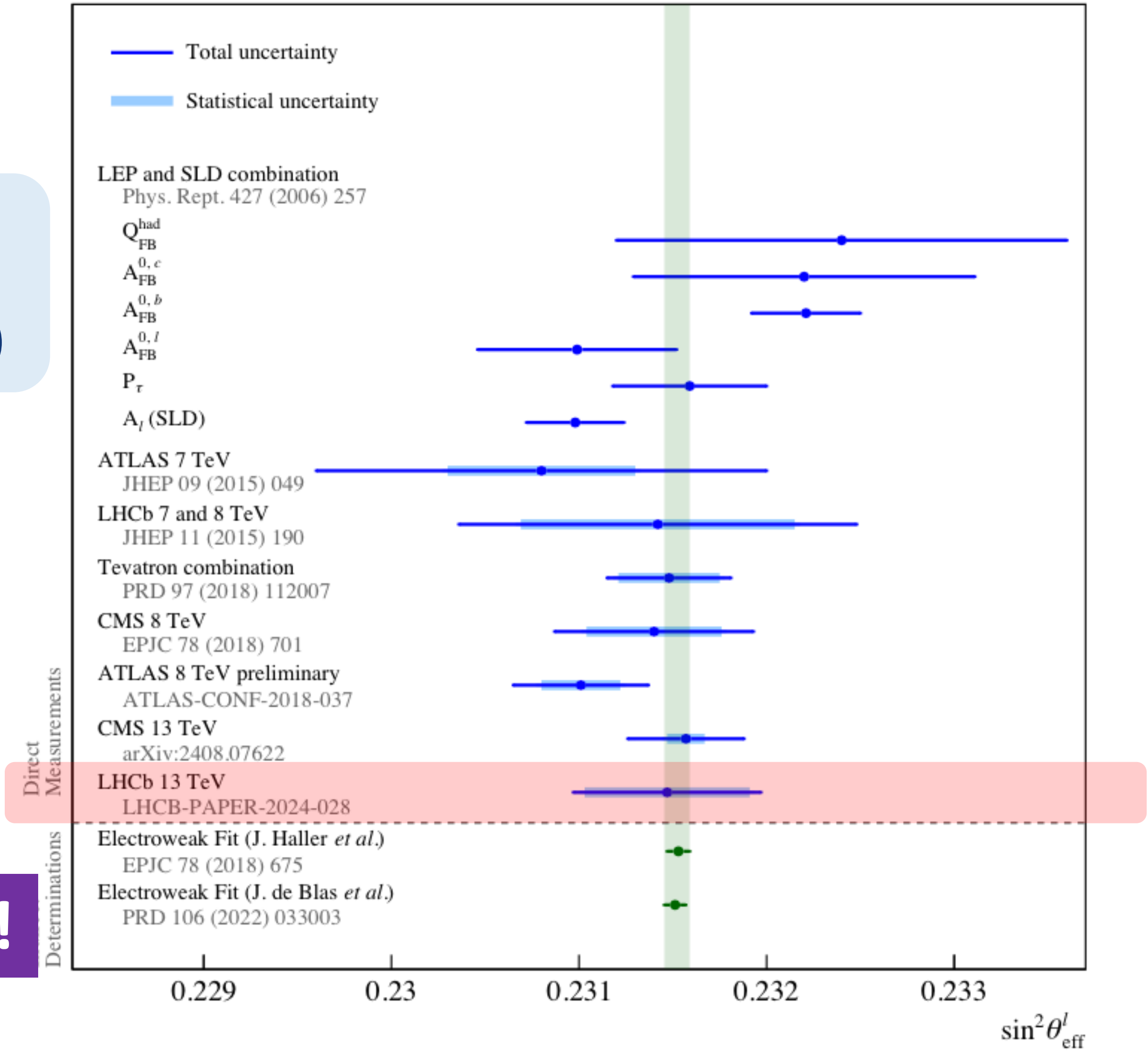
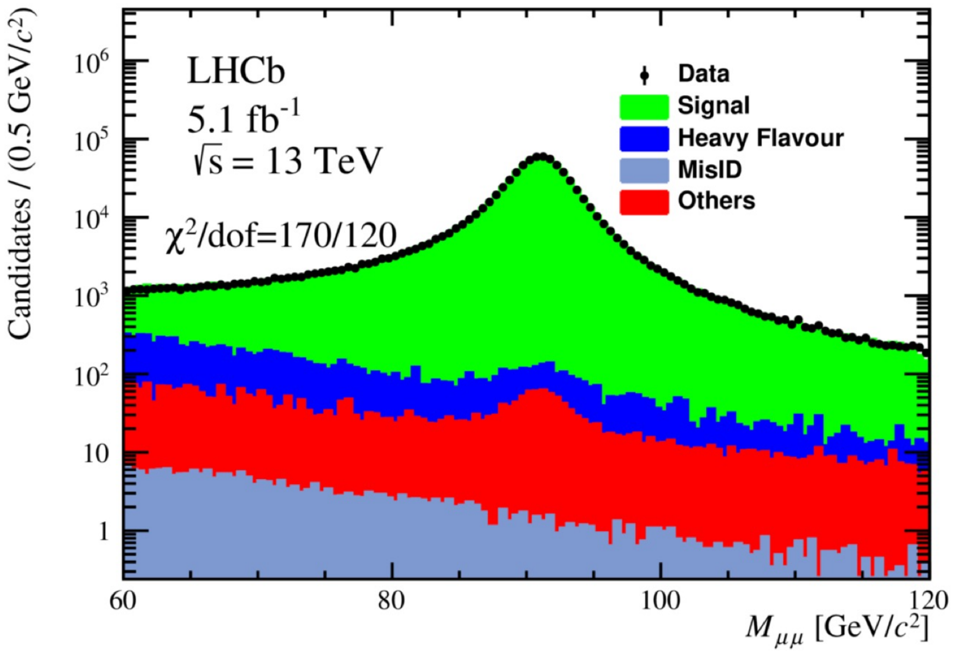


Dominated by the statistics uncertainty!

Z production cross section measurement

- **Dataset: 2016-2018, pp collision data @ 13 TeV, $5.1\ \mathrm{fb}^{-1}$**
- **Event Selections:**
  - $Z \to \mu^+\mu^-$ events, at lease one μ^+ must fire single muon trigger
  - 796k candidates
- **Background contribution 1.5%**
  - Heavy flavour; misidentified hadron; Other physics process

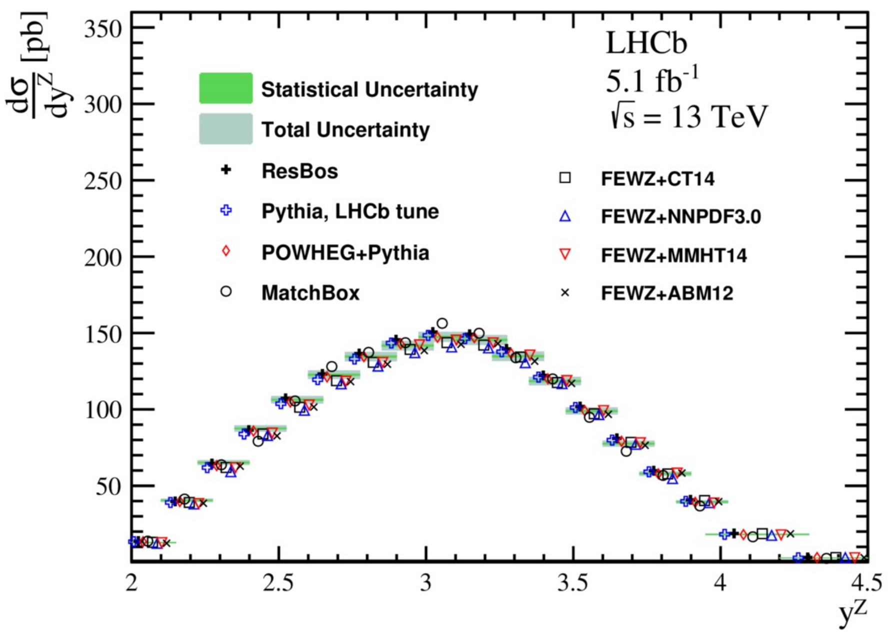
μ	Z
$p_T > 20\,\mathrm{GeV}/c$	$60 < M_{\mu^+\mu^-} < 120\,\mathrm{GeV}/c^2$
$2 < \eta < 4.5$	
$\sigma_P/P < 10\%$	

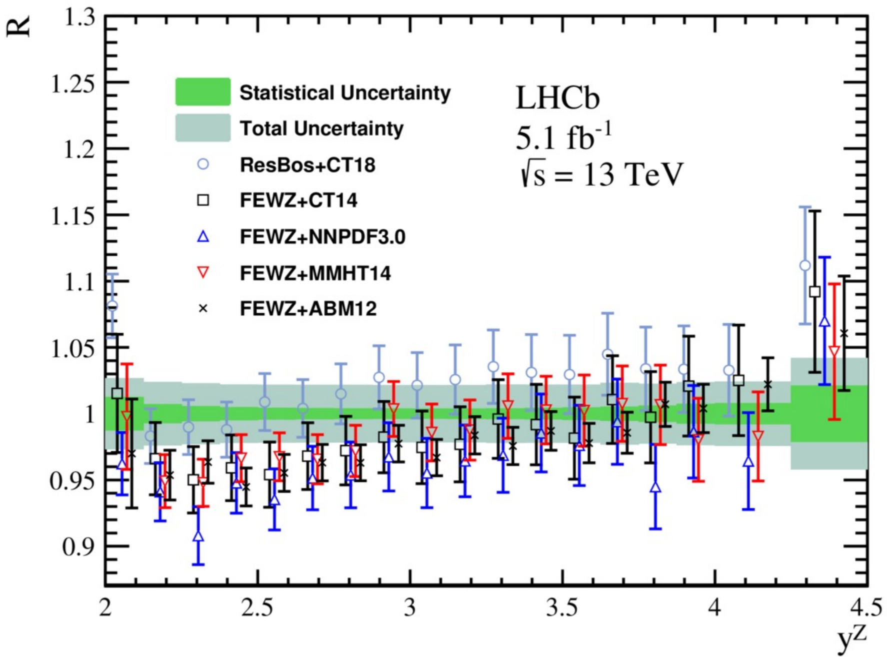


JHEP 07 (2022) 26

Differential cross-section: 1D

- Reasonable agreements between data and predictions
- Predictions are systematically smaller than the measured results in the lower rapidity region
  - Same behaviours are seen in 2015 LHCb data-set





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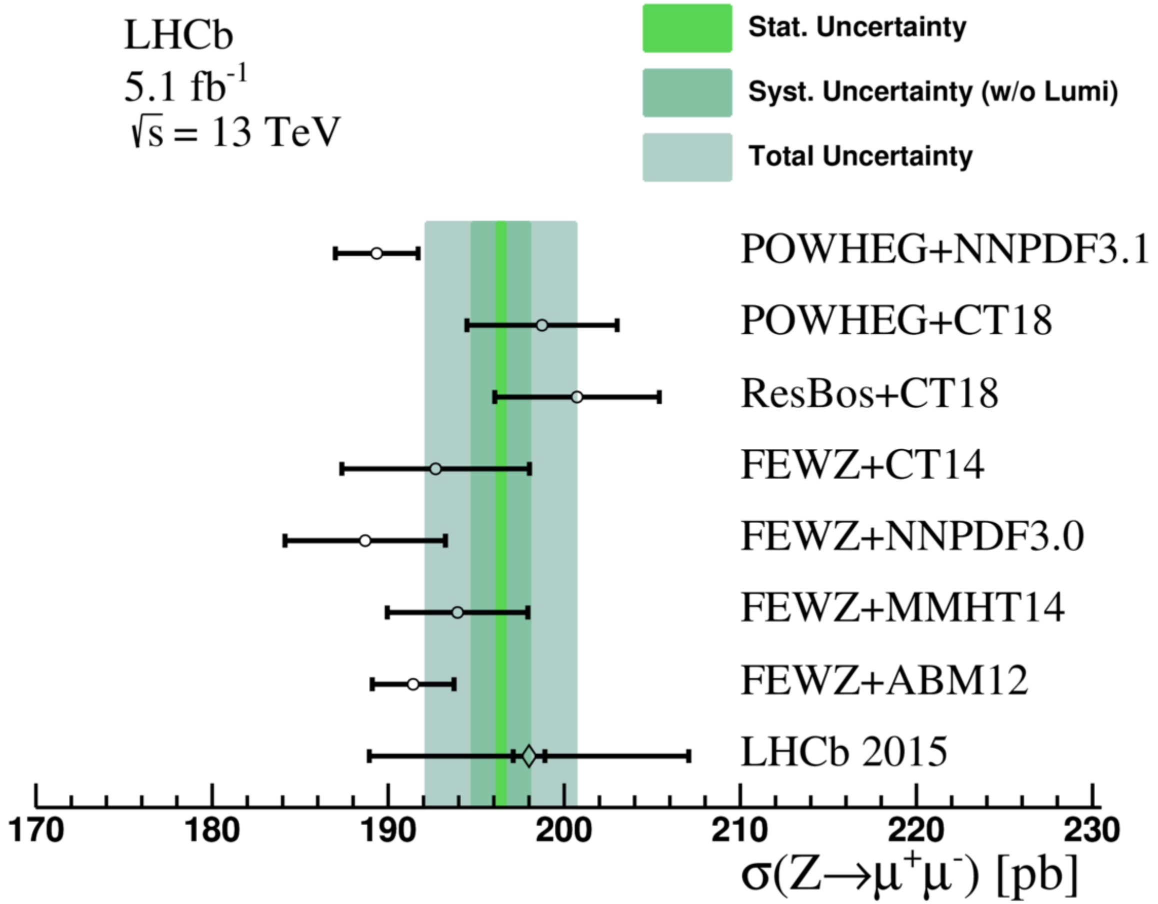
Integrated cross-section

- Good agreement between data and predictions



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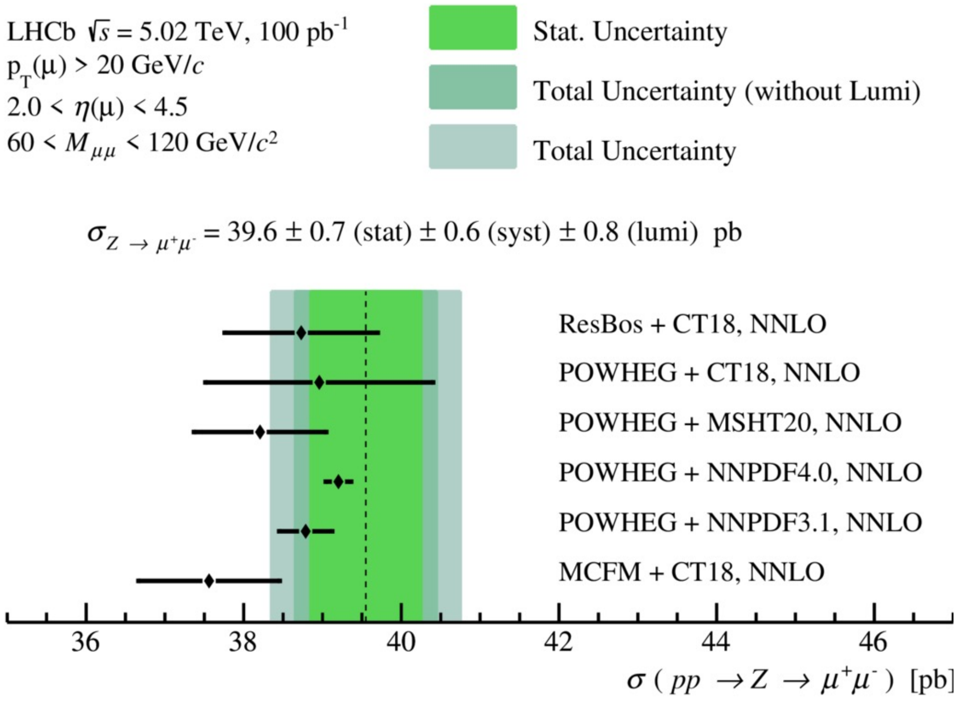
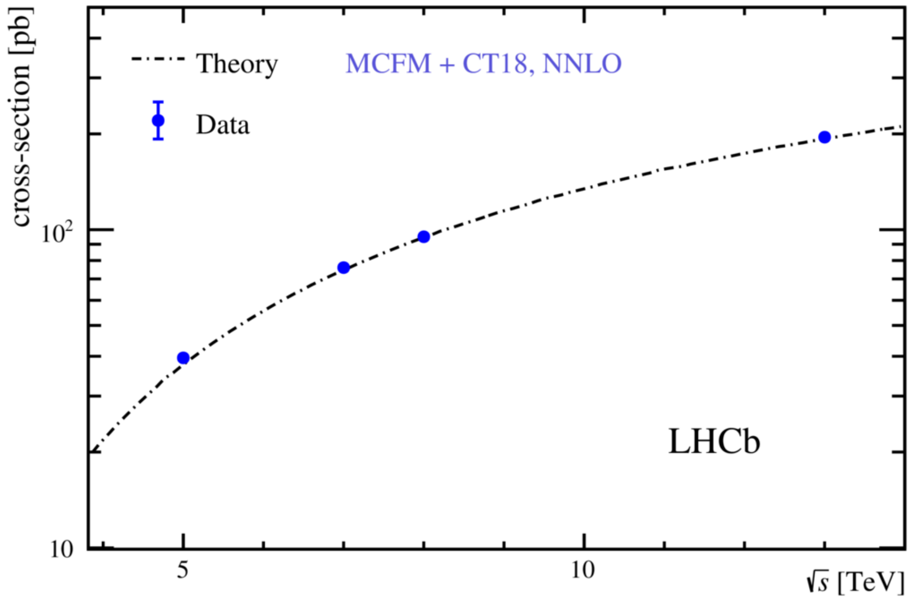
LHCb 5.02 TeV measurement

- 2017 pp reference run data-set: 100 pb^{-1}
- Same analysis framework as 13 TeV publication





JHEP 02 (2024) 070

Z angular coefficient measurement

$$\frac{d\sigma}{dP_T^2\,dy\,d\cos\theta\,d\phi} \propto (1+\cos^2\theta)$$ → **LO term**

$$+\frac{1}{2}A_0(1-3\cos^2\theta)$$ → ***$\cos^2\theta$: higher order term***

$$+A_1\sin 2\theta\cos\phi+\frac{1}{2}A_2\sin^2\theta\cos 2\phi+A_3\sin\theta\cos\phi$$ → ***(θ, ϕ) terms***

$$+A_4\cos\theta$$ → ***LO term : determine A_{fb}***

$$+A_5\sin^2\theta\sin 2\phi+A_6\sin 2\theta\sin\phi+A_7\sin\theta\sin\phi$$ → ***very small terms***

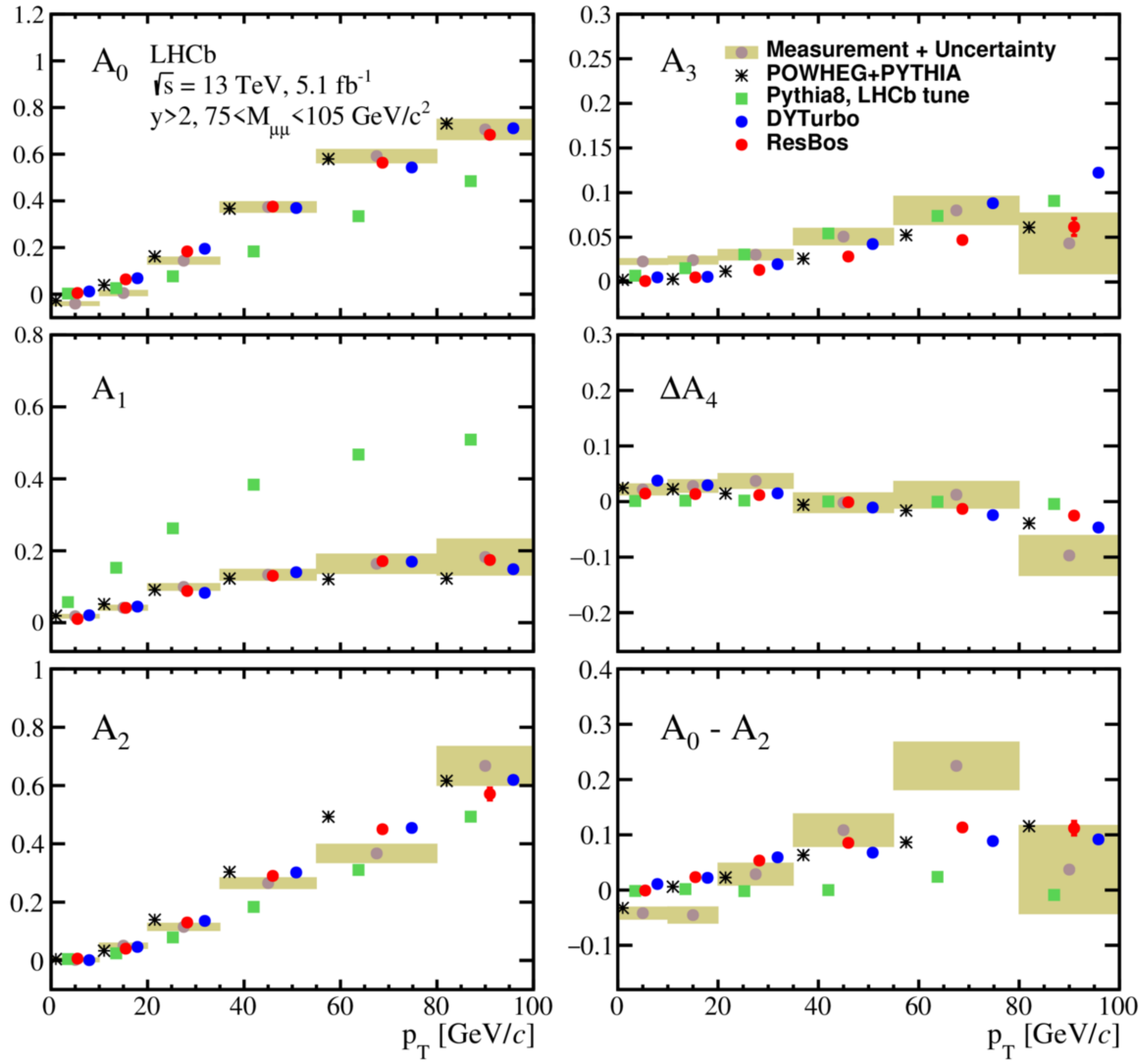
- **A_2 is sensitive to the Boer-Mulders transverse momentum dependent PDFs (TMD)**

- **LHCb Run-2 result:**
  - Low mass, middle mass and high mass region
  - Study A_2 vs. Z p_T

Z boson p_T dependent results

PRL 129 (2022) 091801

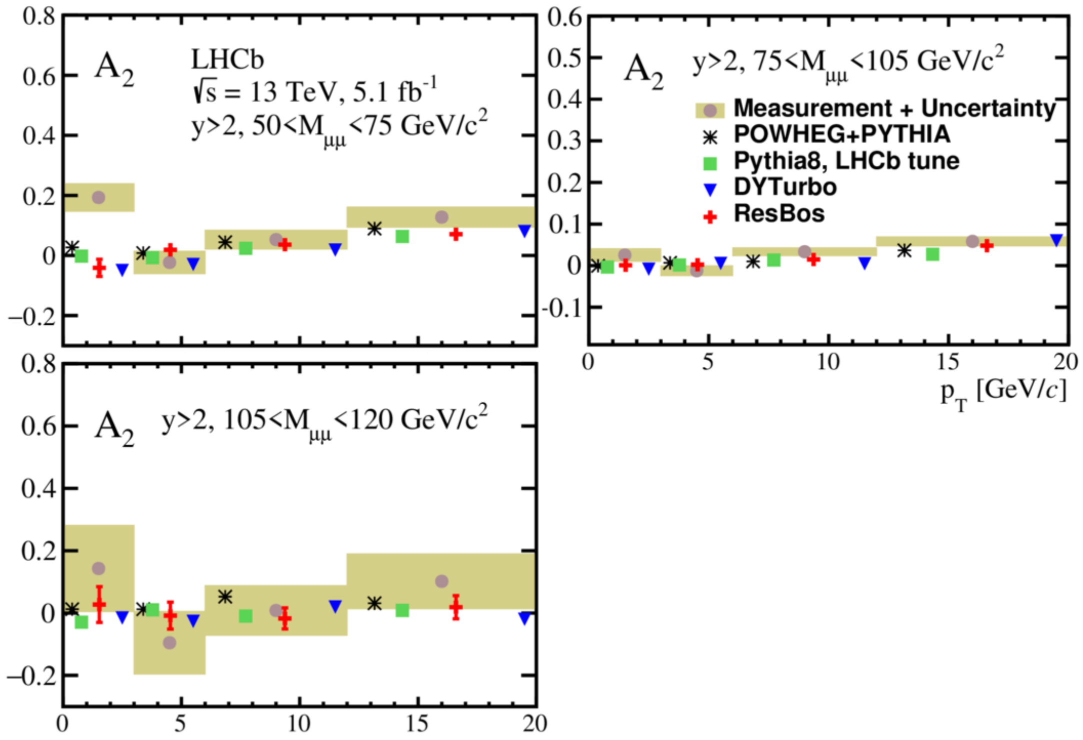
- Measured results are at Born level in QED
- Dominated uncertainty: statistical
- Compared with various predictions
  - POWHEG+PYTHIA
  - DYTurbo
  - RESBOS
  - PYTHIA+LHCb tune



Results in low Z p_T region

PRL 129 (2022) 091801

- Use measured A_2 to probe Boer-Mulders TMD PDFs
- In different mass regions: 50-75, 75-105, 105-120 GeV/c^2
- None of predictions include non-perturbative spin-momentum correlations



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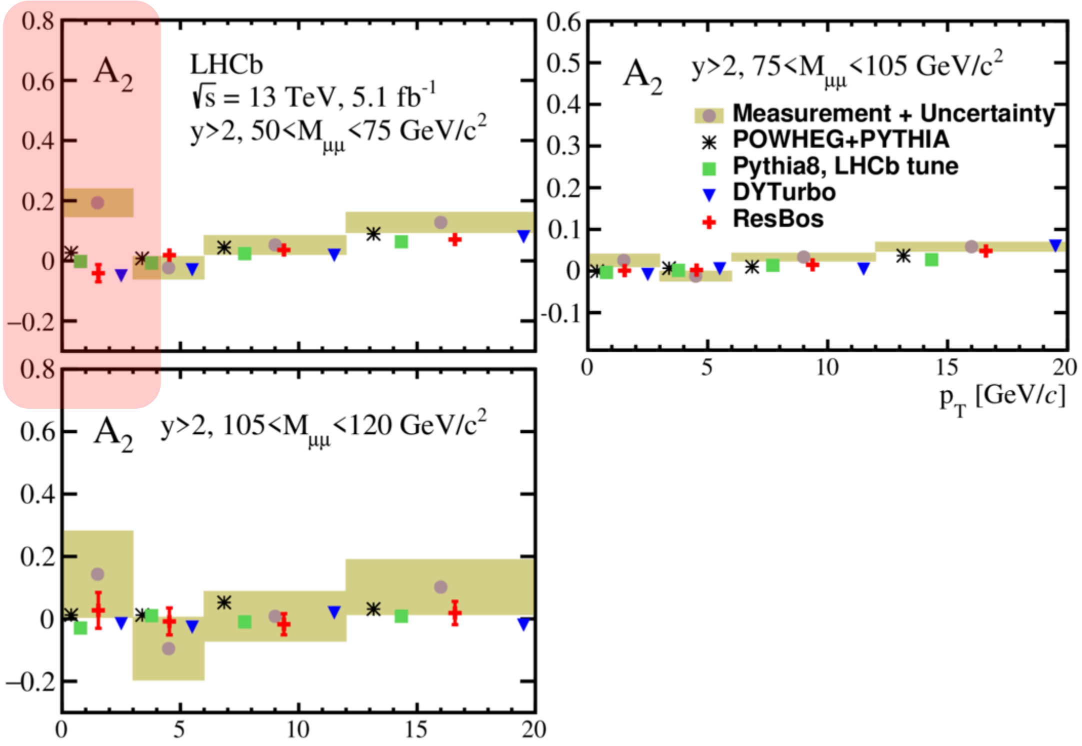
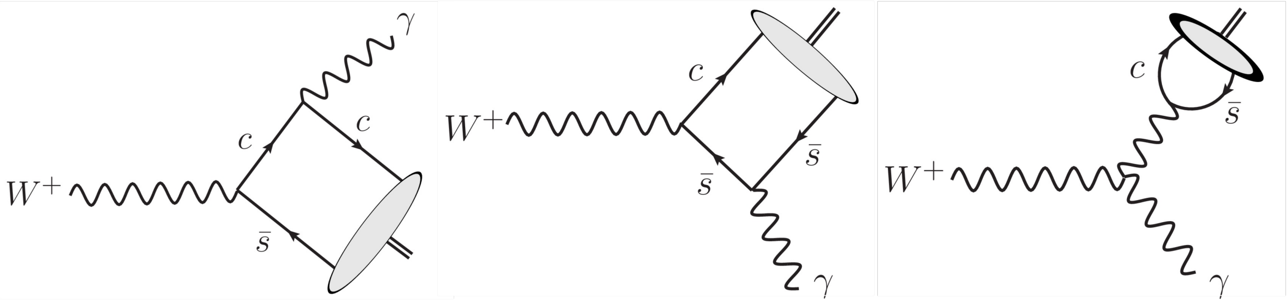
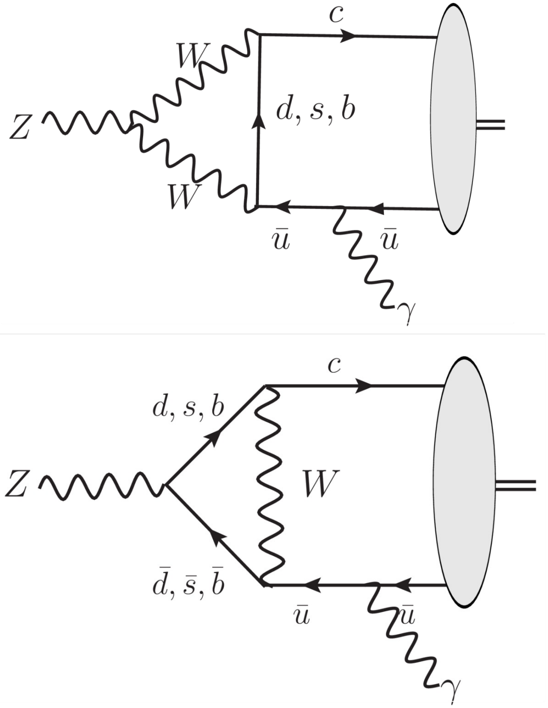


W/Z rare decay

CPC 47 (2023) 093002

- **Very rare radiative decays of W and Z bosons**
  - Search for new physics
  - A good probe for QCD factorization formalism
- **SM branching fraction:**
  - $\sim 10^{-6} - 10^{-15}$
  - enhanced in some NP models

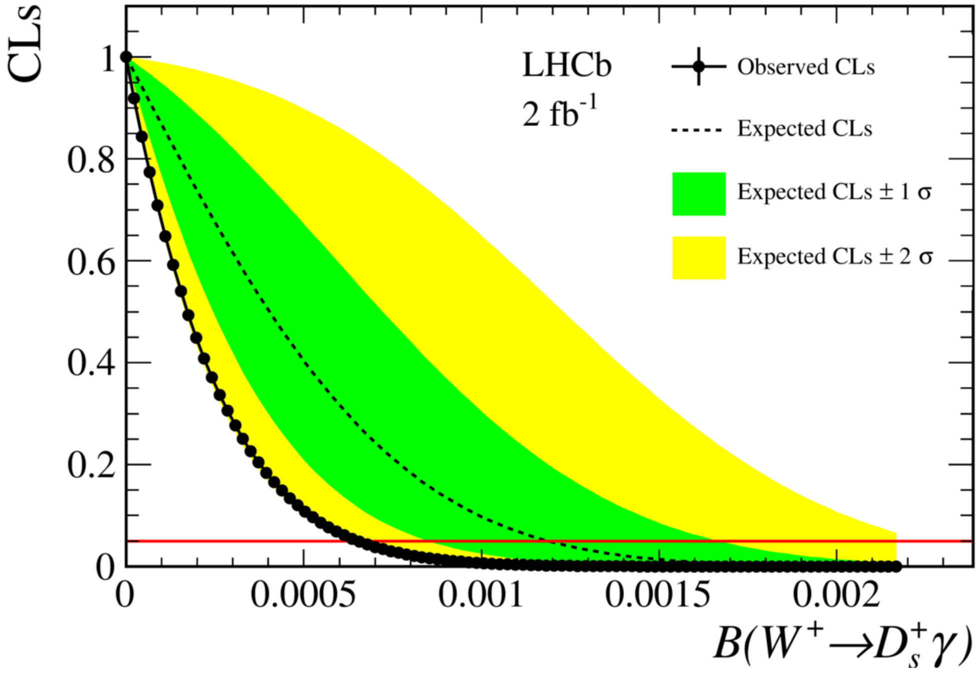




Search for $W^{\pm} \to D_s^{\pm}\gamma$ and $Z \to D^0\gamma$

CPC 47 (2023) 093002

- No significant peaking structure is found
- Set **upper limit** for $W^{+} \to D_s^{+}\gamma$ and $Z \to D^0\gamma$



$$\mathcal{B}(Z \to D^0\gamma) < 2.1 \times 10^{-3} \text{ at } 95\% \text{ C.L.},$$
$$\mathcal{B}(W^{+} \to D_s^{+}\gamma) < 6.5 \times 10^{-4} \text{ at } 95\% \text{ C.L.},$$

Better upper limit from ATLAS
PLB 855 (2024) 138762

Prospects: W mass

W mass measurement:

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

Include 2017 + 2018 data

New strategies/tools

Inputs from the theory community

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 → DYTurbo up to N2LL)
5. New PDF sets (NNPDF4.0) → Have feedback?

Goal: 20 MeV sensitivity

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:**
  - $H \rightarrow \mathrm{bb}/cc$, W+Jet Xsec, semi-leptonic WW Xsec
- **Top physics**

Summary

- **LHCb has an extensive programs on single W/Z boson production measurements**
  - Provide essential inputs for PDFs global fitting: **unique acceptance**
  - Most of systematic uncertainties could be reduce to permil level
- **At LHCb, EW-scale analyses activity is a small group with a huge phase space to cover**
  - Collaboration with theorists to make more impacts measurement with limited manpower
- **Run-3 data pp taking is done**
  - A larger data-set, compared to Run-2

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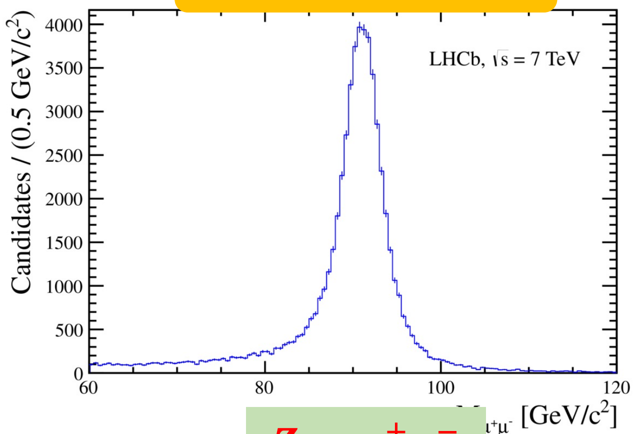
Need your inputs!

Backup

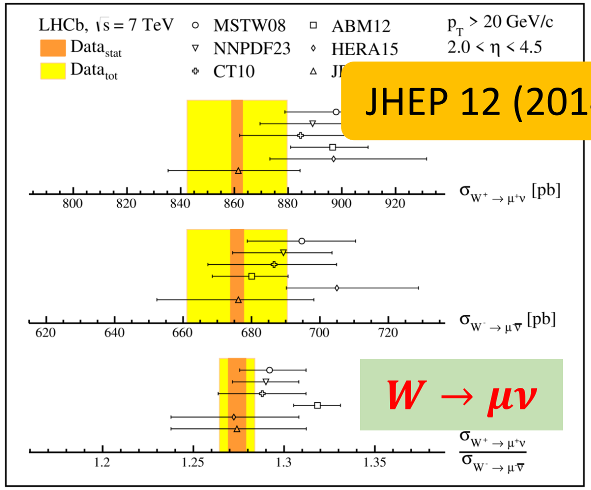
LHCb EW Highlights

JHEP 08 (2015) 039



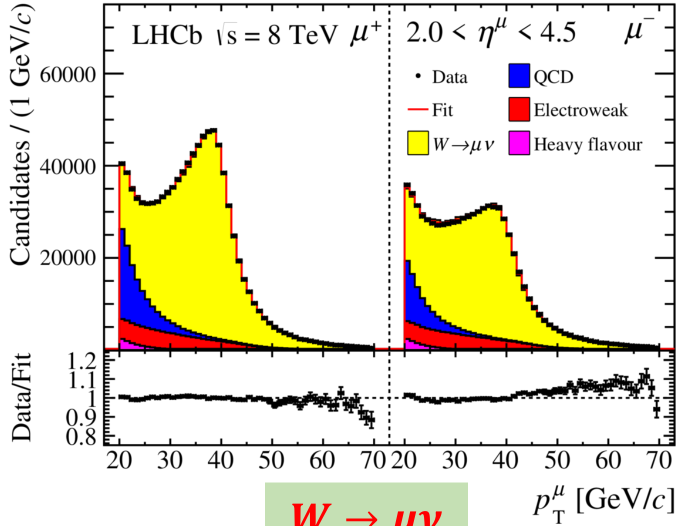
$Z \to \mu^+\mu^-$

JHEP 12 (2014) 079



$W \to \mu\nu$

JHEP 01 (2016) 155



$W \to \mu\nu$

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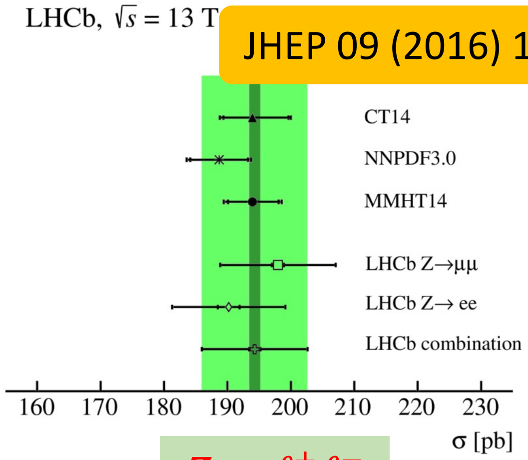

$Z \to \ell^+\ell^-$

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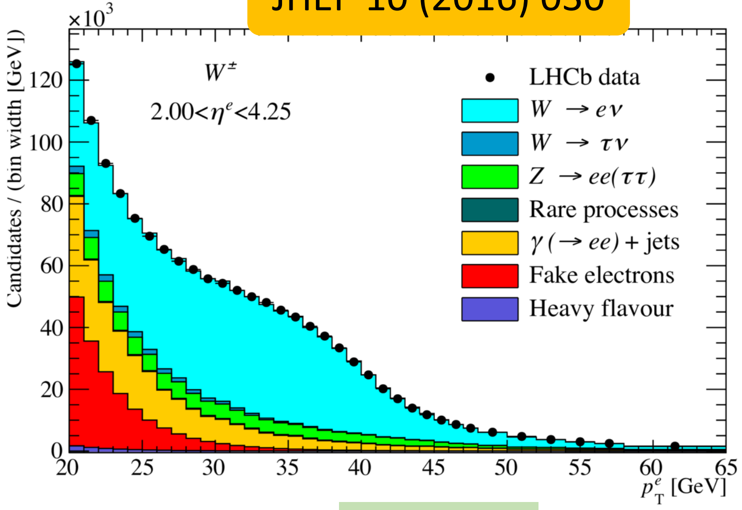

$W \to e\nu$

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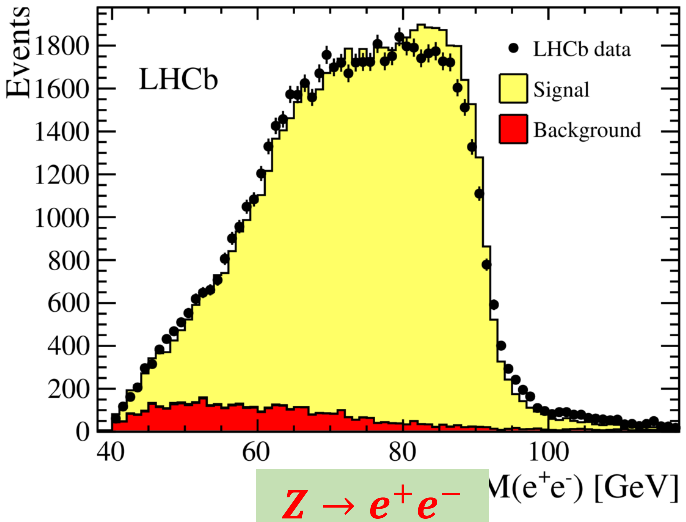
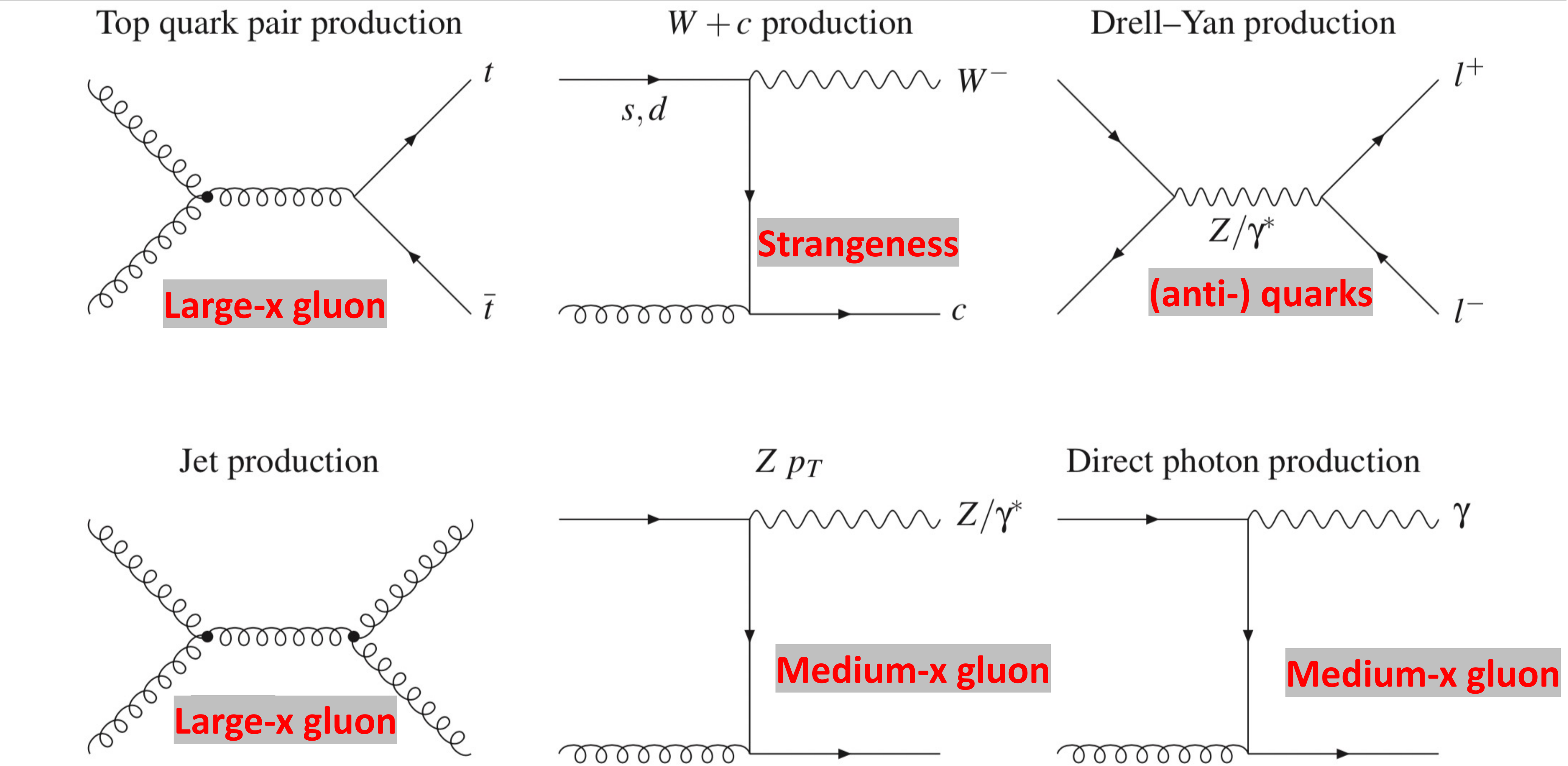


$Z \to e^+e^-$

LHC measurements



Systematic uncertainties

- **Luminosity determination: 2%**
- **Tracking reconstruction: 0.47% for each muon**

Source	$\Delta\sigma/\sigma$ [%]
Statistical	0.11
Background	0.06
Alignment & calibration	-
Efficiency	0.77
Closure	0.23
FSR	0.15
Total Systematic (excl. lumi.)	0.82
Luminosity	2.00
Total	2.16

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