LHCb实验上电弱与顶夸克物理研究

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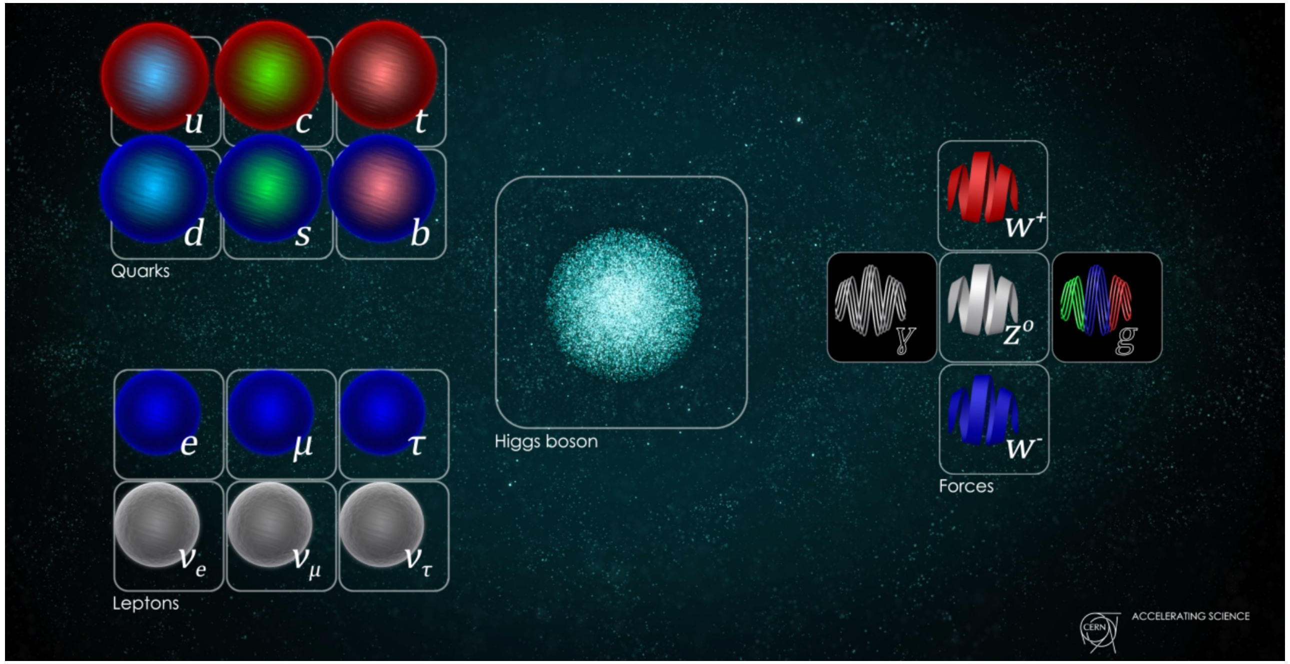
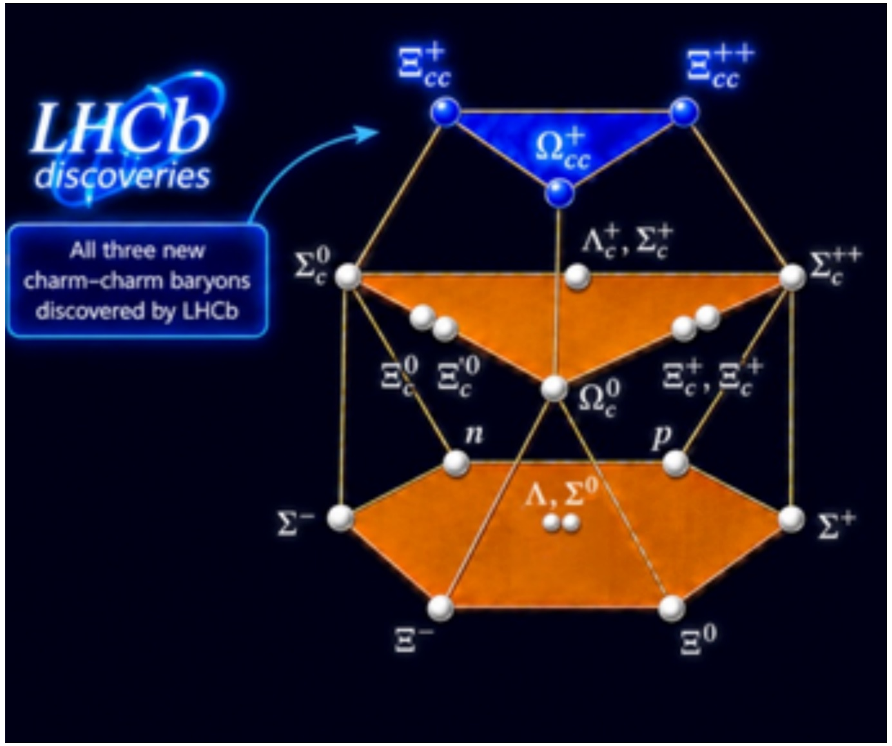
CERN

味物理讲座, 10/7/2026

Standard Model

- The SM widely successful describes the fundamental particles of the universe (that we know about) and how they interact with each other





First observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}$ Phys. Rev. Lett. 121 (2018) 162002

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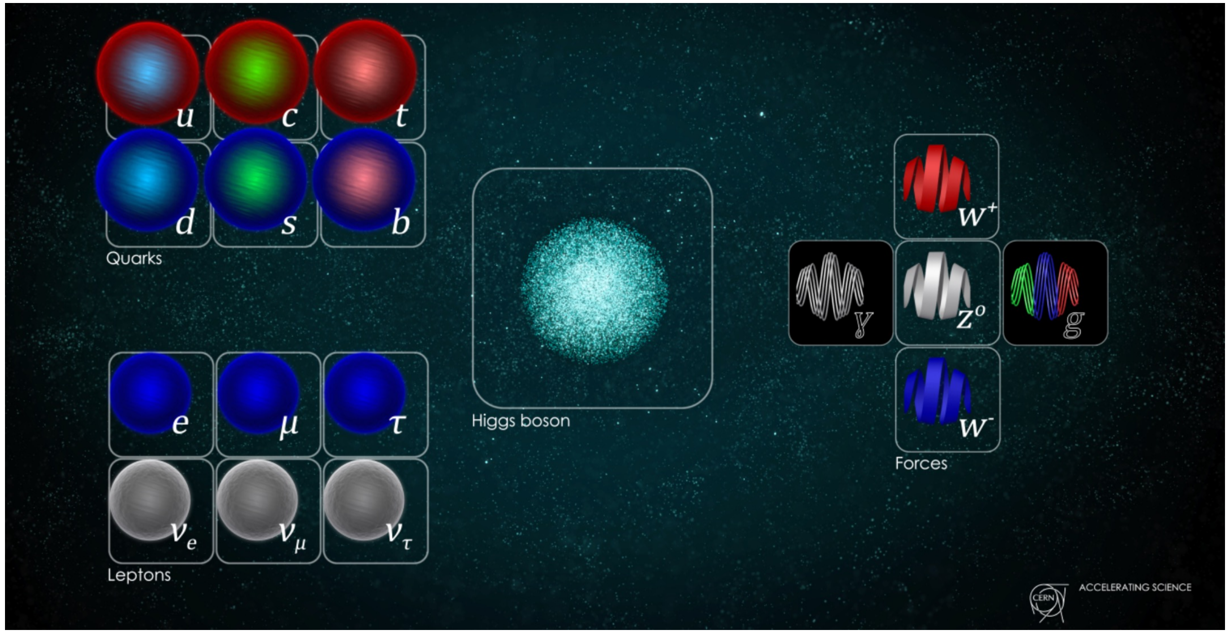
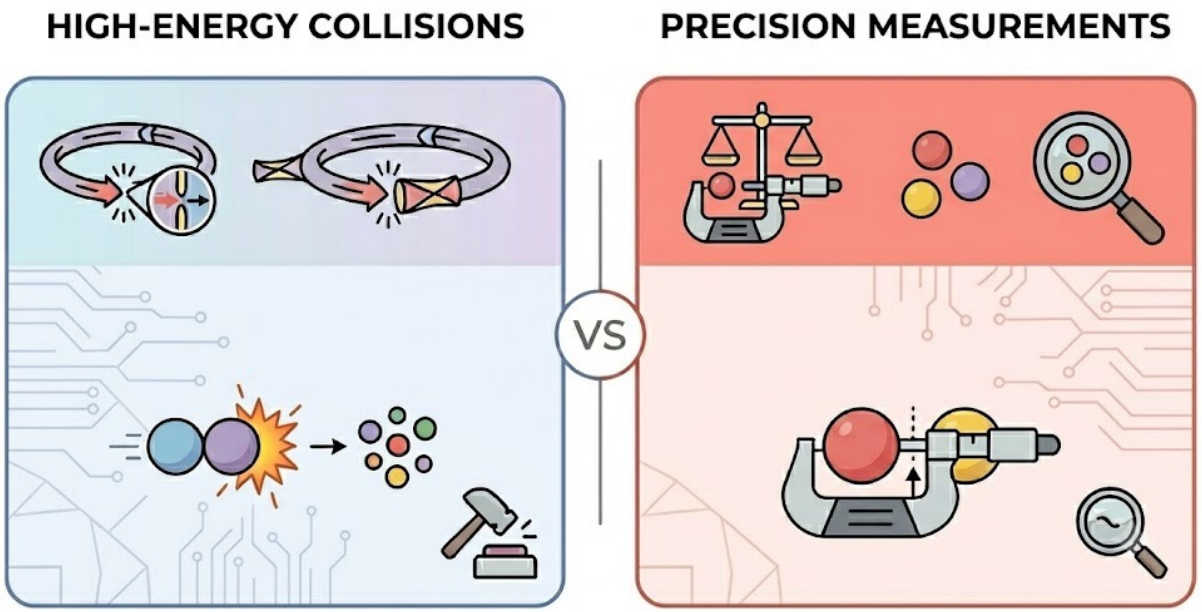


- Many questions remain unanswered:
  - what is origin of the matter-antimatter asymmetry
  - what is the origin of Dark Matter?
  - what about Dark Energy?
  - why are there three generators of fermions?
  - do forces unify?
  - …

New Physics?



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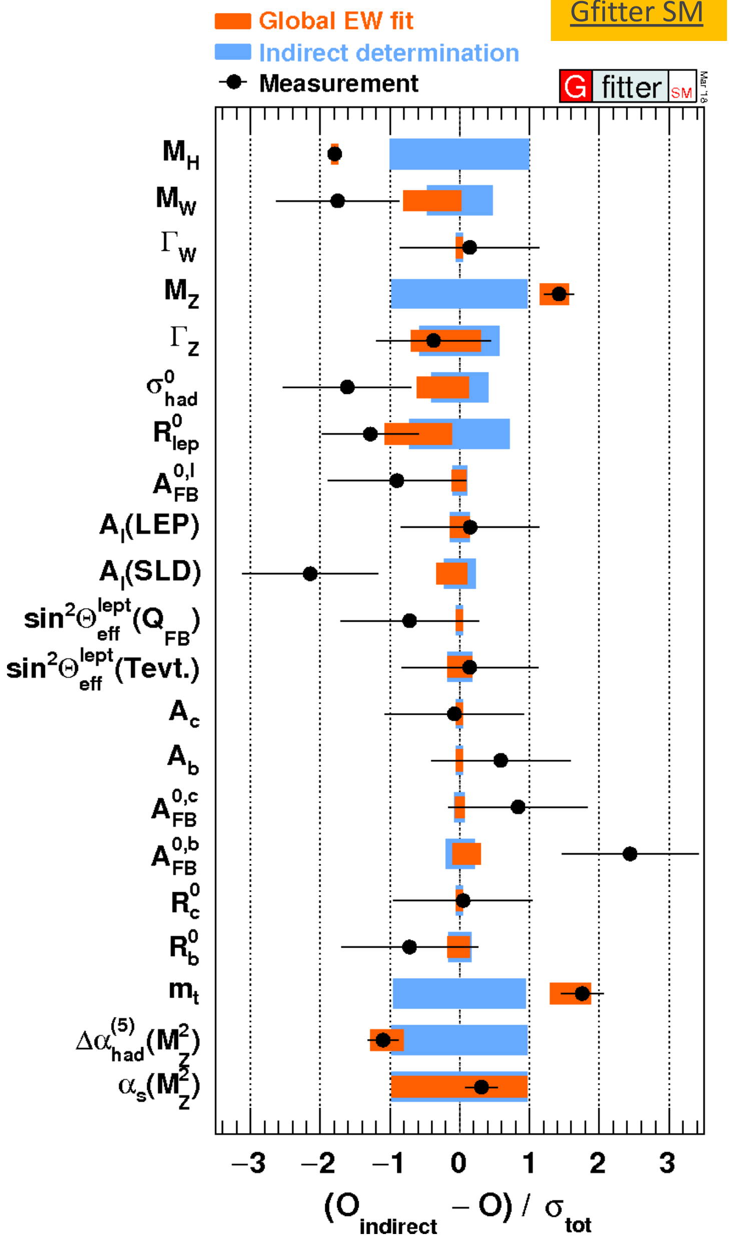
The electroweak sector of the SM

- The Glashow, Weinberg and Salam (GWS) model treats weak and electromagnetic interactions as different manifestations of a single unified electroweak force (Nobel Prize 1979)

- The EW sector is one of the best understood sectors of the SM → deviations from highly precise SM predictions indicate the presence of BSM physics

- High-precision EW physics is sensitive to New Physics at multi-TeV scales, and new particles we might not be able to directly produce

Gfitter SM

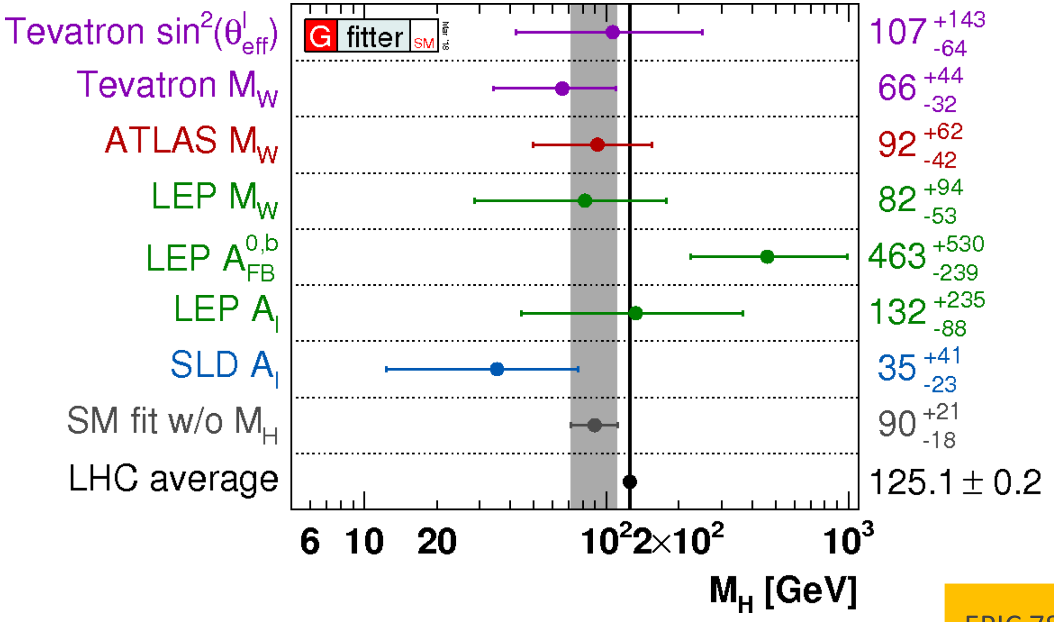


Electroweak fundamental parameters

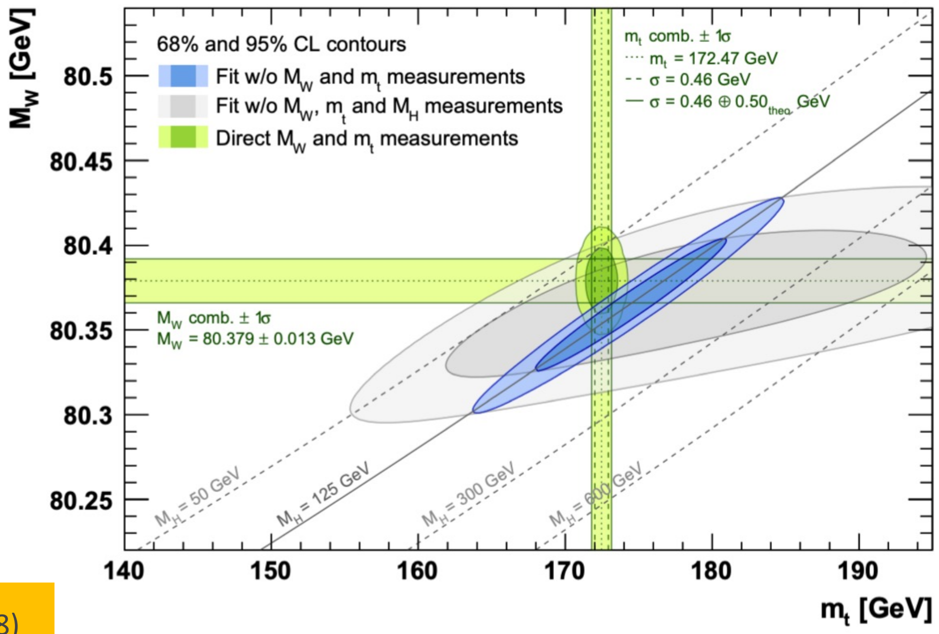
- At tree level, all EW observables can be predicted from just 3 input parameters: g, g', v [1]

$$m_W = \frac{1}{2} g v,\ m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v,\ \cos\theta_w = \frac{g}{\sqrt{g^2 + g'^2}}, \qquad \sin^2\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right)$$

- Radiative corrections connect EW observables to heavy particles like the top quark and Higgs boson

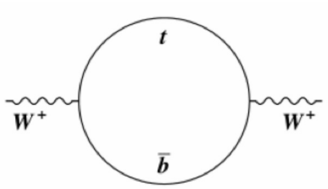


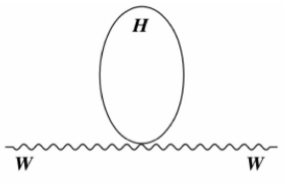
EPJC 78, 675 (2018)



[1] g/g': weak isospin/hypercharge coupling constant, v: Higgs vacuum expectation value

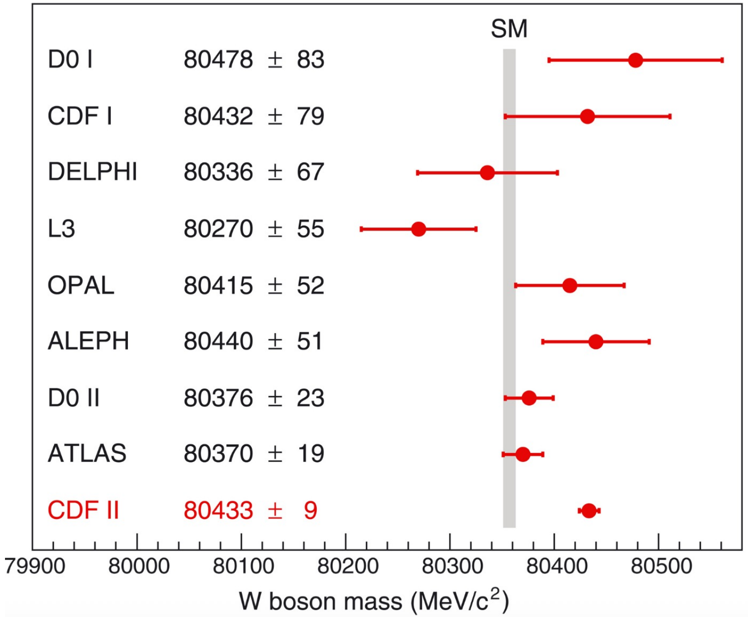
W mass

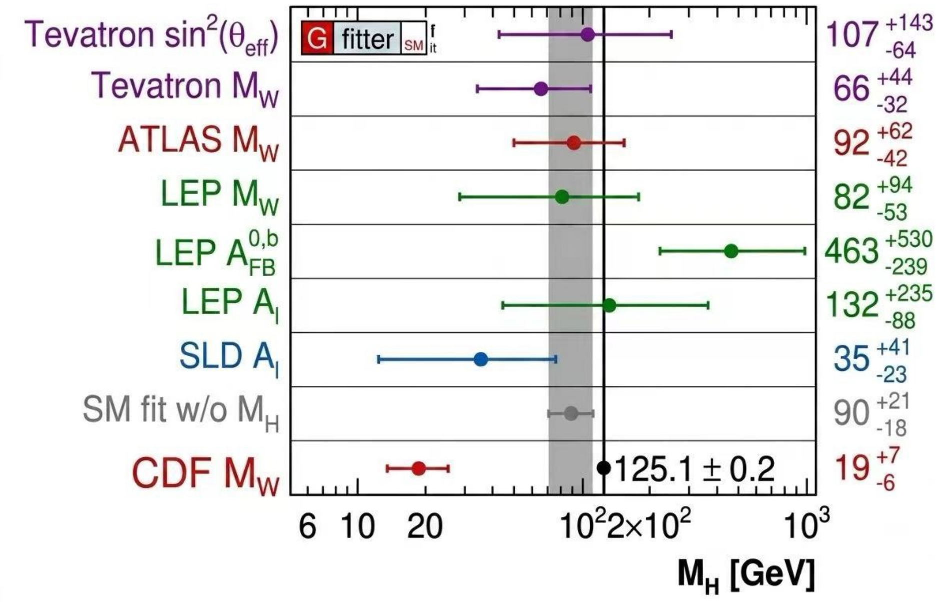




- W mass is at the heart of electroweak theory: $m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$
  - Δ includes higher-order effects and potential new physics contributions
- The precision of direct measurements limits the interpretation of the electroweak fit in terms of new physics

Science 376 (2022) 6589, 170-176

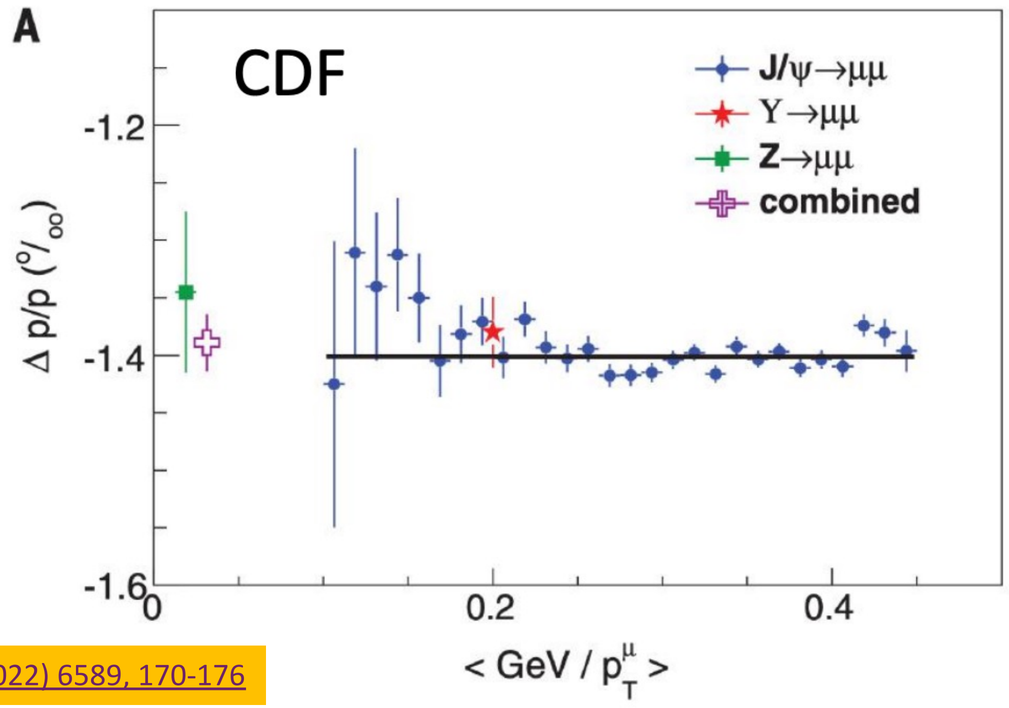




Z mass

- Indirect m_Z = 91204.7 $\pm$ 8.8 MeV
- The most precise measurements come from LEP with beam-energy scan

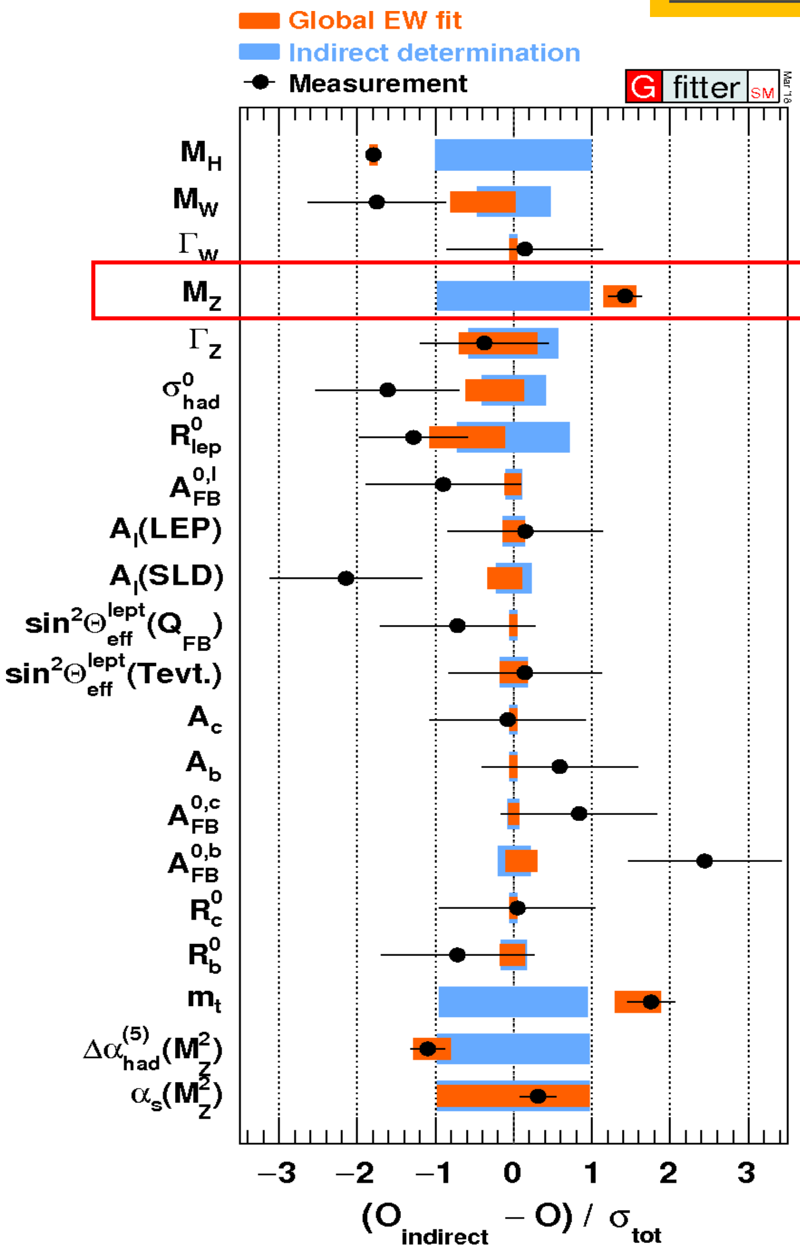
$$m_Z = 91187.6 \pm 2.1 \text{ MeV}$$



Science 376 (2022) 6589, 170-176

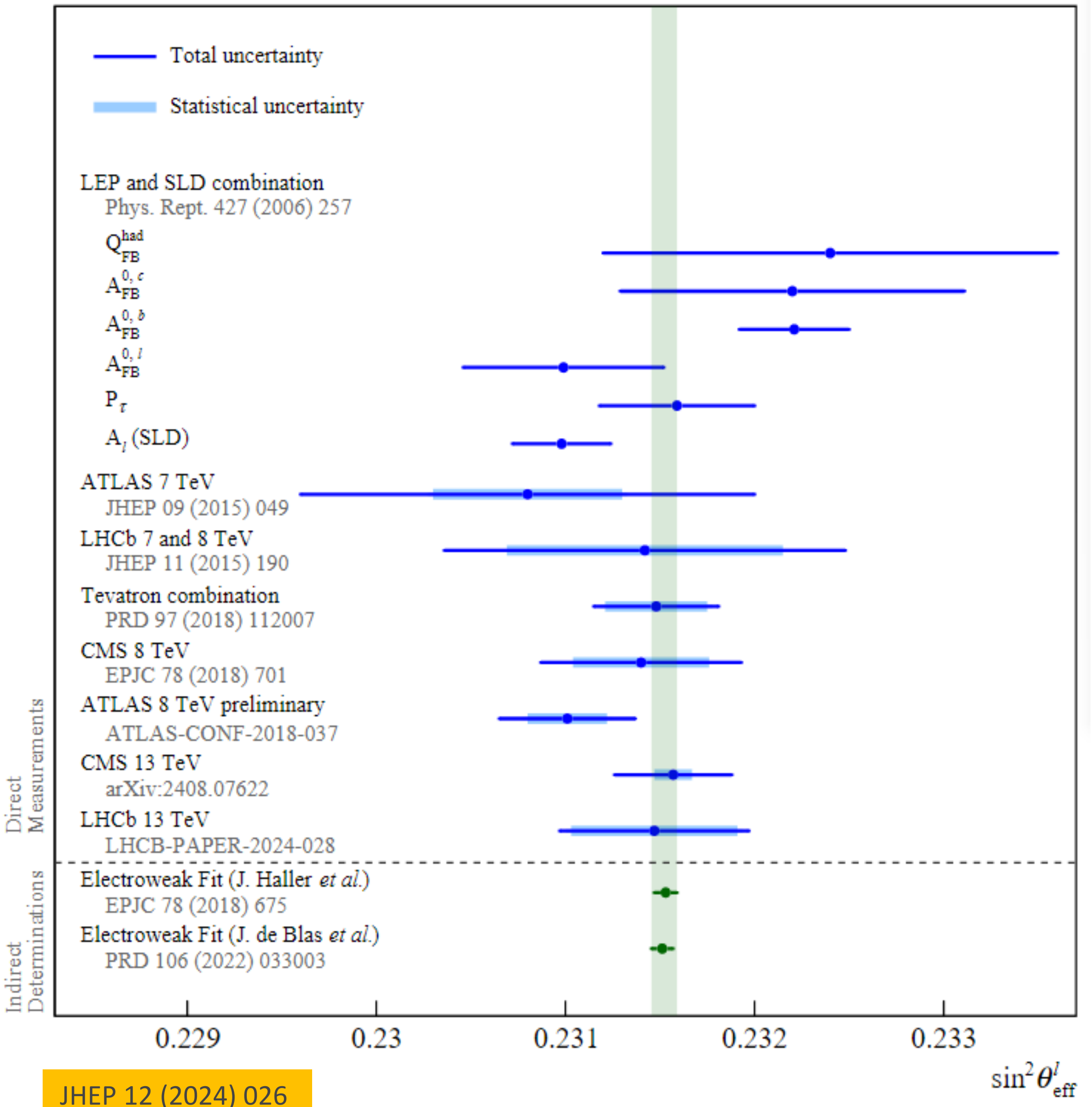
$$m_Z = 91192.3 \pm 7.1 \text{ MeV}$$

Gfitter SM



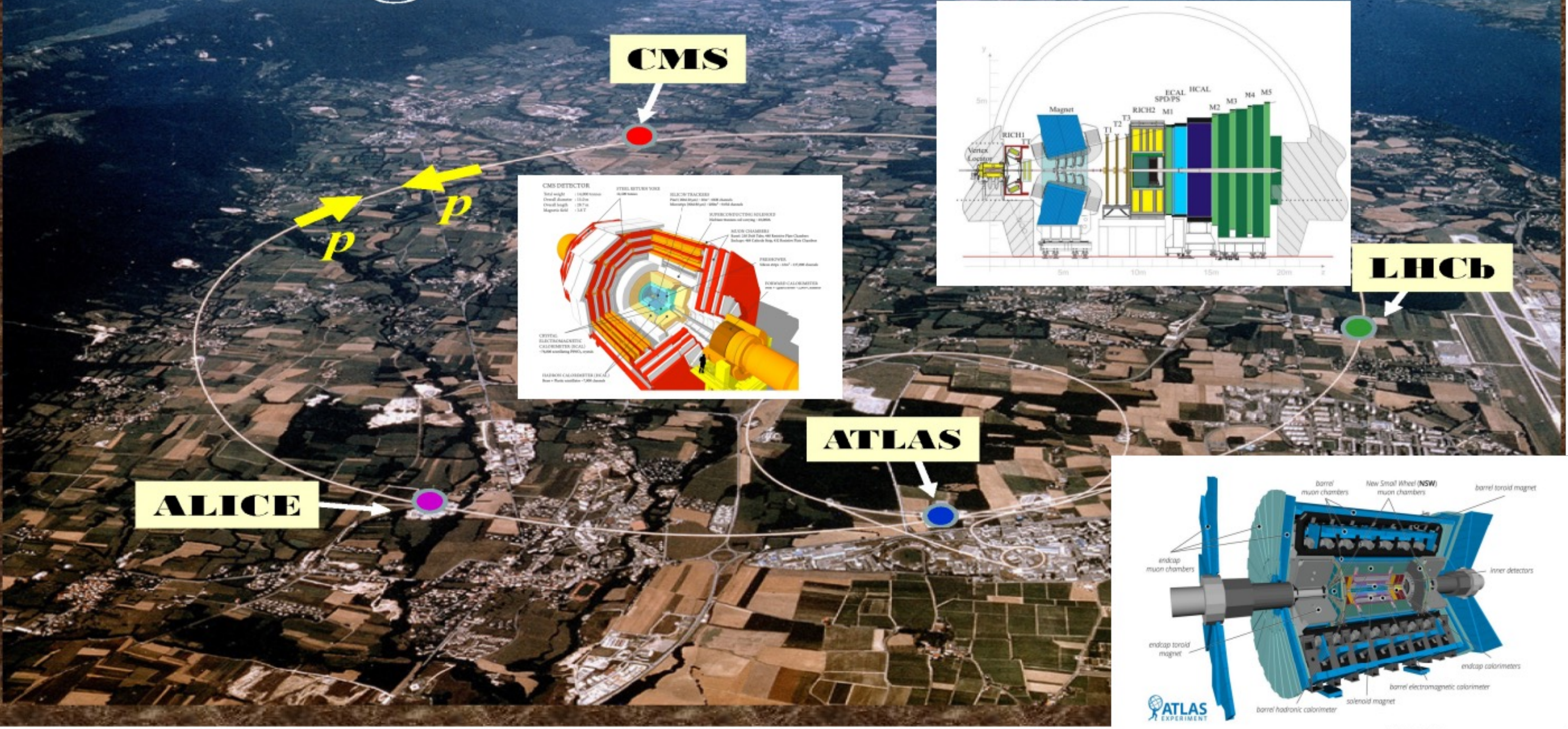
Weak mixing angle

- A 3.2 standard-deviation difference exists between the two most precise individual measurements
- A precise determination by the LHC experiments allows investigation of non-SM process dependence



JHEP 12 (2024) 026

Large Hadron Collider



Large Hadron Collider

13TeV

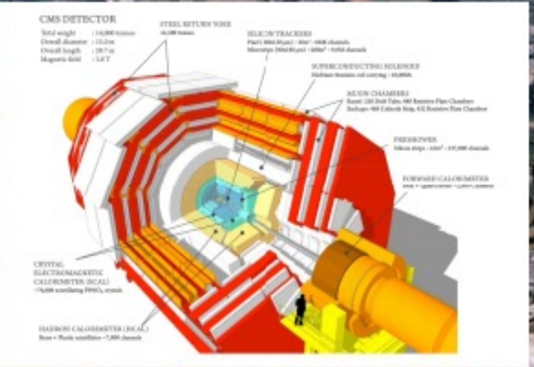
CMS

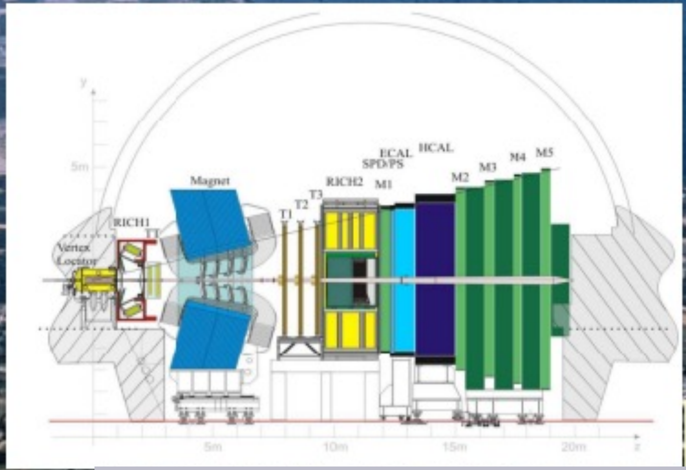
694 ± 6 (syst.) ± 17 (lumi.) pb

$|\eta_\mu| < 2.4, p_T > 25$ GeV

$76 < m_{\mu\mu} < 106$ GeV

JHEP 12 (2019) 061





LHCb

196.4 ± 0.2 (stat). ± 1.6 (syst.) ± 3.9 (lumi.) pb

$2.0 < \eta_\mu < 4.5, p_T > 20$ GeV

$60 < m_{\mu\mu} < 120$ GeV

JHEP 07 (2022) 26

ATLAS

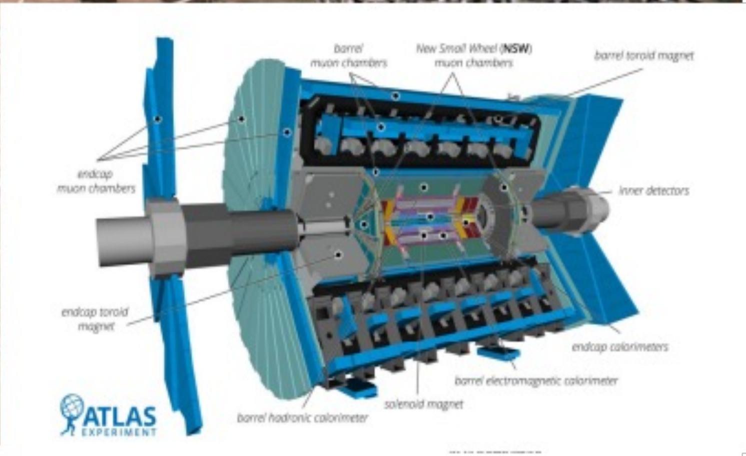
ALICE

780.3 ± 2.6 (stat.) ± 7.1 (syst.) ± 7.1 (lumi.) pb

$|\eta_\mu| < 2.4, p_T > 25$ GeV

$66 < m_{\mu\mu} < 116$ GeV

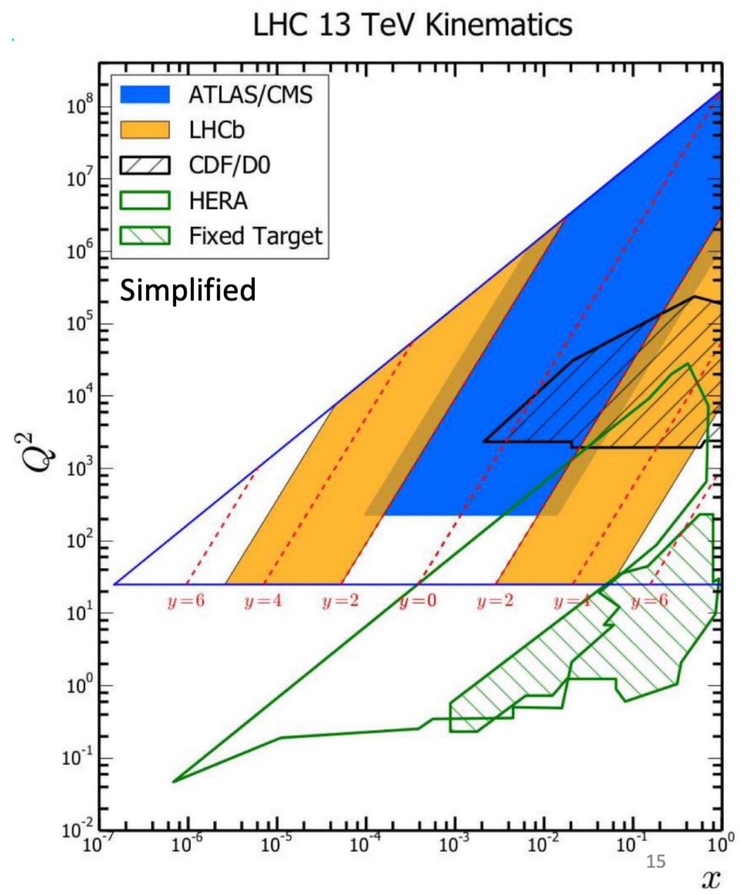
Eur. Phys. J. C 84 (2024) 1126

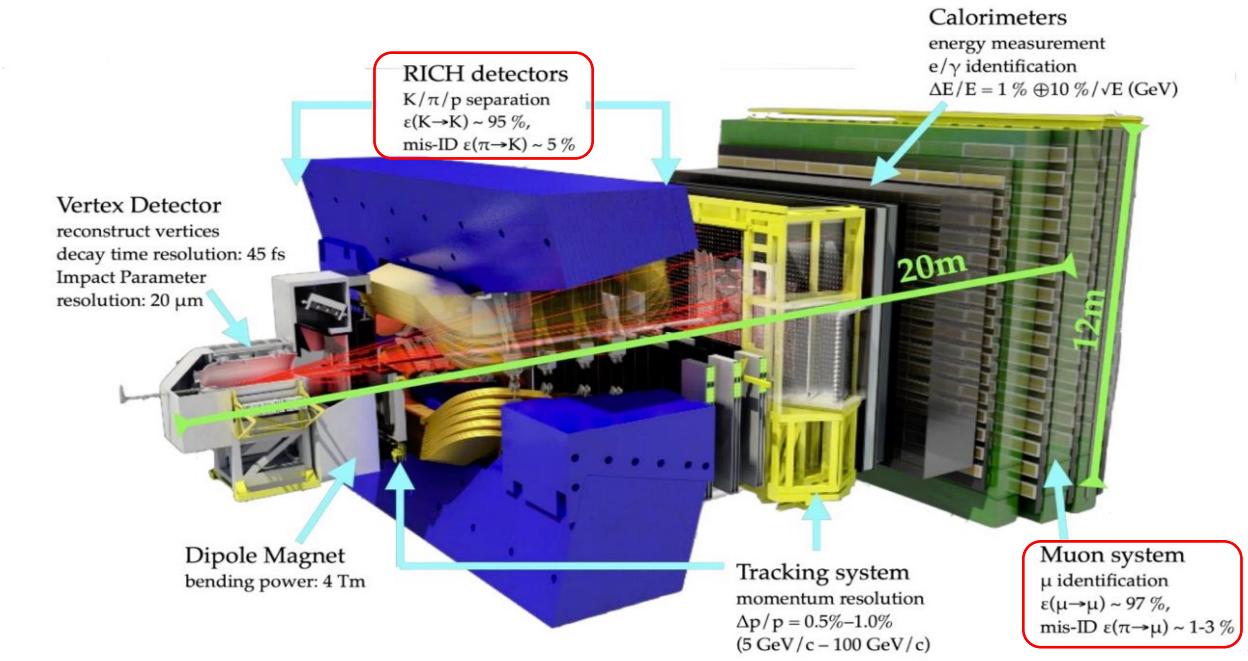


Why LHCb

- A single-arm forward spectrometer, covering $2 < \eta < 5$
  - complementary to ATLAS and CMS
- The high efficiency of muon identification and tracking performance
- Excellent Particle Identification (PID) capabilities and vertex reconstruction

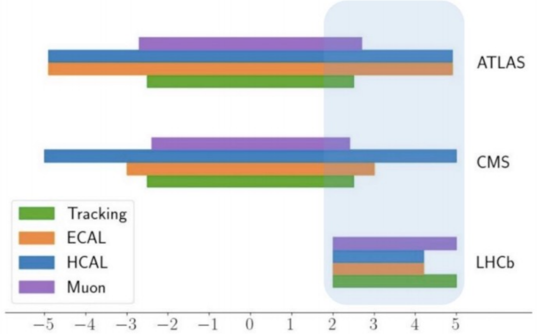
$$y = \frac{1}{2} ln \frac{x_1}{x_2}$$





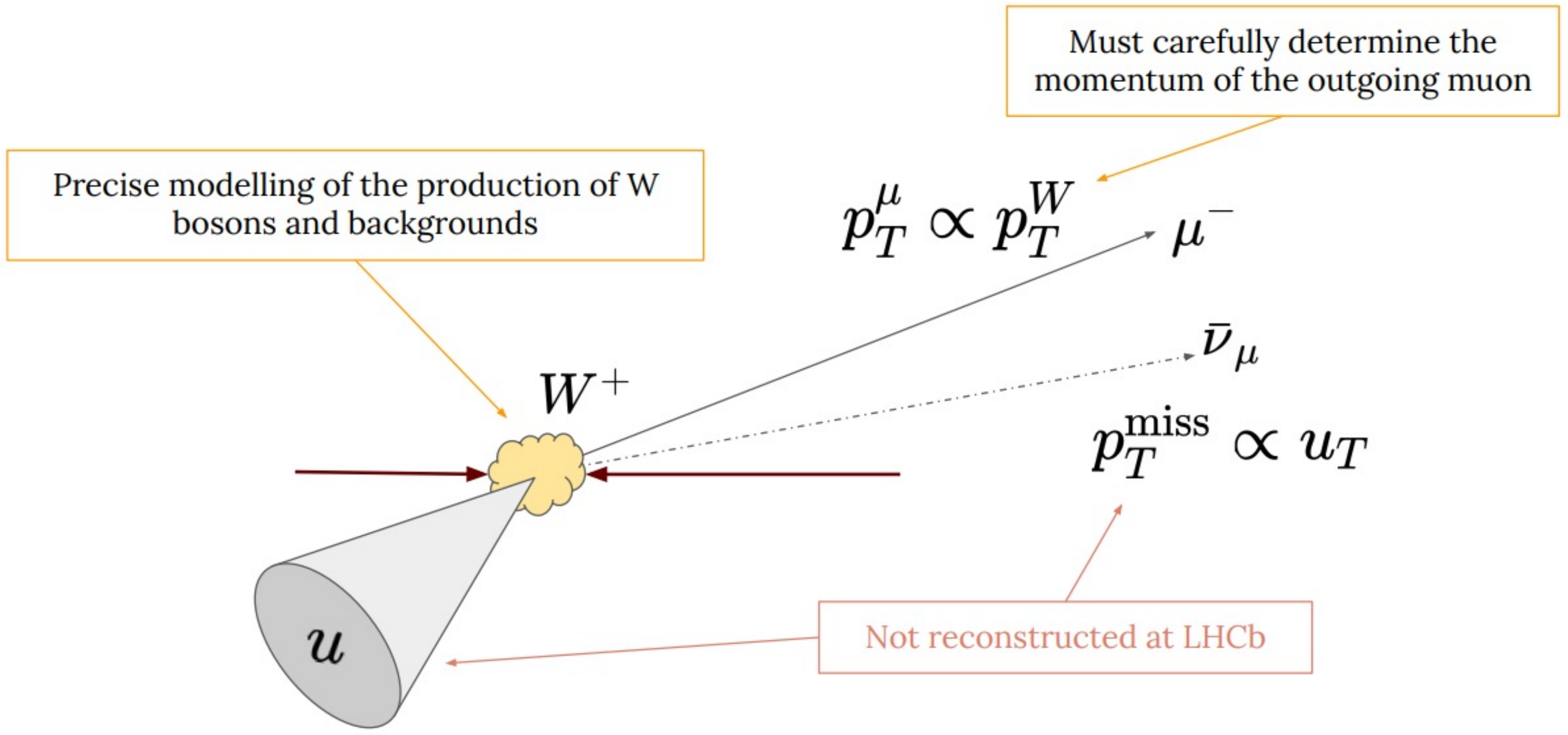
JINST 3, 8005 2008

IJMP A 30 (2015) 1530022



How to measure m_W at LHCb

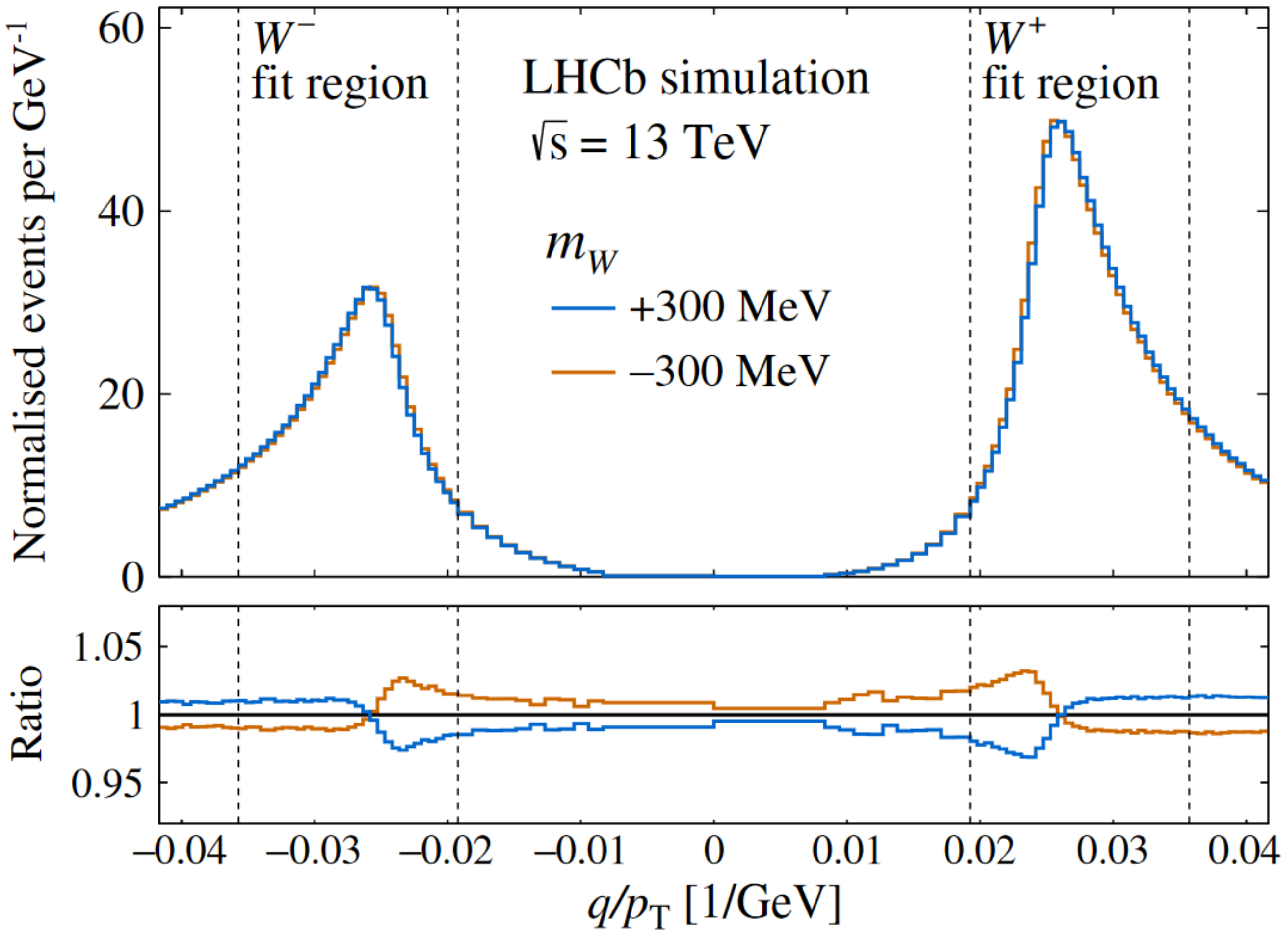
- No possible measuring W boson m_{T} distribution at LHCb - no access to E_{T}^{miss}



How to measure m_W at LHCb

- Measure lepton p_{T} distribution

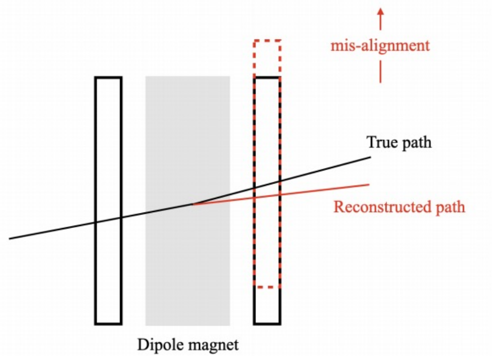
JHEP 01 (2022) 036

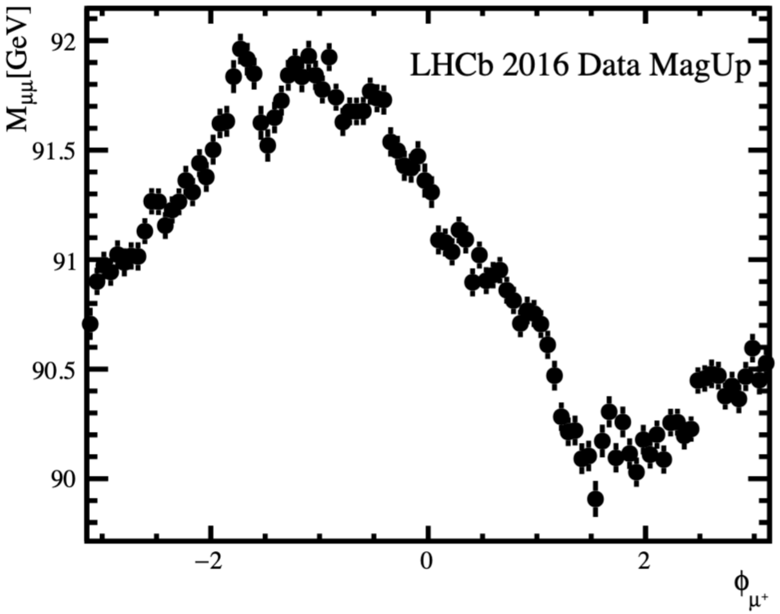


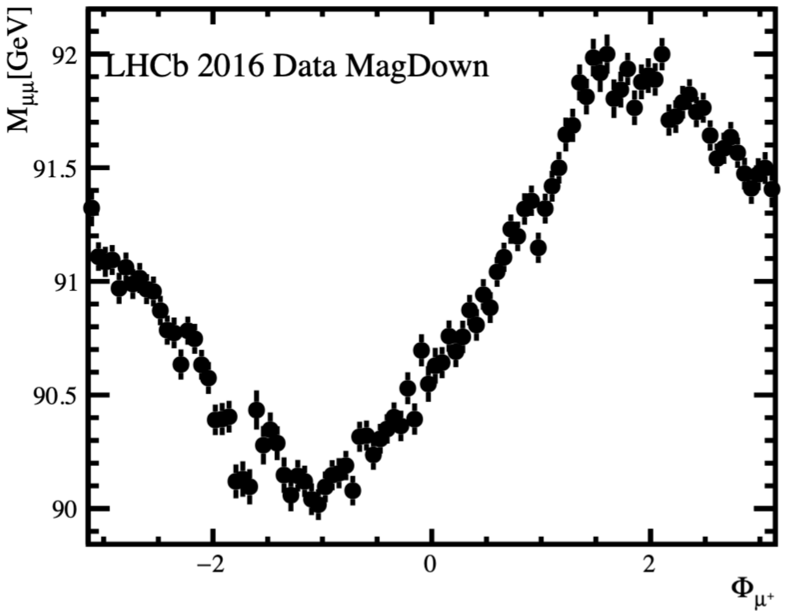
fit region $\Rightarrow \eta \in [2.2,\ 4.4],\ p_T^{\mu} \in [28,\ 52]\,\mathrm{GeV}$

Muon p_{T} - experiment ingredients

- Understand the detector environment to a high degree of precision
  - high-p_{T} muon momentum measurement
  - high-p_{T} muon reconstruction and selection efficiency
- Official alignments are done through $D^0 \rightarrow K\pi$ and $J/\psi \rightarrow \mu\mu$ candidates
- 5 micron misalignment could cause a 50 MeV bias in the m_W

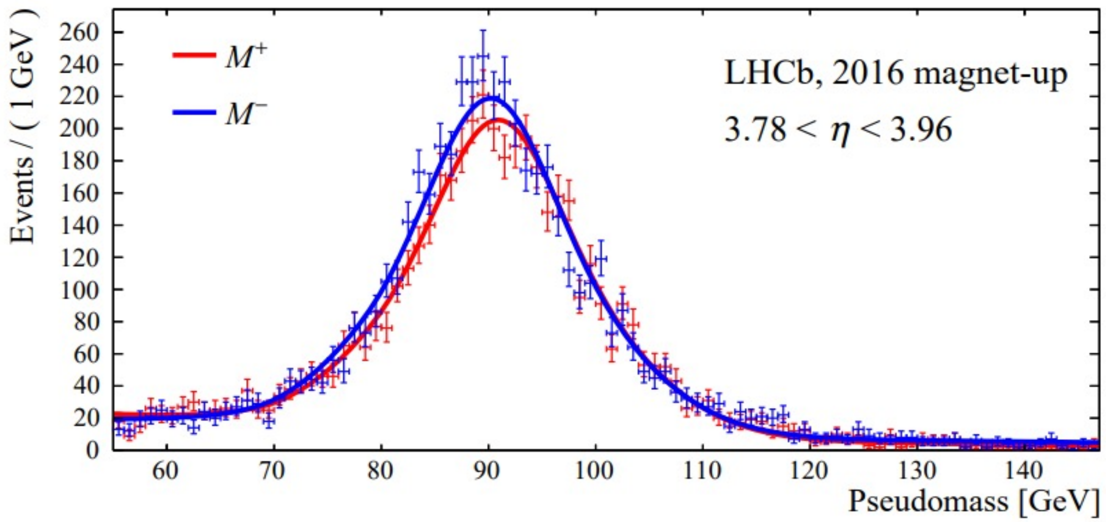






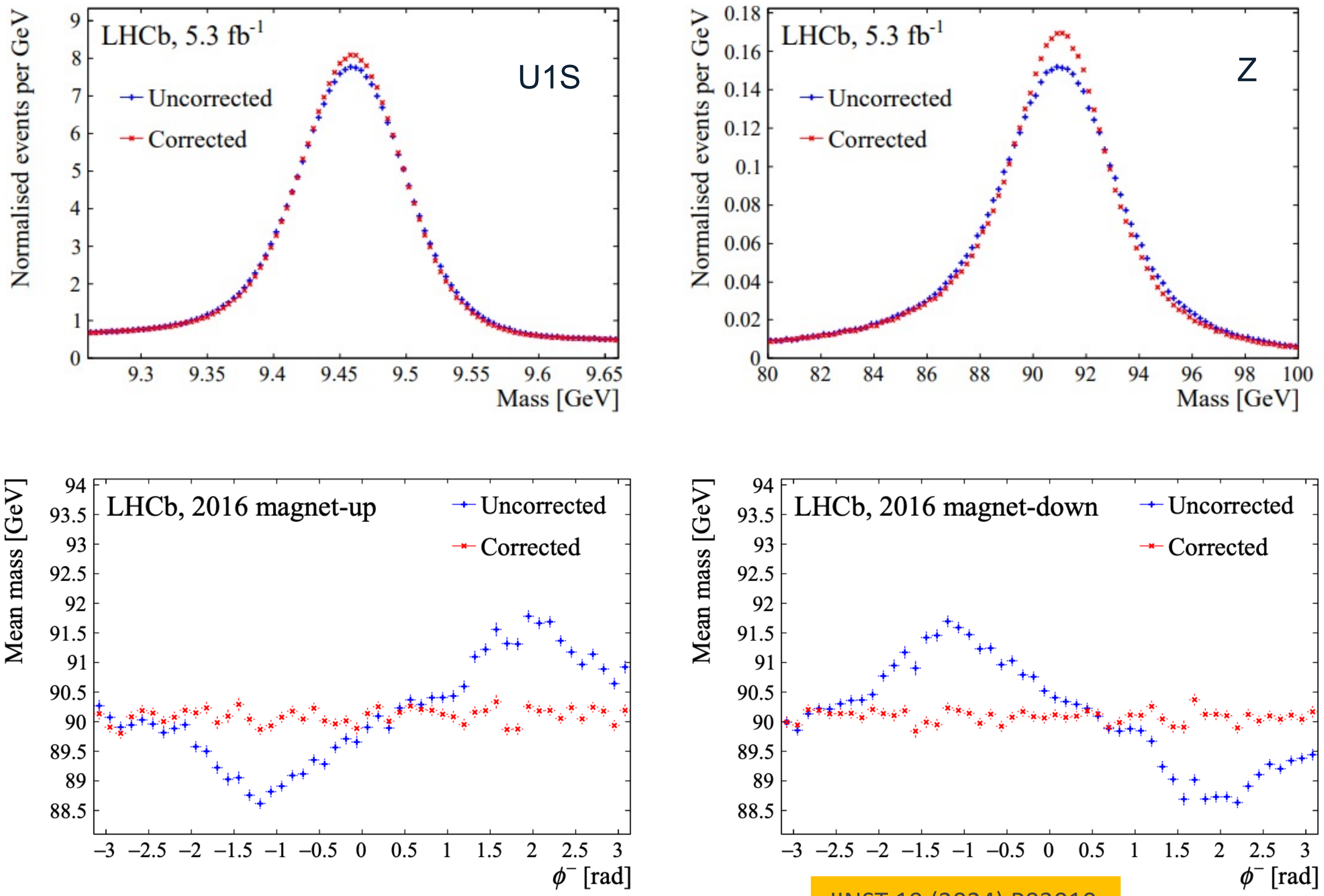
The pseudomass method

JINST 19 (2024) P03010



- Using $Z \rightarrow \mu^+\mu^-$ to study detector alignment
- $M^{\pm} = \sqrt{2p^{\pm}p_{\mathrm{T}}^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1 - \cos\theta)}$
- Z bosons are mostly produced with $\frac{p_{\mathrm{T}}^{Z}}{m_Z} << 1$
  - with a good approximation, M^+ and M^- should peak in the same place
- Simultaneous maximum-likelihood fit to M^+ and M^-, pseudomass asymmetry, A, is set as the asymmetry in the fitted mean mass
- A can be used to determine δ, $\delta \approx \frac{A}{2}(<\frac{1}{p^+}>+<\frac{1}{p^-}>)$

Performance



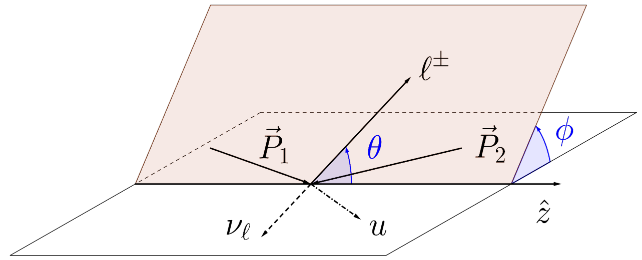
JINST 19 (2024) P03010

- Improve dimuon invariant mass resolution significantly
- The non-physical trends in the mean dimuon mass of Z boson events as a function of the angular variable caused by systematic misalignments of the detector have been successfully corrected.

Muon p_{T} - theoretical ingredients

- Depends on the W boson production model: how much p_{T} does the W boson transfer to the final state particles?
- Depends on the angular distributions of W boson decays: what direction relative to the W boson does the muon travel in?
- Need to understand the internal proton structure – parton distribution functions matter!

Collins-Soper frame



POWHEG + Pythia

Unpolarized part

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{W}\,\mathrm{d}y\,\mathrm{d}M\,\mathrm{d}\cos\vartheta\,\mathrm{d}\varphi} = \frac{3}{16\pi}\frac{\mathrm{d}\sigma^{\mathrm{unpol.}}}{\mathrm{d}p_{\mathrm{T}}^{W}\,\mathrm{d}y\,\mathrm{d}M} \Big\{(1+\cos^2\vartheta) + A_0\frac{1}{2}(1-3\cos^2\vartheta) + A_1\sin 2\vartheta\cos\varphi + A_2\frac{1}{2}\sin^2\vartheta\cos 2\varphi + A_3\sin\vartheta\cos\varphi + A_4\cos\vartheta + A_5\sin^2\vartheta\sin 2\varphi + A_6\sin 2\vartheta\sin\varphi + A_7\sin\vartheta\sin\varphi\Big\}$$

Angular part

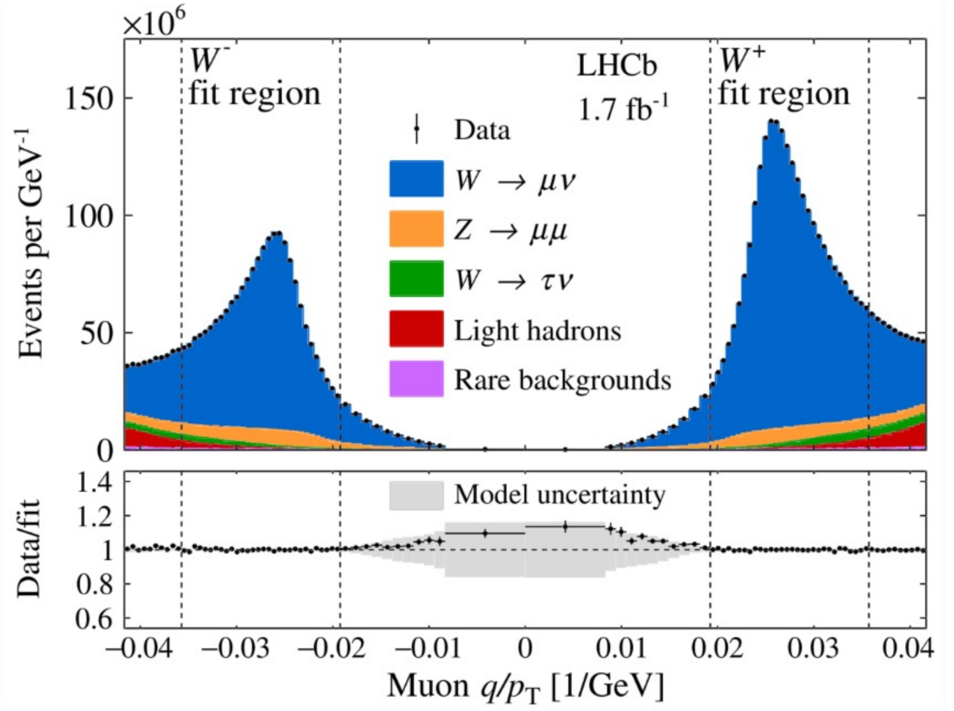
DYTurbo

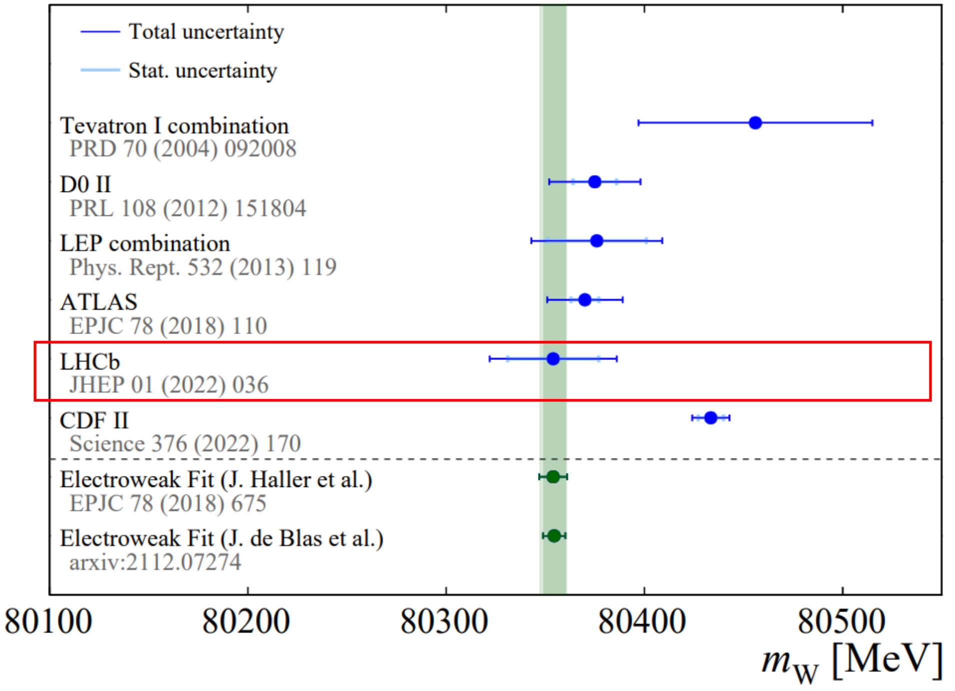
m_W at LHCb - 2016 result

- In a template fit to the q/p_{T}^{μ} distribution
- LHCb achieves a precision of ~ 32 MeV using roughly 1/3 of the Run II dataset

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

LHCB-FIGURE-2022-003



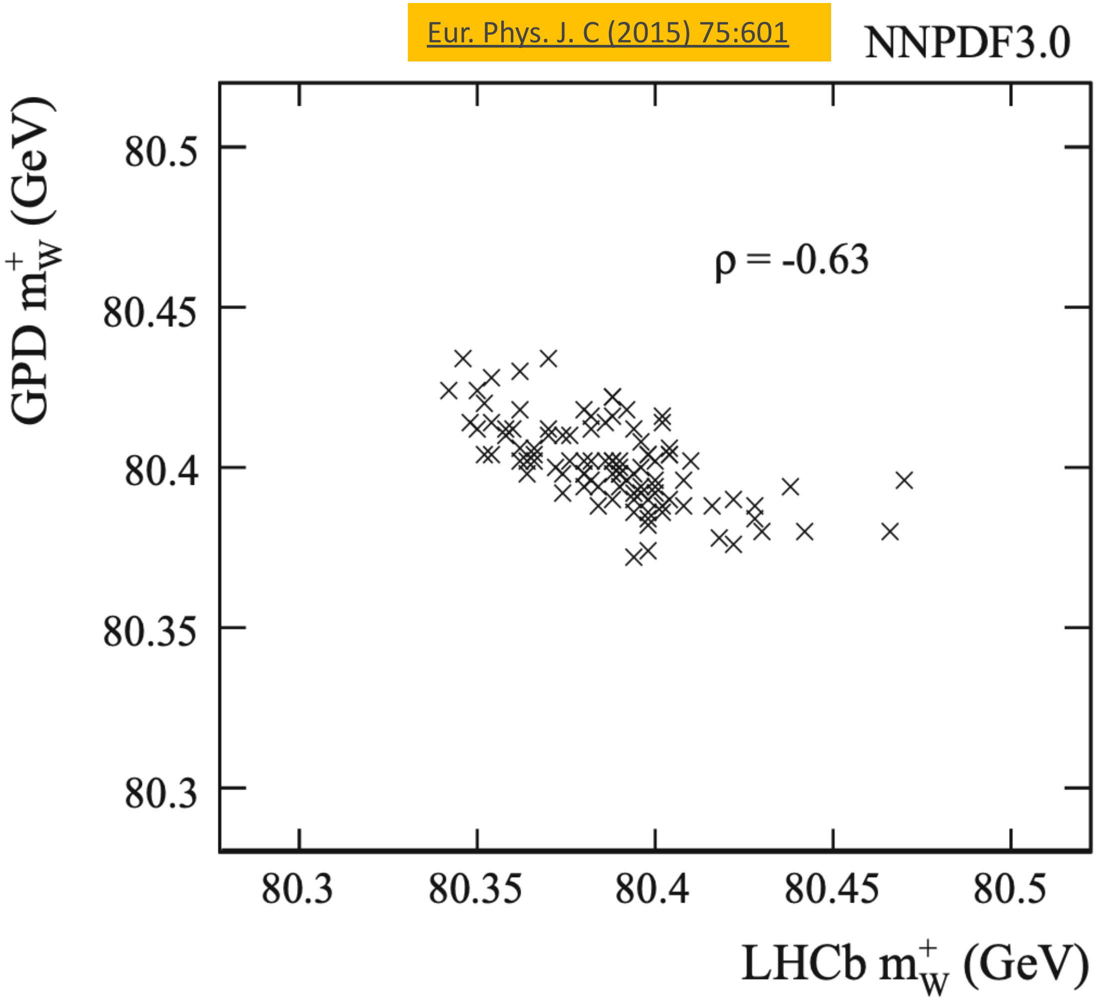


What's LHCb add

- PDF uncertainties are expected to be anti-correlated in m_W measurement between central and forward regions

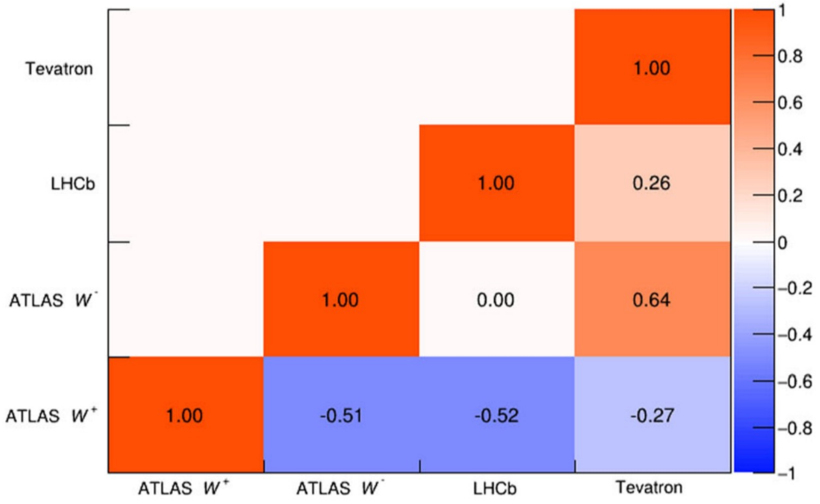
- A measurement from LHCb has the potential to contribute significantly in any LHC-wide average

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



What's LHCb add

- Combinations with CDF excluded have good compatibility
- The difference between the "All-CDF" combination and the updated CDF value here is 3.6σ when the CT18 PDF set is used
- The combination with CMS results is ongoing



$\sigma_{\text{PDF}}(\text{ATLAS}) = 9.2\ \text{MeV}$ $\sigma_{\text{PDF}}(\text{LHCb}) = 9\ \text{MeV}$

PDF set	ATLAS (27 d.o.f)		LHCb		LHC (1 d.o.f)			
	m_W	χ^2	m_W	χ^2	m_W	σ_{PDF}	χ^2	$p(\chi^2, n)$
ABMP16	$80{,}352.8 \pm 16.1$	31	$80{,}361.0 \pm 30.4$	–	$80{,}354.6 \pm 14.2$	2.9	0.1	75%
CT14	$80{,}363.1 \pm 20.4$	30	$80{,}354.4 \pm 32.2$	–	$80{,}360.4 \pm 16.4$	6.5	0.0	100%
CT18	$80{,}374.5 \pm 20.3$	30	$80{,}347.3 \pm 32.7$	–	$80{,}366.5 \pm 16.6$	6.3	0.5	48%
MMHT2014	$80{,}372.8 \pm 18.6$	30	$80{,}342.5 \pm 31.3$	–	$80{,}364.4 \pm 15.4$	5.1	0.6	44%
MSHT20	$80{,}368.9 \pm 17.9$	45	$80{,}351.3 \pm 31.0$	–	$80{,}364.3 \pm 15.0$	4.5	0.2	65%
NNPDF3.1	$80{,}358.4 \pm 17.6$	29	$80{,}359.3 \pm 31.1$	–	$80{,}358.6 \pm 15.0$	5.0	0.0	100%
NNPDF4.0	$80{,}353.5 \pm 16.6$	35	$80{,}361.6 \pm 30.6$	–	$80{,}355.4 \pm 14.5$	3.8	0.1	75%

Eur. Phys. J. C 84 (2024) 5, 451

$W \to \mu\nu$ cross-section @ 5.02 TeV

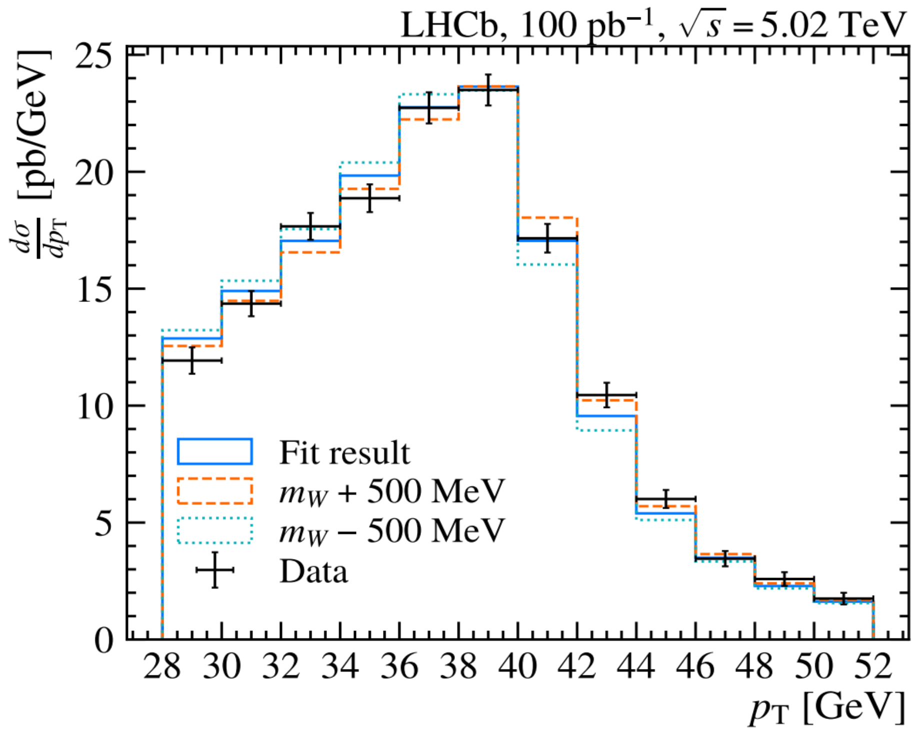
$$m_W = 80369 \pm 130(\text{exp.}) \pm 33\ (\text{theory})\ \text{MeV}$$

Data available on HEPData

$\longrightarrow$ feel free to fit with your own models!

- The production of W boson is the basis of m_W measurement by fitting $\mu\ p_\mathrm{T}$ shape
- Fit $d\sigma/dp_\mathrm{T}^\mu$ with a semi-arbitary model to extract m_W
  - inputs: 24 $d\sigma/dp_\mathrm{T}^\mu$ values and one 24×24 covariance matrix
  - **can be done with any model**
- Traditionally, $\mu\ p_\mathrm{T}$ shape is used to subtract background
  - cross-section measurements in $\mu\ p_\mathrm{T}$ is impossible
  - using muon isolation information to subtract the background
- External analysts can use the result to perform their own extraction of m_W using different theoretical predictions

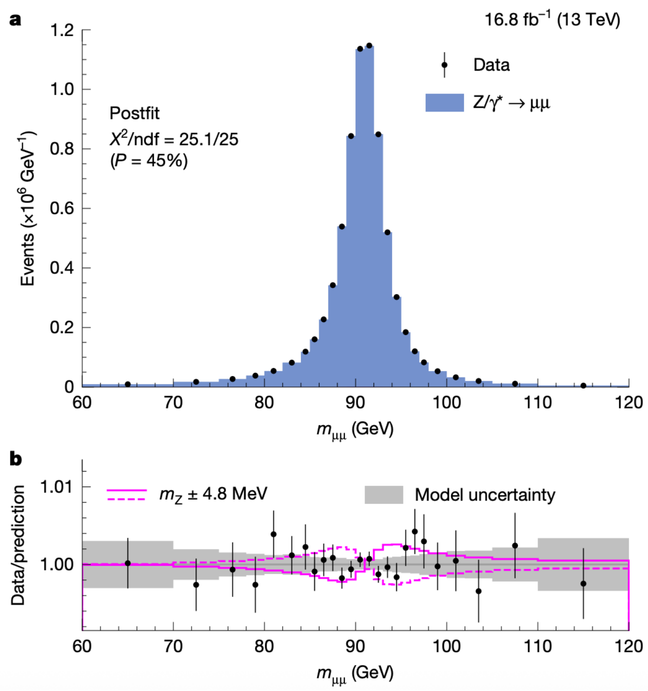
JHEP 03 (2026) 148



Z mass measurements

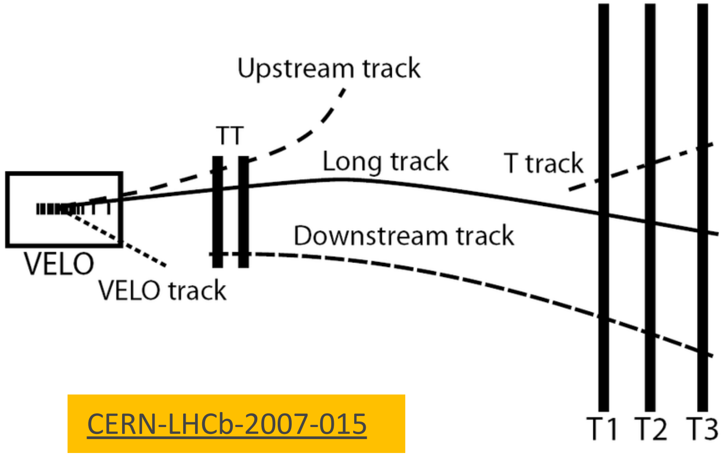
- Indirect $m^2 \simeq 2p^+p^-(1-\cos\theta)$, neglecting the final state particle mass
  - θ is determined with extremely high relative precision for the Z and Υ decays
- The main challenge is
  - detailed detector calibration to control momentum measurement biases
  - can not use Z information to do the calibration

Nature 652 (2026) 321



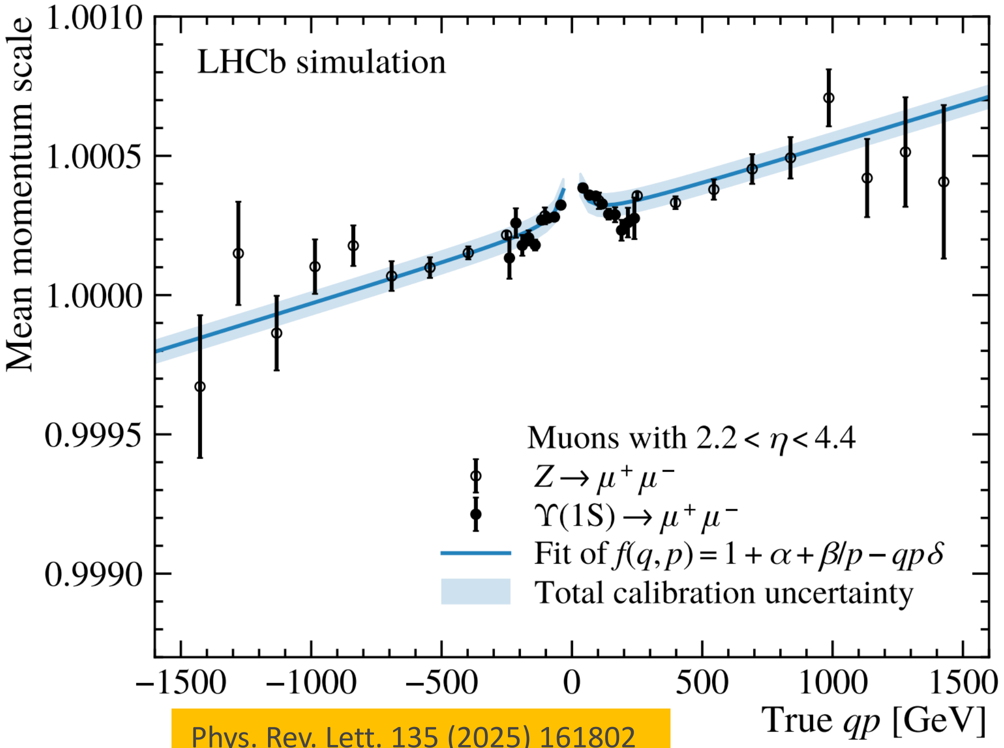
"$Z \to \mu\mu$ evens are used, together with the m_Z PDG value, to define the systematic uncertainties. Therefore, our m_Z value is not a measurement independent of the experimental world average"

Z mass measurements at LHCb

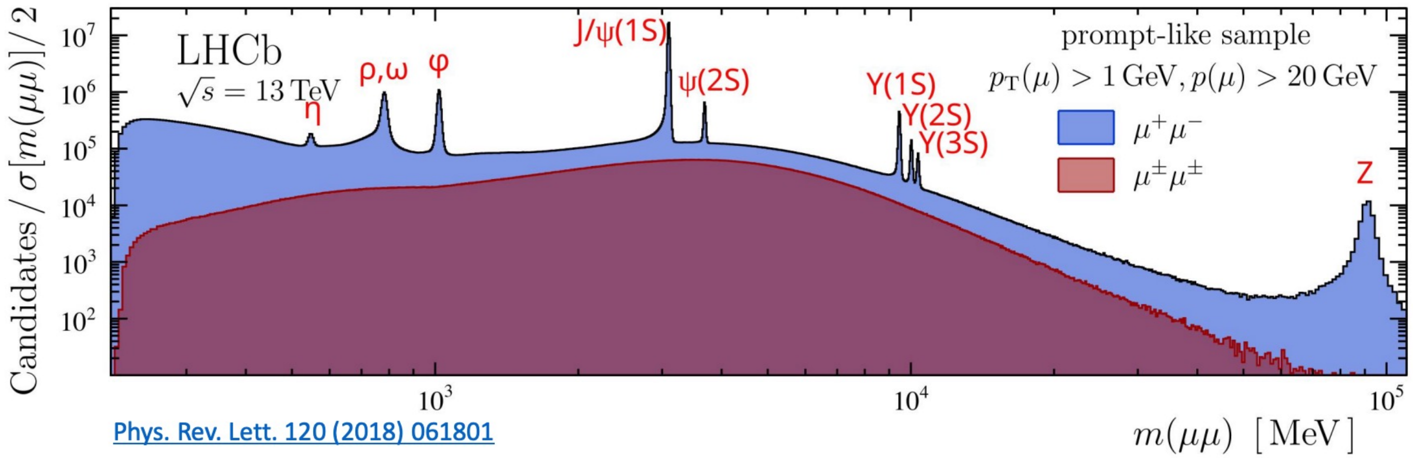


CERN-LHCb-2007-015

- LHCb: a simplified spectrometer with the a track direction from the VELO, an instantaneous kick from the magnet, and a single measurement plane after the magnet



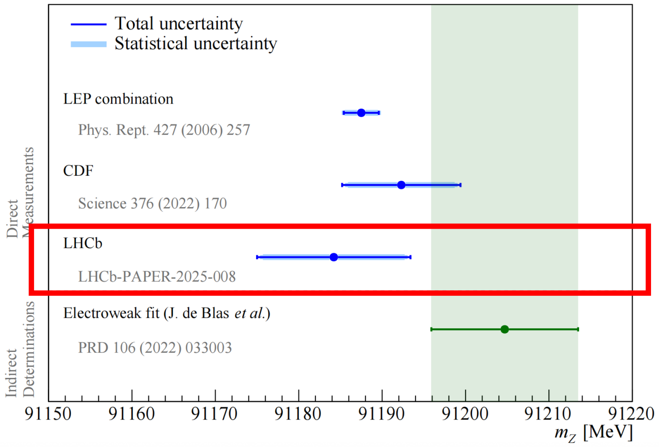
Phys. Rev. Lett. 135 (2025) 161802



Phys. Rev. Lett. 120 (2018) 061801

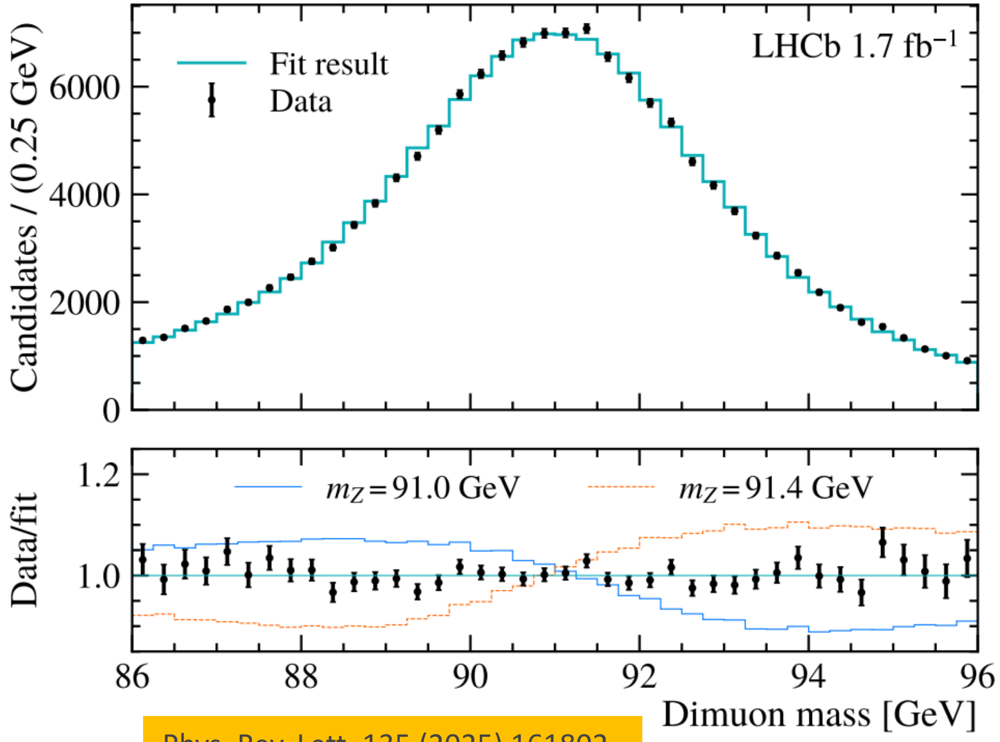
Z mass measurements at LHCb

- Fit compares the full simulation with the data
- m_Z hypothesis varied by reweighting the full simulation with the generator-level events
- Proof-of-principle direct measurement with 2016 dataset
- First dedicated measurement at the LHC



$$m_Z = 91185.7 \pm 8.3_{\text{stat.}} \pm 3.9_{\text{syst.}}$$

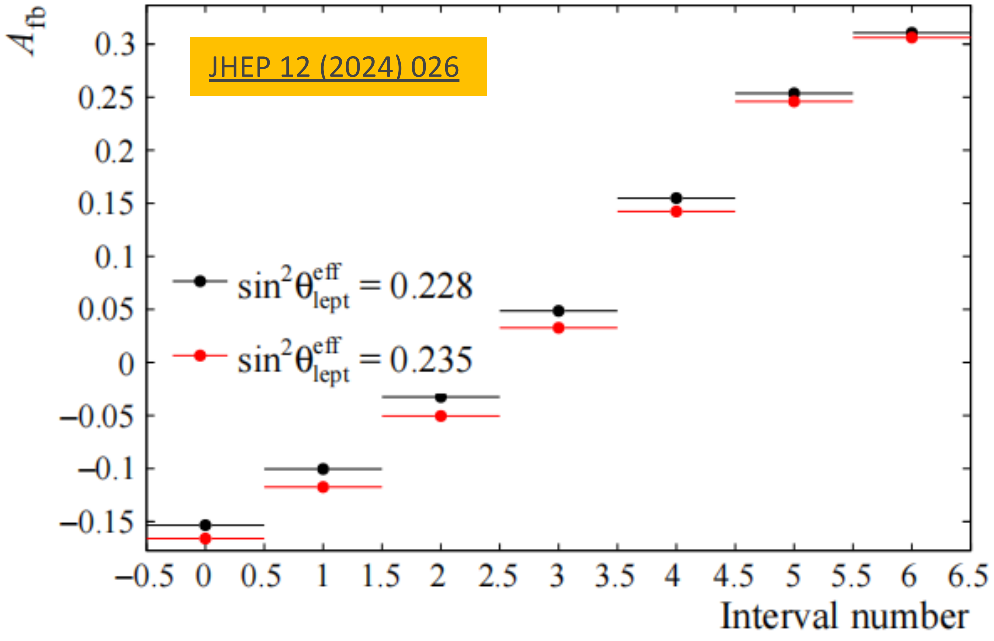
Source	Uncertainty [MeV]
Momentum calibration	3.6
Theory template statistics	1.0
Signal final-state radiation	1.0
Parton distribution functions	0.7
Detection efficiency	0.1
Total systematic uncertainty	3.9



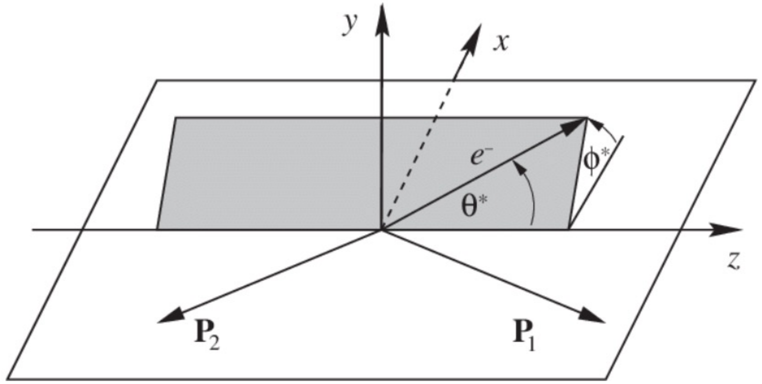
Phys. Rev. Lett. 135 (2025) 161802

How to measure weak mixing angle

- Presence of vector and axial-vector couplings introduces A_{FB}
- The ideal positive $\mathbf{z}$ axis coincides with the direction of the initial state quark
- Crucial to such measurements is the assignation of the z-axis and through this the sign of $\mathbf{cos\theta}^*$
- At the LHC, the quark and anti-quark in each collision are equally likely to come from either proton

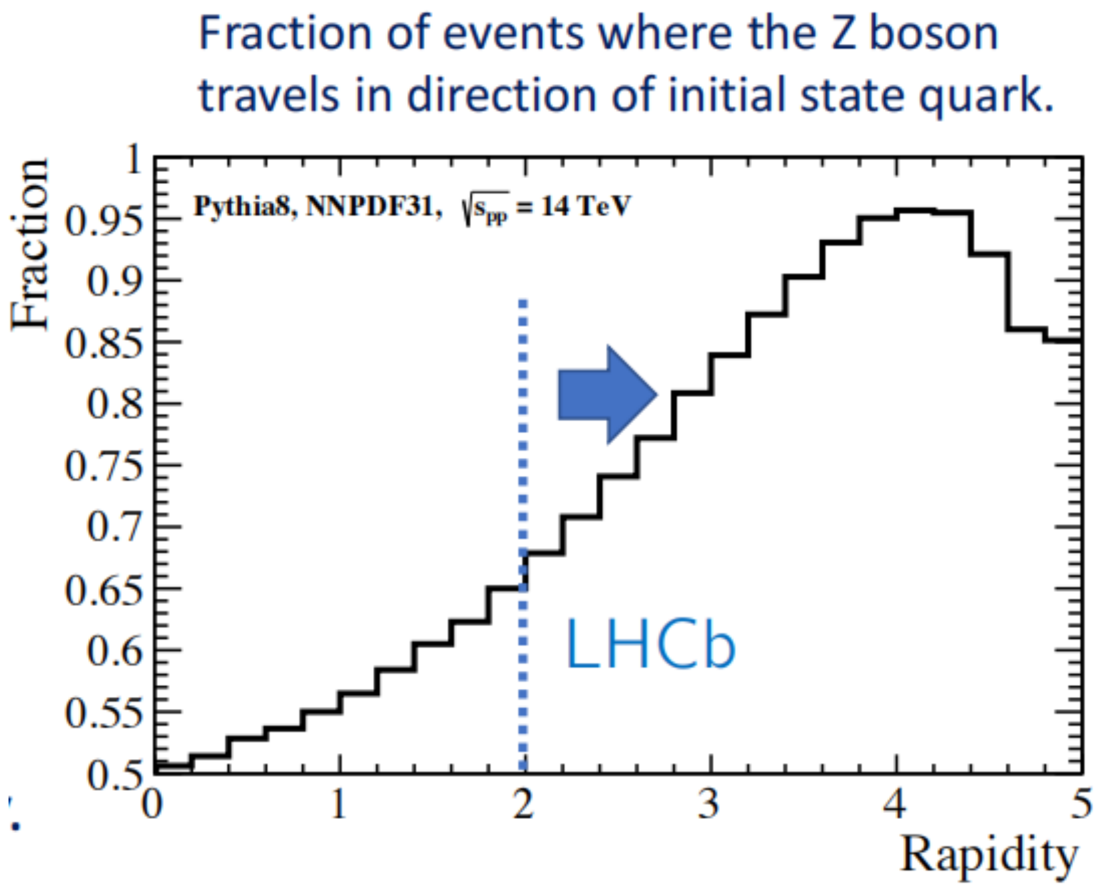


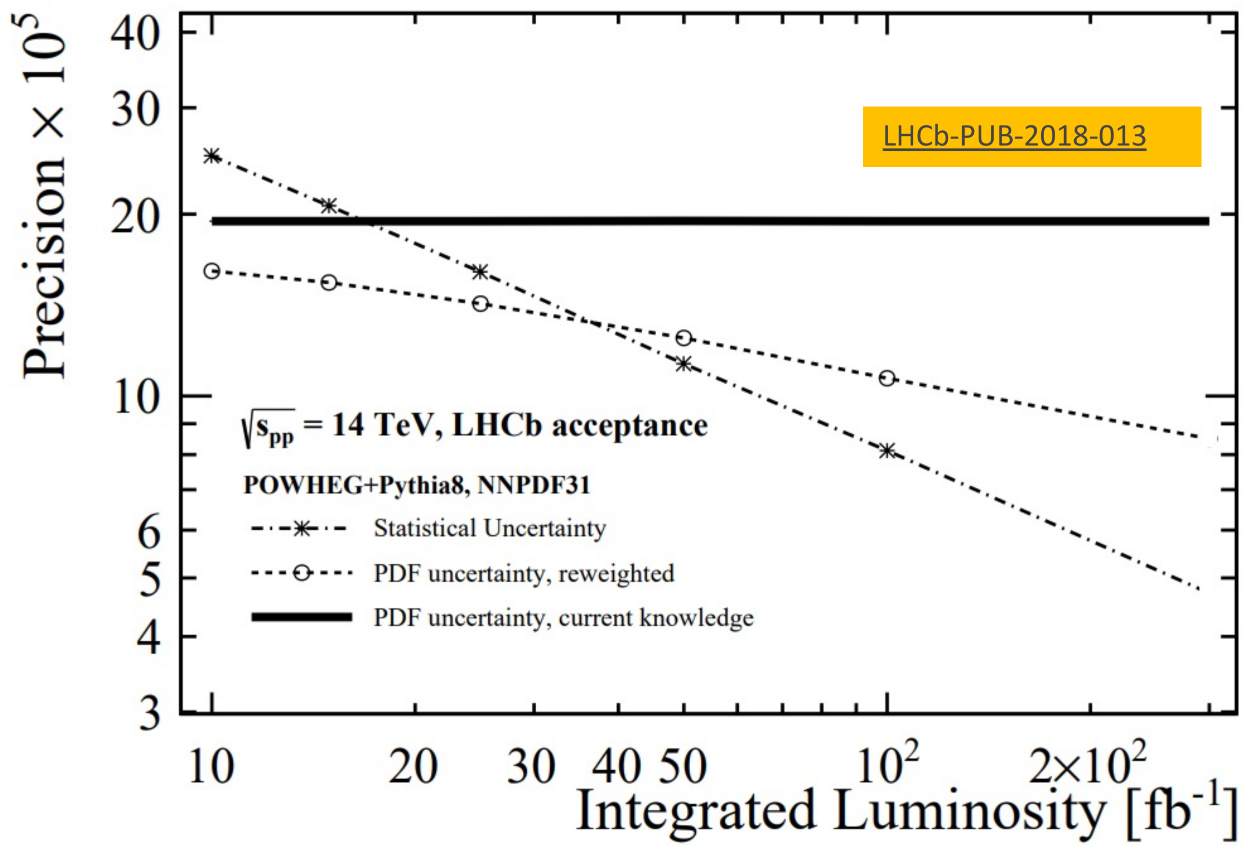
$$A_{FB} = \frac{N(cos\theta^* > 0) - N(cos\theta^* < 0)}{N(cos\theta^* > 0) + N(cos\theta^* < 0)}$$



Why LHCb?

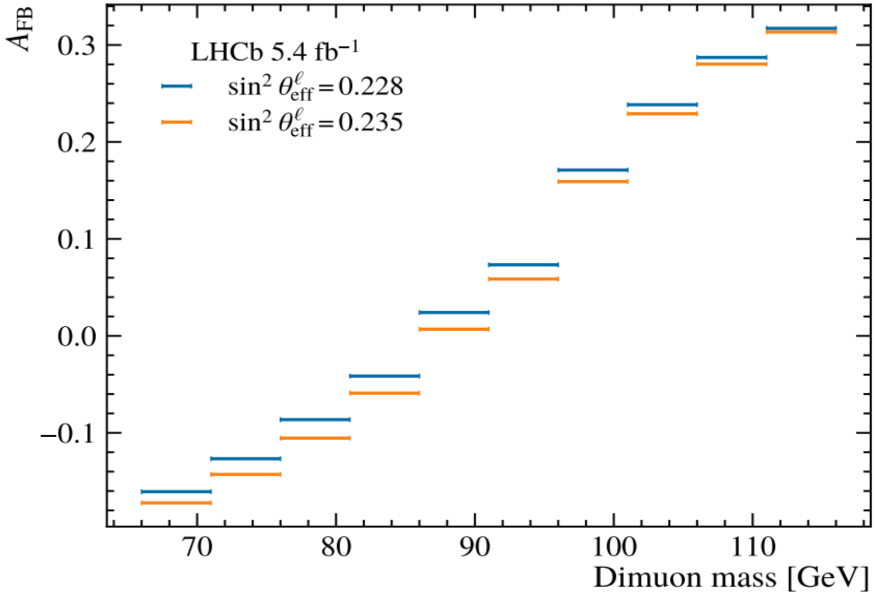
- At larger rapidities, one parton at high x tends to be a valence quark, one parton at low x tend to be an anti-quark

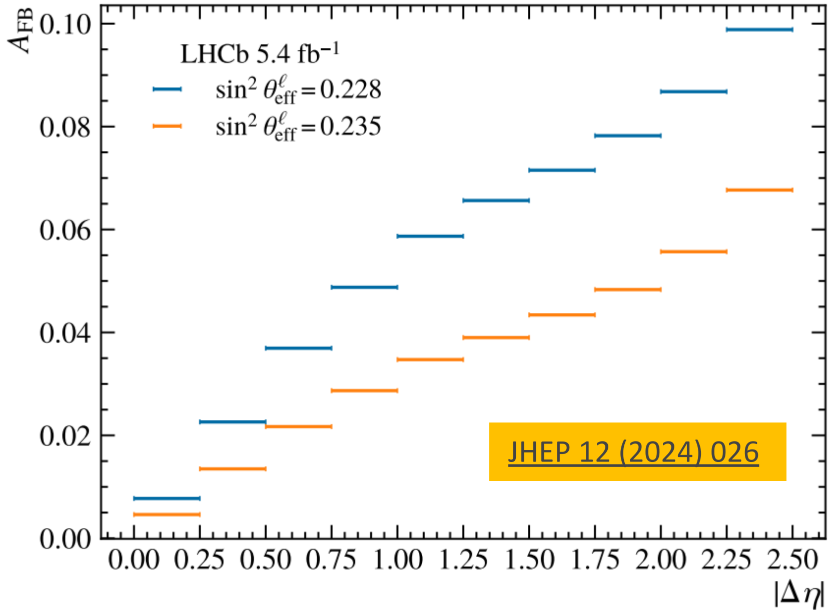




Measure A_{FB} in bins of $|\Delta\eta|$

- Binning in $|\Delta\eta|$ lets us separate the most sensitive events
  - large $|\cos\theta^*|$ are more influenced by changes in $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$
  - small $|\cos\theta^*|$ mostly dilute the measurement
  - $\cos\theta^* \sim \tanh(|\Delta\eta|/2)$, $\Delta\eta = \eta^- - \eta^+$
- The difference in A_{FB} caused by a change in the $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ increases with $|\Delta\eta|$
- Improve the precision on $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ measurement by **14%** in simulation





JHEP 12 (2024) 026

Results

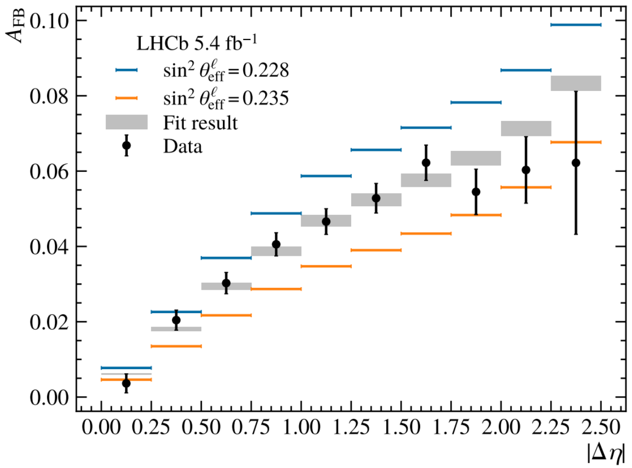
Smaller statistics than ATLAS/CMS (~1/65)

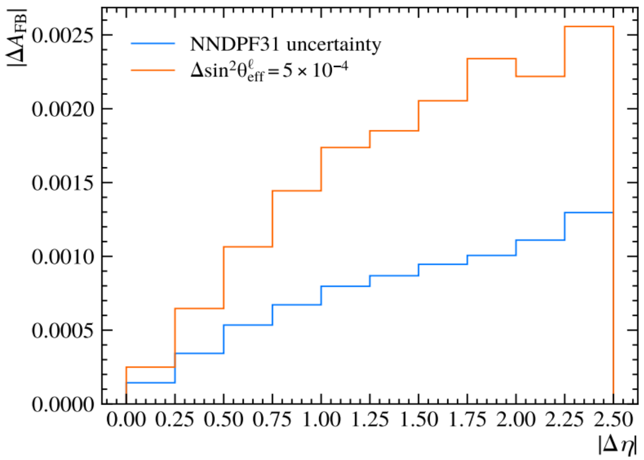
$$\mathbf{0.23152 \pm 0.00044\ (stat.) \pm 0.00005\ (syst.) \pm 0.00022\ (theory)}$$

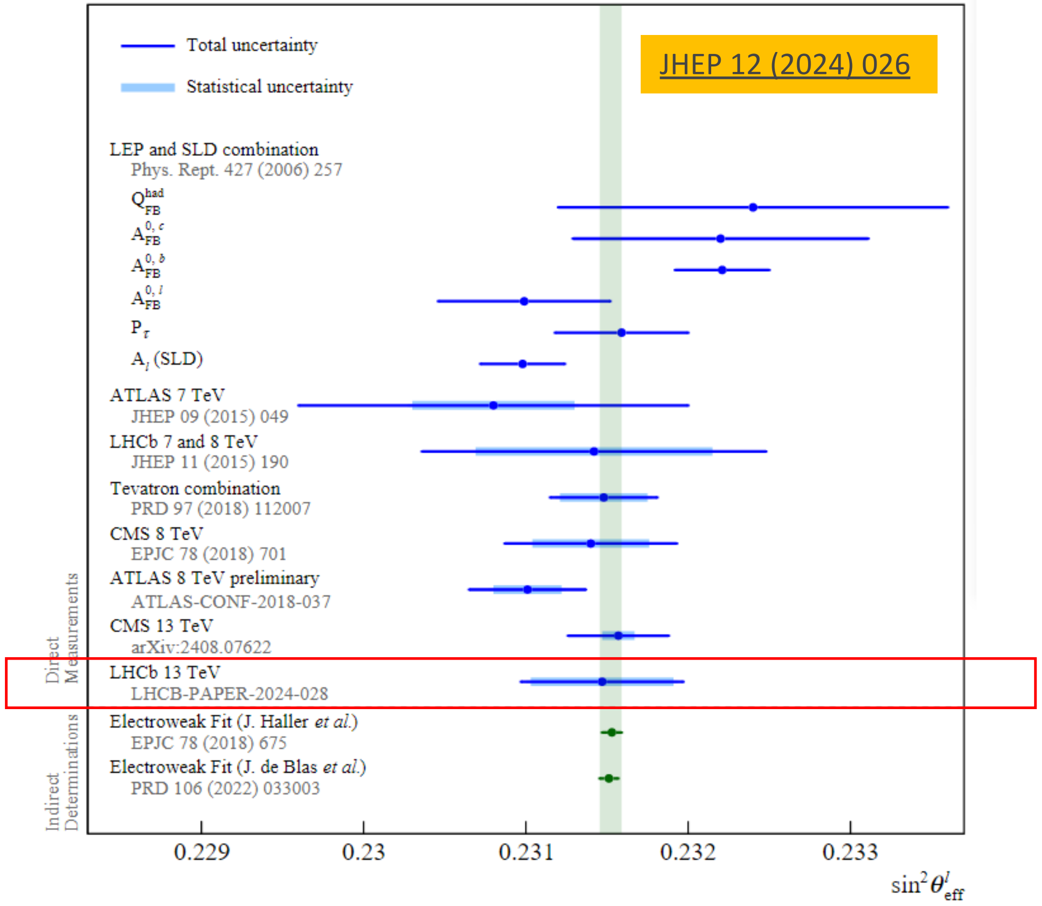
CERN COURIER report

CERN Seminar

- The result is consistent with other direct measurements and with predictions from the global EW fit
  - theory uncertainty includes PDF uncertainty, QCD and EW uncertainty
- **The PDF uncertainty ≪ statistic uncertainty $(\sim 4.4\times10^{-4})$** because of the use of the LHCb acceptance

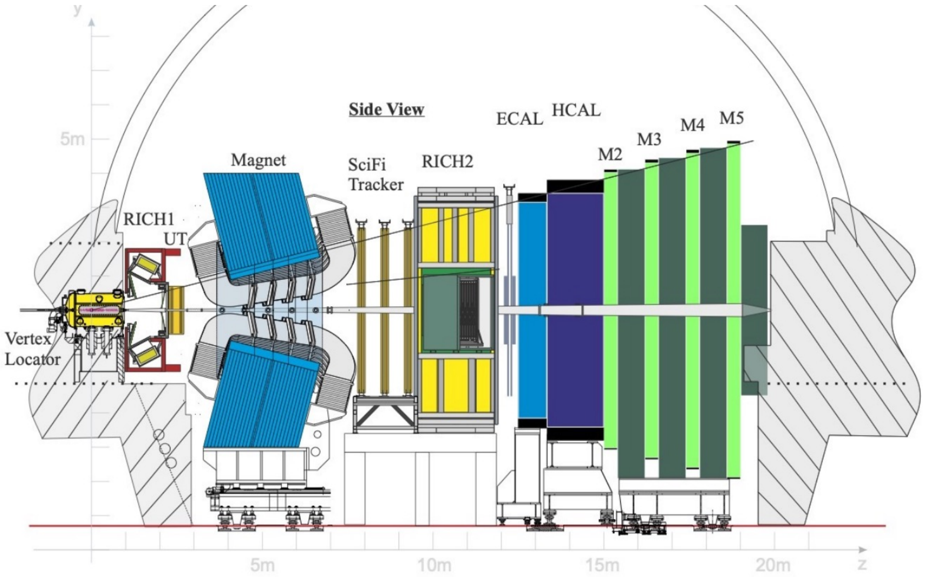


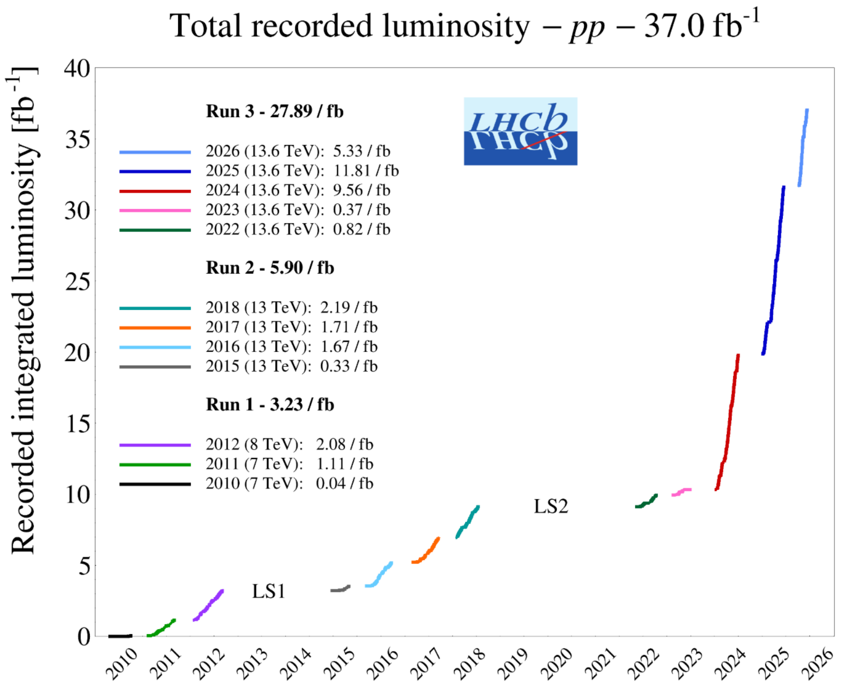




Prospect - upgraded LHCb

- Major detector upgrade for Run 3 and Run 4
  - new detectors for tracking system: Pixel VELO, UT, SciFi (Scintillating Fibre)
- New readout systems for all subdetectors
- **Run 3 has $\times 5$ larger instantaneous luminosity** compared to Run 2



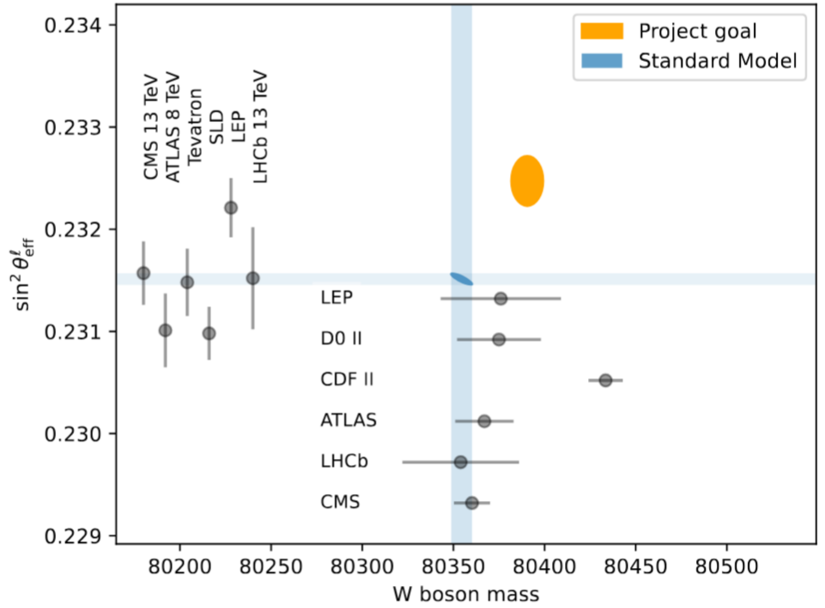


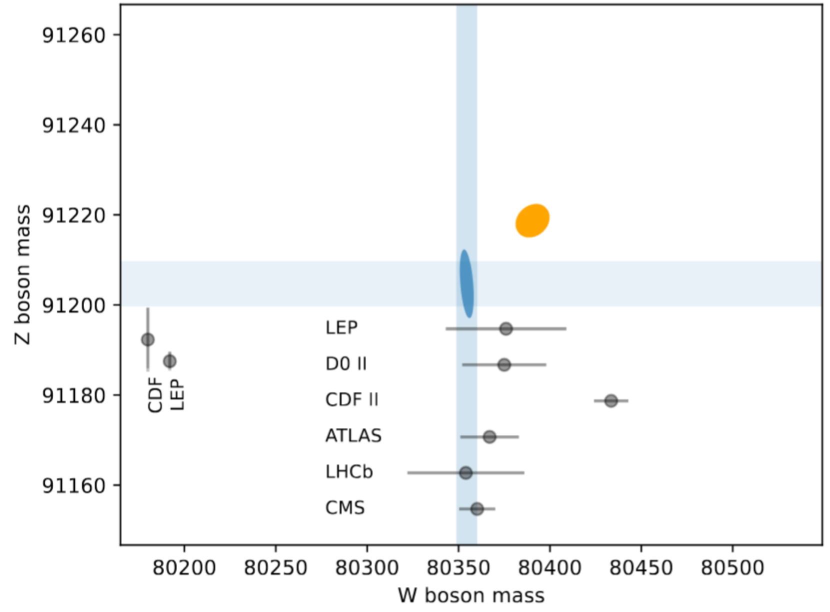
Nucl. Instrum. Meth. A 1089 (2026) 171588

Prospect – EW parameters

- m_W: Run 2 analysis is ongoing, with an expected precision of **20 MeV**
  - more careful treatment of the detector effects
  - improvements in the physics modelling
- m_Z: Run 2 analysis is ongoing, with an expected precision of **6 MeV**
  - detector calibration uncertainties mostly uncorrelated between experiments
  - an LHC average could challenge LEP soon
- $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$: Run 3 analysis is ongoing, is expected to yield the most precise results at the LHC

Simultaneous measurement?





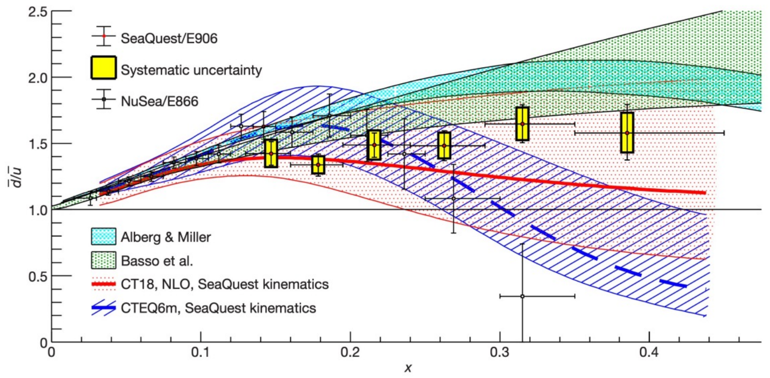
Proton structure

- In proton-proton collisions, it is not the protons themselves that actually collide, but rather the partons within them
- PDF uncertainty is one of the largest theoretical uncertainties affecting the predictions for Higgs boson production
- PDFs contribute to precise extraction of the SM parameters from the LHC data
- **Large-x PDF uncertainties**, driven by limited data, dominate the errors at high-energy tails, where new physics searches focus

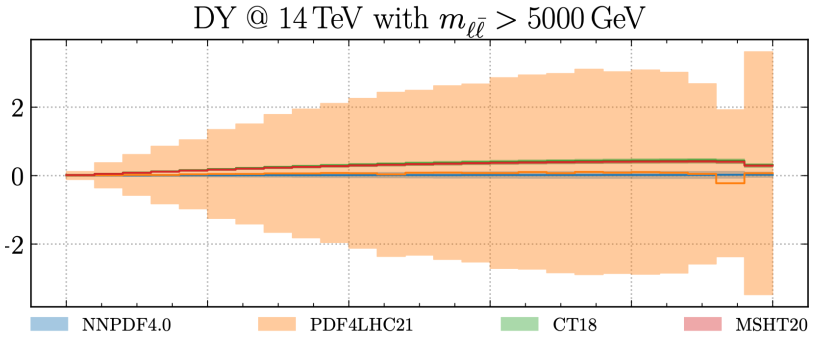
Nature 652 (2026) 321

Source of uncertainty	Impact (MeV) Nominal in m_Z	in m_W	Global in m_Z	in m_W
Muon momentum calibration	5.6	4.8	5.3	4.4
Muon reco. efficiency	3.8	3.0	3.0	2.3
W and Z angular coeffs.	4.9	3.3	4.5	3.0
Higher-order EW	2.2	2.0	2.2	1.9
p_T^V modeling	1.7	2.0	1.0	0.8
PDF	2.4	4.4	1.9	2.8
Nonprompt-muon background	—	3.2	—	1.7
Integrated luminosity	0.3	0.1	0.2	0.1
MC sample size	2.5	1.5	3.6	3.8
Data sample size	6.9	2.4	10.1	6.0
Total uncertainty	13.5	9.9	13.5	9.9

Nature 590, 561 (2021)



Eur. Phys. J. C 82 no. 12, (2022) 1160



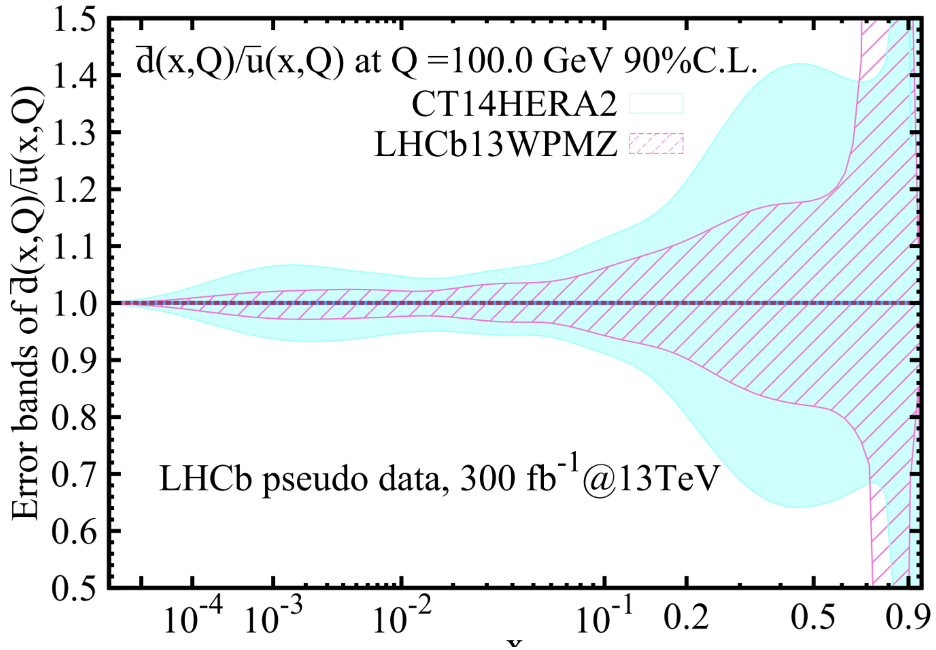
Tensions between SeaQuest and NuSea results

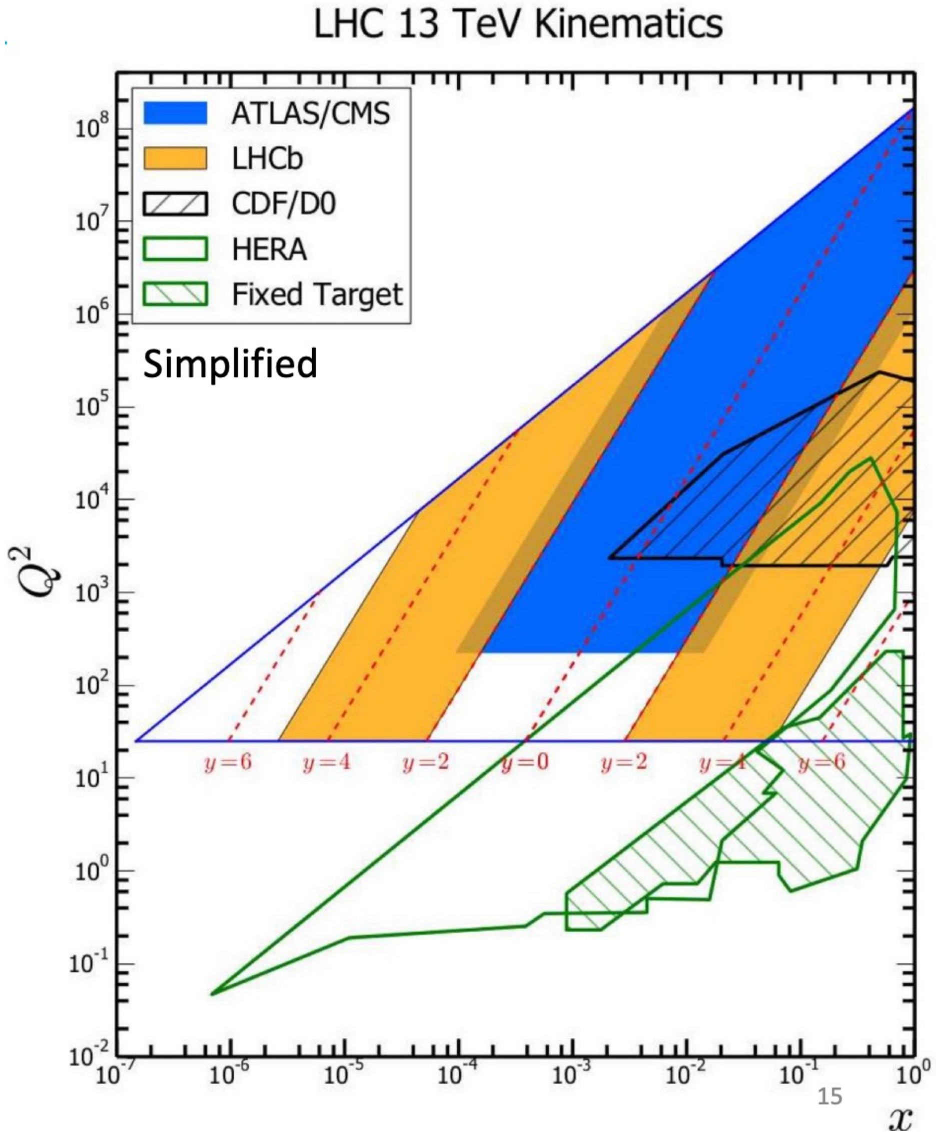
Proton structure study at LHCb

- As a result of the forward acceptance, the candidates collected with the LHCb detector are highly boosted, providing access to PDFs at **high/low Bjorken-x** region

$$x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$$

Chinese Phys. C 45 023110

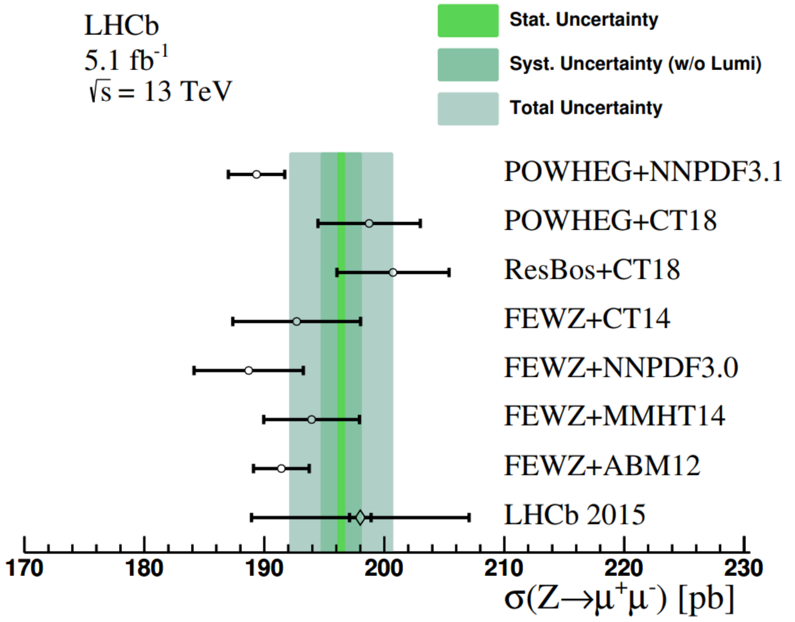




Forward Z production cross-section @ 13TeV

- The x value of interacting partons are correlated with the boson production
- Corrected to the **Born** level in QED

$$\sigma(Z \to \mu^+\mu^-) = 196.4 \pm 0.2\,(\text{stat.}) \pm 1.6\,(\text{sys.}) \pm 3.9\,(\text{lumi.})\ \text{pb}$$



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

JHEP 07 (2022) 26

fiducial region

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

$\mathcal{L} = 100 \pm 2\text{pb}^{-1}$

Z differential cross section: $y(Z)$ and ϕ_η^* @ 13TeV

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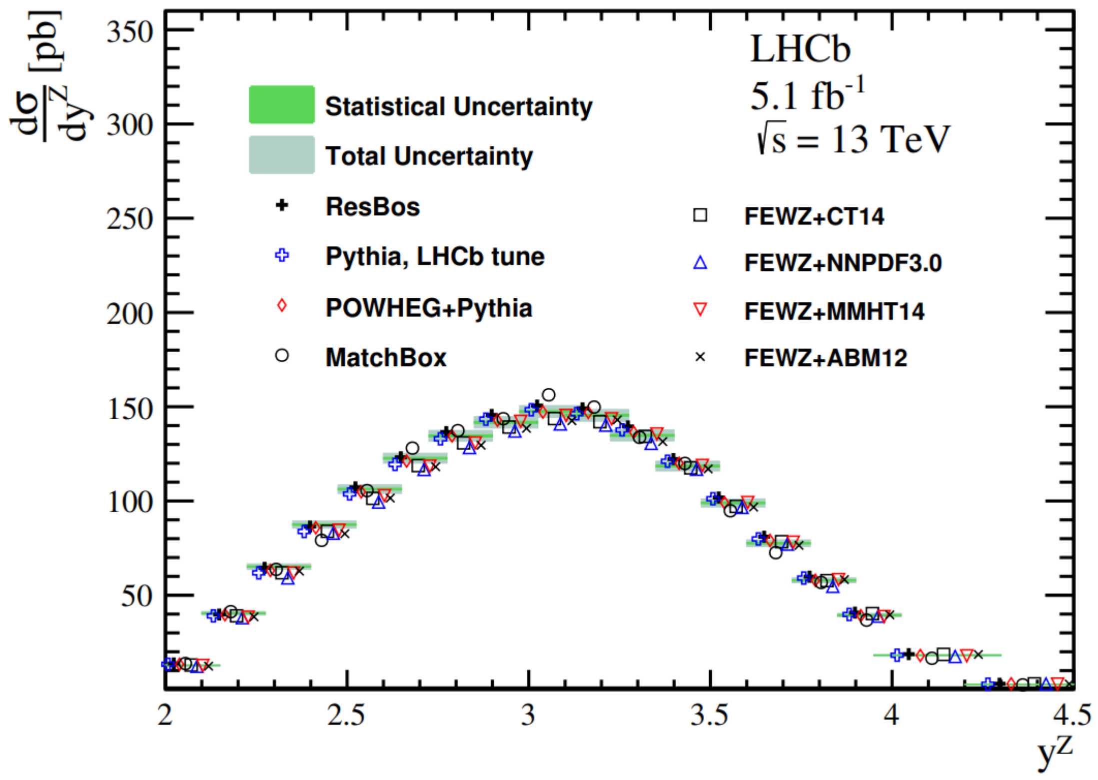
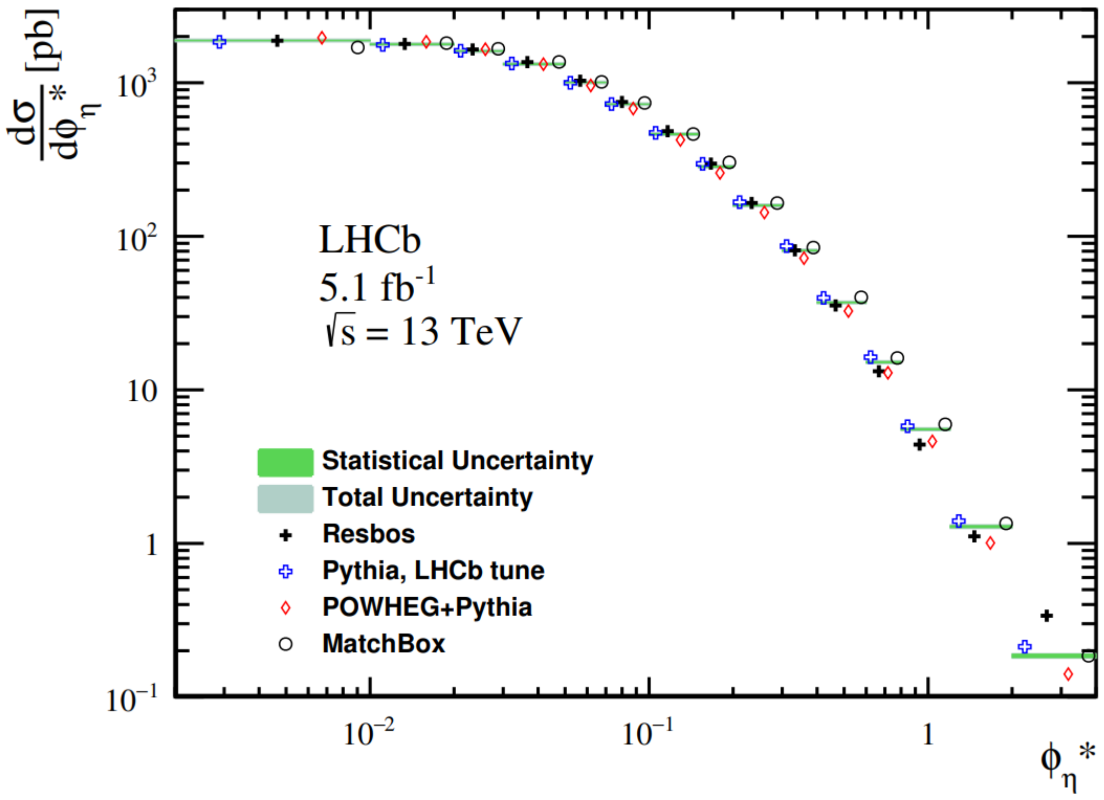


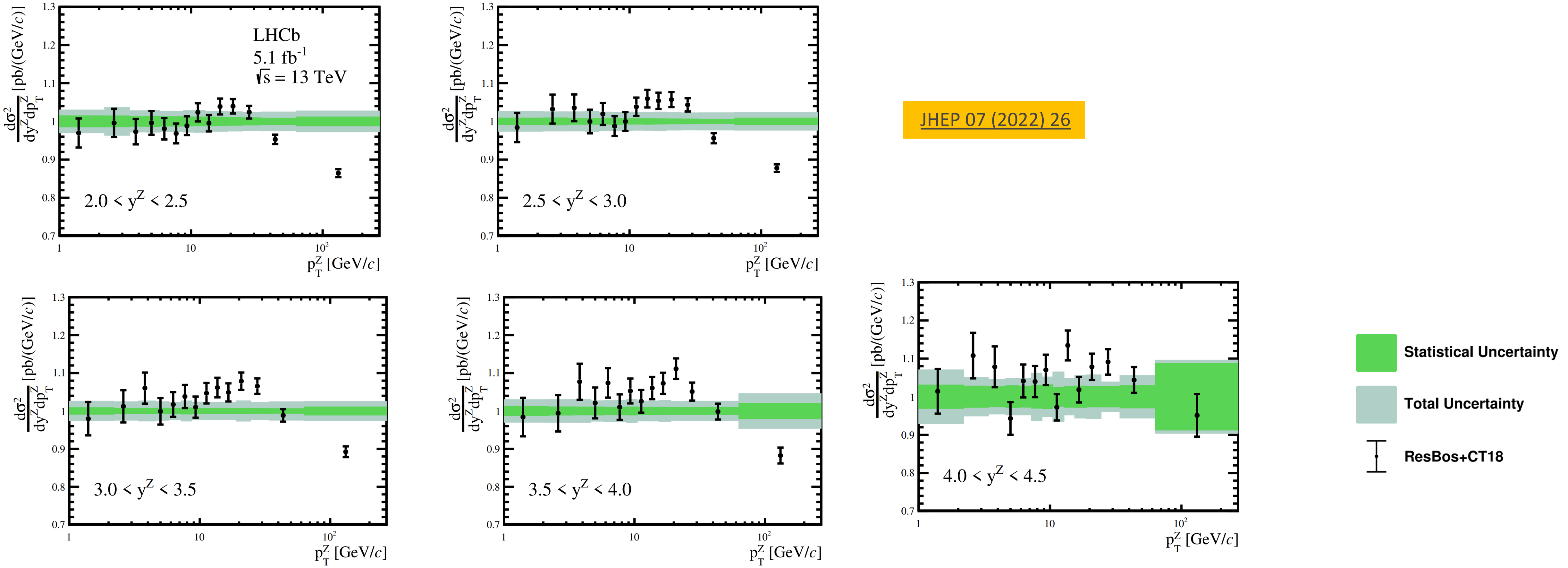
$$\phi_\eta^* = \tan\left(\frac{\phi_{\text{acop}}}{2}\right)\sin(\theta_\eta^*)$$

JHEP 07 (2022) 26



Z double differential cross-section @ 13TeV

- **First** double differential cross-section measurement in the forward region



JHEP 07 (2022) 26

Z cross-section @ 5.02TeV

$$\sigma(Z \to \mu^+\mu^-) = 39.6 \pm 0.7\,(\text{stat.}) \pm 0.6\,(\text{sys.}) \pm 0.8\,(\text{lumi.})\ \text{pb}$$

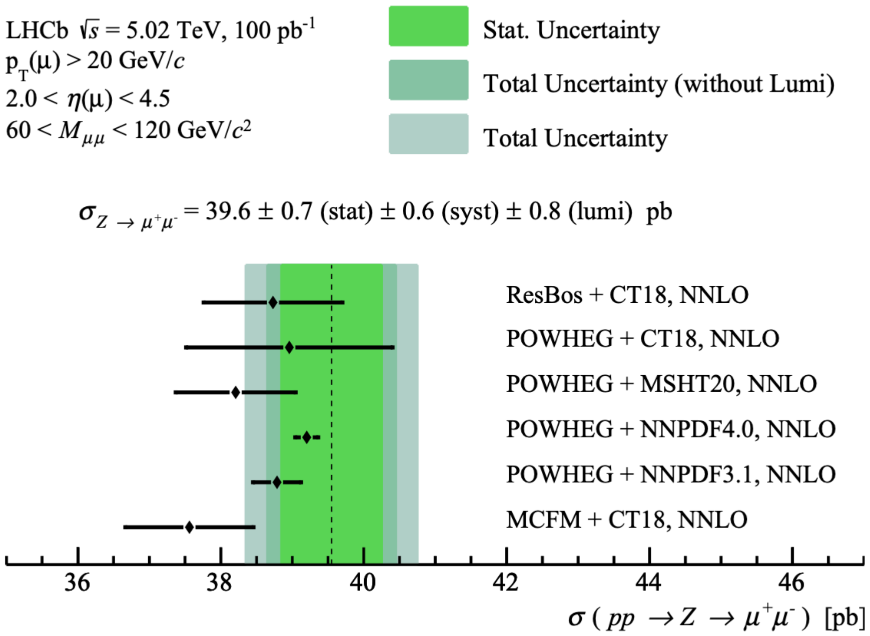
$\mathcal{L} = 100 \pm 2\text{pb}^{-1}$

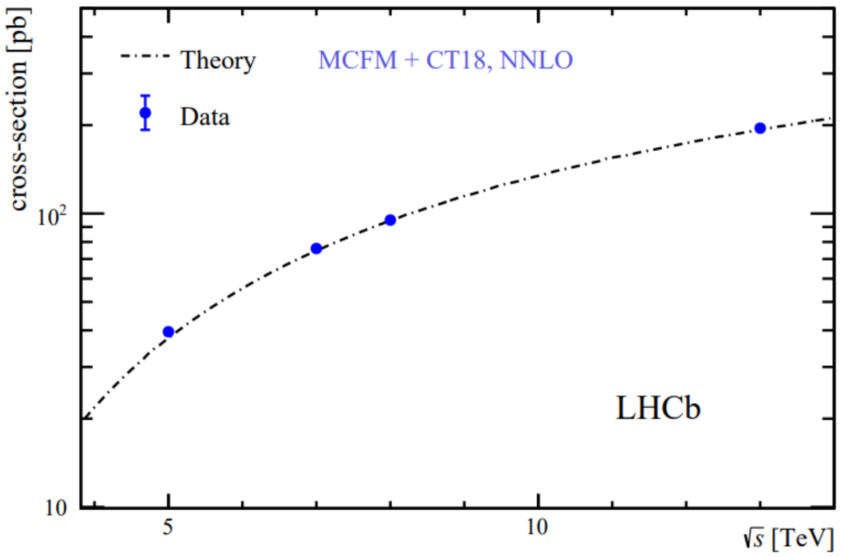
$$R^{\rm B}_{pPb} = \frac{\sigma(p\text{Pb}, 2.0<\eta<4.5)}{\sigma(pp,-4.97<\eta<-2.47)} \cdot \frac{\sigma(p\text{Pb},-4.97<y^*_\mu<-2.47)}{208\cdot\sigma(pp,2.0<\eta<4.5)} = 1.2^{+0.5}_{-0.3}\ (\text{stat}) \pm 0.1\ (\text{syst})$$

$$R^{\rm F}_{pPb} = \frac{\sigma(p\text{Pb}, 2.0<\eta<4.5)}{\sigma(pp,1.53<\eta<4.03)} \cdot \frac{\sigma(p\text{Pb},1.53<y^*_\mu<4.03)}{208\cdot\sigma(pp,2.0<\eta<4.5)} = 3.6^{+1.6}_{-0.9}\ (\text{stat}) \pm 0.2\ (\text{syst})$$

JHEP 02 (2024) 070

208: the number of binary nucleon-nucleon collisions in pPb collisions





Z angular coefficient measurement

- The angular distribution of the final-state leptons provides a direct probe of the polarization of the **intermediate** gauge boson
  - A_0: the longitudinal polarization fraction of the boson
  - A_1: the parity-conserving quantum interference between the longitudinal and boson’s transverse helicity amplitudes
  - A_2: the transverse polarization asymmetry
  - A_3: the parity-conserving transverse-longitudinal interference phase orthogonal to A_1

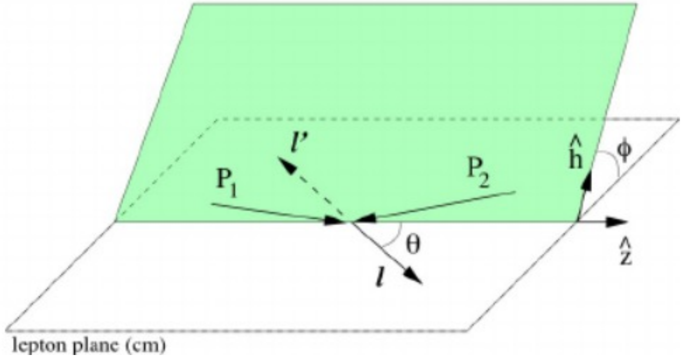
$$\frac{d\sigma}{dP_T^2\,dy\,d\cos\theta\,d\phi} \propto (1+\cos^2\theta) \longrightarrow \textit{LO term}$$

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

$$+\ A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi \longrightarrow (\theta,\phi)\text{ terms}$$

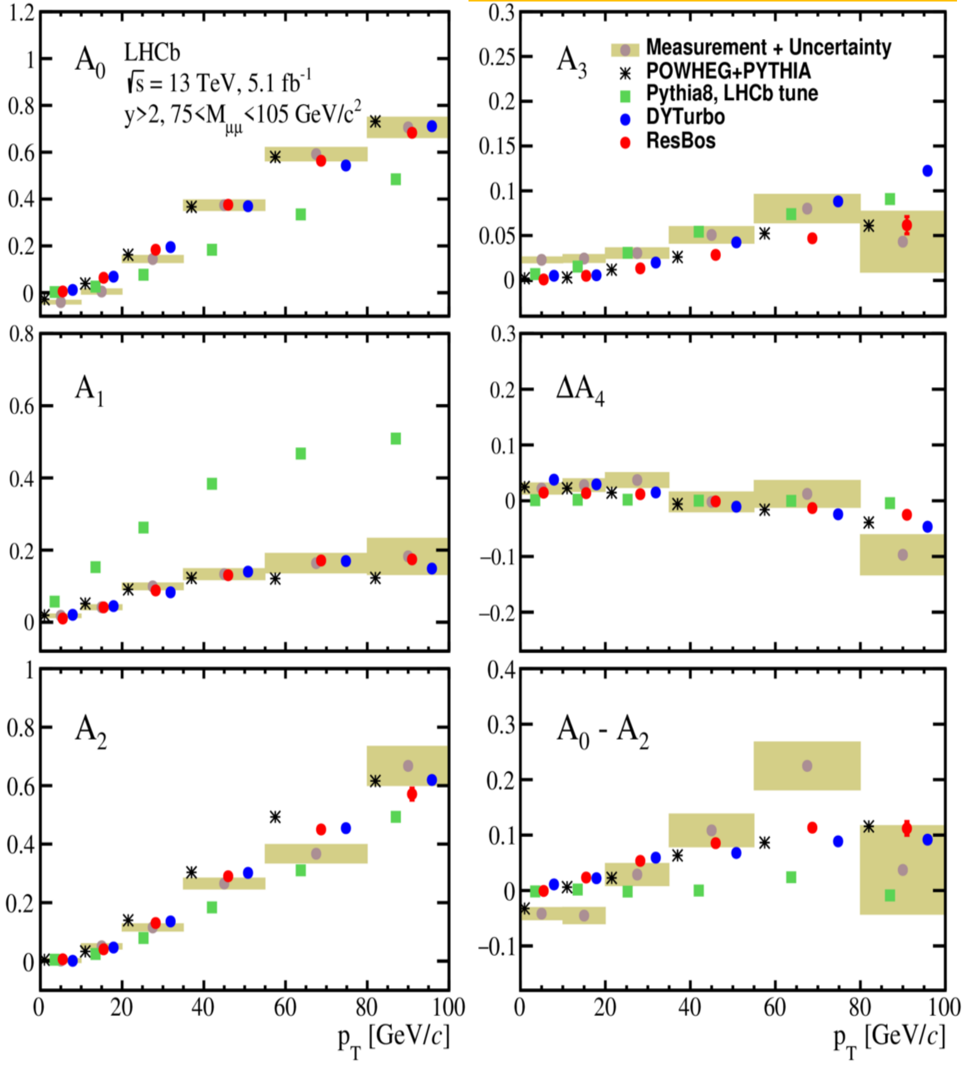
$$+\ A_4\cos\theta \longrightarrow \textit{LO term : determine } A_{fb}$$

$$+\ A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi \longrightarrow \textit{very small terms}$$



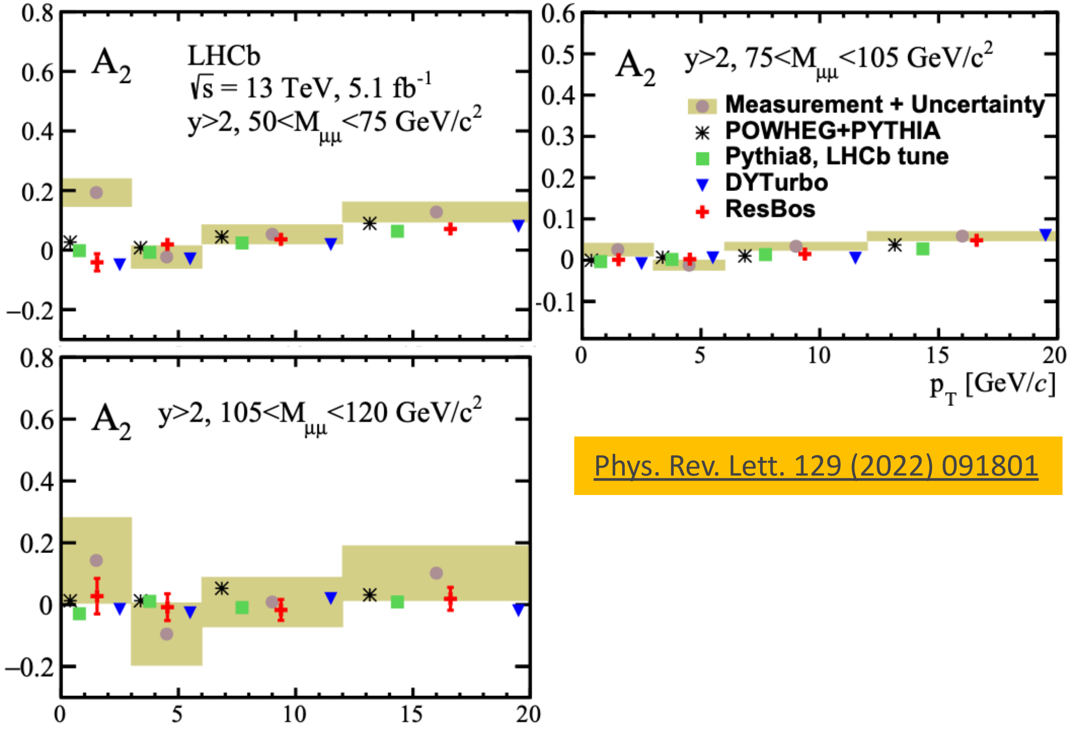
A_i - p_{T} dependent

Phys. Rev. Lett. 129 (2022) 091801



- Measurements are at the Born level
- **The uncertainty is dominated by statistical uncertainty**
- Interesting violation of the Lam-Tung relation, $A_0 = A_2$, in agreement with ATLAS [JHEP08(2016)159] and CMS [Phys. Lett. B 750 (2015) 154] results

A_2 - TMD



Phys. Rev. Lett. 129 (2022) 091801

- The angular coefficients provide sensitive probes for studying the transverse-momentum-dependent (TMD) non-perturbative effects of initial-state quarks
  - the general PDFs: $f_i(x, Q^2)$
  - TMD: $f_i\left(x, \overrightarrow{k_T}, Q^2\right)$

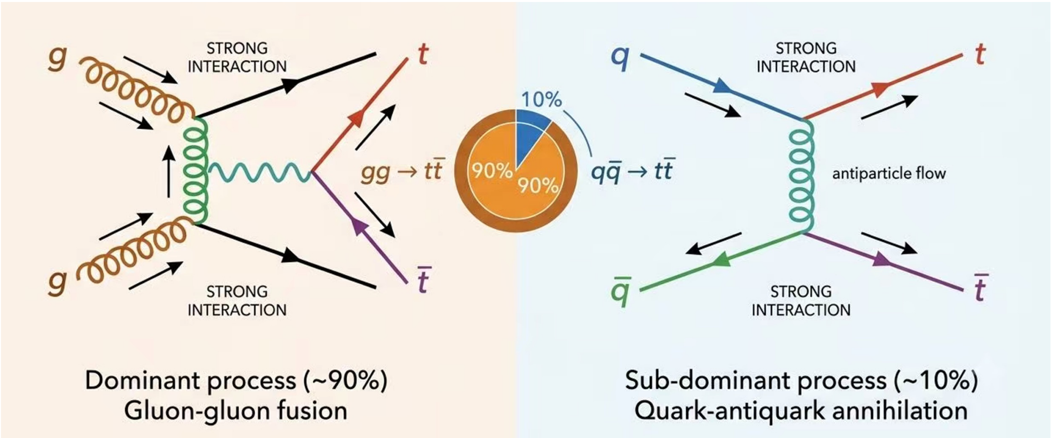
Phys. Rev. D 57 (1998), 5780
Phys. Rev. D 60 (1999), 014012

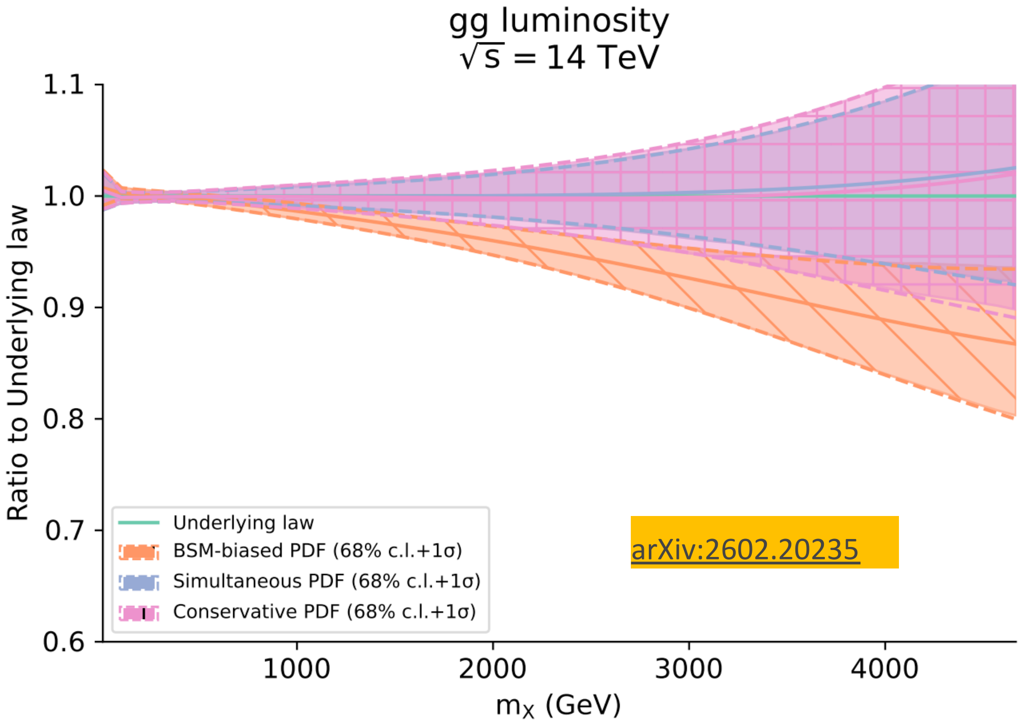
- A_2 is sensitive to the TMD
- The measured A_2 values deviate significantly from all predictions in the lowest p_{T} region for the low-mass region
  - at low Z-boson p_{T}, the transverse momentum effects of initial-state quarks are not negligible

Gluon PDF

- The effective impact of theoretical uncertainties of PDFs on the Higgs cross section (90% of Higgs come from $gg \to H$)

Top quark production measurement at LHC





arXiv:2602.20235

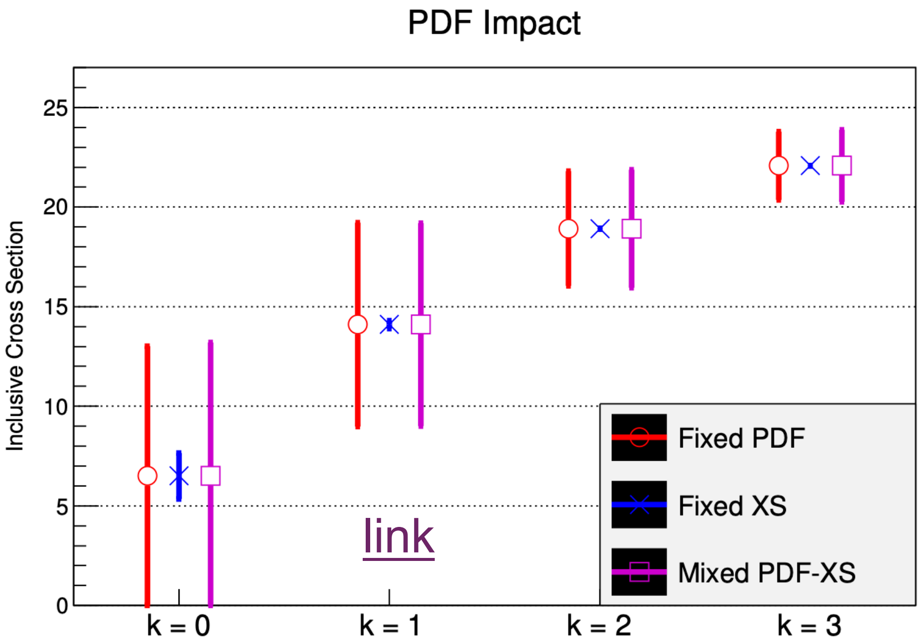
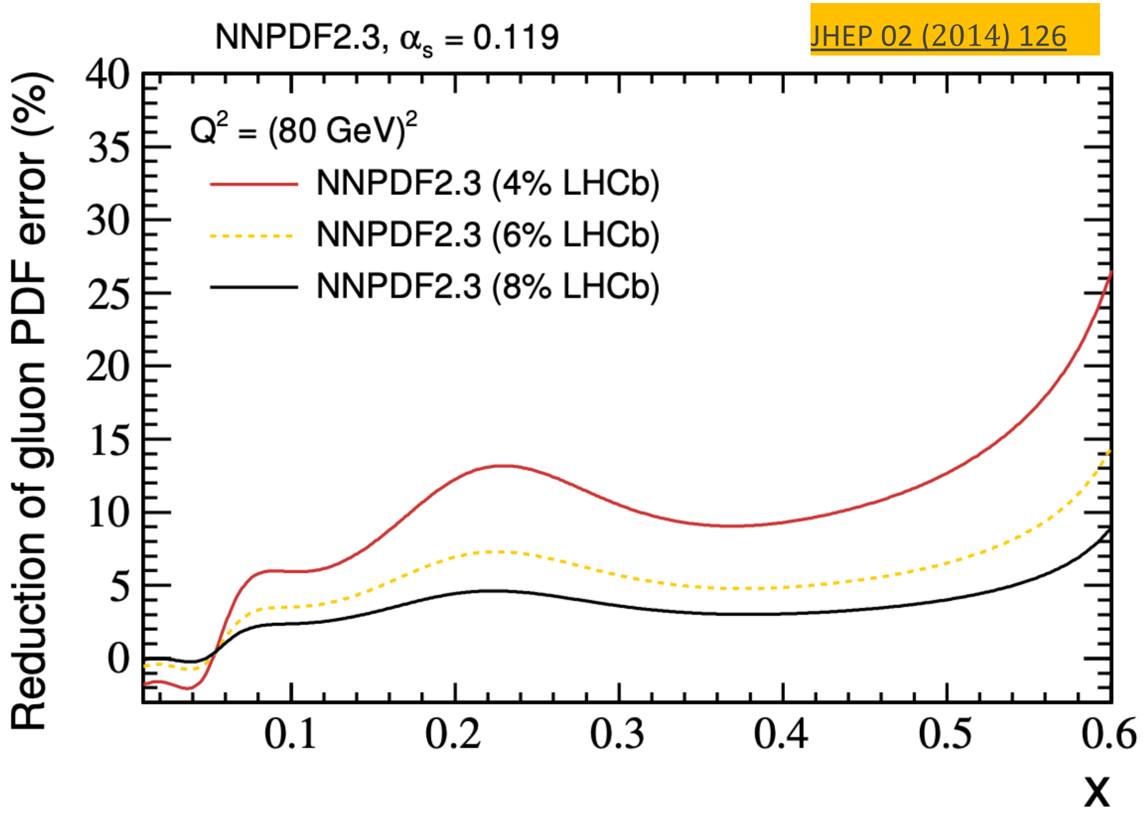


Figure 4.9: Impact of theoretical uncertainties on PDFs on Higgs cross section.

Top quark production at LHCb

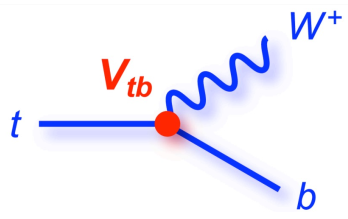
- Top quark production measurement at LHCb can provide constraints on the gluon PDF in the higher-x region than the central region
  - **up to $20-30\%$ reduction possible at large-x**

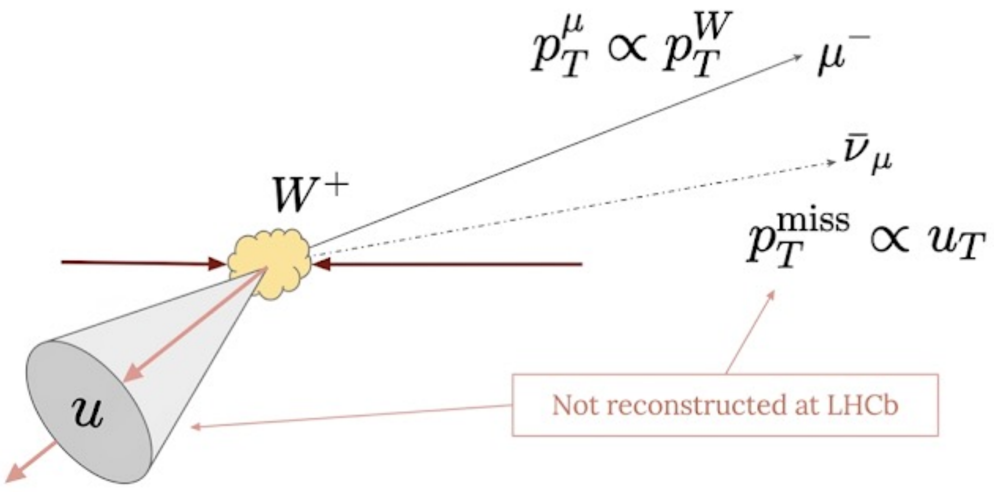
JHEP 02 (2014) 126



Measurement of the top quark production at LHCb

- Measure the top quark cross section using $\mu + b$-jet final state at 13 TeV, do not distinguish single top and $t\bar{t}$
  - Top quarks decay ~100% to Wb, $|V_{tb}| = 0.998 \pm 0.026$ PDG 2026
  - the W bosons are reconstructed using $W \to \mu\nu$ decay
    - hadronic channel not feasible due to huge QCD background and jet energy scale
    - in leptonic channel, W cannot be fully reconstructed





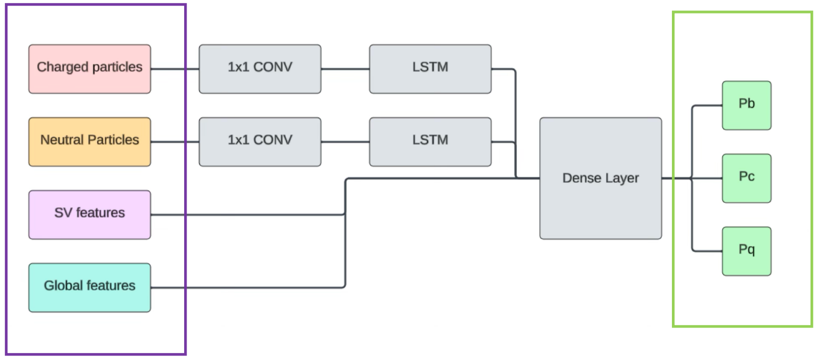
Jet selections:

- $p_{\text{T,jet}} > 50\text{GeV}$
- $4.0 > \eta_{\text{jet}} > 2.2$
- $p_{\text{T}}(\mu + j) > 20$ GeV
- The muon and jet must be separated by $\Delta R(\mu, j) > 0.5$, $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$

Jet tagging

arXiv: 2601.16802, accepted by JHEP

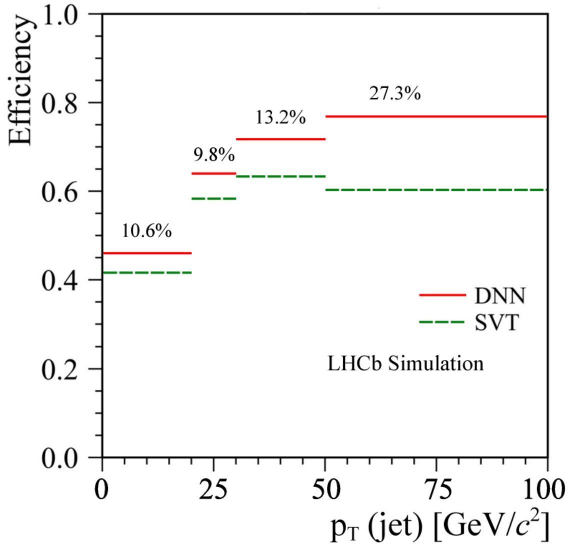
- BDT + secondary vertex requirement (SVT) → Deep Neural Network (DNN)
- Inputs: ~400 observables
- Secondary vertex is not strictly required
- Trained with $b\bar{b}$-, $c\bar{c}$ -, and light dijets simulation
- Outputs: $b/c/$light-probability



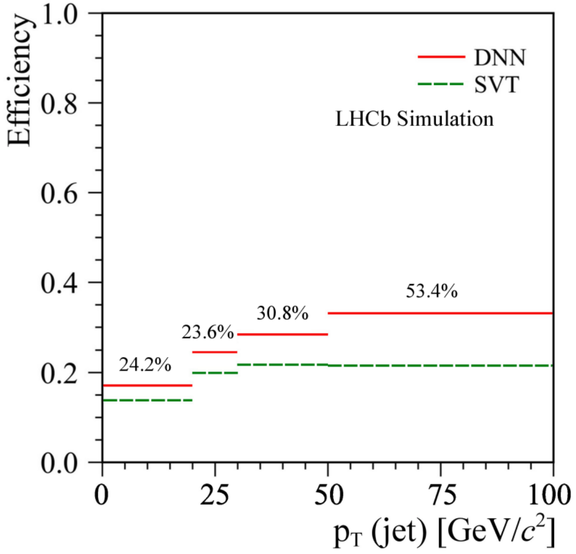
Inspired by CMS DeepJet

$$\varepsilon = \frac{N_{\text{tag}}}{N_{\text{rec}}}$$

b-jet



c-jet

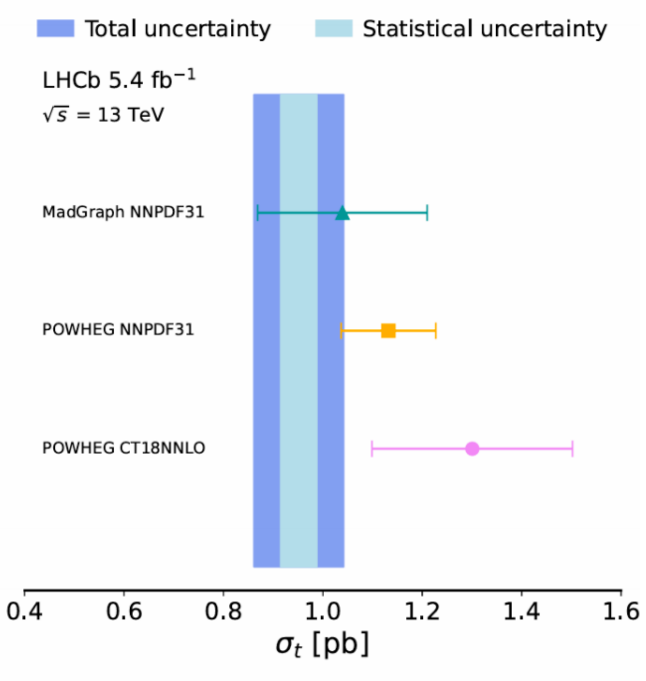


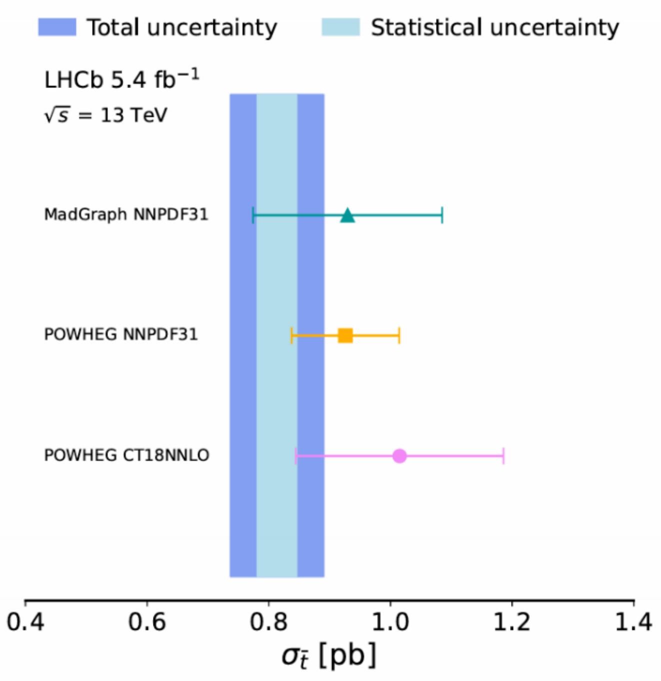
Total cross-section

- The measured results have been corrected for background and detector effects
- Results are consistent with the SM
- The largest source of systematic uncertainty is jet-related

$$\frac{d\sigma_{\rm top}^{\rm fiducial}}{d\eta_\mu} = \frac{(N - N^{\rm bkg}) \cdot \mathcal{A} \cdot P}{\Delta\eta_\mu \cdot \mathcal{L} \cdot \varepsilon_{\rm sel} \cdot \varepsilon_{\rm rec} \cdot \varepsilon_{\rm btag} \cdot \epsilon_{\rm true}}$$

$$\sigma_t = 0.95 \pm 0.04\,({\rm stat}) \pm 0.08\,({\rm syst}) \pm 0.02\,\,({\rm lumi})\,{\rm pb},$$
$$\sigma_{\bar{t}} = 0.81 \pm 0.03\,({\rm stat}) \pm 0.07\,({\rm syst}) \pm 0.02\,\,({\rm lumi})\,{\rm pb},$$





Source	$\Delta\sigma_t/\sigma_t$ [%]	$\Delta\sigma_{\bar{t}}/\sigma_{\bar{t}}$ [%]
b-jet tagging	6.5	6.2
Jet energy scale and resolution	5.0	5.0
ABCD method	2.0	2.1
$Z+b$-jet background	0.2	0.2
$W+b$-jet background	0.9	1.3
Selection efficiency	0.2	0.2
Muon reconstruction efficiency	0.2	0.2
Jet reconstruction efficiency	0.3	0.3
Total systematic (excl. lumi.)	8.5	8.3
Luminosity	2.0	2.0
Statistical	3.8	4.0
Total	9.5	9.4

Phys. Rev. Lett. 136 (2026) 22180

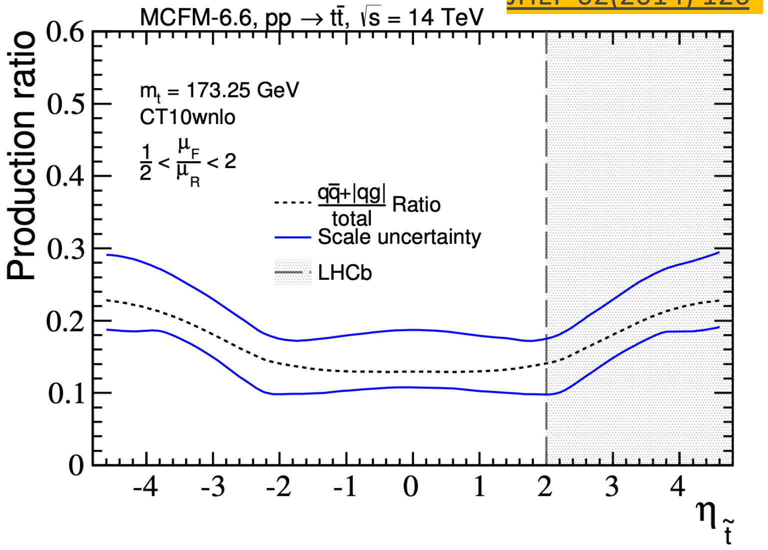
Top quark charge asymmetry

$$A_C^{\mathrm{top}} = \left(\frac{\sigma_t - \sigma_{\bar{t}}}{\sigma_t + \sigma_{\bar{t}}}\right)_{\eta(\mu)}$$

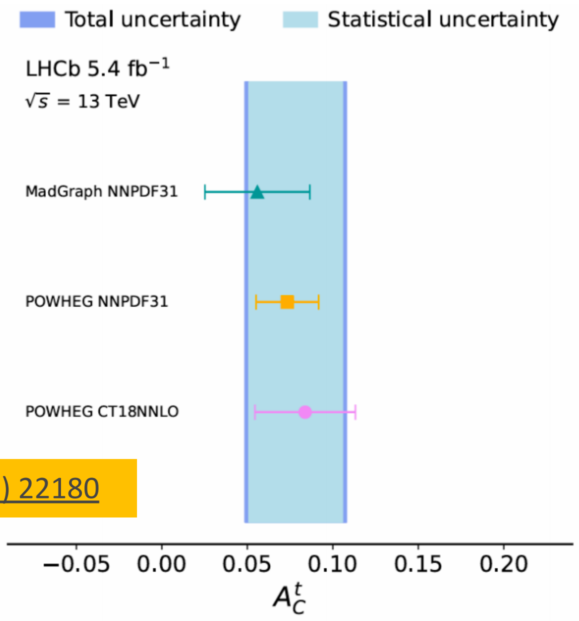
- Measurements of $t\bar{t}$ asymmetry are of interest since discrepancies were seen at the Tevatron in $p\bar{p}$ collisions
  - hints of new physics, such as axigluons and Z' bosons
- Larger charge asymmetries at the forward region
  - the asymmetry is diluted by symmetric gluon-gluon fusion at the LHC
  - the enhancement $t\bar{t}$ production via $q\bar{q}$ annihilation and qg scattering, relative to gg fusion at the forward region

$$A_C^t = 0.08 \pm 0.03\,(\mathrm{stat}) \pm 0.01\,(\mathrm{syst})$$

JHEP 02(2014) 126



- Results are consistent with the SM



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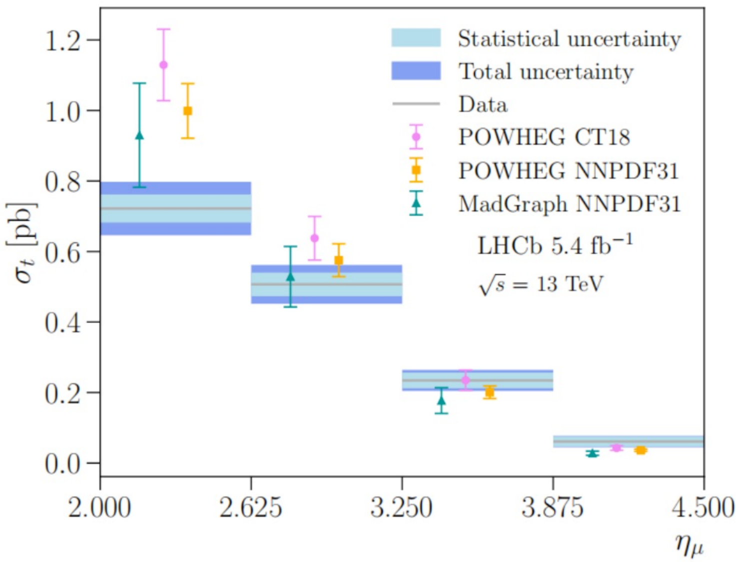
Differential cross-section and charge asymmetry

- The results are well described by the theoretical models
- The data exhibit a trend of **increasing asymmetry with η_μ**, in agreement with theoretical predictions

η_μ range	A_C^t	significance
2.000–2.625	$0.05 \pm 0.04 \pm 0.02$	1.22
2.625–3.250	$0.07 \pm 0.05 \pm 0.02$	1.44
3.250–3.875	$0.15 \pm 0.07 \pm 0.03$	1.91
3.875–4.500	$0.17 \pm 0.18 \pm 0.09$	0.85
2.0–4.5 (combined)	$0.08 \pm 0.03 \pm 0.01$	2.64



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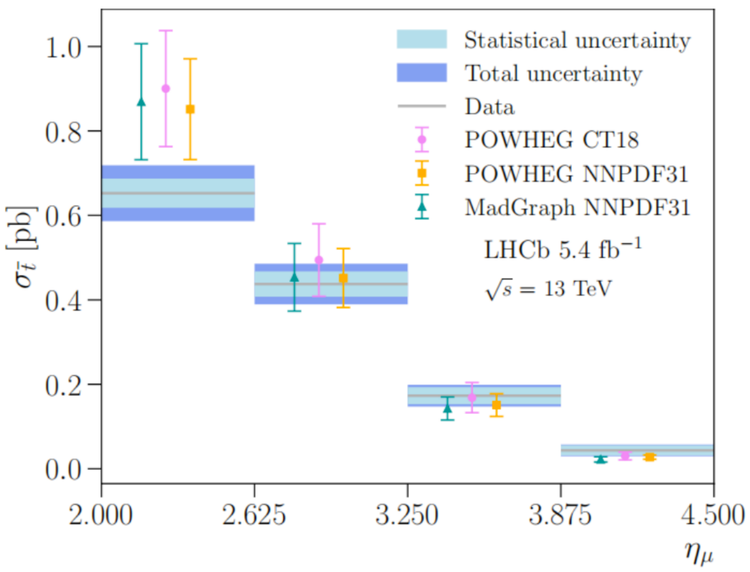
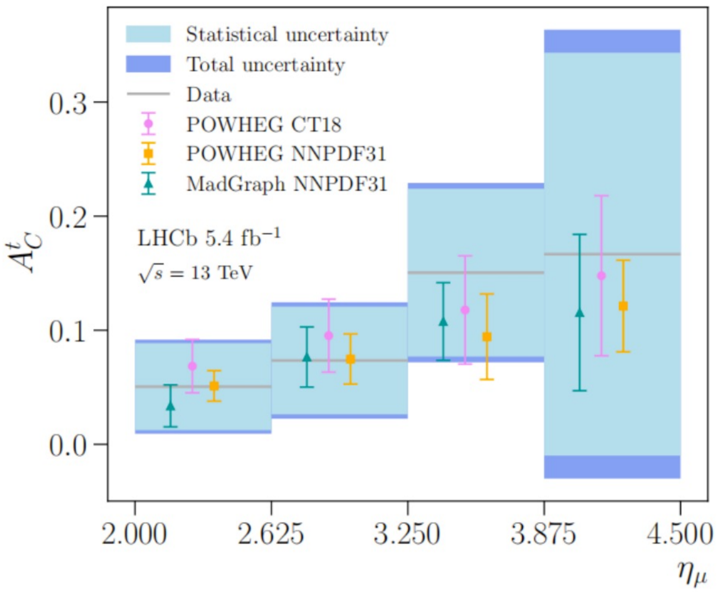


$\bar{t}$

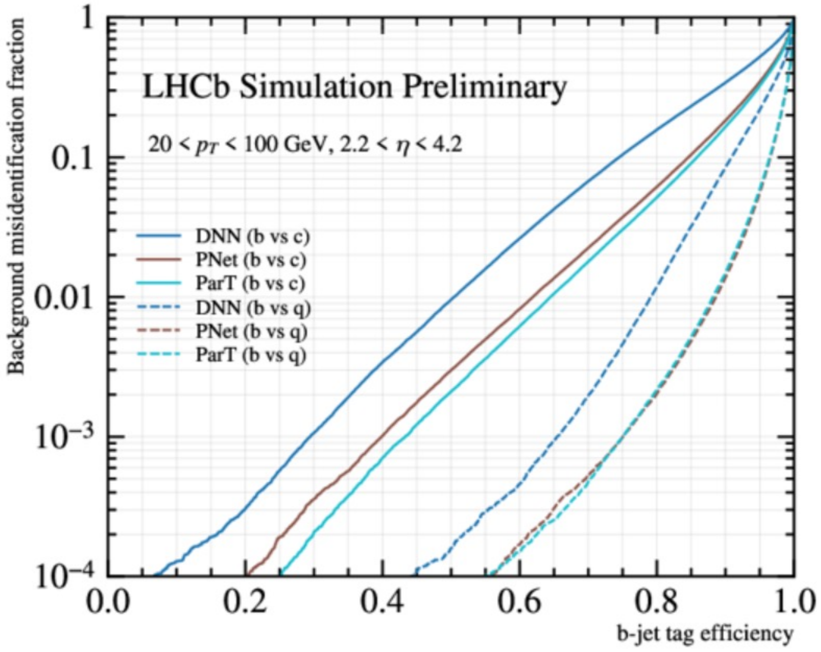


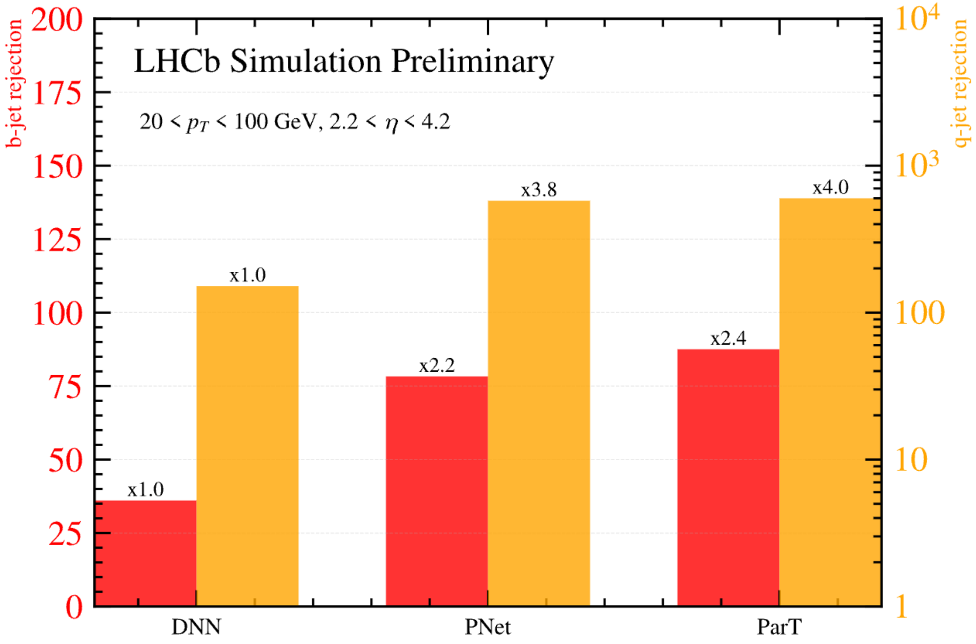
Phys. Rev. Lett. 136 (2026) 22180

Prospect – Top Physics

- Develop advanced jet tagging algorithm
  - b-tagging power $\times\mathbf{4}$
- Explore electron channels to contribute equivalent precision to muon channel
  - distinguish single top and $t\bar{t}$
  - Top mass?

LHCb-FIGURE-2026-001





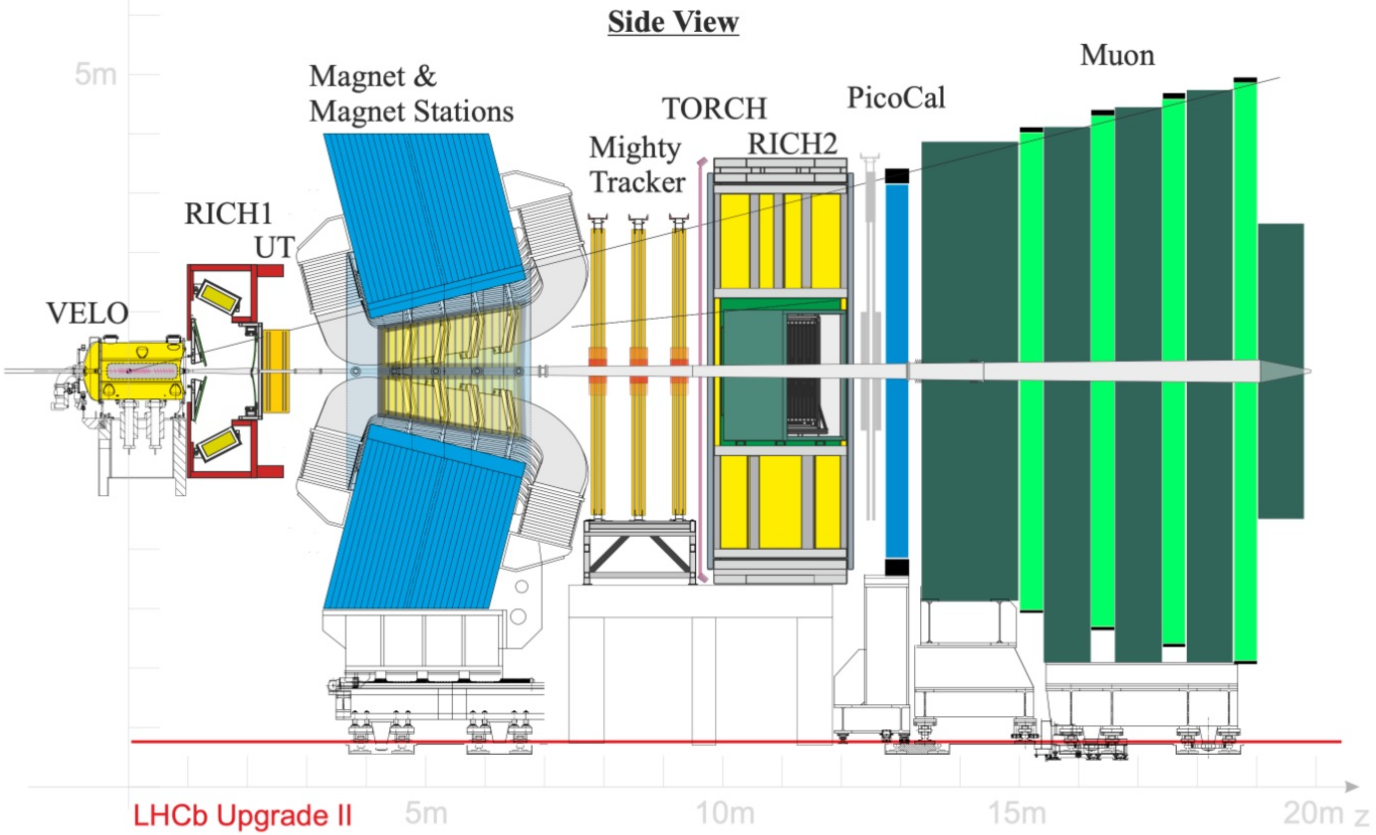
Upgrade II

LHC Run Year	Integrated luminosity fb^{-1}		
$cm^{-1}s^{-1}$	1.0×10^{34}	1.5×10^{34}	2.0×10^{34}
Run 1-4	50	50	50
LS4	–	–	–
Run 5 Year 1	21	25	26
Run 5 Year 2	43	50	51
Run 5 Year 3	43	50	51
LS5	–	–	–
Run 6 Year 1	43	50	51
Run 6 Year 2	43	50	51
Run 6 Year 3	43	50	51
Total	284	325	331

LHCb-TDR-023

LHCb-FIGURE-2026-001

- Timing Cherenkov improve resolution
- Timing calorimeter improve reconstruction
- Timing Pixel detector
- Time-of- flight detector for low-p PID



Summary

- Electroweak precision measurements and Top quark physics are effective probes for testing the Standard Model and exploring new physics

- LHCb's specialized **forward region**
  - enables precise tests of QCD and EW effects in the unique kinematic region
  - grants direct access to **high/low Bjorken-x** region
  - provides unique information that significantly **constrains global PDF fitting**

- LHCb has achieved competitive measurements in electroweak and top quark physics

- We foresee an exciting future ahead of us with new measurements

Back Up

m_W extraction

EPJC 71 1600 (2011)

$$\phi^* \equiv \arctan\left(\frac{\pi-\Delta\phi}{2}\right) / \cosh\left(\frac{\Delta\eta}{2}\right) \sim \frac{p_T}{M}$$

- In a template fit to the q/p_{T}^{μ} distribution
- In a simultaneous fit of W and Z data

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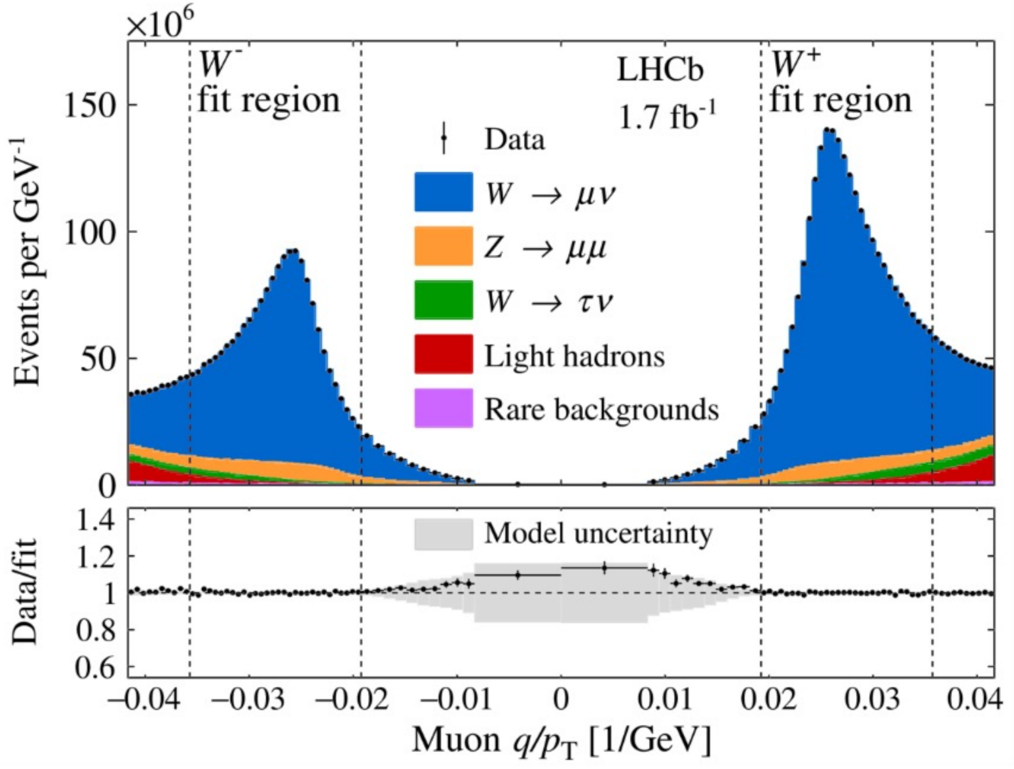
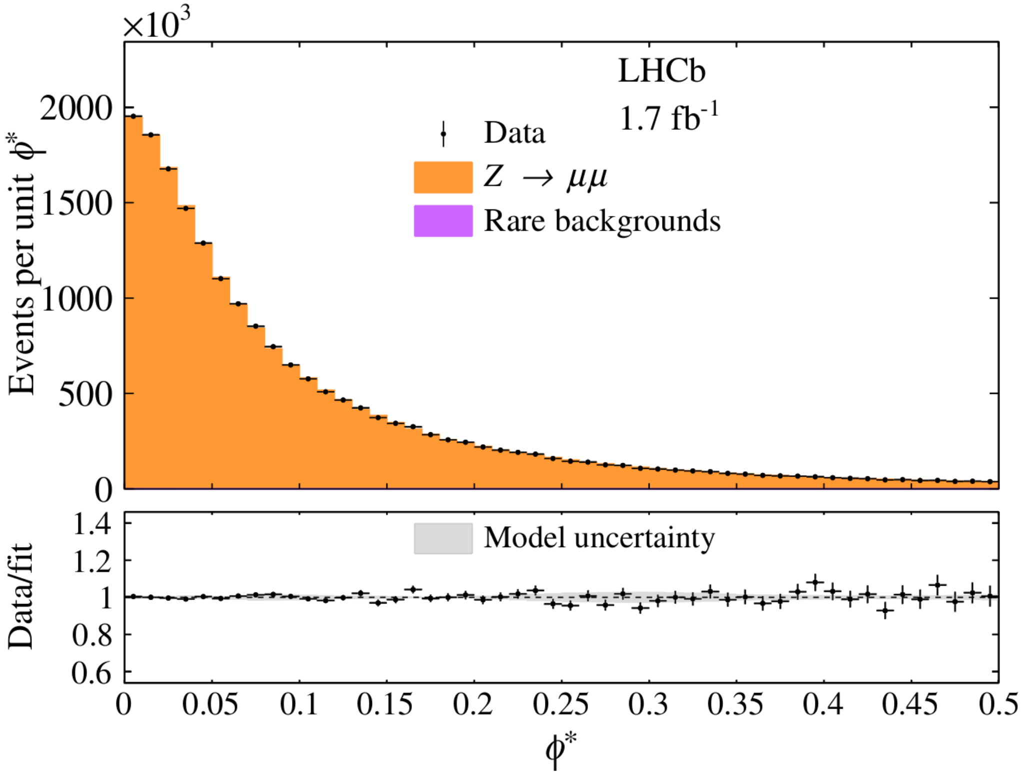




m_W at LHCb - 2016 result

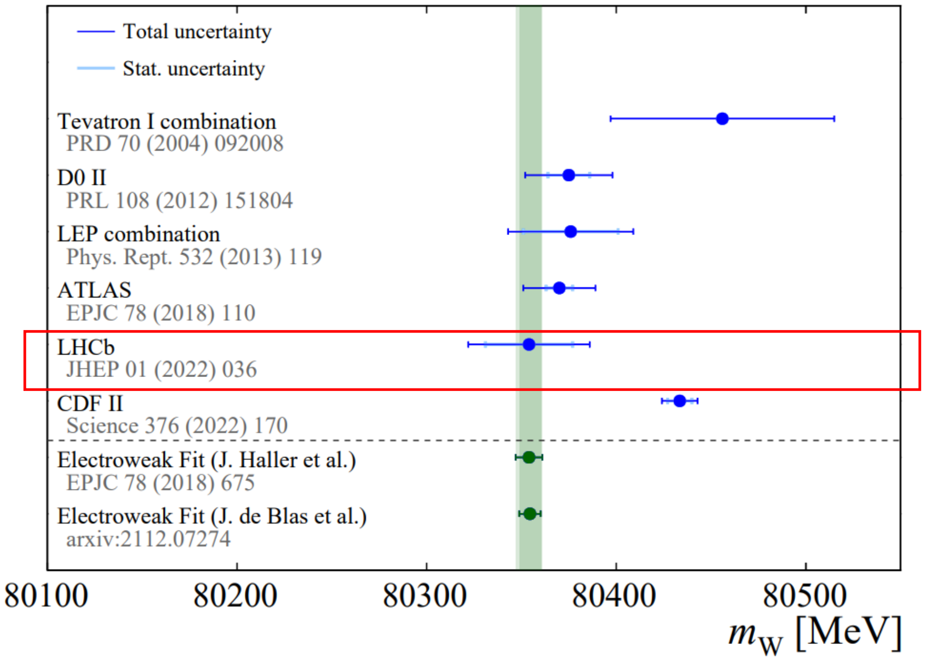
- LHCb achieves a precision of $\sim$ 32 MeV using roughly 1/3 of the Run II dataset
- The uncertainties are evaluated with specific prescriptions from each of the three groups
- Central m_W result is an average of the three results with the individual PDF sets assuming 100% correlation

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

Source	Size [MeV]	
Parton distribution functions	9	Average of NNPDF31, CT18, MSHT20
Theory (excl. PDFs) total	17	
Transverse momentum model	11	Envelope from five different models
Angular coefficients	10	"Uncorrelated" 31 point scale variation
QED FSR model	7	Envelope of Pythia, Photos and Herwig
Additional electroweak corrections	5	Test with POWHEGew
Experimental total	10	
Momentum scale and resolution modelling	7	Includes simple statistical contributions, dependence on external inputs and details of the methods.
Muon ID, trigger and tracking efficiency	6	
Isolation efficiency	4	
QCD background	2	
Statistical	23	
Total	32	

Set	$\sigma_{\text{PDF,base}}$ [MeV]	$\sigma_{\text{PDF},\alpha_s}$ [MeV]	σ_{PDF} [MeV]
NNPDF3.1	8.3	2.4	8.6
CT18	11.5	1.4	11.6
MSHT20	6.5	2.1	6.8

LHCB-FIGURE-2022-003



$W \to \mu\upsilon$ cross-section @ 5.02 TeV

- Traditionally, $\mu\ p_{\mathrm{T}}$ shape is used to subtract background → cross-section measurements in $\mu\ p_{\mathrm{T}}$ is impossible
- The production of W boson is the basis of m_W measurement by fitting $\mu\ p_{\mathrm{T}}$ shape
- The theoretical modelling of the signal process is deeply embedded

- Using muon isolation information to subtract the background, then perform the differential cross-section, $\mathrm{d}\sigma_{W\to\mu\nu}/\mathrm{d}p_{\mathrm{T}}$, model independent
    - muon isolation: the scalar sum of the transverse momenta of all other charged particles and electromagnetic calorimeter clusters within a distance $(\Delta\eta)^2+(\Delta\phi)^2 < 0.5^2$

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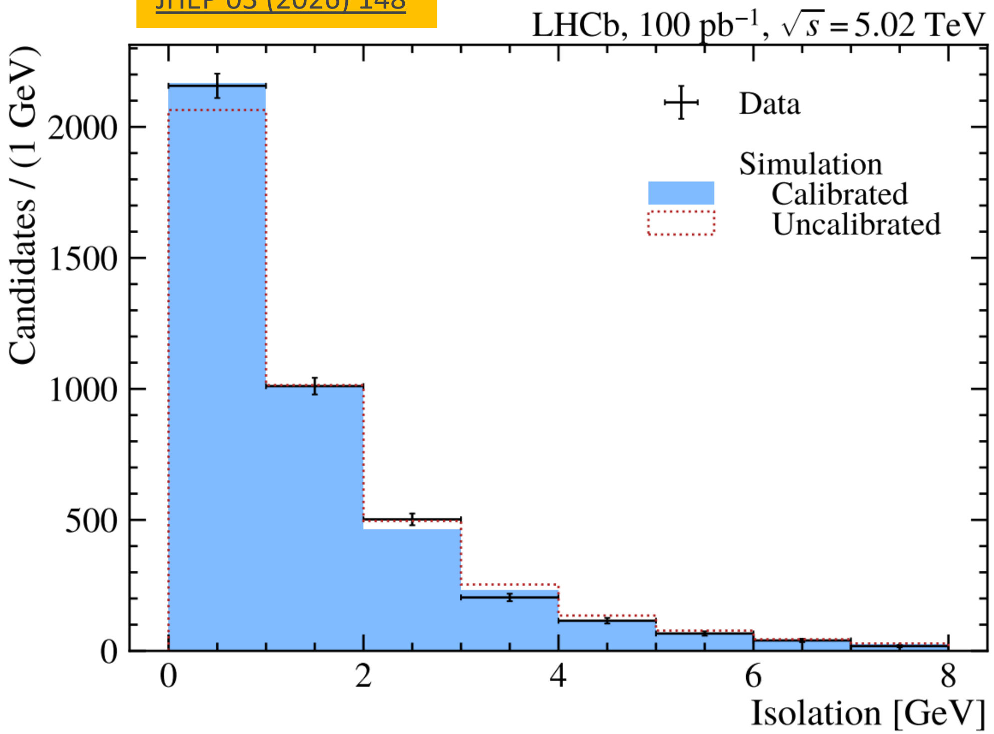


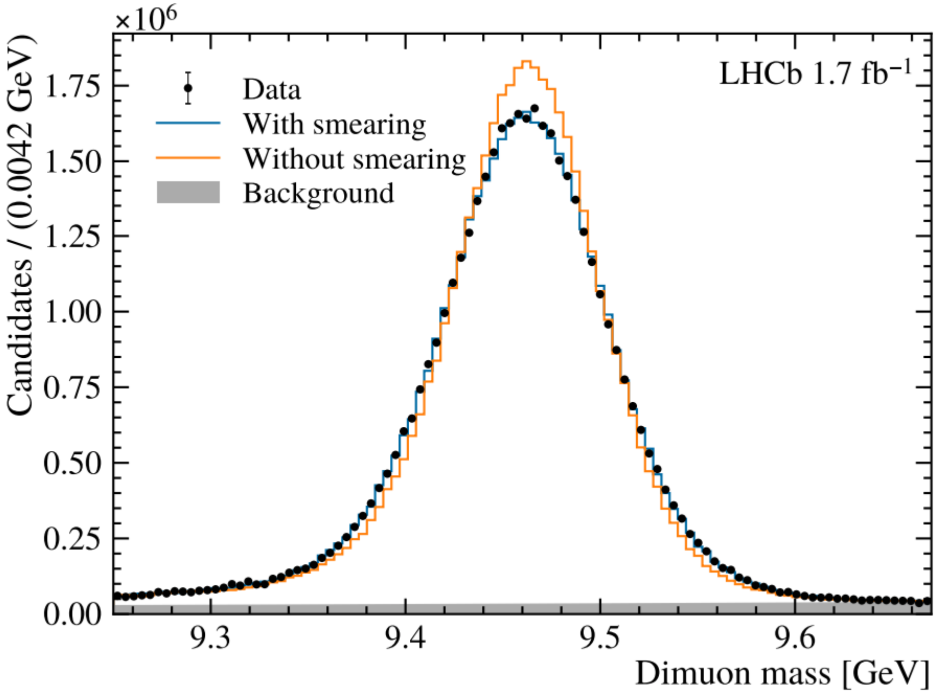
Momentum calibration

- To a good approximation:

$$p \to (1 + \alpha + \beta/p - q\delta p)p$$

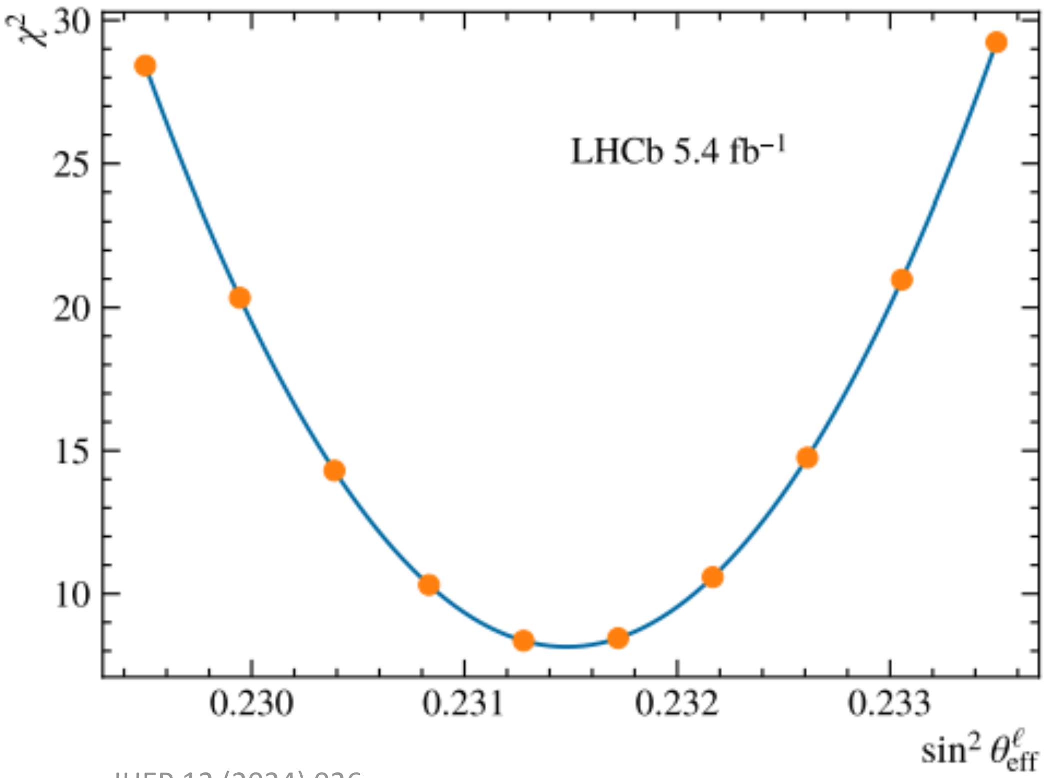
  - α: a momentum-scale offset caused by a miscalibration of the bending power of the magnet and/or the tracker length scale
  - β: a possible inaccuracy in the ionization-energy-loss corrections
  - δ is a q/p bias due to a misalignment of the tracking detectors
- α and β are performed with $\Upsilon \to \mu^+\mu^-$ sample
- The momentum bias model captures the overall trend well
- The $\Upsilon \to \mu^+\mu^-$ mass distribution shows a good agreement between

data and simulation after calibration



Extraction of $\sin^2\theta_{\text{eff}}^{\text{lept}}$

- A_{FB} templates are generated with Powheg-Box in different configurations
- Compare the measured A_{FB} with each A_{FB}template, get a χ^2 value quantifying how well data and the prediction at a given $\sin^2\theta_{\text{eff}}^{\text{lept}}$ value agree
- Fit a second order polynomial to χ^2distribution, the minimum of the parabola is the value of $\sin^2\theta_{\text{eff}}^{\text{lept}}$ favored by data



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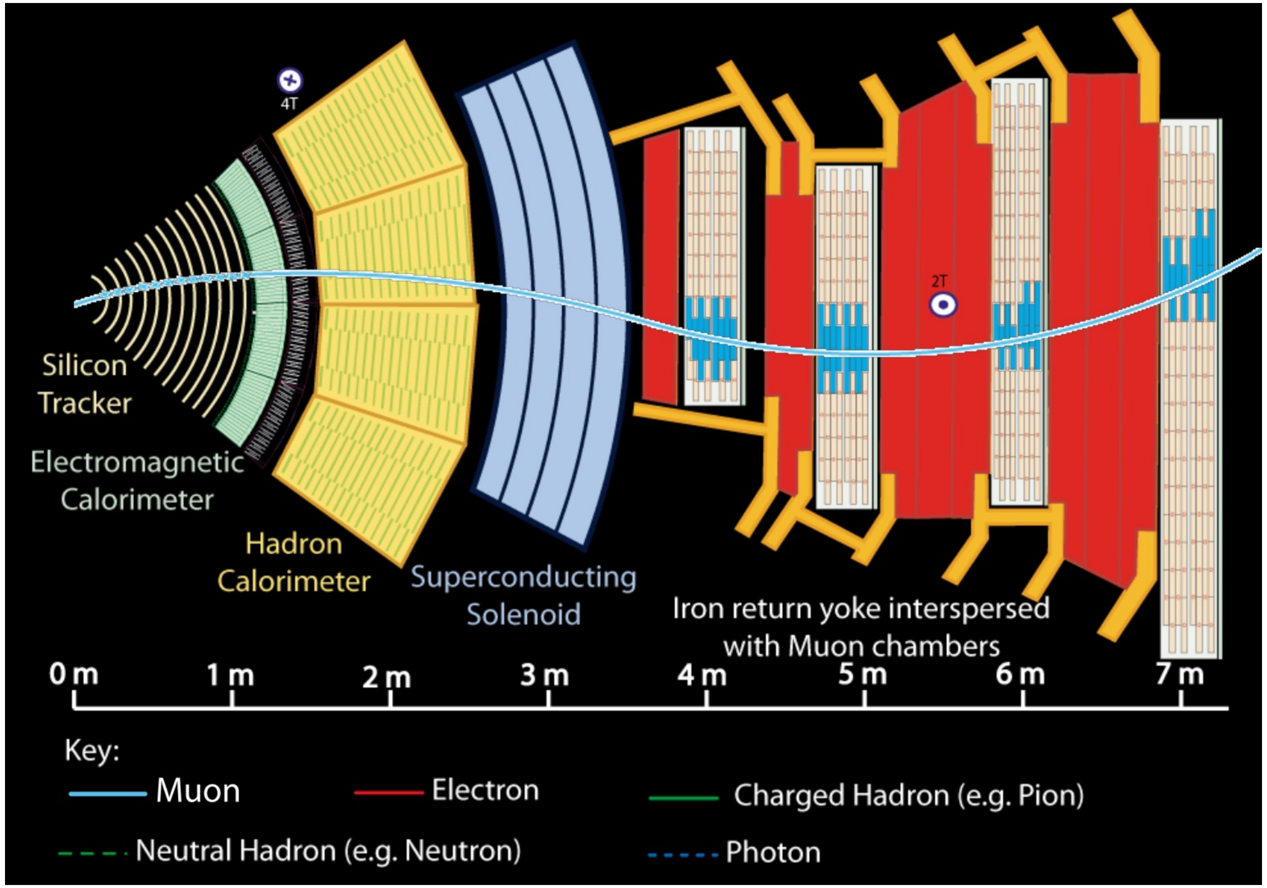
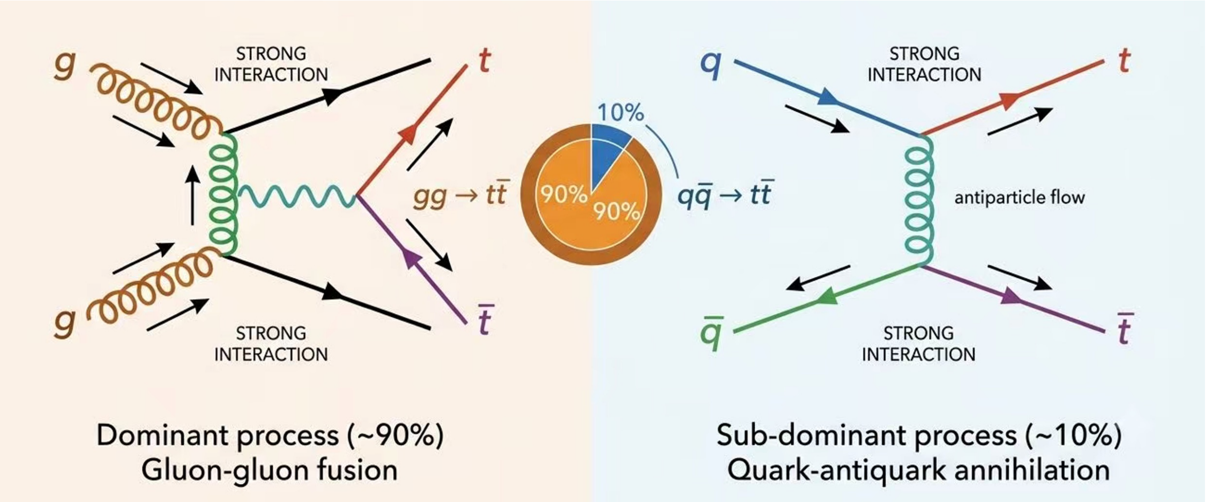
CMS tracking system



Top quark physics

- The top quark is the most massive known elementary particle, $m_t \sim 173$ GeV

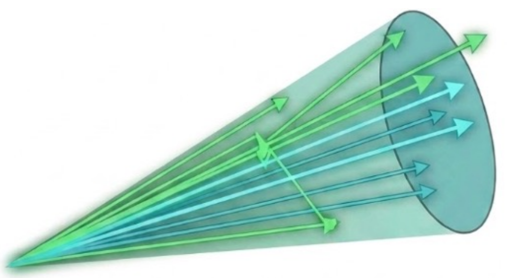
- Large Yukawa coupling to the Higgs boson: λ_t~1
  - plays a key role in electroweak symmetry breaking
  - potential key to finding new (pseudo)scalars



- Short lifetime~$10^{-25}s$: only quark that decays before hadronization
  - preserves spin correlations in decay product, spin and polarization information propagated to decay products
  - bound states are not formed, unique opportunity to study a "bare" quark

Jet reconstruction

- Clustered with the anti-k_{T} algorithm (implemented in FastJet) using a distance parameter $R = 0.5$
  - information from all the detector subsystems is used to create charged and neutral particle input to the jet-clustering algorithm using the particle flow approach

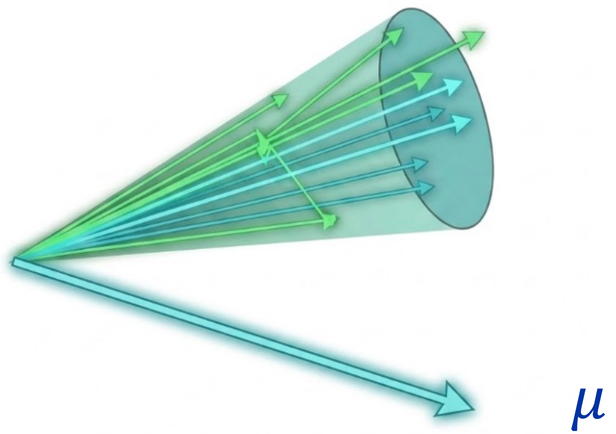


$p_{\mathrm{T,jet}} > 50\mathrm{GeV}$

$4.0 > \eta_{\mathrm{jet}} > 2.2$

Jet and μ combination

- The muon and jet must be separated by $\Delta R(\mu, j) > 0.5$, $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$
  - $\Delta\eta(\Delta\phi)$ is the difference in pseudorapidity (azimuthal angle) between the muon and jet momenta
- $p_{\mathrm{T}}(\mu + j) > 20$ GeV

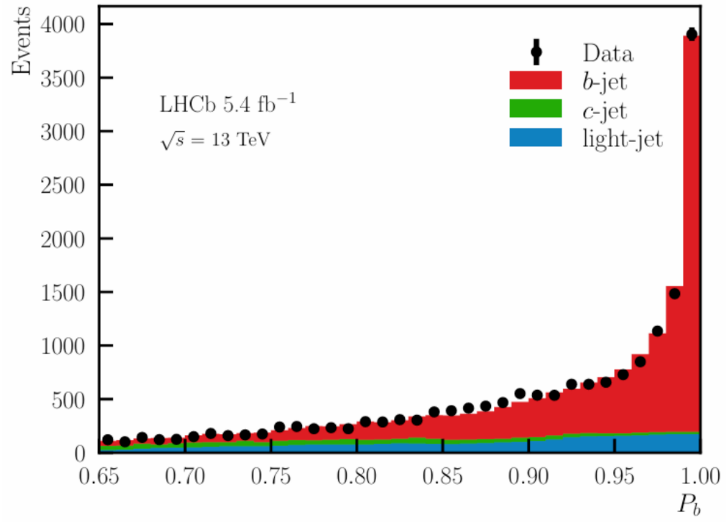


b-jet tagging

- Requirements on the DNN outputs are determined by having the maximize $S = \frac{\mathrm{N(signal\ MC\ events)}}{\mathrm{N(data\ events\ in\ the\ singal\ region)}}$
- Cut point: $P_b > 0.65$ and $P_q < 0.05$
- Flavor composition after selection is evaluated via a template fit to the P_b distribution, with floated the fraction of b and c components

b-tagging efficiency	~56%
b fraction	~74%

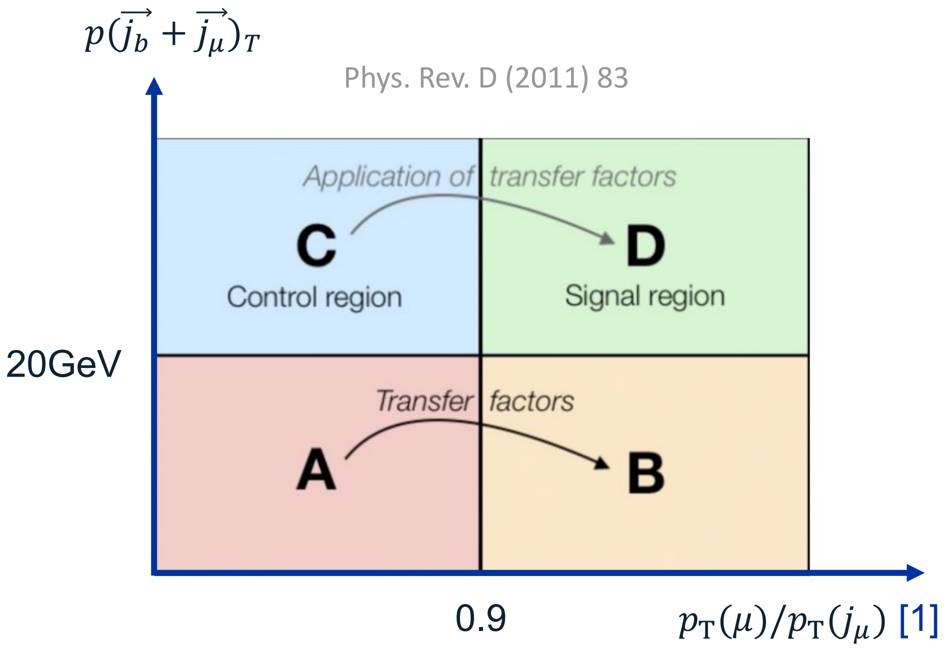
arXiv: 2601.16802, accepted by JHEP



Background - QCD

- High energy muons from non-EW processes
  - decay of heavy-flavour quarks
  - in-flight decay of hadrons

- N_{QCD} in signal region can be estimated by ACBD method
  - partition the phase space into four regions by two independent variables
  - $N_D = N_C \times (N_B/N_A)$



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[1] Muon jet (j_μ): the high- p_{T} muon candidate is not removed from the anti-k_{T} inputs, so is clustered into a jet

Background - Electroweak

- Direct $W + b$-jet production

$$N_{Wb}^{\text{estimate}} = N_{(W\to\mu)+\text{jet}}^{\text{data}} \times \left(\frac{\sigma_{W+b\text{-jet}}^{\text{NLO}}}{\sigma_{W+\text{jet}}^{\text{NLO}}}\right)_{\text{theory}} \times \epsilon_{b\text{-tagging}}$$

- $Z + b$-jet with one muon is undetected in $Z \to \mu\mu$
  - Events with a second, oppositely charged, high-p_{T} muon candidate from the same pp collision are vetoed
  - The remaining contribution is estimated using $Z \to \mu + b$-jet data

$$N_{Zb}^{\text{estimate}} = N_{(Z\to\mu)+b\text{-jet}}^{\text{data}} \times \frac{N_{\text{signal}}^{\text{sim}}}{N_{(Z\to\mu)+b\text{-jet}}^{\text{sim}}}$$

- Di-boson backgrounds (WW, WZ and VH) are checked and found to be negligible

Background subtraction and corrections

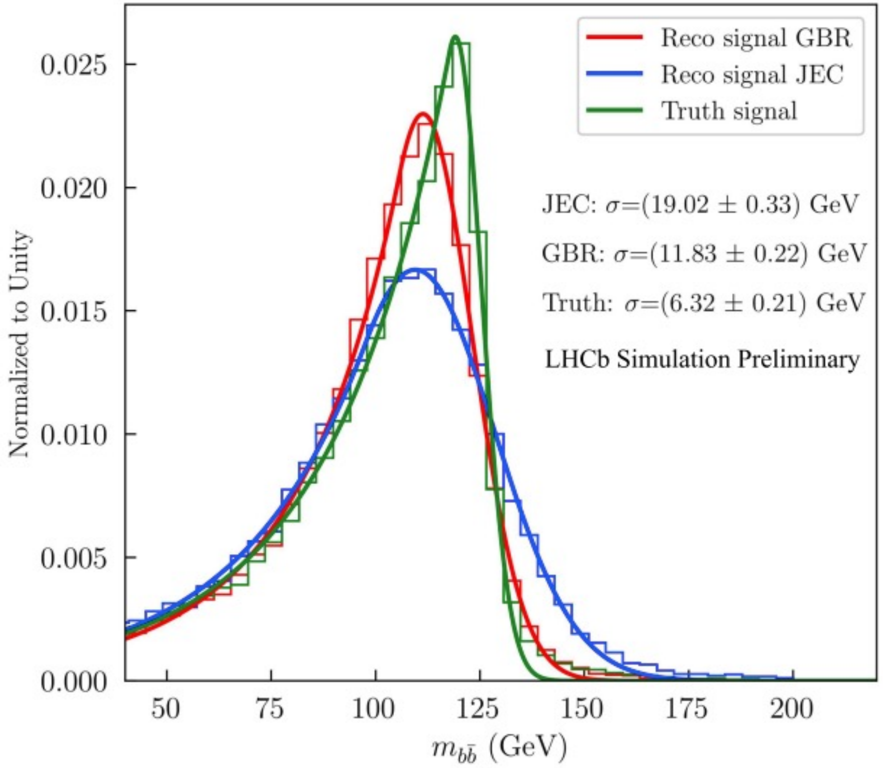
$$\frac{d\sigma_{\text{top}}^{\text{fiducial}}}{d\eta_\mu} = \frac{(N - N^{\text{bkg}}) \cdot \mathcal{A} \cdot P}{\Delta\eta_\mu \cdot \mathcal{L} \cdot \varepsilon_{\text{sel}} \cdot \varepsilon_{\text{rec}} \cdot \varepsilon_{\text{btag}} \cdot \epsilon_{\text{true}}}$$

- Detector-resolution effects (below 1%)
  - P: jet reconstruction purity = $\frac{N_{\text{jets}}^{\text{truth \& rec}} \in \text{fiducial}}{N_{\text{jets}}^{\text{rec}} \in \text{fiducial}}$
  - $\varepsilon_{\text{true}}$: the truth-level jet reconstruction efficiency = $\frac{N_{\text{jets}}^{\text{truth \& rec}} \in \text{fiducial}}{N_{\text{jets}}^{\text{truth}} \in \text{fiducial}}$

- $\mathcal{A}$: acceptance factor
  - account for migrations into and out of the fiducial region
  - including non-negligible contributions from $t \to W^+(\to \tau^+ \upsilon_\tau)b$-jet

Jet energy correction

LHCb-FIGURE-2023-029



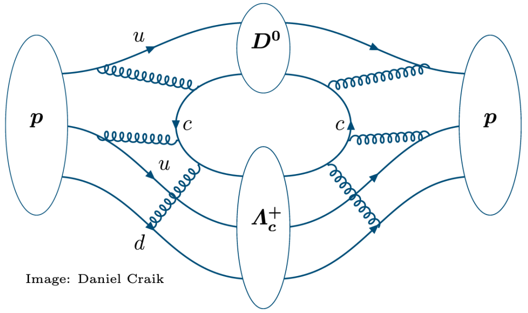
- The Jet energy correction ($k = \frac{E(\text{jet}_{\text{truth}})}{E(\text{jet}_{\text{reco}})}$) → Gradient Boosting Regressor (GBR)
  - input: 51 observables from the jet kinematic and substructure

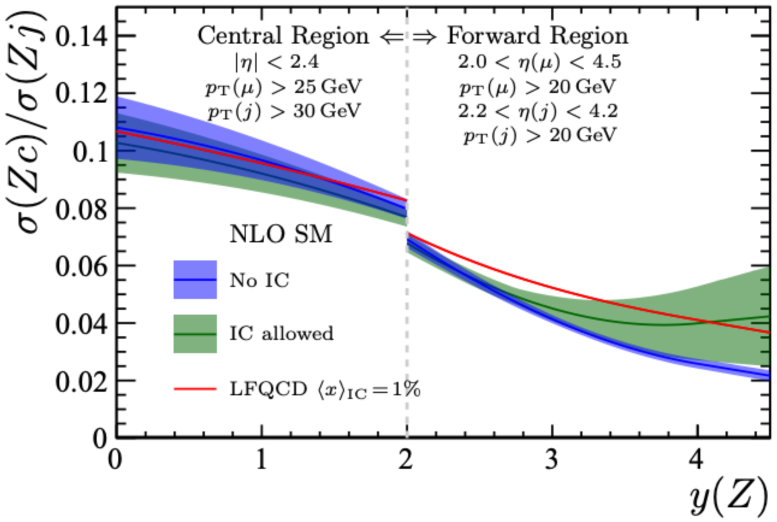
- The GBR method significantly narrows the reconstructed mass distribution, bringing it closer to the generator-level distribution

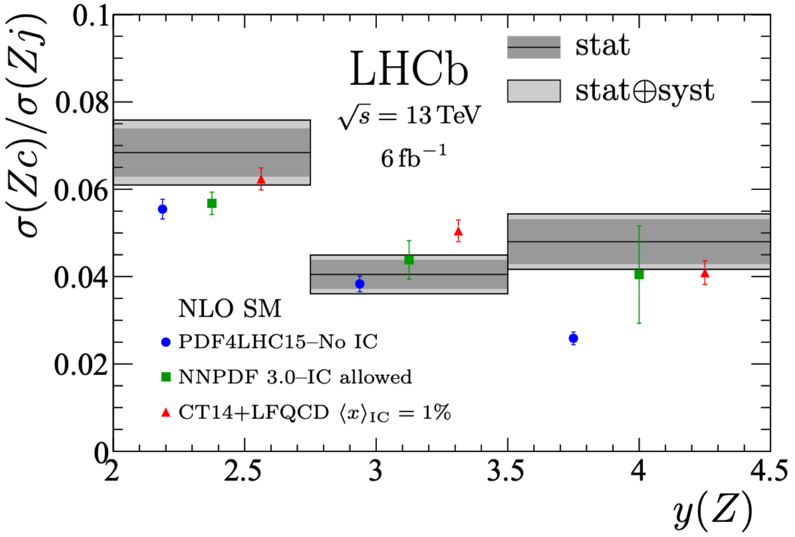
Prospect – Proton Structure

$|\mathbf{proton}\rangle = |uud\rangle + \epsilon|uudc\bar{c}\rangle$?
$\epsilon \lesssim \mathcal{O}(\%)$

- Most PDF fits assume heavy quarks in the proton are generated perturbatively, but non-perturbative "intrinsic" heavy quarks are also possible
- Run 2 dataset see clear enhancement in highest y bin, inconsistent with No-IC theory at $> 3\sigma$, strongly constrain the large-x charm PDF







Phys. Rev. Lett. 128 (2022) 082001

- With advanced jet tagging algorithm and higher statistics
  - intrinsic charm
  - intrinsic strange?