QCD, electroweak physics, and searches for exotic signatures in the forward region at LHCb

Carlos Vázquez Sierra (USC/IGFAE)

on behalf of the LHCb Collaboration

26th March, 2023

57th Rencontres de Moriond QCD

LHCb

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UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

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IJMP A30 (2015) 1530022

LHCb is a 20×5 m GPD in the forward region.

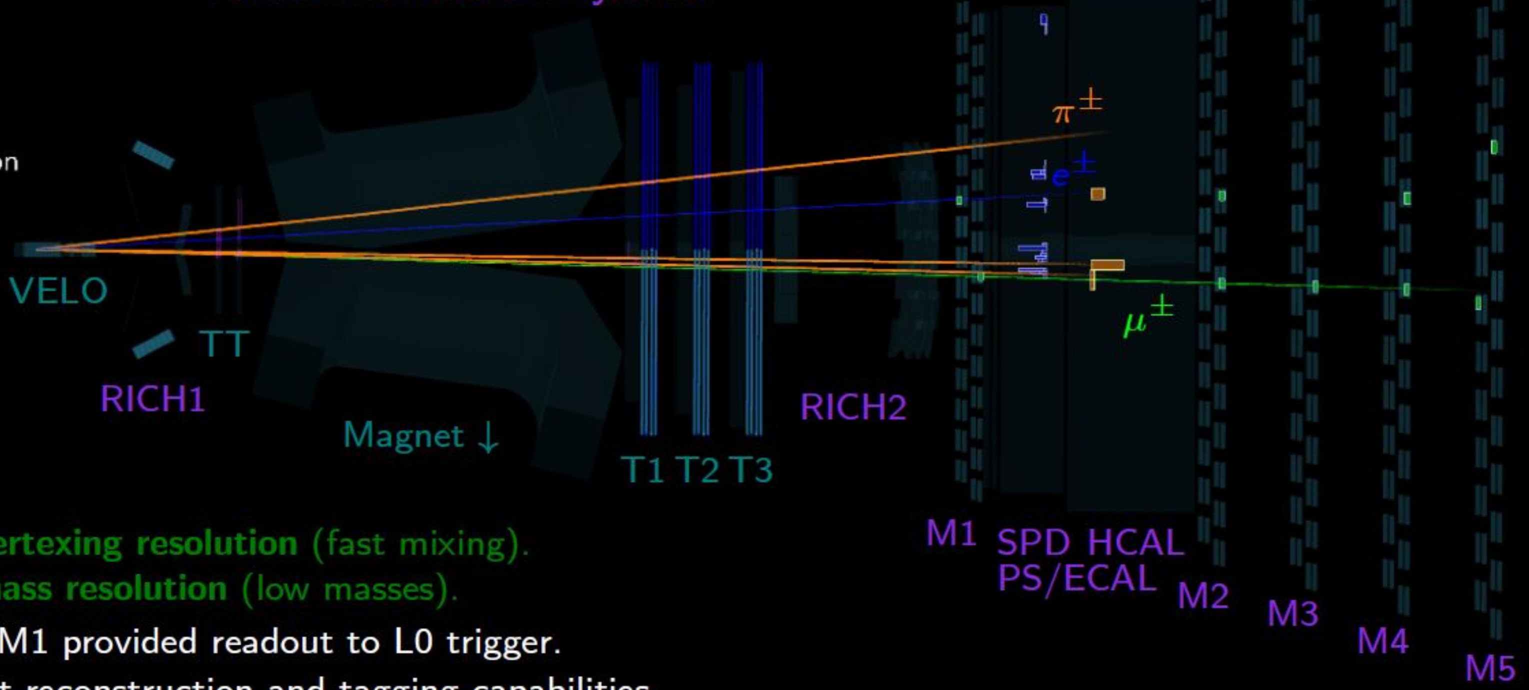
Single-arm **forward** spectrometer ($2 < \eta < 5$) along the beamline (z).

Tracking and vertexing systems

Particle identification systems

Side view

Event 216853
Run 4052454
LHCb Simulation



Excellent **vertexing resolution** (fast mixing).

Excellent **mass resolution** (low masses).

HCAL and M1 provided readout to L0 trigger.

Excellent jet reconstruction and tagging capabilities.

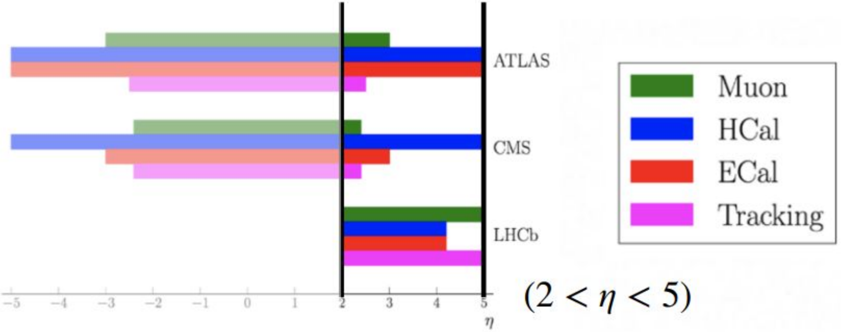
IJMP A30 (2015) 1530022

High pT physics at LHCb

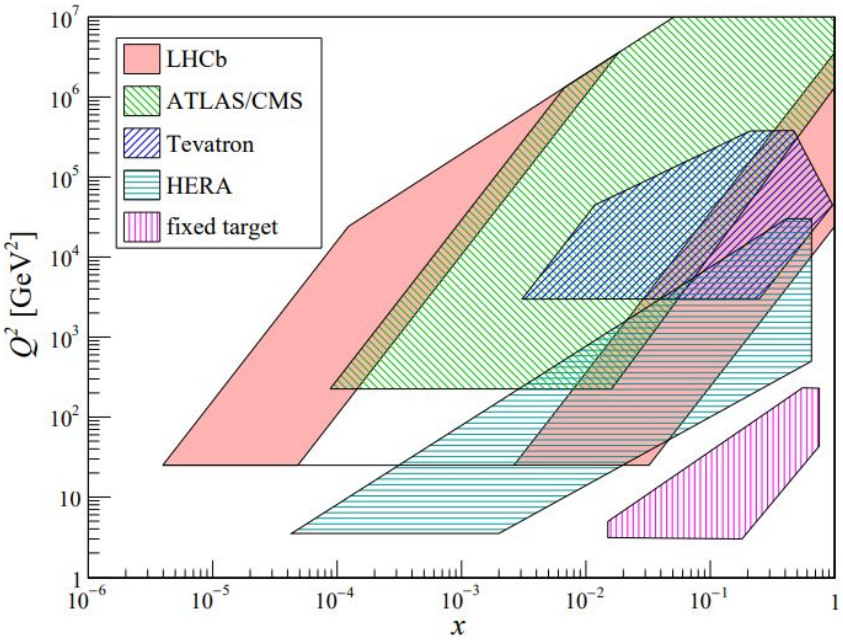
"From a heavy flavor physics experiment to a general purpose detector"

Forward acceptance (2<η<5) access **low** and **high** Bjorken-x values:

Test proton structure in regions complementary to other detectors



Phys. Rev. D 93, 074008 (2016)



Electroweak and QCD measurements

- **Forward Z boson production:** JHEP 07 (2022) 026
  - Precision tests in NNLO pQCD similar to experimental results,
  - High (up to ~0.8) and low (~ 5 x 10^{-5}) Bjorken-x regions have limited information,
  - LHCb can provide complementary information here, **especially for u/d PDFs at high x.**
- **Measurement of Z angular coefficients:** Phys. Rev. Lett. 129 (2022) 091801
  - Measure the angular coefficients of the final state muons in Drell-Yan production,
  - Access the **polarization of the intermediate gauge boson** to study underlying QCD.
- **Charged hadron distributions in Z-tagged jets:** arXiv:2208.11691
  - **First measurement** of jet fragmentation functions (JFFs) for **identified charged hadrons** produced in association with a Z boson in the forward region.
- **Z production in association with charm:** Phys. Rev. Lett. 128 (2022) 082001
  - Proton wave function may contain an intrinsic charm (IC) component,
  - Presence of IC would alter the rate and kinematics of c-hadrons (x-sections, astrophysics),
  - **IC can be measured in Z+c events in the forward region.**

JHEP 07 (2022) 026

Forward Z boson production

Measure production Z cross-section at LHCb → **sensitive to PDFs in low/high x.**
Integrated and **differential** (function of $\mathbf{y^Z}$, $\mathbf{p_T^Z}$, ϕ^*_η) cross-sections are measured:

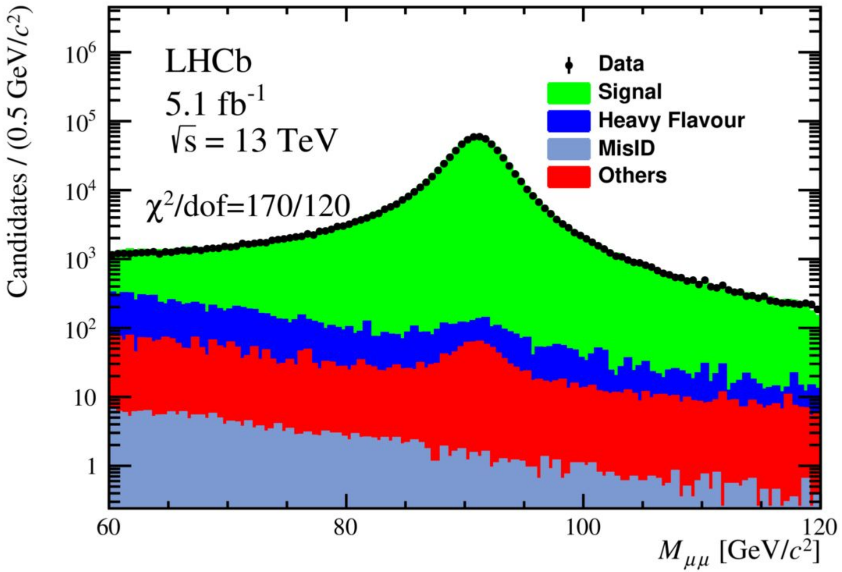
$$\phi^*_\eta = \tan((\pi - \Delta\phi^{\ell\ell})/2)\sin(\theta^*_\eta)$$

Difference in the azimuthal angle between the two muons

$$\cos(\theta^*_\eta) = \tanh[(\eta^- - \eta^+)/2]$$

Fiducial region (LHCb acceptance)		
μ	$2 < \eta < 4.5$	$p_T > 20$ GeV
μμ	$60 < m < 120$ GeV	

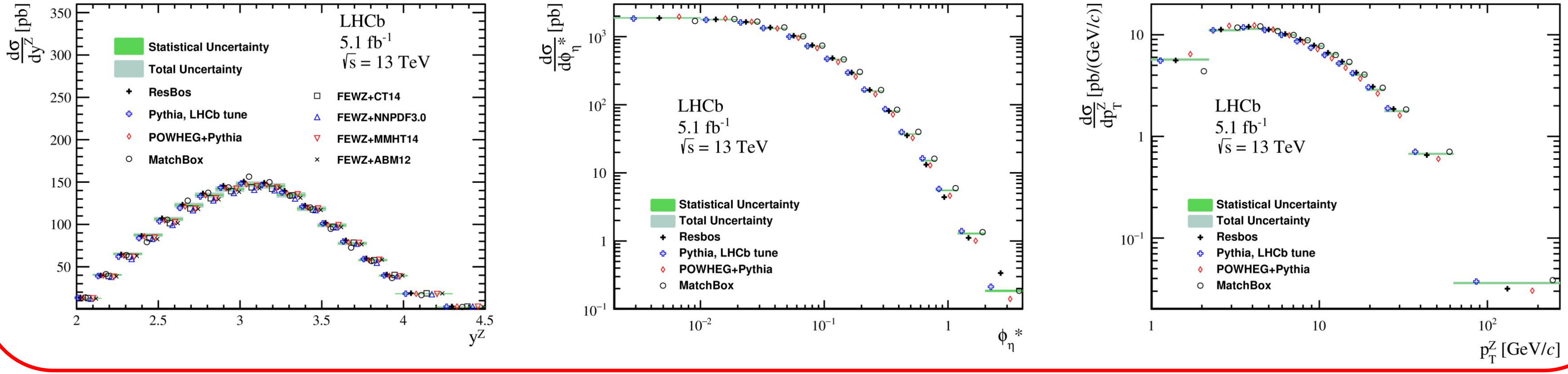
Total background ~ 1.5%



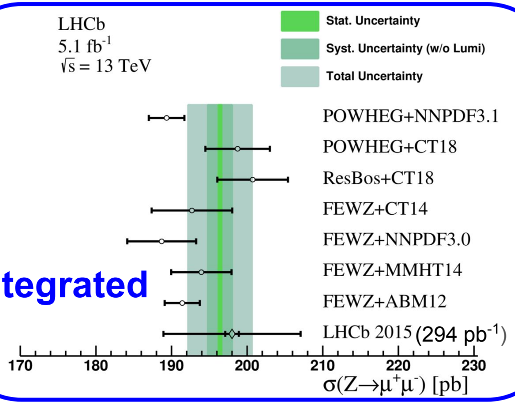
JHEP 07 (2022) 026

Forward Z boson production

Differential (measured at Born level in QED)



Integrated



Most precise measurement in the forward region up to date!

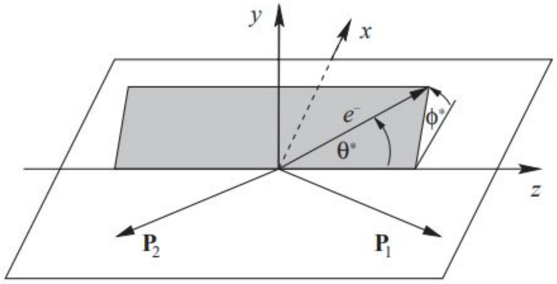
$$\sigma_{Z\to\mu^+\mu^-} = 196.4 \pm 0.2 \pm 1.6 \pm 3.9\,\mathrm{pb}$$

Systematics dominated by **efficiency corrections** (track reconstruction, PID and trigger) and **luminosity** determination.

Measurement of Z angular coefficients

Direct probe of the polarization of the intermediate gauge boson to test QCD
Measure the **polarization fractions** of final state leptons in pp → γ*/Z → μμ + X

$$\frac{d\sigma}{d\cos\theta d\phi} \propto \underbrace{(1+\cos^2\theta)}_{\text{LO}} + \underbrace{\frac{1}{2}A_0(1-3\cos^2\theta)}_{\text{NLO}} + \underbrace{A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi}_{\text{NLO (polar and azimuthal μ angle)}}$$
$$+ \underbrace{A_3 \sin\theta\cos\phi}_{\text{NLO (polar and azimuthal μ angle)}} + \underbrace{A_4 \cos\theta}_{\text{LO } (A_{FB})} + \underbrace{A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi}_{\text{NNLO (very small contributions)}}$$

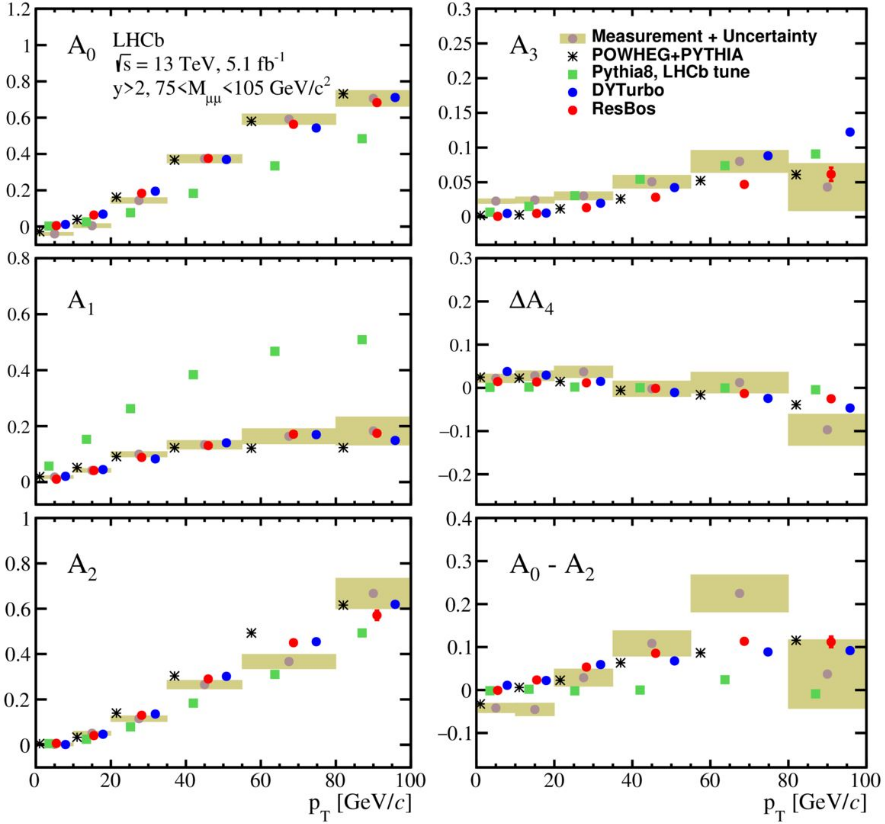


Phys.Rev.D84:012007,2011

1) Measure $A_{0\text{-}3}$ and ΔA_4 as a function of p_T^Z and y^Z for 75 < m(μμ) < 105 GeV,
2) Test the Lam-Tung relation ($A_0 = A_2$) → violation already previously observed,
3) Probe the TMD Boer-Mulders PDF in low (50-75 GeV) and high (105-120 GeV) m(μμ).

Phys. Rev. Lett. 129 (2022) 091801

Measurement of Z angular coefficients



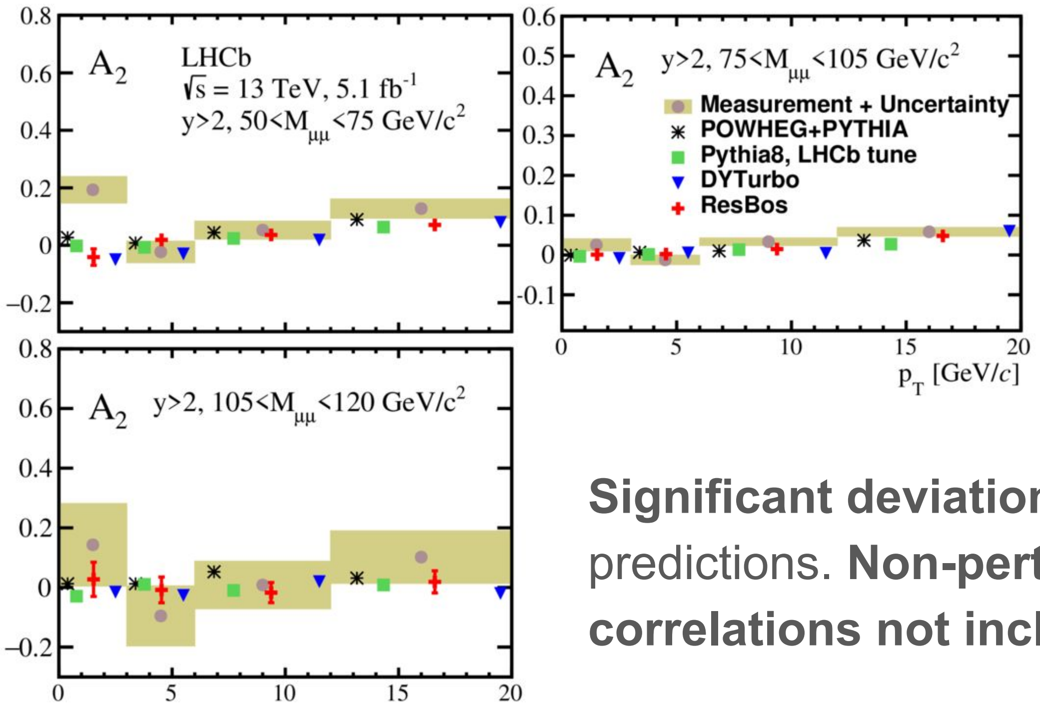
Small high p_T (>50 GeV) data sample allows to fix $A_{5\text{-}7}$ to zero.

Similar dataset to the Z x-section measurement but with **much lower background contamination** (0.2%). **Analysis statistically dominated.**

Agreement with most of the predictions (exc. Pythia8).

Lam-Tung violation present as well, in agreement with ATLAS and CMS.

Measurement of Z angular coefficients



Multiple mass regions studied (dominated by γ* and interference with Z), sensitive to the evolution of TMD Boer-Mulders PDF with the hard scale.

Significant deviations in the lowest pT region from all predictions. **Non-perturbative spin-momentum correlations not included in any of the predictions.**

Charged hadron distributions in Z-tagged jets

First measurement of jet fragmentation functions (JFFs) for **identified charged hadrons** produced in association with a Z boson in the forward region.

Z+j production in LHCb **dominated** by qg → Zq, providing **sensitivity** to quark TMD FFs.

JFFs measured in Z-tagged j as a function of **z** and $\mathbf{j_T}$

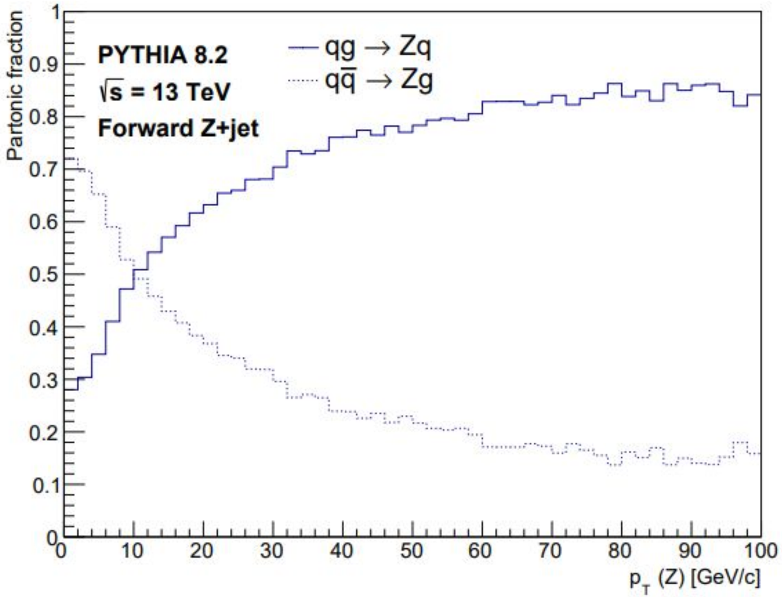
$$j_T = \frac{|\mathbf{p}_{\text{had}} \times \mathbf{p}_{\text{jet}}|}{|\mathbf{p}_{\text{jet}}|}$$

$$z = \frac{\mathbf{p}_{\text{had}} \cdot \mathbf{p}_{\text{jet}}}{|\mathbf{p}_{\text{jet}}|^2}$$

$$F(z) = \frac{1}{N_{Z+\text{jet}}} \frac{\mathrm{d}N_{\text{had}}(z)}{\mathrm{d}z}$$

$$F(j_T) = \frac{1}{N_{Z+\text{jet}}} \frac{\mathrm{d}N_{\text{had}}(j_T)}{\mathrm{d}j_T}$$

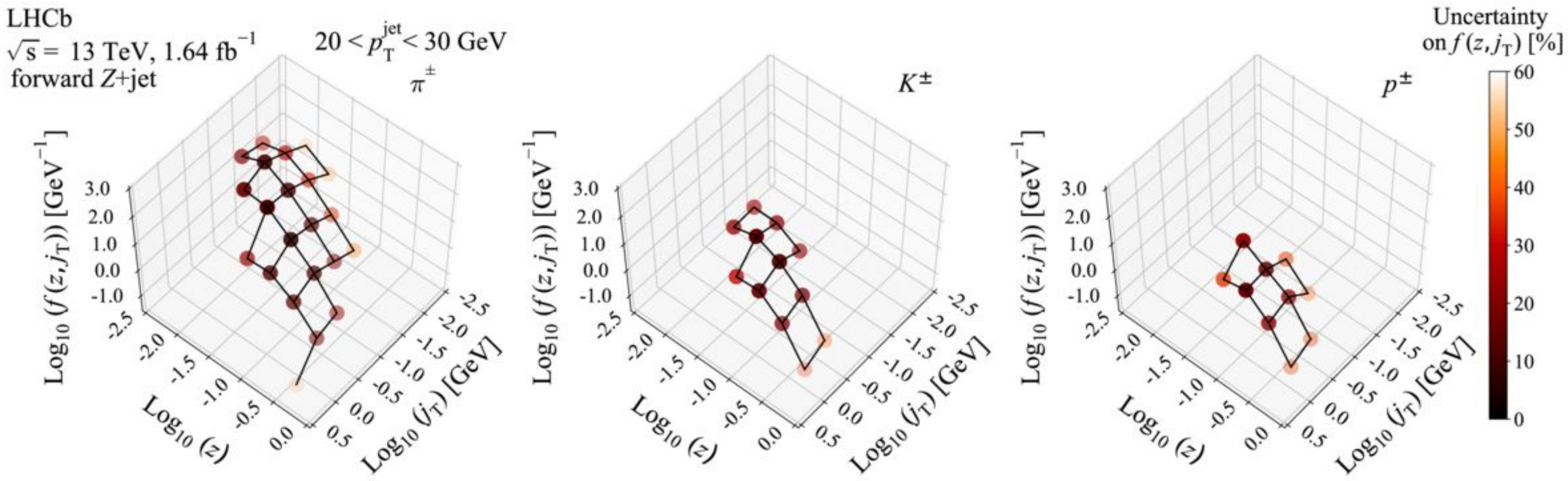
$$f(z, j_T) = \frac{1}{N_{Z+\text{jet}}} \frac{\mathrm{d}N_{\text{had}}(z, j_T)}{\mathrm{d}z\,\mathrm{d}j_T}$$



Charged hadron distributions in Z-tagged jets

PID efficiency ($h^{\pm}$) determined in intervals of p_T, η and track multiplicity.

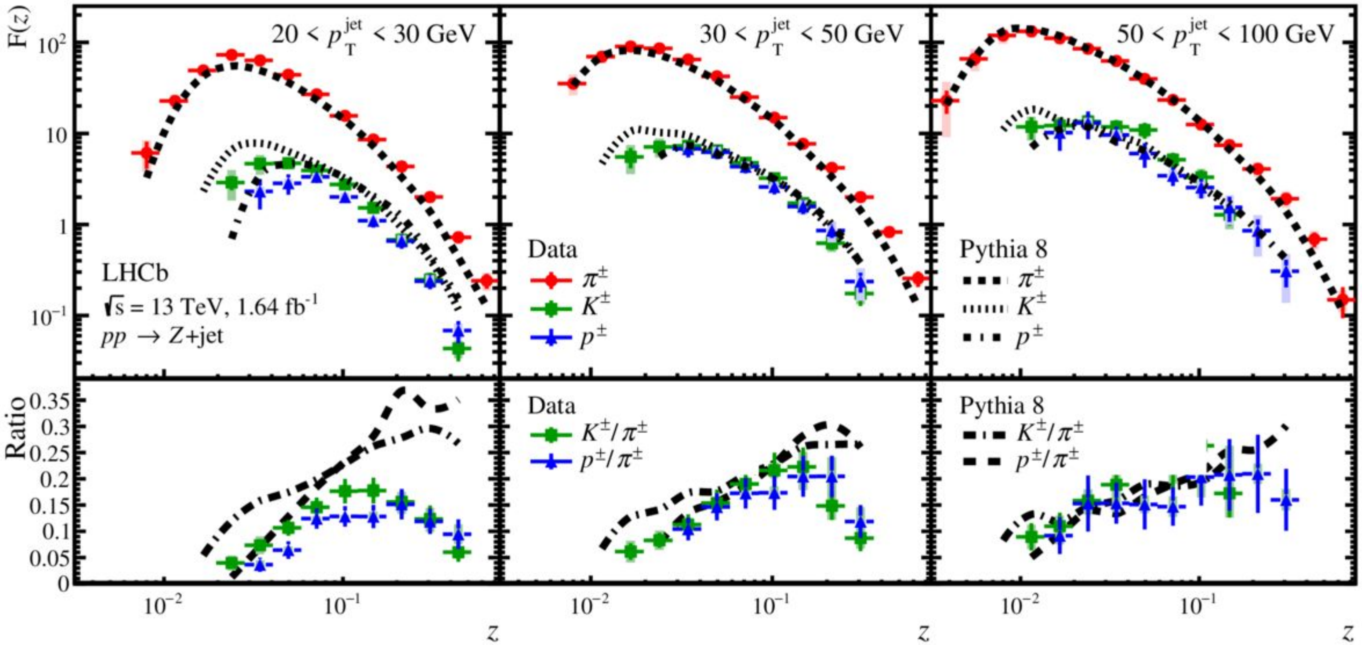
Impurity of the $h^{\pm}$ sample (mis-identified K, p and π) **less than 5%.**



arXiv:2208.11691, submitted to PRD

Charged hadron distributions in Z-tagged jets

Predictions generated with **Pythia 8.186 + CT09MCS PDF:**

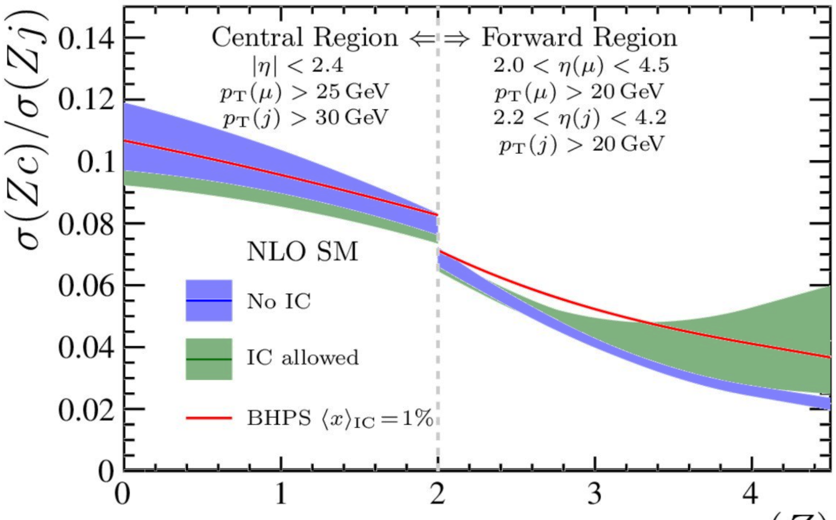


Data can be used to tune MC generators for production of identified $h^{\pm}$

Z boson production in association with charm

Probe IC by studying Z+c events in the forward pp region.

IC would produce an **enhancement** in the $\mathbf{R_j^c}$ **ratio** for **large y(Z) values**, in NLO:



Phys. Rev. D 93, 074008 (2016)

$$\mathcal{R}_j^c \equiv \sigma(Zc)/\sigma(Zj)$$

$\sigma(Zj)$ → **Z + any type of jet**

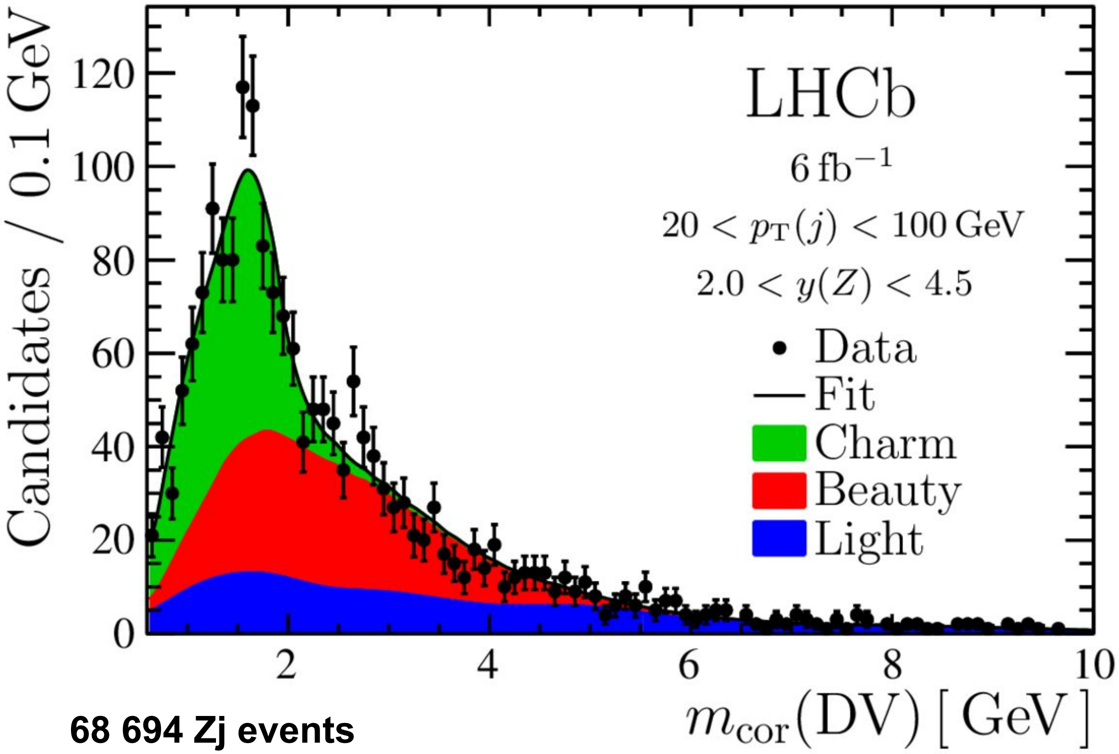
$\sigma(Zc)$ → **Z + c-jet**

Definition of the fiducial region

Z bosons	$p_T(\mu) > 20\,\text{GeV},\ 2.0 < \eta(\mu) < 4.5,\ 60 < m(\mu^+\mu^-) < 120\,\text{GeV}$
Jets	$20 < p_T(j) < 100\,\text{GeV},\ 2.2 < \eta(j) < 4.2$
Charm jets	$p_T(c\text{ hadron}) > 5\,\text{GeV},\ \Delta R(j, c\text{ hadron}) < 0.5$
Events	$\Delta R(\mu, j) > 0.5$

Phys. Rev. Lett. 128 (2022) 082001

Z boson production in association with charm



68 694 Zj events

Jet flavours separated with Displaced Vertex (DV) tagger (function of number of tracks and corrected mass).

Corrected mass → minimum mass the long-lived hadron can have consistent with the flight direction.

Systematic uncertainty dominated by **limited knowledge of c-tagging efficiency.**

Phys. Rev. Lett. 128 (2022) 082001

Z boson production in association with charm

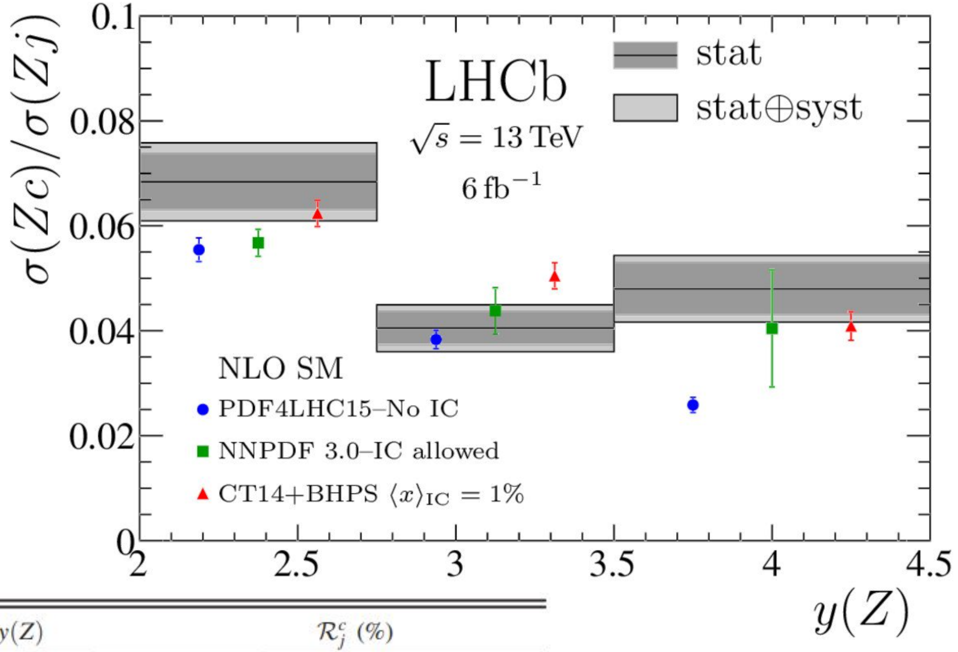
Sizable enhancement is observed in the forward-most y(Z) bin.

Ratio of observed to no-IC-expected values is 1.85 ± 0.25.

Evidence of IC with 3σ using LHCb data from NNPDF collaboration

Nature 608, 483–487 (2022)

(see Tommaso Giani's talk on Thu)



$y(Z)$	$\mathcal{R}_j^c$ (%)
2.00–2.75	$6.84 \pm 0.54 \pm 0.51$
2.75–3.50	$4.05 \pm 0.32 \pm 0.31$
3.50–4.50	$4.80 \pm 0.50 \pm 0.39$
2.00–4.50	$4.98 \pm 0.25 \pm 0.35$

Summary

LHCb has an extensive EW and QCD physics program, which can help to **study complementary Bjorken-x regions to other central experiments**, **tune MC generators**, and **constrain PDFs**.

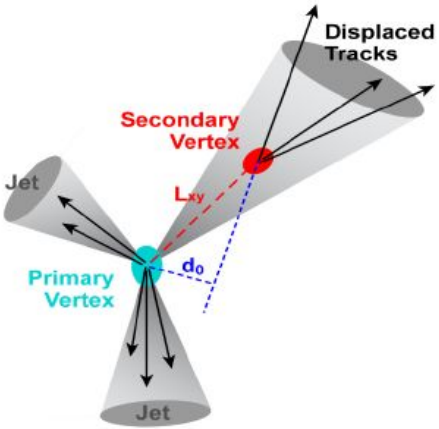
EW measurements with the full Run 2 datasets and complementary final states **in preparation.**

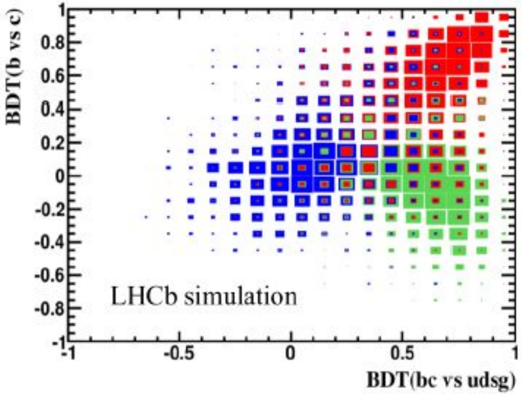
Searches for exotic signatures not covered in this talk → analyses still not complete but almost ready, **stay tuned for Summer conferences!**

Thanks for your attention

Backup

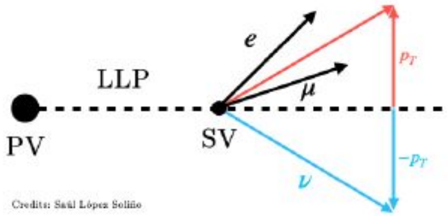
- Jet reconstruction: [JHEP (2014) 01 033]
    - Particle flow algorithm (including neutral recovery) → jet input.
    - Anti-k_T algorithm for clustering (R = 0.5) → efficiency > 95% for p_T > 20 GeV.
    - Jet energy scale calibrated on data (using $Z \to \mu\mu$ + jets),
    - Energy resolution from 10 to 15% for a p_T range between 10 and 100 GeV.
- Secondary Vertex (SV) identification and jet tagging: [JINST 10 (2015) P06013]
    - Reconstruct SV from displaced tracks → kinematic and quality requirements on both,
    - Train two Boosted Decision Trees (BDTs) for a two-step jet flavour tagging:
        - SV displacement from PV, kinematics, charge and multiplicity;
        - SV corrected mass, defined as $\mathrm{M_{corr}(SV)} = \sqrt{\mathrm{M^2 + p^2 sin^2\theta}} + \mathrm{psin\theta}$.
    - BDT(bc|udsg) to separate light and heavy flavour jets, BDT(b|c) to separate b from c-jets.
    - Tagging efficiency of b(c)-jets of 65% (25%) with 0.3% contamination from light jets.





Corrected mass approach:

- LHCb is a non-hermetic spectrometer → we **can not do invisibles.**
- However, we can compute a proxy to X+invisible invariant mass → **corrected mass**.
- **Required** to have only one **massless** invisible in the final state (ν).
- **Required** to know the **direction of flight** of the parent particle.



1. Assume LLP origin vertex approximately be the same as the *pp* collision.
2. Obtain a (pseudo) decay vertex using the di-lepton systems.
3. Project the di-lepton system momenta to the LLP direction of flight.

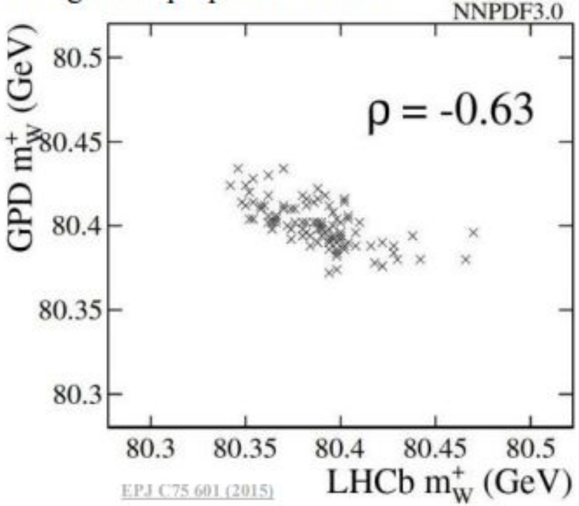
$$m_{\rm corr} = \sqrt{m(e\mu)^2 + p(e\mu)^2 \sin^2\theta} + p(e\mu)\sin\theta$$

Corrected mass as a good proxy to real mass → discriminating variable.

m_W Measurement

- m_W is directly related to electroweak symmetry breaking in the standard model

GPD: general purpose detector



$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F(1 - m_W^2/m_Z^2)(1 - \Delta r)}$$

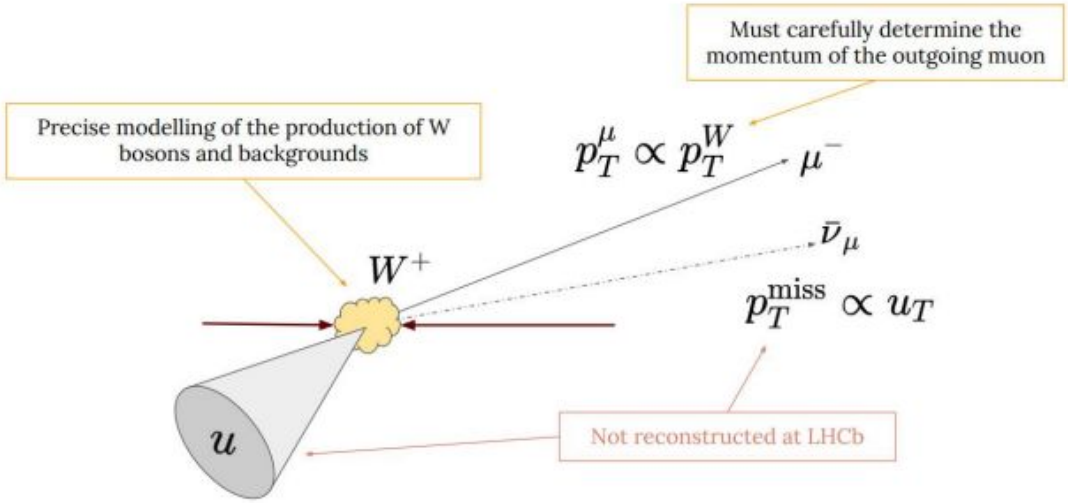
Δr: loop corrections

- Uncertainty from PDFs at LHCb is **anticorrelated** to that of ATLAS/CMS ⇒ LHC experiments can achieve a sensitivity closer to the global EW fit (~7 MeV)

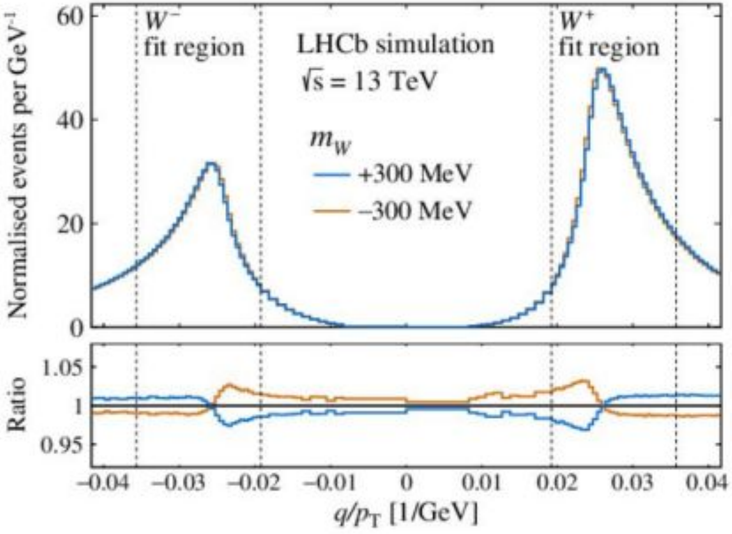
From Menglin Xu's talk at Moriond EW 2023

m_W: Physics & Detector Modelling

- Measurements based on charged lepton p_T
- m_W determination is highly sensitive to misalignments and miscalibrations of the detector



JHEP 01 (2022) 036

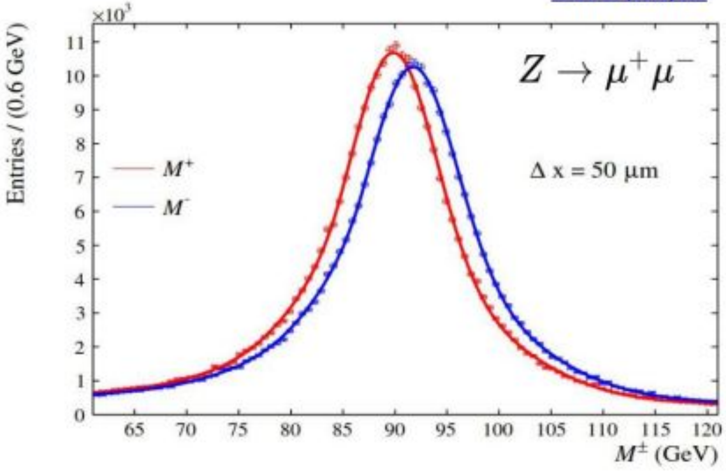


From Menglin Xu's talk at Moriond EW 2023

m_W at LHCb

- p_T^μ peaks at $\sim m_W/2$, extract m_W in a template fit to the q/p_T^μ distribution

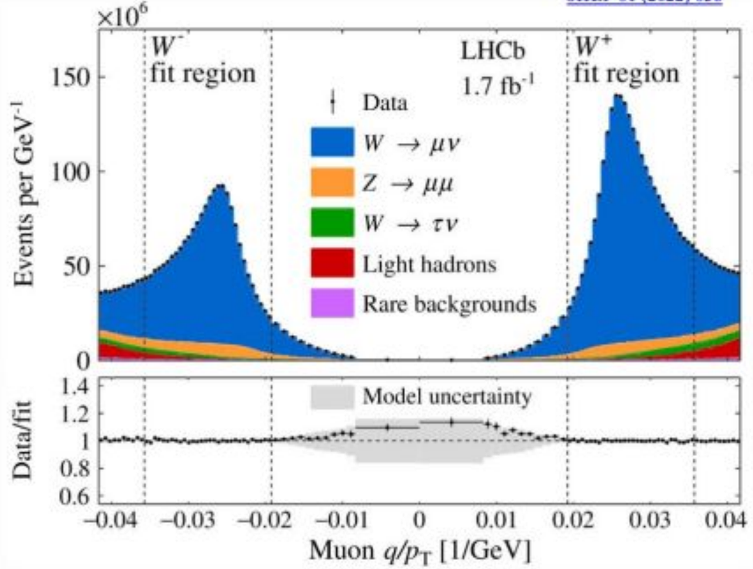
JHEP 01 (2022) 036



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

Phys. Rev. D 91, 072002

JHEP 01 (2022) 036



From Menglin Xu's talk at Moriond EW 2023

m_W: Uncertainties

JHEP 01 (2022) 036

Source	Size (MeV)
Parton distribution functions	**9**
Total theoretical syst. uncertainty (excluding PDFs)	**17**
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Total experimental syst. uncertainty	**10**
Momentum scale and resolution modelling	7
Muon ID, tracking and trigger efficiencies	6
Isolation efficiency	4
QCD background	2
Statistical	**23**
Total uncertainty	**32**

→ average of NNPDF31, CT18 and MSHT20

→ from five different models

→ scale variation

→ envelope of the QED FSR from PYTHIA8 Photos and Herweig

→ statistical uncertainties, details of method (e.g. binning, smoothing)

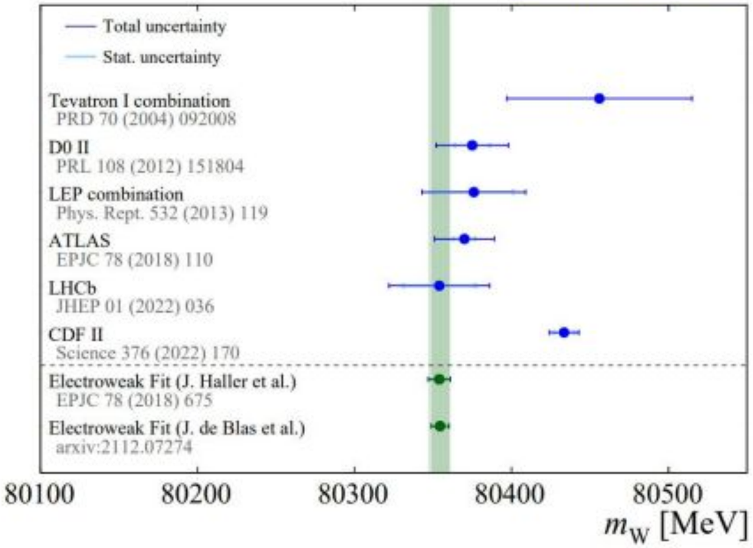
From Menglin Xu's talk at Moriond EW 2023

m_W: Result

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

- LHCb achieves a precision of ~ 32 MeV using roughly 1/3 of the Run-II dataset
- Further ~4 fb^{-1} of Run-II data to add → statistical uncertainties ≈ 14 MeV
- Effort now on improving the modelling and reducing the systematic uncertainties
- An overall precision ~ **20** MeV is achievable with all existing LHCb data

LHCB-FIGURE-2022-003



From Menglin Xu's talk at Moriond EW 2023