Probing proton structure at LHCb

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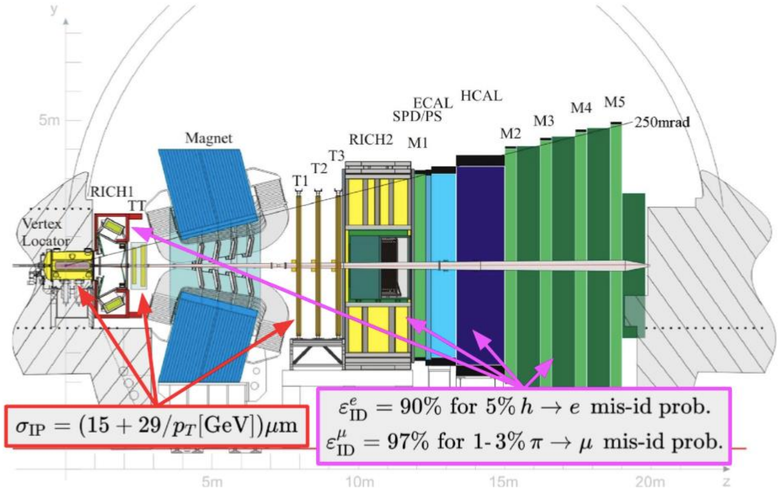
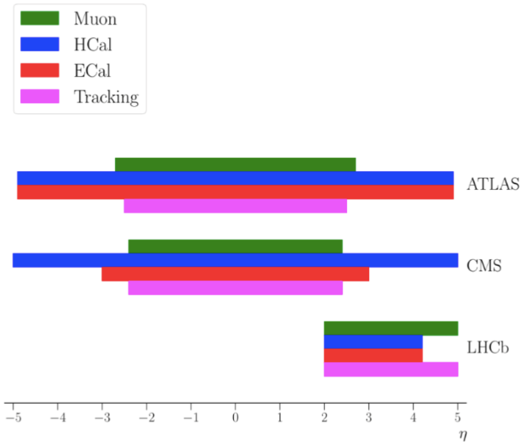
On behalf of the LHCb collaboration
DIS 2022

LHCb detector

[JIST 3 (2008) S08005]
[Int. J. Mod. Phys. A 30. 1530022 (2015)]

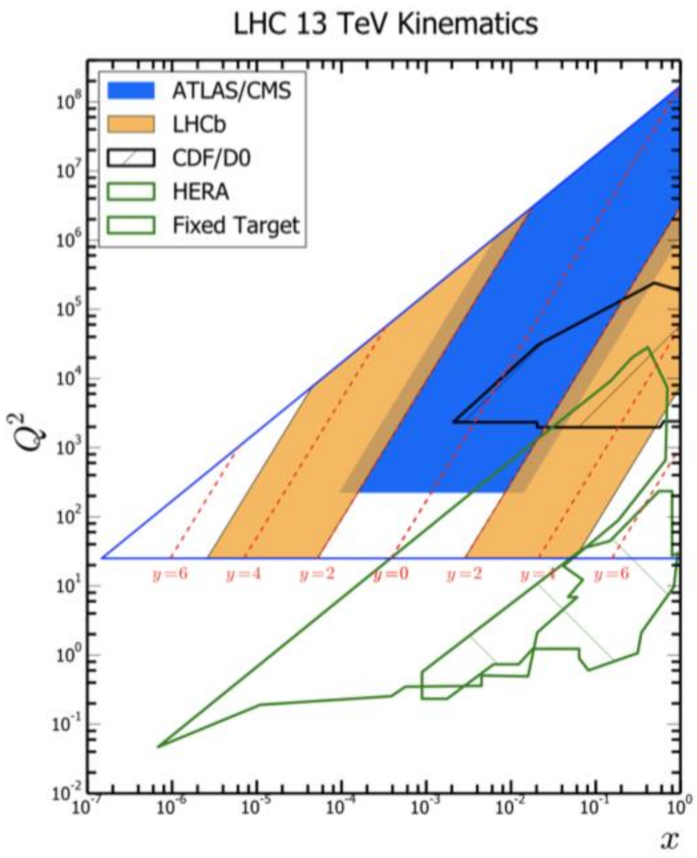
- Single-arm **forward** spectrometer
  - Designed for the heavy flavor physics with $2 < \eta < 5$
  - Coverage is complementary to ATLAS and CMS
  - **Extended to EW measurements**: excellent performance of tracking and muon detector





EW physics at LHCb

- LHCb has already delivered a strong program of physics with W and Z boson mainly probing QCD
- As a result of the forward acceptance, LHCb is ideally placed to study decays of highly boosted Z bosons, provides access to PDFs
  - **High Bjorken-x region**
  - **Low Bjorken-x region**: has not been probed directly at electroweak energy scales before



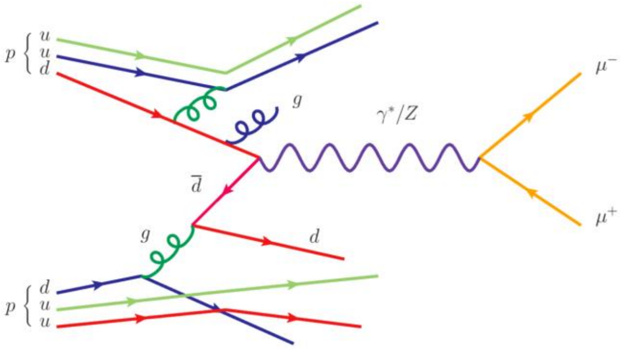
Z production cross-section measurement

- Z boson production at LHC provide insights into the PDFs of the proton and test SM
- Measurements at LHCb are particularly important for constraining **u-, d-quark PDFs at high x region**
- Using LHCb 2016, 2017 and 2018 data: $5.1 \pm 0.1\ \mathrm{fb}^{-1}$
- **Very high purity**, $N_{\mathrm{bkg}}/\ N_{\mathrm{sig}}$ ~2%

$$\frac{d\sigma_{Z\to\mu^+\mu^-}}{dy}(i) = \frac{N_Z(i)\cdot f^Z_{FSR}(i)}{\mathcal{L}\cdot\varepsilon^Z_{REC}(i)\cdot\Delta y(i)}$$

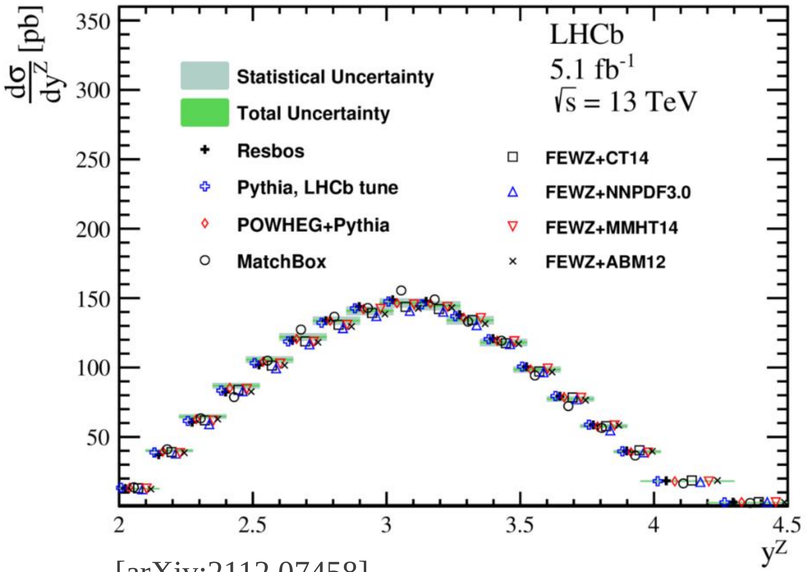
fiducial region

$\mu^{\pm}$	di-muon
$p_{\mathrm{T}} > 20\ \mathrm{GeV}/c$	
$2 < \eta < 4.5$	$60 < M_{\mu^+\mu^-} < 120\ \mathrm{GeV}/c^2$

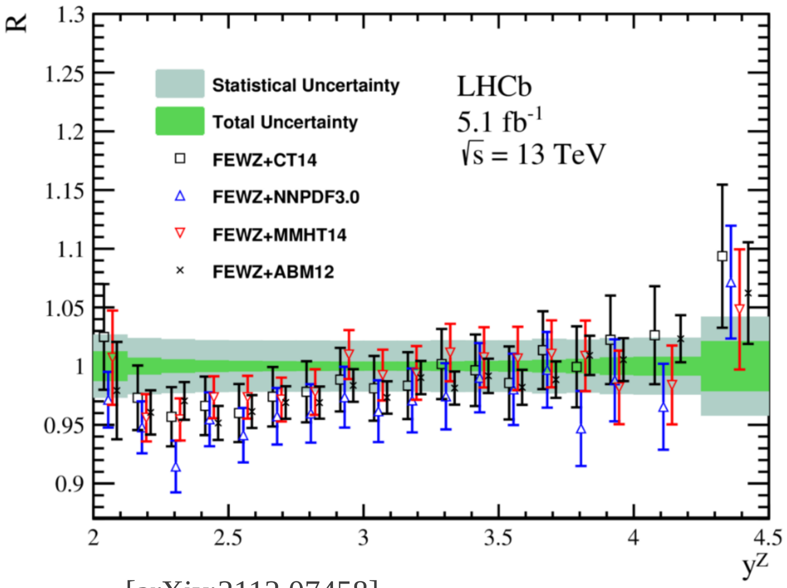


Z differential cross section: $y(Z)$

- Reasonable agreement between data and predictions, ratio(R)$\sim$1
- FEWZ predictions systematically smaller than the measured results in the lower $y(Z)$ region



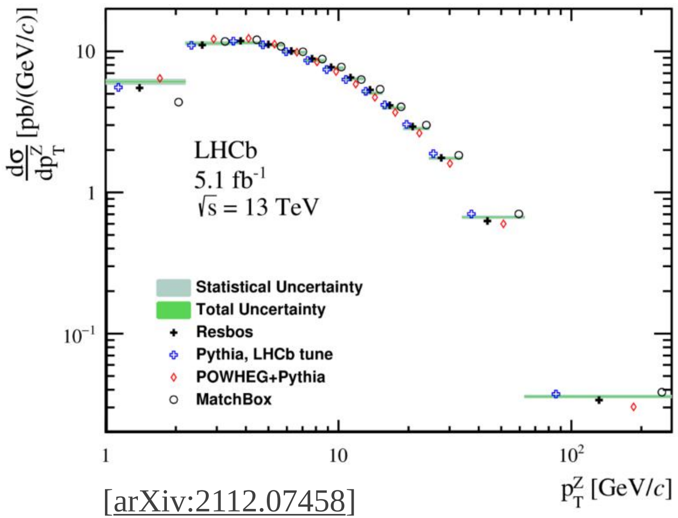
[arXiv:2112.07458]



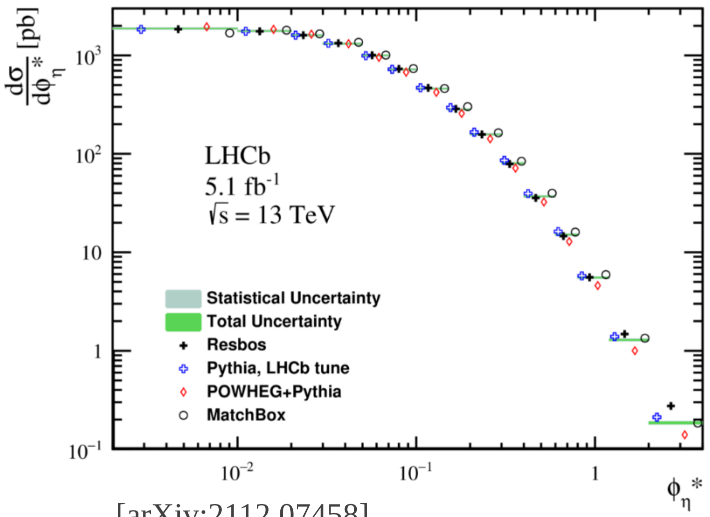
[arXiv:2112.07458]

Z differential cross section: Z- p_T and ϕ_η^*

- ϕ_η^*: the scattering angle of the muons with respect to the proton beam direction in the rest frame of the dimuon system
- Reasonable agreement between data and predictions
- Provide a stringent test on different QCD calculations



[arXiv:2112.07458]

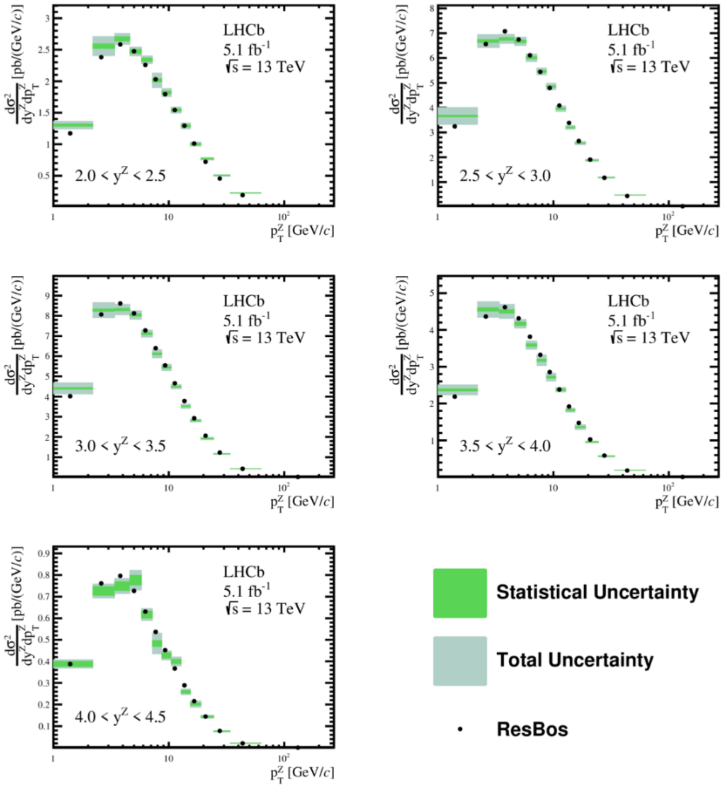


[arXiv:2112.07458]

Z double differential cross-section

[arXiv:2112.07458]

- The **first** double differential cross-section measurement in the forward region
- No significant deviations are seen between measurements and the theoretical predictions

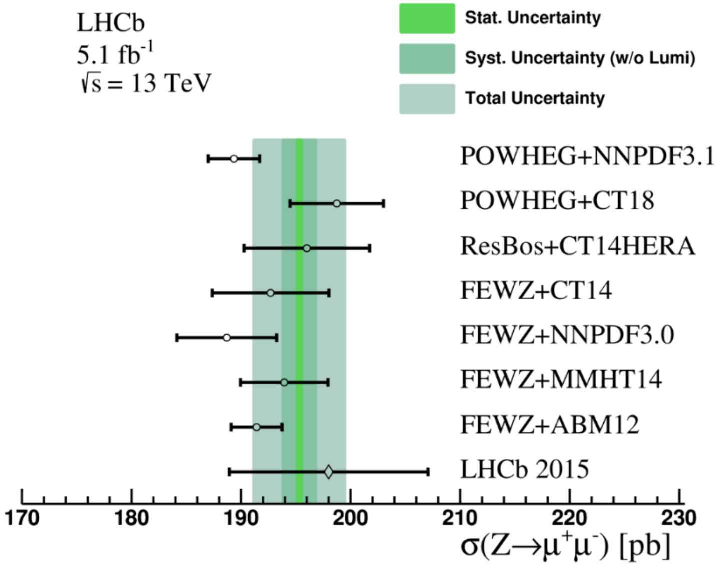


Z Integrated cross section

- The most precise measurement in the forward region @ 13TeV

$$\sigma(Z \to \mu^+\mu^-) = 195.3 \pm 0.23\,(\text{stat.}) \pm 1.5\,(\text{sys.}) \pm 3.9\,(\text{lumi.})\ \text{pb}$$

[arXiv:2112.07458]



[arXiv:2112.07458]

Source	$\Delta\sigma/\sigma$ [%]
Statistical	0.11
✦ Background	0.03
Alignment & calibration	-
Efficiency	0.77
✦ Closure	0.06
✦ FSR	0.04
Total Systematic (excl. lumi.)	0.77
✦ Luminosity	2.00
Total	2.15

Z angular coefficient (A_i) measurement

- The kinematic distribution of the final-state leptons provides
  - A direct probe of the polarization of the intermediate gauge boson
  - Information about the QCD mechanisms underlying the boson production mechanism
- A_i: the ratio of helicity dependent cross-section over the unpolarized cross-section

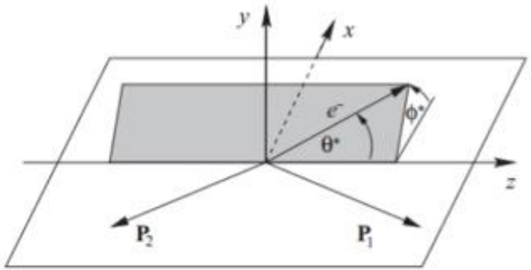
$$\frac{d\sigma}{dP_T^2 dy d\cos\theta d\phi} \propto (1+\cos^2\theta)$$ → LO term

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

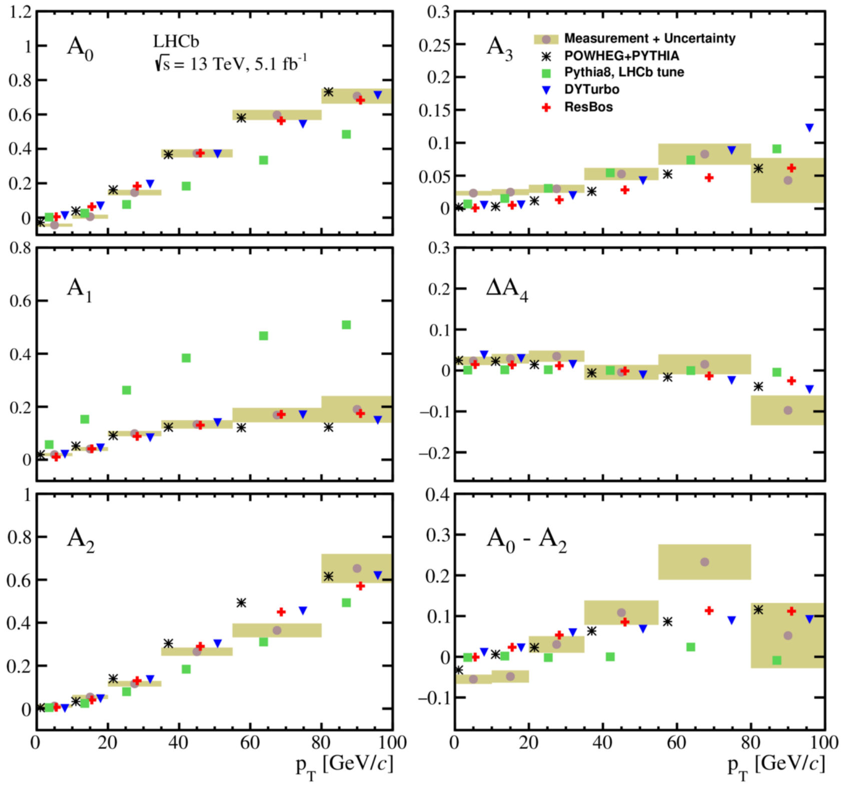
$$+ A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi$$ → very small terms



A_i - $p_T(Z)$

[arXiv:2203.01602]

- The **first** measurements of the angular coefficients of Drell-Yan $\mu^+\mu^-$ pairs in the forward rapidity region of pp collisions @ 13TeV
- Measurements are at **Born level**
- The uncertainty **is dominated by statistical uncertainty**

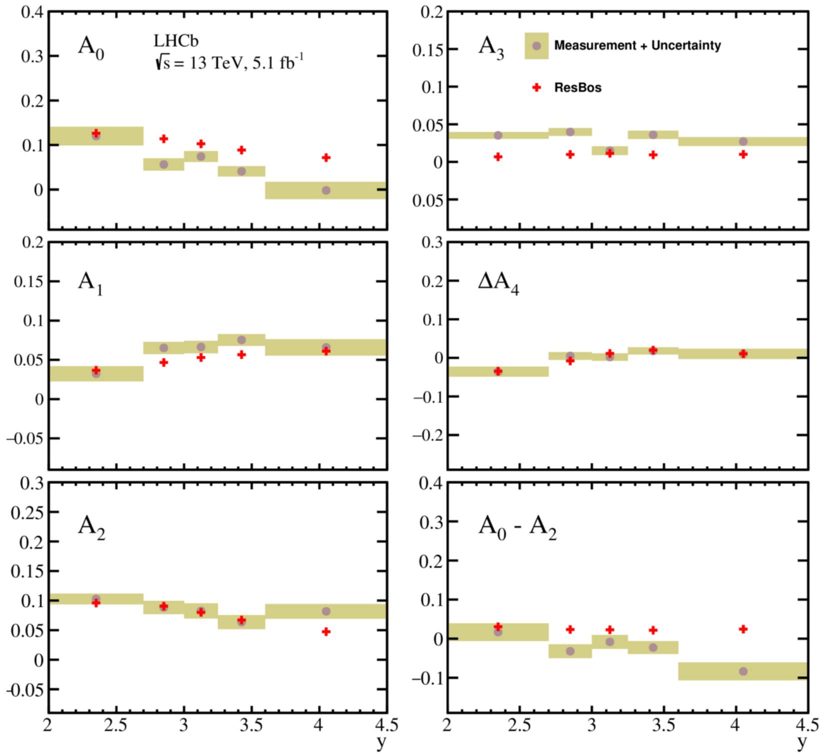


A_i - $y(Z)$

- Reasonable agreement between the measurements and ResBos calculations for A_0 to ΔA_4

- $A_0 - A_2$: differences between measurements and predictions, especially in the highest y region
  - A $y(Z)$ dependence in the QCD resummation or higher-order effects

[arXiv:2203.01602]

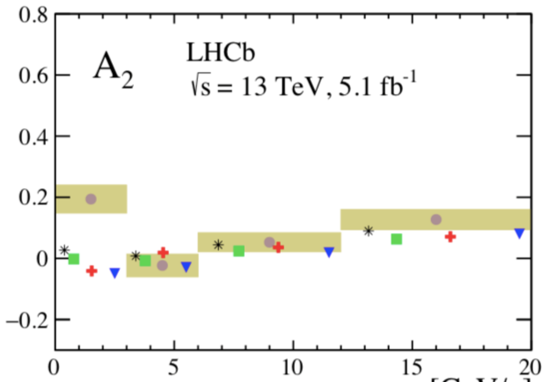


A_i - Boer-Mulders TMD

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

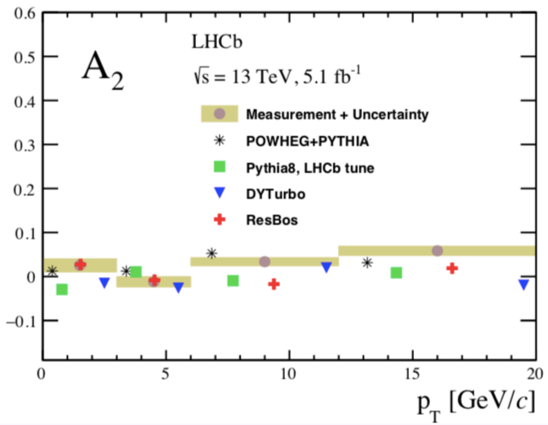
- A_2 is sensitive to the TMD
- The measured A_2 values deviates significantly from all predictions in the lowest p_T region for the low-mass region
  - ➢ Uncelarly nonpertubative spin-momentum correlations in the proton could lead to such variations as no phenomennological calculations are available

$50 - 75\ \mathrm{GeV}/c^2$

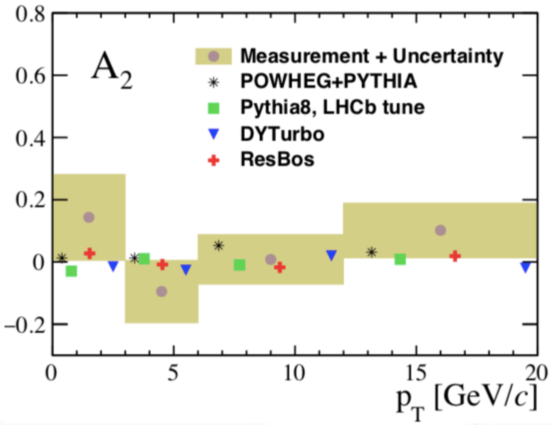


[arXiv:2203.01602]

$75 - 105\ \mathrm{GeV}/c^2$



$105 - 120\ \mathrm{GeV}/c^2$

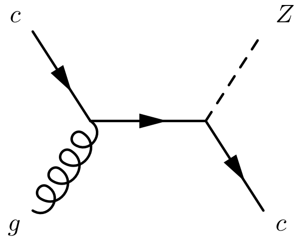


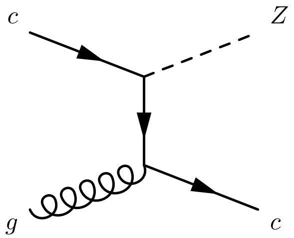
Intrinsic charm

- Extrinsic charm content of the proton arises due to perturbative gluon radiation
- Light front QCD predict non-perturbative intrinsic charm existents as **valence-like** charm content in the PDFs of proton

$$|\mathbf{proton}\rangle = |\boldsymbol{uud}\rangle + \ \boldsymbol{\epsilon}|\boldsymbol{uudc\bar{c}}\rangle \ ?$$

$$\boldsymbol{\epsilon} \lesssim \boldsymbol{\mathcal{O}}(\%)$$





$Z + c$ measurement

- First study of Z boson produced in association with charm in the forward region, using full Run-II data, with optimized charm-jet identification [JINST 17 (2022) P02028]
- Measure $\sigma(Z_c)/\sigma(Z_j)$
  - At NLO a percent-level valence-like IC contribution would produce significant enhancement in the ratio at high $y(Z)$ region
  - IC-allowed model at **high $y(Z)$** is largely unconstrained
  - Many jet-related systematics cancel in the ratio

fiducial region

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

[Phys. Rev. Lett. 128 (2022) 082001]

$Z + c$ - Systematics uncertainties

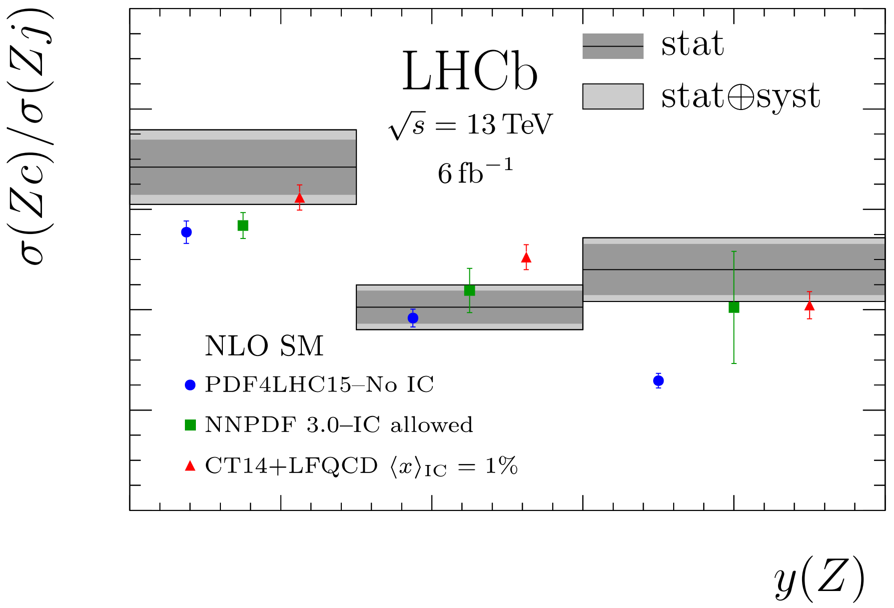
[Phys. Rev. Lett. 128 (2022) 082001]

Source	Relative Uncertainty
c tagging	6–7%
DV-fit templates	3–4%
Jet reconstruction	1%
Jet p_{T} scale & resolution	1%
Total	8%

- Leading systematic uncertainty due to ***c*-tagging calibration** [LHCb-DP-2021-006]
- Systematics almost cancel between $y(Z)$ bins
  - **Double ratios** have good potential for future precision measurements

$Z + c$ - Results

[Phys. Rev. Lett. 128 (2022) 082001]



- Clear enhancement in **highest y bin**
- Inconsistent with No-IC theory at **$>3\sigma$**
- More consistent with expected effect form $|uudc\bar{c}\rangle$ component predicted by LFQCD
- Incorporating forward results into a global analysis should **strongly constrain the large-x charm PDF**
- **Current results are statistically limited**, Run-III dataset will allow for finer binning

Summary

- The knowledge of the PDFs is crucial for precision measurement at hadron colliders
- LHCb detector has proved its capability to do high-precision measumrents of EW observables
- With detector instrumentd in the forward region, LHCb results could provide unique information for the PDFs global fitting
  - The sea quark in the larger x region
  - The transverse momentum dependent PDFs
  - The intrinsic charm in the proton

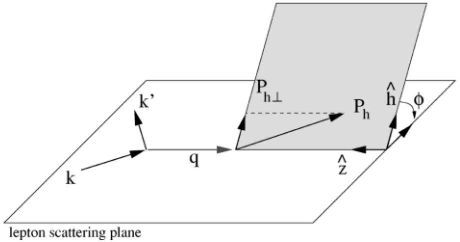
Back Up

Bore-Mulders TMD PDF

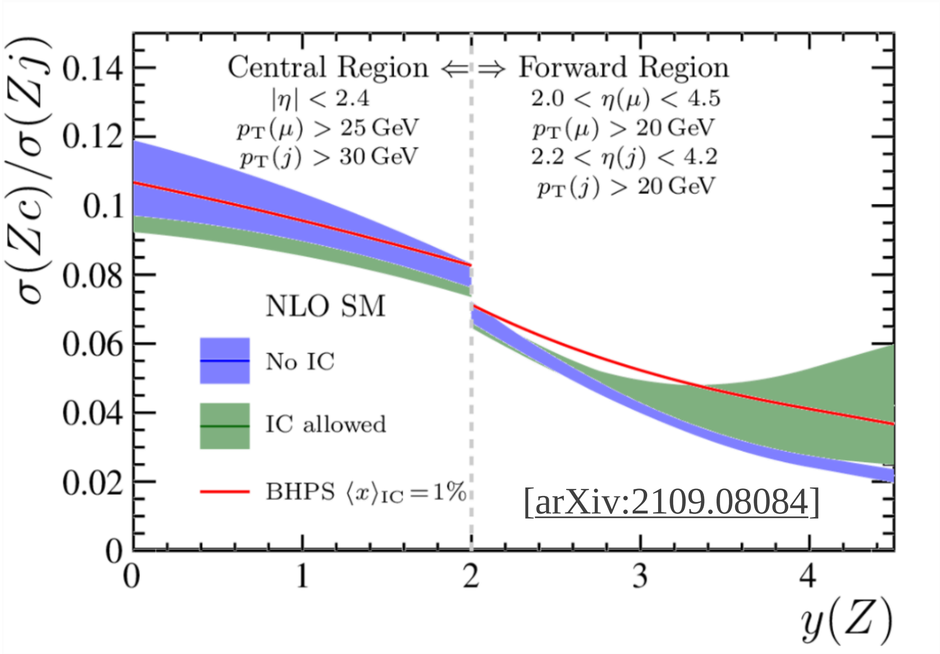
[Phys. Rev. D 57 (1998), 5780]
[Phys. Rev. D 60 (1999), 014012]

- Bore-Mulders function
  - Describes a correlation between a transversely polarized quark (antiquark) in an unpolarized proton and the quarks' own nonperturbative momentum with the proton
    - Lead to an azimuthal $\mathbf{cos(2\theta)}$ dependence in Drell-Yan

- Transvers Momentum Dependent PDFs: TMD
  - The general PDFs describes the parton inside a proton
  - Admit a finite quark transverse momentum k_T
  - **Correlation between parton momentum and hadron spin**



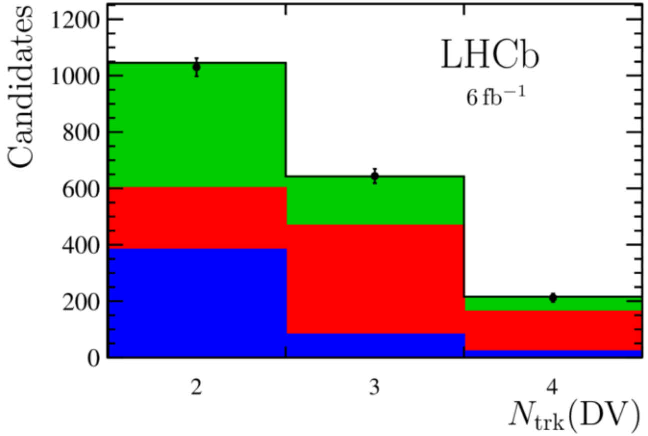
$gc \to Zc$ models

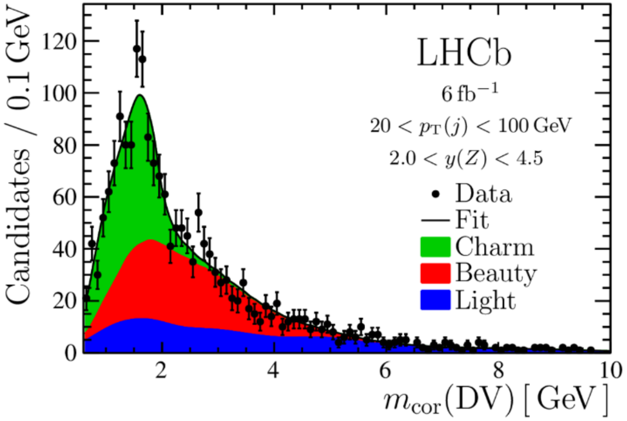


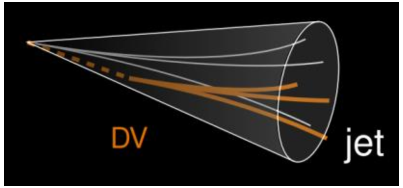
- NO IC [J. Phys. G43 (2016) 023001]
  - PDF4LHC15 – purely extrinsic
- IC allowed [Eur. Phys. J C76 (2016) 647] [JHEP 04 (2015) 040]
  - NNPDF3.0 IC – allows global fit to include intrinsic charm where not excluded by existing measurements
  - Uncertainties: experimental limits
- LFQCD $\langle x \rangle_{\mathrm{IC}} = 1\%$ [JHEP 02 (2018) 059]
  - BHPS3 – PDF set based on LFQCD calculations with a fixed intrinsic charm contribution
  - Uncertainties: model assumptions

$Z + c$ – displaced vertex c-tagger

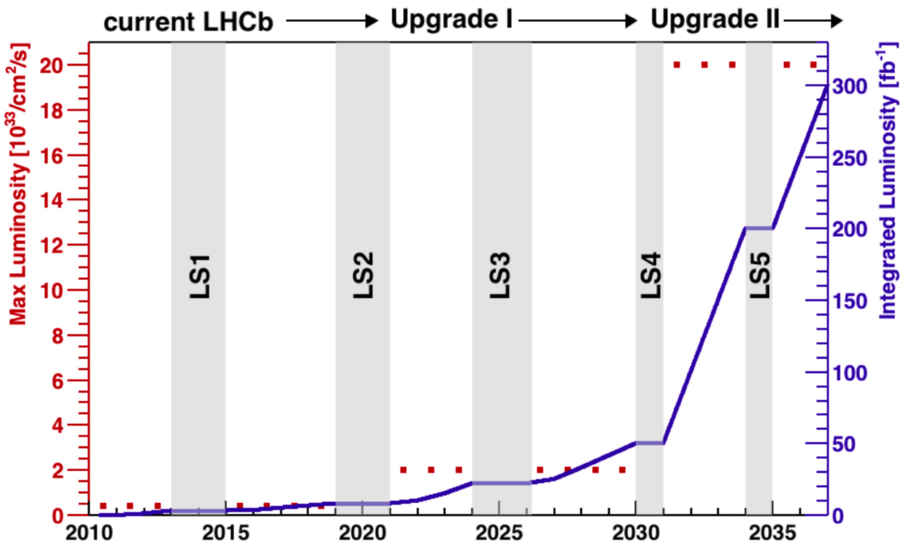
- Reconstruct displaced vertices within jets
- Use 2D fit to corrected mass and number of tracks to distinguish charm jets from beauty and light
- $m_{\text{cor}}(\text{DV}) \equiv \sqrt{m(\text{DV})^2 + [p(\text{DV})\sin\theta]^2} + p(\text{DV})\sin\theta$
- Templates from flavour-enhanced calibration samples







Prospects



- W charge asymmetry
  - Valence quark: u and d
- W cross-section measurement
  - s quark PDFs
- V+jet and other measurements
  - Large-x gluon, Medium-x gluon, strangeness….