Neutral current Drell-Yan angular coefficients at LHCb

Warwick Seminar

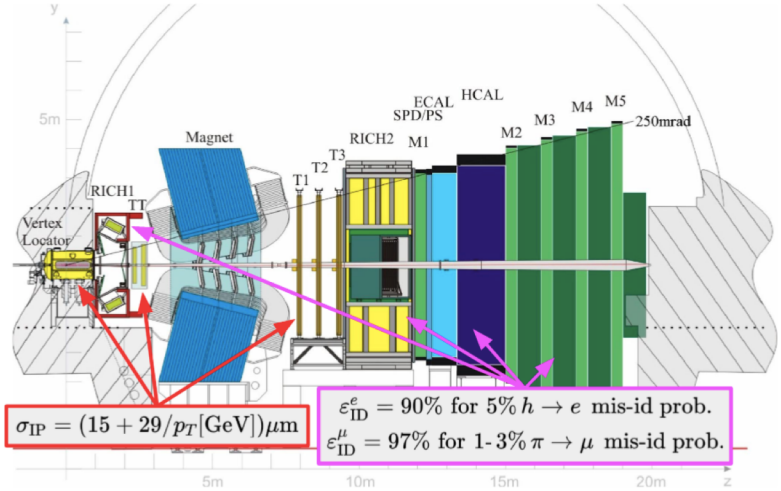
Menglin Xu

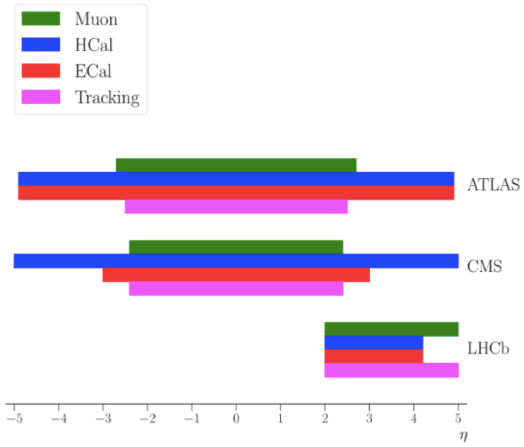
17.03.2022

LHCb detector

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

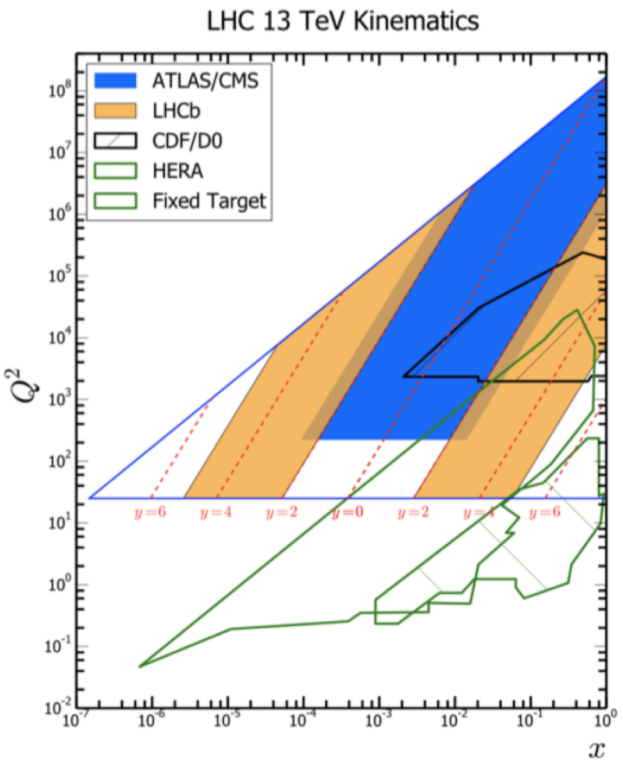
- Single-arm forward spectrometer
  - Designed for the heavy flavor physics with $2 < \eta < 5$
  - Coverage is complementary to ATLAS and CMS
  - Extended to EW measurements: excellent performance of tracking and muon detector





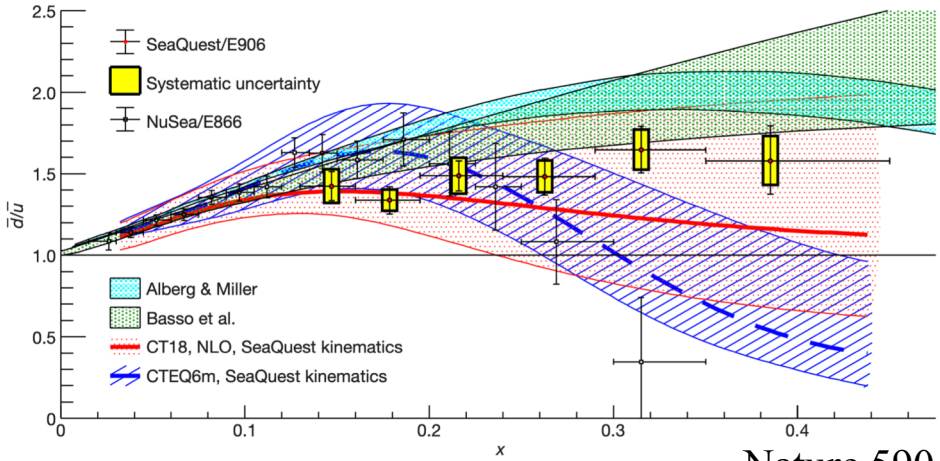
EW physics at LHCb

- LHCb has already delivered a strong programmer of physics with W and Z boson mainly probing QCD
- Potential to improve constraints on PDFs, $y = \frac{1}{2} ln \frac{x_1}{x_2}$
  - High Bjorken-x region
  - **Low Bjorken-x region: unexplored by other experiments**
- Measurements of the Z boson rapidity are particularly important for constraining u-, d-quark PDFs



Constrain $\bar{d}/\bar{u}$ PDFs

- SeaQuest collaboration report the results on the $\bar{d}/\bar{u}$ PDFs
  - Tensions between SeaQuest and NuSea results are seen at high x region
  - SeaQuest and NuSea are lower energy experiments, are largely affected by nuclear effects
- The LHCb data is the only clean data to constraint the $\bar{d}/\bar{u}$ PDFs

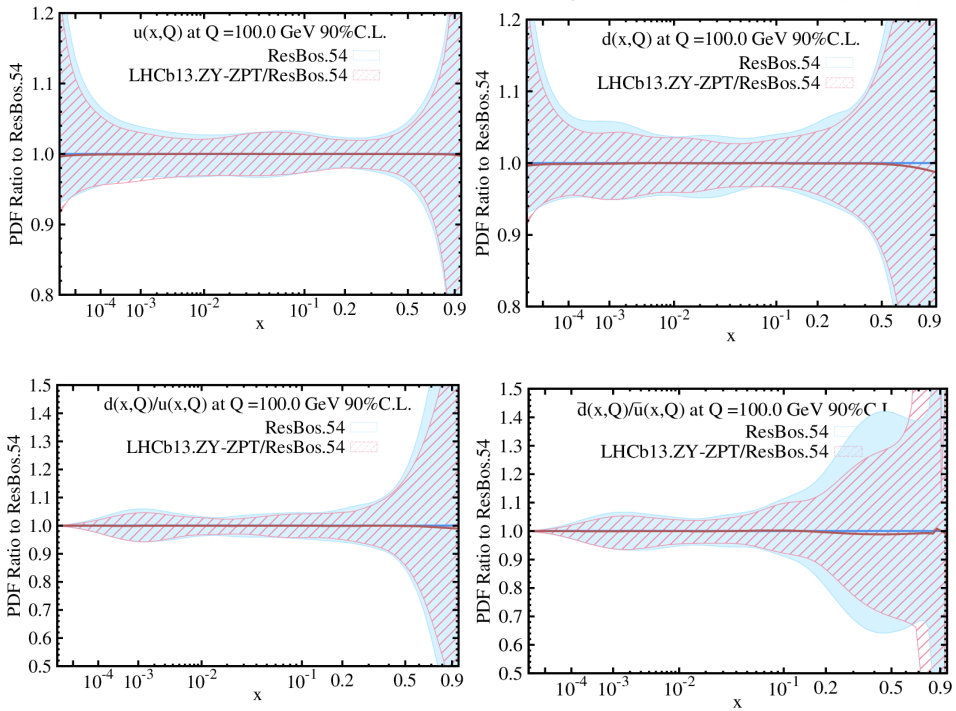


Nature 590, 561 (2021)

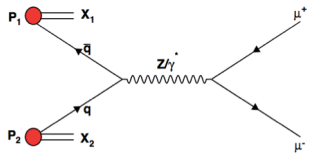
Impact of LHCb 13TeV *Z* pseudo-data on the PDF

[Chin. Phys. C **45**, 023110 (2021)]

- Large impacts on the d quark PDFs
- Impact on u quark PDFs is not as large as that of d quark
- Significant improvements on the d/u ratio in the large x region
- Larger impacts has been found in $\bar{d}/\bar{u}$ PDFs ratio



Z production cross-section - Strategy

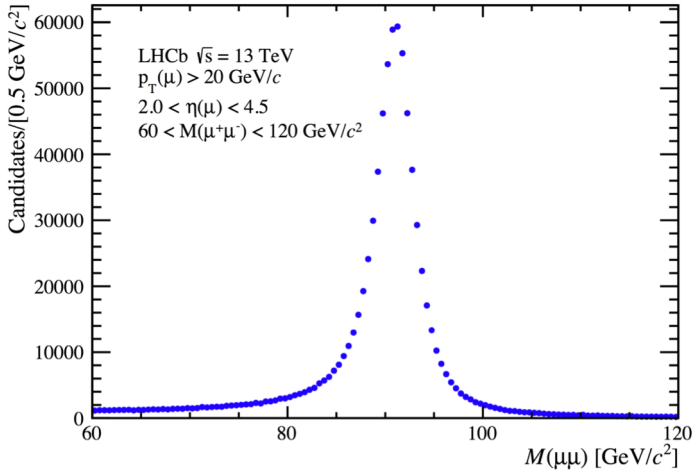


- Datasets: 2016, 2017 and 2018 data: $\mathbf{5.1 \pm 0.1\ fb^{-1}}$
- Very high purity, $N_{bkg}/\ N_{sig}$ ~2%

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

- $\phi^*_\eta = \frac{\tan((\pi-\Delta\phi^{ll})/2)}{\cosh(\Delta\eta/2)}$: the scattering angle of the muons with respect to the proton beam direction in the rest frame of the dimuon system

[arXiv:2112.07458]



fiducial region

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

Systematic uncertainties

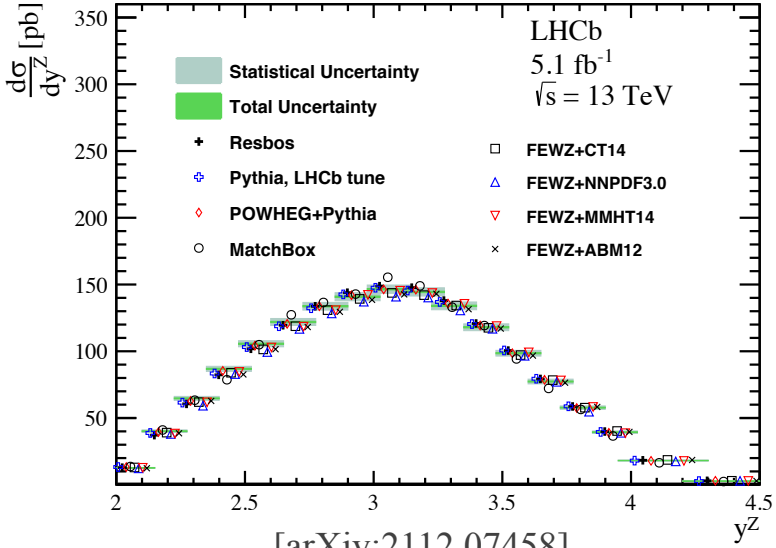
- Luminosity determination precision: 2.0%
  - Uncertainty is quoted separately to the other sources of systematic uncertainty
- Efficiency systematic uncertainties: 0.77%
  - From size of control channel
  - From the track modeling: **dominated one**

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

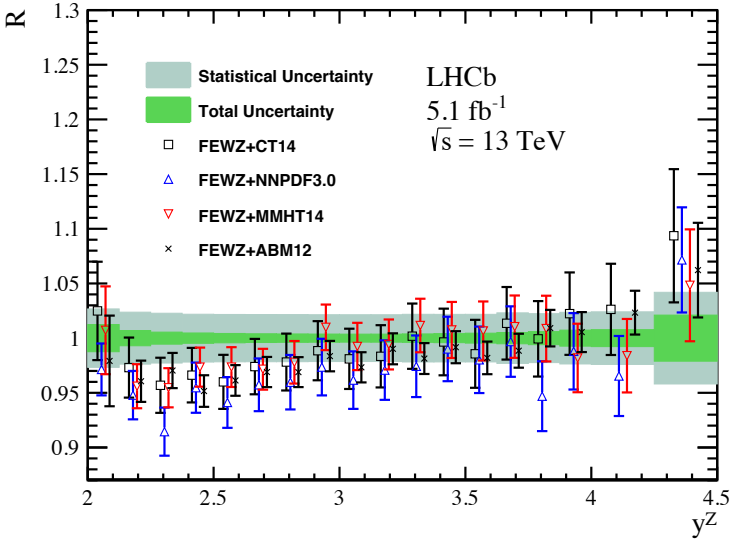
[arXiv:2112.07458]

Z differential cross section: Z - y

- Reasonable agreement between data and predictions, ratio(R)~1
- Fewz predictions for R are systematically smaller than the measured results in the lower y region



[arXiv:2112.07458]

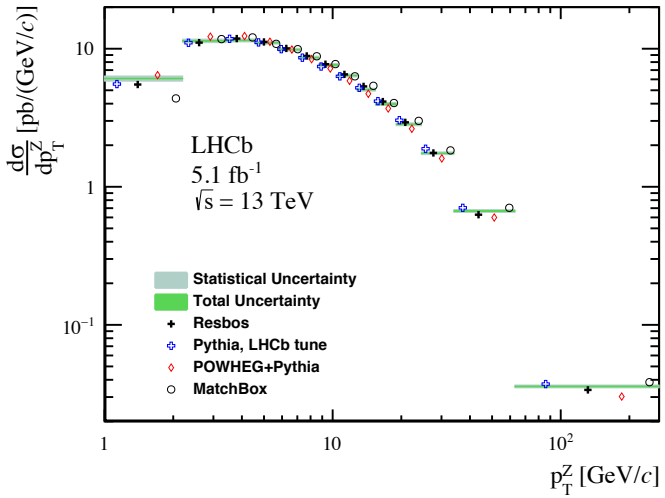


[arXiv:2112.07458]

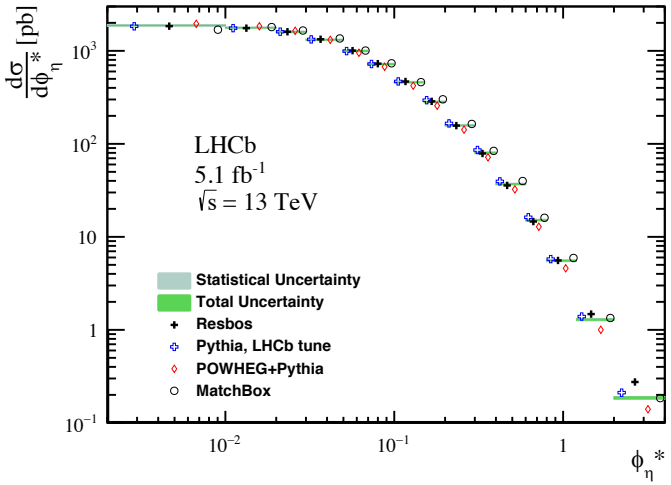
Z differential cross section: Z- p_T and ϕ_η^*

- Reasonable agreement between data and predictions
- Provide a stringent test on different QCD calculations

[arXiv:2112.07458]



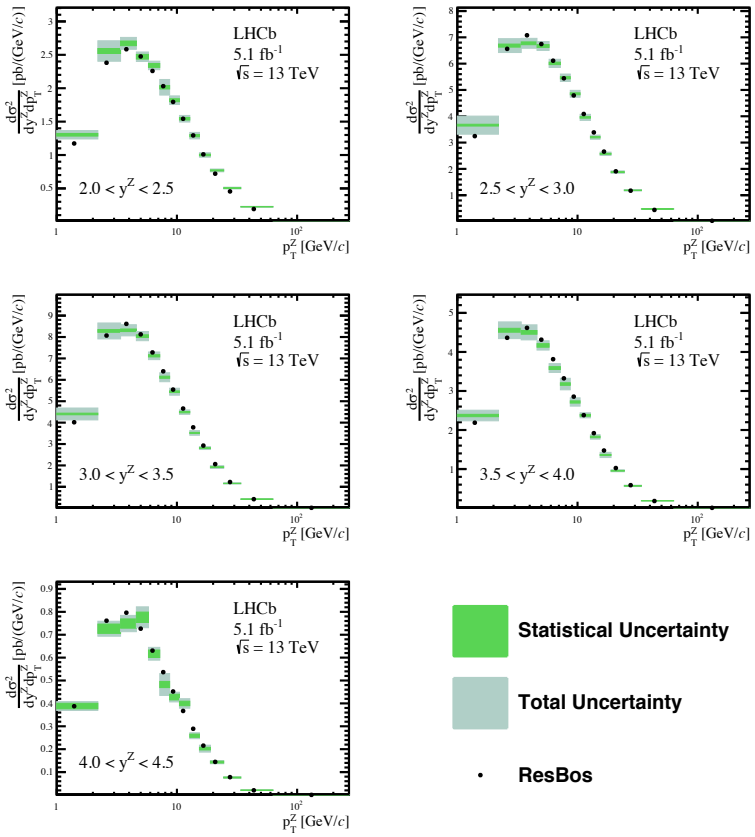
[arXiv:2112.07458]



Z double differential cross-section

[arXiv:2112.07458]

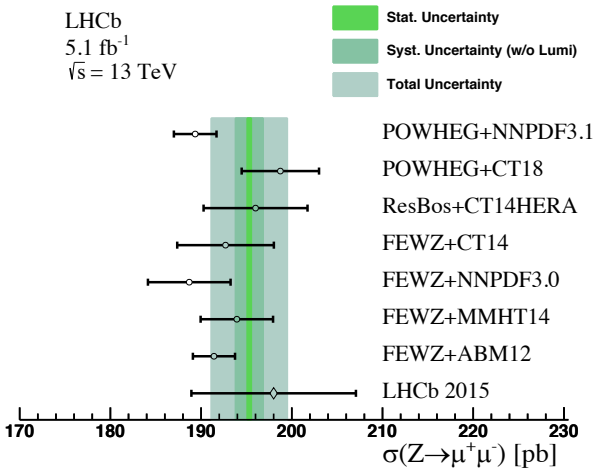
- The first double differential cross-section measurement in the forward region
- No significant deviations are seen between measurements and the theoretical predictions



Z Integrated cross section

- Combined with 'Best Linear Unbiased Estimate' (BLUE)
  - luminosity uncertainty, systematic uncertainties from FSR, background modelling, and closure test are treated as 100% correlated
  - Other systematic uncertainties are treated as having no correlation

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



[arXiv:2112.07458]

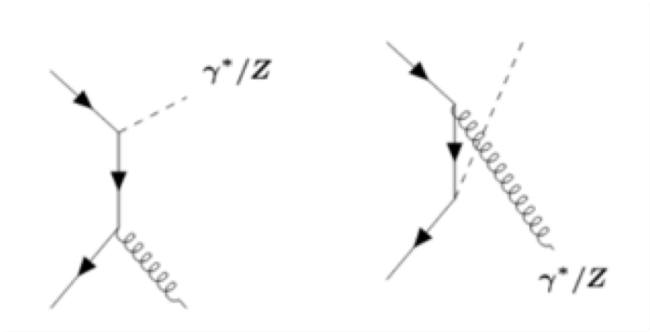
First measurement of the $Z \to \mu^+\mu^-$ angular coefficients in the forward region of pp collisions at $\sqrt{s} = 13$ TeV

[arXiv:2203.01602]
submitted to PRL

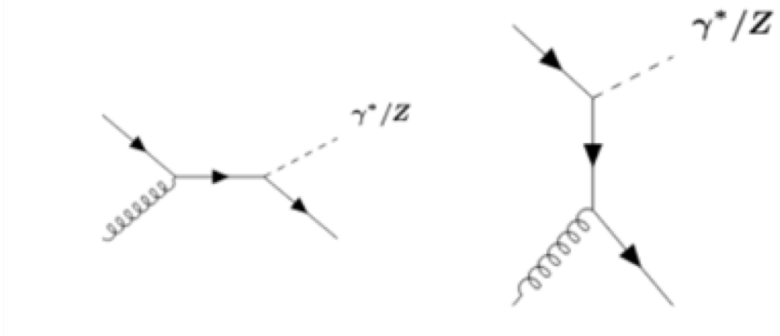
Motivation

- The kinematic distribution of the final-state leptons provides a direct probe of polarization of the intermediate gauge boson, exposes QCD production mechanisms

Annihilation diagram

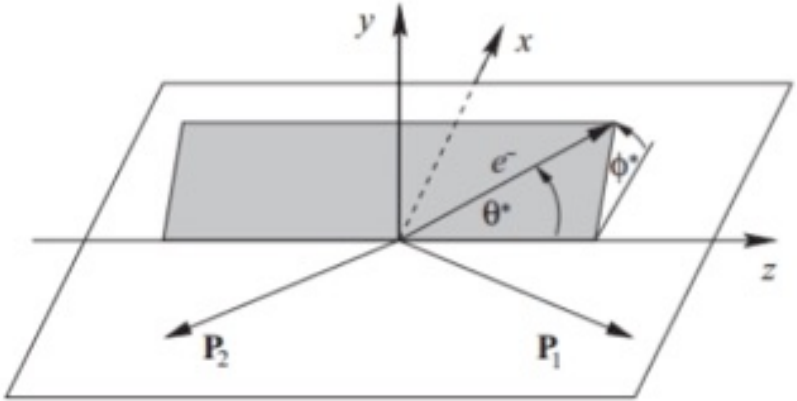


Compton diagram



Collins-Soper frame

- The center of dilepton mass frame
  - Z-axis: bisector of angular between P_1 direction and negative of P_2 direction
  - θ^*: angular between new z-axis and the outgoing negative lepton
  - ϕ^*: angular between the lepton plane (grep) and the plane of the incident hadrons (white)



Angular coefficients (A_i)

- A_i: the ratios of helicity dependent cross-sections over the unpolarized cross-section
- LO: approximation within the framework of QCD, p_T(dilepton) =0 → A_i vanish, with the exception of A_4, due to parity violation in the weak interaction

Born level

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

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

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

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

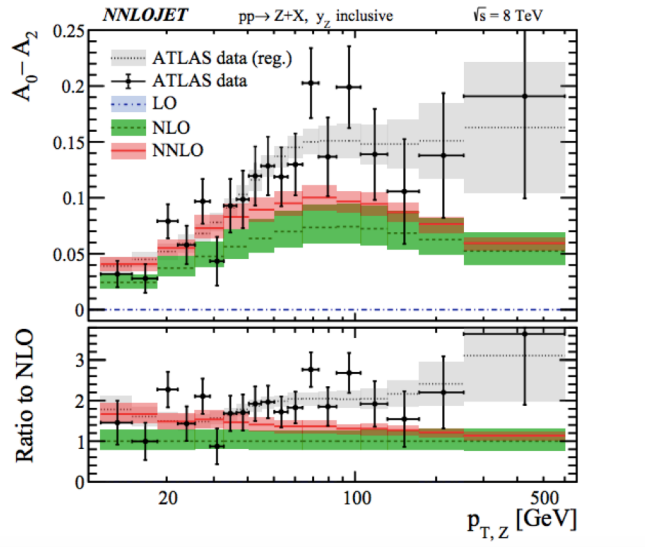
$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \rightarrow \text{very small terms}$$

- NLO: A_0 to A_3 become nonzero
- NNLO: A_5 to A_7 have small deviations from zero

Lam-Tung relation: $A_0 = A_2$

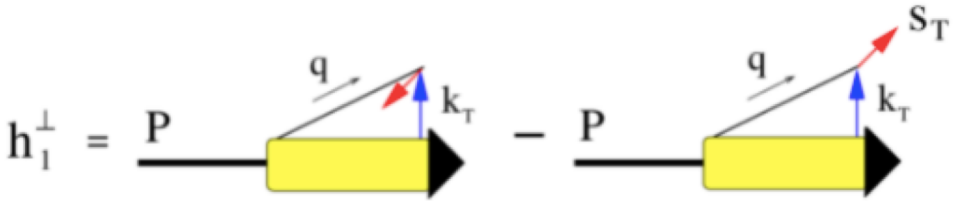
- Valid for both $q\bar{q}$ and gq processes at LO
- Small violations occur in fixed-order perturbative QCD calculations at higher-order, and in QCD resummation calculations to all orders

- Nonperturbative effects can lead to violation of the Lam-Tung relation via a correlation between the transverse spin and transverse momentum of the initial-state quark or antiquark, represented by the Boer-Mulders transverse-momentum-dependent (TMD) PDF



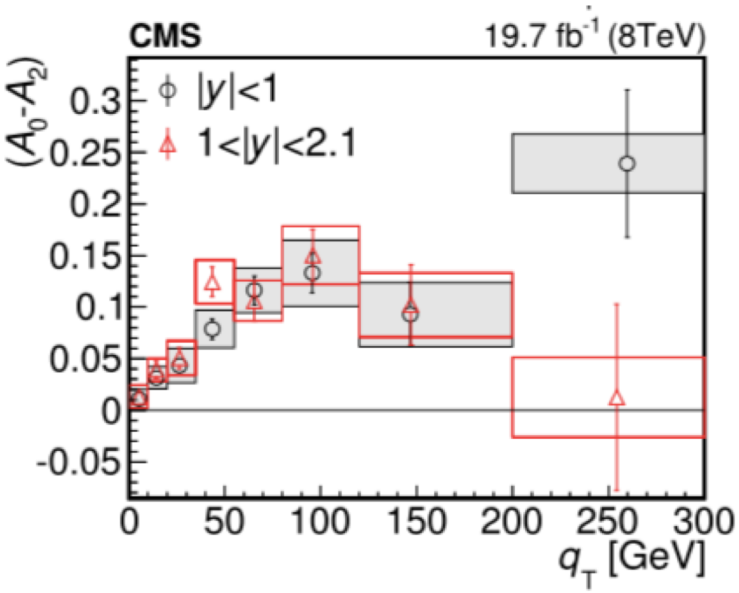
Bore-Mulders TMD PDF ($h_1^\perp$)

- Describes a correlation between a transversely polarized quark (or antiquark) in an unpolarized proton and the quark's own nonperturbative momentum within the proton
- If the proton moves along the z direction, then the quarks can have some transverse momentum k_T with respect to the proton momentum, which together define a plane. The quarks can then have a net polarization orthogonal (or transverse) to that plane. A nonzero Boer-Mulders function means that there is such a net quark polarization



Measurements from hadron colliders

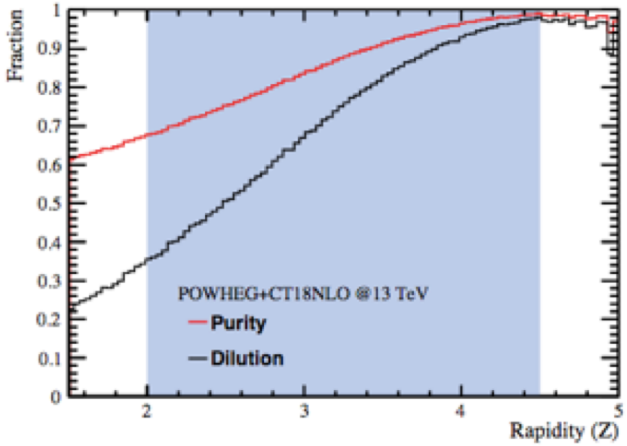
- Window around Z resonance → Z exchange
- Tevatron: CDF [arXiv:1103.5699]
- LHC: CMS [arXiv:1504.03512],
  ATLAS: [arXiv:1606.00689]
  - First clear evidence for $A_0 - A_2 \neq 0$
  - In tension with theory predictions



LHCb advantage

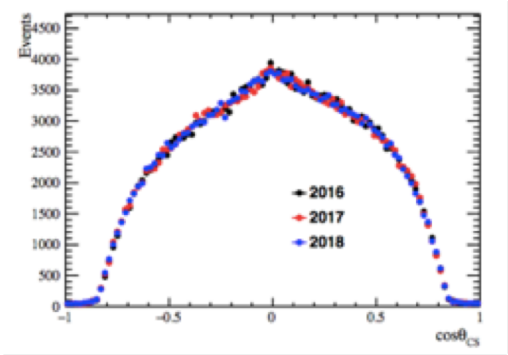
- The sign of $cos\theta$ and ϕ are defined with respect to the direction of the quark, which is ambiguous in pp collisions
  - The longitudinal boost of the final-state dilepton system in the laboratory frame is assumed to be the same direction as quark in the initial state
- Dilution effect(f): the possibility of events with quark direction wrongly determined depends on the input PDFs

Estimated dilution $(1 - f) \sim 85\%$
Purity $(1 - 2f) \sim 70\%$

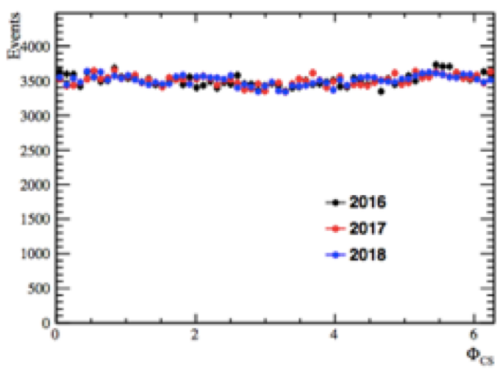


High purity

$cos\theta$



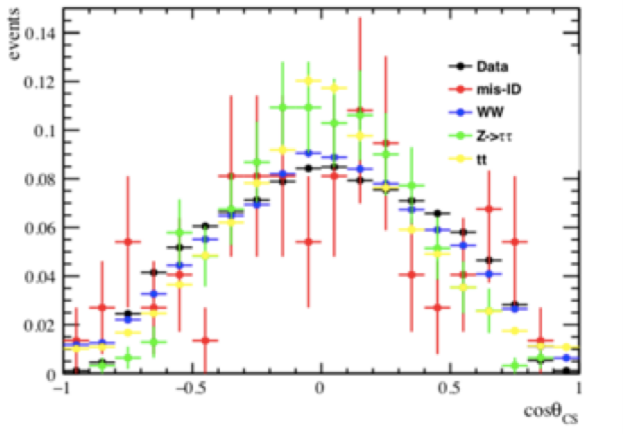
ϕ

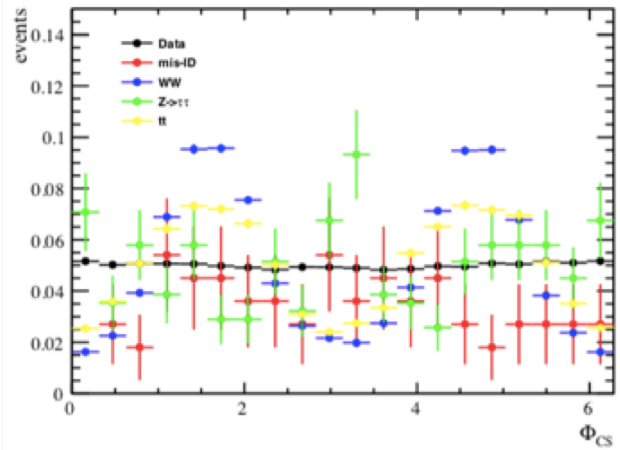


Background	Estimation	2016	2017	2018
Hadron mis-ID	Data-driven	0.003%	0.002%	0.002%
$Z \to \tau^+\tau^-$	PYTHIA 8 (RESBOS)	0.109%	0.101%	0.108%
$t\bar{t}$	PYTHIA 8 (MCFM)	0.081%	0.082%	0.083%
$W^+W^- \to \mu^+\nu_\mu\mu^-\bar{\nu}_\mu$	PYTHIA 8 (MCFM)	0.023%	0.021%	0.023%
Total		0.238%	0.227%	0.238%
Purity		99.761%	99.773%	99.761%

Background subtraction

- Negative-event-weight method [LHCb-PAPER-2014-059]
  - Due to the unbinned likelihood is used to extract, the estimated background events are taken into account with the selected data events with a negative weight (-1. $\times$ wt)





Angular coefficients extraction

- Using the unbinned maximum likelihood fitting method, widely used in the angular analyses of B hadrons
- PDF consists a signal only p.d.f. with detector resolution and acceptance effects
  - PYTHIA events: study corrections with FSR turned at the generator level
  - Signal MC with LHCb detector simulation: study acceptance efficiency by normalization weight which could avoid computing-intensive numerical integration of the PDF in the fit

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

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

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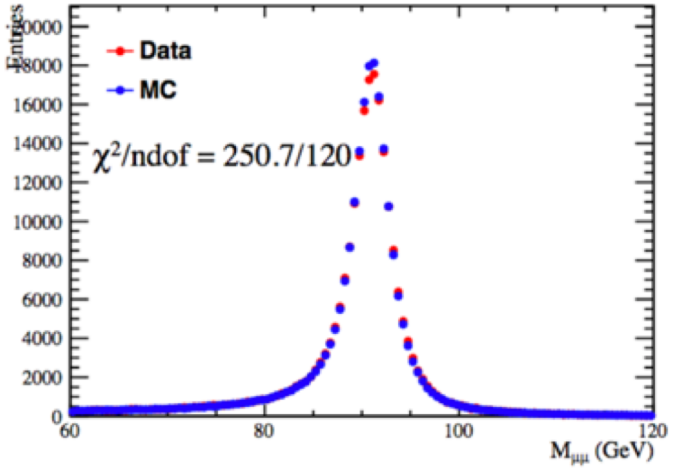
[CERN-THESIS-2010-124]
[Phys. Rev. Let. 87 (2001) 241801]
[Phys. Rev. D 71 (2005) 032005]
[Phys. Rev. Lett. 018(2012) 101803]

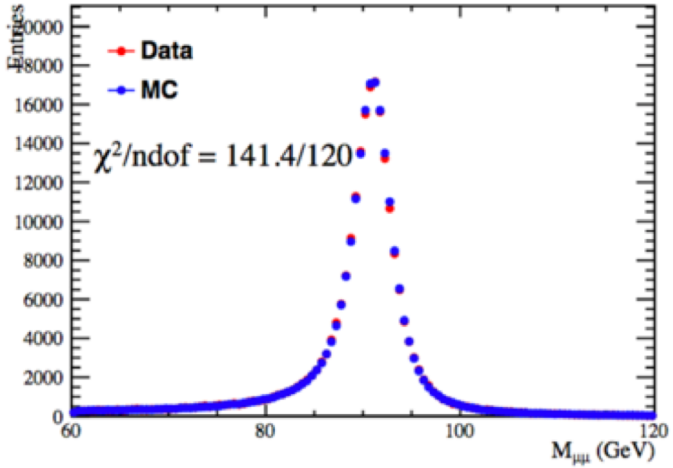
MC smearing

- Achieve good agreement of mass distribution between MC and data
- $p' = p \times (1 + \gamma \times \mathrm{Gauss}(0,1))$

Before



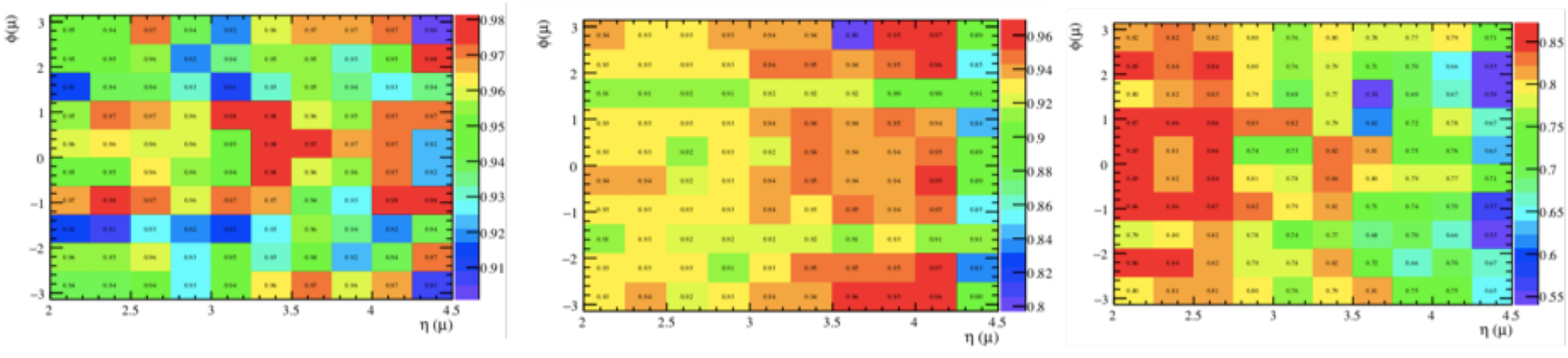
After



MC efficiency correction

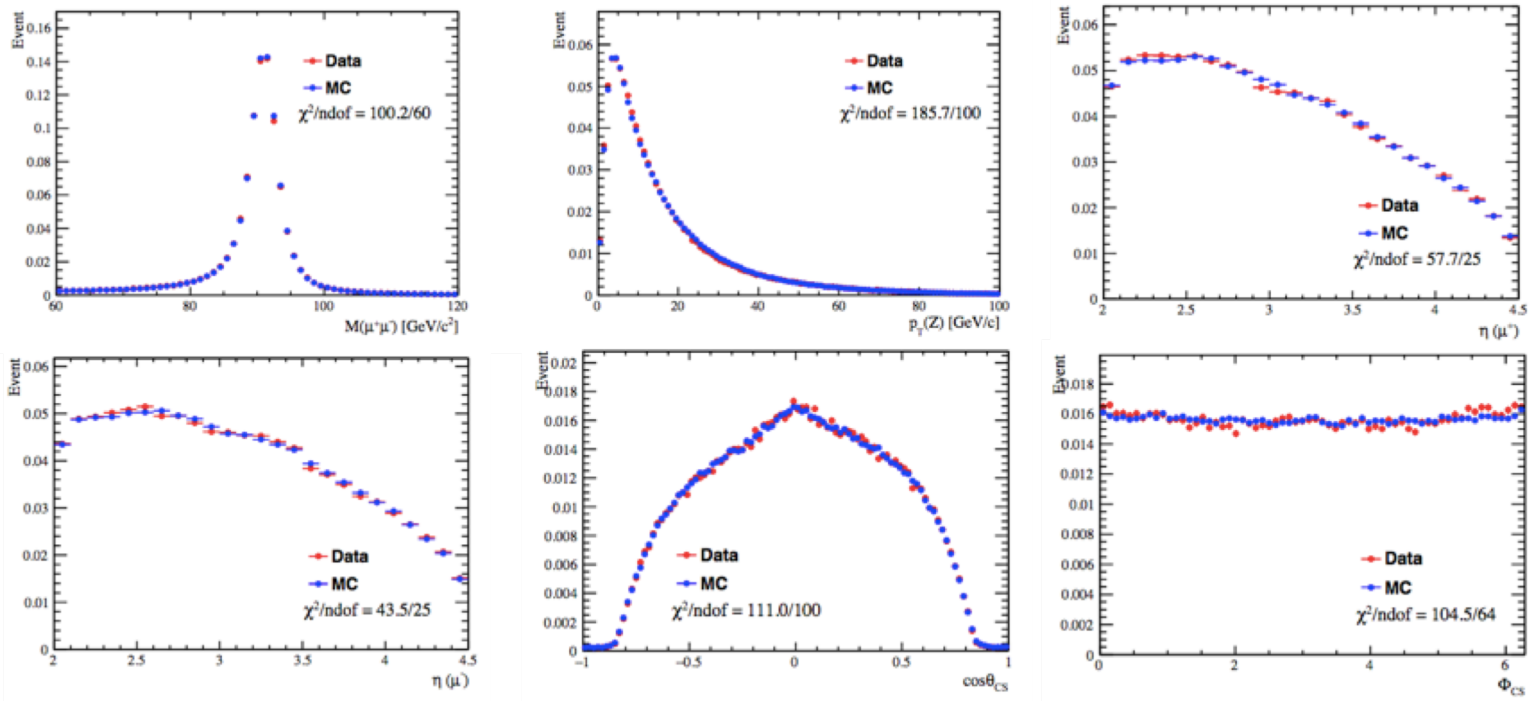
- Efficiency: $\epsilon^{rec} = \epsilon^{trk} \times \epsilon^{id} \times \epsilon^{trg}$
- Strategy: Tag-and-Probe method
- Apply ϵ (Data)/ϵ (MC) to MC sample as a 2D function of muon η and ϕ on an event by event

[LHCb-INT-2020-029]



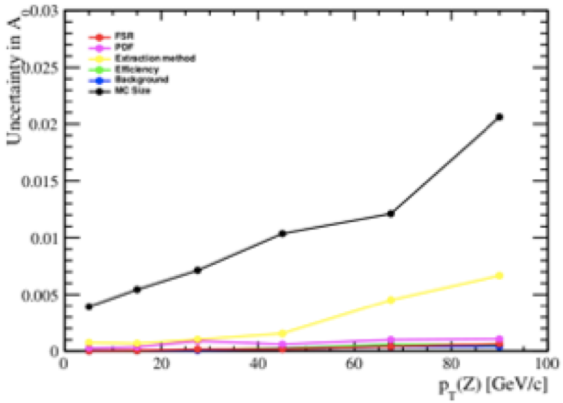
Data and MC comparison

- After applying corrections, reasonable agreements are seen between data and MC



Systematic uncertainties

- PDF uncertainty: reweighing the central PDF to 58 CT18 NNLO error PDF sets
  - prescription: $\Delta A_i^{\pm} = \sqrt{\sum_{j=1}^{29}\left(A_i^{j\pm} - A_i^0\right)^2}$, $\Delta A^{\pm}(68\%) = \frac{1}{1.64485}\Delta A^{\pm}\ (90\%)$
- FSR: the difference of measured results using the simulation sample weighted to the different Powheg prediction, and with the different FSR algorithms of Photos and Pythia
- MC sample size (dominate): Bootstrap method
- Efficiency
- Background estimation
- Extraction method



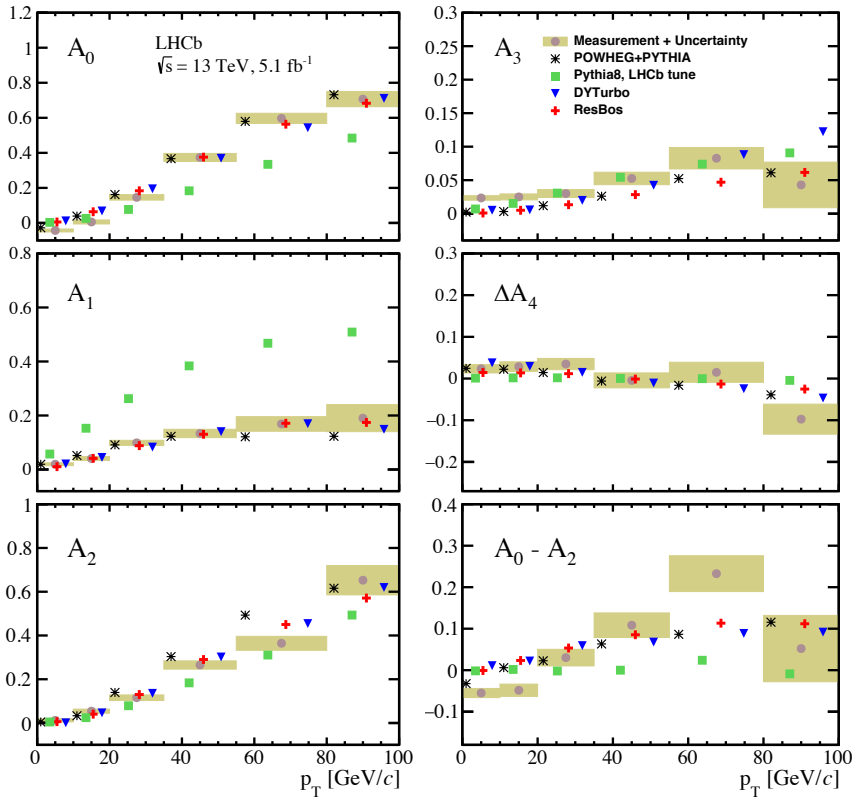
Various theoretical predictions

- ResBos: resummed calculations
  - Predictions are produced using the PDF known as CT14HERA2
  - The calculation combines NLO fixed-order calculations at high boson p_T
- DYTurbo: resumed calculations
  - An NNLO generator for the calculation of the QCD transverse-momentum resummation of Drell-Yan cross sections
- Powheg-BOX : a fixed-order calculation with matching and parton shower
  - An NLO generator and can be interfaced with Pythia for QCD and EW showering, but without the angular damping factors

$p_T(Z)$ dependent results

[arXiv:2203.01602]

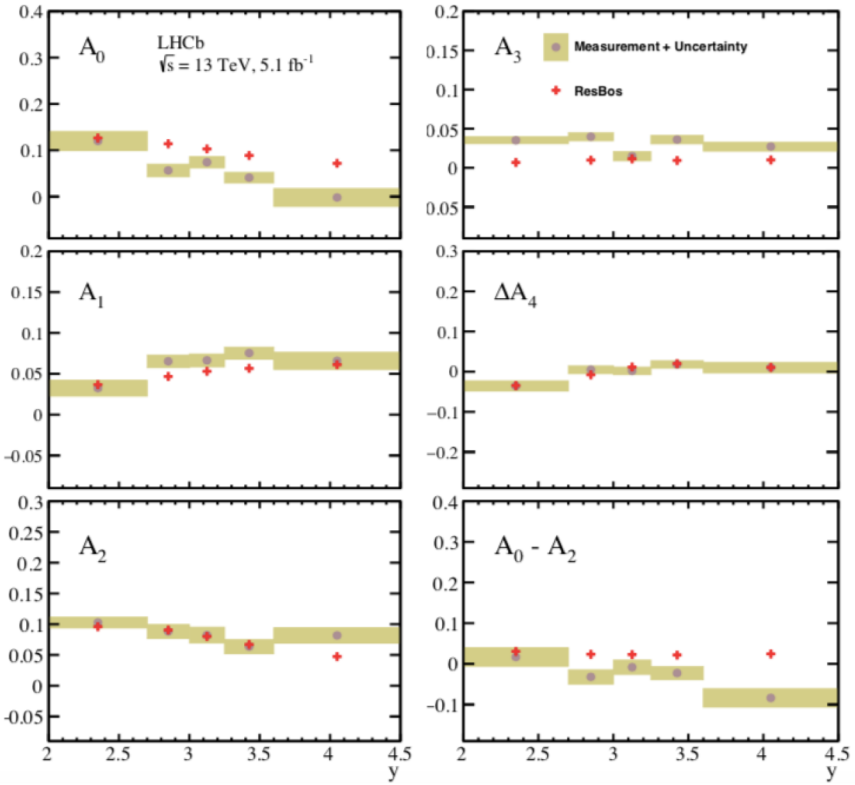
- The first measurements of the angular coefficients of Drell-Yan $\mu^+\mu^-$ pairs in the forward rapidity region of pp collisions at 13TeV
- Measurements are at Born level
- The uncertainty is dominated by statistical uncertainty



$y(Z)$ dependent results

[arXiv:2203.01602]

- Reasonable agreement between the measurements and ResBos calculations for A_0 to ΔA_4
- For $A_0 - A_2$, there are differences between measurements and predictions, especially in the highest y region
  - ➢ There is a y dependence in the QCD resummation or higher-order effects

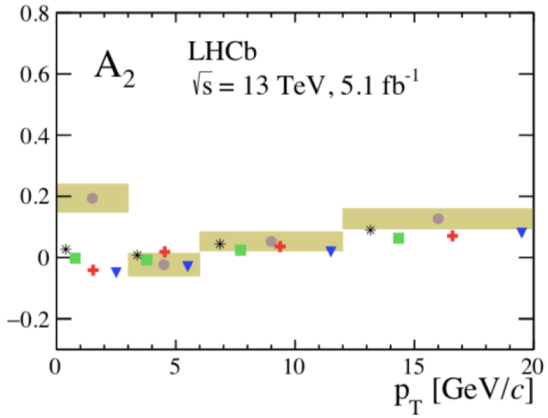


Z angular coefficient measurement - Boer-Mulders TMD

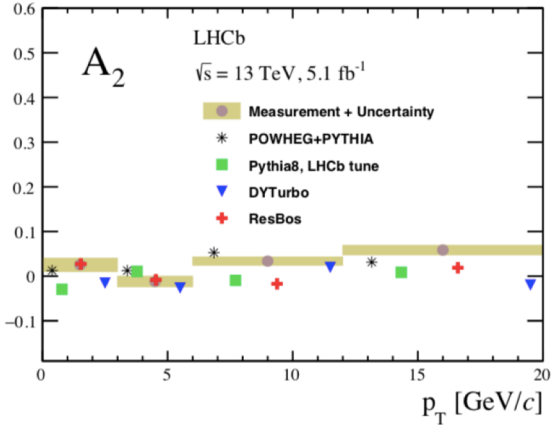
- A_2 is sensitive to the Boer-Mulders TMD
- The measured A_2 values deviates significantly from all predictions in the lowest p_T region for the low-mass region
- None of the predictions include nonperturbative spin-momentum correlations

[arXiv:2203.01602]

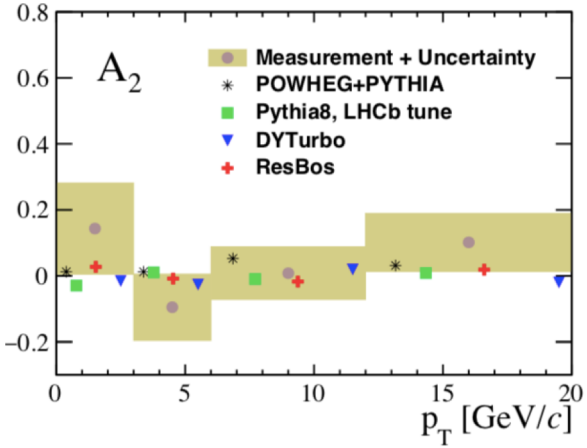
$50 - 75\ \mathrm{GeV}/c^2$



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



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



Summary

- LHCb detector has proved its capability to do **high-precision EW** measurements
- Provide important and unique information to the PDFs global fitting, especially in the **large and small x region**
- The most precise measurement of the Z boson production cross-section in the forward region, using the $\sqrt{s} = 13$ TeV pp collision data in muon channel

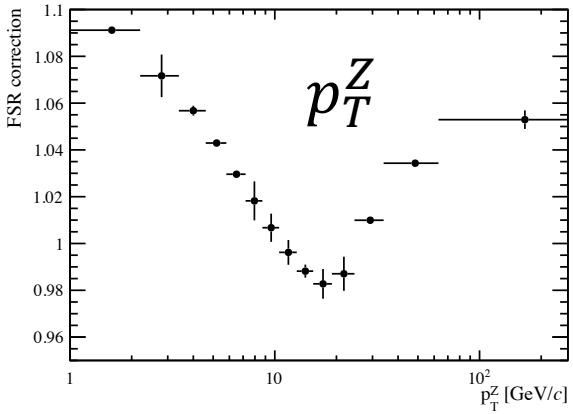
  $\sigma_{Z\to\mu^+\mu^-} = 195.0 \pm 0.2\ (\text{stat}) \pm 1.5\ (\text{sys}) \pm 3.9\ (\text{lumi})$ pb
- First measurement of angular coefficient in the forward rapidity region at LHC
  - Measurements in bins of $y(Z)$ are particularly useful for tests of the resummation calculations, some tensions with theoretical calculations are observed
  - measurements in the low mass region provides important information to probe the Boer-Mulders PDFs TMD

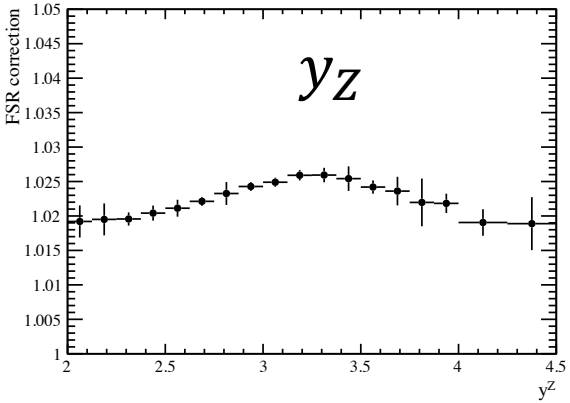
Back Up

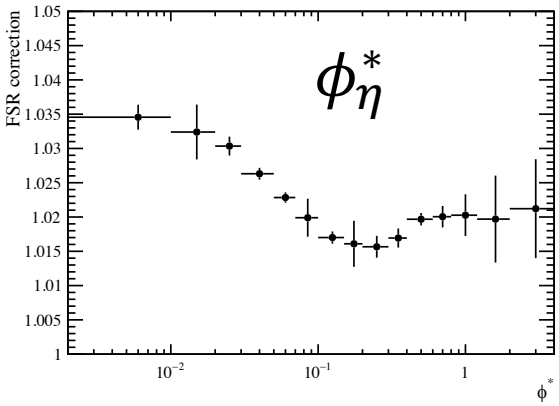
FSR correction

- To directly compare with different theoretical predictions, the measured cross-section is corrected to the **Born level**
- QED FSR correction evaluated through **ResBos**
- Taking differences of FSR corrections between ResBos+Photos and Powheg+Pythia as a systematic uncertainty

[arXiv:2112.07458]



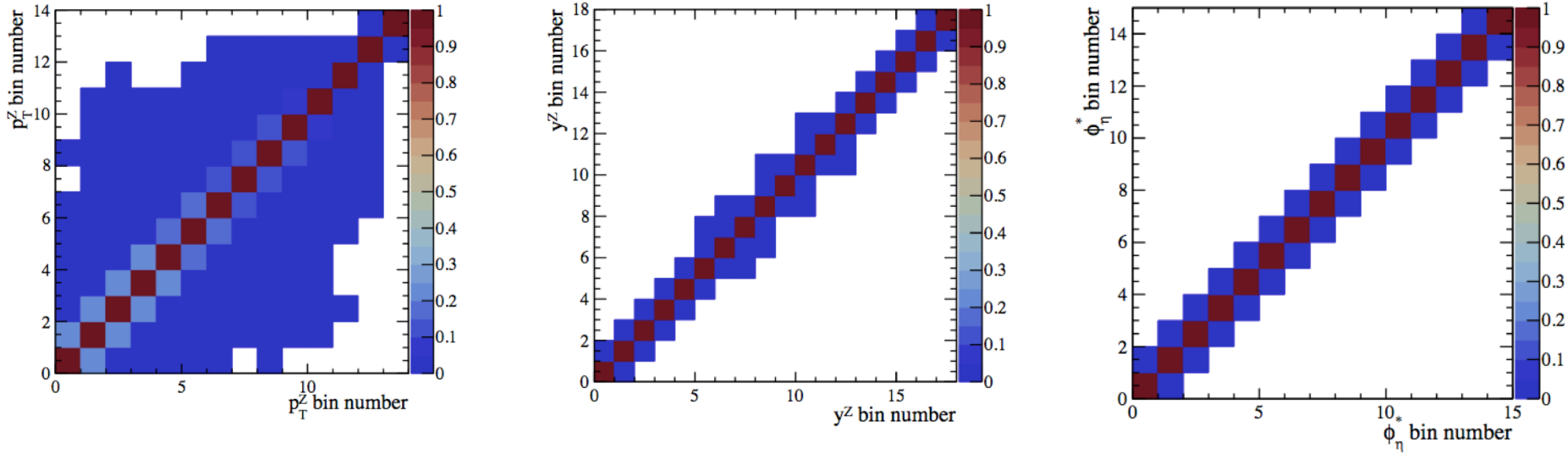




Statistical correlation matrix

- Determined using the simulation events
- Large correlations in low p_T^Z region, small correlations in the high p_T^Z region
- For y_Z and ϕ_η^*, the correlations between different bins are negligible

p_T^Z [arXiv:2112.07458] y_Z ϕ_η^*

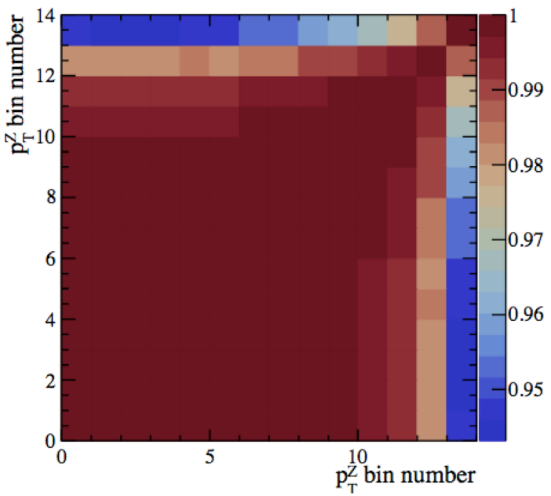


Correlation matrices for efficiency uncertainty

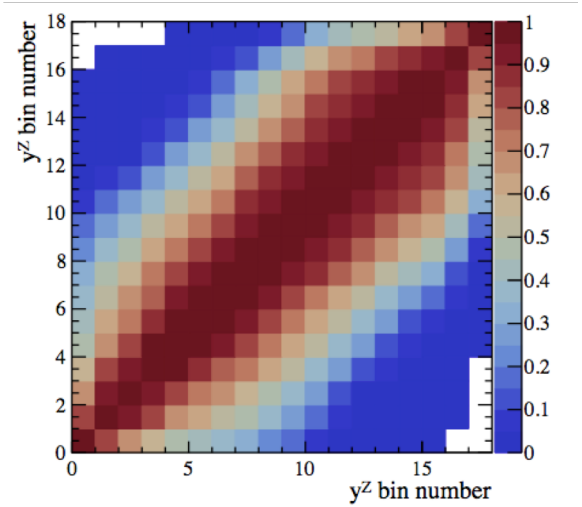
- Luminosity uncertainty, systematic uncertainties from FSR, background modelling, and closure test are treated as 100% correlated

[arXiv:2112.07458]

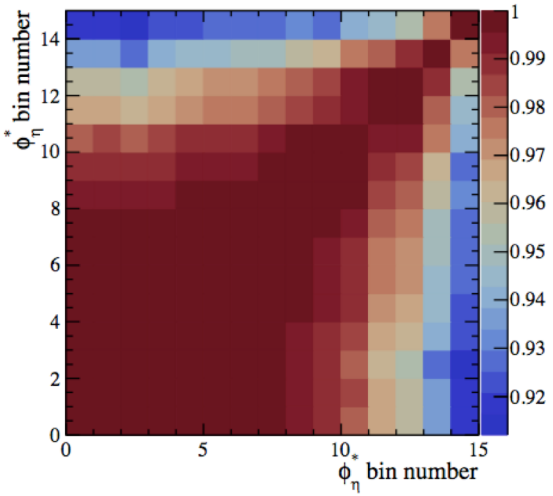
p_T^Z



y_Z

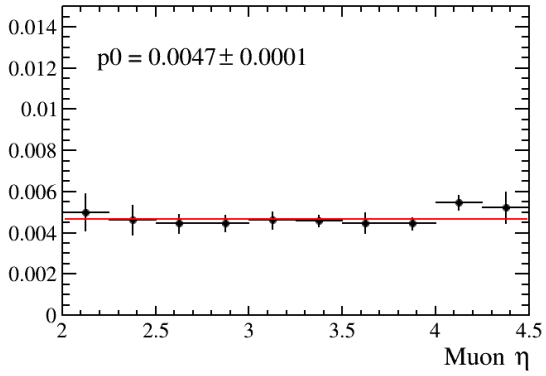


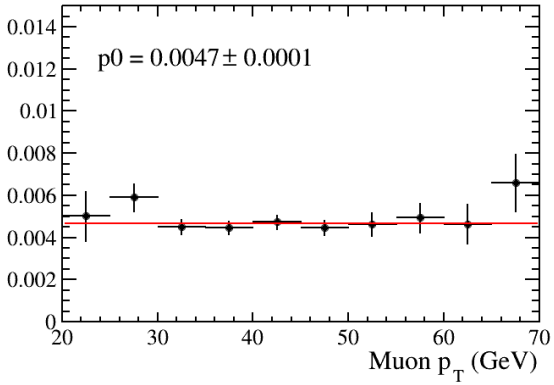
ϕ_η^*



Tracking efficiency

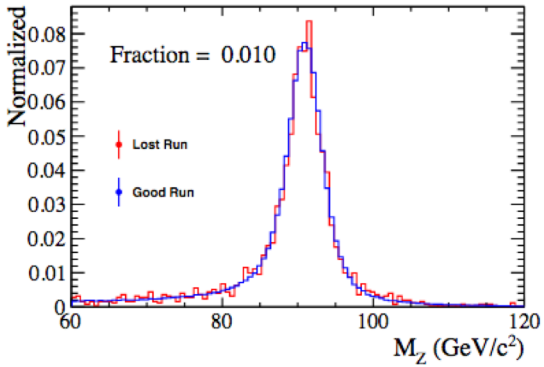
- Total systematic uncertainty from the tracking: 0.47% for each track
  - Matching correction: 0.28%
  - Data and MC matching efficiency differences: 0.33%
  - Data and MC MuonTT finding efficiency differences: 0.1%
  - Differences between the MC-truth eff and the corrected MC tag-and-probe eff
- In previous study, this uncertainty is assigned as 1% for each track

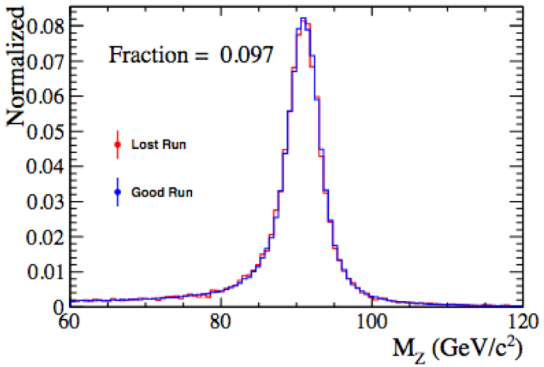


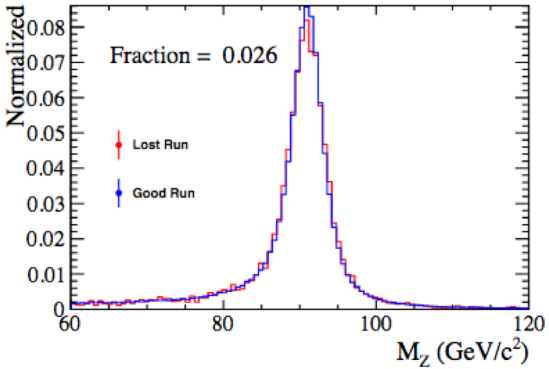


Runs without a determined luminosity

- A small fraction of runs are marked with 'OK' in the bookkeeping, but been removed by the luminosity group in the integrated luminosity calculation
- Overestimated Z signal yields
- Lost run should be removed in any luminosity depended analyses, analyses no depend on the total luminosity should be fine

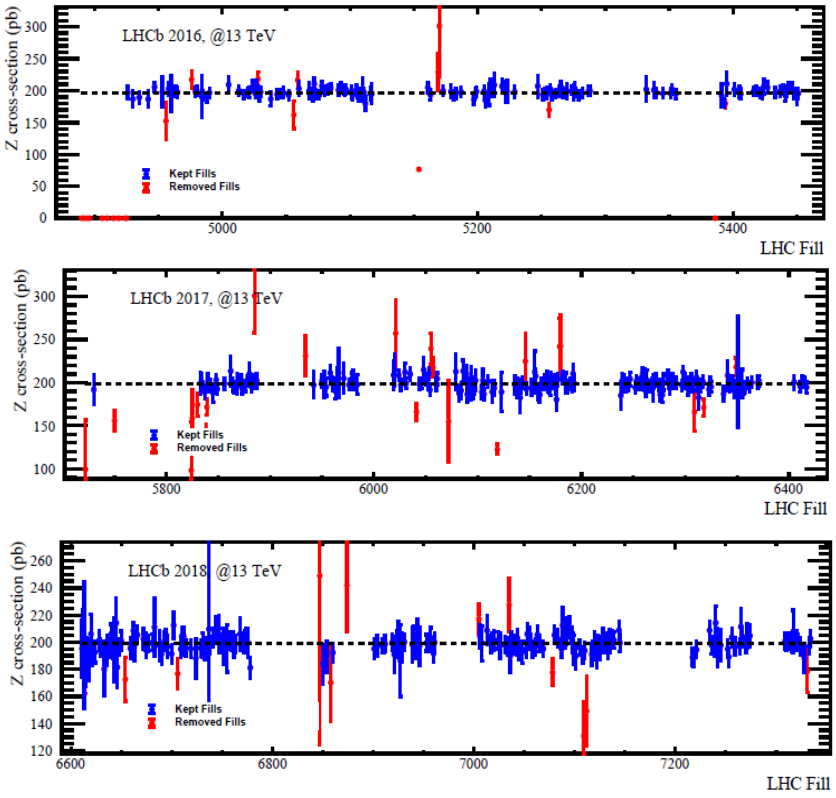






Remove LHC Fill

- Data sample is split into different sub-samples, according to the Fill numbers
- For each sub-sample, the Z signal yield combined with the determined integrated luminosity are used to calculate the total production cross section
- Remove the events in a Fill:
  - If the cross section of this Fill is 3σ (± 18pb) away from the averaged value



Theoretical predictions used in cross-section measurement

- FEWZ:
  - A fixed-order predictions, so FEWZ predictions only works for total cross section and Z-rapidity differential cross section. While for the Z-pT and phi* measurements, the FEWZ predictions do not make any sense, which are far away from the measured results.
  - Only prediction upto NNLO so only use it at the comparison in the ratio
- MathBox and HERWIG are get from the W mass group, only with shape, but not a total cross section
- MathBox: the tunning of a_s will make MatchBox/POWHEG prediction agree with data better

Measurement of forward Z boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV

[arXiv:2112.07458]
submitted to JHEP