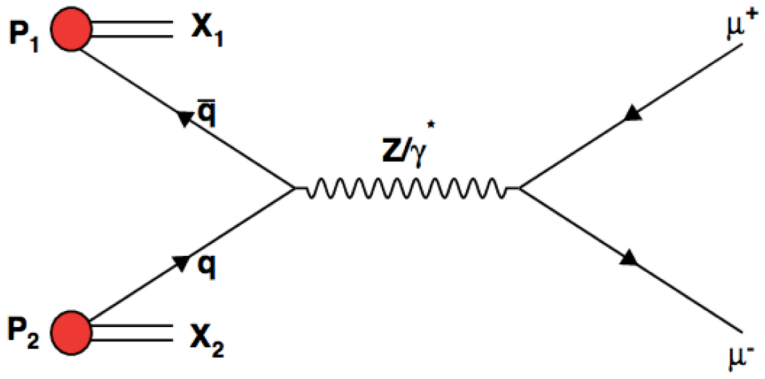
Measurement of forward Z boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV

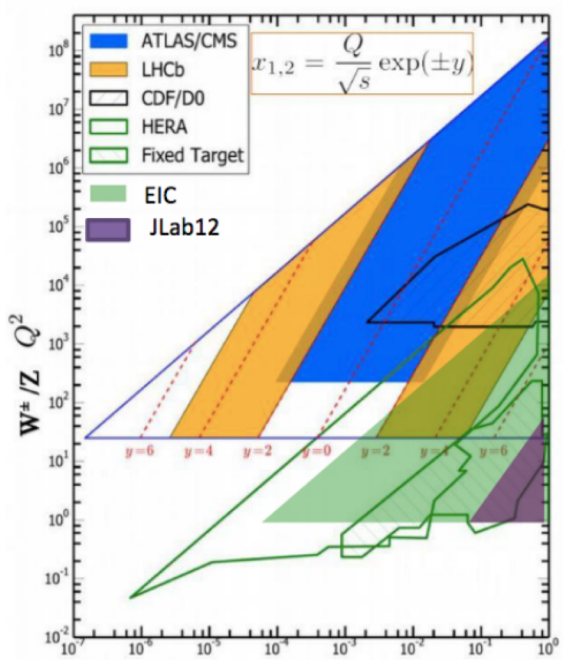
Menglin Xu
On behalf of LHCb Collaboration

Implications Workshop
21. 10. 2021

Motivation

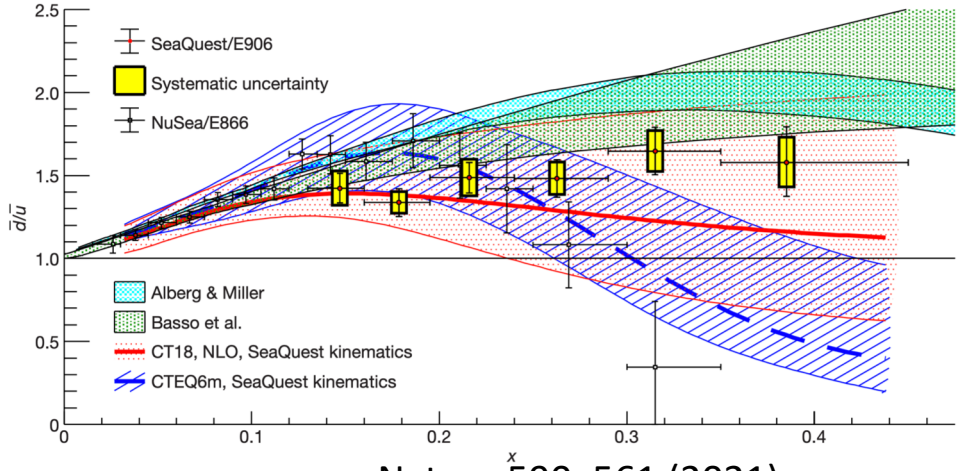
- Precise measurements of W and Z provide an important test of the SM
- Potential to improve constraints on parton distribution functions (PDFs)
- Z boson production decaying into leptons is one of the best understood processes at LHC
- Measurements of the Z boson rapidity are particularly important for constraining u-, d-quark PDFs



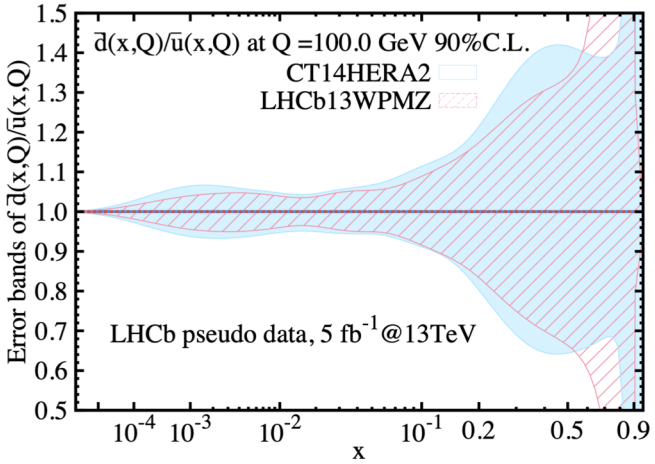


Motivation

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



Nature 590, 561 (2021)



Chin.Phys.C 45 (2021) 2, 023110

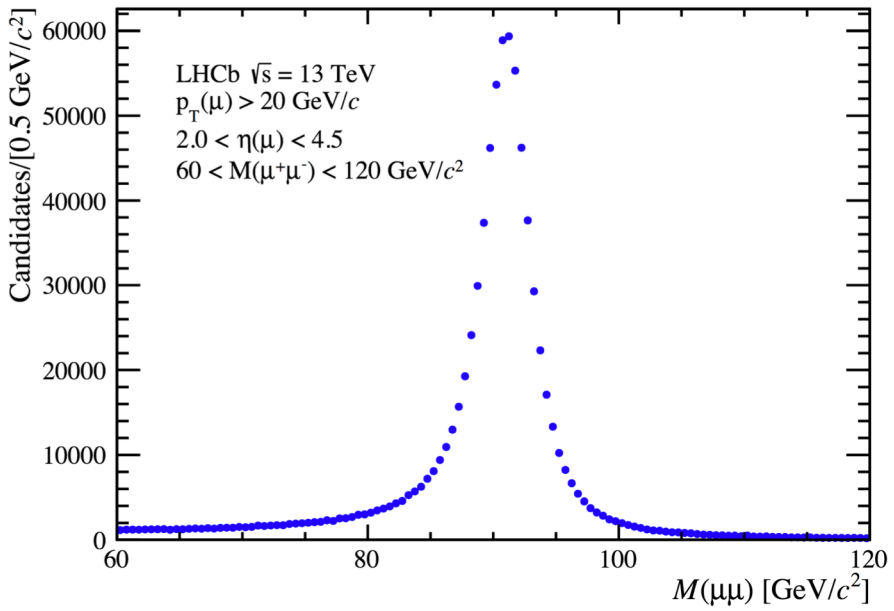
Dataset and fiducial region

- 2016-2018 Data: $5.1 \pm 0.1\ fb^{-1}$
  - $Z \rightarrow \mu^+\mu^-$ sample
  - Same-sign sample: (background study)
- Very high purity, N_{bkg} / N_{sig} ~2%

Fiducial region

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

LHCb preliminary



Cross-section definition

- Cross-section measured in bin of Z y, P_T and ϕ_η^* is given by $$\frac{d\sigma_{Z\to\mu^+\mu^-}}{dy}(i) = \frac{N_Z(i)\cdot f_{FSR}^Z(i)}{\mathcal{L}\cdot\varepsilon_{REC}^Z(i)\cdot\Delta y(i)}$$

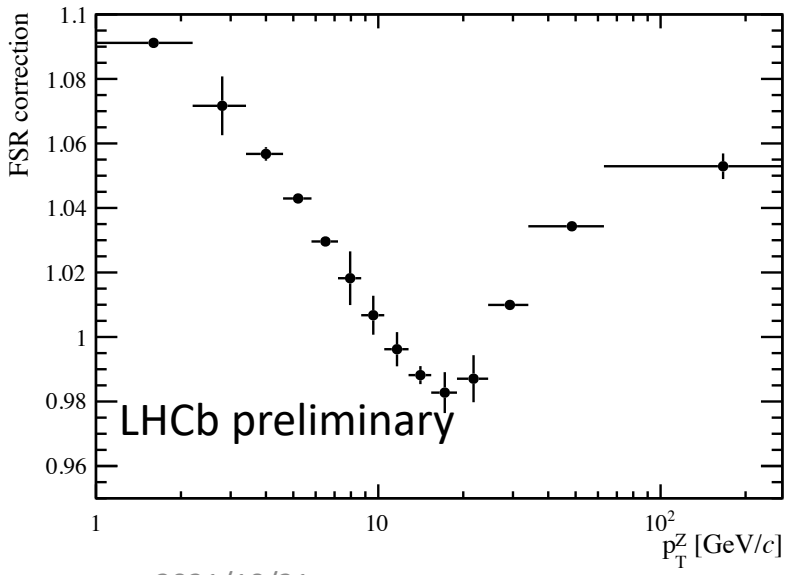
- $\phi_\eta^* = \frac{\tan((\pi-\Delta\phi^{ll})/2)}{\cosh(\Delta\eta/2)}$: similar physics as the boson p_T, but could be measured with better resolution in most detectors
  - $\Delta\phi^{ll}$: the difference in azimuthal angle

- Total cross-section is obtained by summing the differential cross-section

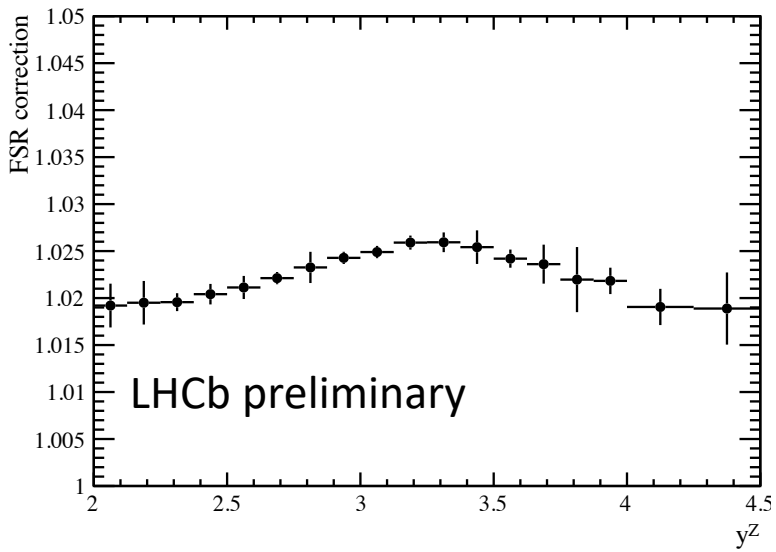
FSR

- In order to be directly compared 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

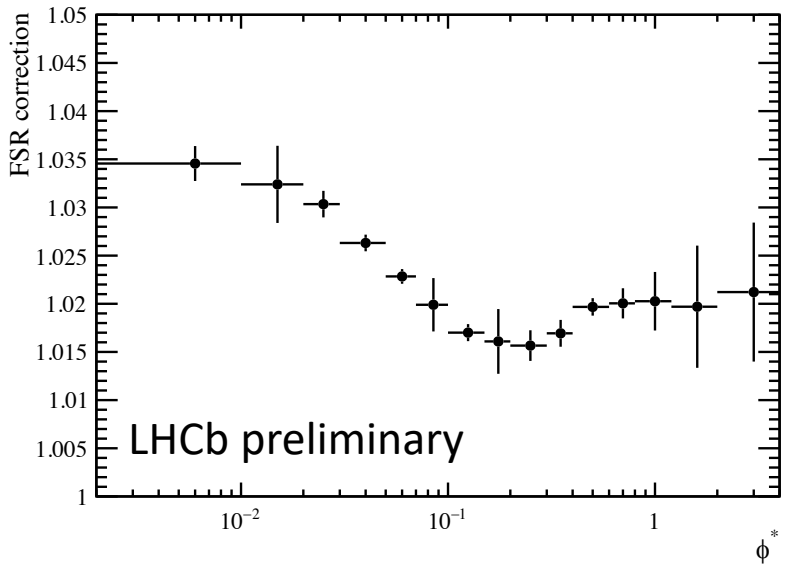
p_T^Z



y_Z



ϕ_η^*



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

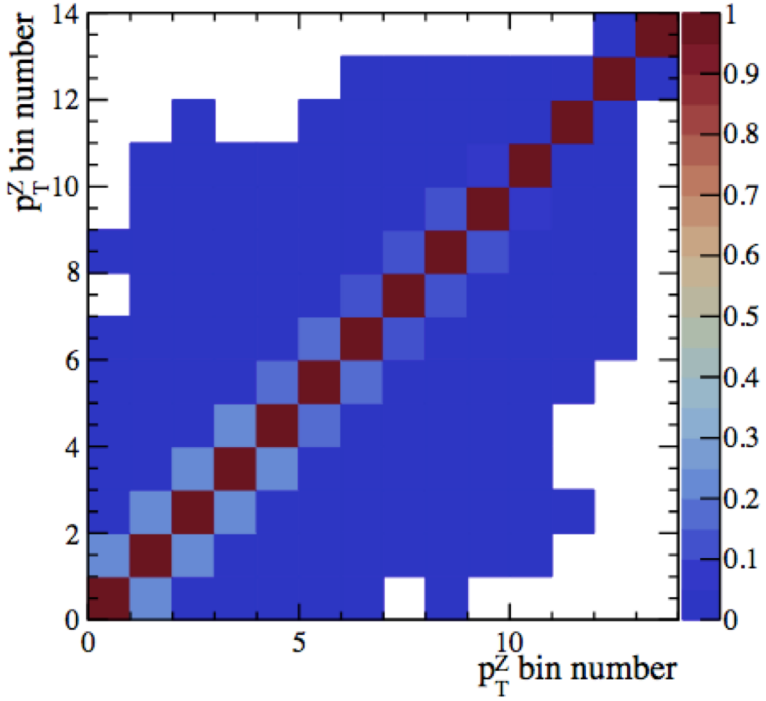
LHCb preliminary

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

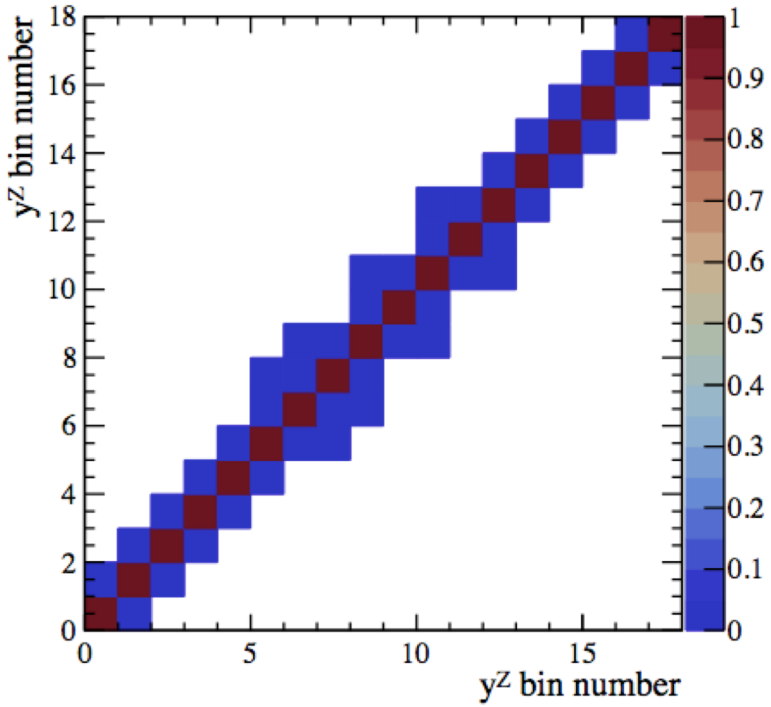
Statistical correlation matrix

- Determined using the simulation events
- Large correlations between events 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

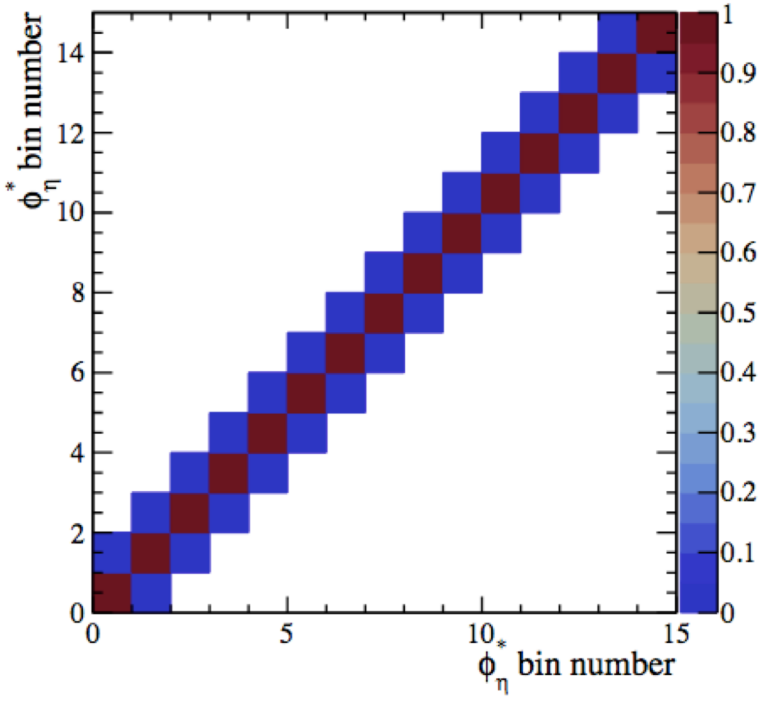
p_T^Z LHCb preliminary



y_Z LHCb preliminary



ϕ_η^* LHCb preliminary

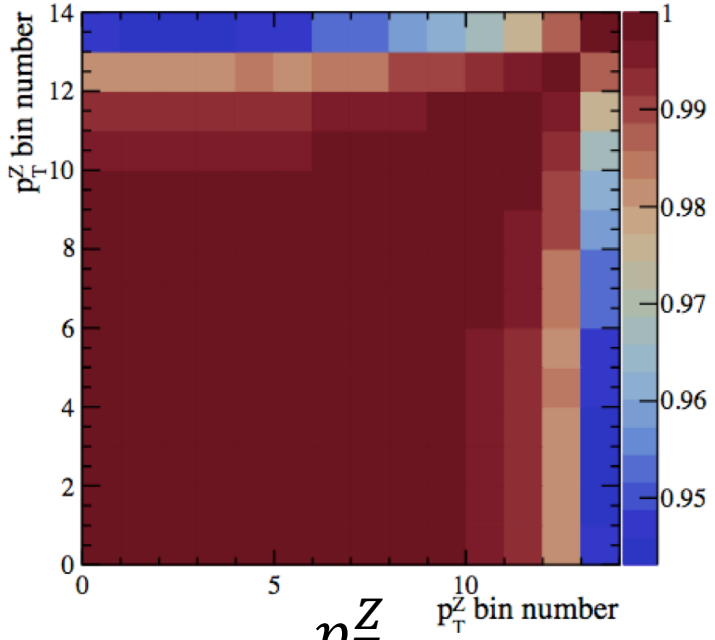


Systematic correlation matrix

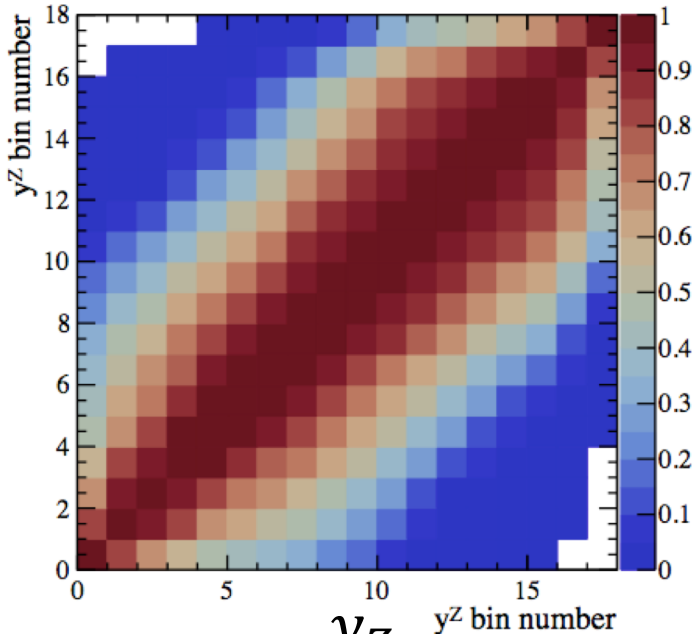
- Systematic uncertainties from background, alignment, efficiency closure test, and FSR are considered to be uncorrelated
- Luminosity uncertainties are considered to be 100% correlated

Efficiency systematic

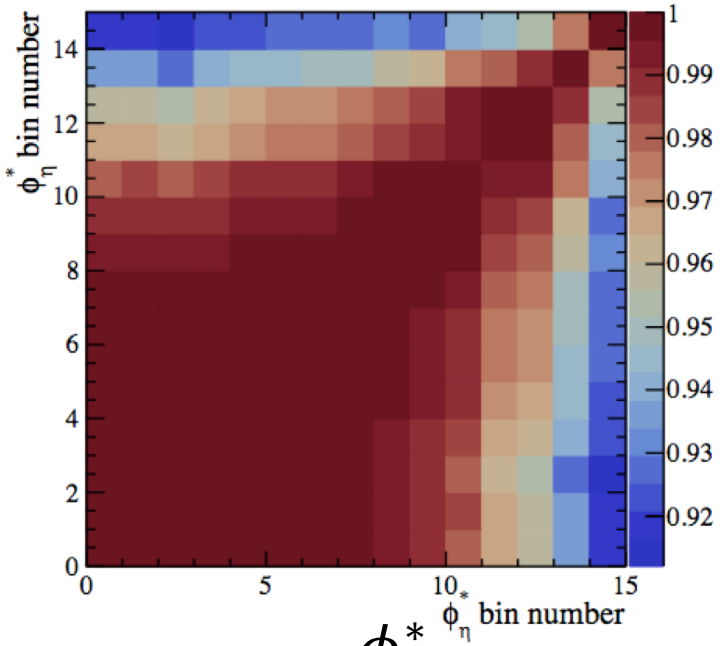
LHCb preliminary



p_T^Z

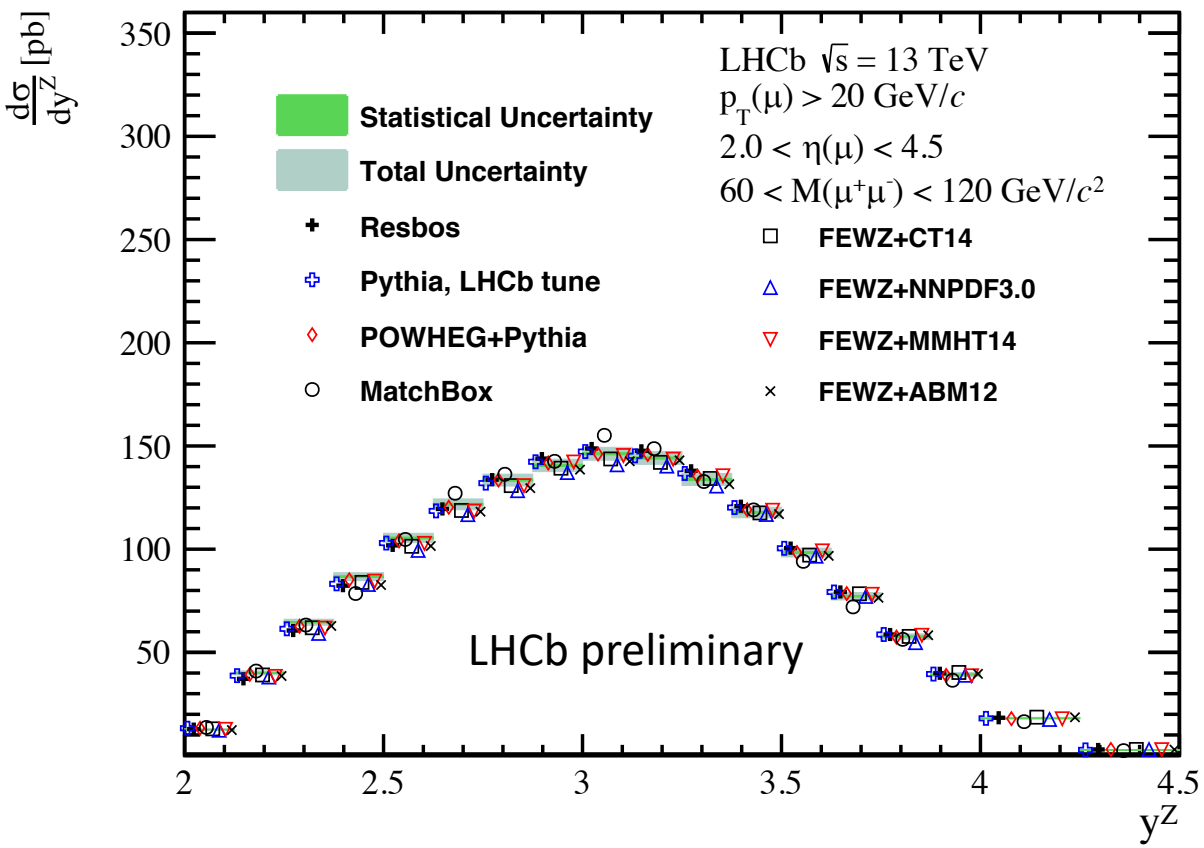


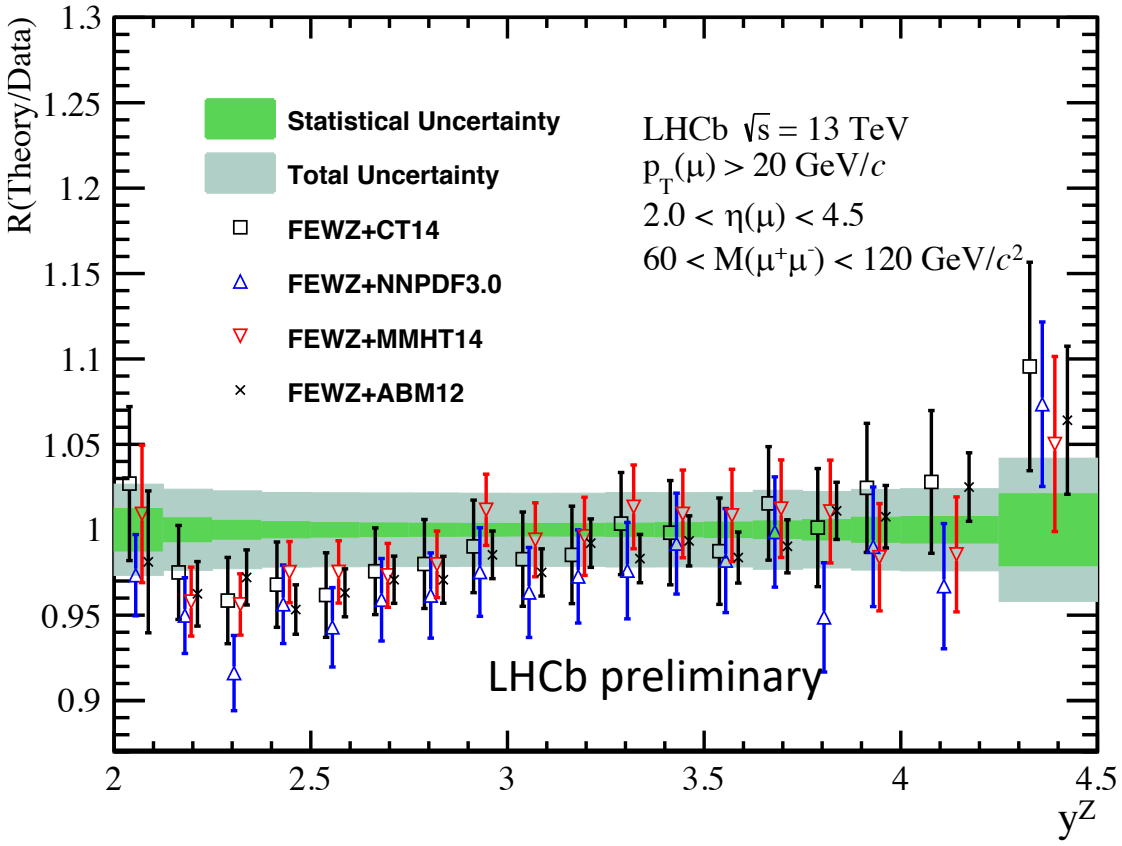
y_Z



ϕ_η^*

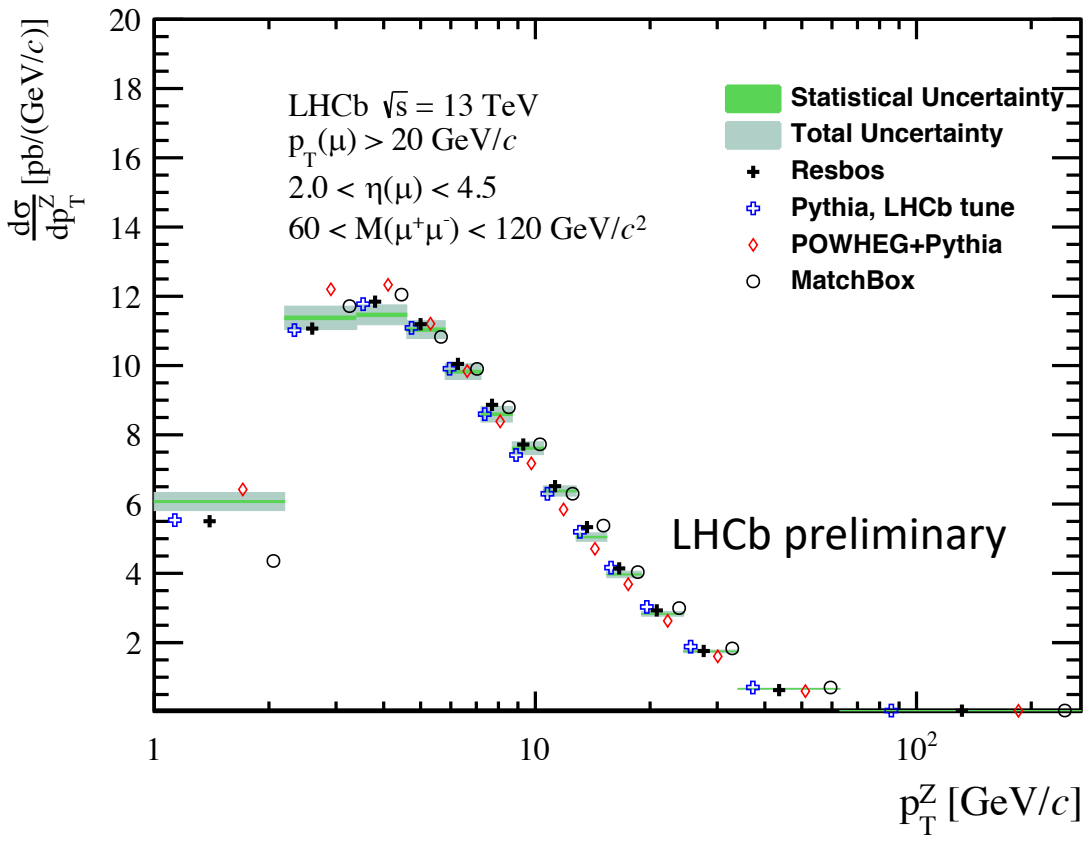
Single differential cross-section: y_Z

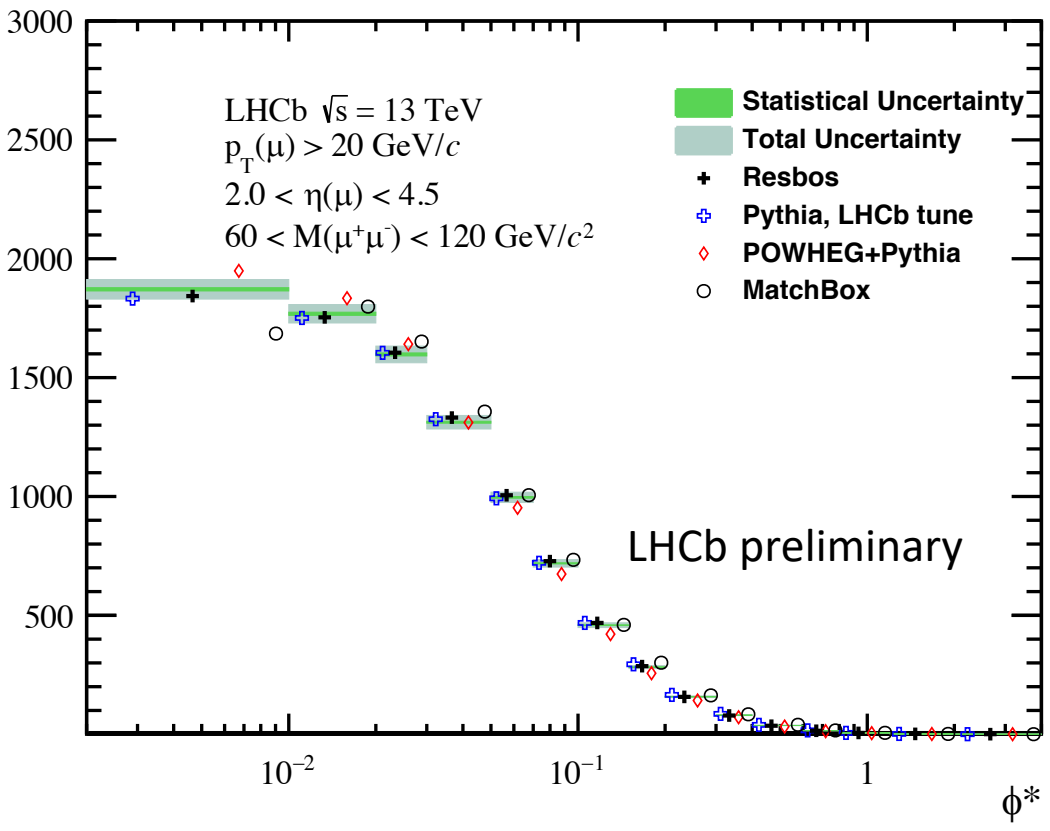




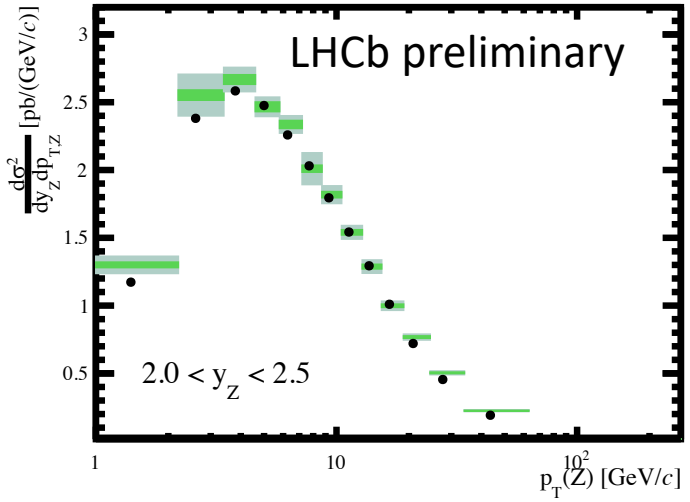
Single differential cross-section: p_T, ϕ^*

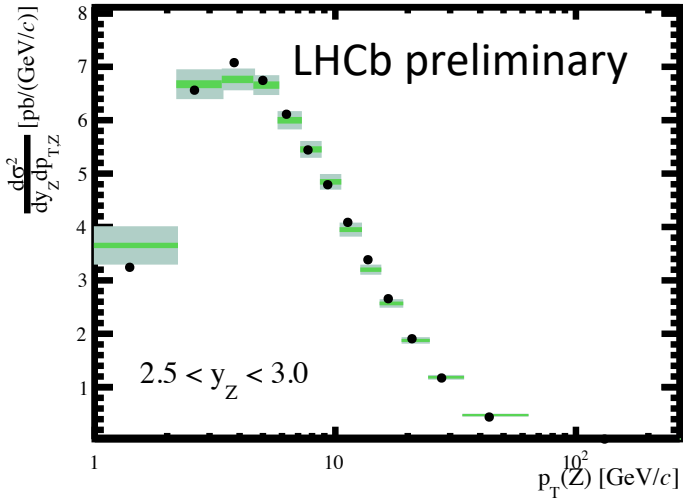
- Reasonable agreement between data and predictions

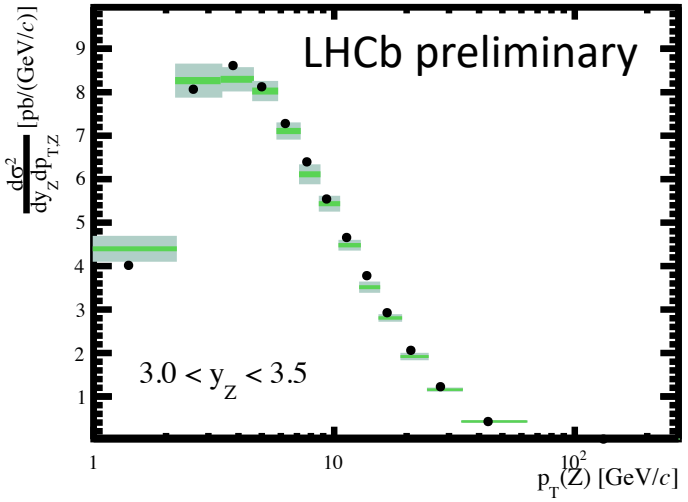


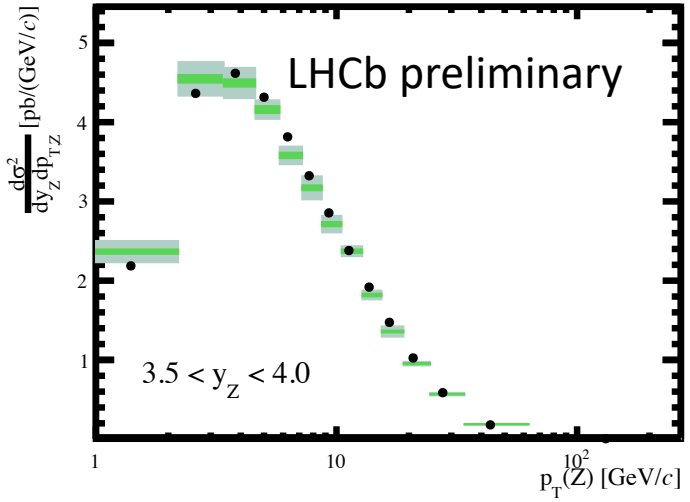


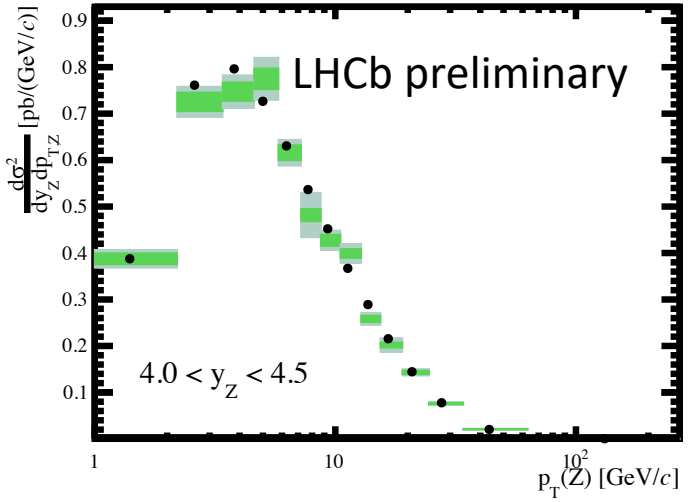
Double differential cross-section: y_Z- P_T







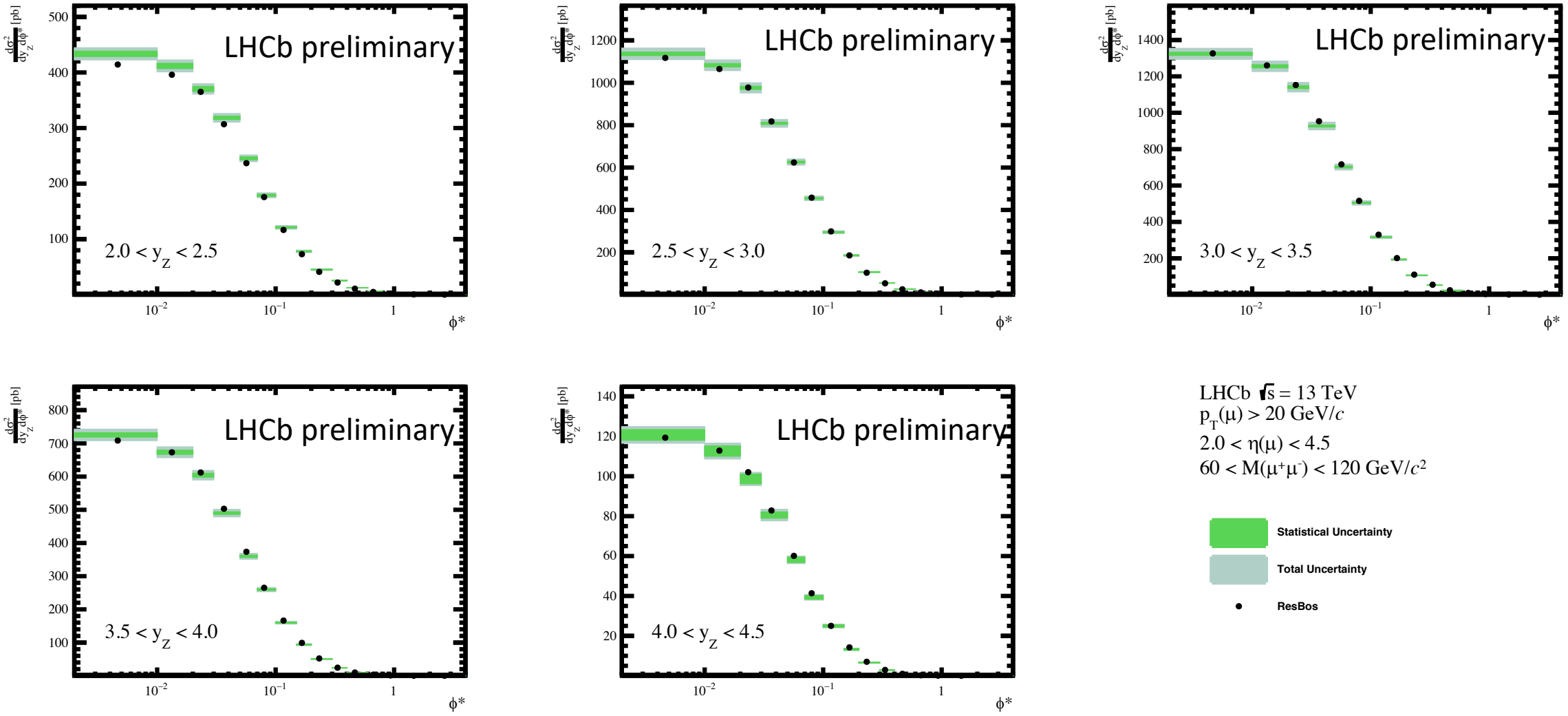




LHCb $\sqrt{s}$ = 13 TeV
$p_T(\mu) > 20$ GeV/c
$2.0 < \eta(\mu) < 4.5$
$60 < M(\mu^+\mu^-) < 120$ GeV/c^2

Statistical Uncertainty
Total Uncertainty
ResBos

Double differential cross-section: y_Z- ϕ_Z^*



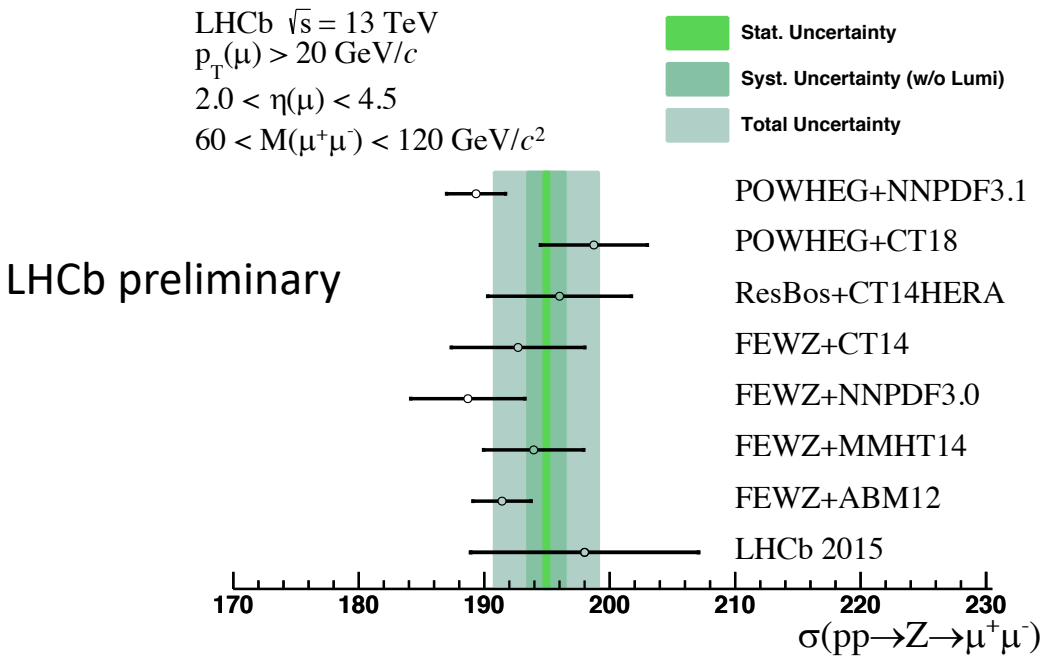
Integrated cross-section

Nucl. Instrum. Meth. A270(1988) 110
Nucl. Instrum. Meth. A500(2003) 391

- 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

$$\text{RunII: } \sigma_{Z\to\mu^+\mu^-} = 195.0 \pm 0.2\ (\text{stat}) \pm 1.5\ (\text{sys}) \pm 3.9\ (\text{lumi})\ \text{pb}$$
$$\text{2015: } \sigma_{Z\to l^+l^-} = 194.3 \pm 0.9\ (\text{stat}) \pm 3.3\ (\text{sys}) \pm 7.6\ (\text{lumi})\ \text{pb}$$

JHEP 09 (2016) 136



LHCb preliminary

Summary

- 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
- The integrated cross-section is measured to be

$$\sigma_{Z\to\mu^+\mu^-} = 195.0 \pm 0.2\ (\text{stat}) \pm 1.5\ (\text{sys}) \pm 3.9\ (\text{lumi})\ \text{pb}$$ (LHCb preliminary)

- Reasonable agreement between the data and the theoretical predictions is seen
- Provide important and unique information to the PDFs global fitting, especially in the large and small x region

Back up

High purity

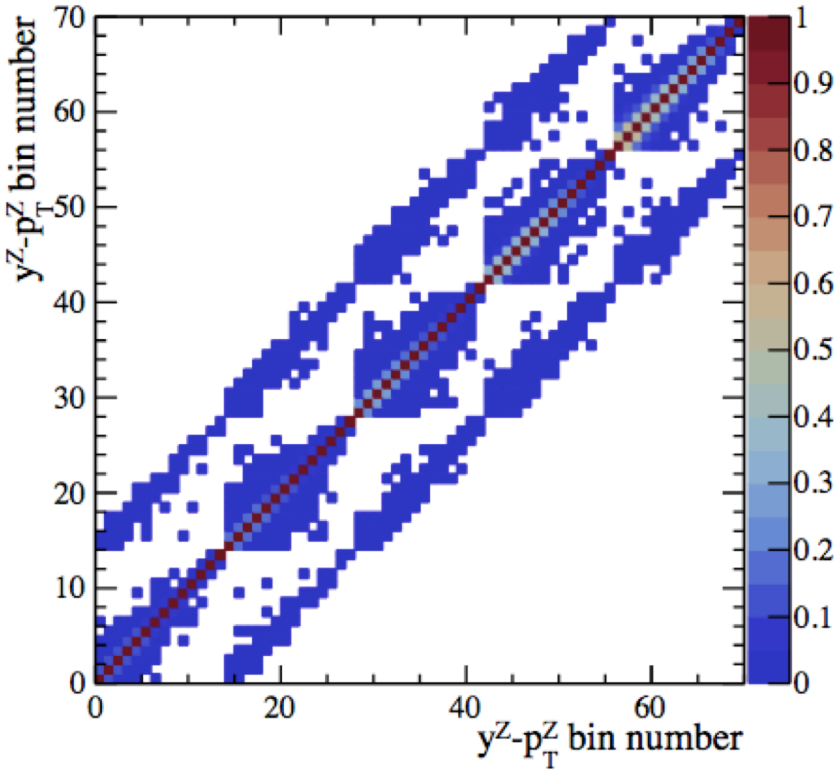
LHCb preliminary

Background	Estimation	Events(2016)	Events(2017)	Events(2018)
HF	data-driven	2469	2298	3352
Mis-ID	data-driven	1626	1442	2130
$Z \to \tau^+\tau^-$	PYTHIA8	259	235	324
$gg \to t\bar{t}$	PYTHIA8	143	130	180
$qq \to t\bar{t}$	PYTHIA8	385	349	482
W^+W^-	PYTHIA8	46	42	58
Total		4929	4496	6528
Bkg/Signal		2.01%	1.97%	2.09%

Statistical correlation matrix – two dimensional

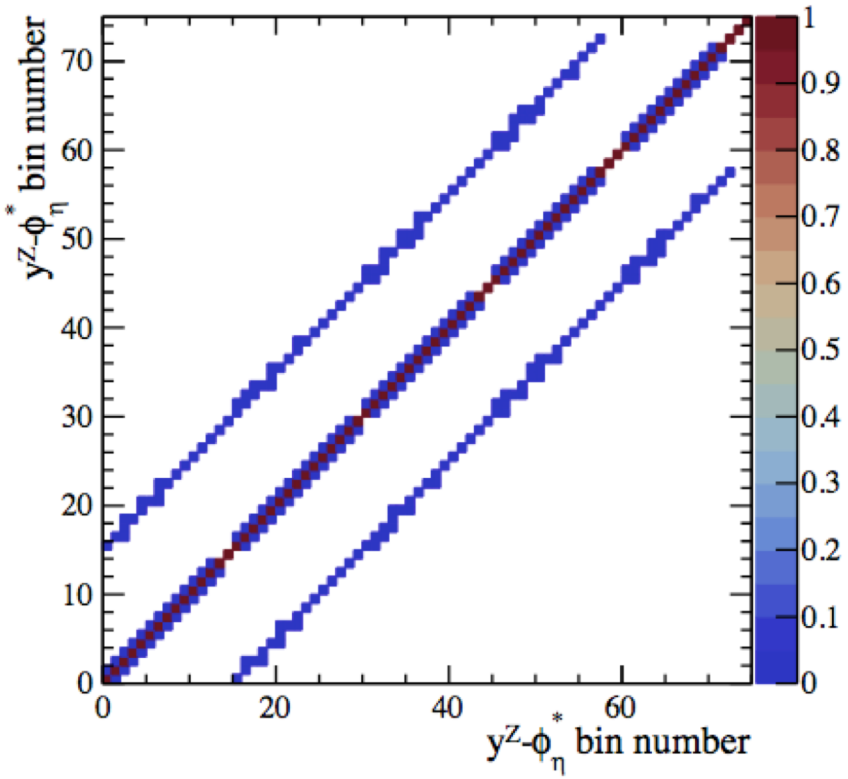
$y_Z - p_T^Z$

LHCb preliminary



$y_Z - \phi_\eta^*$

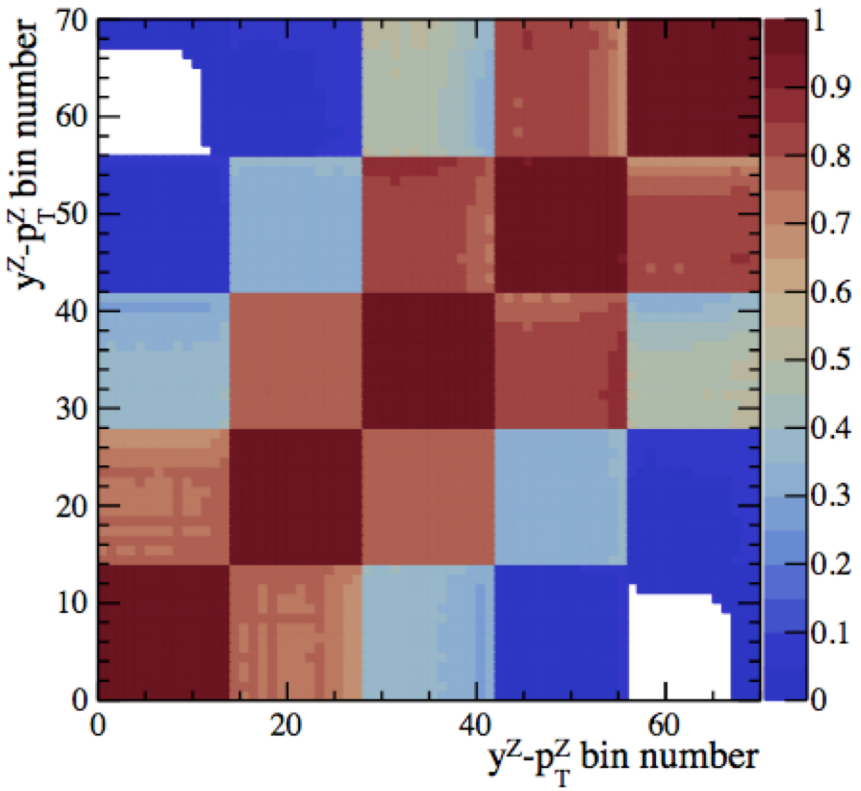
LHCb preliminary



Efficiency uncertainties correlation matrix – 2D

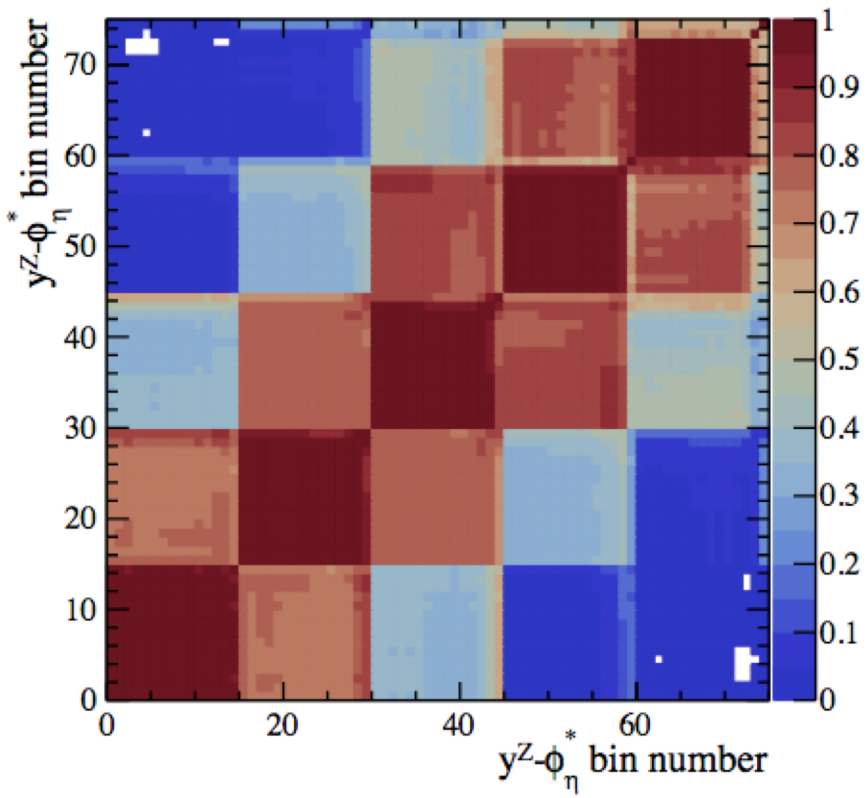
$y_Z - p_T^Z$

LHCb preliminary



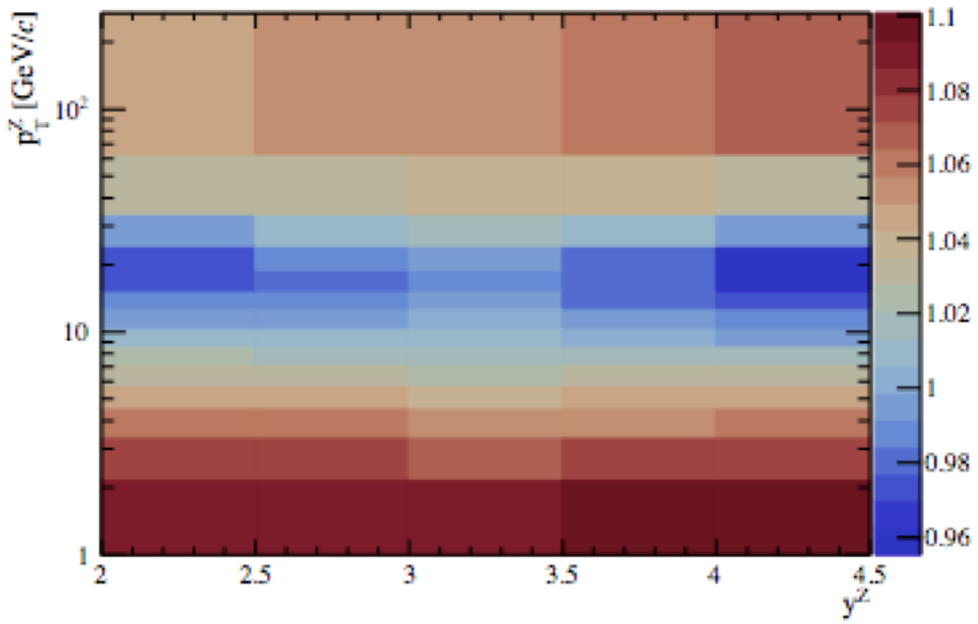
$y_Z - \phi_\eta^*$

LHCb preliminary

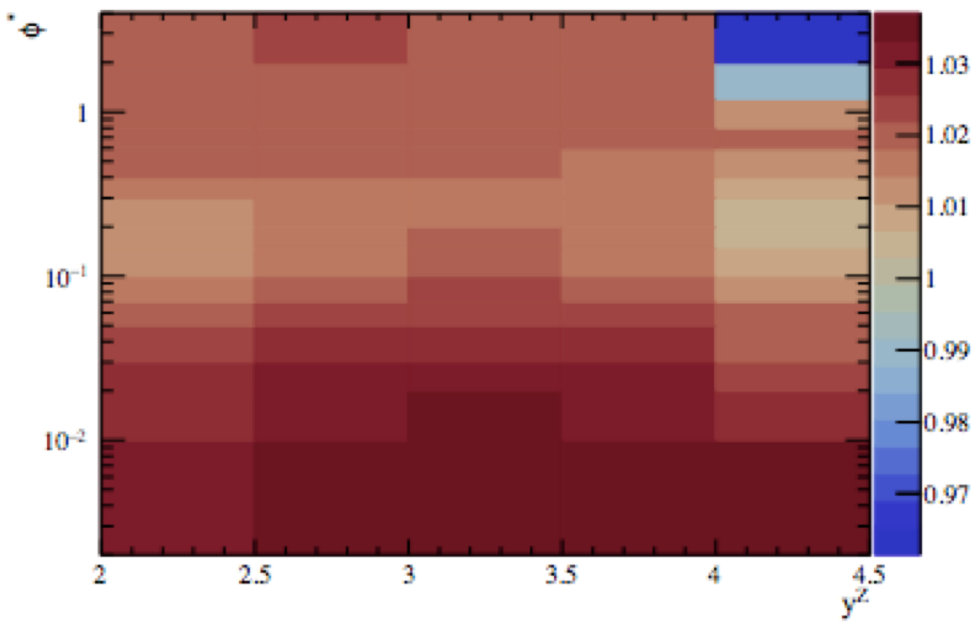


FSR correction

LHCb preliminary



LHCb preliminary



Tracking efficiencies – uncertainty summary

- 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