



PDF4LHC workshop, 23 November 2022



PDF4LHC: News from LHCb

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on behalf of the LHCb collaboration

An incomplete summary of results from LHCb

W, Z, top @ 7 & 8 TeV:

W and Z @ 7 TeV (36 pb ⁻¹ partial dataset)	JHEP 06 (2012) 58
Z @ 7 TeV (1 fb ⁻¹ full dataset)	JHEP 08 (2015) 039
W @ 7 TeV (1 fb ⁻¹ full dataset)	JHEP 12 (2014) 079
Z → ττ @ 7 TeV	JHEP 01 (2013) 111
Z → ee @ 7 TeV	JHEP 02 (2013) 106
Z + jets @ 7 TeV	JHEP 01 (2014) 33
Z + D @ 7 TeV	JHEP 04 (2014) 91
Z + b-jets @ 7 TeV	JHEP 01 (2015) 064
Z → ee @ 8 TeV	JHEP 05 (2015) 109
W + b/c-jets @ 7 & 8 TeV	PRD92 (2015) 052001
W and Z @ 8 TeV	JHEP 01 (2016) 155
W → ev @ 8 TeV	JHEP 10 (2016) 030
t \bar{t} , W + b \bar{b} , W + c \bar{c} @ 7 & 8 TeV	RLB 767 (2017) 110
t \bar{t} @ 7 & 8 TeV	PRL 115 (2015) 112001
Z → b \bar{b} @ 8 TeV	PLB 776 (2018) 430
Z → ττ @ 8 TeV	JHEP 09 (2018) 159

Z @ 13 TeV:

Z @ 13 TeV (294 pb ⁻¹ partial dataset)	JHEP 09 (2016) 136
Z + c-jets @ 13 TeV	PRL 128 (2022) 082001
Z → μμ @ 13 TeV (5 fb ⁻¹ full dataset)	JHEP 07 (2022) 26

Z in pPb collisions:

Z in pPb @ 5.02 TeV	JHEP 09 (2014) 030
Z in pPb @ 8.16 TeV	arXiv:2205.10213 (JHEP accepted)

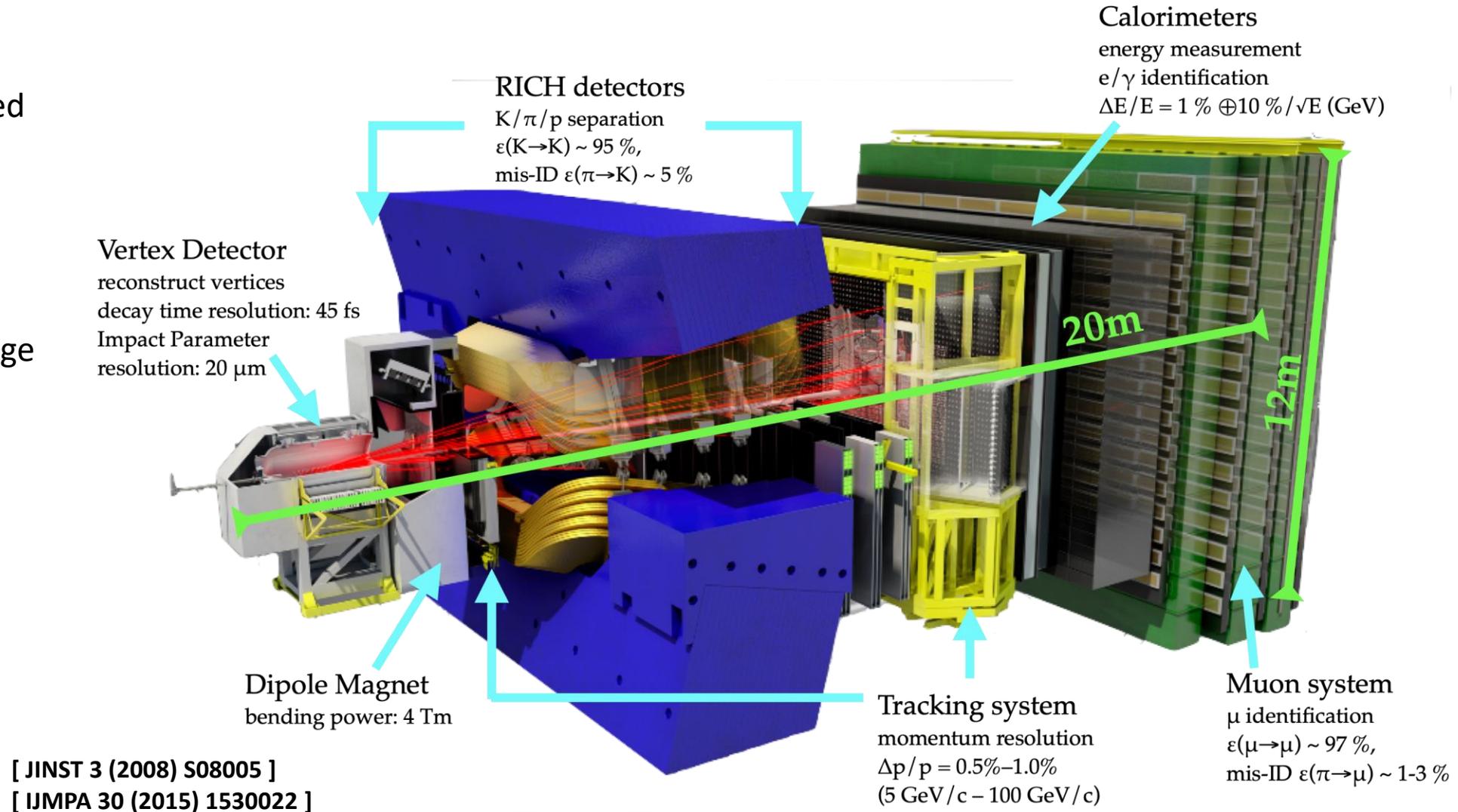
Exclusive photoproduction:

CEP J/ψ and ψ(2S) @ 7 TeV	J. Phys. G40 (2013) 045001
Updated CEP J/ψ and ψ(2S) at 7 TeV	J. Phys. G41 (2014) 055002
CEP Υ @ 7 TeV	JHEP 09 (2015) 084
CEP J/ψ and ψ(2S) @ 13 TeV	JHEP 10 (2018) 167
CEP J/ψ @ 8.16 TeV 2015 PbPb UPC	JHEP 07 (2022) 117
CEP J/ψ and ψ(2S) @ 8.16 TeV 2018 PbPb UPC	arXiv: 2206.08221 (JHEP submitted)

New results to be covered today.

The LHCb detector

- LHCb is the only dedicated detector (at LHC) fully instrumented in forward region
- Unique kinematic coverage
 $2 < \eta < 5$
- A high precision device, down to very low- p_T , excellent particle ID, precise vertex and track reconstruction.



Z boson as a probe

$Z + c$ -jets @ 13 TeV

[PRL 128 \(2022\) 082001](#)

$Z \rightarrow \mu\mu$ @ 13 TeV (5 fb⁻¹ full dataset)

[JHEP 07 \(2022\) 26](#)

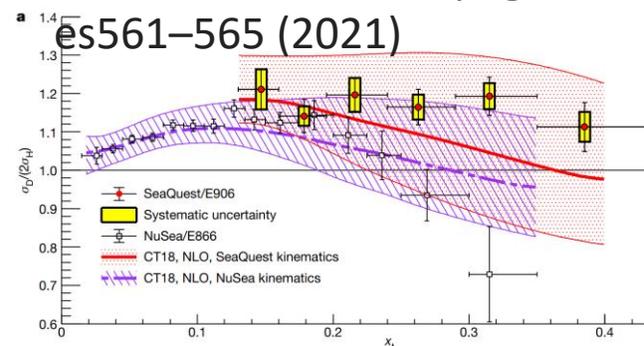
Z in pPb @ 8.16 TeV

[arXiv:2205.10213 \(JHEP accepted\)](#)

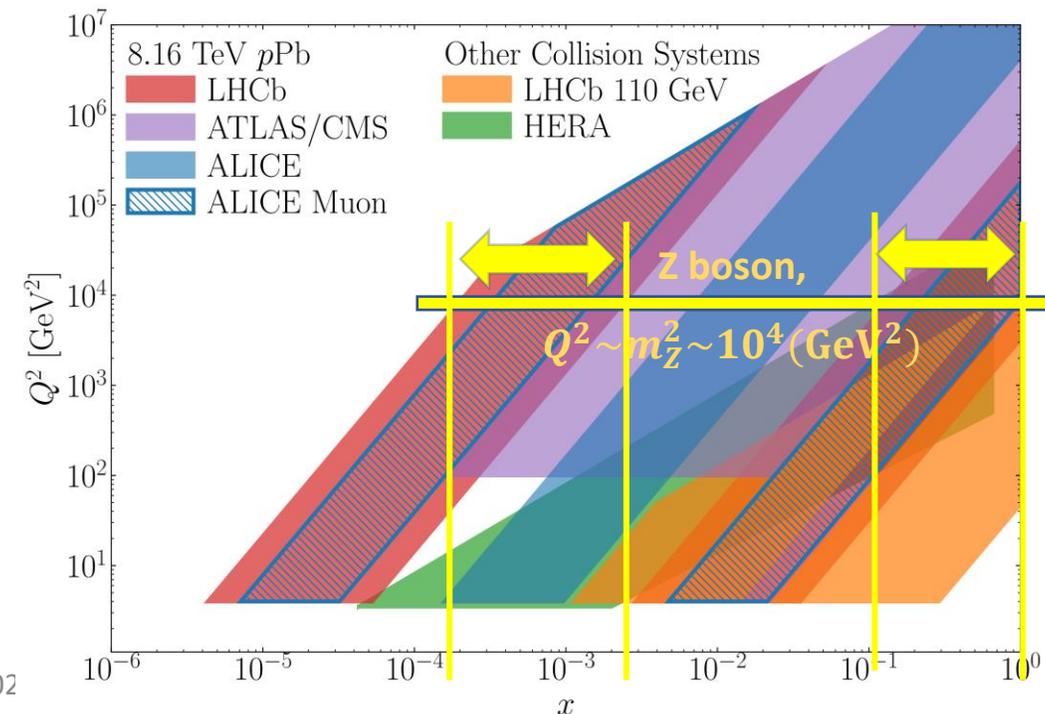
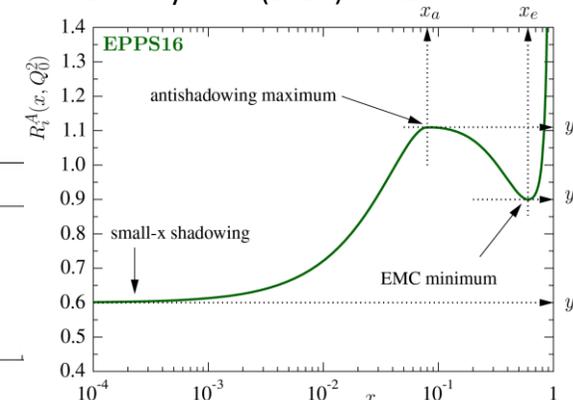
Z boson as probes

- Can be precisely predicted by factorization theory. Once created, do not participate in strong interaction, unaffected by hadronic activities in the final states.
- Ideal probe of the initial conditions, such as proton PDFs, nuclear modifications, etc.
 - Bjorken- x in $10^{-4} < x < 10^{-3}$ and $10^{-1} < x < 1$,
 - with $Q^2 \sim m_Z^2 \sim 10^4 \text{ GeV}^2$.
- Of particular interest in constraining u/d PDFs
 - Inconsistency show up in SeaQuest and NuSea results, LHCb data will be the only clean data to clarify it.
- Z @ LHC also sensitive to the intrinsic heavier quark flavors [Eur. Phys. J. C (2017) 77:488]

Nature volume 590, pages 561–565 (2021)

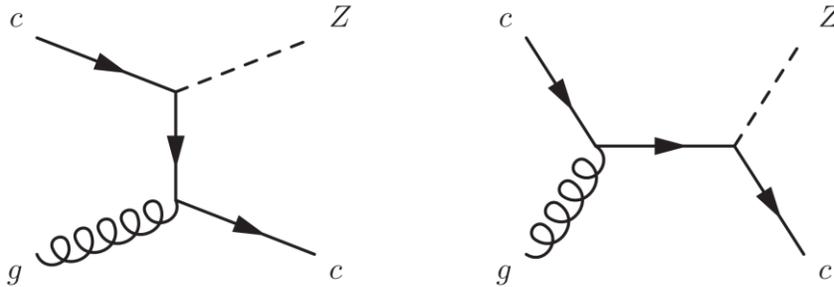


Eur. Phys. J. C (2017) 77 :163



Probe intrinsic charm

- Intrinsic-charm vs. extrinsic-charm.
- $Z + c$ -jets production:



Leading-order Feynman diagrams for $gc \rightarrow Zc$

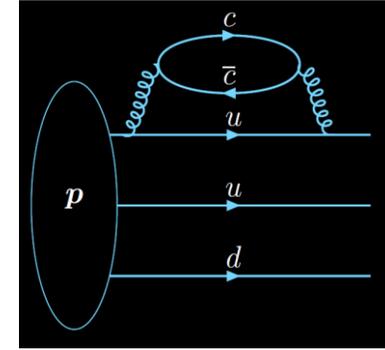
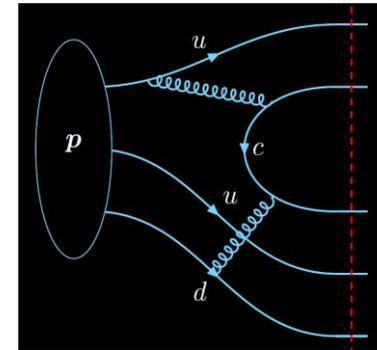
- Valence-like intrinsic charm contents in proton PDFs can enhance c-jet production especially at high Bjorken- x

Intrinsic-charm:

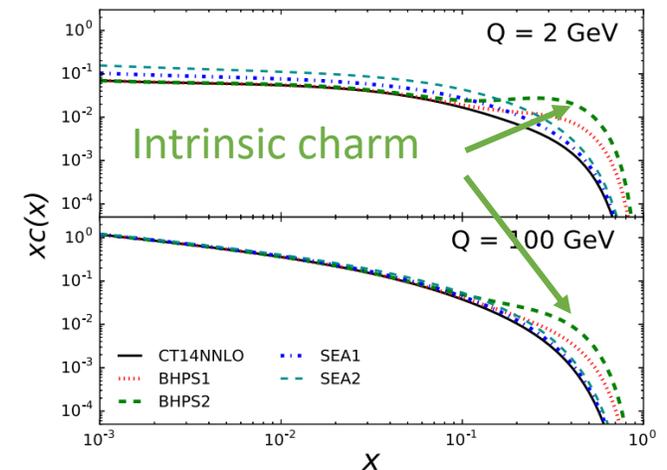
Non-perturbative
valence-quark-like
long time scale

Extrinsic-charm:

Perturbative
short time scale



Phys. Rev. D 93 (2016) 074008

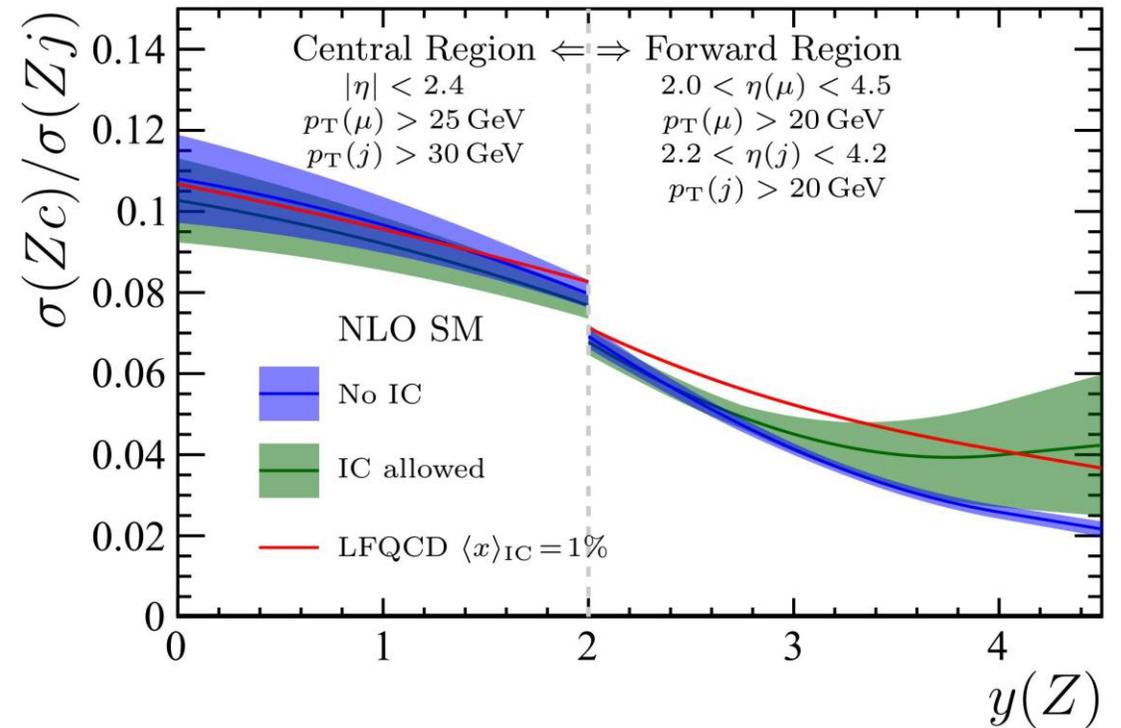


Probe intrinsic charm

- First study of $Z + c$ -jets in the forward region, with optimized c-tagging.
- Measure ratio:

$$\sigma(Z + c \text{ jets})/\sigma(Z + \text{all jets})$$
 - Percent-level intrinsic-charm contribution would significantly enhance the ratio at high $y(Z)$.
 - Models allowing intrinsic-charm are largely unconstrained at high $y(Z)$.
 - Jet-related systematic uncertainties can largely cancel in the ratio.

PRL 128 (2022) 08200



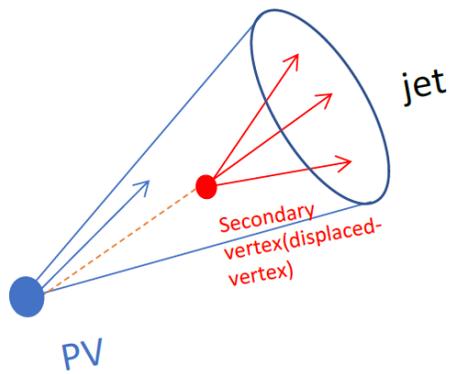
Probe intrinsic charm

PRL 128 (2022) 08200

- LHCb Run2 (2015 – 2018) pp collisions at 13 TeV, about 6 fb^{-1} , using $Z \rightarrow \mu^+ \mu^-$ events:

$$R_j^c = \frac{N(Z + c \text{ jets})}{N(Z + \text{all jets})\epsilon(c - \text{tag})}$$

- C-jet is tagged using method based on displaced-vertex (DV, or secondary vertex)



Fiducial region/event selection

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	$\Delta R(\mu, j) > 0.5$

Systematic uncertainties

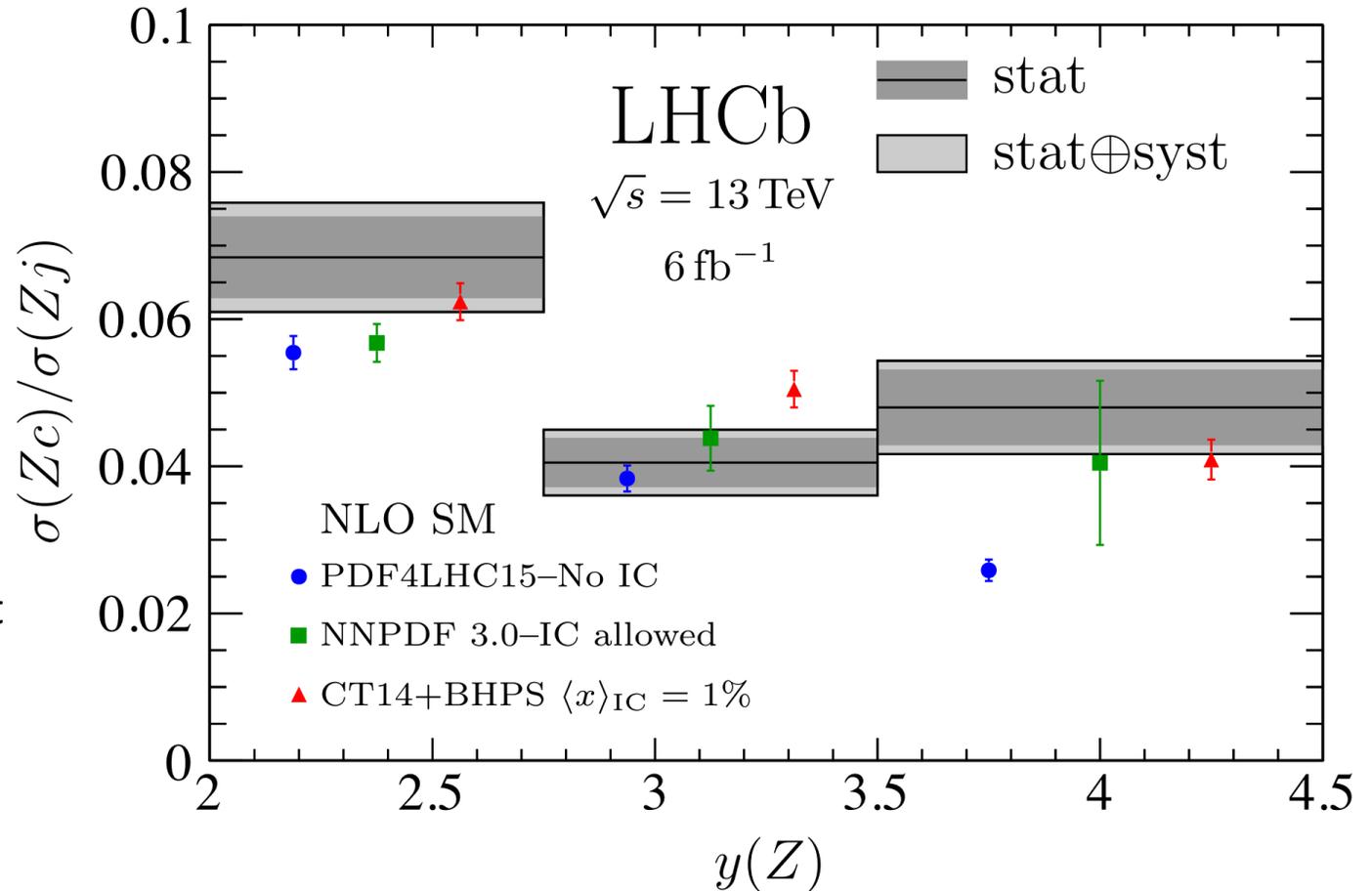
- Leading systematic uncertainty due to **c-tagging calibration**
LHCb-DP-2021-006
- Other systematic uncertainties almost cancelled in the ratio.

Source	Relative uncertainty
c tagging	6%–7%
DV-fit templates	3%–4%
Jet reconstruction	1%
Jet p_T scale and resolution	1%
Total	8%

Probe intrinsic charm

PRL 128 (2022) 08200

- Clear enhancement in highest y bin.
- Inconsistent with No-Intrinsic-Charm theory at $>3\sigma$.
- More consistent with intrinsic-charm-allowed predictions, such as the BHPS model based on light front QCD.
- High rapidity results should strongly constrain the large- x charm PDF.
- Current results are statistically limited, Run3 dataset will allow for finer binning.



Z production in pp collisions

JHEP 07(2022)026

- LHCb pp data@13 TeV: $5.1 \pm 0.1 \text{ fb}^{-1}$ (2016-2018).

- Very high purity: $N_{bkg}/N_{sig} \sim 2\%$

- Fiducial volume:

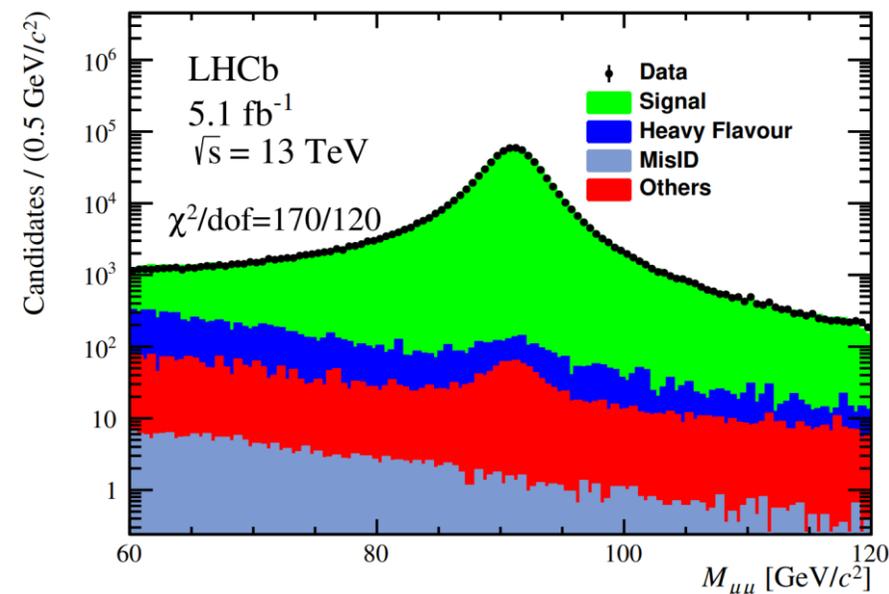
$$p_T^\mu > 20 \text{ GeV}, 2.0 < \eta_\mu < 4.5,$$

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

- Differential Cross-section:

$$\frac{d\sigma_{Z \rightarrow \mu\mu}}{dy} = \frac{\Delta N_Z(y) \cdot f_{\text{FSR}}(y)}{\mathcal{L} \cdot \epsilon(y) \cdot \Delta y}$$

in bins of Z rapidity, p_T^Z , and φ^* .



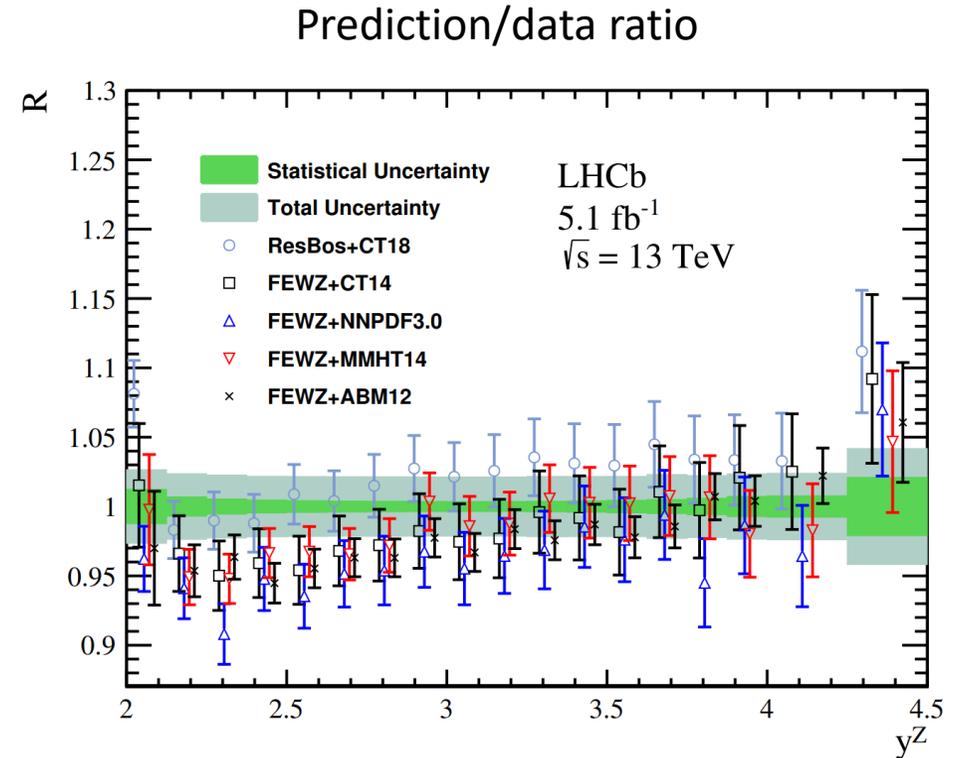
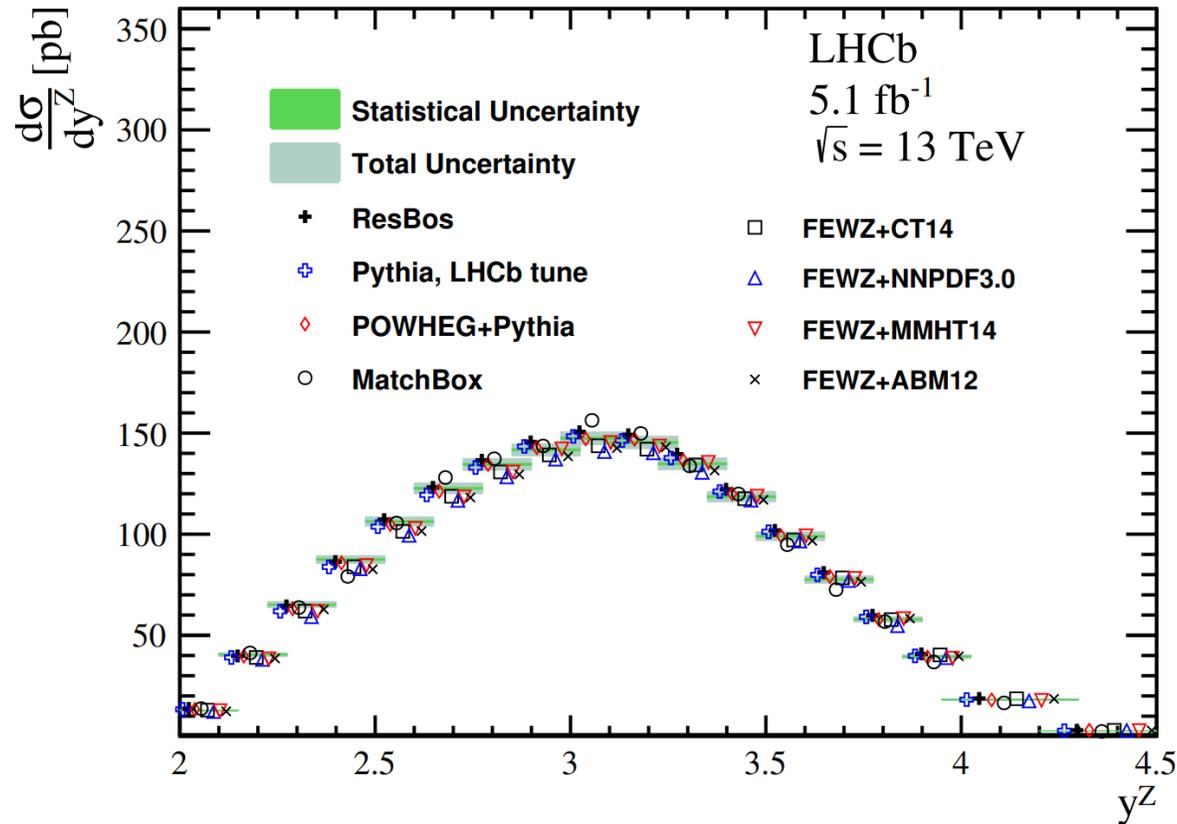
Systematic uncertainties

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

Z production in pp collisions

JHEP 07(2022)026

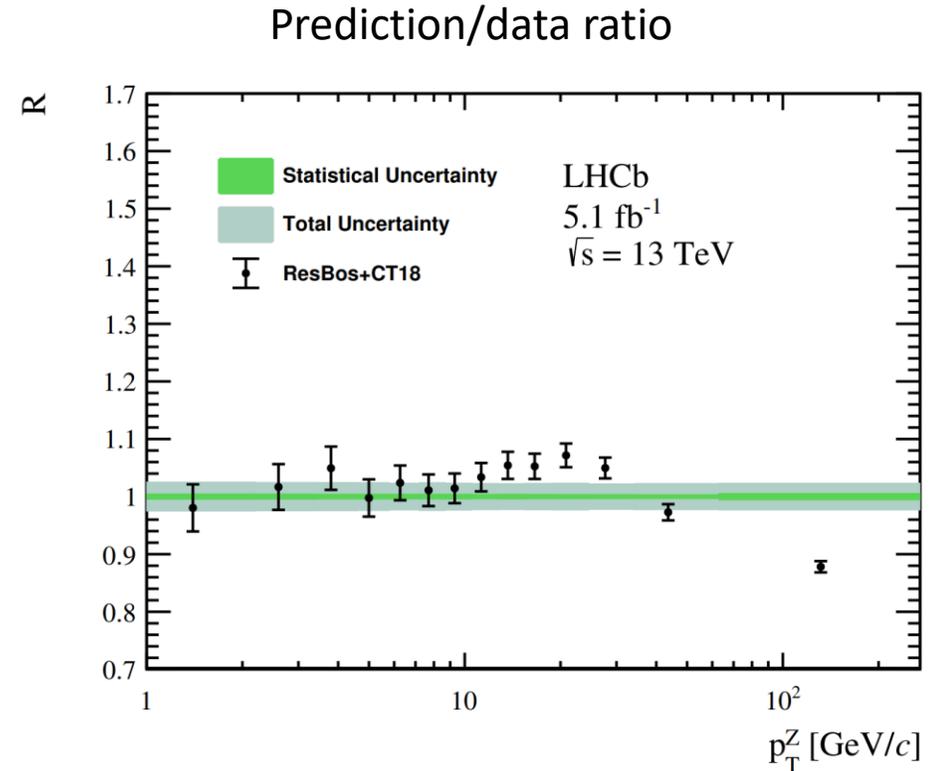
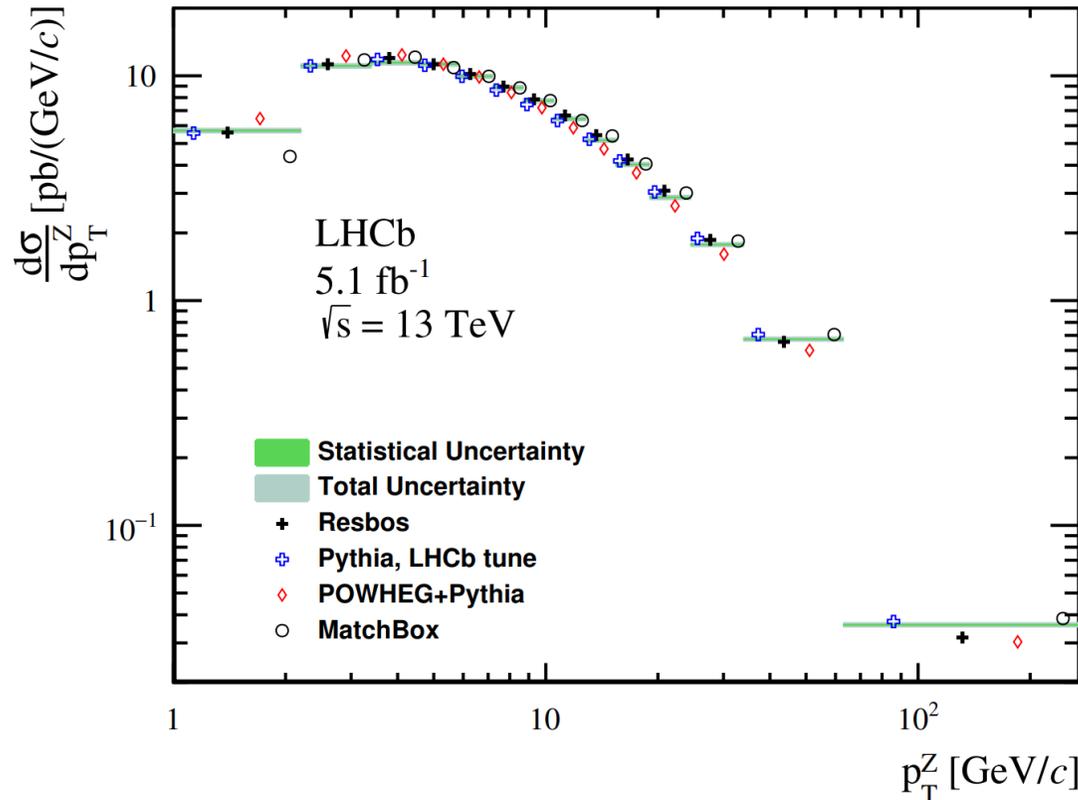
- Single differential cross-section vs Z boson rapidity
 - Compatible with theory prediction, difference observed at rapidity from 2 to 3



Z production in pp collisions

JHEP 07(2022)026

- Single differential cross-section vs. p_T^Z
 - Compatible with theory prediction, difference observed in large p_T^Z

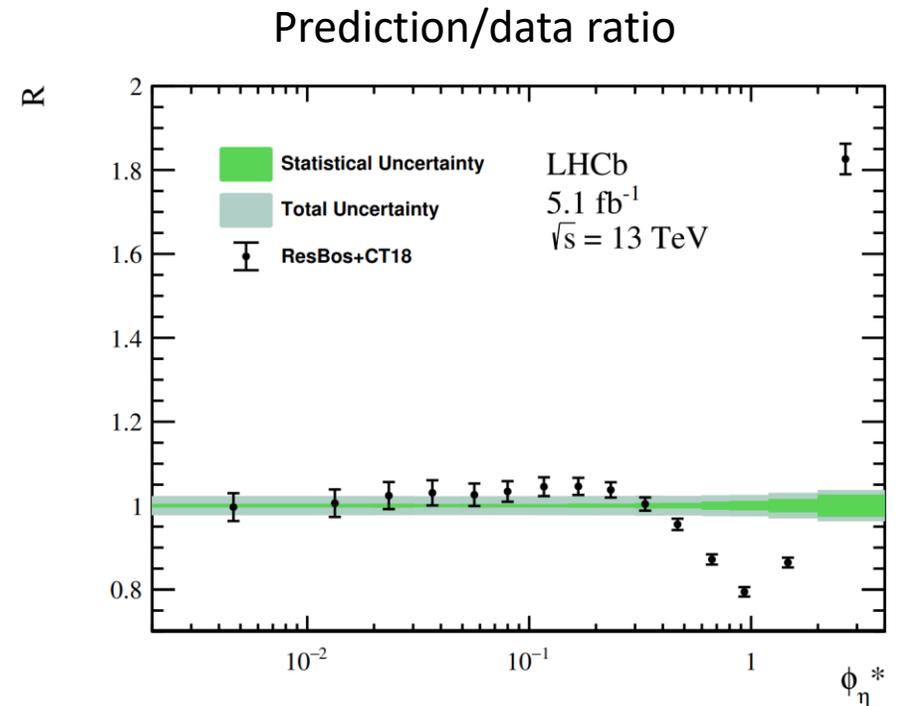
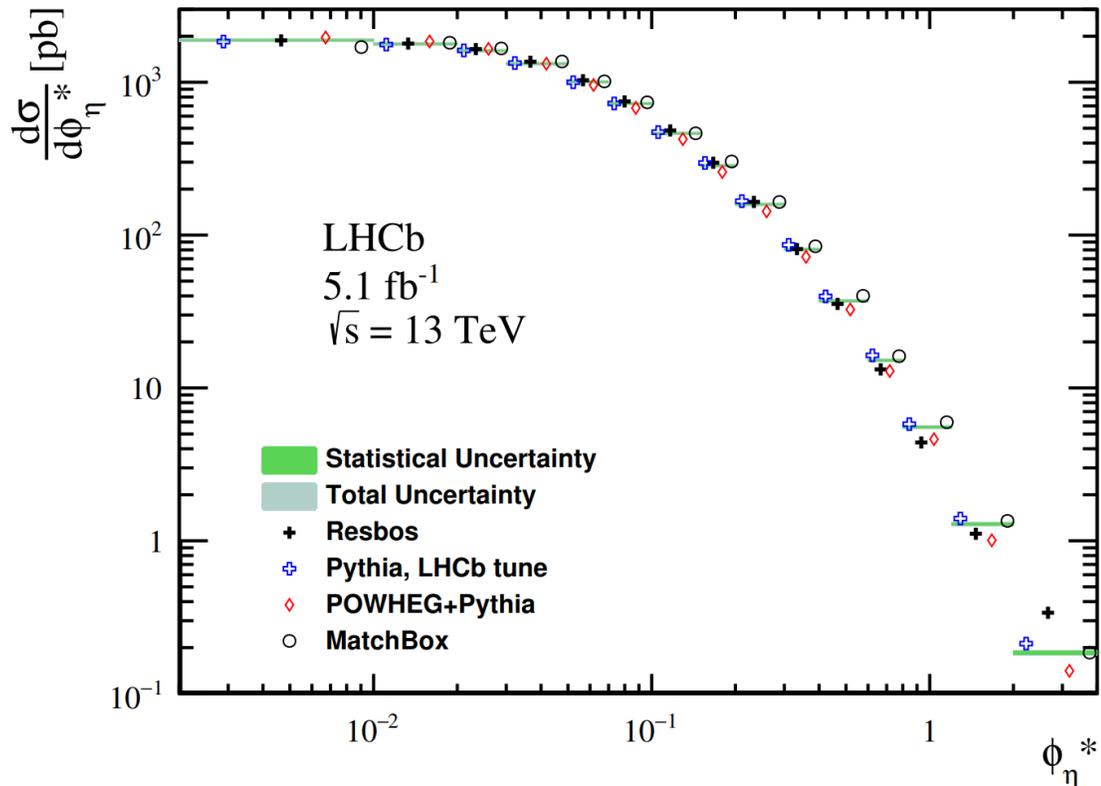


Z production in pp collisions

JHEP 07(2022)026

- Single differential cross-section vs. ϕ^*
 - Compatible with theory prediction,
 - Difference observed at large ϕ^* corresponds to large p_T^Z

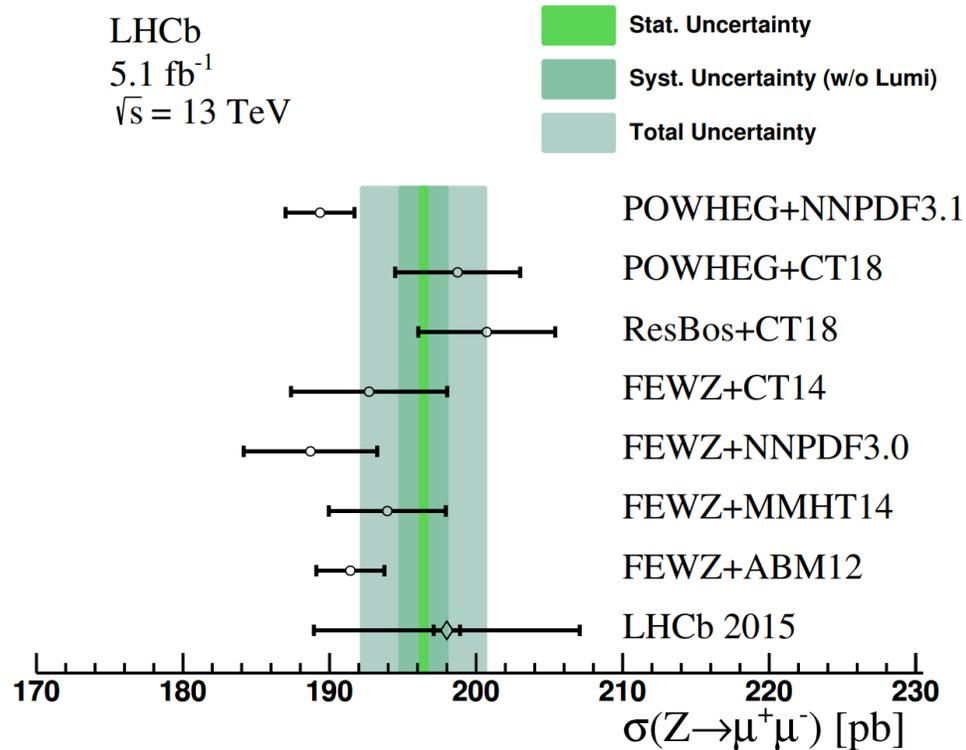
$\phi^* = \tan(\phi_{\text{acop}}/2) / \cos(\Delta\eta/2)$,
equivalent to p_T^Z , less impacted by
detector resolution effects.



Z production in pp collisions

- Integrated cross-section Run2:

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



Most precise measurement in the forward region at the moment.

Combined using “BLUE” method:

[NIM A270(1988) 110, NIM A500(2003) 391]

- Uncertainties from Lumi., FSR corr., background, closure test, are treated as 100% correlated.
- Other uncertainties are treated as not correlated.

$p\text{Pb}$ data at 8.16 TeV about 30 nb^{-1} .

- Fiducial volume:**

$$p_T^\mu > 20 \text{ GeV}, 2.0 < \eta_\mu < 4.5,$$

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

- Cross-section:**

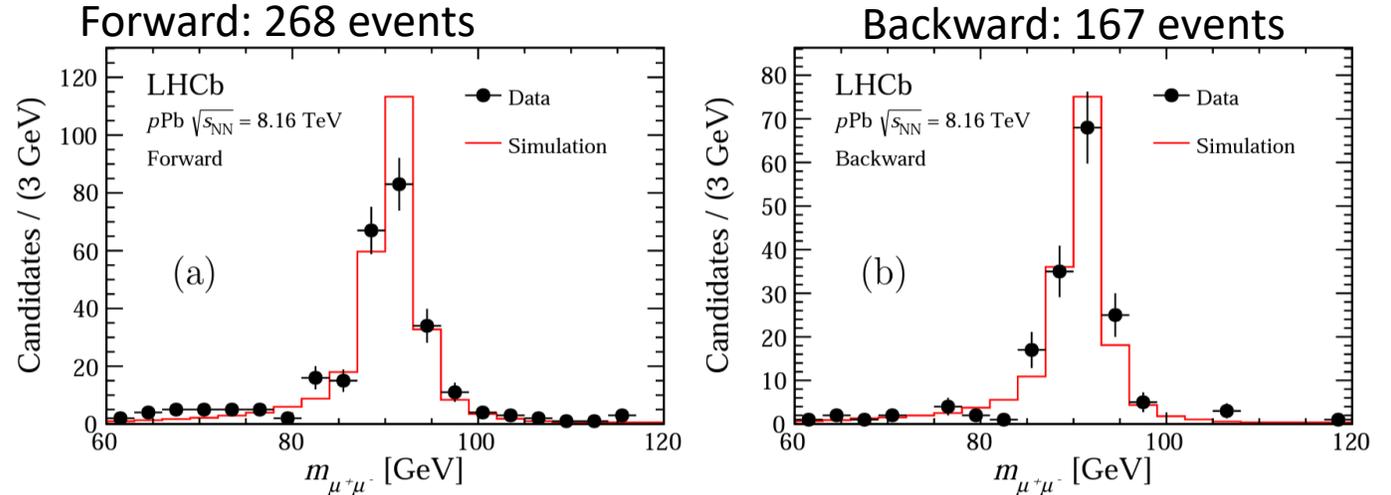
$$\sigma_{Z \rightarrow \mu\mu} = \frac{N_{\text{cand}} \cdot \rho \cdot f_{\text{FSR}}}{\mathcal{L} \cdot \epsilon}$$

- Forward-backward ratio:**

$$R_{\text{FB}} = \frac{\sigma_{(1.53 < y_\mu^* < 4.03)}}{\sigma_{(-4.97 < y_\mu^* < -2.47)}} \cdot k_{\text{FB}}$$

- Nuclear modification factors:**

$$R_{p\text{Pb}}^{\text{fw.}} = \frac{1}{208} \cdot \frac{\sigma_{(p\text{Pb}, 1.53 < y_\mu^* < 4.03)}}{\sigma_{(pp, 2.0 < y_\mu^* < 4.5)}} \cdot k_{p\text{Pb}}$$



- The cross-section, R_{FB} and $R_{p\text{Pb}}$ are measured as a function of y_Z^* , p_T^Z , and ϕ_η^*
 - k_{FB} and $k_{p\text{Pb}}$: muon rapidity acceptance correction factors.
 - pp reference cross-section at 8.16 TeV is interpolated from LHCb 7, 8 and 13 TeV results.

Z production in $p\text{Pb}$ collisions

LHCb-PAPER-2022-009, arXiv:2205.10213

- **Total fiducial cross-section:**

$\sigma_{Z \rightarrow \mu\mu, \text{fwd.}}$

$= 26.9 \pm 1.6(\text{stat.}) \pm 0.9(\text{syst.}) \pm 0.7(\text{lumi.}) \text{nb}$

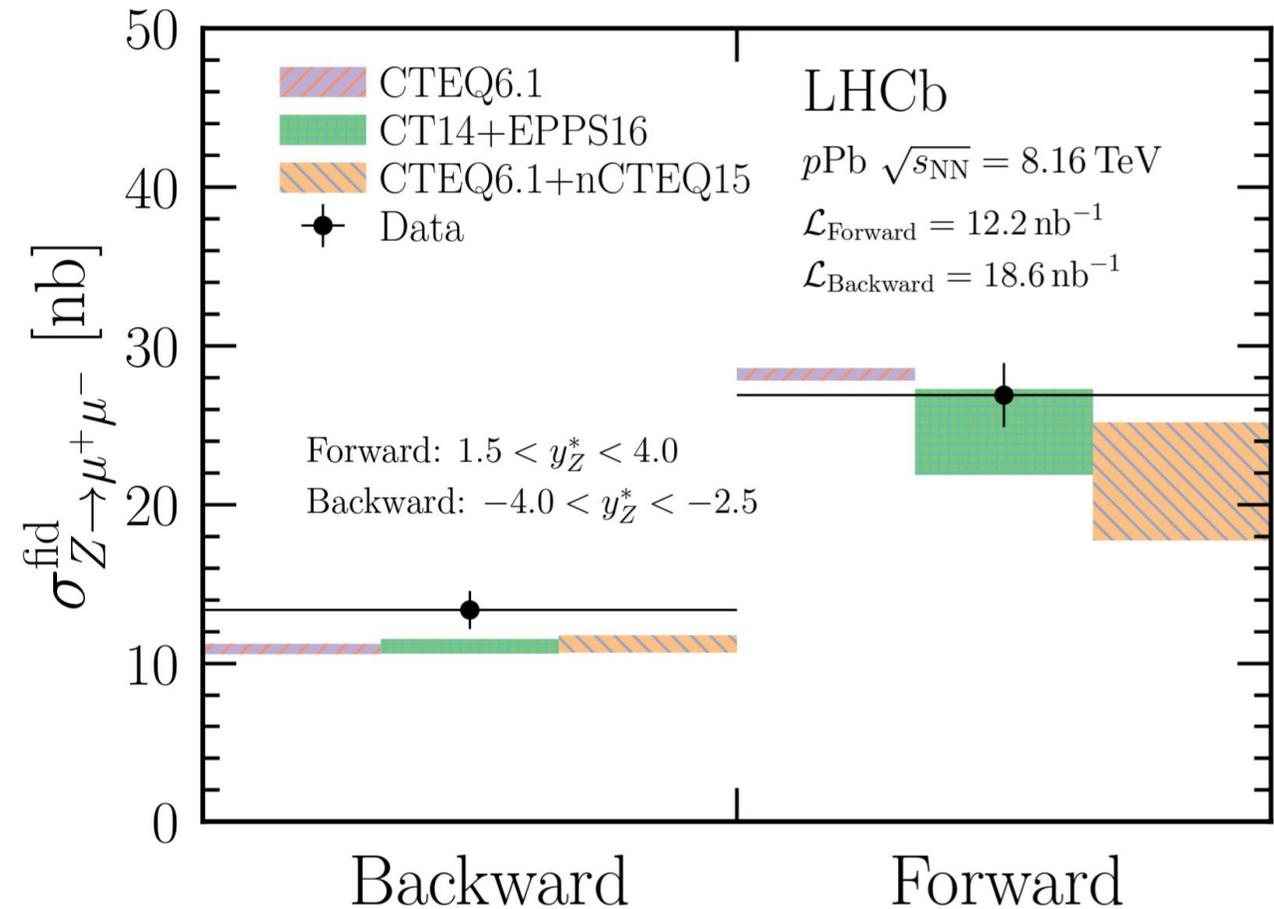
$\sigma_{Z \rightarrow \mu\mu, \text{bwd.}}$

$= 13.4 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.3(\text{lumi.}) \text{nb}$

- Compatible with theoretical calculations using POWHEG v2:

- CTEQ61 (PDF) for both p and Pb
- CT14 (PDF) for p and EPPS16 (nPDF) for Pb
- CTEQ61 (PDF) for p and nCTEQ15 (nPDF) for Pb

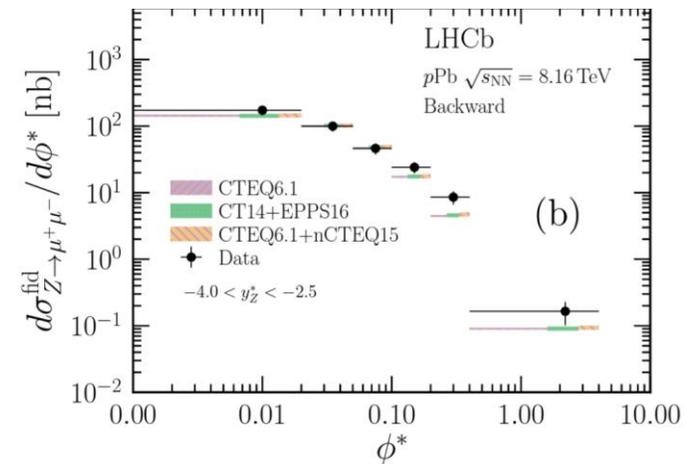
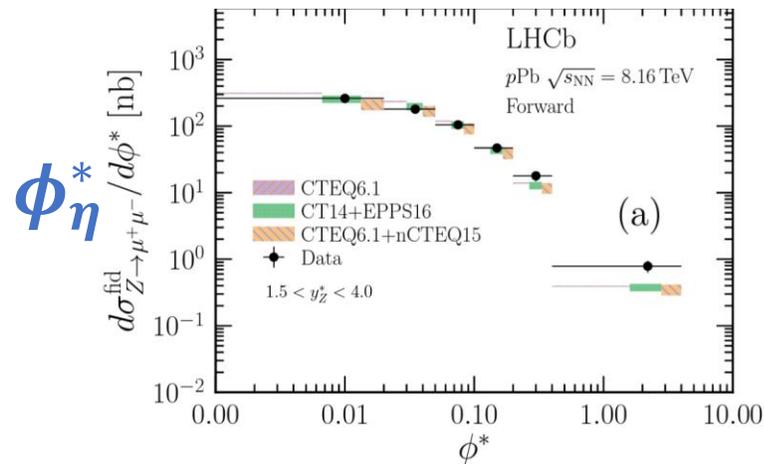
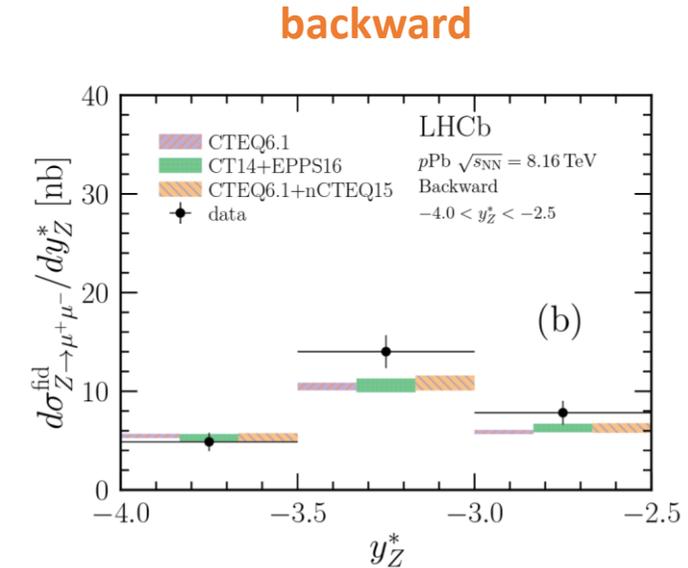
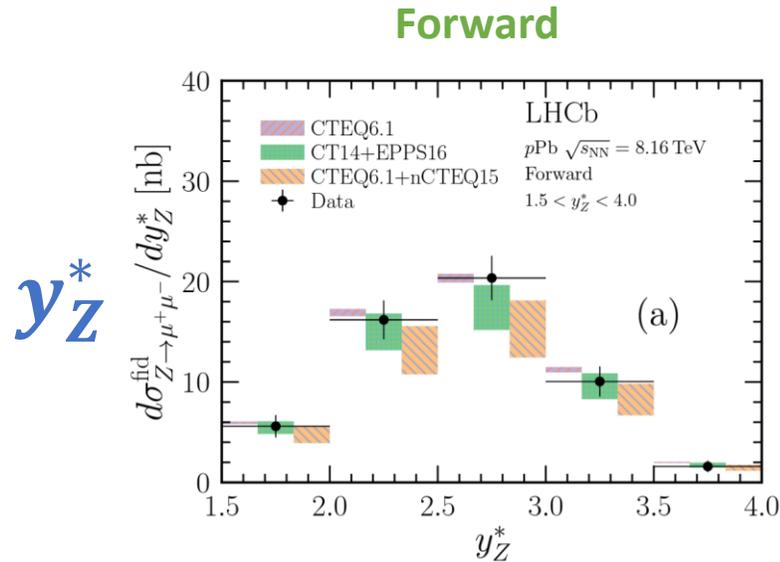
- Forward (small Bjorken- x) results show strong constraining power on the nPDFs.



Z production in $p\text{Pb}$ collisions

- **Differential cross-section as a function of y_Z^* and ϕ_η^* :**

- In good agreement with theoretical predictions.
- **Forward:** smaller uncertainty than prediction, constraints on nPDFs.
- **Backward:** larger uncertainty than predictions.



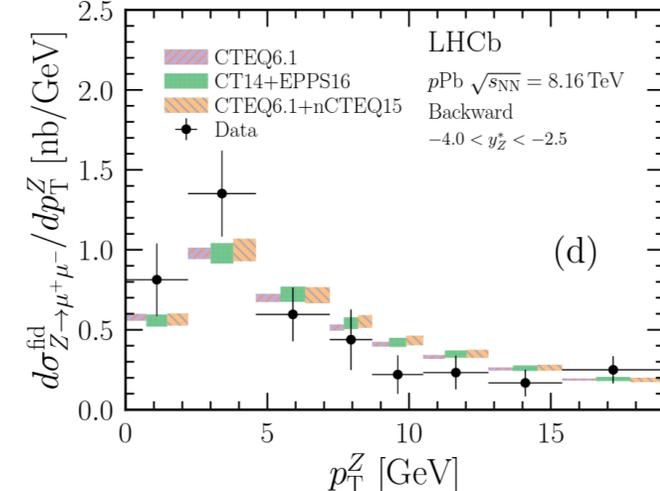
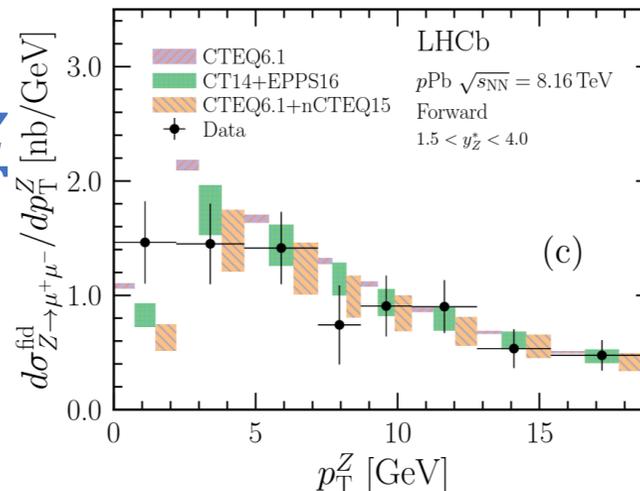
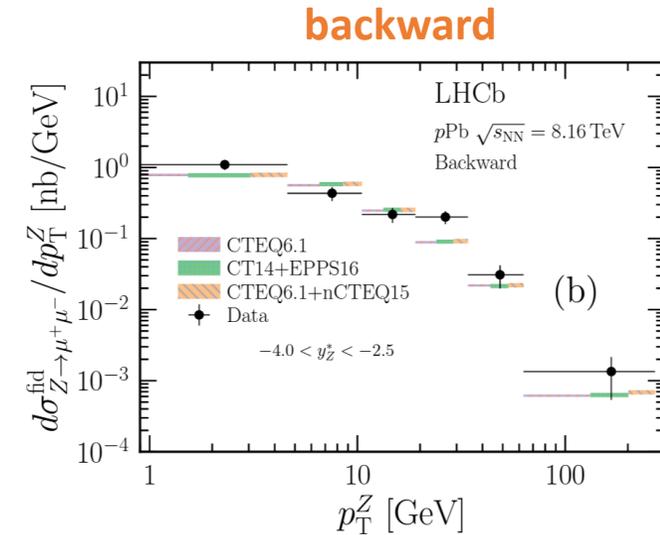
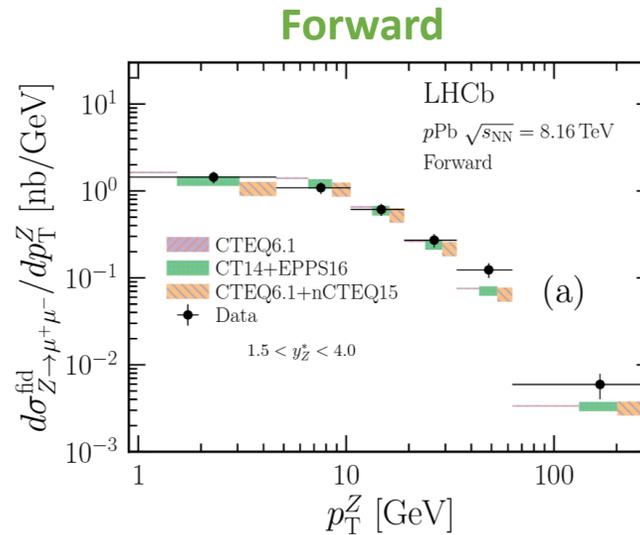
Z production in $p\text{Pb}$ collisions

- **Differential cross-section as a function of p_T^Z :**

- Compatible with theoretical predictions.
- Smaller uncertainty than prediction for **forward** collisions, showing constraints on nPDFs.
- **Low- p_T^Z** results are given, useful for TMD (transverse-momentum-dependent PDFs) studies.

p_T^Z

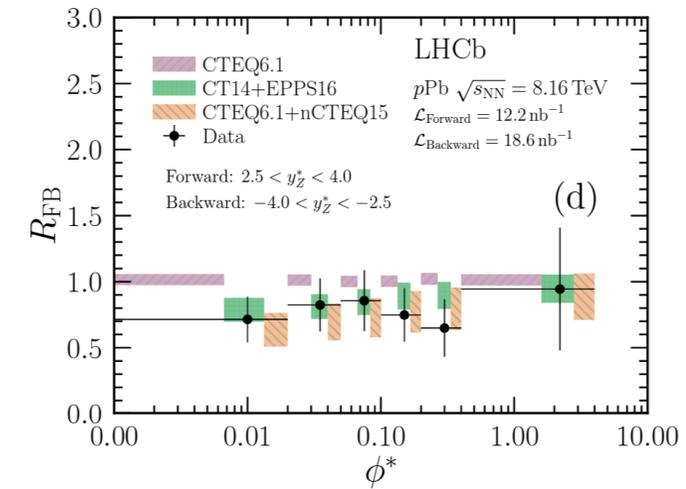
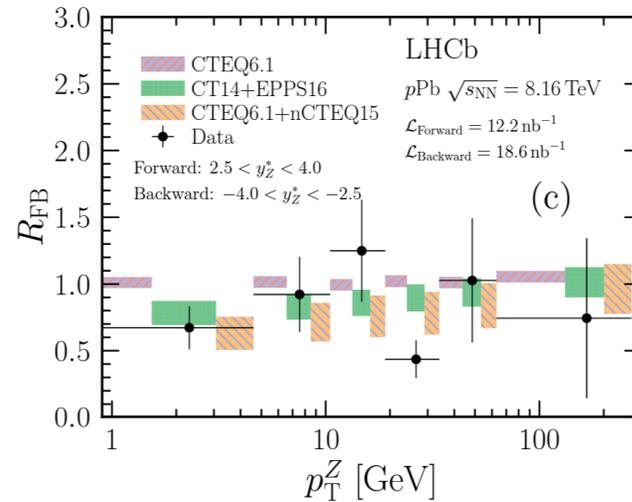
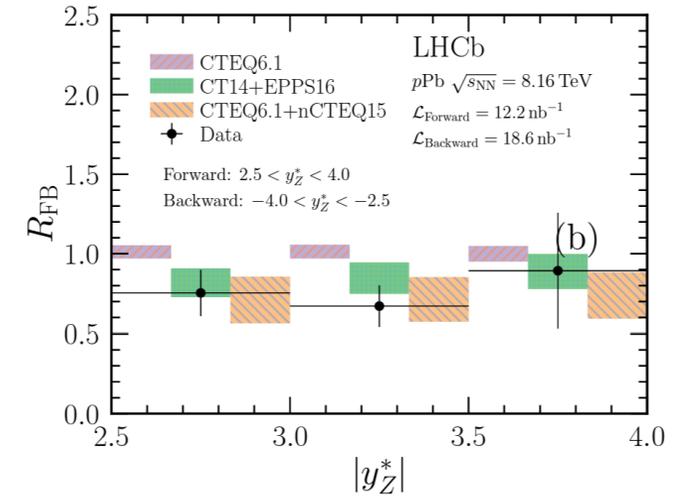
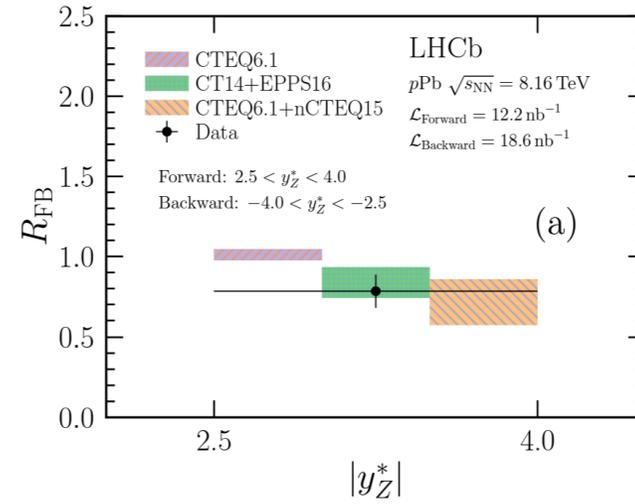
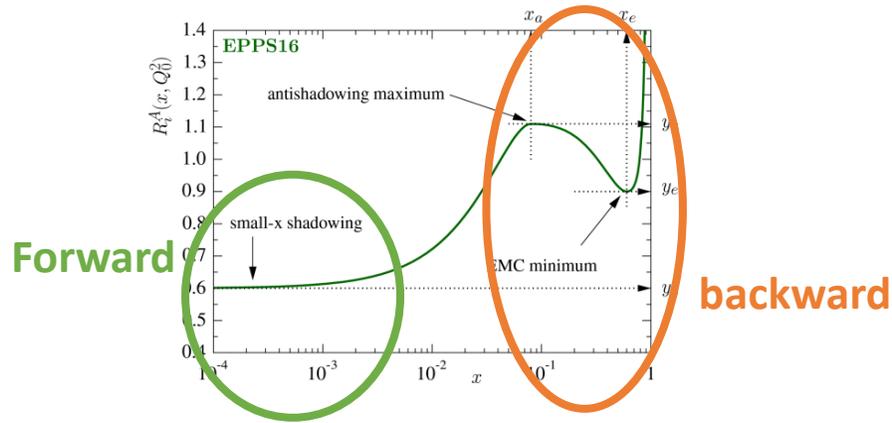
Low- p_T^Z



Z production in $p\text{Pb}$ collisions

LHCb-PAPER-2022-009, arXiv:2205.10213

- **Forward-backward ratio** measured in common rapidity window $2.5 < |y_Z^*| < 4.0$:
 - Total $R_{\text{FB}} = 0.78 \pm 0.10$
 - As a function of y_Z^* , p_T^Z , and ϕ_η^* , see plots
- A general suppression below unity.
- Compatible with theoretical predictions.
- Higher precision in total R_{FB} and certain bins as a function y_Z^* , p_T^Z , and ϕ_η^* can constrain the nPDFs.



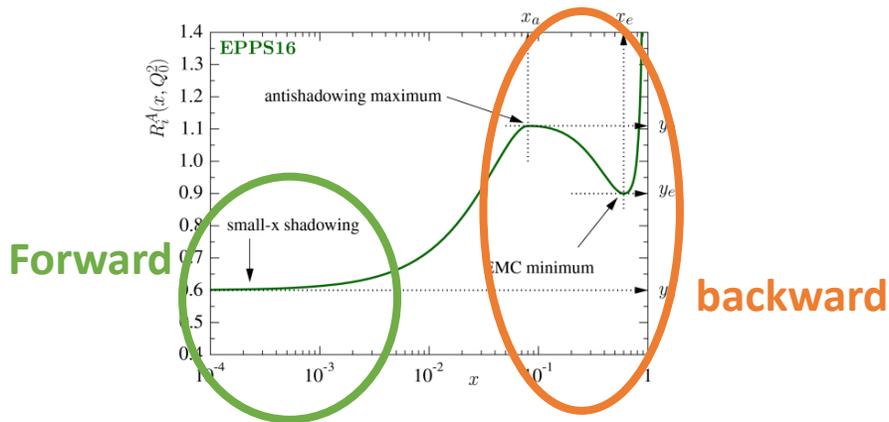
Z production in $p\text{Pb}$ collisions

- Inclusive nuclear modification factors:

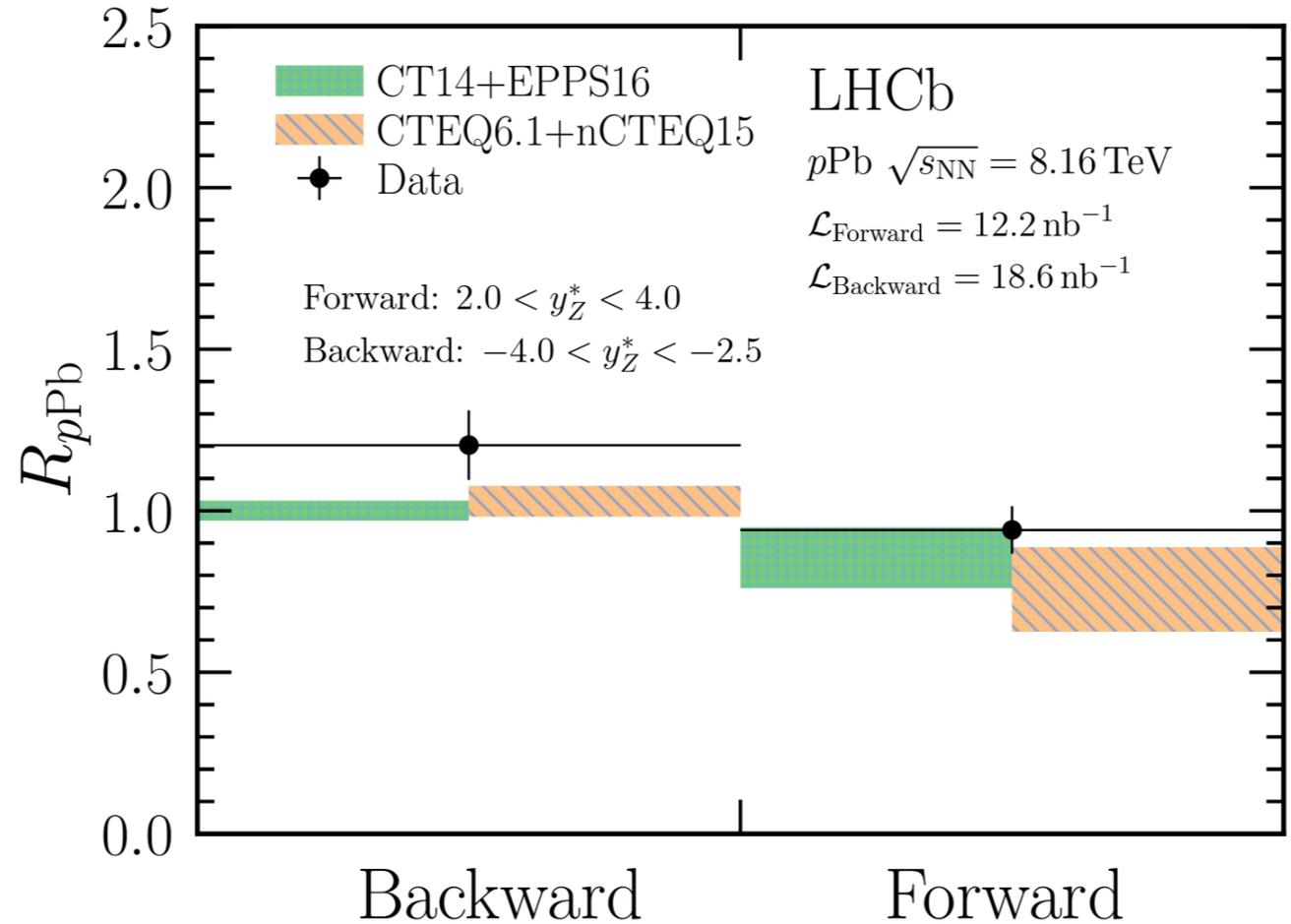
$$R_{p\text{Pb}}^{\text{fw.}} = 0.94 \pm 0.07$$

$$R_{p\text{Pb}}^{\text{bw.}} = 1.21 \pm 0.11$$

- Compatible with theoretical predictions.
- Suppression in the **forward** and enhancement in the **backward** are visible.
- Forward (small Bjorken- x) results show strong constraining power on the nPDFs.



LHCb-PAPER-2022-009, arXiv:2205.10213



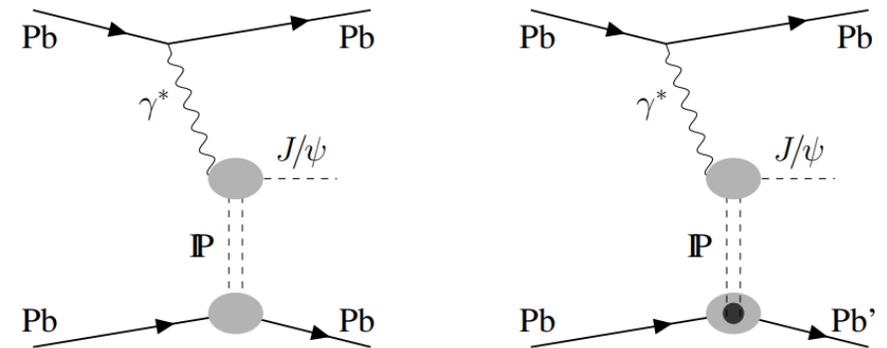
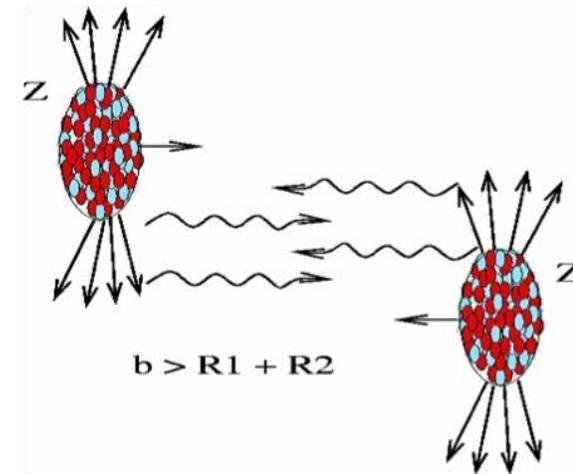


Exclusive photoproduction

CEP J/ψ and $\psi(2S)$ @ 8.16 TeV 2018 PbPb UPC
[arXiv: 2206.08221 \(JHEP submitted\)](#)

CEP in Ultra-peripheral collisions

- **Ultra-peripheral collisions (UPC):** Two nuclei bypass each other with an impact parameter greater than the sum of their radii
- **Photon-induced interactions are enhanced by the strong electromagnetic field of the nucleus**
 - Coherent J/ψ and $\psi(2S)$ production gives constraints on the gluon Probability Density Functions,
 - $(J/\psi) / \psi(2S)$ ratio measurement is helpful to constrain the choice of the vector meson wave function in dipole scattering models [e.g. PLB 772 (2017) 832, PRC (2011) 011902]



Coherent J/ψ production:
photon interact with the
whole nucleus coherently

Incoherent J/ψ production:
photon interact with particular
nucleons in the nucleus

Charmonia in UPC

- PbPb at 5.02 TeV in 2018 ($228 \pm 10 \mu\text{b}^{-1}$)

- Cross-sections:

$$\frac{d\sigma_{\psi}^{\text{coh}}}{dx} = \frac{N_{\psi}^{\text{coh}}}{\mathcal{L} \times \varepsilon_{\text{tot}} \times \mathcal{B}(\psi \rightarrow \mu^+ \mu^-) \times \Delta x}$$

- Event selection:

- require a near empty detector with only two long tracks reconstructed, with acceptance cuts:

$$2.0 < \eta^{\mu} < 4.5, p_T^{\mu} > 700\text{MeV},$$

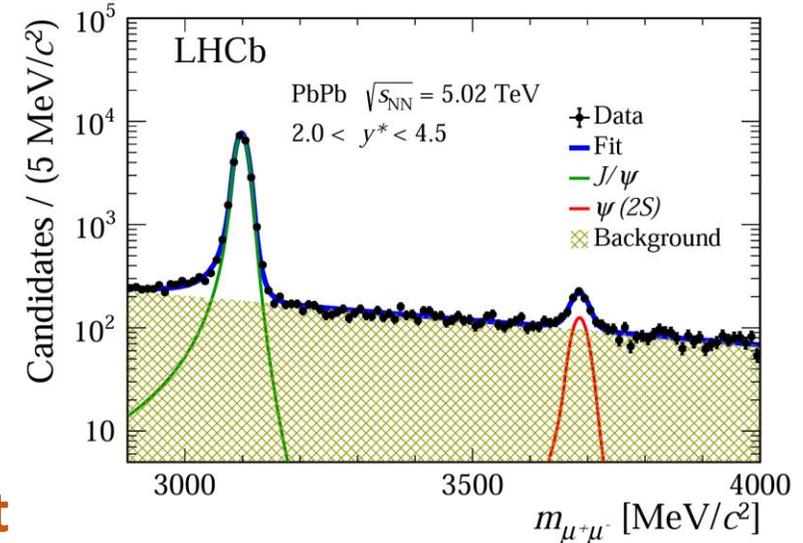
$$p_T^{\mu\mu} < 1\text{GeV}, |\Delta\phi_{\mu\mu}| > 0.9\pi$$

- HERSCHEL detector [JINST 13 (2018) 04 P04017] is used to further purify the selection

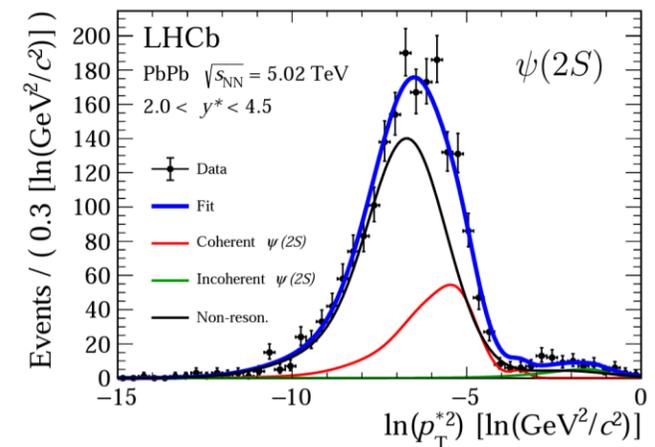
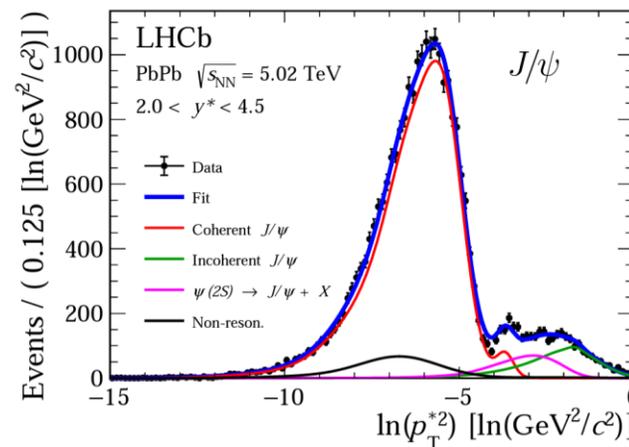
- Signal extraction: The (1) charmonium yields are extracted from dimuon mass fit, then the (2) coherent part is extracted from a $\ln(p_T^2)$ fit

LHCb-PAPER-2022-012, arXiv:2206.08221

Step (1): mass fit

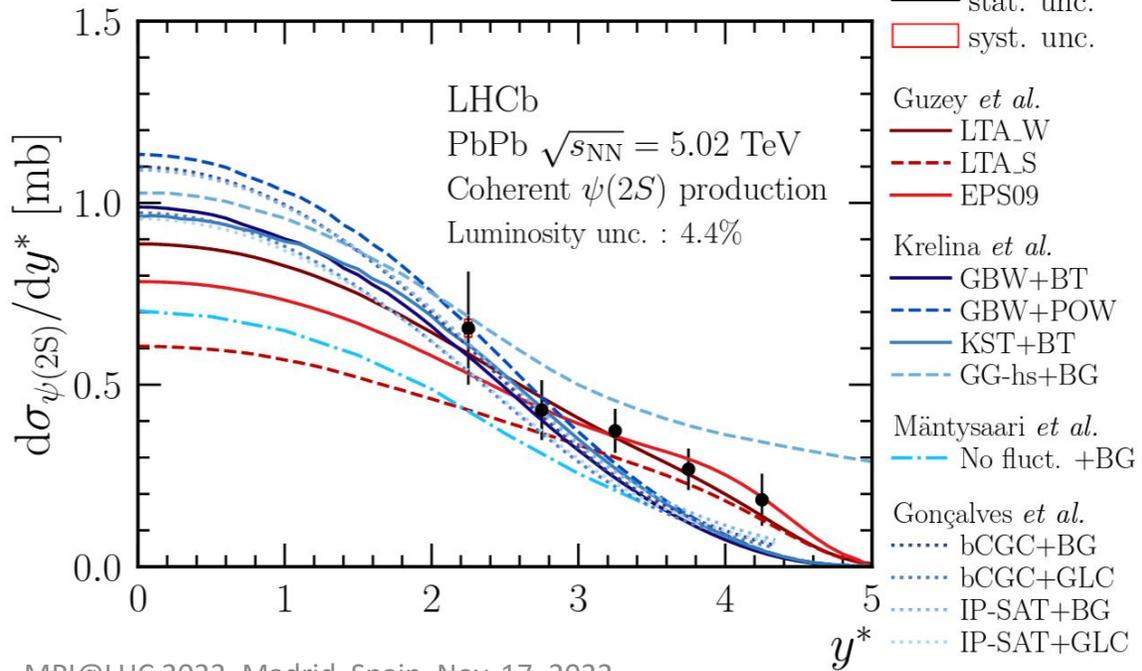
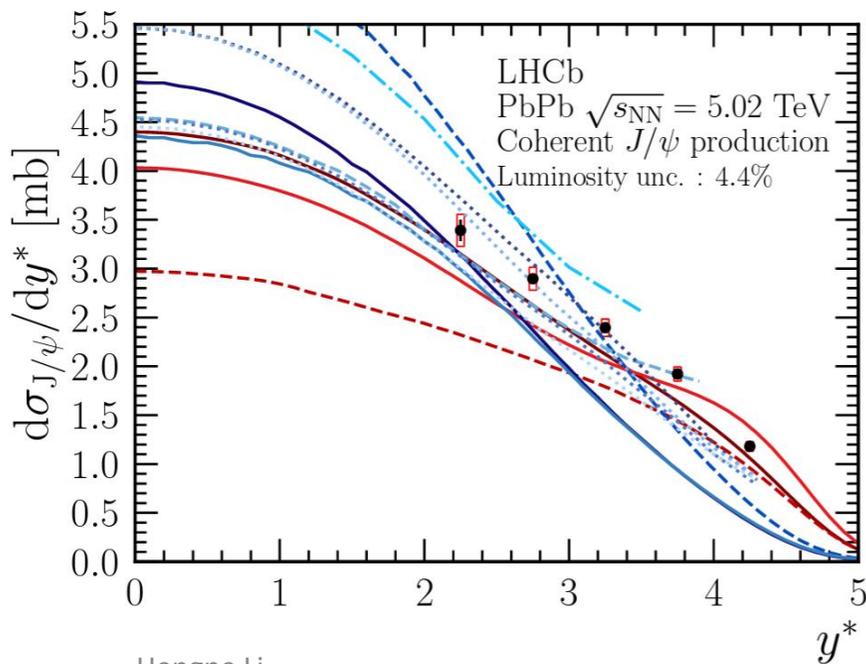


Step (2): $\ln(p_T^2)$ fit



- The **most precise coherent J/ψ production measurement** in PbPb UPC in forward rapidity to date
- The **first coherent $\psi(2S)$ measurement** in forward rapidity at the LHC

Compared to **pQCD** and **color-dipole** models



- data
- stat. unc.
- syst. unc.
- Guzey *et al.*
- LTA_W
- - - LTA_S
- EPS09
- Krelina *et al.*
- GBW+BT
- - - GBW+POW
- KST+BT
- - - GG-hs+BG
- Mäntysaari *et al.*
- - - No fluct. +BG
- Gonçalves *et al.*
- ⋯ bCGC+BG
- ⋯ bCGC+GLC
- ⋯ IP-SAT+BG
- ⋯ IP-SAT+GLC

Guzey et al.: PRC 93 (2016) 055206, PRC 95 (2017) 025204,
Krelina et al.: PRC 97 (2018) 024901, arXiv:2008.05116
Mäntysaari et al.: PLB 772 (2017) 832, PoS DIS2014 (2014) 069, PRD 74 (2006) 074016
Goncalves et al.: PRD 96 (2017) 094027, EPJC 40 (2005) 519,

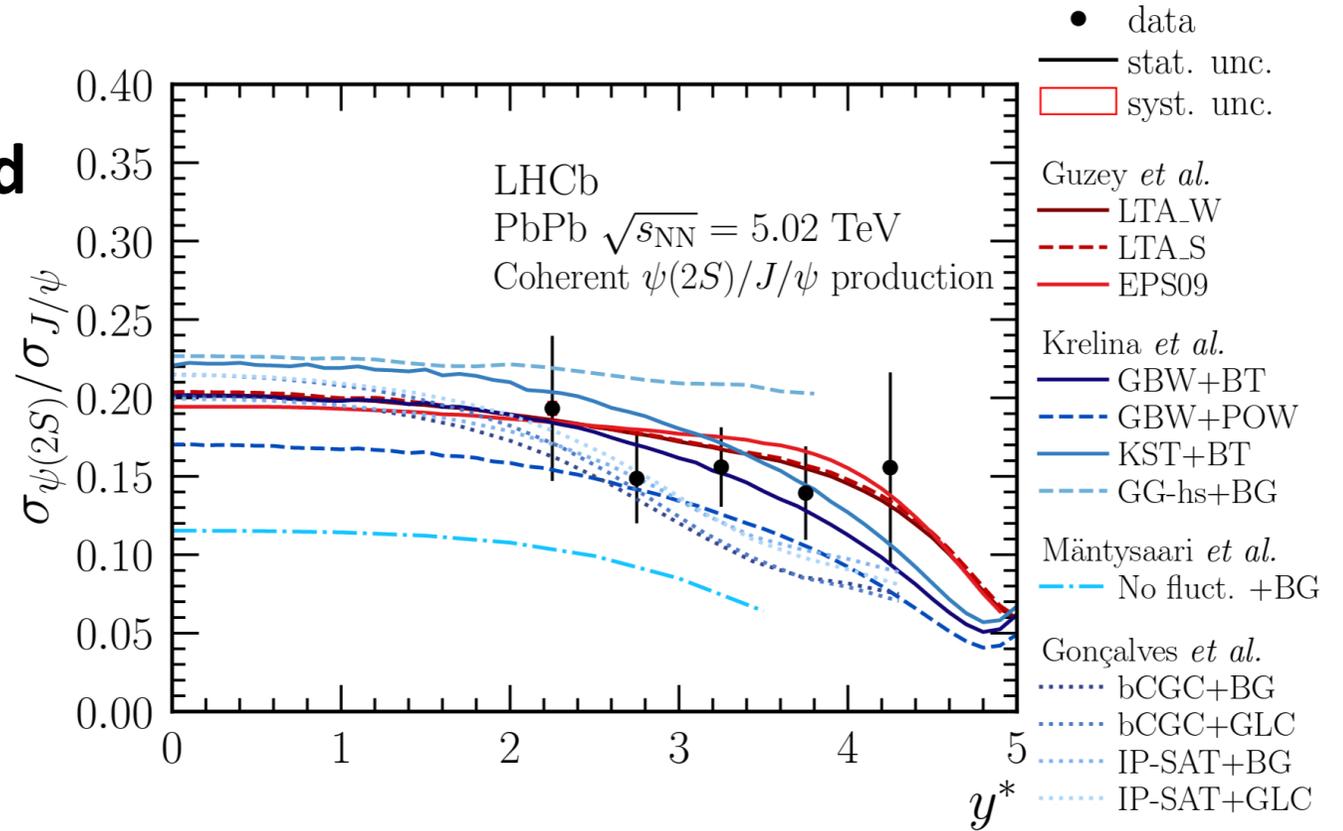
Charmonia in UPC

LHCb-PAPER-2022-012, arXiv:2206.08221

- The first cross-section ratio between J/ψ and $\psi(2S)$ vs. rapidity measurement in forward rapidity region at the LHC

Compared to **pQCD** and **color-dipole models**

Guzey et al.: PRC 93 (2016) 055206, PRC 95 (2017) 025204,
 Krelina et al.: PRC 97 (2018) 024901, arXiv:2008.05116
 Mantysaari et al.: PLB 772 (2017) 832, PoS DIS2014 (2014) 069, PRD 74 (2006) 074016
 Goncalves et al.: PRD 96 (2017) 094027, EPJC 40 (2005) 519,

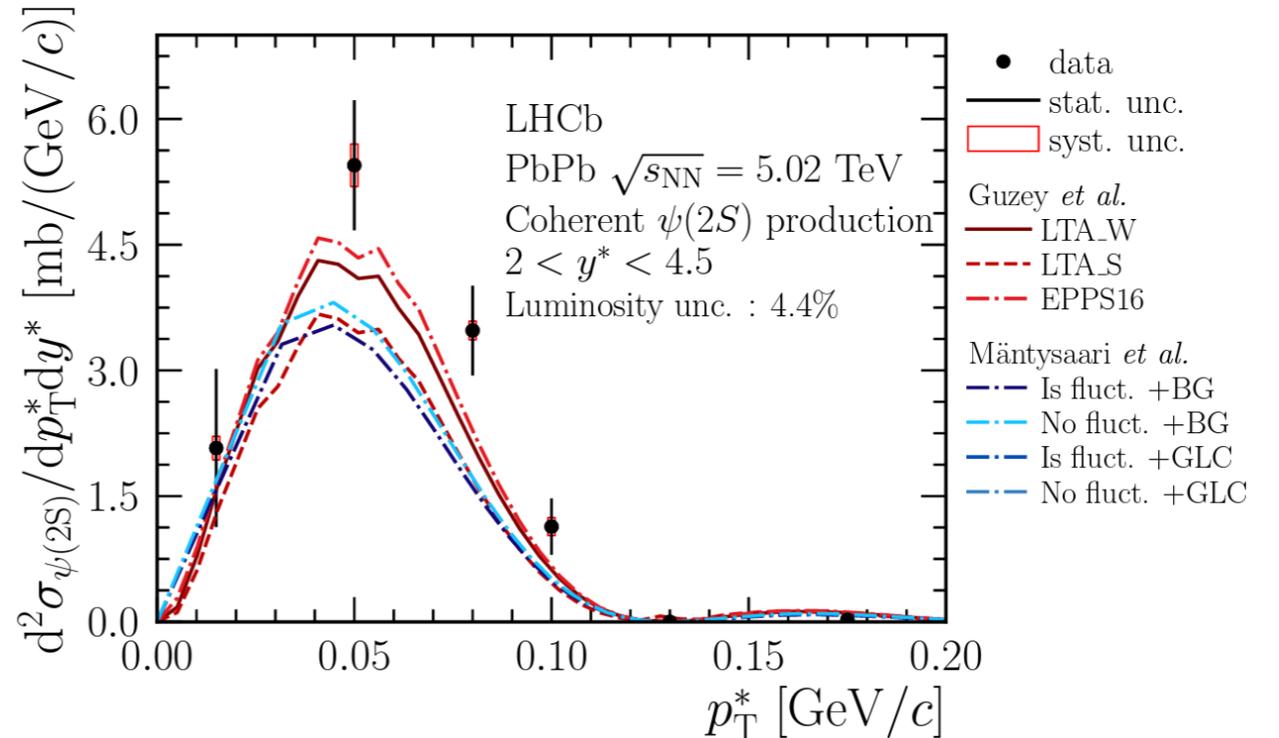
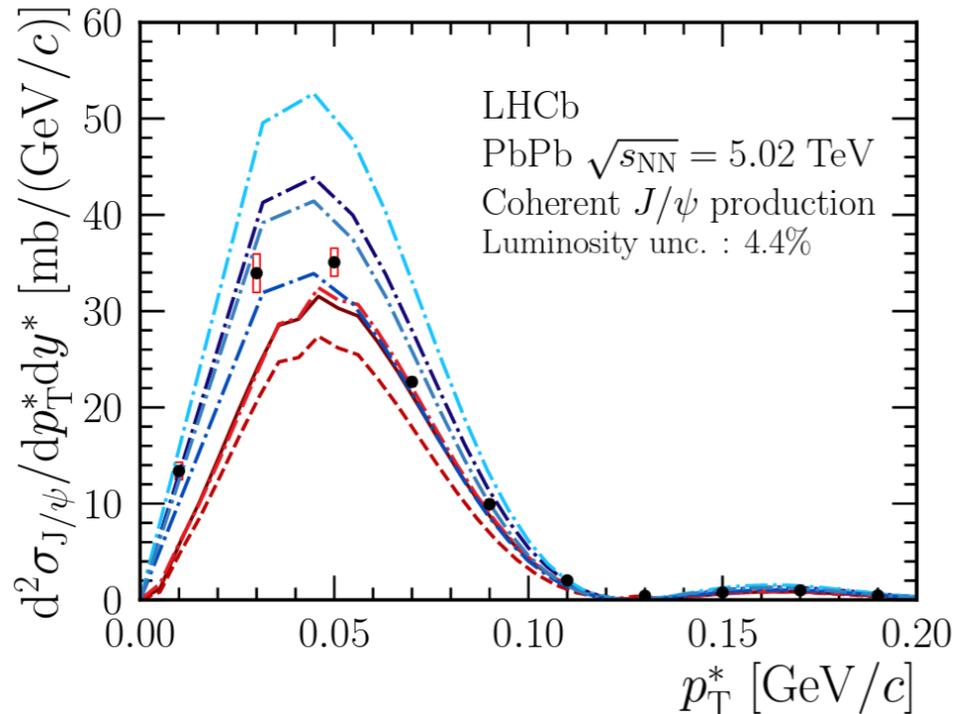


Charmonia in UPC

LHCb-PAPER-2022-012, arXiv:2206.08221

- The first measurement of the coherent J/ψ and $\psi(2S)$ production cross-section vs. p_T in PbPb UPC

Compared to **pQCD** and **color-dipole** models



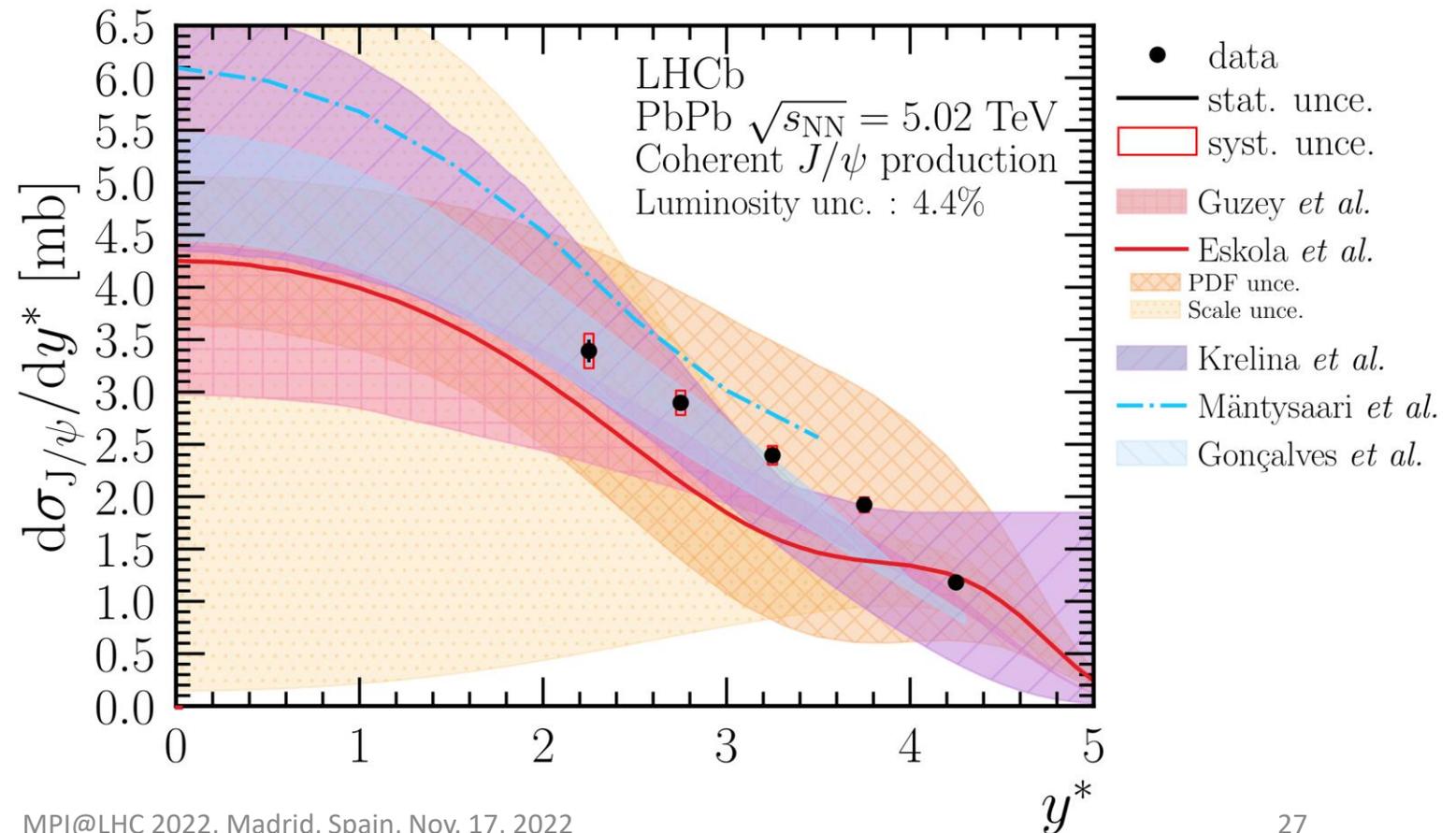
[Guzey et al.:](#) PRC 93 (2016) 055206, PRC 95 (2017) 025204,

[Mantysaari et al.:](#) PLB 772 (2017) 832, PoS DIS2014 (2014) 069, PRD 74 (2006) 074016

Follow up discussion on the theoretical uncertainties

- **Update the theoretical calculations on the same plot:**
 - **p-QCD calculations:** include **new NLO p-QCD calculation** (arXiv:2203.11613), **PDF uncert.** and **factorization / renormalization scale uncert.**
 - **Color-dipole models:** draw different model tuning options as theoretical variations
- **The high precision LHCb data are of great value in theoretical model fine-tuning**

Thanks to Chris Flett, Heikki Mäntysaari, Vadim Guzey, Michal Krelina, Kari Eskola, et.al., for the important discussions after we get public our results!



Conclusion/Outlook

- A summary of previous LHCb results for PDF studies.
- The **first** study of $Z + c$ -jets in the forward region.
- The **most precise** measurement of the Z boson production in pp collisions at 13 TeV in the forward region.
- The **first differential** Z boson result in pPb collisions at 8.16 TeV in the forward region.
- The **most precise** coherent J/ψ production measurement and **the first** coherent $\psi(2S)$ measurement in forward rapidity in PbPb UPC

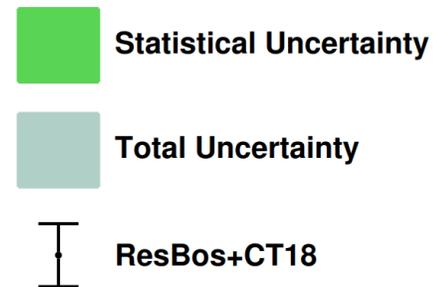
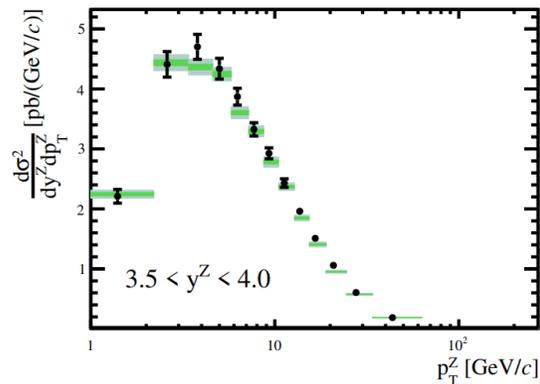
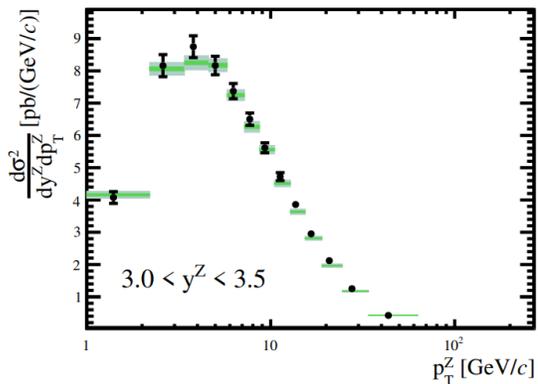
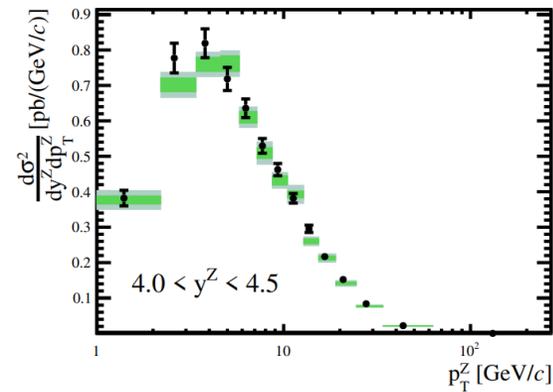
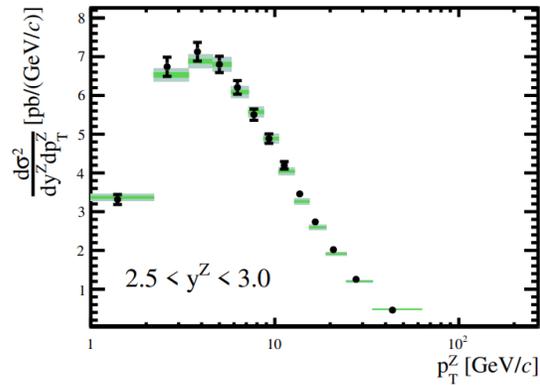
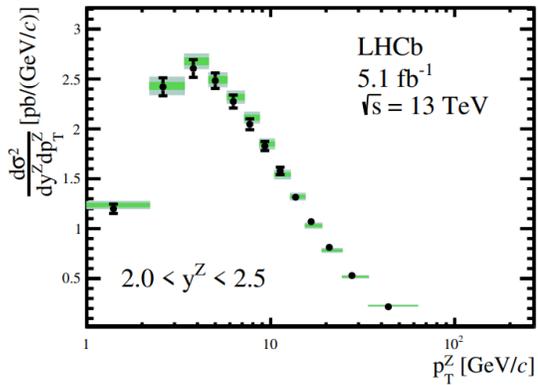


Backups

Z production in pp collisions

JHEP 07(2022)026

- Double differential cross-section: $y_Z - p_T^Z$
 - Compatible with theoretical prediction



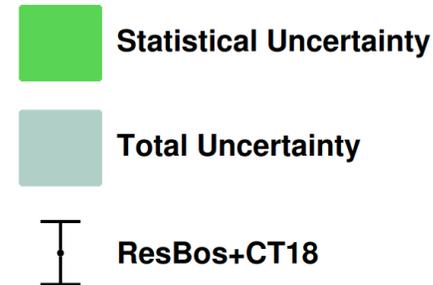
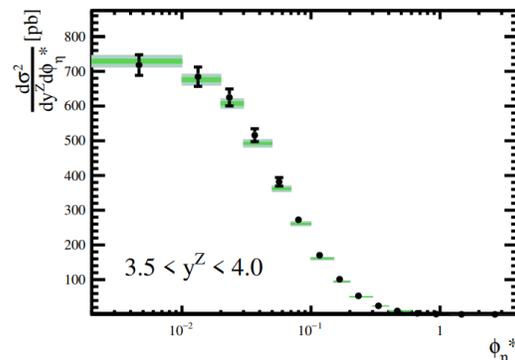
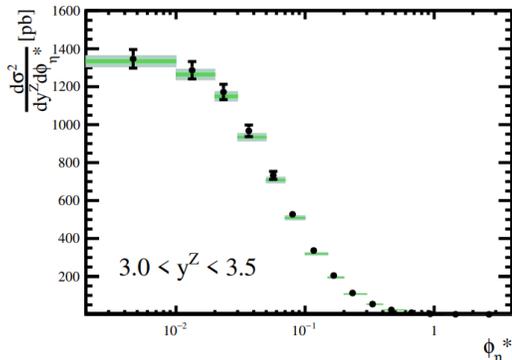
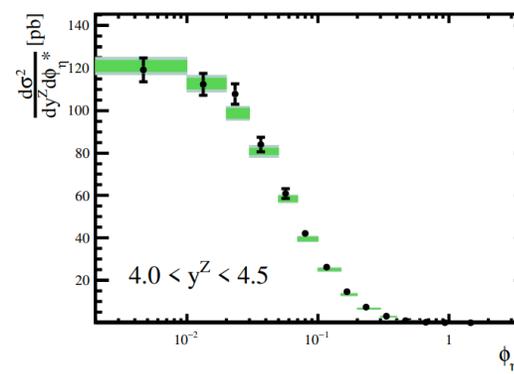
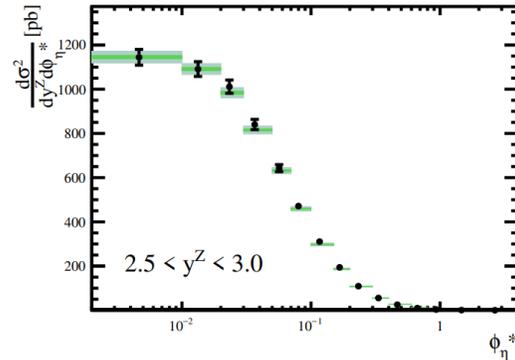
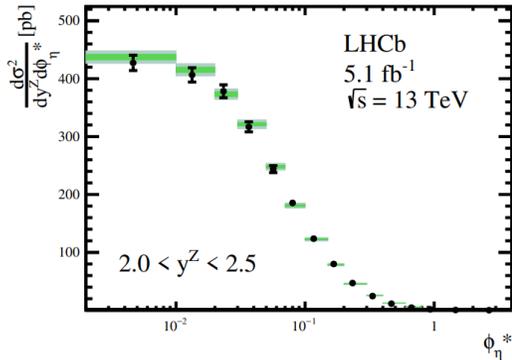
First double differential measurements in the forward region

Z production in pp collisions

JHEP 07(2022)026

- Double differential cross-section: $y_Z - \varphi^*$
 - Compatible with theoretical prediction

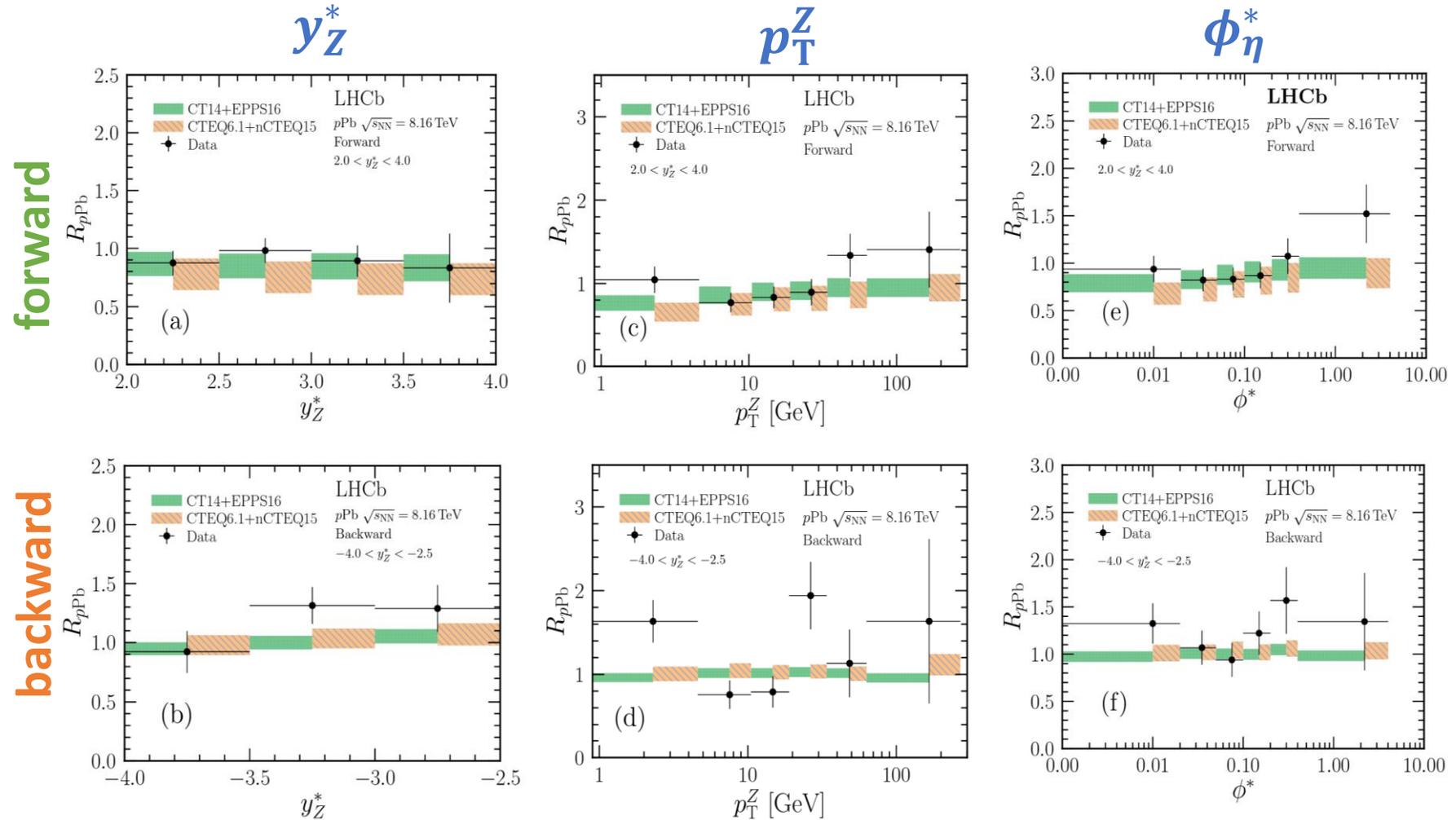
First double differential measurements in the forward region



Z production in $p\text{Pb}$ collisions

LHCb-PAPER-2022-009, arXiv:2205.10213

- Nuclear modification factors as a function of y_Z^* , p_T^Z , and ϕ_η^*
- Compatible with theoretical predictions.
- Constraints on nPDFs are visible in certain bins in case of **forward** collisions.



Integrated cross-section and cross-section ratio

LHCb-PAPER-2022-012, arXiv:2206.08221

- **Integrated cross-section and ratio (most precise measurements in the forward region at the moment):**

$$\sigma_{J/\psi}^{\text{coh}} = 5.965 \pm 0.059(\text{stat}) \pm 0.232(\text{syst}) \pm 0.262(\text{lumi}) \text{ mb},$$

$$\sigma_{\psi(2S)}^{\text{coh}} = 0.923 \pm 0.086(\text{stat}) \pm 0.028(\text{syst}) \pm 0.040(\text{lumi}) \text{ mb},$$

$$\sigma_{J/\psi}^{\text{coh}} / \sigma_{\psi(2S)}^{\text{coh}} = 0.155 \pm 0.014(\text{stat}) \pm 0.003(\text{syst}).$$

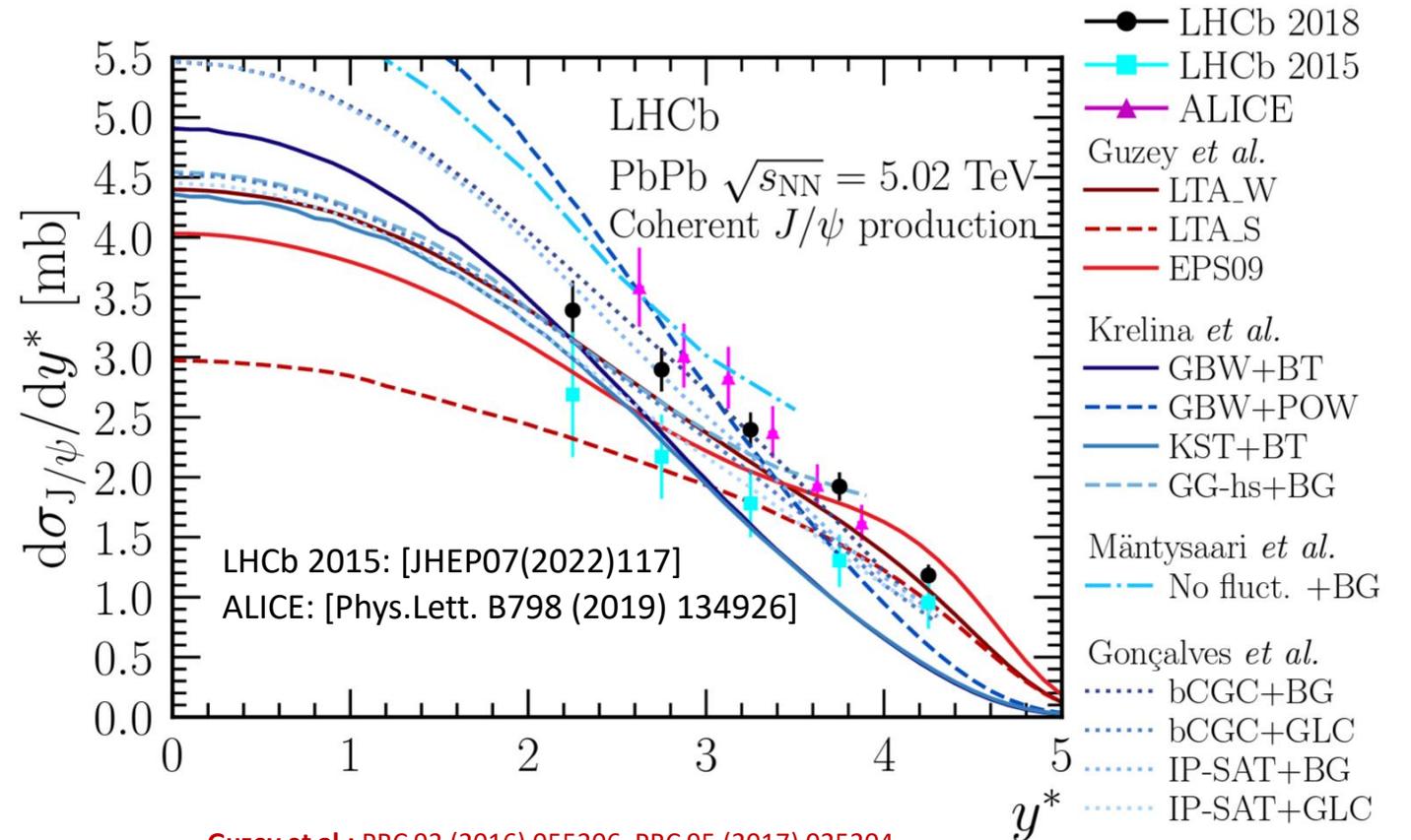
- **Systematic uncertainties:**

Source	Relative uncertainty [%]	
	$\sigma_{J/\psi}^{\text{coh}}$	$\sigma_{\psi(2S)}^{\text{coh}}$
Tracking efficiency	0.5–2.0	0.5–2.0
PID efficiency	0.9–1.6	0.9–1.6
Trigger efficiency	2.7–3.7	2.1–2.5
HERSCHEL efficiency	1.4	1.4
Background estimation	1.2	1.2
Signal shape	0.04	0.04
Momentum resolution	0.9–34	1.3–27
Branching fraction	0.6	2.1
Luminosity	4.4	4.4

Charmonia in UPC

LHCb-PAPER-2022-012, arXiv:2206.08221

- The J/ψ measurement is compatible with 2015 and ALICE results
 - The difference between the new results and 2015 measurement is about 2σ



Guzey *et al.*: PRC 93 (2016) 055206, PRC 95 (2017) 025204,

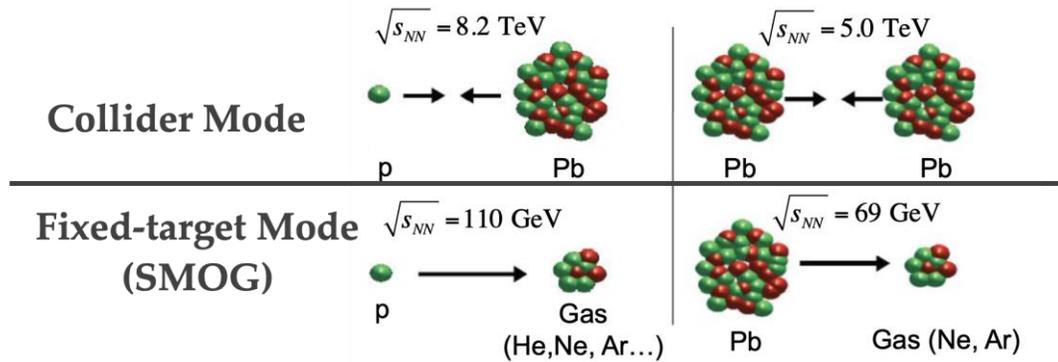
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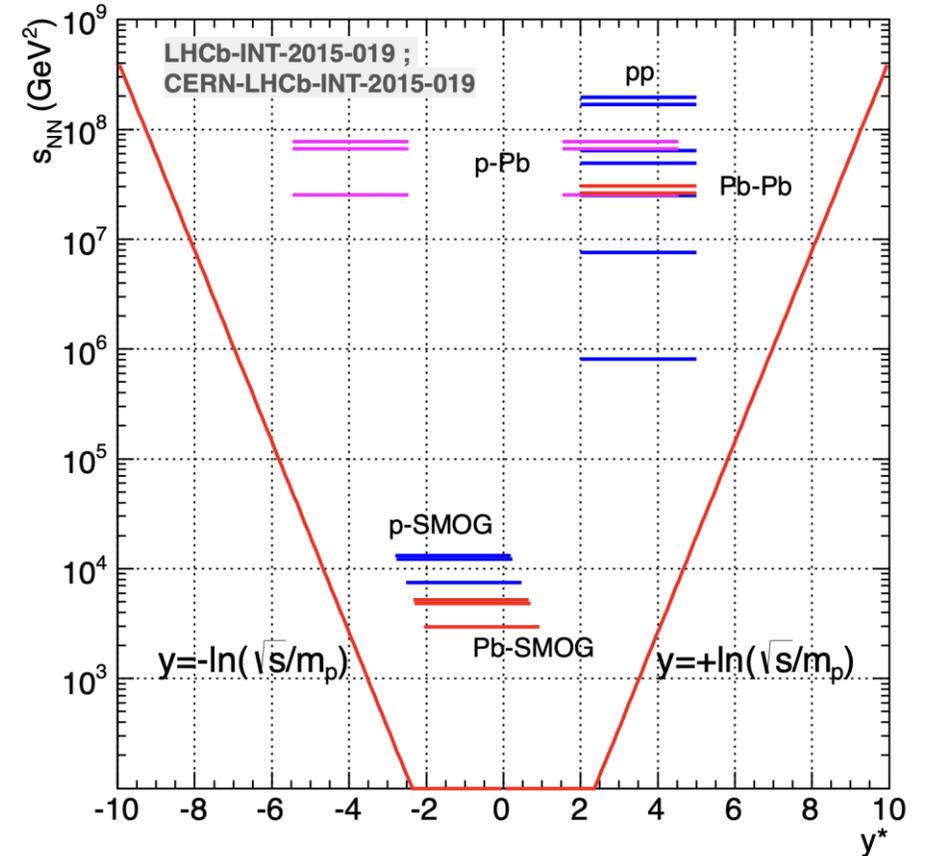
Goncalves *et al.*: PRD 96 (2017) 094027, EPJC 40 (2005) 519,

LHCb running modes and kinematic coverage

Both the collider mode and fixed-target mode running at the same time



Kinematic acceptance



Collider mode datasets:

$\sqrt{s_{NN}}$	2013 5.02 TeV		2016 8.16 TeV		2015 5.02 TeV	2017 5.02 TeV	2018 5.02 TeV
\mathcal{L}	pPb 1.1 nb ⁻¹	Pbp 0.5 nb ⁻¹	pPb 13.6 nb ⁻¹	Pbp 20.8 nb ⁻¹	PbPb 10 μb ⁻¹	XeXe 0.4 μb ⁻¹	PbPb ~ 210 μb ⁻¹