Probing low-x phenomena at LHCb

Murilo Rangel
on behalf of the LHCb Collaboration

Diffraction and Low-x

Outline

--- LHCb experiment overview

--- Results discussed in this talk

Prompt charged particle production in pp and pPb

Nuclear modification factor of neutral pion production in pPb

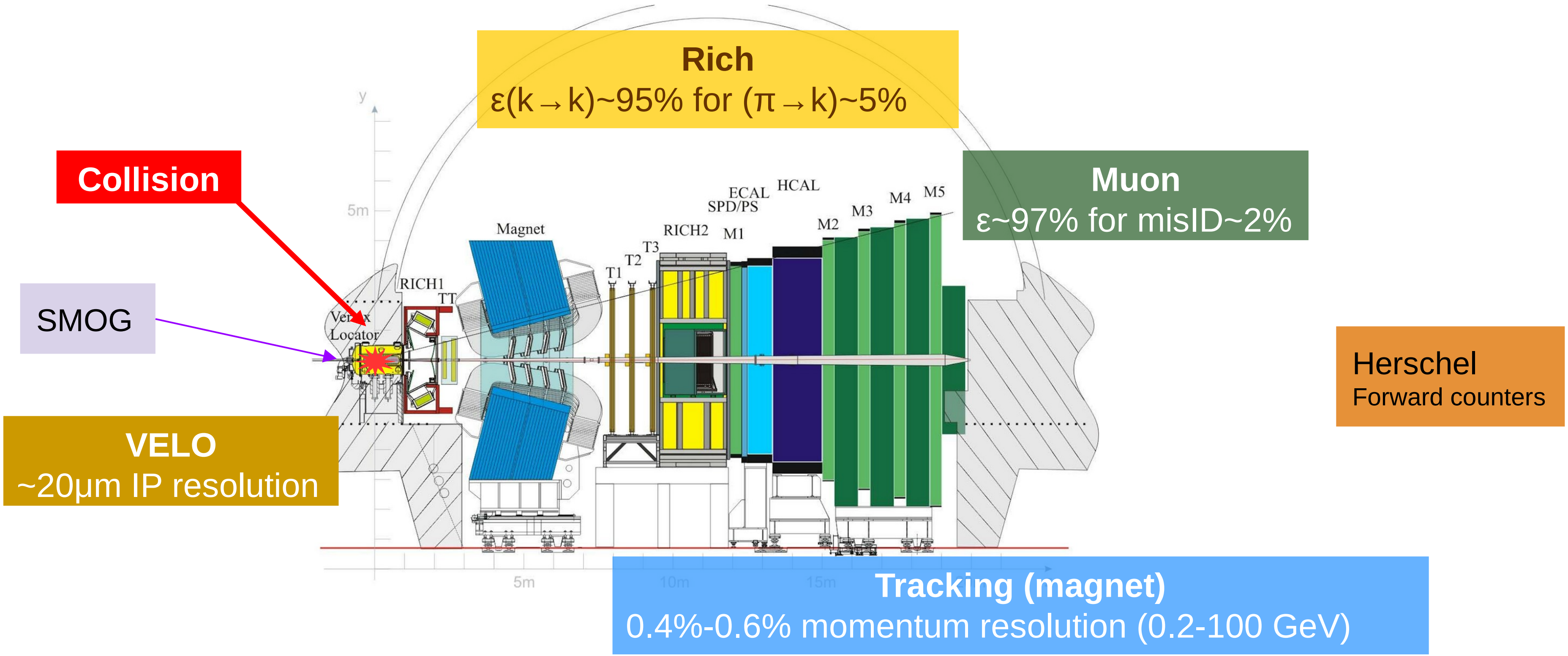
Measurement of the Z boson production cross-section in pPb

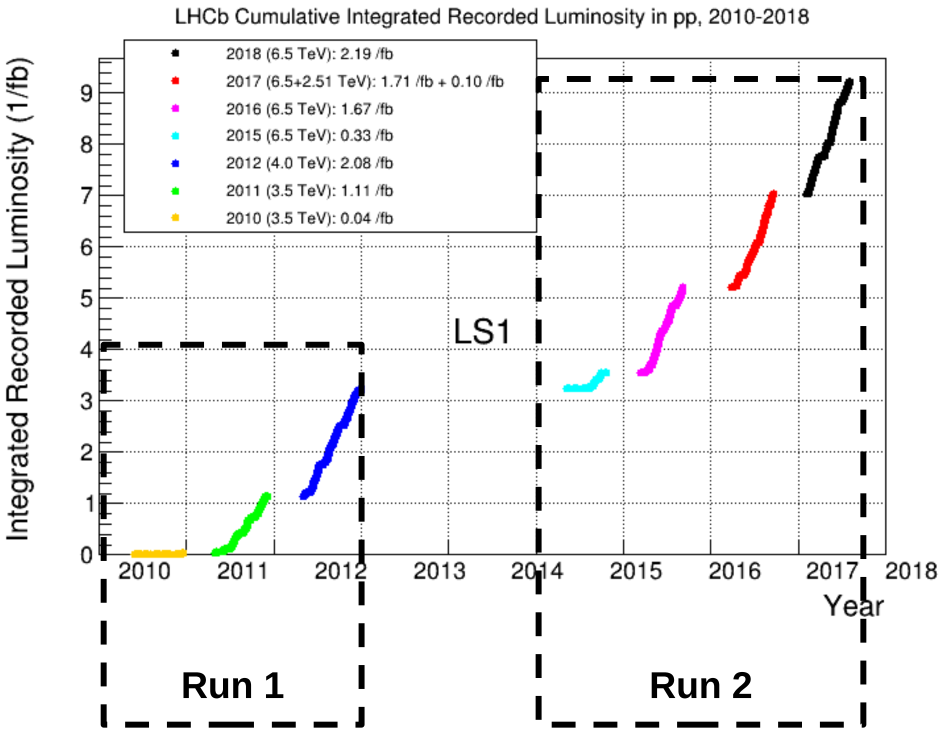
--- Summary

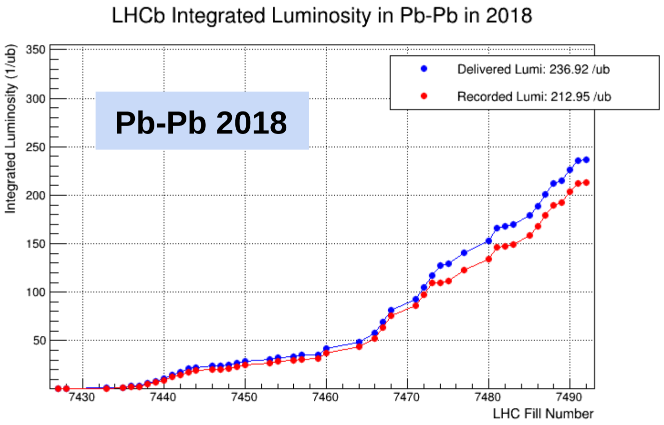
LHCb is a single arm spectrometer fully instrumented in the forward region ($2.0<\eta<5.0$)

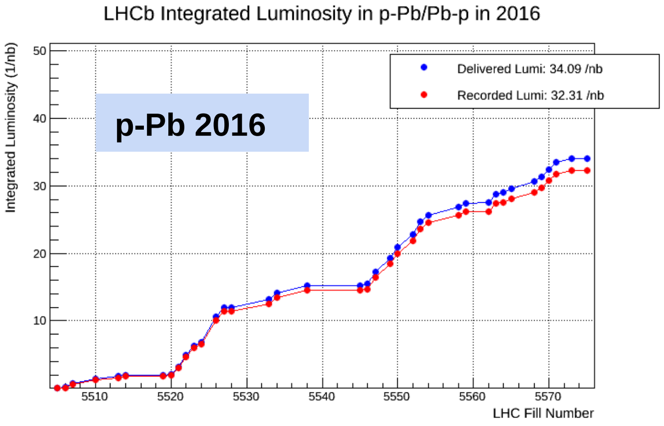
Designed for heavy flavour physics and also exploited for general purpose physics

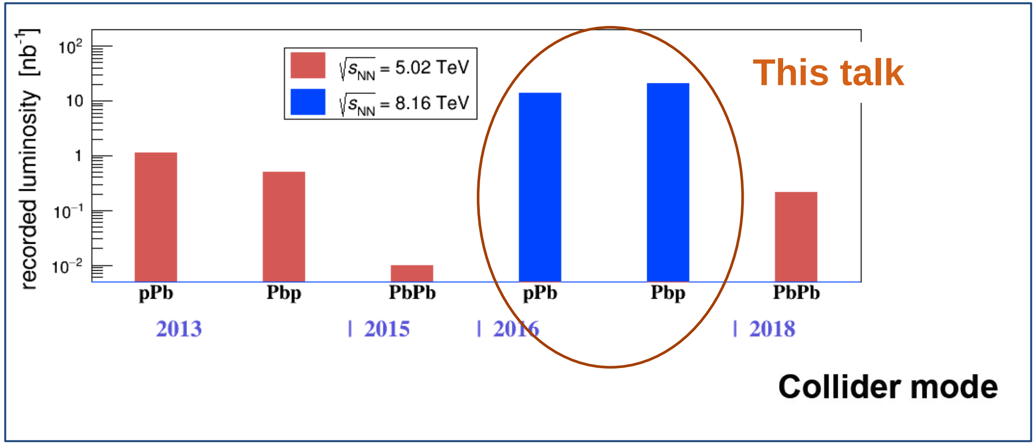
[Int. J. Mod. Phys. A 30, 1530022 (2015)]



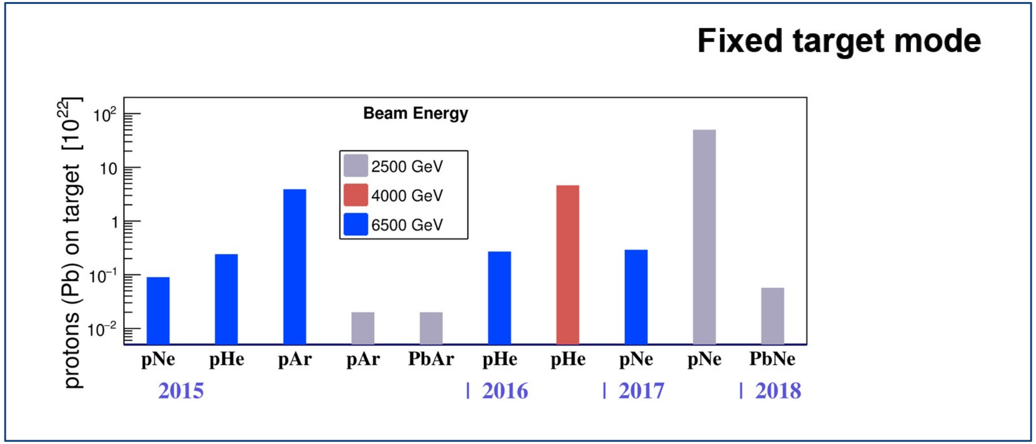

LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
Integrated Recorded Luminosity (1/fb)
Year
LS1
Run 1
Run 2


LHCb Integrated Luminosity in Pb-Pb in 2018
Pb-Pb 2018
Delivered Lumi: 236.92 /ub
Recorded Lumi: 212.95 /ub
Integrated Luminosity (1/ub)
LHC Fill Number

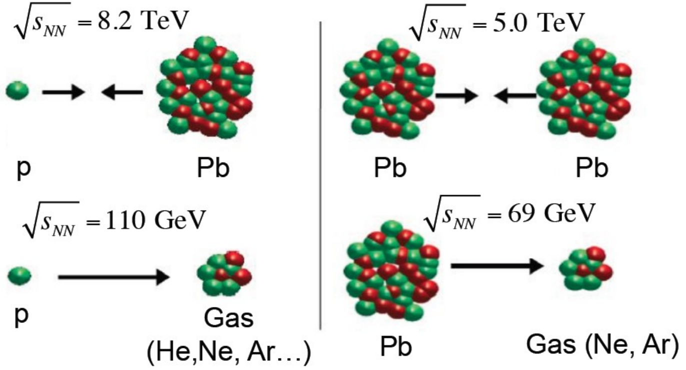

LHCb Integrated Luminosity in p-Pb/Pb-p in 2016
p-Pb 2016
Delivered Lumi: 34.09 /nb
Recorded Lumi: 32.31 /nb
Integrated Luminosity (1/nb)
LHC Fill Number



recorded luminosity [nb^{-1}]
$\sqrt{s_{NN}}$ = 5.02 TeV
$\sqrt{s_{NN}}$ = 8.16 TeV
This talk
pPb
Pbp
PbPb
pPb
Pbp
PbPb
2013
2015
2016
2018
Collider mode



Fixed target mode
Beam Energy
2500 GeV
4000 GeV
6500 GeV
protons (Pb) on target [10^{22}]
pNe
pHe
pAr
pAr
PbAr
pHe
pHe
pNe
pNe
PbNe
2015
2016
2017
2018



$\sqrt{s_{NN}} = 8.2$ TeV
p
Pb
$\sqrt{s_{NN}} = 5.0$ TeV
Pb
Pb
$\sqrt{s_{NN}} = 110$ GeV
p
Gas
(He,Ne, Ar…)
$\sqrt{s_{NN}} = 69$ GeV
Pb
Gas (Ne, Ar)

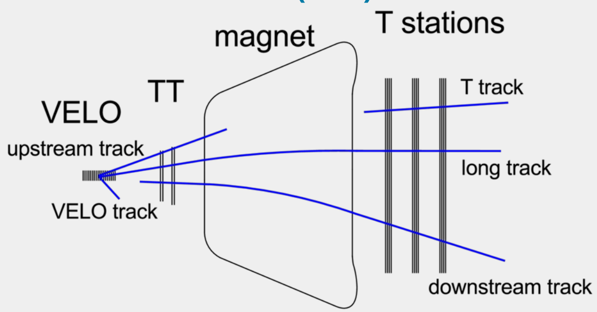
Prompt charged particle production

Phys.Rev.Lett. 128 (2022), 142004

→ pp and pPb data at 5 TeV

→ Prompt charged candidates ($\tau > 0.3 \times 10^{-10}$s)
  Well reconstructed tracks (long):
  $0.2 < p_T < 8.0$ GeV/c and $p > 2$ GeV/c
  $-4.8 < \eta < -2.5$ (backward region)
  $2.0 < \eta < 4.8$ (forward region)

JINST 10 (2015) P02007



→ **N^{ch}**: Number of charged candidates corrected (purity and efficiency) is used to calculate the double differential cross-section and the nuclear modification factor.

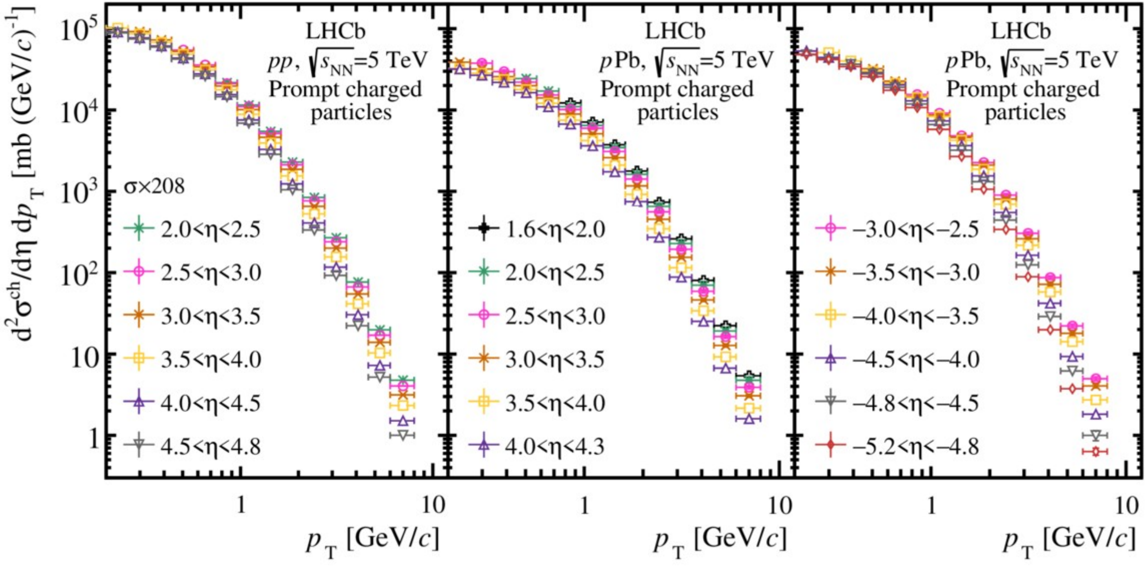
→ Systematic uncertainties are dominated by:
  tracking efficiencies (hadron vs muon)
  particle composition in simulation

Uncertainty source	pPb[%] (forward)	pPb[%] (backward)	pp [%]
Track-finding efficiency	1.5 – 5.0	1.5 – 5.0	1.6 – 5.3
Detector occupancy	0.0 – 2.8	0.6 – 2.9	0.1 – 1.6
Particle composition	0.4 – 4.1	0.4 – 4.6	0.3 – 2.4
Selection efficiency	0.7 – 2.2	0.7 – 3.0	1.0 – 1.7
Purity	0.1 – 1.8	0.1 –11.7	0.1 – 5.8
Truth-matching	0.0 – 0.1	0.0 – 0.1	0.1 – 0.2
Luminosity	2.3	2.5	2.0
Statistical uncertainty	0.0 – 0.6	0.0 – 1.0	0.0 – 1.1
Total (in $d^2\sigma/d\eta dp_T$)	3.0 – 6.7	3.3 –14.5	2.8 – 8.7
Total (in R_{pPb})	4.2 – 9.2	4.4 –16.9	

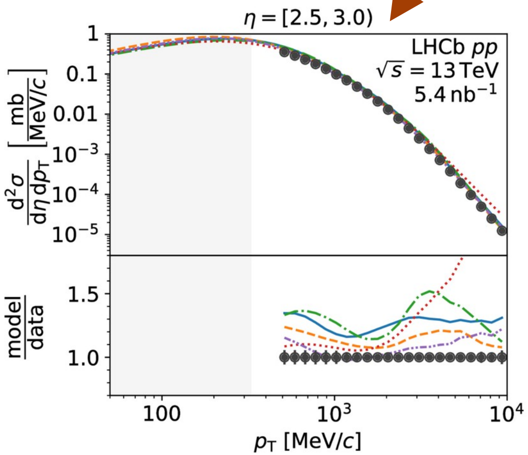
Prompt charged particle production

[Phys.Rev.Lett. 128 (2022), 142004]

$$\frac{\mathrm{d}^2\sigma^{\mathrm{ch}}(\eta, p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta} \equiv \frac{1}{\mathcal{L}} \frac{N^{\mathrm{ch}}(\eta, p_{\mathrm{T}})}{\Delta p_{\mathrm{T}} \Delta\eta}$$



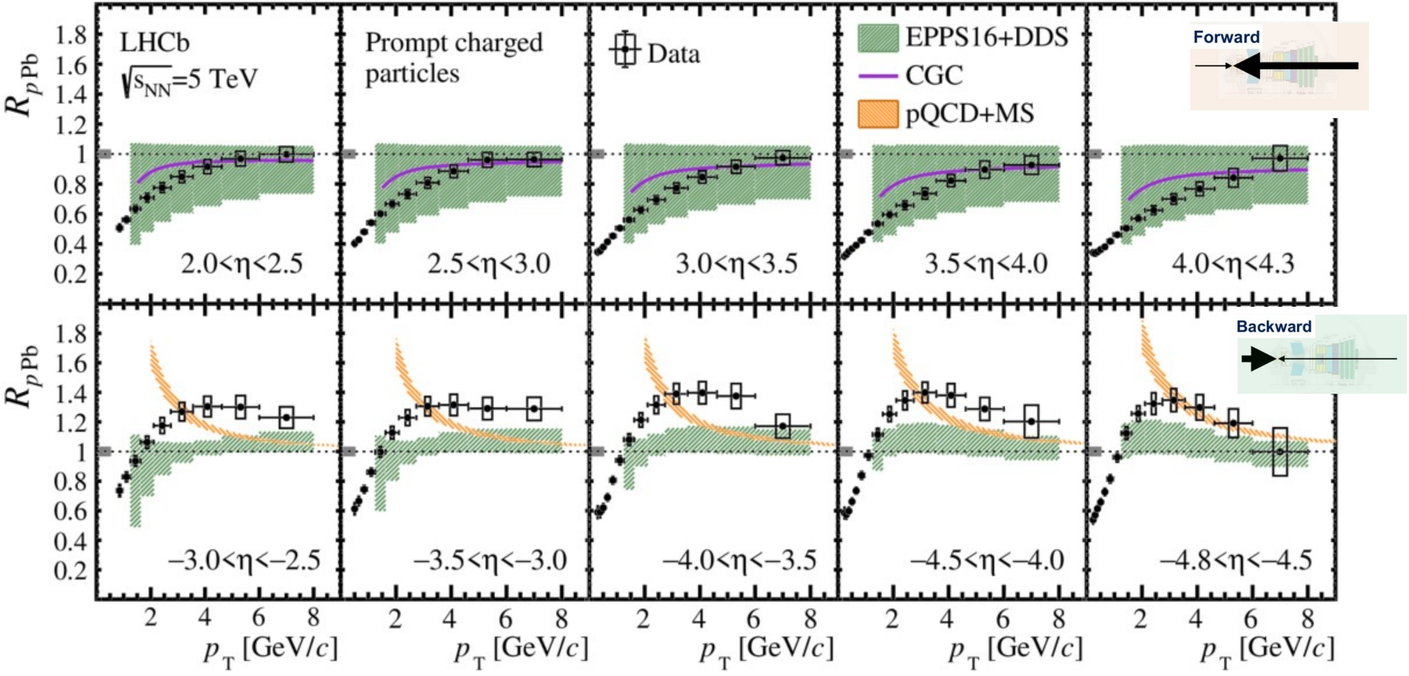
5 and 13 TeV results are consistent, showing an increase in the cross-section at 13 TeV of a factor 1 to 3, depending on p_T [JHEP 01 (2022) 166]



Prompt charged particle production

Phys.Rev.Lett. 128 (2022), 142004

$$R_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}}) \equiv \frac{1}{A} \frac{\mathrm{d}^2\sigma^{\mathrm{ch}}_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}})/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}{\mathrm{d}^2\sigma^{\mathrm{ch}}_{pp}(\eta, p_{\mathrm{T}})/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}$$



Models:

+ EPPS16+DDS
JHEP 09, 138 (2014)

+ CGC
PRD 88, 114020 (2013)

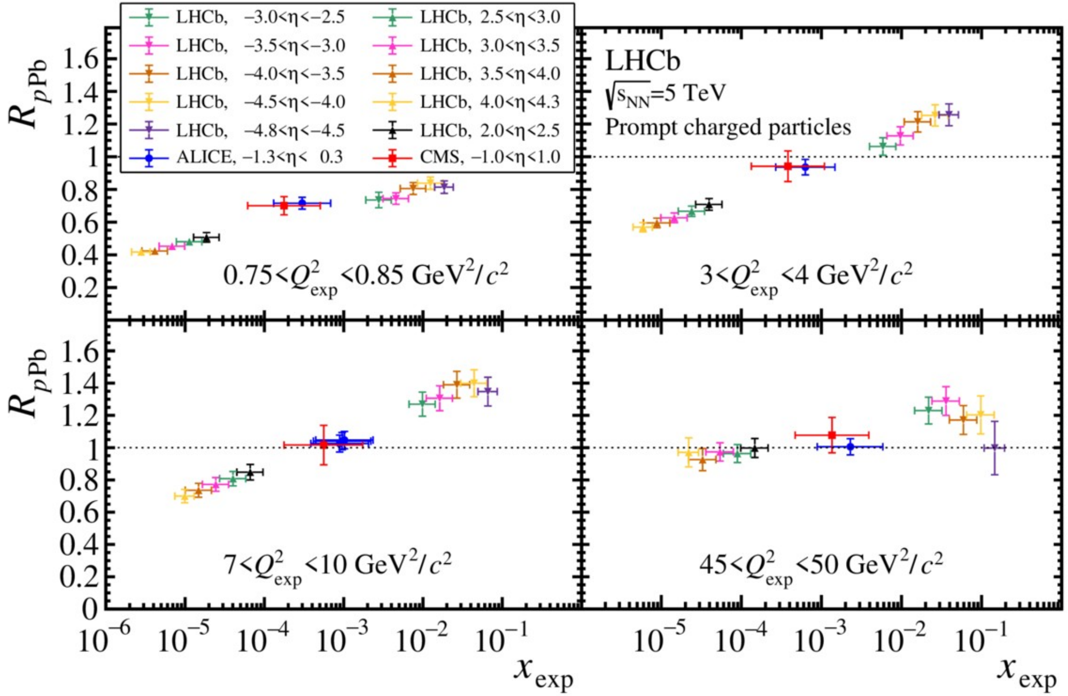
+pQCD+MS
PRD 88, 054010 (2013)

No model can describe data in both regions

Strong suppression at forward rapidities and low p_T / Enhancement at backward region

Prompt charged particle production

Phys.Rev.Lett. 128 (2022), 142004



Experimental proxies for x and Q²

$$Q^2_{\mathrm{exp}} \equiv m^2 + p_{\mathrm{T}}^2 \quad \text{and} \quad x_{\mathrm{exp}} \equiv \frac{Q_{\mathrm{exp}}}{\sqrt{s_{\mathrm{NN}}}} e^{-\eta}$$

Continuous evolution across experiments
ALICE [JHEP 11 (2018) 013]
and
CMS [JHEP 04 (2017) 039]

From small-*x* to large-*x*

Forward measurement probing unexplored *x*

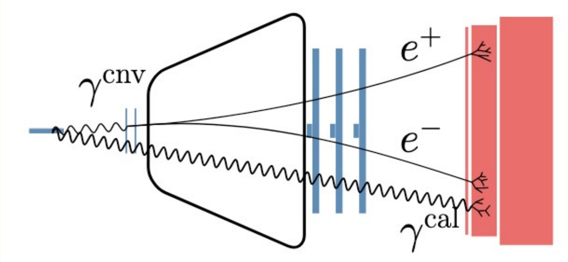
Nuclear modification factor of neutral pion production in pPb

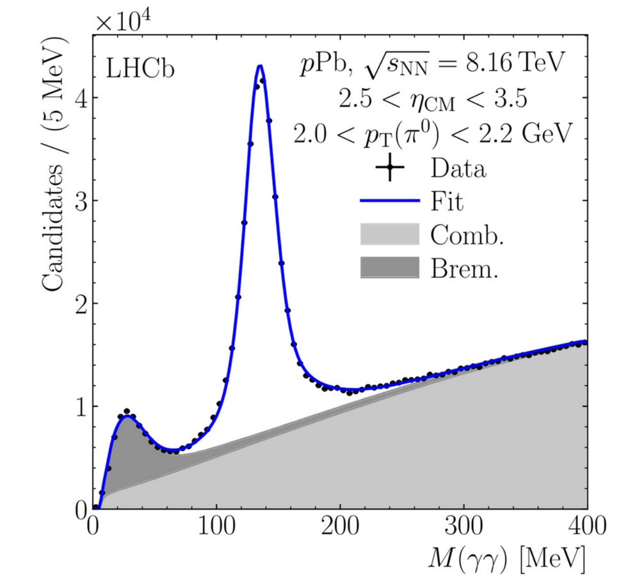
arXiv:2204.10608 (accepted in PRL)

→ pPb data at 8.16 TeV
→ pp samples at 5 TeV and 13 TeV (8 TeV is constructed by interpolating both samples)

→ $\pi^0(\rightarrow\gamma\gamma)$ candidates reconstructed with one ECAL and one converted photon

$\eta_{CM} = \eta_{lab} - 0.465$





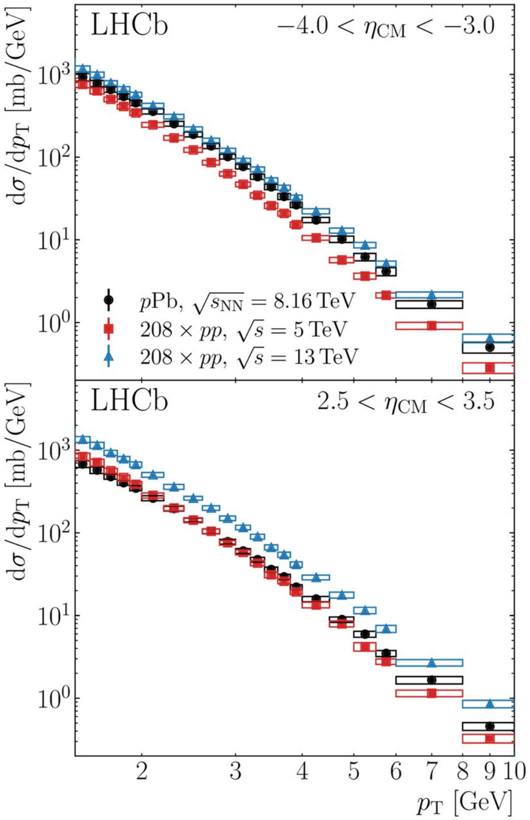
→ $\pi^0(\rightarrow\gamma\gamma)$ yield is obtained using binned maximum likelihood fits in each p_T region.

Background: combinatorial background and photons that are combined with its own bremsstrahlung radiation

Signal: two-sided Crystal Ball function (tails fixed from simulation)

Nuclear modification factor of neutral pion production in pPb

arXiv:2204.10608 (accepted in PRL)



Systematic uncertainties are dominated by fit model and pp reference cross-section interpolation.

Source	$d\sigma/dp_T$ [%]	R_{pPb} [%]
Fit model	2.0 – 12.6	0.9 – 15.8
Unfolding	0.3 – 6.4	0.4 – 6.4
Interpolation	–	0.9 – 4.5
Material	4.0	–
Efficiency	1.3 – 1.9	1.9 – 2.1
Luminosity	2.0 – 2.6	2.2 – 2.3
Total systematic	5.4 – 15.0	4.3 – 17.4
Statistical	1.0 – 9.6	1.4 – 9.1

Nuclear modification factor of neutral pion production in pPb

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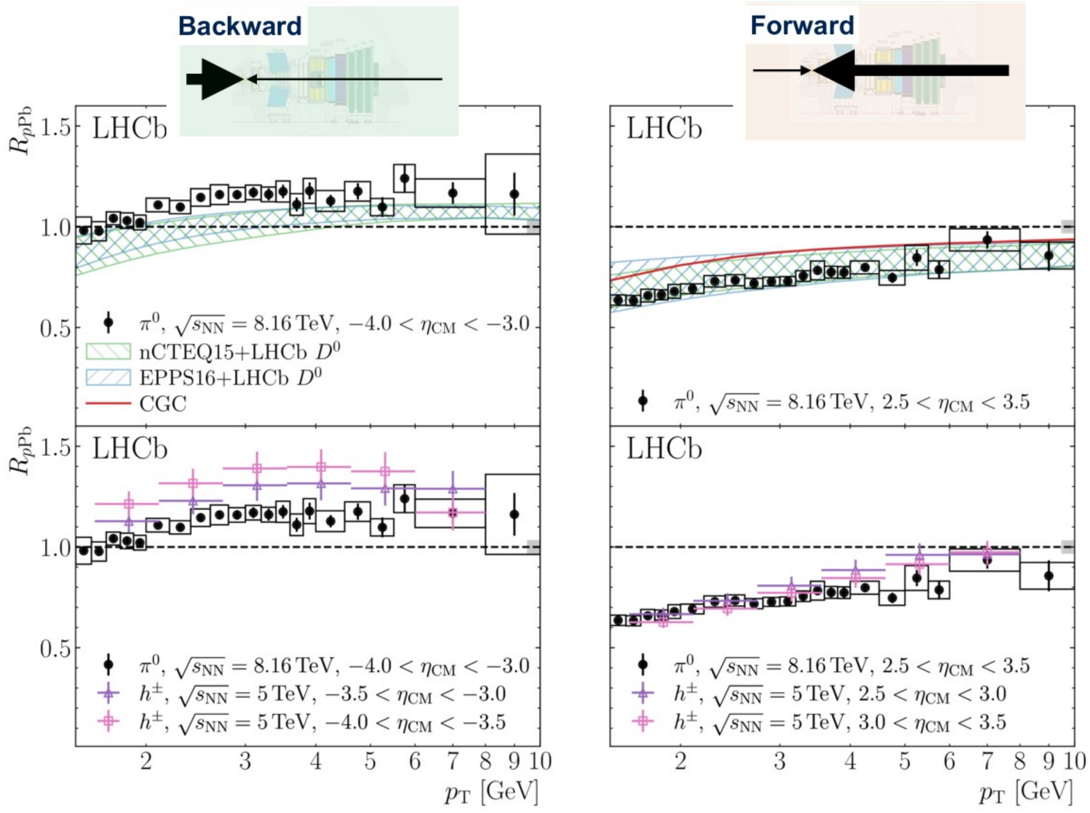


nPDF: JHEP 05 (2020) 037
CGC: Phys. Rev. D88 (2013) 114020

Backward:
- nPDF (reweigthed with LHCb D^0 5TeV**) underestimates observed enhancement

- Less pronounced than the charged hadron results (mass dependence?)

Forward:
- CGC L0 shows similar trend but underestimates suppression

- nPDF (reweigthed with LHCb D^0 5TeV**) agrees with data

- compatible with charged hadron results.

**D^0 measurement at 8.16 TeV provides further constraining [arXiv:2205.03936]

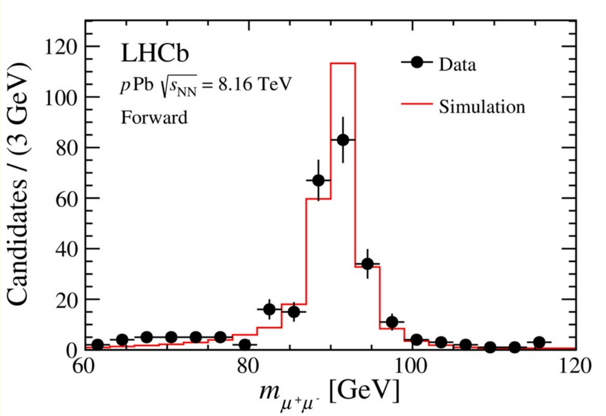
Measurement of the Z boson production cross-section in pPb

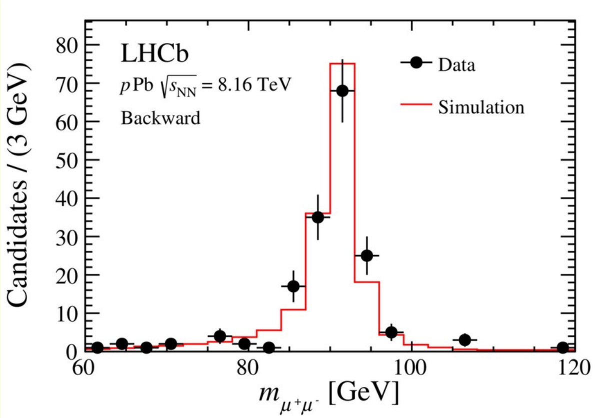
arXiv:2204.10608 (accepted in JHEP)

→ pPb data at 8.16 TeV

→ Z(→μμ) candidates

$2.0 < \eta(\mu) < 4.5$ and $p_T(\mu) > 20$ GeV and $60 < M(\mu\mu) < 120$ GeV





→ Background from heavy-flavor or mis-identification is found to be less than 0.3%

→ Systematic uncertainties dominated by efficiency (2.5%) and luminosity (2.5%)

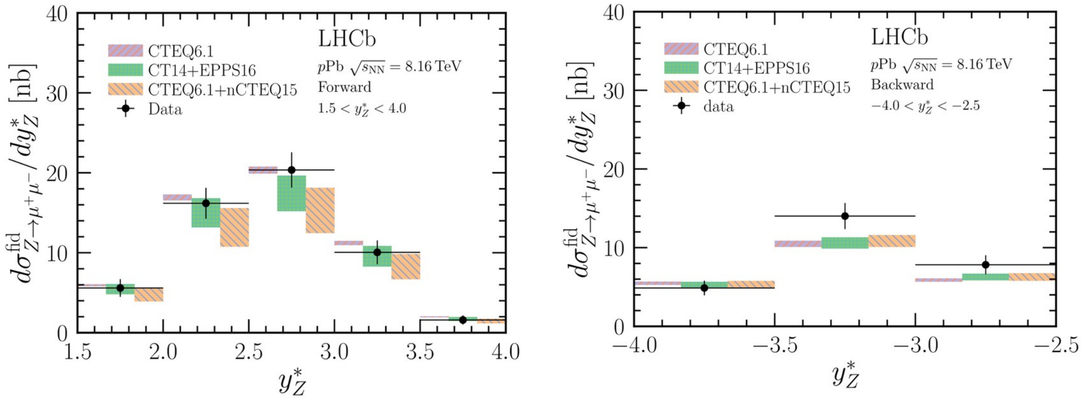
Measurement of the Z boson production cross-section in pPb

arXiv:2204.10608 (accepted in JHEP)

→ Differential cross-section

$$\frac{d\sigma^{\text{fid}}_{Z\to\mu^+\mu^-}}{dx} = \frac{\rho(x)\cdot f_{\text{FSR}}}{\mathcal{L}\cdot\epsilon^{\text{reco\&sel}}(x)\cdot\epsilon^{\text{muon-id}}(x)\cdot\epsilon^{\text{trig}}(x)}\cdot\frac{dN_{\text{cand}}}{dx}$$

x can be y^*_Z, p_T^Z or ϕ^*, where $\phi^* = \frac{\tan(\phi_{\text{acop}}/2)}{\cosh(\Delta\eta/2)}$



+ Forward region is better described by PowhegBOX calculations, but there is space for further model constraining.

+ Backward region is underestimated by predictions similar to 5 TeV analysis JHEP 09 (2014) 030

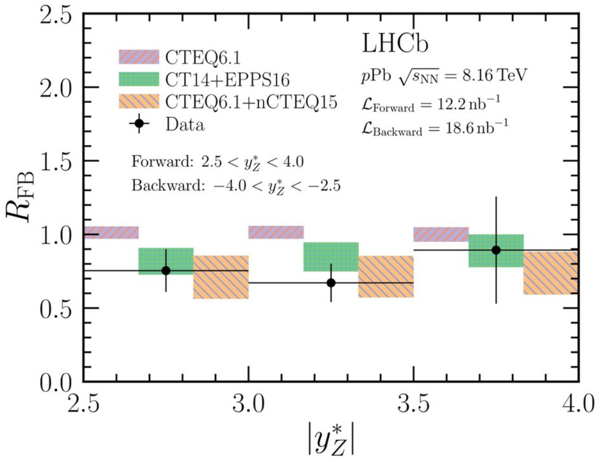
Measurement of the Z boson production cross-section in pPb

arXiv:2204.10608 (accepted in JHEP)

→ The ratio of the production cross-sections between forward and backward directions

$$R_{\mathrm{FB}}(x) = \frac{\mathrm{d}\sigma_{\mathrm{fw}}/\mathrm{d}x}{\mathrm{d}\sigma_{\mathrm{bw}}/\mathrm{d}x} \cdot k_{\mathrm{FB}}(x)\Big|_{2.5<|y_Z^*|<4.0}$$

→ The nuclear modifications are different for forward (small Bjorken-x) and backward (large Bjorken-*x*) rapidity.



R_{FB} is found to be 0.78±0.10

Nuclear shadowing suppression at small-*x*

Good agreement with the EPPS16 and nCTEQ15

Data provides constraining power ($10^{-5} < x < 10^{-4}$)

Differential cross-sections show similar trends.

Summary

--- LHCb experiment collected data in pp/pPb collisions with unique coverage

--- We presented

Charged hadron production in pPb

First neutral pion production measurement in forward and backward rapidities

First measurement of the differential Z-boson production cross-section in the forward region

--- Measurements already can constrain models of different nuclear effects

Sample size limitation will be improved with Run3 data

--- Other measurements not shown can be found here

Thank you

BACKUP

Prompt charged particle production

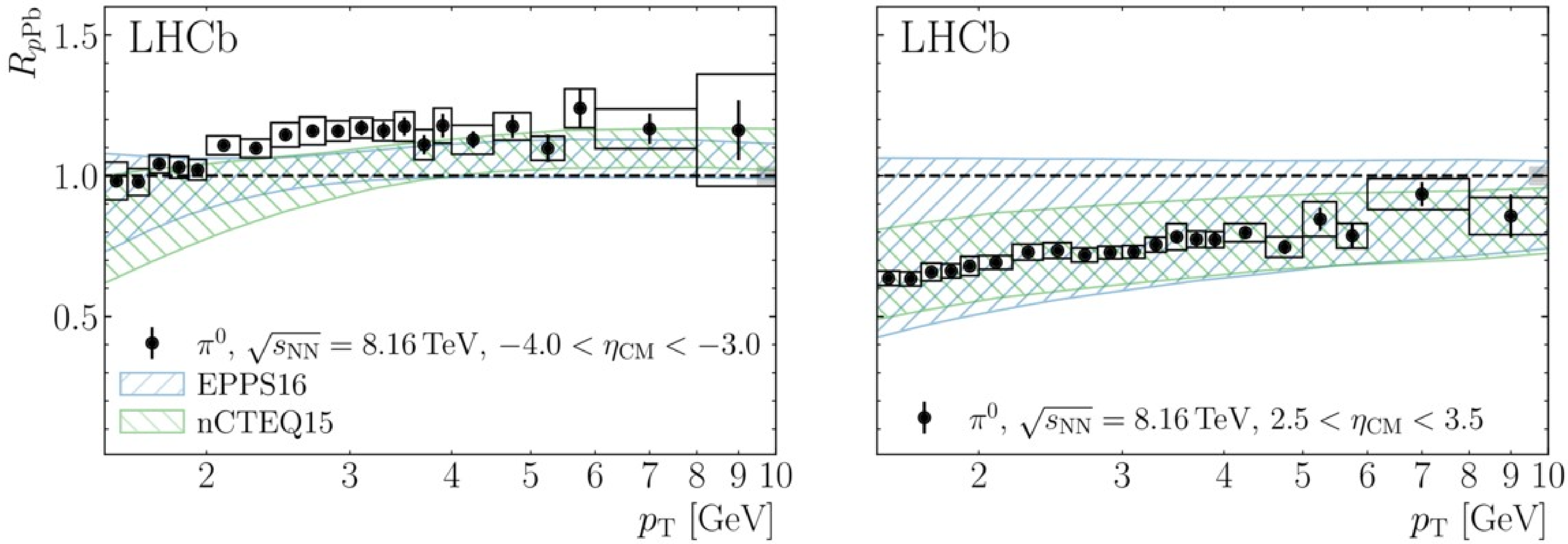
Phys.Rev.Lett. 128 (2022), 142004

$\sqrt{s_{NN}} = 5$ TeV, Datasets:

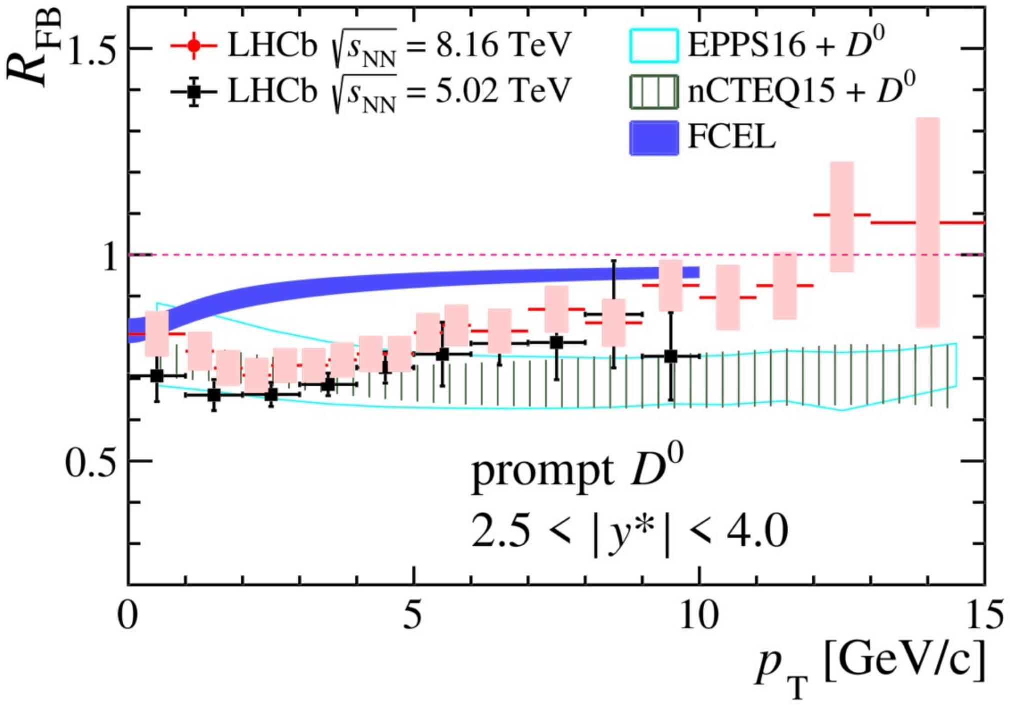
	Beam	Acceptance	Luminosity
2015	pp	$2 < \eta < 4.8$	$3.49 \pm 0.07\,\text{nb}^{-1}$
2013	pPb	$1.6 < \eta < 4.3$	$42.73 \pm 0.98\,\mu\text{b}^{-1}$
2013	Pbp	$-5.2 < \eta < -2.5$	$38.71 \pm 0.97\,\mu\text{b}^{-1}$

Nuclear modification factor of neutral pion production in pPb

arXiv:2204.10608

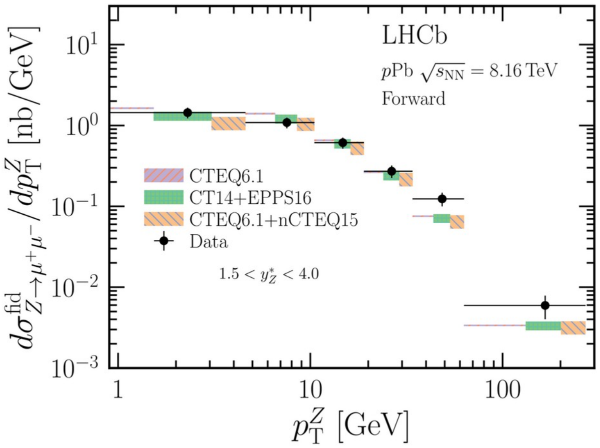


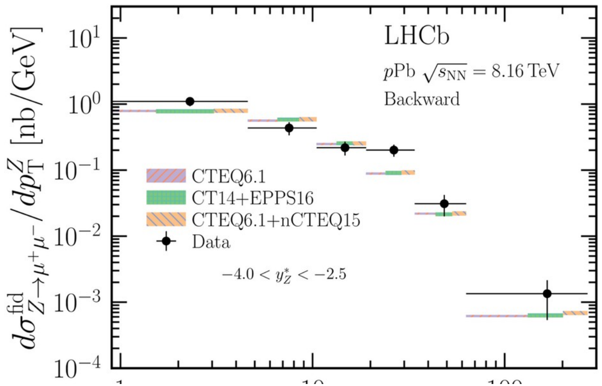
**D^0 measurement at 8.16 TeV provides further constraining [arXiv:2205.03936]

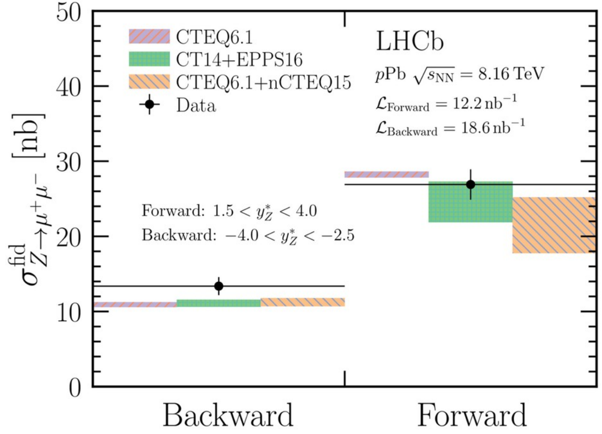


Measurement of the Z boson production cross-section in pPb

[arXiv:2204.10608](https://arxiv.org/abs/2204.10608)







Measurement of the Z boson production cross-section in pPb

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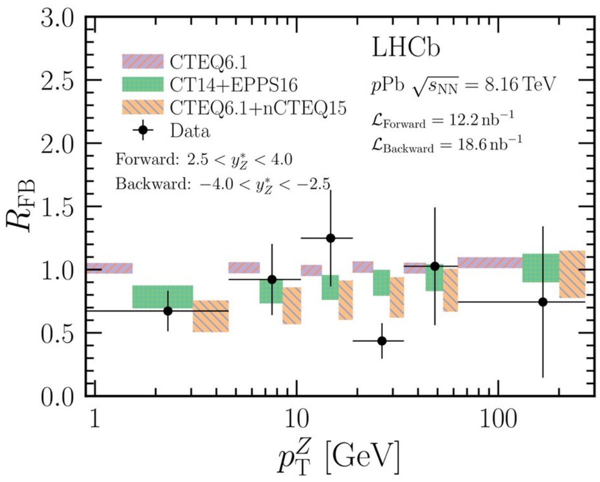

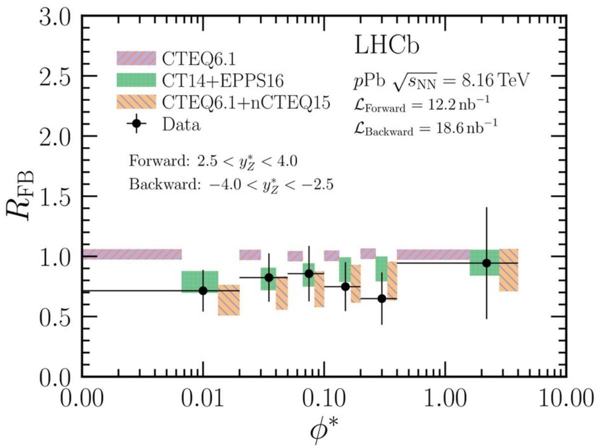

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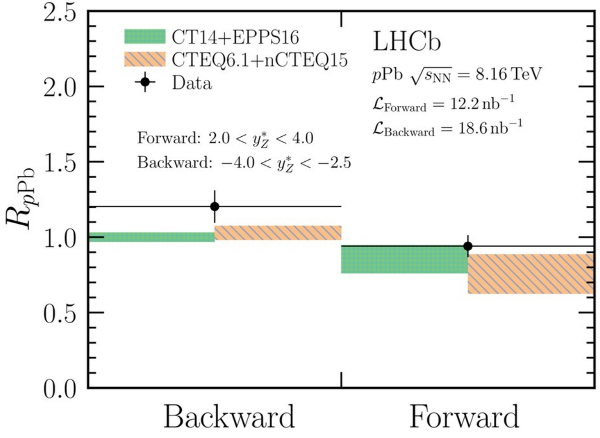
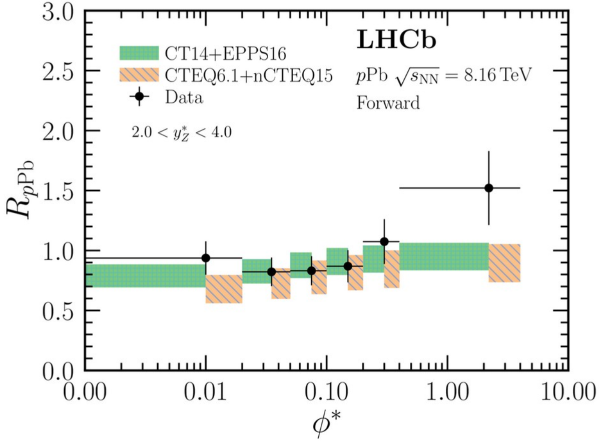
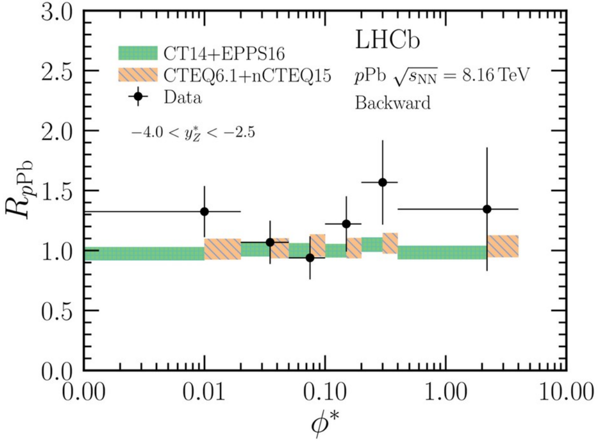






Measurement of the Z boson production cross-section in pPb

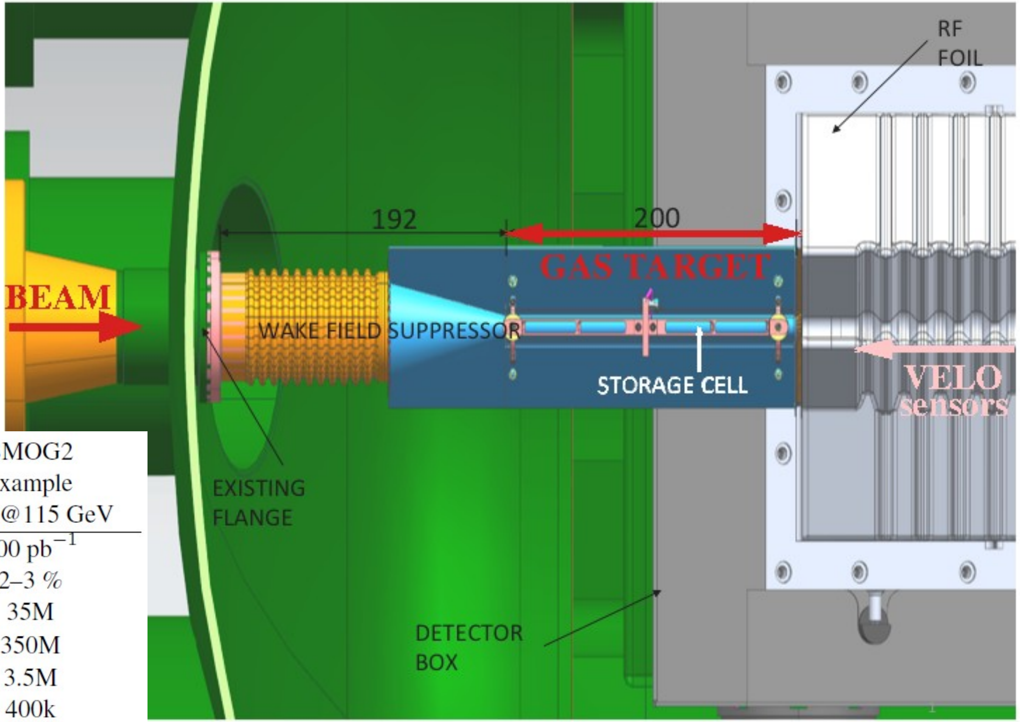
arXiv:2204.10608

Quantity	Forward	Backward
N_{cand} (for σ^{fid})	268	166
N_{cand} (for R_{FB})	160	166
N_{cand} (for $R_{p\mathrm{Pb}}$)	241	166
ρ [%]	99.69 ± 0.07	99.75 ± 0.08
$\epsilon^{\mathrm{reco\&sel}}$ [%]	87.2 ± 2.9	72.0 ± 2.5
$\epsilon^{\mathrm{muon\text{-}id}}$ [%]	97.3 ± 0.3	97.3 ± 0.3
ϵ^{trig} [%]	98.3 ± 0.6	97.1 ± 0.6
$\mathcal{L}$ [nb^{-1}]	12.2 ± 0.3	18.6 ± 0.5
f_{FSR}	1.02 ± 0.01	1.02 ± 0.01
k_{FB} (for R_{FB})	0.65 ± 0.02	–
$k_{p\mathrm{Pb}}$ (for $R_{p\mathrm{Pb}}$)	0.706 ± 0.002	1.518 ± 0.003

The gas target upgrade - SMOG2

LHCC-2019-0051/LHCb TDR 20

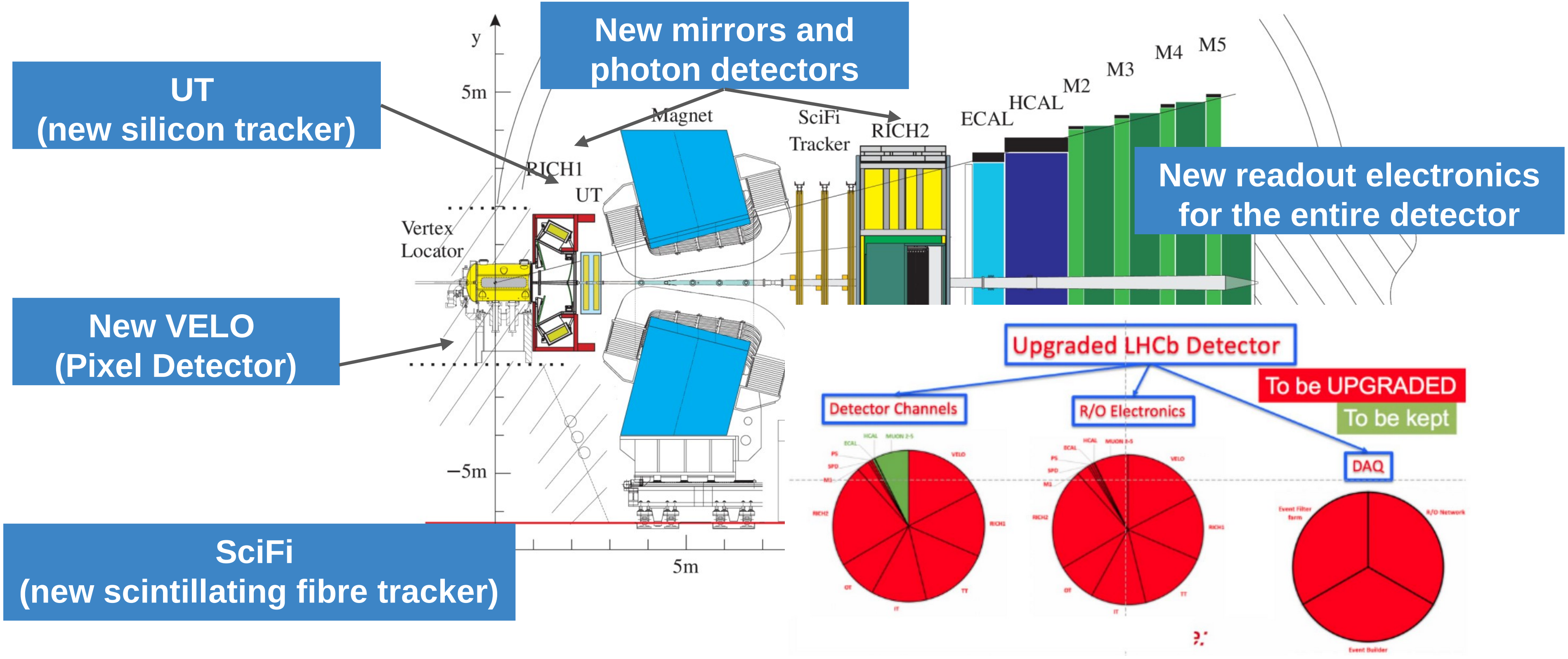
- **o** 20cm long storage cell, 5mm radius around the beam, just upstream the VELO
- **o** possibly inject other gases
- **o** Up to x100 higher gas density with same gas flow of current SMOG
- **o** Faster switch between gas species



	SMOG largest sample p–Ne@68 GeV	SMOG2 example p–Ar@115 GeV
Integrated luminosity	$\sim 100\ \mathrm{nb}^{-1}$	$100\ \mathrm{pb}^{-1}$
syst. error on J/ψ x-sec.	6–7%	2–3 %
J/ψ yield	15k	35M
D^0 yield	100k	350M
Λ_c yield	1k	3.5M
$\psi(2S)$ yield	150	400k
$\Upsilon(1S)$ yield	4	15k
Low-mass ($5 < M_{\mu\mu} < 9\ \mathrm{GeV}/c^2$) Drell-Yan yield	5	20k

LHCb Upgrade I

CERN-LHCC-2012-007



LHCb Upgrade I

CERN-LHCC-2012-007

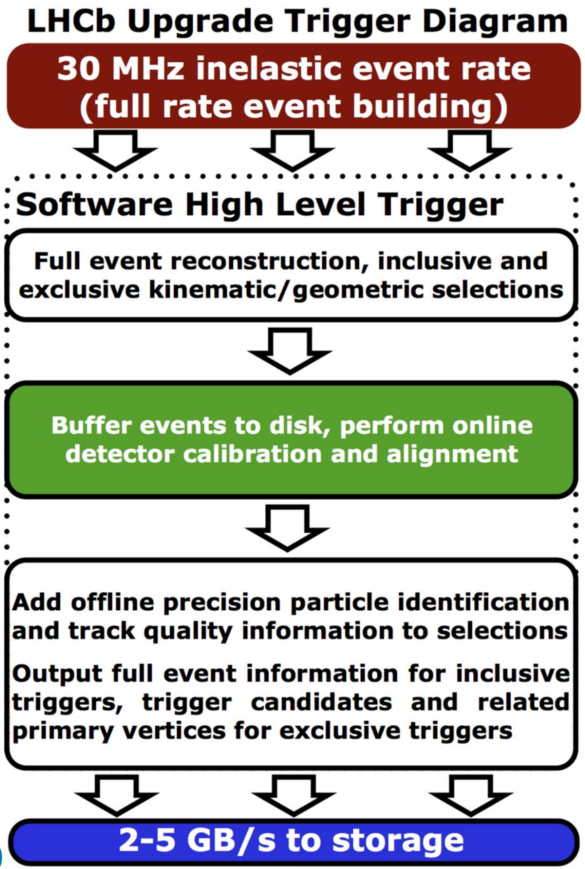
❈ Increase instantaneous luminosity:
$4 \times 10^{32} \rightarrow 2 \times 10^{33}\ cm^{-2}\ s^{-1}$

❈ Replacement of tracking detectors
♯ finer granularity to cope with higher particle density
♯ new front-end electronics compatible with 30 MHz readout

❈ Remove hardware trigger stage and operate software trigger at 30 MHz input rate with 5 x more pileup than Run 2.

❈ Prospects for integrated luminosity for heavy-ion

PbPb	**0.5/nb**
pPb	**150/nb**



LHCB-PUB-2014-0