Heavy ion and fixed target physics at the LHCb experiment

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on behalf of the LHCb Collaboration

LHCb

lape

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XV Hadron Physics 2020

Outline

--- LHCb experiment overview

--- Results discussed in this talk

Charm Production in Fixed-Target

Nuclear modification factor and prompt charged particle production in pPb and pp

Coherent J/ψ photo-production in PbPb

J/ψ photo-production in peripheral in PbPb

--- Prospects for Run3 data

--- Summary

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

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

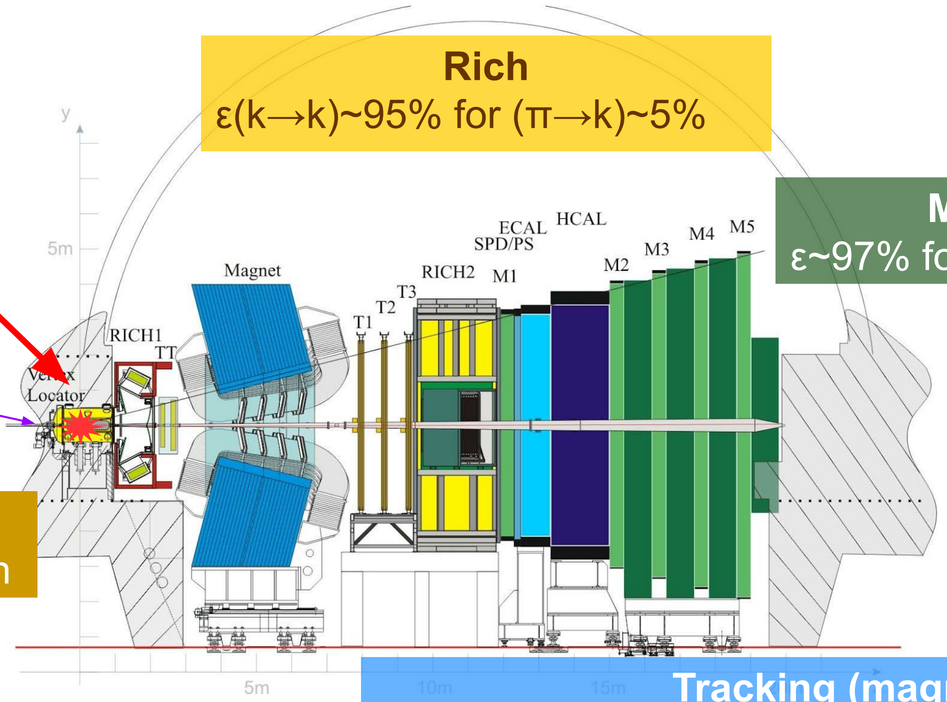
[Int. J. Mod. Phys. A 30, 1530022 (2015)]

Rich
ε(k→k)~95% for (π→k)~5%

Collision

SMOG

Muon
ε~97% for misID~2%

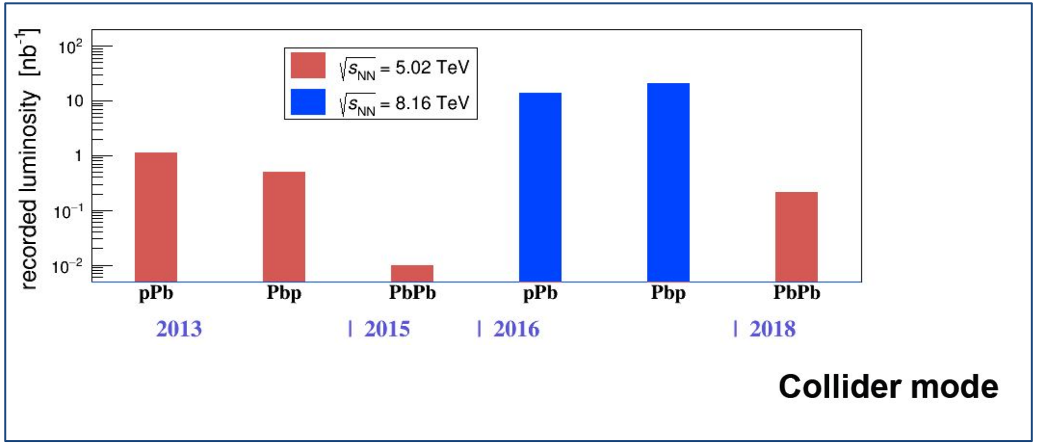


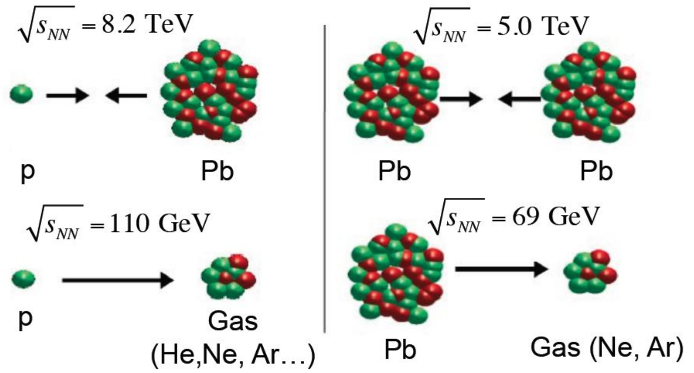
Herschel
Forward counters

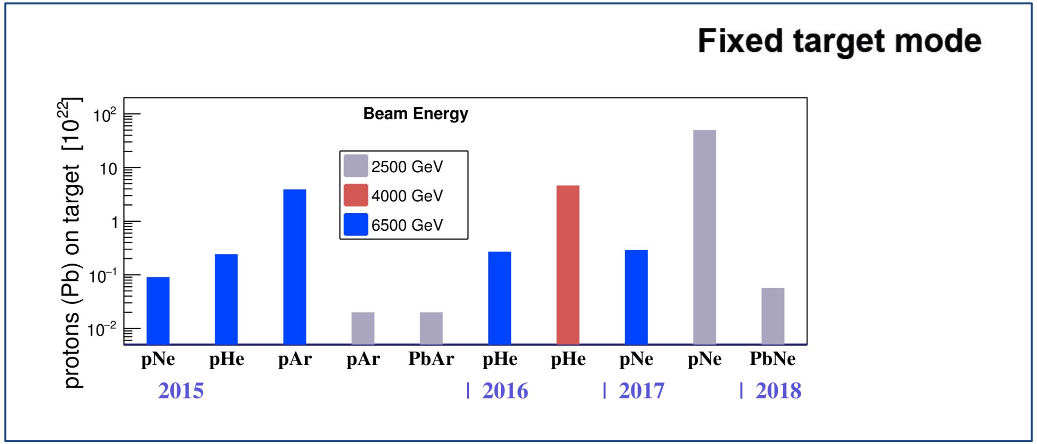
VELO
~20μm IP resolution

Tracking (magnet)
0.4%-0.6% momentum resolution (0.2-100 GeV)

LHCb also studies heavy-ion collider and fixed target mode







First Measurement of Charm Production in its Fixed-Target Configuration at the LHC

PRL 122, 132002 (2019)

→Using **SMOG** (system for measuring overlap with gas) device

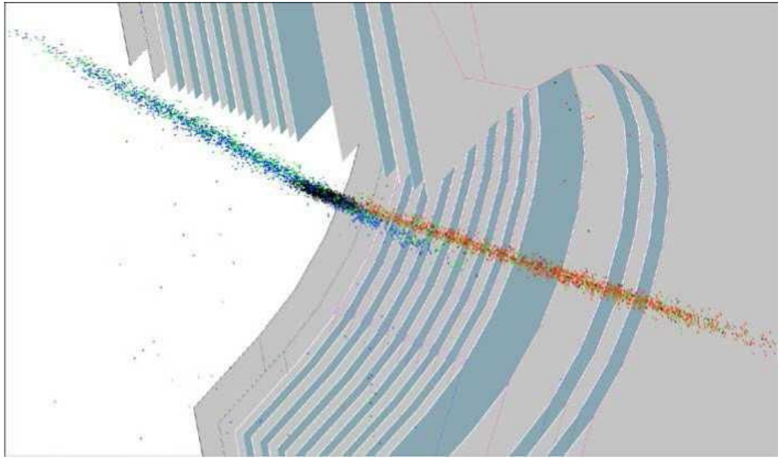
Gas in injected in the interaction region

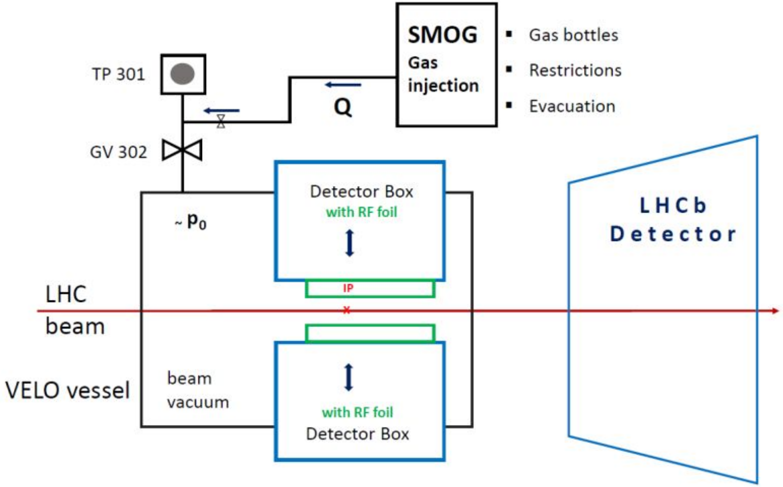
LHCb becomes a fixed target experiment

→Protons with 4.0 (6.5) TeV collide with He (Ar) nuclei at $\sqrt{s_{NN}}$ = (86.6) 110.5 GeV

→Luminosity for pHe = 7.58±0.47/nb

→Large Bjorken-x is probed for D^0 (up to 0.37)



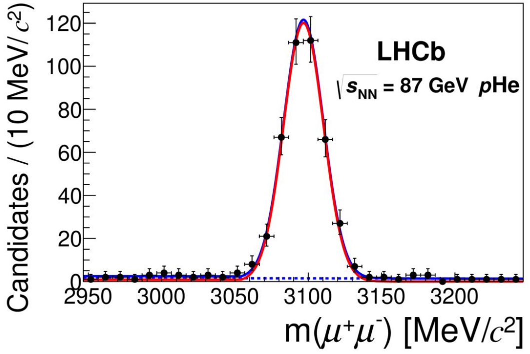


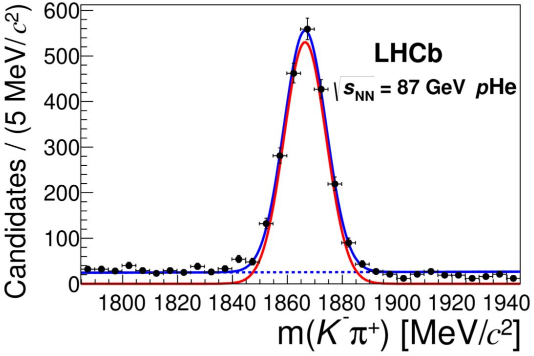
OBJ

First Measurement of Charm Production in its Fixed-Target Configuration at the LHC

PRL 122, 132002 (2019)

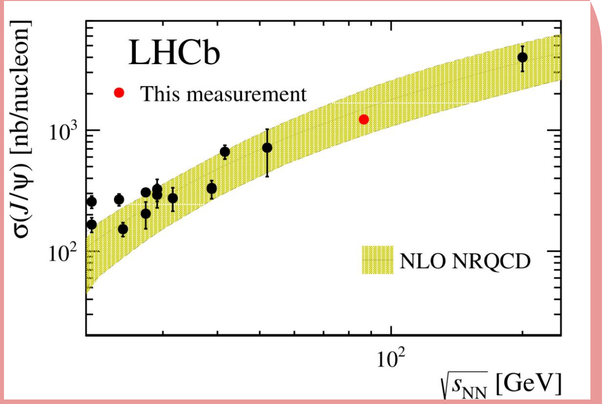
- Prompt production of J/ψ(→μμ) and D^0(→Kπ) is studied in pHe and pAr

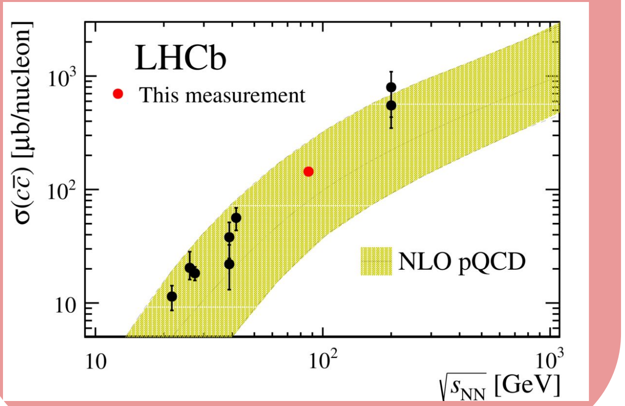




- measured cross-sections using pHe data are extrapolated to compare with other experiments and NLO pQCD [M. L. Mangano et al, NPB373,295 (1992)]

$$\sigma_{J/\psi} = 652 \pm 33(\text{stat}) \pm 42(\text{syst})\ \text{nb/nucleon},$$
$$\sigma_{D^0} = 80.8 \pm 2.4(\text{stat}) \pm 6.3(\text{syst})\ \mu\text{b/nucleon}.$$

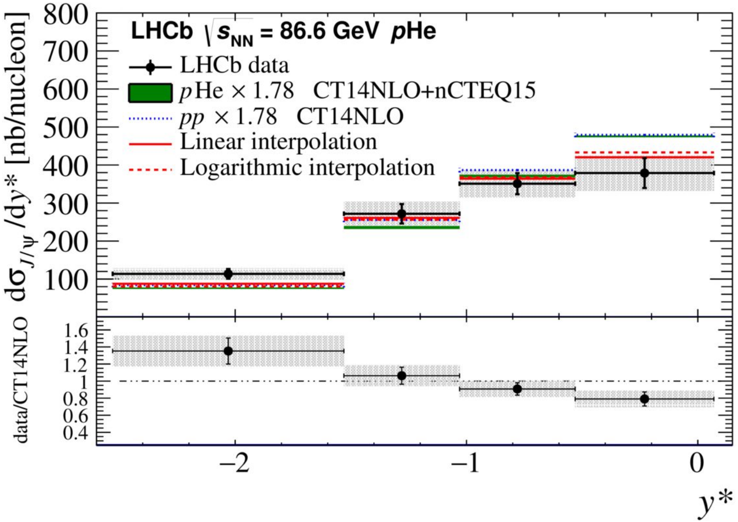


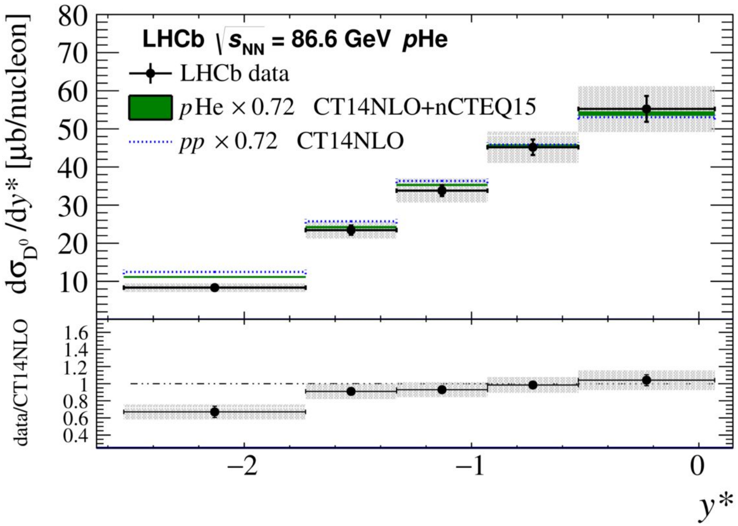


First Measurement of Charm Production in its Fixed-Target Configuration at the LHC

PRL 122, 132002 (2019)

o Differential yields of J/ψ as functions of y^* and p_T are compared with phenomenological parametrizations, interpolated to the present data energies.



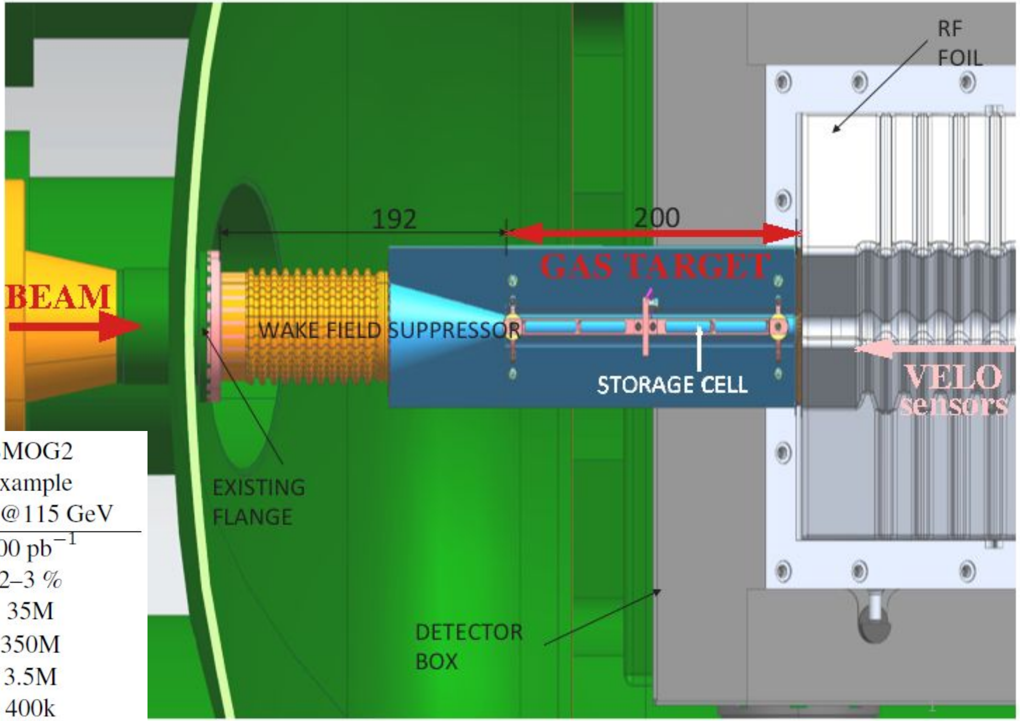


o No evidence of substantial intrinsic charm content of the nucleon is observed in the data

o Measurements limited by data sample size

The gas target upgrade - SMOG2
LHCC-2019-0051/LHCb TDR 20

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



	SMOG largest sample p–Ne@68 GeV	SMOG2 example p–Ar@115 GeV
Integrated luminosity	$\sim 100\ \text{nb}^{-1}$	$100\ \text{pb}^{-1}$
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 ($5 < M_{\mu\mu} < 9\ \text{GeV}/c^2$) Drell-Yan yield	5	20k

Nuclear modification factor and prompt charged particle production in pPb and pp

arXiv:2108.13115

→Double-differential production cross-section for prompt charged particles

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

$\eta = \eta_{lab} - 0.465$ for pPb

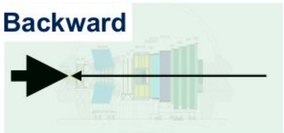
→The nuclear modification factor is defined as

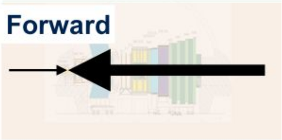
$$R_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}}) \equiv \frac{1}{A}\frac{\mathrm{d}^2\sigma^{\mathrm{ch}}_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}})/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}{\mathrm{d}^2\sigma^{\mathrm{ch}}_{pp}(\eta, p_{\mathrm{T}})/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}$$

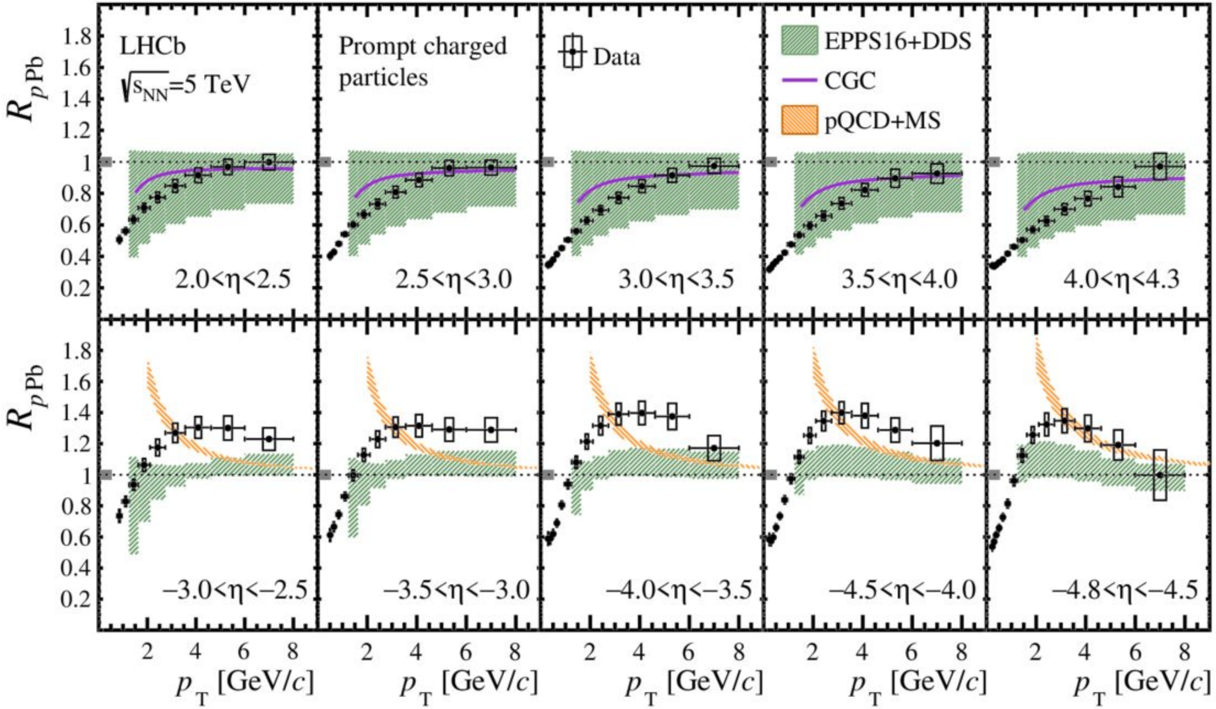
➪ **R_{pPb} = 1** if pPb collision is superposition of 208 pp collisions

Nuclear modification factor and prompt charged particle production in pPb and pp

arXiv:2108.13115







→R_{pPb} evolution with p_T

Forward region (upper plots)
Backward region (bottom plots).

clear pseudorapidity dependence is observed

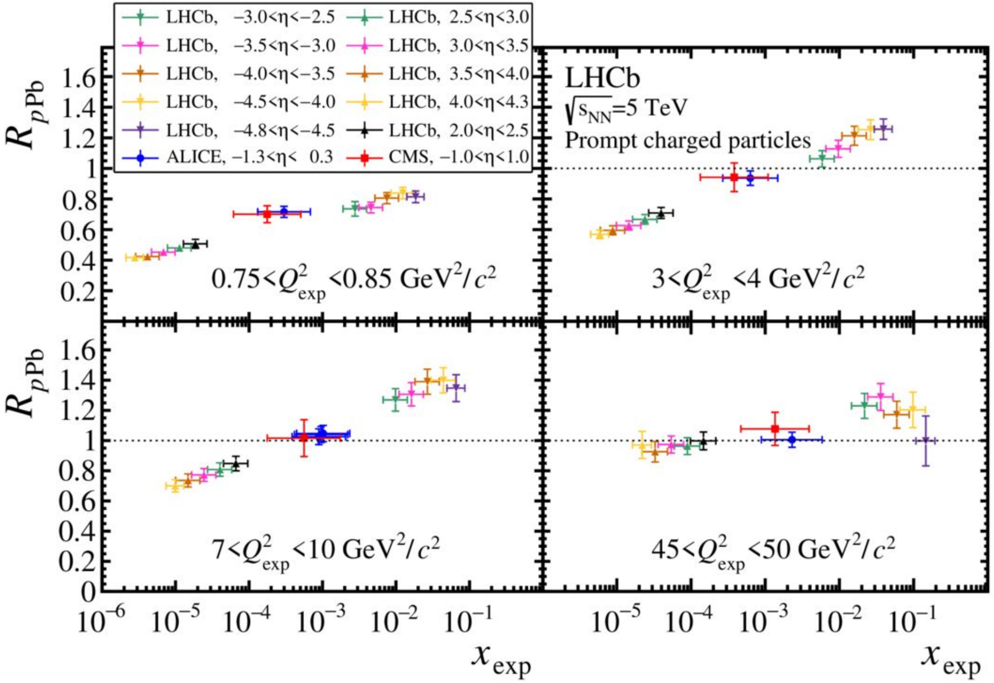
Forward region: inconsistency with CGC calculations at the lowest p_T

Backward region: production of charged particles with p_T>1.5GeV/c is enhanced

Nuclear modification factor and prompt charged particle production in pPb and pp

arXiv:2108.13115

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

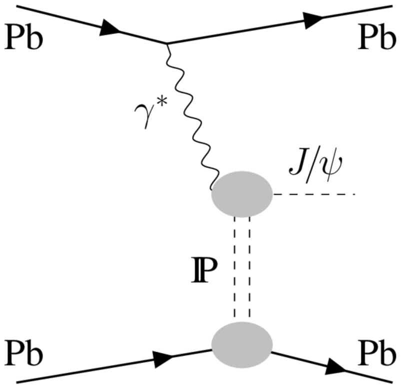


The CMS, LHCb and Alice experiments show a consistent trend in the forward region.

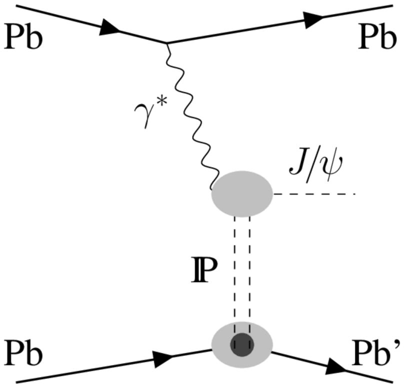
Strong constraints on nuclear PDFs at the lowest accessible x ranges

Study of coherent J/ψ production in ultraperipheral PbPb collisions

arXiv:2107.03223



coherent scatter with the Pb nucleus



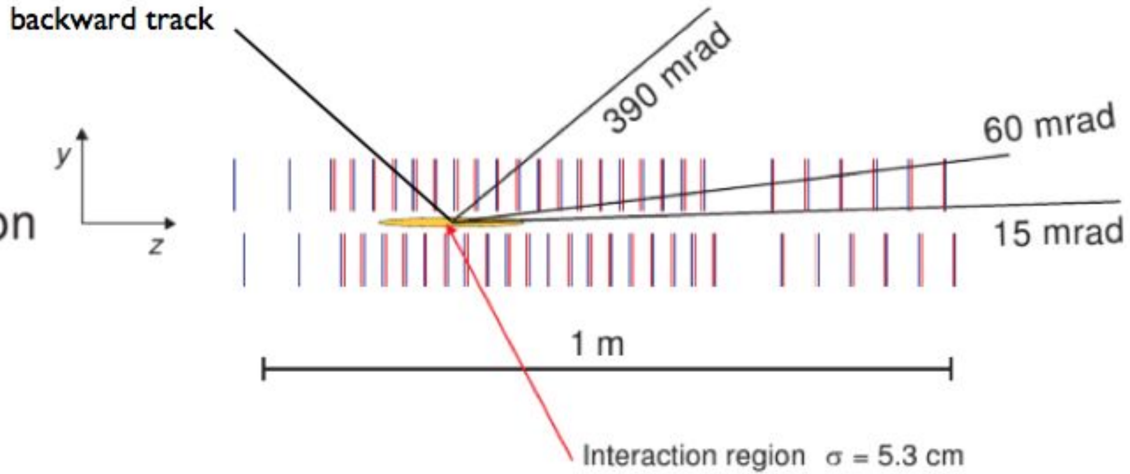
incoherent interaction with a single nucleon

Ultraperipheral collisions: interaction of photons with gluons

single object with vacuum quantum numbers - pomeron

Values of the Bjorken variable can be studied down to 10^{-5} (large theoretical uncertainties)

Experimental strategy: Very clean events can be selected using VELO and Herschel detector (2015 data) cross section at $x=0$:



VELO (Vertex Locator)

- → surrounds the interaction point
- → no magnetic field
- → reconstructs backward tracks $(-3.5<\eta<-1.5)$

High **R**apidity **S**hower **C**ounters for **L**HCb – HERSCHEL

- installed at the end of 2014 → increase pseudorapidity coverage
- 5 stations with 4 scintillators with PMT
- able to detect forward particle showers and veto events with these

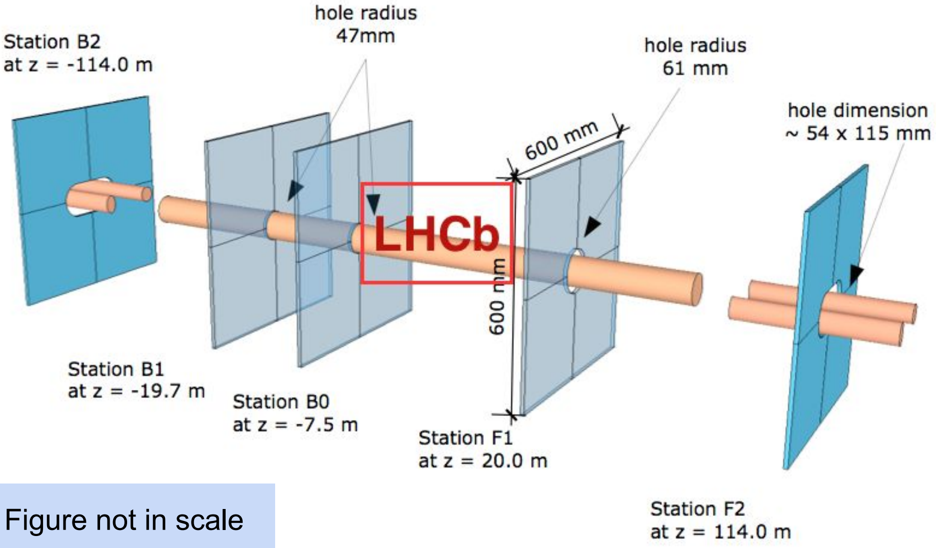
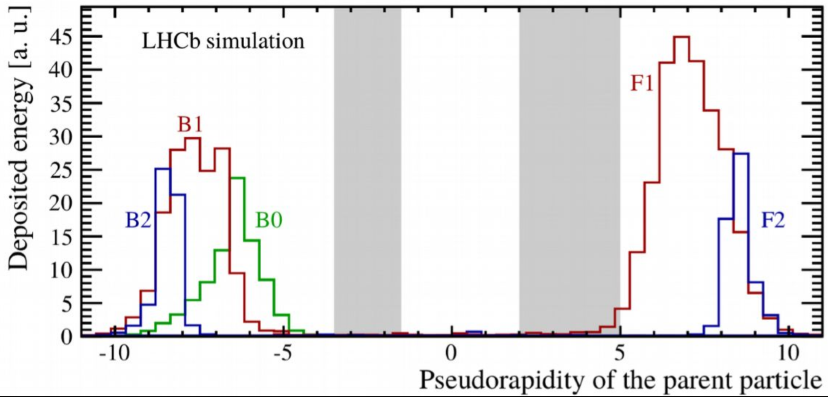


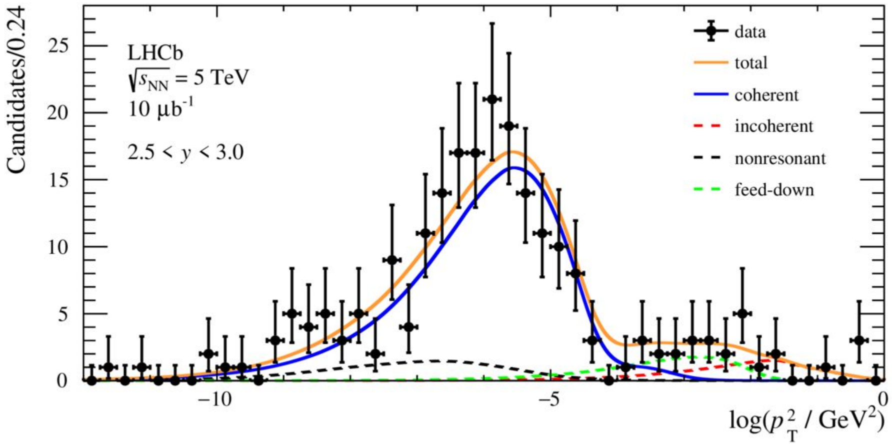
Figure not in scale

JINST 13 (2018) no.04, P04017



Study of coherent J/ψ production in ultraperipheral PbPb collisions
arXiv:2107.03223

Coherent yields are obtained from a fit to the $\log(p_T^2)$ distribution



Rapidity y	Total J/ψ yield	Coherent J/ψ yield
2.0 – 2.5	69 ± 9	53 ± 8
2.5 – 3.0	208 ± 15	153 ± 14
3.0 – 3.5	233 ± 16	176 ± 15
3.5 – 4.0	131 ± 12	95 ± 11
4.0 – 4.5	32 ± 6	12 ± 5

Good signal to background ratio assuming only coherent includes only intact Pb interactions.

Study of coherent J/ψ production in ultraperipheral PbPb collisions

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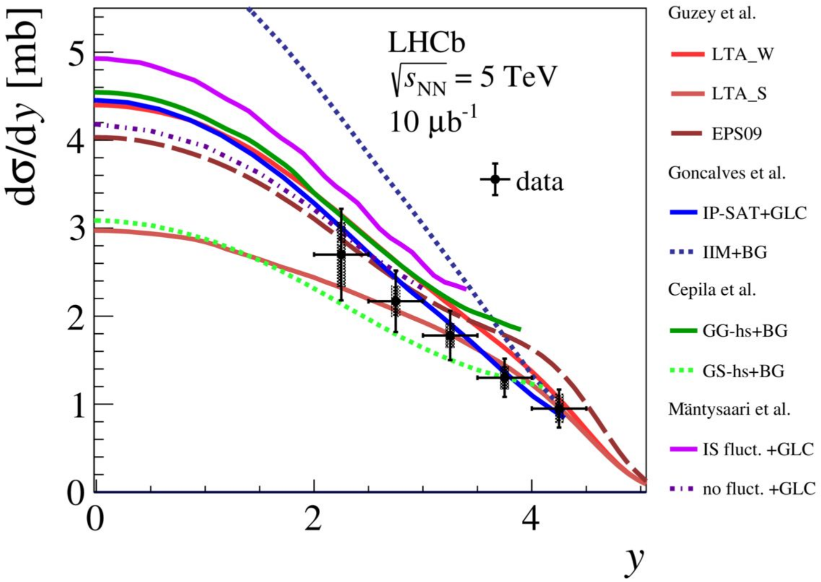


Differential cross-sections are compared to predictions from different phenomenological models

Some prescriptions are disfavored by data

Future measurements will help further constrain the existing models

Study of J/ψ photo-production in peripheral PbPb collisions

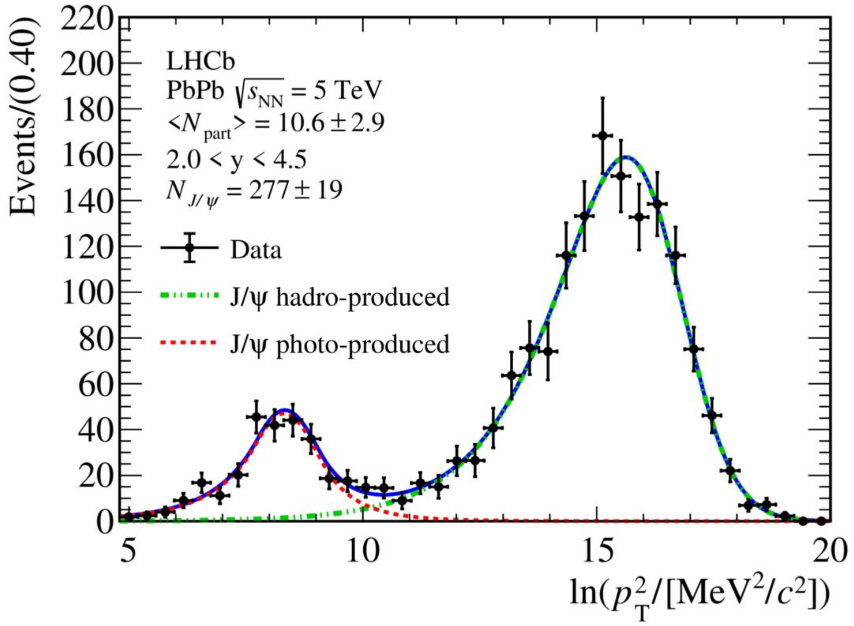
arXiv:2108.0268

→Photo-production of J/ψ(→μμ) is measured at very low p_T

study coherent interaction in hadronic collisions and the profile of the photon flux

→2018 data with 210/μb is used

→Projections of $\log(p_T^2)$ are used to determine the coherent photo-production and hadronic production



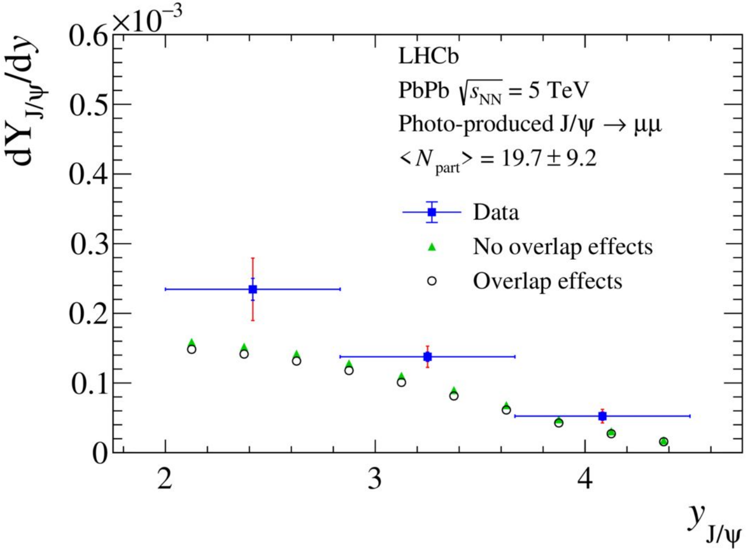
Study of J/ψ photo-production in peripheral PbPb collisions

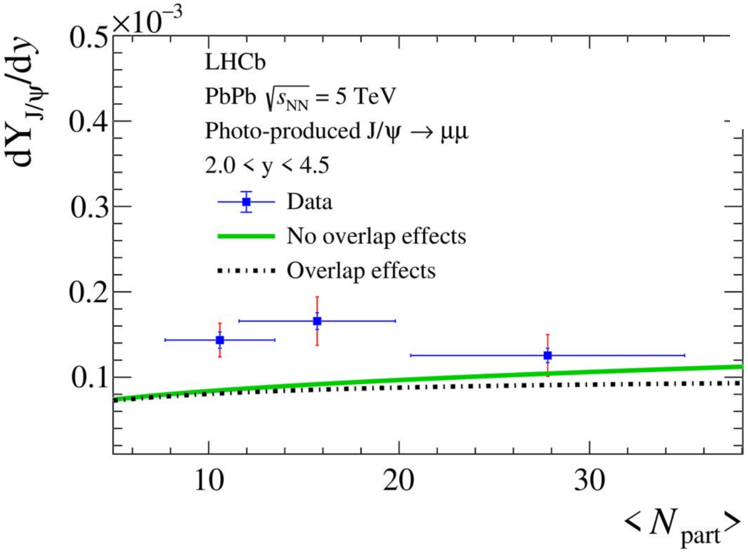
arXiv:2108.0268

Differential yields of photo-produced J/ψ candidates as a function of rapidity and as a function of $\langle N_{part} \rangle$

$$\frac{\mathrm{d}Y^i_{J/\psi}}{\mathrm{d}y} = \frac{N^i_{J/\psi}}{\mathcal{B}\, N^i_{\mathrm{MB}}\, \varepsilon^i_{\mathrm{tot}}\, \Delta y},$$

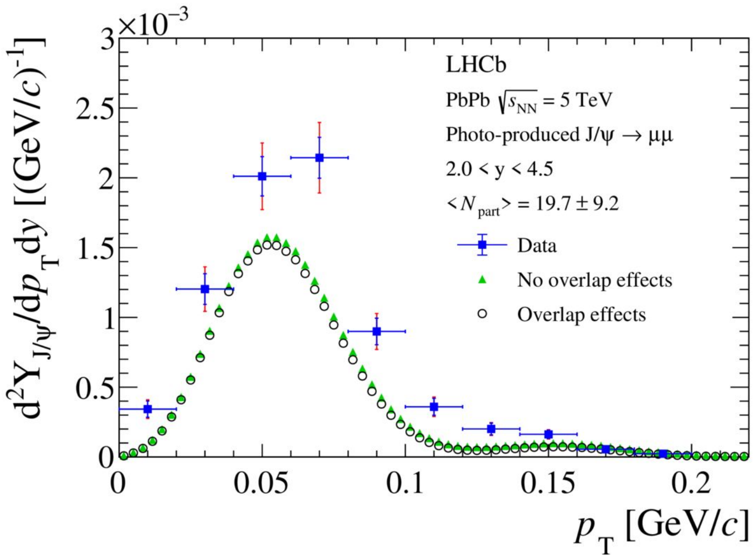
$$\frac{\mathrm{d}^2 Y^i_{J/\psi}}{\mathrm{d}p_{\mathrm{T}} dy} = \frac{\mathrm{d}Y^i_{J/\psi}}{\mathrm{d}y} \frac{1}{\Delta p_{\mathrm{T}}},$$





Study of J/ψ photo-production in peripheral PbPb collisions
arXiv:2108.0268

Differential yields of photo-produced J/ψ candidates as a function of rapidity and as a function of $<N_{part}>$



$$\frac{dY^i_{J/\psi}}{dy} = \frac{N^i_{J/\psi}}{\mathcal{B}\, N^i_{MB}\, \varepsilon^i_{tot}\, \Delta y},$$

$$\frac{d^2Y^i_{J/\psi}}{dp_T dy} = \frac{dY^i_{J/\psi}}{dy}\frac{1}{\Delta p_T},$$

Coherent J/ψ photo-production in peripheral hadronic collisions is confirmed
(in agreement with other experiments)
Shape of the results are qualitatively described by the theoretical prediction
Normalisation discrepancy is observed

LHCb Upgrade I

CERN-LHCC-2012-007

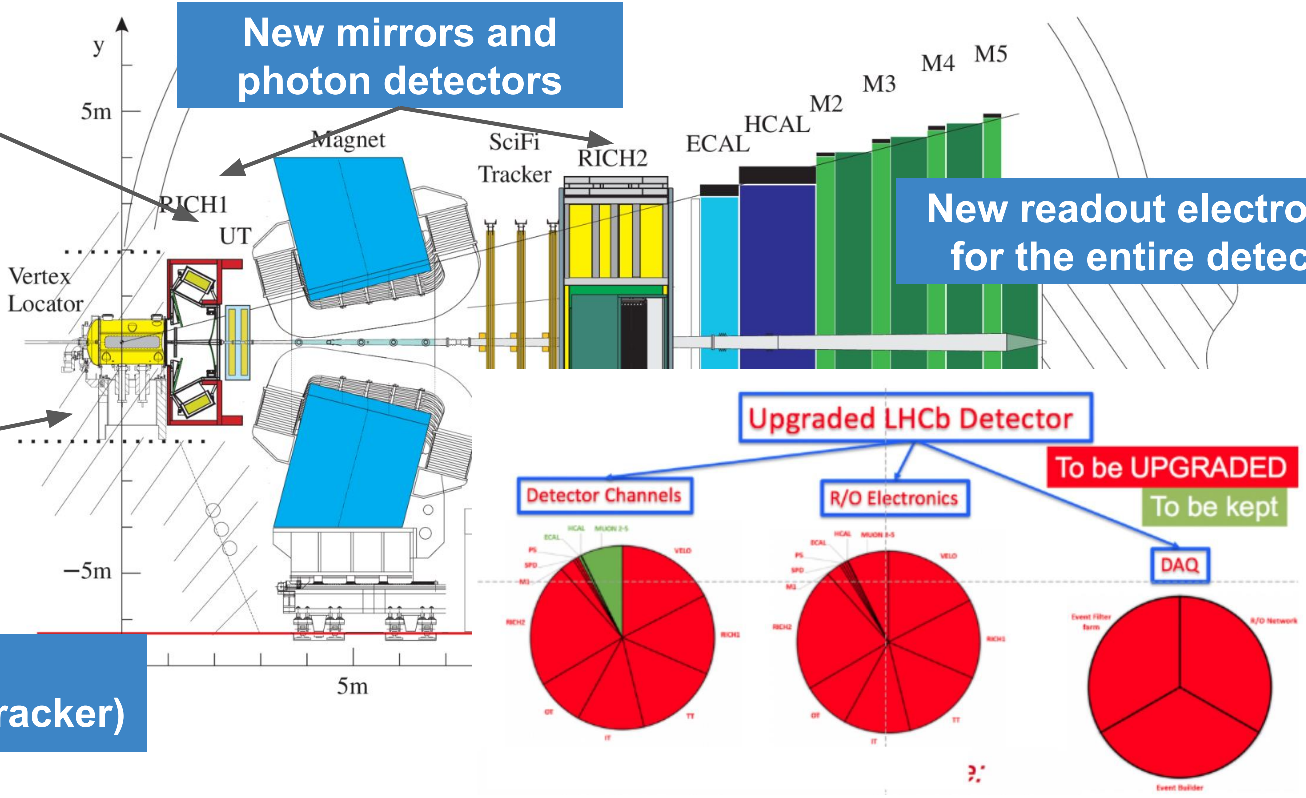
UT (new silicon tracker)

New mirrors and photon detectors

New readout electronics for the entire detector

New VELO (Pixel Detector)

SciFi (new scintillating fibre tracker)



LHCb Upgrade I

CERN-LHCC-2012-007

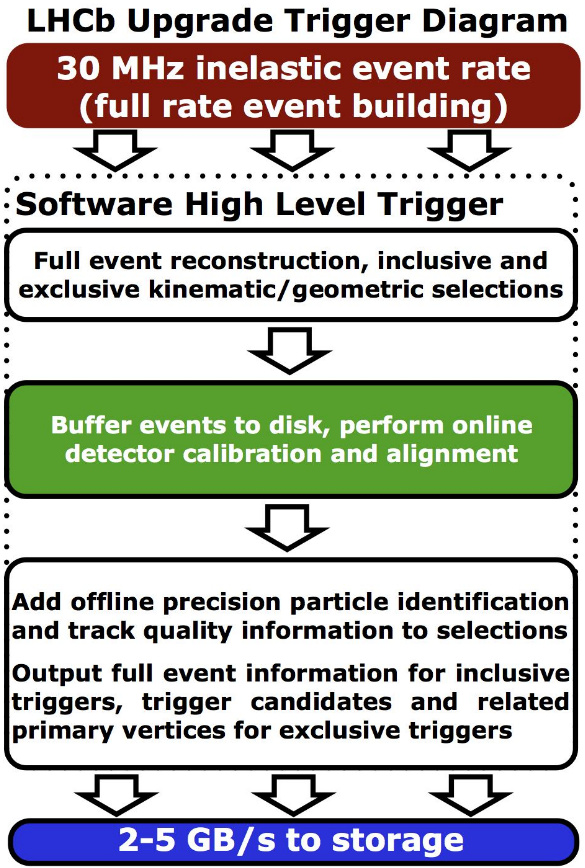
❈ Increase instantaneous luminosity:
$4 \times 10^{32} \rightarrow 2 \times 10^{33}$ cm^{-2} s^{-1}

❈ 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-2014-027

Summary

--- LHCb experiment collected data in heavy-ion collisions and fixed-target mode with unique coverage

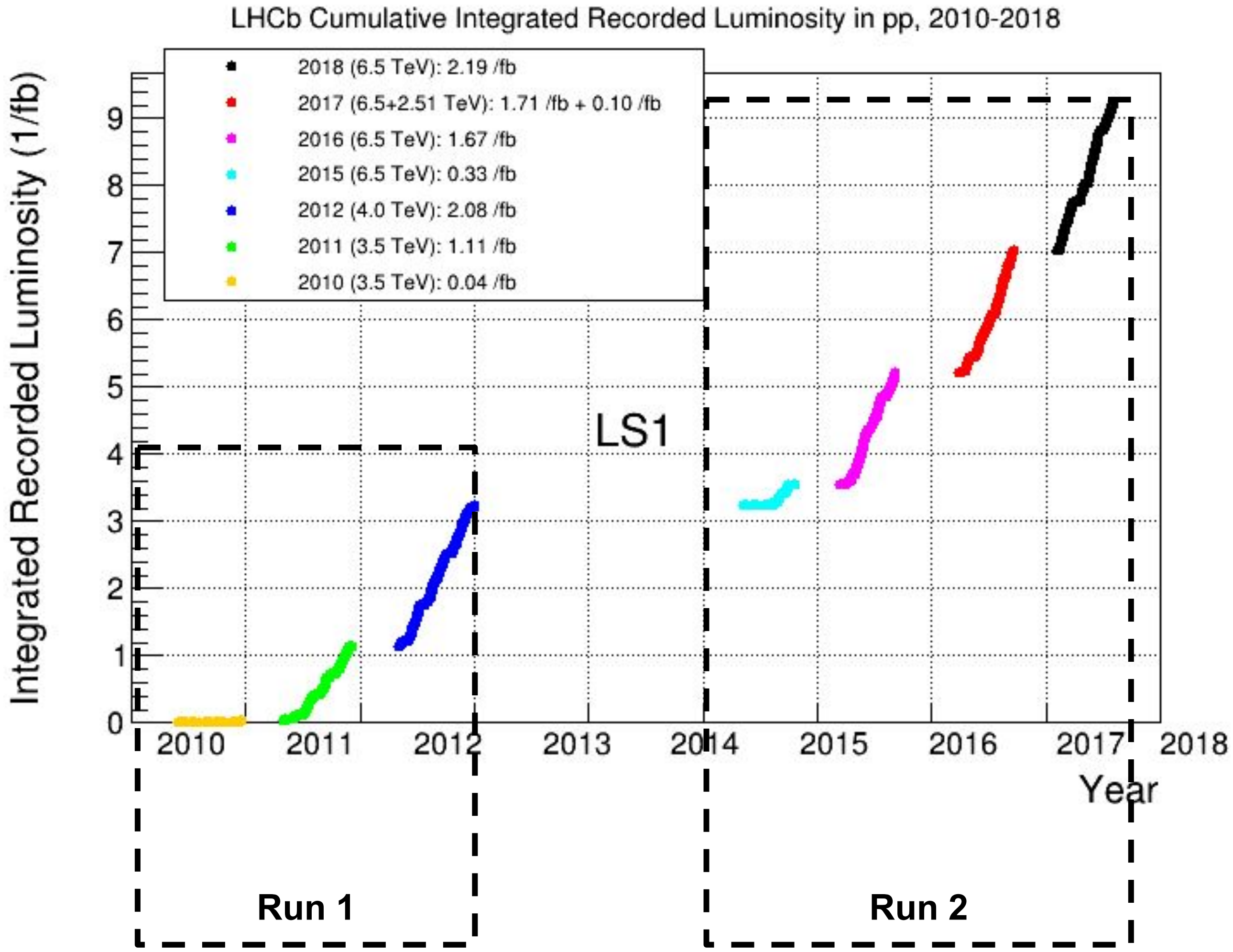
--- Measurements already can constrain models of different nuclear effects

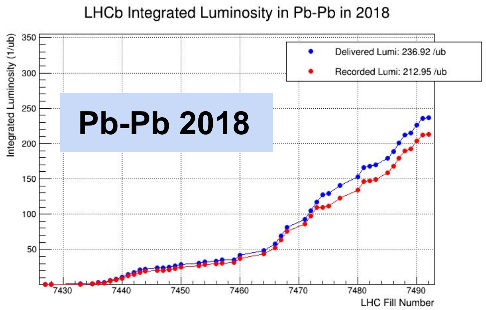
--- Sample size is a limitation to be improved with Run3 data

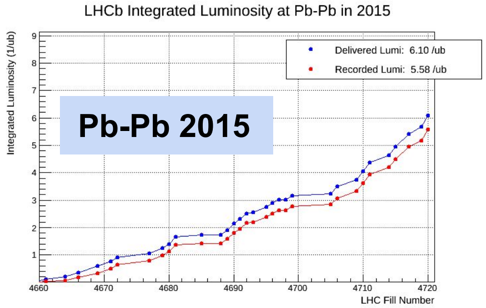
--- More results here

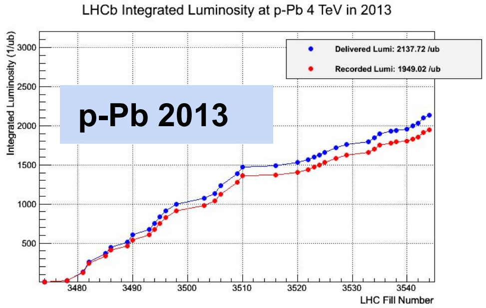
Thank you

BACKUP


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


LHCb Integrated Luminosity at Pb-Pb in 2015
Delivered Lumi: 6.10 /ub
Recorded Lumi: 5.58 /ub
Pb-Pb 2015
Integrated Luminosity (1/ub)
LHC Fill Number


LHCb Integrated Luminosity at p-Pb 4 TeV in 2013
Delivered Lumi: 2137.72 /ub
Recorded Lumi: 1949.02 /ub
p-Pb 2013
Integrated Luminosity (1/ub)
LHC Fill Number

https://www.sciencedirect.com/science/article/pii/S0370269319305404?via%3Dihub

2015 data

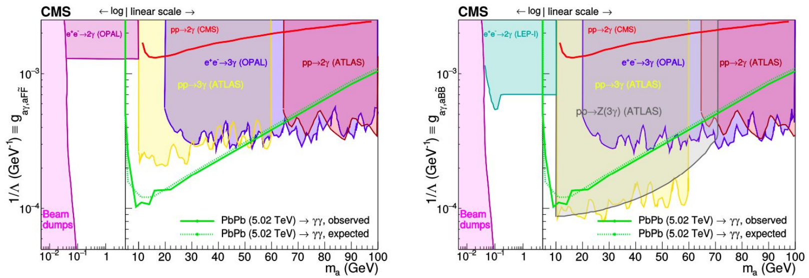


Figure 7: Exclusion limits at 95% CL in the ALP-photon coupling $g_{a\gamma}$ versus ALP mass m_a plane, for the operators $aF\widetilde{F}/4\Lambda$ (left, assuming ALP coupling to photons only) and $aB\widetilde{B}/(4\Lambda\cos^2\theta_W)$ (right, including also the hypercharge coupling, thus processes involving the Z boson) derived in Refs. [30, 56] from measurements at beam dumps [60], in e^+e^- collisions at LEP-I [56] and LEP-II [57], and in p p collisions at the LHC [13, 58, 59], and compared to the present PbPb limits.

https://cds.cern.ch/record/2719516

2018 data

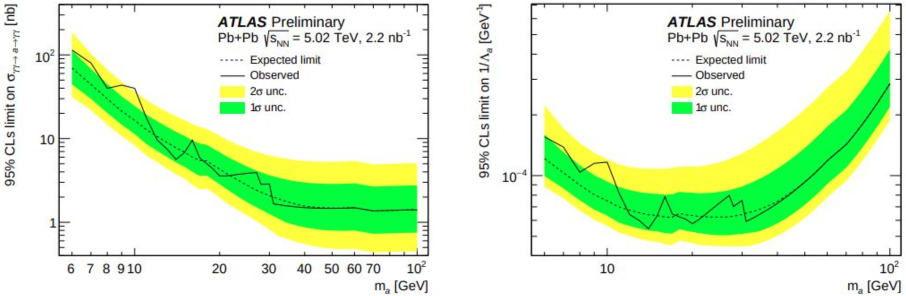
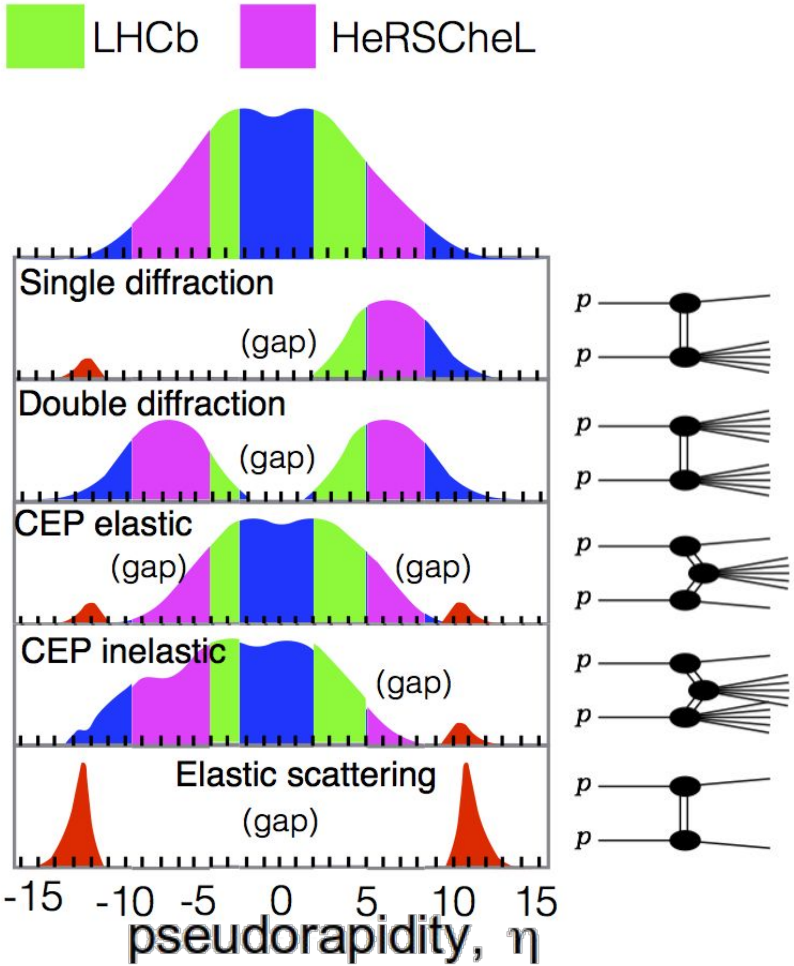


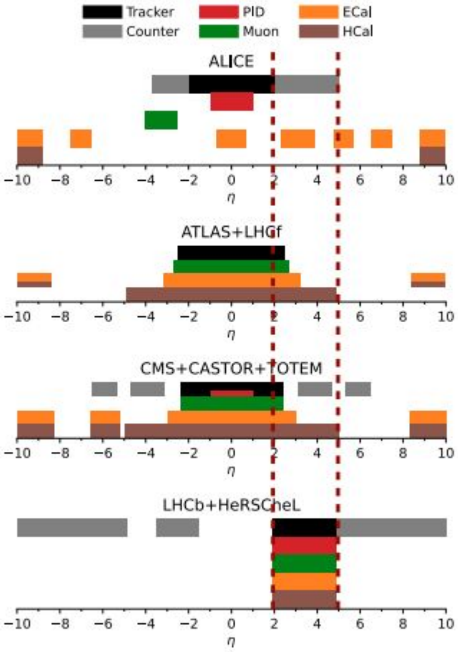
Figure 9: The 95% CL upper limit on the ALP cross section $\sigma_{\gamma\gamma\to a\to\gamma\gamma}$ (left) and ALP coupling $1/\Lambda_a$ (right) for the $\gamma\gamma \to a \to \gamma\gamma$ process as a function of ALP mass m_a. The observed upper limit is shown as a solid black line and the expected upper limit is shown by the dashed black line, with a green $\pm1\sigma$ and a yellow $\pm2\sigma$ band.

Typical acceptance for pp collisions

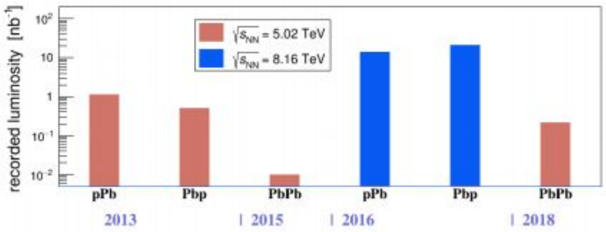


Heavy ion collisions at LHCb

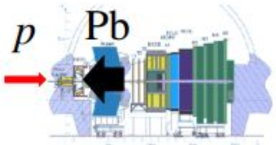
- Only detector at LHC fully equipped in forward region



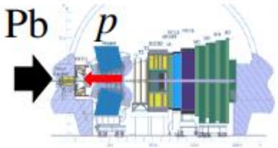
- Full run 1+2 dataset from HI collisions:



- Two configurations in pPb collisions:



Forward $\eta > 0$

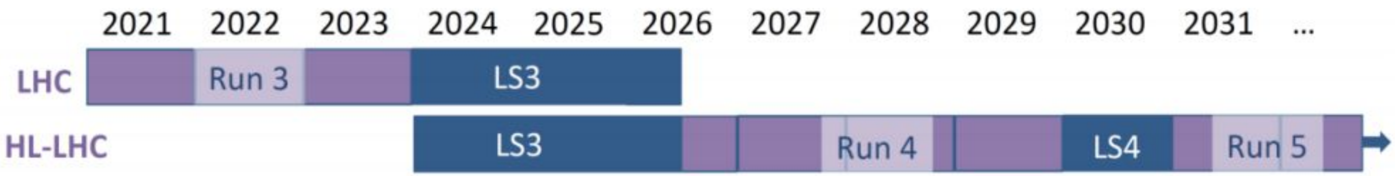


Backward $\eta < 0$

Boost of nucleon-nucleon cms system: $\eta = \eta_{lab} - 0.465$

Óscar Boente García **Recent results from heavy ion collisions at LHCb** 13/04/2021 3

Future samples (possible schedule)



LS2 – LHCb upgrade 1a →

LS3 – LHCb upgrade 1b →

LS4 – LHCb upgrade 2 →

Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

arXiv:1812.06772 - CERN-LPCC-2018-07

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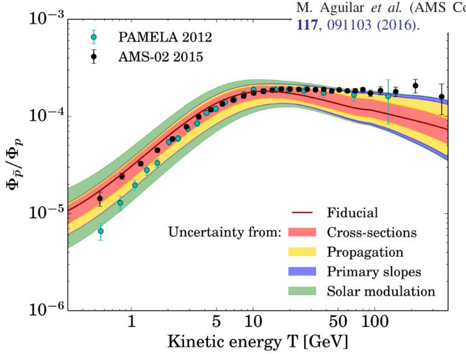
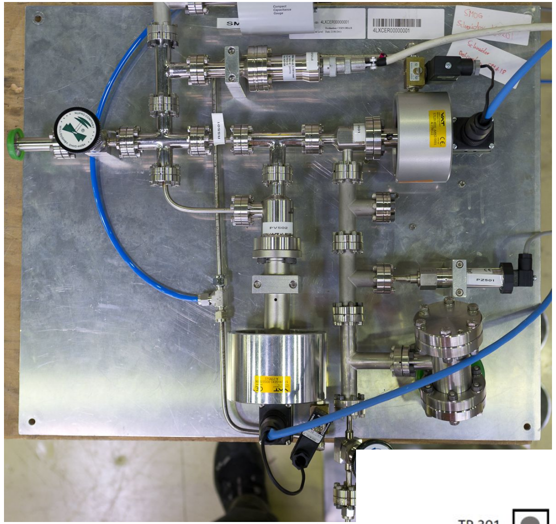
Antiproton production in pHe collisions

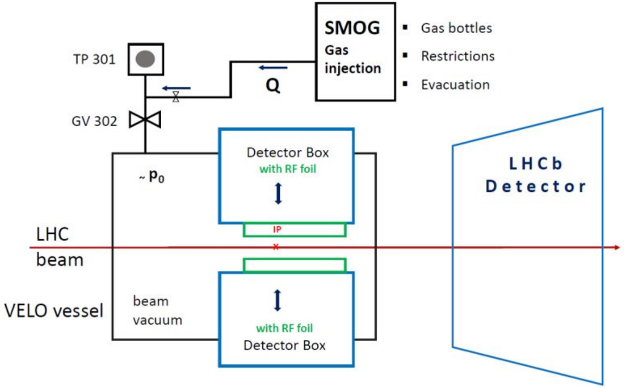
PRL 121, 222001 (2018)

Astroparticle experiments probe dark matter in the universe, but large uncertainties due to the antiproton production cross-section limit their sensitivity.

O. Adriani *et al.* (PAMELA Collaboration), JETP Lett. **96**, 621 (2013).
M. Aguilar *et al.* (AMS Collaboration), Phys. Rev. Lett. **117**, 091103 (2016).





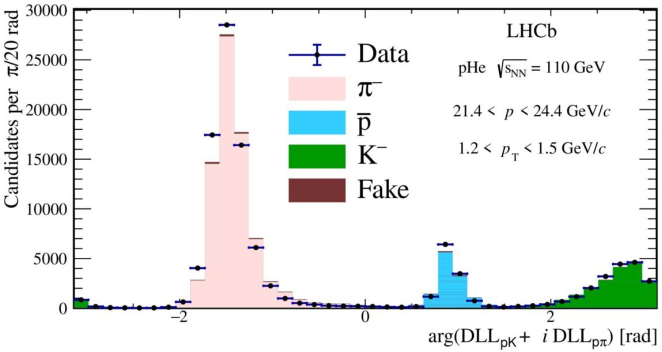


→LHCb is able to inject gas in the interaction region and become a fixed target experiment using SMOG device.
→6.5 TeV protons collide with He at $\sqrt{s}$ = 110.5 GeV
→0.4/nb acquired in 2016

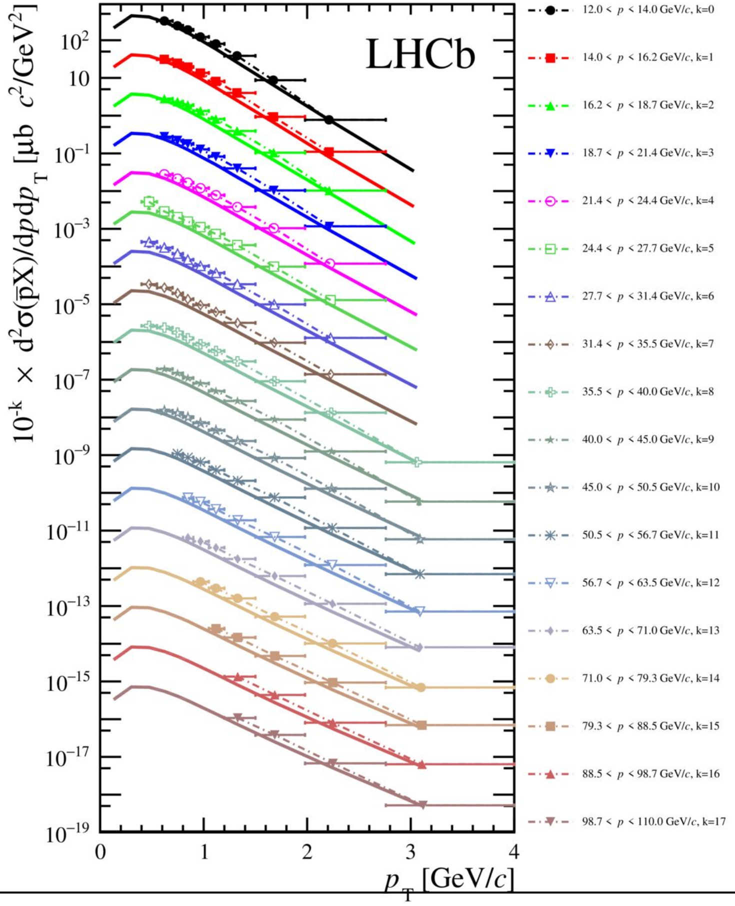
Antiproton production in pHe collisions

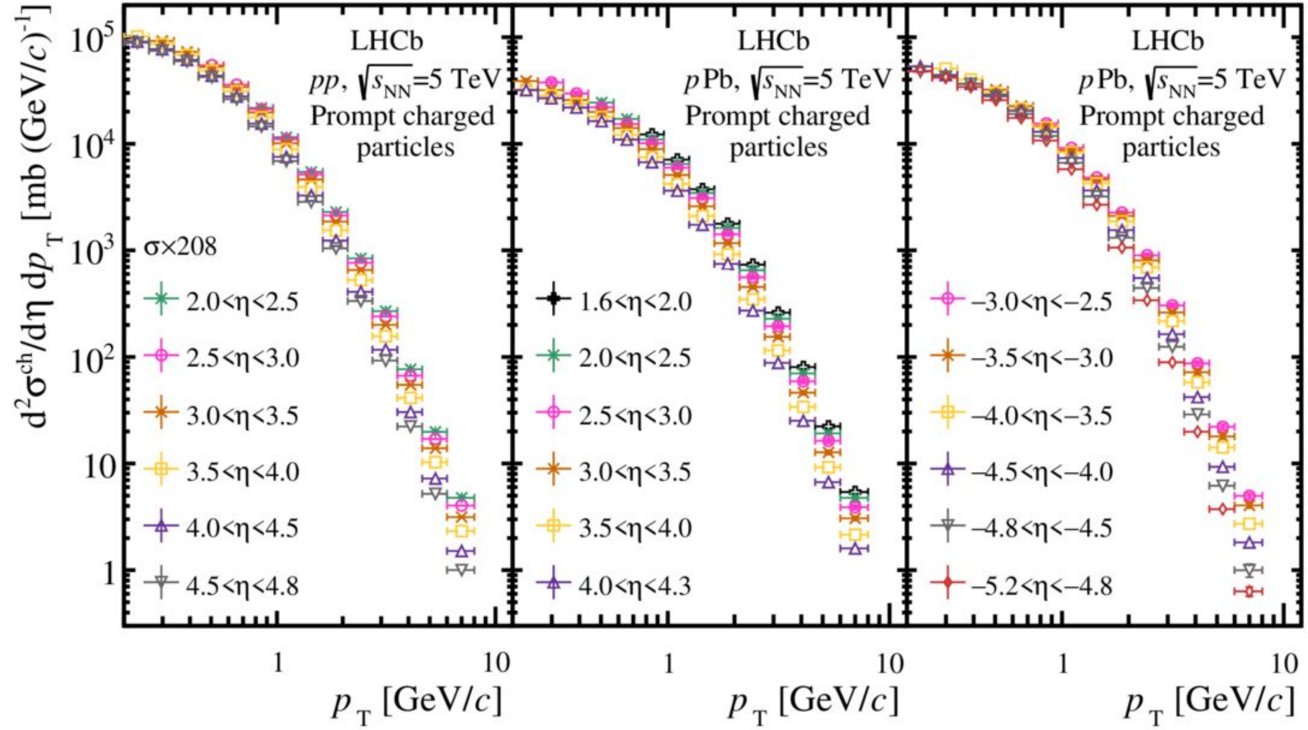
PRL 121, 222001 (2018)

33.7 million reconstructed pHe collisions for about 1.4 million antiprotons



→ First measurement of antiproton production in p-He collisions
→ Significant excess of anti-proton production over the EPOS
→ Measured range of the antiproton kinematic spectrum are crucial for interpreting the precise anti-proton cosmic ray measurements from the PAMELA and AMS-02 experiments by improving the precision of the secondary anti-proton cosmic ray flux prediction





LHCb
pp, $\sqrt{s_{NN}}$=5 TeV
Prompt charged particles
σ×208
2.0<η<2.5
2.5<η<3.0
3.0<η<3.5
3.5<η<4.0
4.0<η<4.5
4.5<η<4.8
LHCb
pPb, $\sqrt{s_{NN}}$=5 TeV
Prompt charged particles
1.6<η<2.0
2.0<η<2.5
2.5<η<3.0
3.0<η<3.5
3.5<η<4.0
4.0<η<4.3
LHCb
pPb, $\sqrt{s_{NN}}$=5 TeV
Prompt charged particles
−3.0<η<−2.5
−3.5<η<−3.0
−4.0<η<−3.5
−4.5<η<−4.0
−4.8<η<−4.5
−5.2<η<−4.8
$d^2\sigma^{ch}/d\eta\, dp_T$ [mb (GeV/c)$^{-1}$]
p_T [GeV/c]