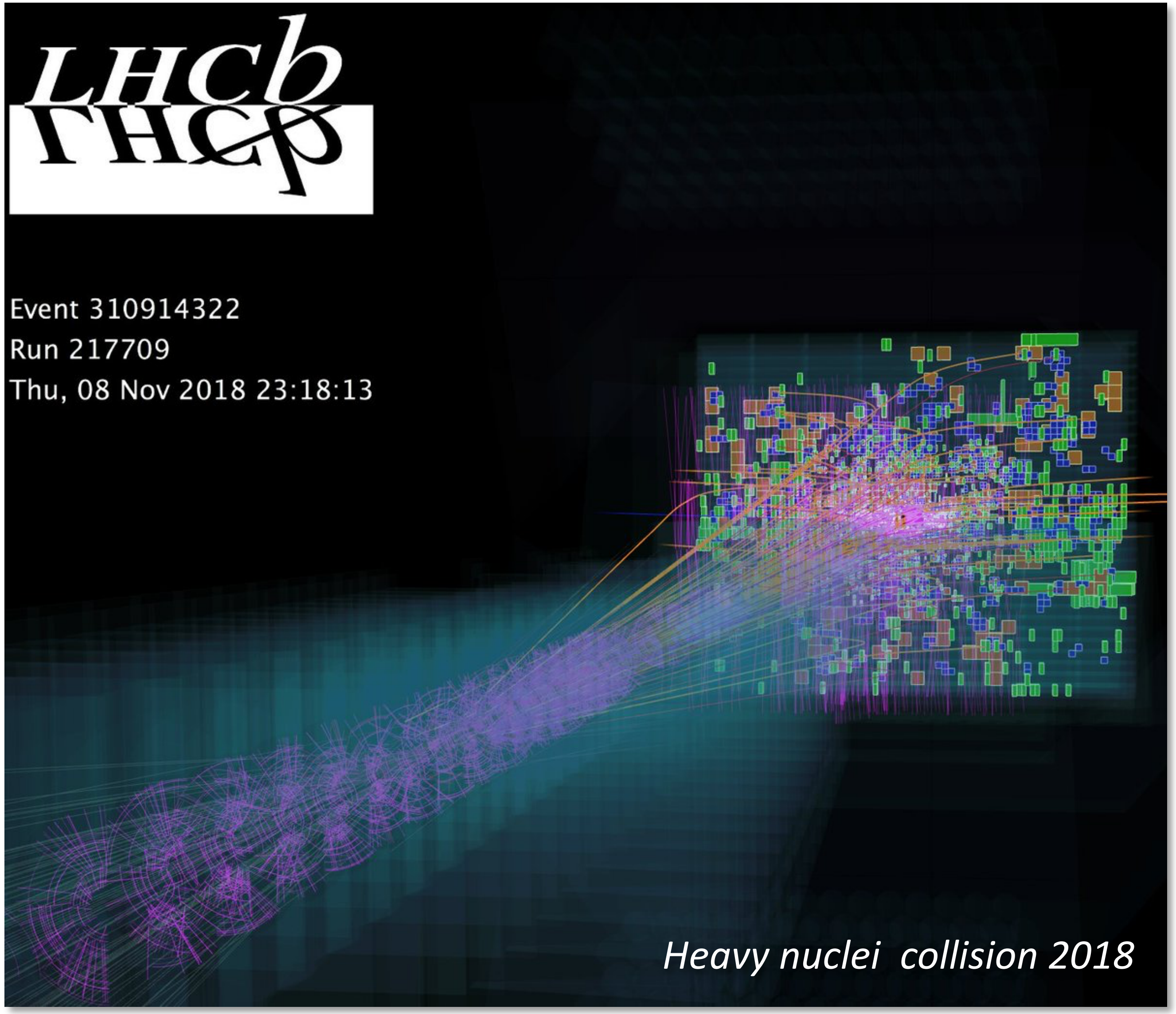
31st Rencontres de Blois on particle physics and cosmology



Heavy nuclei collision 2018

"Results from proton-lead and fixed-target collisions at LHCb"

Elisabeth Niel

On behalf of the LHCb collaboration

Laboratoire de l'Accélérateur Linéaire d'Orsay

06/06/2019

LHCb heavy ions latest results

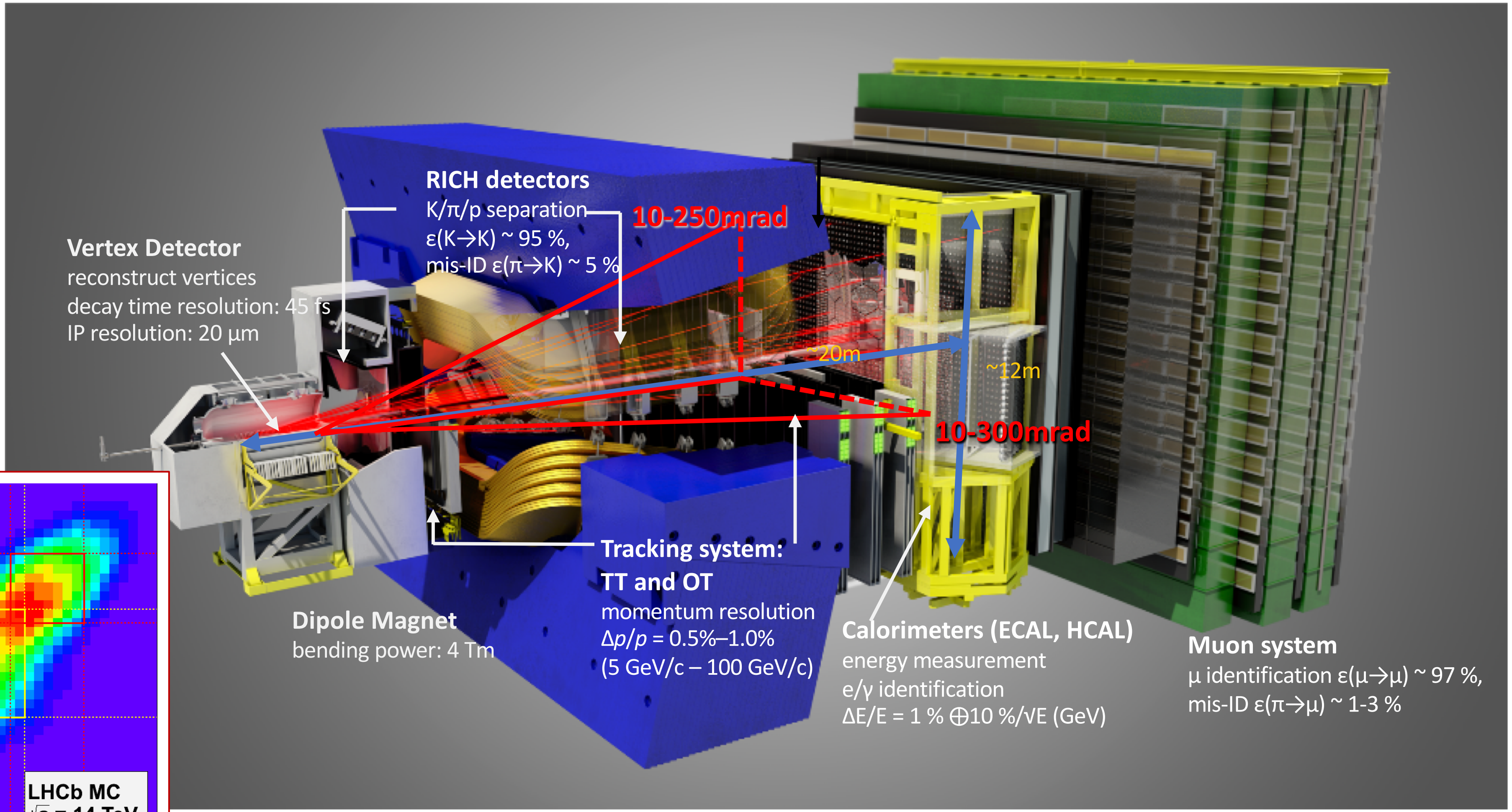
Heavy Flavour production in *p*Pb and PbPb

- Λ_c production in *p*Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [arXiv:1809.01404 , JHEP 02 (2019) 102]
- B^+, B^0 and Λ_b^0 production in *p*Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [arXiv: 1902.05599 , Phys. Rev. D 99, 052011 (2019)]
- $\Upsilon(nS)$ production in *p*Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [arXiv:1810.07655v2 , 10.1007/JHEP11(2018)194]
- Exclusive photonuclear J/ψ production in ultra-peripheral PbPb collisions [LHCb-CONF-2018-003]

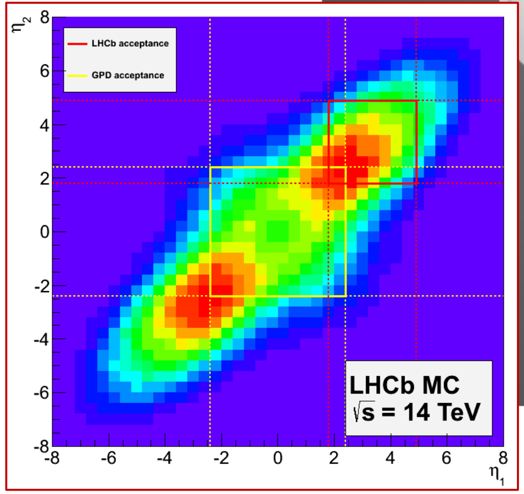
Fixed target mode (unique at LHC)

- J/ψ and D^0 production cross-section in *p*He collisions [arXiv:1810.07907, Phys. Rev. Lett. 122, 132002 (2019)]
- Anti-proton production in *p*He [arXiv:1808.06127, Phys. Rev. Lett. 121, 222001 (2018)]

The LHCb experiment



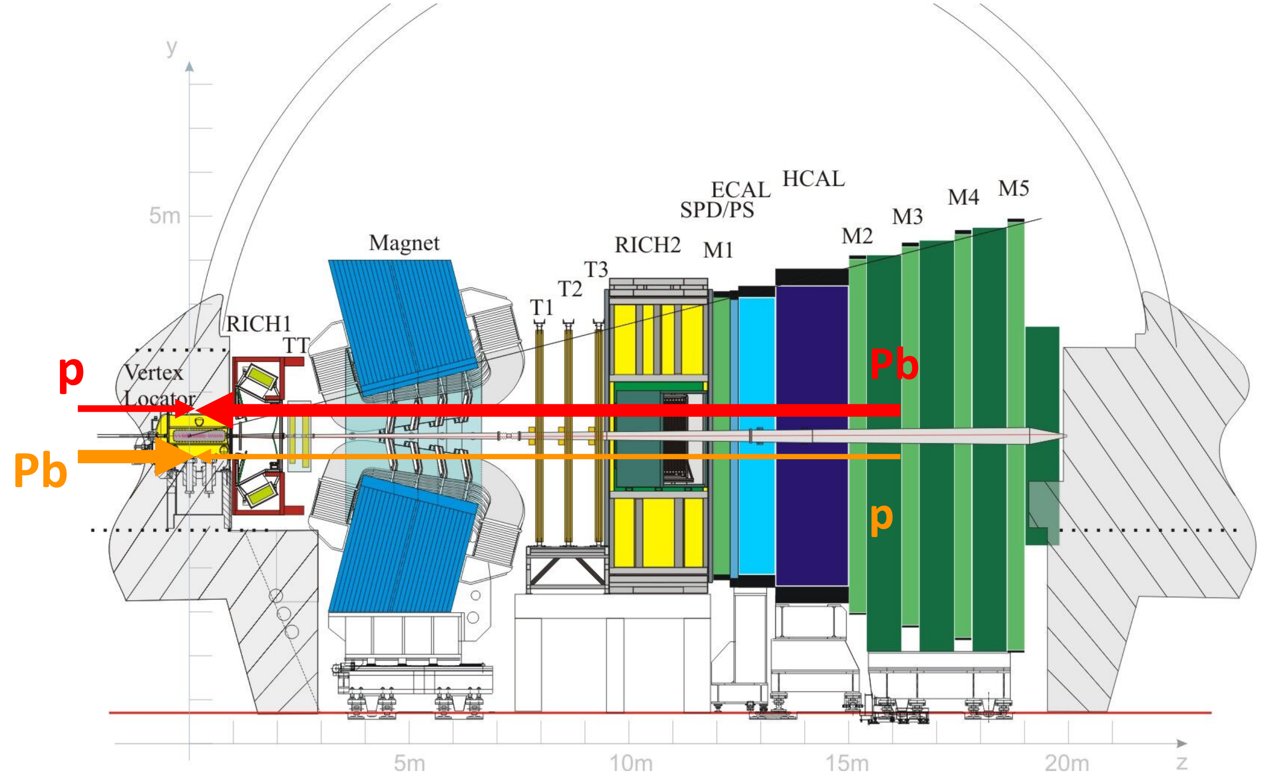
$b\bar{b}$ **acceptance**



[IJMPA 30 (2015) 1530022]
[JINST 3 (2008) S08005]

Single arm forward spectrometer with excellent vertexing, tracking, PID (acceptance $2 < \eta < 5$)

LHCb heavy ion : proton lead modes



pPb and Pbp

2013 data : $\sqrt{s_{NN}} = 5.02$ TeV

$1.1\ nb^{-1}\ (Fwd), 0.5\ nb^{-1}\ (Bwd)$

2016 data : $\sqrt{s_{NN}} = 8.16$ TeV

$13.6\ nb^{-1}\ (Fwd), 20.8\ nb^{-1}\ (Bwd)$

Pb-Pb

2015 data : $\sqrt{s_{NN}} = 5$ TeV , $10\ \mu b^{-1}$

2018 data : $\sqrt{s_{NN}} = 5$ TeV , $210\ \mu b^{-1}$

Forward region:

- $y^* = y_{lab} - 0.465$
- pPb: $1.5 < y < 4.0$

Backward region:

- $y^* = -(y_{lab} + 0.465)$
- Pbp: $-5.0 < y < -2.5$

Physics motivations:

- Allow us to study QGP
- Study of cold nuclear matter effects and their disentangling from QGP effects
- Sensitivity to small x (down to $\sim 10^{-5}$) → gluon saturation and to anti-shadowing region

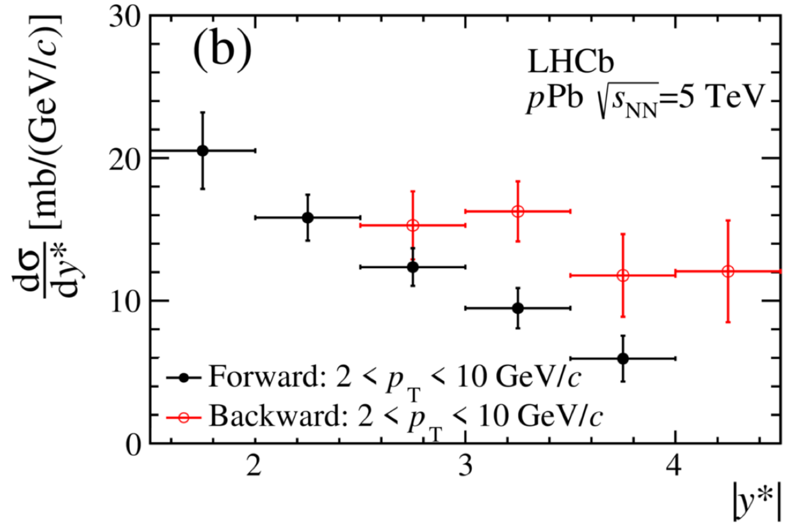
Λ_c production in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Measurements of the differential cross-section and the forward- backward production ratio

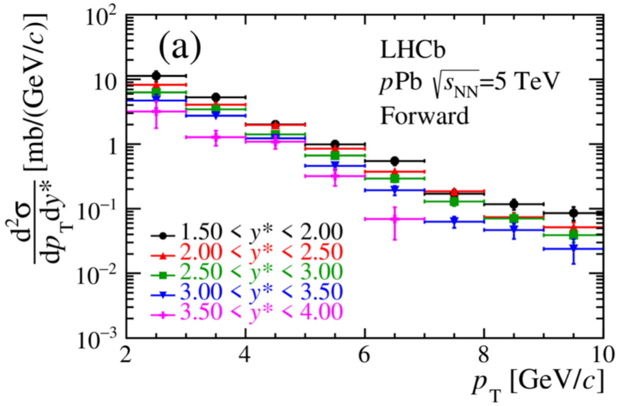
- Larger production rate in the backward rapidity region compared to the forward region observed

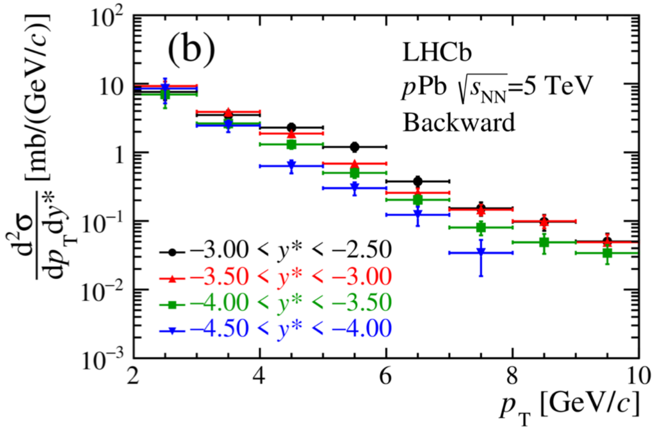
- The total measured cross-section (integrated over the full kinematic range) is :

$$\sigma(2 < p_T < 10\,\mathrm{GeV}/c, \quad 1.5 < y^* < 4.0) = 32.1 \pm 1.1 \pm 3.2\,\mathrm{mb},$$
$$\sigma(2 < p_T < 10\,\mathrm{GeV}/c, -4.5 < y^* < -2.5) = 27.7 \pm 1.8 \pm 3.9\,\mathrm{mb}.$$



[JHEP 02 (2019) 102]
[LHCb-PAPER-2018-021]

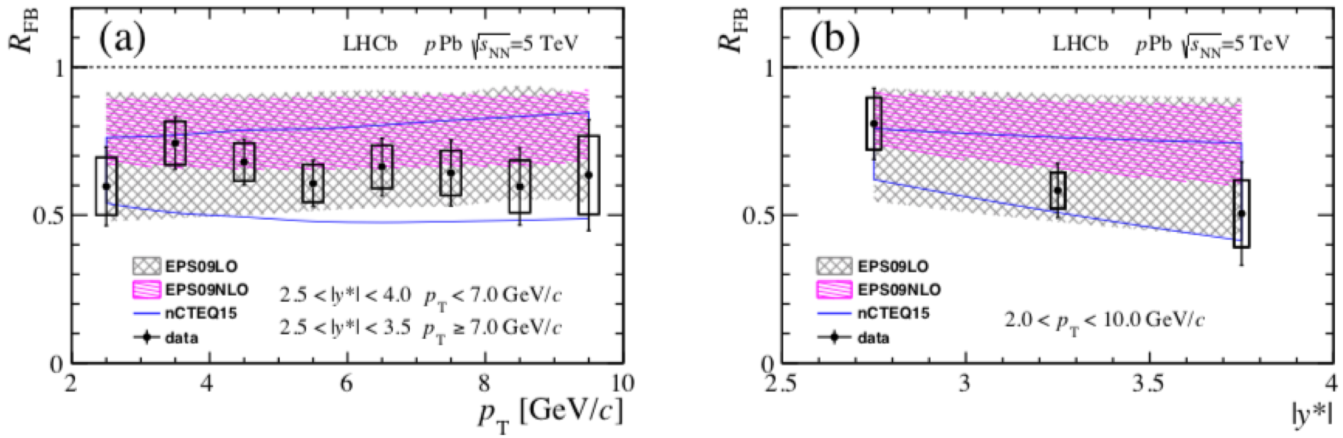




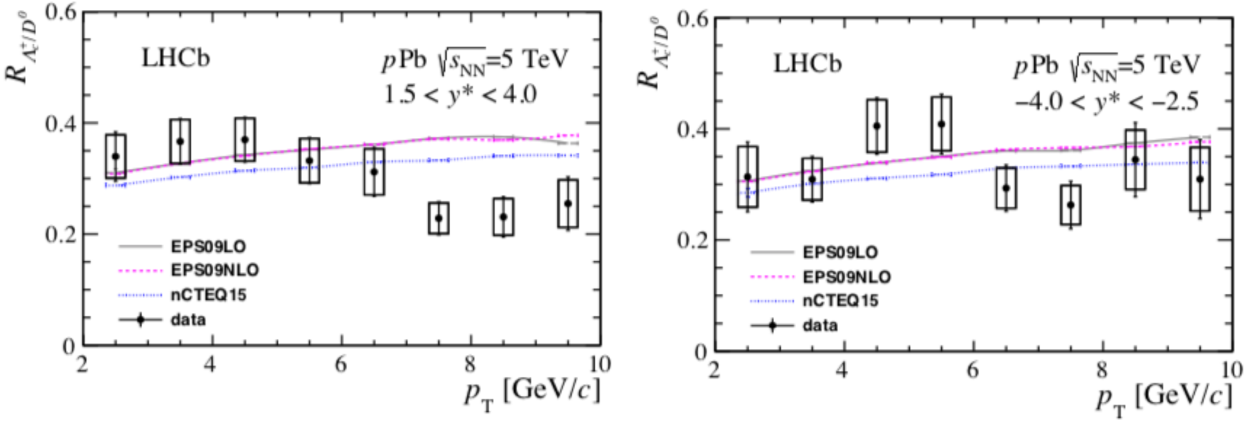
Λ_c production in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- Forward-backward production ratio consistent with calculations from Helac-ONIA with nuclear PDF [Computer Physics Communications 184 (2013) pp. 2562-2570].

$$R_{\mathrm{FB}}(y^*, p_{\mathrm{T}}) \equiv \frac{\mathrm{d}^2\sigma(y^*, p_{\mathrm{T}}; y^* > 0)/\mathrm{d}y^*\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2\sigma(y^*, p_{\mathrm{T}}; y^* < 0)/\mathrm{d}y^*\mathrm{d}p_{\mathrm{T}}}$$



- Ratio with D^0 production to probe heavy quark hadronization in heavy ion collisions



$$R_{\Lambda_c^+/D^0}(y^*, p_{\mathrm{T}}) = \frac{\mathrm{d}^2\sigma_{\Lambda_c^+}(y^*, p_{\mathrm{T}})/\mathrm{d}y^*\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2\sigma_{D^0}(y^*, p_{\mathrm{T}})/\mathrm{d}y^*\mathrm{d}p_{\mathrm{T}}}$$

- Ratio to D^0 production also consistent with nuclear PDF computations

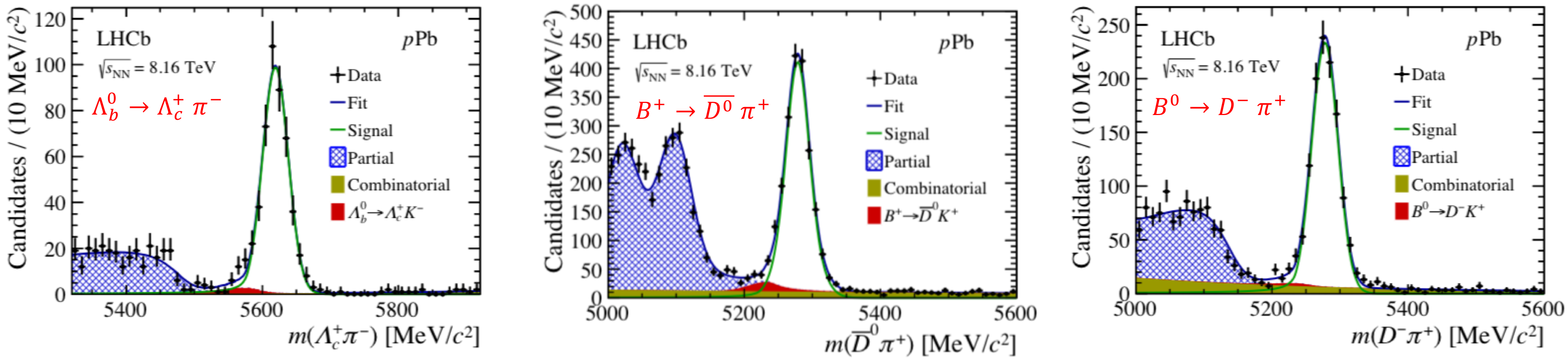
[JHEP 02 (2019) 102, LHCb-PAPER-2018-021]

B^+, B^0 and Λ_b^0 production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

- B^+, B^0 *and* Λ_b^0 production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV
- Measurement of differential cross section, forward-backward R_{FB} ratios and nuclear modification factors R_{pPb} for B^+, B^0 and Λ_b^0 in pPb collisions

Signal yields

Decay	pPb	Pbp
$B^+ \to \overline{D}^0\pi^+$	1958 ± 54	1806 ± 55
$B^+ \to J/\psi K^+$	883 ± 32	907 ± 33
$B^0 \to D^-\pi^+$	1151 ± 38	889 ± 34
$\Lambda_b^0 \to \Lambda_c^+\pi^-$	484 ± 24	399 ± 23



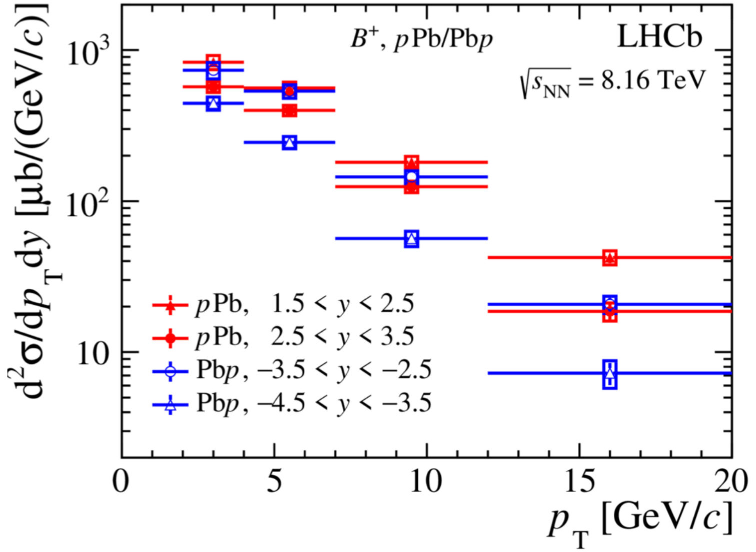
[Phys. Rev. D 99, 052011 (2019), LHCb-PAPER-2018-048]

B^+, B^0 *and* Λ_b^0 production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

- Consistent with R_{pA} of D^0 mesons [JHEP (102017)90]
- Confirm the nuclear suppression seen with non- prompt J/ψ [Phys. Lett. B Volume 774, (2017)]

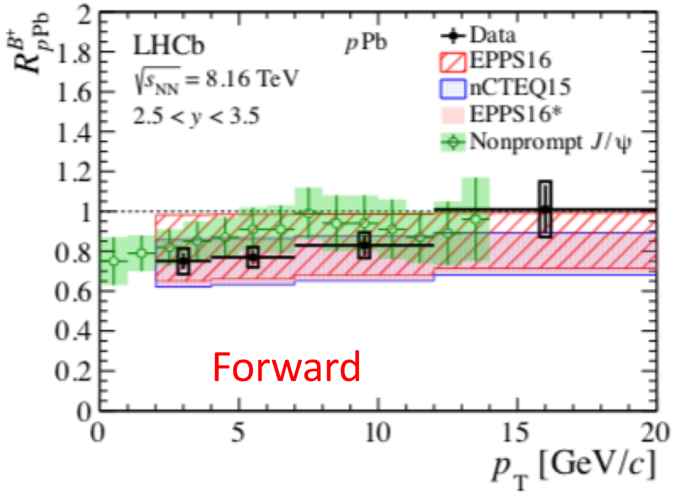
- Significant suppression in forward rapidity, decreasing at large p_T
- Consistent with unity at backward rapidity

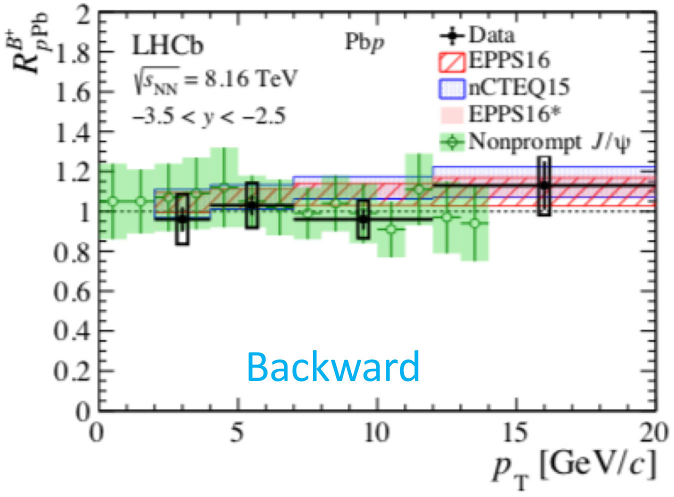
Differential cross section for B^+ vs. p_T



Nuclear modification factor vs. p_T

$$R_{p\mathrm{Pb}}(p_T, y) \equiv \frac{1}{A_{\mathrm{Pb}}} \frac{d^2\sigma_{p\mathrm{Pb}}(p_T, y)/dp_T dy}{d^2\sigma_{pp}(p_T, y)/dp_T dy}$$



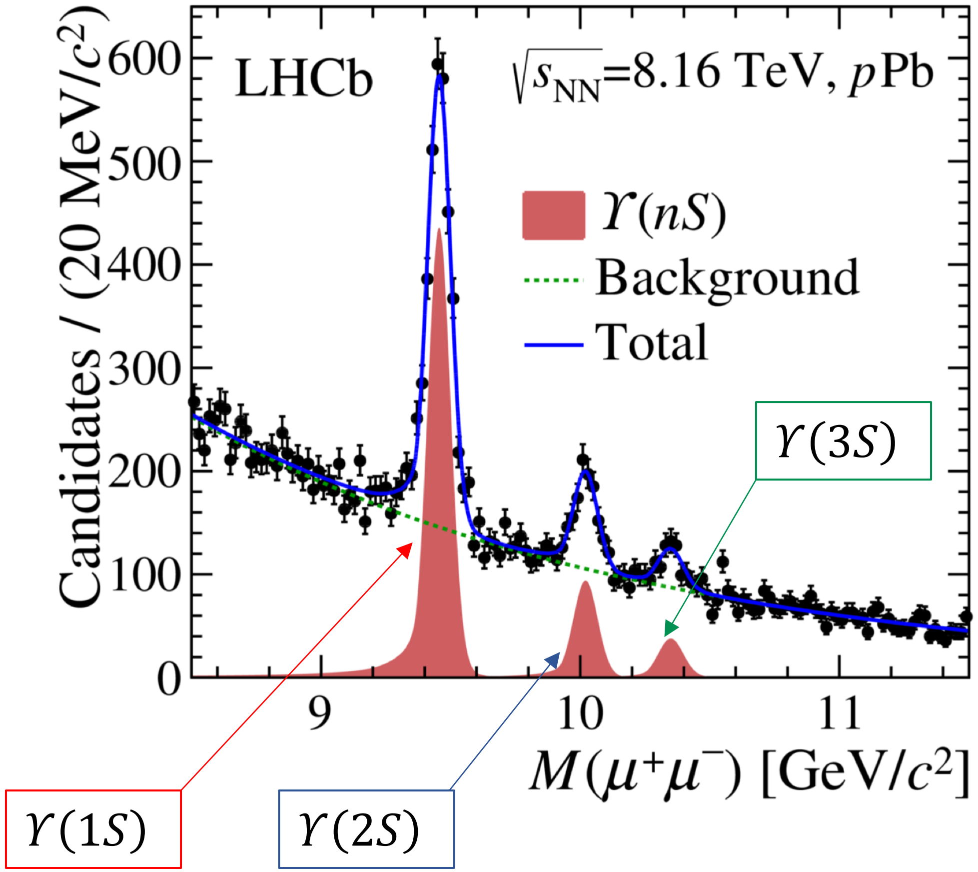


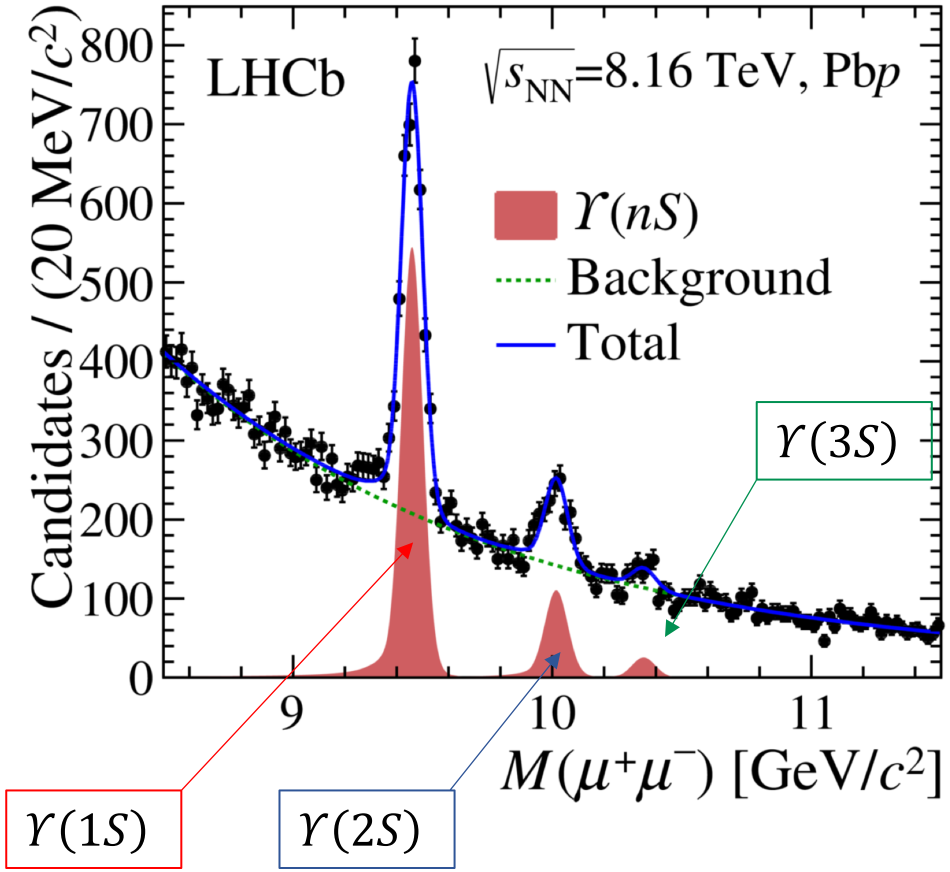
Experimental uncertainties are smaller than the nPDF, provides constrains for future nPDFs fits.

[Phys. Rev. D 99, 052011 (2019), LHCb-PAPER-2018-048]

$\Upsilon(nS)$ production in pPb collisions at $\sqrt{s_{NN}} = 8.16\ TeV$

[10.1007/JHEP11(2018)194 , LHCb-PAPER-2018-035]



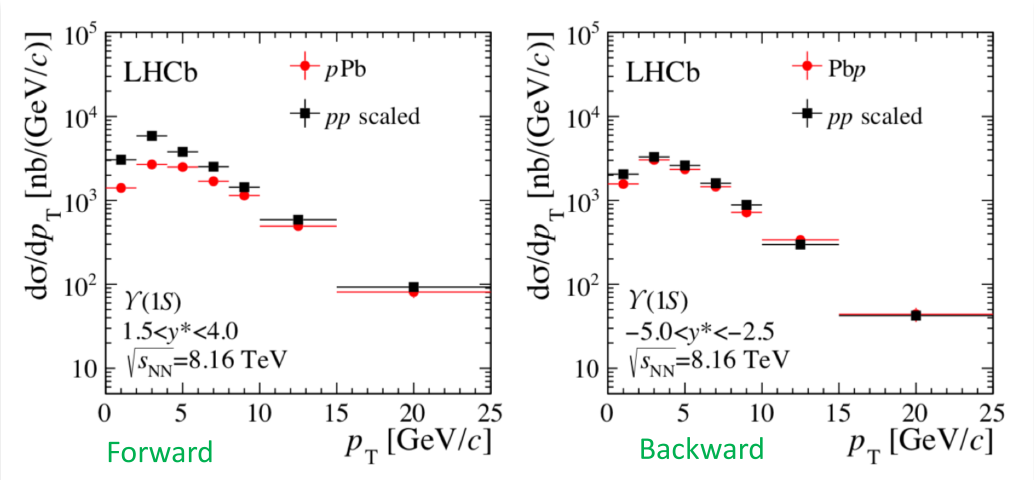


At the first three resonances, the Upsilon system can only decay by the *b* quark and anti *b* quark annihilating. Here the $\Upsilon(nS)$ mesons are reconstructed through their decays into two opposite-sign muons .

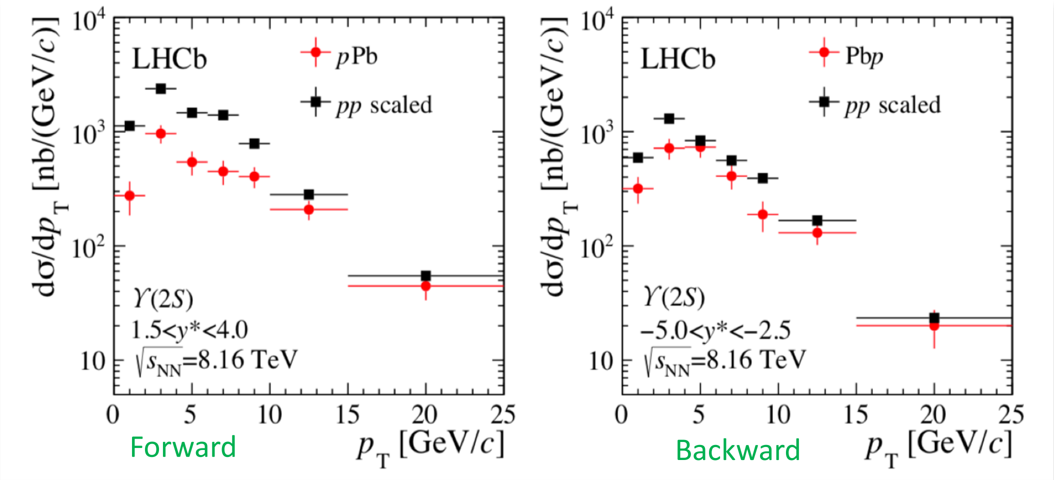
$\Upsilon(nS)$ production in pPb collisions at $\sqrt{s_{NN}} = 8.16\ TeV$

[10.1007/JHEP11(2018)194 , LHCb-PAPER-2018-035]

$\Upsilon(1S)$



$\Upsilon(2S)$



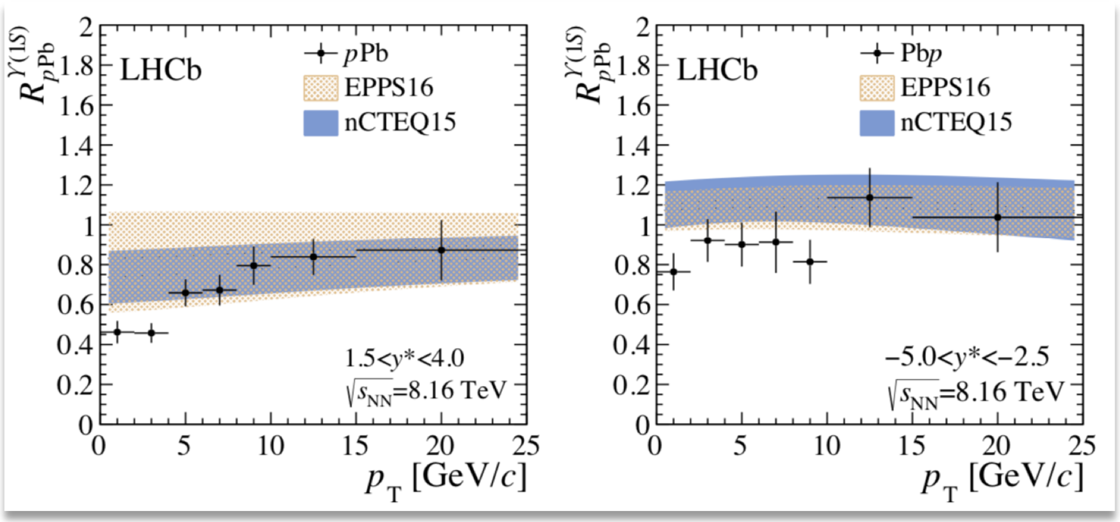
- Cross sections integrated over y^*.
- No direct measurement in *pp* at 8.16 TeV: the value of the $\Upsilon(nS)$ cross-section is obtained by interpolation between the values measured in *pp* at 2.76, 7, 8 and 13 TeV.

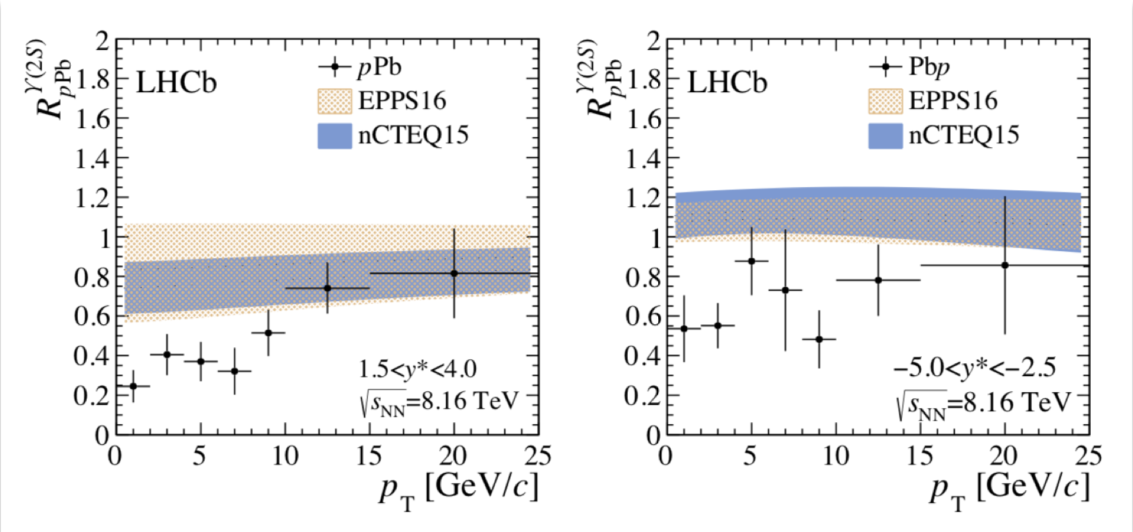
$\Upsilon(nS)$ suppressed in the forward region as already seen for J/ψ [Phys. Lett. B Volume 774, (2017)]

$\Upsilon(nS)$ production in pPb collisions at $\sqrt{s_{NN}} = 8.16\ TeV$

[10.1007/JHEP11(2018)194 , LHCb-PAPER-2018-035]

- The nuclear modification factor are evaluated for $\Upsilon(1S)$ and $\Upsilon(2S)$.
- Two different theoretical calculations are shown, here HELAC-Onia framework + nPDFS.



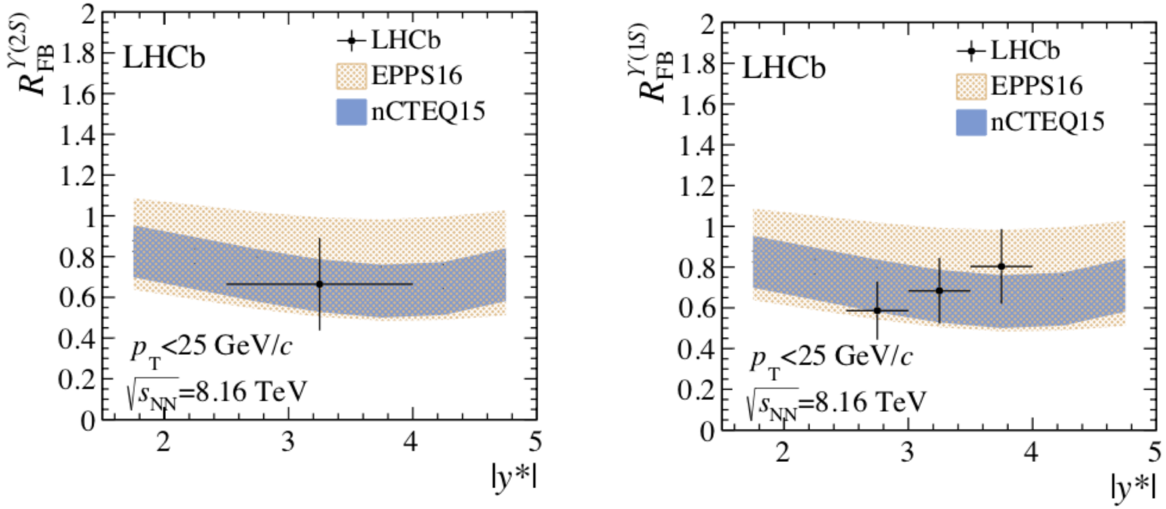


For $\Upsilon(1S)$: consistent with unity for $p_T > 10\ GeV/c$ with a suppression at low p_T (0.5 forward and 0.8 backward)

For $\Upsilon(2S)$: smaller values, which is still consistent with the comovers model

$\Upsilon(nS)$ production in pPb collisions at $\sqrt{s_{NN}} = 8.16\ TeV$

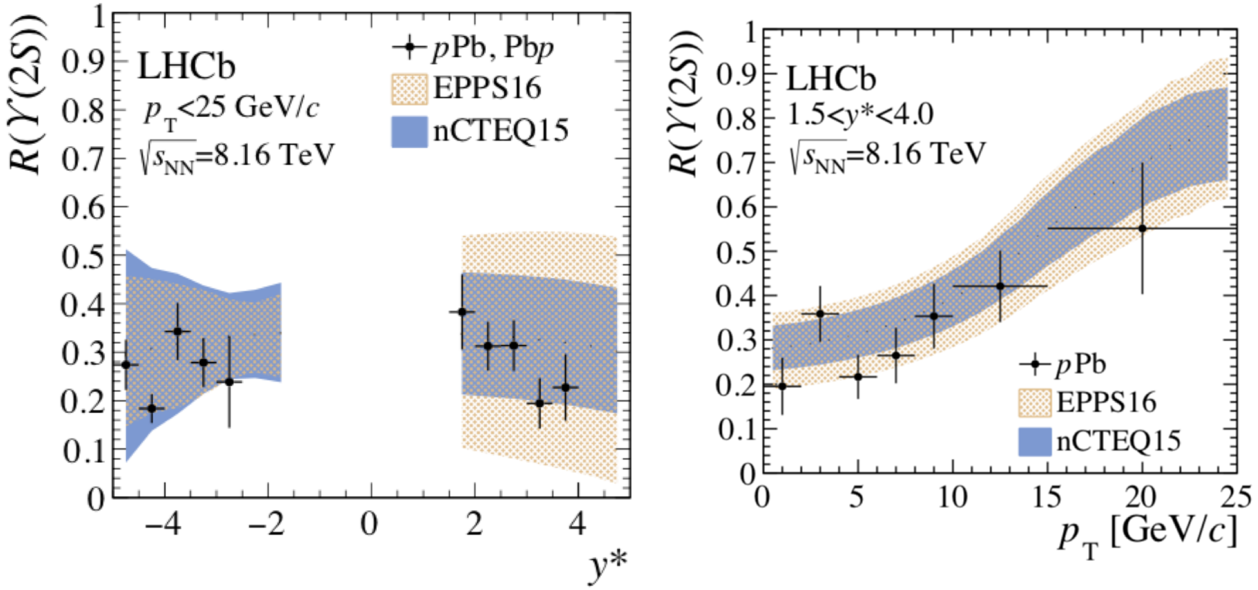
Forward-backward asymmetry



$$R_{\mathrm{FB}}(p_{\mathrm{T}}, |y^*|) = \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_{\mathrm{T}}, +|y^*|)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{\mathrm{Pb}p}(p_{\mathrm{T}}, -|y^*|)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*},$$

[10.1007/JHEP11(2018)194 , LHCb-PAPER-2018-035]

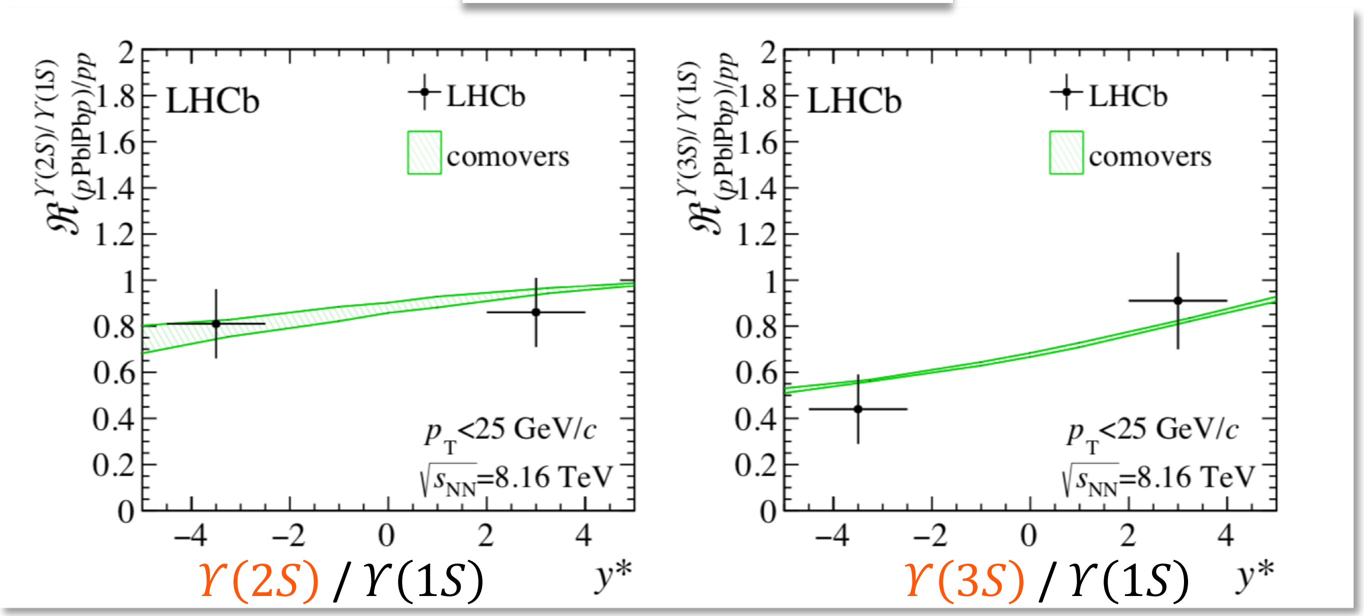
$$R(\Upsilon(nS)) = \frac{[\mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}dy^*]\,(\Upsilon(nS))}{[\mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}dy^*]\,(\Upsilon(1S))}.$$



The ratio of the cross-sections confirmed a larger suppression for the excited states with respect to the ground state in *p*Pb compared to *pp* collisions

$\Upsilon(nS)$ production in pPb collisions at $\sqrt{s_{NN}} = 8.16\ TeV$

Double ratios



$$\mathfrak{R}^{\Upsilon(nS)/\Upsilon(1S)}_{(p\mathrm{Pb}|\mathrm{Pb}p)/pp} = \frac{R(\Upsilon(nS))_{p\mathrm{Pb}|\mathrm{Pb}p}}{R(\Upsilon(nS))_{pp}}$$

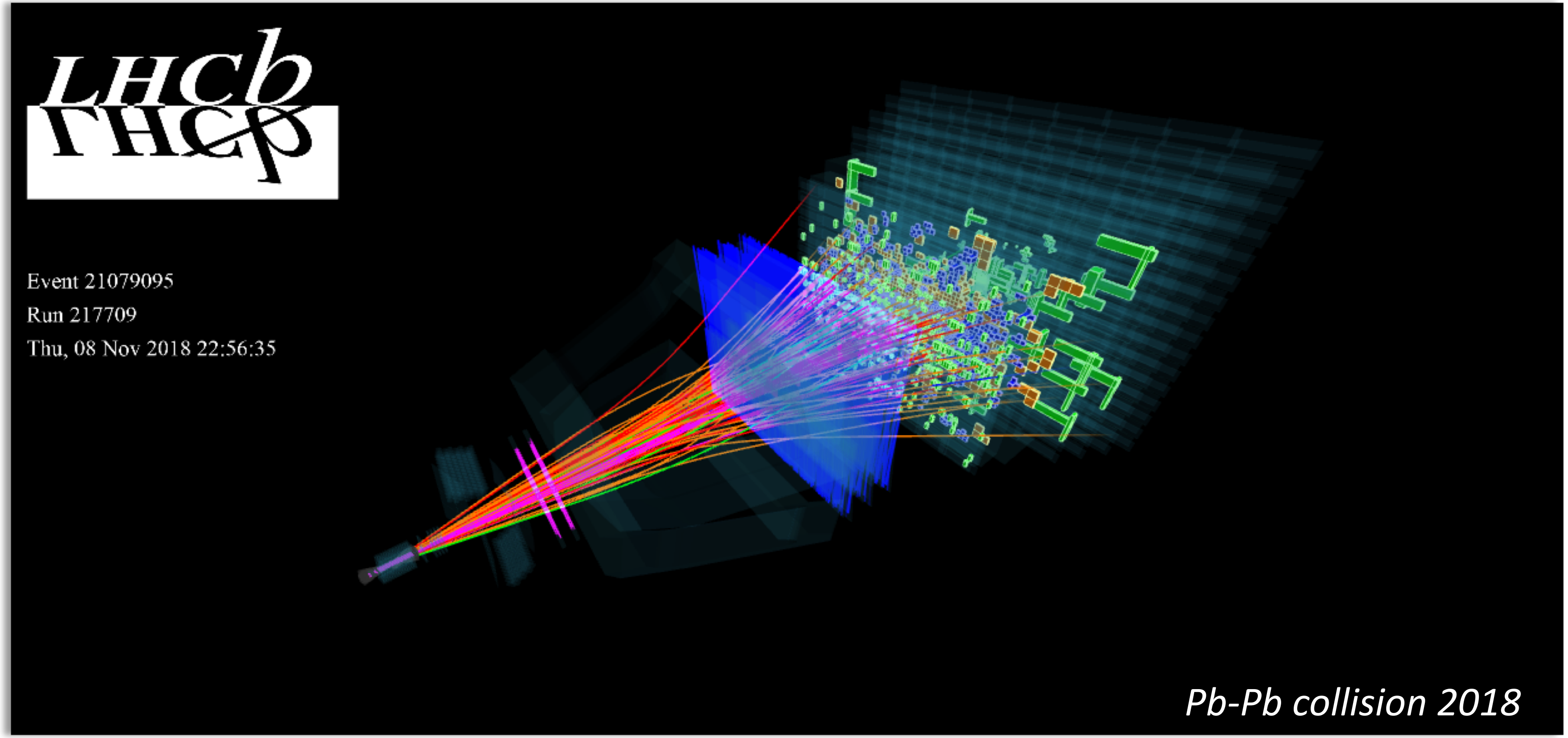
Sample		$R(\Upsilon(2S))$	$R(\Upsilon(3S))$
pp	$2.0 < y^* < 4.0$	0.328 ± 0.004	0.137 ± 0.002
pp	$-4.5 < y^* < -2.5$	0.325 ± 0.004	0.137 ± 0.002
pPb	$2.0 < y^* < 4.0$	0.282 ± 0.050	0.11 ± 0.02
Pbp	$-4.5 < y^* < -2.5$	0.296 ± 0.070	0.06 ± 0.02

$$\mathfrak{R}^{\Upsilon(2S)/\Upsilon(1S)}_{p\mathrm{Pb}/pp} = 0.86 \pm 0.15,$$
$$\mathfrak{R}^{\Upsilon(3S)/\Upsilon(1S)}_{p\mathrm{Pb}/pp} = 0.81 \pm 0.15,$$
$$\mathfrak{R}^{\Upsilon(2S)/\Upsilon(1S)}_{\mathrm{Pb}p/pp} = 0.91 \pm 0.21,$$
$$\mathfrak{R}^{\Upsilon(3S)/\Upsilon(1S)}_{\mathrm{Pb}p/pp} = 0.44 \pm 0.15.$$

- Suppression of $\Upsilon(nS)$ production in proton-lead collisions up to about 40%, more pronounced for the excited Υ states (particularly in the region of negative rapidity)
- Data support the *comover* model [0.1007/JHEP10(2018)094]

[10.1007/JHEP11(2018)194 , LHCb-PAPER-2018-035]

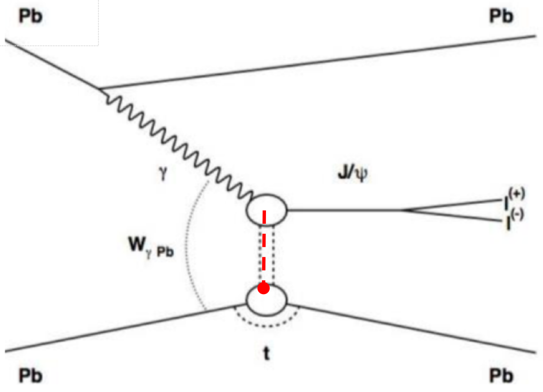
Moving to lead-lead



Exclusive photonuclear J/ψ production in ultra-peripheral PbPb collisions

[LHCb-CONF-2018-003]

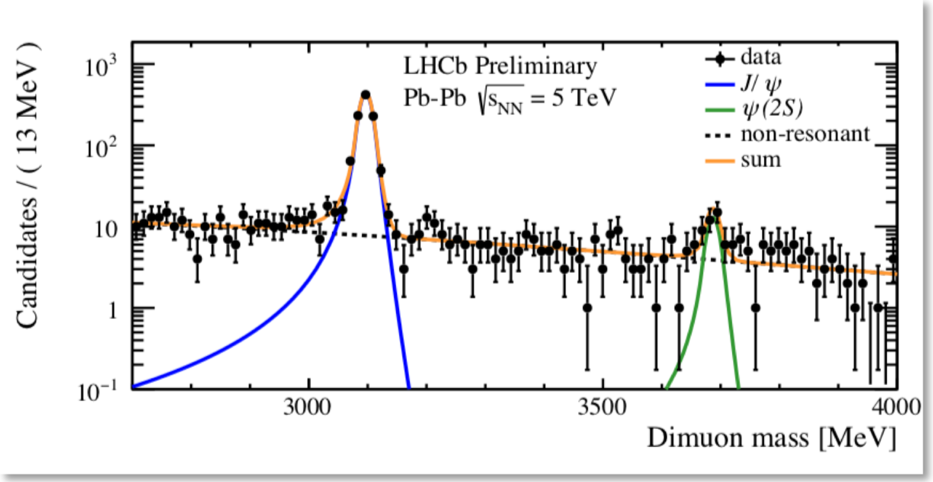
Coherent production of J/ψ mesons is studied in Pb-Pb 2015 collisions at $\sqrt{S_{NN}} = 5$ TeV.



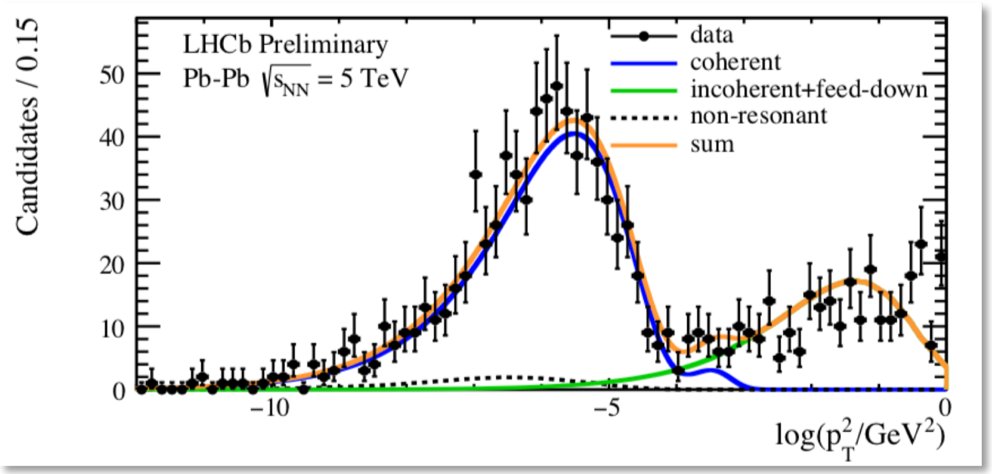
→ Two-photon and photonuclear interaction enanched in ultraperipheral collisions (UPC) (i.e. the impact parameters larger than the sum of two radii)

→ Incoherent /coherent production: photon couples to a single/all nucleon.

→ Background sources: incoherent J/ψ and feed-down from photonuclear $\psi(2S)$



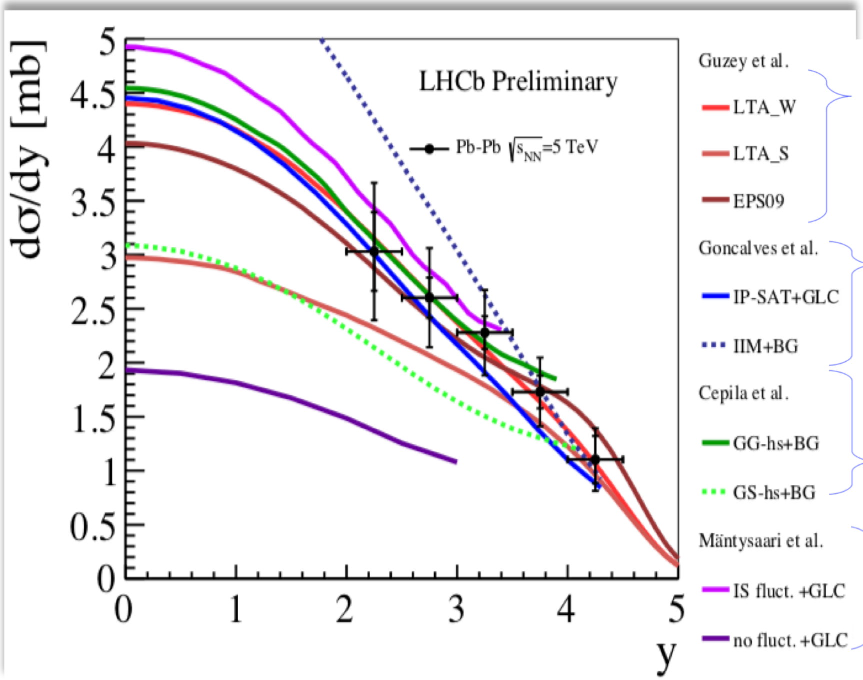
J/ψ are reconstructed in the dimuon final state with muons in the pseudorapidity region $2.0 < \eta < 4.5$



Use transverse momentum fit to distinguish between the coherent and incoherent J/ψ

Exclusive photonuclear J/ψ production in UPCs: results

[LHCb-CONF-2018-003]



Perturbative QCD calculations
With different nuclear structure descriptions
[Phys. Rev. C93 (2016) 055206]

Colour-dipole model
Different parametrisations of the dipole-proton cross-section
[Phys. Rev. C84 (2011) 233 011902, Phys. Rev. D96 279 (2017) 094027]

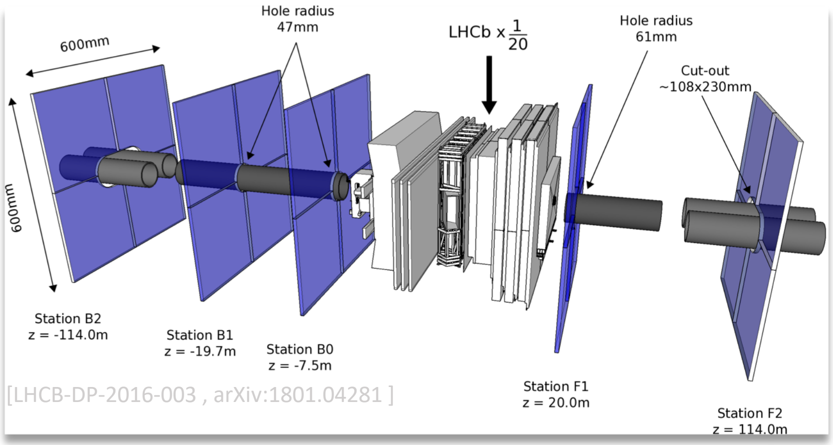
Variation of colour-dipole model
[Phys. Rev. C97 (2018) 024901]

Variation of colour-dipole model
Includes subnucleon scale fluctuations
[Phys. Lett. B772 (2017) 832]

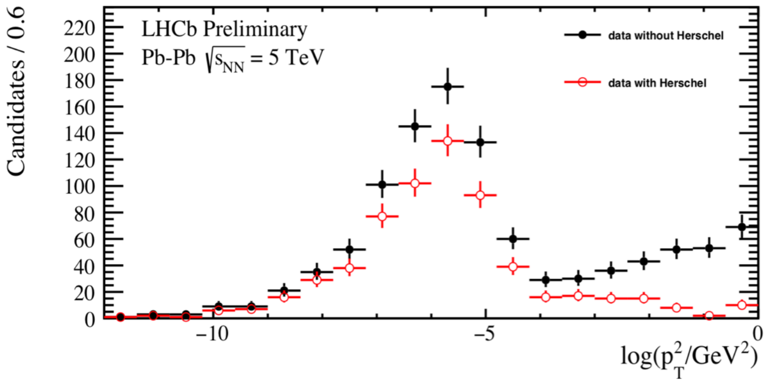
Preliminary results in 5 rapidity bins

J/ψ rapidity	$d\sigma/dy$ (mb)
2.00-2.50	$3.0 \pm 0.4 \pm 0.3$
2.50-3.00	$2.60 \pm 0.19 \pm 0.25$
3.00-3.50	$2.28 \pm 0.15 \pm 0.21$
3.50-4.00	$1.73 \pm 0.15 \pm 0.17$
4.00-4.50	$1.10 \pm 0.22 \pm 0.13$

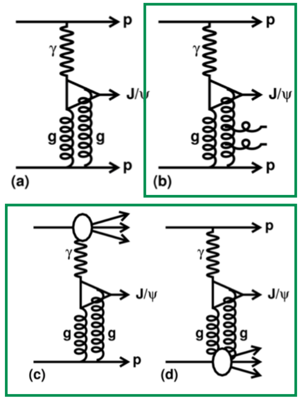
Ongoing studies using the HeRSChel forward shower counters to reduce the background



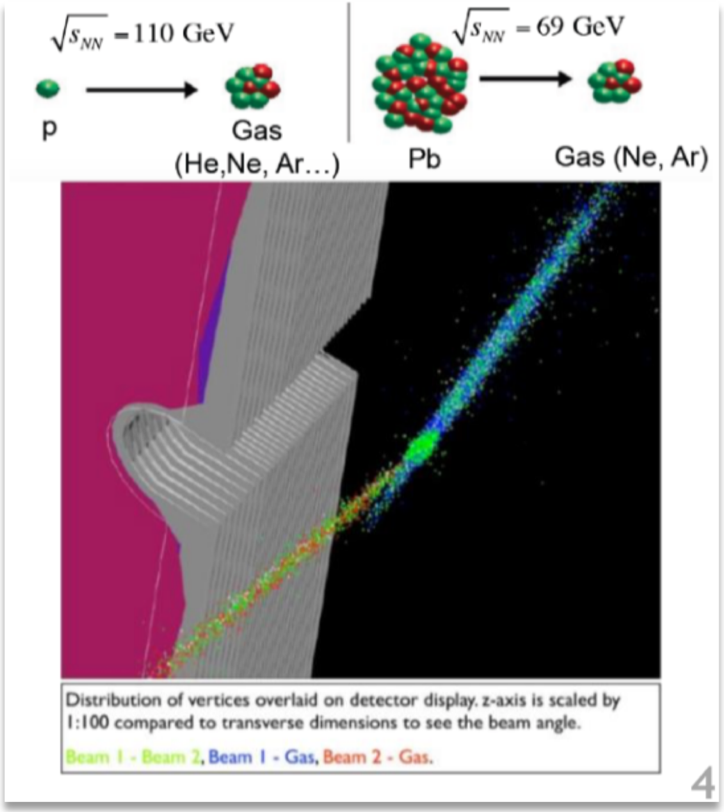
[LHCB-DP-2016-003 , arXiv:1801.04281]

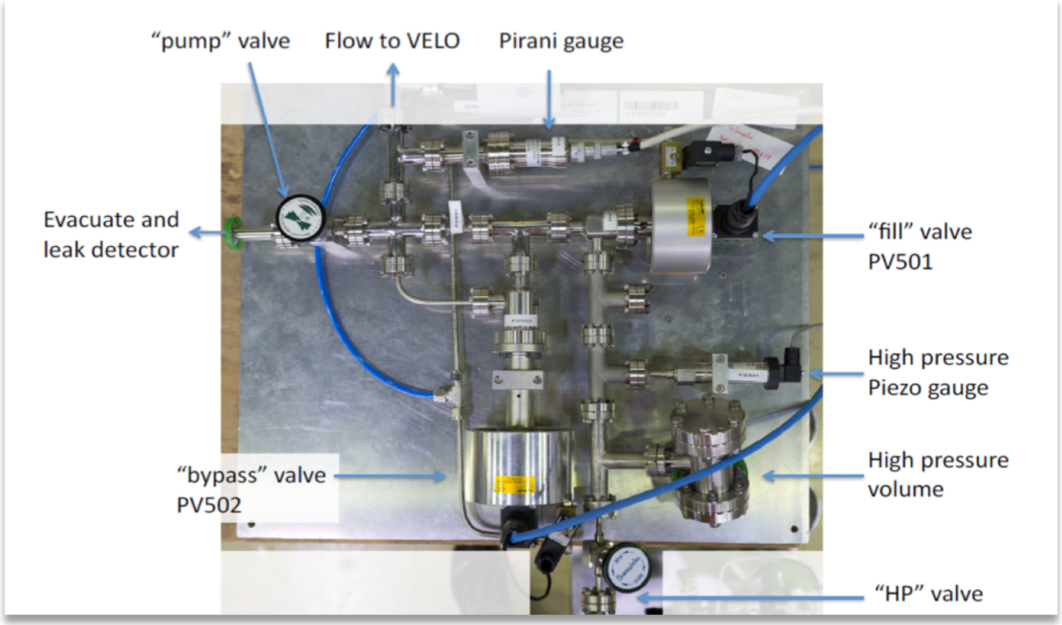


Background sources



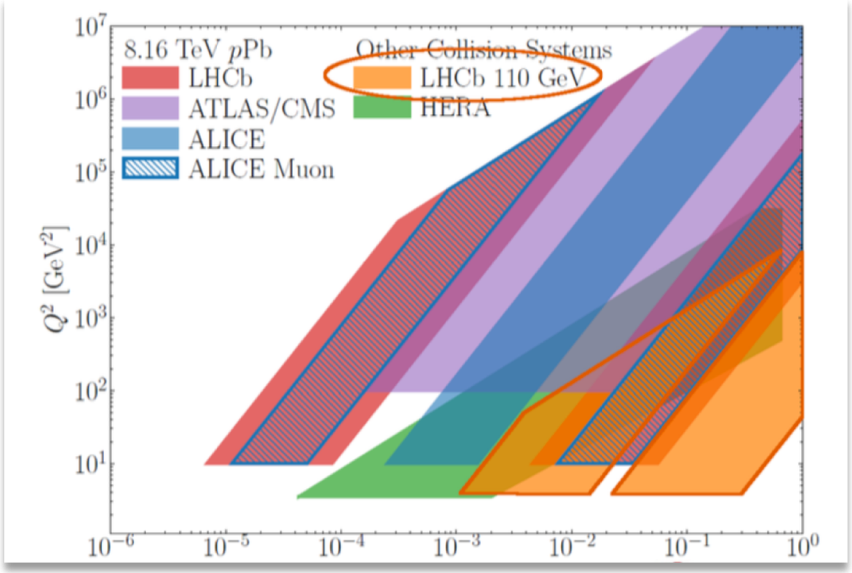
Fixed-target mode: The SMOG system

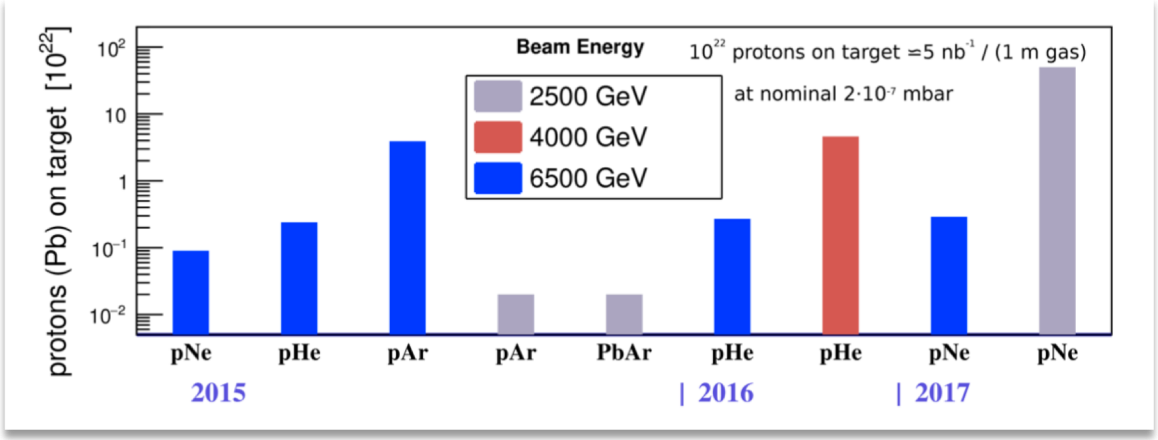




SMOG (The System for Measuring Overlap with Gas) enables injection of gas (He, Ne, Ar…) in the beam pipe section crossing the VELO (unique at LHC).

Fixed-target mode





- Gas pressure : 10^{-7} to 10^{-6} mbar.
- Collisions at $\sqrt{s_{NN}} = \sqrt{2E_{beam}m_p} = 41 - 110\ GeV$ for $E_{beam} = 0.9 - 6.5\ TeV$
  → relative unexplored energy scale between SPS and LHC experiments.
- At $\sqrt{s_{NN}} = 110\ GeV$, c.m. rapidity is $-2.8 < y^* < 0.2$ backward detector with access to large x value in target nucleon, for different nuclear targets.

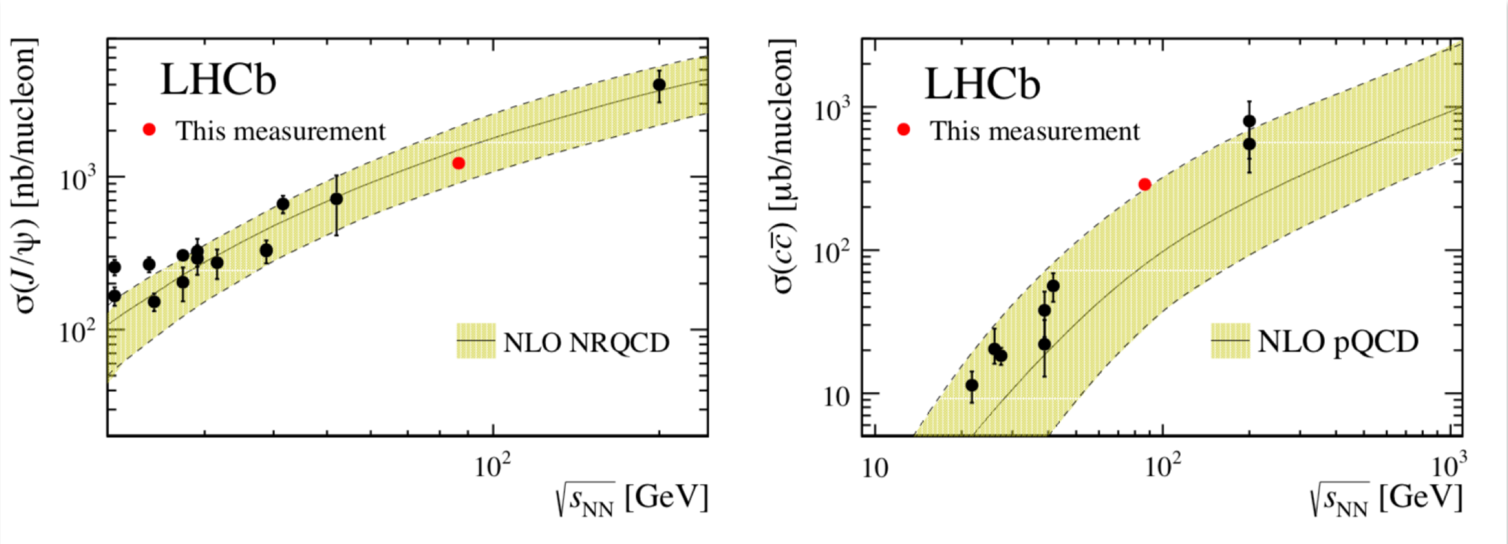
First measurement of charm production in fixed-target at LHC

Measurement of J/ψ and D^0 production cross section in pHe collisions in the rapidity range [2,4.6] at $\sqrt{s_{NN}} = 86.6\ GeV$ and $110.4\ GeV$

- Scaling the D^0 cross-section with the global fragmentation ratio $f(c \to D^0) = 0.542 \pm 0.024$ the $c\bar{c}$ production cross section can be obtained:

$$\boxed{\sigma_{c\bar{c}} = 288 \pm 24.2 \pm 6.9\ \mu b/nucleon}$$

- LHCb results in good agreement with NLO NRQCD fit (J/ψ) and NLO pQCD prediction ($c\bar{c}$) and other experimental measurements at various energies

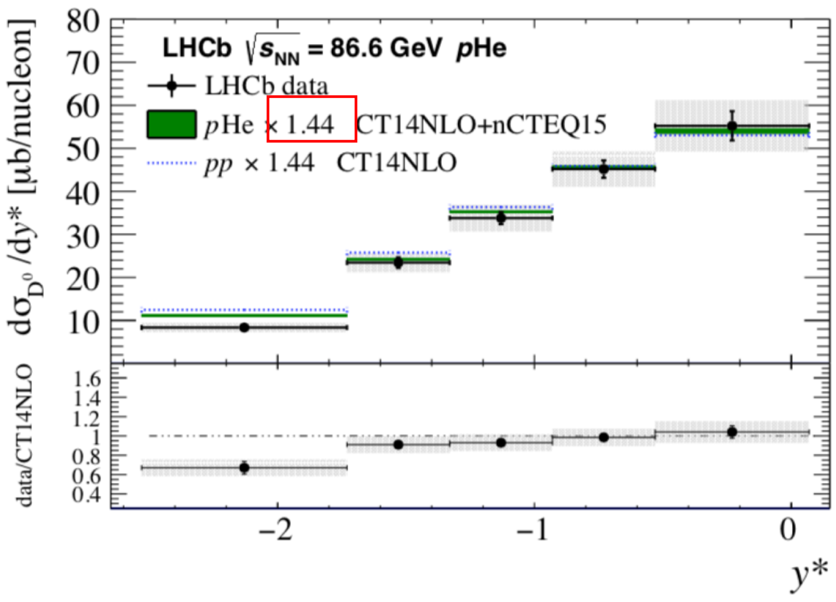


[Phys. Rev. Lett. 122, 132002 (2019)
LHCb-PAPER-2018-023]

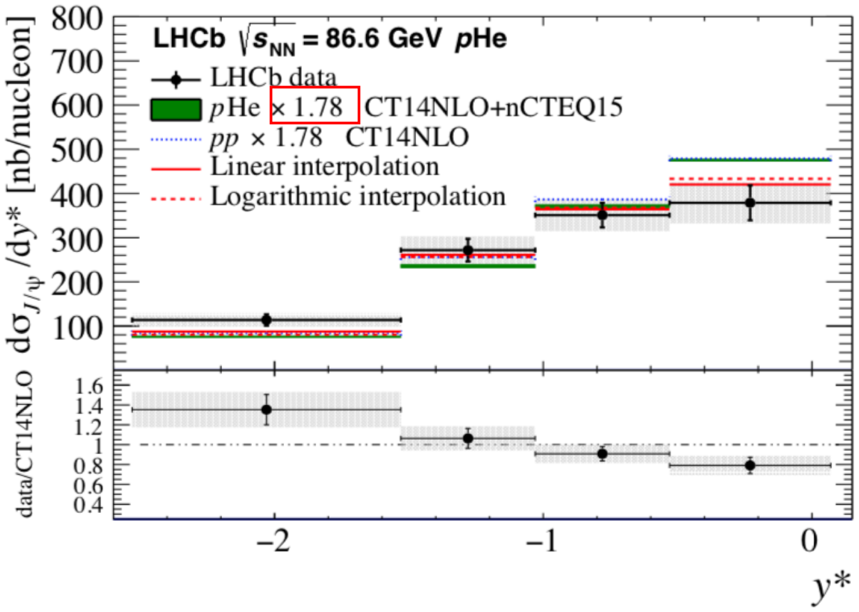
First measurement of charm production in fixed-target at LHC

[Phys. Rev. Lett. 122, 132002 (2019) , LHCb-PAPER-2018-023]

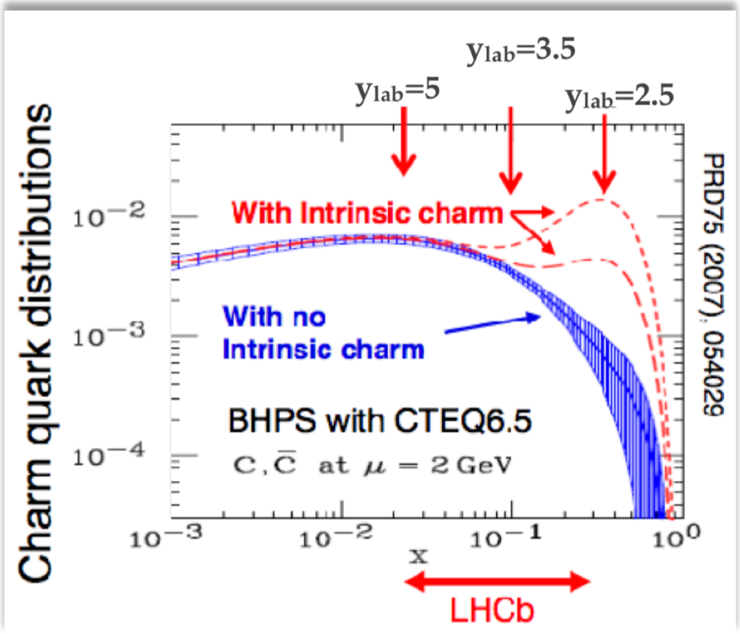
- No strong intrinsic charm contribution is observed
- HELAC-ONIA under-estimate the cross section by a factor 1.78 (J/ψ) and 1.44 (D^0)



$$\sigma_{D^0} = 80.8 \pm 2.4\,(\text{stat}) \pm 6.3\,(\text{syst})\ \mu\text{b/nucleon}$$



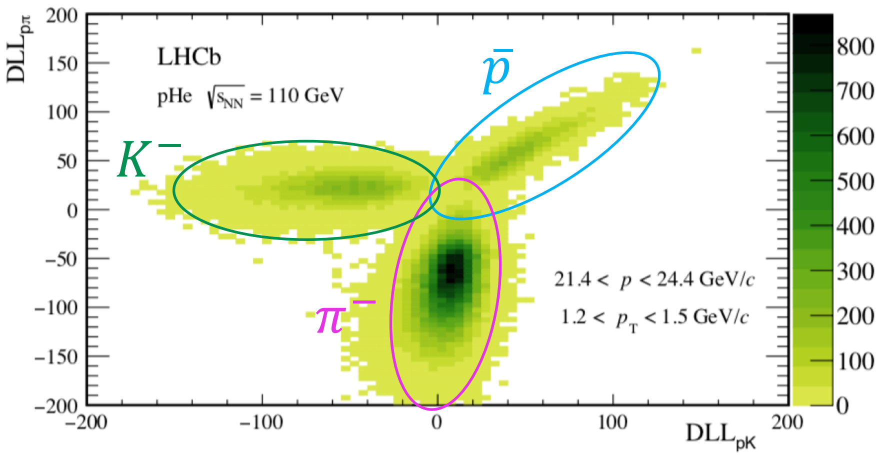
$$\sigma_{J/\psi} = 652 \pm 33\,(\text{stat}) \pm 42\,(\text{syst})\ \text{nb/nucleon}$$

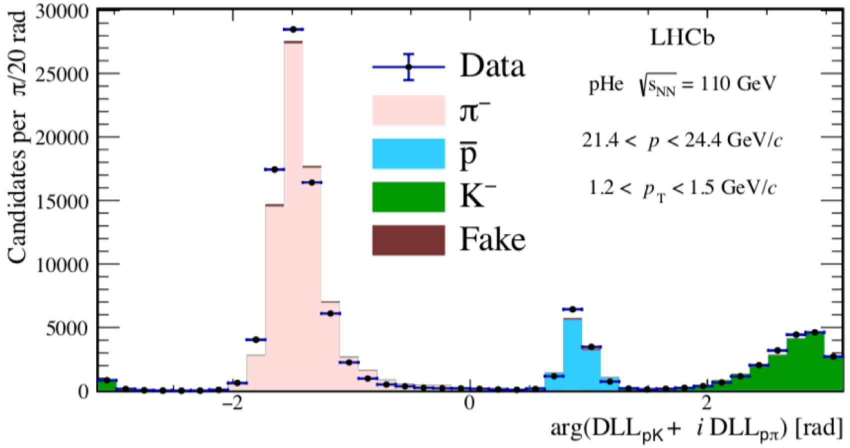


PRD 75 (2007) 054029

Anti-proton production in pHe $\sqrt{s_{NN}} = 110$ GeV

The cross-section for prompt antiproton production pHe at 6.5 TeV is measured .

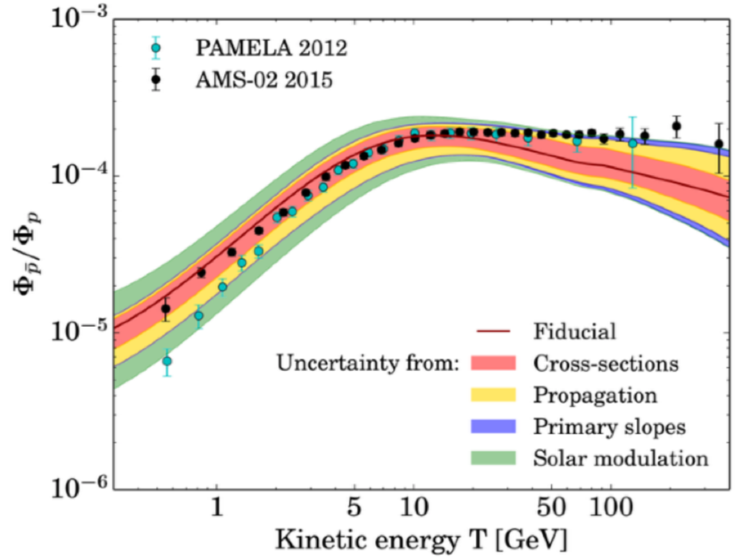




Antiproton/proton ratio known with great precision in cosmic rays

- AMS02 (PRL 117, 091103 (2016))
- PAMELA (JETP Letters 96 (2013) 621)

The interstellar medium is mainly composed by helium and hydrogen, SMOG allows to reproduce this system.



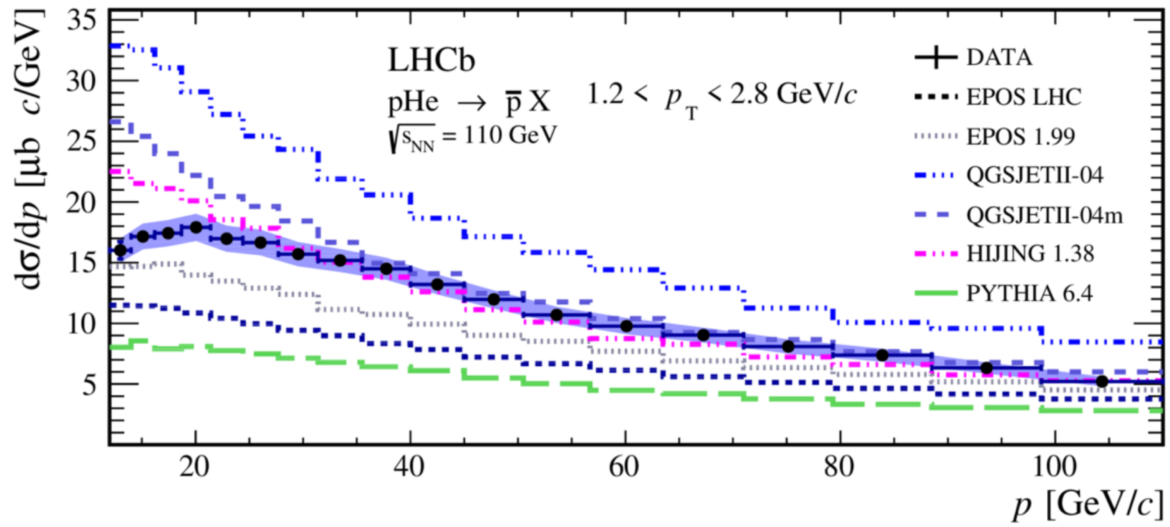
Flux prediction uncertainties in 10-100 GeV kinetic energy range: dominated by production cross-sections uncertainties

→ pHe scattering cross-section results can serve as external input

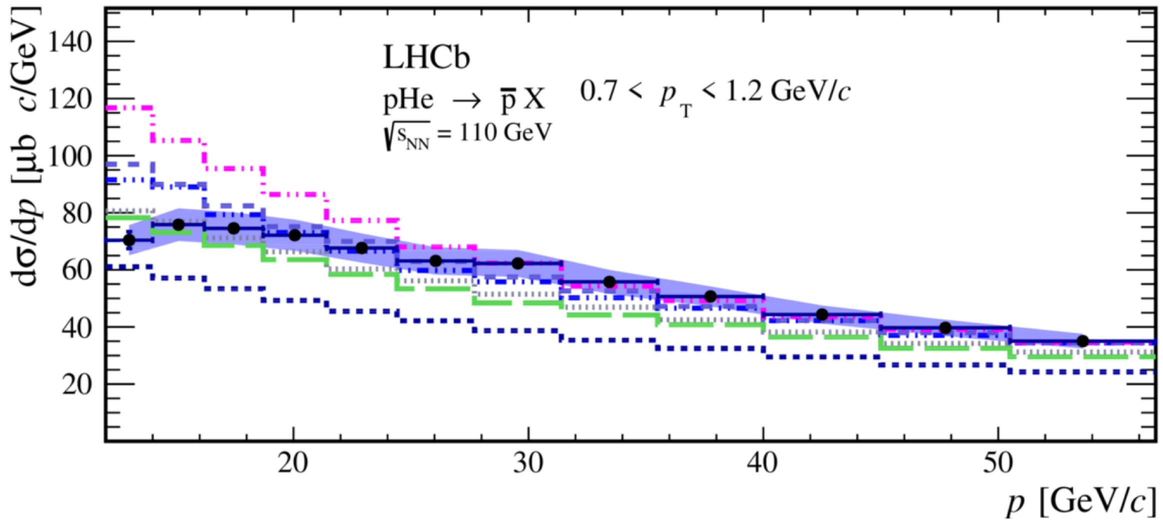
[Phys. Rev. Lett. 121, 222001 (2018), LHCb-PAPER-2018-031]

Anti-proton production in pHe $\sqrt{s_{NN}} = 110$ GeV

- Data collected in 2016 in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV.
- 33.7×10^6 reconstructed p-He collisions,
  → yielding 1.5×10^6 antiprotons
- Access to range $12\ \mathrm{GeV/c} < p < 110\ \mathrm{GeV/c}$
  $p_T > 0.4\ \mathrm{GeV/c}$, PID with 2 RICH detectors .
- Luminosity from *pe* (elastic scattering) since the gas pressure is not precisely known, measured value: $\boxed{484 \pm 7 \pm 29\ \mu b^{-1}}$



- Compared with simulation from:
  EPOS LHC, EPOS 1.99, QGSJET-II, QGSJETII-04m, Hijing, PYTHIA 6.4. ICRC '17: difference summary by T. Pierog
- Uncertainties smaller than model spread
- EPOS LHC tuned on LHC collider data underestimates $\bar{p}$-production



[Phys. Rev. Lett. 121, 222001 (2018), LHCb-PAPER-2018-031]

Conclusions

LHCb developed a rich heavy-ion program, with very specific capabilities and unique acceptance at a hadron collider.

- Fully performant in *p*Pb
- Peripheral studies in Pb-Pb
- Fixed-target program unique at the LHC
- Chance to measure soft QCD.
- Probe the partonic content of nucleons and nuclei.
- Possibility to investigate in detail nPDFs.

Recent results shown today

- Λ_c production in *p*Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
- B^+, B^0 *and* Λ_b^0 production in *p*Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV
- $\Upsilon(nS)$ production in *p*Pb collisions at $\sqrt{s} = 8.16$ TeV
- Exclusive photonuclear J/ψ production in ultra-peripheral PbPb collisions
- J/ψ and D^0 production cross section in *p*He collisions
- Anti-proton production in *p*He

Future prospects

More results to come e.g. Drell-Yan, vector bosons, more quarkonia states, dihadron correlations, Bose-Einstein condensates, flow studies.
Lot of interesting measurements on-going :

- *p*Pb: Drell-Yan, correlation, exotics, Ξ_C, open charm, W/Z
- PbPb 2018 data : UPC collisions and $D^0, J/\psi$ productions.
- Fixed-target: photoproduction in *p*A, antihyperon in *p*He, Λ_c polarization in *p*Ne, quarkonia and D0 in *p*Ne and PbNe .
- Upgrade of the SMOG system: SMOG2 100 times more luminosity

Planned a factor >10 more integrated luminosity in Run 3!

Thank you