SMOG: experimental results

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on behalf of the LHCb collaboration

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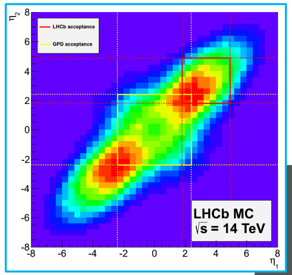
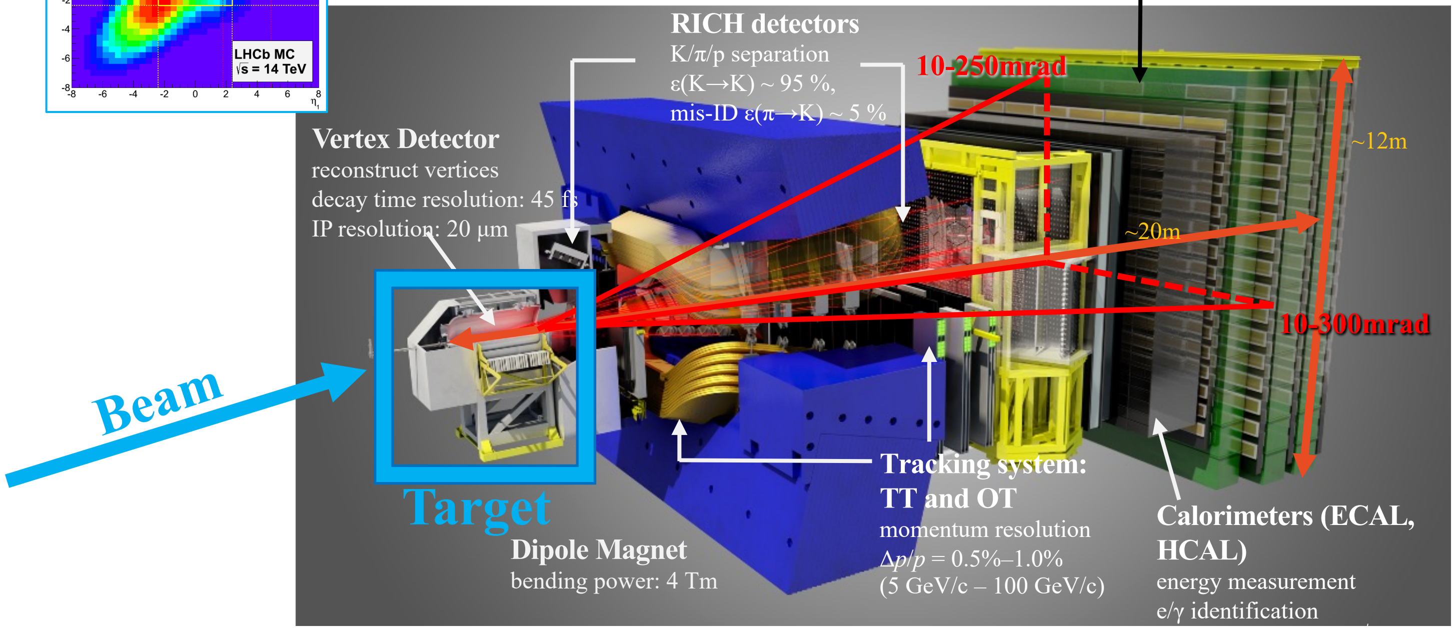
The LHCb detector

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

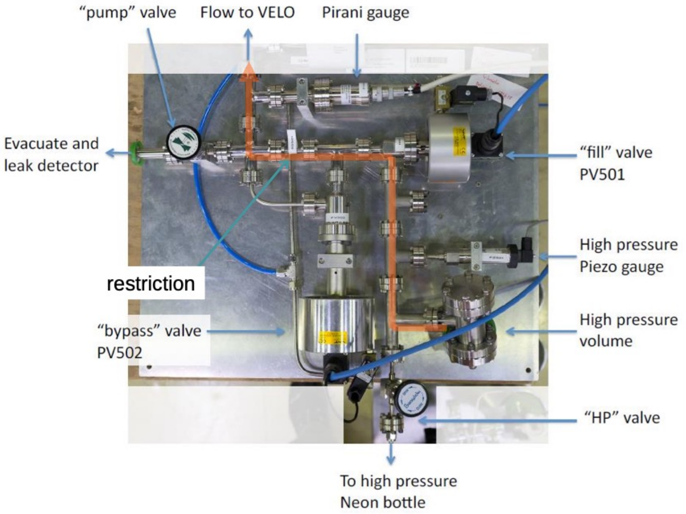


[IJMPA 30 (2015) 1530022]
[JINST 3 (2008) S08005]



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

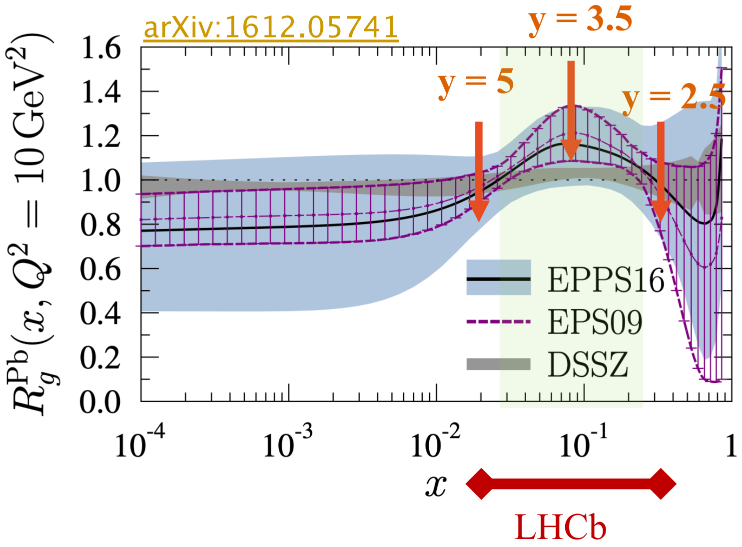
- Excellent performances
- It is a "charm factory": for *pp* collisions,
  - $4 \times 10^{32}\ cm^{-2}s^{-1}$ luminostiy for Run 2: the rate of $c\bar{c}$ pairs is 0.96 MHz
  - rate of Λ_c^+ seen by the LHCb detector ~602 Hz
- Unique system to inject gas (SMOG) originally designed for luminosity measurements. Re-used to transform LHCb in a fixed-target experiment. [JINST 9 (2014) P12005]
- Injection valve:



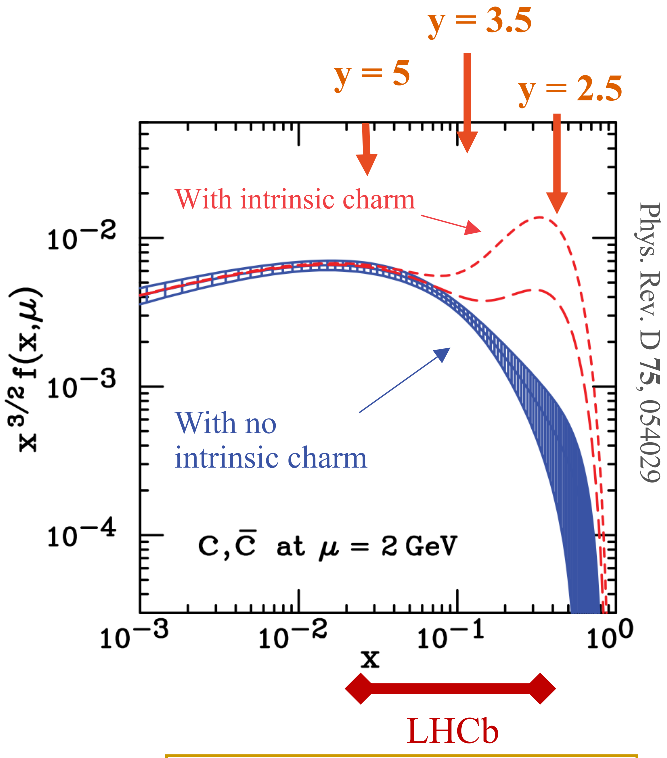
SMOG

- SMOG: System for Measuring Overlap with Gas
- A noble gas (He, Ne, Ar) at $\sim 2 \times 10^{-7}$ mbar pressure injected into the LHC vacuum around the LHCb interaction region
- Energy between SPS and RHIC
- Rapidity: $-3.0 < y^* < 0$

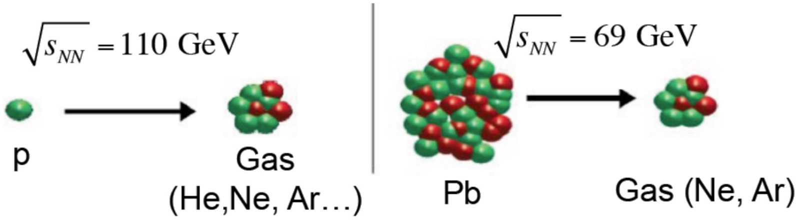
Bjorken x = fraction of proton momentum carried by the quark

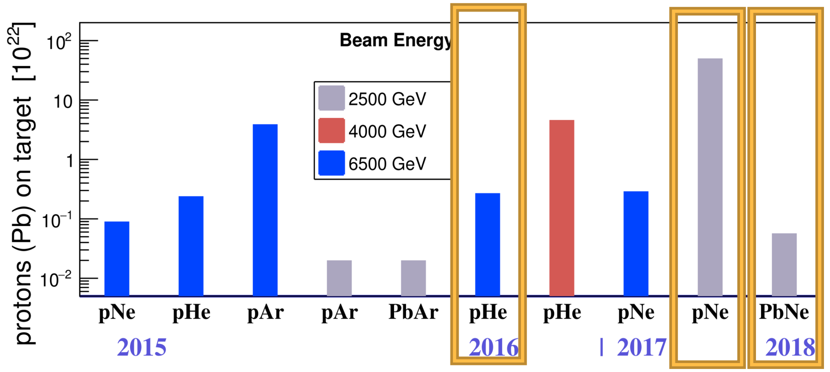


$$\frac{PDF(Pb\ nucleus)}{PDF(single\ nucleon)}$$



Charm distributions



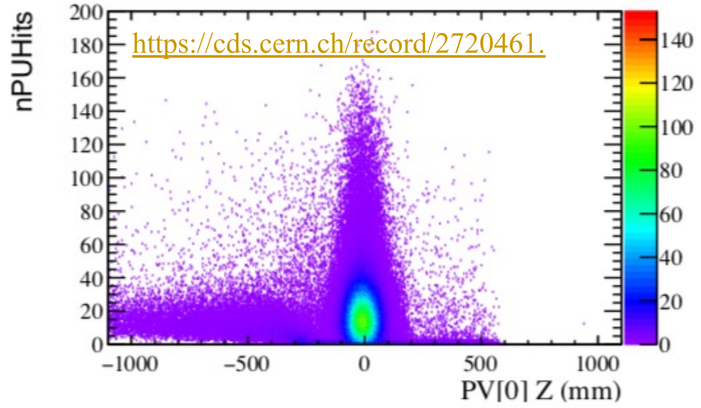


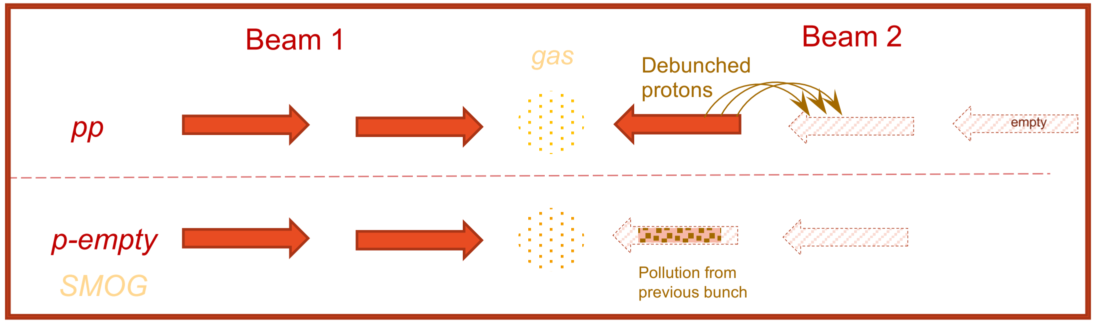
- Access nPDF anti-shadowing region
- Can probe intrinsic charm content of nucleon
- Important input for astrophysics measurements

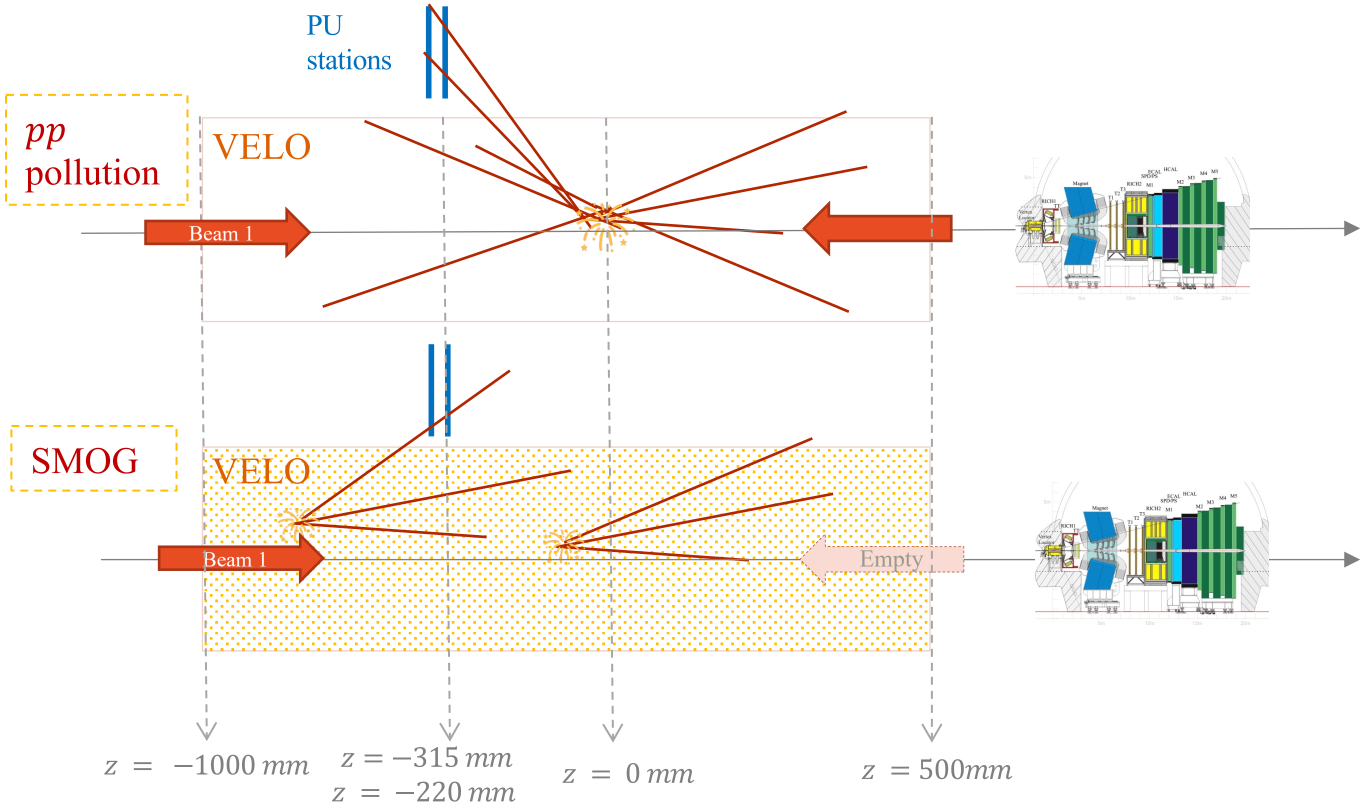
SMOG pollution

- Data are taken simultaneously with *pp* collisions at 5 TeV, no special runs pollution from *pp* collisions « ghost charges ».
  - ❖ pp and p-Gas data are taken at the same time alternating full and empty bunches.
  - ❖ Some debunched protons from the previous beam go to the following bunch which is supposed to be empty.

Cleaning using the event topology: Z-coordinate and number of hits pile-up stations



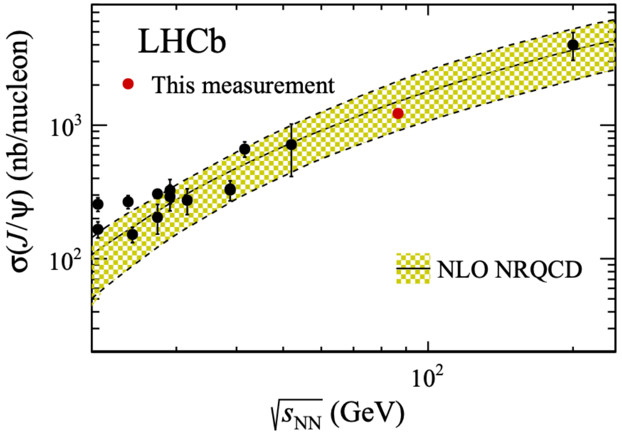


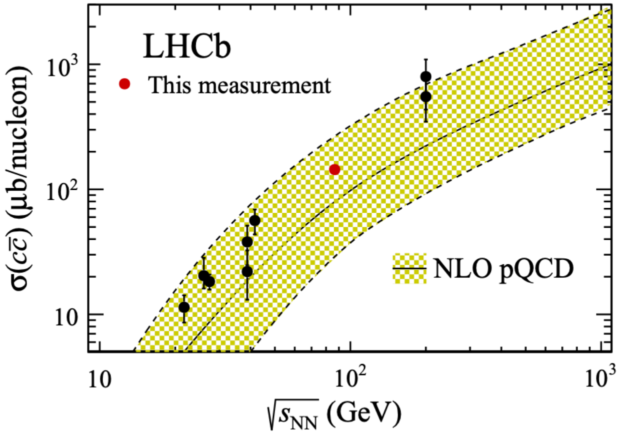


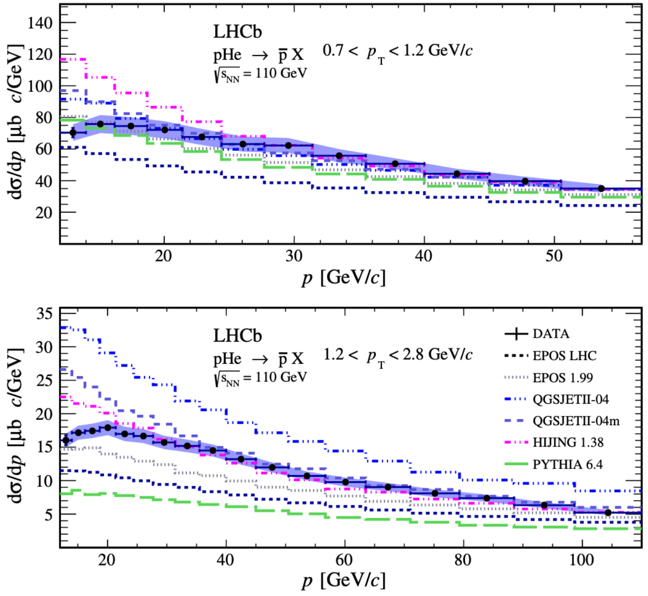
Physics results with SMOG

Previous SMOG results:

1. Charm production in pAr, pHe collisions Phys. Rev. Lett. 122 (2019) 132002
2. Prompt antiproton in pHe collisions at 110 GeV Phys. Rev. Lett. 121 (2018) 222001







New Results :

1. Charmonia production in pNe collisions at $\sqrt{s_{NN}} = 68.5$ GeV LHCb-PAPER-2022-014
2. D^0 and J/ψ production in PbNe collisisons at $\sqrt{s_{NN}} = 68.5$ GeV LHCb-PAPER-2022-012
3. Detached antiproton production in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV LHCb-PAPER-2022-006

New technical publications

1. A Neural-Network-defined Gaussian Mixture Model for PID with SMOG data JINST 17 (2022) P02018
2. Centrality determination in heavy-ion collisions with the LHCb detector CERN-LHCb-DP-2021-002

Charm production as a probe for QCD

Charmonium production

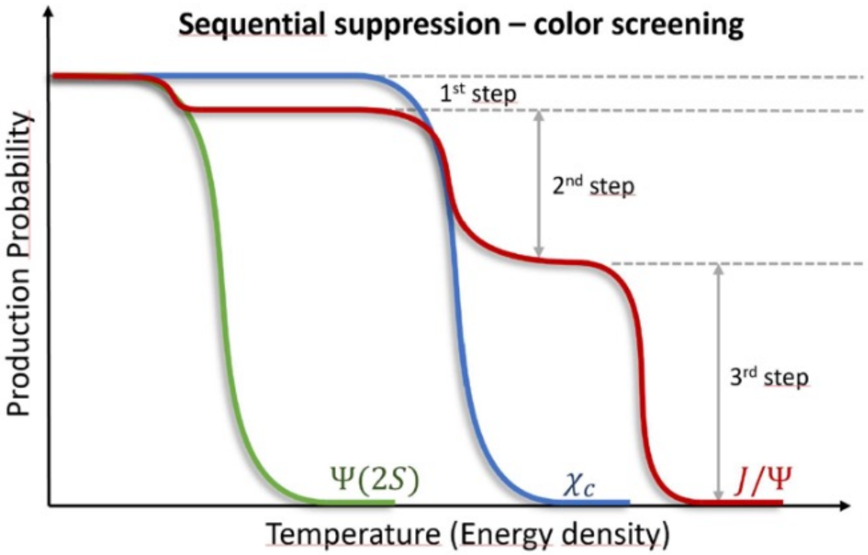
1. It's a smoking gun of QGP production via the color screen mechanism T. Matsui, H. Satz, Physics Letters B 178 (1986), no. 4 . *Phys.Rev.D* 64 (2001) 094015
   J/ψ suppression has been studied in several fixed-target experiment, however the underlying mechanism is still not fully understood→ new measurements in different colliding systems are fundamental to constraint cold nuclear matter effects
2. Other charmonium states also affected : $\psi(2S)$ and χ_c with lower binding energy (suppressed at lower temperature). For J/ψ produced from excited states → sequential suppression.
3. Suppression compensated by statistical recombination at high $\sqrt{s}_{NN}$

Why Open Charm?

1. D^0 open charm, not affected by QGP and gives an estimate of the total amount of $c\bar{c}$ pairs
2. Compare the ratio J/ψ to D^0 in pNe and PbNe systems
3. Cross-section and asymmetry relevant to study the nucleon content

Today's measurement with SMOG LHCb data:

1. J/ψ cross-section (integrated and as a function of p_T and y^*)
2. J/ψ / $\psi(2S)$ ratio using di-muon decay
3. J/ψ / D^0 ratio , using $D^0 \to K^-\pi^+$

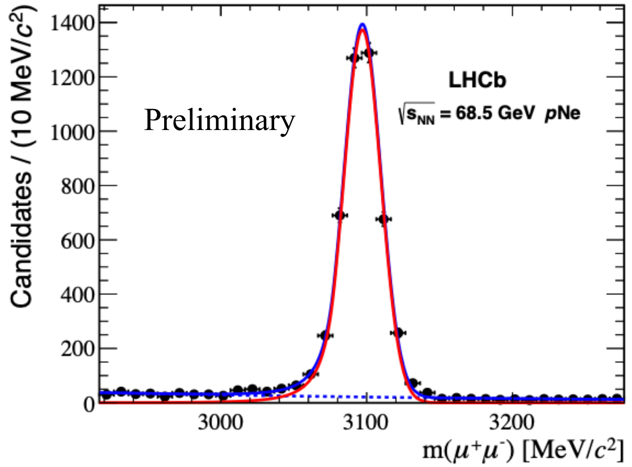


Charmonium production in pNe

- J/ψ and $\psi(2S)$ reconstructed via di-muon decay:

  $N_{sig} = 4\ 542\ J/\psi \rightarrow \mu^+\mu^-$

  $N_{sig} = 76\ \psi(2S) \rightarrow \mu^+\mu^-$



Cross section σ defined as:

$$\sigma = \frac{N_{\text{Signal}}^{\text{After correction}}}{\mathcal{L} \times A_{\text{nucleus}} \times BR}$$

Number of efficiency corrected events after selections

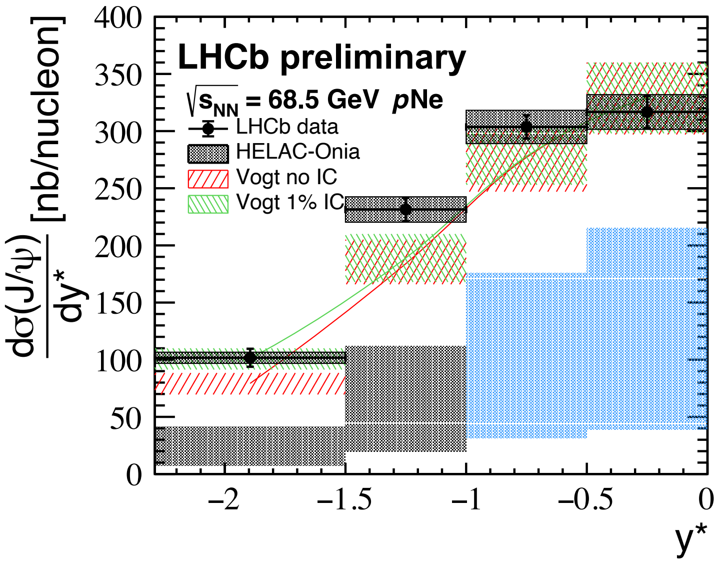
luminosity

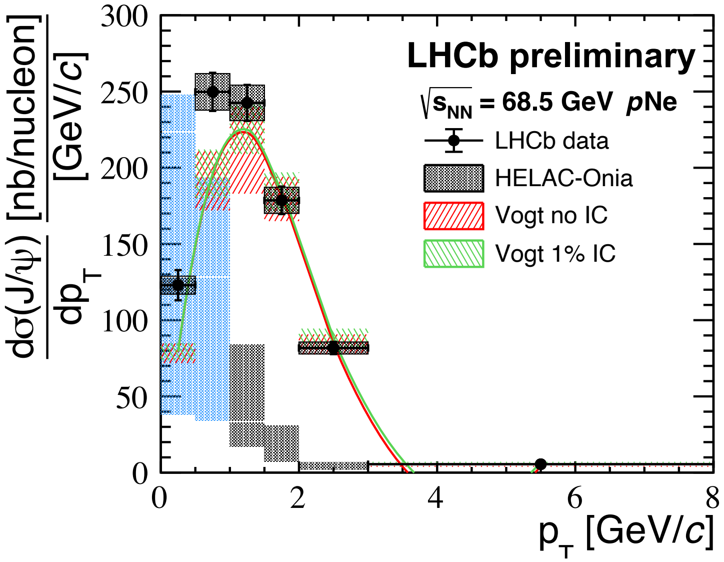
Atomic number Ne

Branching ratio

$$\sigma_{y* \in [-2.29,0]}^{J/\psi} = 444.1 \pm 6.9\ (\text{stat})\ \pm 4.5\ (\text{uncorr syst})\ \pm 21.2\ (\text{corr syst})\text{nb/A}.$$

- Results:





- HELAC-ONIA using CT14NLO and nCTEQ15 under shoot the data
- Good agreement with predictions with (1%) Intrinsic Charm (IC) and without it

Charmonium production pNe

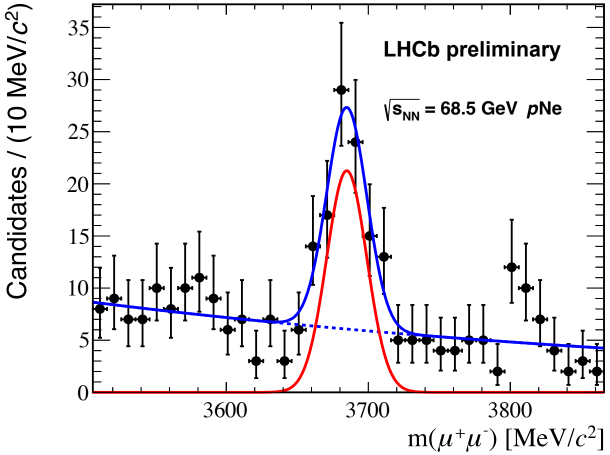
***J/ψ* cross section measurement:**

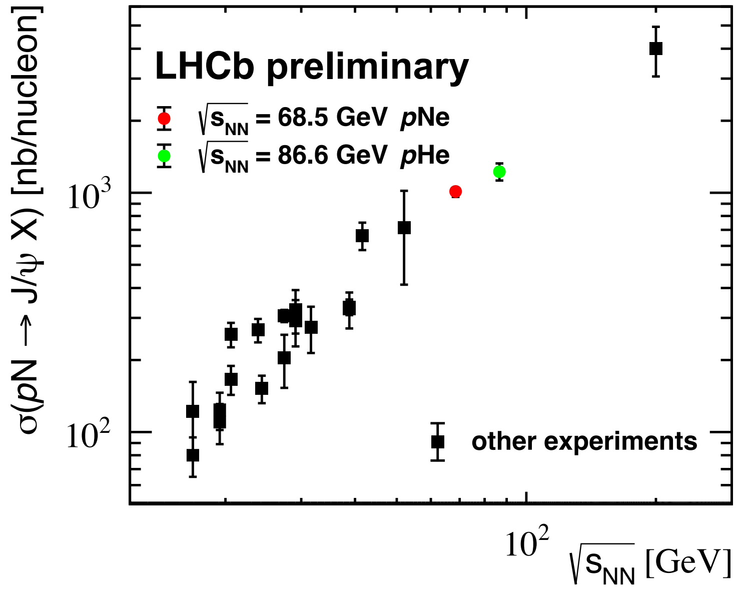
- Total cross-section: extrapolation to full phase space using Pythia8+CT09MCS PDF
- Power-law dependency with $\sqrt{s_{NN}}$ found

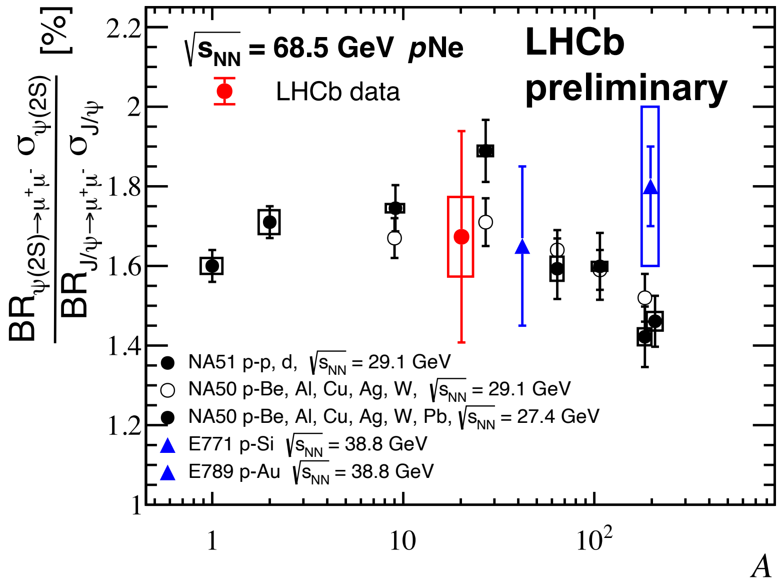
Ratio $\psi(2S)/J/\psi$ first measurement in SMOG:

In line with other measurements for different values of target atomic mass number (A):

$$\frac{Br_{\psi(2S)\to\mu^+\mu^-}\sigma_{\psi(2S)}}{Br_{J/\psi\to\mu^+\mu^-}\sigma_{J/\psi}} = 1.67 \pm 0.27\ (\text{stat.}) \pm 0.10\ (\text{syst.})\ \%,$$



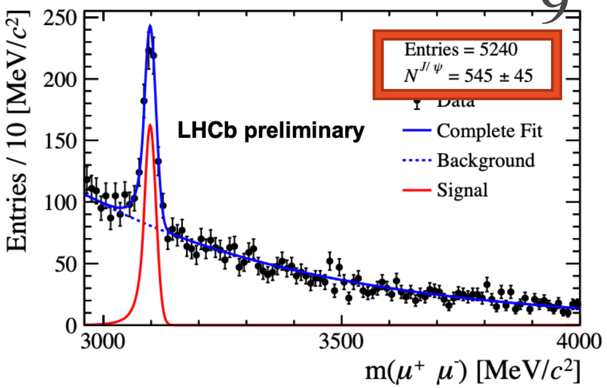


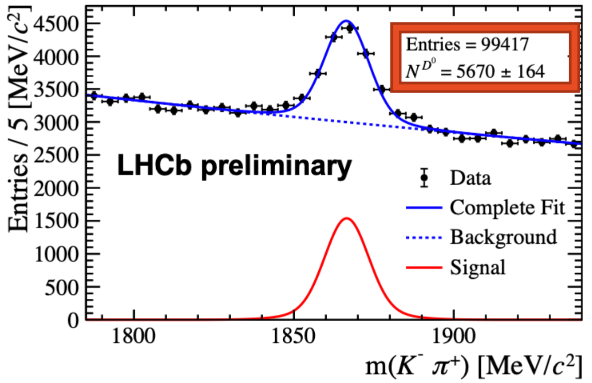


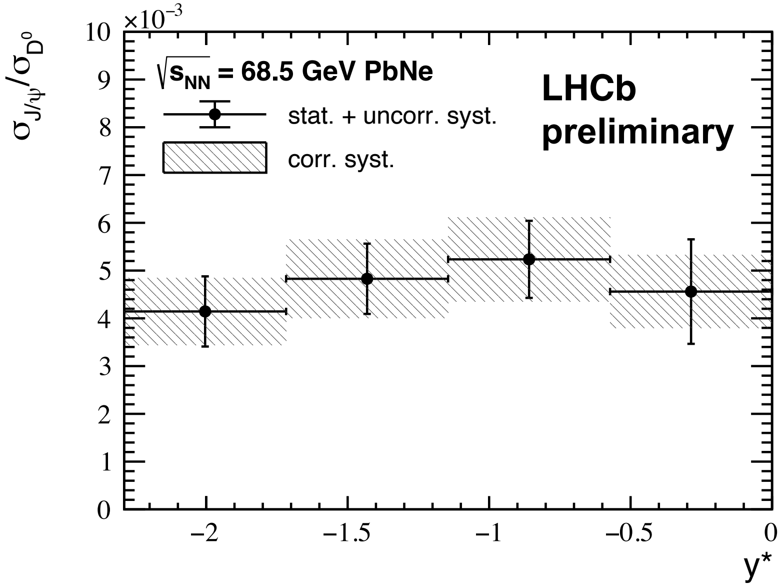
D^0 and J/ψ in PbNe collisions

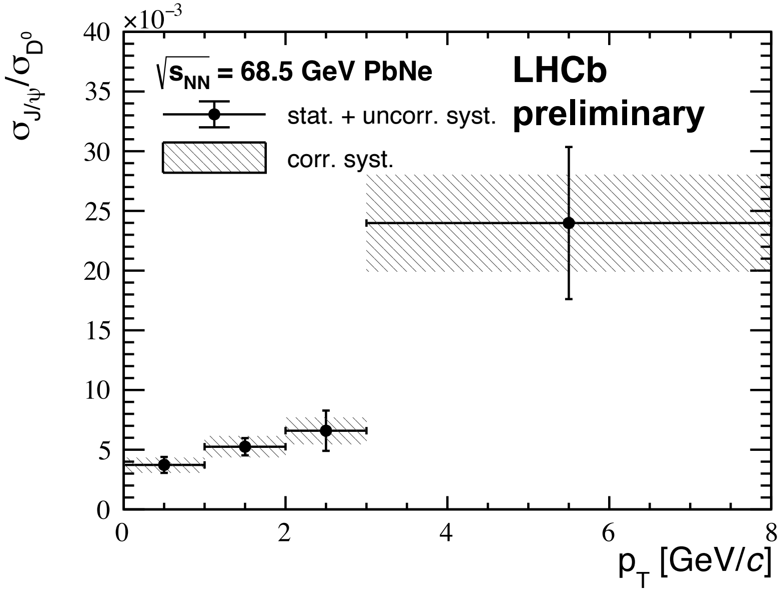
- **First measurement of J/ψ and D^0 in fixed target nucleus-nucleus collisions**
- Centrality determined by energy deposit in electromagnetic calorimeter arXiv:2111.01607
- The ratio of J/ψ over D^0 is evaluated integrated and binned in y and p_T.
- Luminosity measurement on-going, no absolute cross section available yet
- Ratio integrated:

$$\frac{\sigma_{J/\psi}}{\sigma_{D^0}} = (5.1 \pm 0.4 \pm 0.9) \times 10^{-3}$$









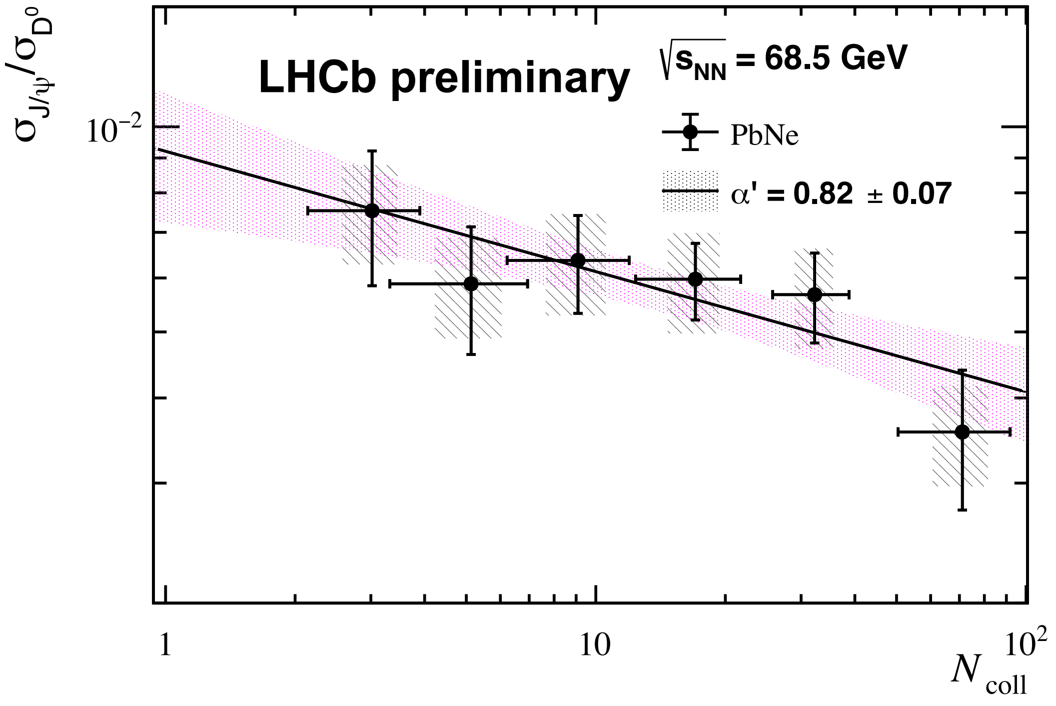
- ➢ No dependence on rapidity
- ➢ Strong dependence on p_T

LHCb-PAPER-2022-011
In preparation

Charm in pNe vs PbNe

- Evaluate suppression as a function of the number of binary nucleon-nucleon collisions N_{coll} (estimated from Glauber model to data)
- pNe collisions = very peripheral PbNe collisions
- Ratio for PbNe and pNe vs N_{coll} fitted with a power law:
  - assuming → $\sigma_{\rm AB}^{D^0} \propto N_{\rm coll}$
  - J/ψ supressed by CNM + QGP → $\sigma_{\rm AB}^{J/\psi} \propto N_{\rm coll}^{\alpha'}$

$$\sigma^{J/\psi}/\sigma^{D^0} \propto N_{\rm coll}^{\alpha'-1} \Rightarrow \boxed{\alpha' = 0.82 \pm 0.07}$$



Conclusions:

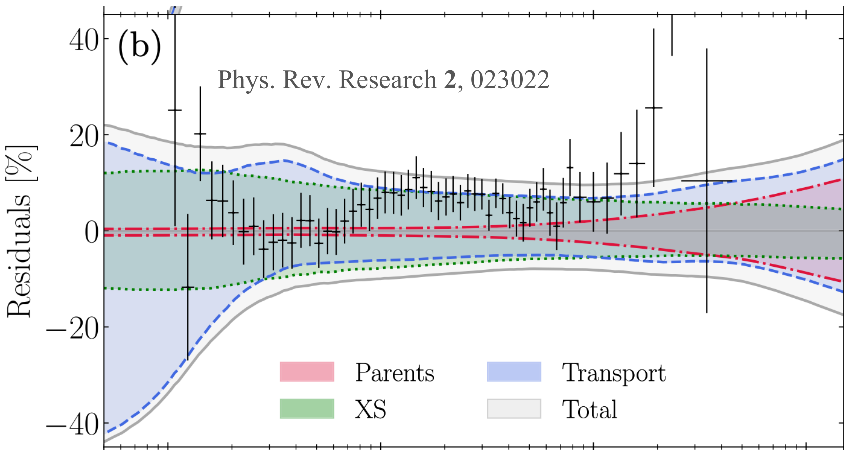
J/ψ suppression is consistent with CNM without additional QGP effects

Detached antiproton in pHe collisions at 110 GeV

Space-borne experiments PAMELA and AMS-02 improved **measurements of the abundance of the $\bar{p}$ component** in cosmic rays, which is sensitive to a possible **dark matter** contribution

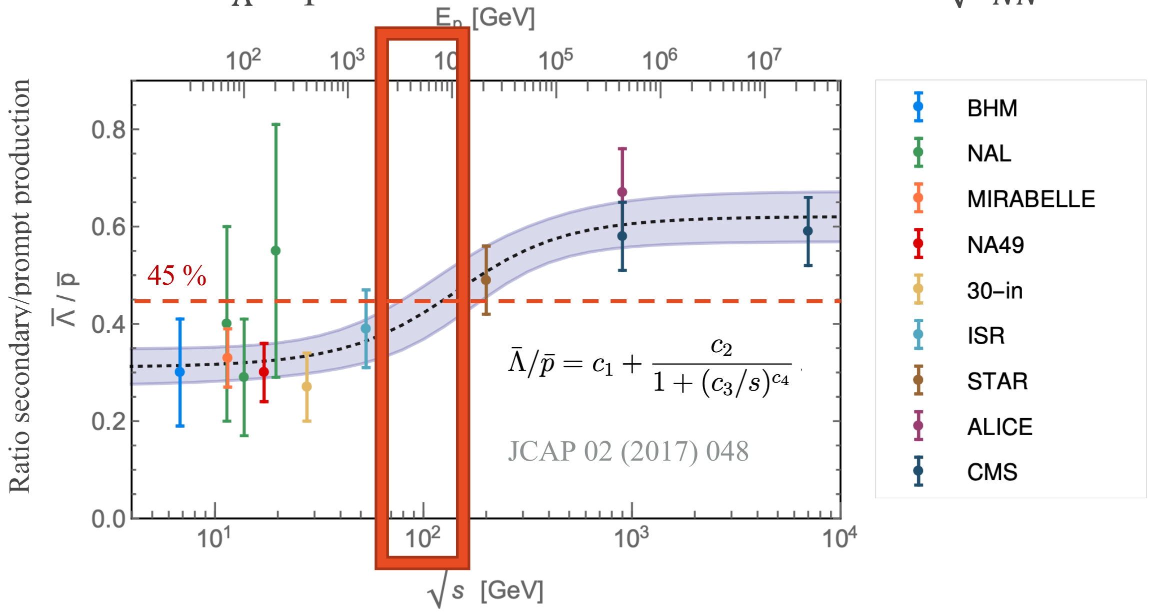
→Requires knowledge of the $\bar{p}$ production cross-sections in the spallation of cosmic rays in the interstellar medium

- Uncertainty still dominated by XS :



Residuals predictions vs data

- The ratio $R_{\bar{\Lambda}}$ is predicted to increase as a function of $\sqrt{s_{NN}}$



Previous SMOG measurement → prompt (produced directly at the primary vertex) $\bar{p}$ production Phys. Rev. Lett. 121 (2018) 222001

NEW $\bar{p}$ production from anti-hyperons weak decays (non-prompt)

Detached antiproton in pHe collisions at 110 GeV

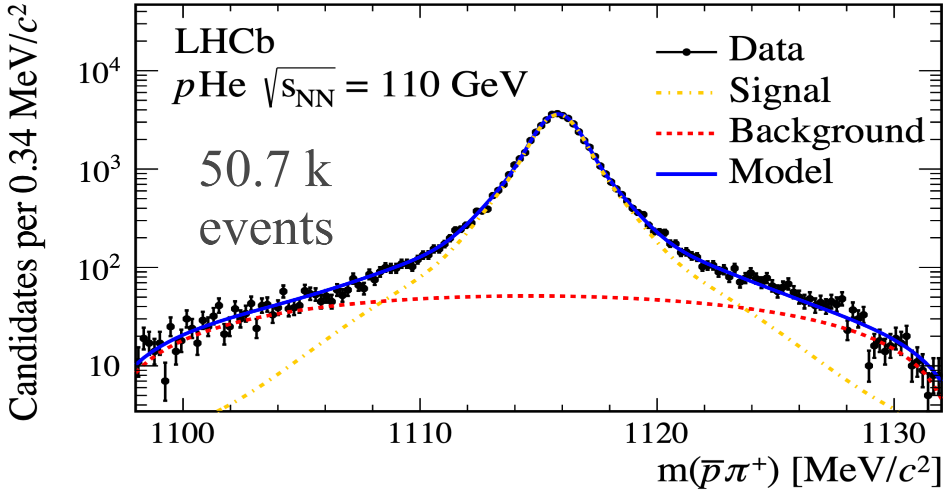
- Mesure detached $\boldsymbol{\bar{p}}$ in pHe collisions and compare to the prompt $\boldsymbol{\bar{p}}$
- Measure it exclusively exploting $\bar{\Lambda}$ decays and inclusively → ratio as a cross check (better constrained)

Exclusive: $$R_{\bar{\Lambda}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{\Lambda}X \to \bar{p}\pi^+X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}}X)}$$

Inclusive: $$R_{\overline{H}} \equiv \frac{\sigma(p\mathrm{He} \to \overline{H}X \to \bar{p}X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}}X)}$$

- 6. 5 TeV proton beam on He target → $\sqrt{s_{NN}} = 110$ GeV , with a luminosity of 0.5 nb^{-1}
- The detached decay vertex and the invariant-mass resolution + decay kinematics (asymmetry momenta) allow identificaiton of $\bar{p}$

arXiv:2205.09009



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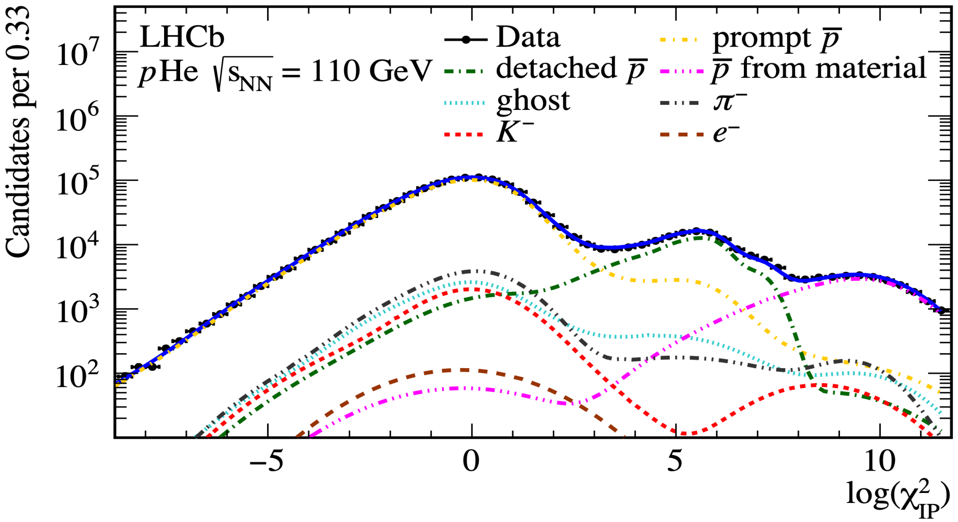
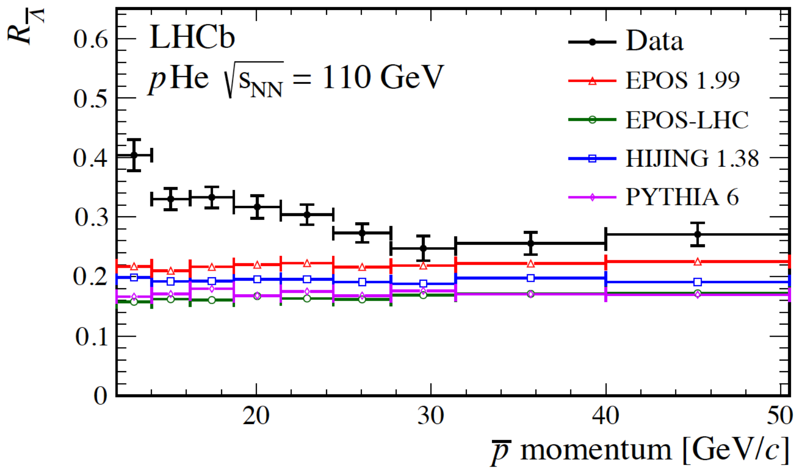


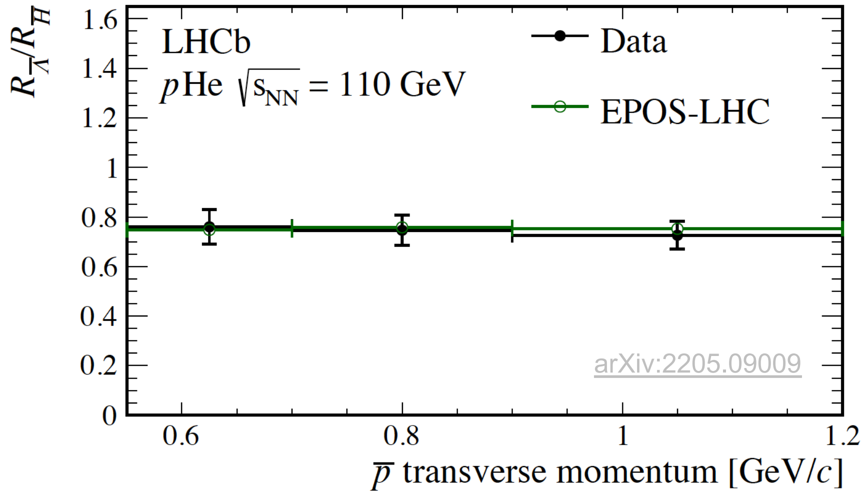
Detached antiproton in pHe collisions at 110 GeV

arXiv:2205.09009

$$R_{\bar{\Lambda}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{\Lambda}X \to \bar{p}\pi^+X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}}X)}$$

- Most generators undershoot data and do not describe the momentum dependance

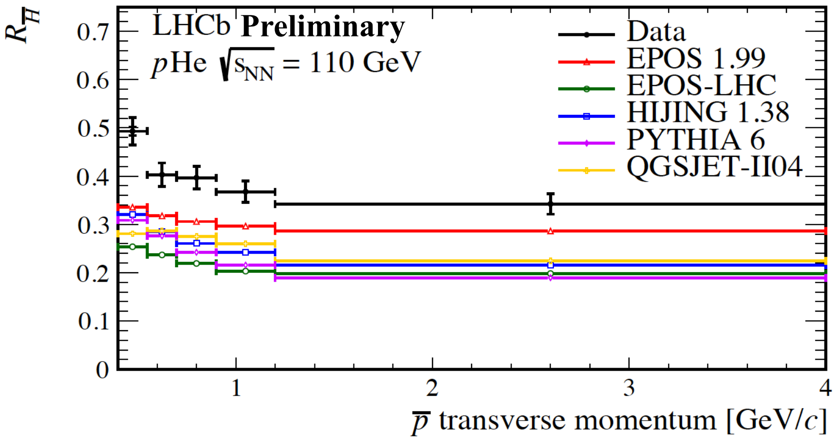




Ratio is predicted reliably and used to check the consistency of the two complementary approaches

$$R_{\bar{H}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{H}X \to \bar{p}X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}}X)}$$

- Most generators undershoot data at low momentum, however general behavior reproduced



Conlusions:

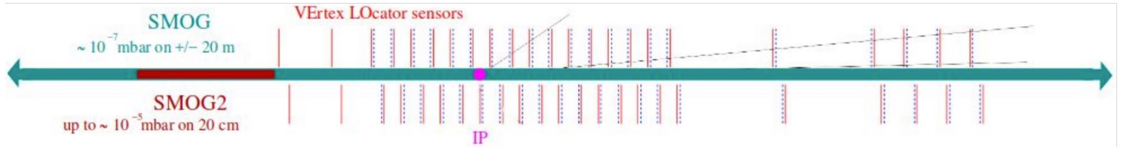
- Found increased anti-hyperon contribution wrt previous measurement at $\sqrt{s_{NN}} = 10$ GeV underestimated in most of hadronic production models used in cosmic ray physics
- $R_{\bar{H}}$ dependance as fct of transverse momenutm also need to be included in the models

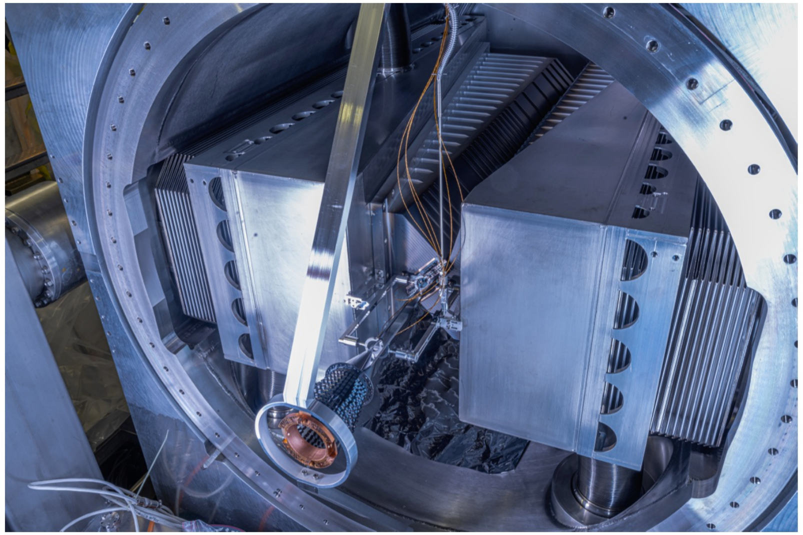
These results are a valuable input to improve the predictions for the secondary $\bar{p}$ cosmic flux

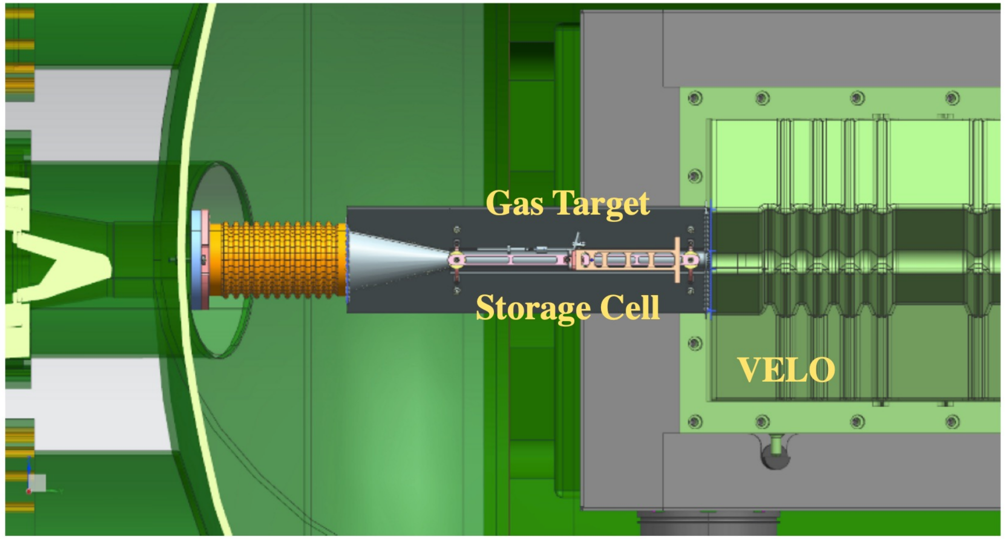
SMOG2

- Upgraded SMOG system with storage cell placed upstream nominal IP at z [-500,-300] mm, with dedicated Gas Feed System.
- Gas density increased of 2 orders of magnitude → higher luminosity
- Gas target possible: $H_2, D_2, He, N_2\ , O_2, Ne, Ar, Kr, Xe$
- Separated luminous region from *pp* allowing for simultaneous data-taking → more statistics

Reaction	DAQ time	Non coll. bunches	Lumi (nb^{-1})	Decays	SMOG yields	Scale factor	SMOG2 proj. yields
pAr	18 h	684	~ 2	$D^0 \to K^-\pi^+$	6450	62	400 k
				$D^+ \to K^-\pi^+\pi^+$	975		60 k
				$D_s^+ \to K^-K^+\pi^+$	131		8 k
				$D^{*+} \to D^0\pi^+$	2300		140 k
				$\Lambda_c^+ \to pK^-\pi^+$	50		3 k
				$J/\psi \to \mu^+\mu^-$	500		30 k
				$\psi(2S) \to \mu^+\mu^-$	20		1.2 k
pHe	84 h	648	7.6	$J/\psi \to \mu^+\mu^-$	500	19.6	10 k
				$\psi(2S) \to \mu^+\mu^-$	20		0.4 k







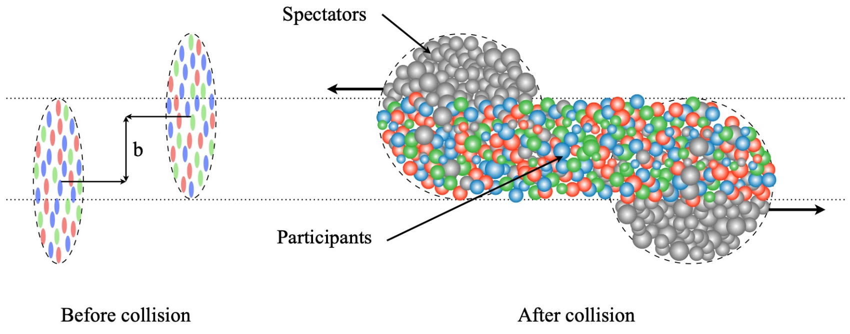
LHCb-TDR-020

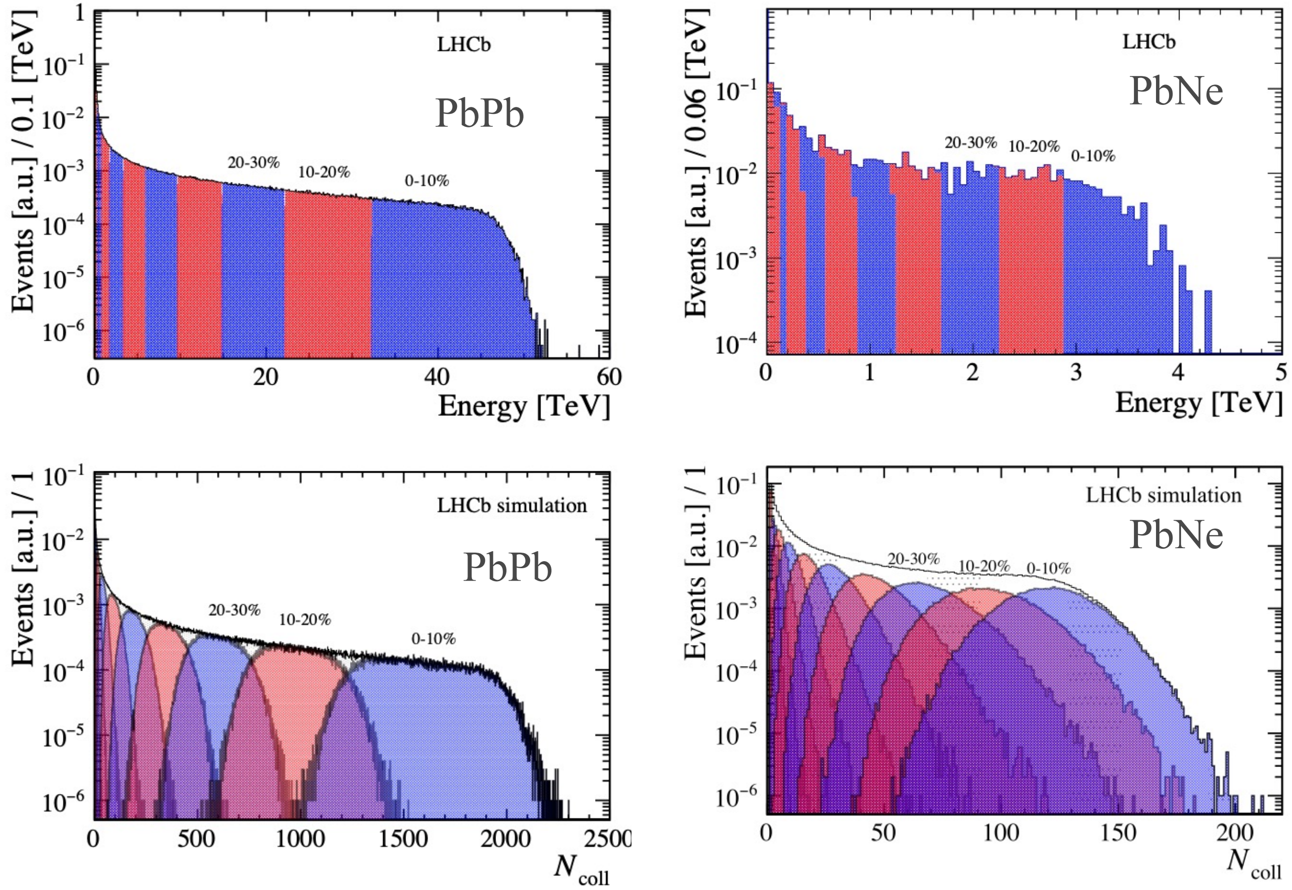
Conclusions

- SMOG data have produced unique results and more results are to come!
- Today :
  1. Charmonia production in pNe at 68.5 GeV
  2. Open charm and charmonia production PbNe at 68.5 GeV
  3. Detached $\bar{p}$ production *in* pHe at 110 GeV
- Future: charm baryons (Λ_c^+ and Ξ_c^+) polarization, production cross-section and asymmetry
- SMOG2 successfully installed, first runs are coming soon!

Centrality determination in PbNe

- The centrality of a nucleus-nucleus → overlap region between the nuclei where the nucleons are colliding.
- MC Glauber model used to to isolate the hadronic part and subsequently define the centrality classes
- Proxy: energy deposit in the ECAL (VELO clusters saturates)





CERN-LHCb-DP-2021-002
https://arxiv.org/pdf/2111.01607.pdf