Fixed-target and astroparticle physics at LHCb

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on behalf of the LHCb collaboration

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2023 LHCb Implications Workshop

25 October 2023

Outline

1. **The fixed-target program at LHCb**

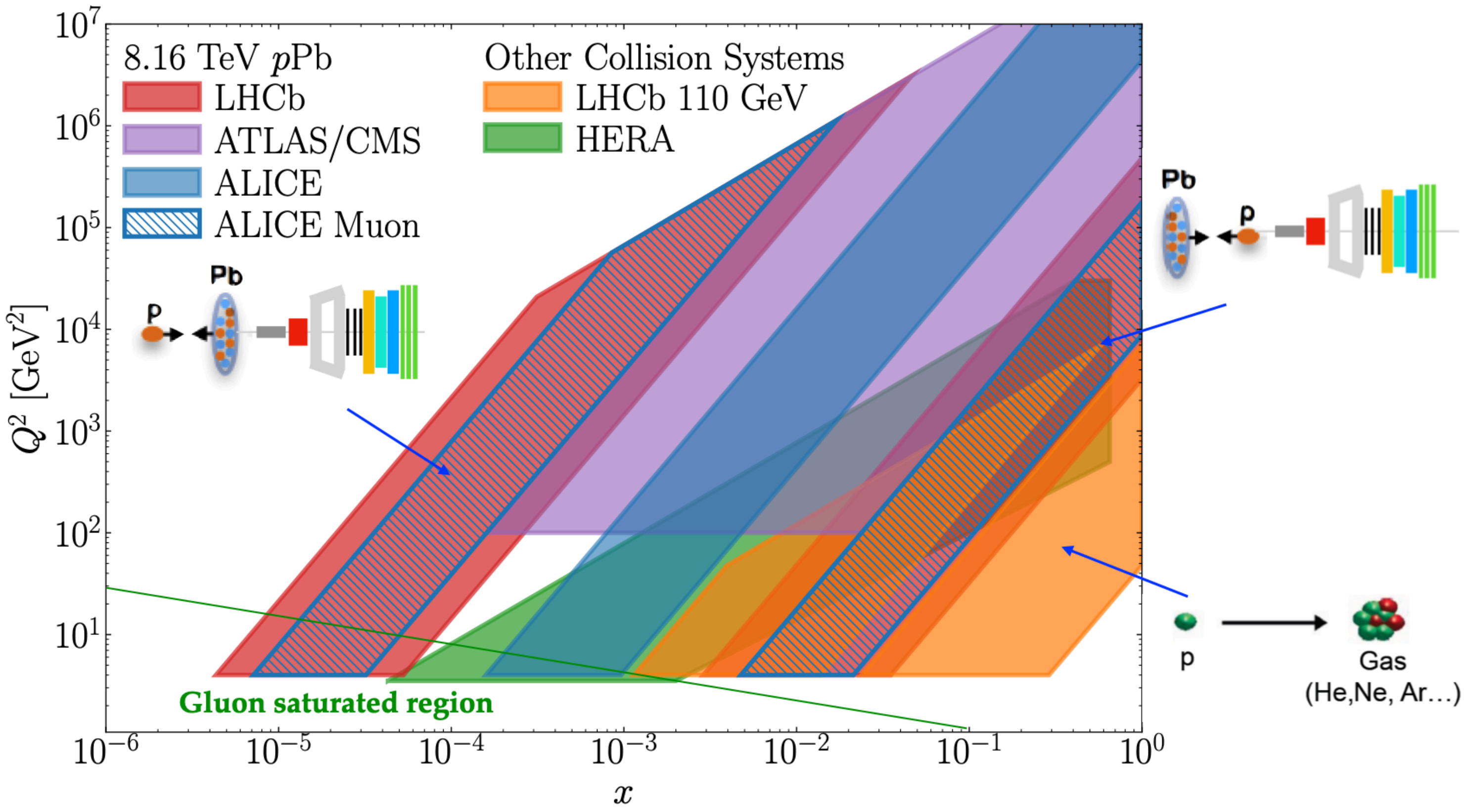
2. **Implications of recent results for heavy ion physics:** quarkonia and open charm production in *p*A and PbA collision systems

3. **Implications of recent results for astroparticle physics:** $\bar{p}$ production in *p*He collisions

4. **Future prospects for Run 3**

Fixed target kinematics at LHCb

- **Unique access** to high Bjorken x
  - Probe nuclear anti-shadowing at $x \sim 0.02 - 0.3$
  - Complementary phase space to LHC collider experiments
- **Variety** of nuclear targets
  - Constrain nuclear PDFs
  - Study nuclear absorption (vary path length by varying A)



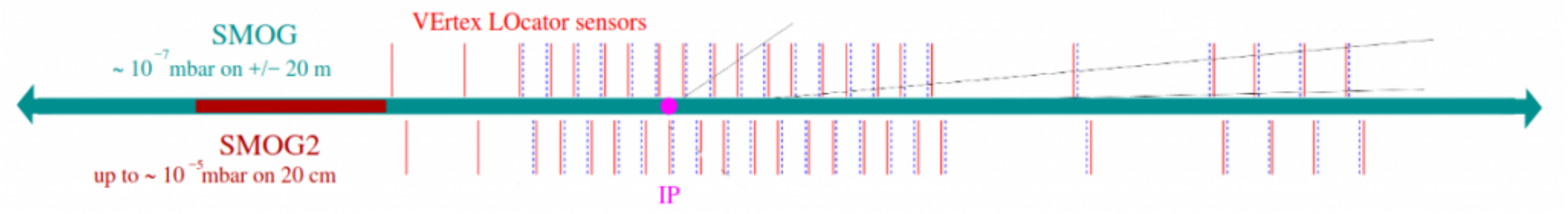
- **Unexplored center of mass energy** of $\sqrt{s}$ = 41 - 115 GeV

$\sqrt{s}$ **(incident p or A beams)**

2.42 - 7.7 GeV	5.1 - 29.1 GeV	41-115 GeV	200 GeV	5 TeV
RHIC and GSI fixed-target	NA50, NA61 (SPS)	LHC fixed-target	RHIC AA collisions	LHC PbPb collisions

- **LHCb is the only LHC experiment able to operate in a fixed-target mode**
  - Access to rapidity in the center-of-mass system $-2.5 \lesssim y^* < 0$

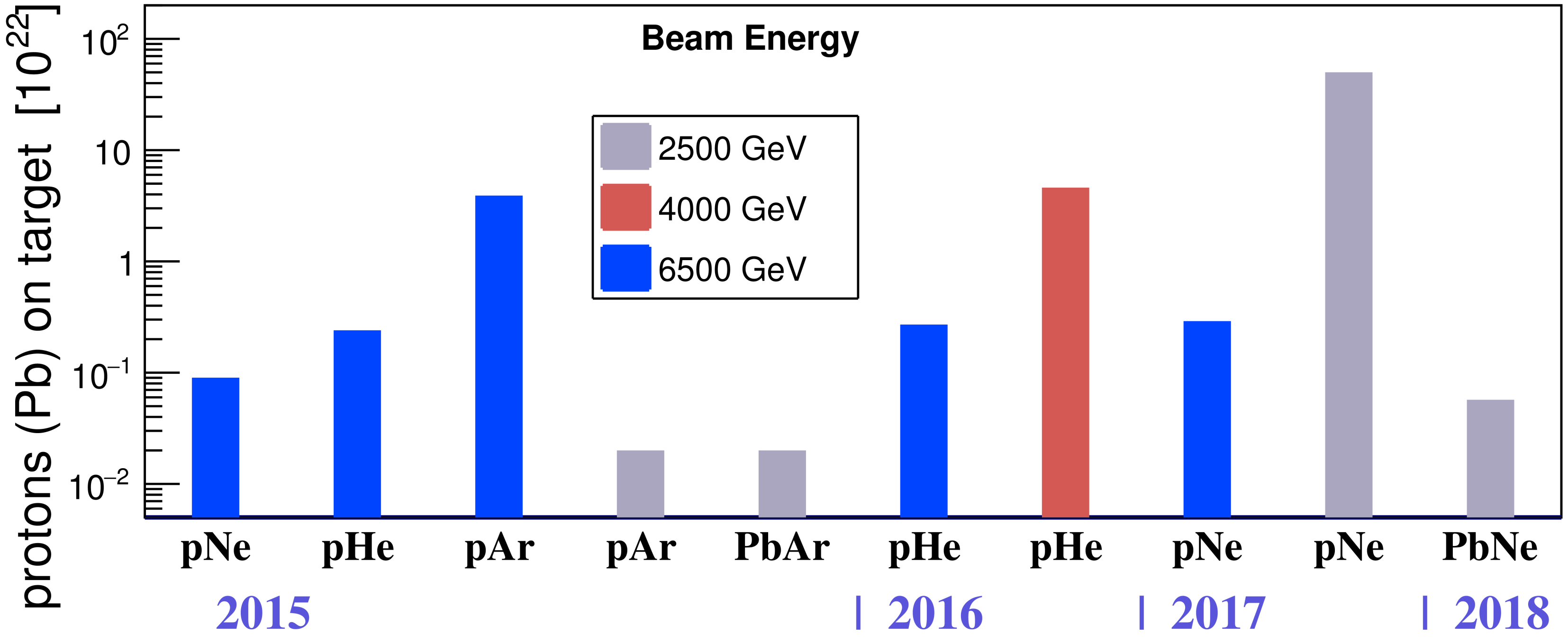
SMOG: System for Measuring Overlap with Gas



- Noble gases (Ar, He, Ne) injected near the LHCb interaction point (IP) with a pressure of ~ 10^{-7} mbar
- Luminosity of ~6×10^{29} cm^{-2} s^{-1}

• Several *p*A and PbA data samples collected in LHC Run 2:

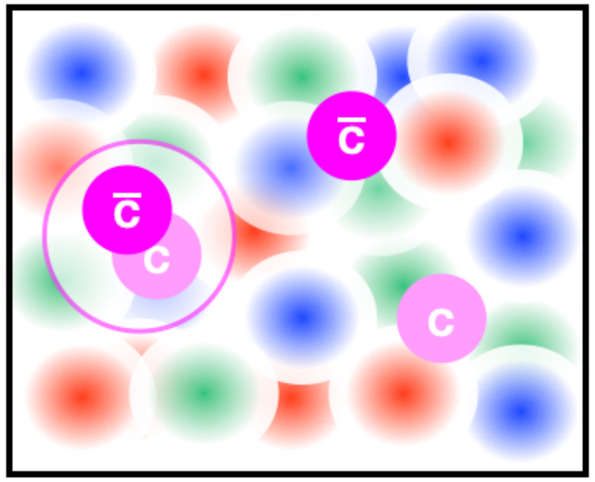
SMOG Run 2 data samples

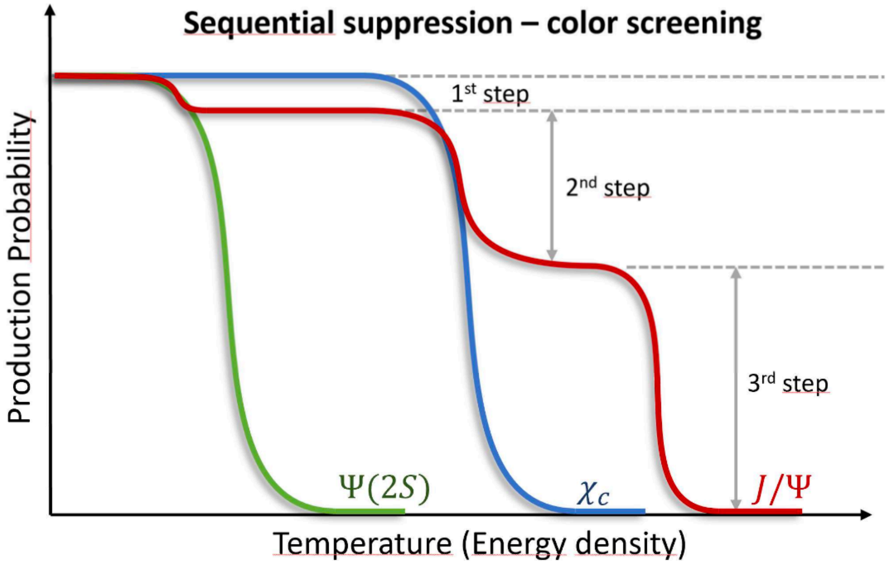


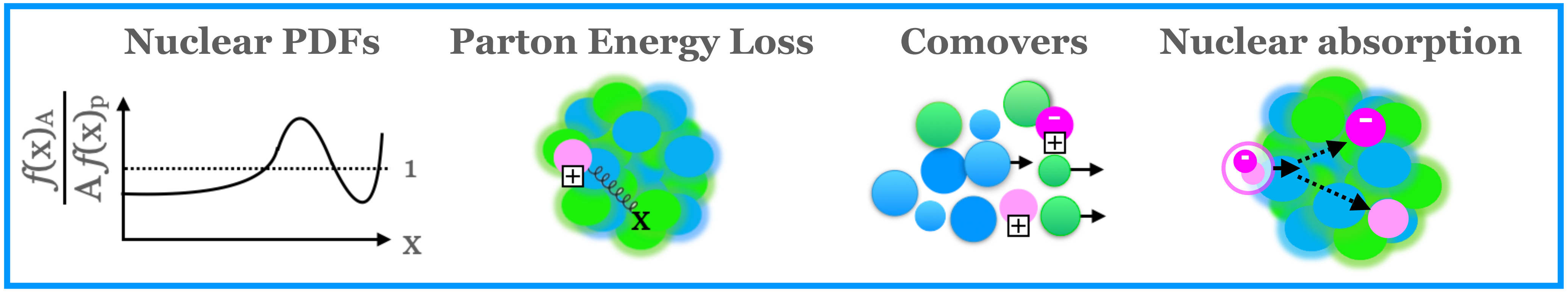
LHCb-PUB-2018-015

Towards a complete picture of quarkonia formation and dissociation in nuclear matter

- Quarkonia "melting", or dissociation due to color charge screening, is a predicted signature of QGP formation
- A definitive observation of melting would be achieved by measuring the predicted "sequential suppression mechanism" **fully corrected for cold nuclear matter effects**







Nuclear PDFs **Parton Energy Loss** **Comovers** **Nuclear absorption**

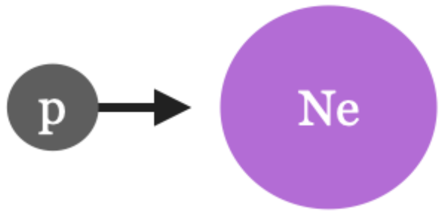
- A comprehensive understanding of CNM effects requires measuring charmonia production in a variety of nuclear systems and kinematic phase space

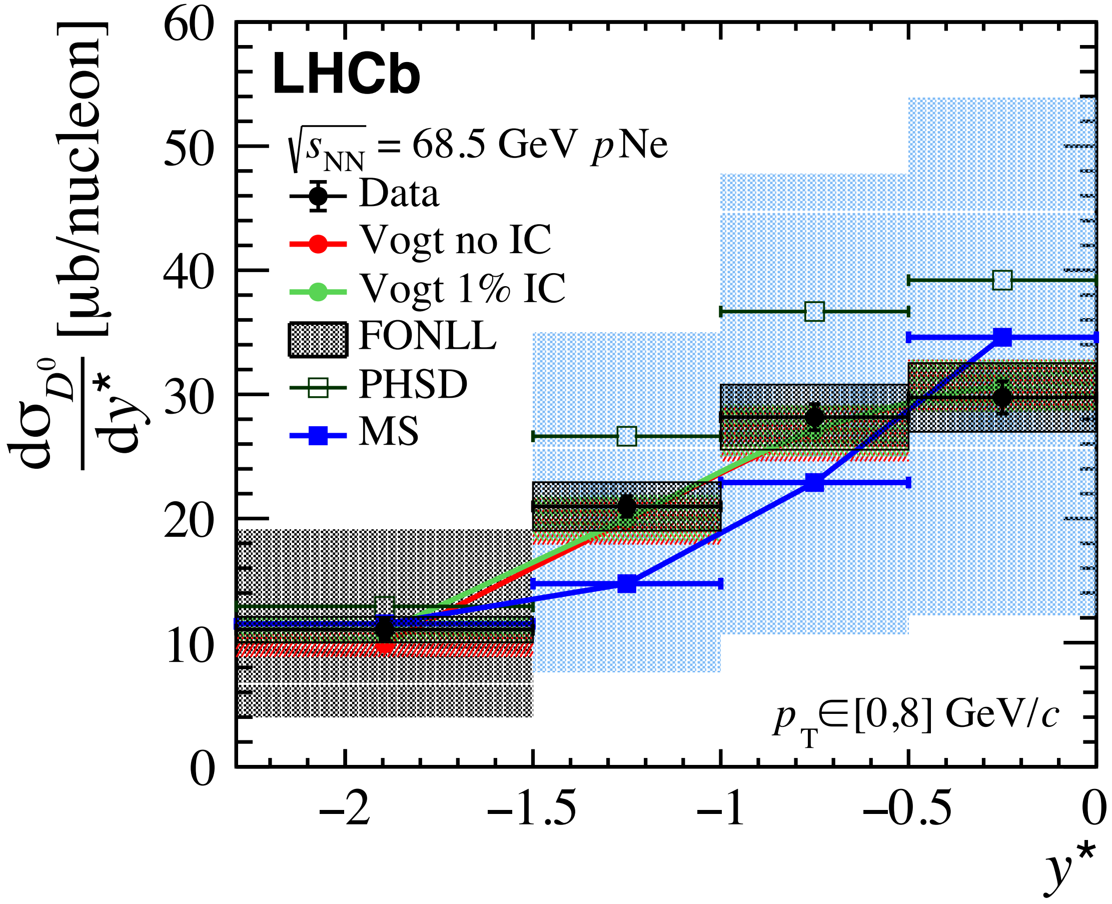
Charm measurements with SMOG

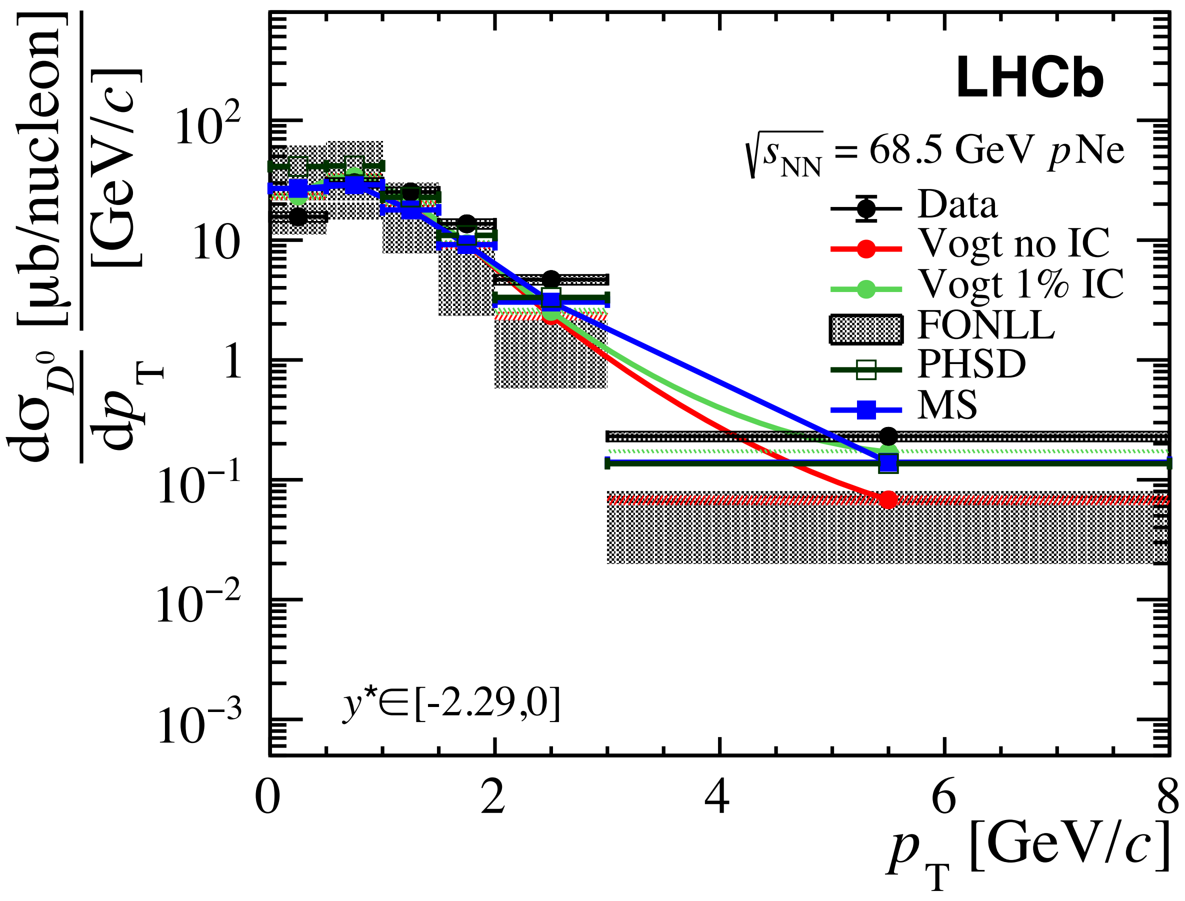
System	$\sqrt{s_{NN}}$	**Measurement**	**Publication**
p → He	86.6 GeV	• J/ψ and D^0 total and differential cross sections in y^* and p_T	PRL 122 (2019) 132002
p → Ne	68.5 GeV	• J/ψ and ψ(2S) cross sections and production ratio • D^0 cross section and asymmetry	EPJC 83 (2023) 625 EPJC 83 (2023) 541
p → Ar	110.4 GeV	• J/ψ and D^0 differential distributions in y^* and p_T	PRL 122 (2019) 132002
Pb → Ne	68.5 GeV	• J/ψ and D^0 cross section ratio	EPJC 83 (2023) 658

first fixed-target AB measurement at the LHC!

D^0 differential cross sections





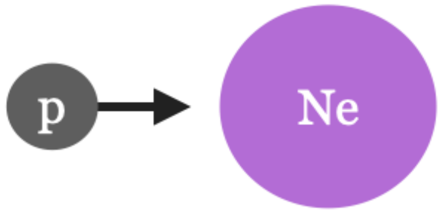


- FONLL and PHSD predictions fail to reproduce the p_T distribution seen in data
- The Vogt 1% IC and the MS predictions both include 1% intrinsic charm contribution in the proton
- MS includes 10% recombination contributions, Vogt includes shadowing effects
- PDF and factorisation scale uncertainties are only included in FONLL calculations

LHCb data: EPJC 83 (2023) 541 **Vogt:** PRC 103 (2021) 035204 **MS:** PLB 835 (2022) 137530

FONLL: PRL 95 (2005) 122001, JHEP 05 (1998) 007 **PHSD:** PRC 96 (2017) 014905

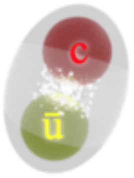
D^0 Production Asymmetry



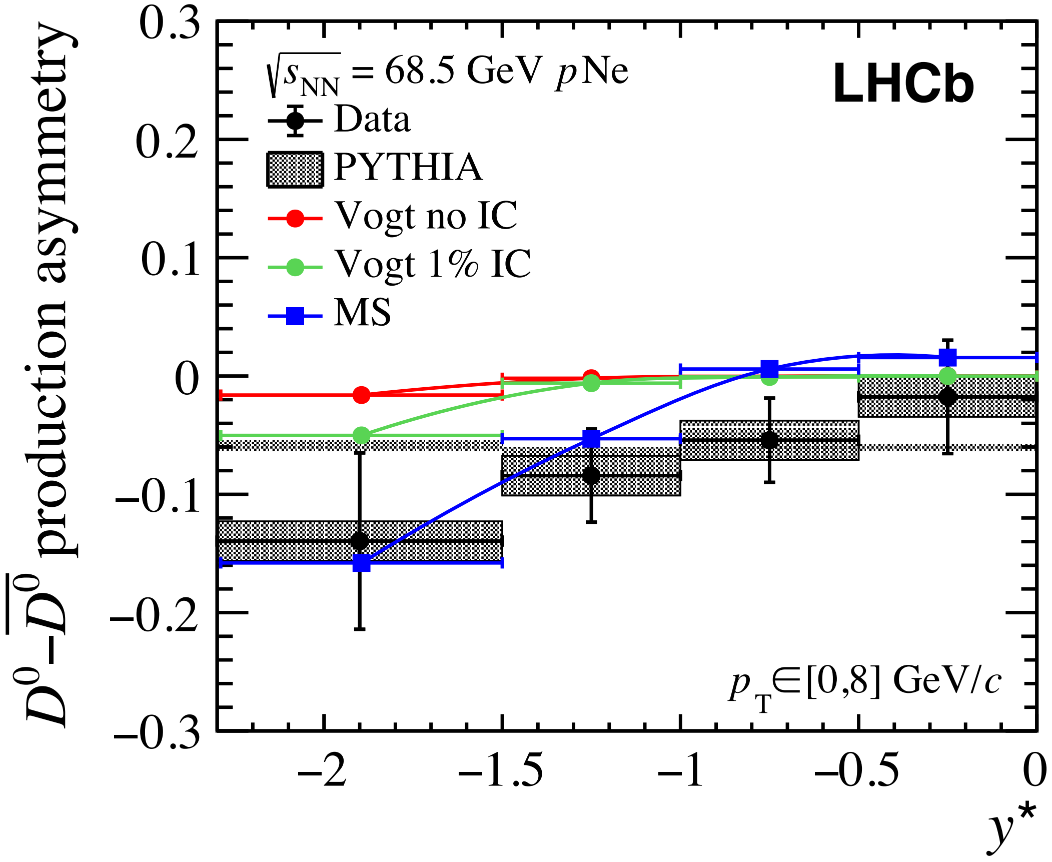
- The production asymmetry probes charm hadronization with a high-*x* valence quark:

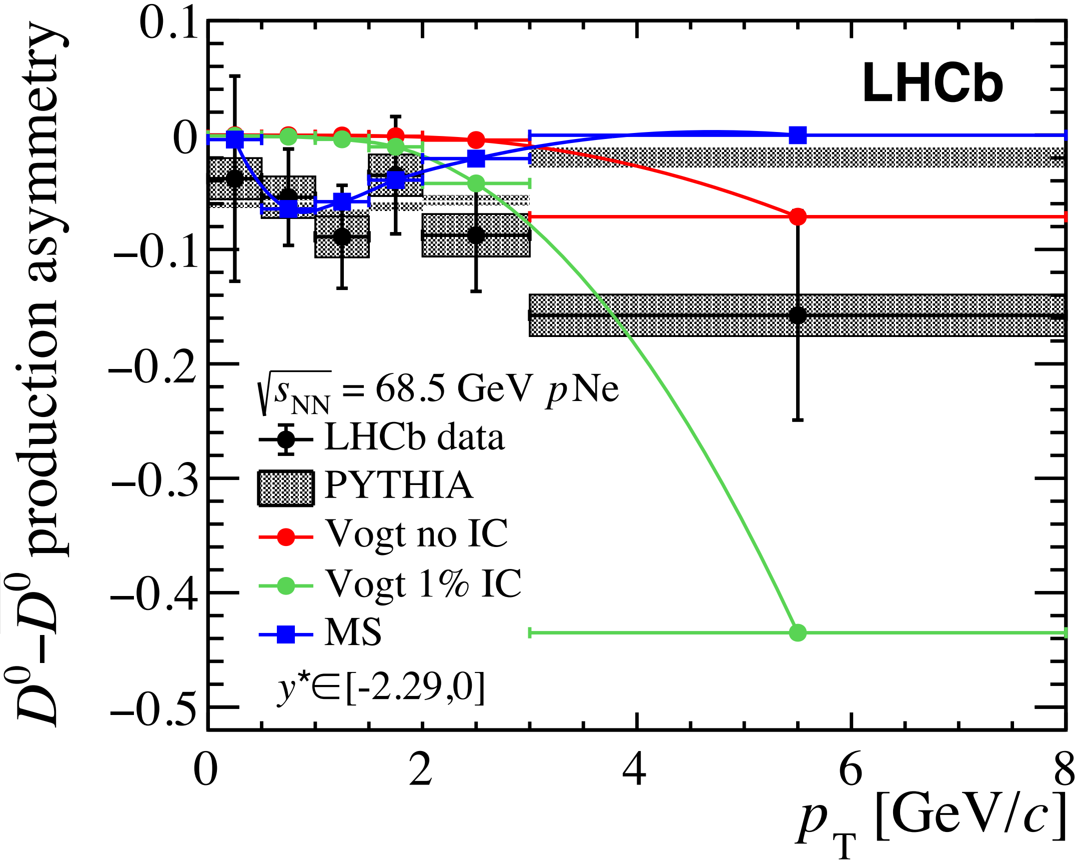
$$\mathcal{A}_{\text{prod}} = \frac{Y_{\text{corr}}(D^0) - Y_{\text{corr}}(\overline{D}^0)}{Y_{\text{corr}}(D^0) + Y_{\text{corr}}(\overline{D}^0)}$$

D^0



$\overline{D^0}$

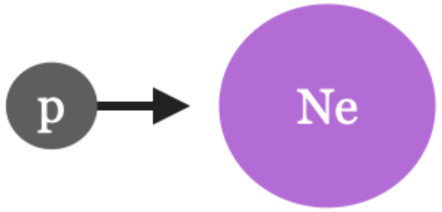




- An asymmetry of ~-15% is observed in the most negative y^* bin
- PYTHIA 8 comparisons do not capture the trends observed in the data
- Vogt predictions represent an upper limit on the asymmetry

LHCb data: EPJC 83 (2023) 541 **Vogt:** PRC 103 (2021) 035204 **MS:** PLB 835 (2022) 137530

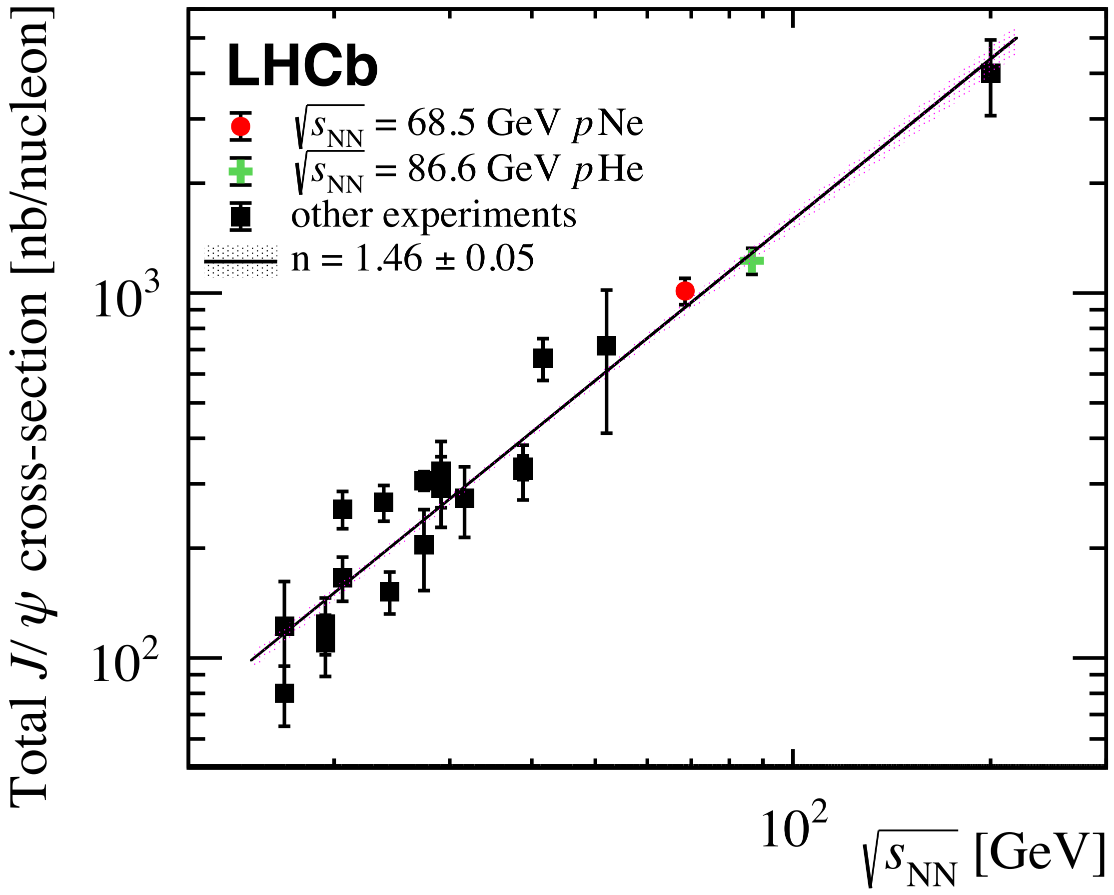
J/ψ cross section measurement at $\sqrt{s_{NN}}$ = 68.5 GeV



- The measured J/ψ cross section in the fiducial measurement region of y^* in [-2.29, 0] was extrapolated to the full backward (negative) hemisphere using PYTHIA 8 and the CT09MCS PDF set:

$$\sigma(pNe \rightarrow J/\psi\ X) = 1013 \pm 16\ (\text{stat.}) + 83\ (\text{sys.})\ \text{nb}^{-1}/\text{nucleon}$$

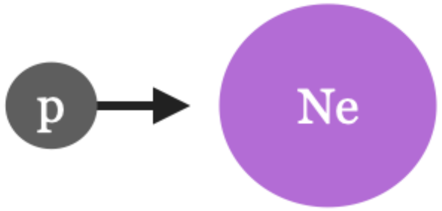
- Comparison to cross section measurements from other experiments shows a power law dependence on the center of mass energy:

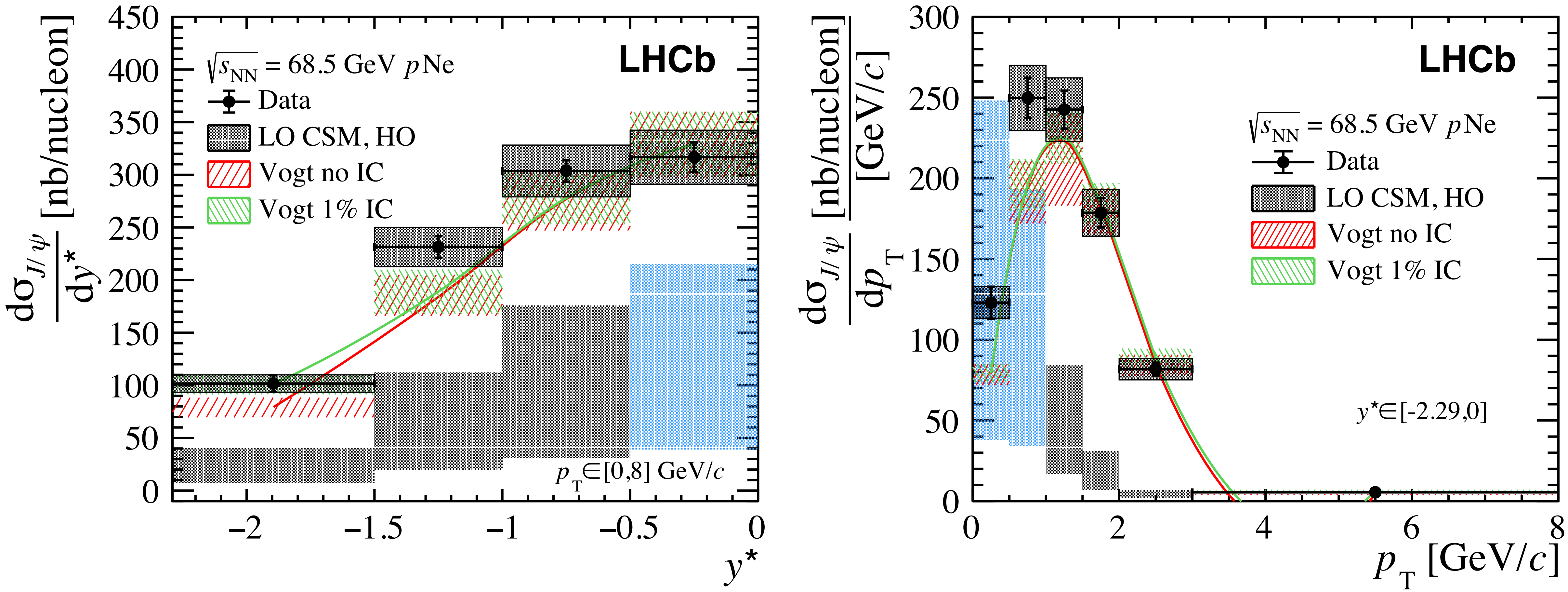


LHCb fixed-target data (pNe, pHe) is filling in gaps in this data!

LHCb data: EPJC 83 (2023) 625

J/ψ differential cross sections

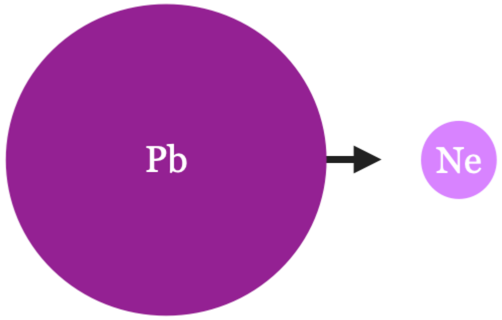




- LO CSM, HO: LO Color Singlet Model (CSM) predictions made using the HELAC-Onia generator with CT14NLO and nCTEQ15 PDF sets
- Vogt predictions use the Color Evaporation Model, EPPS16 nPDFs, and include contributions from nuclear absorption and multiple scattering
- The data does not differentiate between predictions with or without an intrinsic charm component included

LHCb data: EPJC 83 (2023) 625
LO CSM Helac-Onia: CPC 198 (2016) 238, CPC 184 (2013) 2562 **Vogt:** PRC 103 (2021) 035204

From *p*A to PbA collisions



- With **PbNe** collisions, LHCb can begin to probe the energy density region where NA50 observed an anomalous J/ψ suppression

- On average, only 1 $c\bar{c}$ pair is expected to be produced per $\sqrt{s}$ = 68.5 GeV PbNe collision

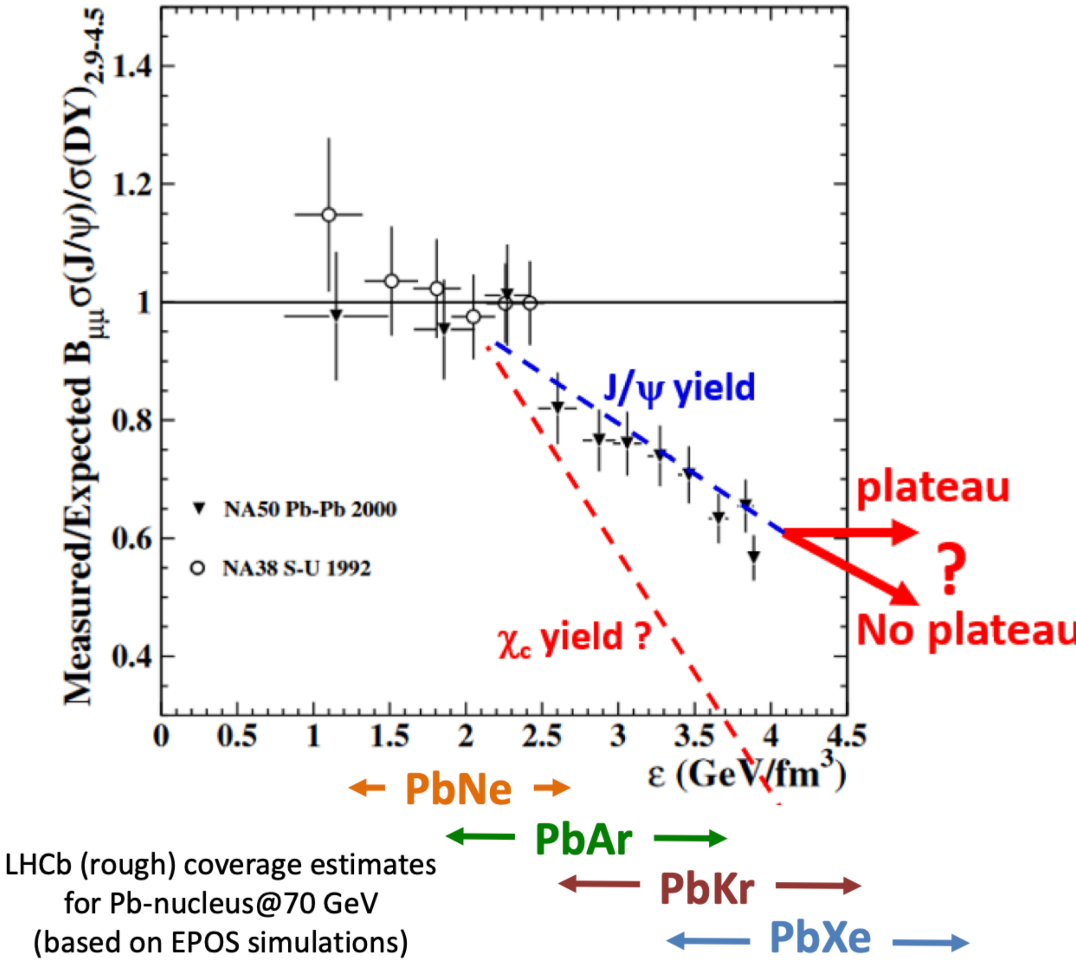
  - $\sigma_{c\bar{c}}^{5.5\ TeV} \approx 10 \times \sigma_{c\bar{c}}^{200\ GeV} \approx 100 \times \sigma_{c\bar{c}}^{70\ GeV} \approx 1000 \times \sigma_{c\bar{c}}^{20\ GeV}$

  - Measurements at RHIC give $N_{c\bar{c}} \approx 13$, giving $N_{c\bar{c}} \approx 1$ at $\sqrt{s}$ = 68.5 GeV

  - With $N_{c\bar{c}} \approx 1$ on average, no significant effects from recombination are expected in PbA fixed-target collisions

- LHCb can also measure *p*Ne collisions at the same energy to measure the cold nuclear matter effects in Ne

- Can measure charmonium suppression **fully controlled for recombination and CNM effects**



LHCb (rough) coverage estimates
for Pb-nucleus@70 GeV
(based on EPOS simulations)

NA50 : EPJC 39, (2005) 335-345

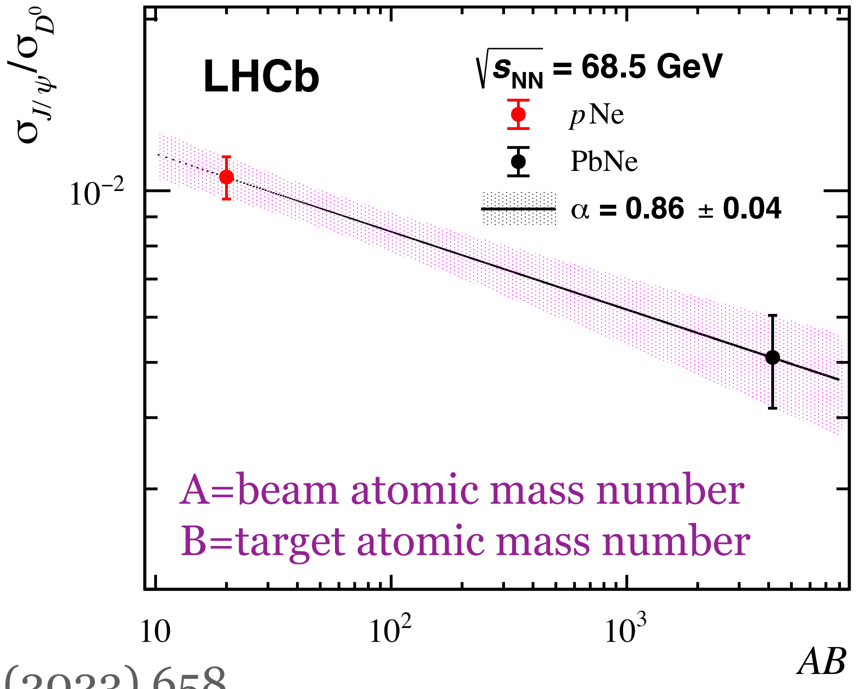
PHENIX: PRL 94, 082301 (2005)

Nuclear effects on hidden vs open charm

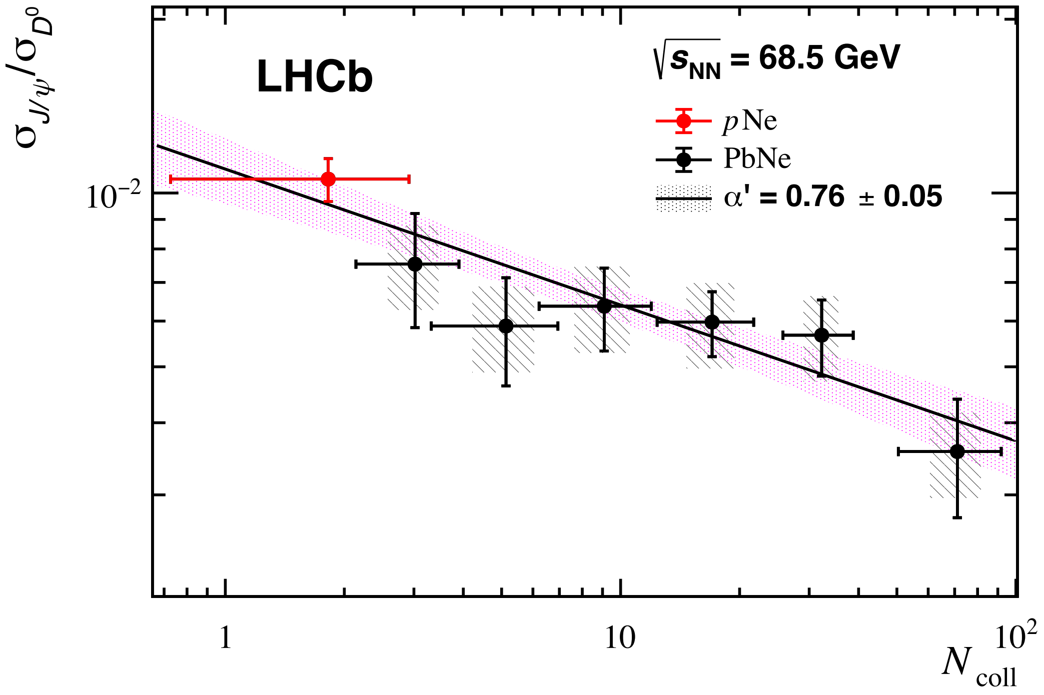
- Assuming: $\sigma_{D^0}^{AB} = \sigma_{D^0}^{pp} \times AB$ and $\sigma_{J/\psi}^{AB} = \sigma_{J/\psi}^{pp} \times AB^{\alpha}$, the cross section ratio is:

$$\frac{\sigma_{J/\psi}^{AB}}{\sigma_{D^0}^{AB}} = \frac{\sigma_{J/\psi}^{pp}}{\sigma_{D^0}^{pp}} \times AB^{\alpha-1} = C \times AB^{\alpha-1}$$

- Same functional form for the ratio as a function of the number of collisions (N_{coll})
- $\alpha < 1$: indicates that J/ψ mesons experience additional nuclear effects than D^0 mesons
- Within the current precision, a linear trend is observed between *p*Ne and central PbNe events and no conclusive evidence of anomalous J/ψ suppression or formation of a hot deconfined medium is observed



A=beam atomic mass number
B=target atomic mass number



PbNe: EPJC 83 (2023) 658
***p*Ne:** EPJC 83 (2023) 625

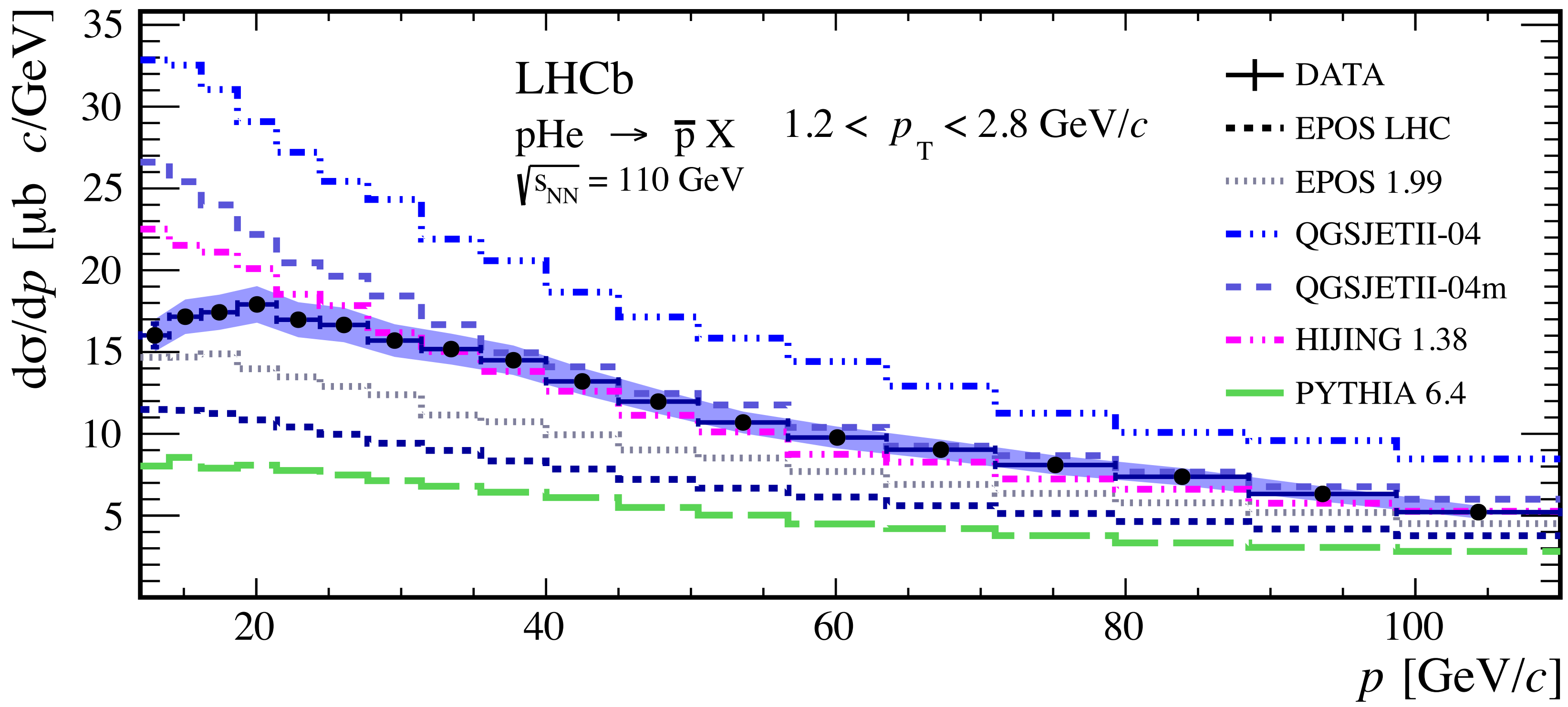
Towards an improved understanding of cosmic ray interactions in the interstellar medium

p → He

- The antimatter fraction in cosmic rays is predicted to be a sensitive probe of dark matter, but the relevant antimatter production cross sections suffer from large uncertainties

- Relevant cross-sections include anti-particle production in *p*He collisions at energies of $\sqrt{s_{NN}}$ ~ 100 GeV - exactly what LHCb can do with SMOG data!

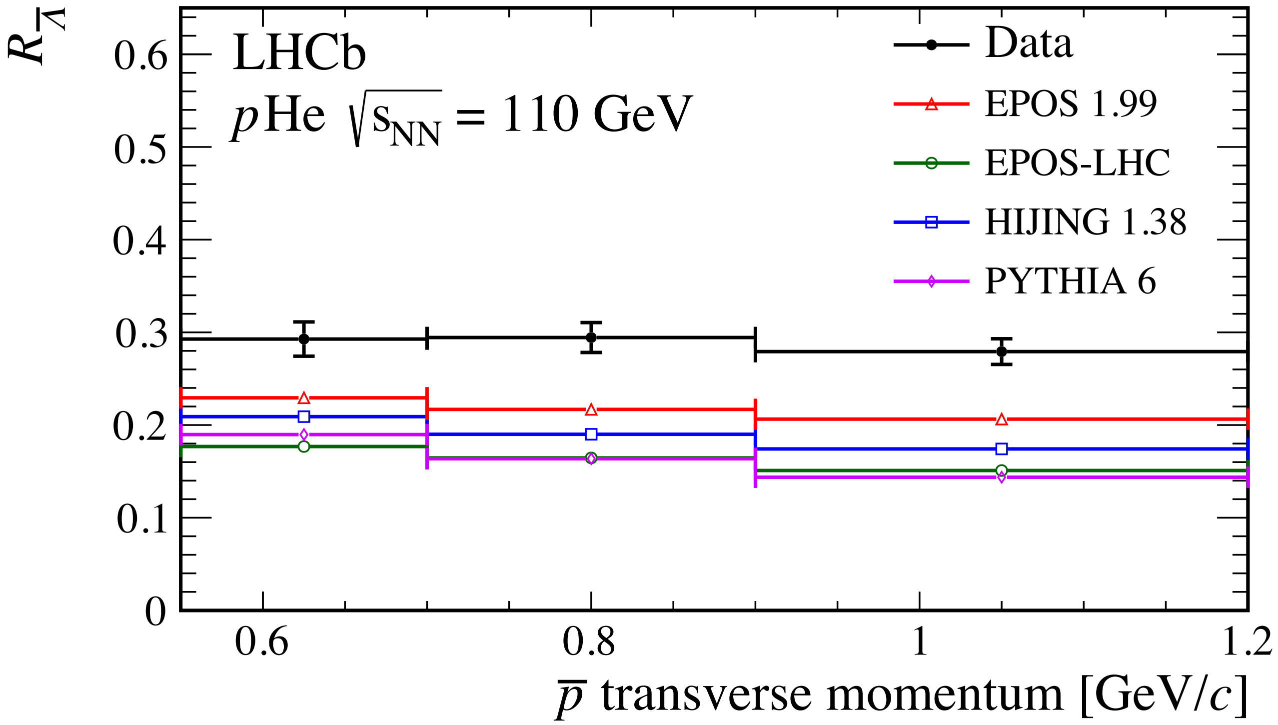
- First LHCb measurement in this area was prompt $\bar{p}$ production in *p*He collisions at $\sqrt{s_{NN}}$ = 110 GeV, which provided strong constraints on models

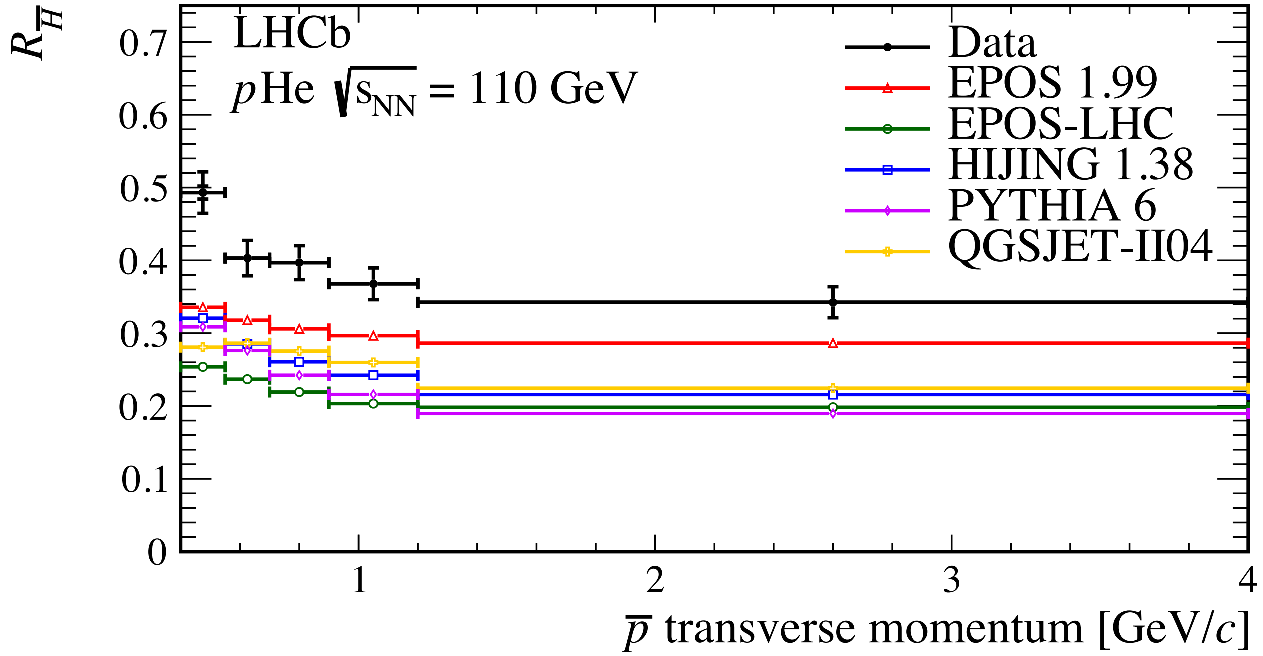


LHCb data provided strong constraints on models and **led to an improved modelling of the secondary $\bar{p}$ cosmic flux**

PRL 121 (2018) 222001

Measurement of $\overline{p}$ production from antihyperon decays in pHe collisions





EPJC 83 (2023) 543

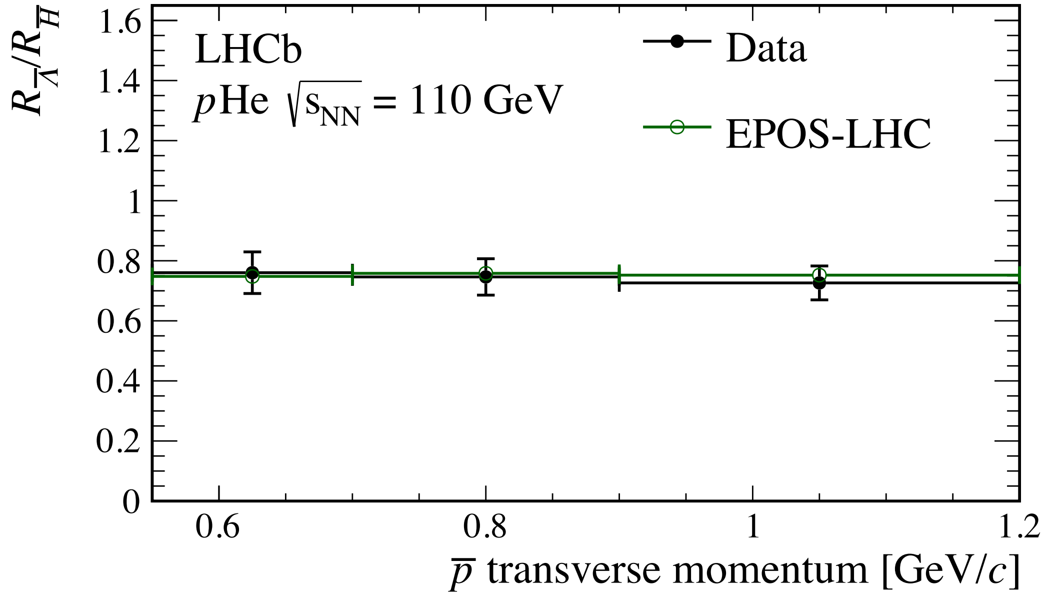
- LHCb recently measured the ratio of the $\overline{p}$ cross section from antihyperon ($\overline{H}$) decays to the prompt $\overline{p}$ cross section:

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

- Ratio with $\overline{H} = \overline{\Lambda}$ was also measured:

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

- All compared models underpredict the observed ratios $R_{\overline{H}}$ and $R_{\overline{\Lambda}}$



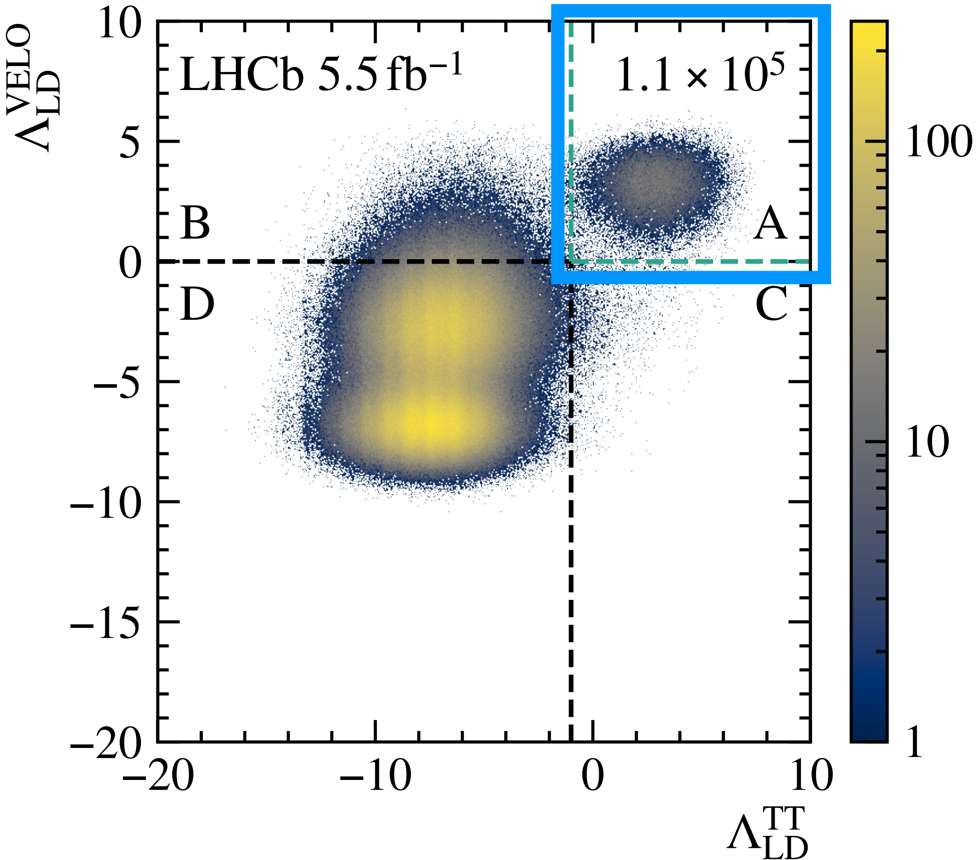
Expanding our astrophysical horizons: Helium and Hypertriton identification at LHCb

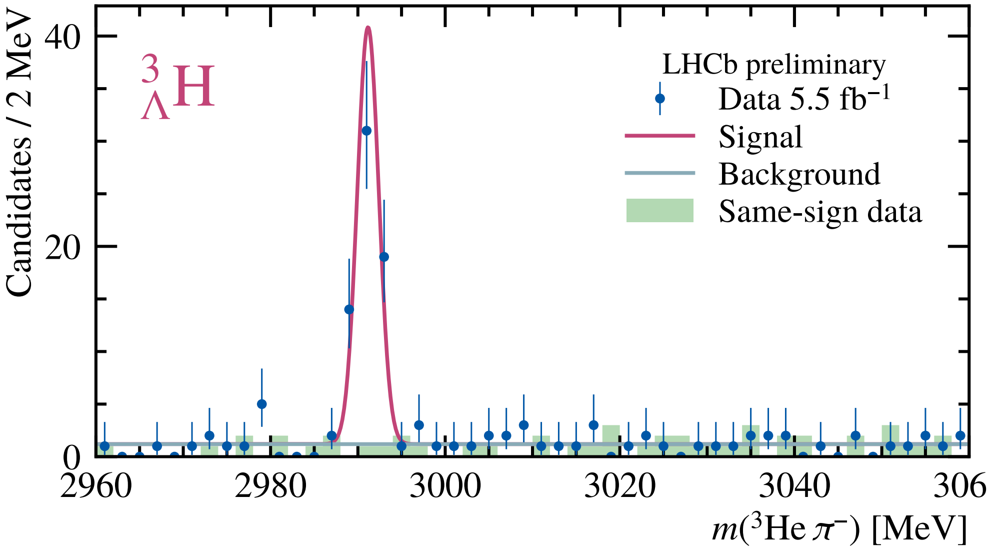
- By performing a dE/dx measurement with the LHCb tracking detectors, LHCb can identify helium nuclei!
- Log-likelihoods were constructed for helium and background hypotheses for each tracking detector:

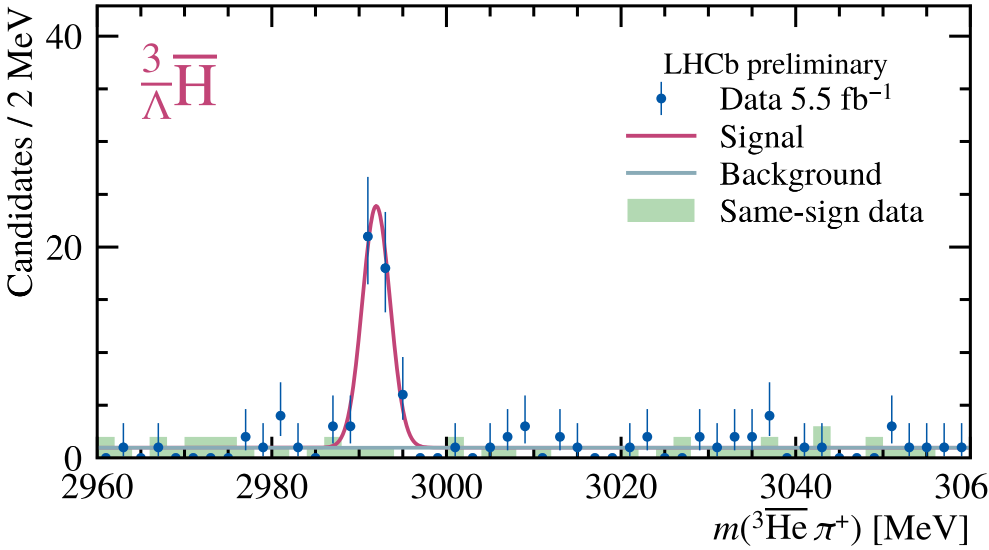
$$\Lambda_{\mathrm{LD}} = \log \frac{\mathcal{L}^{\mathrm{He}}}{\mathcal{L}^{\mathrm{bkg}}} = \log \mathcal{L}^{\mathrm{He}} - \log \mathcal{L}^{\mathrm{bkg}}$$

Many **Helium candidates** were found! (Region A)

- Helium identification enables background-free (anti-)hypertriton measurement



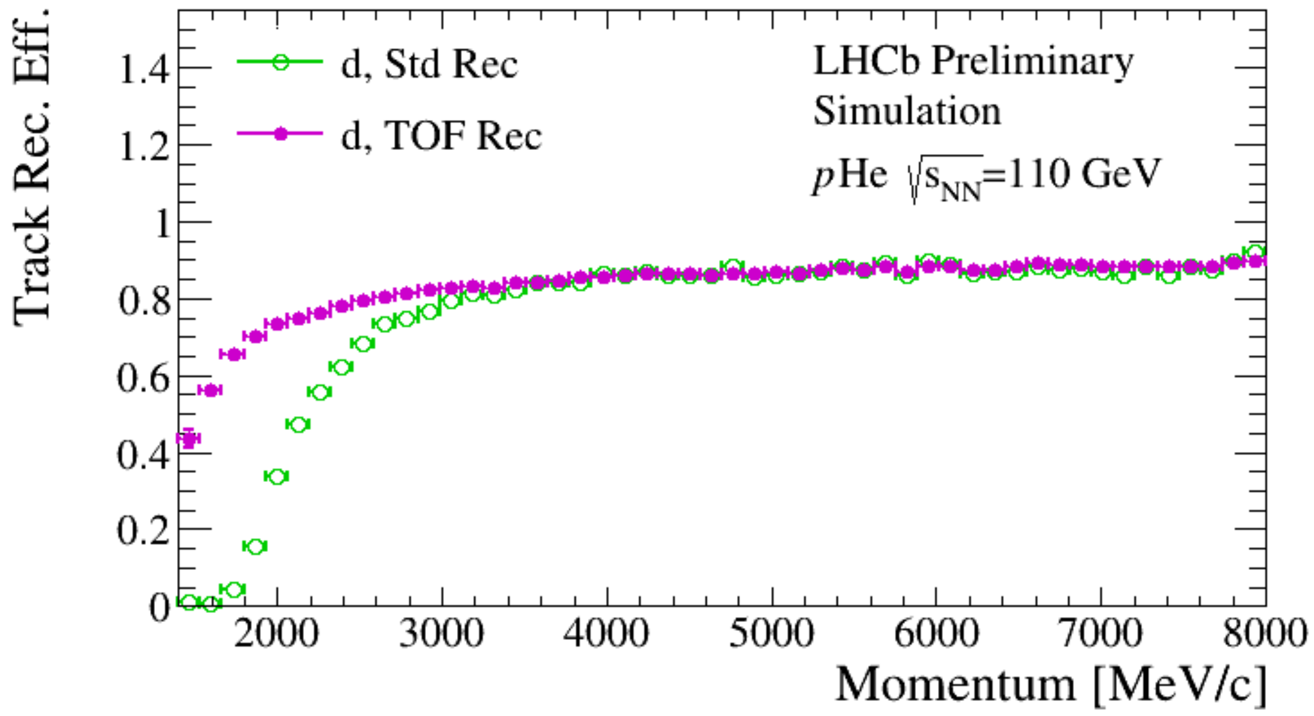


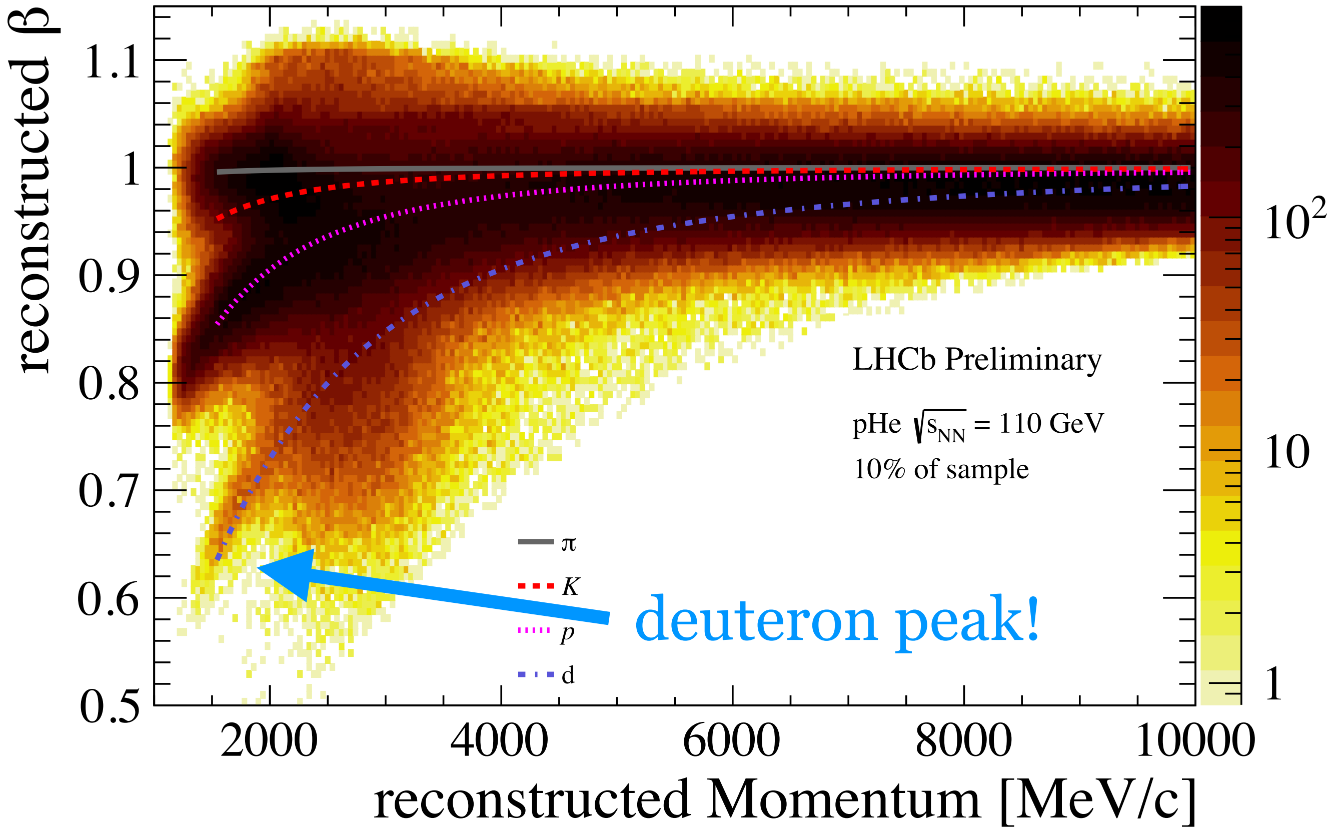


Helium: arXiv:2310.05864 **Hypertriton:** LHCB-CONF-2023-002

Expanding our astrophysical horizons: Deuteron identification at LHCb

- A time-of-flight measurement is performed using the LHCb Outer Tracker to identify **deuterons** in LHCb!
- Required modification of the default LHCb tracking algorithm, which assumes all particles travel at the speed of light (assumption $\beta = v/c = 1$)
- Significant improvement in deuteron reconstruction efficiency with TOF reconstruction with β correction compared to standard LHCb reconstruction ($\beta = 1$)



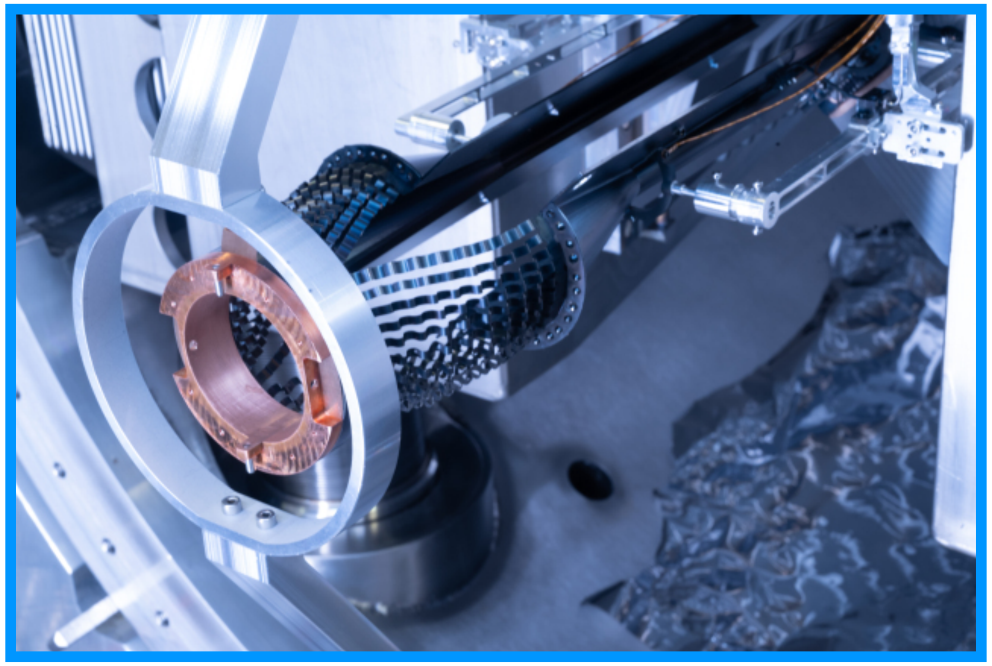


deuteron peak!

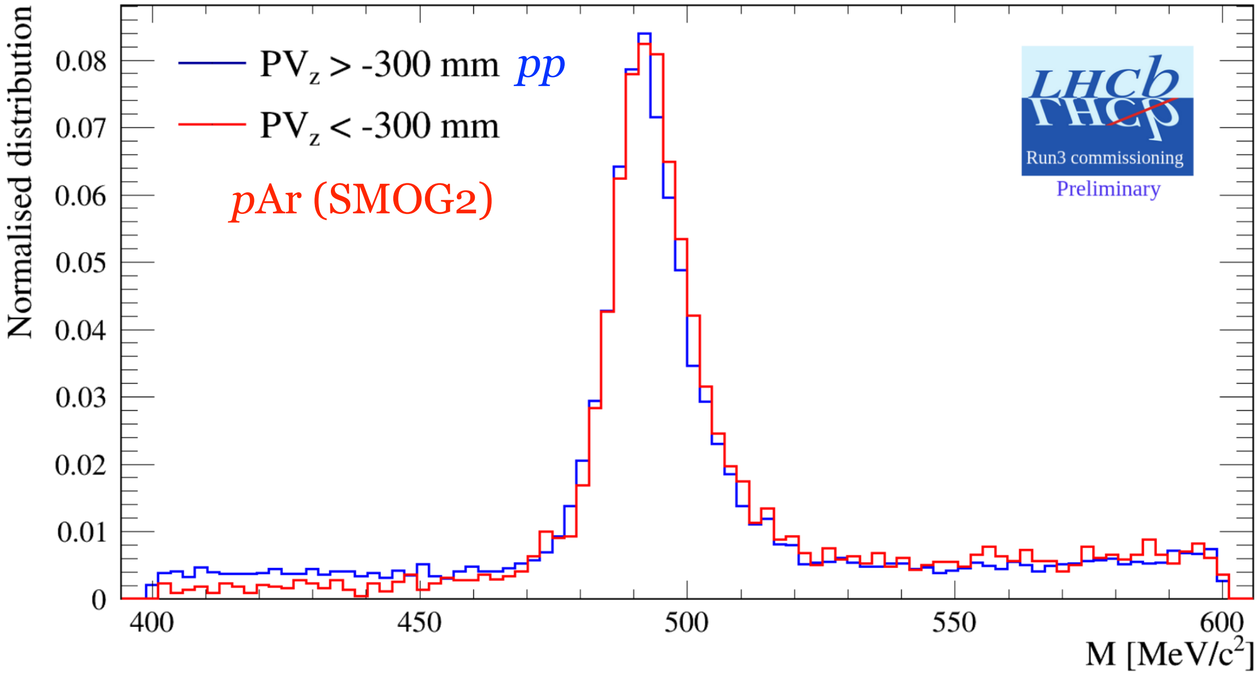
LHCb-FIGURE-2023-017

SMOG2 - the SMOG upgrade for Run 3

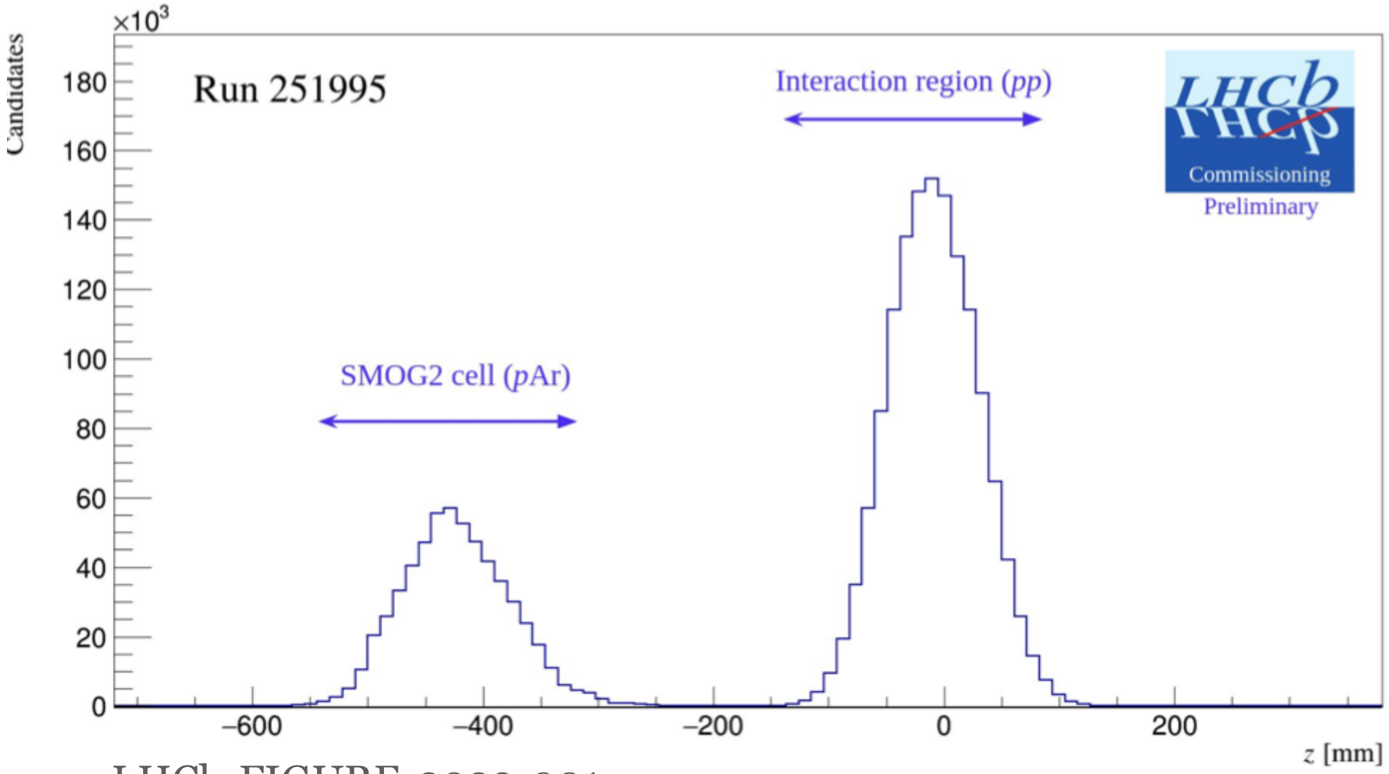
- SMOG2 is a dedicated cell (20cm long, 1cm diameter) for gas injection installed just before the LHCb VELO
- Smaller cell size allows for increased gas densities and therefore higher luminosities with respect to SMOG, with a luminosity uncertainty of 1-2%
- Can run in parallel with collider mode *pp* physics data taking at LHCb
- Equipped with a sophisticated Gas Feed System that allows the injection of more gases: H_2, D_2, Ar, Kr, Xe, He, Ne, N_2, O_2 all possible!



LHCb-PUB-2018-015 LHCb TDR 20

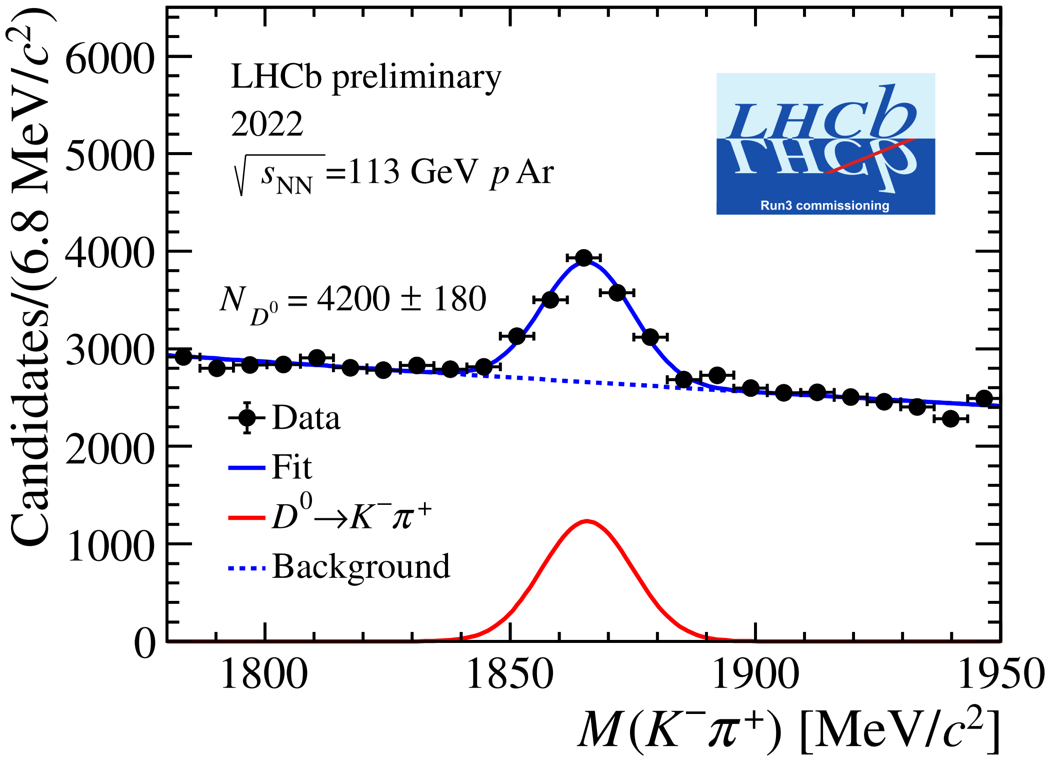


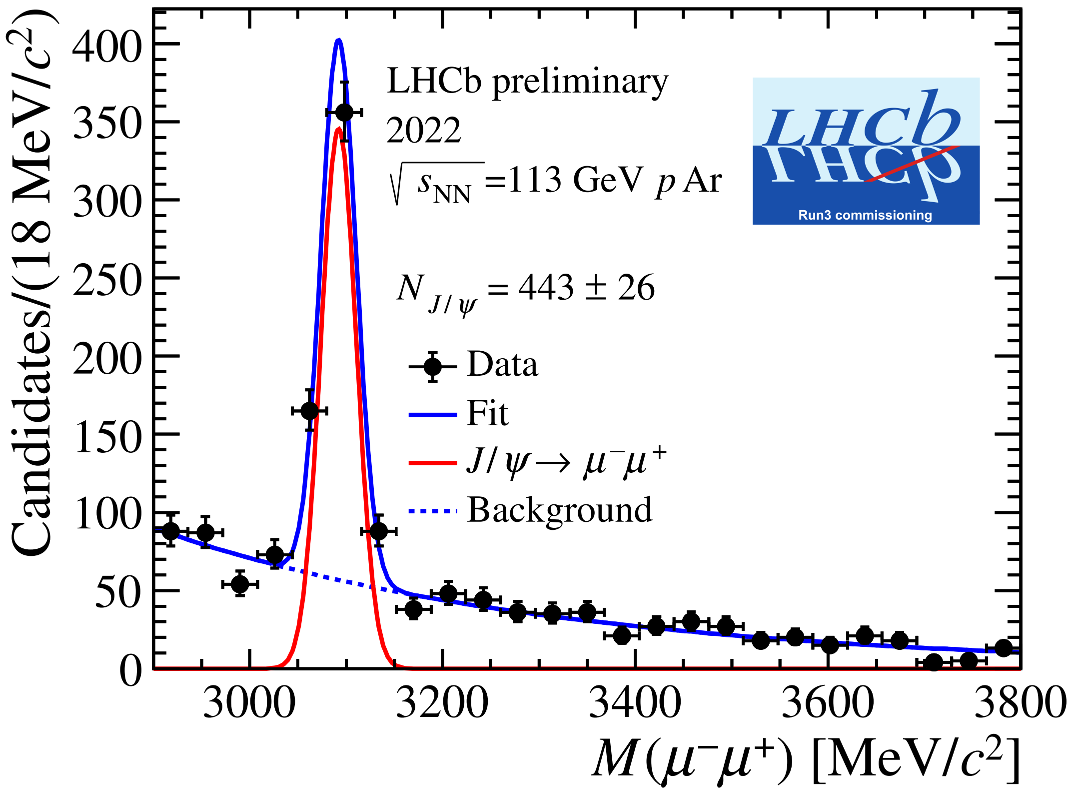
LHCb-FIGURE-2022-002



LHCb-FIGURE-2023-001

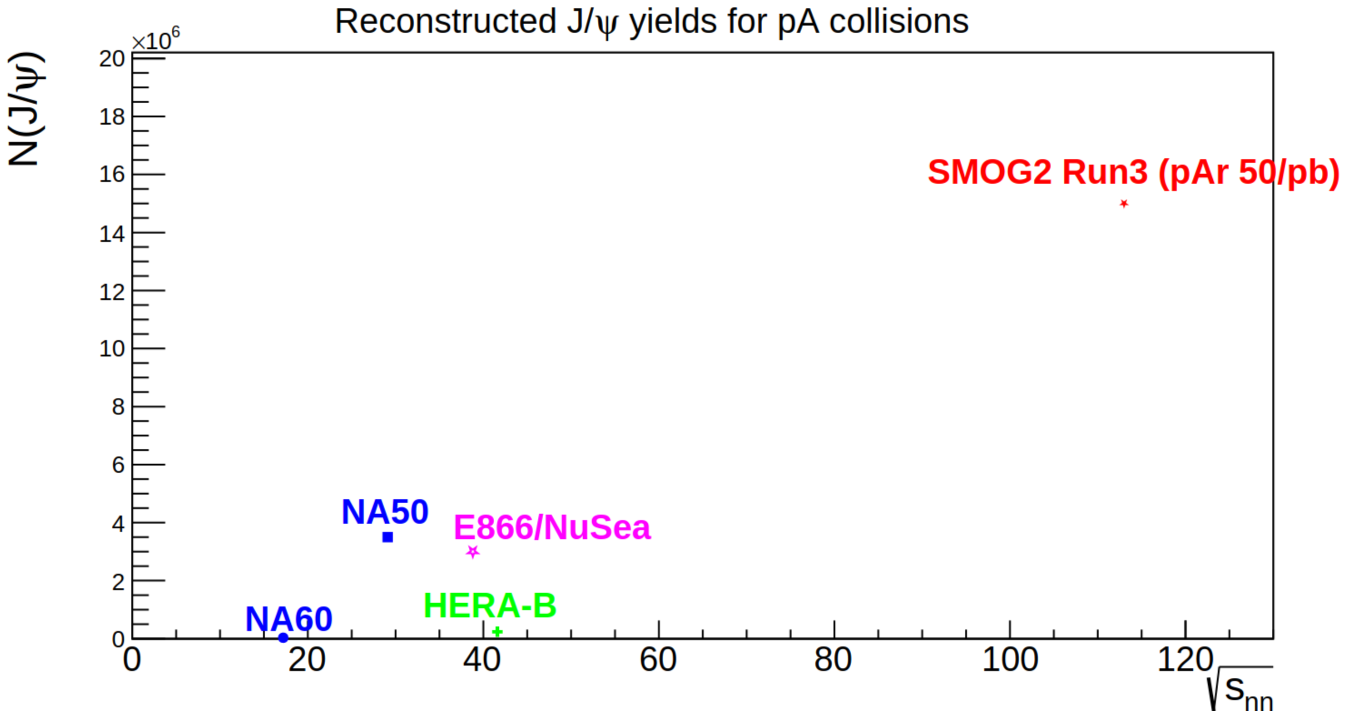
SMOG2 performance in Run 3





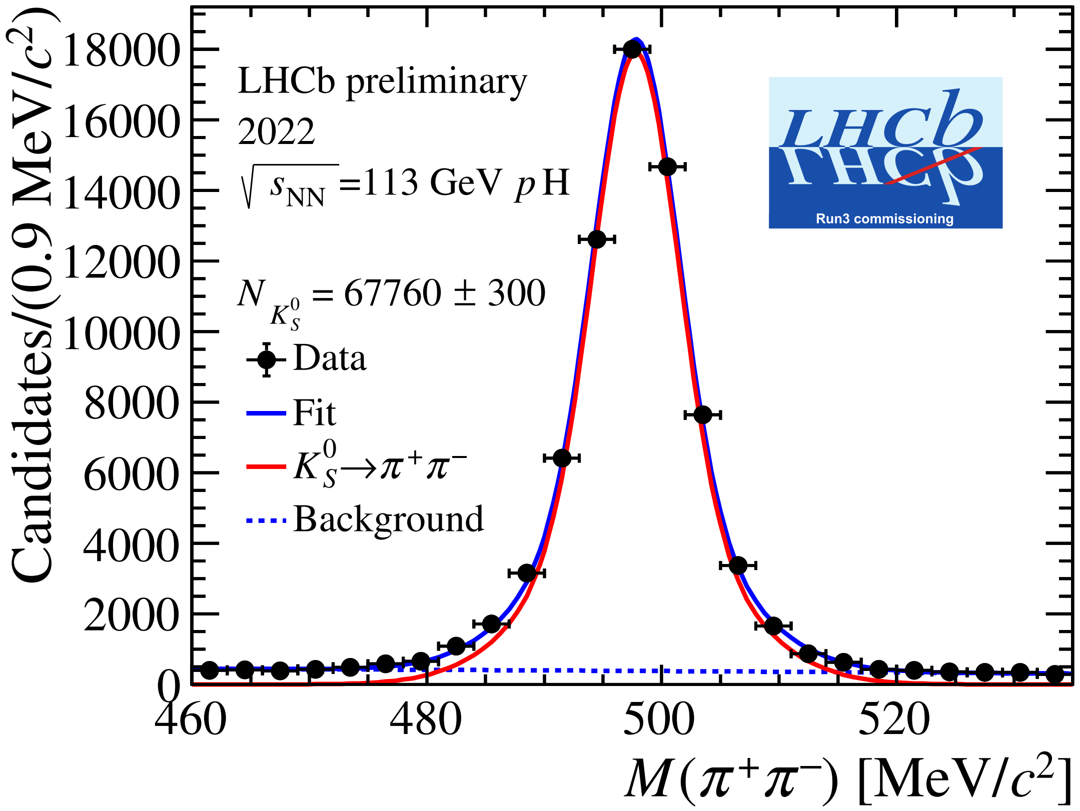
- Excellent D^0 and J/ψ yields from just **18 minutes** of *p*Ar data-taking in 2022!

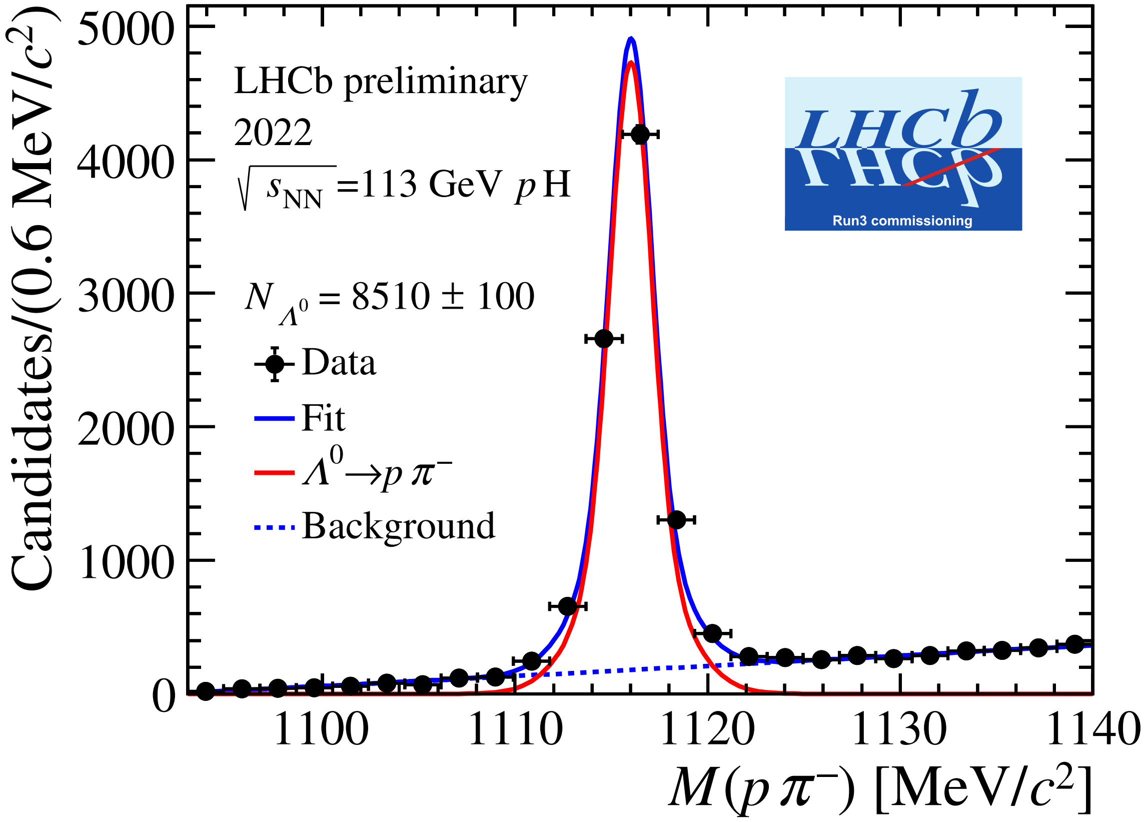
- With 50 pb^{-1} of *p*Ar data, we expect > 15 million J/ψ candidates!



LHCb-FIGURE-2023-008

SMOG2 performance in Run 3 - first hydrogen gas injection!





- K^0_s and Λ yields from **21 minutes** of pH₂ data-taking in 2022

- Successful hydrogen injection is a major milestone for the SMOG2 physics program and will enable many more measurement possibilities!

LHCb-FIGURE-2023-008

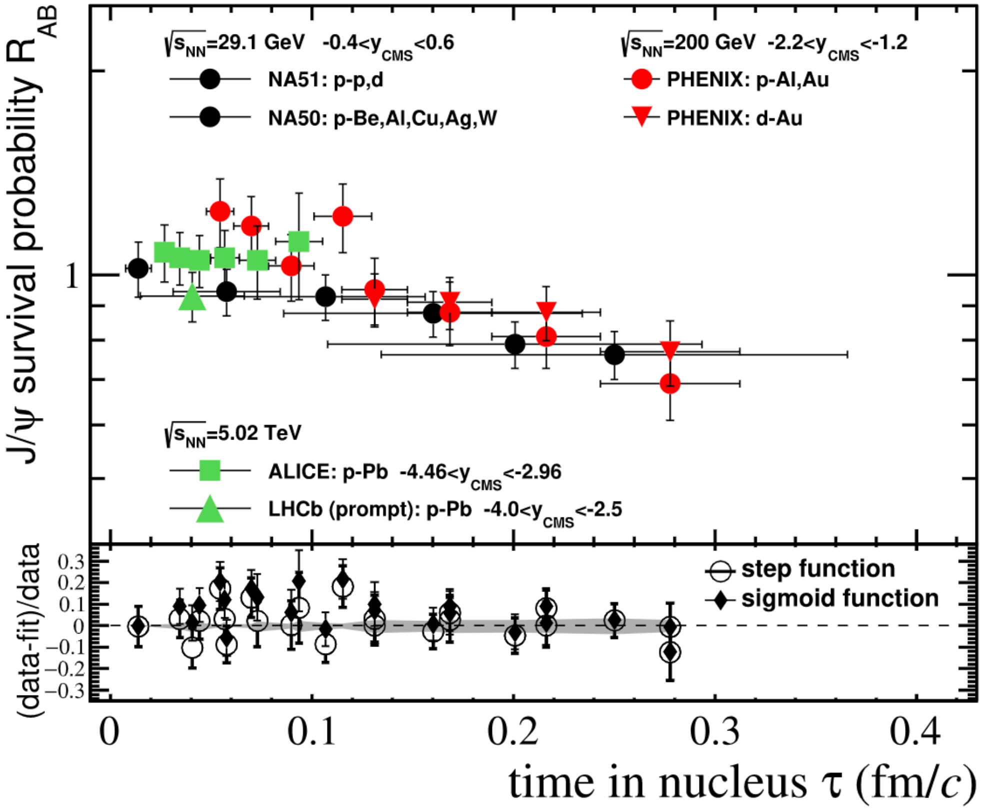
Future prospects: QGP and nuclear structure

- With high statistics from SMOG2, can measure **higher charmonium states** and the **full charmonium suppression pattern**
- **J/ψ production in pH_2 collisions** - necessary baseline for J/ψ R_{AA} measurements
  - Will be able to compare J/ψ production in a nuclear system (pA) to that in pp collisions at the same $\sqrt{s}$ to study nuclear effects on charmonium production
- **Flow in PbA collisions,** following first LHCb flow measurement (LHCb-PAPER-2023-031, in preparation)
  - Of theoretical interest due to sensitivity to nuclear structure
- **Possible determination of $c\bar{c}$ hadronization time**
  - Parameterization of nuclear absorption mechanism proposed by E. Ferreiro, E. Maurice, and F. Fleuret
  - Proper time of $c\bar{c}$ pair of mass m traversing length L in a nucleus:

$$\tau = \frac{t}{\gamma} = \frac{Lm}{p} = \frac{Lm}{\sqrt{p_z^2 + p_T^2}} = \frac{Lm}{\sqrt{m_T^2 \sinh^2 y + p_T^2}}$$

  - More pA data in a variety of nuclear targets needed for hadronization time extraction - possible with SMOG2!

EPJC 82, (2022) 201



Future prospects: cosmic rays and astrophysics

- ***p*H₂, *p*D₂ collisions** open the possibility for many interesting astrophysically motivated measurements
  - $\overline{p}$ production cross section measurements, following what was done for *p*He collisions
- **Production cross section measurements of light nuclei and anti-nuclei**
  - Utilising new Helium and deuteron identification techniques developed in LHCb
  - Measurement of $^{3}\overline{\mathrm{He}}$ from Λ_b decays, strongly constraining for dark matter models

    PRL 126 (2021) 101101
  - Cross section measurements of hypertriton and anti-hypertriton
- **Charm production in *p*Ne, pN₂, and pO₂** and the resulting constraints on the large-x charm PDF are important for constraining models of neutrino production in Ultra-High Energy atmospheric showers

  arXiv: 2212.07865, PRC 108 (2023) 015201, PRD 107 (2023), 034002
- **Projected OO collisions at LHC**
  - In LHCb, we will be able to collect Oxygen-Oxygen collisions at two different center of mass energies simultaneously (fixed-target OO and collider OO), a very unique capability!
  - Some theoretical input for this special data run has already been collected arXiv: 2103.01939

Conclusions

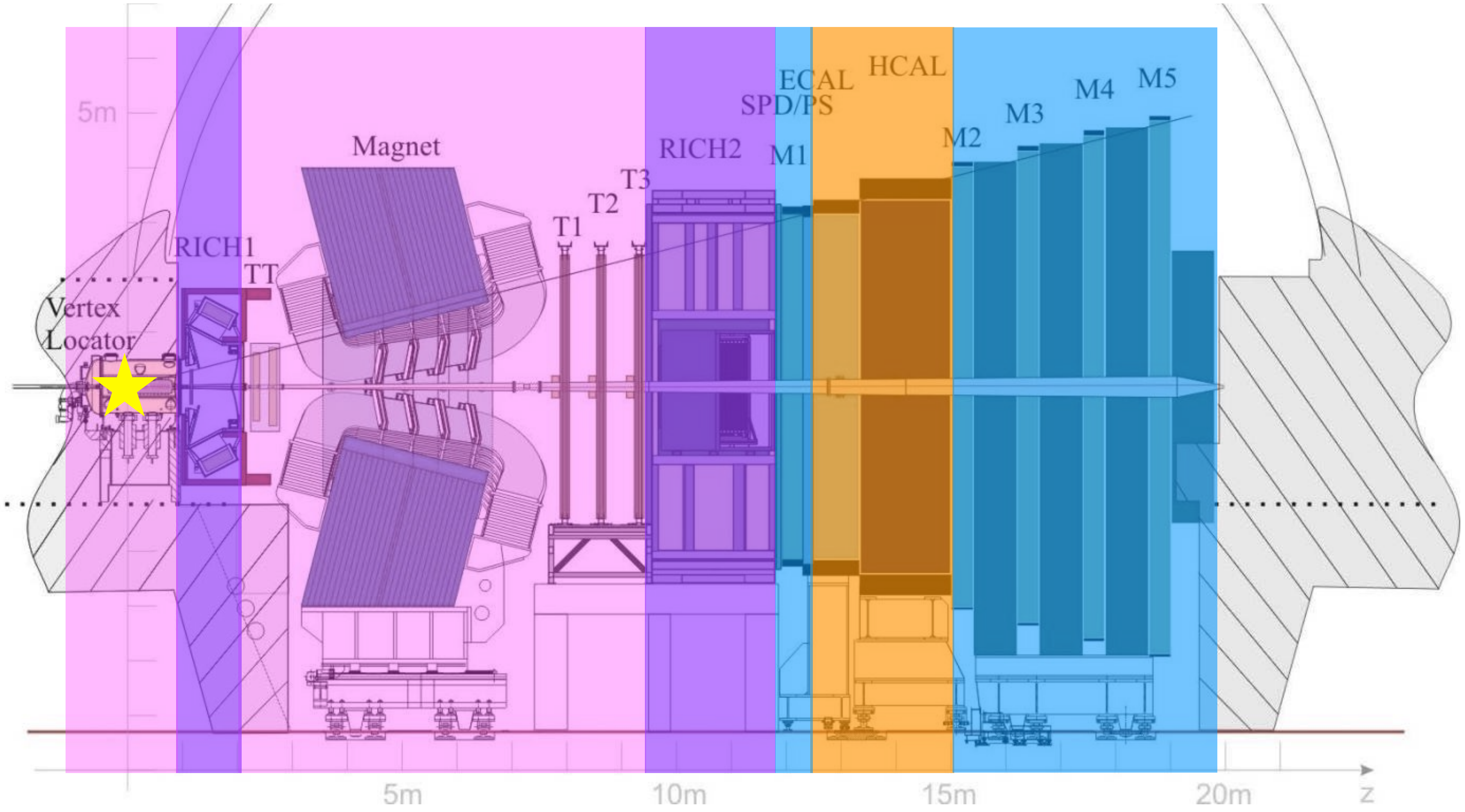
- Fixed target experiments at LHCb provide measurement opportunities in a **wide variety of nuclear systems** and in a **unique region** of phase space
- Measurements of the D^0 and J/ψ production cross sections and the D^0 production asymmetry in pNe collisions have been compared to several theoretical models with different **charm hadronization mechanisms** and **cold nuclear matter** effects
- SMOG measurements of $\overline{p}$ production in pHe provide **strong constraints on cosmic ray models**
- LHCb can now identify **Helium nuclei and deuterons**
- The **first Run 3 data** has been taken with LHCb's fixed target upgrade, SMOG2, and includes excellent signal yields collected in pAr and pH$_2$ collisions
- **Many impactful measurements** are possible with SMOG2 and will have significant impacts in heavy ion physics and astrophysics

Thank you for your attention!

Backup

The Large Hadron Collider beauty (LHCb) Experiment: a collider and fixed-target experiment!

The LHCb Detector: Full **tracking**, **particle identification**, **hadronic and electromagnetic calorimetry** and **muon ID** in $2 < \eta < 5$



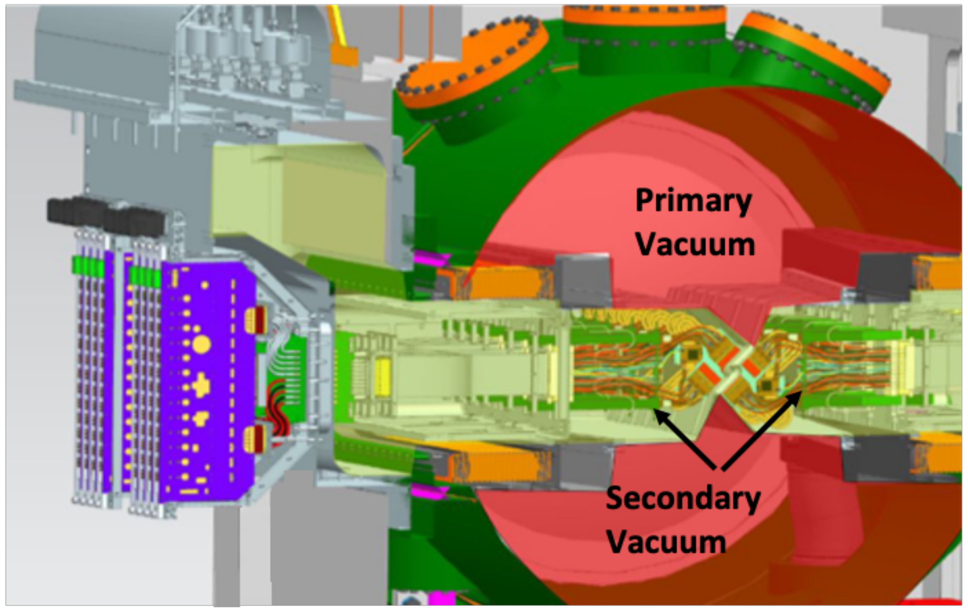
- Fixed-target mode in Run 2 possible by injecting gas into the Vertex Locator with a pressure of ~ 10^{-7} mbar
- One of the circulating proton or Pb beams was used to produce *p*A or PbA collisions

JINST 3, S08005 (2010)
Int. J. Mod. Phys. A 30, 1530022 (2015)

LHCb VELO Vacuum Incident in January 2023

The VELO detector is installed in a secondary vacuum inside the LHC primary vacuum.

The primary and secondary volumes are separated by two thin walled Aluminium boxes, the RF foils



On 10th January 2023, during a VELO warm up in neon, there was a loss of control of the protection system

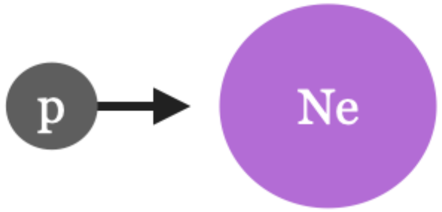
A pressure differential of 200 mbar built up between the two volumes, whereas the foils are designed to withstand 10 mbar only

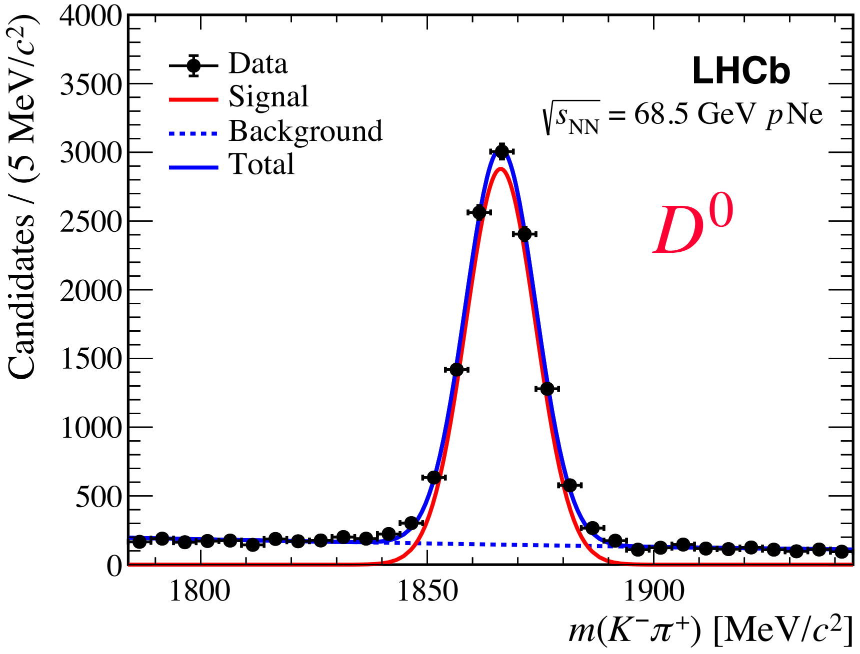
Initial investigations show no damage to the VELO modules; sensors show correct leakage currents, microchannels show no leaks

RF foils have suffered plastic deformation up to 14 mm and have to be replaced. Major intervention, planning under study

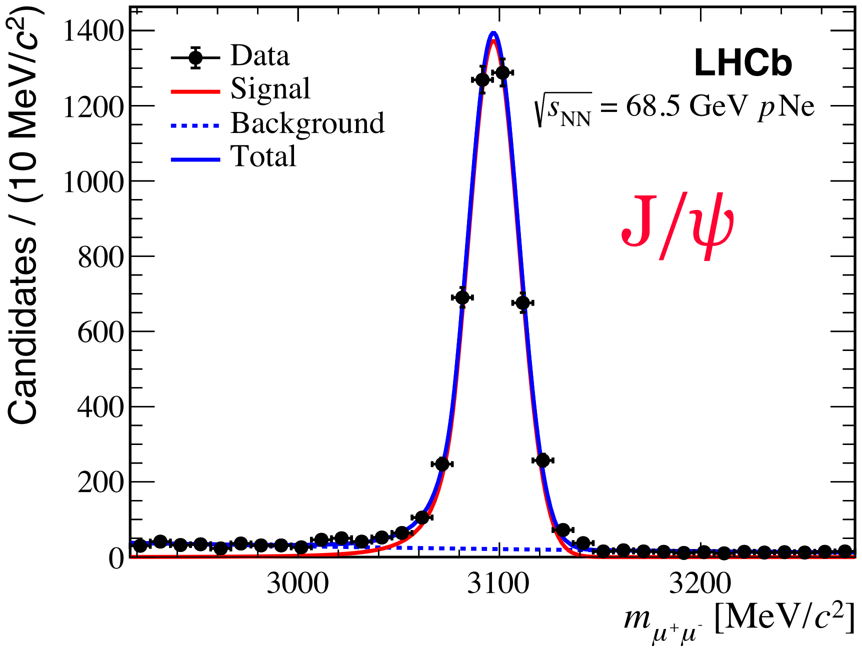
- Replace now (delay), or replace at the end of the year (run in 2023 with VELO partially open)
- Physics programme of 2023 is significantly affected, commissioning of Upgrade I systems can proceed as planned

Heavy flavor signal yields in pNe collisions

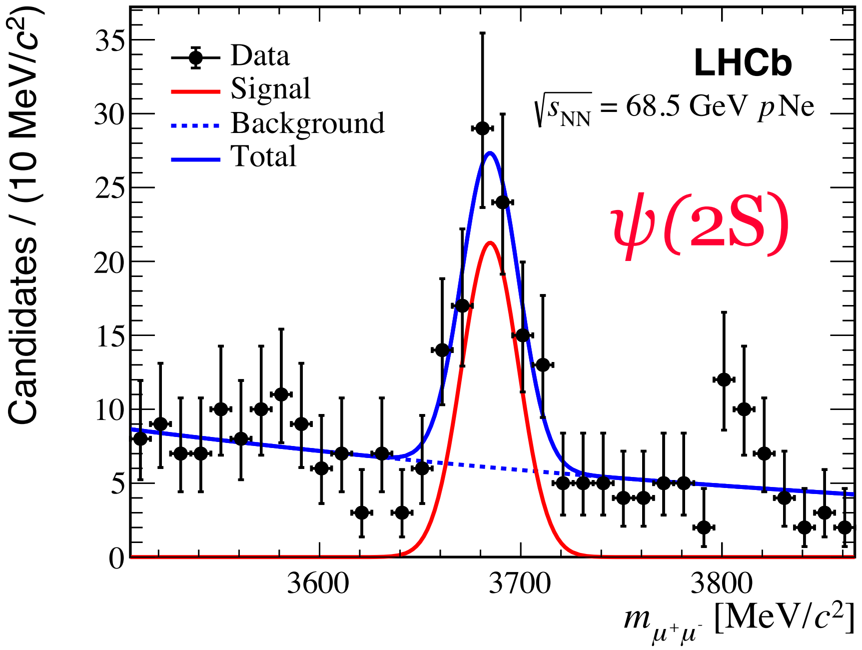




24, 408 D^0



4542 J/ψ



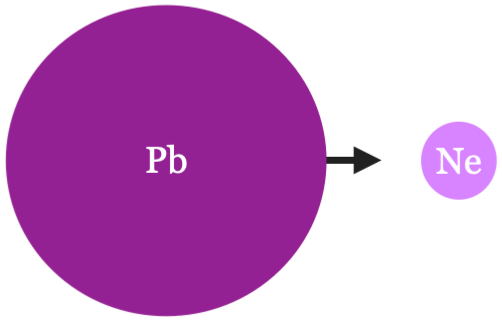
76 $\psi(2S)$

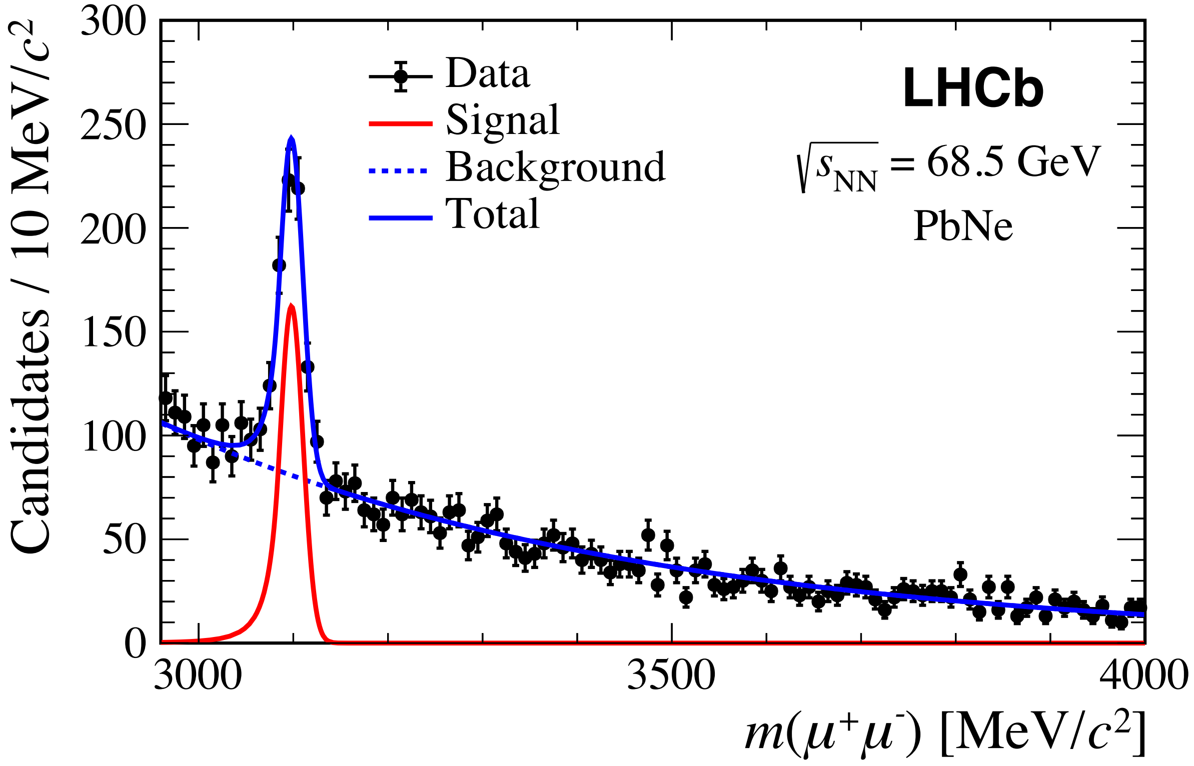
Event Selection:

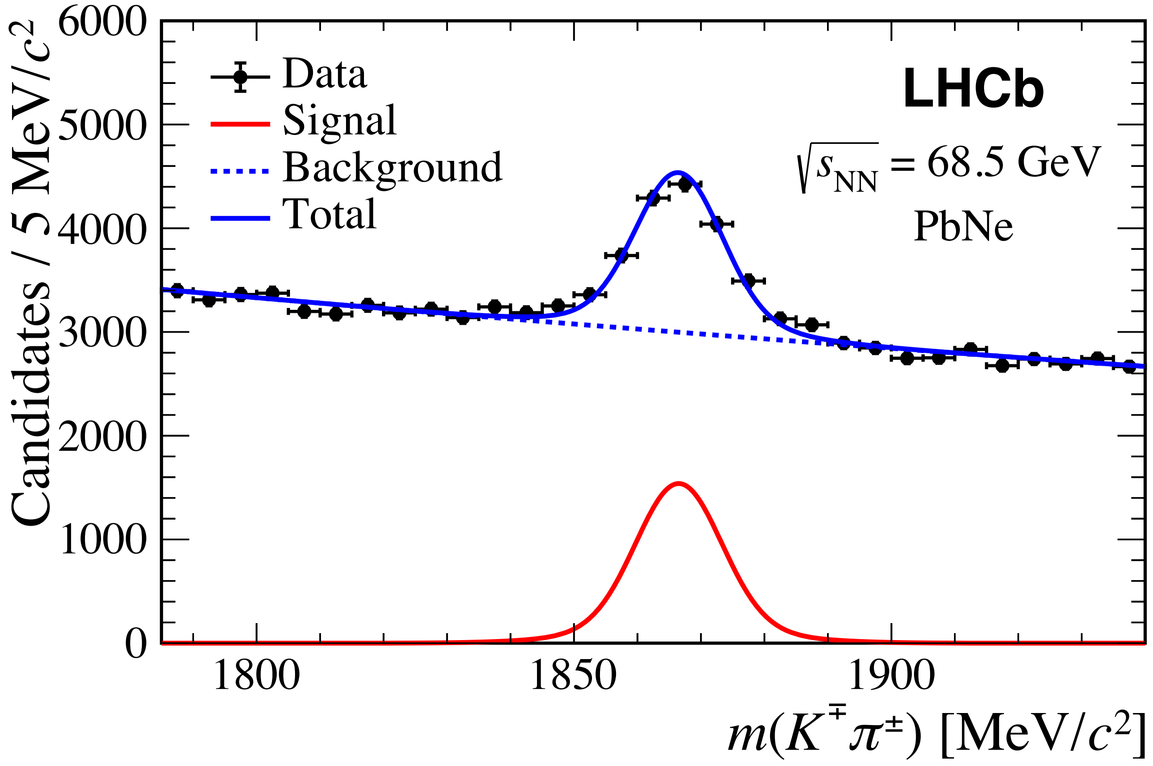
- Primary vertex in [-200, -100] mm or [100, 150] mm to avoid residual *pp* collisions
- Heavy flavor hadron p_T < 8 GeV
- Heavy flavor hadron rapidity in $2.0 < y < 4.29$
- For charmonia, two reconstructed muons with p_T > 500 MeV
- For D^0, identified K^- and π^+ tracks with p_T > 250 MeV

D^0: EPJC 83 (2023) 541   Charmonia: EPJC 83 (2023) 625

Heavy flavor signal yields in PbNe collisions







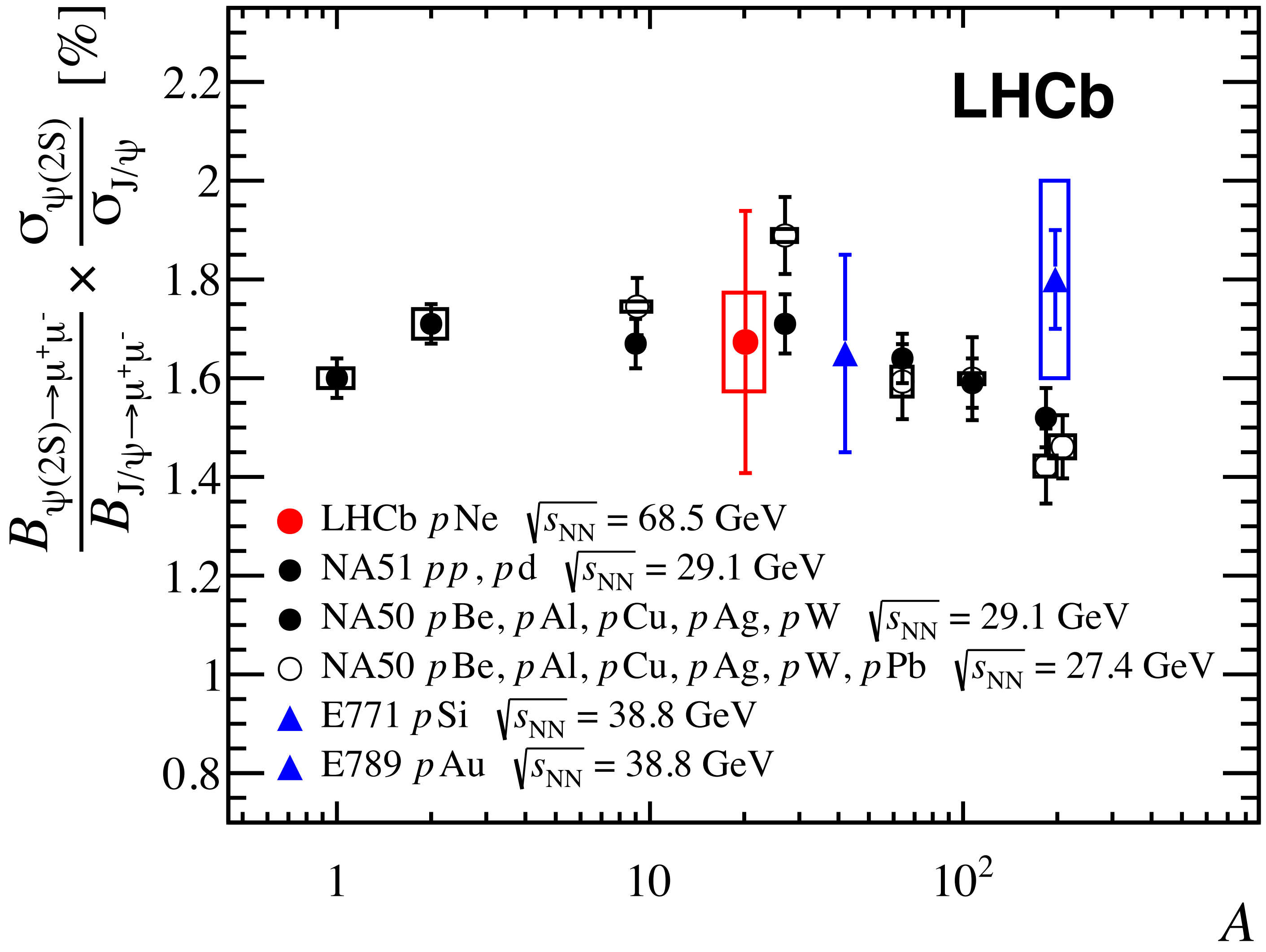
- Larger background than in *p*A collisions, but clean signal peaks are still observed - proof of measurement feasibility in larger PbA systems
- Similar candidate selection as in *p*Ne measurement
- Heavy flavor hadron $p_T < 8$ GeV
- Heavy flavor hadron y in $2.0 < y < 4.29$

Candidate yields: 545 J/ψ, 5670 D^0

EPJC 83 (2023) 658

Relative production rate of J/ψ and ψ(2s) mesons

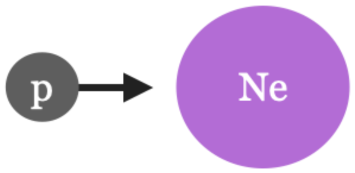
p → Ne

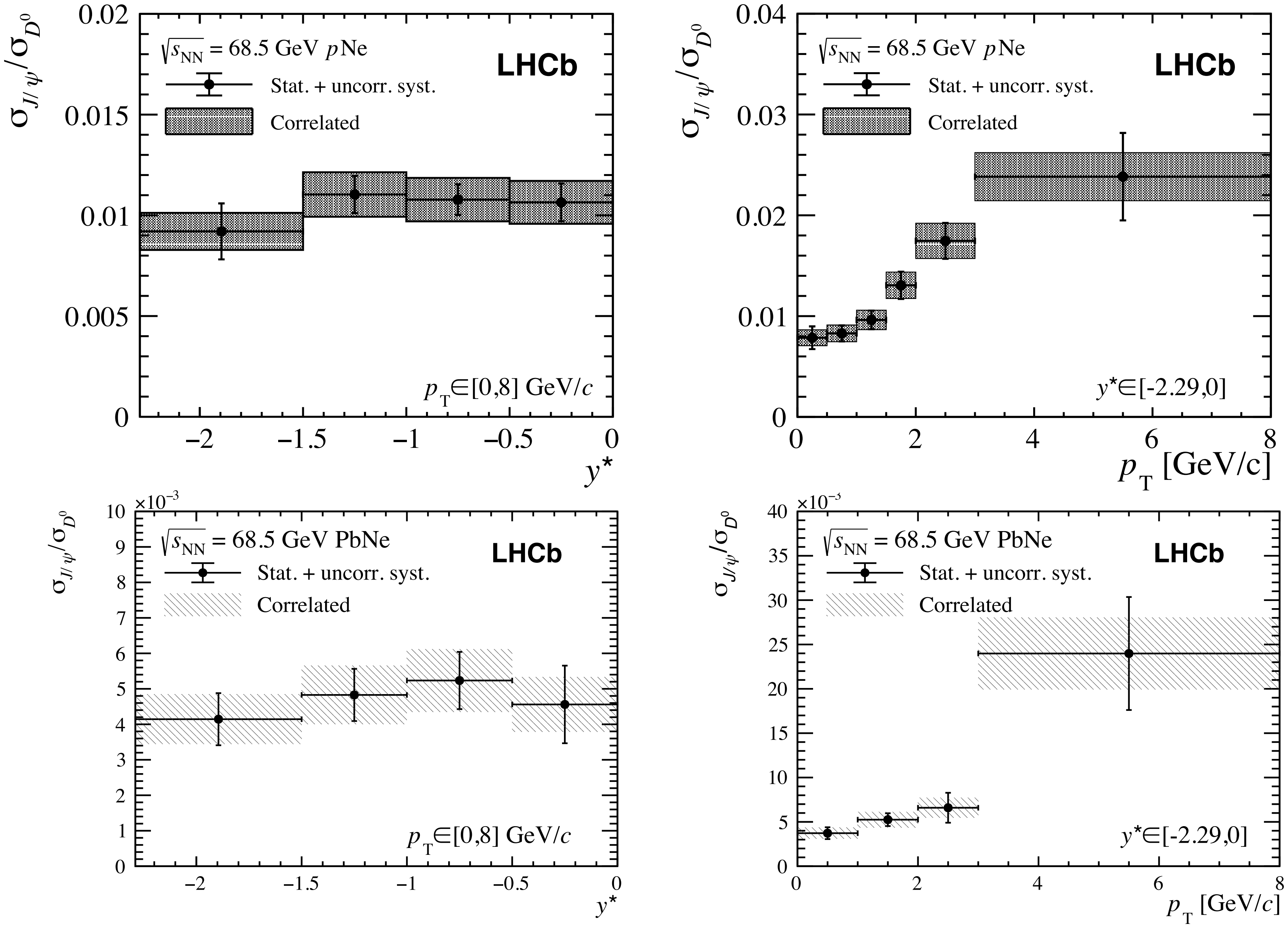


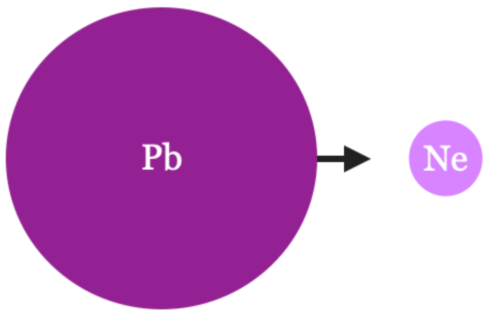
- LHCb measurement: 1.67 ± 0.27 (stat) ± 0.10 (sys) %
- The relative production rate of ψ(2S) to J/ψ mesons in *p*Ne collisions is consistent with the rates measured on other nuclear targets and at other center of mass energies

LHCb data: EPJC 83 (2023) 625

Cross section ratios of J/ψ and D^0 production in PbNe and pNe collisions



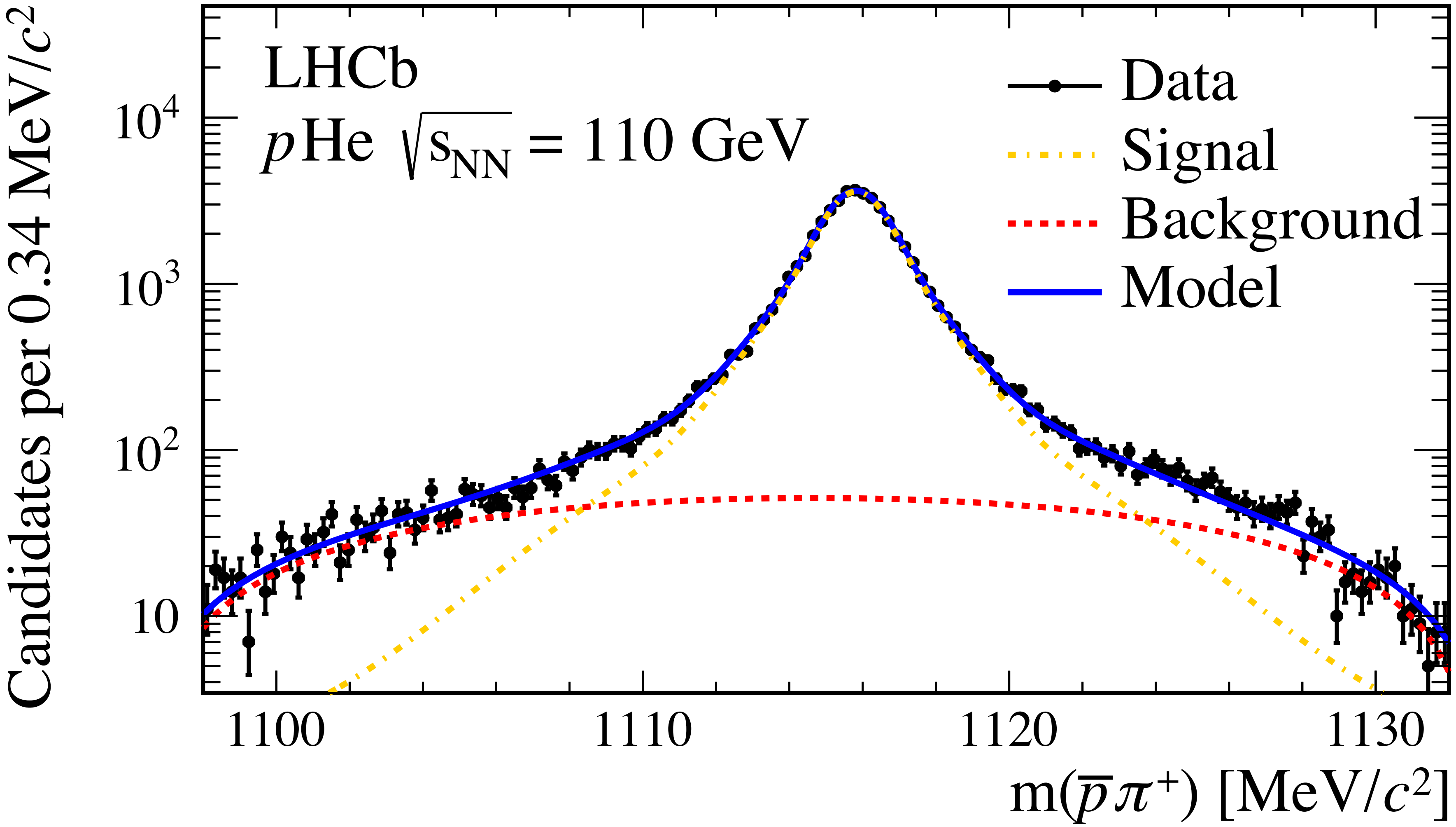




- Compare J/ψ production in large (PbNe) vs small (pNe) nuclear environment at the same $\sqrt{s}$
- $\sigma_{J/\psi}/\sigma_{D^0}$ shows little dependence on y^* and a strong dependence on p_T

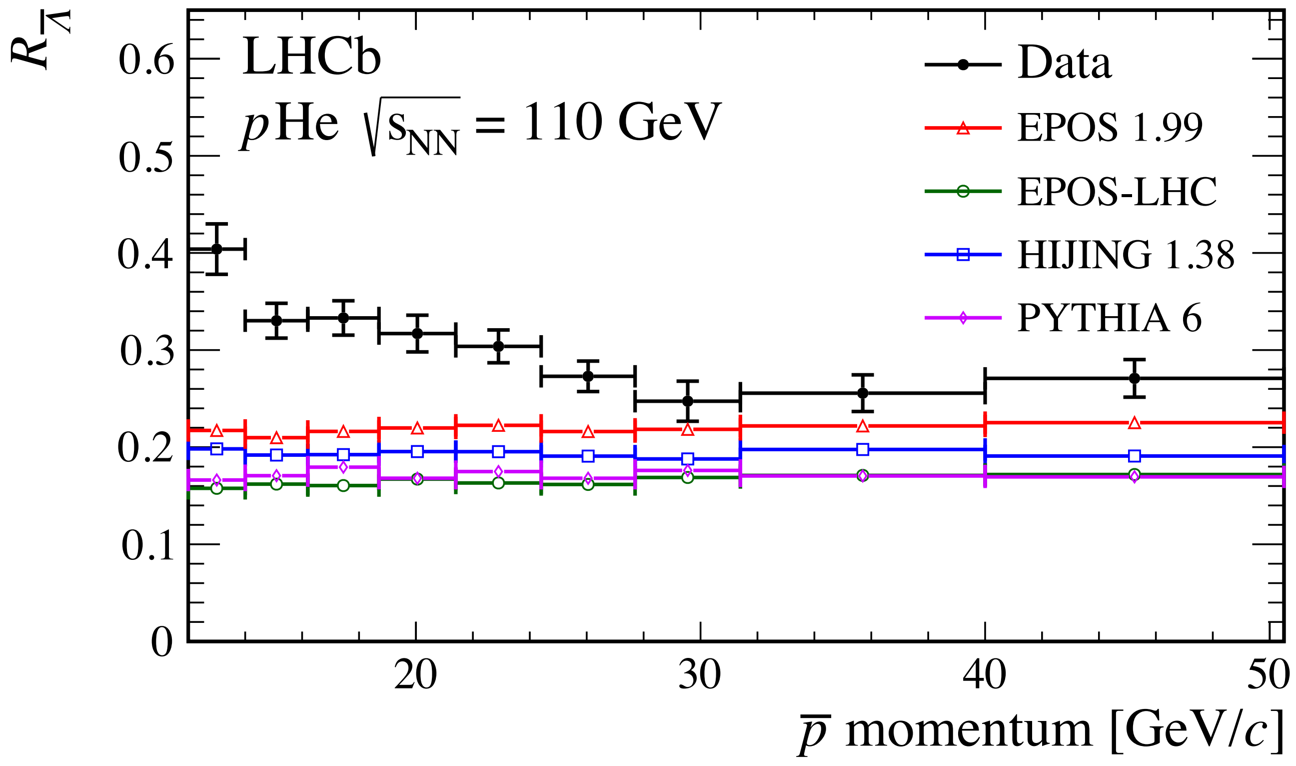
PbNe: EPJC 83 (2023) 658 **pNe:** EPJC 83 (2023) 625

$\overline{\Lambda}$ yield in pHe collisions



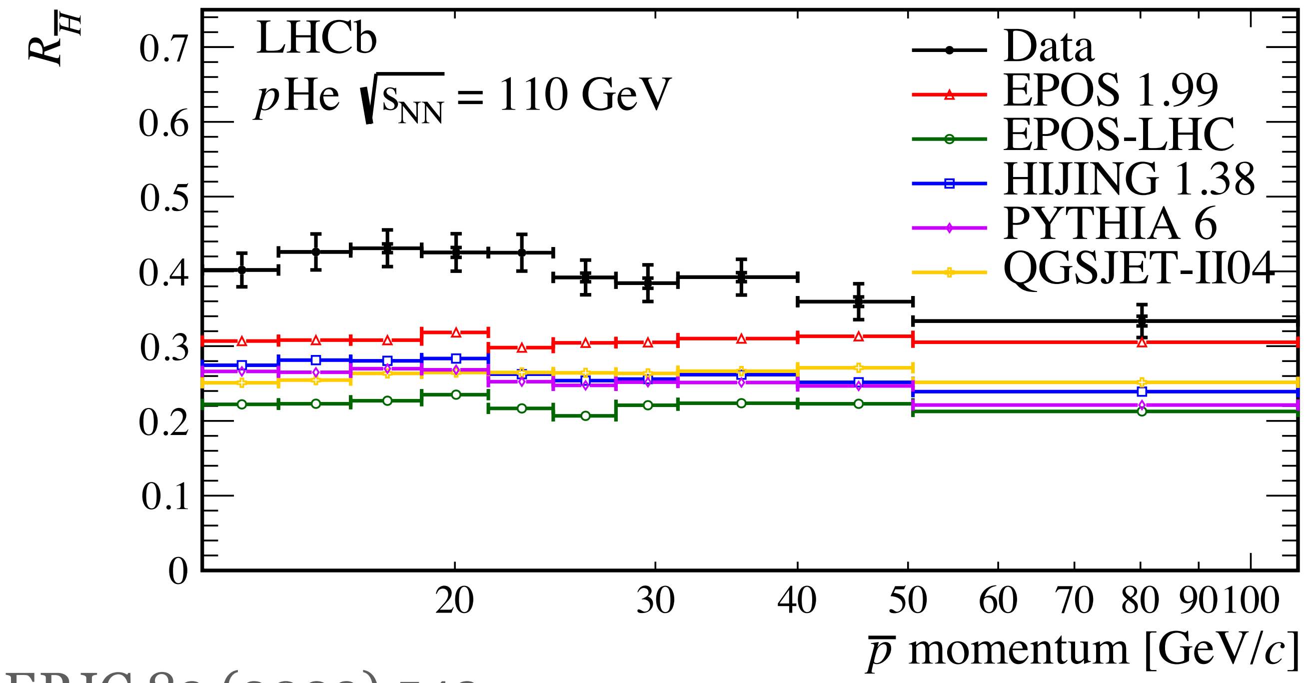
EPJC 83 (2023) 543

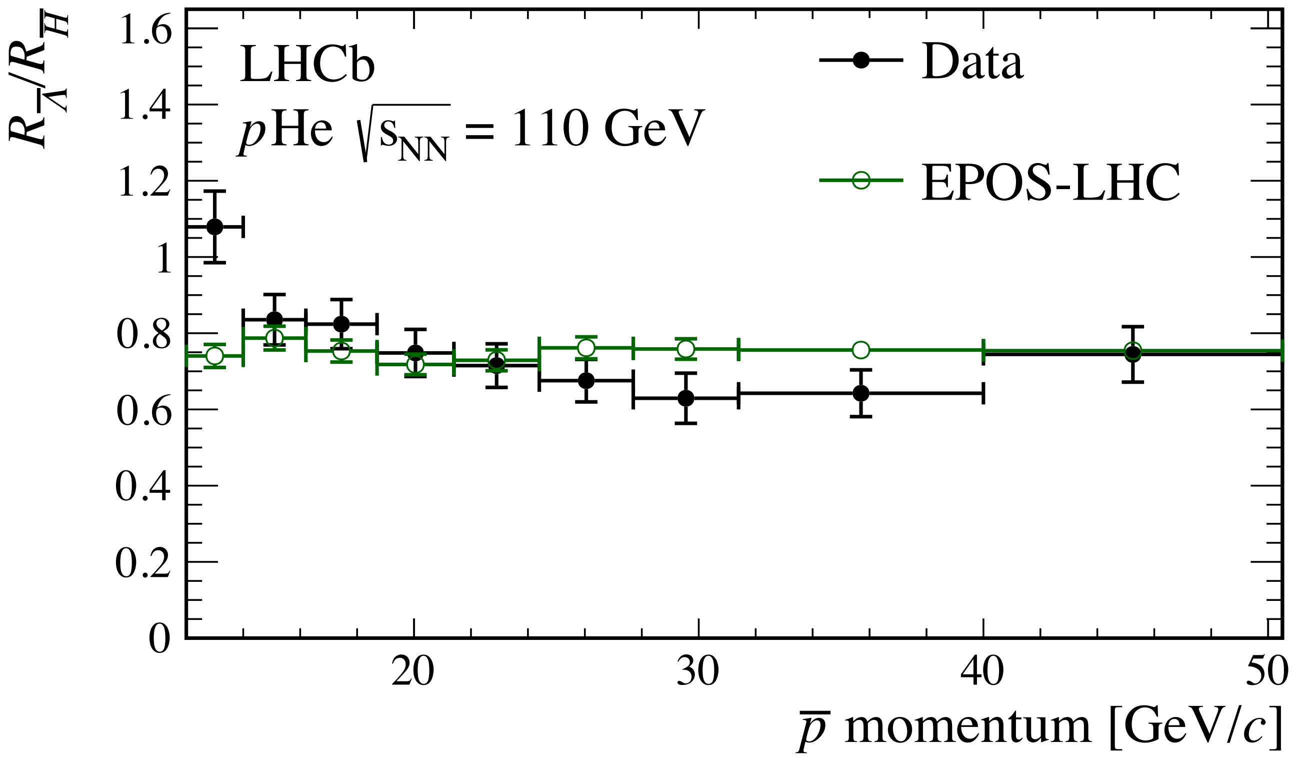
Fractions of $\overline{p}$ from antihyperon decays vs momentum



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

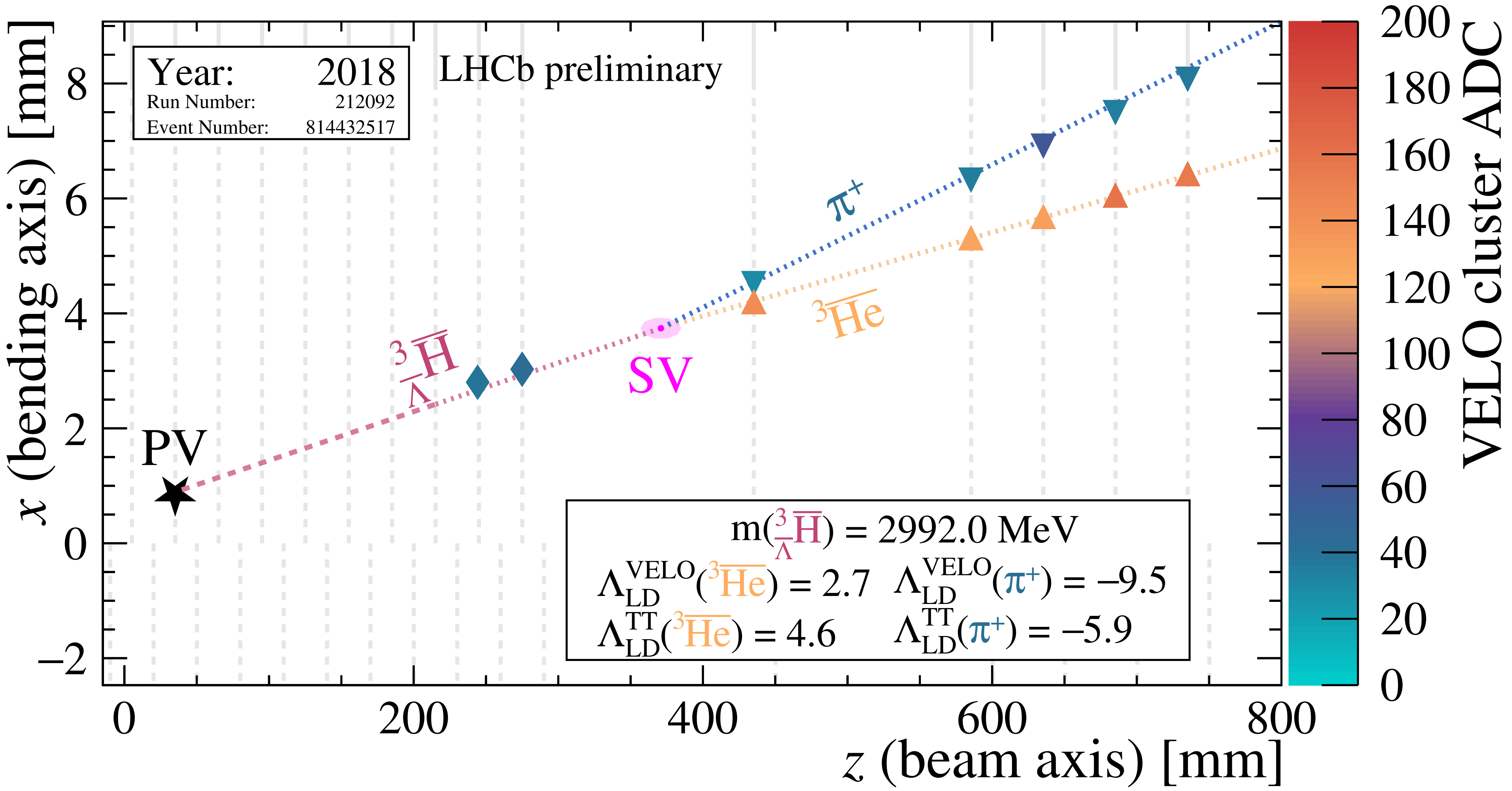
$$R_{\bar{\Lambda}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{\Lambda}X \to \overline{p}\pi^{+}X)}{\sigma(p\mathrm{He} \to \overline{p}_{\mathrm{prompt}}X)}$$





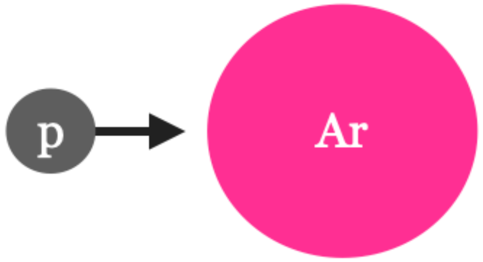
EPJC 83 (2023) 543

Anti-Hypertriton -> $^{3}\overline{\mathrm{He}}\,\pi^{+}$ Event display

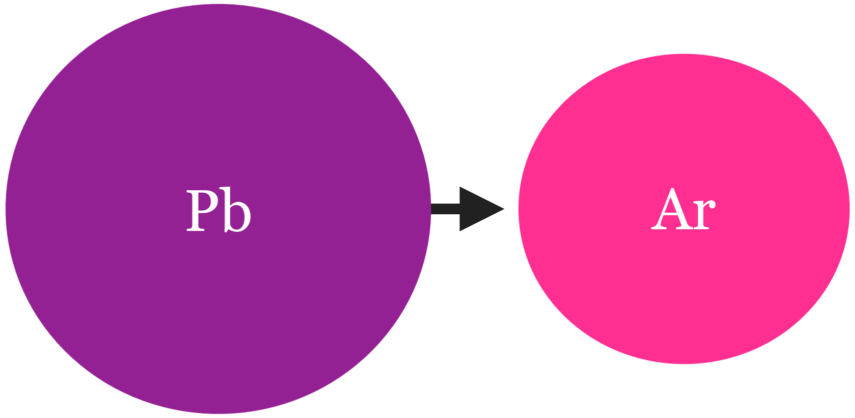


LHCB-CONF-2023-002

Early measurements possible with SMOG2



- **J/ψ and ψ(2S) production in pAr collisions**
  - Baseline for measurement in PbAr collisions
  - Comparison to pNe measurement to probe CNM effects as a function of system size
  - Both quarkonia states are needed for future comparison with a χ_c measurement in pAr to provide a baseline for suppression measurements in PbAr



- **J/ψ and D^0 production in PbAr collisions**
  - QGP expected to be produced
  - pAr, PbAr, PbNe measurements can help disentangle hot vs. cold nuclear effects that contribute to quarkonia dissociation

<u>Later timescale (high statistics needed):</u>

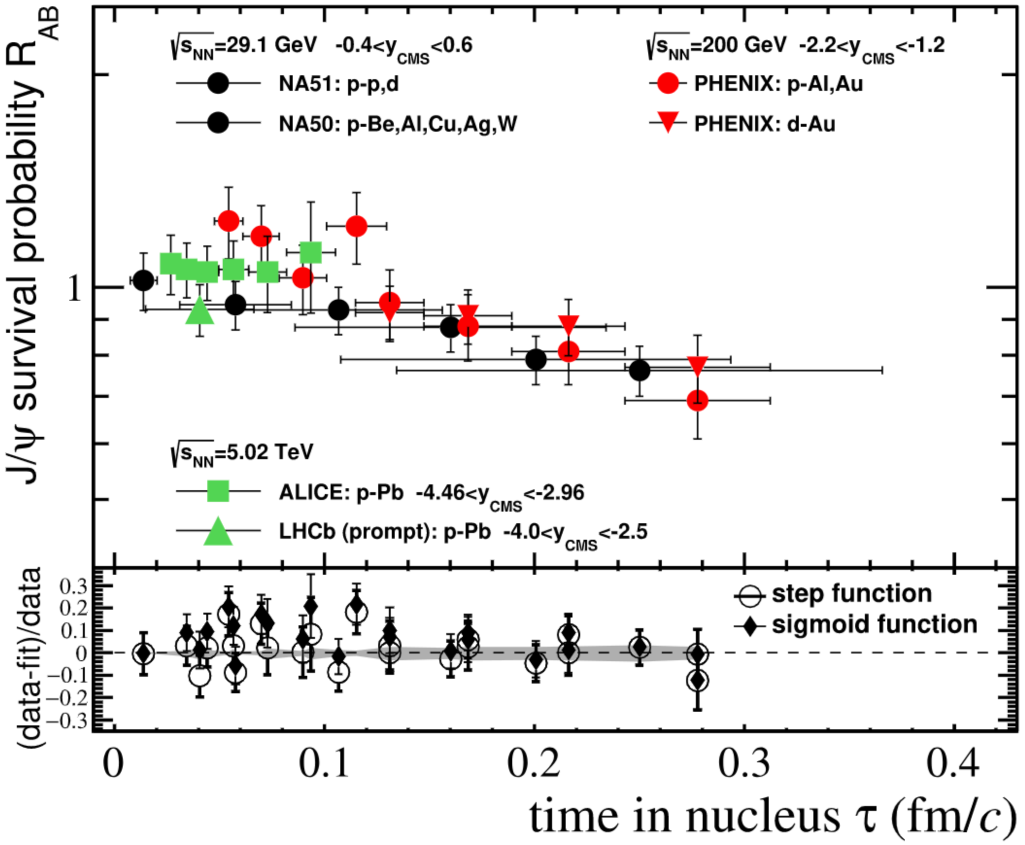
- **Upsilon production in pAr collisions** - study CNM effects as a function of bound state size and quark flavor content (e.g. parton energy loss effects)
- **Multi-differential ψ(2S) measurements in pAr collisions** - complement differential J/ψ measurements and test theoretical models of quarkonium production
- **J/ψ production in pH_2 collisions** - necessary baseline for J/ψ R_{AA} measurements

Other measurements possible with SMOG2

- **Possible determination of $c\bar{c}$ hadronization time**
  - Parameterization of nuclear absorption mechanism proposed by E. Ferreiro, E. Maurice, and F. Fleuret
  - Proper time of $c\bar{c}$ pair of mass m traversing length L in a nucleus:

$$\tau = \frac{t}{\gamma} = \frac{Lm}{p} = \frac{Lm}{\sqrt{p_z^2 + p_T^2}} = \frac{Lm}{\sqrt{m_T^2 \sinh^2 y + p_T^2}}$$

  - More pA data in a variety of nuclear targets needed for hadronization time extraction - possible with SMOG2!



- **Quarkonia production in additional collision systems**
  - pD_2, pKr, pXe, pN_2, pO_2 collisions all possible
  - PbH_2, PbKr, PbXe…

- **Drell-Yan** measurements

- **Exclusive production (photoproduction) of J/ψ** on a variety of nuclear targets

$c\bar{c}$ formation time: EPJC 82, (2022) 201

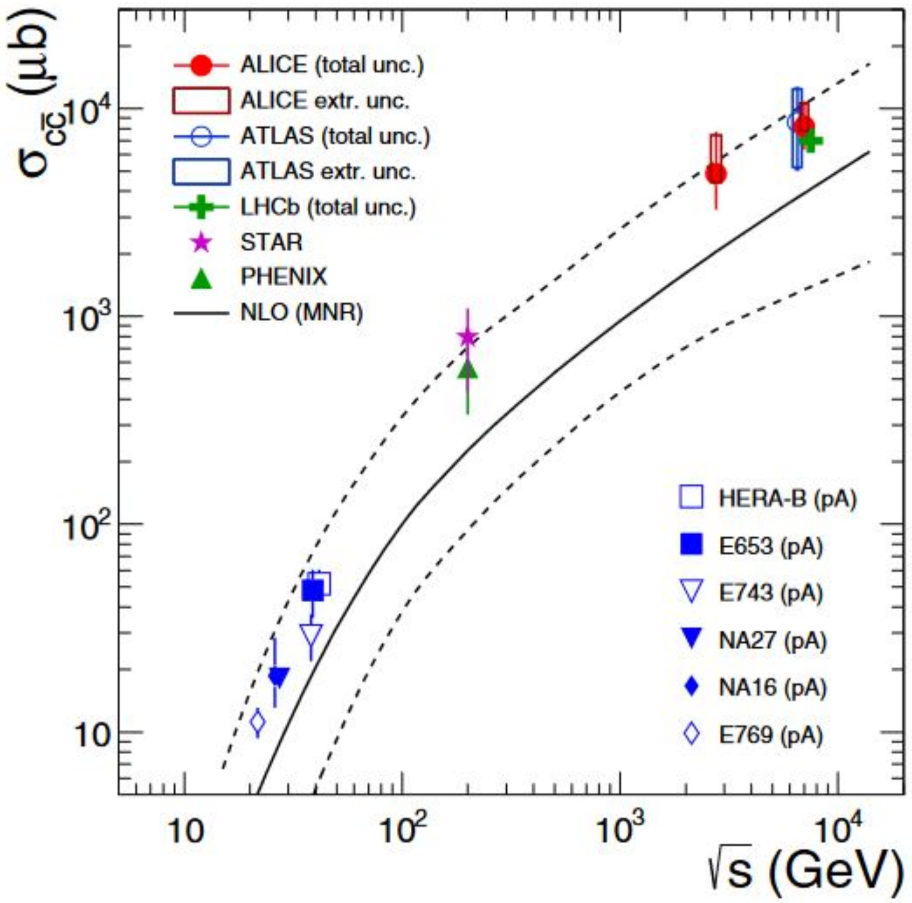
Expected number of $c\bar{c}$ pairs in PbNe collisions

- From previous measurements of inclusive $c\bar{c}$ pair production at different centre of mass energies:

$$\sigma_{c\bar{c}}^{5.5\ TeV} \approx 10 \times \sigma_{c\bar{c}}^{200\ GeV} \approx 100 \times \sigma_{c\bar{c}}^{70\ GeV} \approx 1000 \times \sigma_{c\bar{c}}^{20\ GeV}$$

- PHENIX measured the number of electrons from semileptonic charm hadron decays in AuAu collisions at $\sqrt{s}$ = 200 GeV. The yield scales with N_{coll} (expected if no nuclear effects on the total $c\bar{c}$ production)

$$N_{c\bar{c}} = \frac{N_{c\bar{c}}}{T_{AA}} \times T_{AA} = (597x10^{-3})\ \text{mb} \times 22.8\ \text{mb}^{-1} \approx 13$$



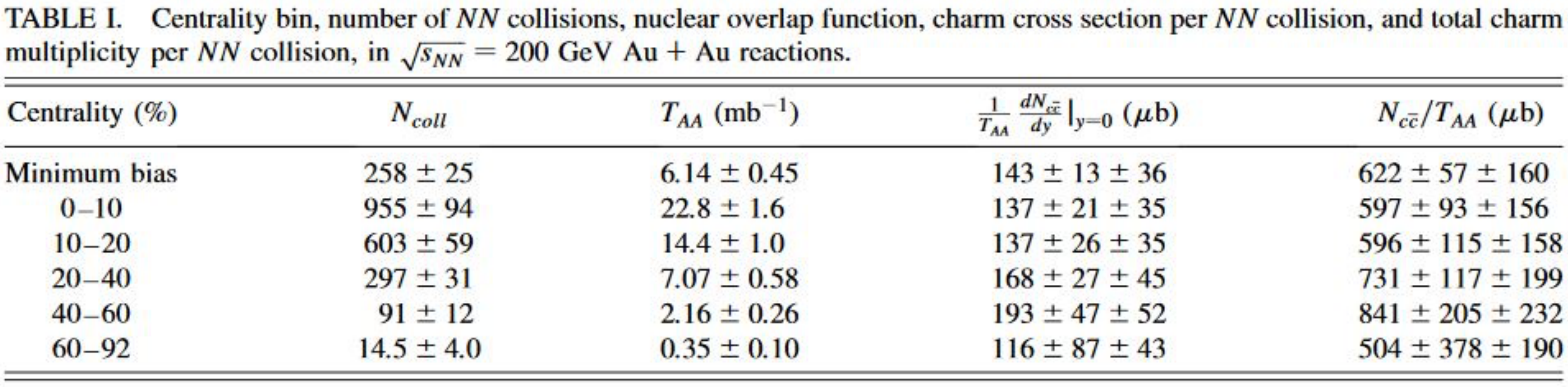
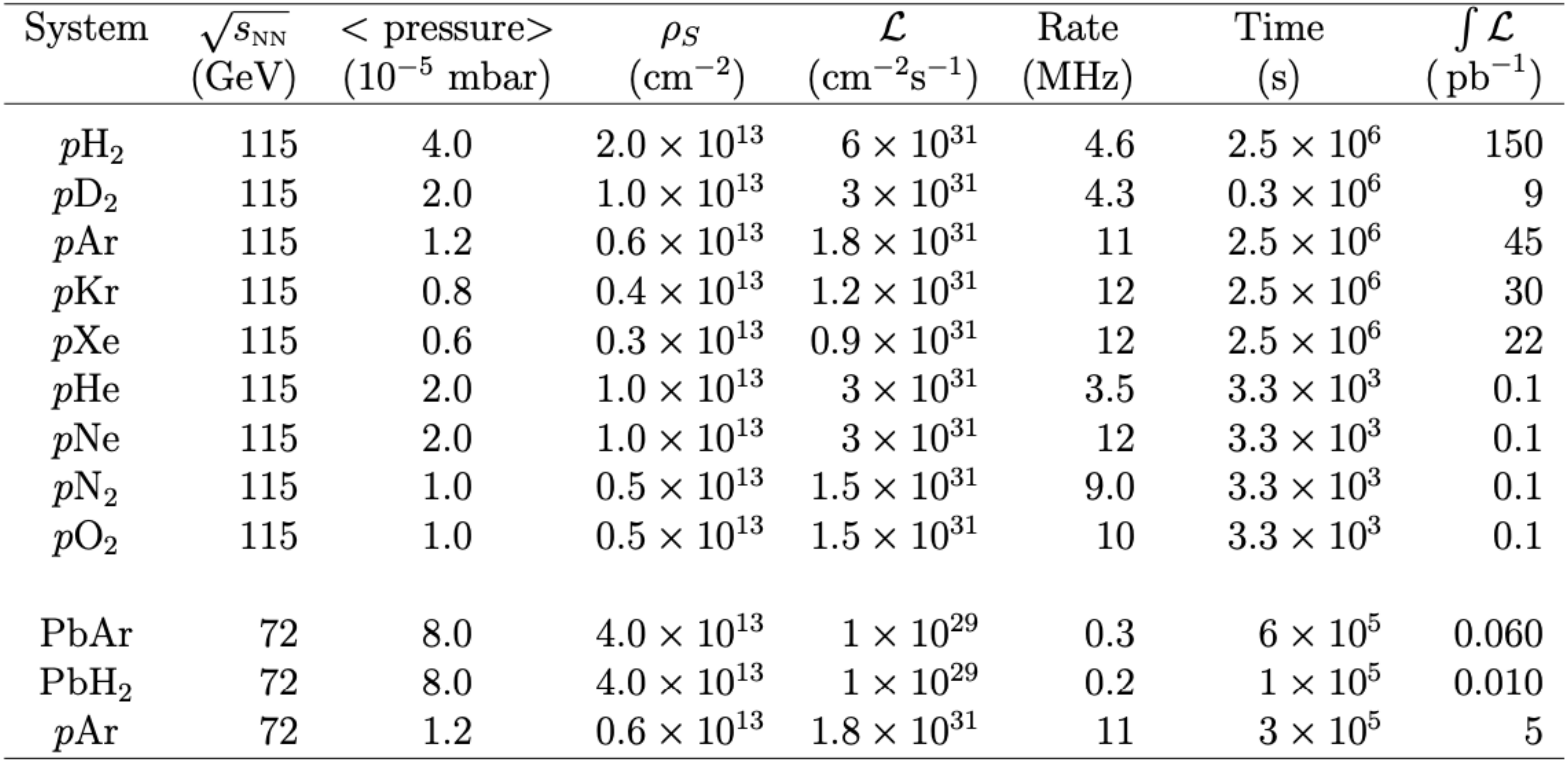


TABLE I. Centrality bin, number of *NN* collisions, nuclear overlap function, charm cross section per *NN* collision, and total charm multiplicity per *NN* collision, in $\sqrt{s_{NN}}$ = 200 GeV Au + Au reactions.

Centrality (%)	N_{coll}	T_{AA} (mb^{-1})	$\frac{1}{T_{AA}}\frac{dN_{c\bar{c}}}{dy}\|_{y=0}$ (μb)	$N_{c\bar{c}}/T_{AA}$ (μb)
Minimum bias	258 ± 25	6.14 ± 0.45	143 ± 13 ± 36	622 ± 57 ± 160
0–10	955 ± 94	22.8 ± 1.6	137 ± 21 ± 35	597 ± 93 ± 156
10–20	603 ± 59	14.4 ± 1.0	137 ± 26 ± 35	596 ± 115 ± 158
20–40	297 ± 31	7.07 ± 0.58	168 ± 27 ± 45	731 ± 117 ± 199
40–60	91 ± 12	2.16 ± 0.26	193 ± 47 ± 52	841 ± 205 ± 232
60–92	14.5 ± 4.0	0.35 ± 0.10	116 ± 87 ± 43	504 ± 378 ± 190

$\sigma_{c\bar{c}}$: PRC 94 (2016) 054908 PHENIX results: PRL 94, 082301 (2005)

Projected luminosities for different SMOG2 gas species in Run 3

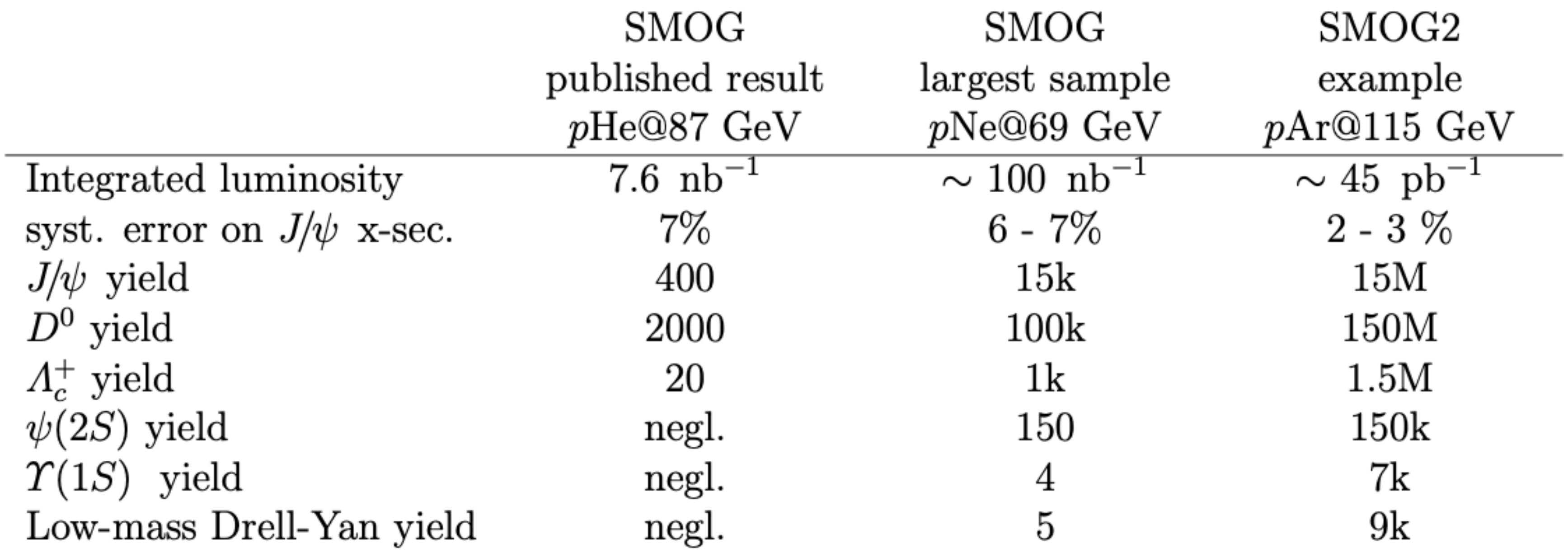


System	$\sqrt{s_{\mathrm{NN}}}$ (GeV)	< pressure> (10^{-5} mbar)	ρ_S (cm^{-2})	$\mathcal{L}$ ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	Rate (MHz)	Time (s)	$\int \mathcal{L}$ (pb^{-1})
$p\mathrm{H}_2$	115	4.0	2.0×10^{13}	6×10^{31}	4.6	2.5×10^{6}	150
$p\mathrm{D}_2$	115	2.0	1.0×10^{13}	3×10^{31}	4.3	0.3×10^{6}	9
$p\mathrm{Ar}$	115	1.2	0.6×10^{13}	1.8×10^{31}	11	2.5×10^{6}	45
$p\mathrm{Kr}$	115	0.8	0.4×10^{13}	1.2×10^{31}	12	2.5×10^{6}	30
$p\mathrm{Xe}$	115	0.6	0.3×10^{13}	0.9×10^{31}	12	2.5×10^{6}	22
$p\mathrm{He}$	115	2.0	1.0×10^{13}	3×10^{31}	3.5	3.3×10^{3}	0.1
$p\mathrm{Ne}$	115	2.0	1.0×10^{13}	3×10^{31}	12	3.3×10^{3}	0.1
$p\mathrm{N}_2$	115	1.0	0.5×10^{13}	1.5×10^{31}	9.0	3.3×10^{3}	0.1
$p\mathrm{O}_2$	115	1.0	0.5×10^{13}	1.5×10^{31}	10	3.3×10^{3}	0.1
PbAr	72	8.0	4.0×10^{13}	1×10^{29}	0.3	6×10^{5}	0.060
PbH_2	72	8.0	4.0×10^{13}	1×10^{29}	0.2	1×10^{5}	0.010
$p\mathrm{Ar}$	72	1.2	0.6×10^{13}	1.8×10^{31}	11	3×10^{5}	5

LHCb-PUB-2018-015

Expected heavy flavor yields with SMOG2

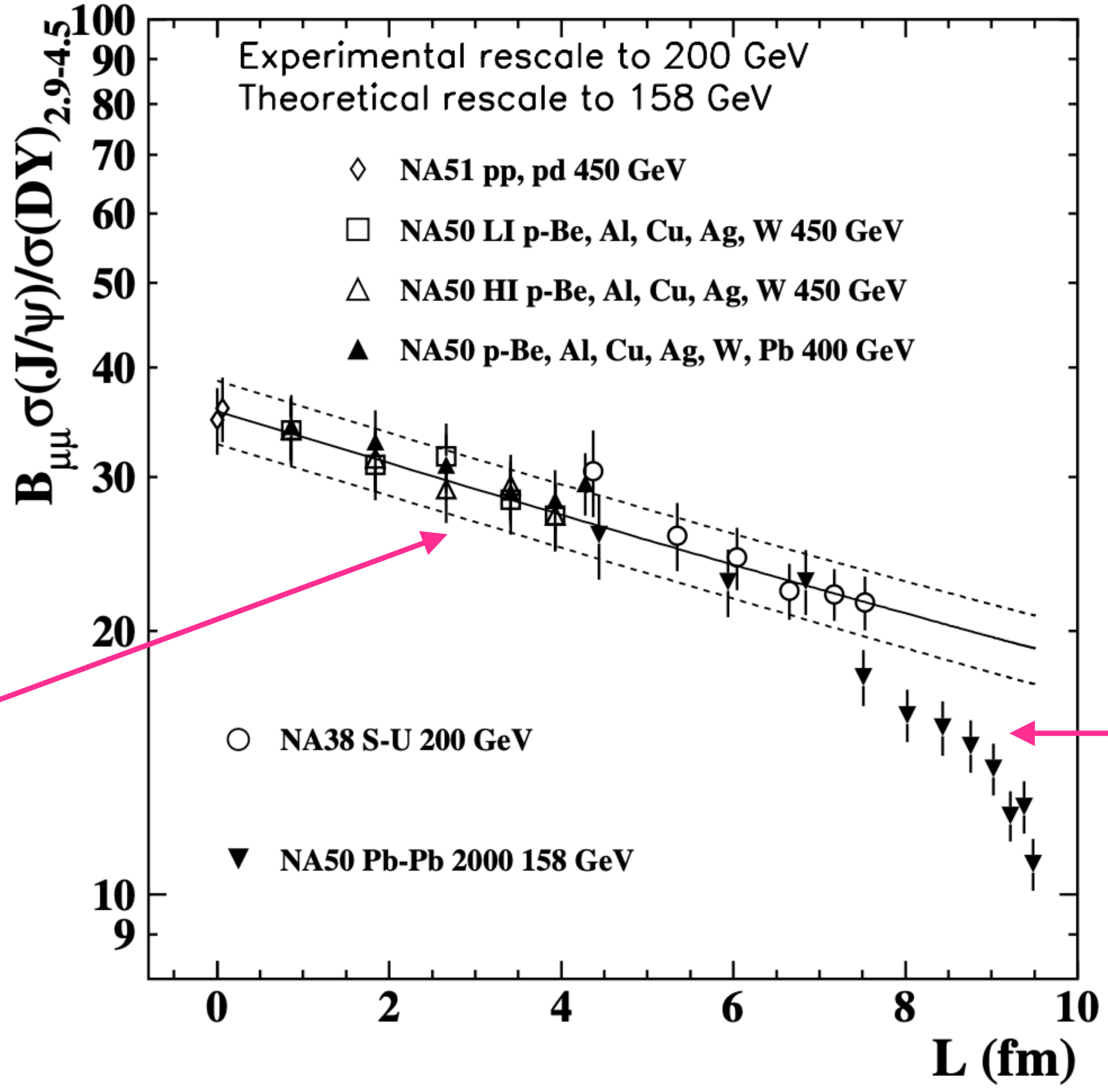
- Large increase in heavy flavor statistics compared to SMOG:



	SMOG published result pHe@87 GeV	SMOG largest sample pNe@69 GeV	SMOG2 example pAr@115 GeV
Integrated luminosity	7.6 nb^{-1}	$\sim$ 100 nb^{-1}	$\sim$ 45 pb^{-1}
syst. error on J/ψ x-sec.	7%	6 - 7%	2 - 3 %
J/ψ yield	400	15k	15M
D^0 yield	2000	100k	150M
Λ_c^+ yield	20	1k	1.5M
$\psi(2S)$ yield	negl.	150	150k
$\Upsilon(1S)$ yield	negl.	4	7k
Low-mass Drell-Yan yield	negl.	5	9k

LHCb-PUB-2018-015

Anomalous J/ψ suppression observed by NA50



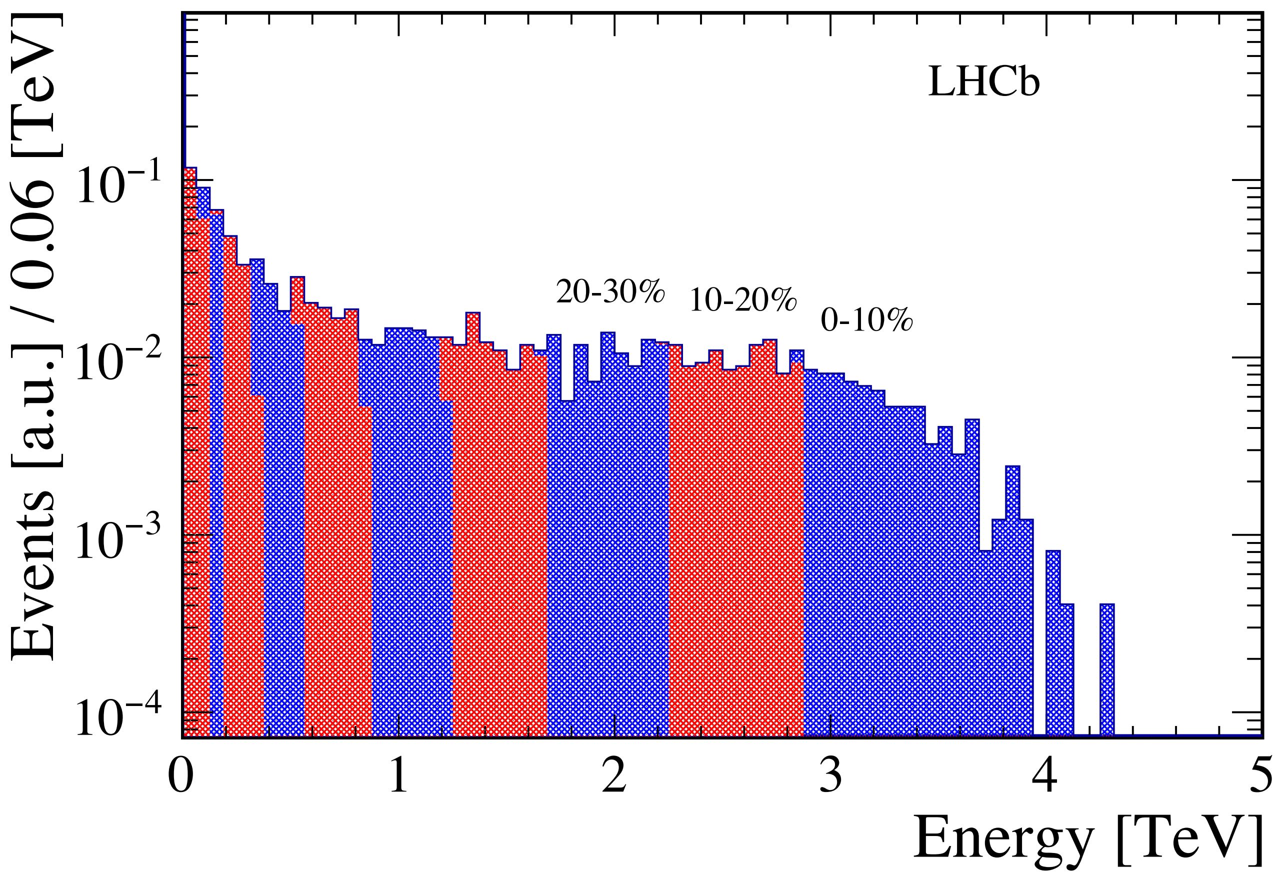
Expected suppression
due to nuclear
absorption

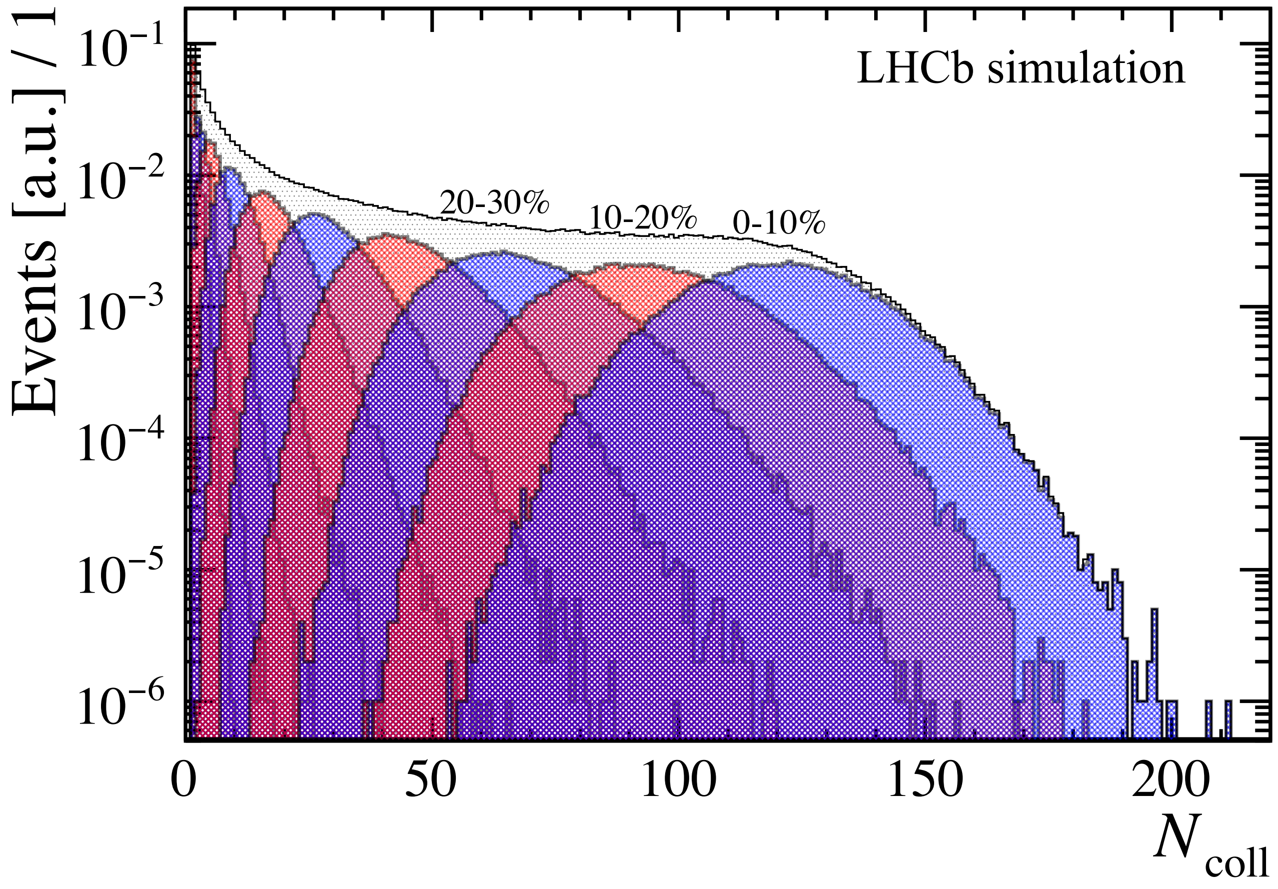
Anomalous
suppression

EPJC 39, (2005) 335-345

Centrality at LHCb

Centrality classes for PbNe collisions





JINST 17 (2022) P05009

Charged particle multiplicities for SMOG2 PbA and NA50 PbPb

	Peripheral collisions					Central collisions	
System \ centrality	**100 – 60%**	**60 – 50%**	**50 – 40%**	**40 – 30%**	**30 – 20%**	**20 – 10 %**	**10 – 0%**
PbNe – 71 GeV	108.6	254.4	392.5	588.0	814.5	1086.0	1494.9
PbAr – 71 GeV	**123,6**	**308,8**	**496,5**	**806,6**	**1228,3**	**1711,9**	**2372,7**
PbKr – 71 GeV	196,9	533,6	919,1	1451,2	2205,5	2986,6	4084,3
PbXe – 71 GeV	201,4	581,7	1031,0	1587,3	2400,2	3541,7	5065,7
PbPb – 17 GeV	**124,2**	**331,6**	**605,9**	**919,6**	**1338,7**	**2035,8**	**2980,5**

(based on EPOS-LHC-v3400)