New measurements in fixed-target collisions at LHCb

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On behalf of the LHCb Collaboration

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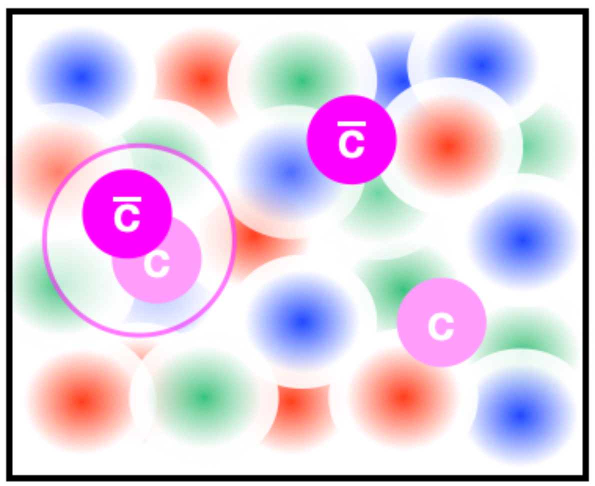
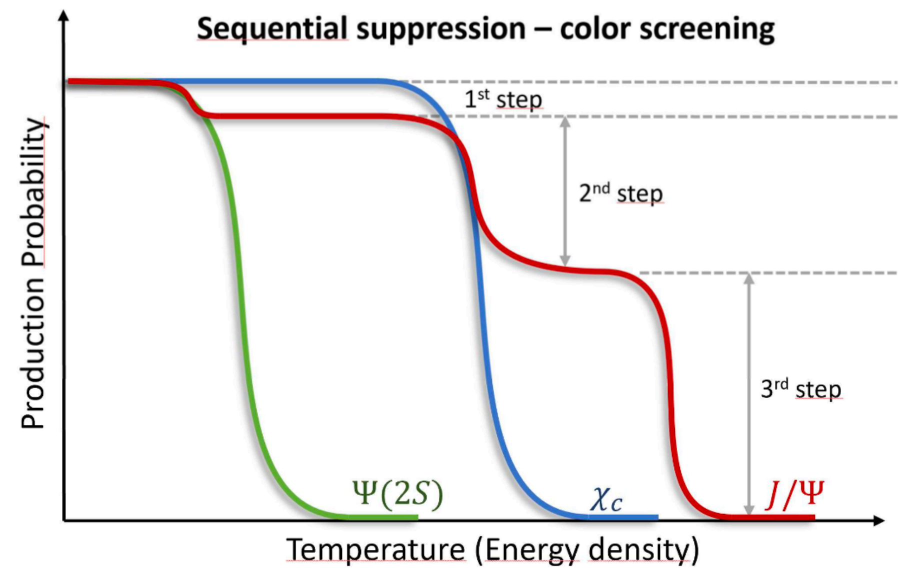
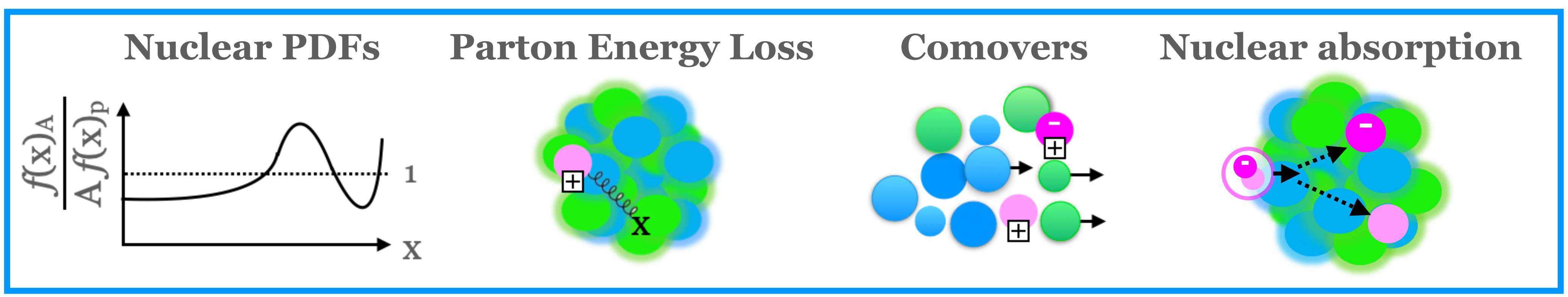
Motivation: a complete picture of quarkonia formation and dissociation in nuclear matter

- 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**



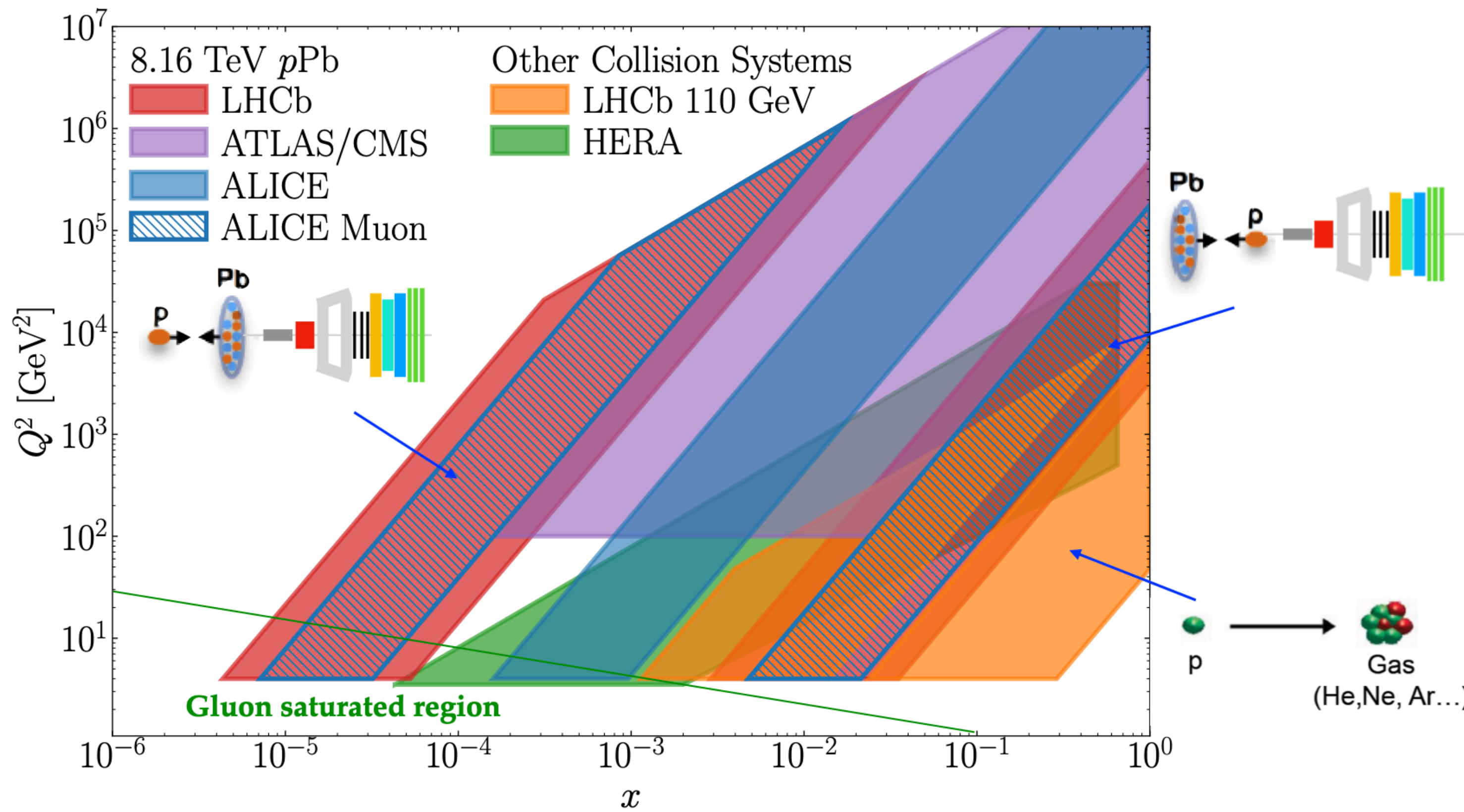




- A comprehensive understanding of CNM effects requires measuring charmonia production in a variety of nuclear systems and kinematic phase space

Fixed target kinematics at the LHC

- **Unique access** to high Bjorken x and low Q² phase space
  - Probe nuclear anti-shadowing at x ~ 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 √s = 41 - 115 GeV
  - No $c\bar{c}$ recombination expected in PbA collisions



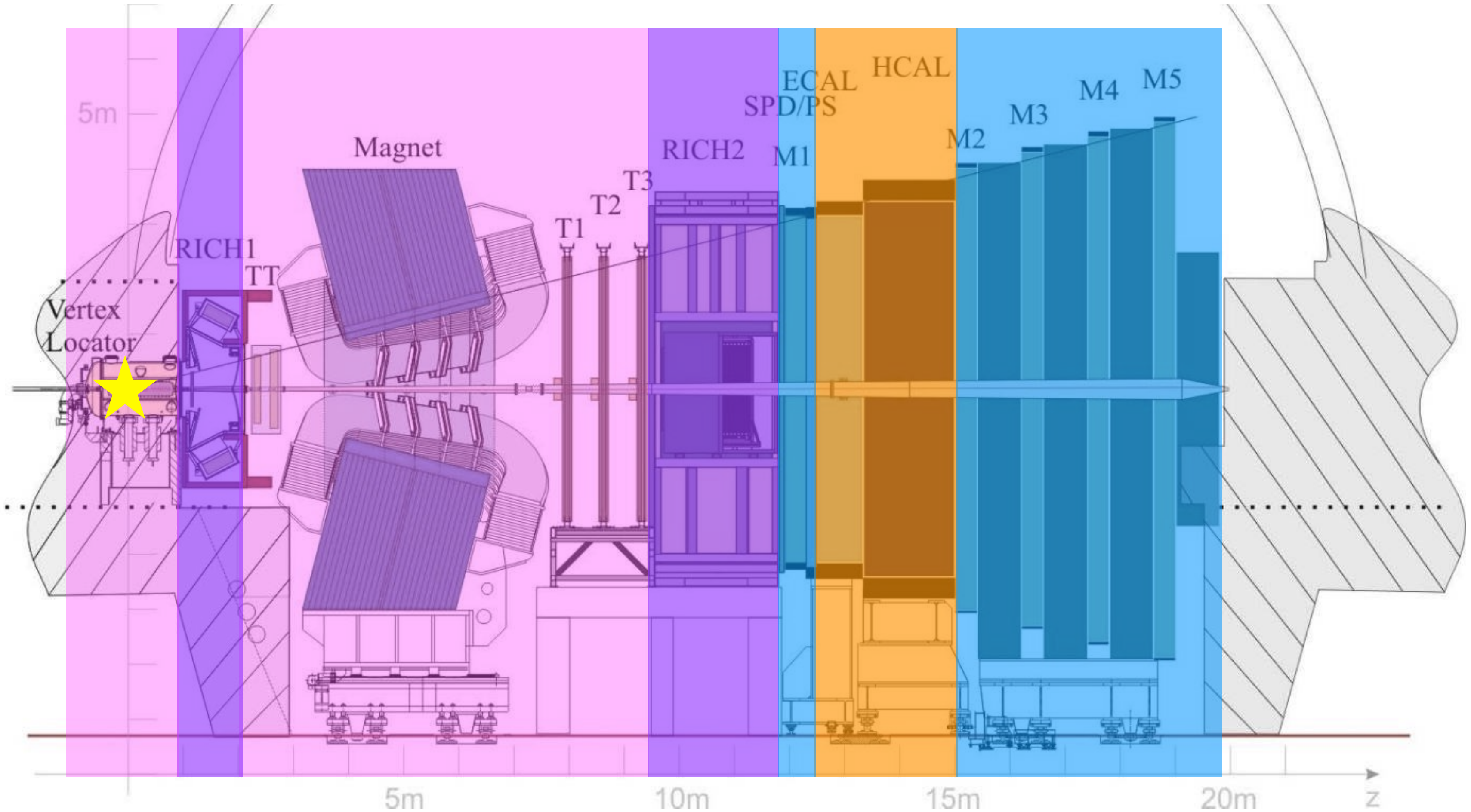
√s (incident p or A beams)

3 - 7.7 GeV	29.1 GeV	41-115 GeV	200 GeV	5 TeV
RHIC fixed-target	NA50 (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 -2.29 < y^* < 0

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

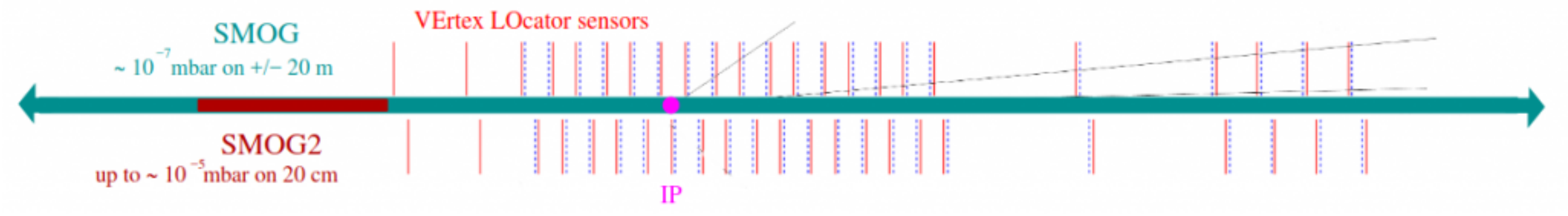
The LHCb Detector: Full **tracking**, **particle identification**, **hadronic and electromagnetic calorimetry** and **muon ID** in $2 < \eta < 5$



- 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 pA or PbA collisions

The LHCb fixed-target program

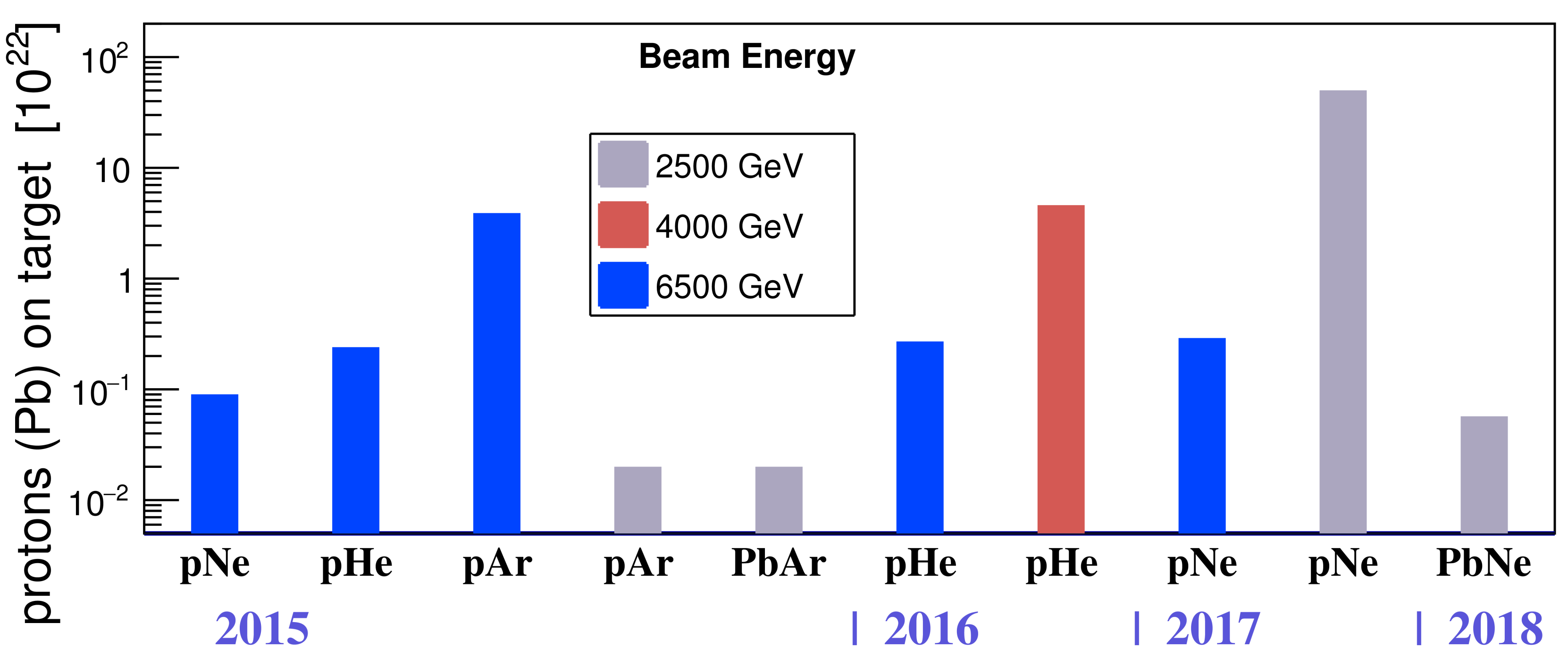
- SMOG: System for Measuring Overlap with Gas



  - Noble gases (Ar, He, Ne) injected with a pressure of 10^{-7} mbar
  - Luminosity of ~6 x 10^{29} cm^{-2} s^{-1}

- Several pA and PbA data samples collected:

SMOG Run 2 data samples



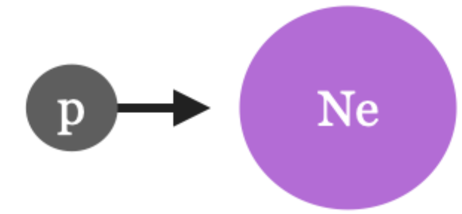
Charmonia measurements with SMOG

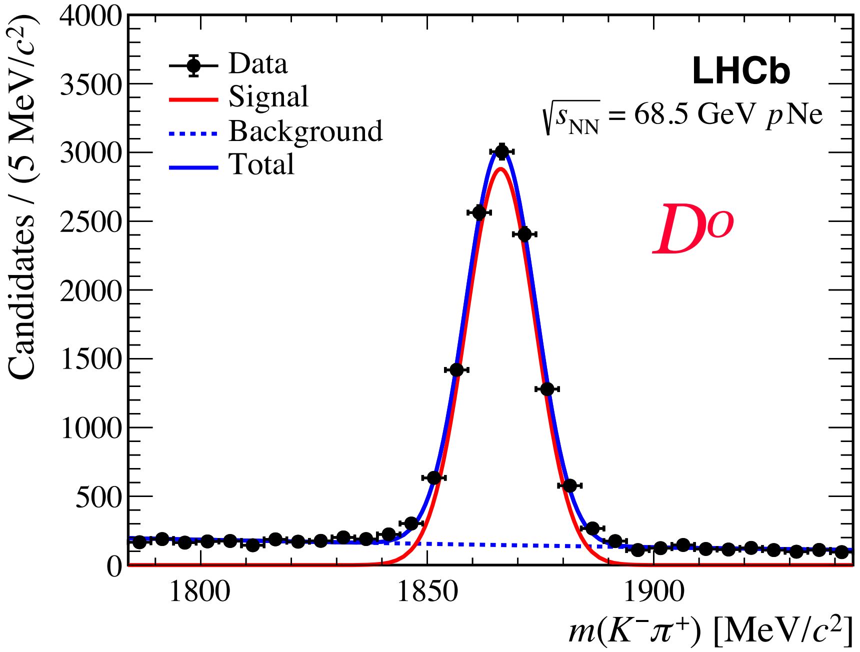
System	$\sqrt{s_{NN}}$	Quarkonia measured	Reference measurement	Publication
p → He	86.6 GeV	J/ψ	D^0	PRL 122 (2019) 132002
p → Ne	68.5 GeV	J/ψ, $\psi(2S)$	D^0	***new!*** arXiv:2211.11645 arXiv:2211.11633
p → Ar	110.4 GeV	J/ψ	D^0	PRL 122 (2019) 132002
Pb → Ne	68.5 GeV	J/ψ	D^0	***new!*** arXiv:2211.11652

first fixed-target AA measurement at the LHC!

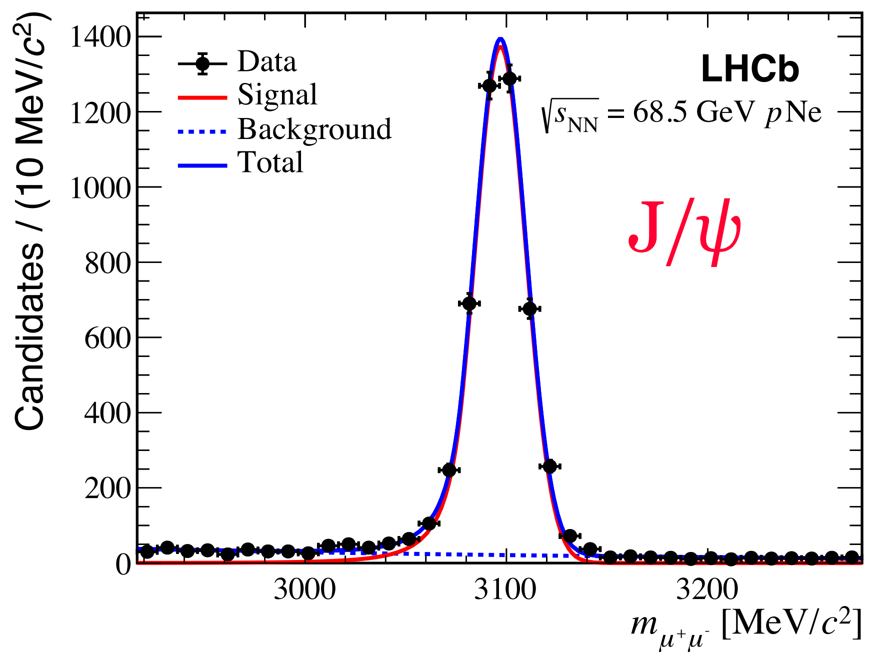
- D^0 production is measured in each system as a proxy for the total charm production cross section

Heavy flavor signal yields in pNe collisions

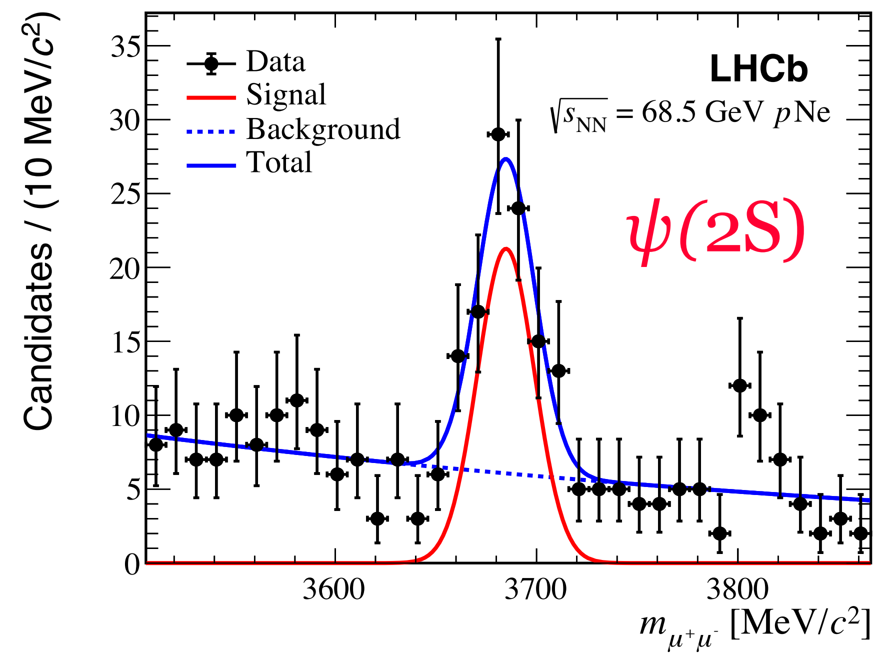




24, 408 D^0



4542 J/ψ

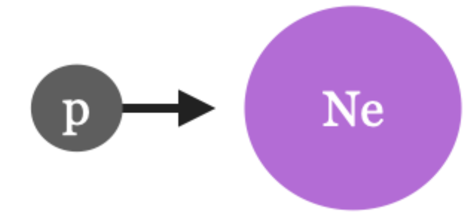


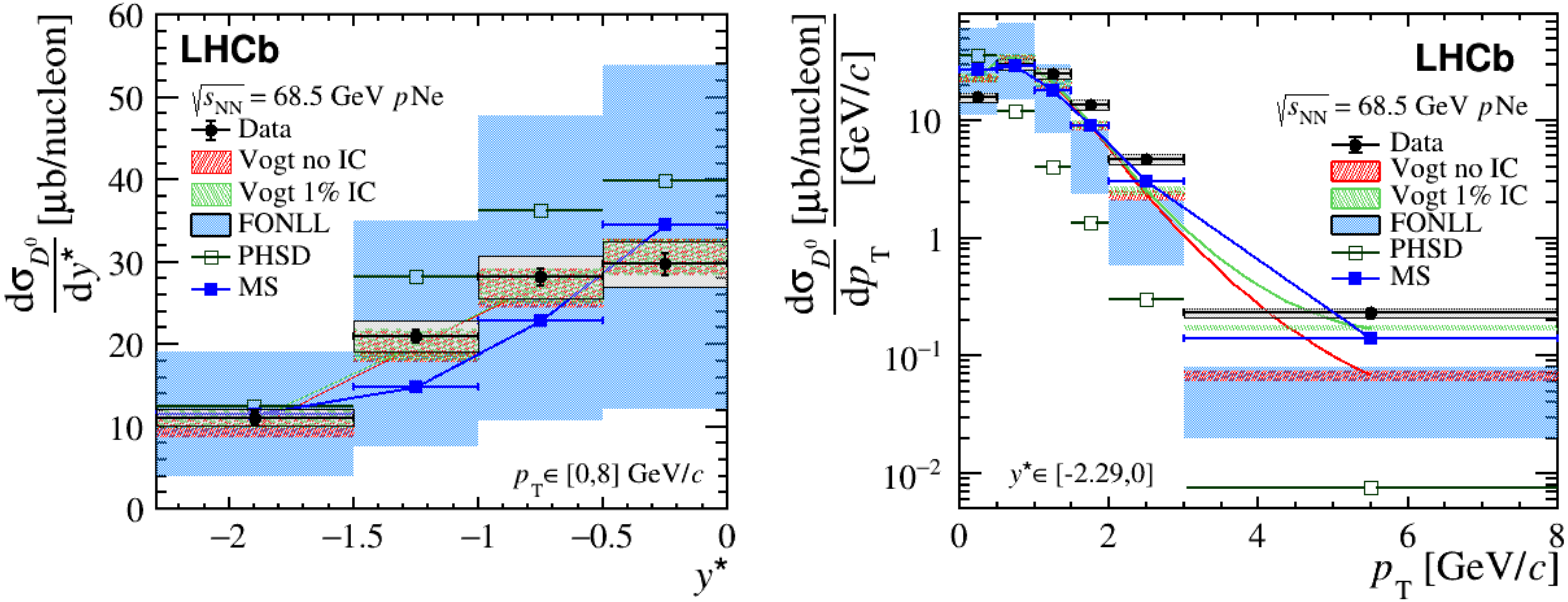
76 ψ(2S)

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

D⁰ differential cross sections





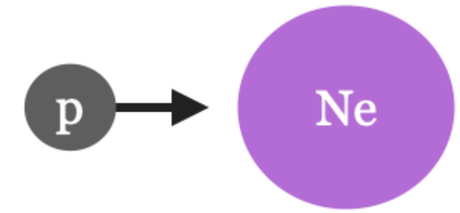
- FONLL and PHSD predictions fail to reproduce the p_T distribution seen in data
- The Vogt 1% IC and the MS predictions both include 1% intrinsic charm contribution in the proton
- MS includes 10% recombination contributions, Vogt includes shadowing effects

See talk by R. Vogt (Tues. 9h40) for more details

- PDF and factorisation scale uncertainties are only included in FONLL calculations

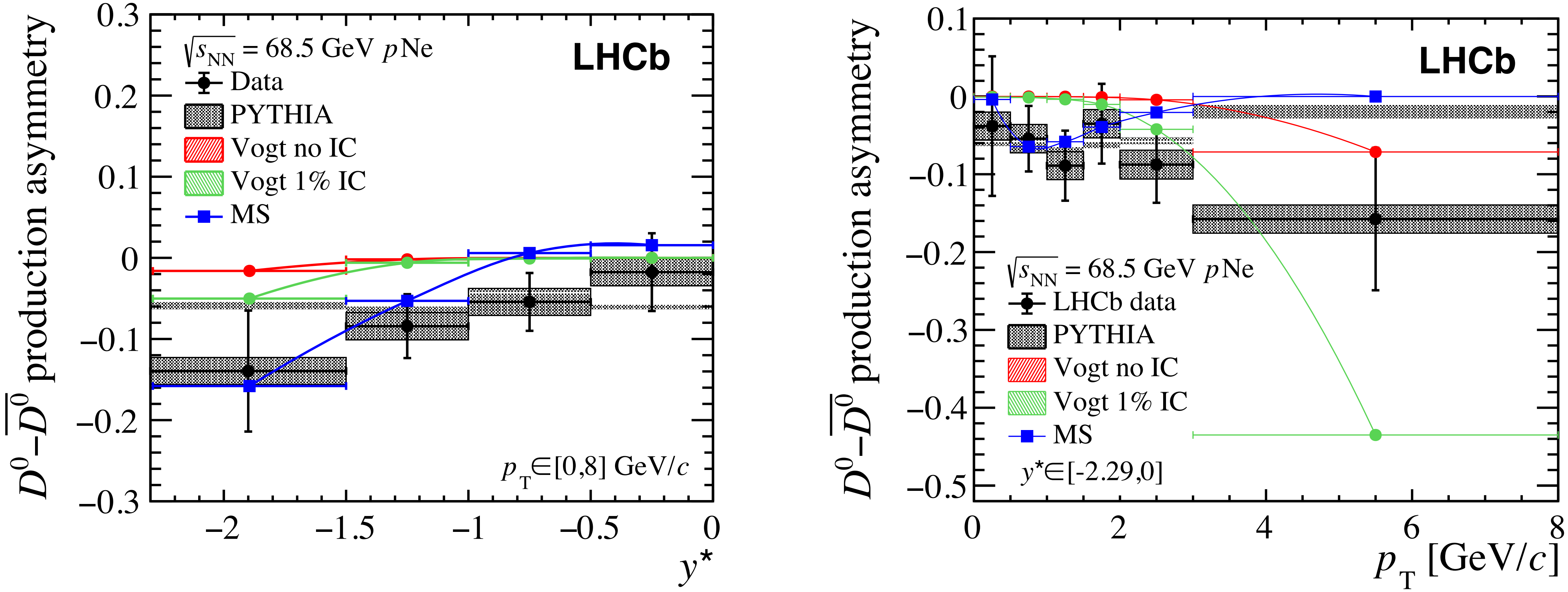
LHCb data: arXiv:2211.11633 **Vogt:** PRC 103 (2021) 035204 **MS:** PLB 835 (2022) 137530
FONLL: PRL 95 (2005) 122001, JHEP 05 (1998) 007 **PHSD:** PRC 96 (2017) 014905

D⁰ Production Asymmetry



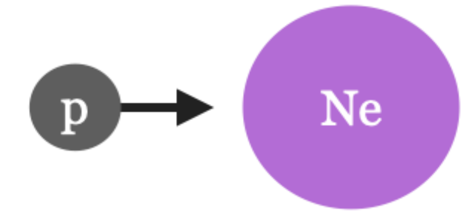
- The production asymmetry probes charm hadronization with a high-x valence quark:

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



- 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

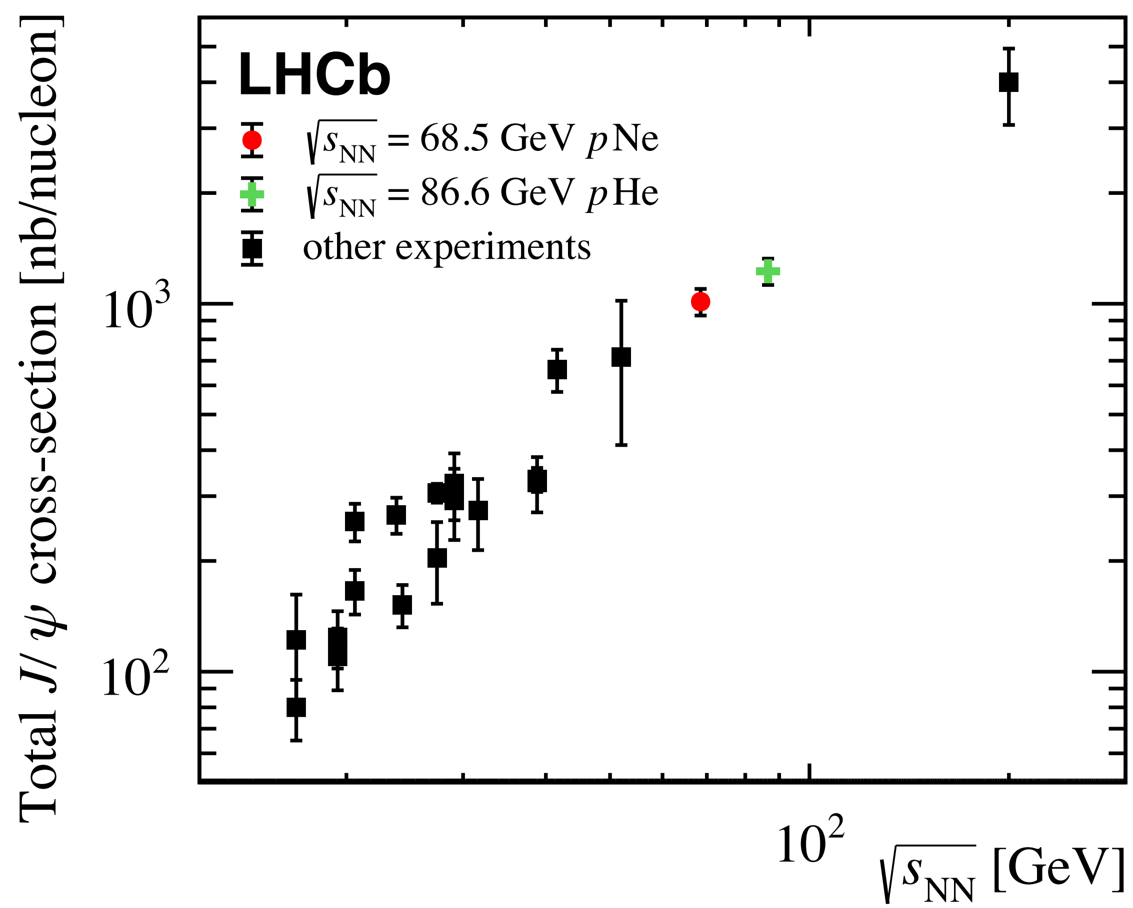
J/ψ cross section measurement at $\sqrt{s_{NN}} = 68.5$ GeV



- 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:

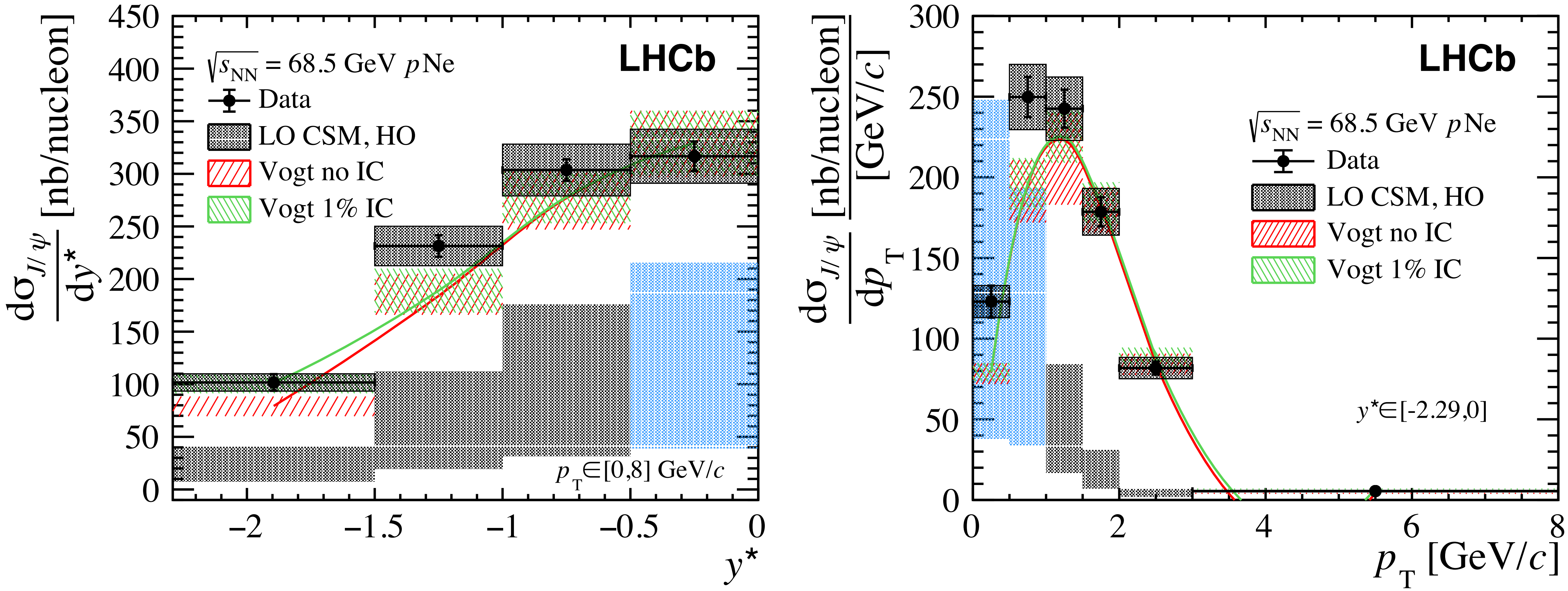
$$\sigma(pNe \to J/\psi\ X) = 1013 \pm 16\ (\text{stat.}) + 83\ (\text{sys.})\ \text{nb}^{-1}/\text{nucleon}$$

- 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!

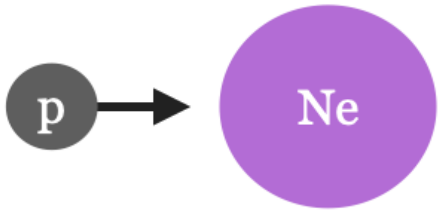
J/ψ differential cross sections

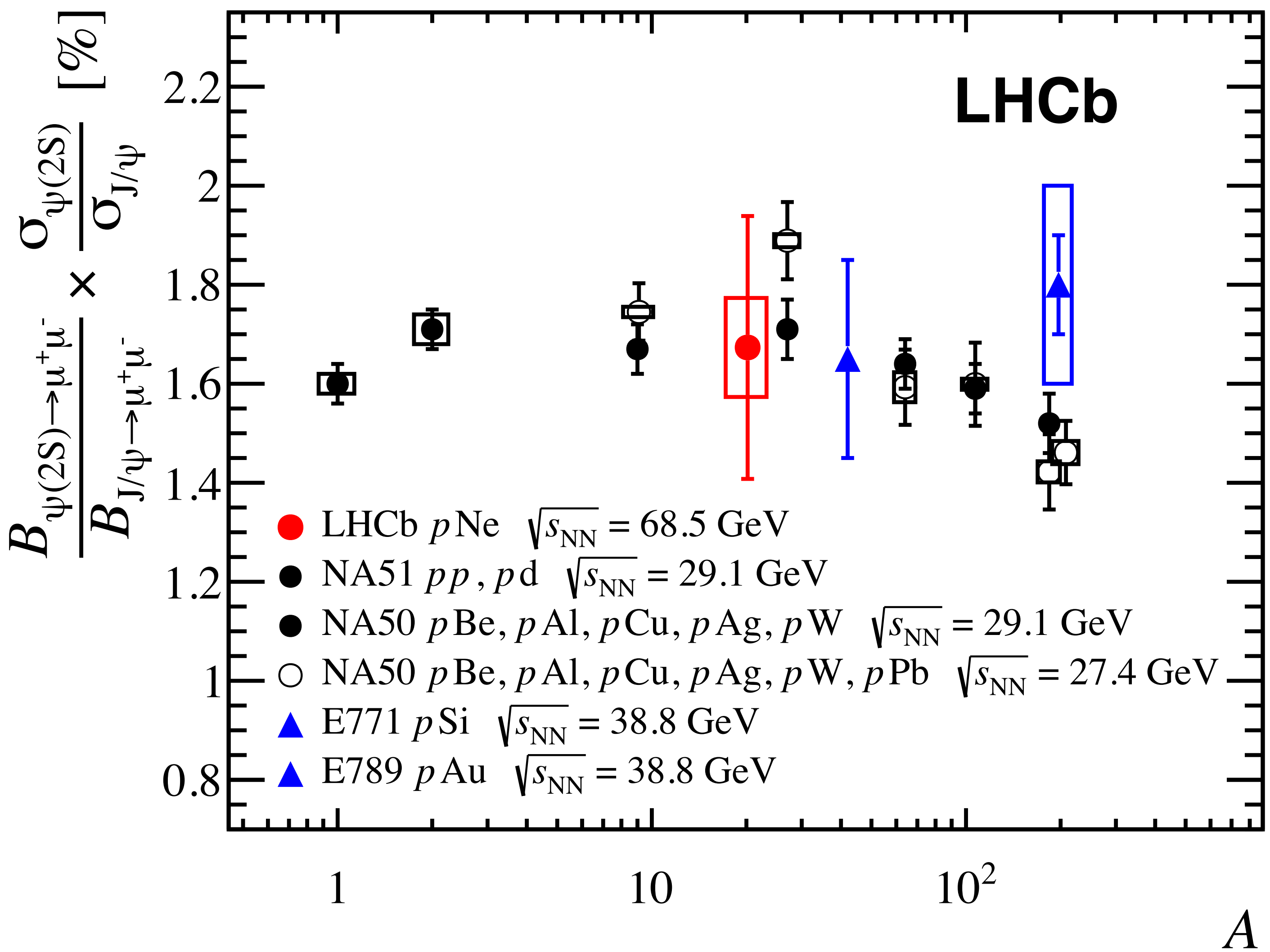


- LO CSM, HO: LO Color Singlet Model (CSM) predictions made using the HELAC-Onia generator with CT14NLO and nCTEQ15 PDF sets
- Vogt predictions use the Color Evaporation Model, EPPS16 nPDFs, and include contributions from nuclear absorption and multiple scattering
- The data does not differentiate between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

LHCb data: arXiv:2211.11645 **Vogt:** PRC 103 (2021) 035204
LO CSM Helac-Onia: CPC 198 (2016) 238, CPC 184 (2013) 2562

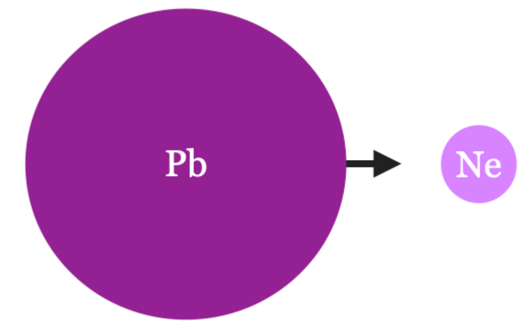
Relative production rate of J/ψ and ψ(2s) mesons

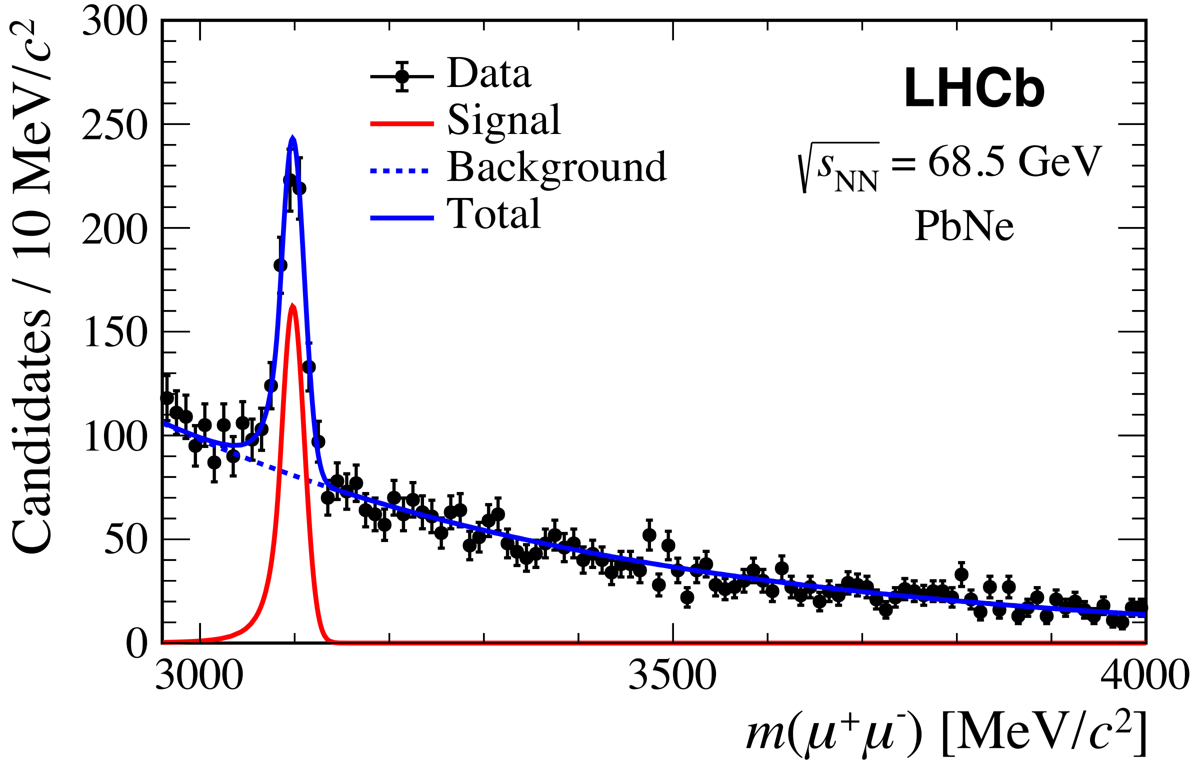


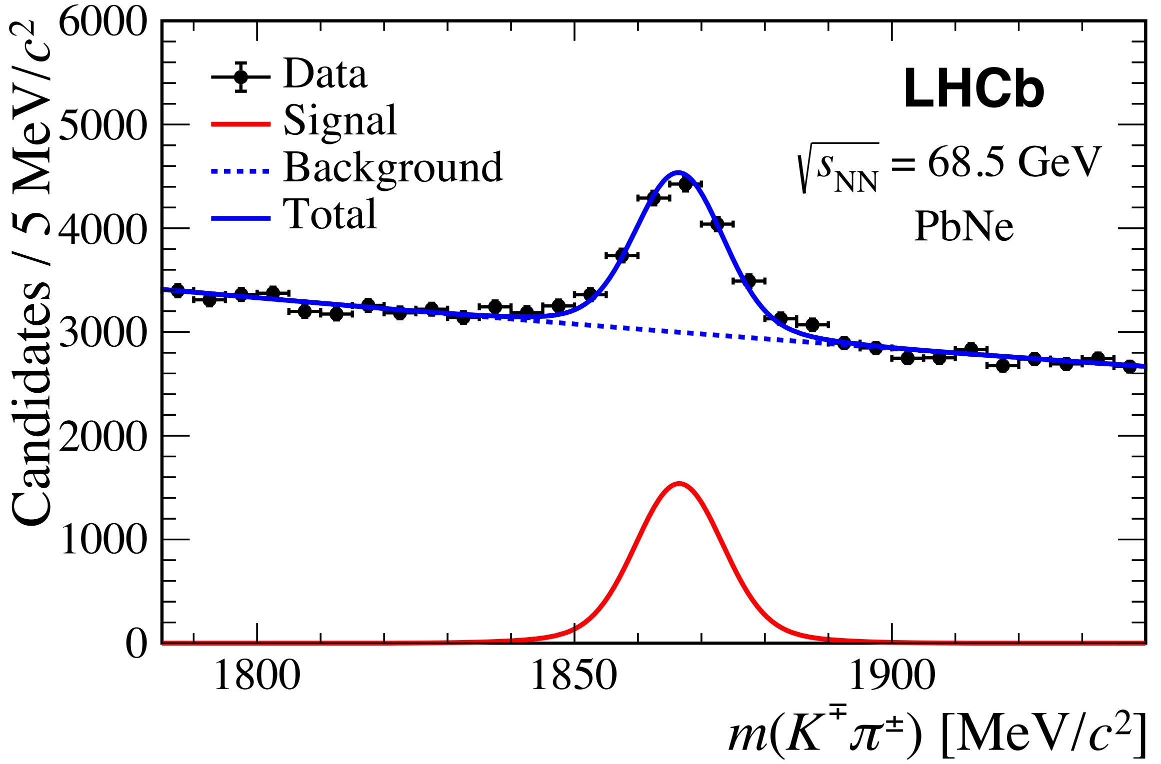


- LHCb measurement: 1.67 ± 0.27 (stat) ± 0.10 (sys) %
- The relative production rate of ψ(2S) to J/ψ mesons in pNe collisions is consistent with the rates measured on other nuclear targets and at other center of mass energies

J/ψ and D^0 production in PbNe collisions at $\sqrt{s_{NN}} = 68.5$ GeV



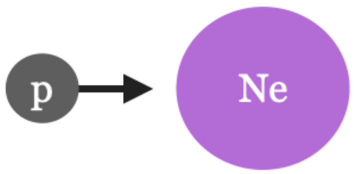


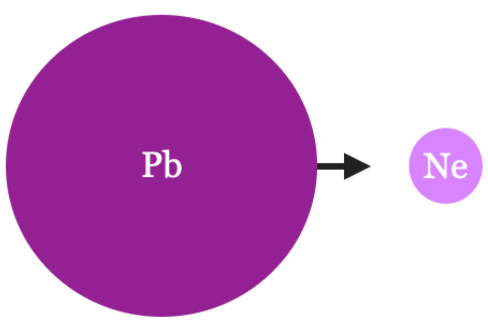


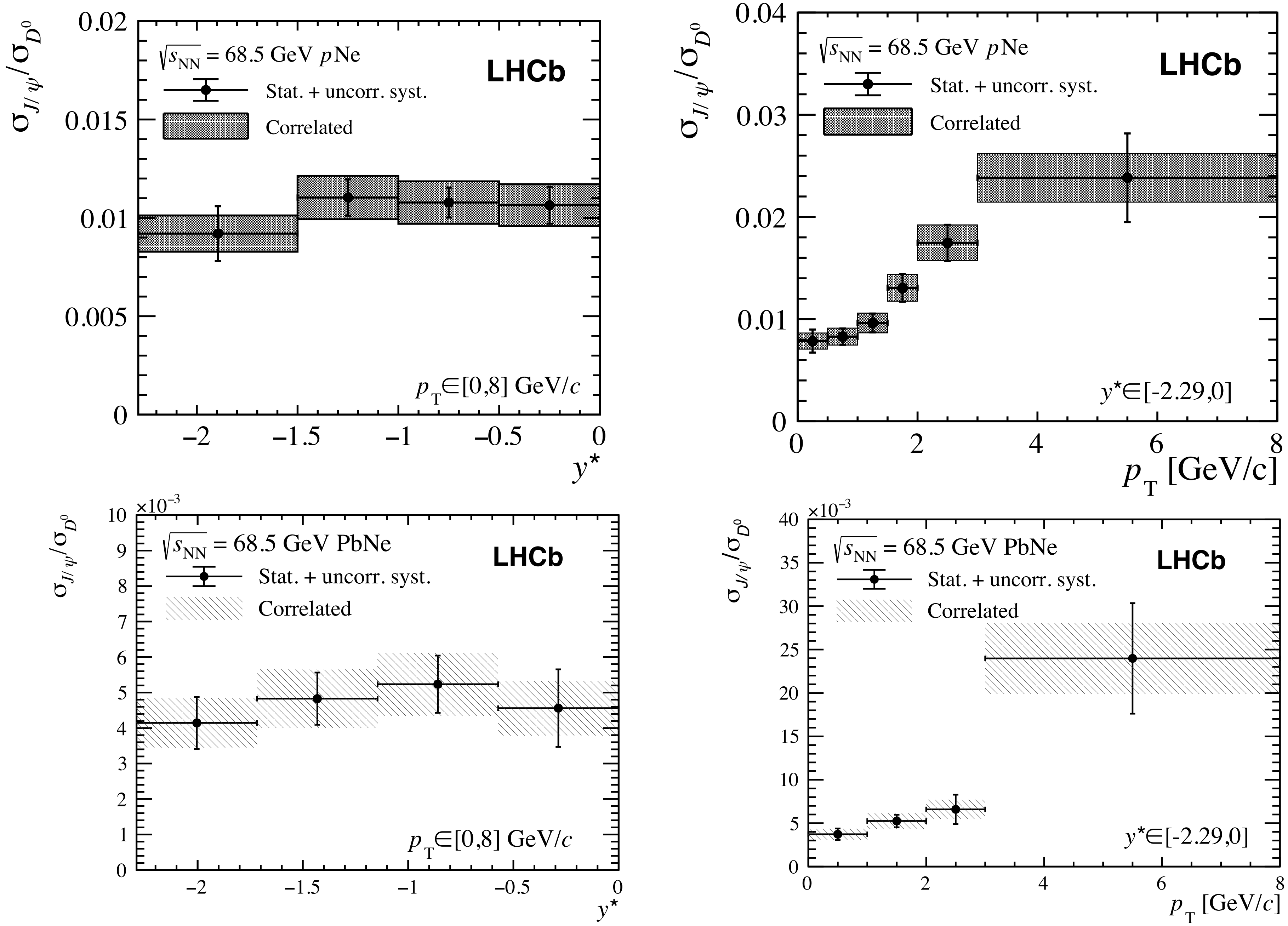
- Larger background than in pA collisions, but clean signal peaks are still observed - proof of measurement feasibility in larger PbA systems
- Similar candidate selection as in pNe measurement
- Heavy flavor hadron $p_T < 8$ GeV
- Heavy flavor hadron y in $2.0 < y < 4.29$

Efficiency-corrected candidate yields: 545 J/ψ, 5670 D^0

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







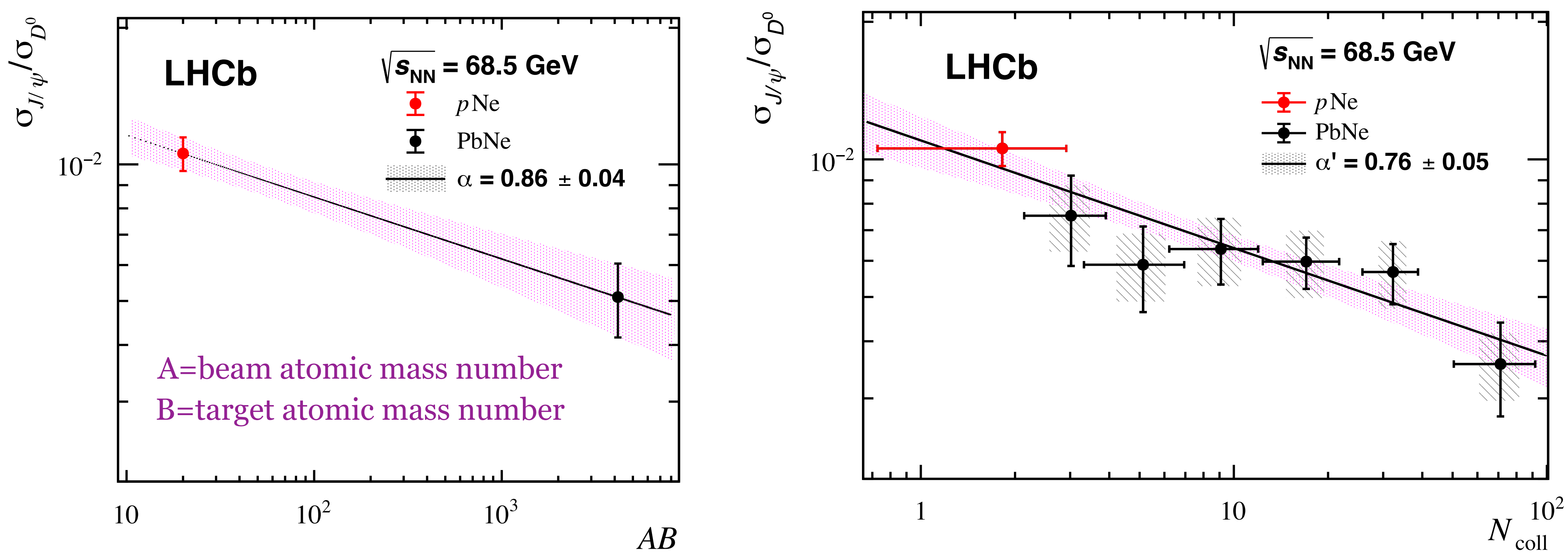
- Compare J/ψ production in large (PbNe) vs small (pNe) nuclear environment at the same √s
- $\sigma_{J/\psi}/\sigma_{D^0}$ shows little dependence on y* and a strong dependence on p_T

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:

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

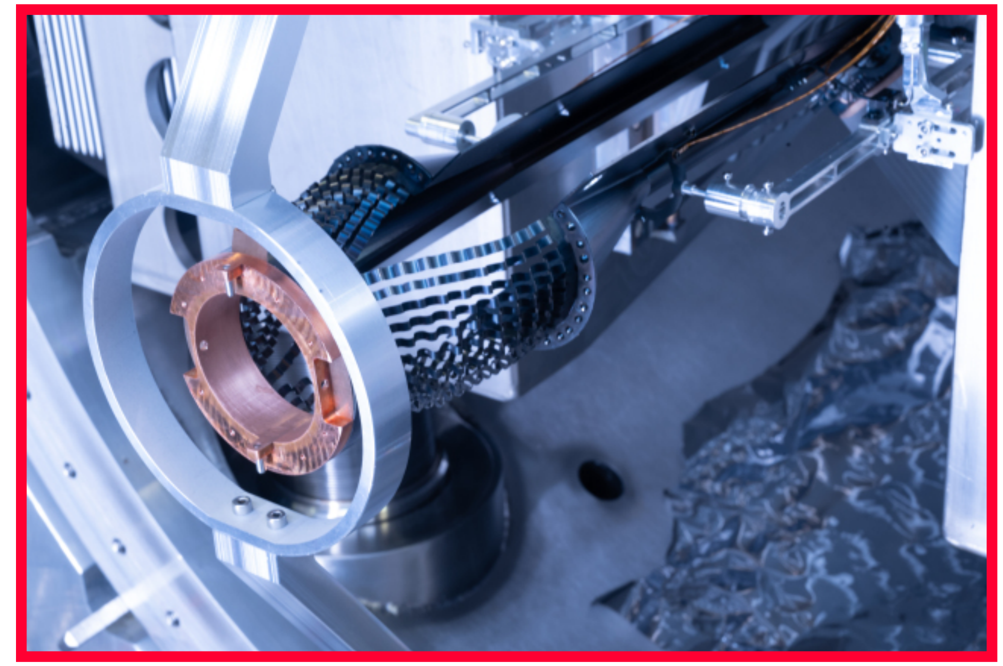
- Same functional form for the ratio as a function of the number of collisions (N_{coll})
- α < 1: indicates that J/ψ mesons experience additional nuclear effects than D^0 mesons
- Since a linear trend is observed between pNe and central PbNe, it is unlikely that anomalous J/ψ suppression or formation of a hot deconfined medium is observed



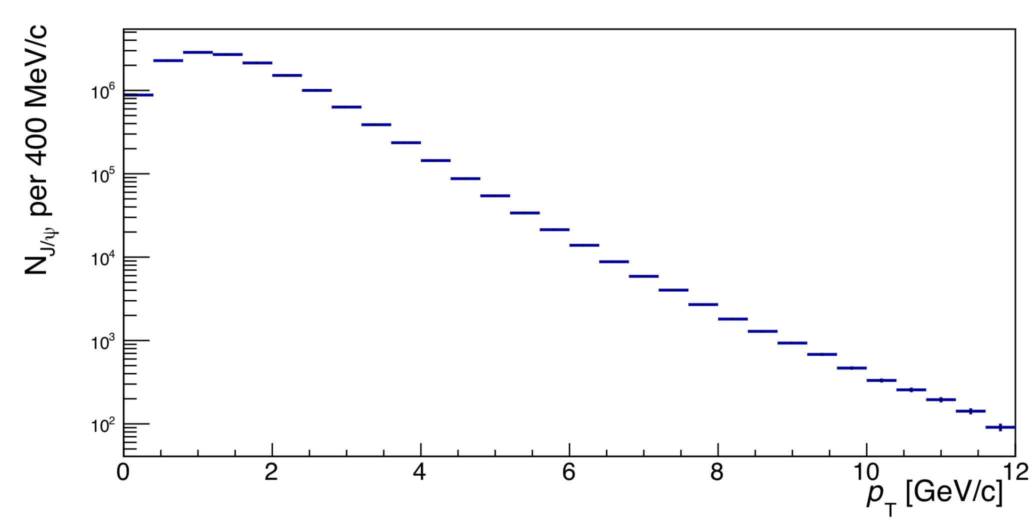
Prospects for Run 3 with LHCb SMOG2

- SMOG2 is a dedicated cell for gas injection installed just before the LHCb VELO
- Smaller cell size (20cm long, 1cm diameter) allows for increased gas densities and therefore higher luminosities with respect to SMOG1
- Can run in parallel with collider mode pp physics data taking at LHCb
- Equipped with a sophisticated Gas Feed System to store and inject 8 different gases: H_2, D_2, Ar, Kr, Xe, He, Ne, N_2, O_2
- 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

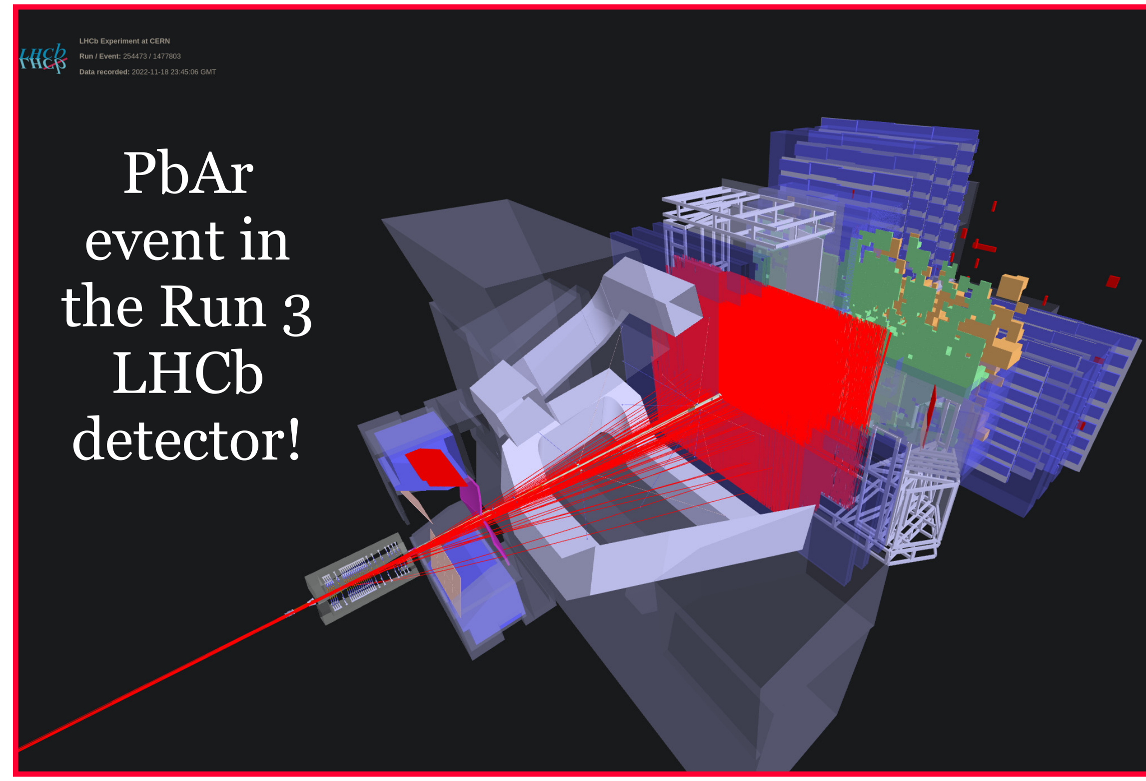


Projected J/ψ p_T spectrum with statistical uncertainties for 45 pb^{-1} of SMOG2 pAr data:

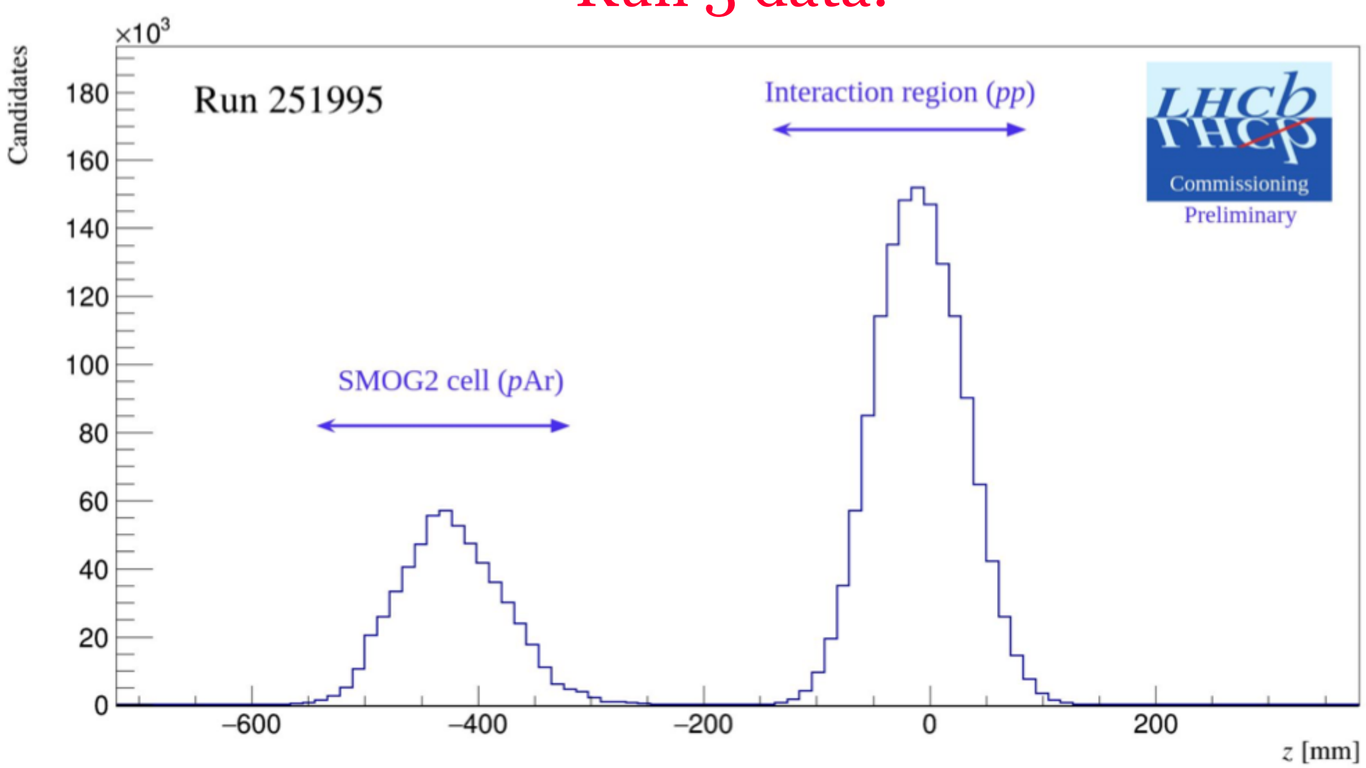


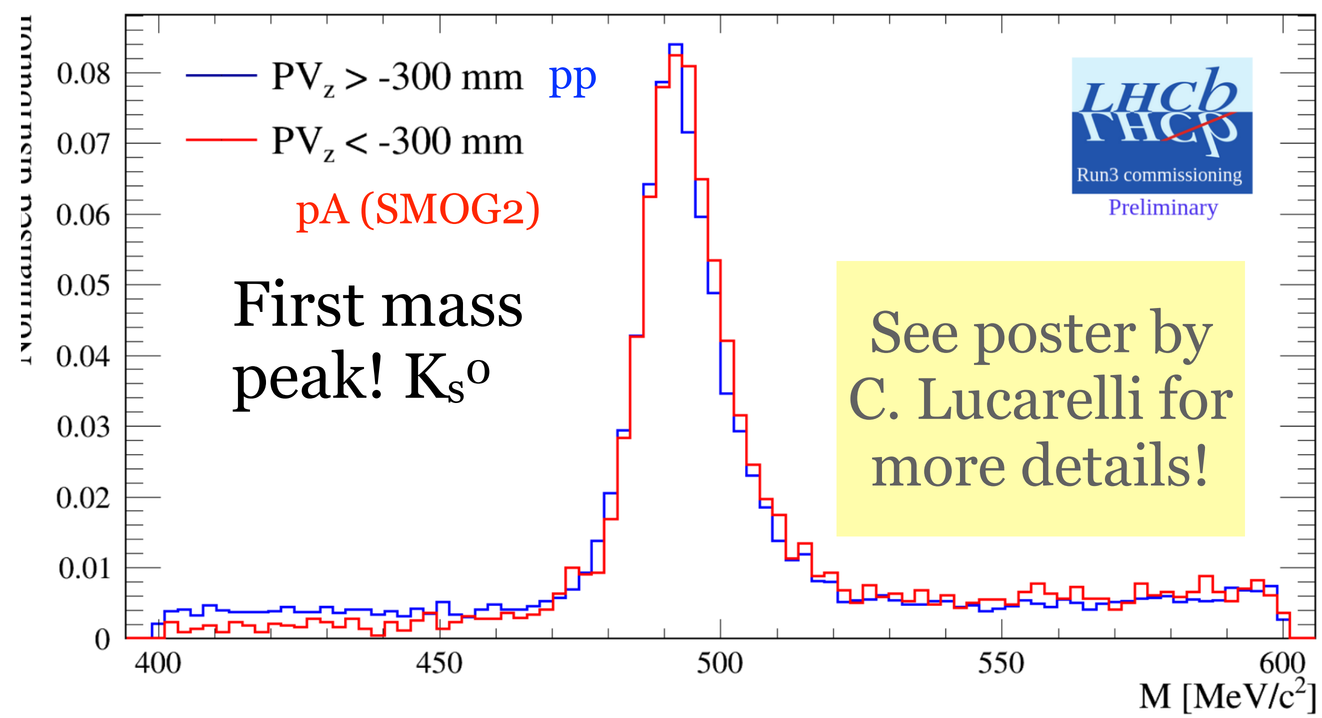
First look at Run 3 SMOG2 data

- First Run 3 data successfully taken in 2022!
- Commissioning performed with Argon, Helium, and Hydrogen gases
- Preliminary data shows good separation between SMOG2 and pp vertices, in agreement with previous simulation studies
- Analysis of 2022 data ongoing



Run 3 data:





Conclusions

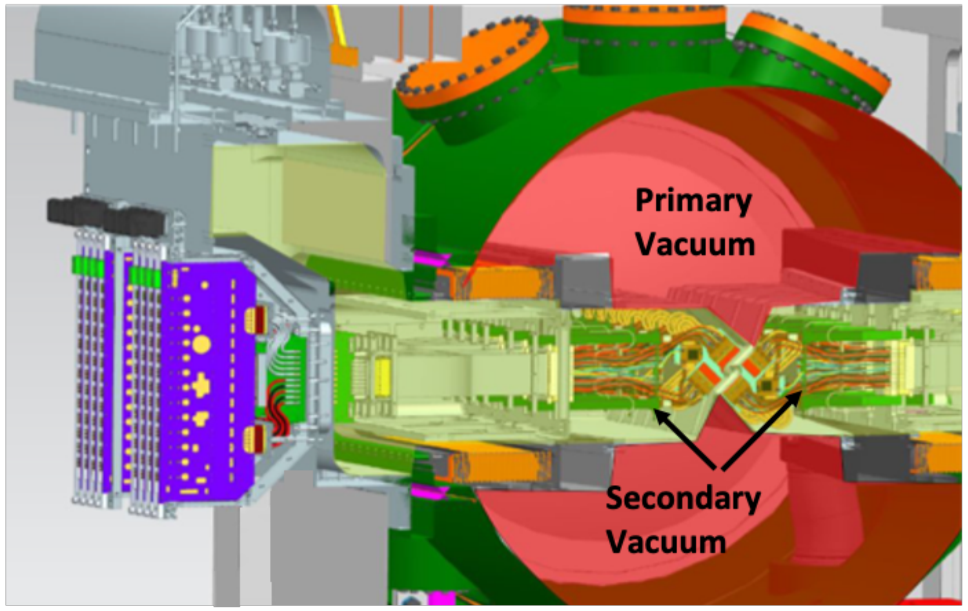
- Fixed target experiments at the LHC provide opportunities to study quarkonia production in a wide variety of nuclear systems and in a unique region of phase space
- LHCb has studied quarkonia production in pHe, pAr, pNe and PbNe fixed-target collisions
- New measurements of D^0 and charmonium production in pNe and PbNe collisions at $\sqrt{s_{NN}} = 68.5$ GeV have been performed by LHCb
- Comparisons of the J/ψ and D^0 cross sections in PbNe collisions do not suggest the presence of anomalous suppression or the formation of a hot nuclear medium
- The first Run 3 data has been taken with LHCb's fixed target upgrade, SMOG2, in parallel with the collider pp physics data-taking
- Many quarkonia measurments are possible with SMOG2 and can help disentangle different CNM effects and hot vs. cold QCD matter effects

Thank you for your attention!

Backup

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

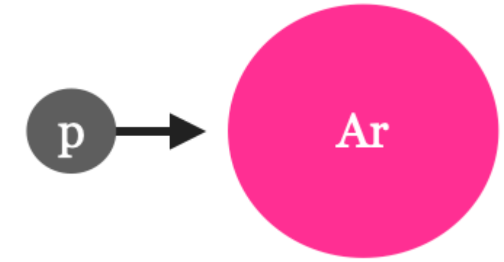
RF foils have suffered plastic deformation up to 14 mm and have to be replaced. Major intervention, planning under study

- 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

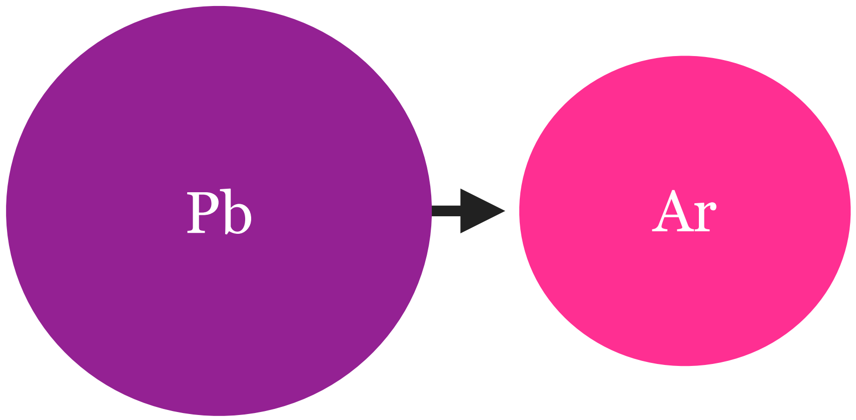
- Evaluating impact on SMOG2 for 2023
- SMOG injection as in Run 2 is still possible

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>

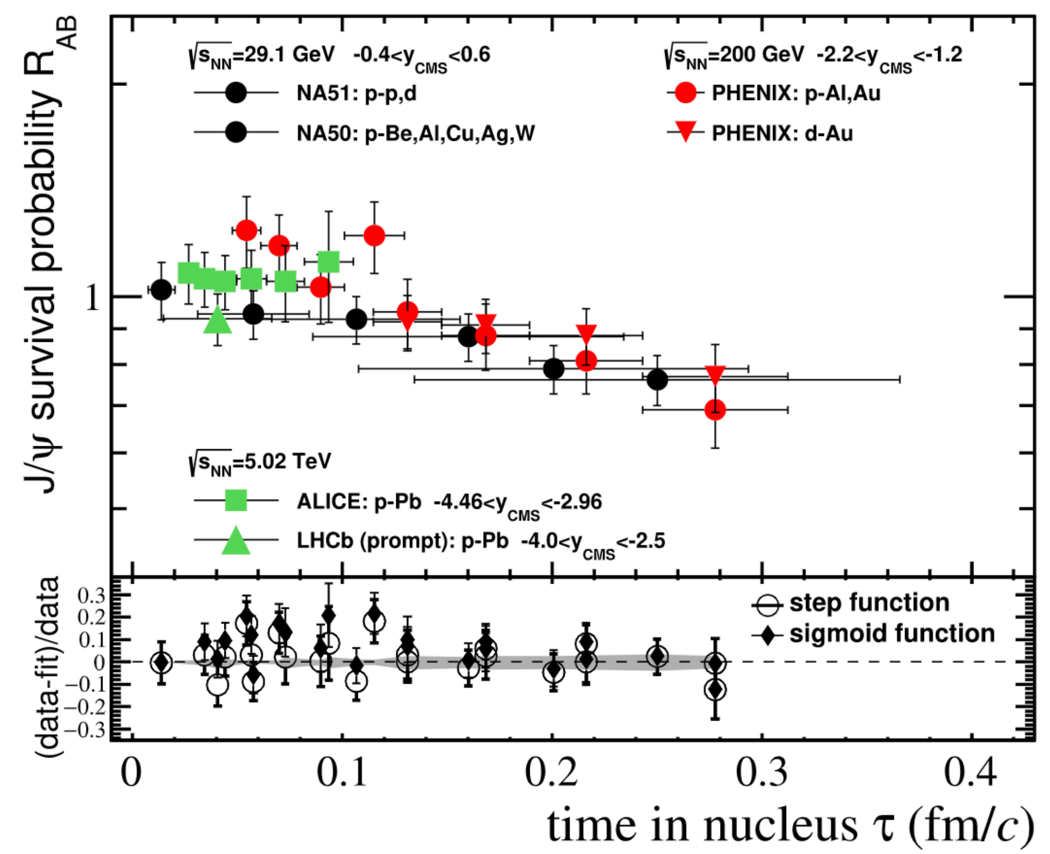
- **Upsilon production in pAr collisions** - study CNM effects as a function of bound state size and quark flavor content (e.g. parton energy loss effects)
- **Multi-differential ψ(2S) measurements in pAr collisions** - complement differential J/ψ measurements and test theoretical models of quarkonium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

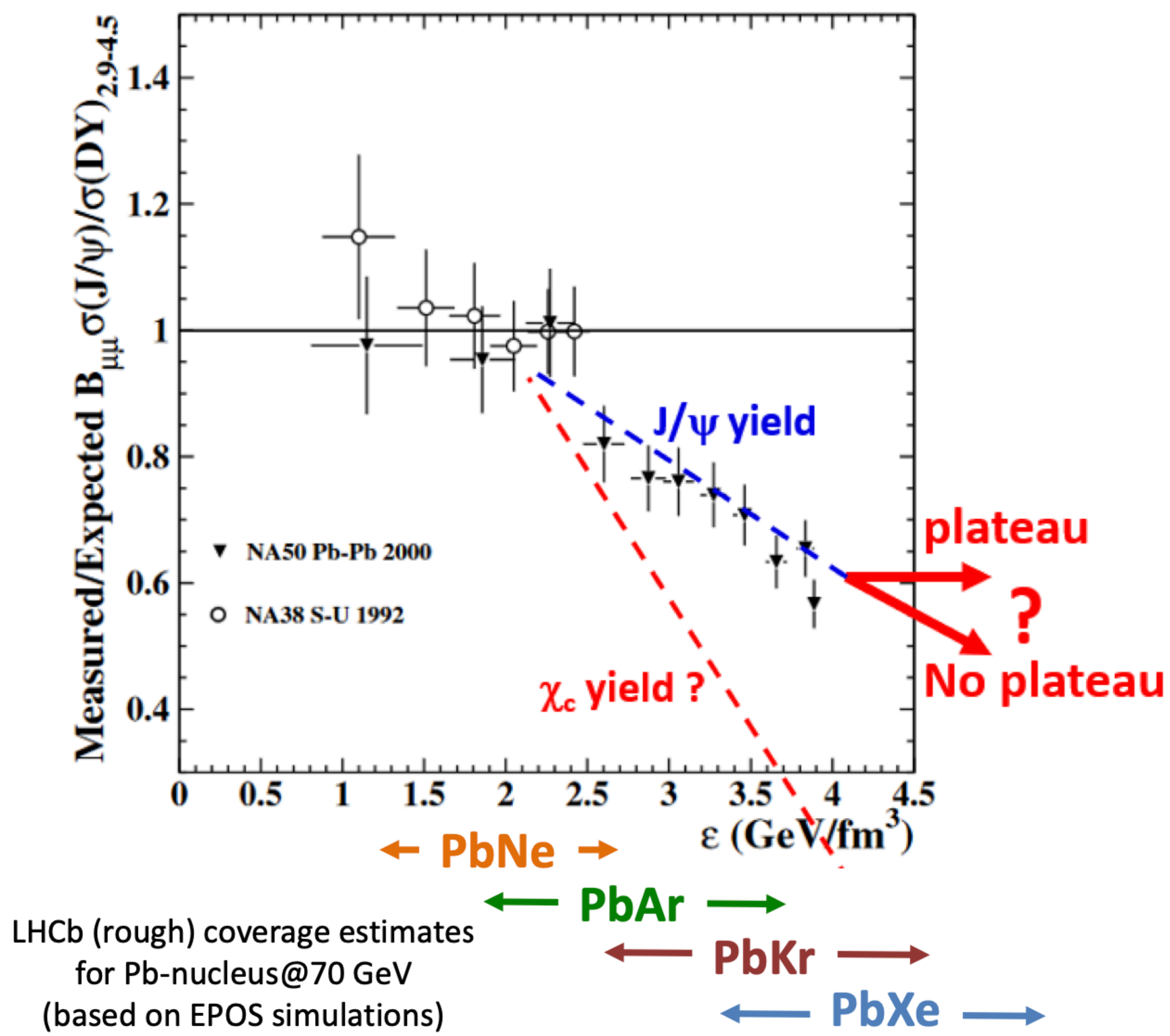


- **Quarkonia production in additional collision systems**
  - pD_2, pKr, pXe, pN_2, pO_2 collisions all possible
  - PbH_2, PbKr, PbXe…

- **Drell-Yan** measurements

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

PbA Collisions with SMOG2



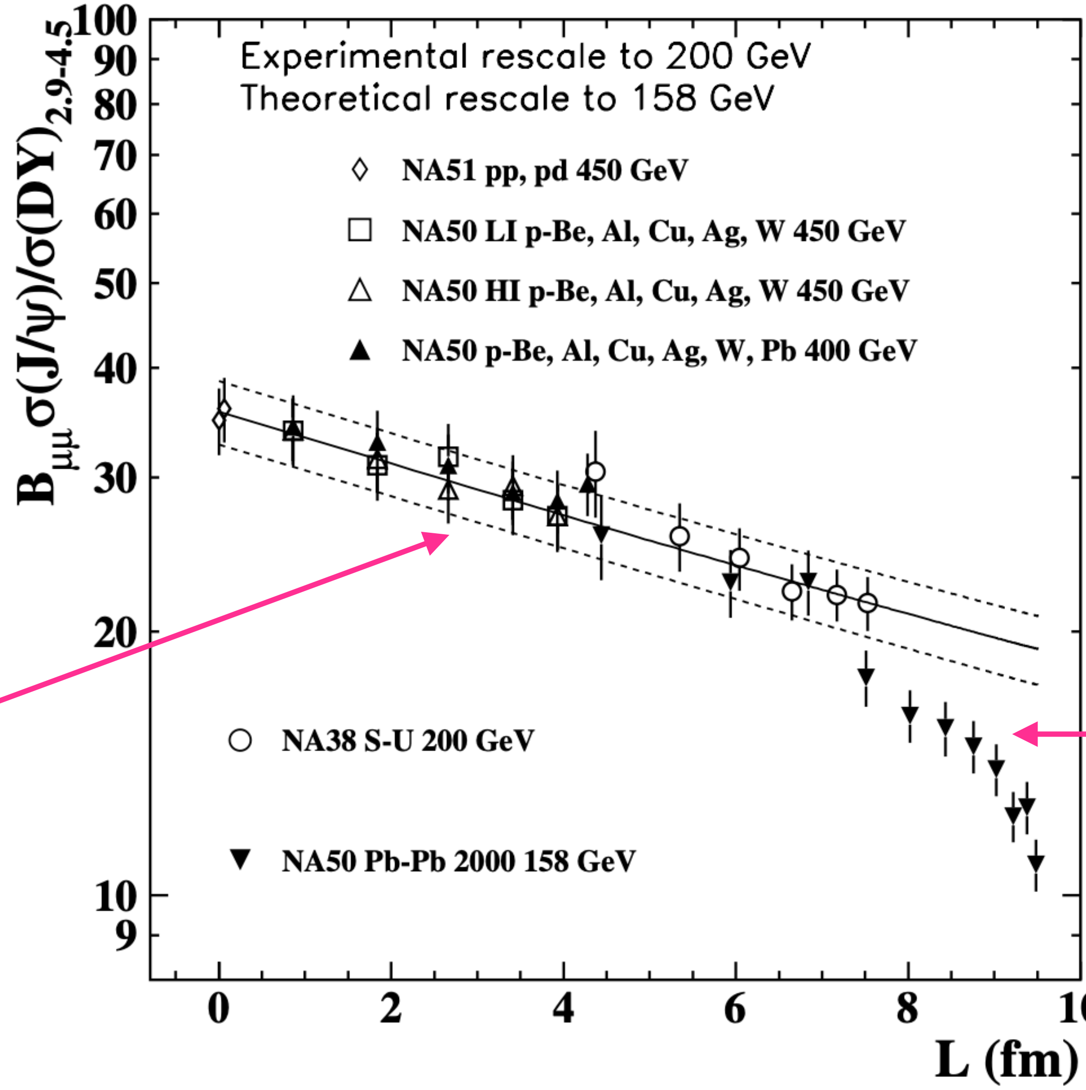
- Depending on the specific nucleus-nucleus collision, QGP may or may not be formed
- With **PbAr** collisions, LHCb can probe the energy density region where NA50 observed an anomalous J/ψ suppression
- LHCb can also measure **pAr collisions at the same energy** to measure the cold nuclear matter effects

Figure from F. Fleuret

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

Anomalous J/ψ suppression observed by NA50



Expected suppression due to nuclear absorption

Anomalous suppression

Centrality at LHCb

Centrality classes for PbNe collisions