Charm production with LHCb fixed-target

Kara Mattioli

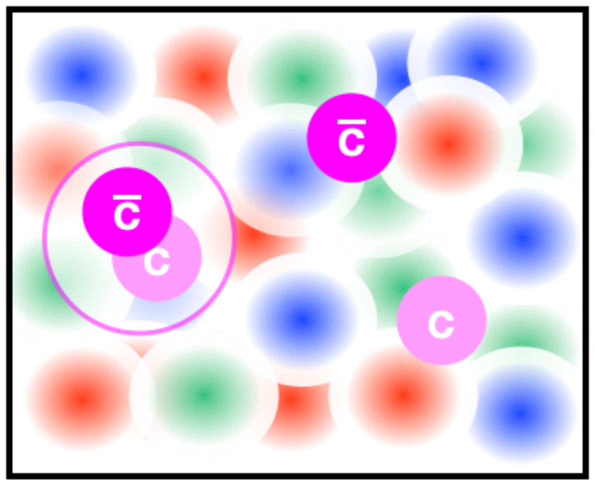
Laboratoire Leprince Ringuet, CNRS

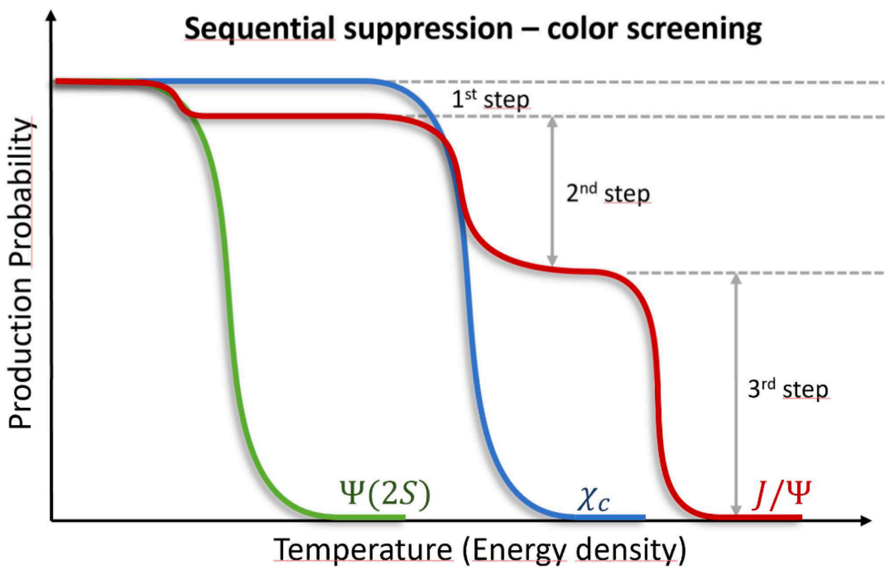
Rencontres QGP France 2023

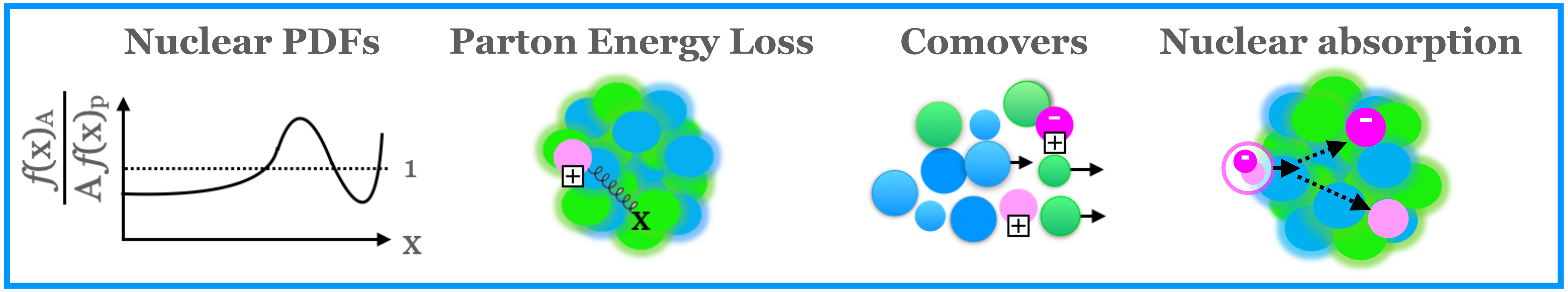
27 June 2023

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**



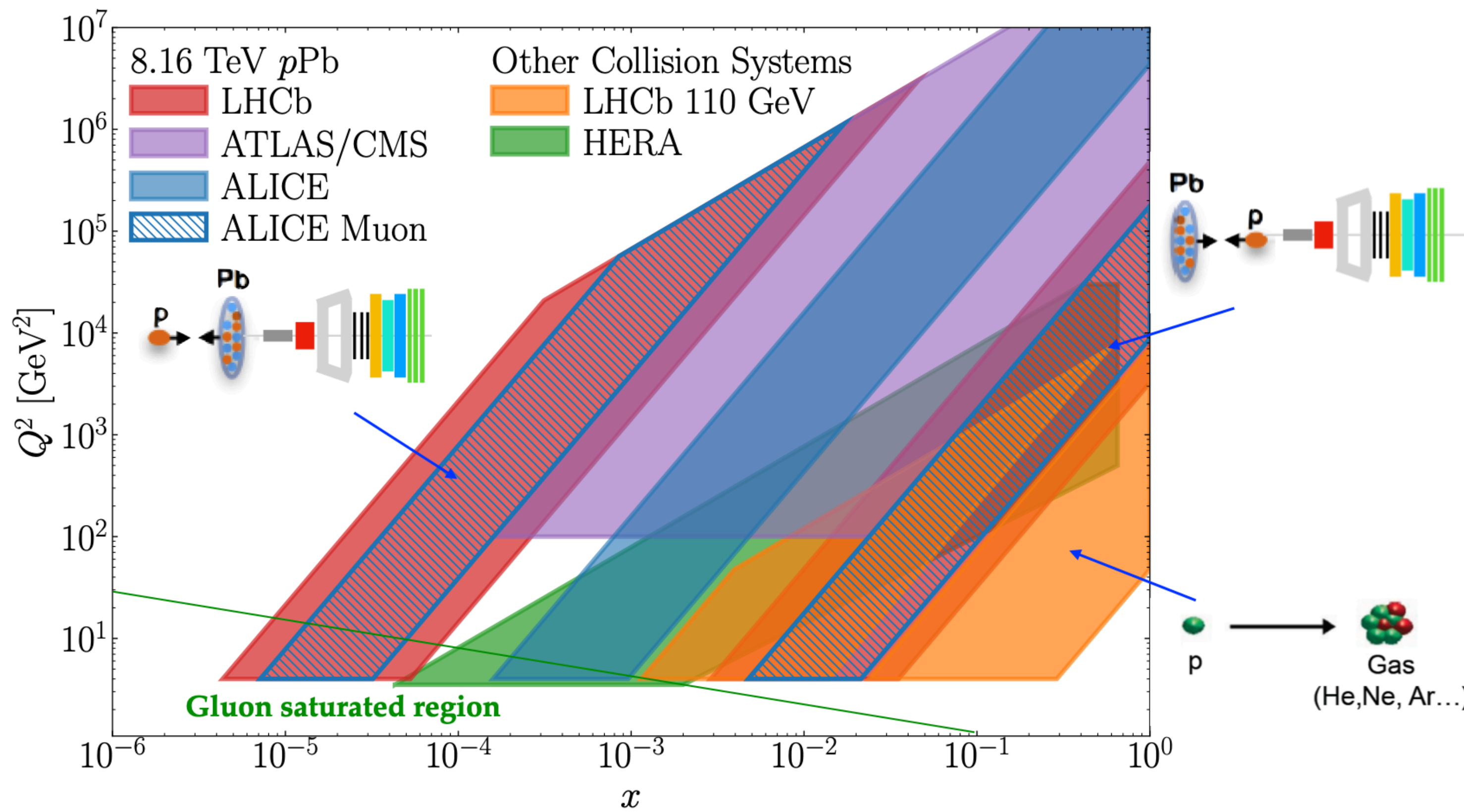




- A comprehensive understanding of CNM effects requires measuring charmonia production in a variety of nuclear systems and kinematic phase space

Fixed target kinematics at the LHC

- **Unique access** to high Bjorken x and low Q^2 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

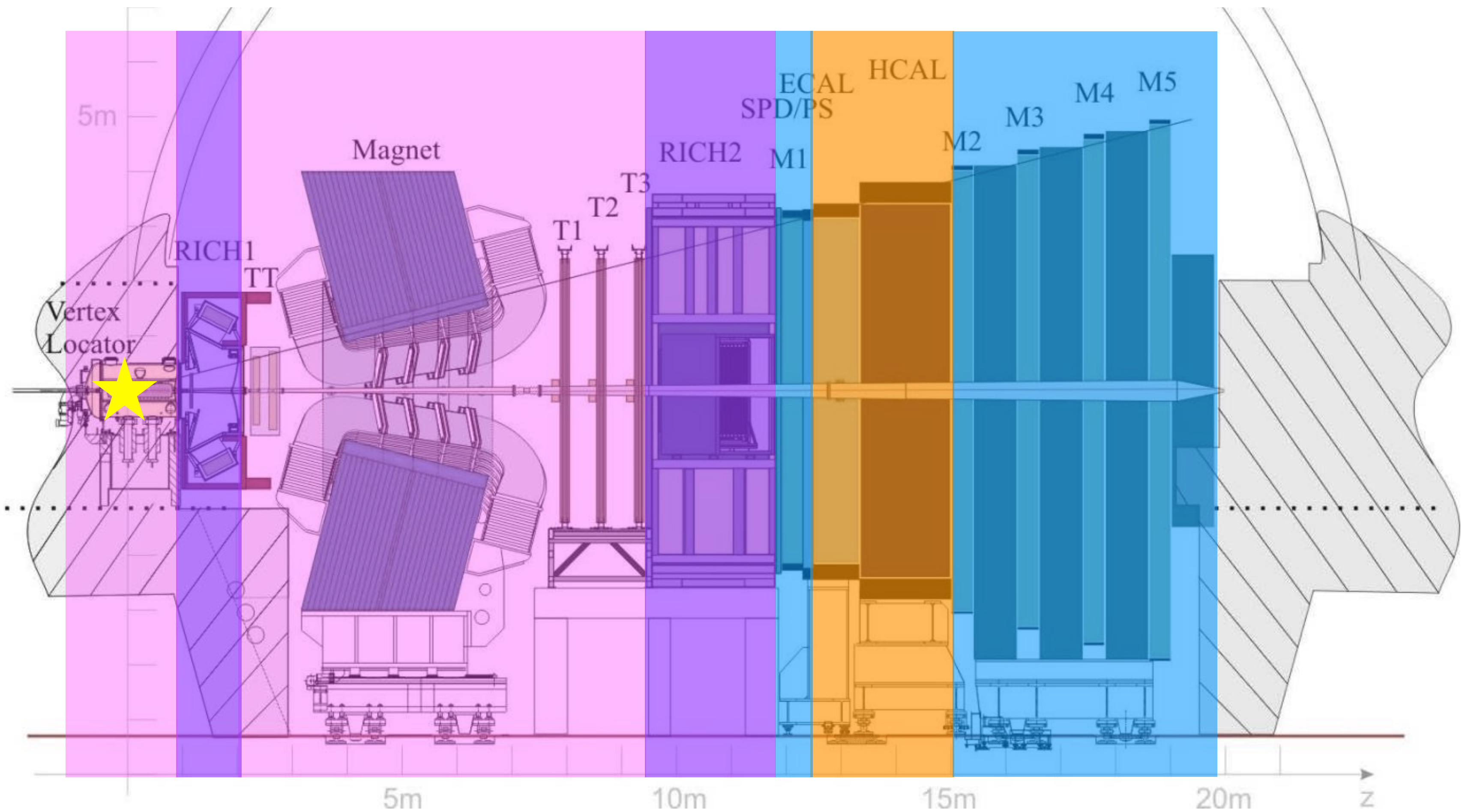
√s (incident p or A beams)

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!

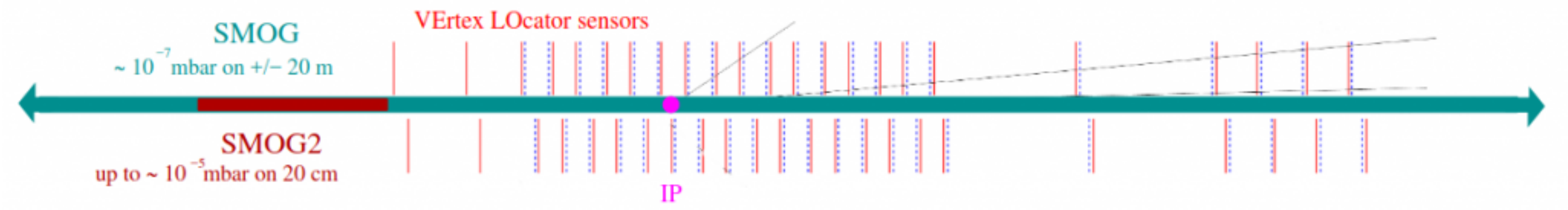
The LHCb Detector: Full **tracking**, **particle identification**, **hadronic and electromagnetic calorimetry** and **muon ID** in $2 < \eta < 5$



- 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

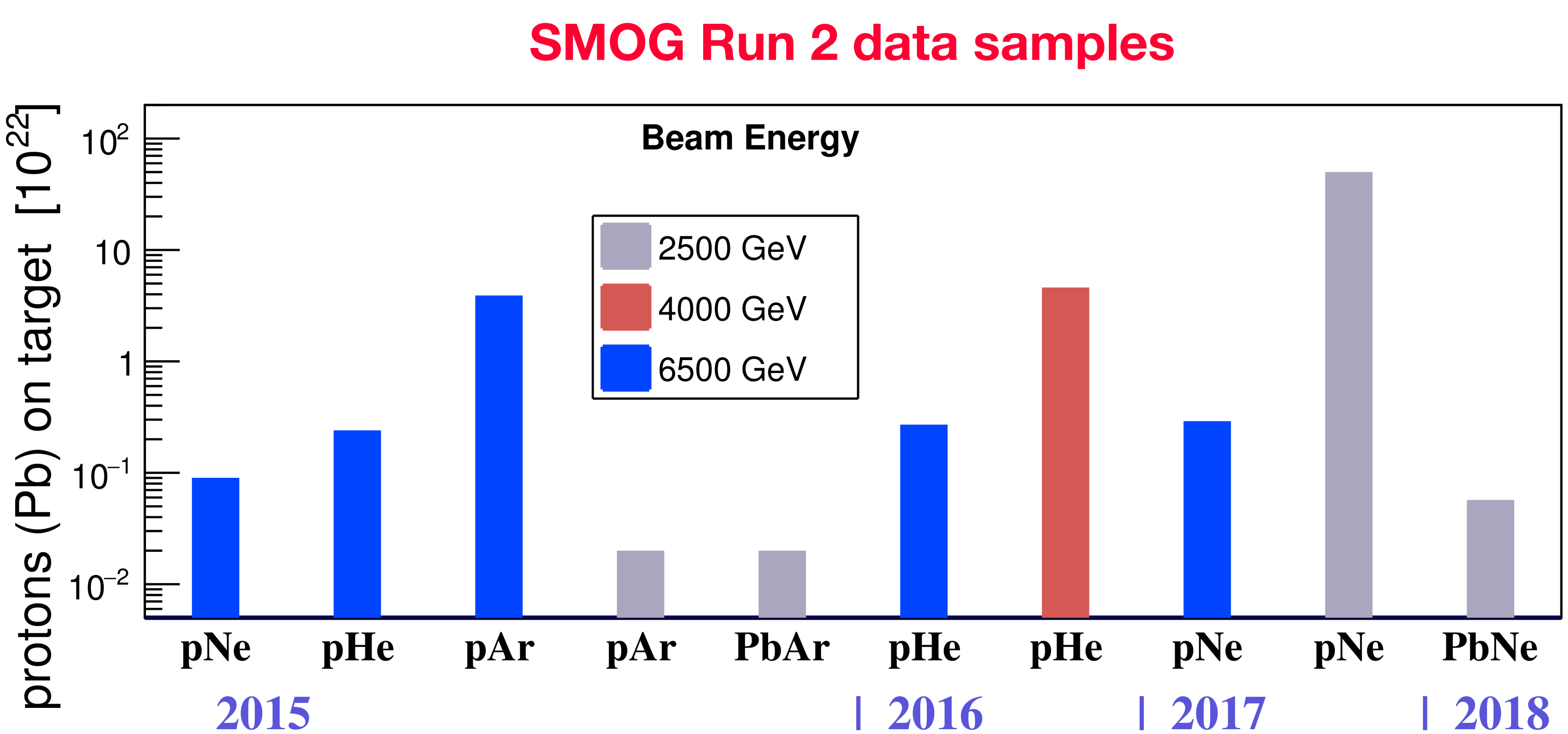
The LHCb fixed-target program

- 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}

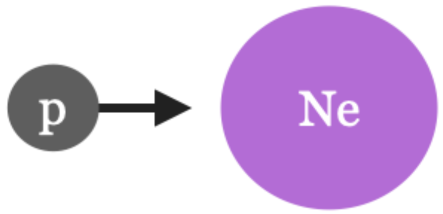
- Several pA and PbA data samples collected:

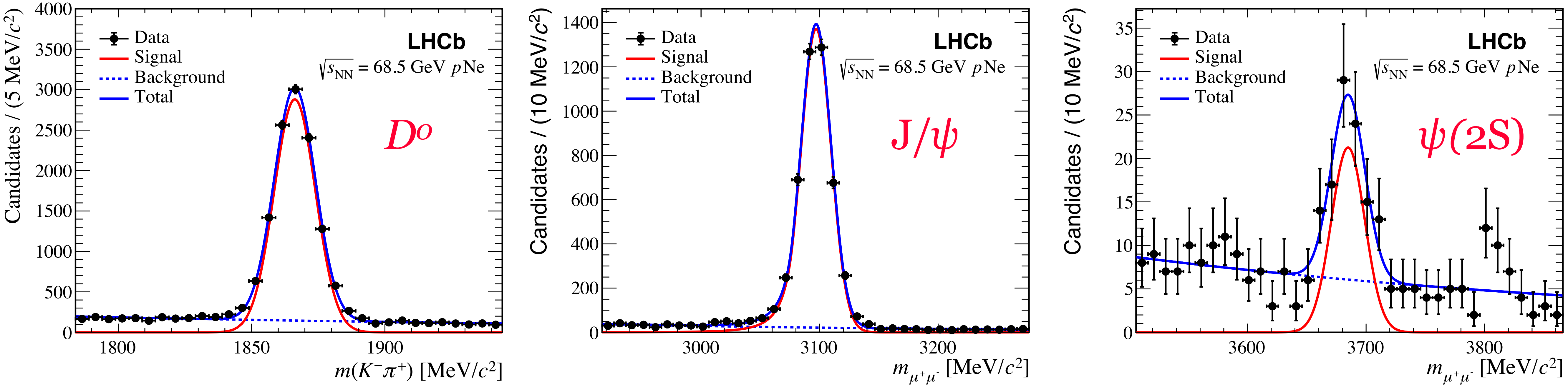


Charm measurements with SMOG

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 $\psi(2S)$ cross sections and production ratio • D^0 cross section and asymmetry See talk today by Gabriel Ricart for discussion of D^0 asymmetry results!	***new!*** arXiv:2211.11645 arXiv:2211.11633
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 ***first fixed-target AA measurement at the LHC!***	***new!*** arXiv:2211.11652

Heavy flavor signal yields in pNe collisions



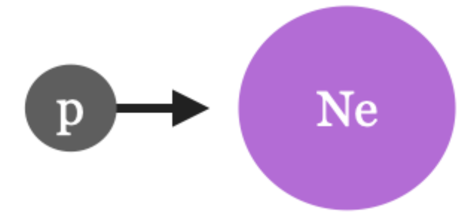


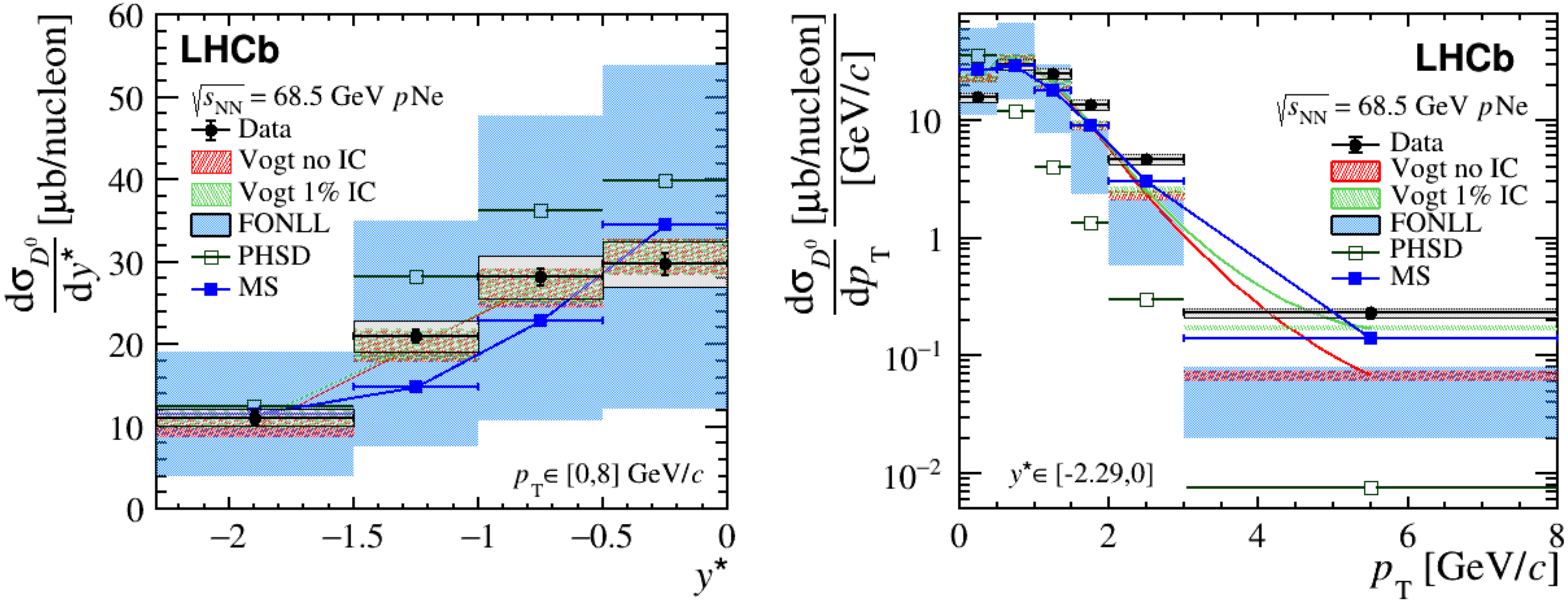
24, 408 D^0 — 4542 J/ψ — 76 ψ(2S)

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
- For D^0, identified K^- and π^+ tracks with p_T > 250 MeV

D^0 differential cross sections



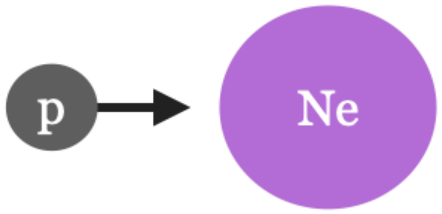


- FONLL and PHSD predictions fail to reproduce the p_T distribution seen in data
- The Vogt 1% IC and the MS predictions both include 1% intrinsic charm contribution in the proton
- MS includes 10% recombination contributions, Vogt includes shadowing effects
- PDF and factorisation scale uncertainties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

See talk by Gabriel Ricart for D^0 charge asymmetry in pNe!

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

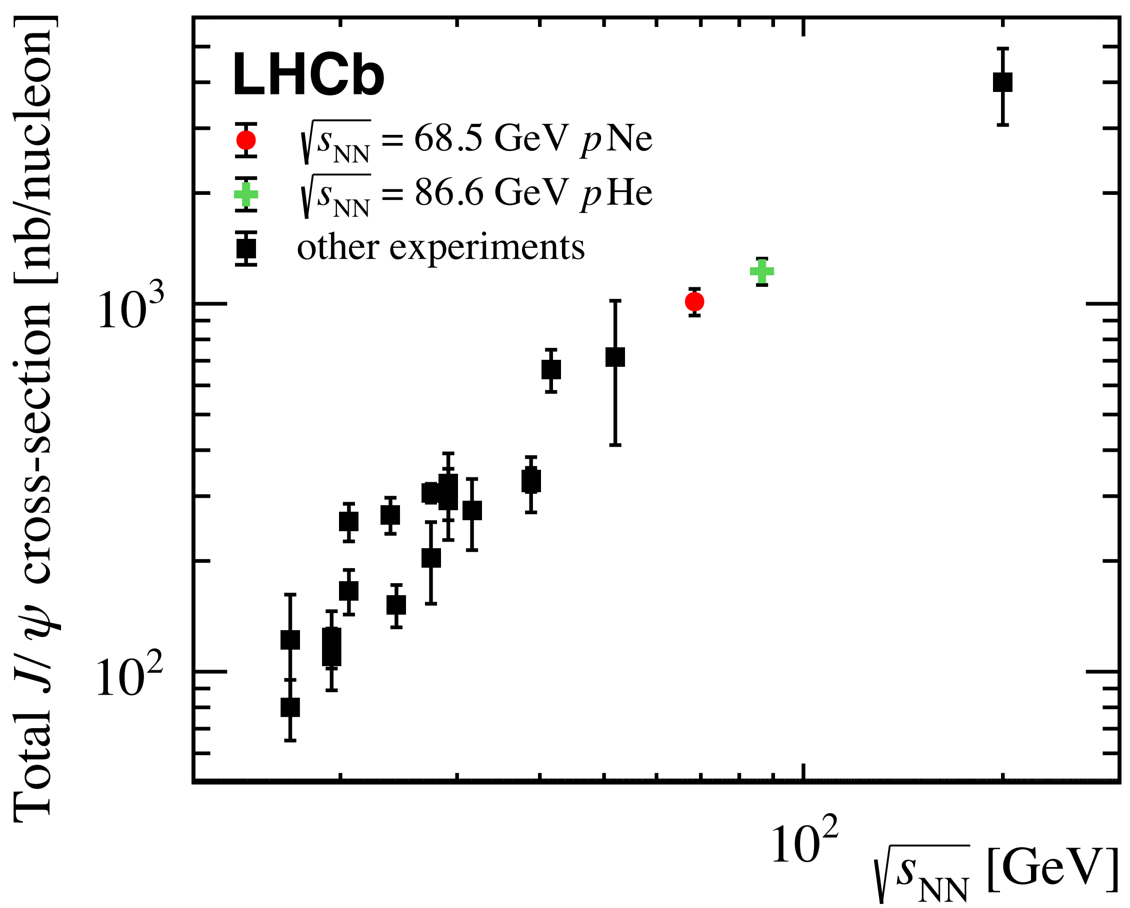
J/ψ cross section measurement at $\sqrt{s_{NN}}$ = 68.5 GeV



- 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:

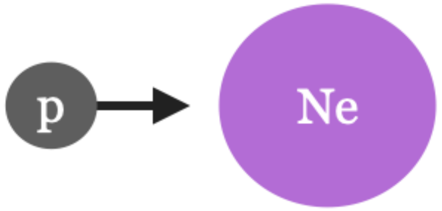
$$\sigma(pNe \rightarrow J/\psi\ X) = 1013 \pm 16\ (\text{stat.}) + 83\ (\text{sys.})\ \text{nb}^{-1}/\text{nucleon}$$

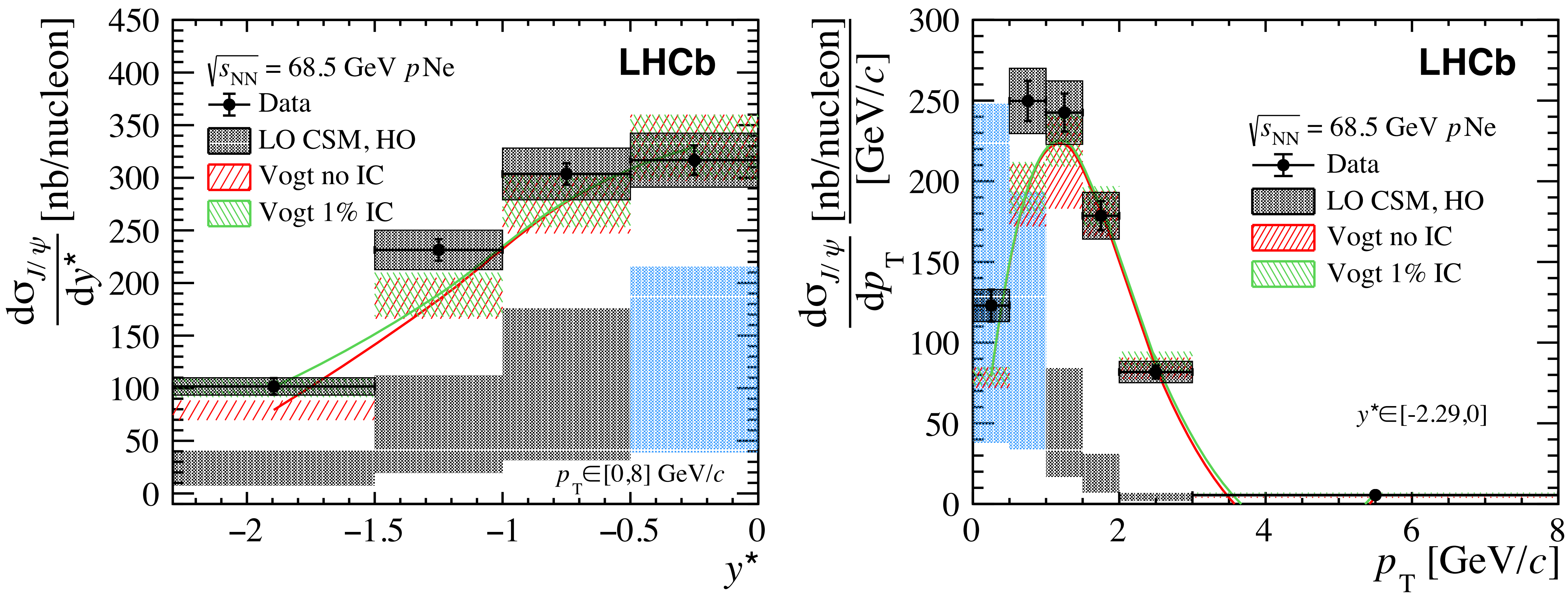
- Comparison to cross section measurements from other experiments shows a power law dependence on the center of mass energy:



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

J/ψ differential cross sections

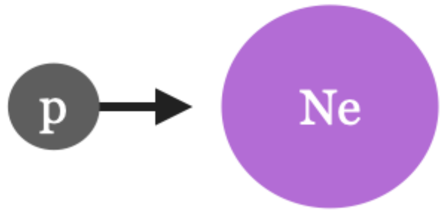


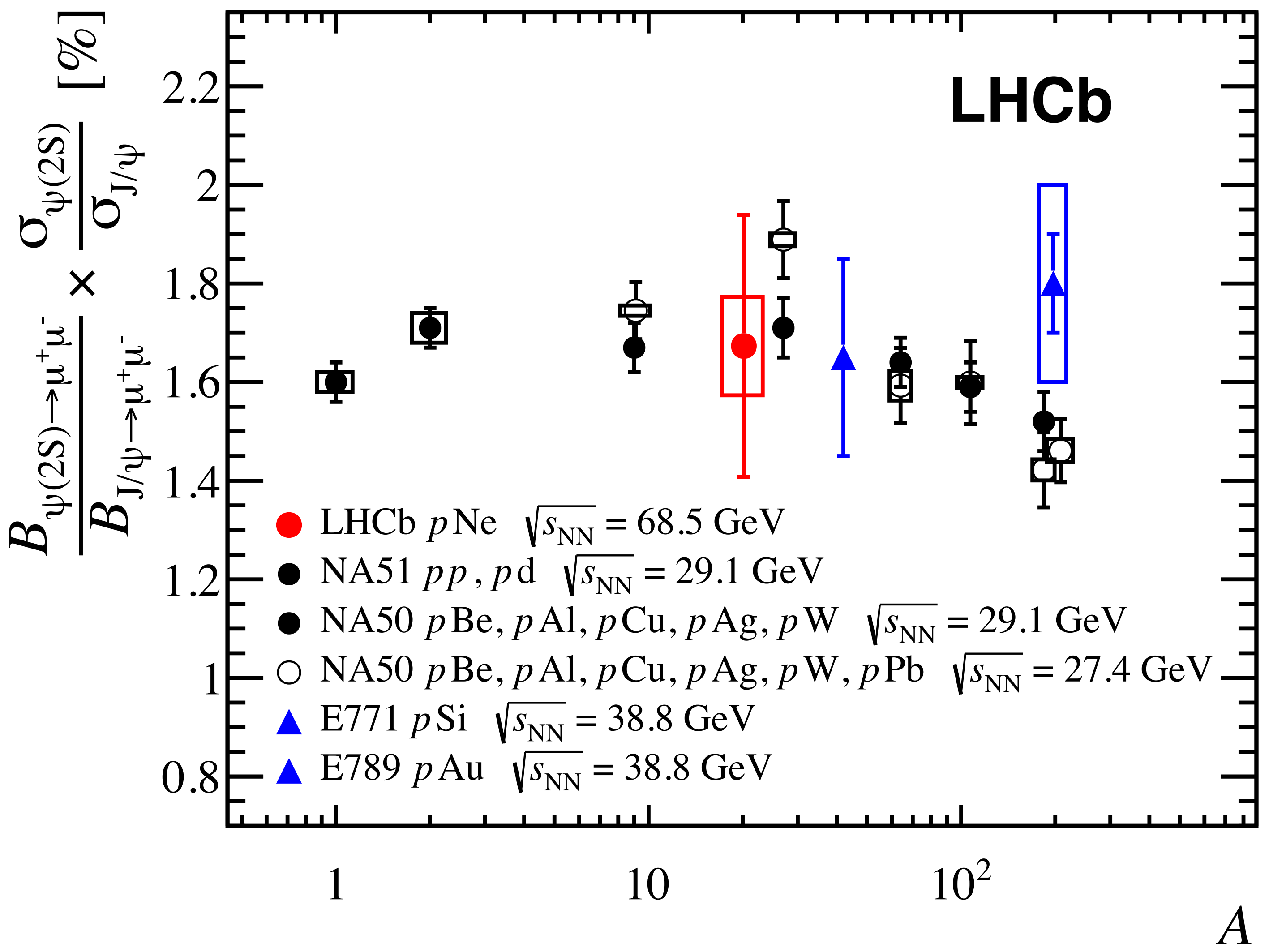


- LO CSM, HO: LO Color Singlet Model (CSM) predictions made using the HELAC-Onia generator with CT14NLO and nCTEQ15 PDF sets
- Vogt predictions use the Color Evaporation Model, EPPS16 nPDFs, and include contributions from nuclear absorption and multiple scattering
- The data does not differentiate between 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

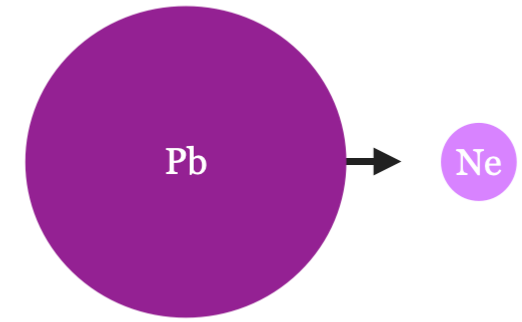
Relative production rate of J/ψ and ψ(2s) mesons





- 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

From pA to PbA collisions



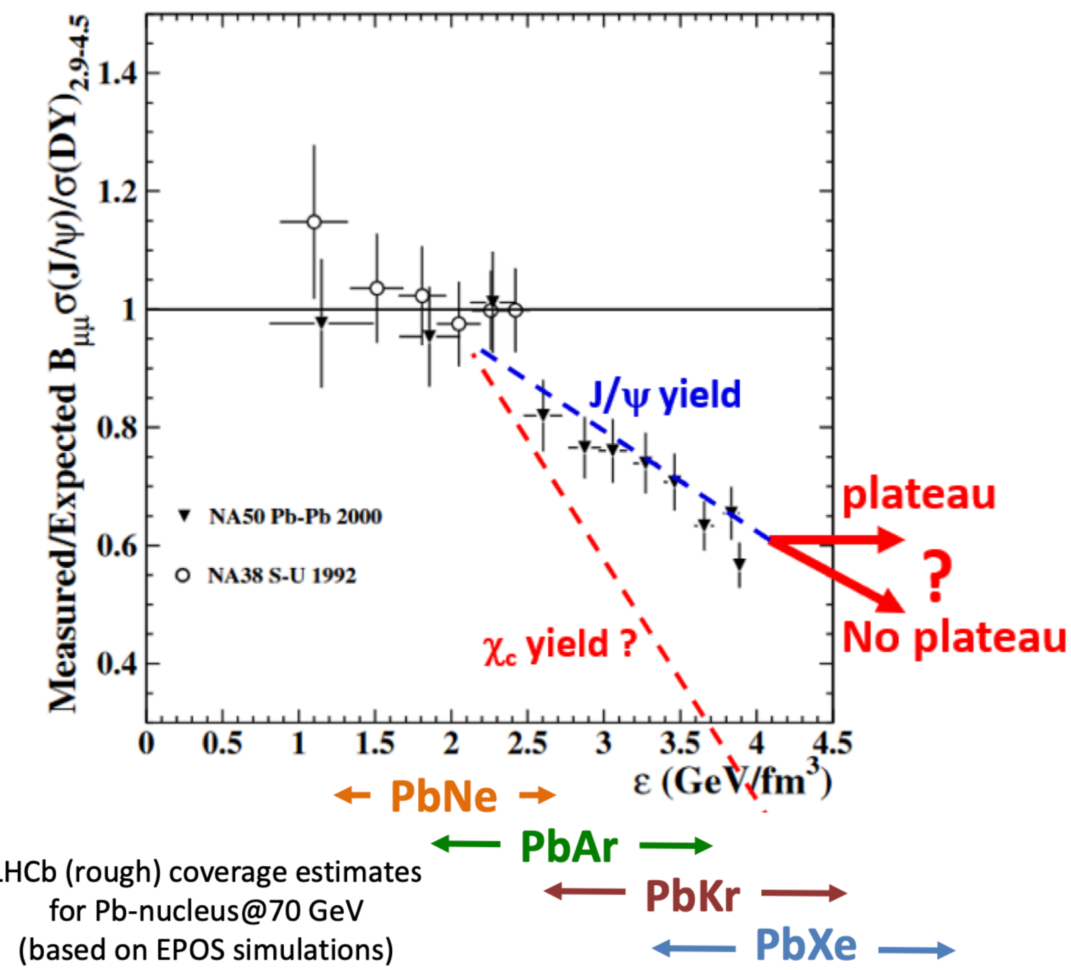
- With **PbNe** collisions, LHCb can begin to probe the energy density region where NA50 observed an anomalous J/ψ suppression

- 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

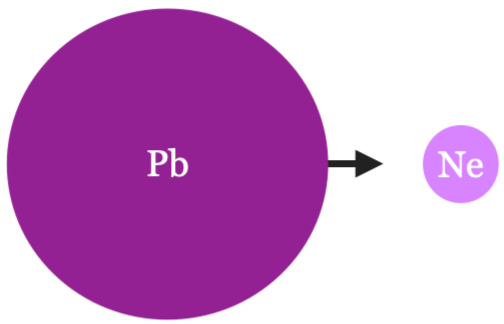
  - With $N_{c\bar{c}} \approx 1$ on average, no significant effects from recombination are expected in PbA fixed-target collisions

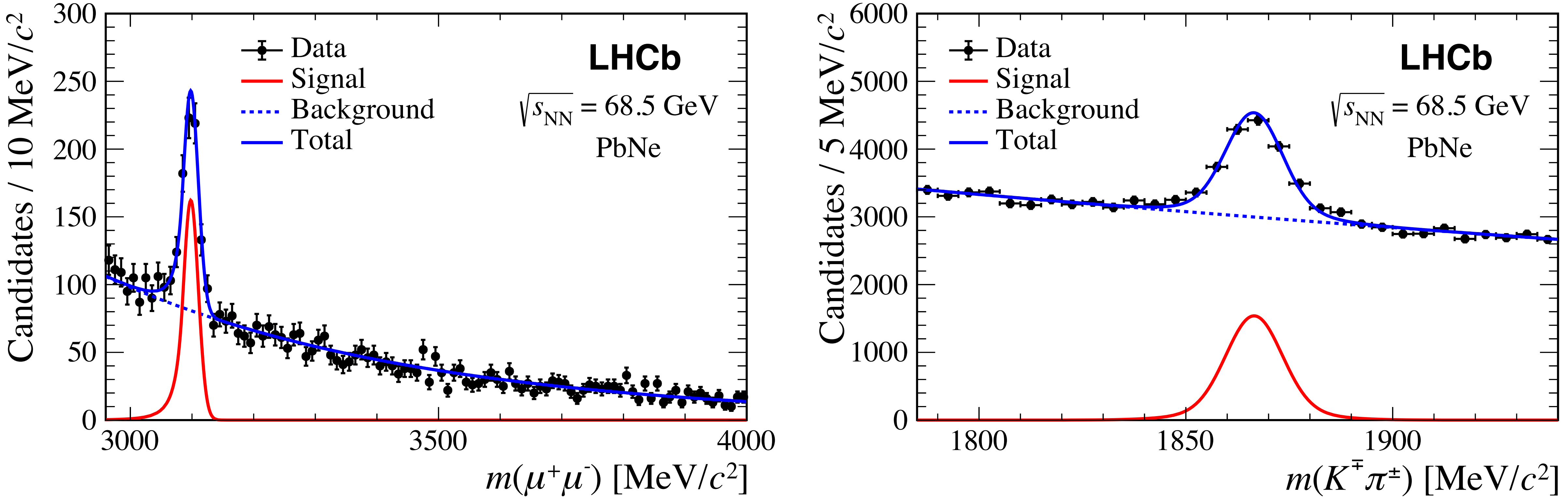


- LHCb can also measure pAr collisions at the same energy to measure the cold nuclear matter effects in Ar

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

Heavy flavor signal yields in PbNe collisions

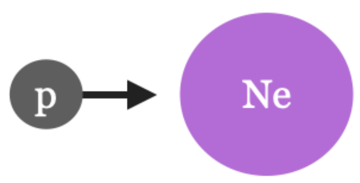


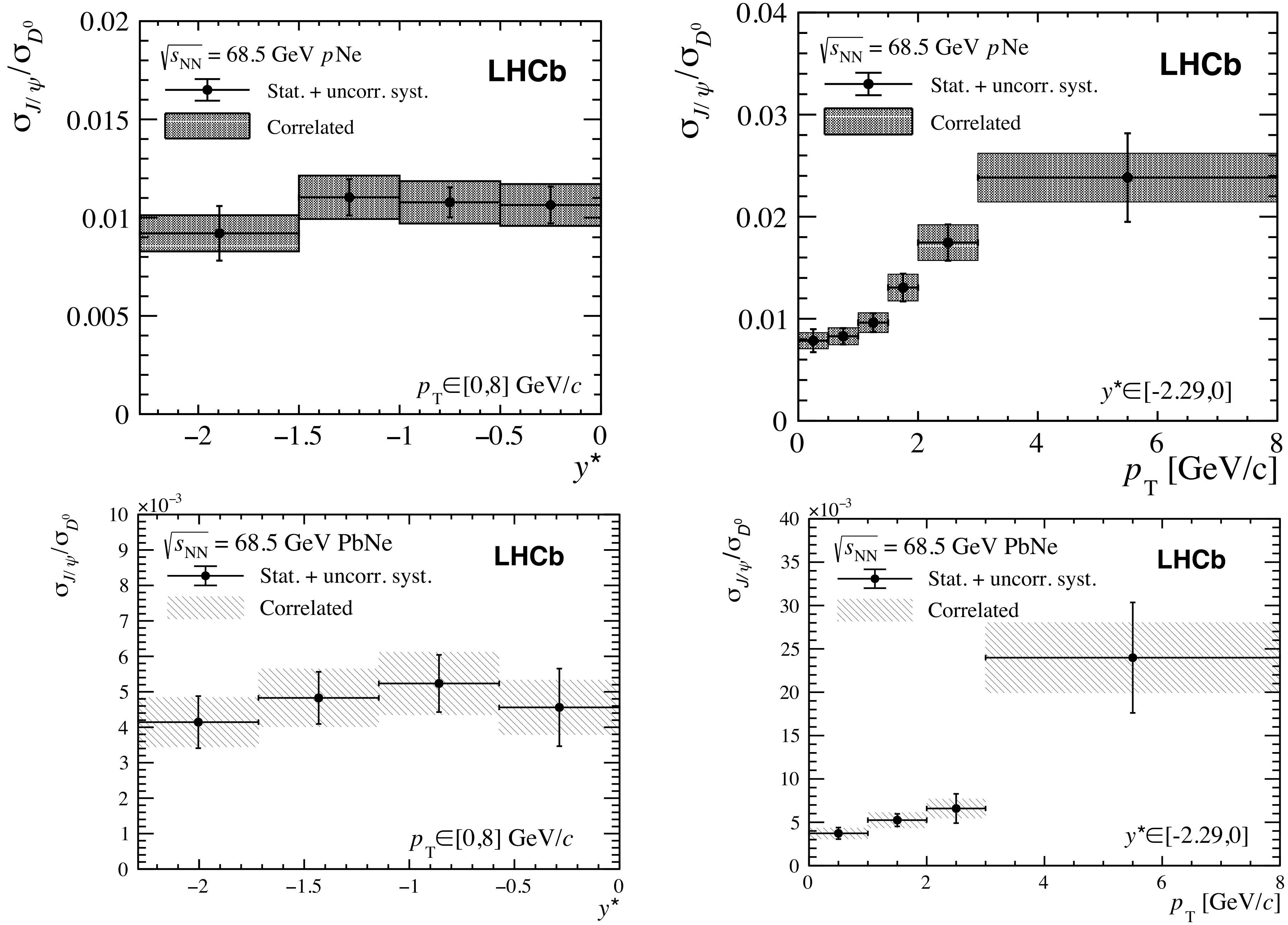


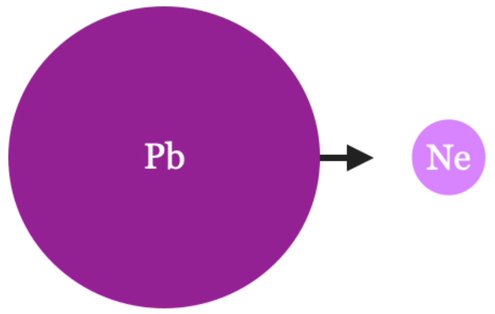
- Larger background than in pA collisions, but clean signal peaks are still observed - proof of measurement feasibility in larger PbA systems
- Similar candidate selection as in pNe measurement
- Heavy flavor hadron $p_T < 8$ GeV
- Heavy flavor hadron y in $2.0 < y < 4.29$

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







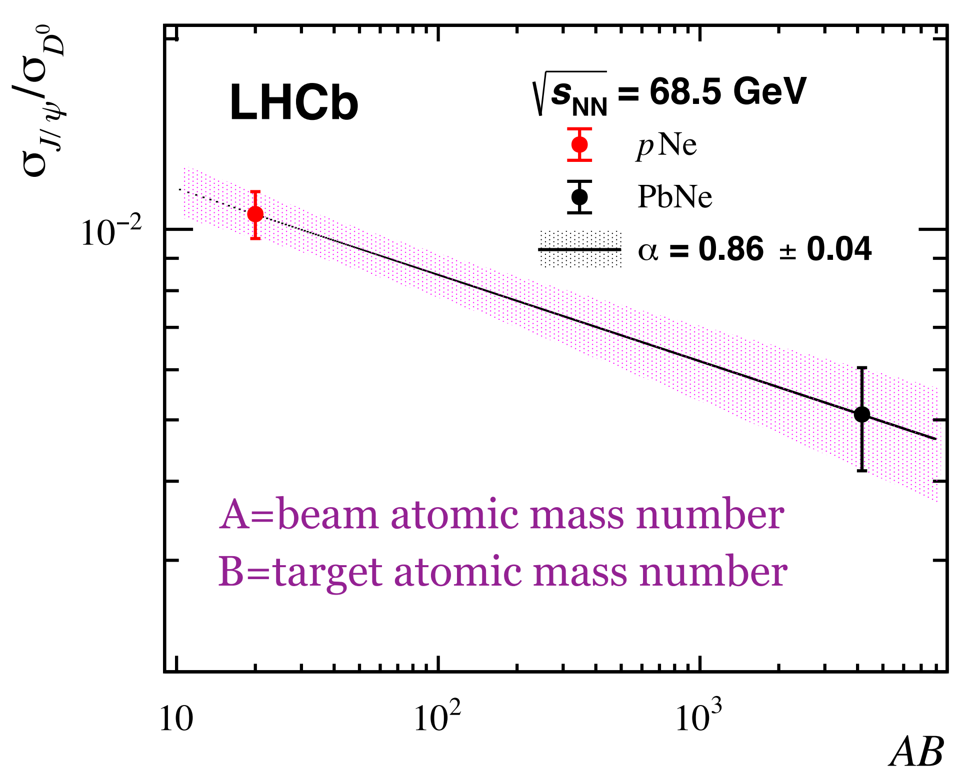
- Compare J/ψ production in large (PbNe) vs small (pNe) nuclear environment at the same $\sqrt{s}$
- $\sigma_{J/\psi}/\sigma_{D^0}$ shows little dependence on y* and a strong dependence on p_T

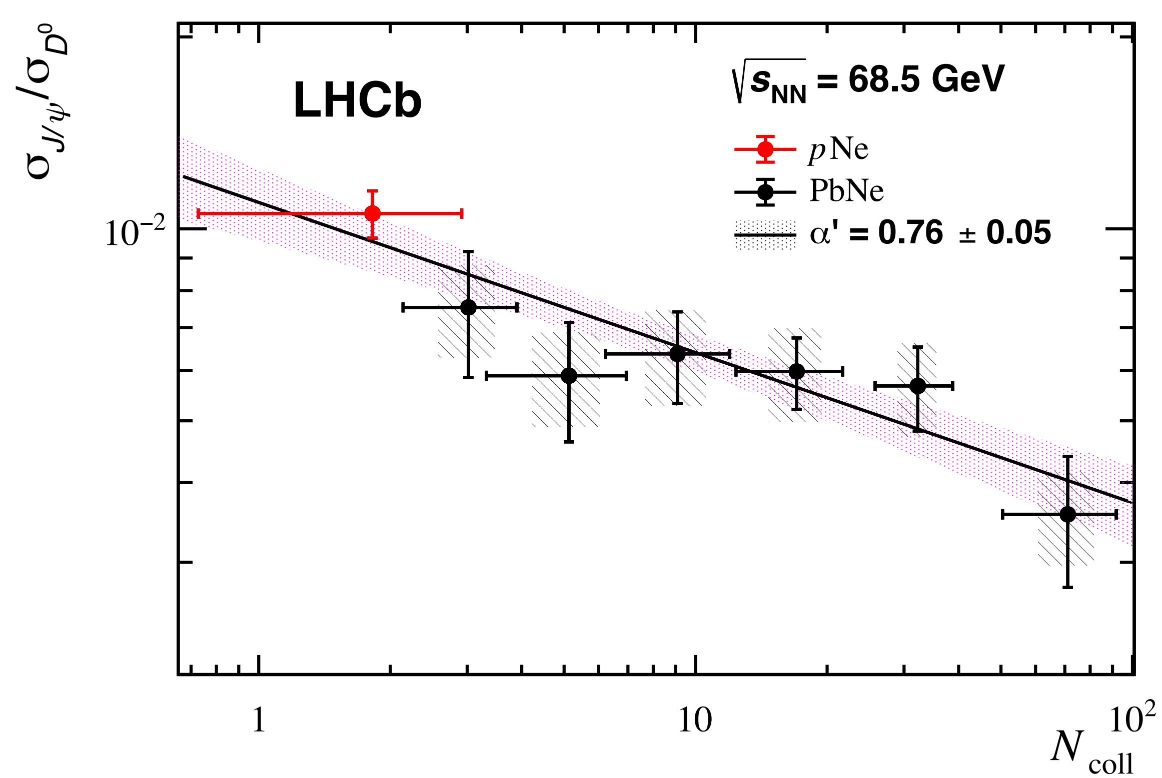
Nuclear effects on hidden vs open charm

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

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

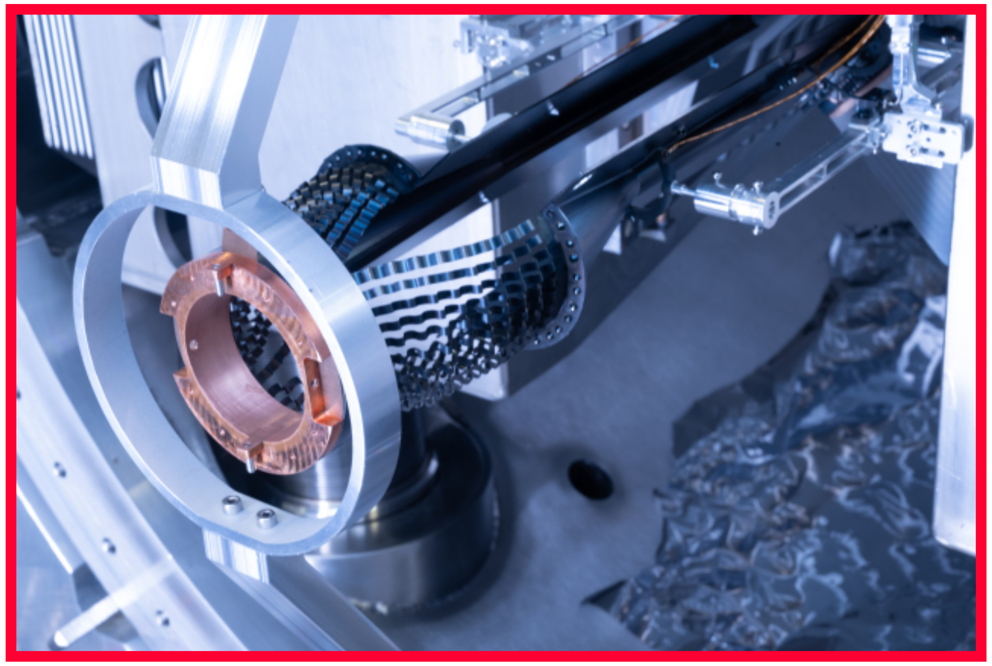
- Same functional form for the ratio as a function of the number of collisions (N_{coll})
- $\alpha < 1$: indicates that J/ψ mesons experience additional nuclear effects than D^0 mesons
- Within the current precision, a linear trend is observed between pNe and central PbNe events and no conclusive evidence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





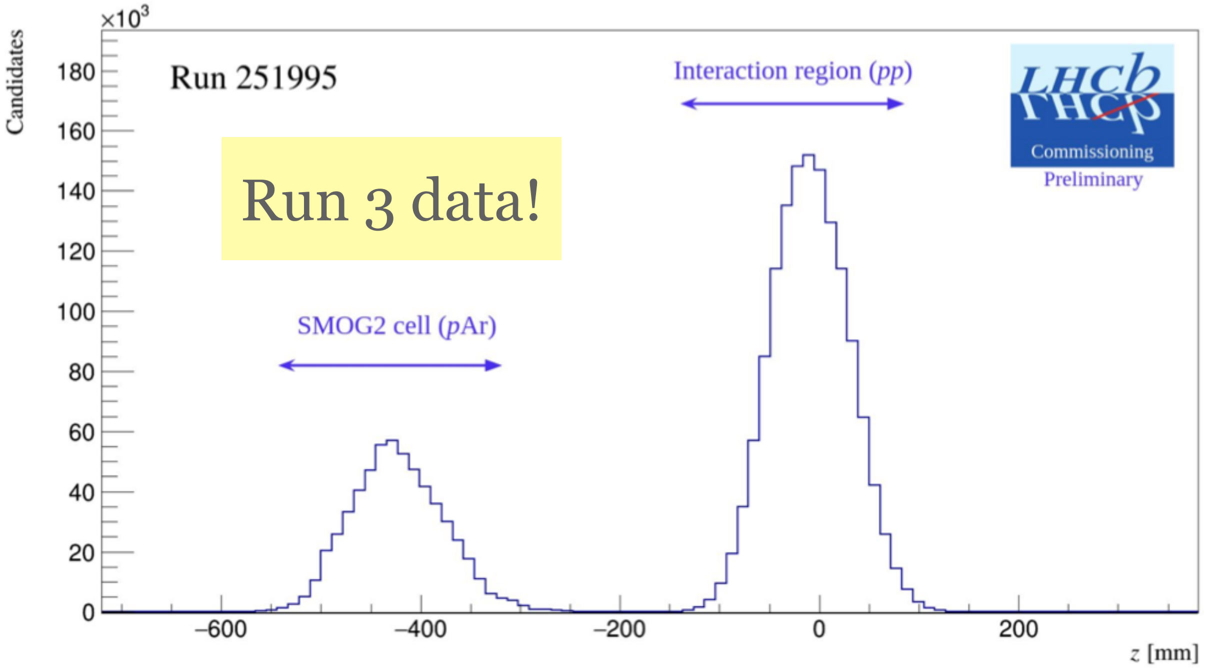
Run 3 with LHCb SMOG2

- 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:



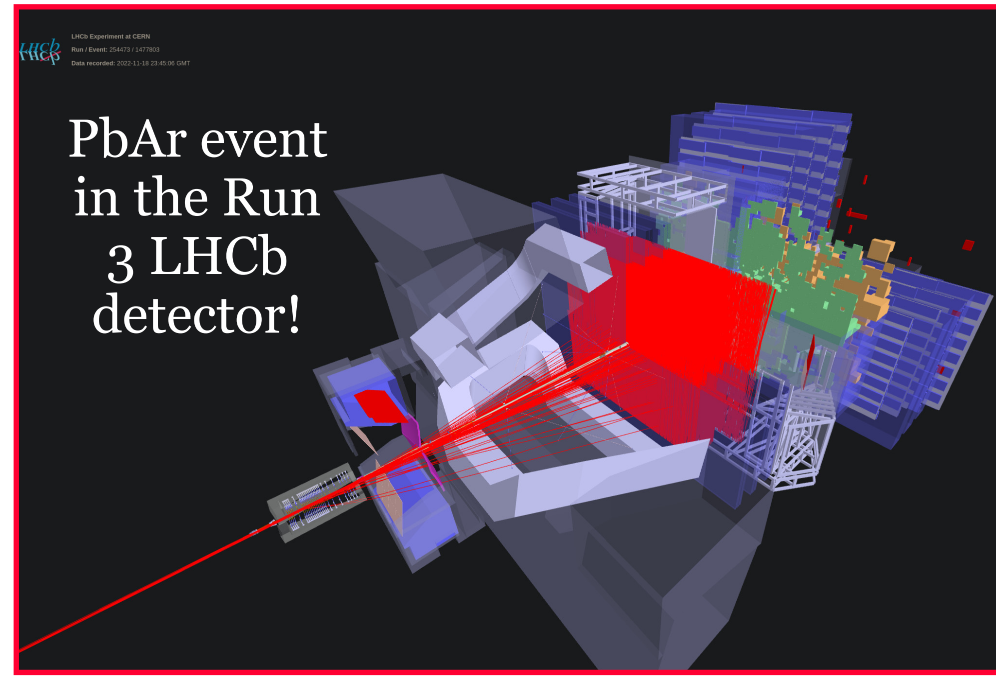
The open SMOG2 cell installed in front of the LHCb VELO

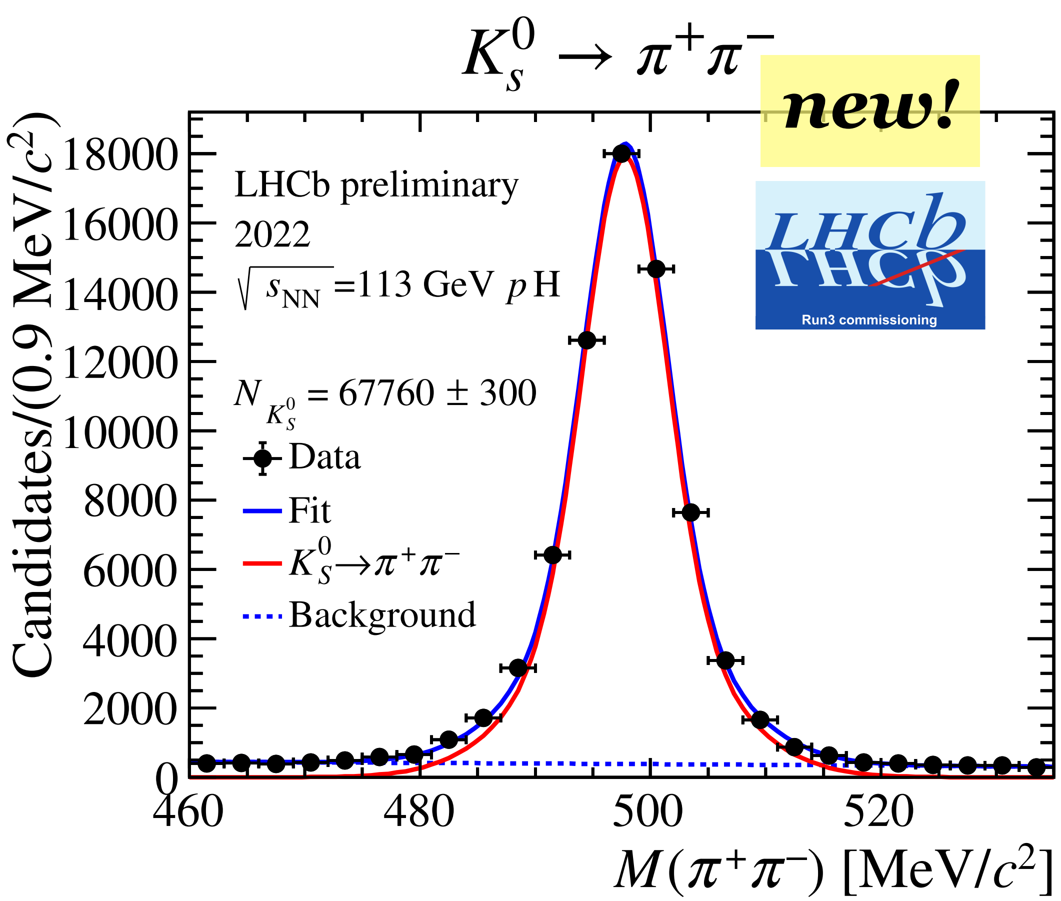
	SMOG published result pHe@87 GeV	SMOG largest sample pNe@69 GeV	SMOG2 example pAr@115 GeV
Integrated luminosity	7.6 nb^{-1}	$\sim$ 100 nb^{-1}	$\sim$ 45 pb^{-1}
syst. error on J/ψ x-sec.	7%	6 - 7%	2 - 3 %
J/ψ yield	400	15k	15M
D^0 yield	2000	100k	150M
Λ_c^+ yield	20	1k	1.5M
$\psi(2S)$ yield	negl.	150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

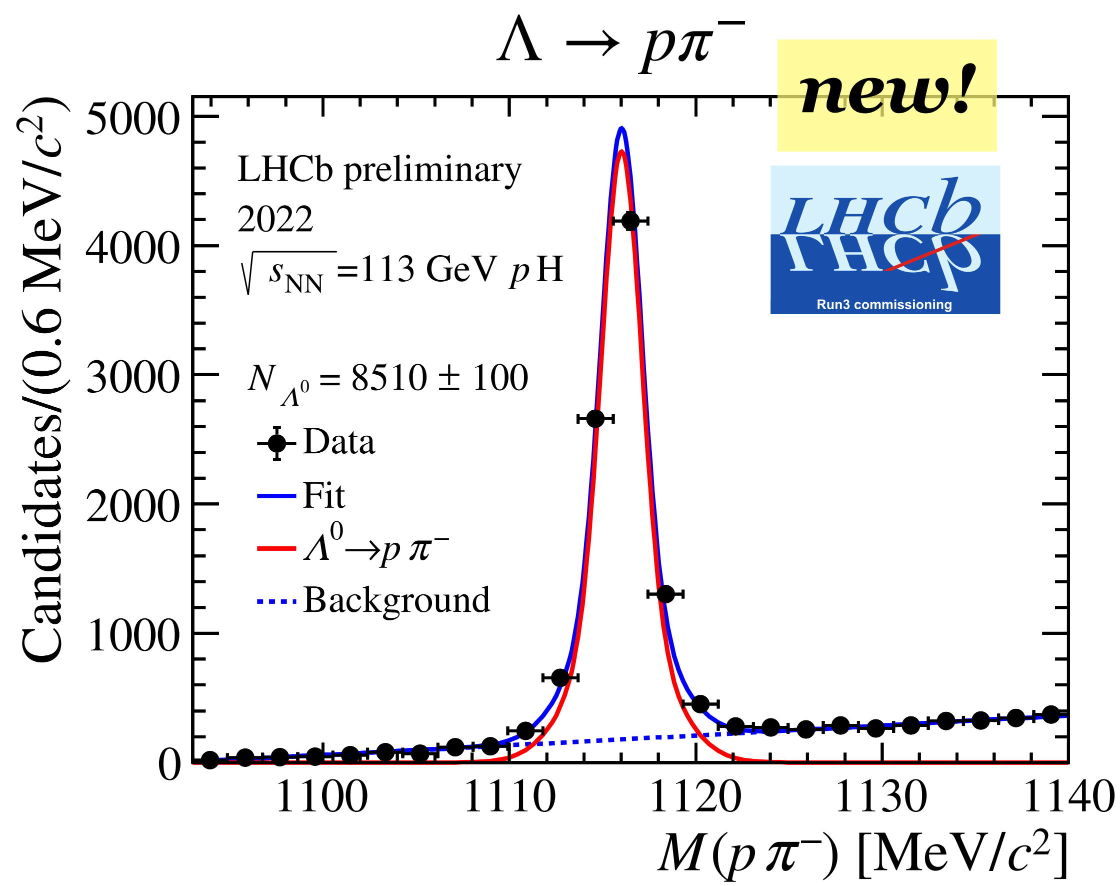


SMOG2 performance in Run 3

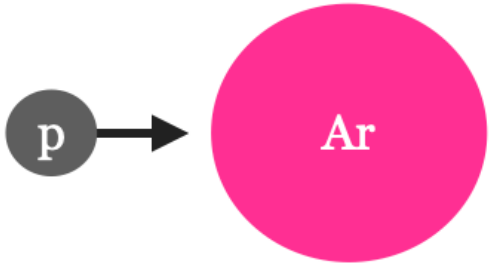
- First Run 3 data successfully taken in 2022!
- Commissioning performed with Argon, Helium, and Hydrogen gases
- Successfully reconstructed mass peaks from a 21-minute pH injection!
  - Important milestone for performing R_{AA} measurements with SMOG2

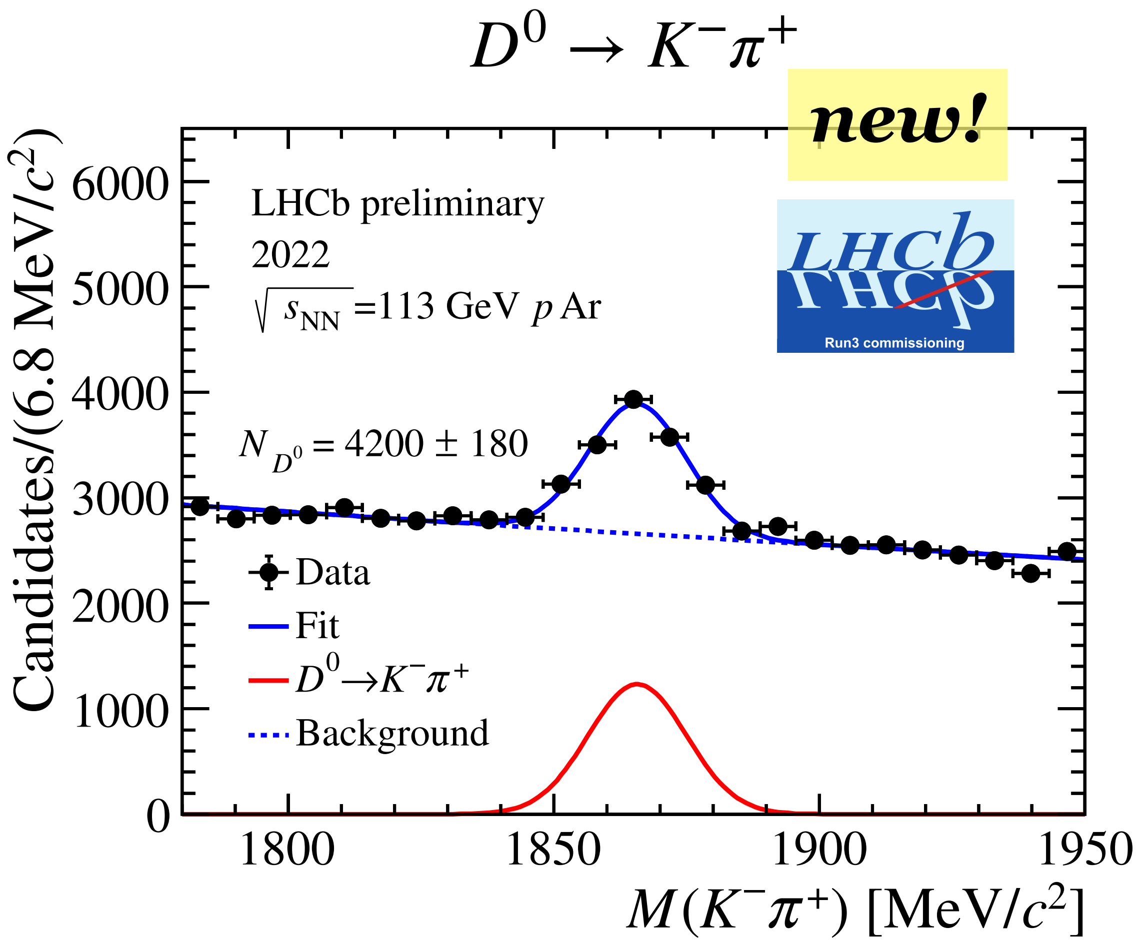


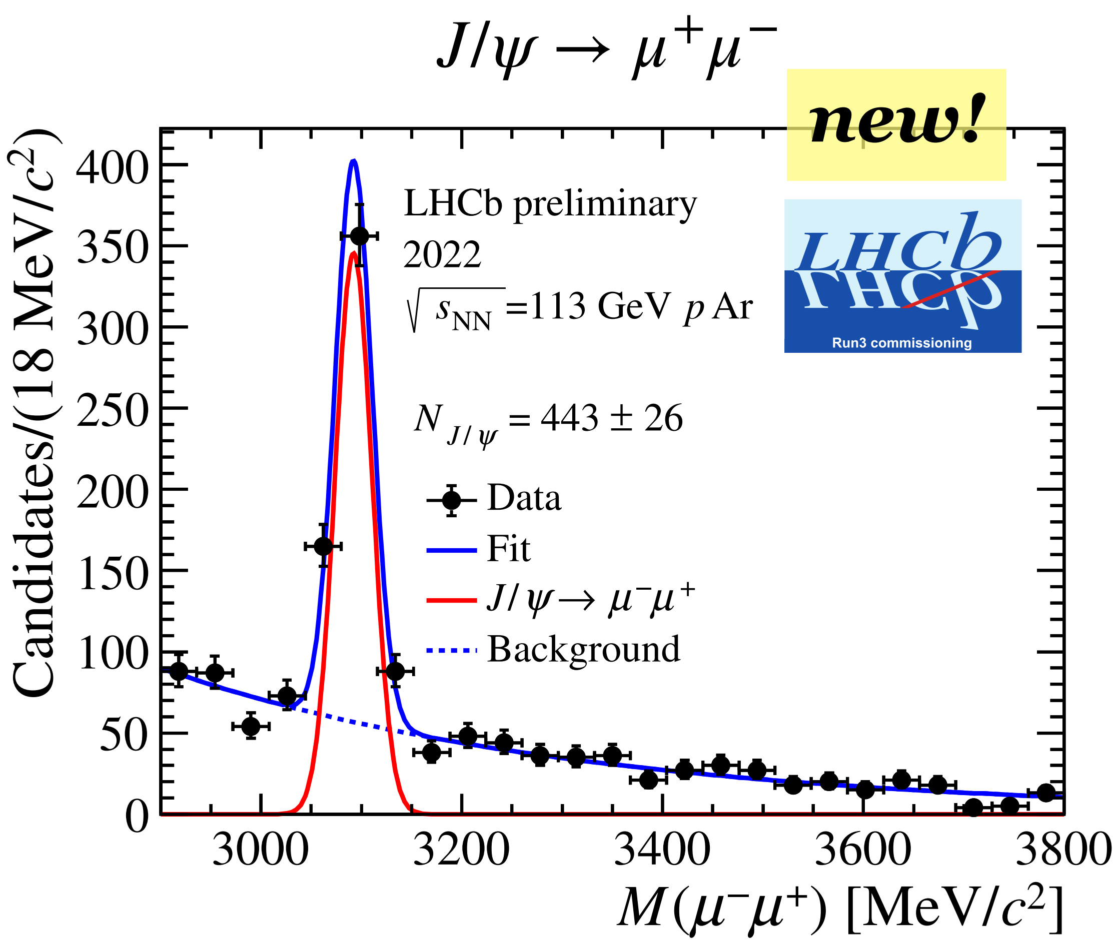




Charm in SMOG2 Run 3 Data

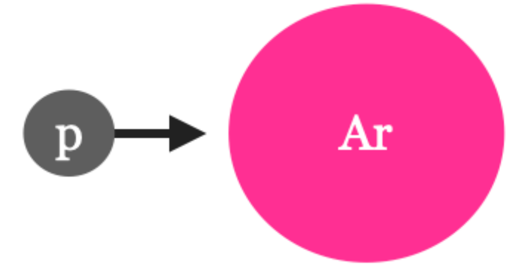






- From **18 minutes of data-taking** during an Ar injection, we obtained 4,200 D^0 and 443 J/ψ candidates!
- Excellent preliminary yields given that the detector was still in a commissioning phase - "nominal" Run 3 performance is expected to be even better!
- SMOG2 physics trigger chain fully tested and validated on real data

Outlook for SMOG2 in 2023



- In 2023, the LHCb VELO detector will run in a partially open configuration as a result of the LHC VELO vacuum incident (see backup for details)
- The partially open VELO means that the SMOG2 cell will also be open, which results in a loss of pressure and therefore, statistics for our measurements
- However, **we still plan to inject Ar in the SMOG2 cell for 170 hours and take data for physics analysis**

> "Life (2023 partially-open VELO data) is a desert, but we can transform our corner (SMOG2) into a garden (largest pAr sample we've ever collected?!)." - Voltaire

- Our SMOG2 physics trigger lines have already been updated with loosened cuts to maximise signal with the partially-open VELO conditions
- We also plan to inject during the PbPb run to collect PbAr collision data
- In 2024, we will return to our "normal conditions" with a fully closed VELO, fully closed SMOG2 cell, and a fully commissioned LHCb detector, which will enable our full SMOG2 physics program!

Conclusions

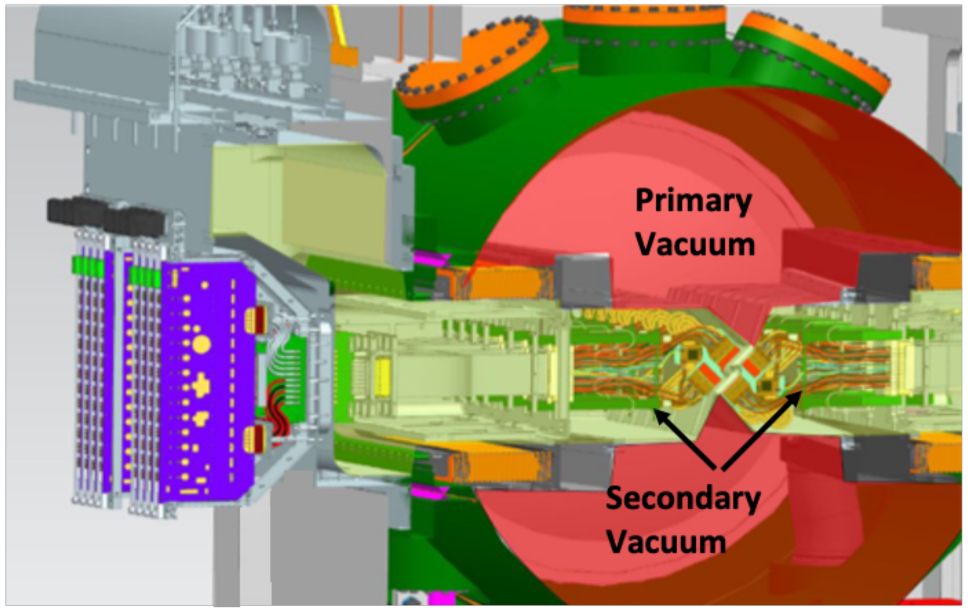
- Fixed target experiments at the LHC provide opportunities to study quarkonia production in a wide variety of nuclear systems and in a unique region of phase space
- New measurements of D^0 and charmonium production in pNe and PbNe collisions at $\sqrt{s_{NN}}$ = 68.5 GeV have been performed by LHCb
- Within the current experimental precision, comparisons of the J/ψ and D^0 cross sections in PbNe collisions do not show conclusive evidence for the presence of anomalous suppression or the formation of a hot nuclear medium
- Mass peaks of K_s^0 and Λ in pH collisions and of J/ψ and D0 in pAr collisions have already been obtained with LHCb Run 3 data from LHCb's fixed target upgrade, SMOG2
- Many more measurements coming soon with SMOG2!

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



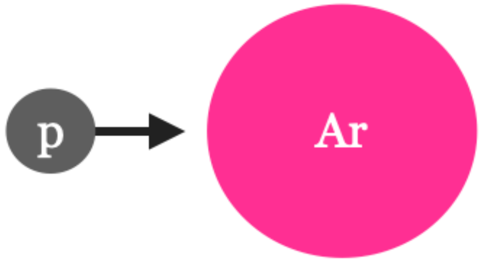
On 10th January 2023, during a VELO warm up in neon, there was a loss of control of the protection system
A pressure differential of 200 mbar built up between the two volumes, whereas the foils are designed to withstand 10 mbar only
Initial investigations show no damage to the VELO modules; sensors show 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

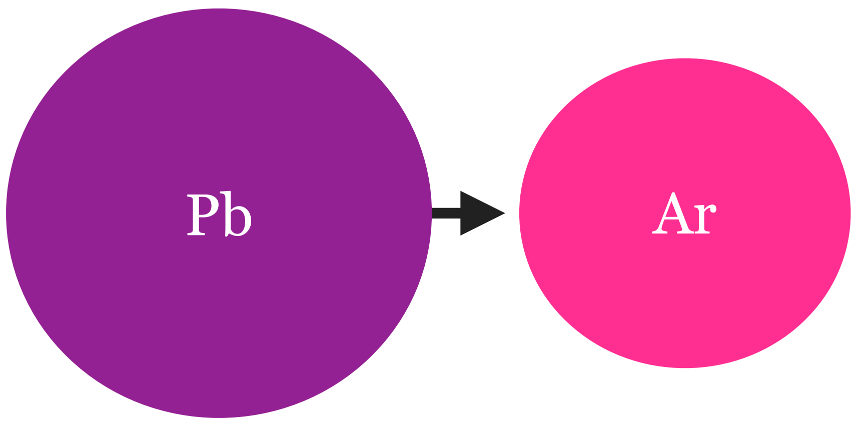
- Replace now (delay), or replace at the end of the year (run in 2023 with VELO partially open)
- Physics programme of 2023 is significantly affected, commissioning of Upgrade I systems can proceed as planned

Early measurements possible with SMOG2

- **J/ψ and $\psi(2S)$ 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>

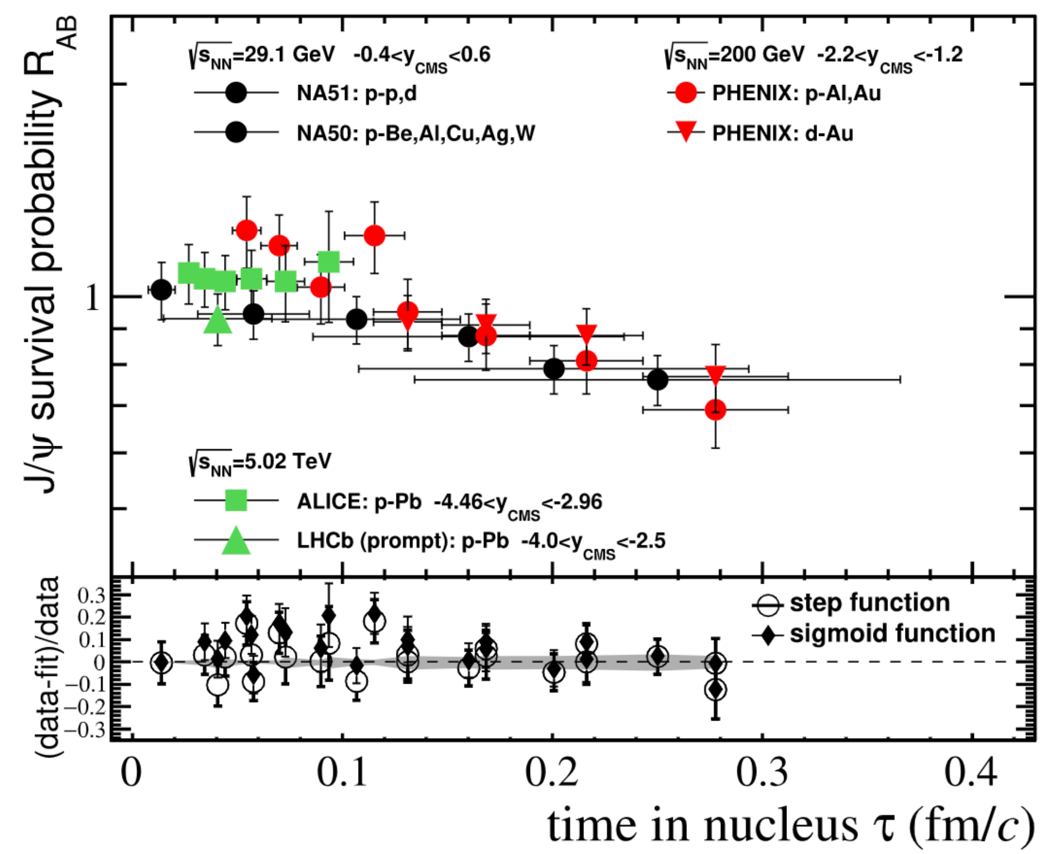
- **Upsilon production in pAr collisions** - study CNM effects as a function of bound state size and quark flavor content (e.g. parton energy loss effects)
- **Multi-differential $\psi(2S)$ measurements in pAr collisions** - complement differential J/ψ measurements and test theoretical models of quarkonium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

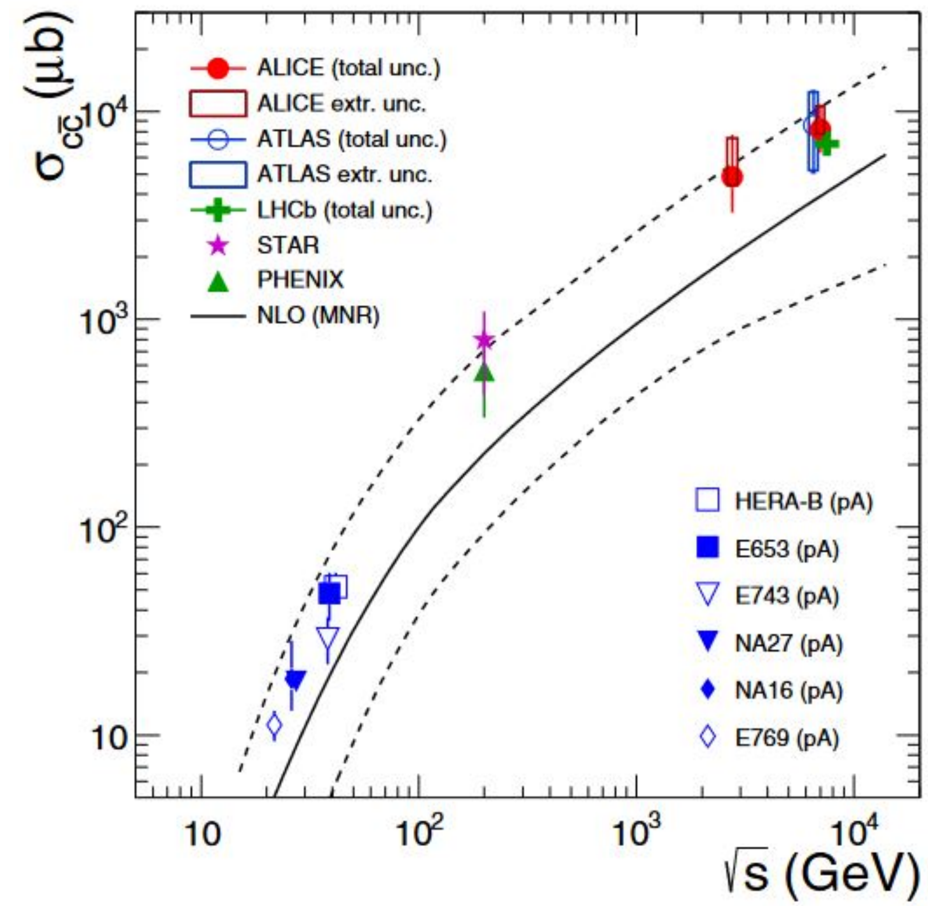
- **Exclusive production (photoproduction) of J/*ψ*** on a variety of nuclear targets

 cc 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.

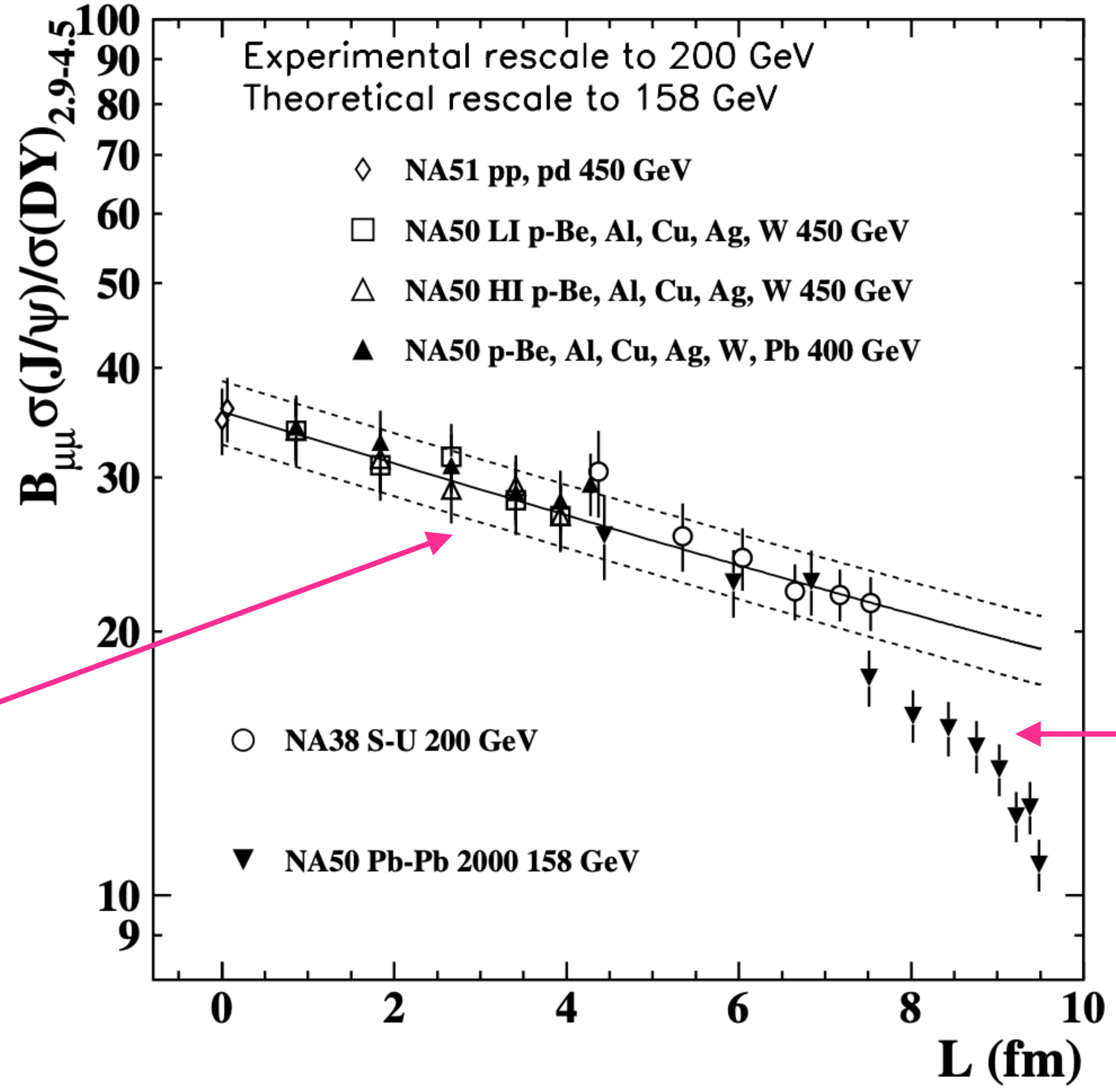
Centrality (%)	N_{coll}	T_{AA} (mb^{-1})	$\frac{1}{T_{AA}} \frac{dN_{c\bar{c}}}{dy}\|_{y=0}$ (μb)	$N_{c\bar{c}}/T_{AA}$ (μb)
Minimum bias	258 ± 25	6.14 ± 0.45	143 ± 13 ± 36	622 ± 57 ± 160
0–10	955 ± 94	22.8 ± 1.6	137 ± 21 ± 35	597 ± 93 ± 156
10–20	603 ± 59	14.4 ± 1.0	137 ± 26 ± 35	596 ± 115 ± 158
20–40	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	$\sqrt{s_{\rm NN}}$ (GeV)	< pressure> (10^{-5} mbar)	ρ_S ($\rm cm^{-2}$)	$\mathcal{L}$ ($\rm cm^{-2}s^{-1}$)	Rate (MHz)	Time (s)	$\int \mathcal{L}$ ($\rm pb^{-1}$)
$p\rm H_2$	115	4.0	2.0×10^{13}	6×10^{31}	4.6	2.5×10^6	150
$p\rm D_2$	115	2.0	1.0×10^{13}	3×10^{31}	4.3	0.3×10^6	9
$p\rm Ar$	115	1.2	0.6×10^{13}	1.8×10^{31}	11	2.5×10^6	45
$p\rm Kr$	115	0.8	0.4×10^{13}	1.2×10^{31}	12	2.5×10^6	30
$p\rm Xe$	115	0.6	0.3×10^{13}	0.9×10^{31}	12	2.5×10^6	22
$p\rm He$	115	2.0	1.0×10^{13}	3×10^{31}	3.5	3.3×10^3	0.1
$p\rm Ne$	115	2.0	1.0×10^{13}	3×10^{31}	12	3.3×10^3	0.1
$p\rm N_2$	115	1.0	0.5×10^{13}	1.5×10^{31}	9.0	3.3×10^3	0.1
$p\rm O_2$	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
$\rm PbH_2$	72	8.0	4.0×10^{13}	1×10^{29}	0.2	1×10^5	0.010
$p\rm Ar$	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