Recent results from fixed-target collisions at LHCb

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on behalf of the LHCb collaboration

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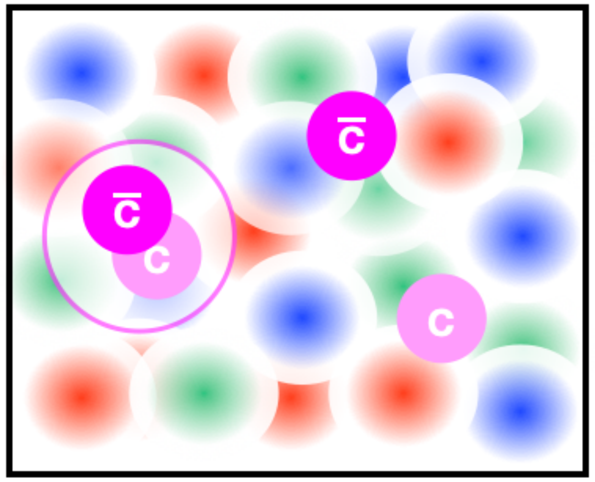
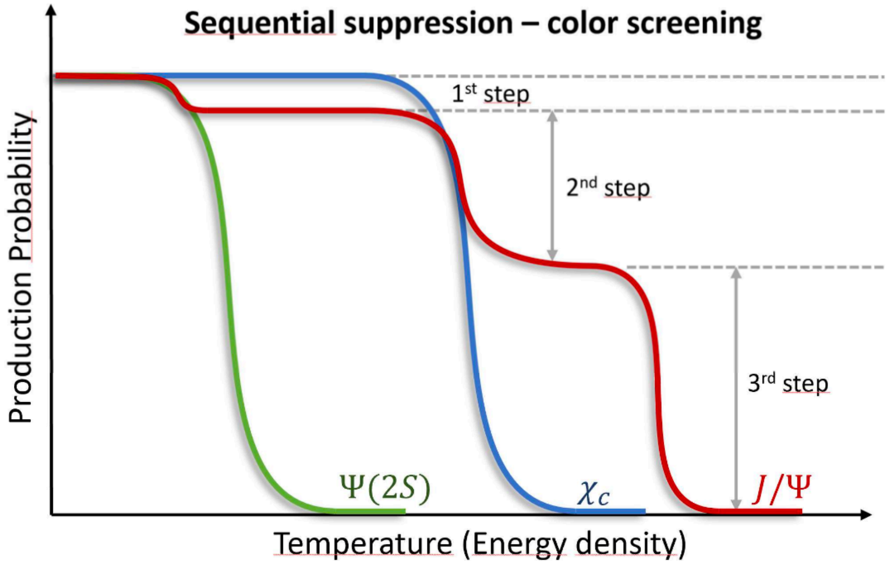
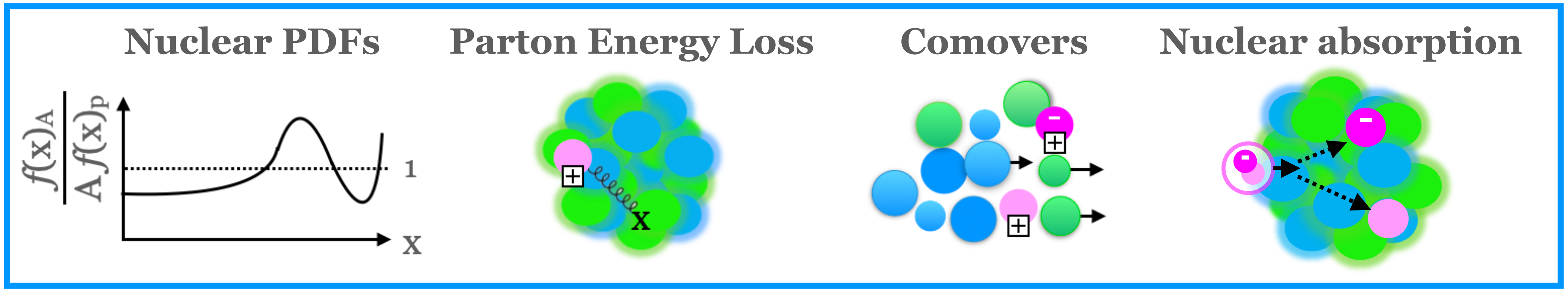
Motivation: a complete picture of quarkonia formation and dissociation in nuclear matter

- 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**



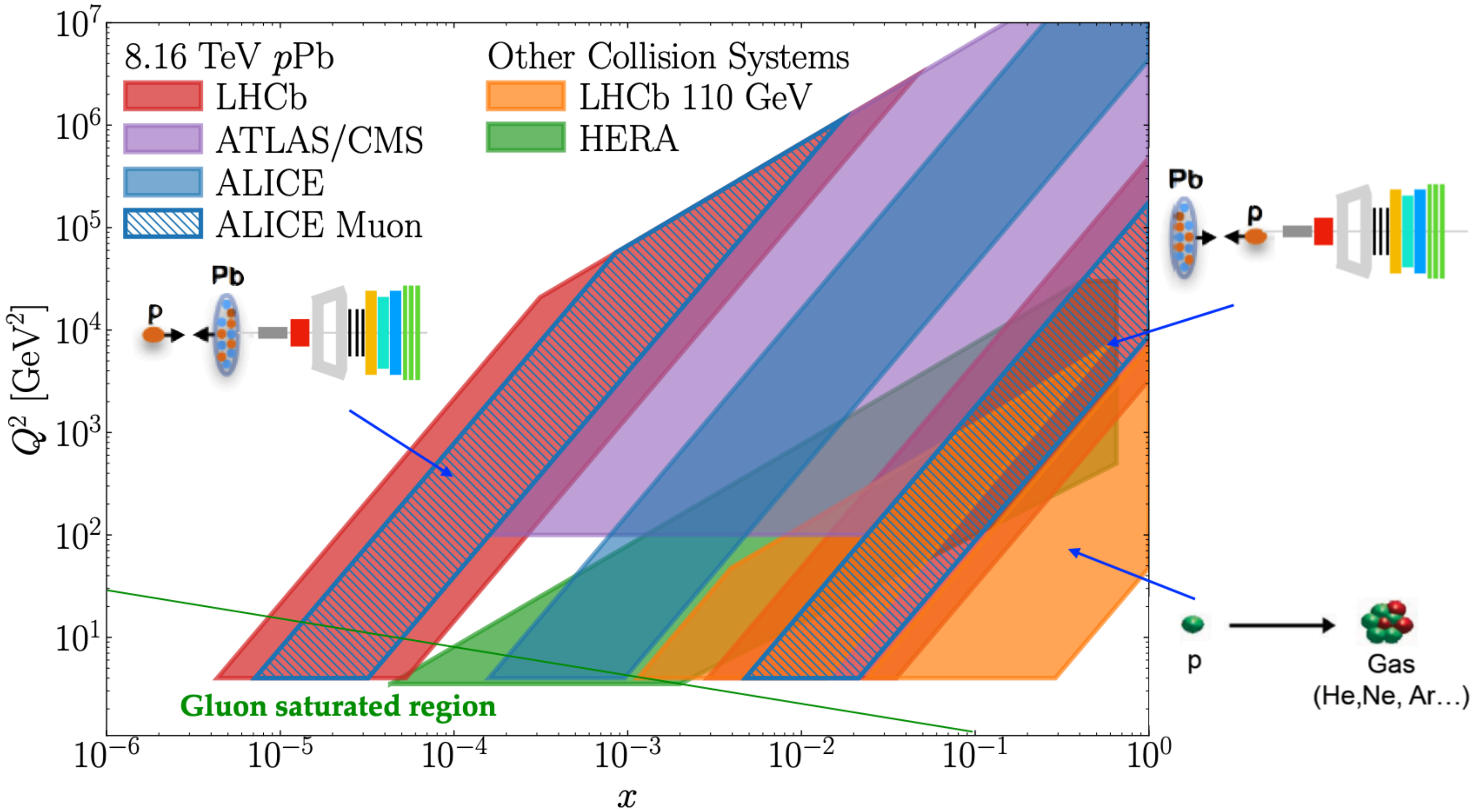




- A comprehensive understanding of CNM effects requires measuring charmonia production in a variety of nuclear systems and kinematic phase space

Fixed target kinematics at the LHC

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



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

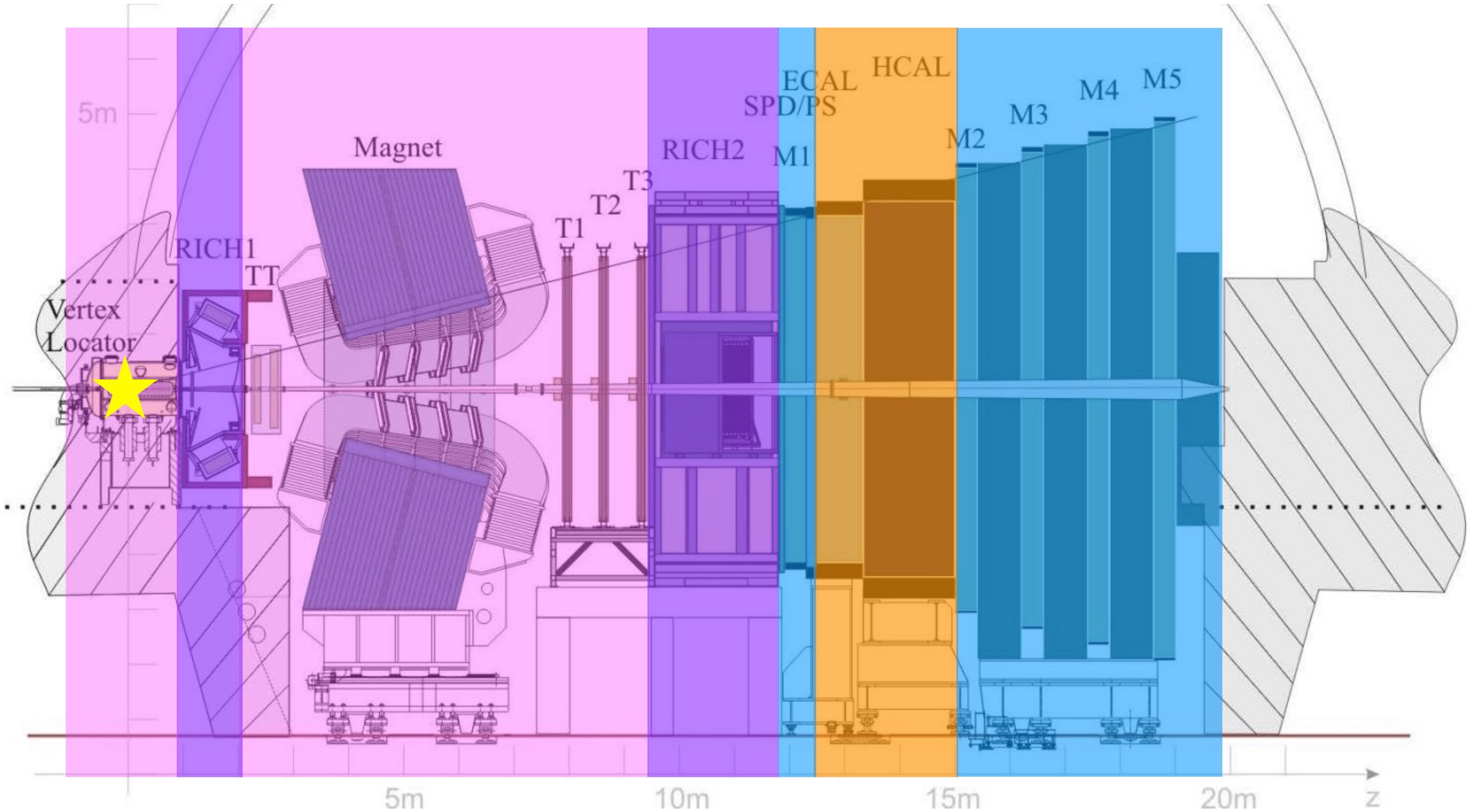
2.42 - 7.7 GeV	5.1 - 29.1 GeV	41-115 GeV	200 GeV	5 TeV
RHIC and GSI fixed-target	NA50, NA61 (SPS)	LHC fixed-target	RHIC AA collisions	LHC PbPb collisions

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

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

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 $2 < \eta < 5$

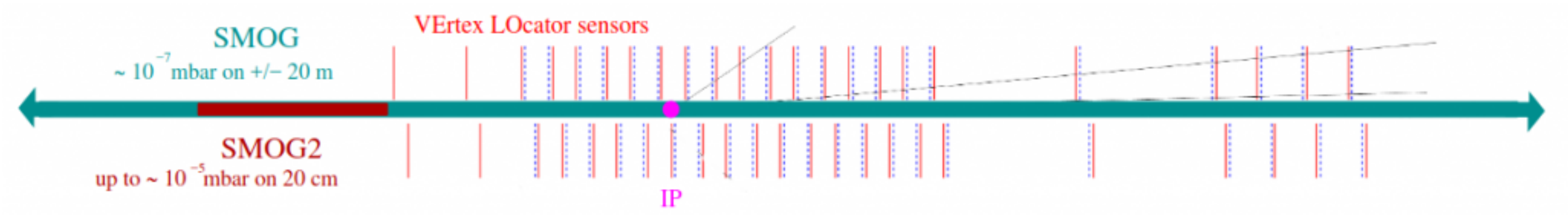


- Fixed-target mode in Run 2 possible by injecting gas into the Vertex Locator with a pressure of ~ 10^{-7} mbar
- One of the circulating proton or Pb beams was used to produce *p*A or PbA collisions

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

The LHCb fixed-target program

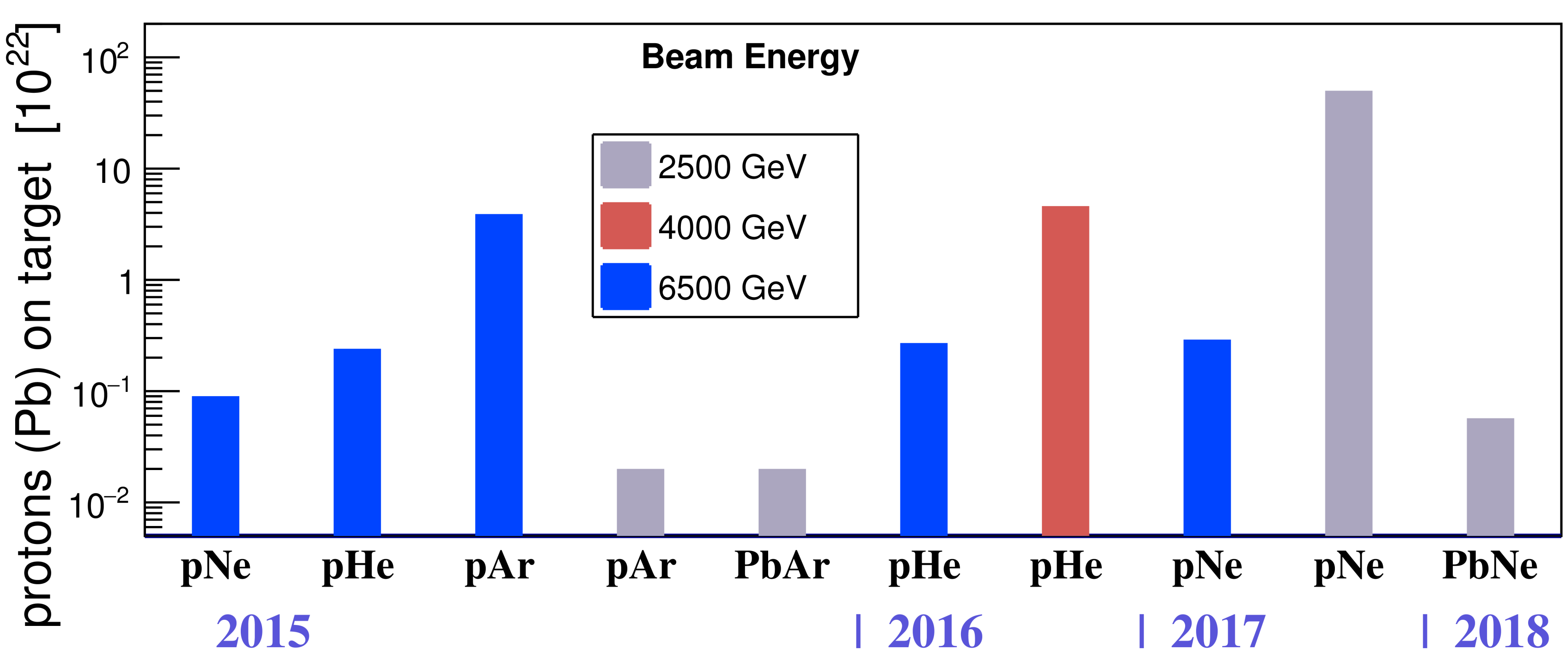
- SMOG: System for Measuring Overlap with Gas



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

- Several *p*A and PbA data samples collected:

SMOG Run 2 data samples



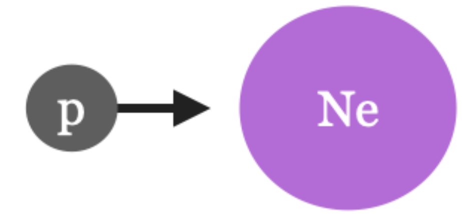
LHCb-PUB-2018-015

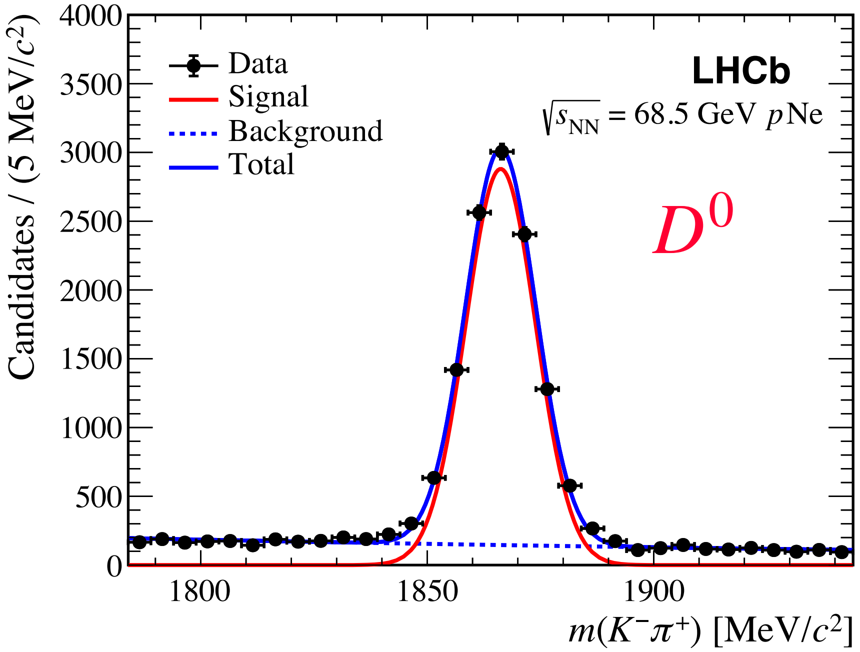
Charm measurements with SMOG

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	***new!*** 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	***new!*** EPJC 83 (2023) 658

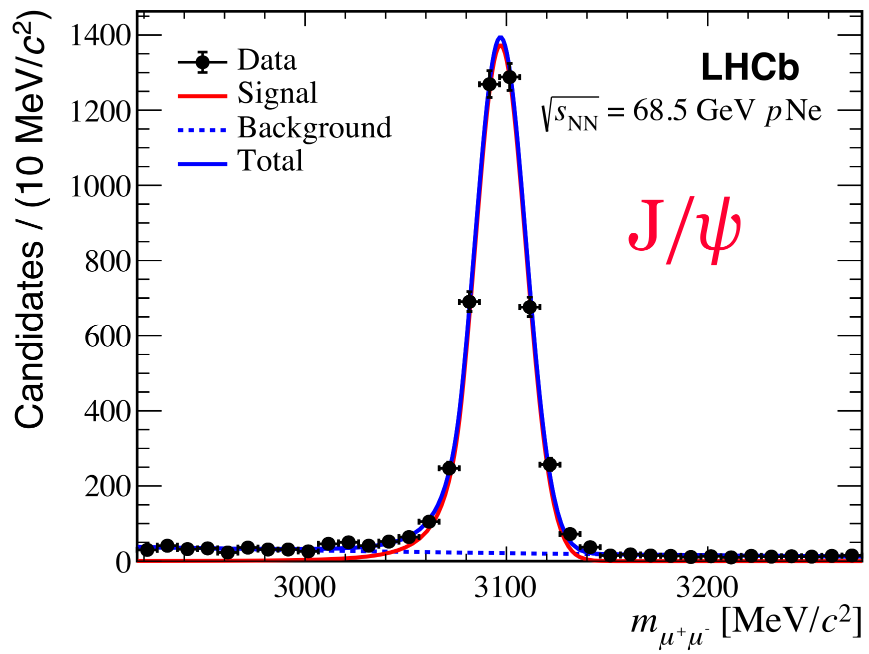
first fixed-target AB measurement at the LHC!

Heavy flavor signal yields in pNe collisions

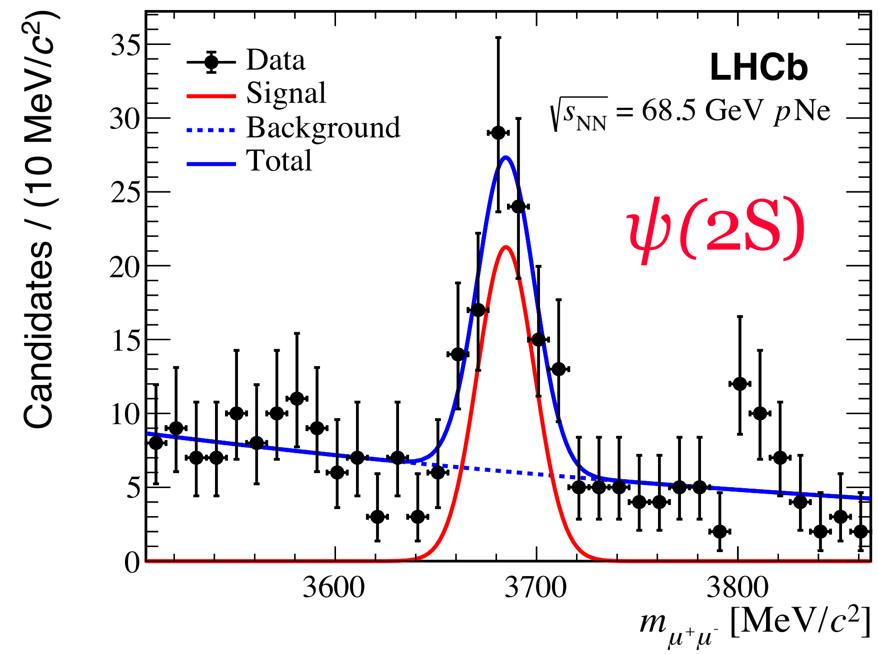




$24,408\ D^0$



4542 J/ψ



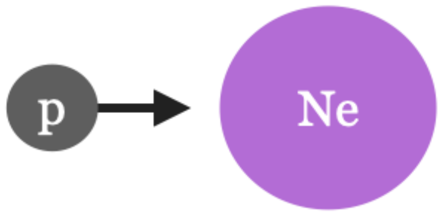
76 ψ(2S)

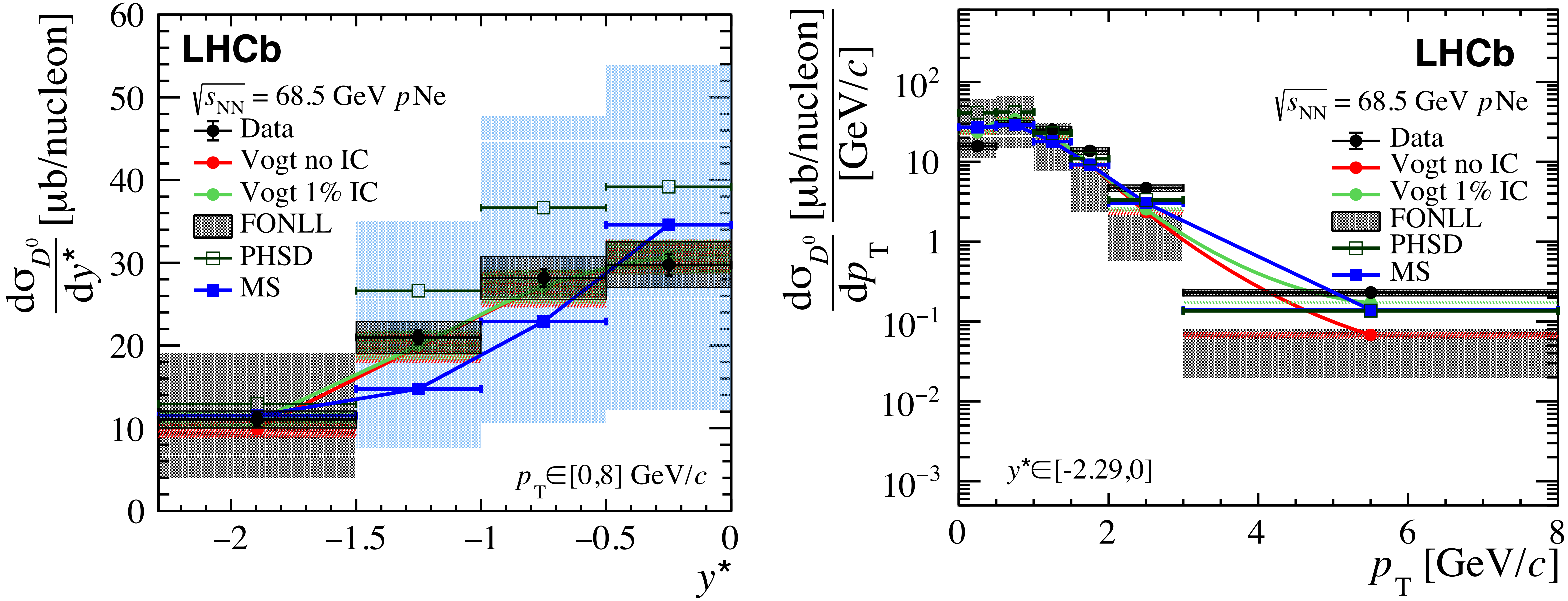
Event Selection:

- 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: EPJC 83 (2023) 541   Charmonia: EPJC 83 (2023) 625

D^0 differential cross sections

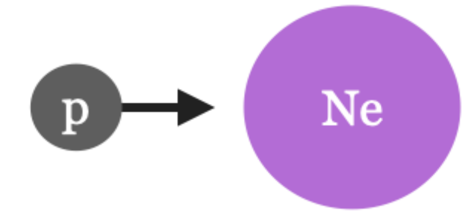




- FONLL and PHSD predictions fail to reproduce the p_T distribution seen in data
- The Vogt 1% IC and the MS predictions both include 1% intrinsic charm contribution in the proton
- MS includes 10% recombination contributions, Vogt includes shadowing effects
- PDF and factorisation scale uncertainties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

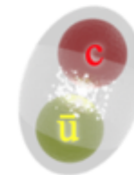
LHCb data: EPJC 83 (2023) 541 **Vogt:** PRC 103 (2021) 035204 **MS:** PLB 835 (2022) 137530
FONLL: PRL 95 (2005) 122001, JHEP 05 (1998) 007 **PHSD:** PRC 96 (2017) 014905

D^0 Production Asymmetry

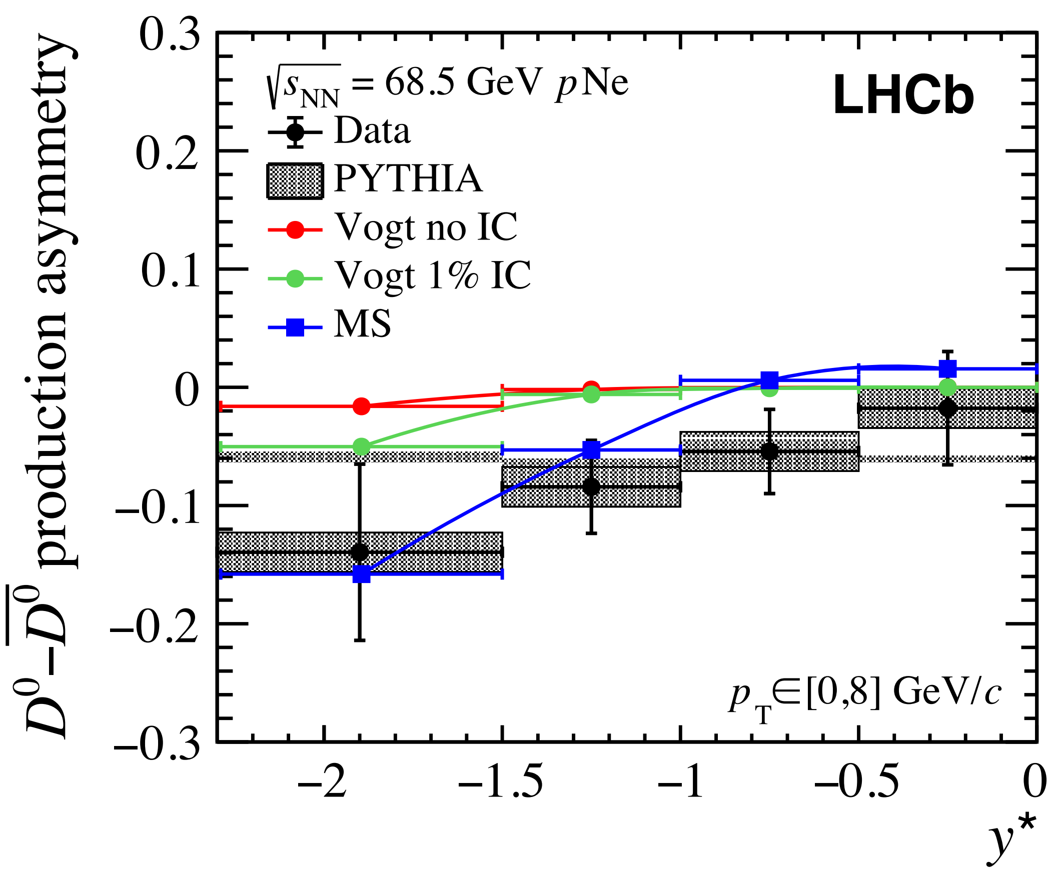


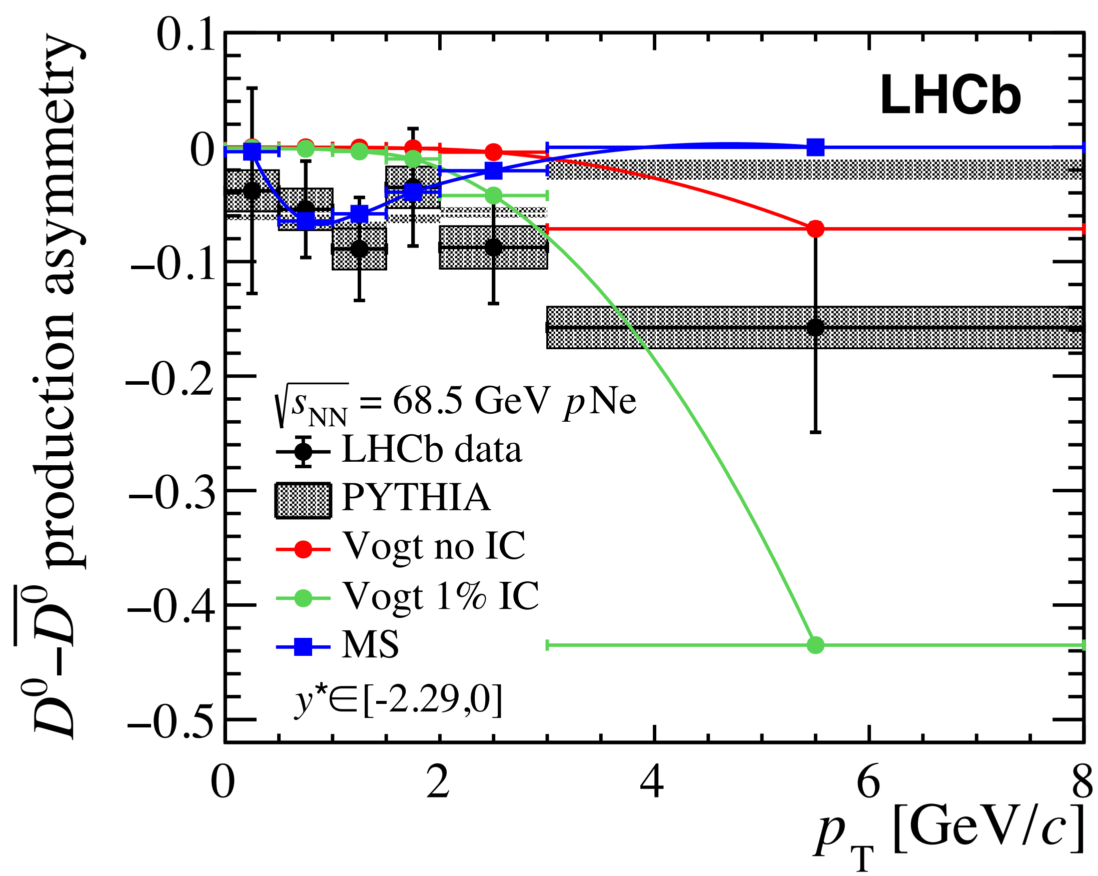
- The production asymmetry probes charm hadronization with a high-x valence quark:

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

D^0 

$\overline{D^0}$ 

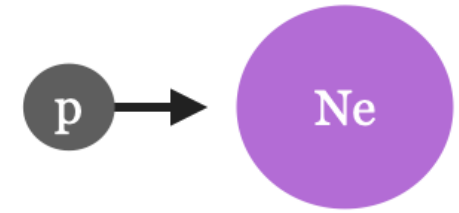




- An asymmetry of ~-15% is observed in the most negative y^* bin
- PYTHIA 8 comparisons do not capture the trends observed in the data
- Vogt predictions represent an upper limit on the asymmetry

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

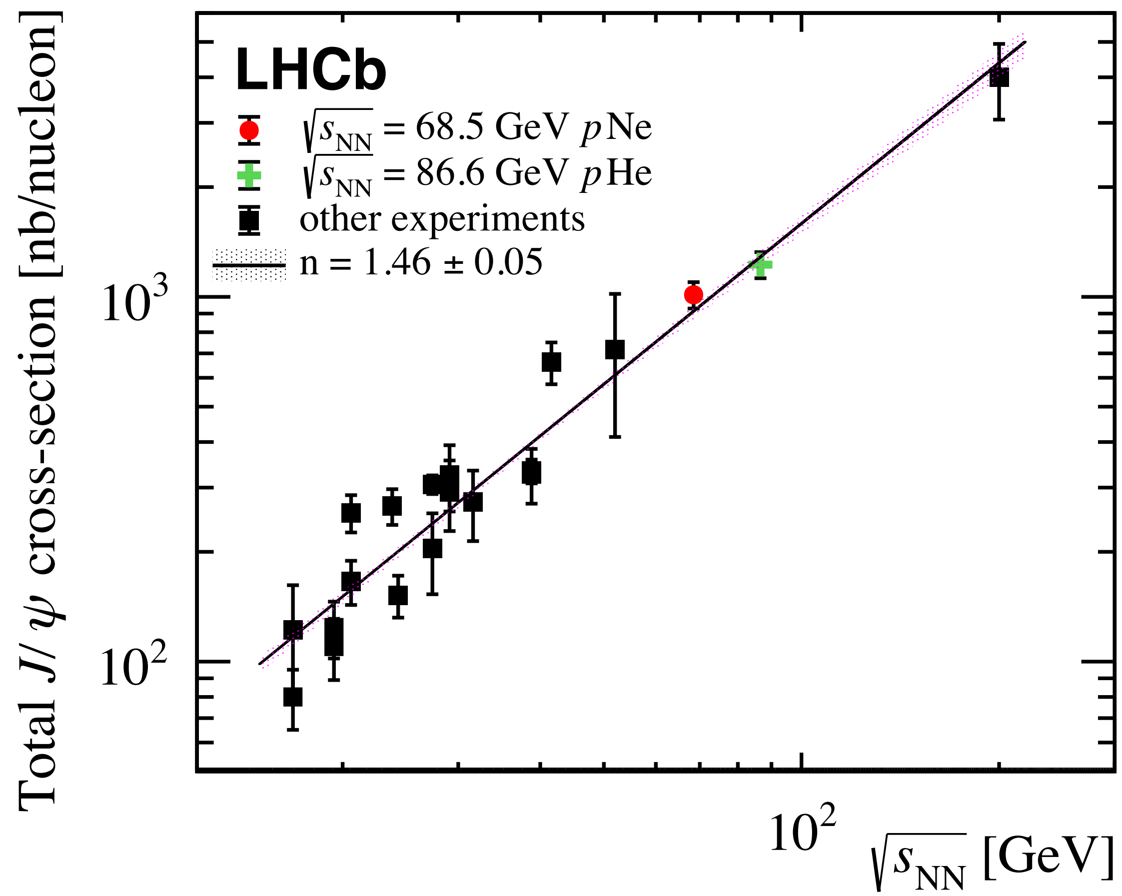
J/ψ cross section measurement at $\sqrt{s_{NN}}$ = 68.5 GeV



- 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:

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

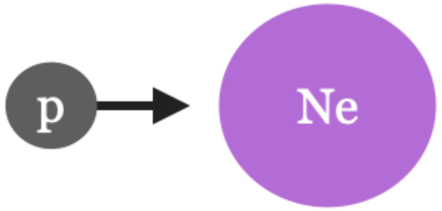
- Comparison to cross section measurements from other experiments shows a power law dependence on the center of mass energy:

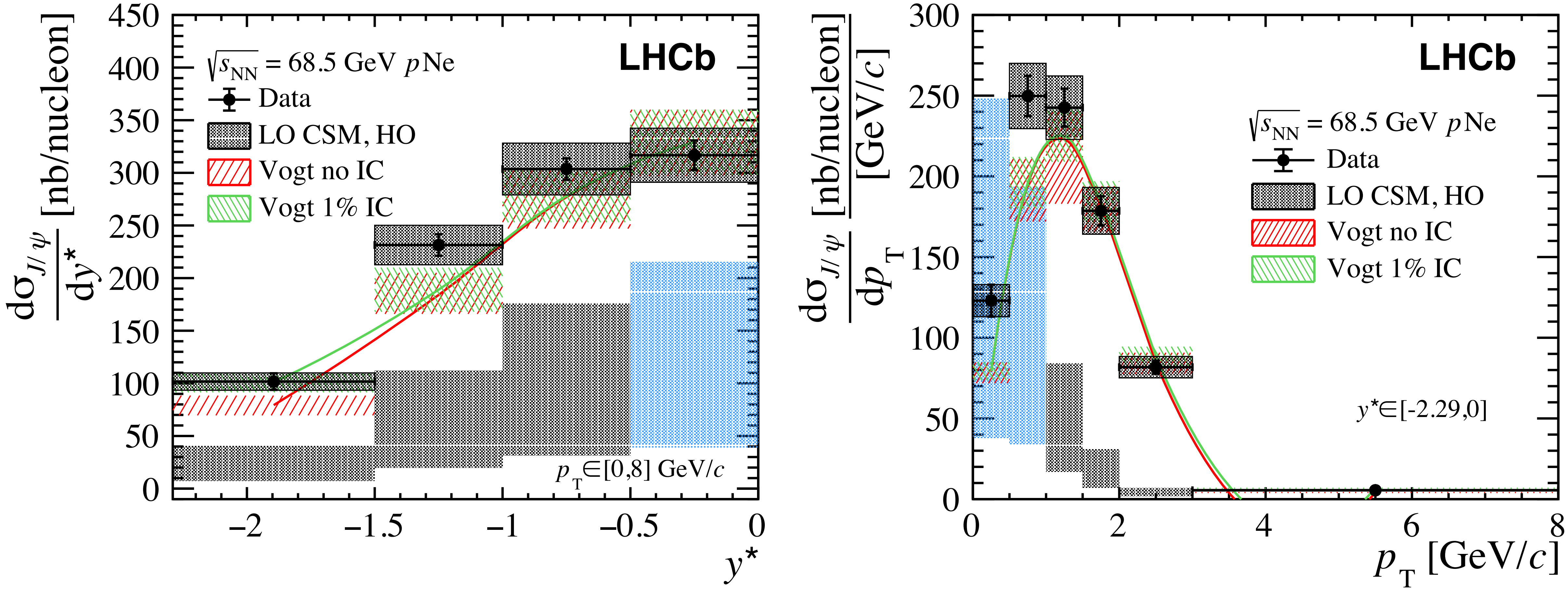


LHCb fixed-target data (*p*Ne, *p*He) is filling in gaps in this data!

LHCb data: EPJC 83 (2023) 625

J/ψ differential cross sections

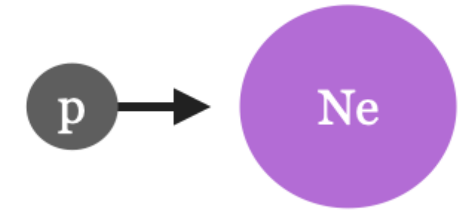


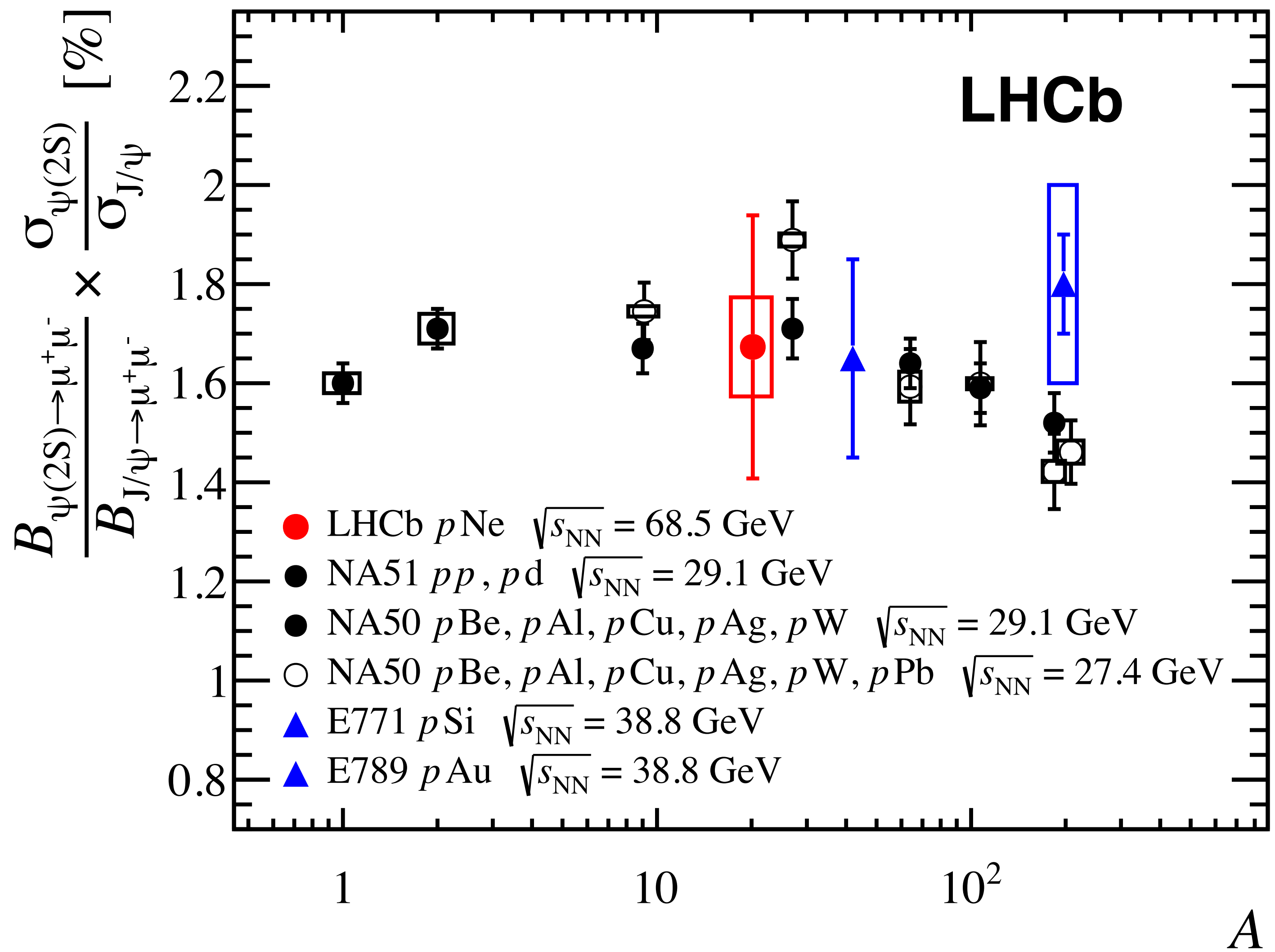


- LO CSM, HO: LO Color Singlet Model (CSM) predictions made using the HELAC-Onia generator with CT14NLO and nCTEQ15 PDF sets
- Vogt predictions use the Color Evaporation Model, EPPS16 nPDFs, and include contributions from nuclear absorption and multiple scattering
- The data does not differentiate between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

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

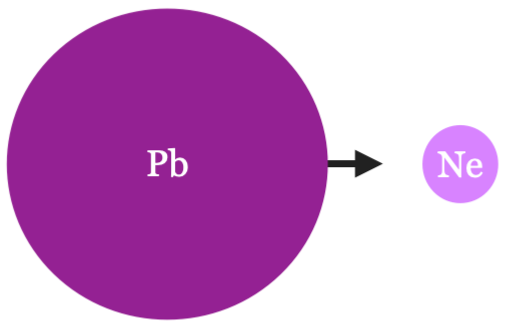




- LHCb measurement: 1.67 ± 0.27 (stat) ± 0.10 (sys) %
- The relative production rate of ψ(2S) to J/ψ mesons in *p*Ne collisions is consistent with the rates measured on other nuclear targets and at other center of mass energies

LHCb data: EPJC 83 (2023) 625

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

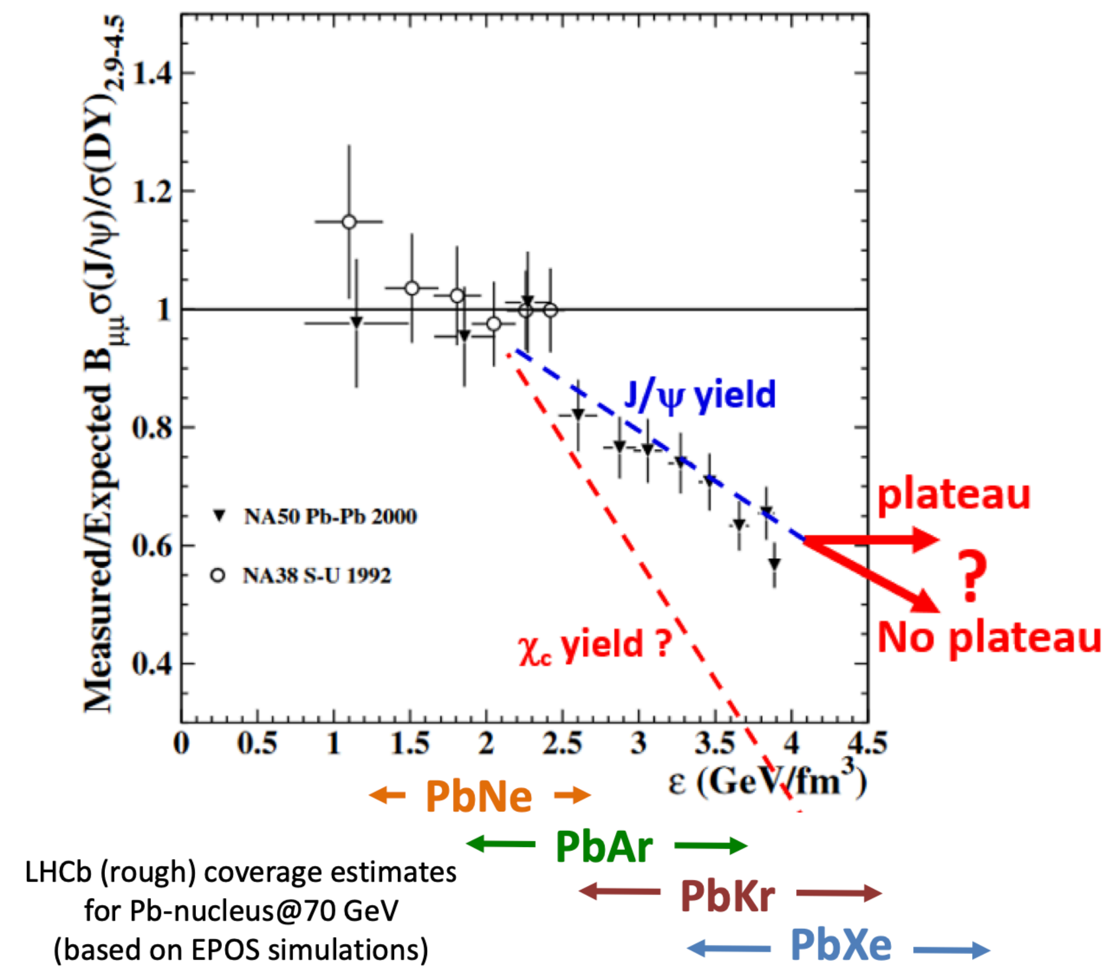
  - $\sigma_{c\bar{c}}^{5.5\ TeV} \approx 10 \times \sigma_{c\bar{c}}^{200\ GeV} \approx 100 \times \sigma_{c\bar{c}}^{70\ GeV} \approx 1000 \times \sigma_{c\bar{c}}^{20\ GeV}$

  - 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 pNe collisions at the same energy to measure the cold nuclear matter effects in Ne

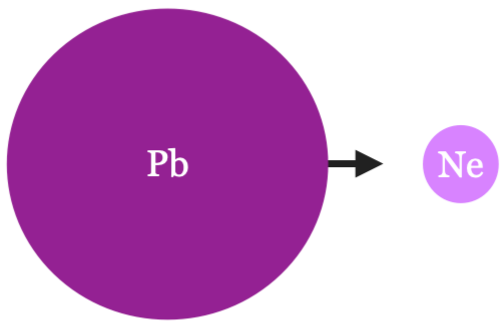
- Can measure charmonium suppression **fully controlled for recombination and CNM effects**

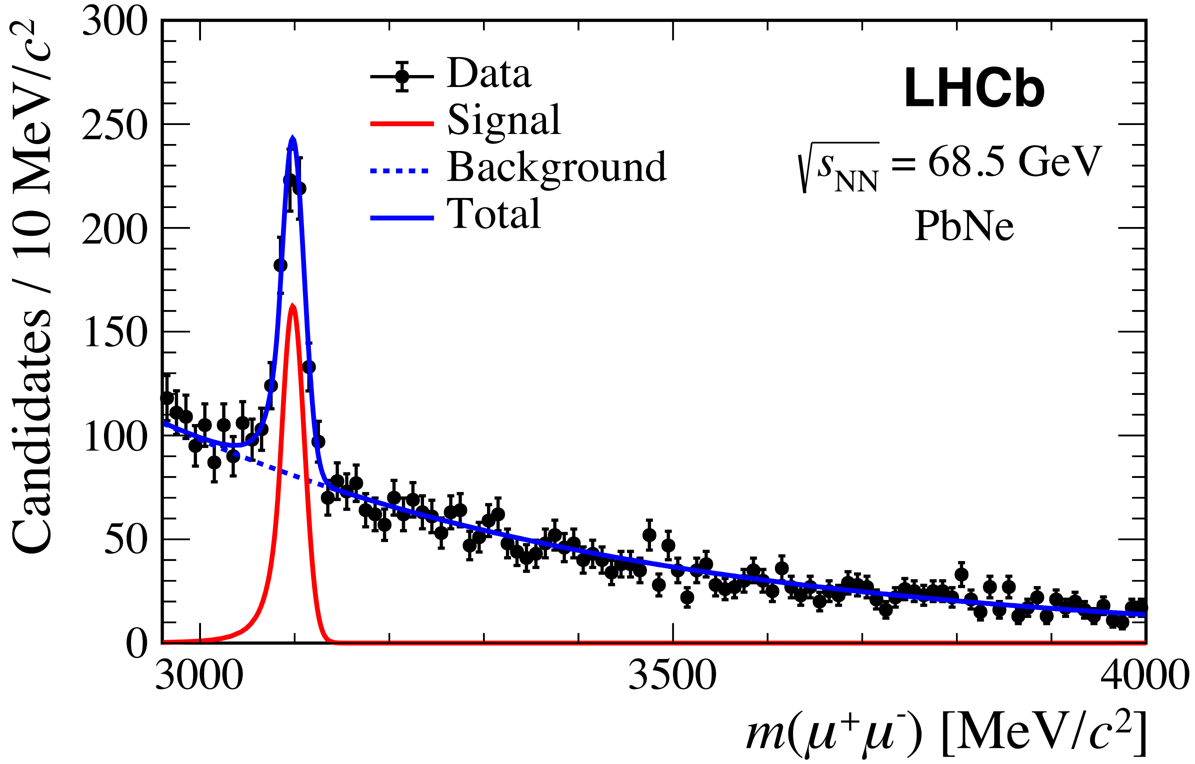


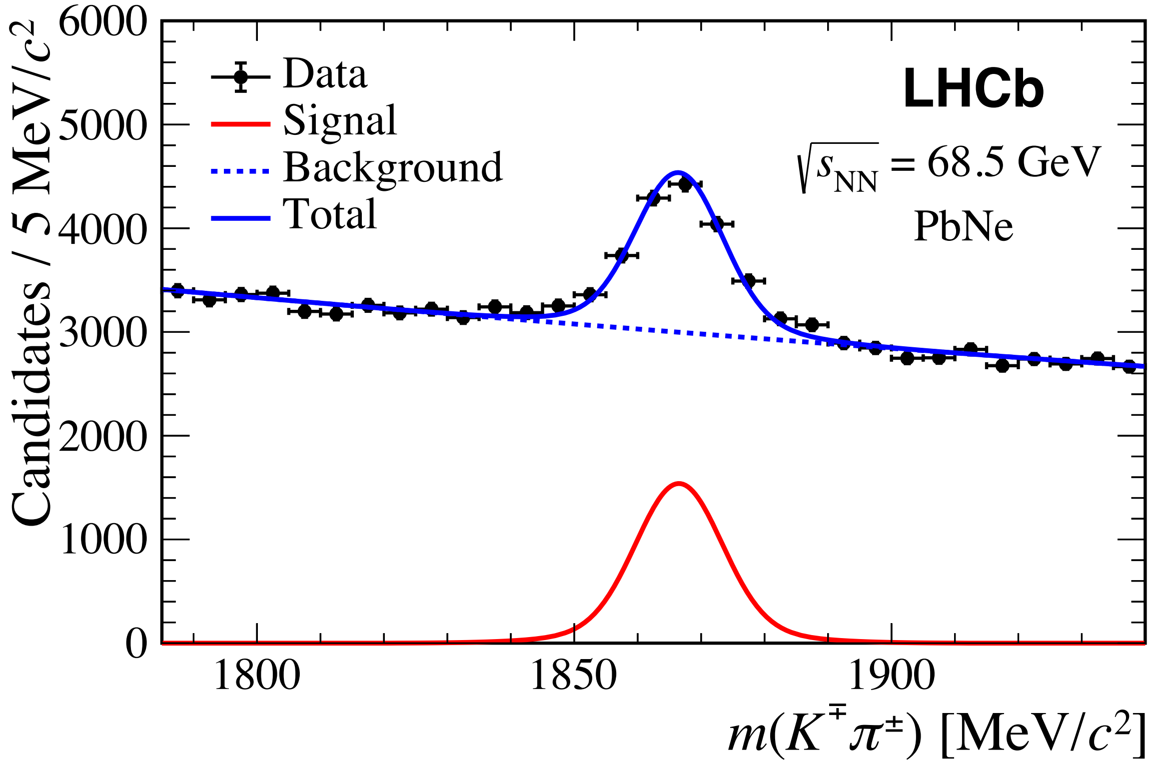
EPJC 39, (2005) 335-345

PRL 94, 082301 (2005)

Heavy flavor signal yields in PbNe collisions





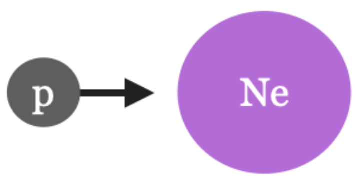


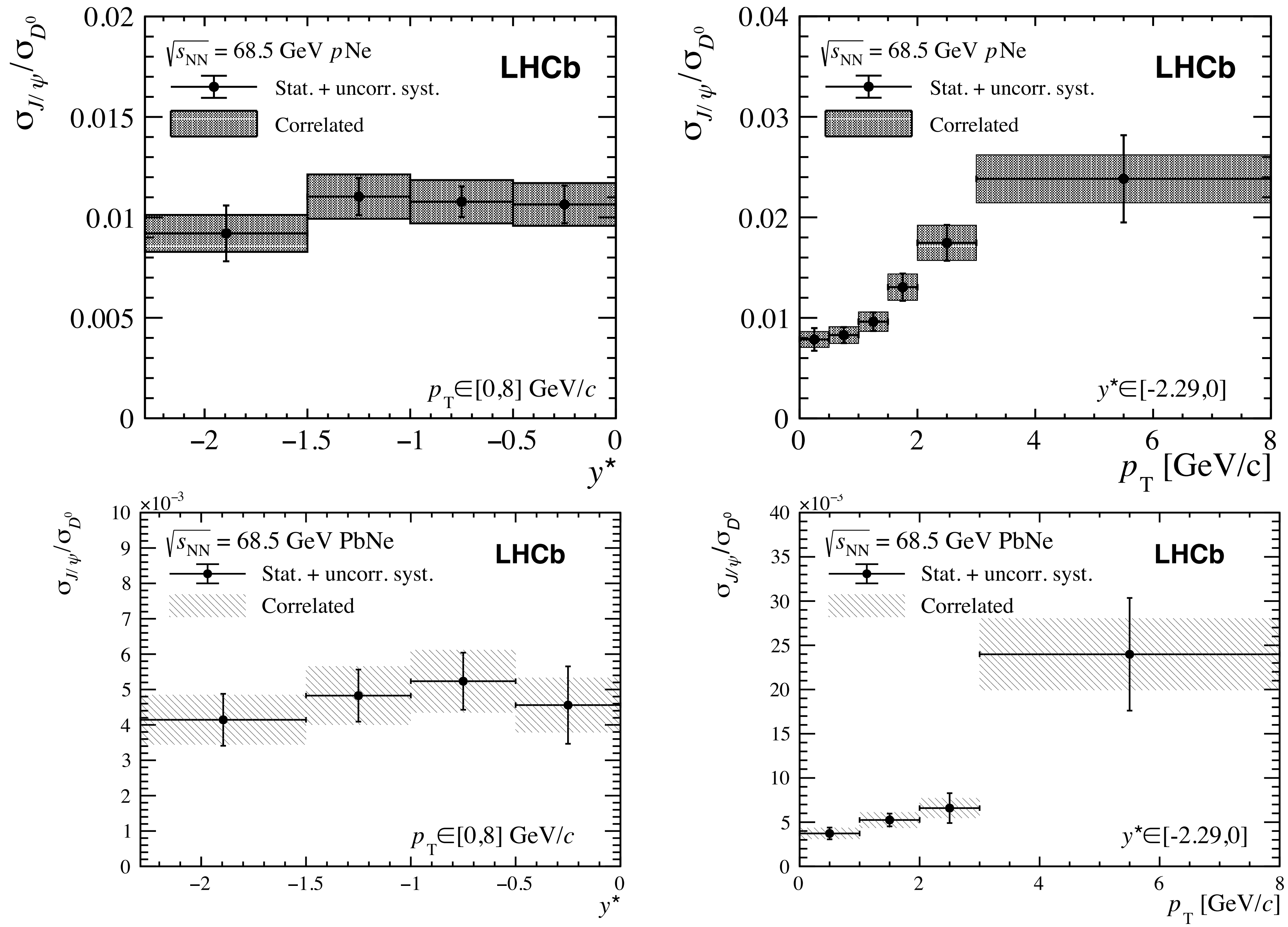
- Larger background than in *p*A collisions, but clean signal peaks are still observed - proof of measurement feasibility in larger PbA systems
- Similar candidate selection as in *p*Ne measurement
- Heavy flavor hadron p_T < 8 GeV
- Heavy flavor hadron y in 2.0 < y < 4.29

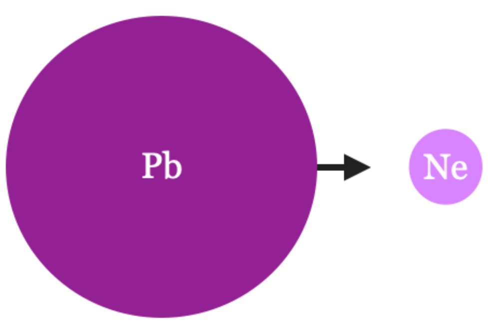
Candidate yields: 545 J/ψ, 5670 D^0

EPJC 83 (2023) 658

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

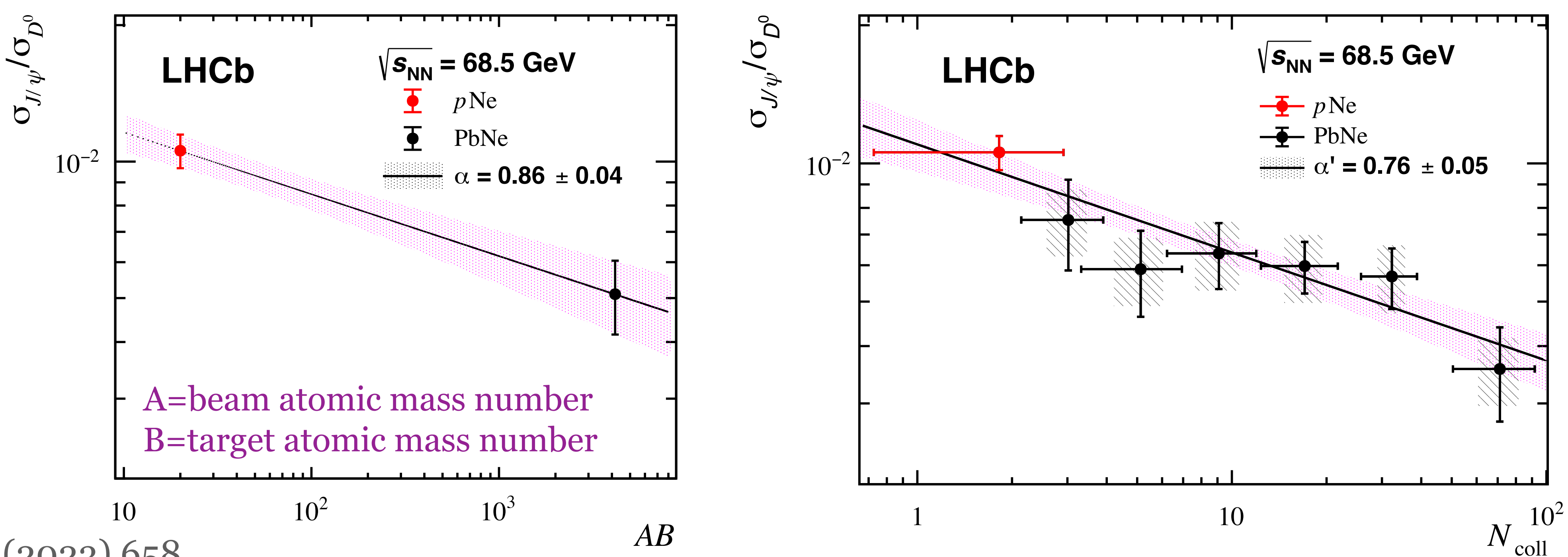
PbNe: EPJC 83 (2023) 658 **pNe:** EPJC 83 (2023) 625

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:

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

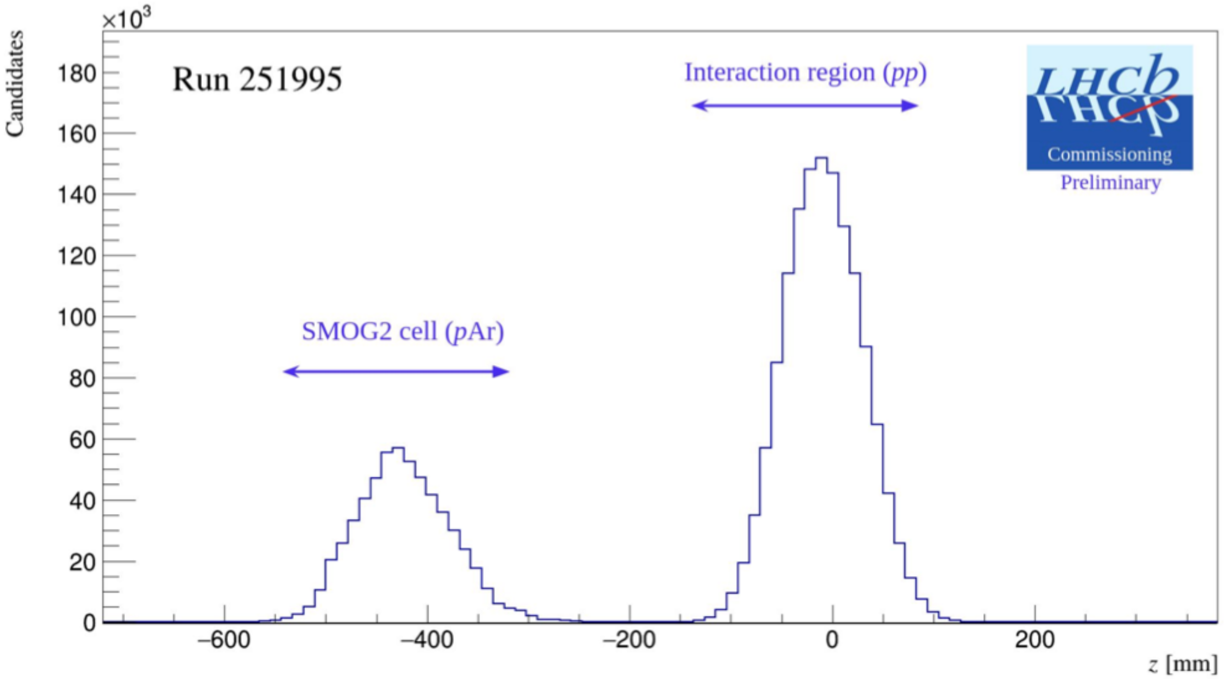
- Same functional form for the ratio as a function of the number of collisions (N_{coll})
- α < 1: indicates that J/ψ mesons experience additional nuclear effects than D^0 mesons
- Within the current precision, a linear trend is observed between pNe and central PbNe events and no conclusive evidence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



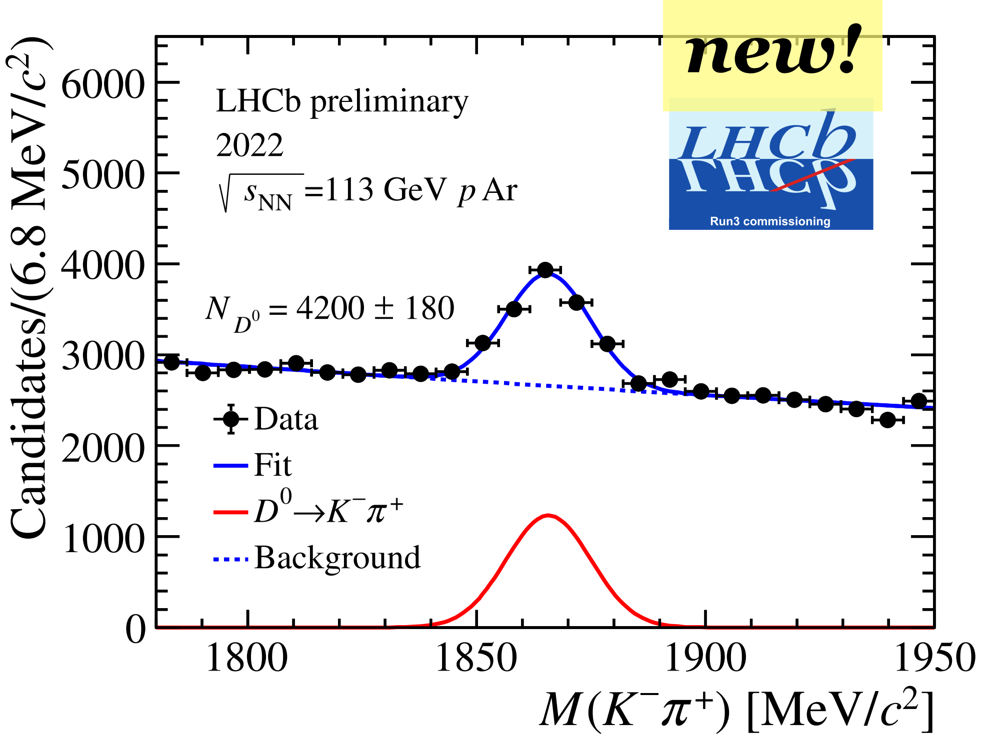
PbNe: EPJC 83 (2023) 658
pNe: EPJC 83 (2023) 625

Charm in Run 3 with LHCb SMOG2

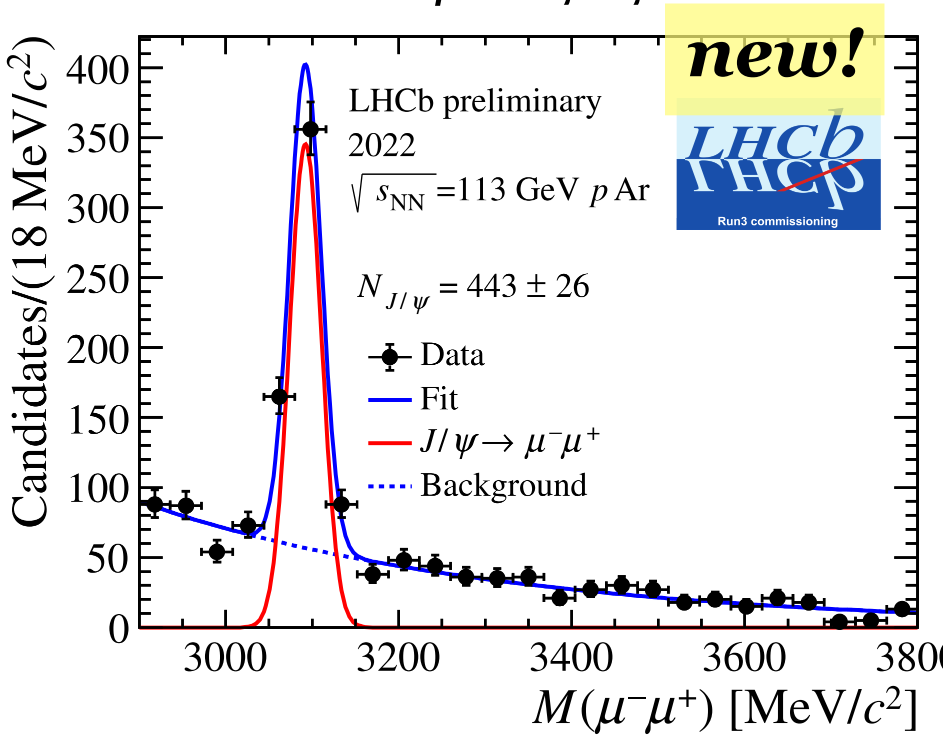
- SMOG2 is a dedicated cell for gas injection installed just before the LHCb VELO
- Can run in parallel with collider mode pp physics data taking at LHCb
- Equipped with a sophisticated Gas Feed System to store and inject 8 different gases: H_2, D_2, Ar, Kr, Xe, He, Ne, N_2, O_2
- From **18 minutes of *p*Ar data-taking** in 2022: 4200 D^0 and 443 J/ψ candidates!



$D^0 \rightarrow K^-\pi^+$



$J/\psi \rightarrow \mu^+\mu^-$



See talk by S. Mariani Wed. at 12:20pm for more details on SMOG2 commissioning!

LHCb-FIGURE-2022-002

LHCb-FIGURE-2023-008

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
- 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
- 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
- The first Run 3 data has been taken with LHCb's fixed target upgrade, SMOG2, and includes excellent D^0 and J/ψ signal yields collected during an 18-minute Ar injection
- Many quarkonia measurements are possible with SMOG2 and can help disentangle different CNM effects and hot vs. cold QCD matter effects

Thank you for your attention!

Backup

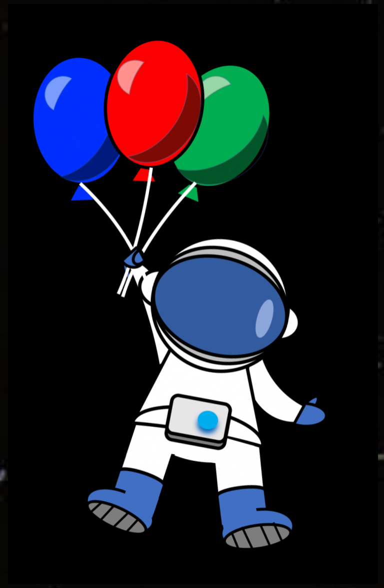
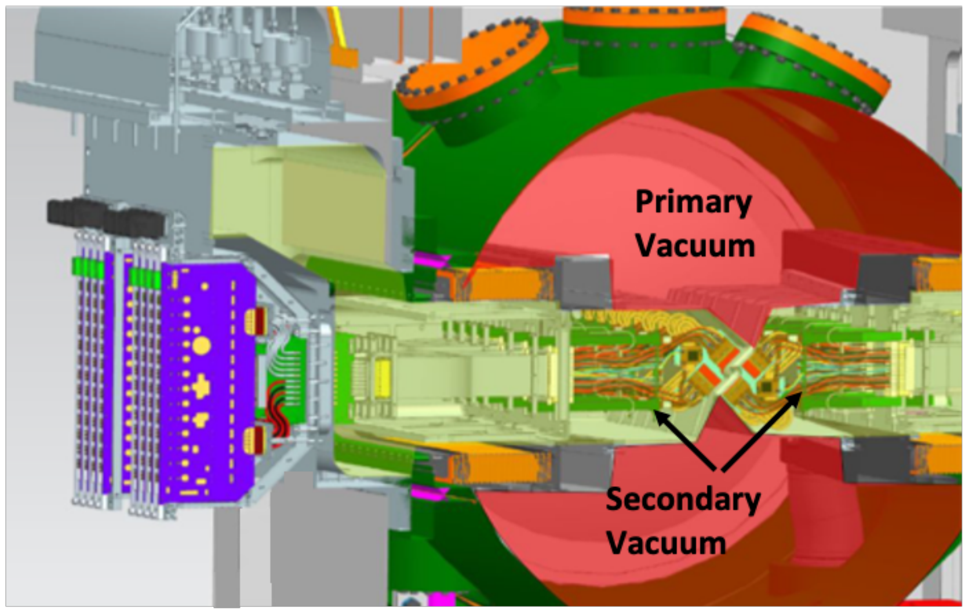


image: NASA

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

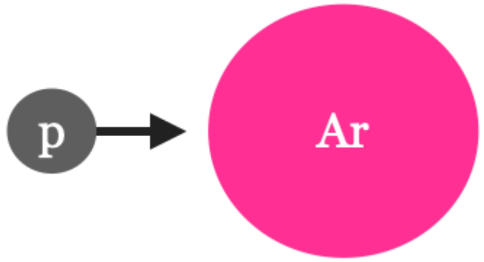


On 10th January 2023, during a VELO warm up in neon, there was a loss of control of the protection system
A pressure differential of 200 mbar built up between the two volumes, whereas the foils are designed to withstand 10 mbar only
Initial investigations show no damage to the VELO modules; sensors show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

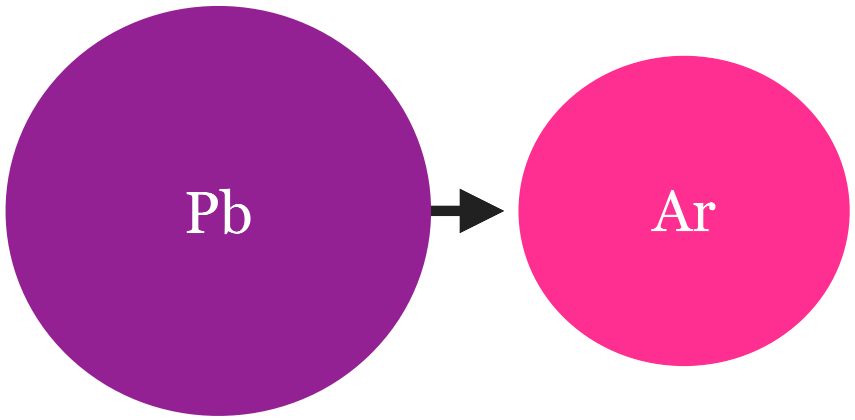
Early measurements possible with SMOG2

- **J/ψ and ψ(2S) production in *p*Ar collisions**



  - Baseline for measurement in PbAr collisions
  - Comparison to *p*Ne 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 *p*Ar to provide a baseline for suppression measurements in PbAr

- **J/ψ and D^0 production in PbAr collisions**



  - QGP expected to be produced
  - *p*Ar, PbAr, PbNe measurements can help disentangle hot vs. cold nuclear effects that contribute to quarkonia dissociation

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

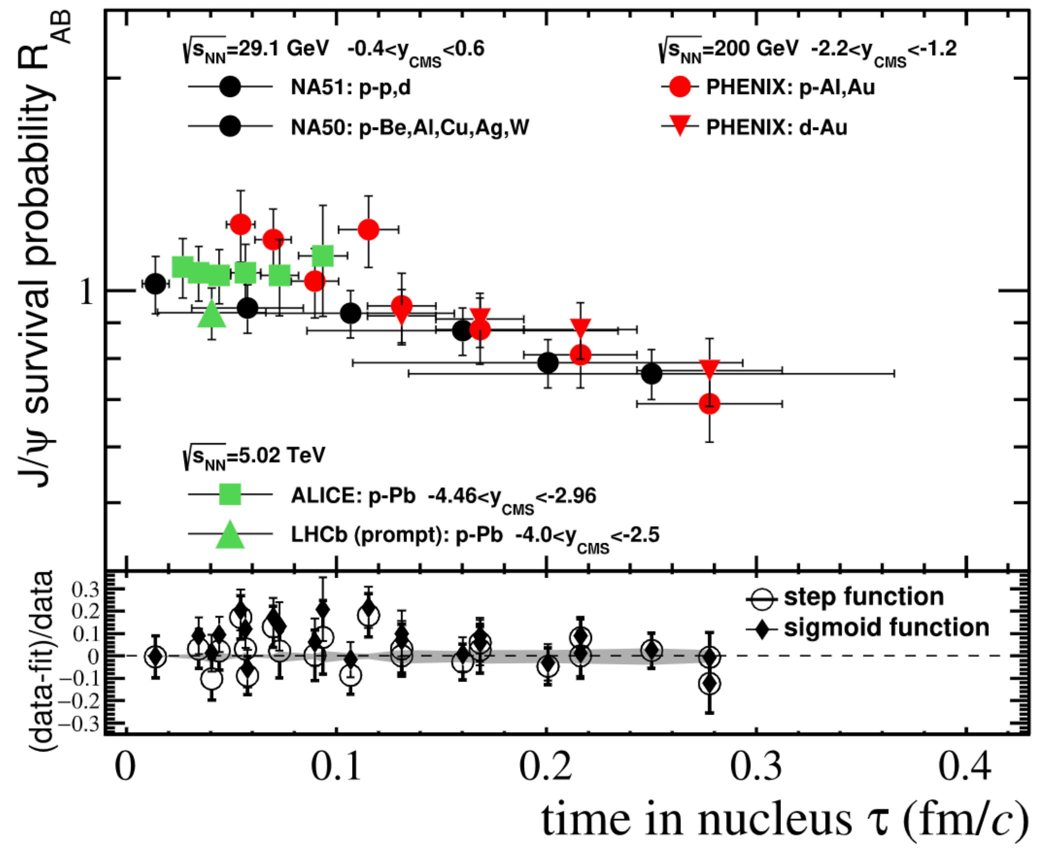
- **Upsilon production in *p*Ar collisions** - study CNM effects as a function of bound state size and quark flavor content (e.g. parton energy loss effects)
- **Multi-differential ψ(2S) measurements in *p*Ar collisions** - complement differential J/ψ measurements and test theoretical models of quarkonium 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**
  - pD₂, pKr, pXe, pN₂, pO₂ collisions all possible
  - PbH₂, 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)

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

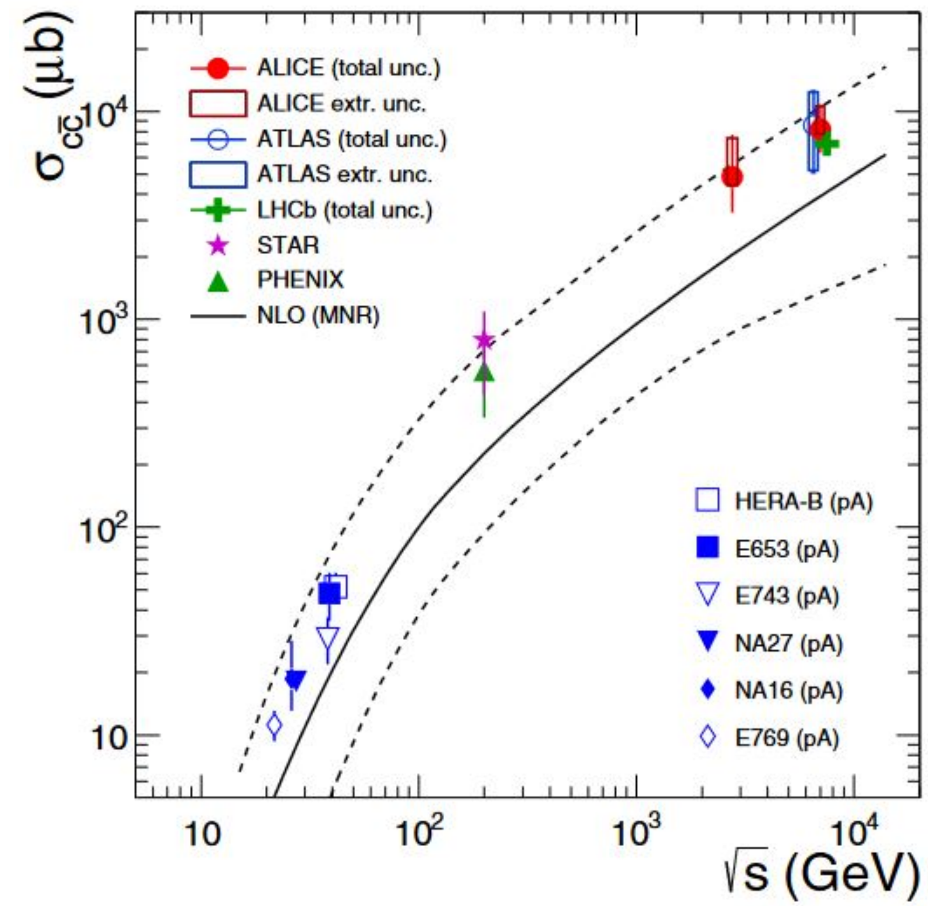


TABLE I. Centrality bin, number of NN collisions, nuclear overlap function, charm cross section per NN collision, and total charm multiplicity per NN collision, in $\sqrt{s_{NN}} = 200$ GeV Au + Au reactions.

Centrality (%)	N_{coll}	T_{AA} (mb^{-1})	$\frac{1}{T_{AA}} \frac{dN_{c\bar{c}}}{dy}\vert_{y=0}$ (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	$\sqrt{s_{NN}}$ (GeV)	$<$ pressure$>$ (10^{-5} mbar)	ρ_S (cm^{-2})	$\mathcal{L}$ ($cm^{-2}s^{-1}$)	Rate (MHz)	Time (s)	$\int \mathcal{L}$ (pb^{-1})
pH_2	115	4.0	2.0×10^{13}	6×10^{31}	4.6	2.5×10^6	150
pD_2	115	2.0	1.0×10^{13}	3×10^{31}	4.3	0.3×10^6	9
pAr	115	1.2	0.6×10^{13}	1.8×10^{31}	11	2.5×10^6	45
pKr	115	0.8	0.4×10^{13}	1.2×10^{31}	12	2.5×10^6	30
pXe	115	0.6	0.3×10^{13}	0.9×10^{31}	12	2.5×10^6	22
pHe	115	2.0	1.0×10^{13}	3×10^{31}	3.5	3.3×10^3	0.1
pNe	115	2.0	1.0×10^{13}	3×10^{31}	12	3.3×10^3	0.1
pN_2	115	1.0	0.5×10^{13}	1.5×10^{31}	9.0	3.3×10^3	0.1
pO_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
pAr	72	1.2	0.6×10^{13}	1.8×10^{31}	11	3×10^5	5

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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

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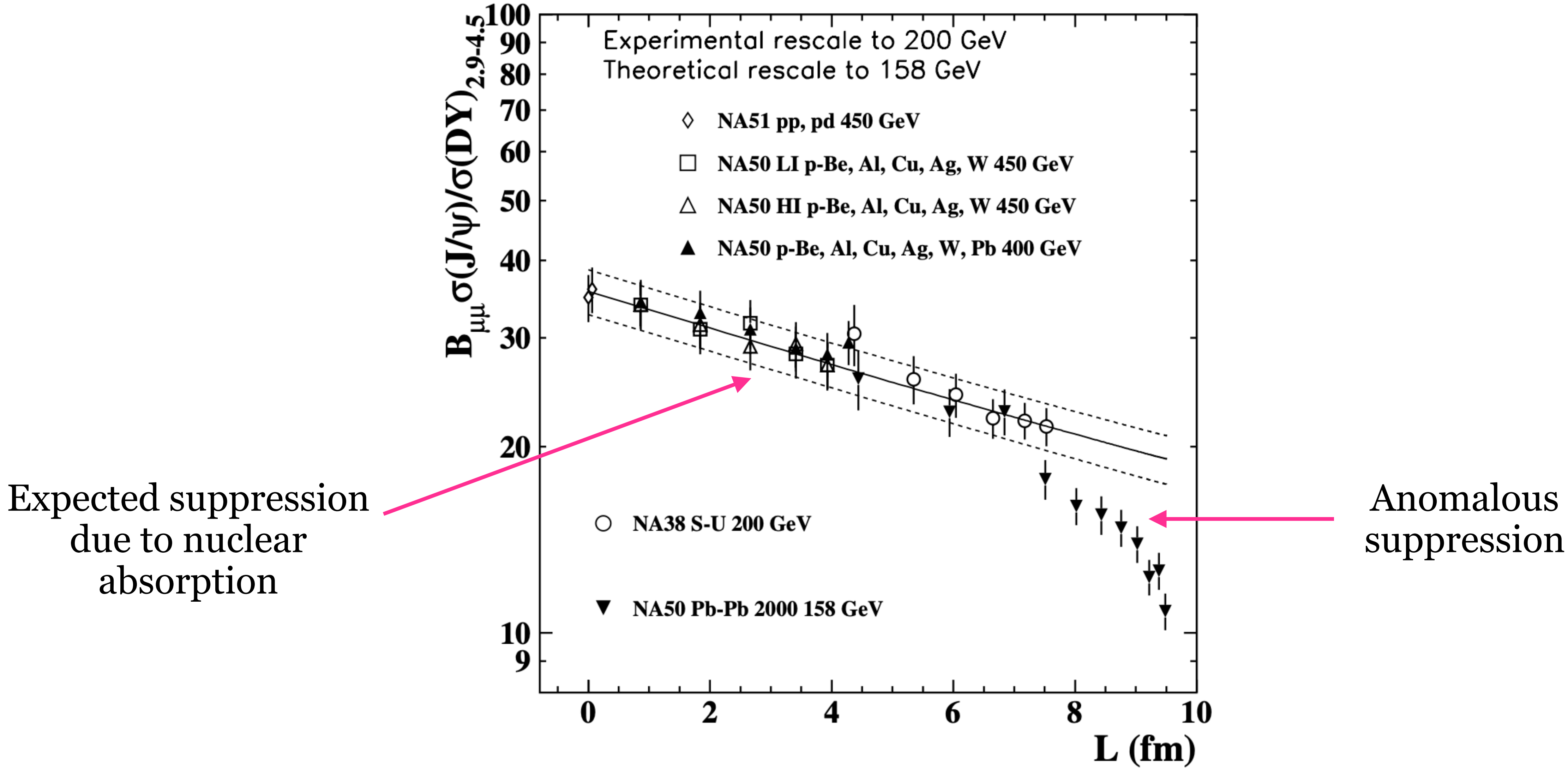
Anomalous J/ψ suppression observed by NA50



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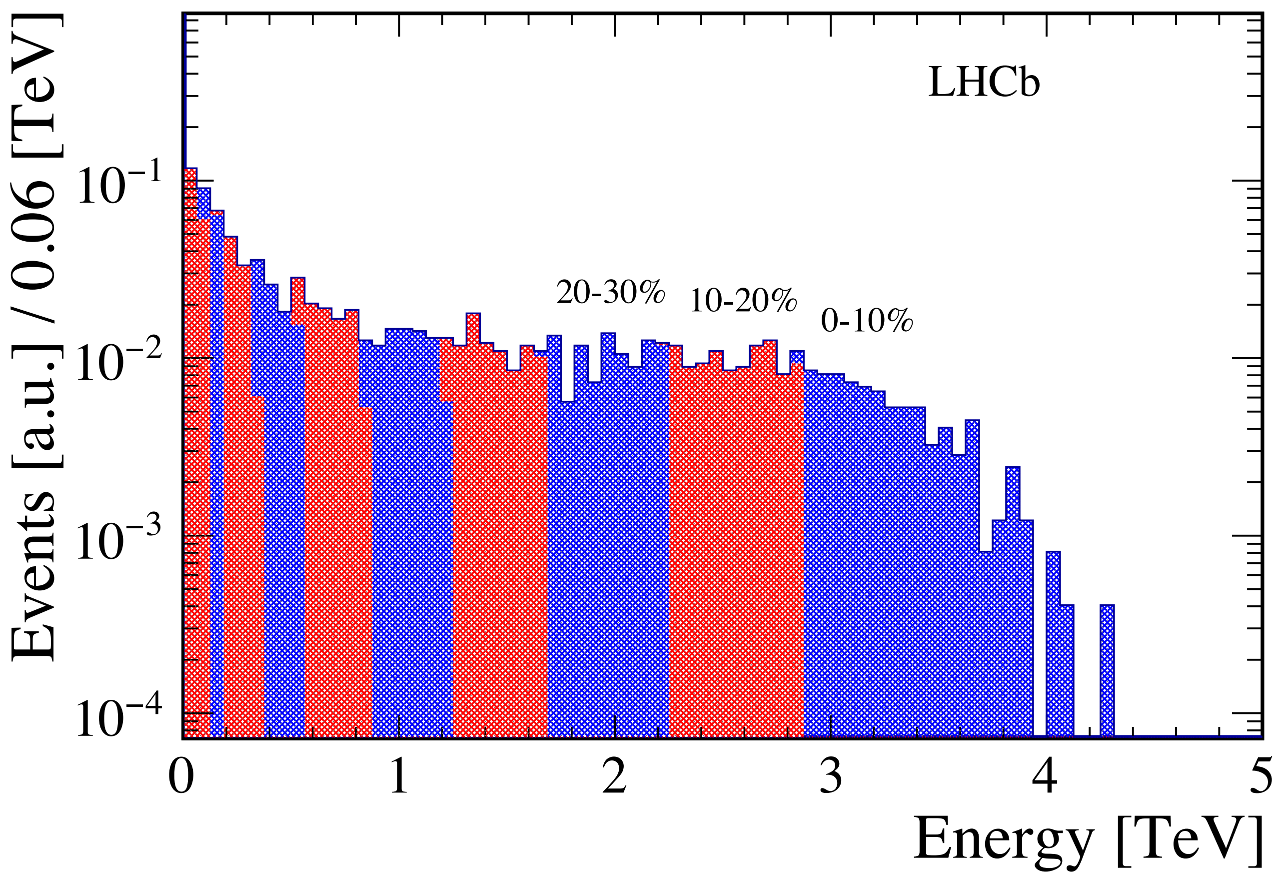
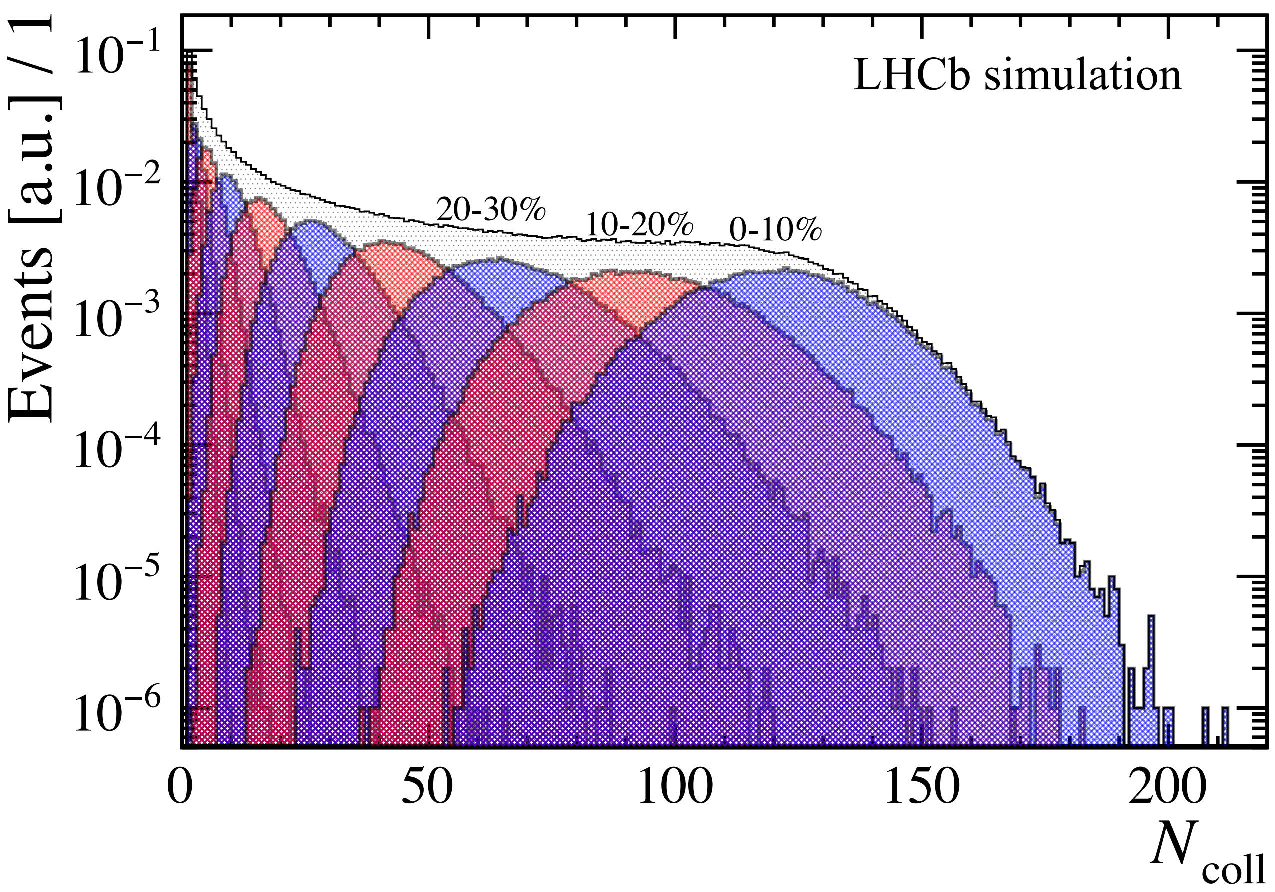
Centrality at LHCb

Centrality classes for PbNe collisions





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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)