Experimental results for quarkonia production in the fixed-target mode at the LHC

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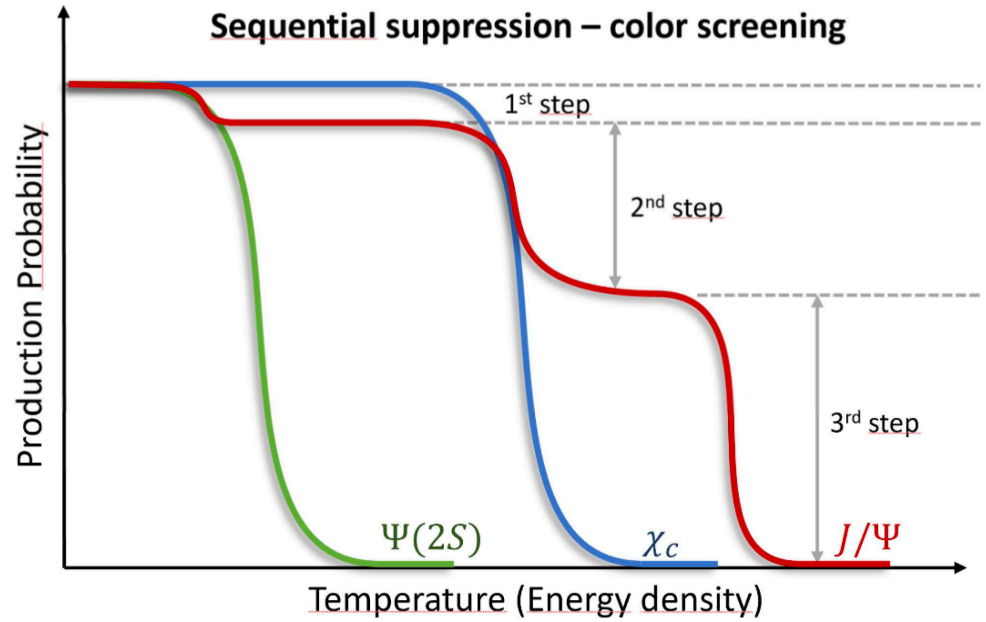
Quarkonia as tools to probe nuclear effects

- Heavy quarkonia are powerful probes of the QGP as they are produced early in the collision and can therefore experience the full evolution of the QGP medium

- Charmonium states can serve as "temperature probes" of the QGP as different states break apart or "melt" at different temperatures

- However, other non-QGP mechanisms can also cause break-up of charmonium states:
  - Saturation, Comovers interactions, parton energy loss in nuclear media, nuclear PDFs, nuclear absorption, …



Quarkonia as temperature probes

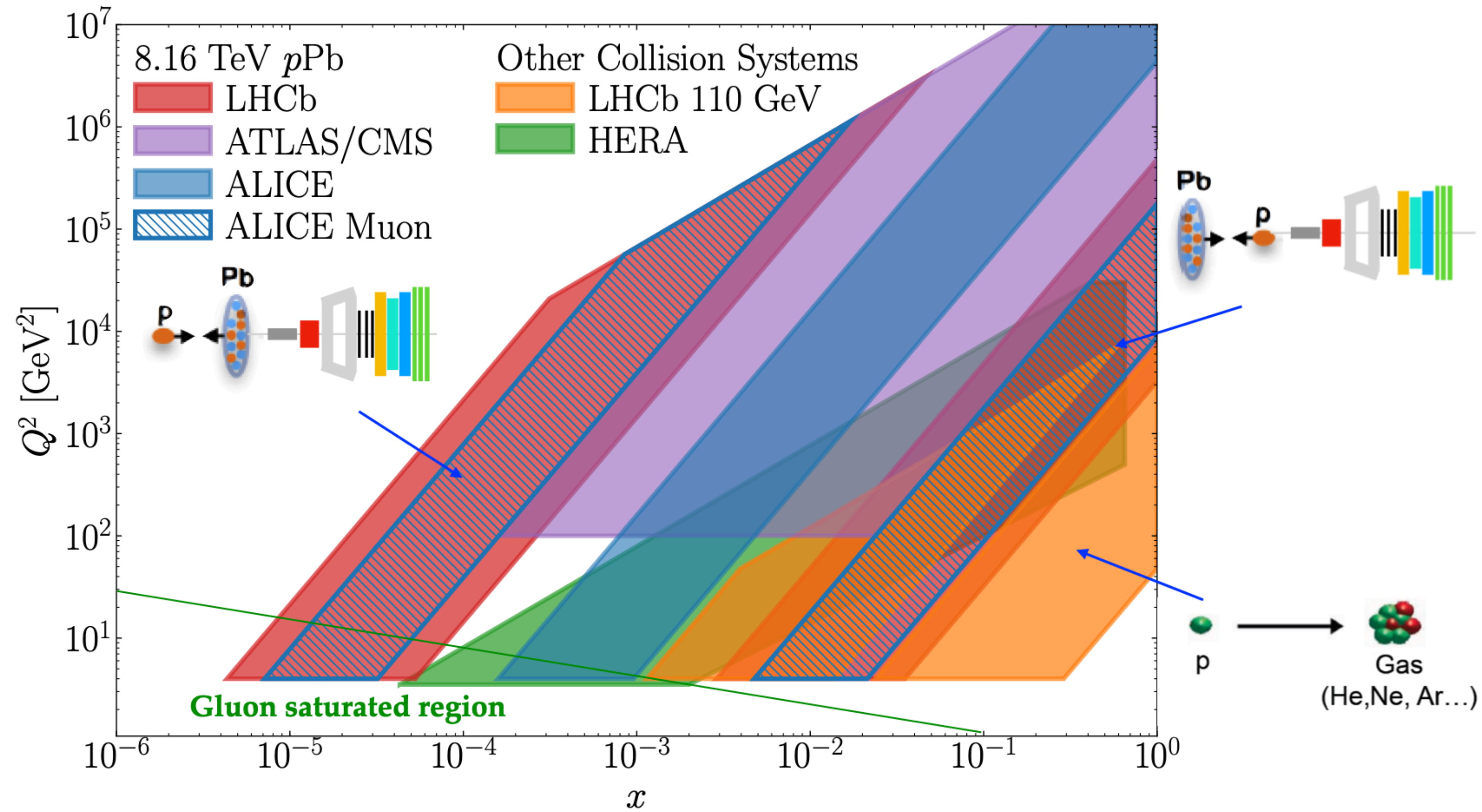
To confirm the sequential suppression pattern and use quarkonia as temperature probes of the QGP, the cold nuclear effects on charmonia dissociation must be well understood

→ Study quarkonium production in a wide range of nuclear systems to constrain CNM effects *See O. Boente Garcia talk for LHC pPb measurements*

→ This is ***more than just a baseline for heavy ion measurements:*** we also learn about how nuclear structure emerges from fundamental QCD, and about QCD dynamics and hadronization

Fixed target kinematics at the LHC

- Center of mass energies between 41 - 115 GeV
  - Between RHIC and LHC energies, similar to future EIC energy
- Access to unexplored region of phase space complementary to that accessed by LHC collider experiments
  - High Bjorken x and low Q^2

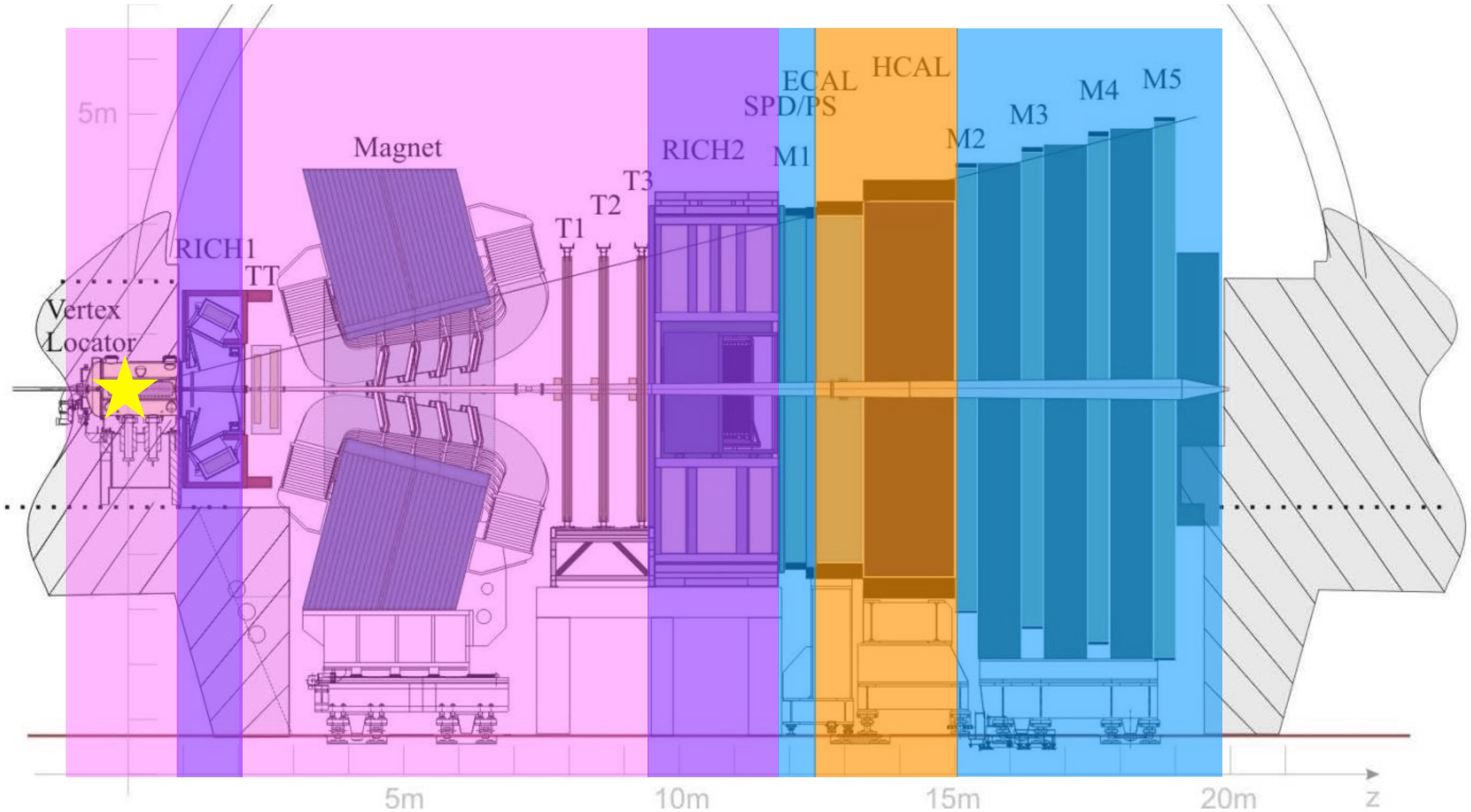


- Variety of nuclear targets
- In Runs 2 & 3, LHCb is the only LHC experiment able to operate in a fixed-target mode
  - Access to rapidity in the center-of-mass system -2.29 < y^* < 0

Can study quarkonium production in novel collision systems and phase space!

The Large Hadron Collider beauty (LHCb) Experiment

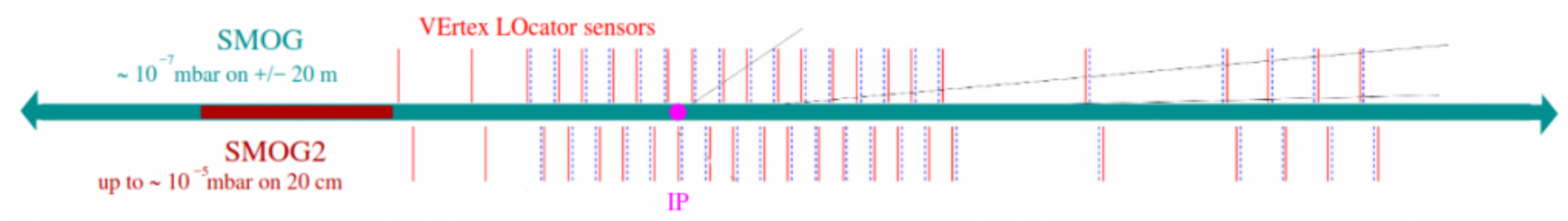
The LHCb Detector: Full **tracking**, **particle identification**, **hadronic and electromagnetic calorimetry** and **muon ID** in $2 < \eta < 5$



- 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

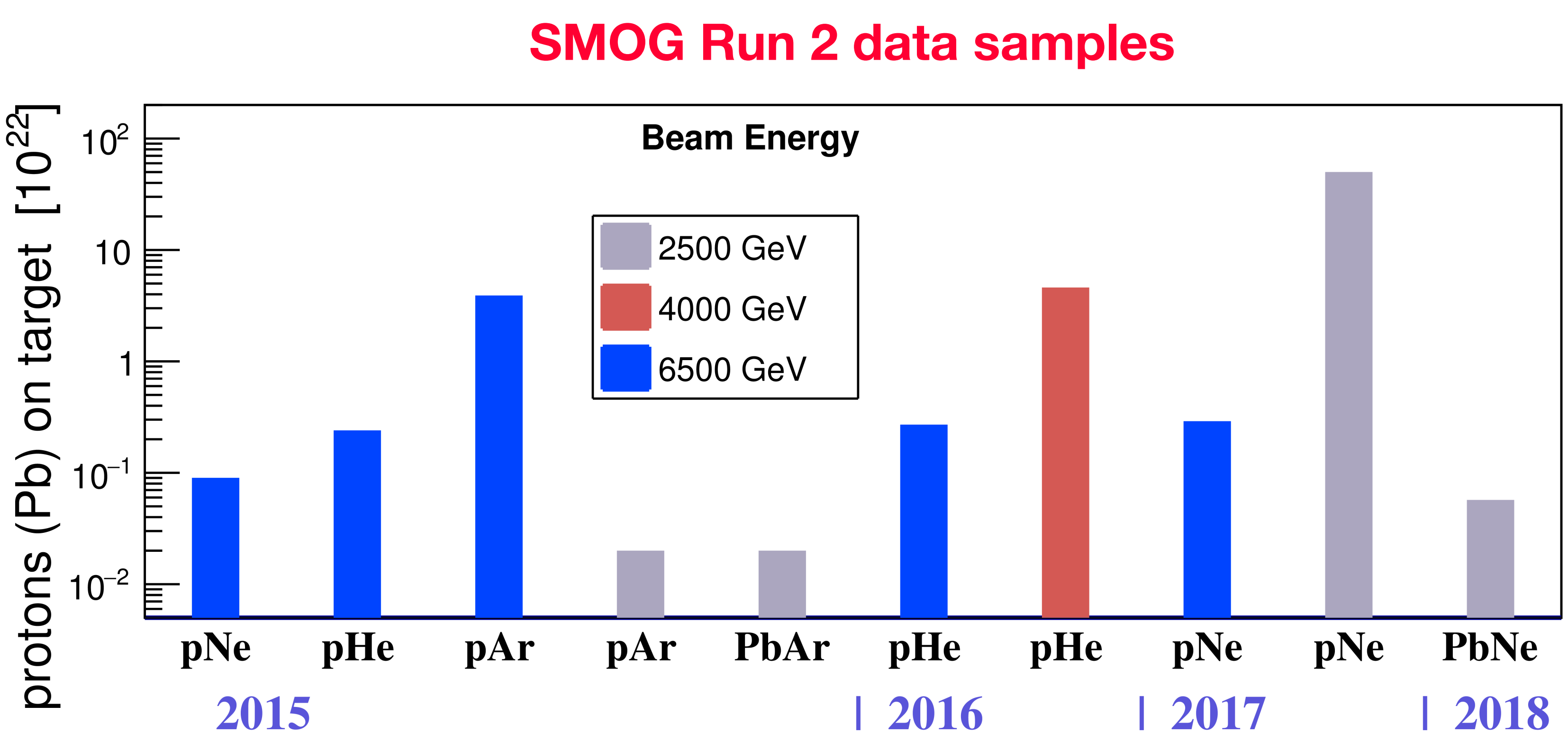
The LHCb fixed-target program in Run 2

- 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}

- Several pA and PbA data samples collected:



Results in pA collisions

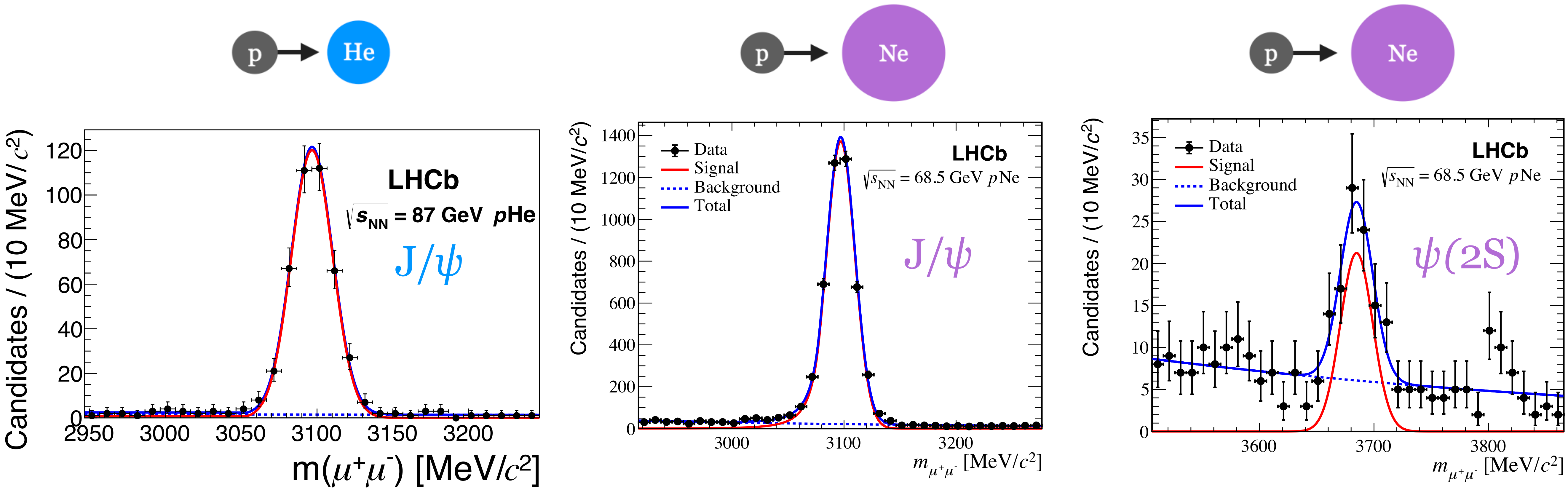
Quarkonia production studied in pA collisions with a variety of nuclear species:

System	Atomic number	$\sqrt{s_{NN}}$	Quarkonia measured	Reference measurement
p → He	N = 2	86.6 GeV	J/ψ	D^0
p → Ne	N = 10	68.5 GeV	J/ψ, $\psi(2S)$	D^0
p → Ar	N = 18	110.4 GeV	J/ψ	D^0

- D^0 production is measured in each system as a proxy for the total charm production cross section
- Only one nucleus involved, so excellent sensitivity to cold nuclear matter effects including nPDF effects (EMC, (anti-)shadowing), parton energy loss and nuclear absorption of the $c\bar{c}$ state
  - *however, disentangling these effects is difficult!*

See C. Hadjidakis talk for LHC fixed-target prospects for QGP studies

Quarkonia yields in pA collisions



Event Selection:

- Two reconstructed muons with p_T > 500 MeV (700 MeV) in pNe (pHe) collisions
- Dimuon vertex consistent with originating from primary vertex
- J/ψ or $\psi(2S)$ candidate $p_T < 8$ GeV
- J/ψ or $\psi(2S)$ candidate y in $2.0 < y < 4.29$ (4.6) in pNe (pHe) collisions

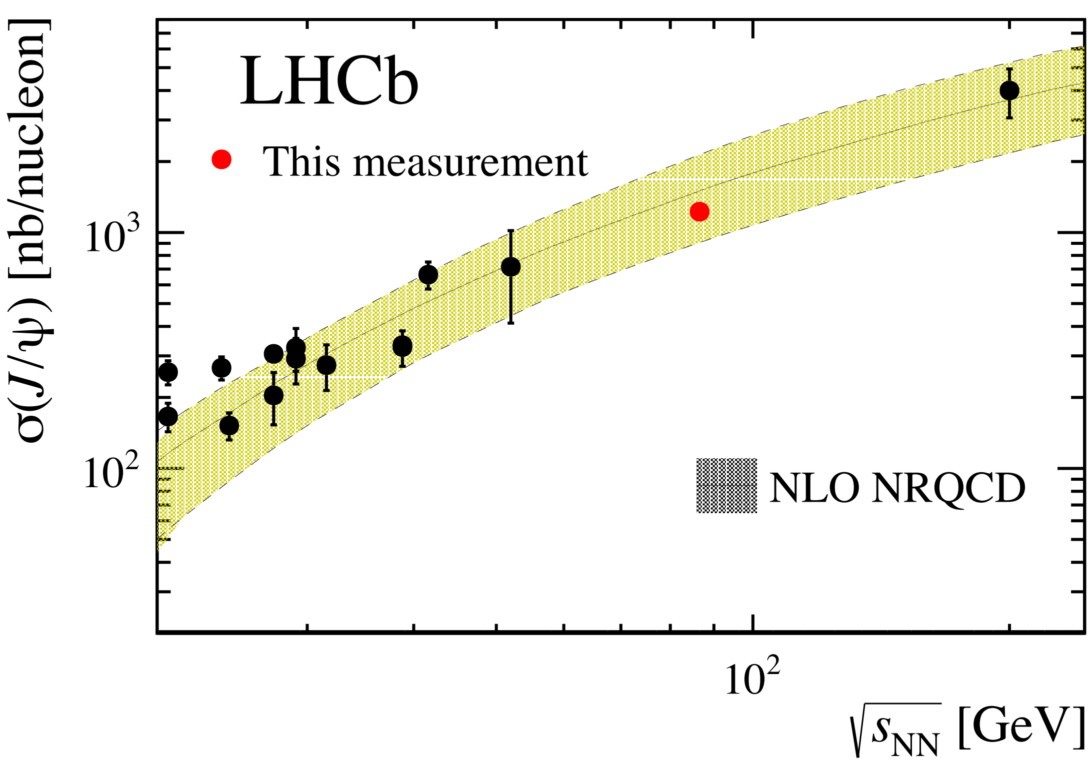
J/ψ and $c\bar{c}$ cross section measurement in pHe collisions at $\sqrt{s_{NN}} = 86.6$ GeV

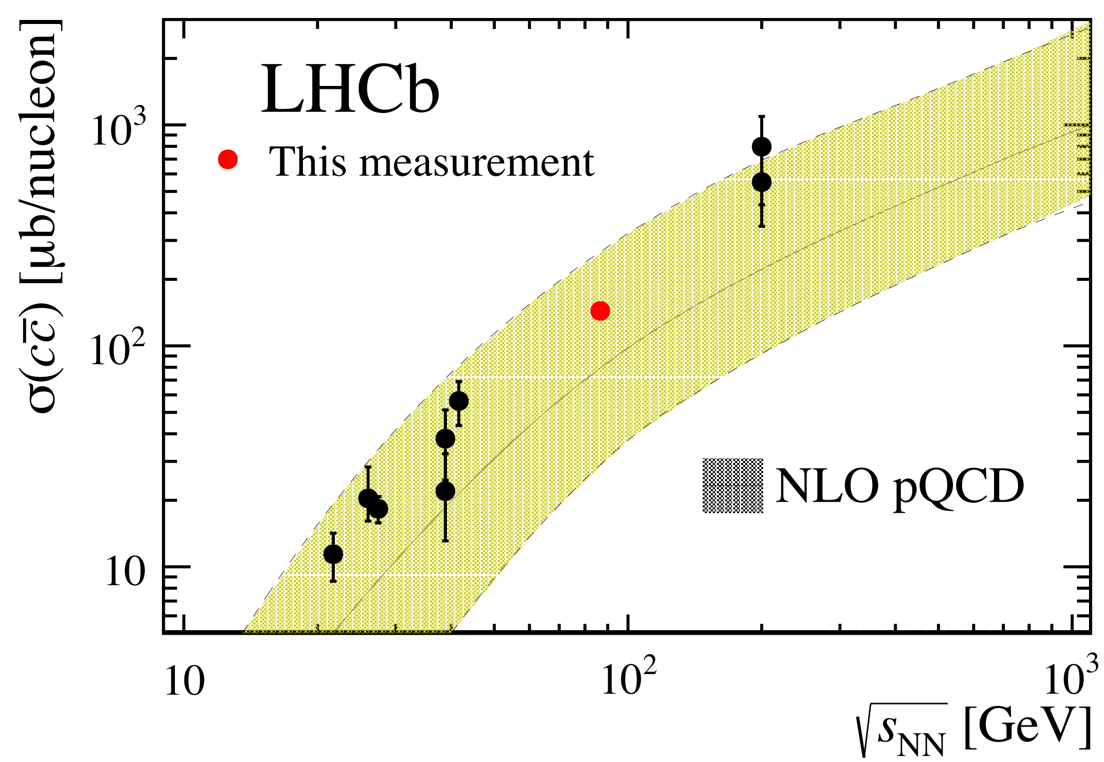
- Measured J/ψ and D^0 cross sections in the fiducial measurement region of y^* in [-2.53, 0.07] were extrapolated to the full backward (negative) hemisphere using Pythia 8 and the CT09MCS PDF set:

  $\sigma(\text{pHe} \rightarrow J/\psi\ X) = 1225.6 \pm 100.7\ \text{nb}^{-1}/\text{nucleon}$

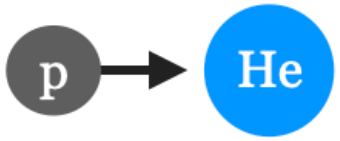
  $\sigma(\text{pHe} \rightarrow D^0\ X) = 156.0 \pm 13.1\ \mu\text{b}^{-1}/\text{nucleon}$

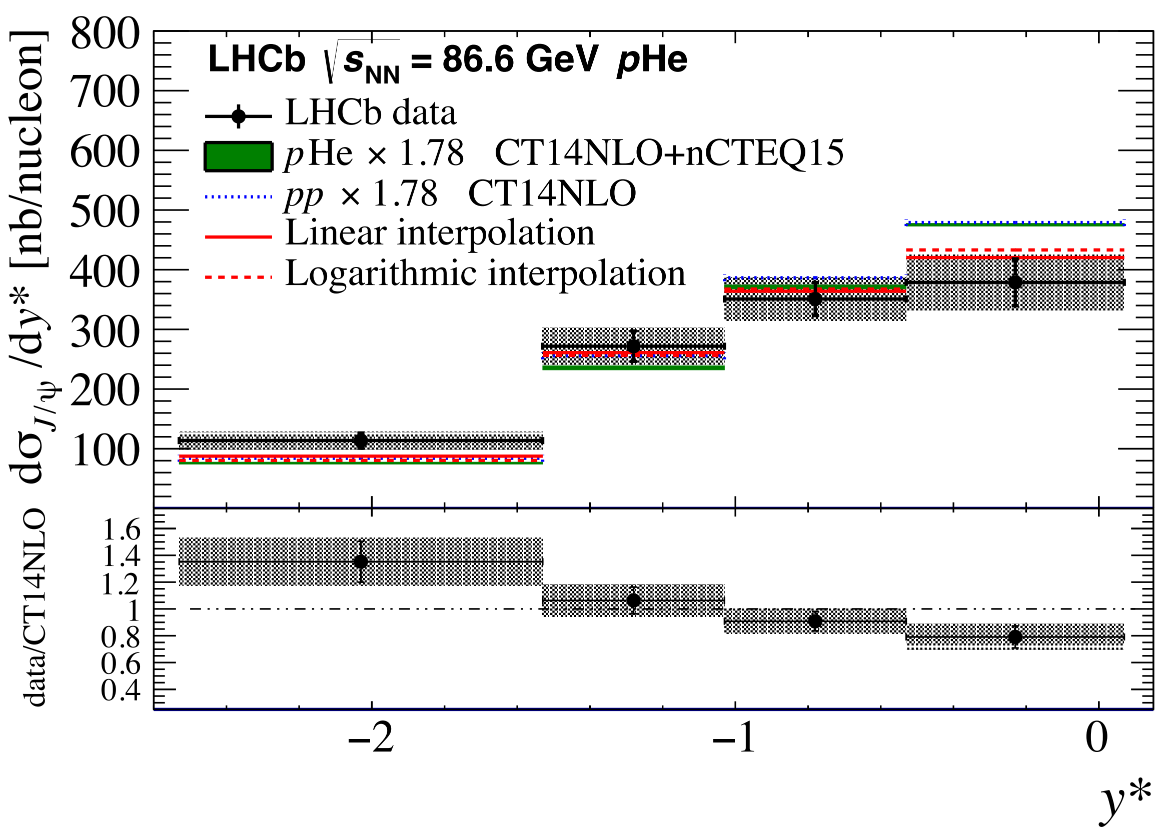
- D^0 cross section scaled by the $c \rightarrow D^0$ fragmentation function to obtain the total $c\bar{c}$ cross section: $\sigma(\text{pHe} \rightarrow c\bar{c}\ X) = 144 \pm 12\ (\text{stat+sys}) \pm 4\ (\text{FF})\ \mu\text{b}^{-1}/\text{nucleon}$

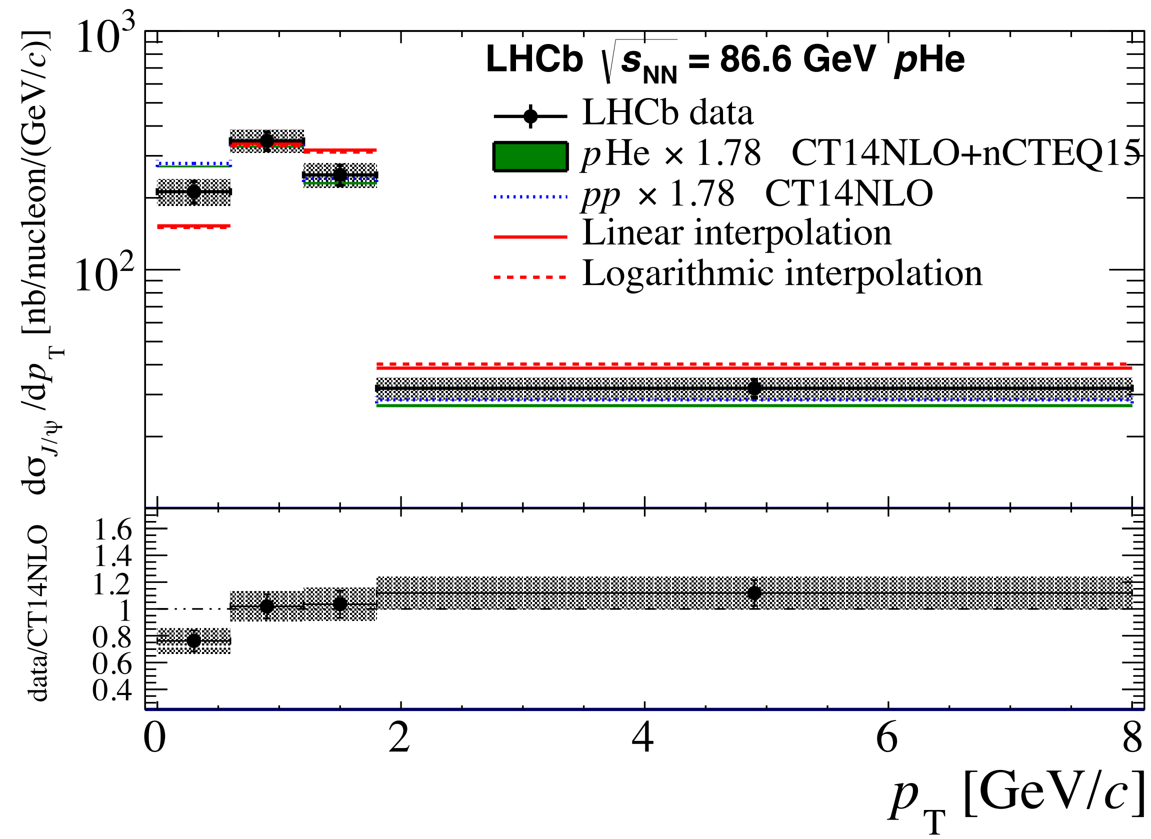




J/ψ differential production cross sections in pHe collisions

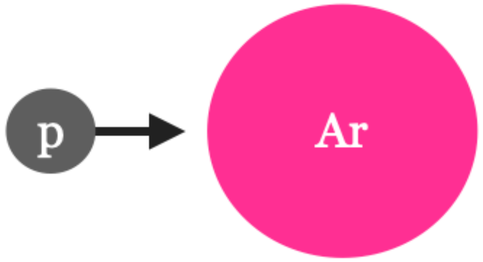


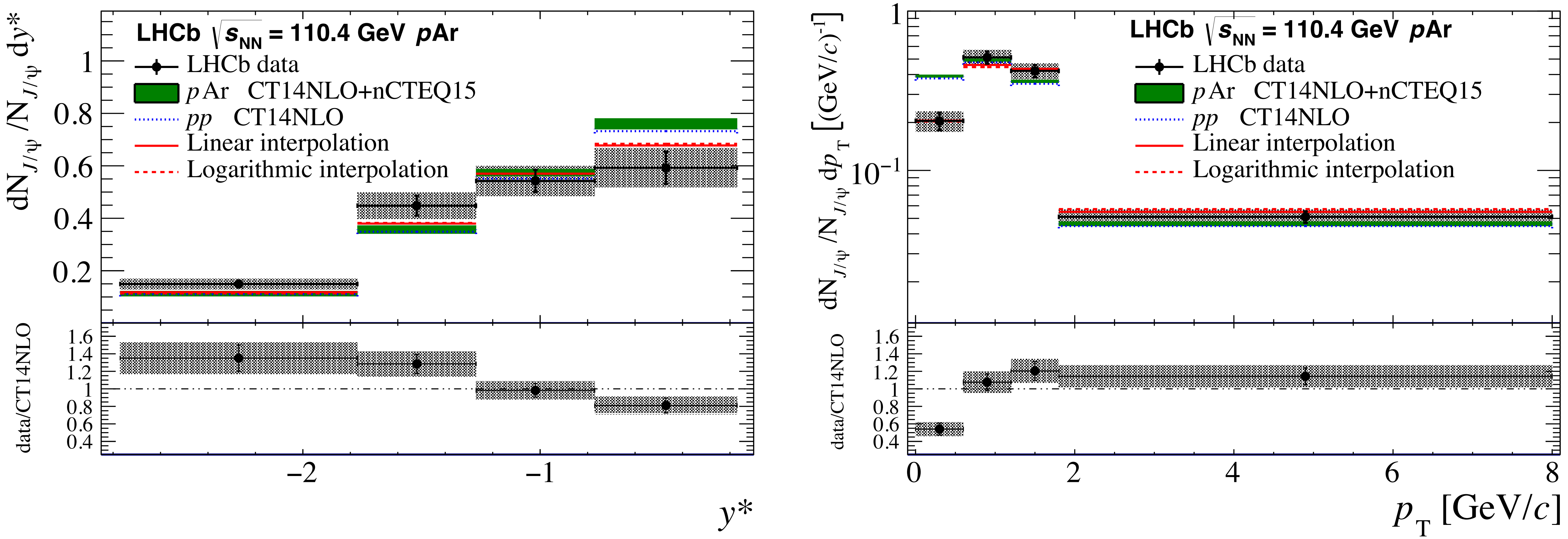




- Helac-Onia predictions for pp and pHe collisions describe the shape of the distributions reasonably well, but underestimate the cross section (predictions are scaled by 1.78 to compare to data)
- Phenomenological parameterisations interpolated to measurement energy of 86.6 GeV using the following datasets:
  - E789 pAu → J/ψ X at $\sqrt{s_{NN}}$ = 38.7 GeV
  - HERA-B pC → J/ψ X at $\sqrt{s_{NN}}$ = 41.5 GeV
  - PHENIX pp → J/ψ X at $\sqrt{s}$ = 200 GeV

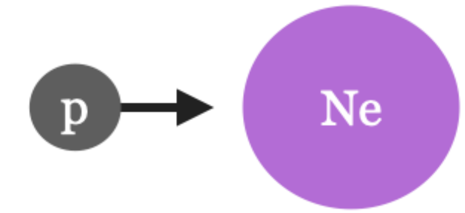
J/ψ differential yields in pAr collisions at $\sqrt{s_{NN}}$ = 110.4 GeV





- No cross section measurement in pAr collisions because the luminosity measurement was not available
- Theoretical predictions overestimate the data in the lowest p_T bin (~0 - 0.5 GeV), but the interpolation captures the trend
- More nuclear effects expected in pAr collisions than pHe, e.g. parton energy loss, nuclear absorption of the $c\bar{c}$ state - one way to have a handle on “disentangling” CNM effects

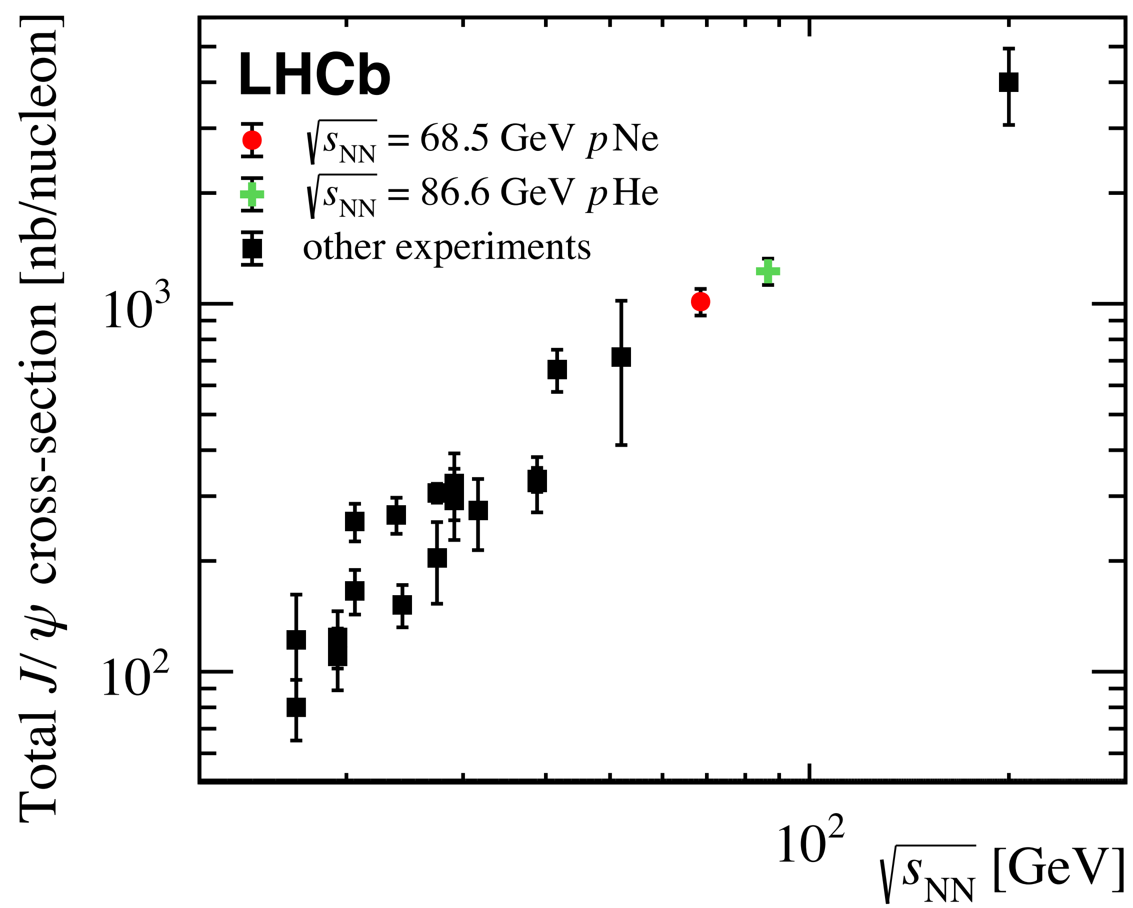
J/ψ cross section measurement in pNe collisions at $\sqrt{s_{NN}}$ = 68.5 GeV



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

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

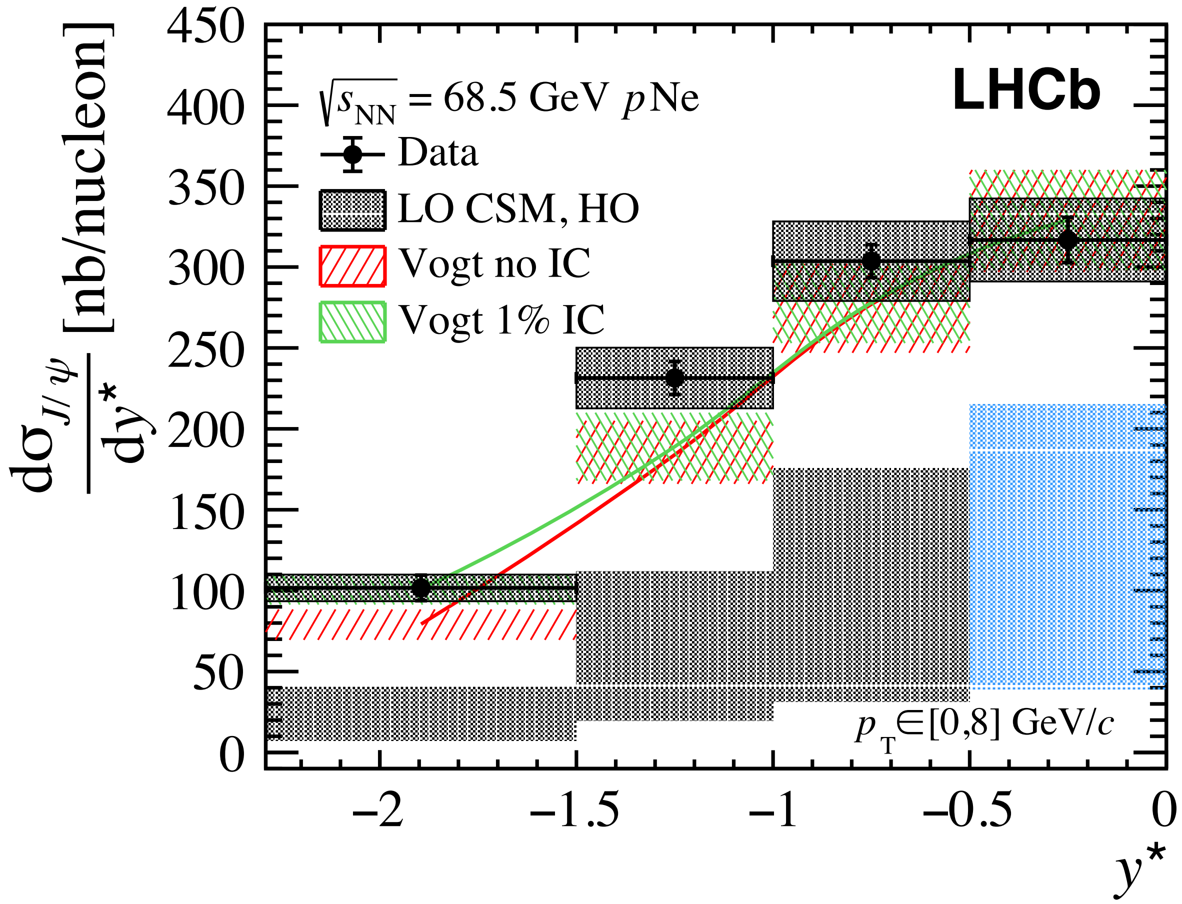
- Comparison to cross section measurements from other experiments shows a power law dependence on the center of mass energy:

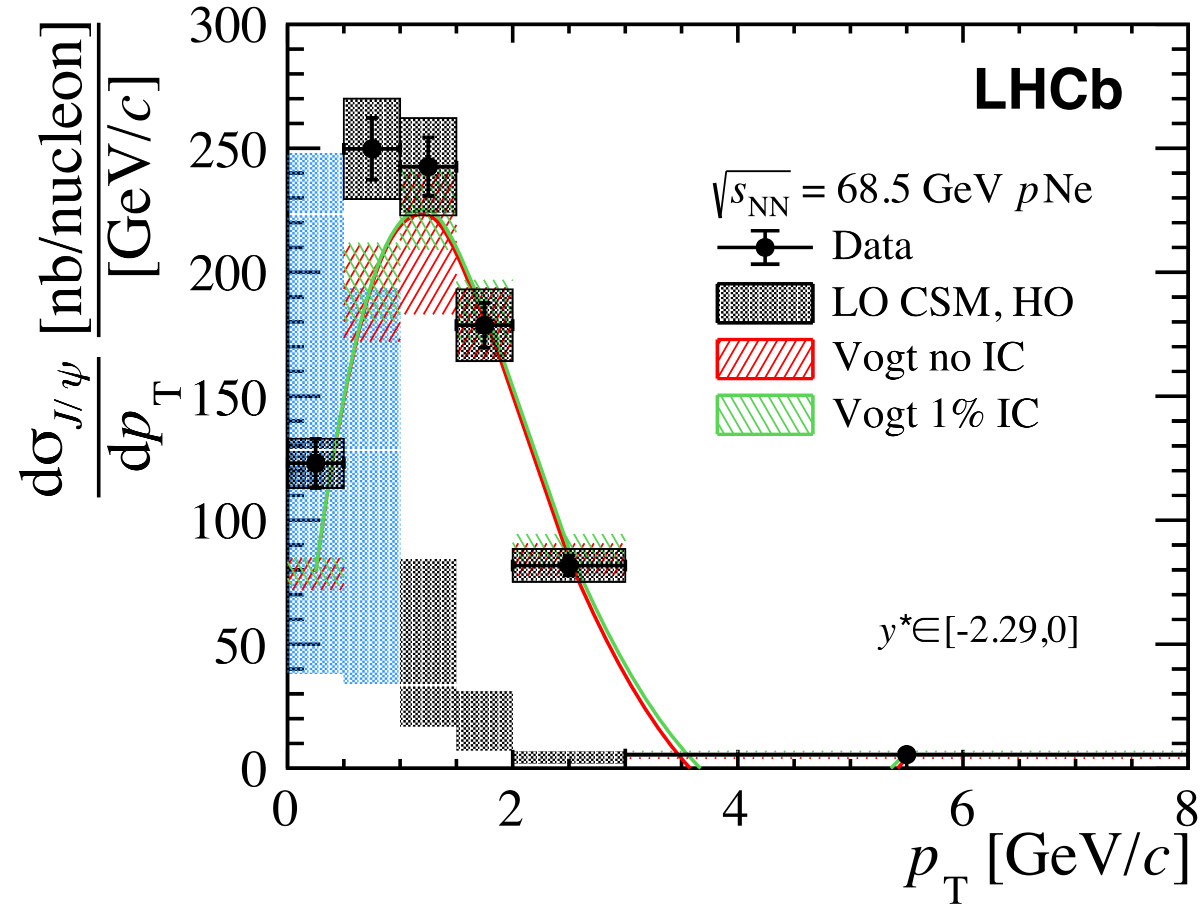


LHCb fixed-target data (pNe, pHe) is filling in gaps in this data!

J/ψ differential production cross sections in pNe collisions

p → Ne

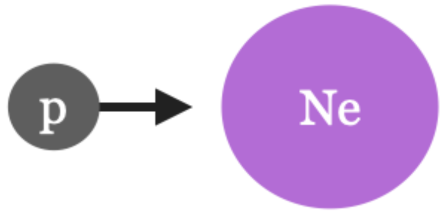


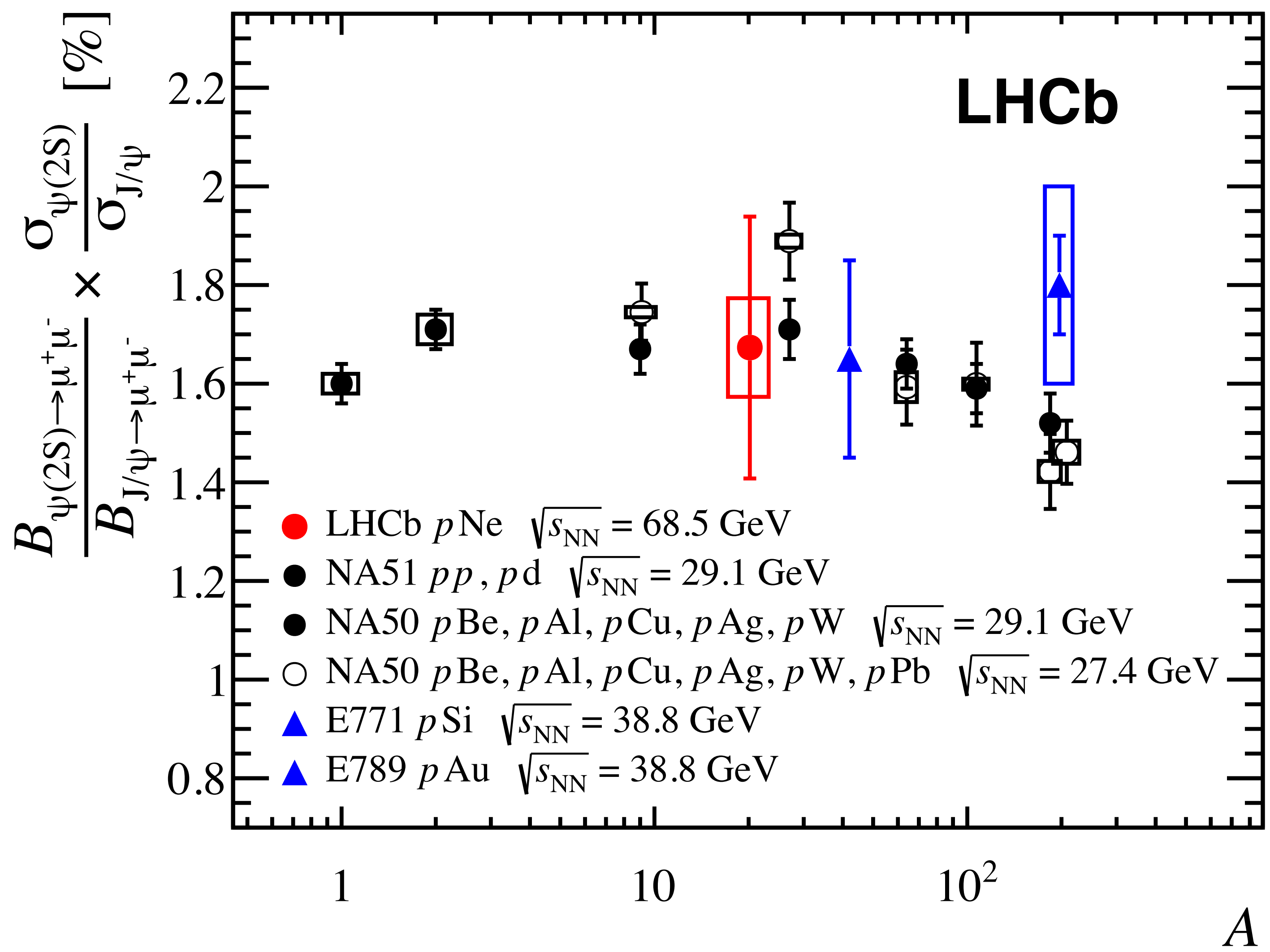


- LO CSM, HO: LO Color Singlet Model (CSM) predictions made using the HELAC-Onia generator with CT14NLO and nCTEQ15 PDF sets
- Vogt predictions use the Color Evaporation Model, EPPS16 nPDFs, and include contributions from nuclear absorption and multiple scattering
- The data does not differentiate between 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 $\psi(2s)$ production in pNe collisions



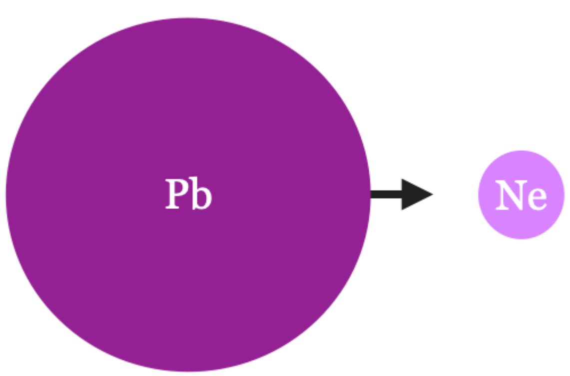


- LHCb measurement: 1.67 ± 0.27 (stat) ± 0.10 (sys) %
- The relative production rate of $\psi(2S)$ to J/ψ mesons in pNe collisions is consistent with the rates measured on other nuclear targets and at other center of mass energies

Results in PbA collisions

Unique systems for probing cold nuclear matter effects:

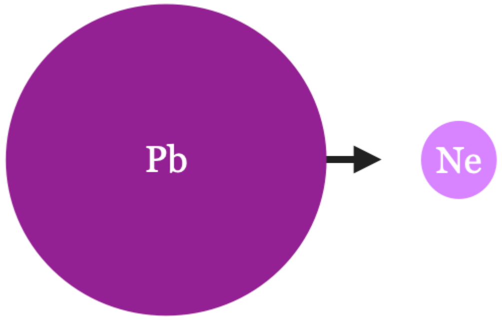
- Depending on the specific nucleus-nucleus collision, QGP may or may not be formed
  - Can study quarkonia production in AA collisions with or without QGP
  - System size is an additional handle besides centrality to look at QGP formation
- Two nuclei involved: Comovers interactions, parton energy loss, nuclear absorption potentially play a larger role in quarkonia dissociation
  - again trying to "disentangle" cold nuclear matter effects, or at least isolate systems/regions where some are more dominant than others
- At LHCb, PbNe fixed-target collisions are not limited in centrality (unlike PbPb collisions)

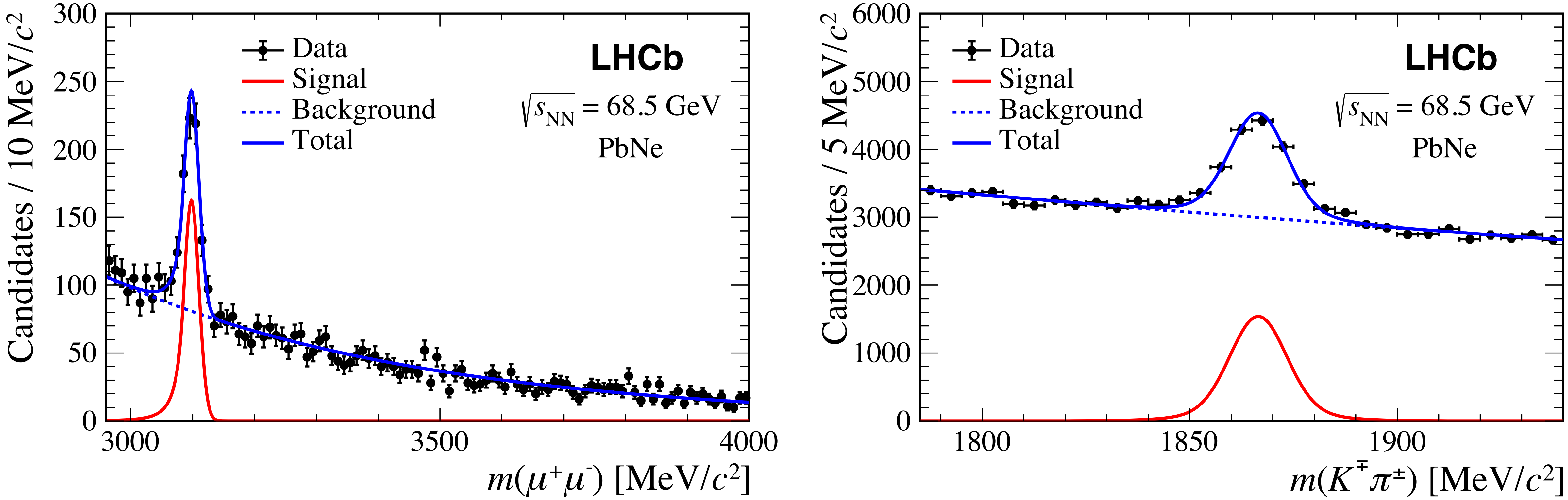


System	$\sqrt{s_{NN}}$	**Quarkonia measured**	**Reference measurement**
Pb → Ne	68.5 GeV	J/ψ	D^0

First measurement in a fixed-target AA collision at the LHC!

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

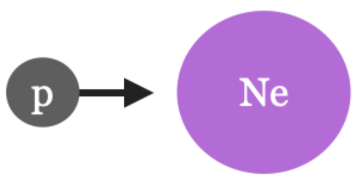


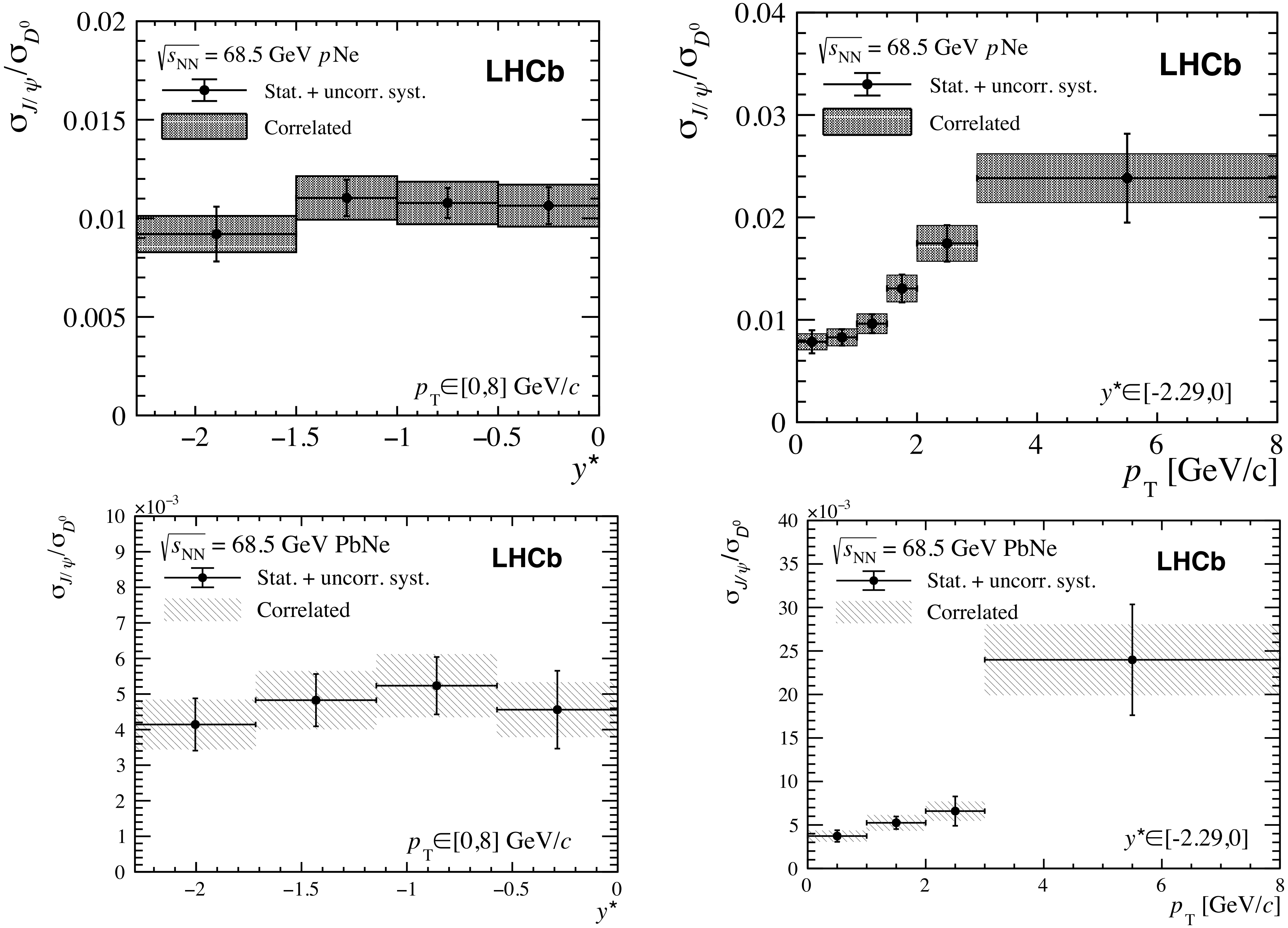


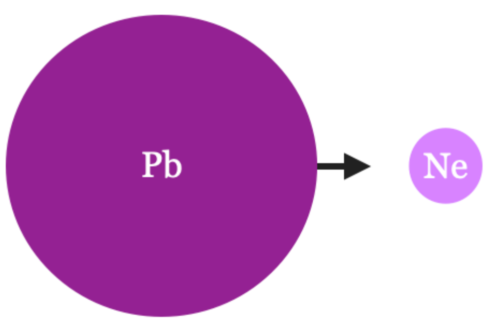
- Larger background than in pA collisions, but clean signal peaks are still observed - proof of measurement feasibility in larger PbA systems
- Similar candidate selection as in pNe measurement
- J/ψ or ψ(2S) candidate p_T < 8 GeV
- J/ψ or ψ(2S) candidate y in 2.0 < y < 4.29 (4.6) in pNe (pHe) collisions

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







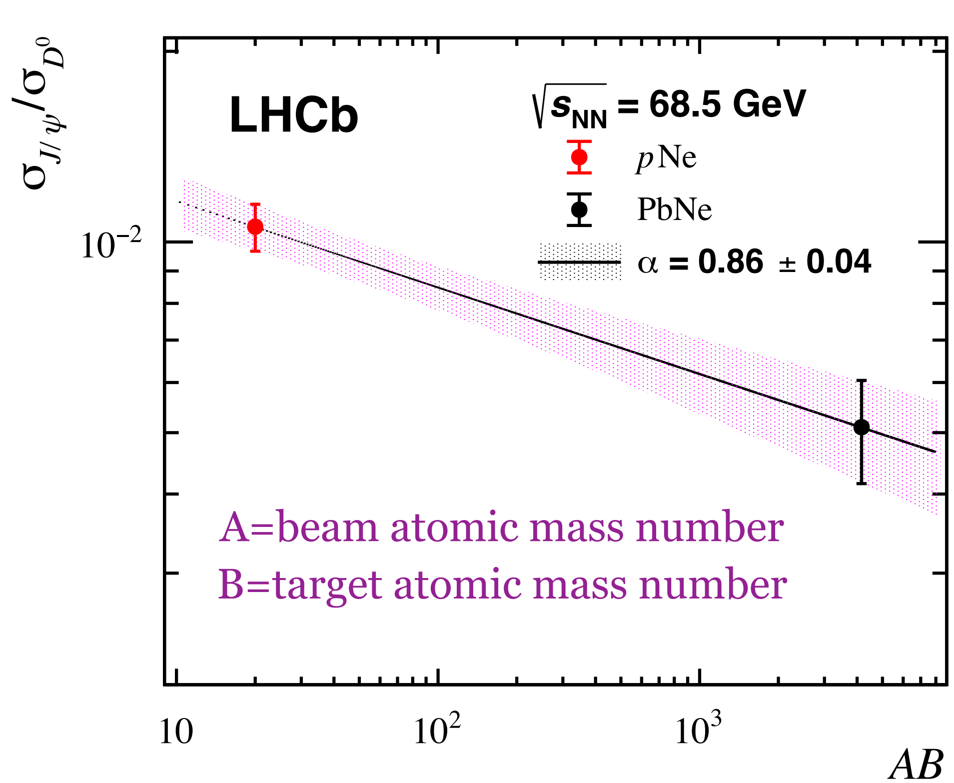
- Compare J/ψ production in large (PbNe) vs small (pNe) nuclear environment at the same $\sqrt{s}$
- $\sigma_{J/\psi}/\sigma_{D^0}$ shows little dependence on y* and a strong dependence on p_T

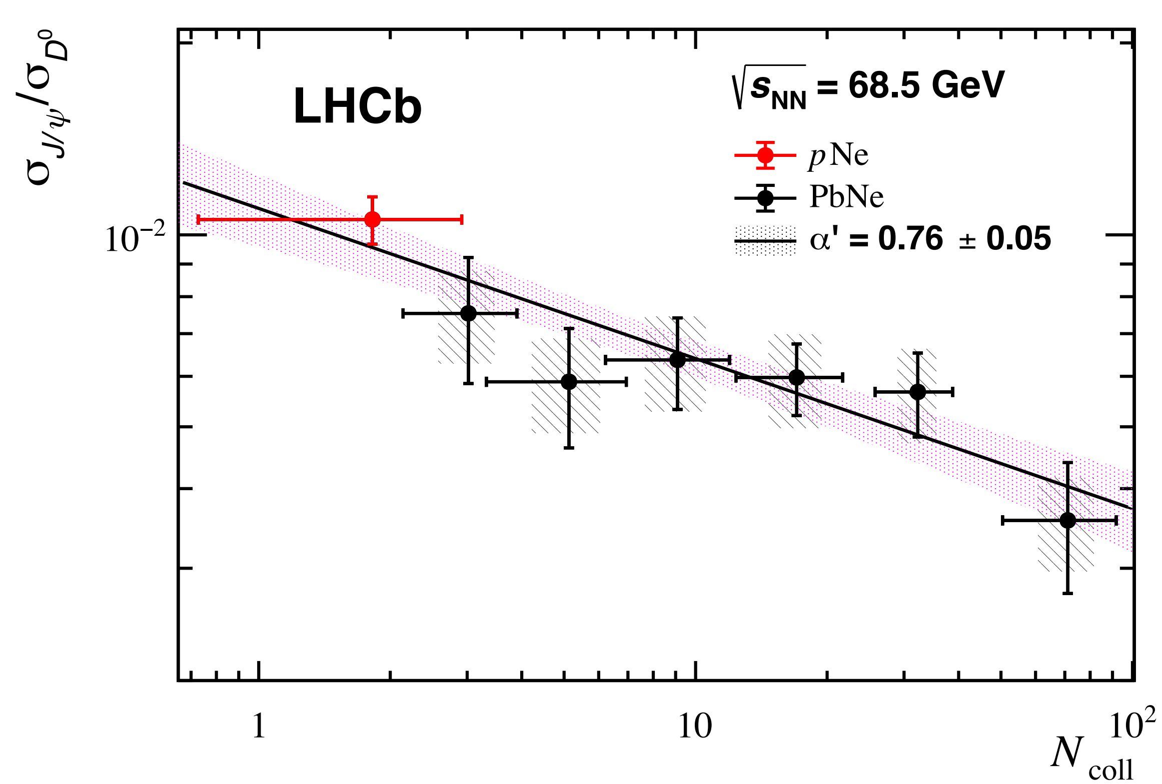
Nuclear effects on hidden vs open charm

- Assuming: $\sigma_{D^0}^{AB} = \sigma_{D^0}^{pp} \times AB$ 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^o mesons
- The α values are consistent with those previously measured in pA collisions, indicating no 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
- Projected heavy flavor yields for 45 pb^{-1} pAr at $\sqrt{s}$ = 115 GeV:

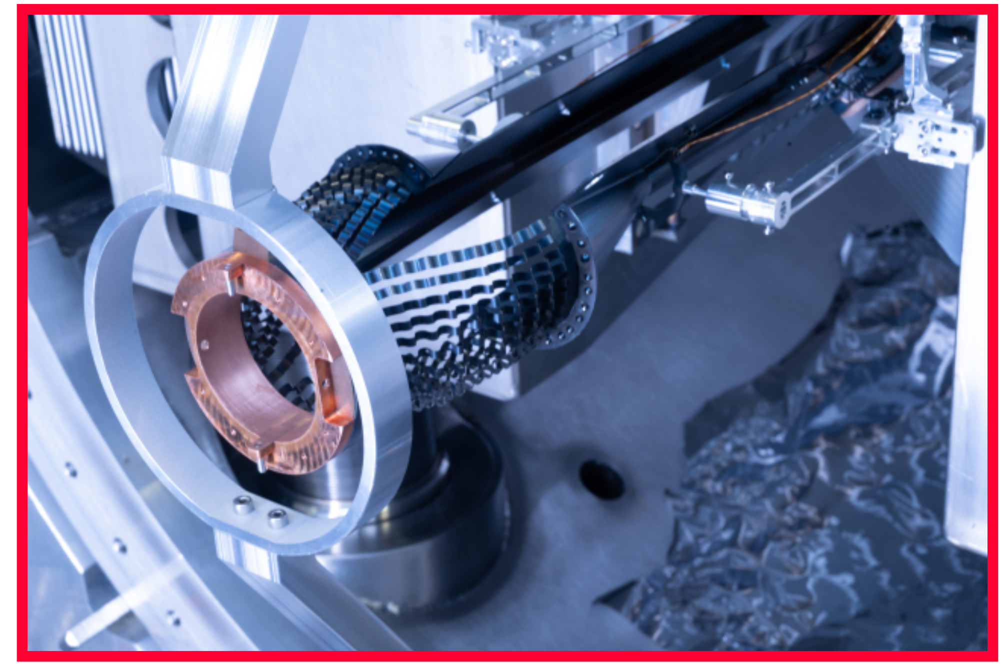
D^0: 150 million

Λ_c: 1.5 million

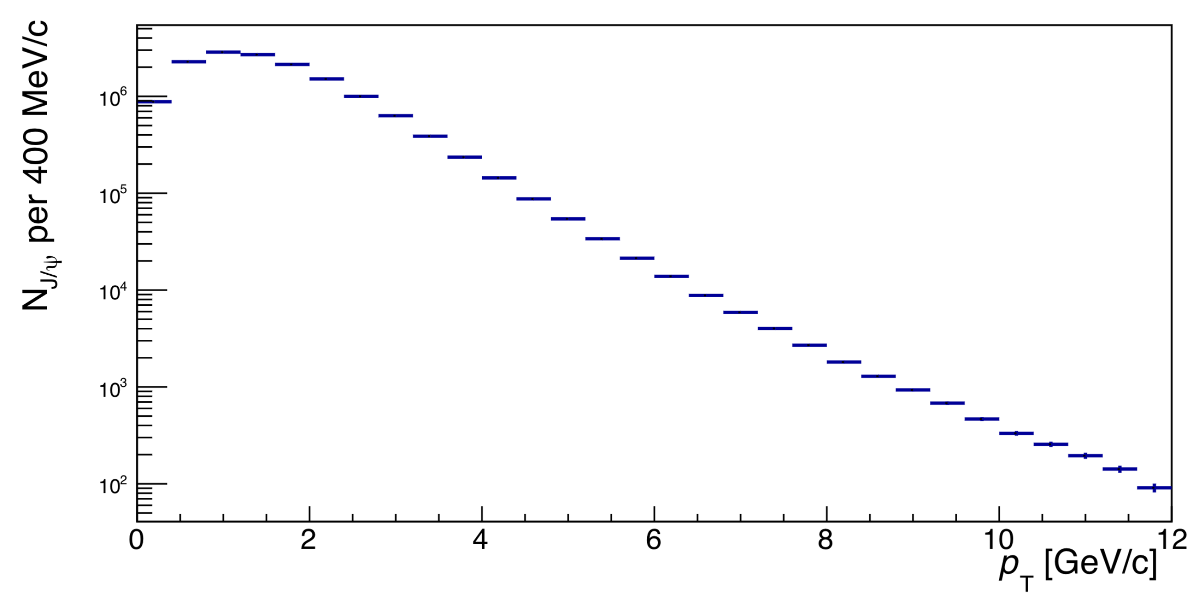
J/ψ: 15 million

$\psi(2S)$: 150,000

$\Upsilon(1S)$: 7,000

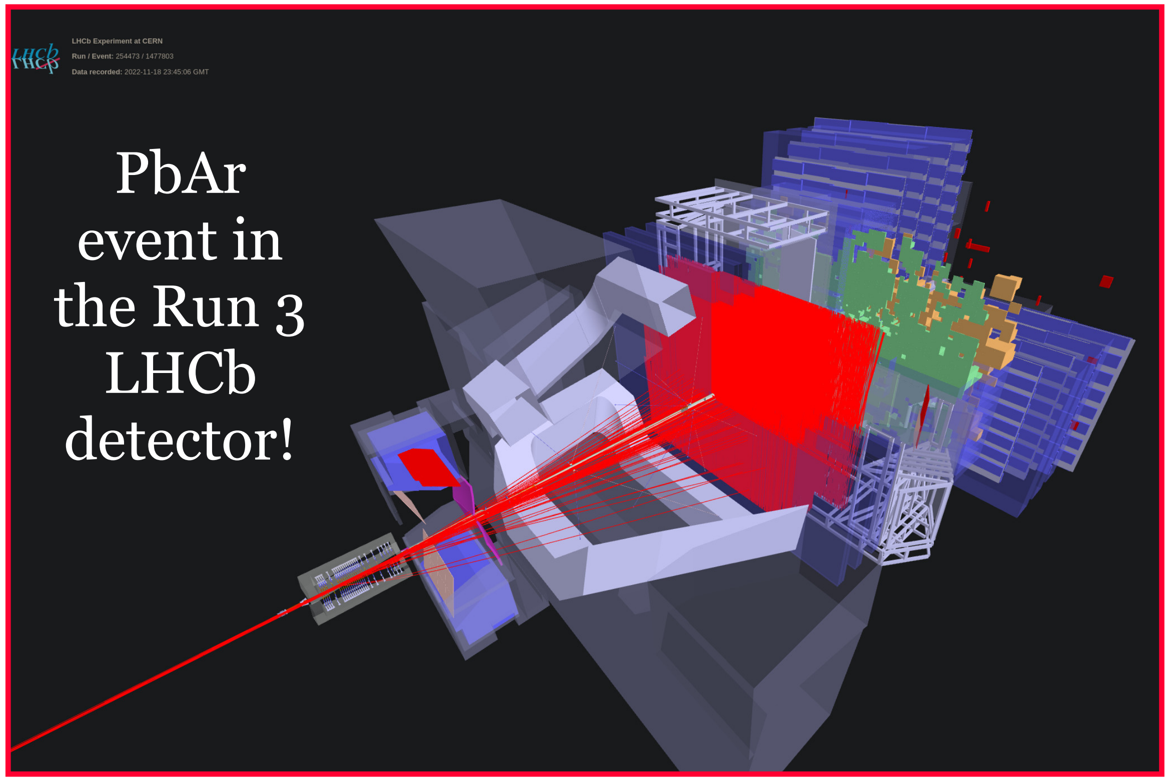


Projected J/ψ p_T spectrum with statistical uncertainties for 45 pb^{-1} of SMOG2 pAr data:

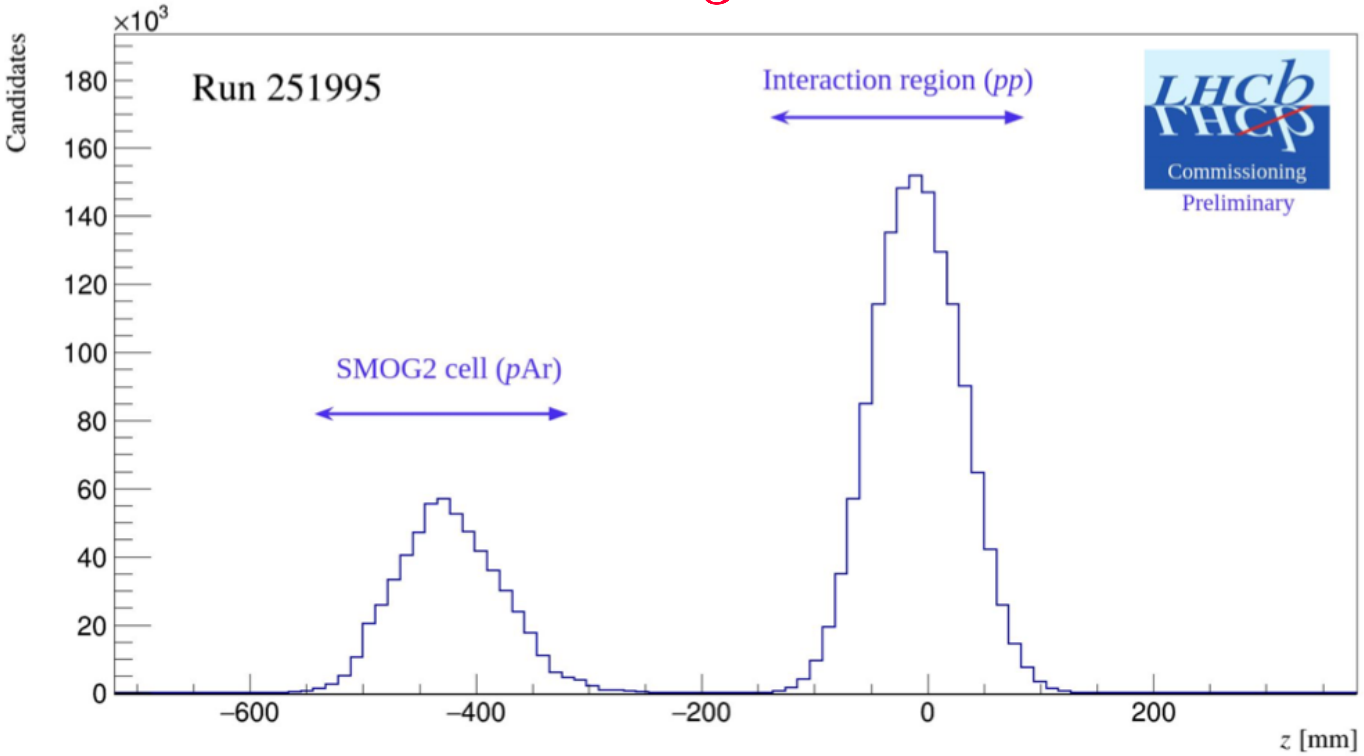


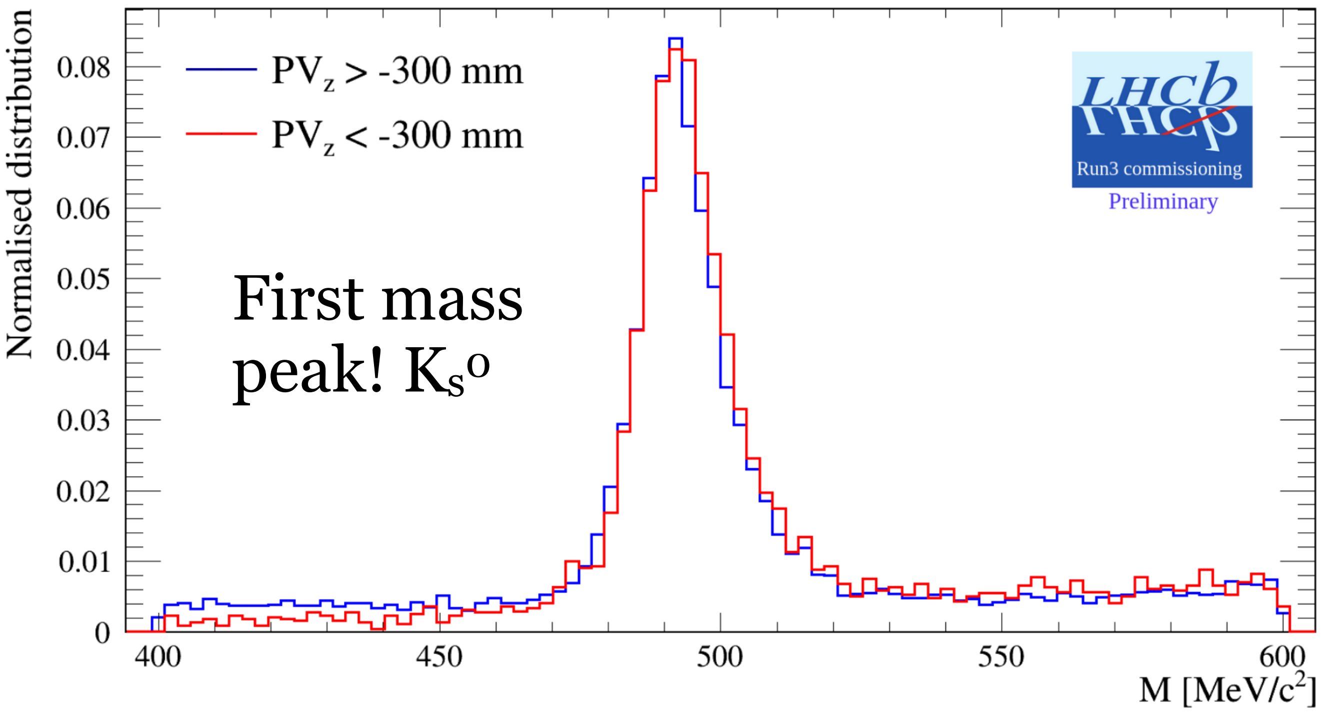
First look at Run 3 SMOG2 data

- First Run 3 data successfully taken this year!
- 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

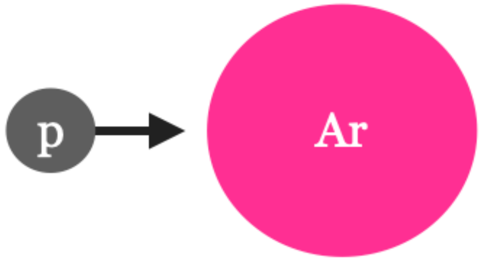


Run 3 data:

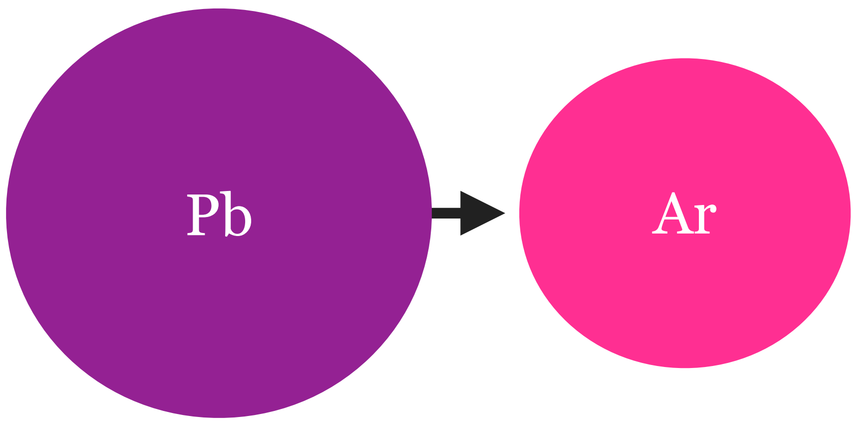




Early measurements possible with SMOG2



- **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

Later timescale (high statistics needed):

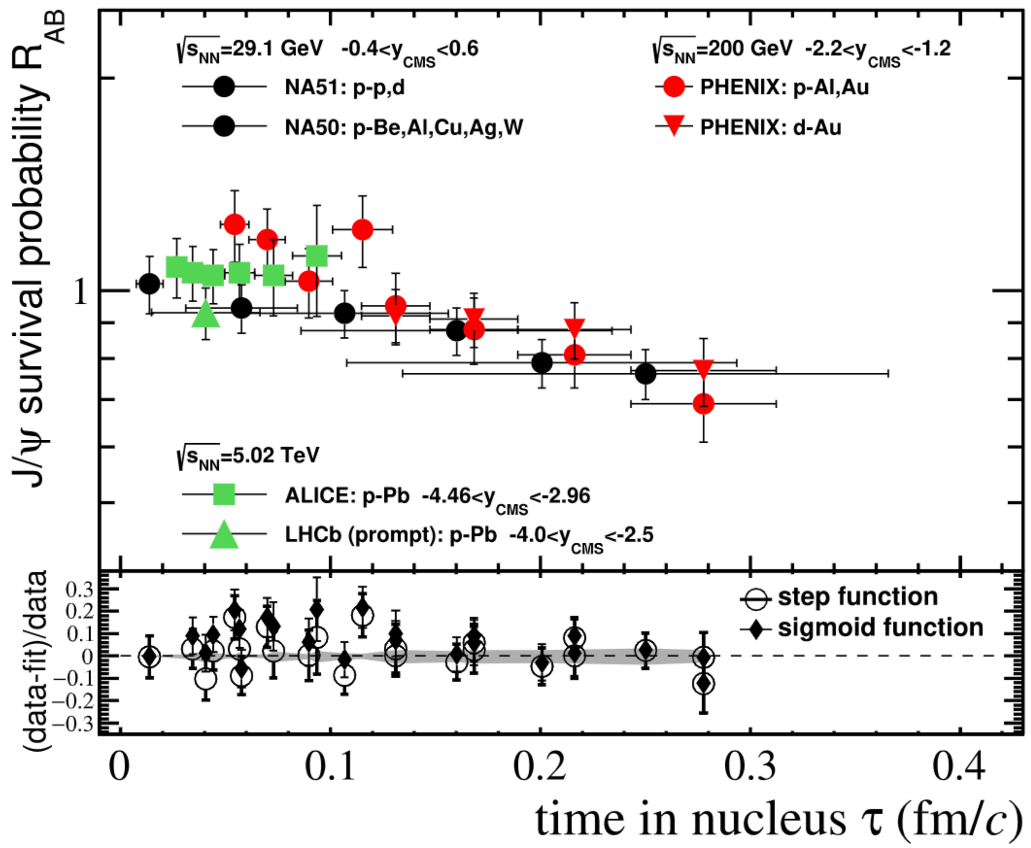
- **Upsilon production in pAr collisions** - study CNM effects as a function of bound state size and quark flavor content (e.g. parton energy loss effects)
- **Multi-differential ψ(2S) measurements in pAr collisions** - complement differential J/ψ measurements and test theoretical models of quarkonium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

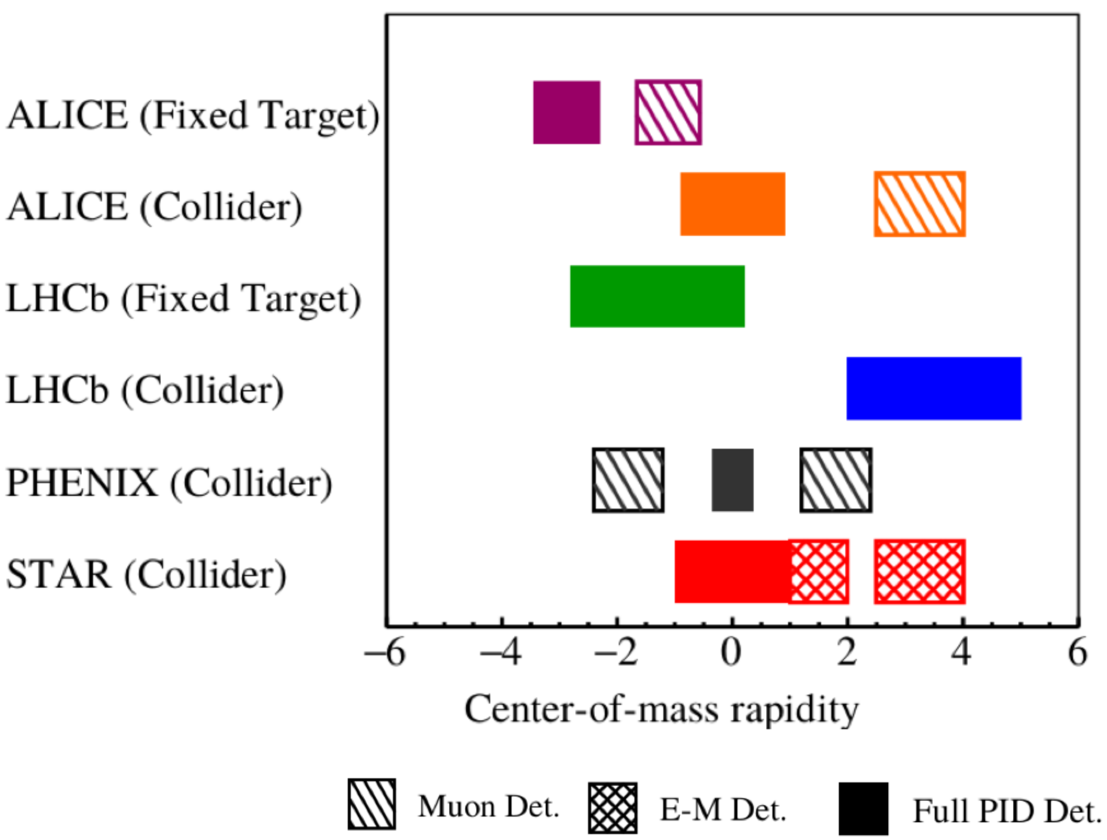
- **Drell-Yan** measurements

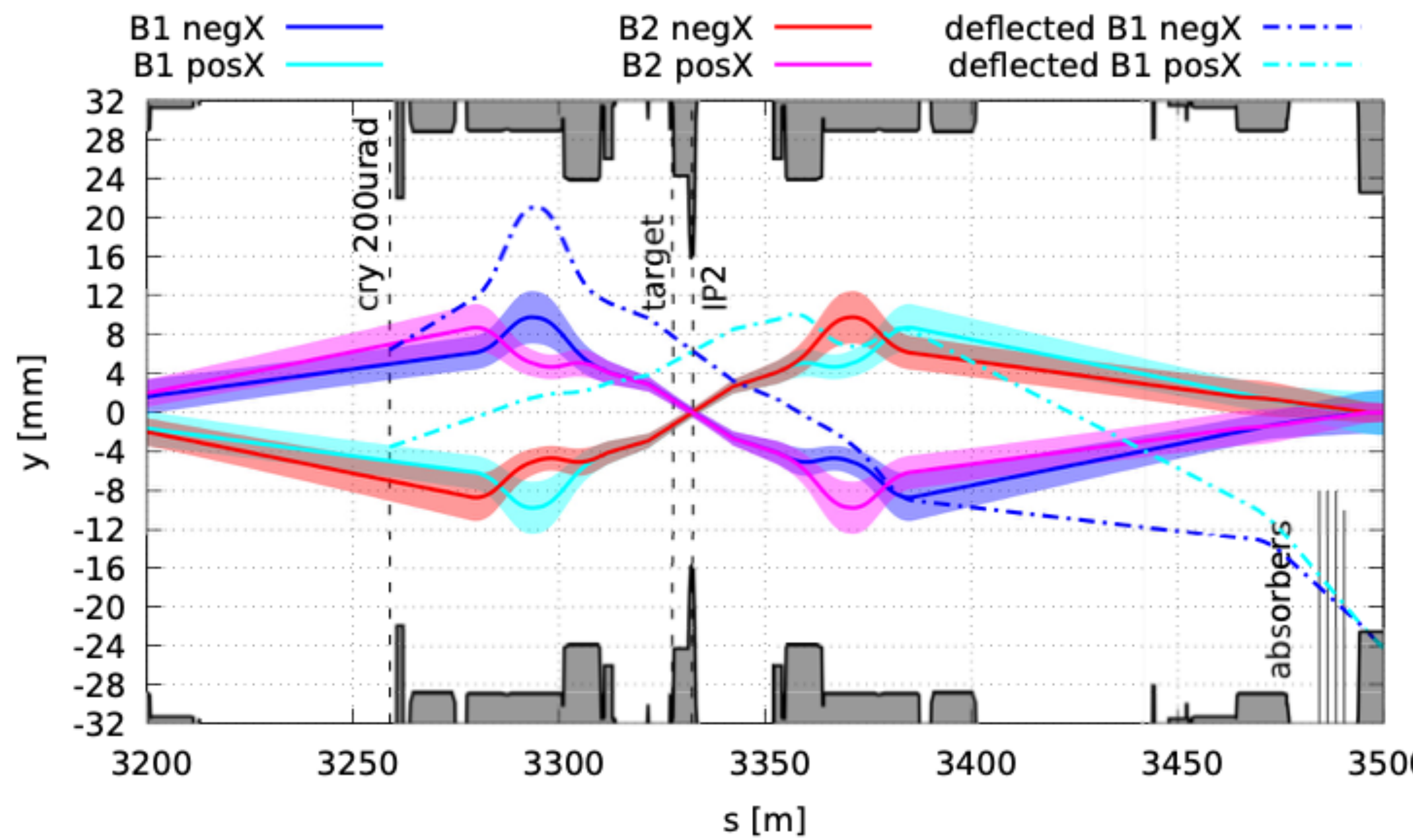
- **Exclusive production (photoproduction) of J/*ψ*** on a variety of nuclear targets

If you have other ideas for measurements, don't hesitate to let us know, or join us!

Prospects with a Fixed-Target Program at ALICE

- The ALICE experiment is investigating the feasibility of a fixed-target program that would start taking data during the LHC Run 4
- A bent crystal would deflect the LHC beam halo to a solid fixed target located ~ 4.7 to 5 m before the ALICE interaction point
- Detailed studies are currently underway for the target integration
- Opportunity to study quarkonia production at lower y^* values, high luminosities with solid targets, and a different variety of nuclear targets than available at LHCb (W, C, Ti)





Experiment y* coverage figure: Daniel Kikola, Physics Beyond Colliders Annual Workshop
ALICE Fixed-Target Layout studies: arXiv:2210.13299

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
- A future fixed-target experiment with ALICE would reach more negative values of y^* and have access to large luminosities with solid targets

Thank you for your attention!

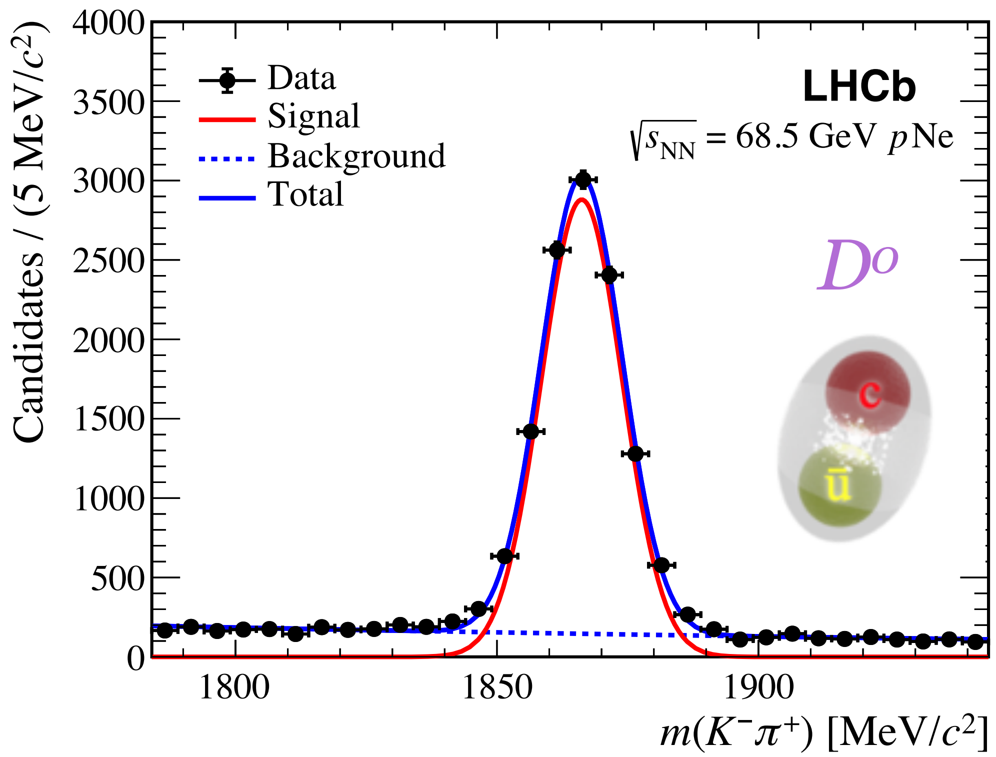
Backup

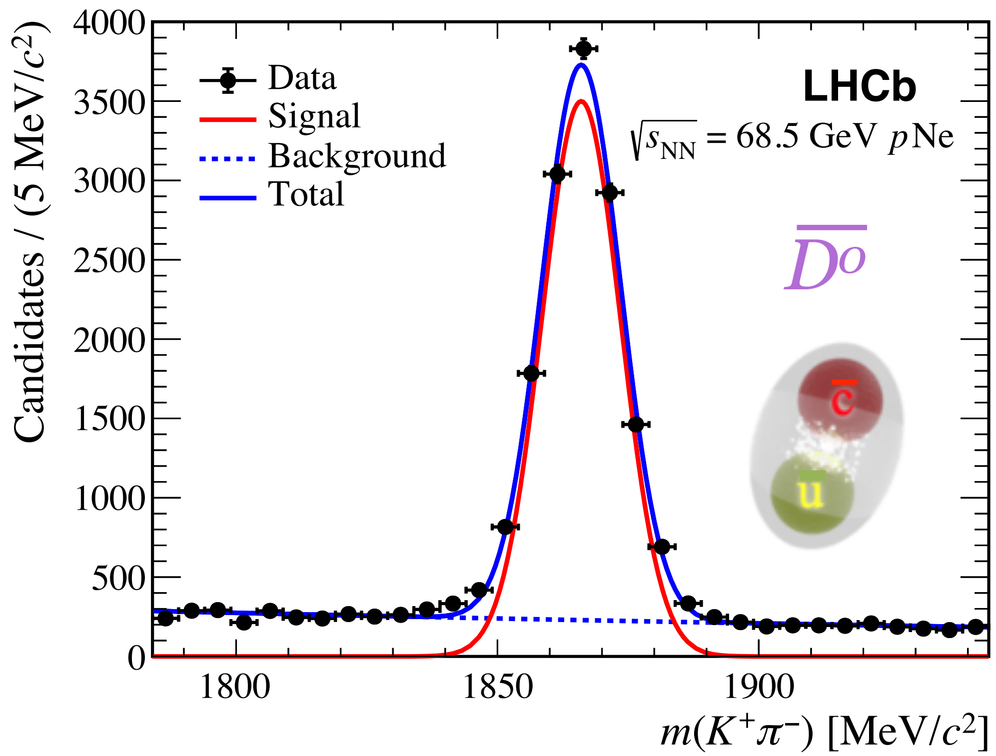
D^0 production in pNe collisions at $\sqrt{s_{NN}} = 68.5$ GeV

Event Selection:

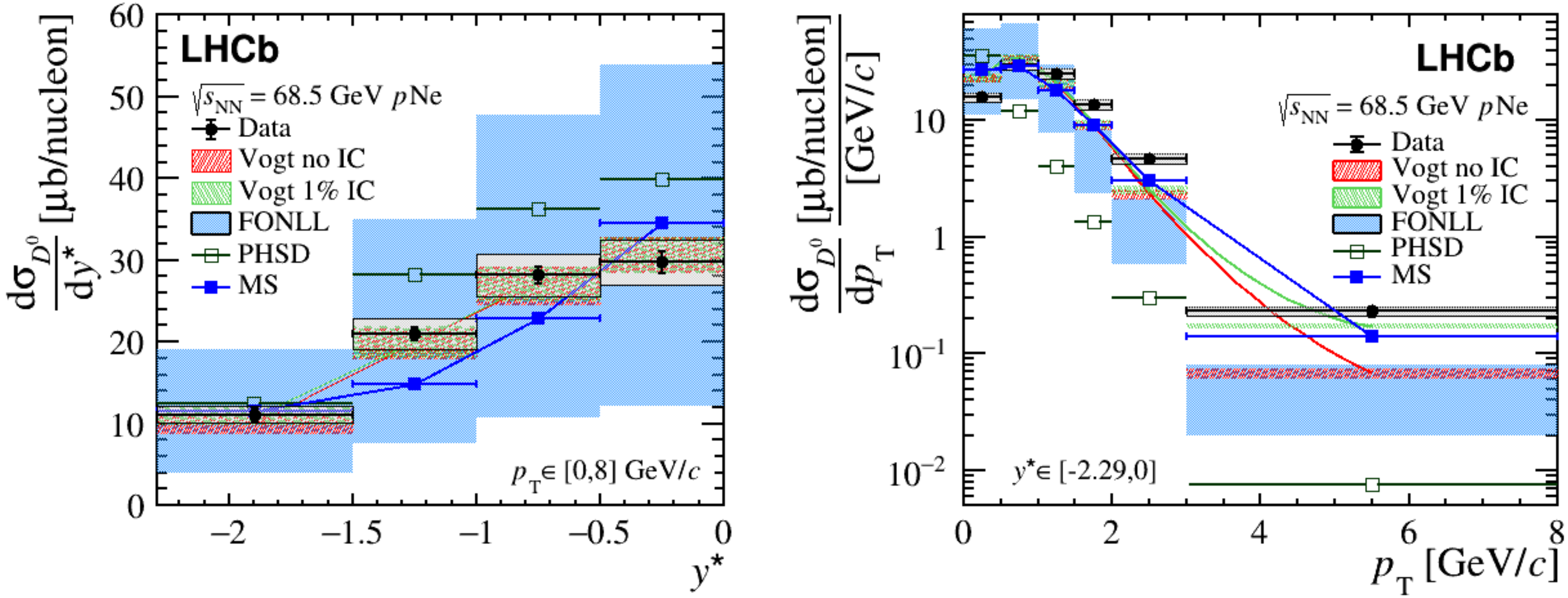
- Identified kaon and pion tracks with a common vertex
- Primary vertex in [-200, -100]mm or [100, 150]mm to avoid residual *pp* collisions
- D^0 candidate proper decay time > 0.5 ps
- D^0 candidate $p_T < 8$ GeV
- D^0 candidate rapidity $2.0 < y < 4.29$

pNe sample luminosity: $21.7 \pm 1.4\ nb^{-1}$





D^0 differential production cross sections in pNe collisions



- FONLL and PHSD predict a more steeply falling p_T distribution than that observed 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: 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