Heavy-flavour production in fixed-target mode

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LHCP 2023, Belgrade

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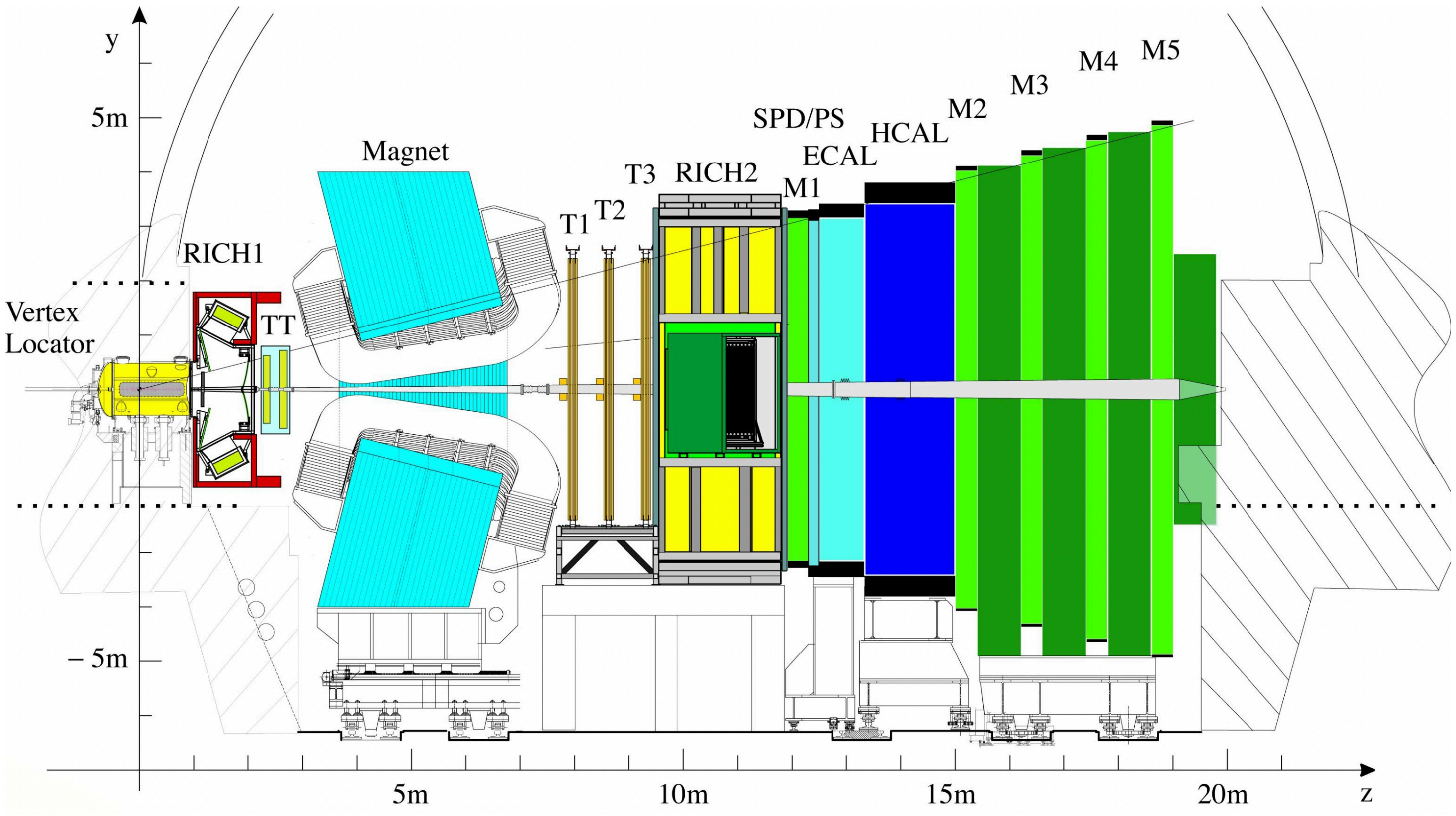
The LHCb experiment



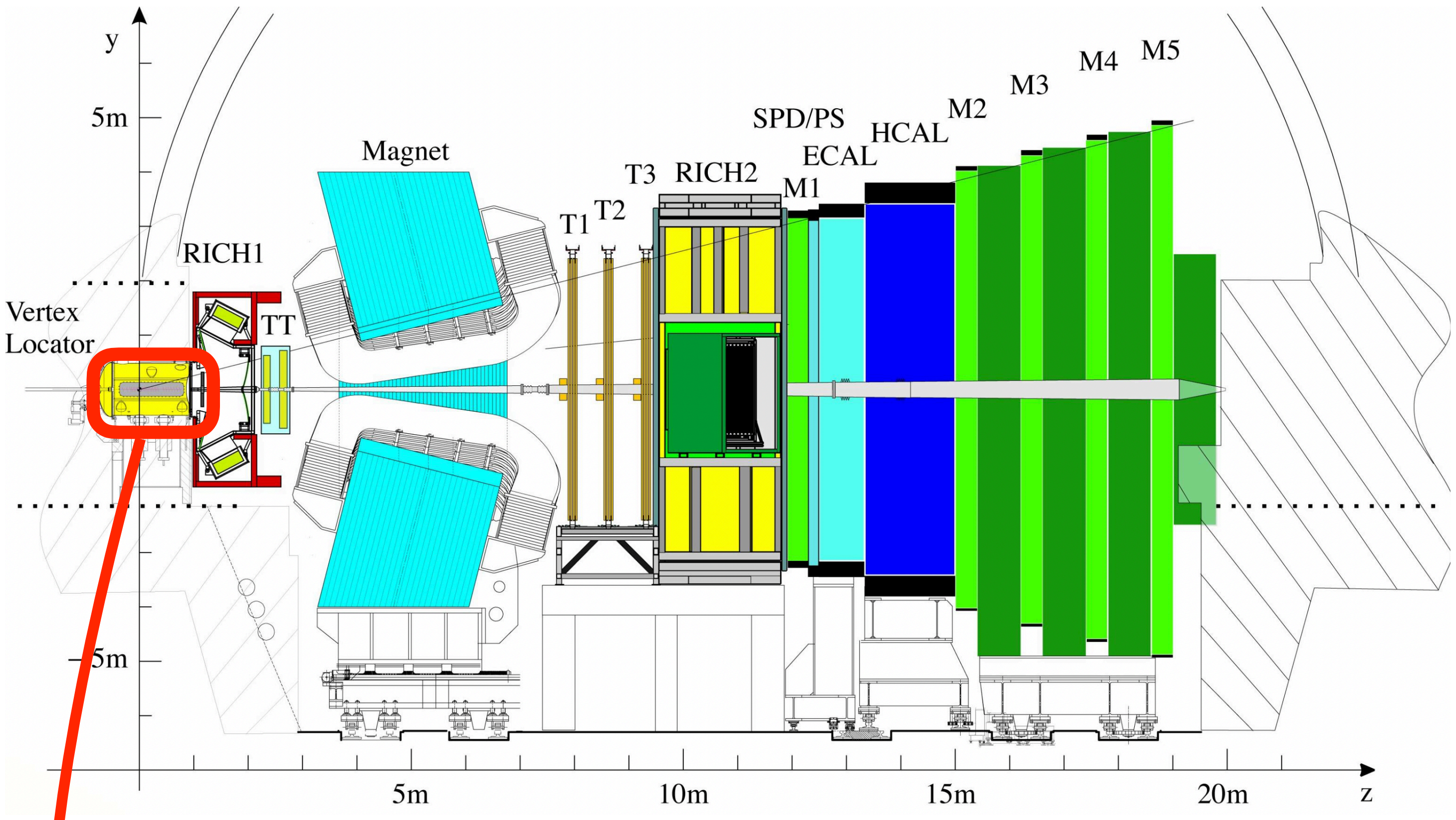
- One-arm spectrometer at LHC fully instrumented in $2 < \eta < 5$
  - Tracking system with excellent hadron and muon ID
  - Precise vertex reconstruction, for primary and decay vertices
  - Calorimeters ECAL, HCAL

Tailored capabilities to study heavy-flavour

LHCb JINST 3 (2008) S08005

LHCb performance IJMPA 30 (2015) 1530022

The LHCb experiment



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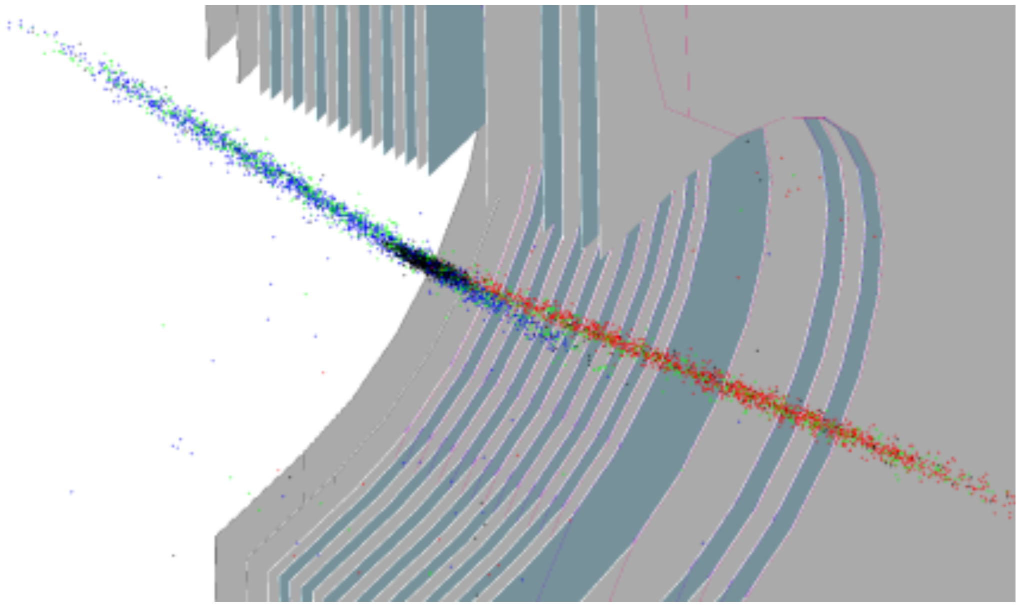
Tailored capabilities to study heavy-flavour

LHCb JINST 3 (2008) S08005

LHCb performance IJMPA 30 (2015) 1530022

… and a unique fixed-target configuration at LHC using gas injection



- In place originally for luminosity measurements JINST 9 (2014) 12, P12005
- Local increase LHC beam pipe pressure:
  - from $\approx 10^{-9}$ mbar to $\approx 10^{-7}$ mbar
- Use circulating LHC beams to produce $p\mathrm{A}$ or PbA collisions

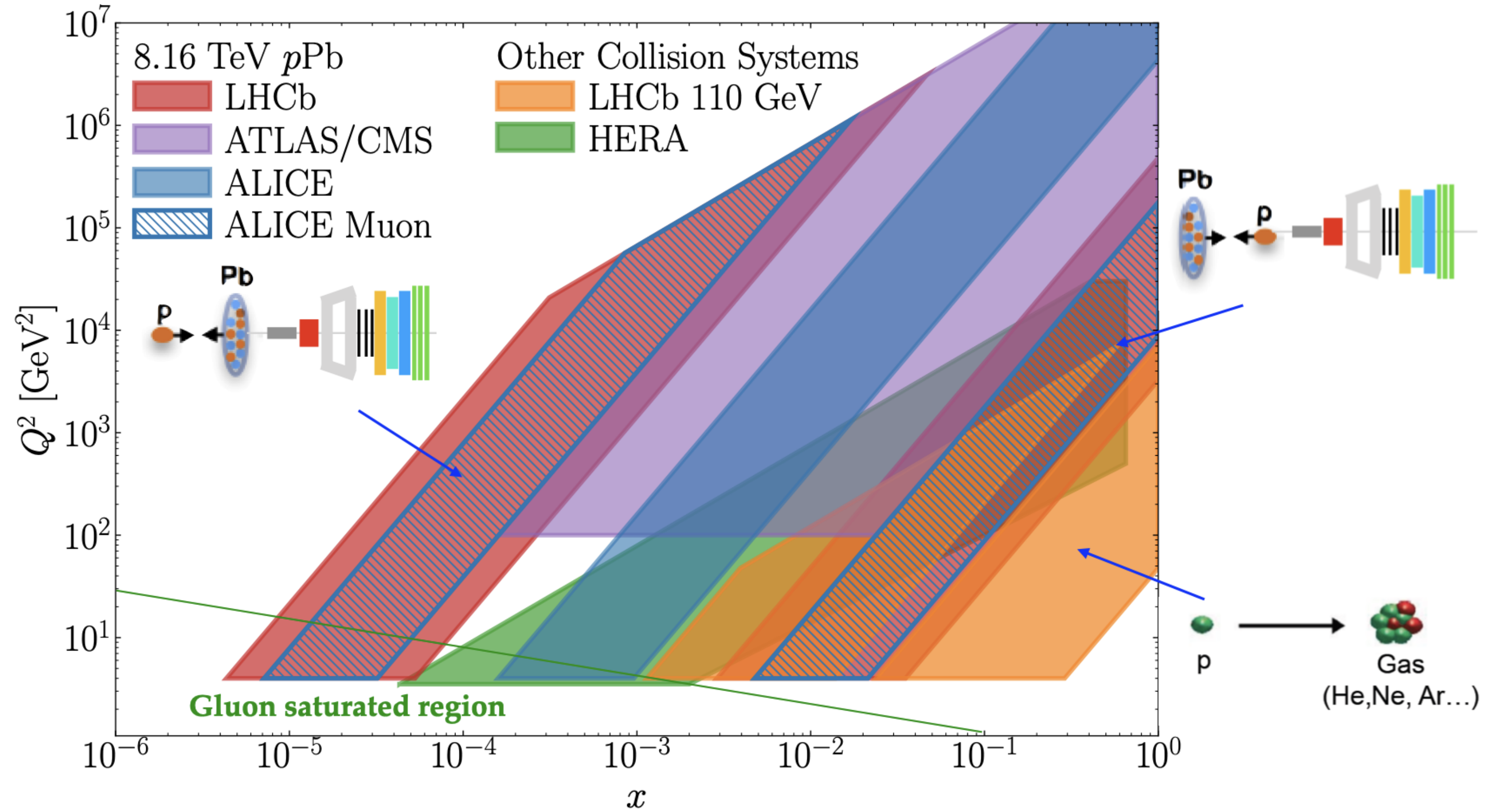
LHCb as a fixed-target experiment

- Heavy-flavour: carry information of initial stage of collision (nuclear structure)
- In the fixed-target system:

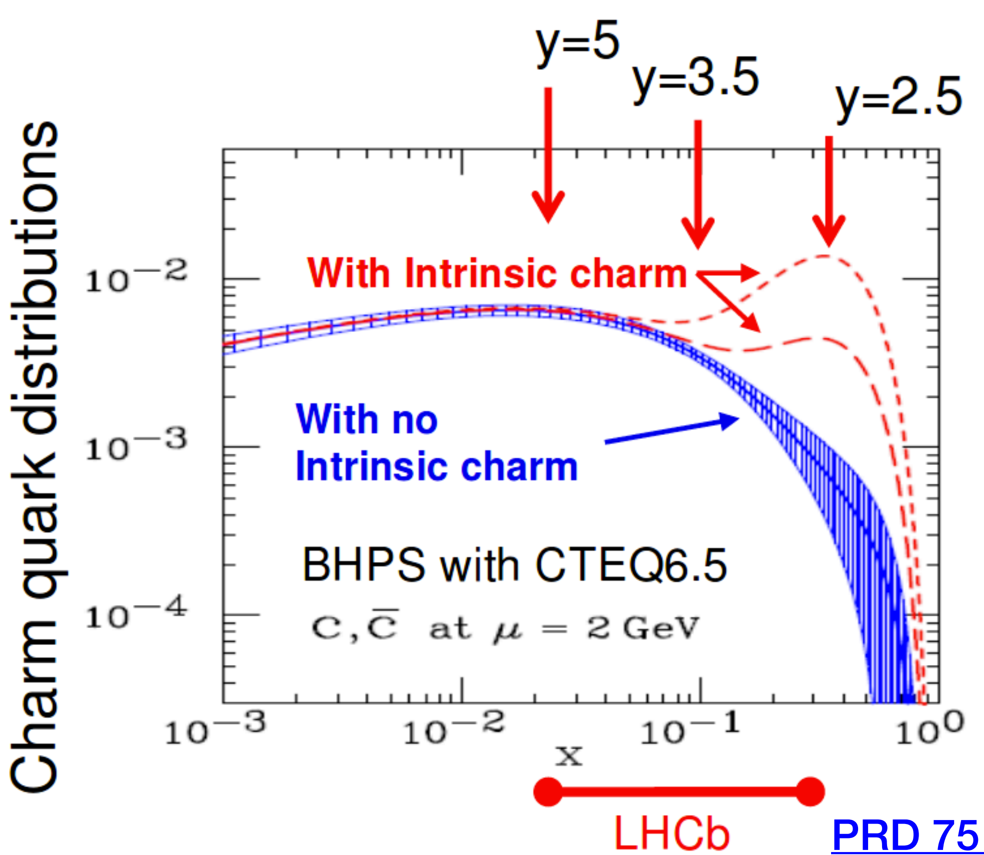
$$y^* \in [-3,0],\ \sqrt{s_{\mathrm{NN}}} = 70 - 110\,\mathrm{GeV}$$

y^*: **rapidity in center-of-mass system**

- Highly complementary to other fixed-target and collider experiments
  - between NA50 and RHIC collider energy
- Nuclear target size scan by injecting different noble gases: He → Ne → Ar



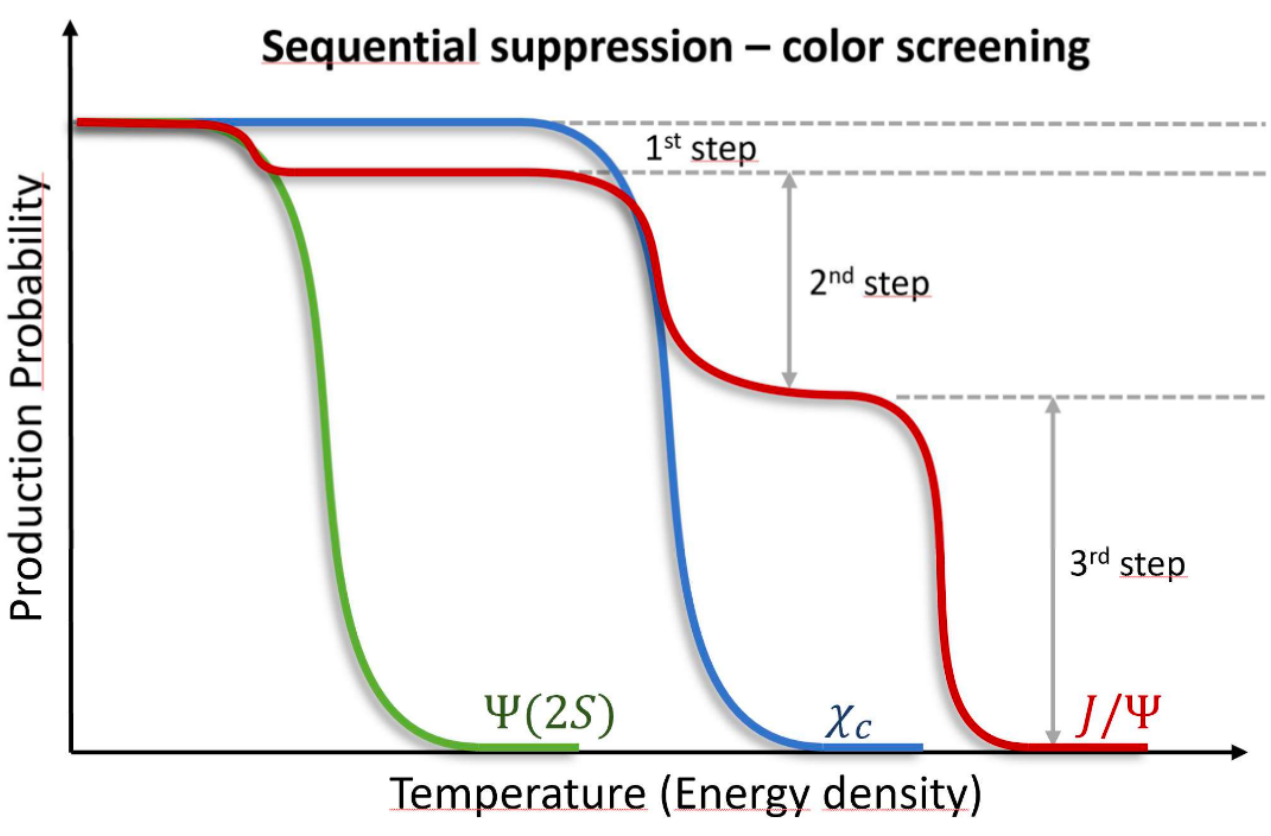
- **Unique constrains to nuclear structure at LHC**
  - Access to high-x region in the target
    - ✳ probe nuclear anti-shadowing and EMC region ($x \approx 0.02 - 0.3$)
    - ✳ explore intrinsic charm content in the proton and nucleus
  - constrains to nuclear absorption and other non-QGP effects



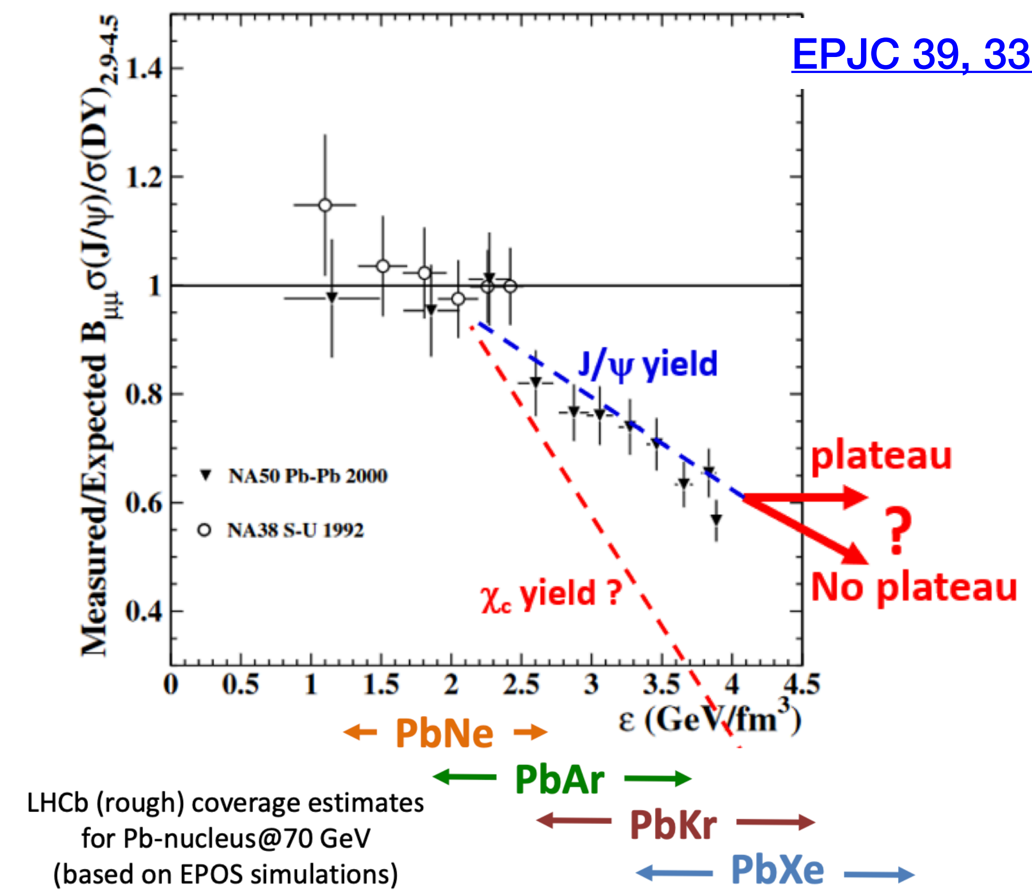
PRD 75 (2007) 054029

Understanding QGP through charmonia

- Gas injection also during LHC ion runs → PbA collisions → QGP studies at low energy
- Charmonia dissociation in QGP due to color screening:
  - sequential suppression is a smoking gun of QGP formation, **BUT**:
    - need to measure **full spectra of charmonia states** ($J/\psi \rightarrow \chi_c \rightarrow \psi(2S)$) to correlate with feed-down contributions
    - confirmation requires a **comprehensive description of non-QGP nuclear effects**
- At $\sqrt{s_{\mathrm{NN}}} \sim 70\,\mathrm{GeV}$, charmonia production by recombination is not expected (only $\approx 1\; c\bar{c}$ per collision)
  - no enhanced production via recombination, present at LHC collider energies (ALICE $\psi(2S)$, arXiv:2210.08893)



EPJC 39, 335–345 (2005)

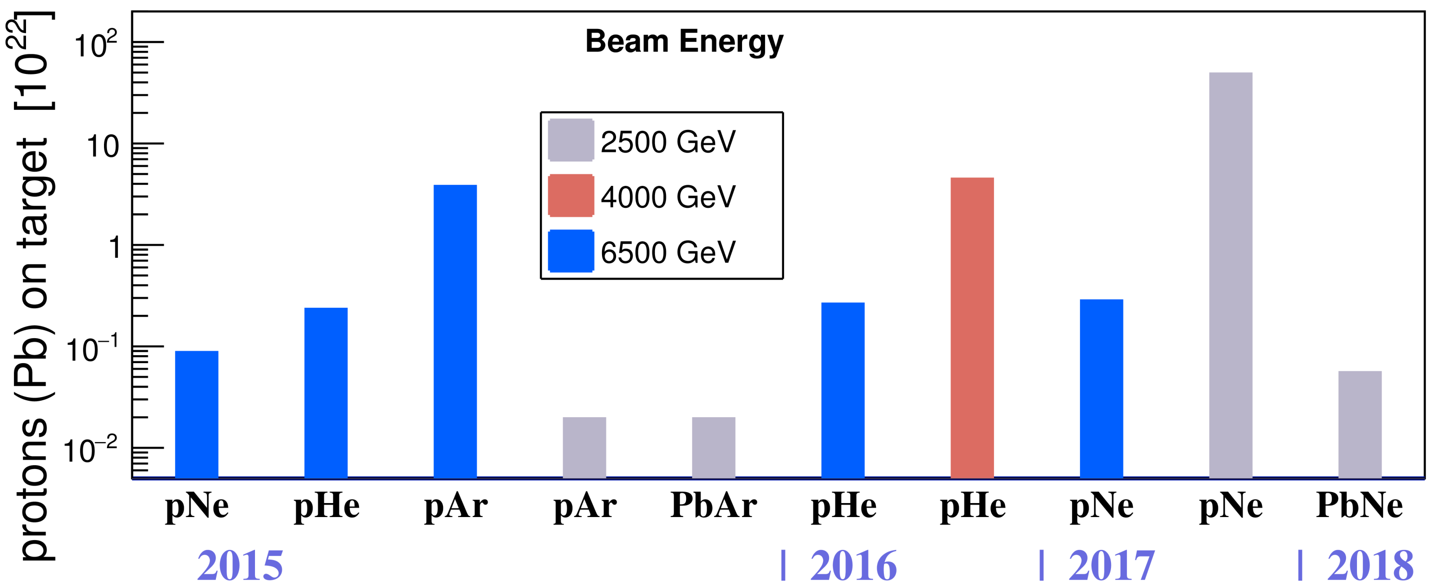


Recent heavy-flavour fixed-target results

Run 2 results for today

Recent results with Ne injection

- Open charm (D^0) production and asymmetry in pNe (arXiv:2211.11633, accepted by EPJC)
- Hidden charm ($J/\psi, \psi(2S)$) production in pNe (arXiv:2211.11645, accepted by EPJC)
- Hidden vs open charm ratio in PbNe collisions (arXiv:2211.11652)



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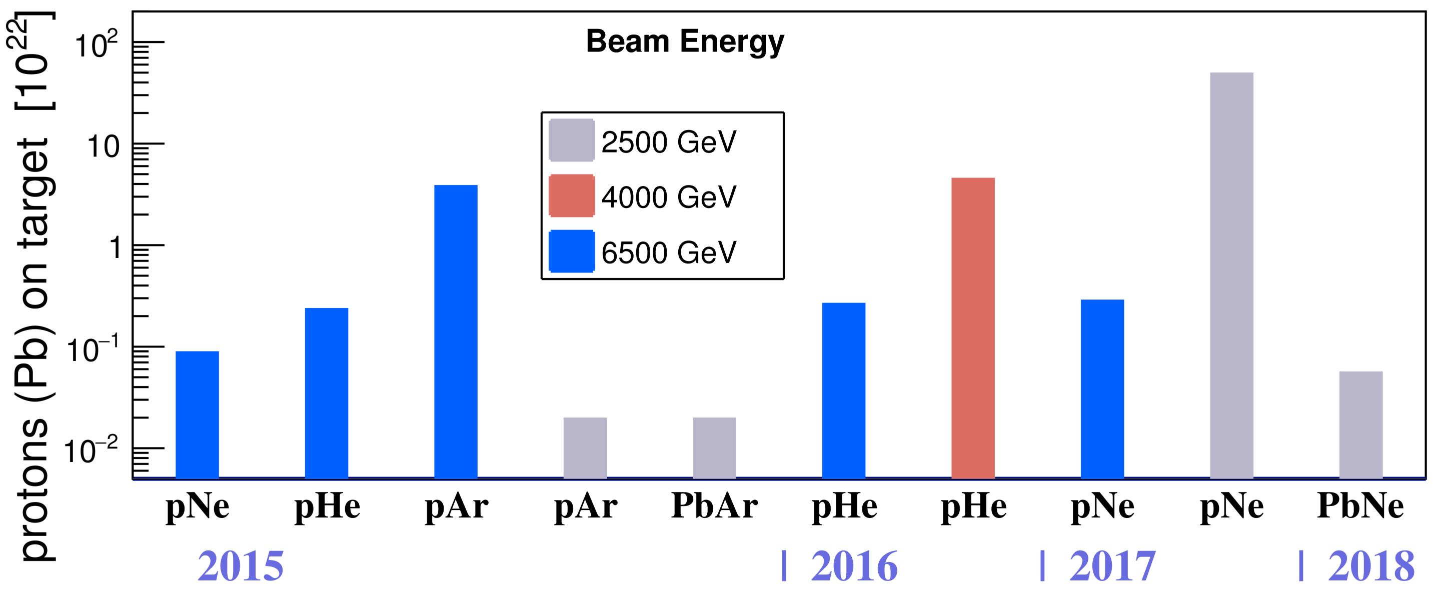
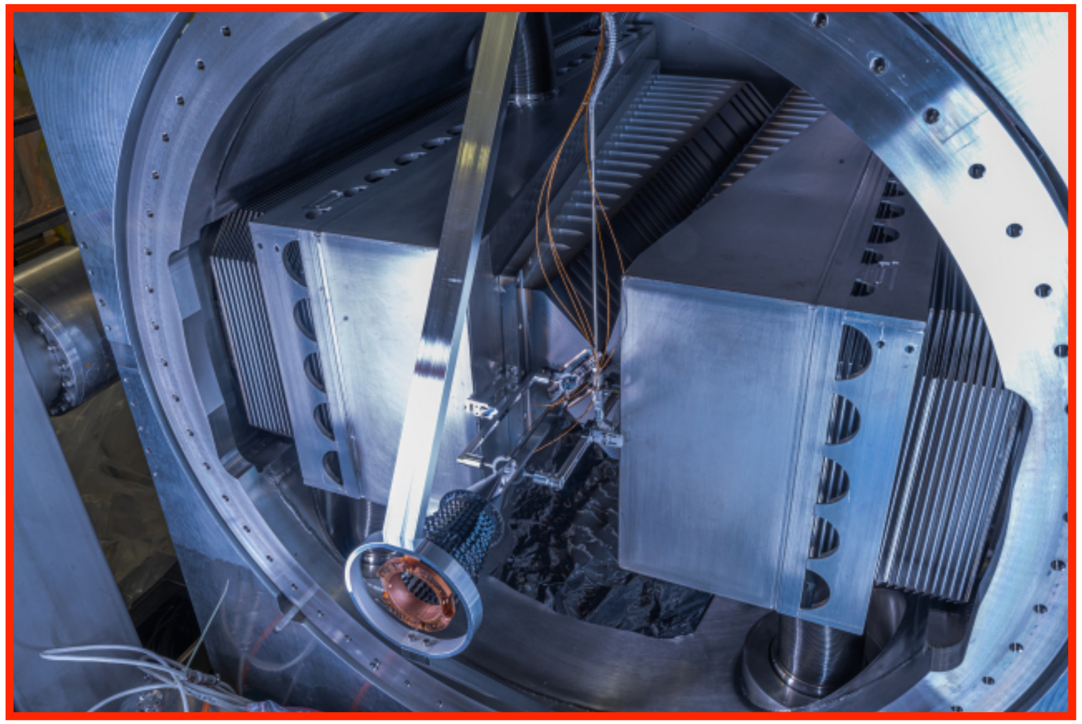


The ~~future~~ present!

- The SMOG2 system: gas storage cell in Run 3
- Local pressure increased to $\sim 10^{-5}$ mbar → factor ~ 100 gain in luminosity
- Injection of non-noble gases: H_2, O_2, D_2
  - pH runs can be used as reference for nuclear effects!
- Endless physics opportunities: LHCb-PUB-2018-015

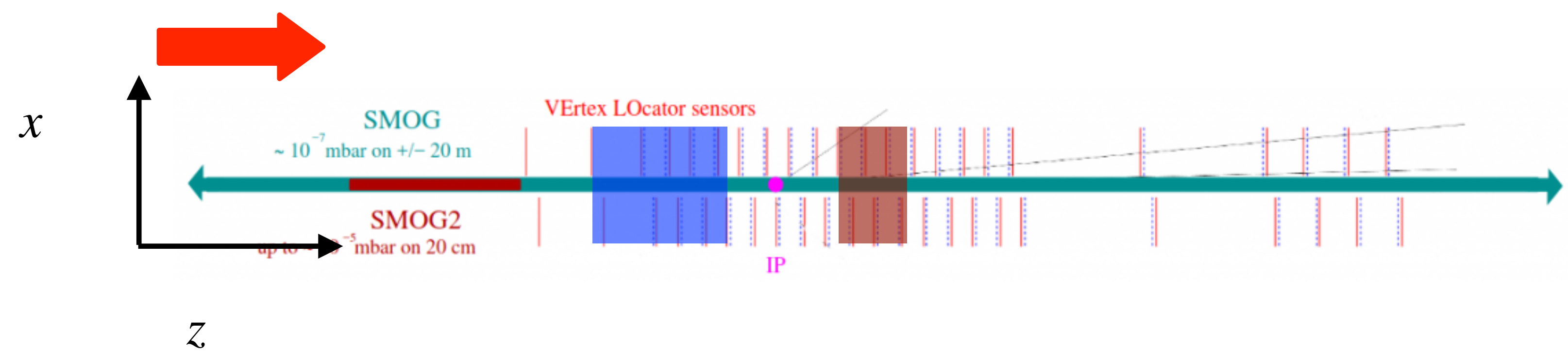


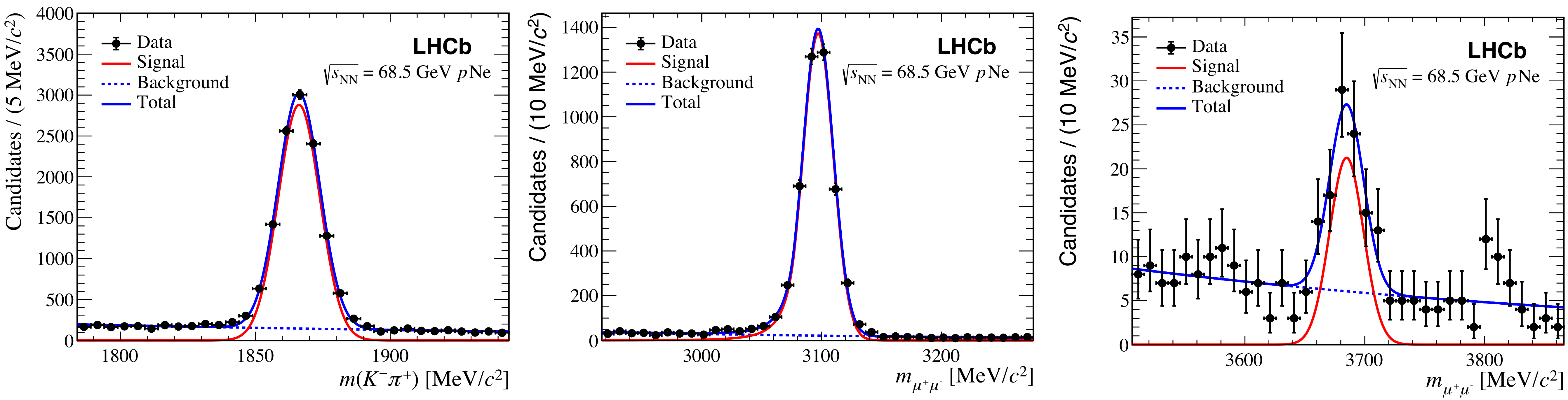
SMOG2 storage cell after installation

Heavy-flavour samples in pNe

D^0: arXiv:2211.11633
$c\bar{c}$: arXiv:2211.11645

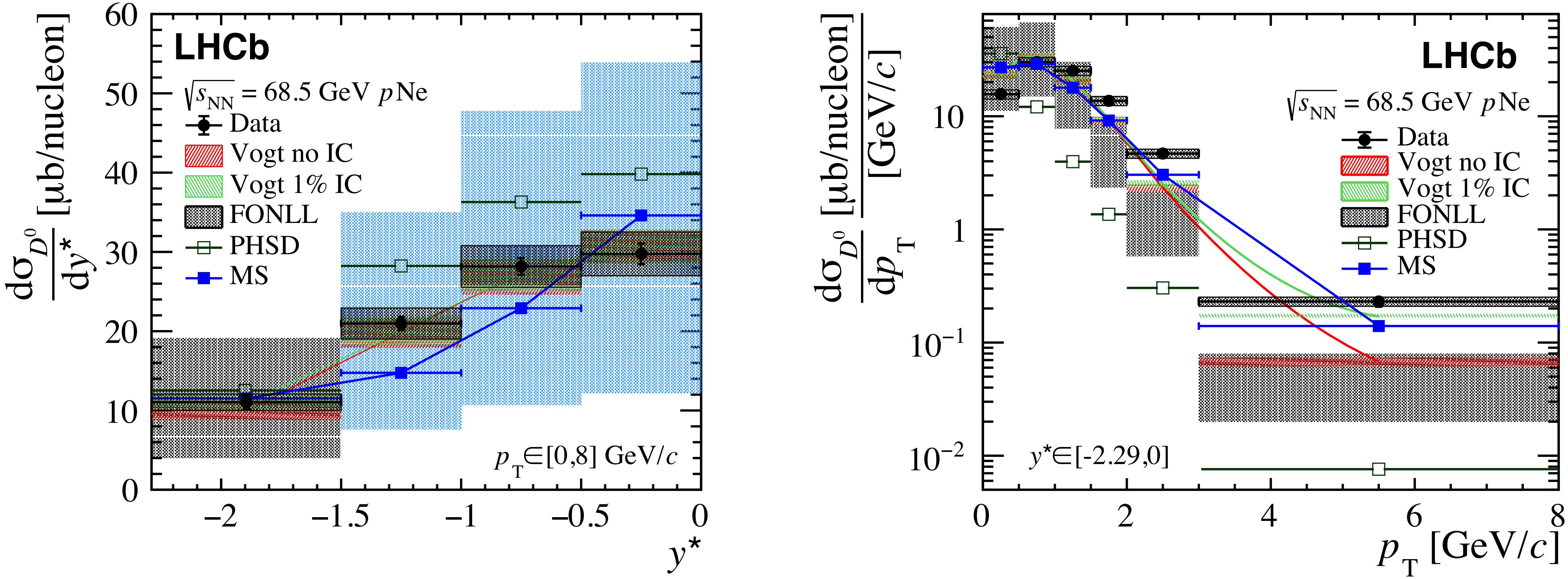
- Data from pNe at $\sqrt{s_{NN}} = 68.5\,\text{GeV}$; $\mathscr{L}_{p\text{Ne}} = 21.7 \pm 1.4\,\text{nb}^{-1}$
- Primary vertex selected between $[-200, -100]\,\text{mm}$ or $[100,150]\,\text{mm}$ in z
  - avoid significant residual background from pp collisions
- Kinematic coverage: $0 < p_T < 8\,\text{GeV}/c$, $-2.29 < y^* < 0$
- Reconstruction:
  - $D^0 \to K^-\pi^+$, $\overline{D^0} \to K^+\pi^-$
  - $J/\psi \to \mu^+\mu^-$
  - $\psi(2S) \to \mu^+\mu^-$





D^0 differential cross-section in pNe

arXiv:2211.11633

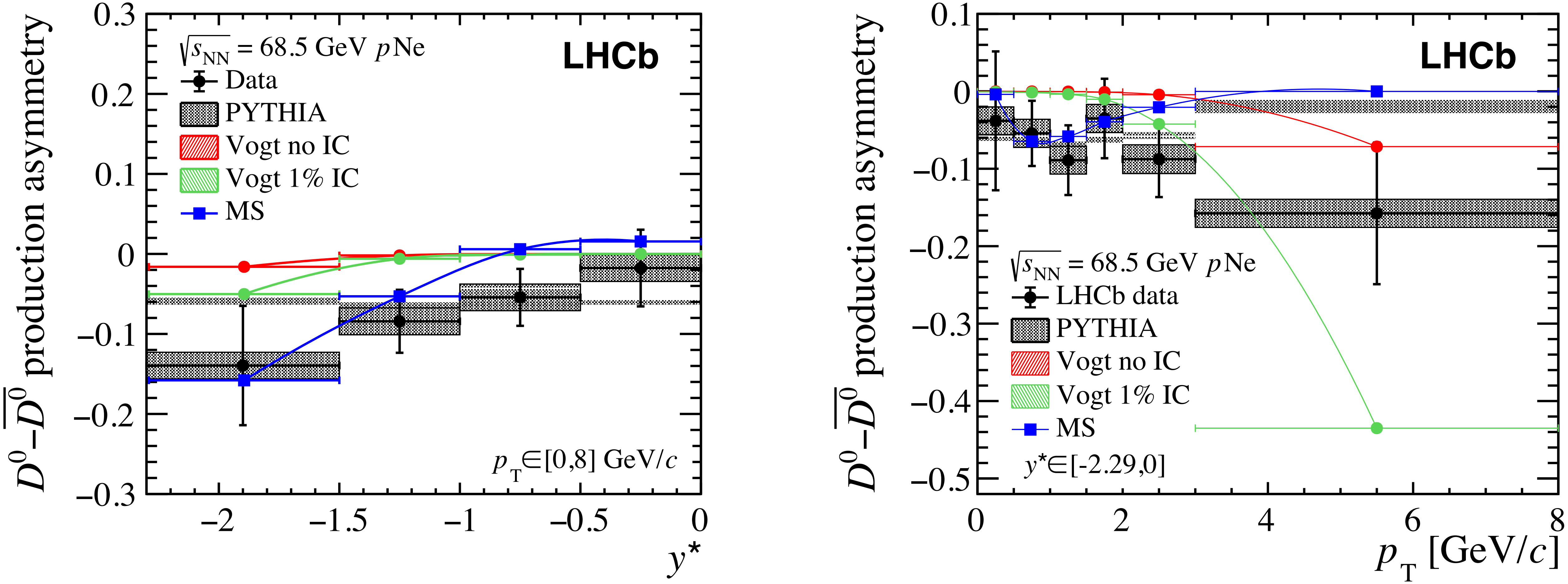


- FONLL and PHSD predictions fail to reproduce p_T distribution
- Vogt $1\,\%$ IC and MS predictions include $1\,\%$ intrinsic charm contribution in the proton
- MS includes $10\,\%$ recombination contributions, Vogt includes shadowing effects
- PDF factorisation scale uncertainties are only included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

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

D^0 and $\overline{D^0}$ production asymmetry

arXiv:2211.11633

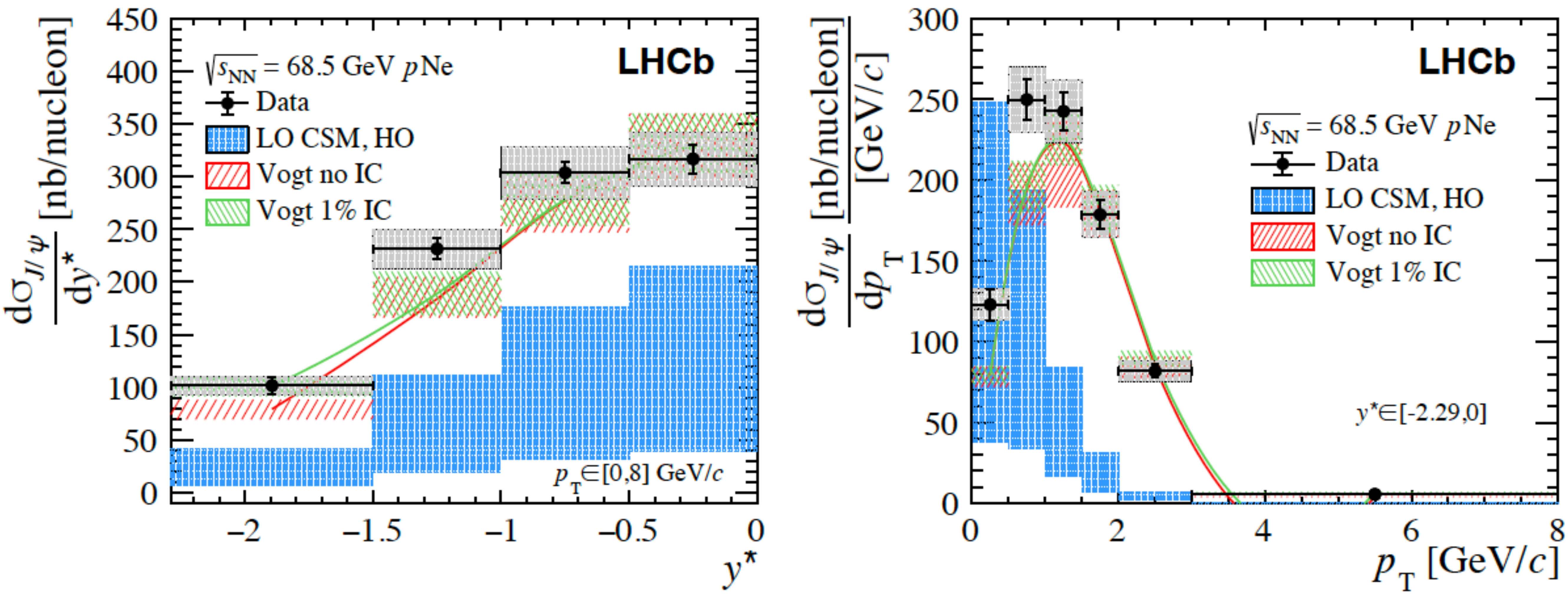


- $D^0, \overline{D^0}$ asymmetry: $$\mathcal{A}_{\text{prod}} = \frac{Y_{\text{corr}}(D^0) - Y_{\text{corr}}(\overline{D}^0)}{Y_{\text{corr}}(D^0) + Y_{\text{corr}}(\overline{D}^0)}$$
- Probe of charm hadronization at high-x
- Asymmetry of $\sim 15\,\%$ observed in the most negative y^*
- In general, simultaneous description of p_T and y^* trend is hard for models
  - **Double-differential measurements** can be very helpful → **more statistics is needed!**

Vogt: PRC 103 (2021) 035204 MS: PLB 835 (2022) 137530

Differential J/ψ cross-sections in pNe

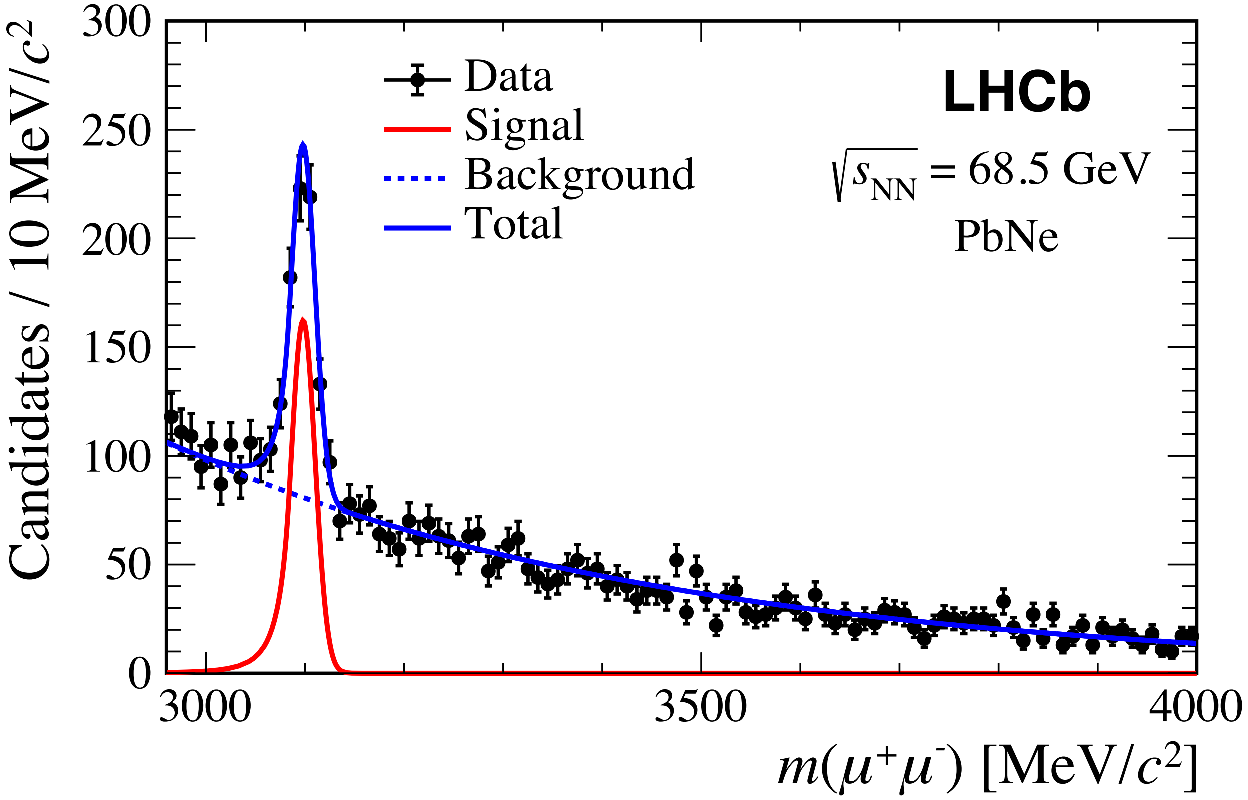
arXiv:2211.11645

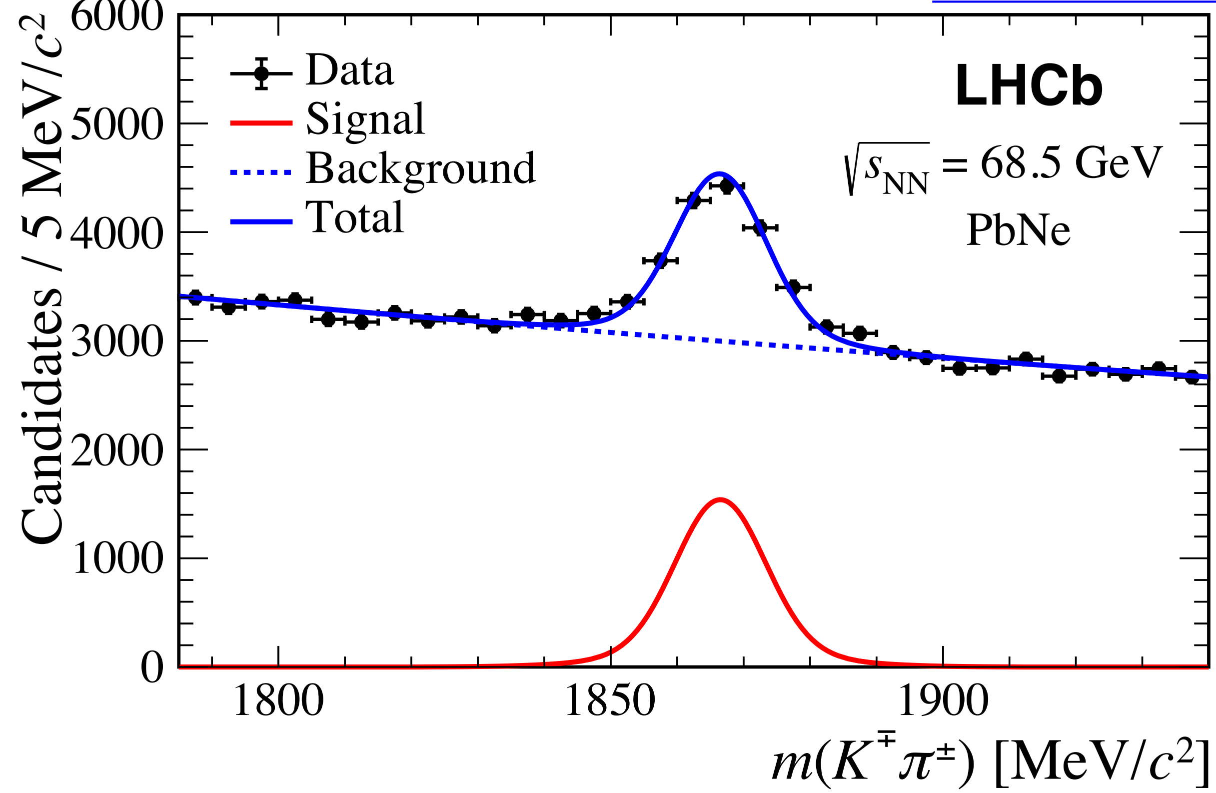


- Testing quarkonia production models and nuclear effects in an **unexplored kinematic region**:
  - LO CSM, HO: LO Color Singlet Model (CSM) predictions made using the HELAC-Onia generator with CT14NLO and nCTEQ15 PDF sets
  - Vogt predictions use the Color Evaporation Model, EPPS16 nPDFs, and include contributions from nuclear absorption and multiple scattering
- Intrinsic charm contribution has an impact in prediction of most negative y^* bin, but more precision is needed for a conclusive answer

Hidden vs open charm in PbNe collisions

arXiv:2211.11652





- Goal: are there any signs of QGP formation?
- Larger detector occupancy makes PbNe ($A_{\text{Pb}} = 208$, $A_{\text{Ne}} = 20$) a more challenging system:
  - larger background than in pNe, but still clean J/ψ and D^0 signals in 2018 PbNe dataset
  - LHCb tracking system operates well down to most central PbNe collisions at $\sqrt{s_{\text{NN}}} = 68.5\,\text{GeV}$
- Analysis made using non-colliding bunches to avoid potential UPC contamination from nominal PbPb collisions
- Same kinematic coverage as in pNe: $0 < p_{\text{T}} < 8\,\text{GeV}/c$, $-2.29 < y^* < 0$

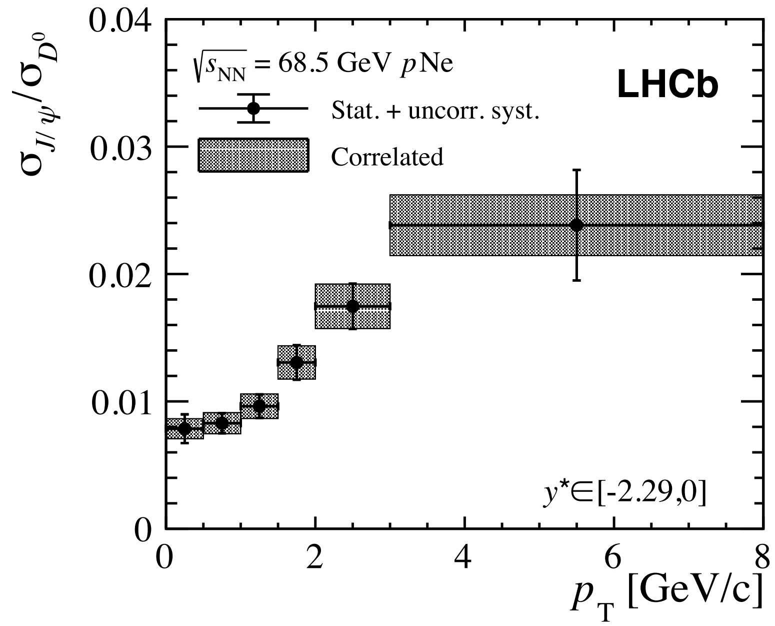
Hidden vs open charm ratio in PbNe and $p\mathrm{Ne}$

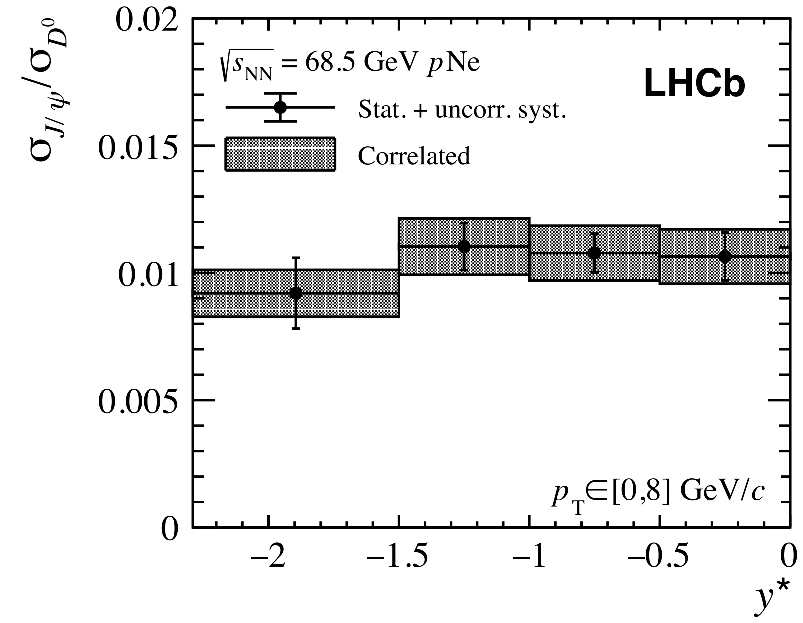
J/ψ: arXiv:2211.11645

D^0: arXiv:2211.11633

$p\mathrm{Ne}$

$\sqrt{s_{\mathrm{NN}}} = 68.5\,\mathrm{GeV}$

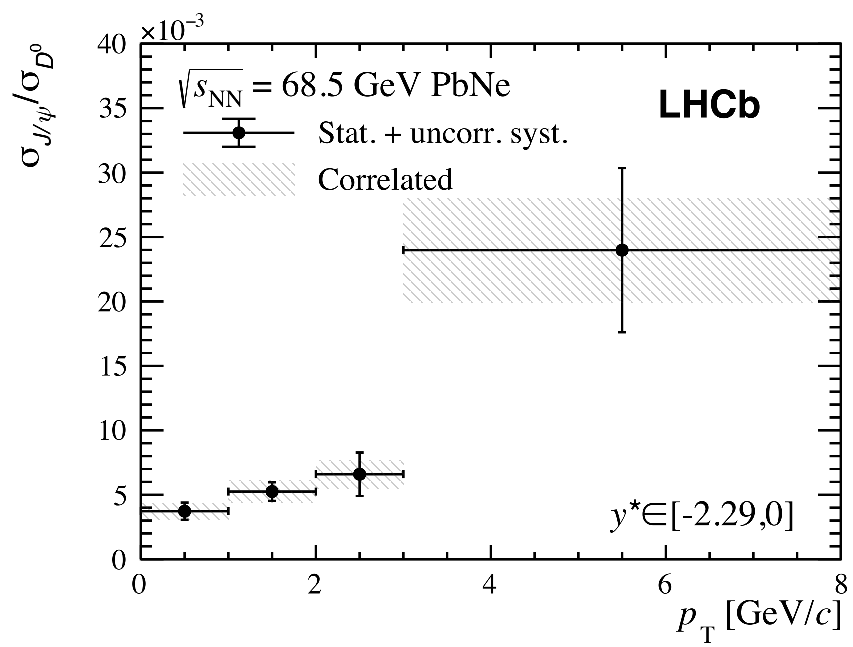


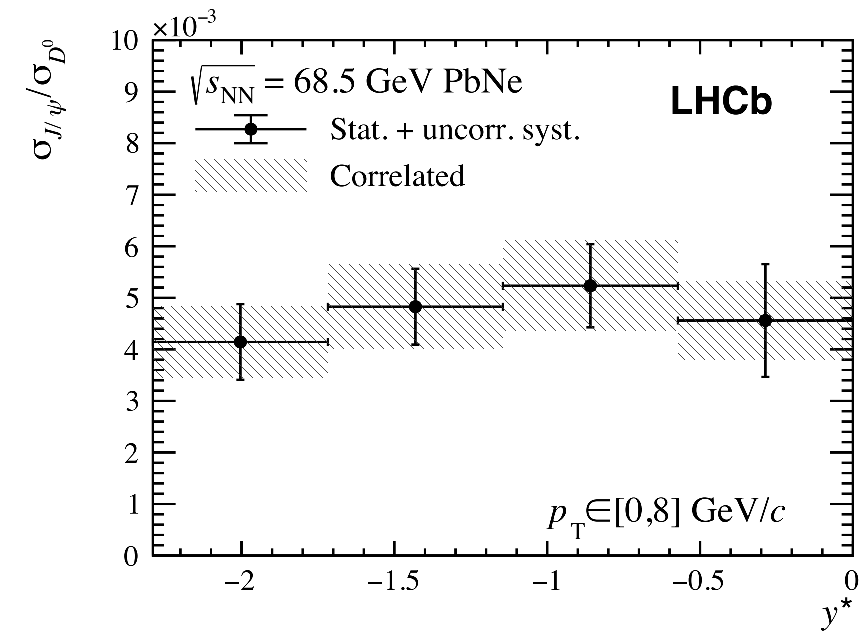


PbNe:
arXiv:2211.11652

PbNe

$\sqrt{s_{\mathrm{NN}}} = 68.5\,\mathrm{GeV}$





- D^0 is a proxy of total charm cross-section → reference for charmonia modification in PbA and $p\mathrm{A}$ collisions
- $\sigma_{J/\psi}/\sigma_{D^0}$ shows little dependence on y^* and a strong dependence on p_{T}

Hidden vs open charm ratio in PbNe collisions

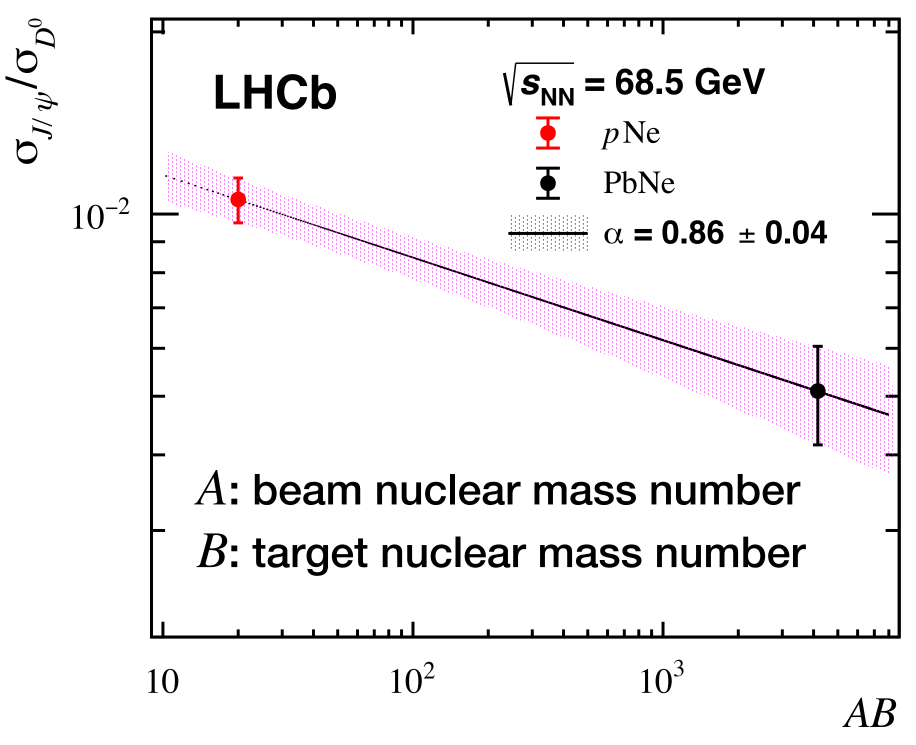
arXiv:2211.11652

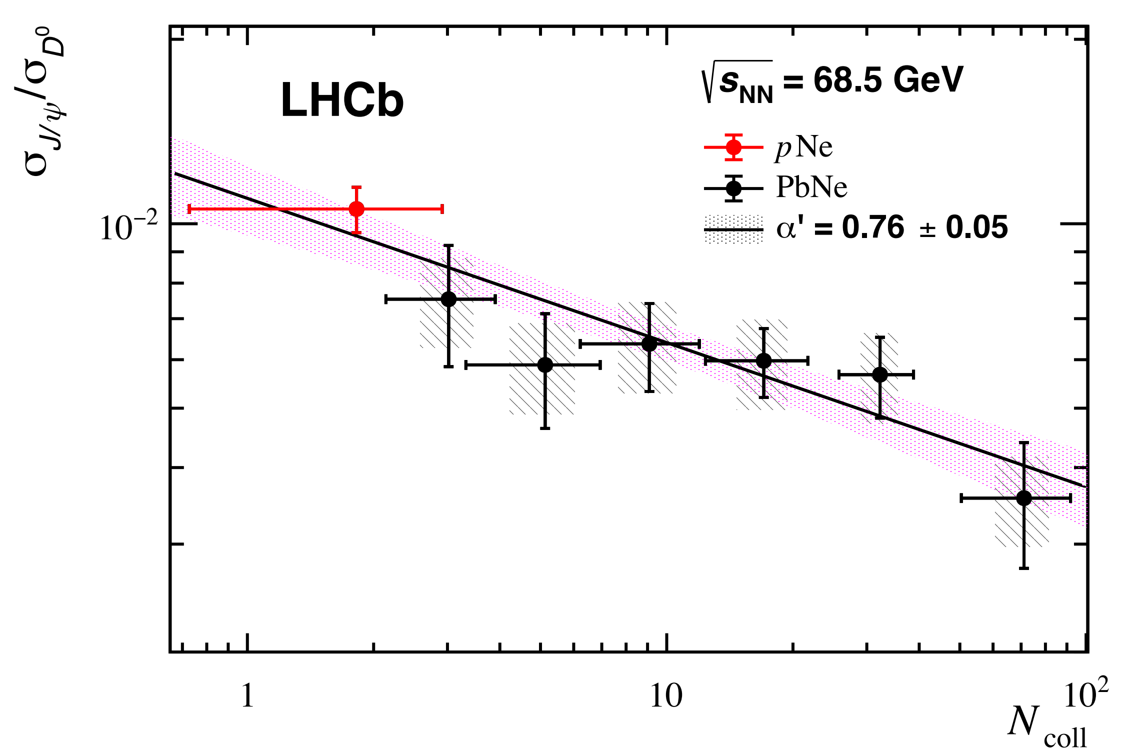
- Assuming: $\sigma_{D^0}^{AB} = \sigma_{D^0}^{pp} \times AB$ and $\sigma_{J/\psi}^{AB} = \sigma_{J/\psi}^{pp} \times AB^{\alpha}$:

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

(functional form expected from nuclear absorption)

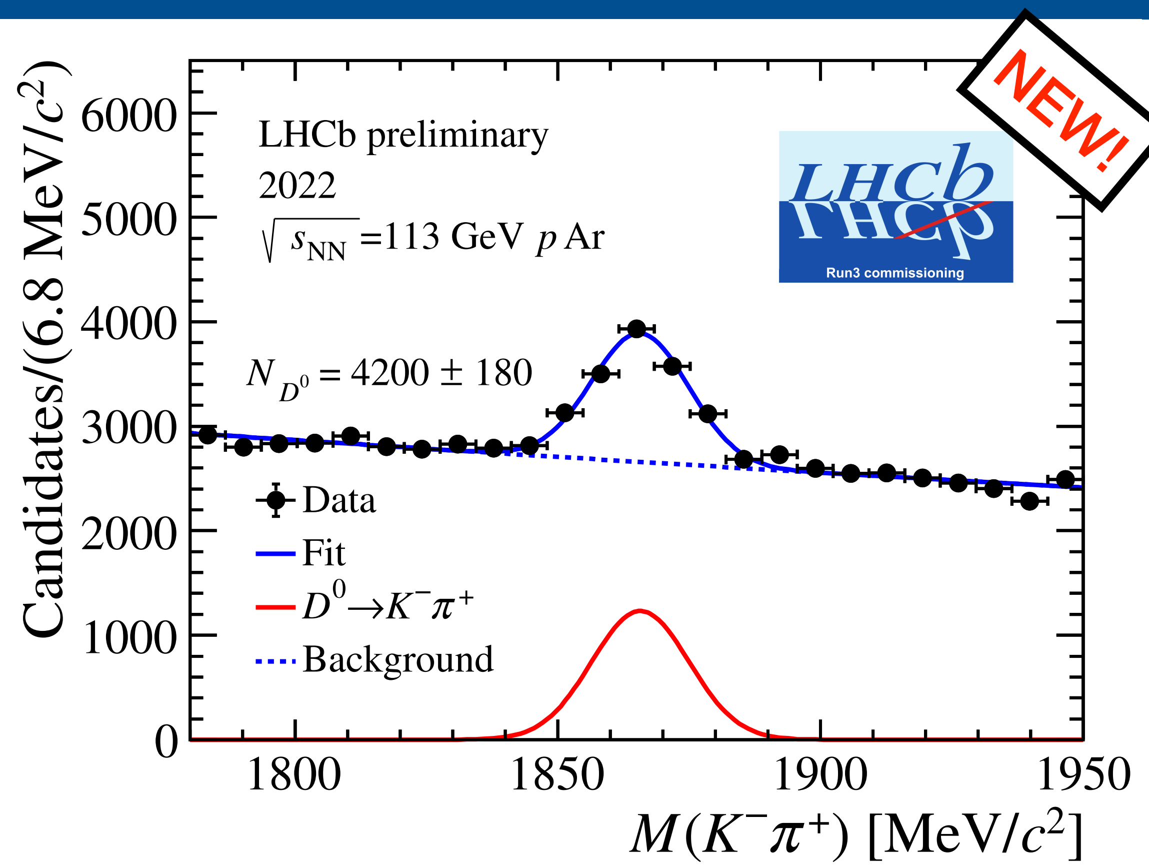
- $\alpha < 1 \implies J/\psi$ experiments additional nuclear effects with respect to D^0
  - α is compatible with NA50 values from proton-nucleus collisions (PLB 410 (1997) 337)
- Ratio with respect to $\langle N_{\mathrm{coll}} \rangle$ (measured in a Glauber analysis JINST 17 (2022) 05, P05009):
  - within current precision at the largest reachable $\langle N_{\mathrm{coll}} \rangle$, **anomalous suppression is not observed in PbNe**
- Search of anomalous suppression at LHCb will continue:
  - SMOG2 will increase precision, and larger $\langle N_{\mathrm{coll}} \rangle$ will be accessible injecting larger nucleus (Ar) and thanks to the upgraded LHCb tracking system for Run 3

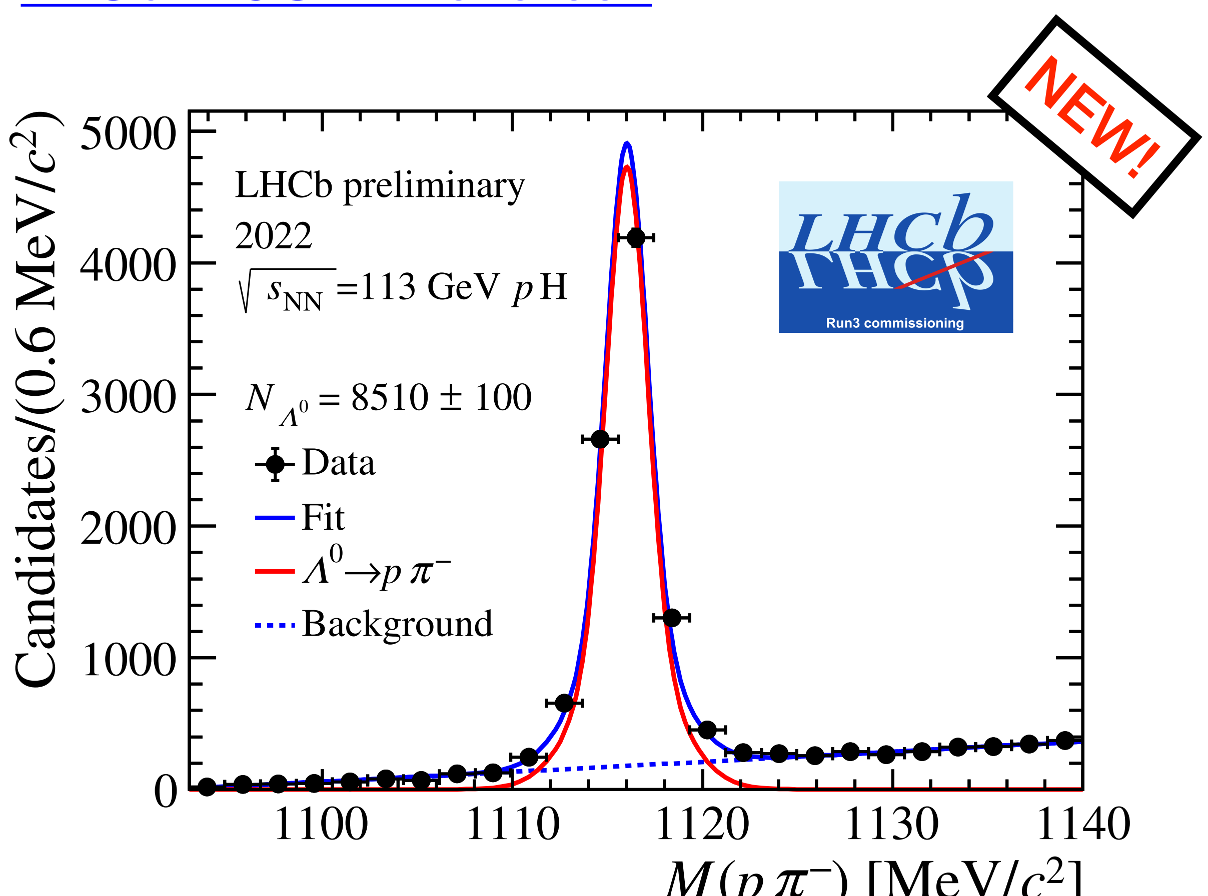


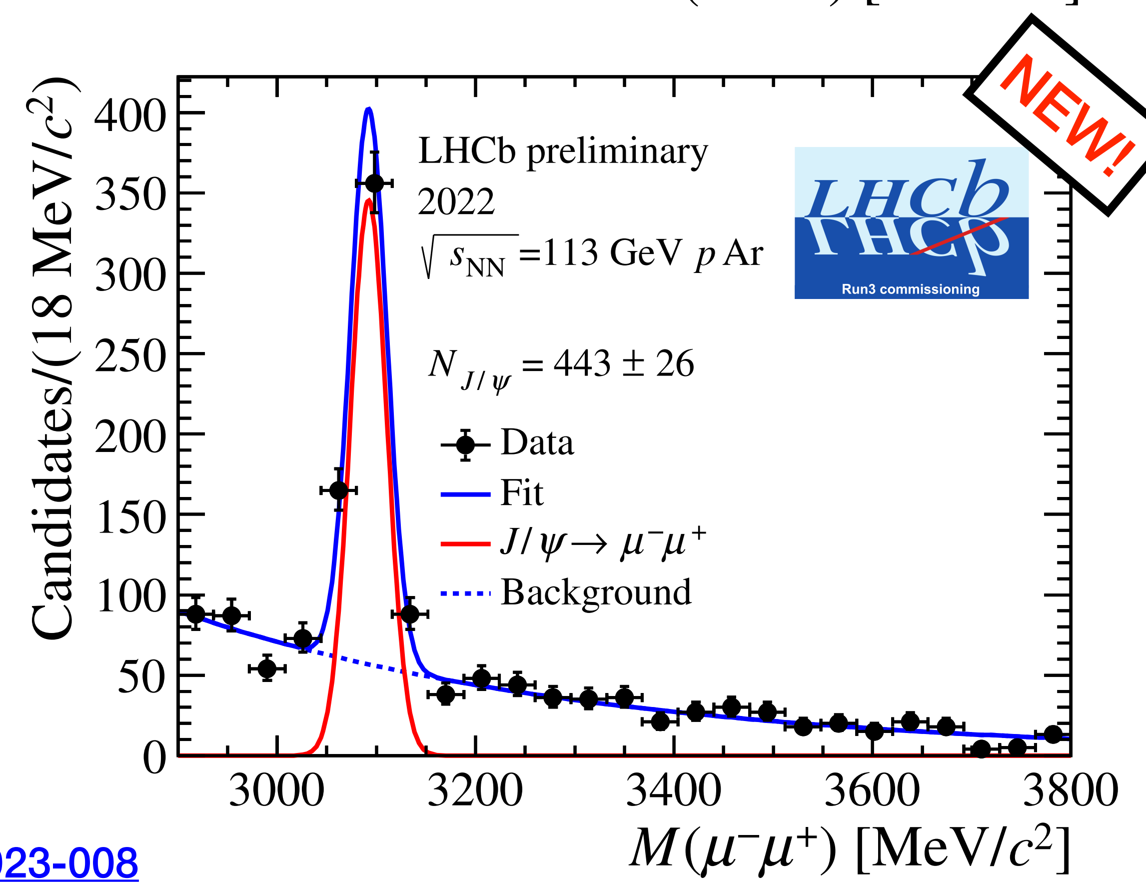


Outputs of SMOG2 from 2022 commissioning

- New figures from analysis of 2022 data
- Data collected during short periods ($\sim 20\,\mathrm{min}$) of gas injection aimed to commission the SMOG2 system
  - **D^0 and J/ψ samples obtained in only 18 minutes of data-taking of Ar injection!**
  - **First data taken in $p\mathrm{H}$ collisions at $\sqrt{s_{\mathrm{NN}}} = 113\,\mathrm{GeV}$!**
- More commissioning figures from online reconstruction: [LHCb-FIGURE-2023-001]







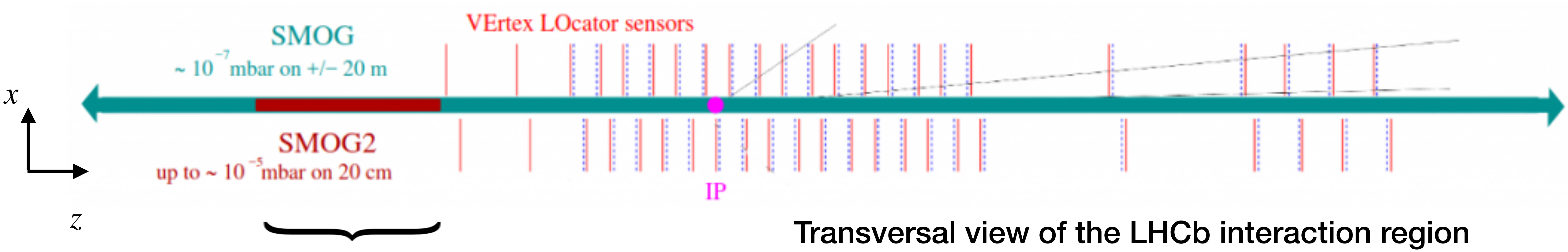
[LHCb-FIGURE-2023-008]

Conclusions and outlook

- LHCb as a fixed-target experiment provides unique opportunities to study heavy-flavour production from small to large systems at unexplored kinematic region and $\sqrt{s_{\mathrm{NN}}}$
- Talk focused on heavy-flavour results, but more fixed-target results $\rightarrow$ see G. Graziani talk for cosmic-ray related results
- New measurements of D^0 and J/ψ production in $p\mathrm{Ne}$ collisions (arXiv:2211.11633, arXiv:2211.11645):
  - D^0 vs $\overline{D^0}$ asymmetry of $\sim 15\,\%$ observed, constraining models of heavy quark hadronization at high x
  - Differential cross-sections set constrains to intrinsic charm content in the proton and the production mechanisms
- New measurement of $J/\psi/D^0$ ratio in PbNe collisions (arXiv:2211.11652)
  - data does not suggest anomalous suppression
  - SMOG2 and LHCb upgrade will improve precision and allow to explore higher energy densities
- SMOG2 physics program is becoming a reality, new mass peaks from 2022 data (LHCb-FIGURE-2023-008):
  - A sample of $\approx 440\ J/\psi$ and $\approx 4200\ D^0$ in $p\mathrm{Ar}$ was taken in only 18 minutes of data-taking!
  - first mass-peaks of data from $p\mathrm{H}$ collisions!
- **Bright future for fixed-target physics at LHC!**

Backup

The SMOG and SMOG2 systems



$PV_z \in [-541, -341]$ mm

Transversal view of the LHCb interaction region

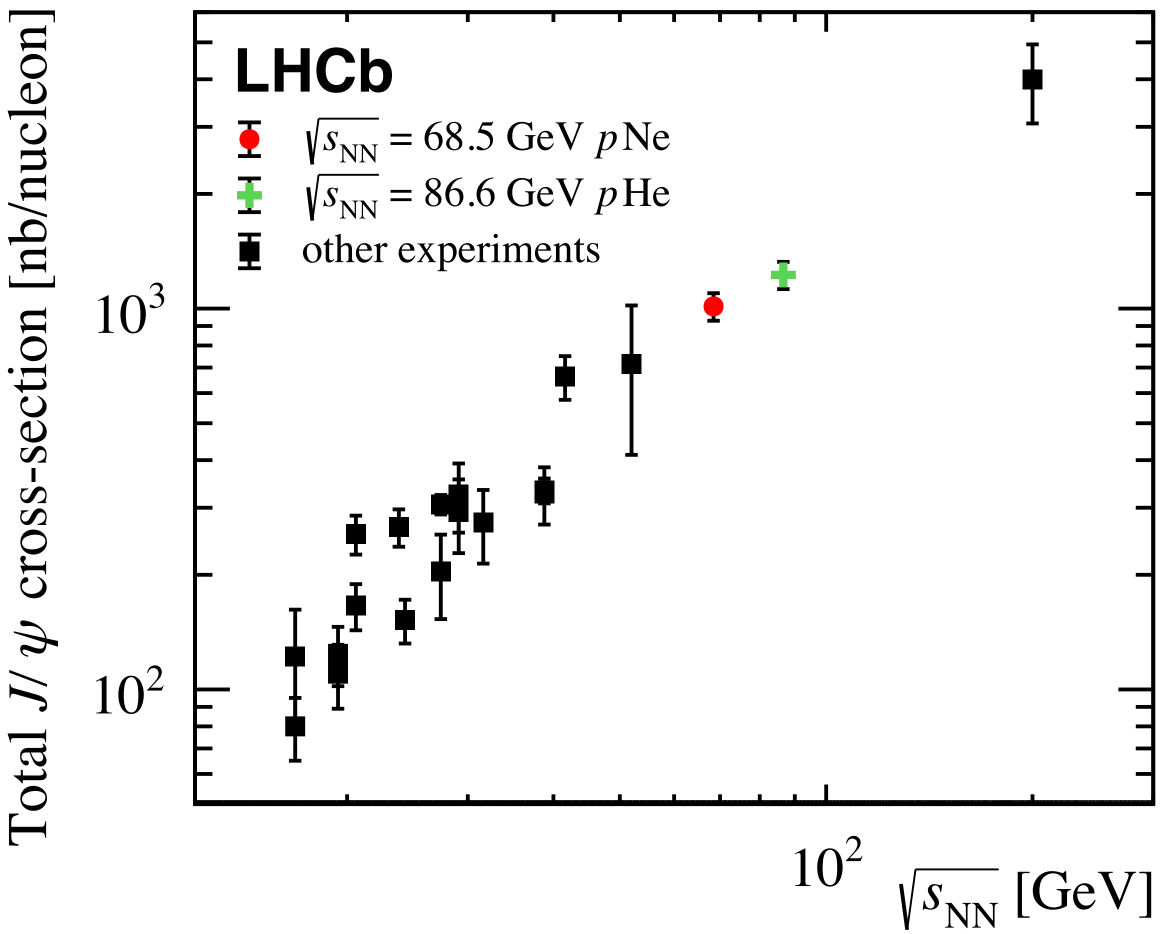
PV_z: z position of the Primary Vertex of the beam-gas collision

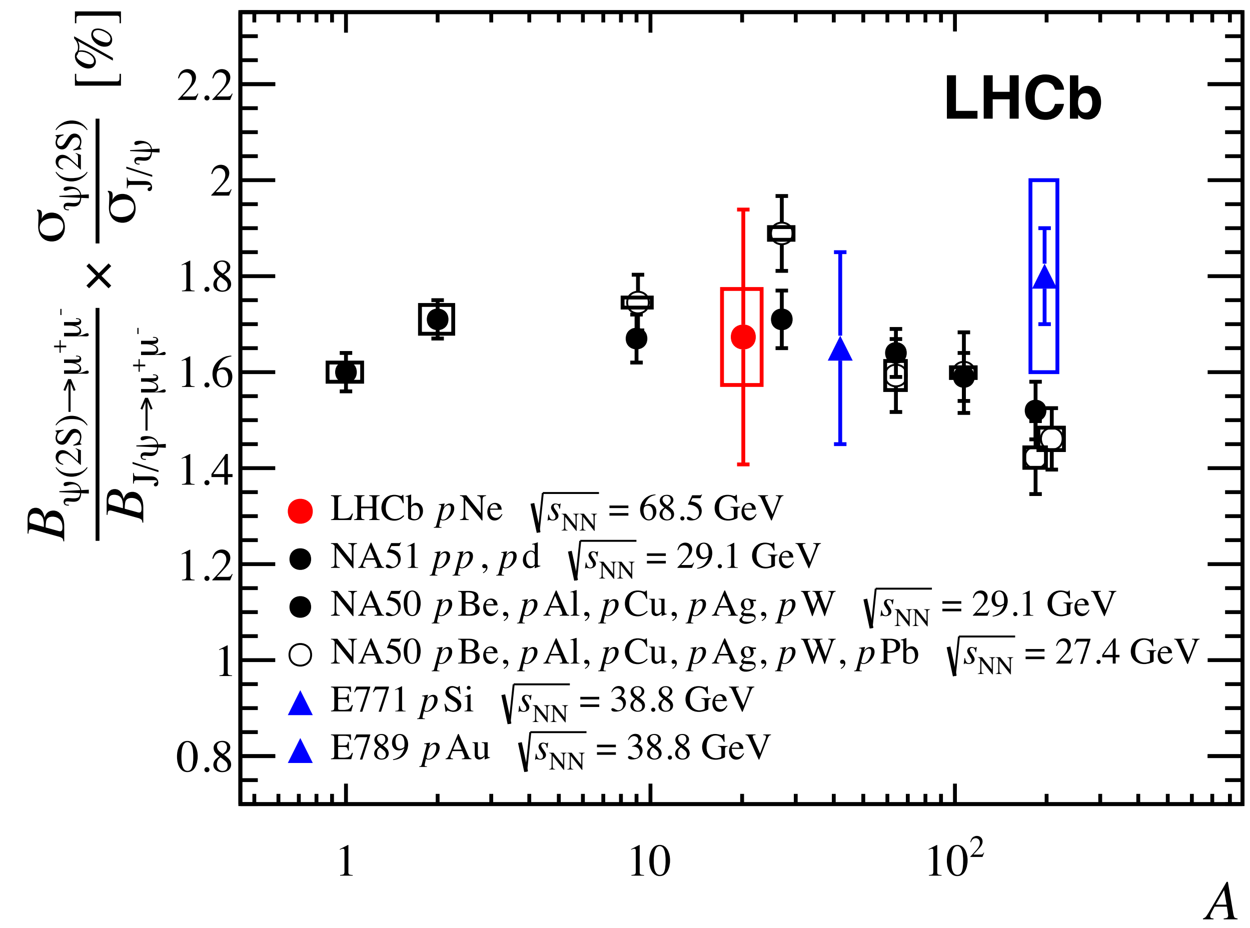
- **The SMOG system in Run 2**
  - interaction region is spread-out in PV_z
    - ✳ only non-colliding bunches can be used
    - ✳ ghost charge pollution (debunched pp collider interactions from protons)
  - luminosity determination: $p + e^-$ elastic scattering as a standard candle
    - ✳ $\approx 6\,\%$ systematic uncertainty

- **The new SMOG2 system:**
  - separate beam-beam and beam-gas interaction regions
    - ✳ both colliding and non-colliding bunches can be used
    - ✳ simultaneous data-taking with pp
  - precise luminosity determination: direct measurement of the pressure in storage cell
    - ✳ expecting $1-2\,\%$ systematic uncertainty

Charmonium in pNe

pNe: arXiv:2211.11645
pHe: PRL 122 (2019) 132002





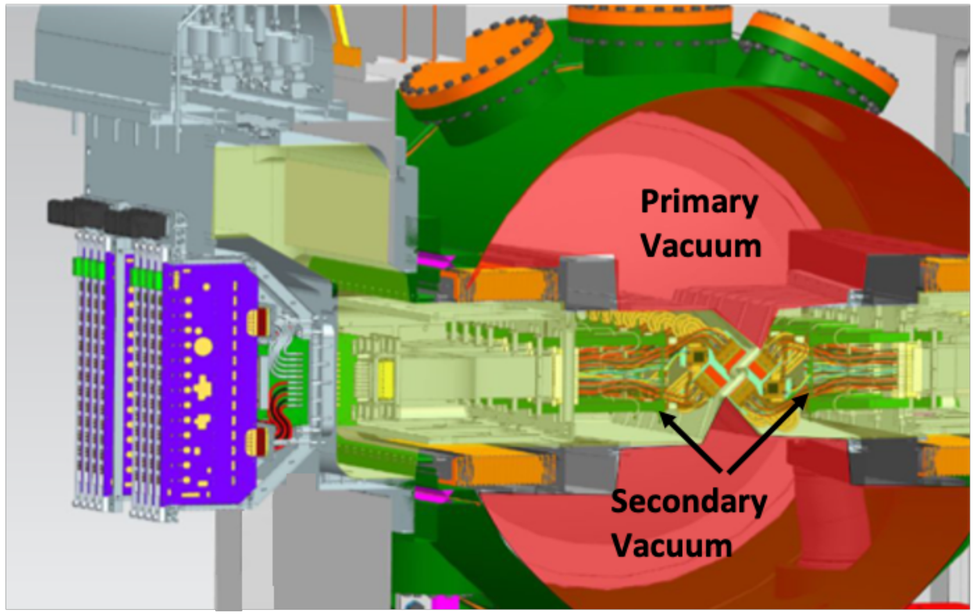
- Extrapolated J/ψ cross-section in fiducial region $y^* \in [-2.29,0]$ to full phase space with PYTHIA8 and CT09MCS PDF:

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

- Power-law dependence of $\sigma_{J/\psi}$ with $\sqrt{s_{\mathrm{NN}}}$
- Ratio $\psi(2S)/J/\psi$ consistent with ratio measured in other nuclear targets and at lower $\sqrt{s_{\mathrm{NN}}}$

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

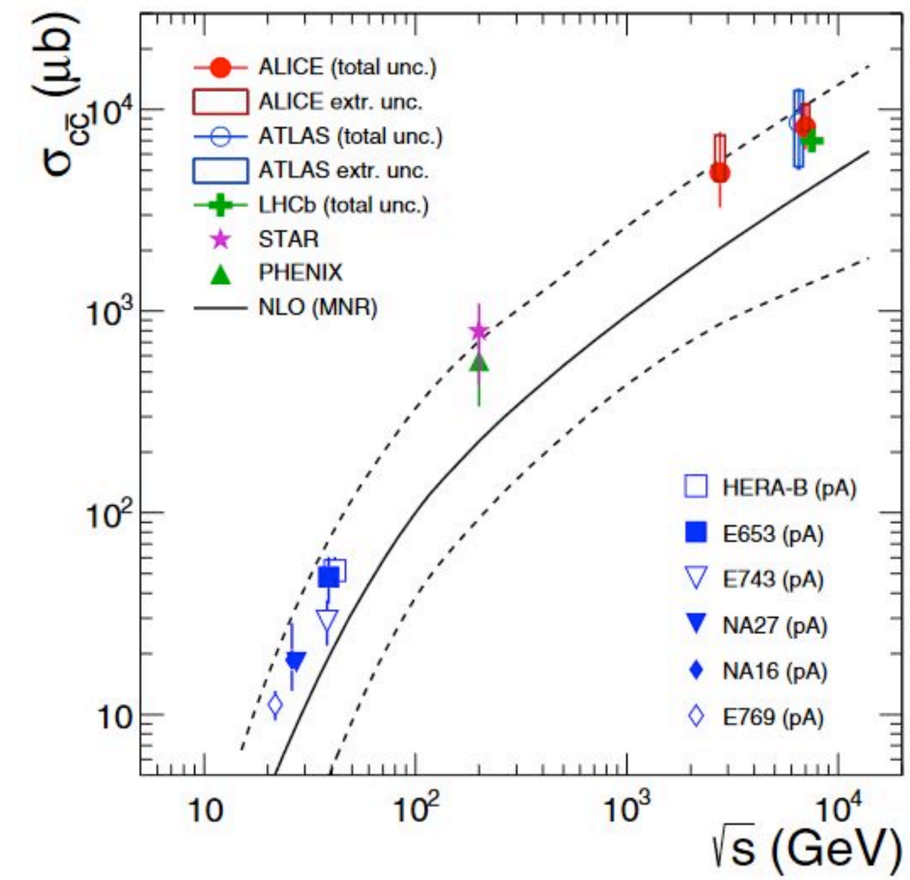
RF foils have suffered plastic deformation up to 14 mm and have to be replaced. Major intervention, planning under study

- 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

- Impact on SMOG2 for 2023 being evaluated
- SMOG injection as in Run 2 still possible

How many $c\bar{c}$ pairs are produced in PbA SMOG2 conditions?

- Charm cross-section across $\sqrt{s_{\mathrm{NN}}}$:
  - $\sigma_{c\bar{c}}^{5.5\ TeV} \sim 10 \times \sigma_{c\bar{c}}^{200\ GeV} \sim 100 \times \sigma_{c\bar{c}}^{70\ GeV} \sim 1000 \times \sigma_{c\bar{c}}^{20\ GeV}$
- Then, for $0-10\,\%$ centrality at RHIC:
  - $N_{c\bar{c}} = 597.10^{-3}\,\mathrm{mb} \times 22.8\,\mathrm{mb}^{-1} = 13$
- Therefore, we expect, on average:
  - $\sim 100\ c\bar{c}$ pairs produced at $5.5\,\mathrm{TeV}$
  - $\sim 10\ c\bar{c}$ pairs produced at $200\,\mathrm{GeV}$
  - $\sim 1\ c\bar{c}$ pairs produced at $70\,\mathrm{GeV}$
  - $\sim 0.1\ c\bar{c}$ pairs produced at $20\,\mathrm{GeV}$



PRC 94, 054908 (2016)

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

PRL 94, 082301 (2005)

Centrality determination in PbNe

JINST 17 (2022) 05, P05009

- PbNe; $\sqrt{s_{NN}} = 69\,\text{GeV}$