Charm and charmonia production in fixed-target collisions with LHCb

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on behalf of the LHCb collaboration

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The LHCb detector

General purpose detector, initially designed to **study heavy flavours**

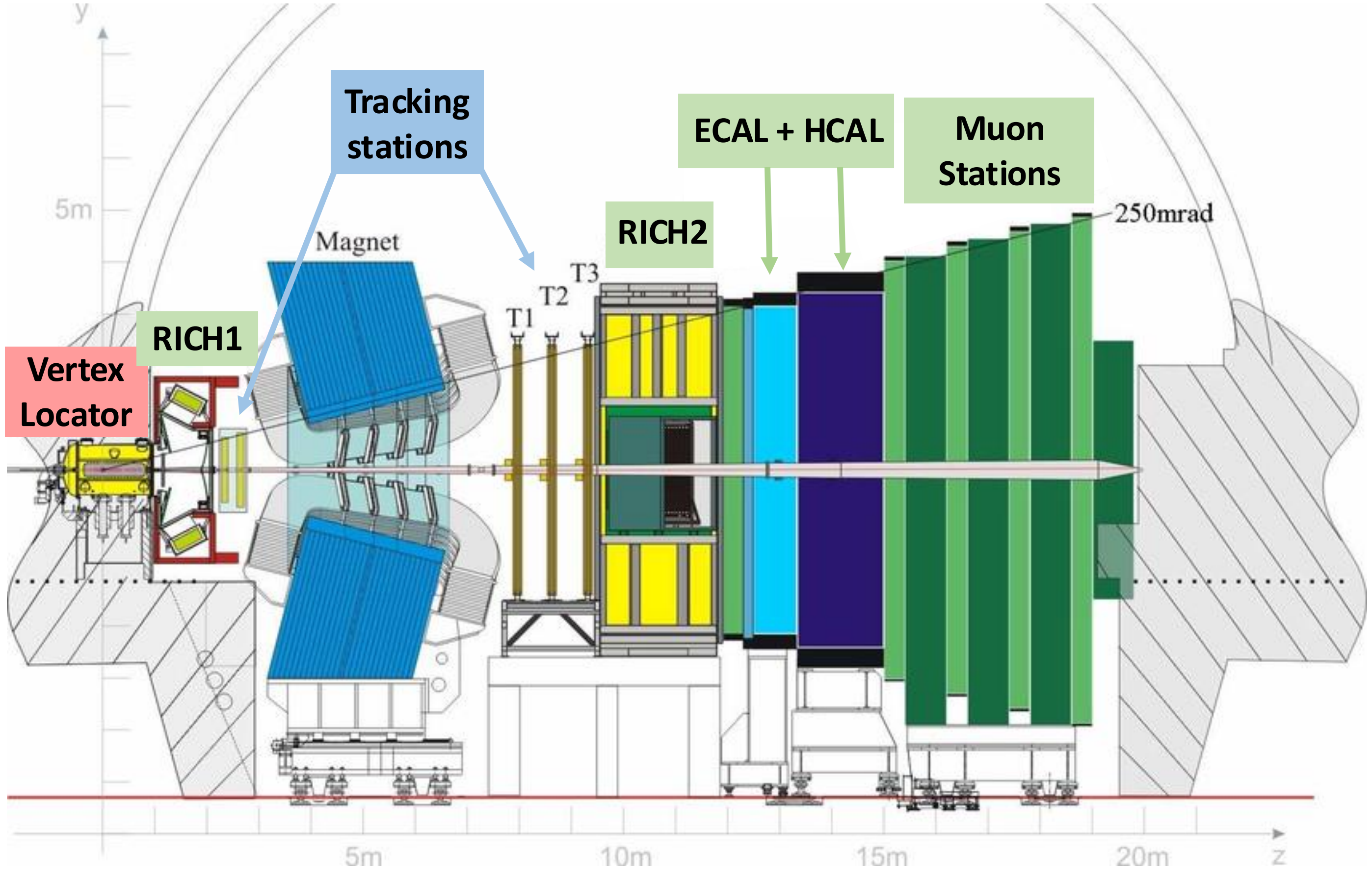
- Single-arm forward spectrometer:
  covers $2 < \eta < 5 \rightarrow$ **well suited to *pA* collisions**

- **Excellent vertexing**
  → precise position of the interaction vertex and reconstruction of secondary vertices

- Excellent **tracking down to low p_T**
  $\rightarrow \Delta p/p = 0.5\% - 1.0\%$ for $5 - 200$ GeV/c

- Excellent **particle identification**
  $\rightarrow p, K, \pi$ separation in $p \in [10,100]$ GeV/c

The LHCb detector during Run 2
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

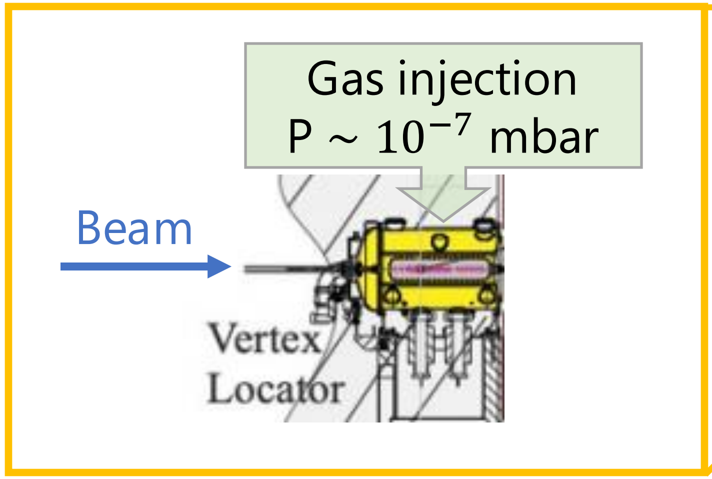


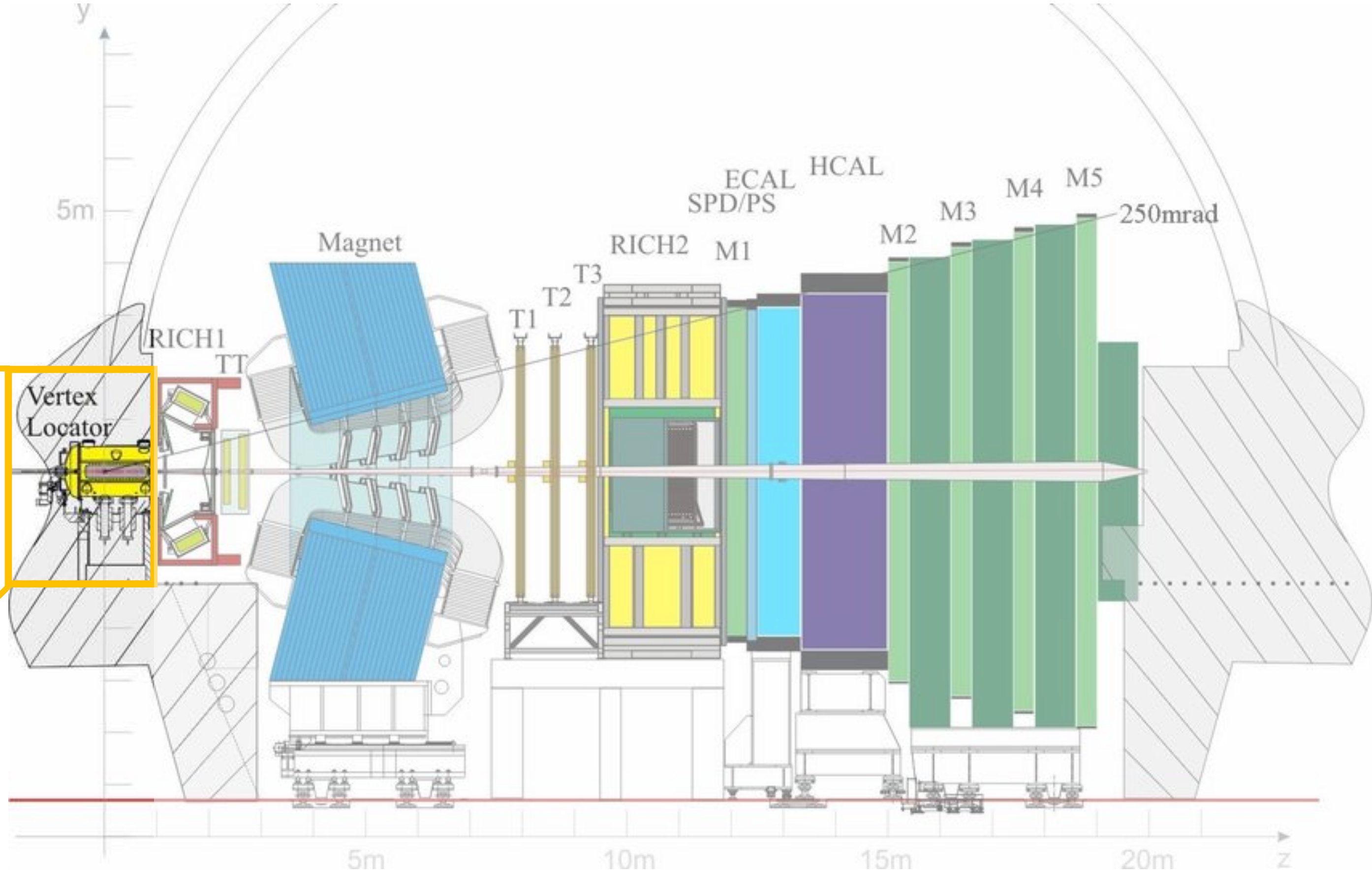
Fixed-target configuration in Run 2

Highest-energy fixed target experiment, the only one at LHC!

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

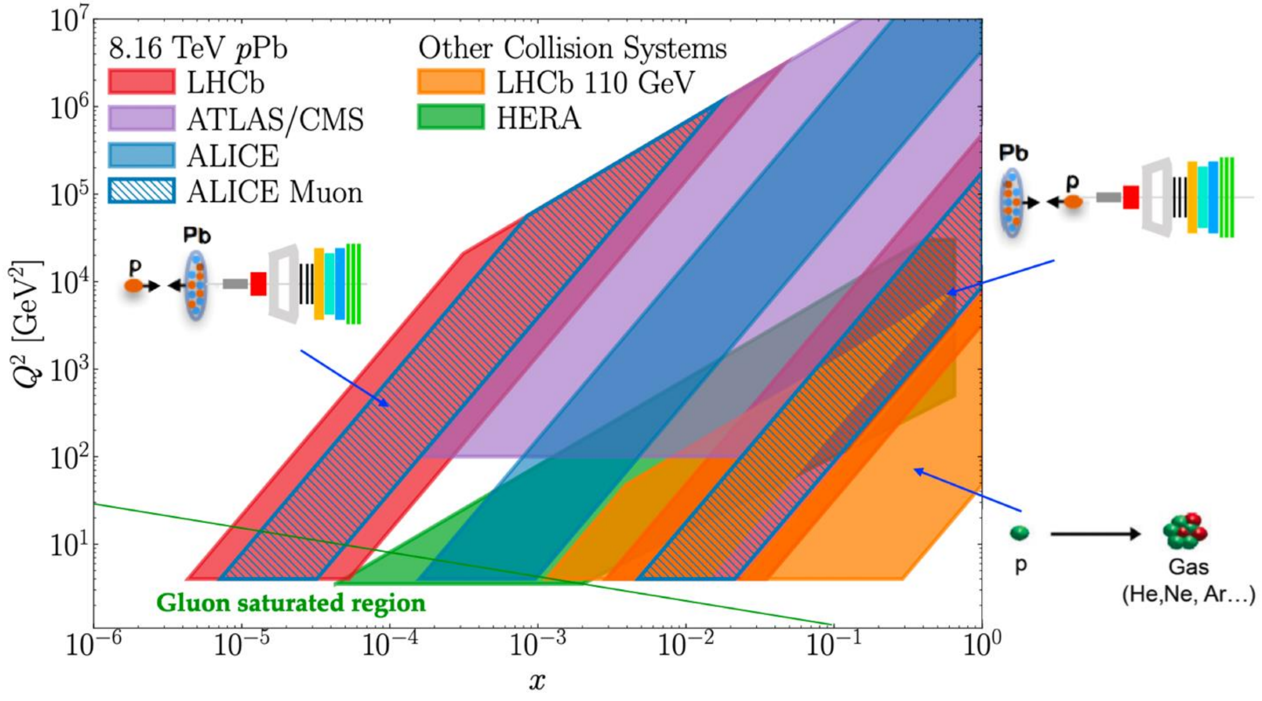
- **SMOG** (**S**ystem for **M**easuring the **O**verlap with **G**as)
- Injection of noble gas (He, Ne, Ar) in the beam pipe around LHCb Interaction Point (IP)
- Uses LHC beam to produce *p*A or PbA collisions





Fixed-target configuration in Run 2

J.Phys.Conf.Ser. 1271 (2019) 1, 012008



Unique physics opportunities!

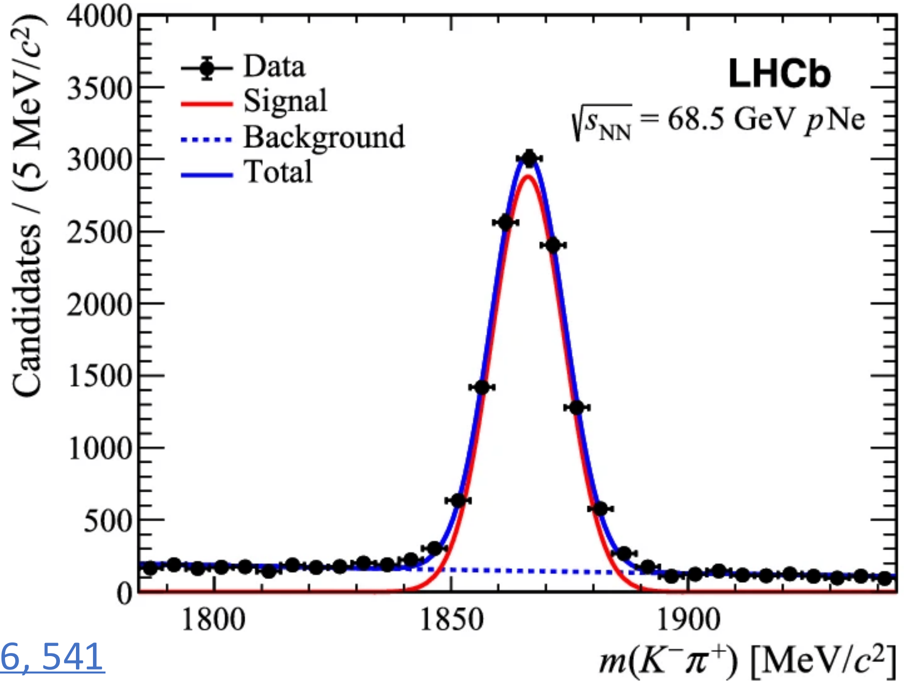
- Target mass number A between *p* and Pb
- **Unexplored energy range** $\sqrt{s_{NN}} = 68.5 - 110.4$ GeV between SPS and RHIC
- **Central rapidity coverage** in the centre-of-mass $y^* \sim [-2.5, 0]$
- **Probing large Bjorken-x of the target** nucleons at intermediate Q^2

Perfect to study charm hadronisation!

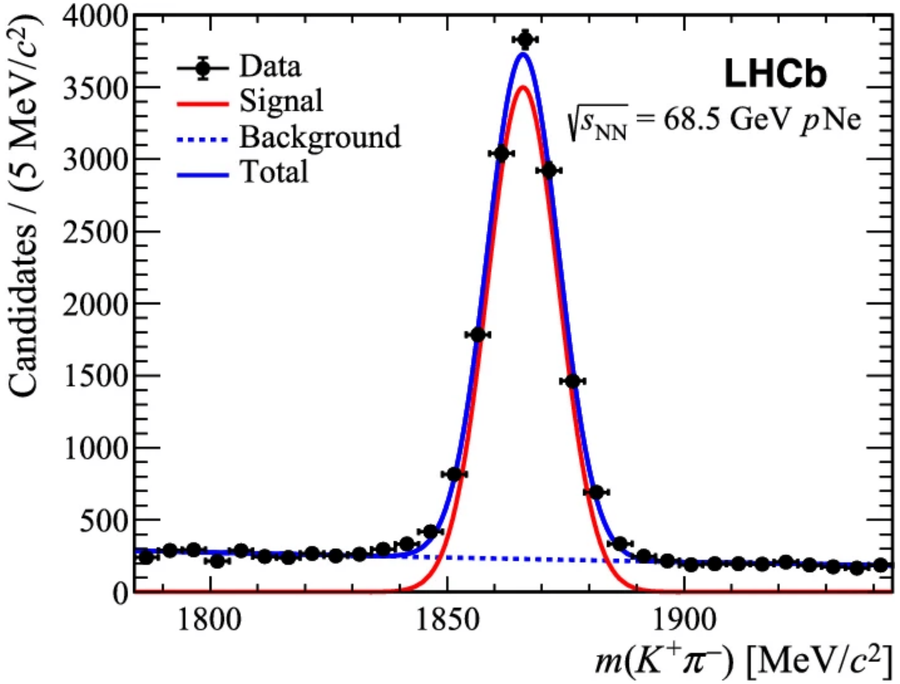
Open charm production

- Open-charm produced at the beginning of the collision → sensitive to the partonic content of the nucleon
- $D^0(\bar{u}c)$ meson is the most abundantly produced → **good proxy of the overall charm quark production**
- At **large** $x \sim 0.01 - 0.4$ → valence region → **test hadronisation mechanisms via D^0 - $\overline{D^0}$ asymmetry**
- Measured in pNe collisions during Run 2 with $L_{pNe} = 21.7 \pm 1.4$ nb^{-1}

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



$\overline{D^0} \to K^+\pi^-$

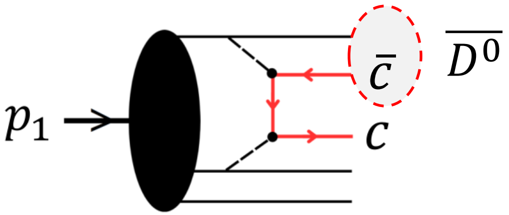


EPJ C83 (2023) 6, 541

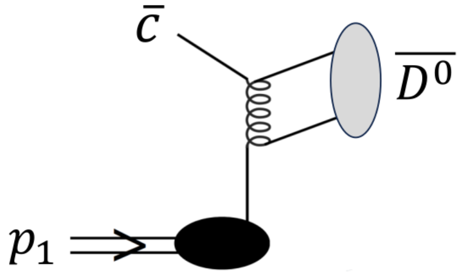
Open charm asymmetry

$$A_{prod} = \frac{Y_{corr}(D^0) - Y_{corr}(\overline{D^0})}{Y_{corr}(D^0) + Y_{corr}(\overline{D^0})}$$

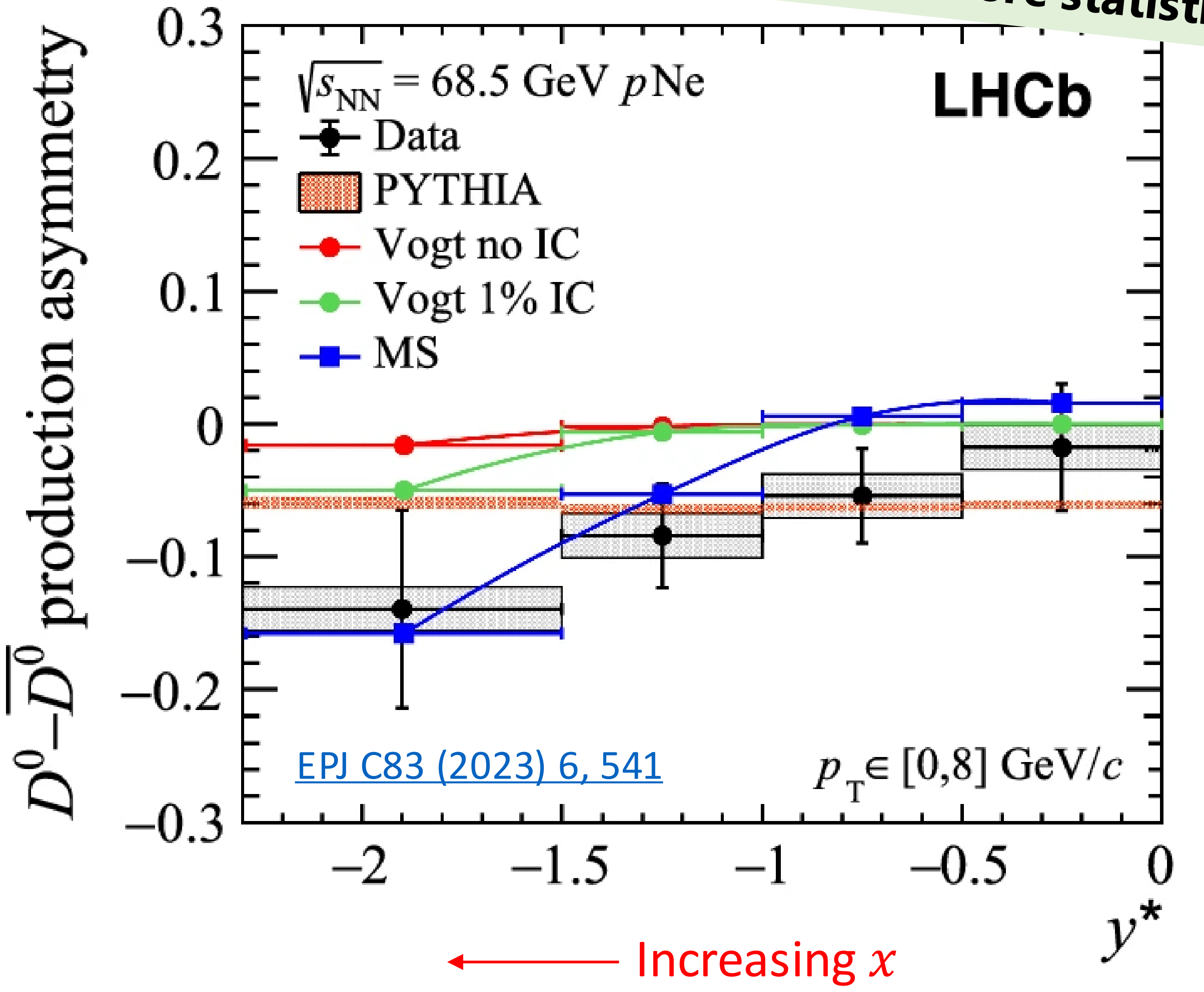
- Vogt predictions **with** and **without intrinsic charm** (IC) (PRC 103 (2021) 035204)



- MS with 1% intrinsic charm and **10% coalescence** (*Phys.Lett.B* 835 (2022) 137530)



Need more statistics!



Charmonia production

- **Charmonium states sensitive to the medium**
  - Cold nuclear matter (CNM) effects in *p*A collisions
  - Hot and dense matter effects in nucleus-nucleus collisions
    → excellent probes of QGP

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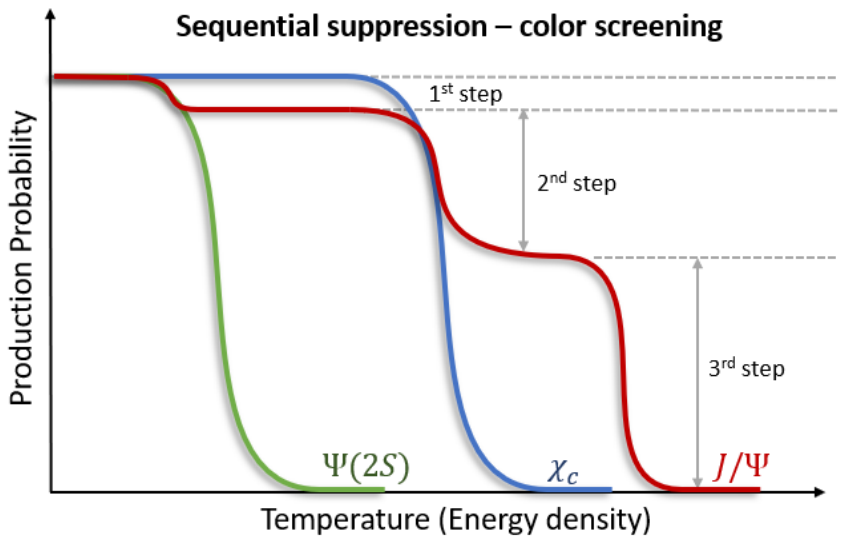
- **Sequential suppression of quarkonia**: key measurement to evidence colour screening and QGP production
  - Full spectra of charmonium states needed ($\Psi(2S), \chi_c, \mathrm{J}/\psi$) → **not yet entirely measured!**



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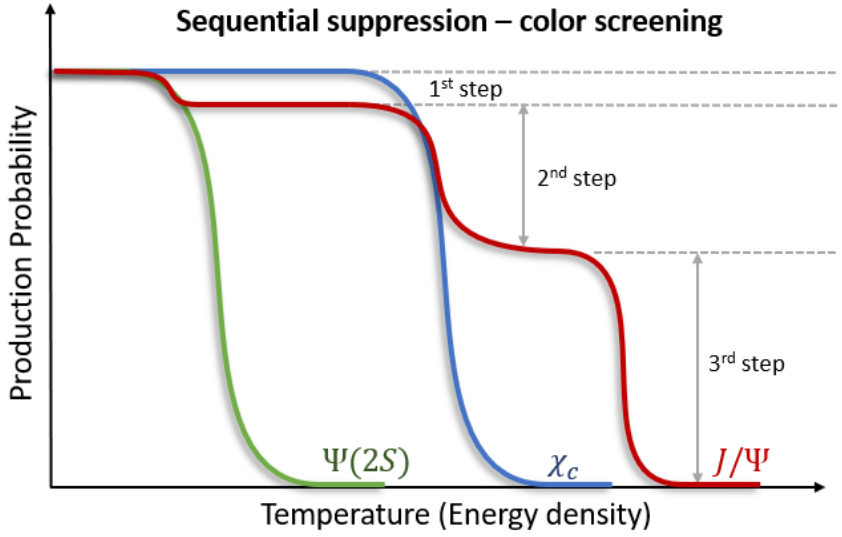
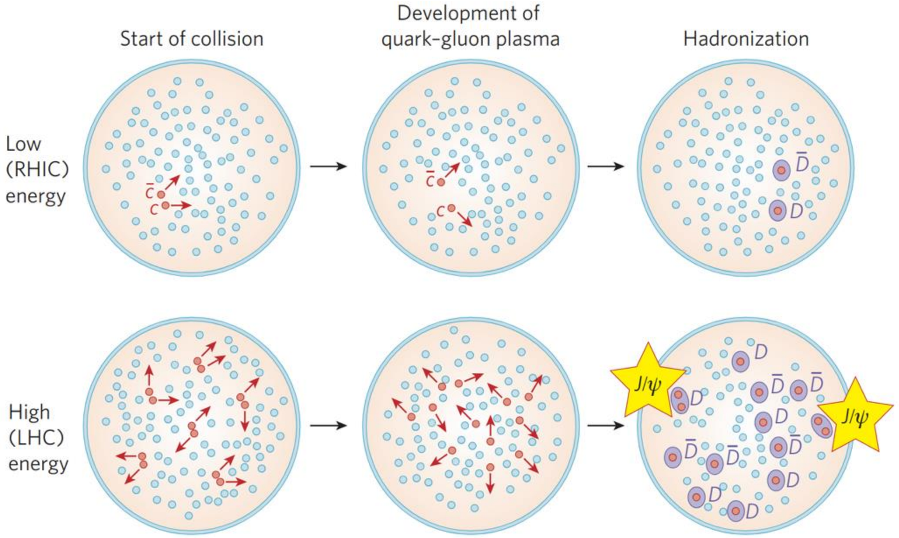
  - At high energy **statistical recombination competing with dissociation** → negligible recombination with **SMOG** ($\sqrt{s_{NN}} \leq 100$ GeV)
  - Various *p*A and PbA systems available thanks to different injectable gases



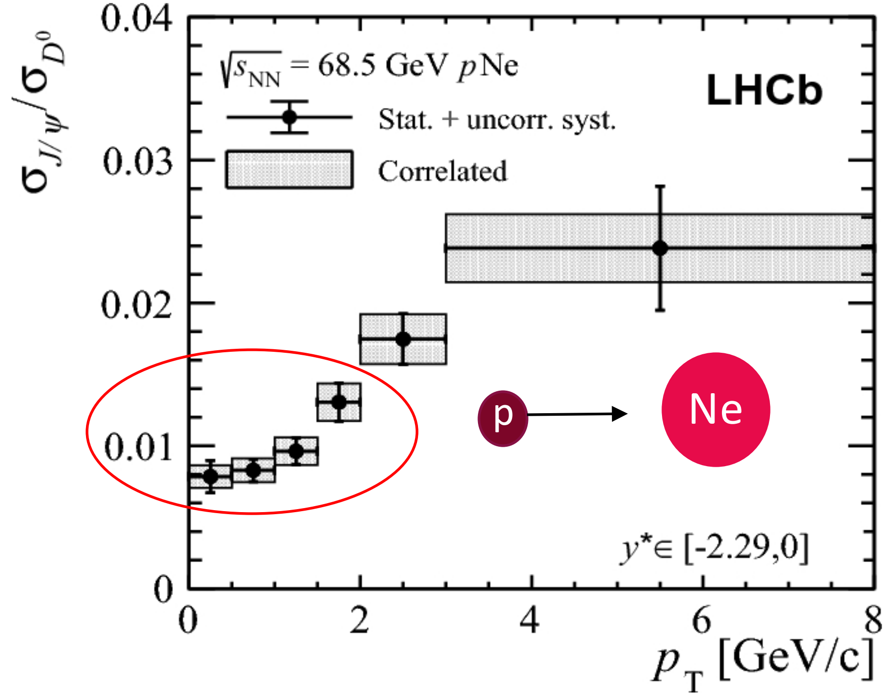


Nature 448 (2007) 302

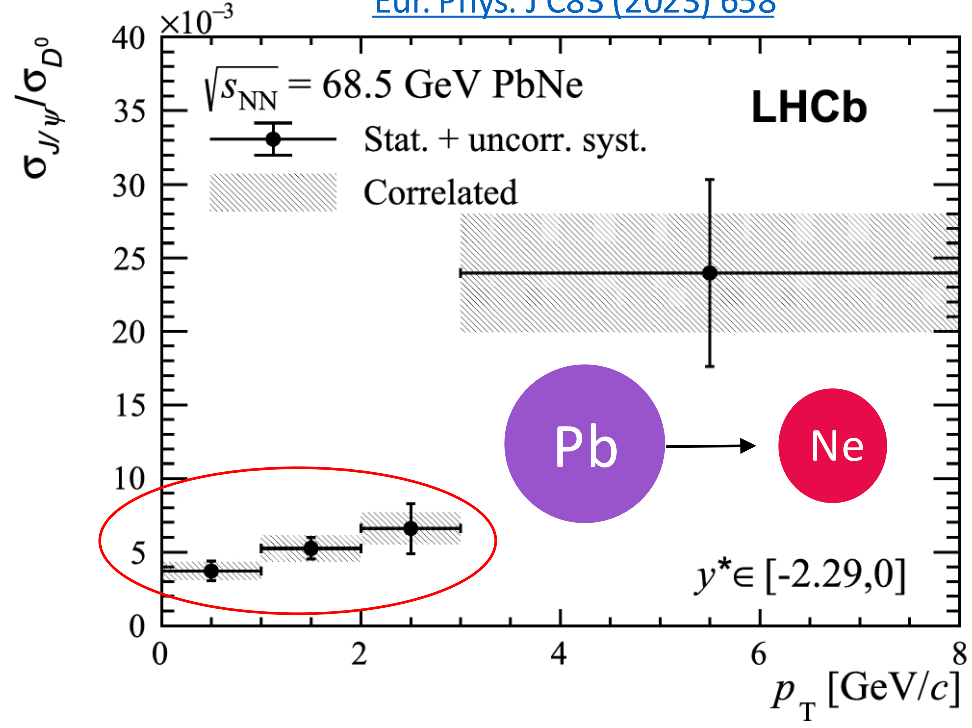
J/ψ production in pNe and PbNe

- J/ψ and D^0 cross-sections measured in pNe and PbNe collisions
- **Strong p_T dependence** in pNe
  - → different p_T distributions for J/ψ and D^0
  - → final states effects? Reference system needed
- **PbNe/pNe ratio smaller than 1 in lower p_T bins** → J/ψ undergoes more nuclear effects than D^0

Eur. Phys. J. C83 (2023) 7, 625

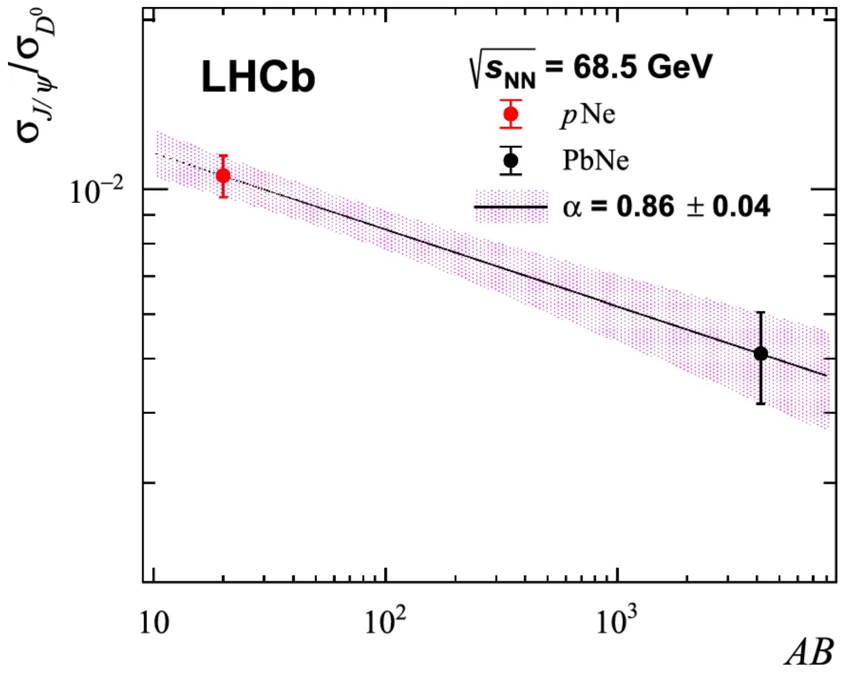


Eur. Phys. J C83 (2023) 658



J/ψ production in pNe and PbNe

- Functional form expected from nuclear absorption: $\frac{\sigma^{AB}_{J/\psi}}{\sigma^{AB}_{D^0}} = \frac{\sigma^{pp}_{J/\psi}}{\sigma^{pp}_{D^0}} \times AB^{\alpha-1}$ A (B) : beam (target) atomic mass number
- $\boldsymbol{\alpha < 1}$ $\rightarrow J/\psi$ is affected by additional nuclear effects compared to D^0



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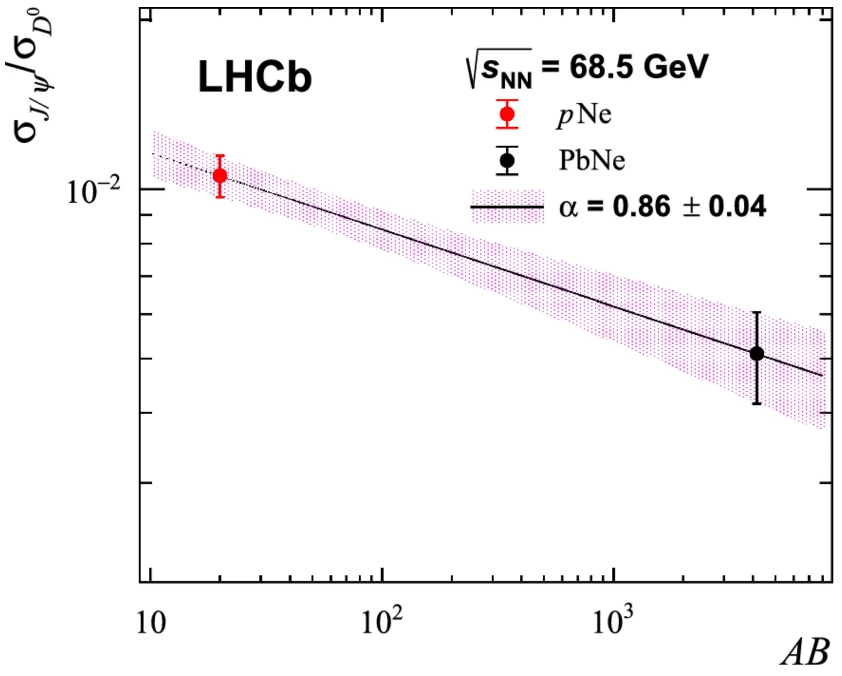
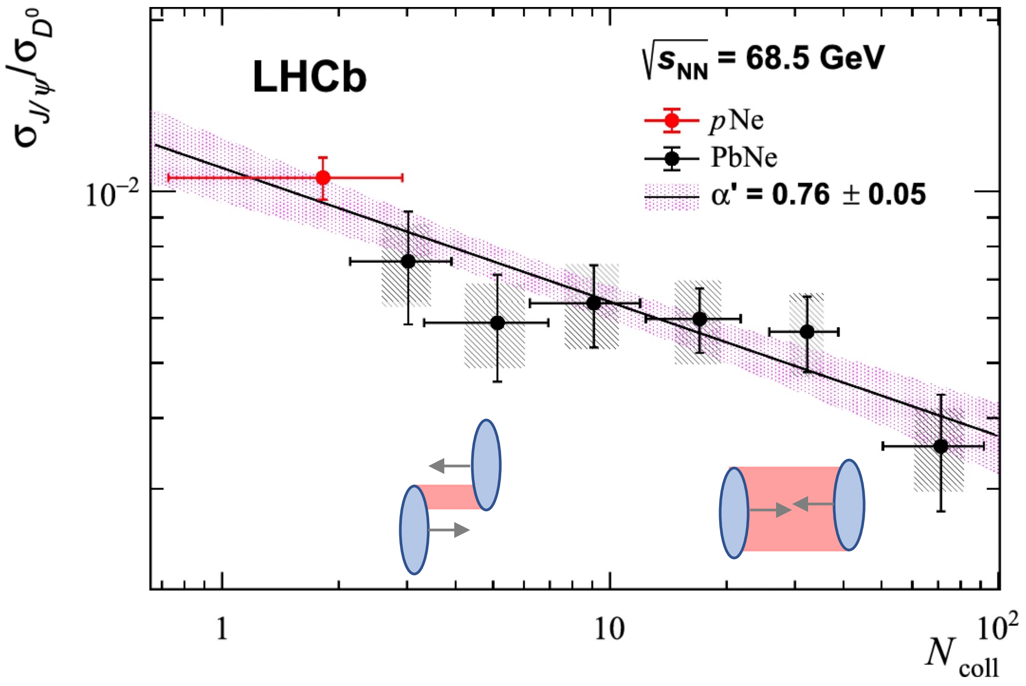
- $\boldsymbol{\alpha < 1}$ $\rightarrow J/\psi$ is affected by additional nuclear effects compared to D^0
- **No indication of an anomalous J/ψ suppression in PbNe** peripheral and central collisions with respect to pNe





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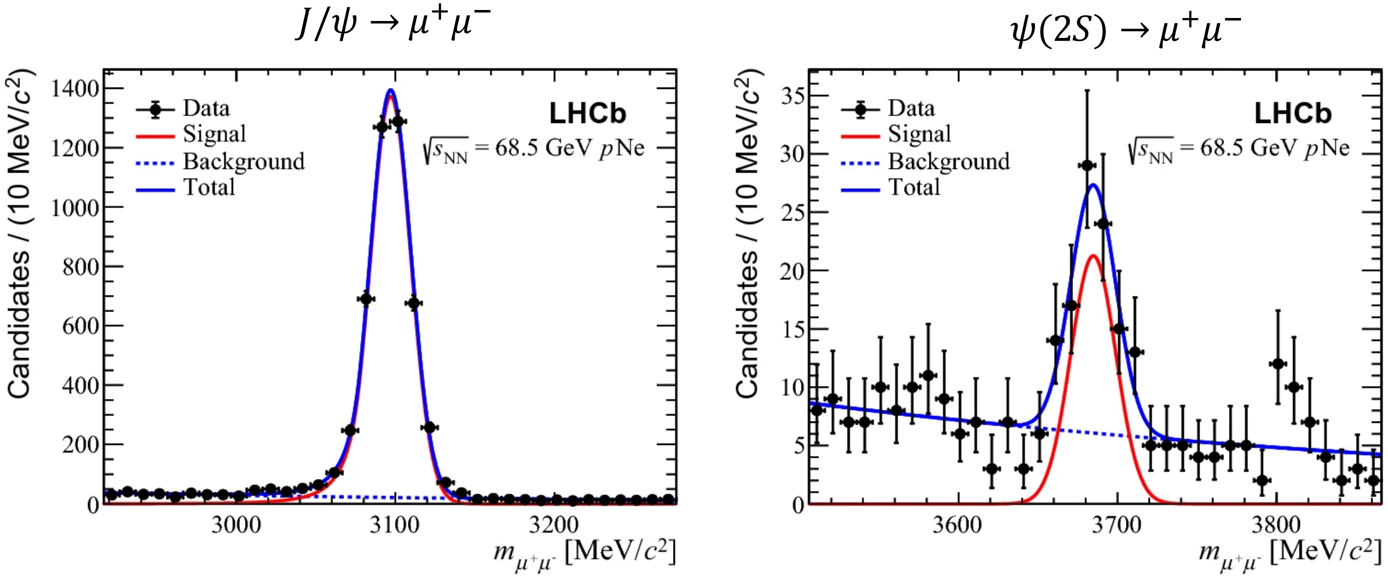
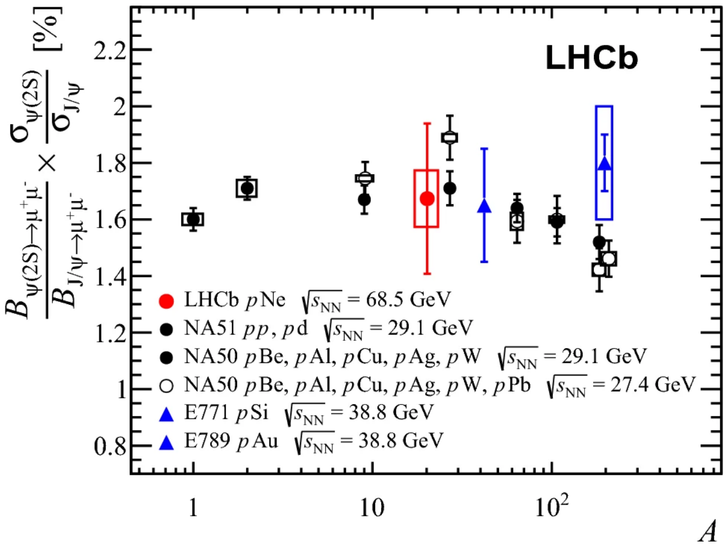
Charmonium production in *p*Ne

Eur. Phys. J. C83 (2023) 7, 625

- **First measurement of $\psi(2S)$ in fixed-target collisions at LHCb!**



- **$\psi(2S)$ / J/ψ ratio** → key probe of final-states effects
- Relative production rate of $\psi(2S)$ / J/ψ **in agreement with other measurements at similar value of A**



More statistics needed!

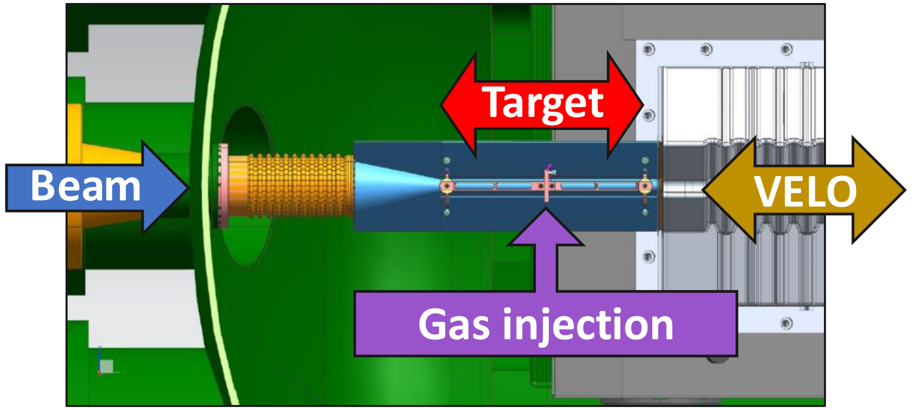
Fixed-target configuration in Run 3

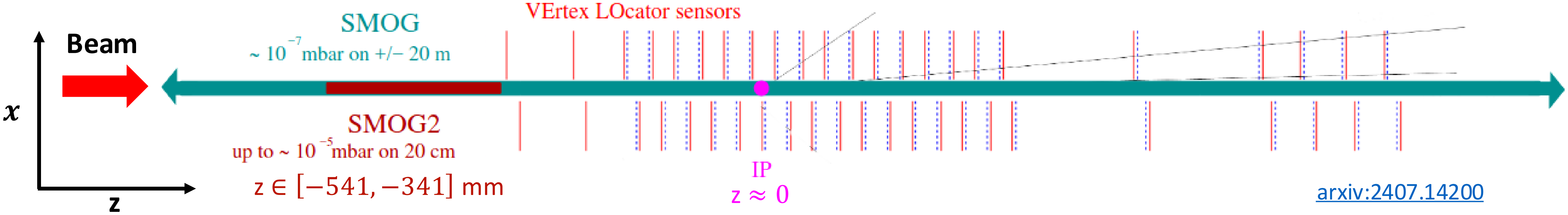
- **SMOG2**: dedicated cell to contain the gaseous target
- **Higher pressure** than SMOG → increased luminosity
- **Simultaneous data-taking** with collider mode

x100 more statistics!

- Possibility to inject **non-noble gases**:
  - $\mathbf{H_2}$ for reference
  - $\mathbf{D_2}$ to test isospin symmetry
  - $\mathbf{O_2}$ and larger nuclei Kr, Xe

LHCB-PUB-2018-015

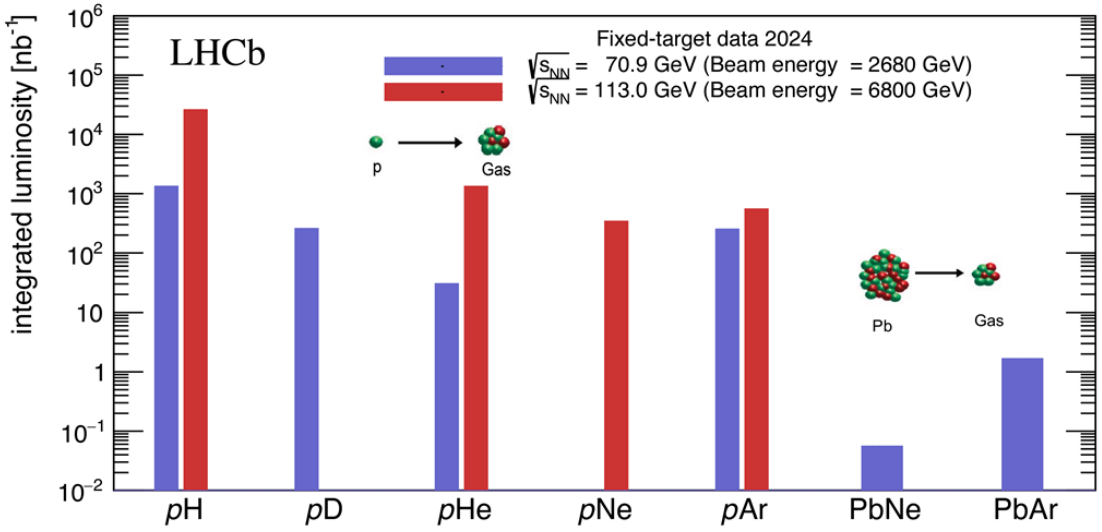




arxiv:2407.14200

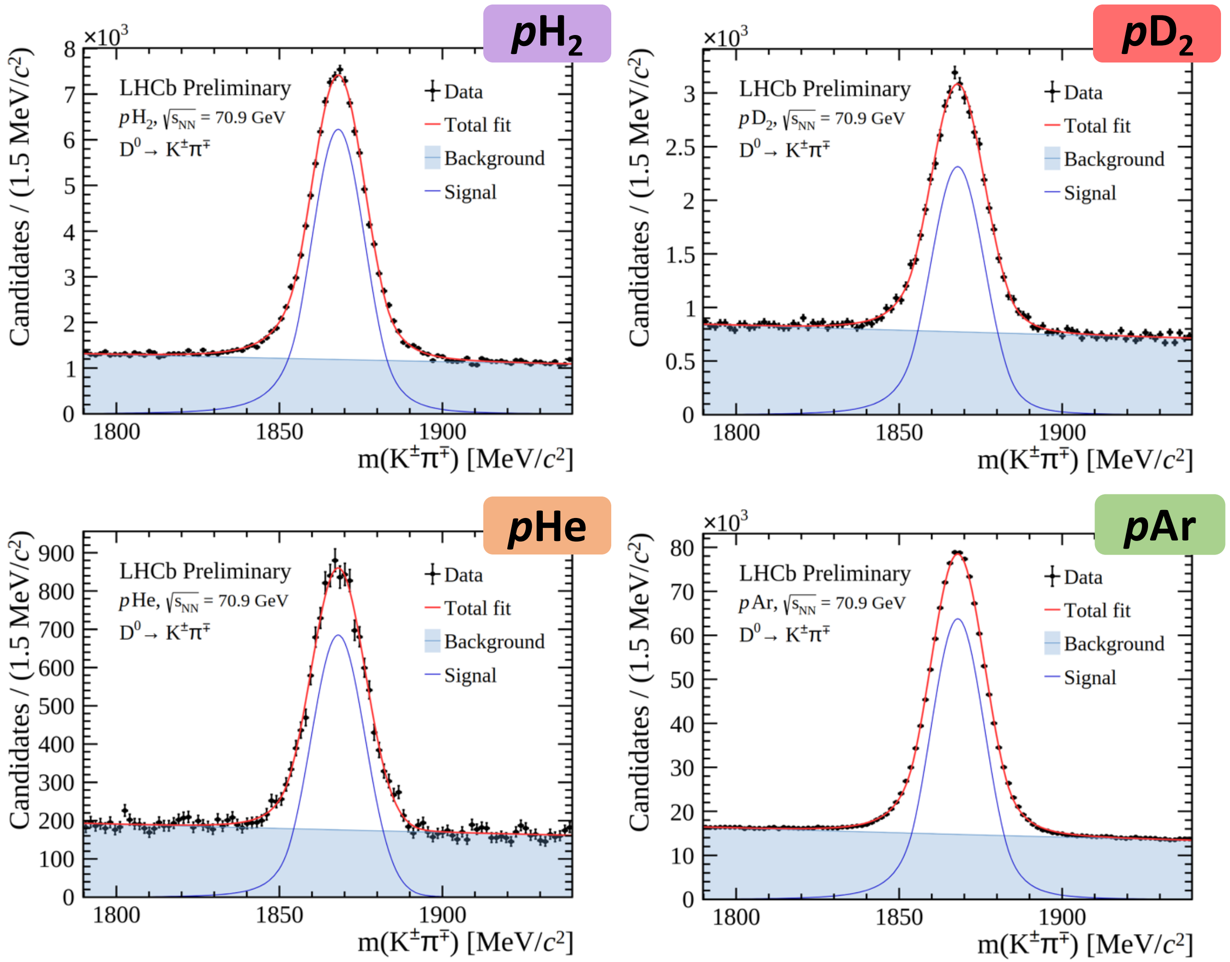
Run 3 data taking with SMOG2

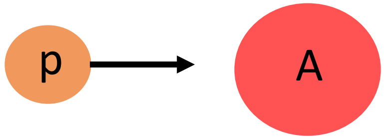
- **5 different gases** injected since the beginning of Run 3: H_2, D_2, He, Ne, Ar
- **4 different beam types**: *p*, Pb, O and Ne
- **2 different colliding energies**:
  - $E_{beam} = 2.68$ TeV $\rightarrow \sqrt{s_{NN}} = 70.9$ GeV
  - $E_{beam} = 6.8$ TeV $\rightarrow \sqrt{s_{NN}} = 110$ GeV

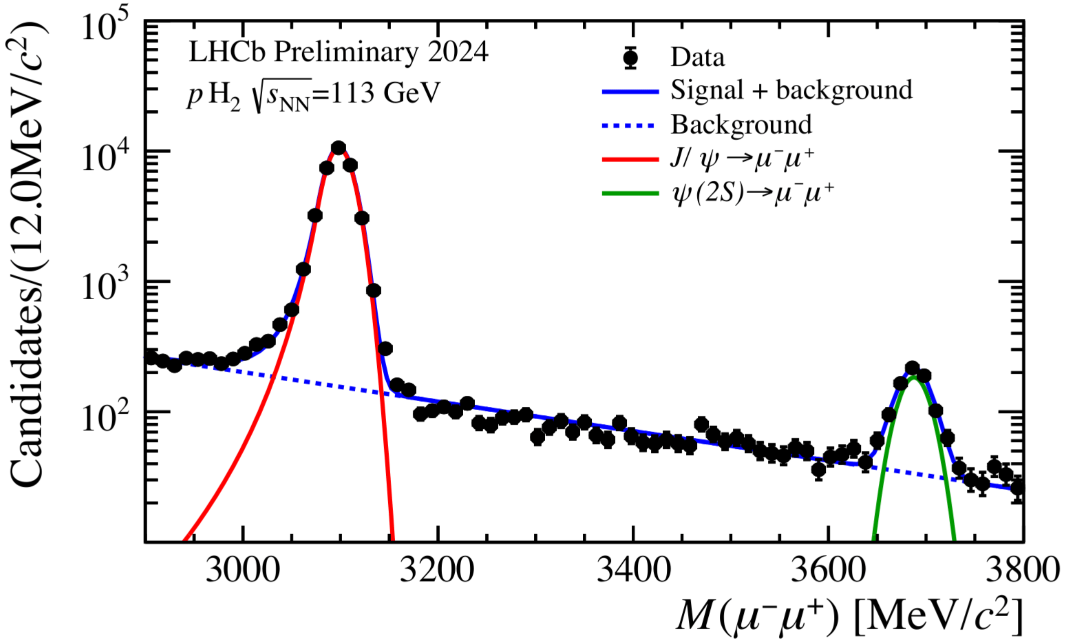


Unprecedented fixed-target samples over a wide range of experimental conditions!

Charm in pSMOG2 collisions







Clear D^0 peak in 4 different systems in only 4 days!

LHCb-FIGURE-2025-013

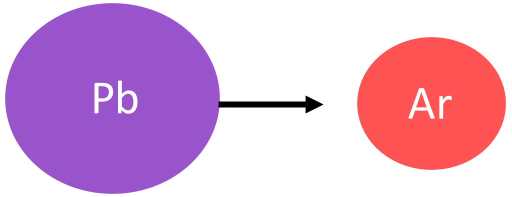
Clear $\psi(2S)$ and J/ψ signals!

LHCb-FIGURE-2024-023

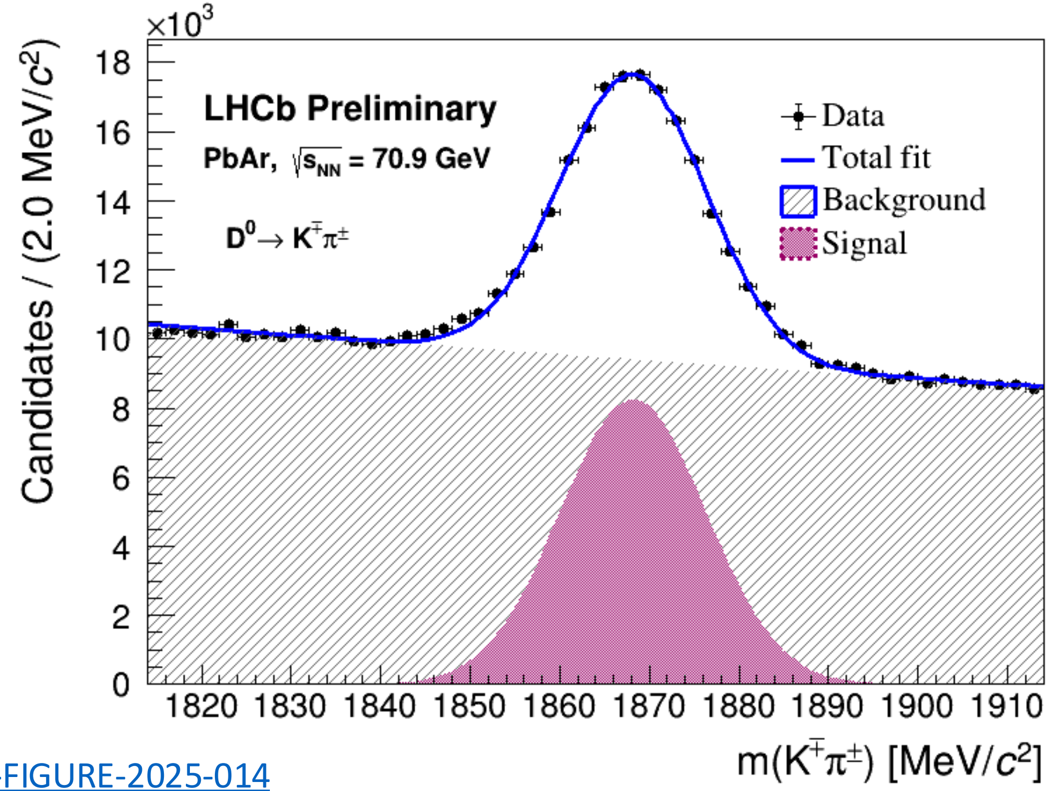
Charm in Pb-SMOG2 collisions

New!

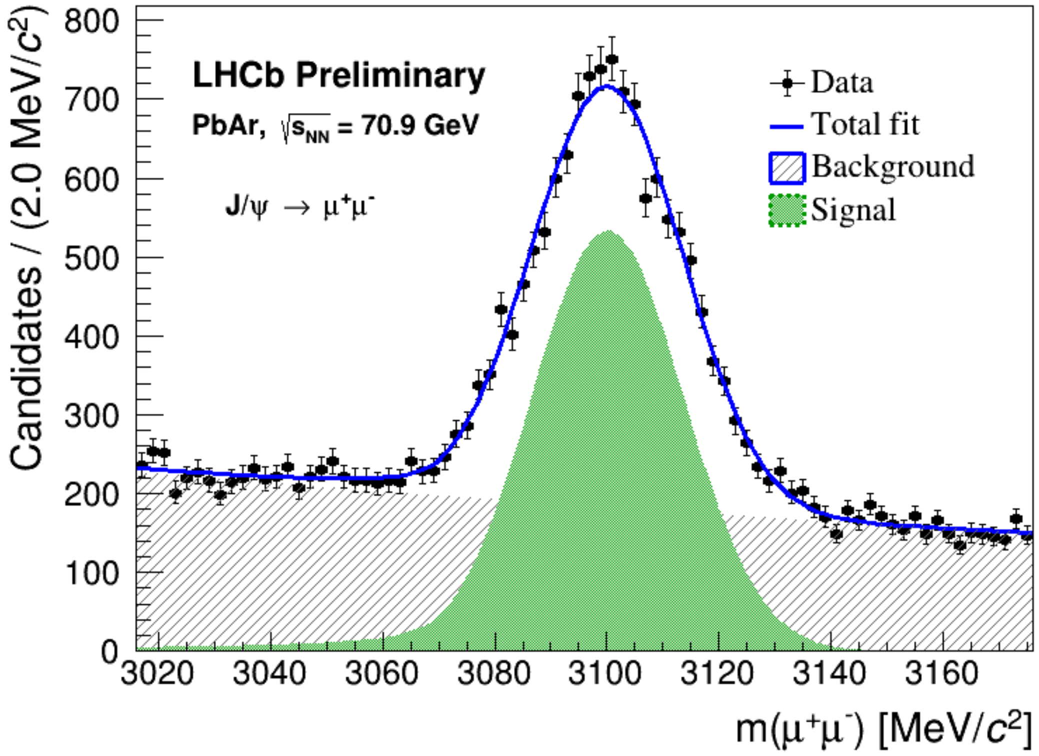
The largest charm sample in fixed-target configuration!



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



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



LHCb-FIGURE-2025-014

Conclusion

Unique fixed-target program at LHC!

- Access to an **unexplored kinematical region perfect to study charm and charmonia production**:
  - high Bjorken-x region → charm hadronisation
  - intermediate centre-of-mass energy → charmonia dissociation without recombination
- **Wide range of system size**:
  - characterise cold nuclear matter effects
  - investigate hot matter effects and QGP!
- SMOG (Run 2) → evidence of the **various physics opportunities**
  - $D^0 - \overline{D^0}$ **asymmetry**
  - J/ψ **suppression with respect to** D^0
- **SMOG2 in Run 3** provides greater statistics → **lots of exciting ongoing analyses!**

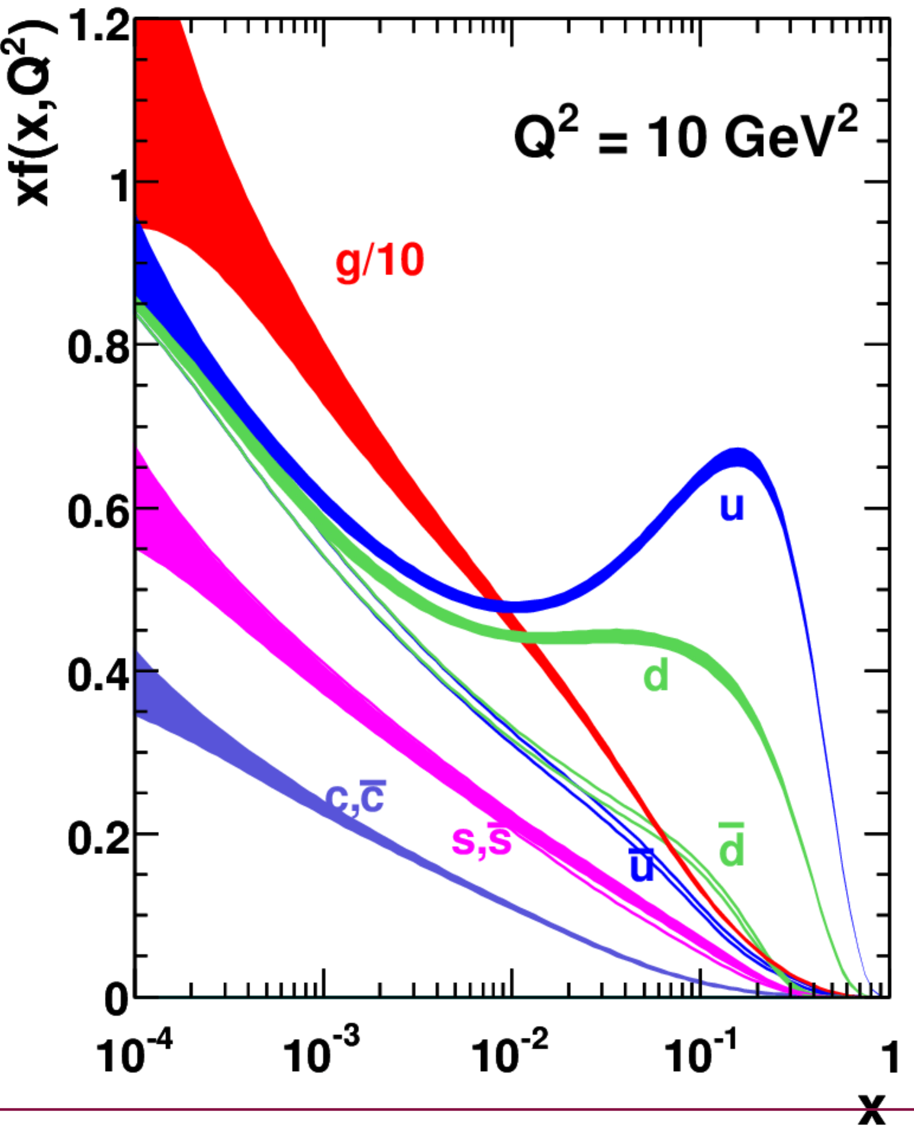
Stay tuned!

Thank you for your attention!

Back up

proton PDFs

Eur. Phys. J. C69, 379-397 (2010)



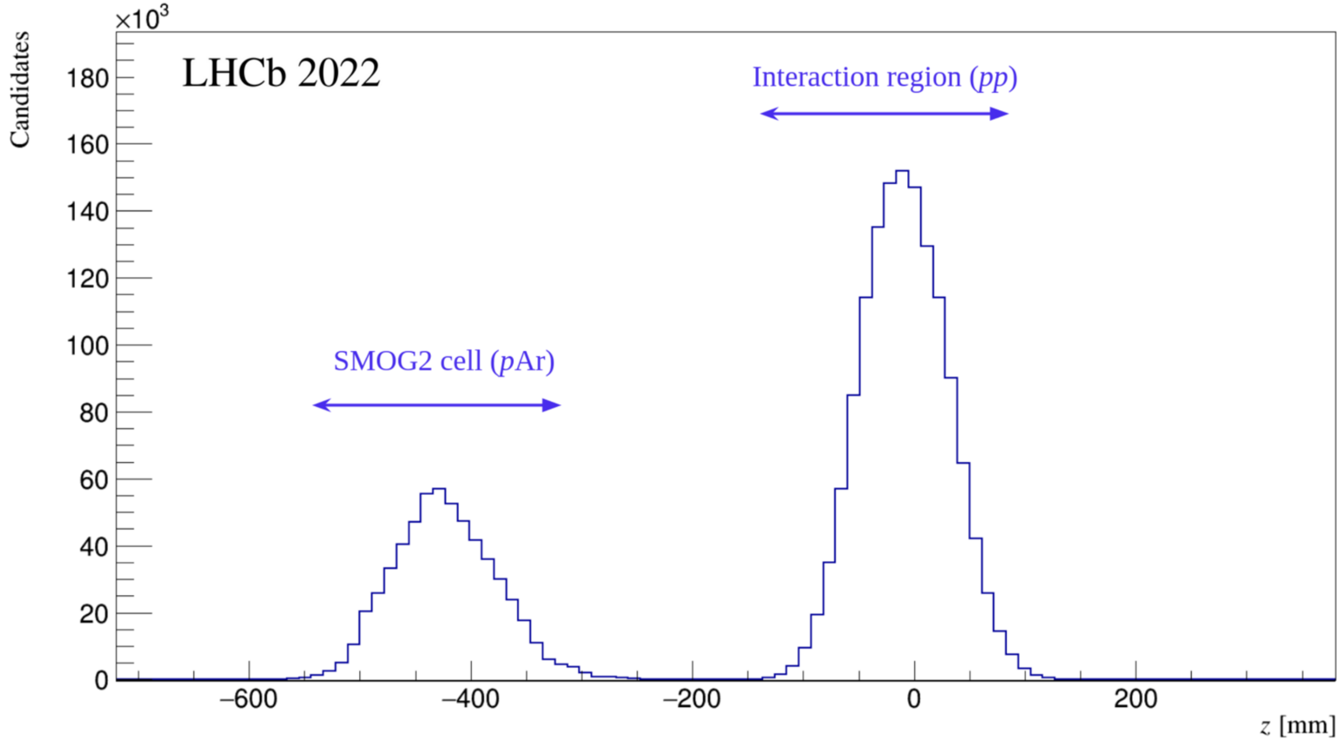
PVz in SMOG(2)

With SMOG (Run 2)

- No bunch crossing
- PV selection to eliminate residual pp collisions $z_{PV} \in [-200, -100] \cup [100, 150]$ mm ($z_{PV} \in [-200, 150]$ for PbNe)
- Veto on events with large number of hits in the backward region wrt the beam direction

With SMOG2 (Run 3)

https://arxiv.org/abs/2407.14200



Open charm asymmetry

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Systematic uncertainties	
Correlated between bins	
Signal determination	2.3%
Tracking efficiency	3.0%
Particle identification efficiency	3.6%
PV reconstruction efficiency	4.1%
Neon purity	1.2%
Luminosity	6.5%
Uncorrelated between bins	
Signal & background model	[0.3, 5.6]%
Simulation sample	[0.7, 8.0]%
Total correlated uncertainty	9.3%
Total uncorrelated uncertainty	[1.1, 9.2]%
Total statistical uncertainty	[2.3, 7.7]%

Uncertainties which do not cancel in the ratio

- Signal determination includes b-hadrons decays (1.1%) and residual pp contamination
- Detector induced asymmetry: 2.8%

Charmonium production in *p*Ne

Eur. Phys. J. C83 (2023) 7, 625

Systematic uncertainties (J/ψ)	
Uncorrelated between bins	
Simulation sample size	[1.4, 7.0]%; 2.3 %
Signal determination	[1.4, 11.0]%; 3.5 %
Correlated between bins	
Proton-proton collisions	2.0%
Neon purity	1.2%
Tracking efficiency	1.1%
Particle identification efficiency	1.1%
PV	3.9%
Luminosity	6.5%
Statistical uncertainty	1.6%

b contamination < 0.1% (negligible)

$$\frac{\sigma_{J/\psi}}{\sigma_{D^0}} = 1.06 \pm 0.02\,(stat) \pm 0.09\,(syst)\,\%$$

Uncertainties which do not cancel in the ratio:

- Efficiency differences
- Signal extraction
- Finite size of simulation sample

$$\frac{B(\psi(2S) \to \mu^+\mu^-)}{B(J/\psi \to \mu^+\mu^-)} \times \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}} = 1.67 \pm 0.27\,(stat) \pm 0.10\,(syst)\,\%$$

Uncertainties which do not cancel in the ratio:

- Total efficiency differences: 0.09%
- Signal extraction: 0.05%
- Finite size of simulation sample: 0.01%

Charmonium production in PbNe

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$$\frac{\sigma_{J/\psi}}{\sigma_{D^0}} = 0.51 \pm 0.04\,(stat) \pm 0.10\,(syst)\ \%$$

Systematic uncertainties	$J/\psi/D^0$
Correlated bin uncertainties	
Simulation weighting	16.0%
MC-truth matching efficiency	4.1%
PV efficiency	0.3%
Tracking efficiency	2.9%
Particle identification	1.2%
Overall $J/\psi/D^0$ determination	7.8%
Uncorrelated bin uncertainties	
Signal mass model	[1.1, 14.7]%
Simulation statistical error	[0.5, 1.8]%
Tracking calibration sample stat.	$< 0.1\%$
Particle identification calibration stat.	[6.5, 6.9]%
Overall systematic uncertainty	19.6%

Considered negligible:

- Residual PbPb collisions contamination: 0.23%
- b contamination < 0.1%

Charmonium production in PbNe

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	Hit multiplicity	$\langle N_{\text{coll}} \rangle$	RMS(N_{coll})
p**Ne**		1.81	1.10
PbNe	0 – 200	3.02	0.88
	200 – 300	5.13	1.81
	300 – 446	9.09	2.87
	446 – 715	17.04	4.67
	715 – 960	32.26	6.51
	960 – 1700	71.12	20.70

Glauber model

- $\sigma_{D^0}^{AB} = \sigma_{D^0}^{pp} \times AB$

  $\sigma_{J/\psi}^{AB} = \sigma_{J/\psi}^{pp} \times AB^{\alpha}$ (nuclear absorption $\alpha \leq 1$)

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

- $N_{coll} = c_1 \times AB^{\beta}$

  $$\Rightarrow \frac{\sigma_{J/\psi}^{AB}}{\sigma_{D^0}^{AB}} = \frac{\sigma_{J/\psi}^{pp}}{\sigma_{D^0}^{pp}} \times \left(\frac{N_{coll}}{c_1}\right)^{\frac{\alpha-1}{\beta}} = const \times N_{coll}^{\alpha'-1}$$

$$\alpha = 1 + \beta(\alpha' - 1)$$

Anomalous J/ψ suppression at SPS

Eur. Phys. J. C 39, 335–345 (2005)