Cold Nuclear Matter effects with LHCb fixed-target

Émilie Maurice

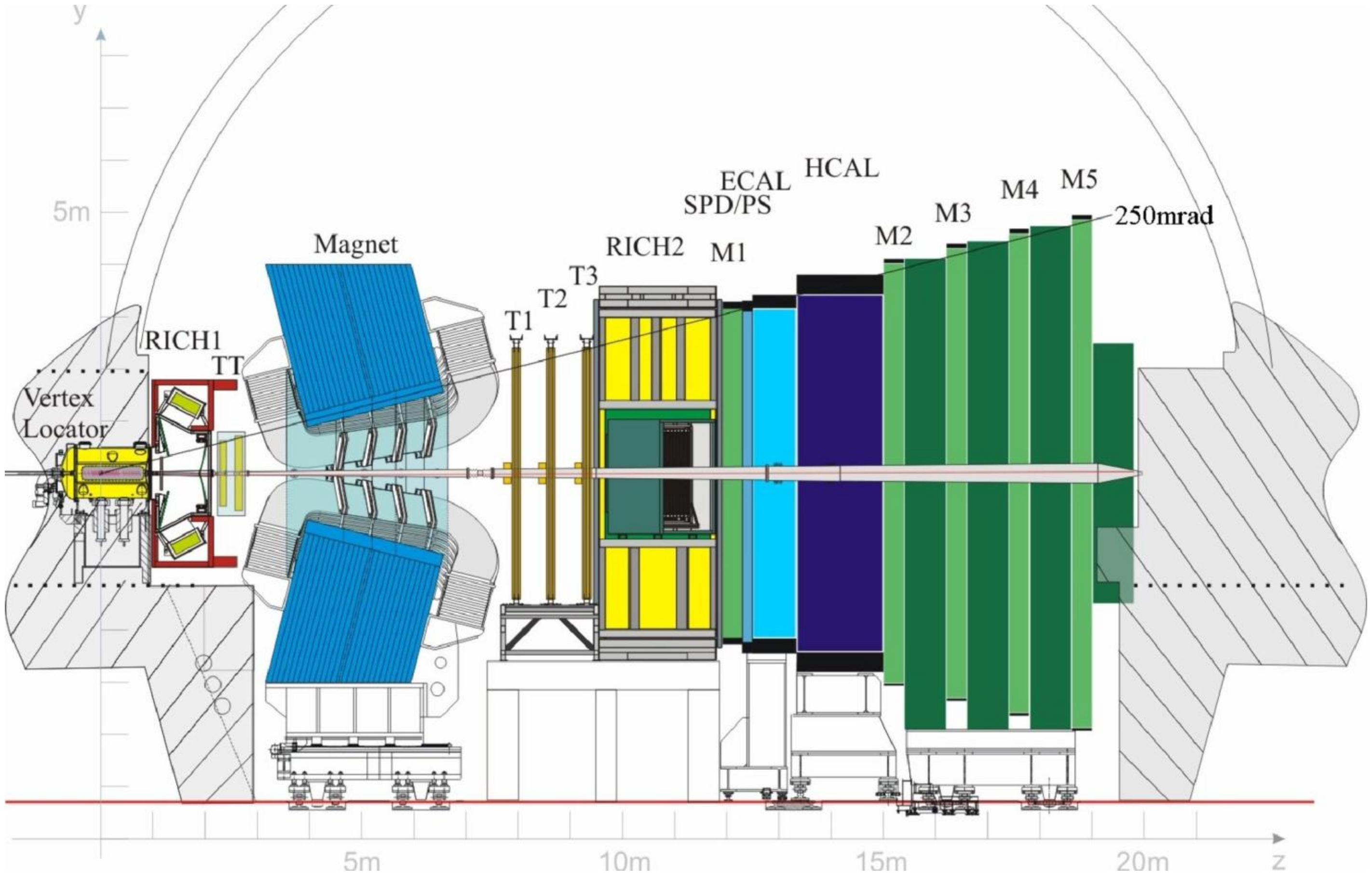
Cold Nuclear Matter Effects: from the LHC to the EIC, 13–16 janv. 2025

Overview

1. LHCb experiment and its fixed target
2. An opportunity for QCD studies ?
3. Charm results from LHC Run 2 (SMOG)
4. The fixed-target upgrade: SMOG2
5. Soft QCD studies with SMOG
6. Conclusions

The LHCb experiment [JINST 3 (2008) S08005]

LHCb was designed for heavy flavor physics but serves now as a general purpose detector



Fully instrumented in 2 < y < 5

Excellent performance :

[Int. J. Mod Phys. A30 (2015) 1530022]

- ✓ Vertex, IP and decay time resolution
- ✓ Momentum resolution
- ✓ Particle identification

$\epsilon_{K\rightarrow K} \approx 95\%$, $\epsilon_{\pi\rightarrow K} \approx 5\%$

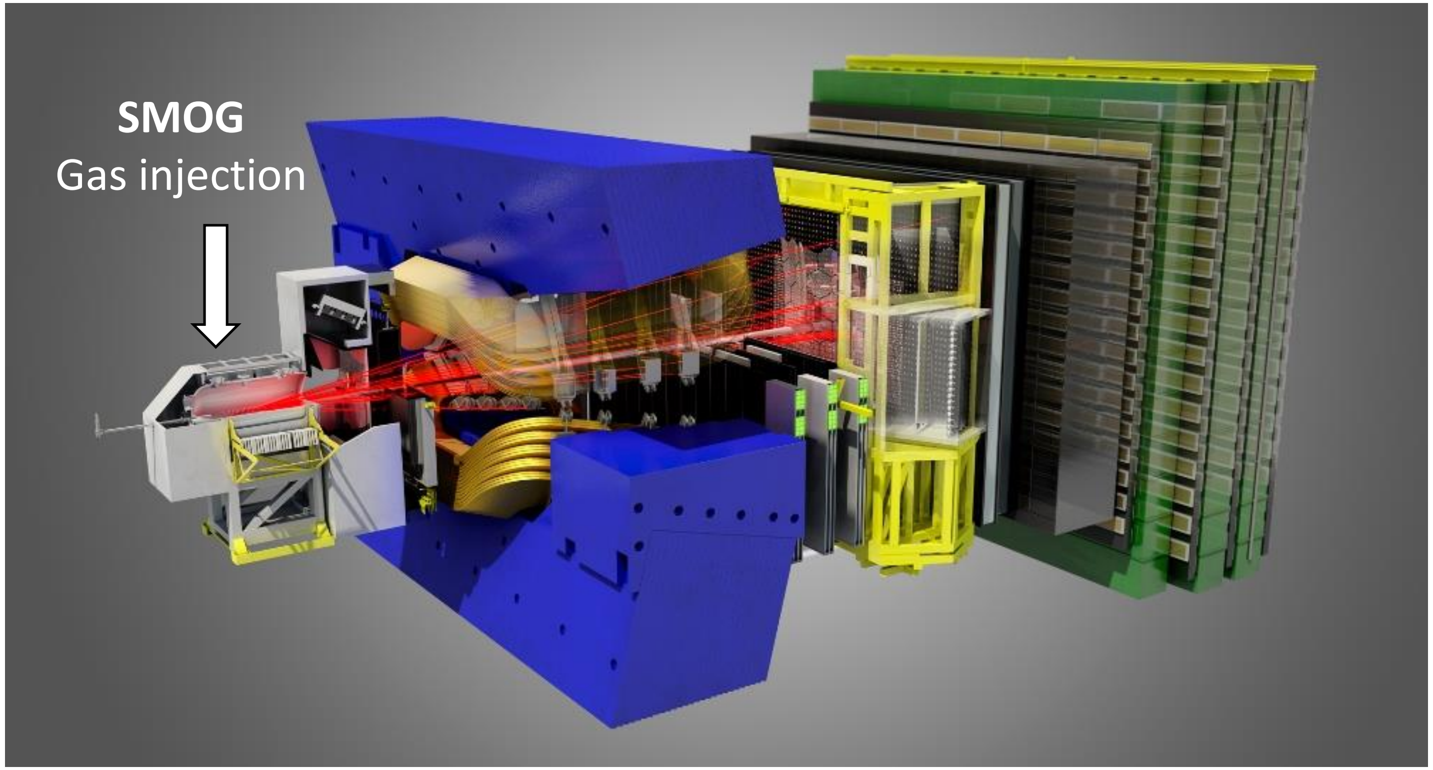
$\epsilon_{\mu\rightarrow\mu} \approx 97\%$, $\epsilon_{\pi\rightarrow\mu} \approx$ 1-3%

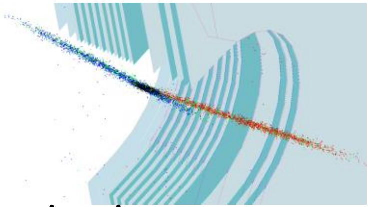
- ✓ **Flexible trigger down to low-p_T**

- ✓ **Unique fixed-target configuration**

[JINST 9 (2014) P12005]

System for Measuring the Overlap with Gas : SMOG





Why ?
Installed for beam-gas imaging
Improvement of LHC luminosity determination

How ?
Pumping configuration is adapted
Injected **noble gas** spread out +/- 20 m around LHCb
Pressure O(10^{-7}) mbar

Fixed-target physics

- Differents colliding systems thanks to the LHC beams: proton – nucleus and Pb – nucleus collisions
- Access to an unexplored energy range, $\sqrt{s} \approx \mathbf{100}$ **GeV**, and to a unique rapidity range y* $\in [-2.3, 0]$
- Forward spectrometer ➔ **LHCb is perfectly suited for studying QCD in fixed-target collisions**

Quantum Chromodynamics studies with LHCb fixed target ?

LHCb was designed to study b and c hadrons

→ Unique opportunity to study precisely heavy flavour production in proton-nucleus and nucleus-nucleus collisions

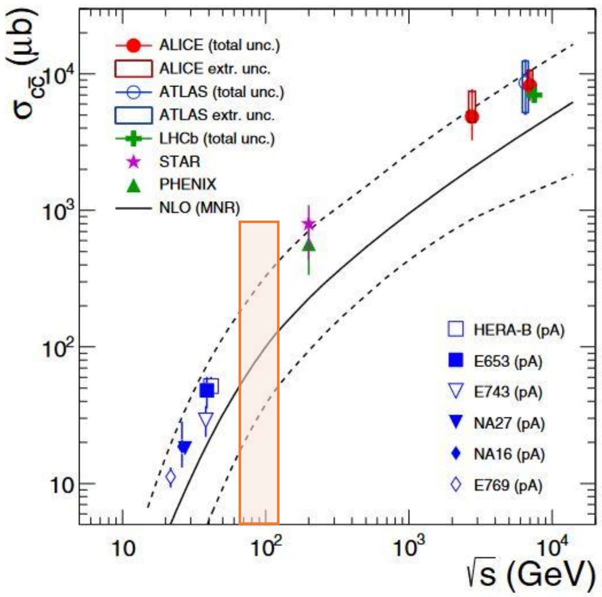
At $\sqrt{s_{NN}} \approx 100$ GeV, $\sigma(c\bar{c})$ ~ 1000 $\sigma(b\bar{b})$

✓ Prompt charmonia dominate

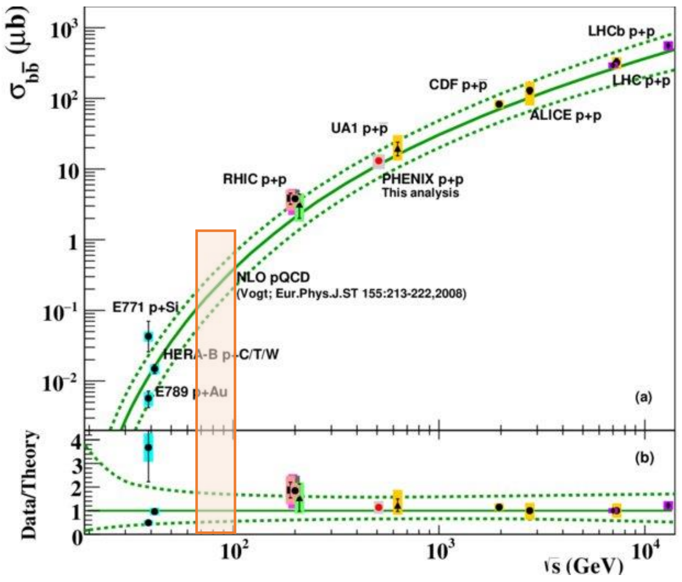
✓ Limited $b\bar{b}$ candidates in current samples

Extensive heavy flavour program !
→ Focus on charm production

Phys. Rev C94, 054908 (2016)



Phys. Rev. D 102, 092002 (2020)



But not only: with LHCb PID performances, **light flavour hadrons are also being investigated**:

Polarization of Λ^{+}, measurement of $\phi(1020)$ and many more to come !

Charm heavy flavour program with LHCb fixed-target

Charmonia ($c\bar{c}$ bound state) production is still an open question

Color Evaporation Model / Color Singlet Model / Color Octet Model / NRQCD ?

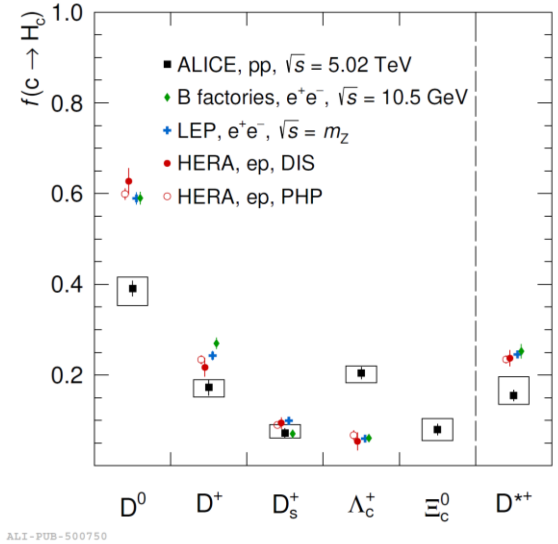
Open charm production (hadronisation) is also puzzling

Fragmentation functions are not universal

Coalescence : overlap of individual parton wave functions in position and velocity space

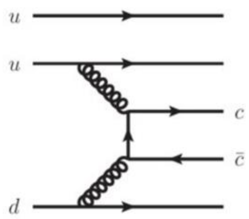
Parton density

Parton Björken-x

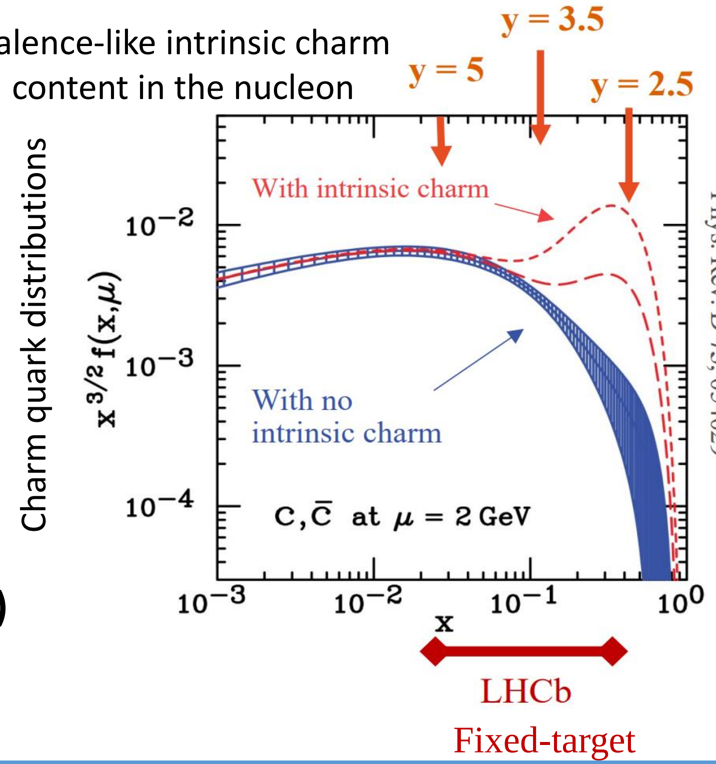


Phys. Rev. D 105, L011103 (2022)

Probe the intrinsic charm content in the nucleon



Valence-like intrinsic charm content in the nucleon



Phys. Rev. D 75, 054029

With LHCb fixed-target, unique opportunity to study extensively charm production

1. Study hadronization mechanims in 'simple' collisions (proton-hydrogen)
2. Characterize the cold nuclear matter effects with proton-nucleus collisions (from *p*D to *p*Xe)
3. Investigate the deconfinement with charm probes in lead-nucleus collisions

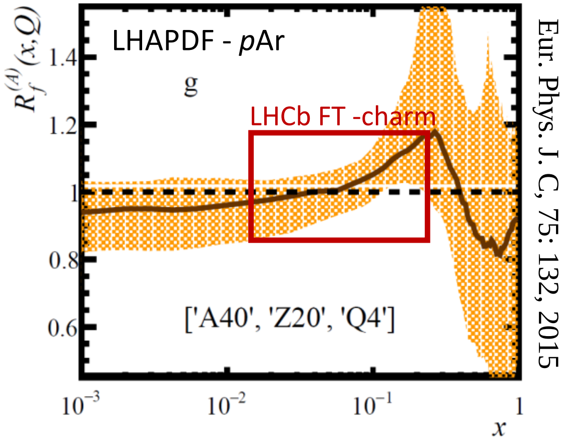
Impact of the cold nuclear environment on the charm production with LHCb-FT

Initial state effects

Final state effects

Modification of the nuclear parton distribution functions (nPDF)

→ Limited effect (< 20%)



Cronin effect

Energy loss

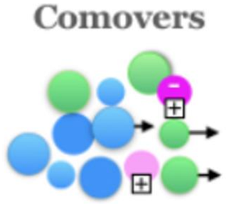
→ Limited effect in our current sample (<10%)

→ But may be relevant for inverse kinematics such as PbH

Comovers

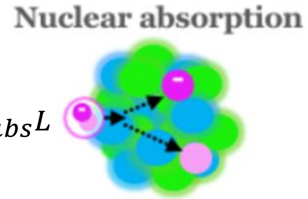
→ Limited effect (< 10%)

→ But relevant in PbH



Nuclear absorption

Surviving probability $S = \exp^{-\rho\sigma_{abs}L}$



Main cold nuclear matter effect !

Precise characterization of these cold nuclear matter effects is important to improve our understanding of the QCD medium and crucial to disentangle them from quark gluon plasma

Precise characterization of charmonia melting accessible with LHCb-FT

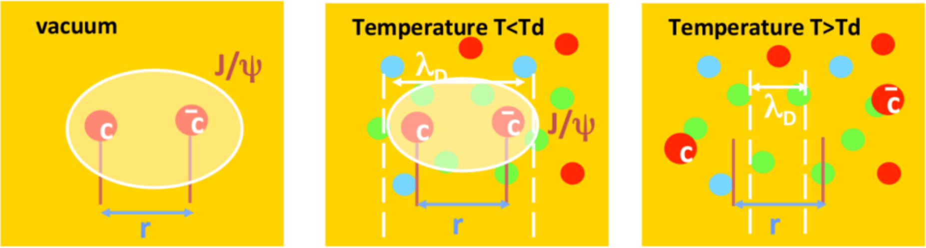
Charmonia, $c\bar{c}$, priviledged probe of phase transition

- 1986 : Matsui and Satz predicted **colour screening** prevents $c\bar{c}$ binding depending on the medium energy density and the $c\bar{c}$ states dissociation temperature Phys. Lett. B, 178: 416-422, 1986

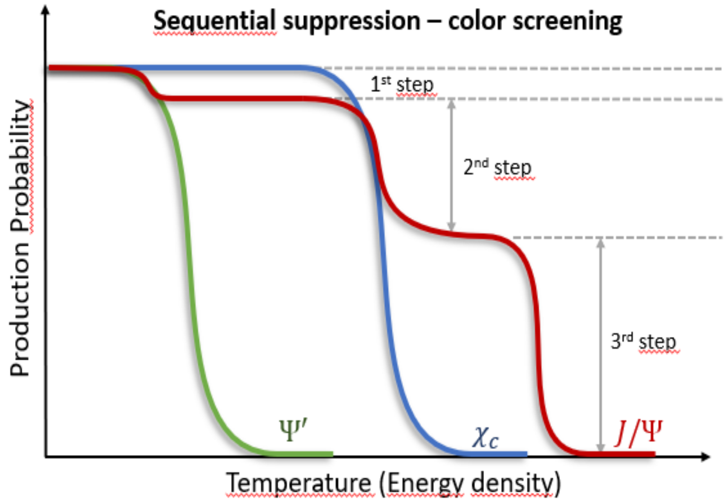
- J/ψ production : 10% from ψ' decays, 30% from χ_c decays

- J/ψ and ψ' suppression observed :
  - By NA38/NA50 experiments, 20GeV@SPS
    but limited energy density to observe a plateau for J/ψ and no capabilities to measure χ_c
  - By RHIC (200GeV) and LHC (5 TeV) experiments
    but the suppression is counterbalanced by the **statistical recombination:**
    → Nb of $c\bar{c}$ pairs increased with $\sqrt{s}$
    Difficult to properly interpret LHC measurements without disentangling the possible sequential suppression from the possible statistical recombination

    No χ_c measurement (except from LHCb in *pp* and *p*Pb collisions)



$r_{q\bar{q}} \sim 1/E_{binding} > \lambda_D \sim 1/T$



$E_{binding}$: $\psi' \sim 50$ MeV, $\chi_c \sim 200$ MeV, $J/\psi \sim 500$ MeV

A definitive observation of sequential melting would be achieved by measuring the sequential suppression mechanism fully corrected for cold nuclear matter effects

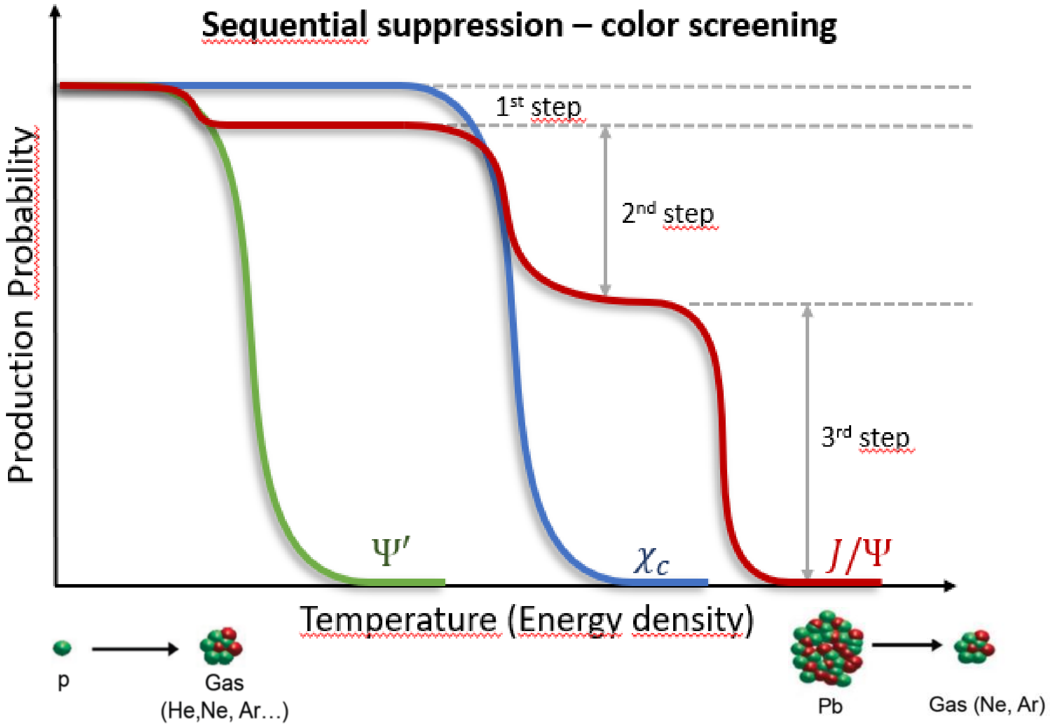
How to fully study the $c\bar{c}$ sequential suppression with LHCb-FT?

Collisions

- ✓ Energy density scan : from *p*H to PbXe collisions
- ✓ $\sqrt{s}$ ϵ [20 ; 200] GeV
  - Produce QGP (SPS fixed-target experiments)
  - Avoid $c\bar{c}$ recombination due to large amounts of $c\bar{c}$ pairs produced at high energies

Detector

- ✓ Dilepton final states reconstruction : $J/\psi \to \mu^+ \mu^-, \psi' \to \mu^+ \mu^-$
- ✓ Photon reconstruction : $\chi_c \to J/\psi\, \gamma$
- ✓ Reference (proxy of the total amount of $c\bar{c}$ pairs)
  Drell-Yan: very limited statistics… Open charm ?
  → D^0 relevant proxy



LHCb detector and its fixed-target fulfilled these requirements !

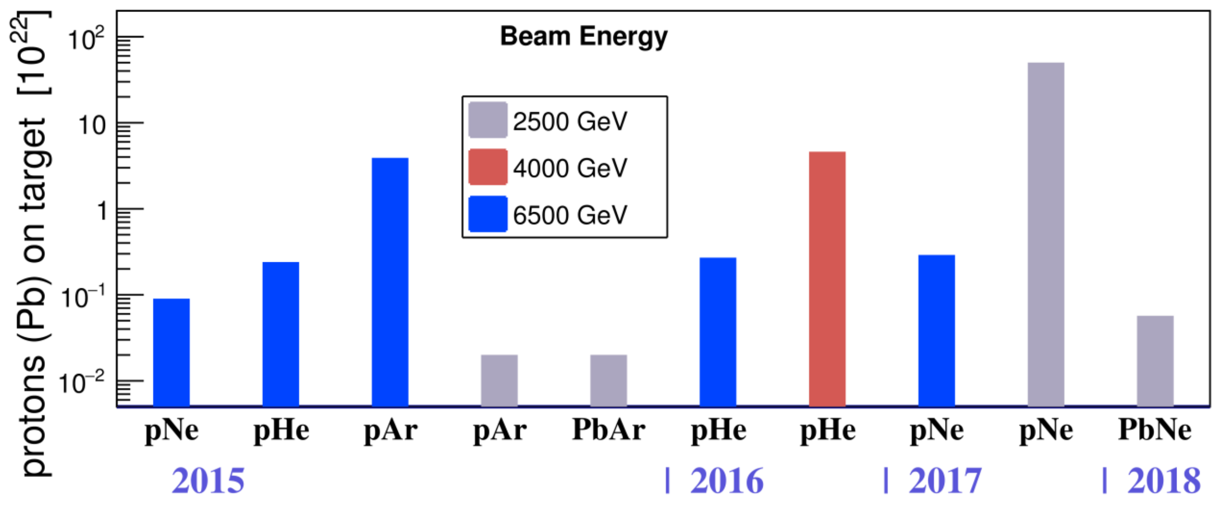
Collisions between protons and Pb beam and noble gases at $\sqrt{s} \approx 100$ GeV

2015-2018: SMOG data taking

From 2015, several pioneering SMOG samples:

- ✓ Inject different noble gases : He, Ne, Ar
- ✓ Exploit proton and Lead beams
- ✓ Different beam energies
- ✓ Statistically limited (only several hours of collisions)

Only 4 samples are relevant for $c\bar{c}$ studies

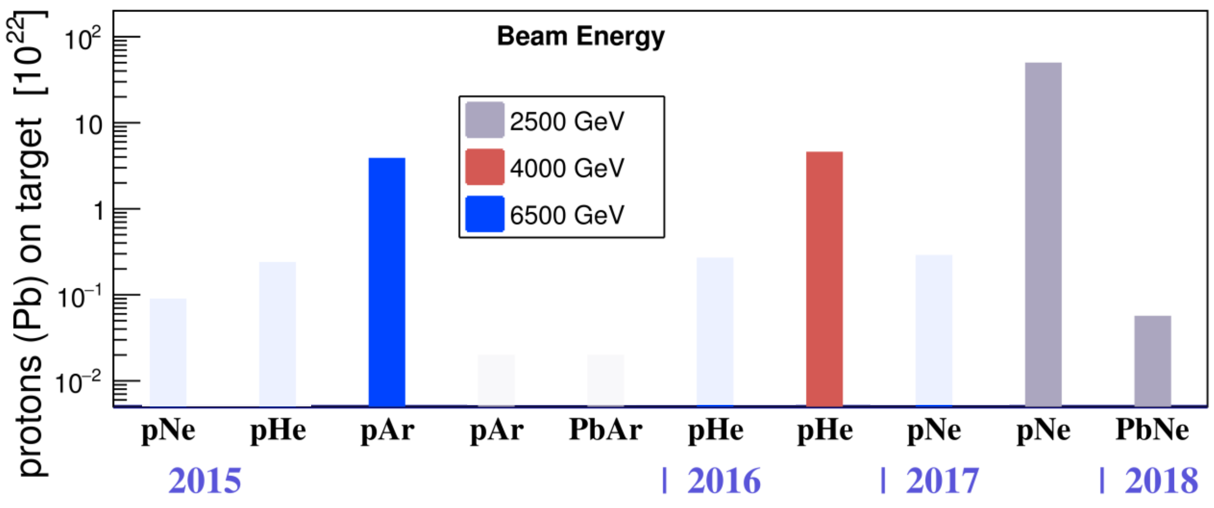


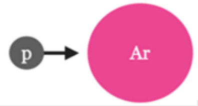
2015-2018: SMOG data taking

From 2015, several pioneering SMOG samples :

- ✓ Inject different noble gases : He, Ne, Ar
- ✓ Exploit proton and Lead beams
- ✓ Different beam energies
- ✓ Statistically limited (only several hours of collisions)

Only 4 samples are relevant for $c\bar{c}$ studies

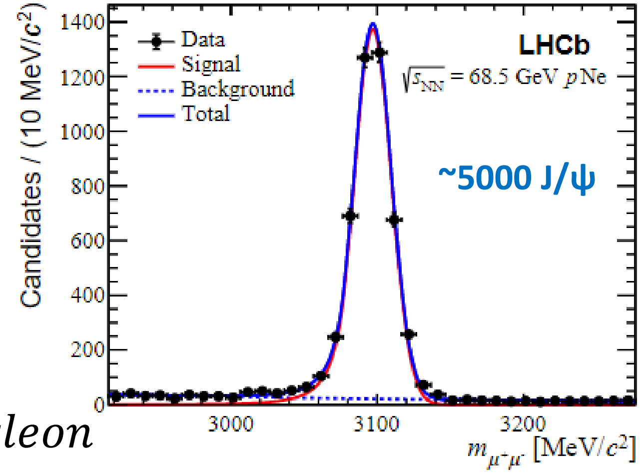


System	$\sqrt{s_{NN}}$	Measurement	Publication
	86.6 GeV	J/ψ and D^0 total and differential cross sections in y* and p_T	PRL 122 (2019) 132002
	110.4 GeV	J/ψ and D^0 differential distributions in y* and p_T	PRL 122 (2019) 132002
	68.5 GeV	• **J/ψ and ψ' cross sections and production ratio** • **D^0 cross section and asymmetry**	EPJC 83 (2023) 625 EPJC 83 (2023) 541
	68.5 GeV	**J/ψ and D^0 cross section ratio**	EPJC 83 (2023) 658

Eur. Phys. J. C83 (2023) 625

J/ψ production – Total cross-section in *p*Ne collisions

- The largest SMOG sample collected during 11 days: *p*Ne at √s = 68.5 GeV



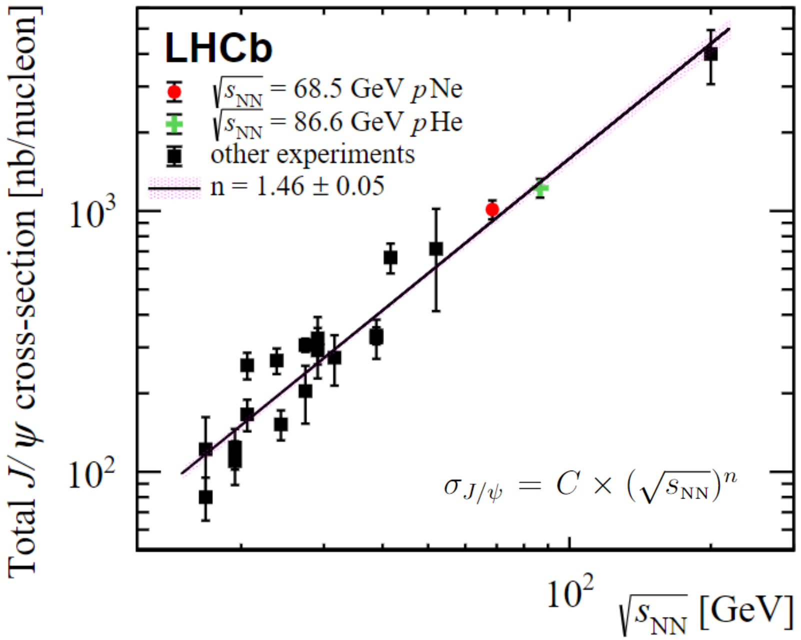
- Signal studied vs y* and p_T

- Total cross-section with y* in [-2.29, 0] : $\sigma_{J/\psi} = 506 \pm\ 8\ (stat.) + 46\ (syst)\ nb/nucleon$

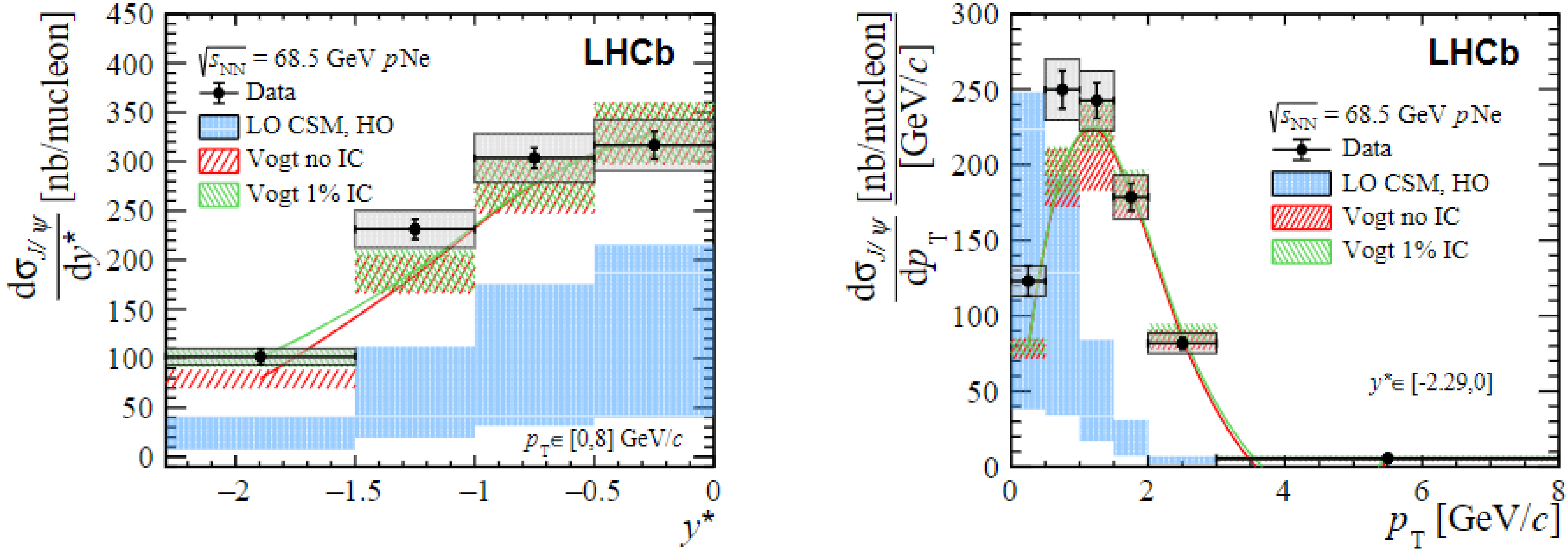
- Extrapolation to the whole phase space using PYTHIA8 and CT09MCS PDF set

$$\sigma(pNe \to J/\psi\ X) = 1013 \pm 16\ (stat.) + 83\ (syst)\ nb/nucleon$$

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



J/ψ production – Differential cross-section in *p*Ne collisions



- **LO CSM, HO**: LO Color Singlet Model (CSM) predictions made using the HELAC-Onia generator with CT14NLO and nCTEQ15 PDF sets [*CPC 198 (2016) 238, CPC 184 (2013) 2562*]
- **R. Vogt** predictions use the Color Evaporation Model, EPPS16 nPDFs, and include contributions from nuclear absorption and multiple scaterring [PRC 103 (2021) 035204]
- The data does not differentiate between predictions **with** or **without** an intrinsic charm component included

Eur. Phys. J. C83 (2023) 625

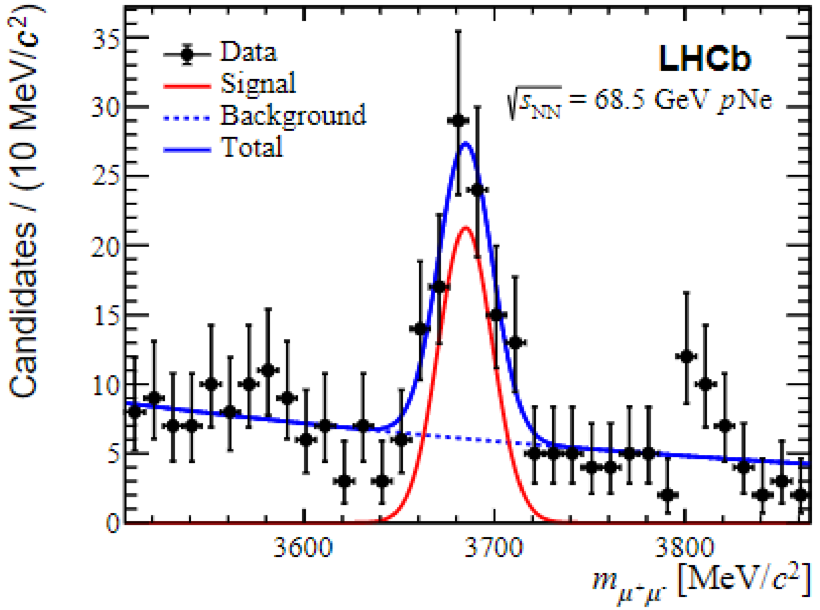
ψ' production and ratio with J/ψ in pNe collisions

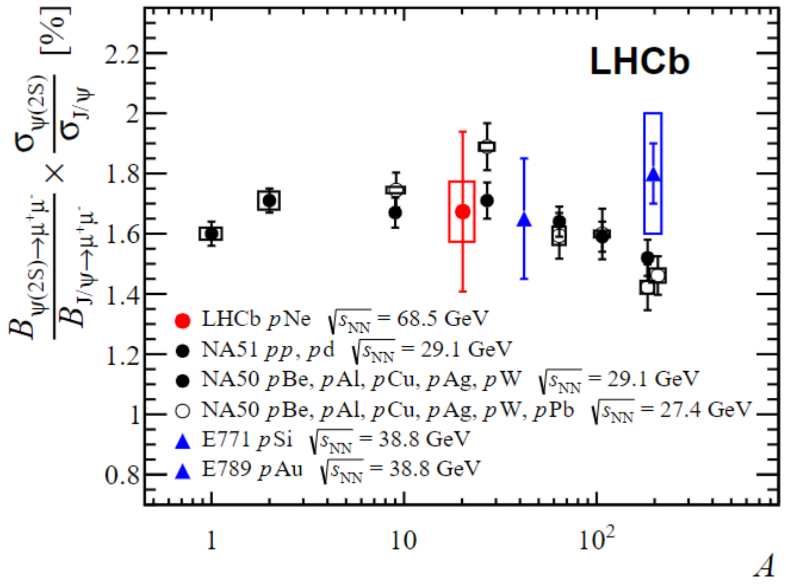
- The largest SMOG sample is still statistically limited !

  Only 76 ψ' candidates

➔ Measurement of the $\psi'/J/\psi$ cross-section ratio

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





The relative production rate of ψ' to J/ψ meson in pNe collisions is **consistent** with the rates measured on other nuclear targets and at other center of mass energies

Eur. Phys. J. C83 (2023) 541

D^0 cross-section measurement in *p*Ne collisions

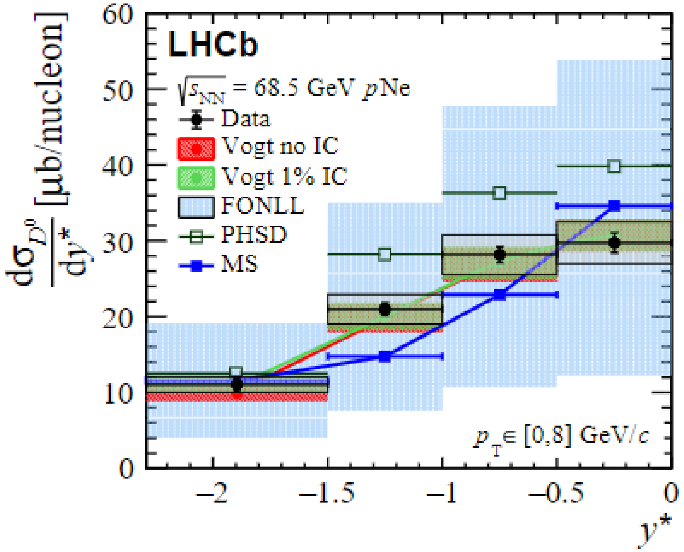
➔ Reference for charmonium production: J/ψ / D^0 measurement

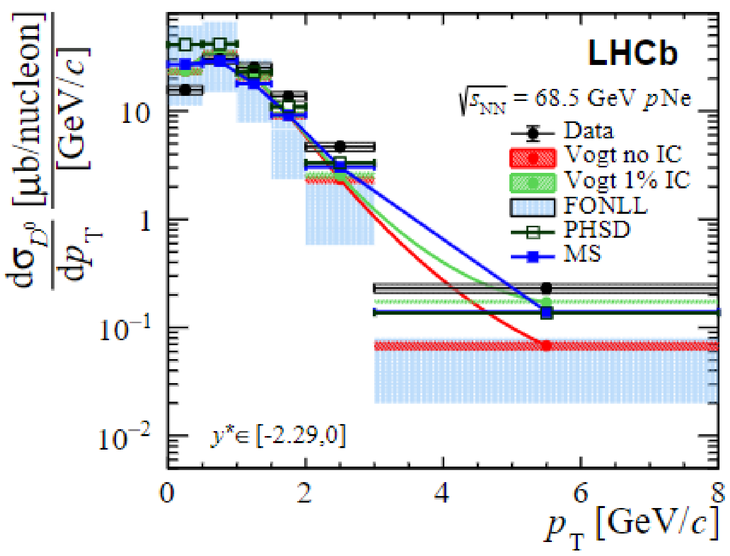
➔ **Cross-section relevant to investigate the nucleon content, specially regarding the intrinsic charm component**

- ~ 25k D^0 and $\overline{D}^0$ candidates
- Total cross-section for y* in [-2.29, 0]

$$\sigma_{D^0}^{y^\star\in[-2.29,0]} = \frac{Y_{D^0\to K^-\pi^+}}{\mathcal{B}_{D^0\to K^-\pi^+}\times\varepsilon_{D^0}\times\mathcal{L}_{p\mathrm{Ne}}} = 48.2\pm0.3\,(\mathrm{stat.})\pm4.5\,(\mathrm{syst.})\,\mu\mathrm{b/nucleon},$$

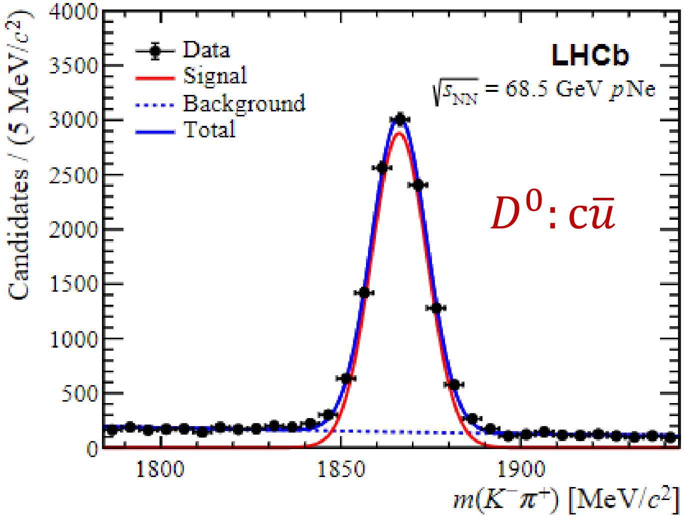
- y* and p_T dependency
- The data does not differentiate between predictions **with** or **without** an intrinsic charm component included

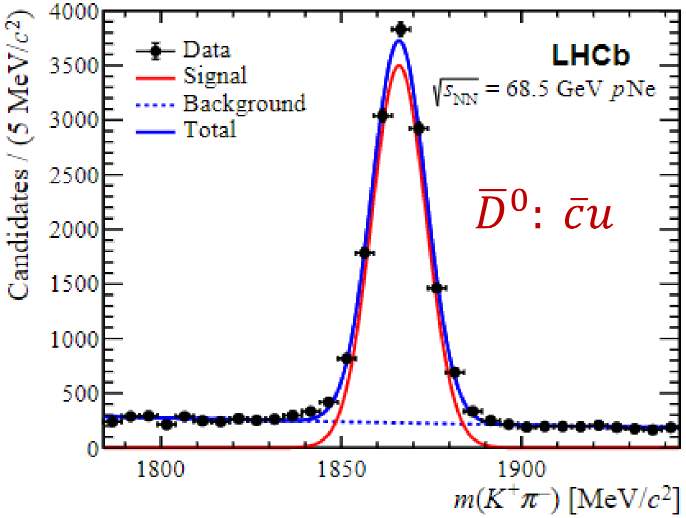




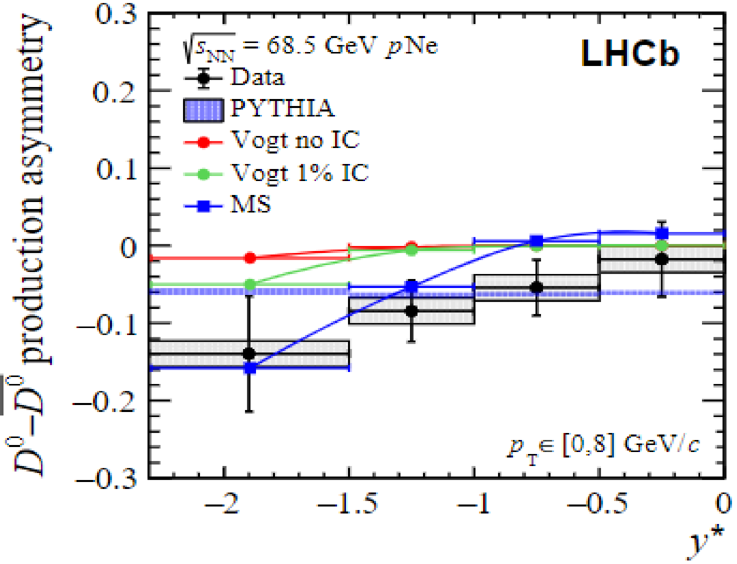
Eur. Phys. J. C83 (2023) 541

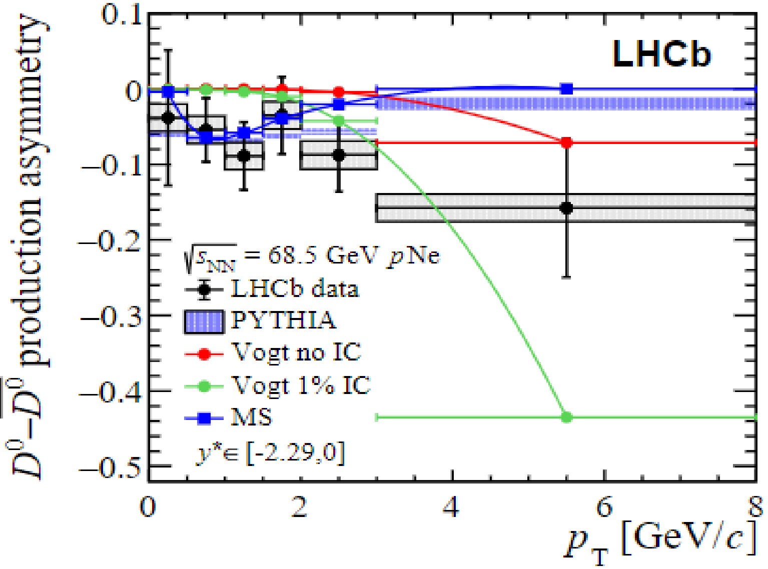
D^0 - $\overline{D^0}$ asymmetry measurement in *p*Ne collisions





→ Evident asymmetry



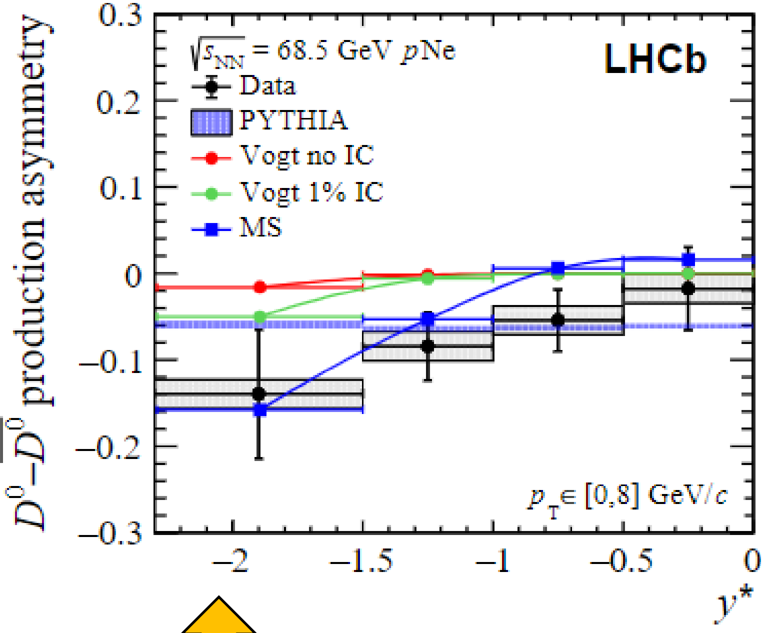


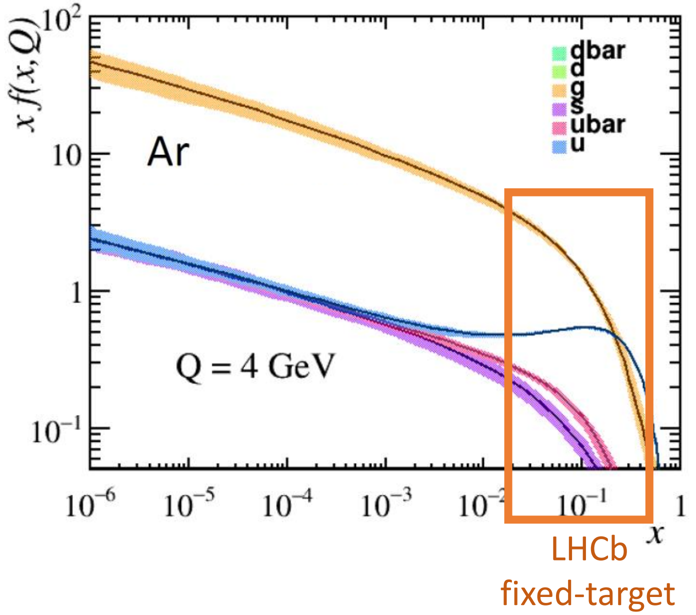
$$\mathcal{A}_{\rm prod} = \frac{Y_{\rm corr}(D^0) - Y_{\rm corr}(\overline{D}^0)}{Y_{\rm corr}(D^0) + Y_{\rm corr}(\overline{D}^0)},$$

Eur. Phys. J. C83 (2023) 541

D^0 - $\overline{D^0}$ asymmetry measurement in *p*Ne collisions

Probe the nucleus content : target valence region & IC content ?





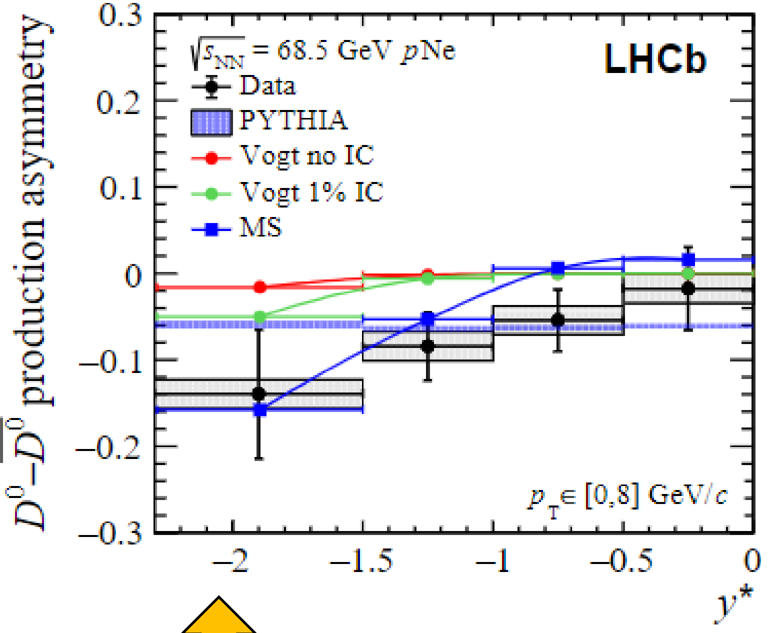
$x_{1,2} \sim \frac{M_T}{\sqrt{s}} e^{\pm y^*}$

Target valence region

Eur. Phys. J. C83 (2023) 541

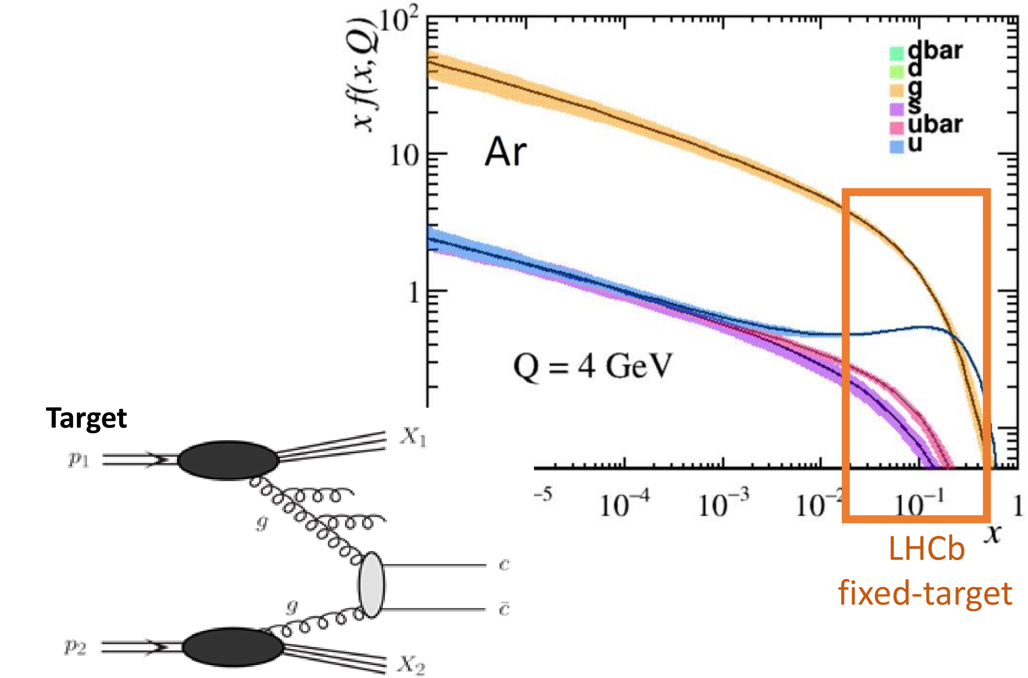
D^0 - $\overline{D^0}$ asymmetry measurement in *p*Ne collisions

Probe the nucleus content : target valence region & IC content ?

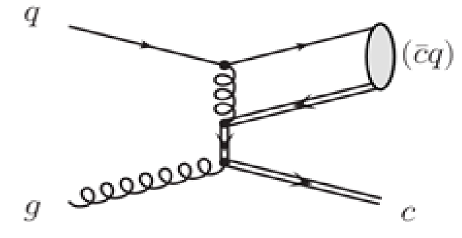


$x_{1,2} \sim \frac{M_T}{\sqrt{s}} e^{\pm y^*}$

Target valence region



Gluon fusion
→ No open charm asymmetry expected



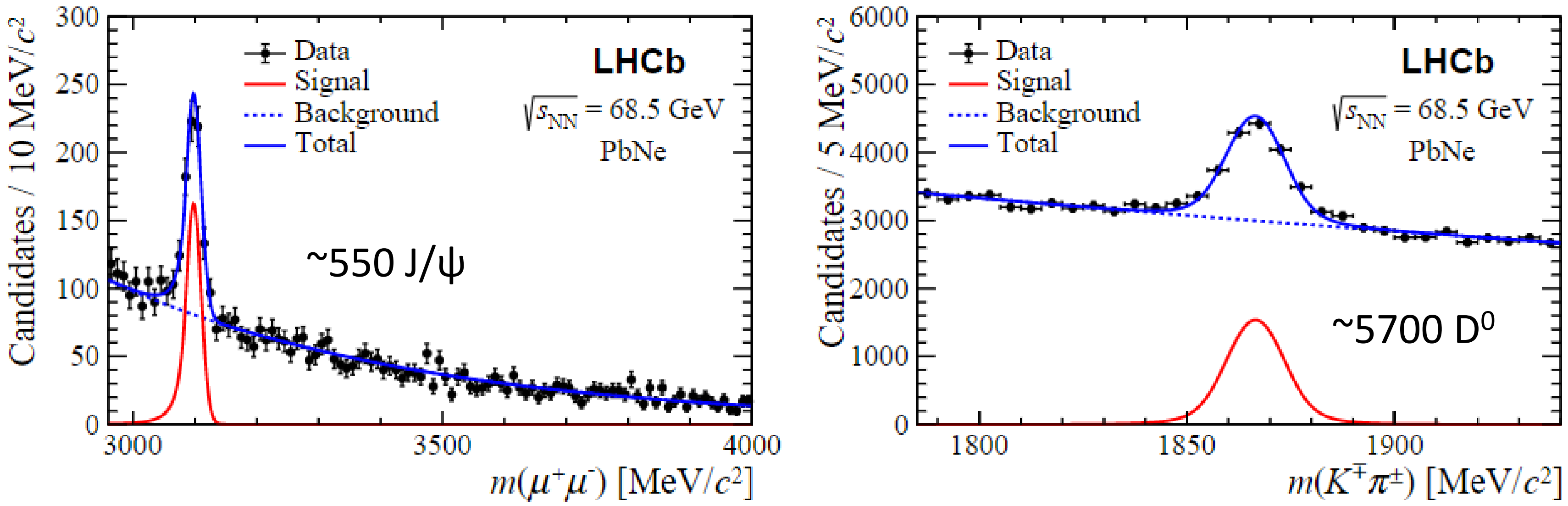
Coalescence
→ Open charm asymmetry expected

→ Tendency requiring complementary measurements (including other D hadrons measurements) with larger datasets

Eur. Phys. J. C83 (2023) 658

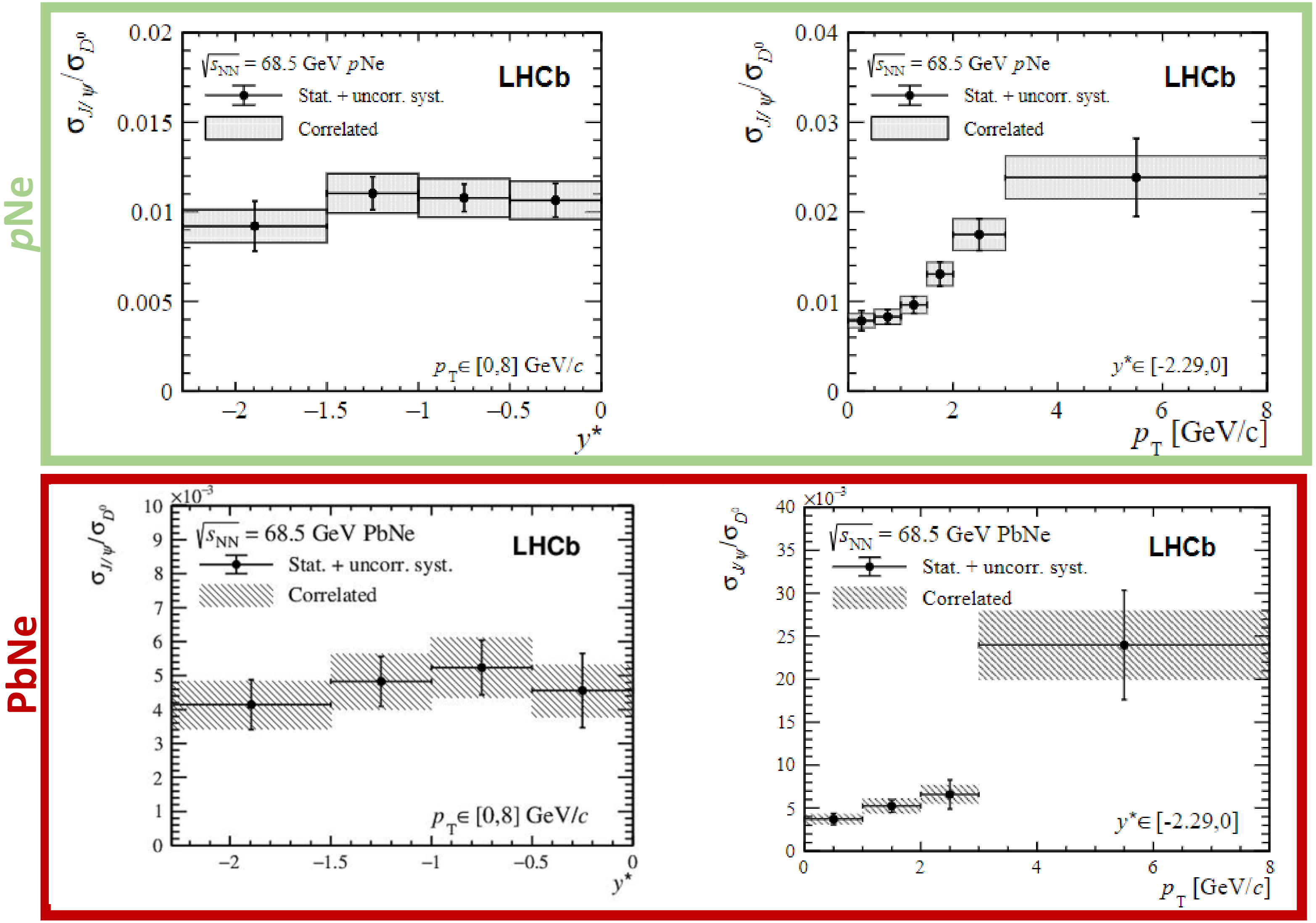
2018 PbNe analysis

- 1st statistically significant Pb-induced collisions with SMOG
- Beam configuration not optimal (small number of non-colliding bunches)
- $\sqrt{s}$ identical to pNe collisions
- J/ψ / D^0 cross-section measurement in PbNe to be compared with pNe



[Eur. Phys. J. C83 (2023) 658]

J/ψ / D^0 vs y* or p_T



***p*Ne vs PbNe :**

- No dependence on y* (within the incertainties)
- Strong dependence on p_T

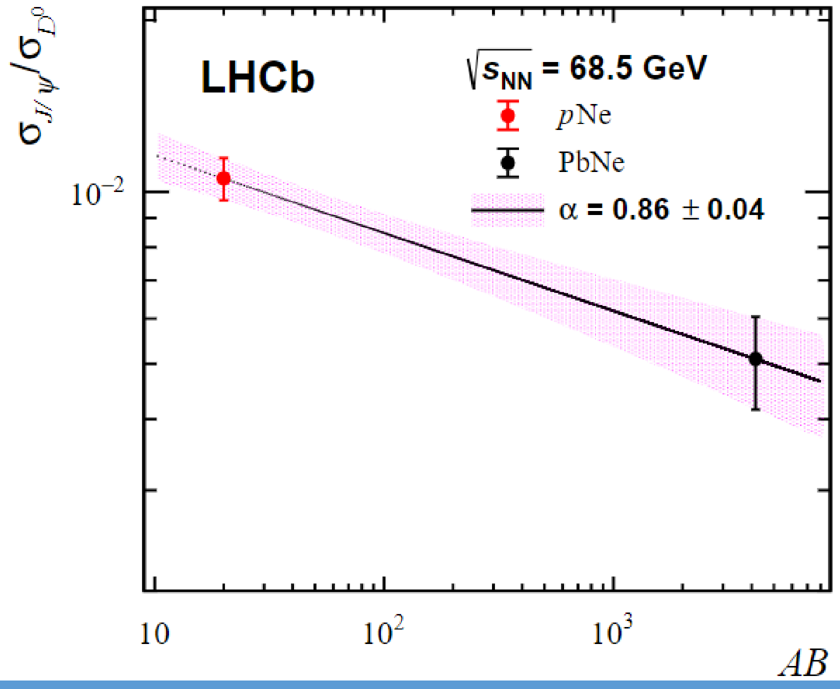
Eur. Phys. J. C83 (2023) 658

J/ψ / D^0 vs AB

J/ψ and D^0 hard probes production cross sections scale AB → $\boxed{\sigma_{AB}^{D^0} = (AB)\,\sigma_{pp}^{D^0}}$

When produced in a nucleus, J/ψ production is suppressed. The parameter α encompasses this suppression → $\boxed{\sigma_{AB}^{J/\psi} = (AB)^{\alpha}\sigma_{pp}^{J/\psi}}$

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



Fitting J/ψ / D^0 ratio as function of AB, we measure :

$$\boxed{\alpha = 0.86 \pm 0.04}$$

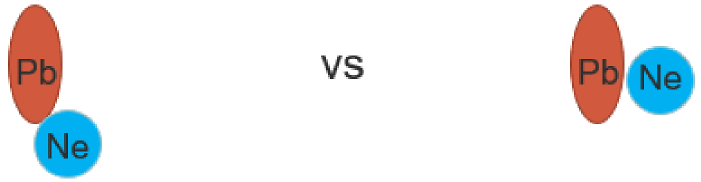
Compatible with previous experiments measurements in similar kinematic range

→ J/ψ suppression in PbNe is compatible with normal suppression

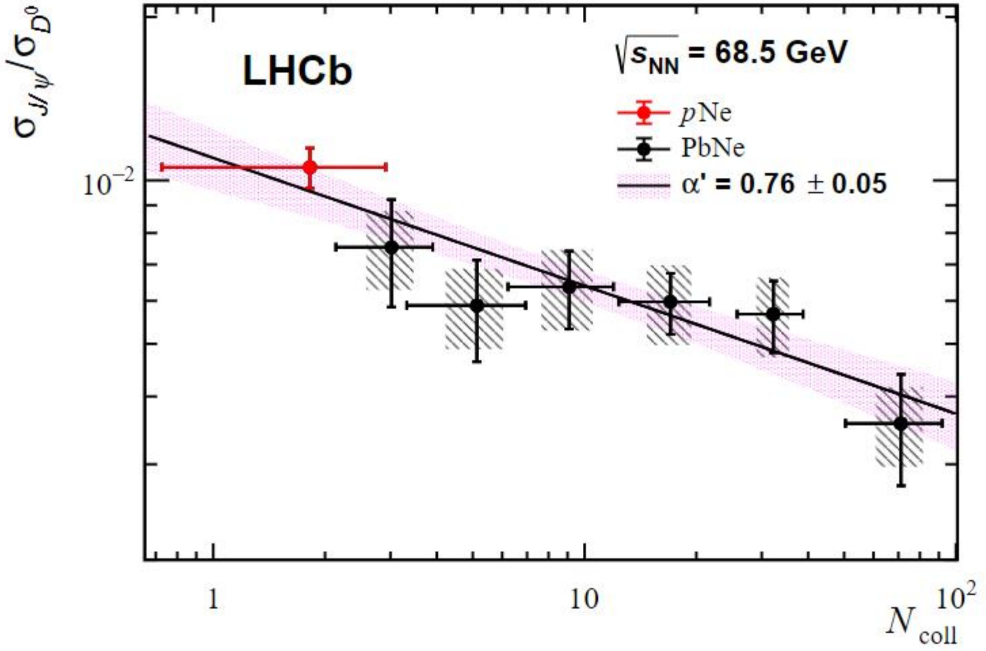
Eur. Phys. J. C83 (2023) 658

J/ψ / D^0 vs multiplicity

Translate multiplicity information into geometric quantities with the centrality tool, see *JINST* 17 (2022) P05009 (arXiv:2111.01607)



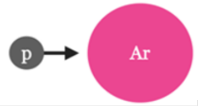
→ J/ψ / D^0 ratio as a function of binary nucleon-nucleon collisions



	Hit multiplicity	$\langle N_{coll} \rangle$	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

***J/ψ* suppression shows similar trend from *p*Ne to most central PbNe collisions**

Summary of the charm exploitation of 2015-2018 SMOG samples

System	$\sqrt{s_{NN}}$	Measurement	Publication
	86.6 GeV	J/ψ and D^0 total and differential cross sections in y* and p_T	PRL 122 (2019) 132002
	110.4 GeV	J/ψ and D^0 differential distributions sections in y* and p_T	PRL 122 (2019) 132002
	68.5 GeV	• **J/ψ and $\psi(2S)$ cross sections and production ratio** • **D^0 cross section and asymmetry**	EPJC 83 (2023) 625 EPJC 83 (2023) 541
	68.5 GeV	**J/ψ and D^0 cross section ratio**	EPJC 83 (2023) 658

SMOG configuration is well suited for charm production analysis, but main limitation: STATISTICS

- Gas pressure
  - → **Increase locally the gas pressure ?**
- Dedicated LHCb-SMOG campaigns: only few days per year
  Special LHC filling scheme : only protons in Beam 1 (entering into LHCb) and no proton in Beam 2
  - → **Distinguish the beam gas interaction point from proton-proton collisions ?**

LHCb upgrade

2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
Run 3				LS3			Run 4				LS4		Run 5			

LHCb Upgrade I
~ 5 visible *pp* interactions

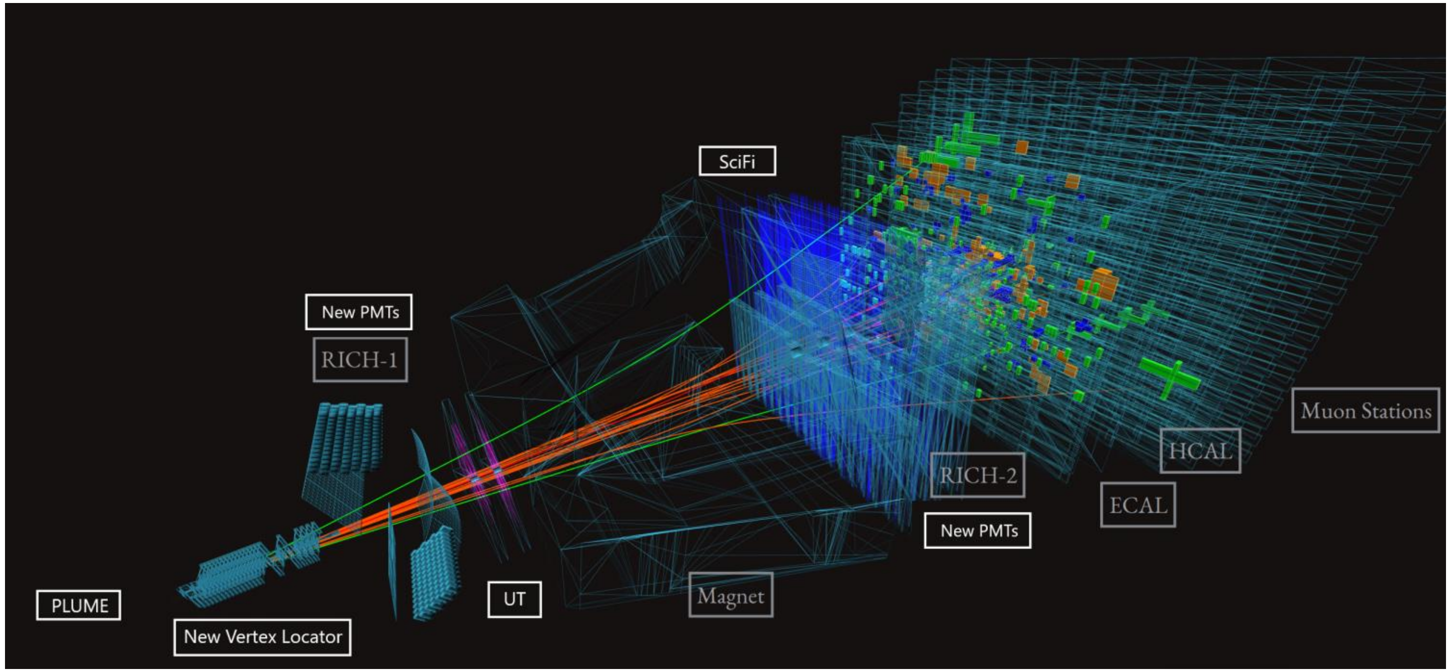
LHCb Upgrade II
~ 40 visible *pp* interactions

Major upgrade (FTDR)

LHCb Upgrade I
- ❑ New tracking detectors, vertex locator, RICH, PLUME
- ❑ Full software trigger
- ❑ Readout all detectors at 40 MHz

Fixed-target collisions :
➔ **Run 3: up to PbAr collisions**

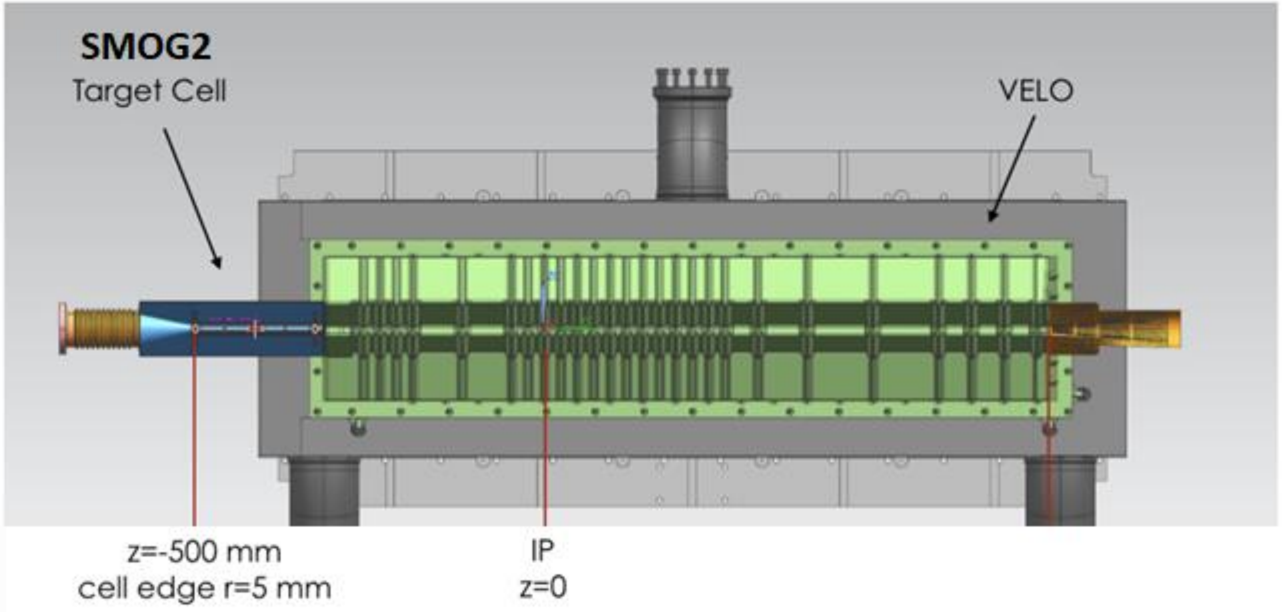
- ❑ **New fixed-target device : SMOG2**



SMOG2

Gas is injected into a storage cell : SMOG2

- ❑ [-500, -300] mm from the *pp* interaction point
  - → Interaction point different from *pp* collisions
  - → Exploitation of all LHC bunches crossing
  - → Simultaneous data-taking with pp



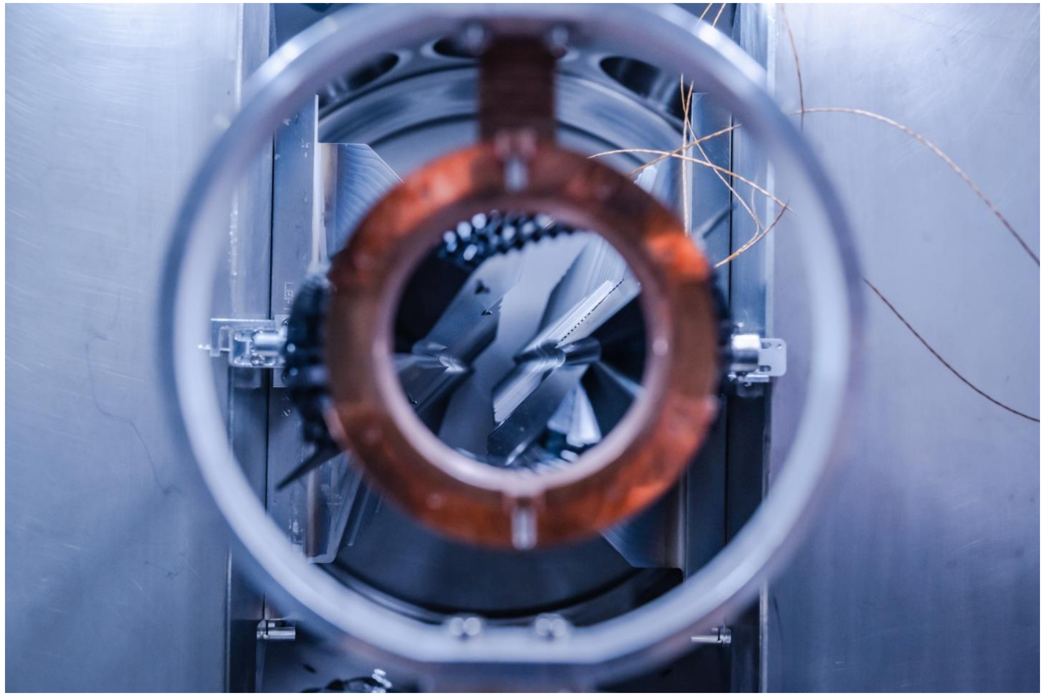
SMOG2

Gas is injected into a storage cell : SMOG2

- [-500, -300] mm from the *pp* interaction point
  → Interaction point different from *pp* collisions
  → Exploitation of all LHC bunches crossing
  → Simultaneous data-taking with pp

- Physical aperture of 5 mm
  → Local pressure will be drastically increased

- New LHC coating allows now the injection of non noble gases
  → *p*H collisions for reference

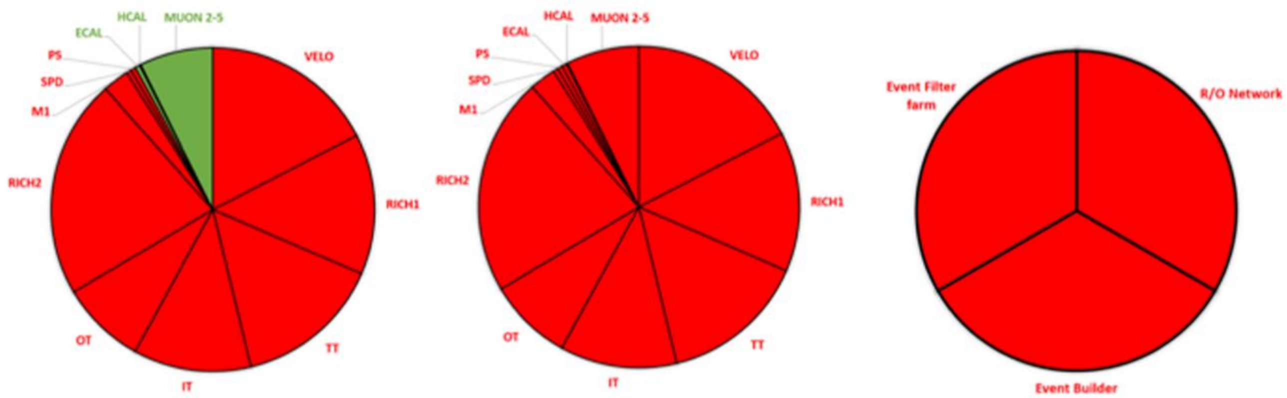


Significant improvement of the performances of the LHCb fixed-target system

→ Study charm and beauty production with unprecedent precision

2022 : a new detector

Detector R/O Electronics DAQ



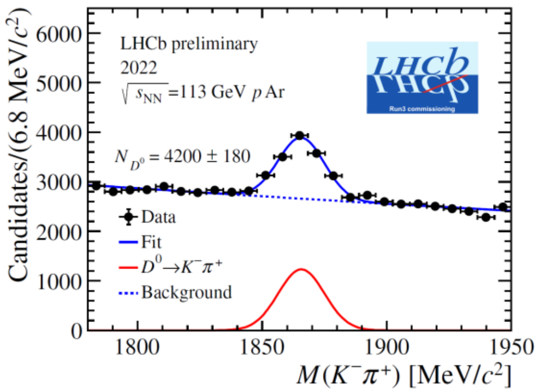
Upgraded
Kept

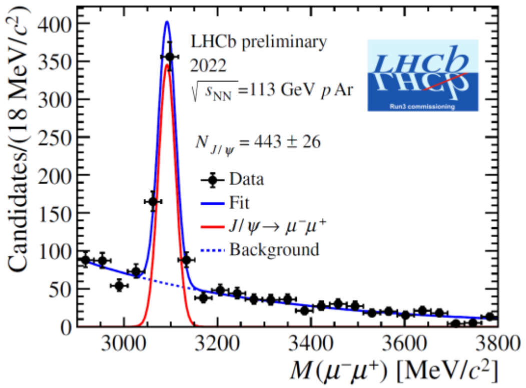
2022 : dedicated to the detector commissioning

Nov 2022 : tests of several short gas injections in SMOG2

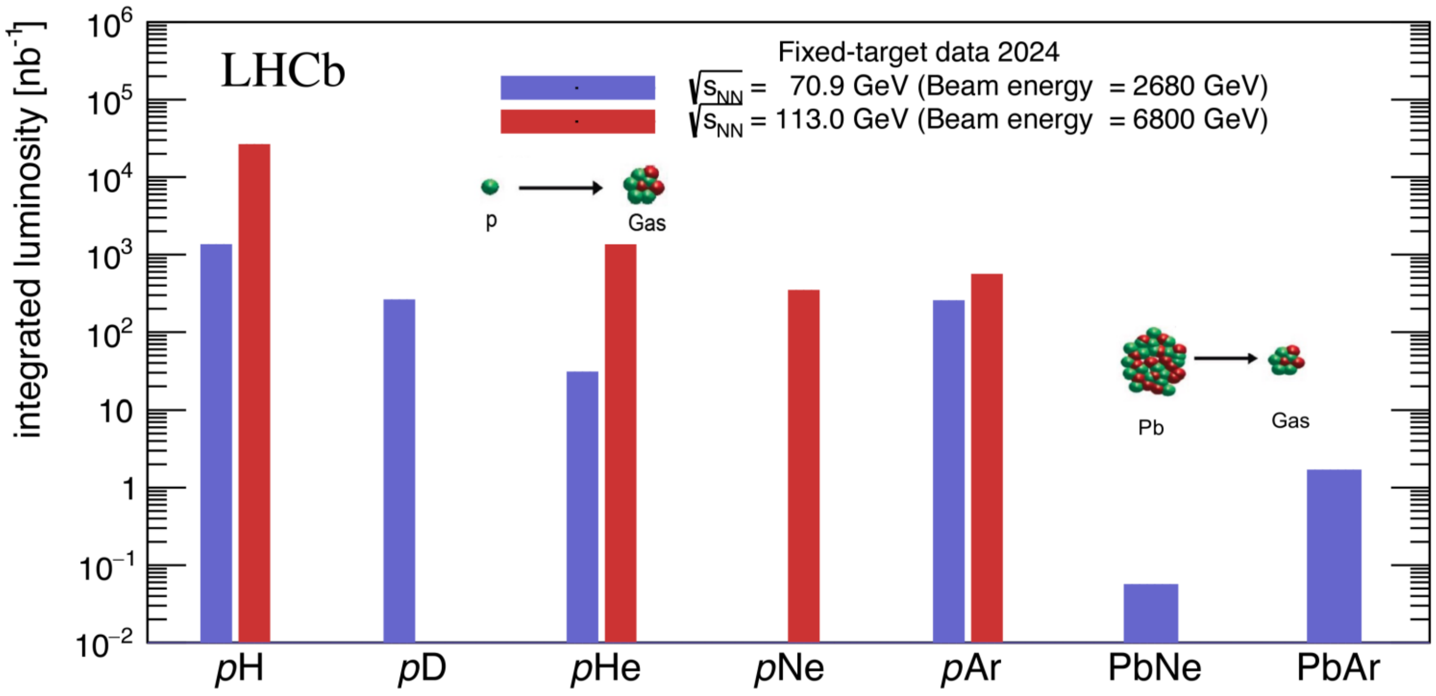
- Hydrogen → only 21 min
- Argon → only 18 min

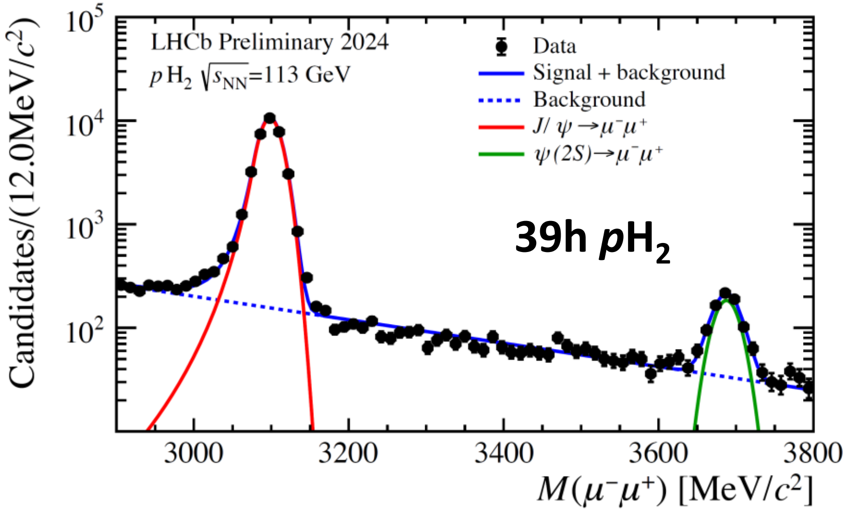
  18 min of SMOG2 *p*Ar equivalent to 18h of 2015 *p*Ar !

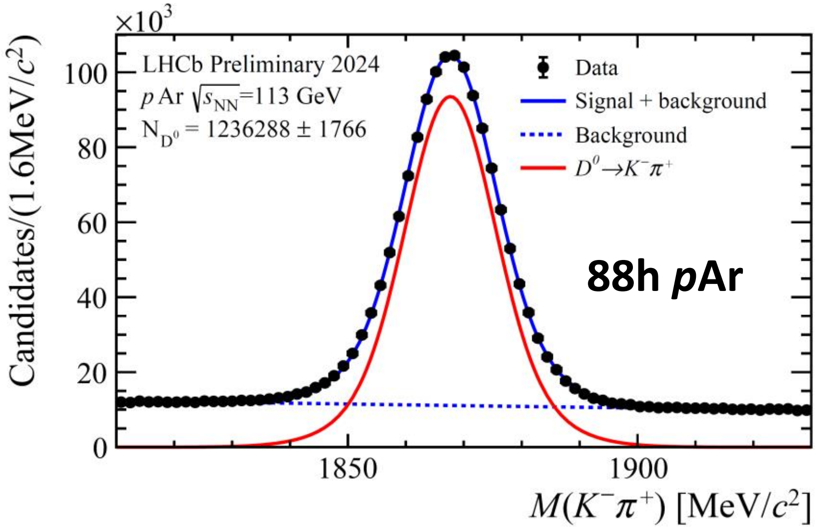




2024 : SMOG2 data taking





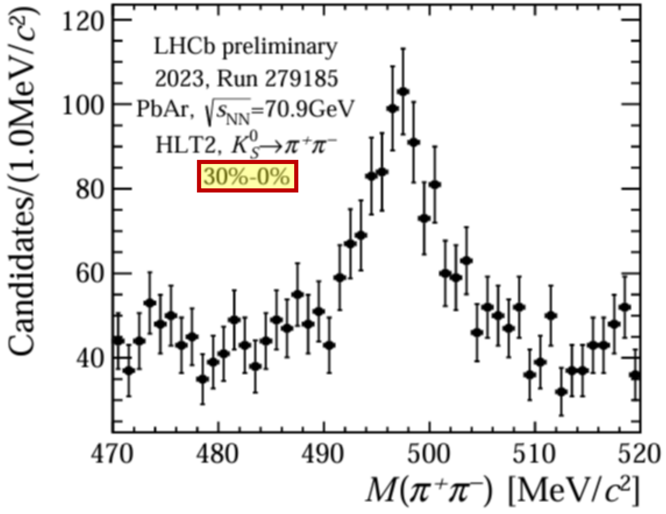


In addition to nominal *p*A collisions, successful pp_{ref} run

Charm production and upsilon analyses are ongoing !

Summary of SMOG2 lead induced collisions

LHCb-FIGURE-2023-030



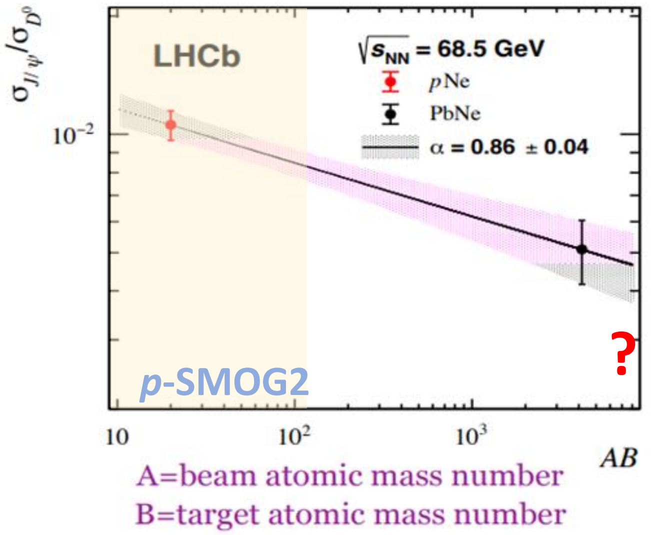
Even without optimal conditions (VELO opened, no UT), 2023 PbAr collisions

→ Access to the most central collisions of PbAr

PbAr collisions collected with nominal condition in 2024

		Centralité						
		Collisions périphériques						Collisions centrales
	Système	100 – 60%	60 – 50%	50 – 40%	40 – 30%	30 – 20%	20 – 10%	10 – 0%
NA50	PbPb, $\sqrt{s_{NN}} = 17$ GeV	124.2	331.6	605.9	919.6	1338.7	2035.8	2980.5
LHCb fixed-target	PbNe, $\sqrt{s_{NN}} = 71$ GeV	108.6	254.4	392.5	588.0	814.5	1086.0	1494.9
	PbAr, $\sqrt{s_{NN}} = 71$ GeV	123.6	308.8	496.5	806.6	1228.3	1711.9	2372.7
	PbKr, $\sqrt{s_{NN}} = 71$ GeV	196.9	533.6	919.1	1451.2	2205.5	2986.6	4084.3
	PbXe, $\sqrt{s_{NN}} = 71$ GeV	201.4	581.7	1031.0	1587.3	2400.2	3541.7	5065.7

From F. Fleuret

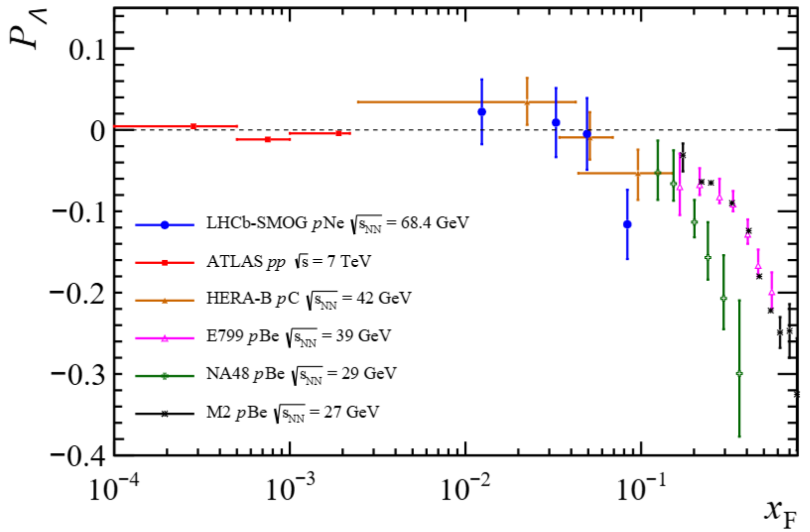


Stay tuned !

Fixed-target program : soft probes

Λ^0 polarization in *p*Ne collisions - JHEP 09 (2024) 082

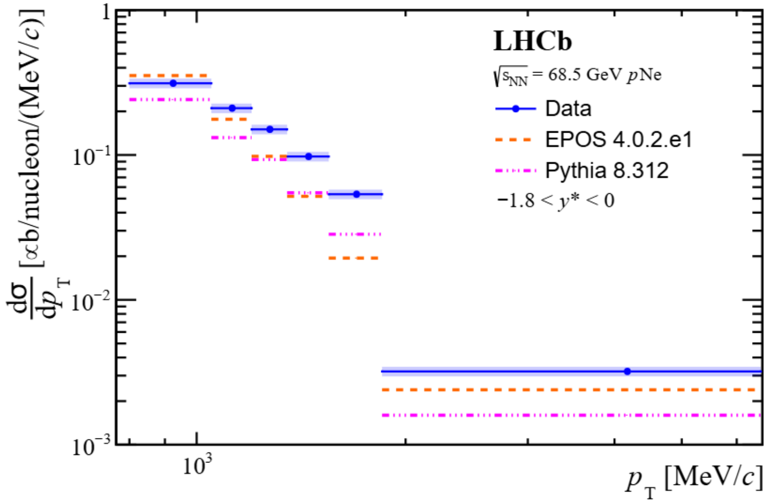
Unexpected discovery of Λ^0 polarization in 1976 in *p*Be collisions using 300 GeV unpolarized beam
Polarization value increases with increasing x_F and p_T (up to few GeV)
Roughly independent of the beam energy and the atomic mass number of the colliding nuclei
→ Polarization extracted from the angular coefficient of the angular distribution

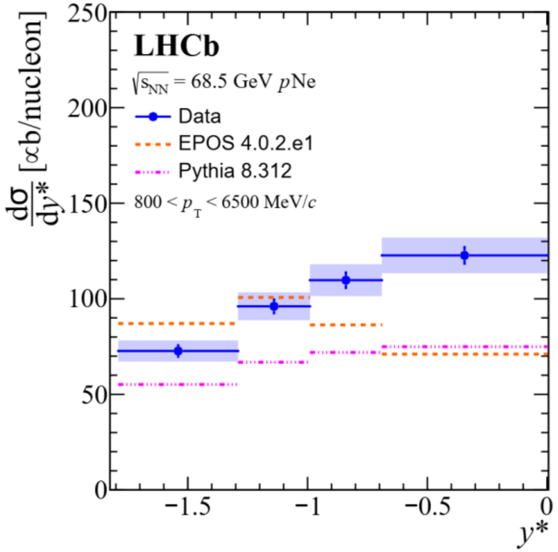


ϕ production in *p*Ne collisions - arXiv:2411.09343

Study strangeness enhancement study
Characterization of CNM effects in *p*Ne collisions

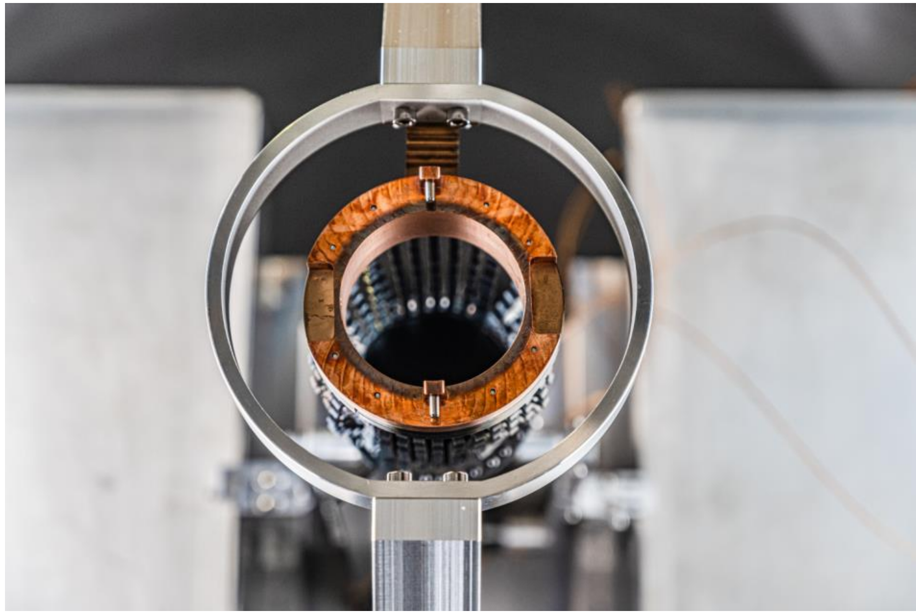
Theoretical predictions from the most common
MC generators slightly underestimate the result in regions





Also measurements of prompt $\bar{p}$ (PRL 121 (2018) 222001) and detached $\bar{p}$ (EPJC83, 543 (2023) 036 → astrophysics constraints

Conclusions



LHCb in its fixed-target mode provides a unique environment to study QCD in a variety of collision systems in an unexplored region of the phase-space

Recent measurements with Run 2 data provide unique inputs:

- $D^0 - \overline{D^0}$ production and asymmetry in *p*Ne collisions probes nuclear partonic structure and hadronization in an unexplored regime
- Charmonium production in *p*Ne and PbNe collisions tests the presence of nuclear effects and the presence of a hot nuclear medium
- Λ^0 polarization and strangeness (ϕ) production in a mostly unexplored region !

The new gas storage target SMOG2 is a huge step forward: high statistics, H_2 and D_2 injection

Many more new analyses to come !

From 2024 : we are entering into the QCD precision era with SMOG2