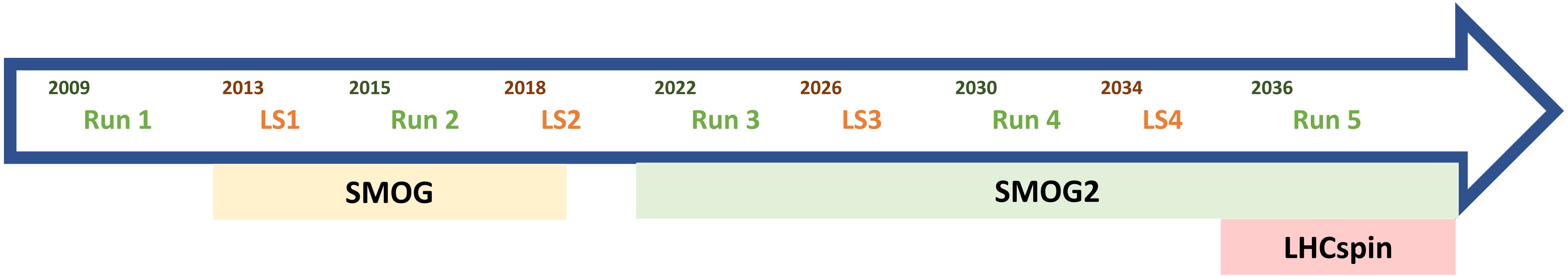
Fixed target programme within LHCb

Emilie Maurice, GdR QCD – Sep. 2025

Summary

The LHCb experiment has a unique System for Measuring Overlap with Gas (SMOG) since 2013, used as a fixed-target for physics since 2015



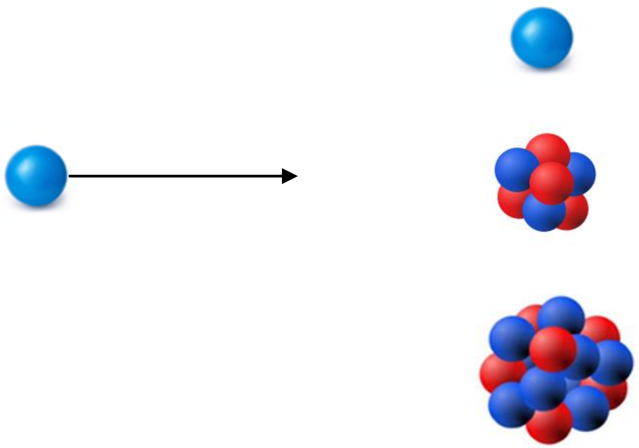
Why the LHCb fixed-target configuration matters at the LHC ?

1. Access to a mostly unexplored phase space
2. A broad QCD physics programme
3. An overview of SMOG and SMOG2 targets
4. LHCSpin : the LHC polarized target

Fixed-target mode

Exploit the LHC proton beam (450 GeV – 7 TeV)

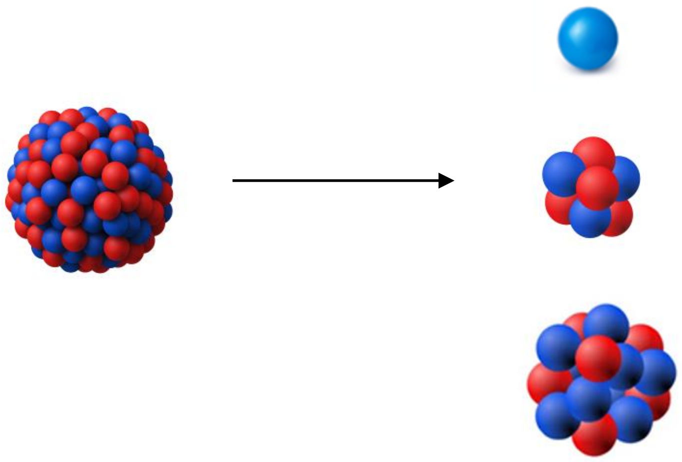
***p*H and *p*-Nucleus collisions**



$\sqrt{s_{NN}} = \sqrt{2m_N E_p} \simeq [68.5 \; - 115]$GeV

Exploit the LHC Pb beam (2.76 or 2.56 TeV)

Pb-Nucleus collisions



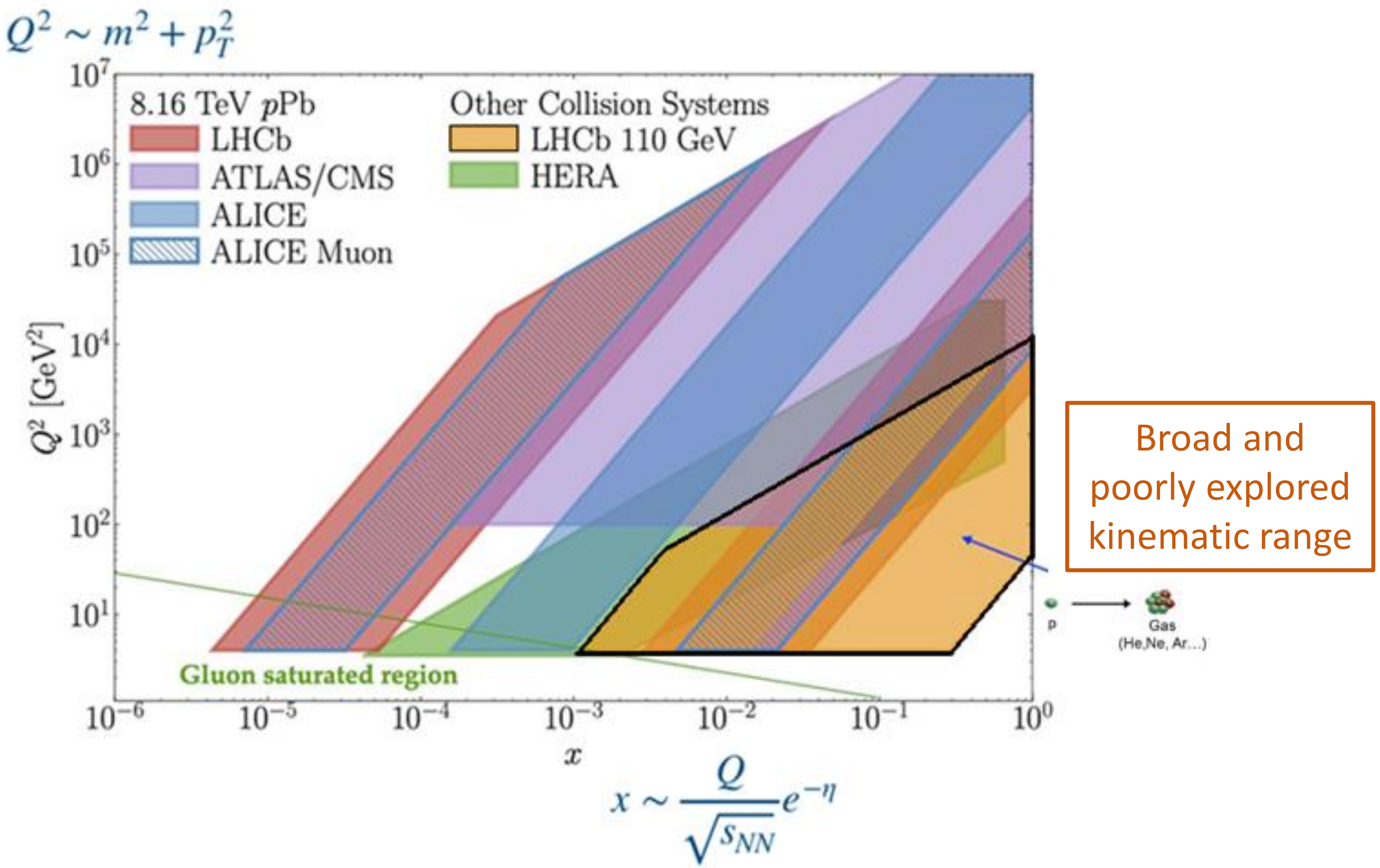
$\sqrt{s_{NN}} = [68.5 \; - \; 72]$ GeV

- The highest-energy fixed-target experiment
- Boost ($\gamma \sim 60$) → Rapidity shift leads to $y^* \in [-2.5, 0]$, so large x_{target} and small x_{beam}

→ Access to a unique region of the phase space (medium and large x_B of the target), mostly unexplored !

Probing QCD across scales: from proton to cold nuclear matter and QGP

Unique access to medium and high x in *p*-Nucleus, Pb-Nucleus collisions



Study proton's internal structure by exploring how quarks and gluons are distributed in momentum, position, and spin

→ Constrain PDF, TMDs, GPDs

→ Probe the intrinsic charm content in the proton

→ Measure polarization

Study how quarks and gluons are modified inside nuclei, revealing **cold nuclear matter effects**

→ Constrain nPDFs

→ Probe cold nuclear matter effects in high-x region

How do quarks and gluons combine to **form confined hadronic states**?

→ Test hadronization mechanisms in nuclear matter, versus x_B

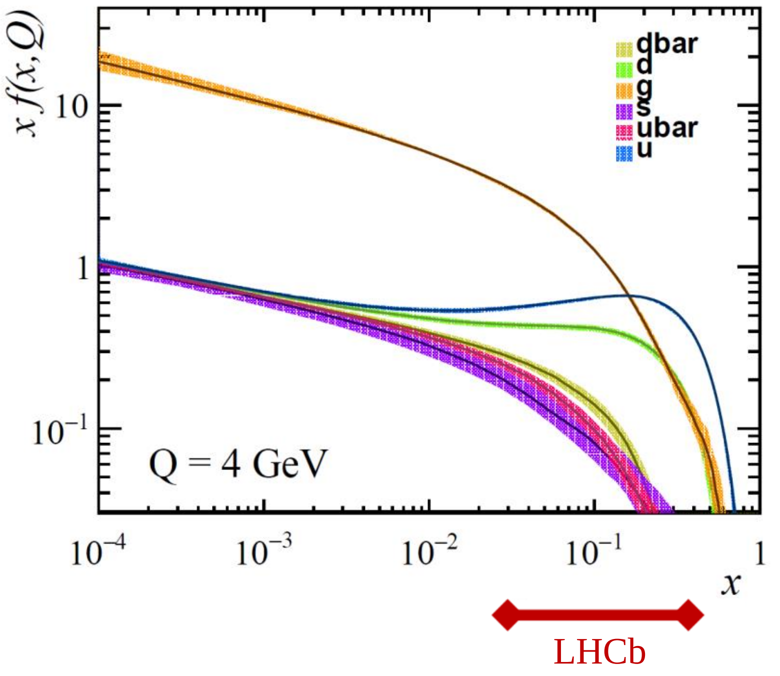
Characterize the **quark-gluon deconfinement**

→ Investigate the phase transition

→ Study the experimental probes of the quark gluon plasma

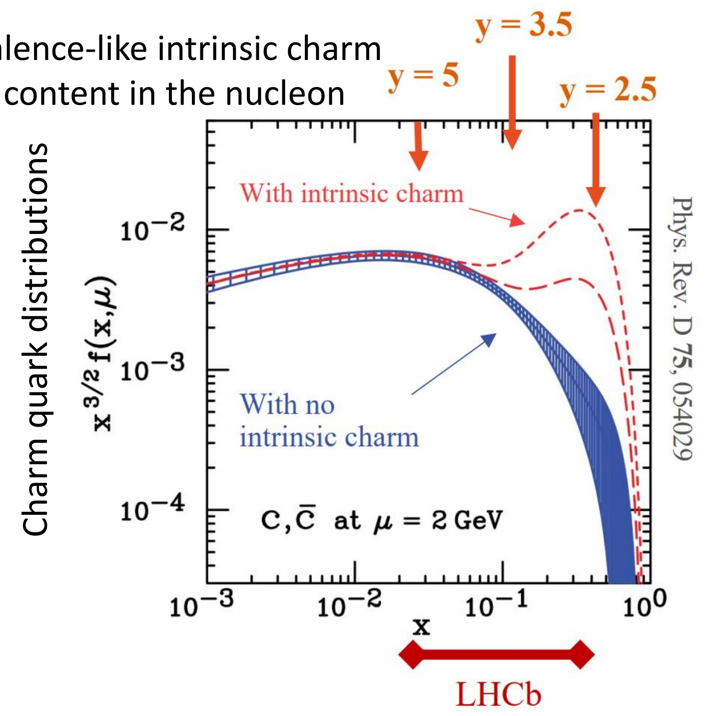
Characterize quarks and gluon pdf

Proton PDF calculated with LHAPDF (nNNPDF30 NLO) for a momentum transfer of 4 GeV/c.



Probe the intrinsic charm content in the proton

Valence-like intrinsic charm content in the nucleon



LHCb fixed-target has access to

- Medium x, where gluon pdf dominates
- Large x, where valence quark pdf dominates

Unique access to the intrinsic charm content of the proton !

(proton's Fock state$|uudc\bar{c}\rangle$)

Predictions in Phys. Rev. C 108, 015201 (R.Vogt)

By characterizing hadron production at medium and high x, opportunity to probe various hadronisation processes

Characterize nuclear pdf

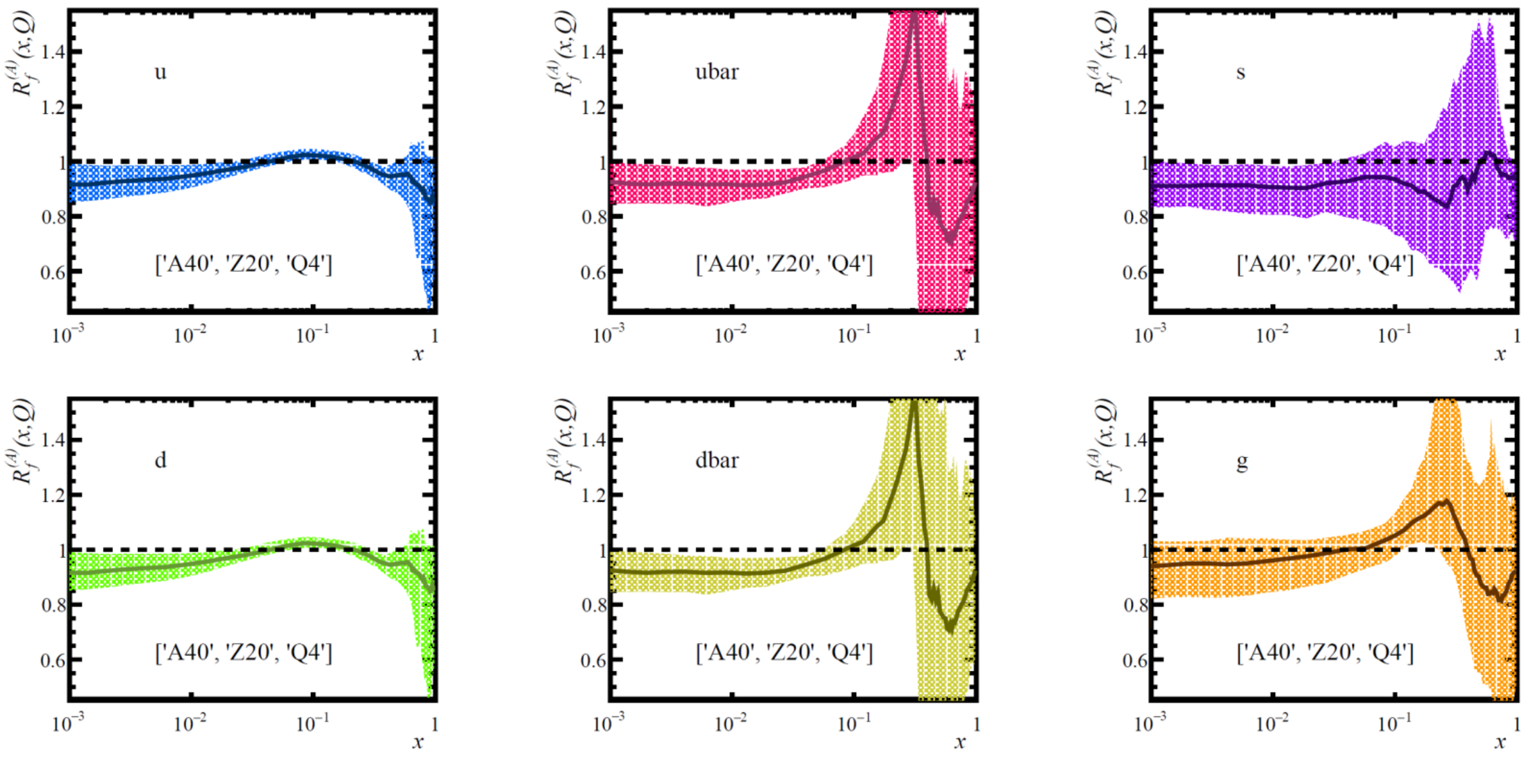
Parton dynamics inside a nucleus are described by nuclear PDFs (nPDFs)

The differences between proton PDFs and nPDFs are captured by the **nuclear modification factor** R_f^A
where A denotes the nucleus and f the parton flavor.

$$R_f^{\mathrm{A}}(x,Q) = \frac{\mathrm{nPDF}_f(x,Q)}{\frac{Z}{A}\,\mathrm{PDF}^{\mathrm{proton}}(x,Q) + \frac{(A-Z)}{A}\,\mathrm{PDF}^{\mathrm{neutron}}(x,Q)}$$

Regardless of the parton flavor, the distributions show
- Shadowing for $x < 0.05$
- Antishadowing for $x \in [0.05, 0.3]$

Expected nuclear modifications for an argon nucleus



Obtained with LHAPDF (nNNPDF30 NLO)

LHCb fixed-target configuration is an excellent opportunity to constrain gluon nPDFs and light quark nPDFs

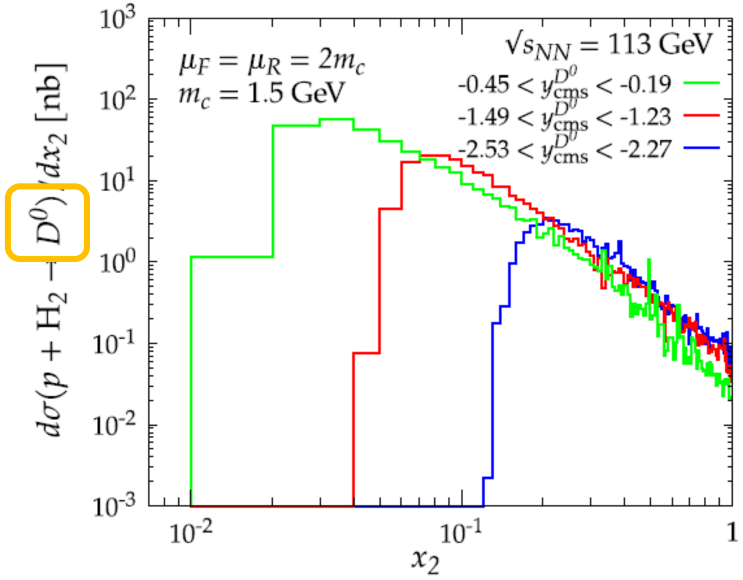
Constrain gluon nPDF with LHCb fixed target

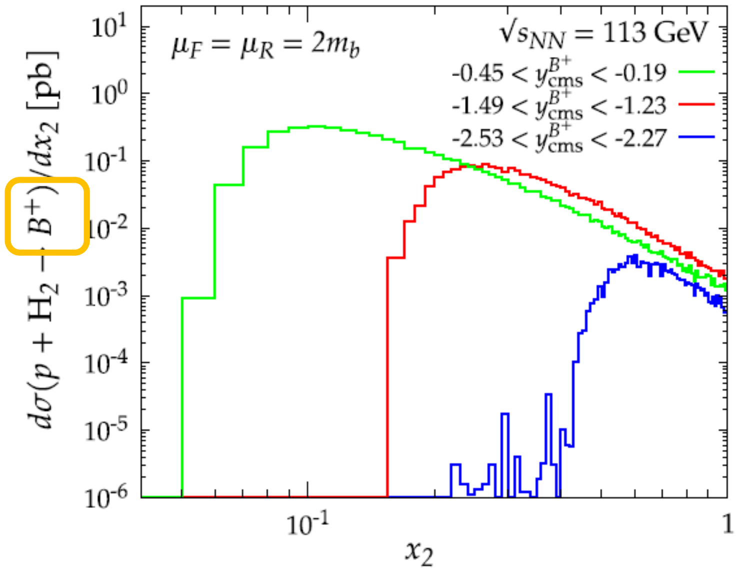
Phys. Lett. B 866 (2025) 139554, C. Hadjidakis et al.

c, b quarks are predominantly produced via gluon fusion

→ **Robust study of gluon nPDFs via measurement of D^0 and B^+ mesons in proton-nucleus collisions across various ion species**

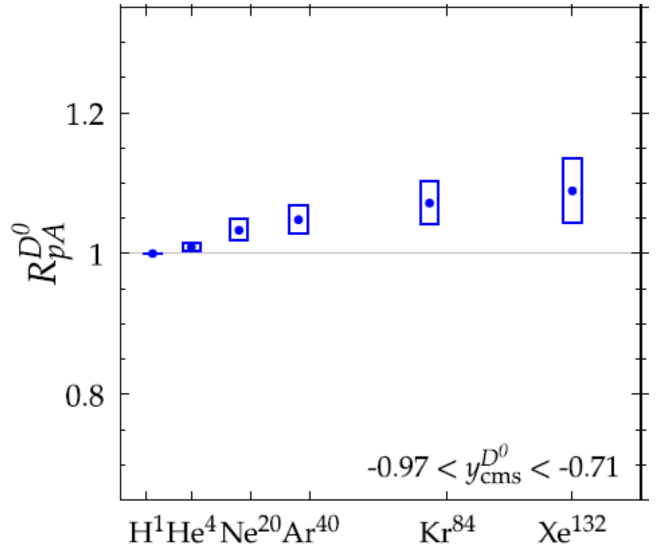
D^0 quark production accesses smaller x values than B-meson production





Backward rapidities probing up to $\langle x \rangle \sim 0.68$ (large nPDF uncertainties)

Current knowledge of the A-dependence in nPDFs is limited



R_{pA} predictions for D^0production in proton-nucleus collisions for different nuclei (He, Ne, Ar, Kr, Xe). The nPDF uncertainties are from nCTEQ15HQ.

Open charm and beauty R_{pA} measurements can significantly improve nPDF constraints in poorly known x regions (antishawoding/EMC)

LHCb fixed-target offers the first opportunity to systematically test nuclear mass dependence

What is the origin of hadron polarisation ?

arXiv:2508.02009v1

Spontaneous transverse polarization of Λ baryons discovered in ~1970s

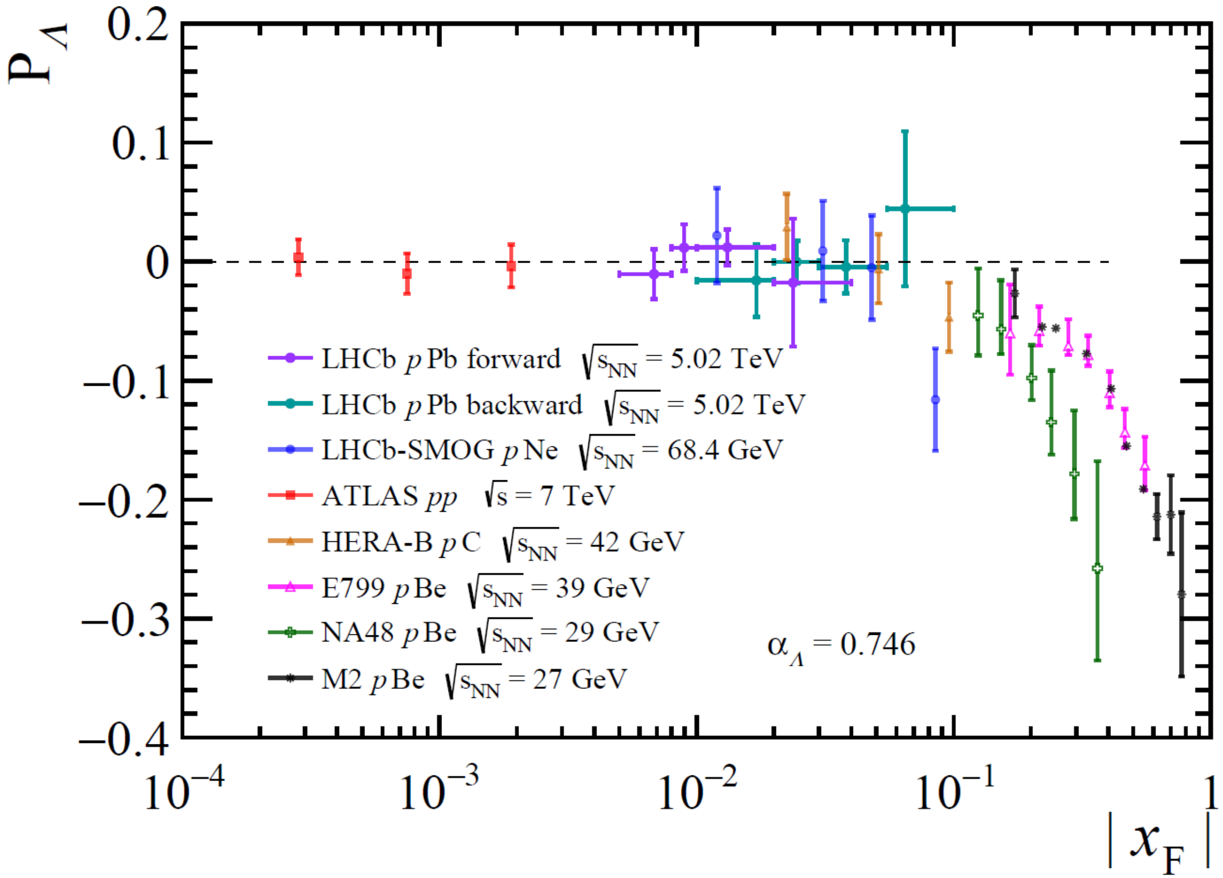
- Up to 30% in unpolarized *pp* and *p*A collisions

Measurements with various beams and targets at different energies

- Polarization measurements are generally negative
- No beam-energy dependence ?
- Grows with Feynman-x (x_F) and p_T

Even observed in e^+e^- collisions (Belle, BESIII)

Hadron polarization is **still a theoretical challenge in QCD**.



Λ polarization remains a benchmark problem in QCD spin physics

Other baryons (Λ_c, Λ_b, …) and vector mesons (D^{*0}, …) measurements are complementary probes of spin dynamics

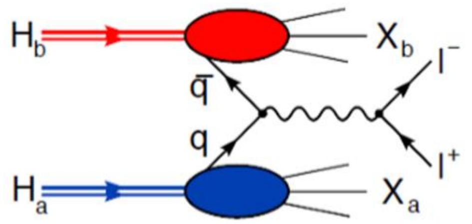
Hadronic structure: going beyond 1D parton distribution functions with TMDs

TMDs : Transverse-Momentum Dependent distributions

- Extend PDFs by including parton transverse momentum k_T
- Provide 3D momentum-space imaging of hadrons
- Investigate parton dynamics, spin-orbit correlations, transverse spin effects

Examples of relevant LHCb fixed-target measurements

✓ **Drell-Yan lepton pair production in *p*A collisions → Sensitive to quark TMDs**



Theoretically clean process / LHCb has excellent muon identification and reconstruction

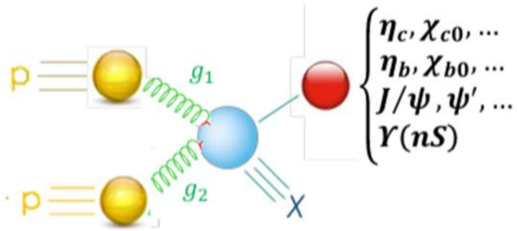
Fixed-target configuration: access to large x_{target} and low x_{beam}

Dominant process: $q(x_{target}) + \bar{q}(x_{beam}) \rightarrow \mu^+ \mu^-$

→ **Probe beam sea quarks, target valence quarks**

→ **Test flavour sensitivity using H_2 vs D_2 targets**

✓ **Quarkonium production (J/ψ, Υ) at low transverse momentum → Sensitive to unpolarized gluon TMDs**



LHCb trigger goes down to $p_T = 0$ for quarkonia

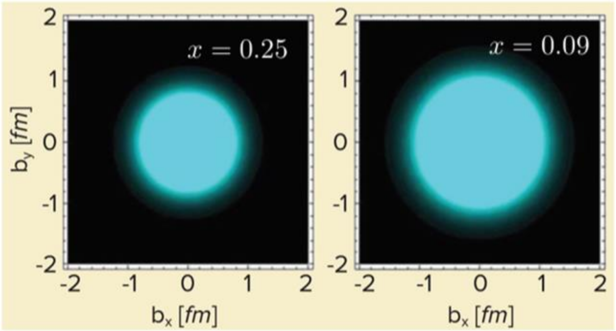
Bottomonium studies allows to go at large q_T

Great opportunity to constraint unpolarized gluon TMDs

LHCb fixed-target: unique window on valence quarks and gluons TMDs

Hadronic structure: going beyond 1D parton distribution functions with GPDs

2015 Long Range Plan for Nuclear Science



GPDs : Generalized Parton Distributions

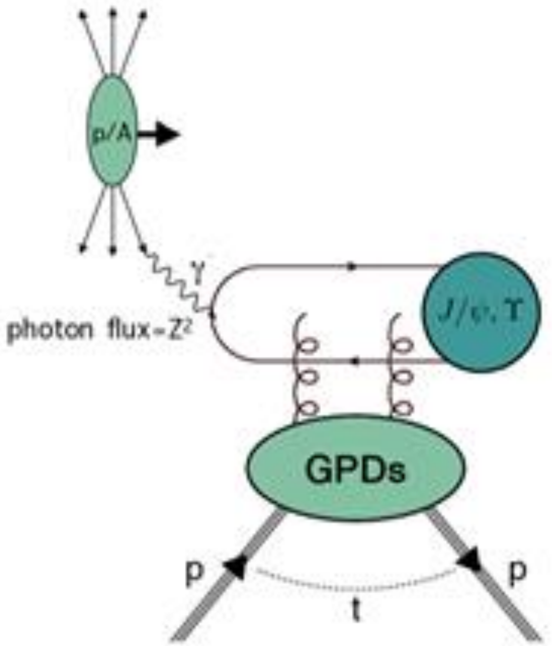
- Provide 3D spatial imaging of hadrons (impact parameter space)
- Investigate spatial distributions, angular momentum of partons

→ Exclusive processes: deeply virtual Compton scattering (DVCS), exclusive meson production

Ultra Peripheral Collisions (UPC) in fixed-target configuration are particularly relevant

UPC:

- Impact parameter larger than sum of nuclear radii → suppressing hadronic interactions
  → Clean photon probe (quasi-real photon from the beam)
- Exclusive quarkonia production, sensitive to gluon GPDs !
- Exclusive production = Quarkonia without additional particles
  → **Clean signal in the LHCb detector**



Exclusive meson production

LHCb fixed-target: opportunity to constraint unpolarized gluon GPDs at moderate – high x
→ Complementary regime to HERA or LHC collider

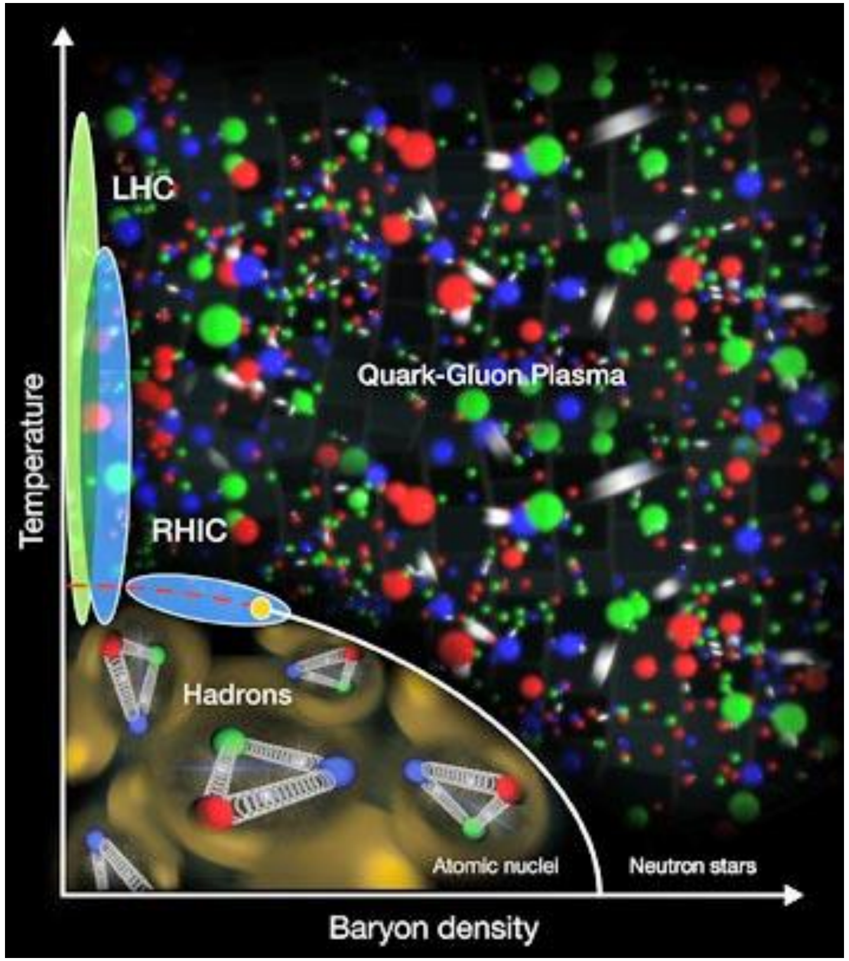
Characterize the Quark Gluon Plasma (QGP)

Deconfined state of matter where quarks are gluons are no longer bound inside hadrons

Created within extreme conditions: very high temperature ($\sim 10^{12}$K) and/or densities ($\sim 10 \times$ nuclear density)

Nearly perfect liquid: very low shear viscosity → flows almost without resistance

- Collective behavior: anisotropic flow reflecting collective hydrodynamic expansion
- Jet quenching: high-energy partons lose energy when traversing QGP
- Color screening: the color charge of quarks/gluons is screened, altering hadronisation



LHCb fixed-target configuration $\sqrt{s_{NN}} \sim \mathbf{70 - 110}$ GeV

- Fill the gap between the SPS and RHIC / LHC energy
- Large variety of colliding systems
  - Proton-Nucleus collisions: *p*H, *p*D, *p*He, *p*Ne, *p*Ar, *p*Kr, *p*Xe

    → **Strict constrains on the cold nuclear matter effects**
  - Pb-Nucleus collisions: PbNe, PbAr, PbKr, PbXe

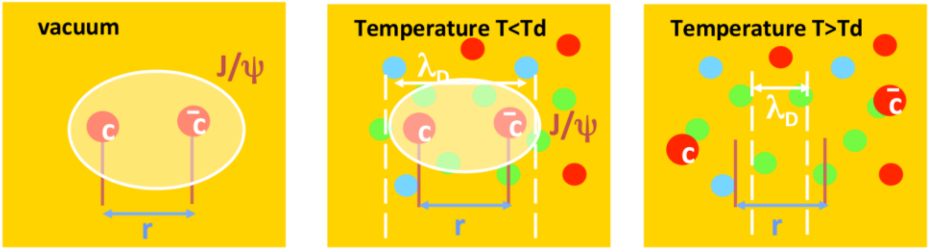
    → **Large energy density scan to study QGP characteristics**

LHCb fixed-target configuration provides a unique laboratory to study the QGP properties

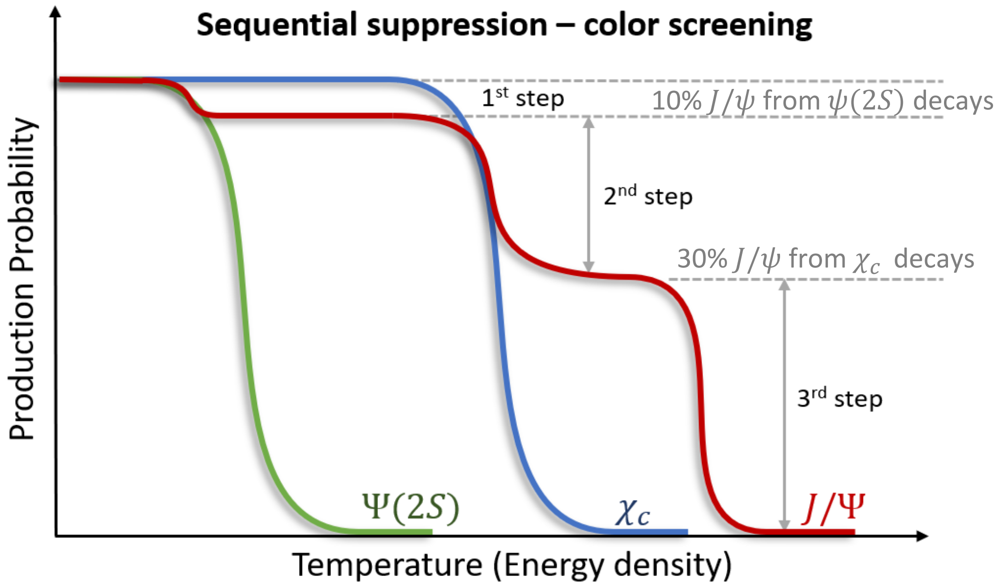
Precise characterization of charmonia melting accessible with LHCb-FT

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



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



E$_{binding}$: $\psi(2S) \sim$ **50 MeV**, $\chi_c \sim$ **200 MeV**, $J/\psi \sim$ **500 MeV**

J/ψ and $\psi(2S)$ 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 $\sqrt{s}$

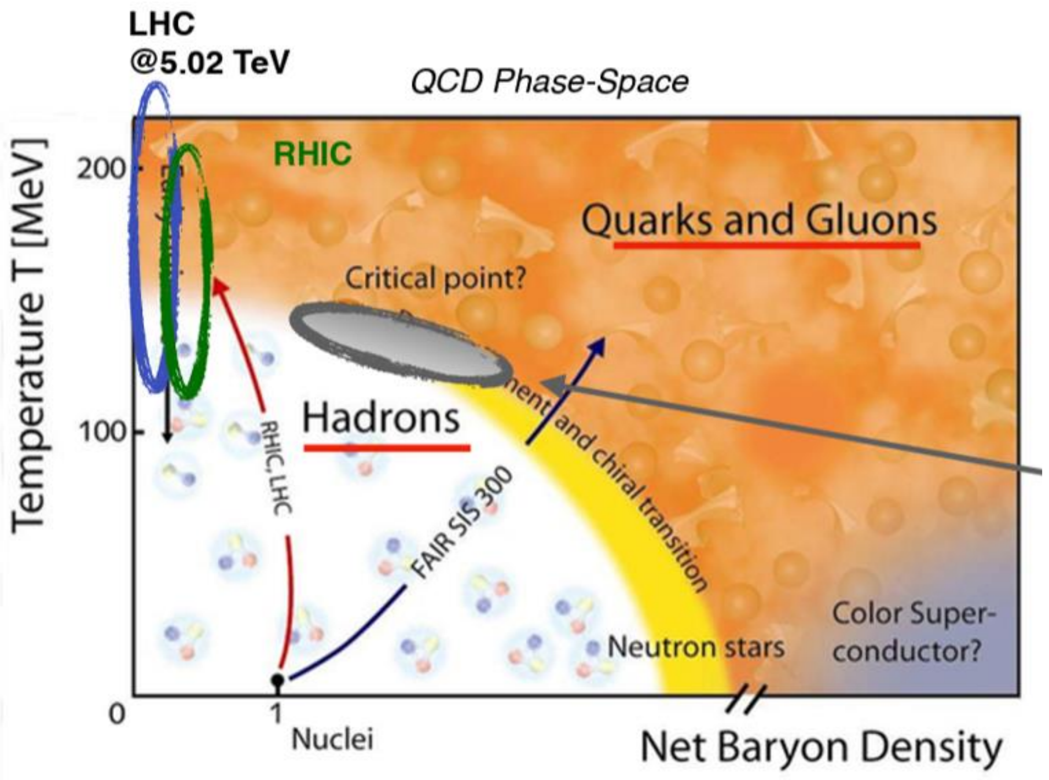
Difficult to properly interpret LHC measurements without disentangling the possible sequential suppression from the possible statistical recombination

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

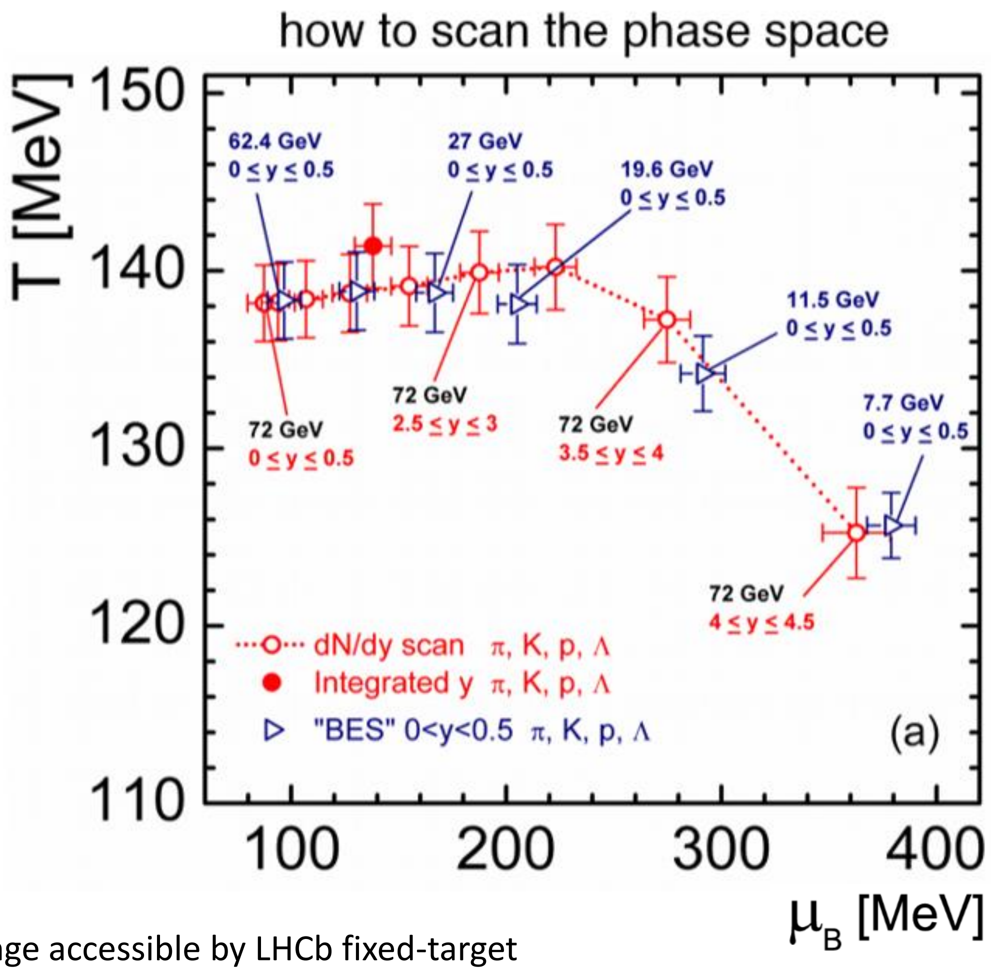
LHCb detector and its fixed-target perfectly fitted to fully characterize the sequential suppression

- ✓ **Energy density scan** from *p*H to PbXe collisions
- ✓ $\sqrt{s}$ **ϵ [20 ; 200] GeV** : enough for QGP (SPS fixed-target experiments), no $c\bar{c}$ recombination (1 $c\bar{c}$ pair in most central PbPb collisions at $\sqrt{s_{NN}} \sim 100$ GeV)
- ✓ **$\chi_c \to J/\psi\,\gamma$ reconstruction is at hand with LHCb** (production already measured in *pp*, *p*Pb/Pb*p*)

Looking for the critical point



Region potentially covered by fixed-target collisions



Recent calculations show that the baryon chemical potential, μ_B, varies with rapidity in the range accessible by LHCb fixed-target

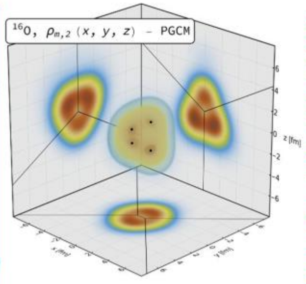
Measuring correlations or fluctuations of conserved quantities in small rapidity bins, and exploiting different colliding systems, provides a new way to search for the QCD critical point.

LHCb Fixed-target can complement RHIC beam energy scan

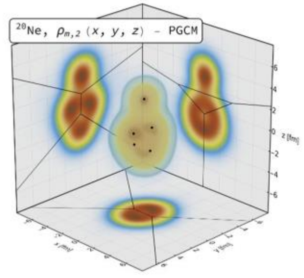
Example of other relevant observables for QGP with LHCb Fixed-target

- **Collective behavior**: anisotropic flow reflecting collective hydrodynamic expansion and initial state geometry
  Various target: H, He, O, Ne, Ar, Kr, Xe

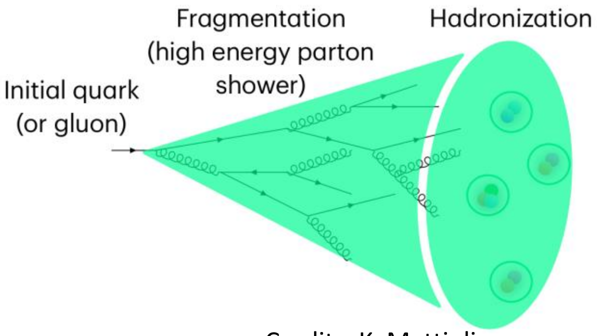
Phys. Rev. Lett. 135, 012302



Phys. Rev. Lett. 134, 082301



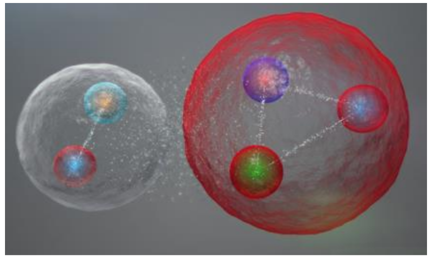
- **Jet quenching**: Precise studies of parton energy loss in nuclear matter as a function of the nuclear size



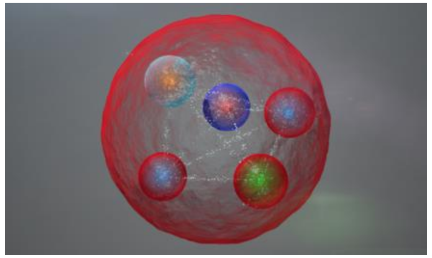
Credits: K. Mattioli

A jet correlates hadrons to the original quark or gluon they originated from

With large luminosity, flavour-dependent (inclusive / photon-tagged/charm jets) studies of parton energy loss with increasing nuclear size are possible



- **Hadronisation mechanisms** at medium and high-x over a large range of multiplicity
  → Beyond the standard charmonia measurements and meson/baryon ratio
  → Access to η_c, χ_c(3872), double charmed baryons and exotica
  → Spectroscopy



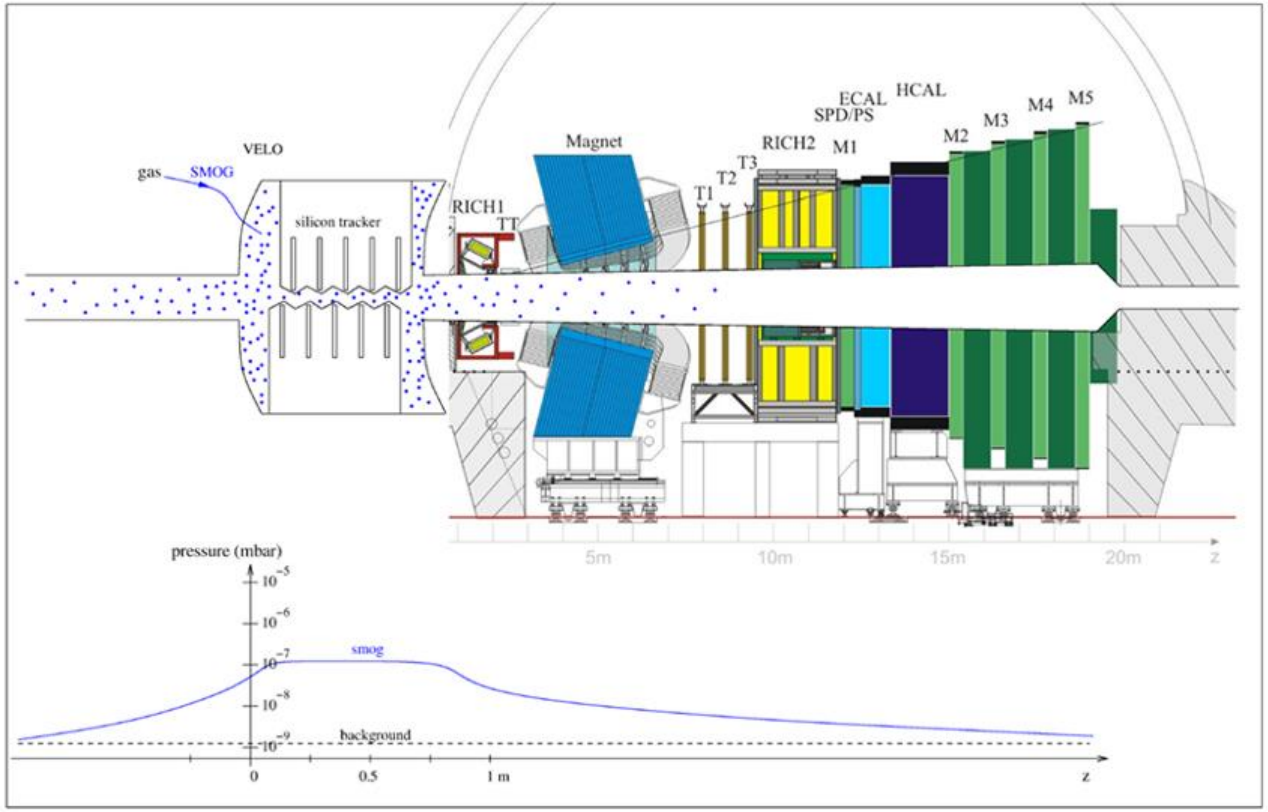
- **Electromagnetic observables** (photons and dileptons): information about the different stages of the evolution
  Ex: Phys.Lett.B 821 (2021) 136626

SMOG: the LHC fixed-target

Since 2013: SMOG – System Measurement Overlap with Gas

During Run 2, LHCb used SMOG to inject noble gases into the LHC beam-pipe, acting as the highest-energy fixed-target experiment ever

- Gaseous fixed-target with low pressure ($O(10^{-7}\mathrm{mbar})$)
- Gas spread within +/- 20 m in the LHC beam pipe
- Dedicated data taking campaign → Few days / year
- Only noble gases can be injected → No hydrogen (= no *pp* collisions)



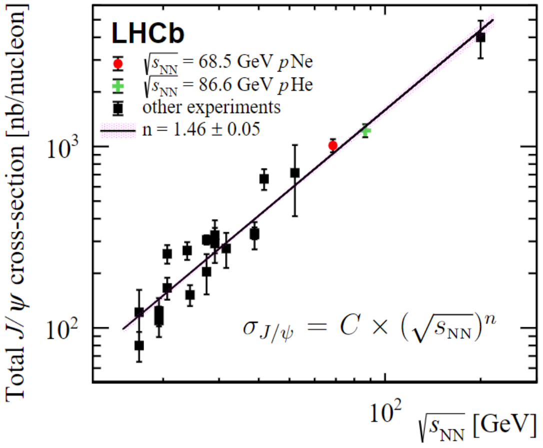
→ **Very limited statistics**

First results with SMOG

Charmonia production in pHe, pNe, pAr collisions

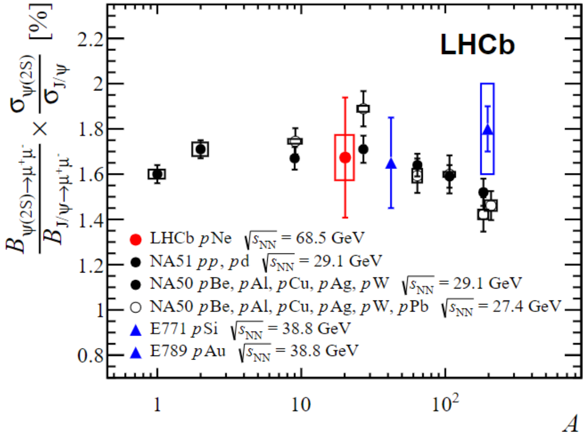
PRL 122 (2019) 132002

Eur. Phys. J. C83 (2023) 625



J/ψ cross section measurements

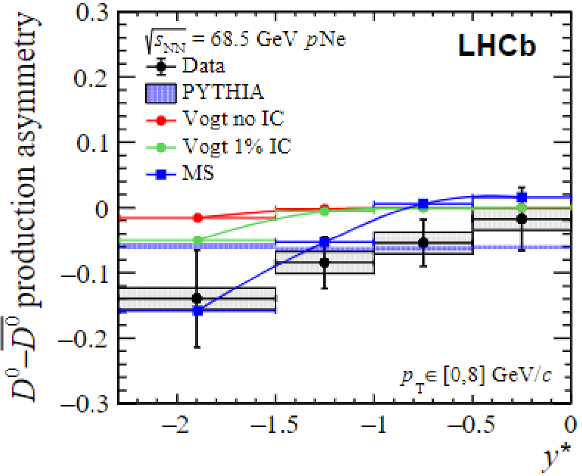
→ Power law dependence on $\sqrt{s_{NN}}$



$\psi'/J/\psi$ cross-section ratio

Open charm production in pHe, pNe, pAr collisions

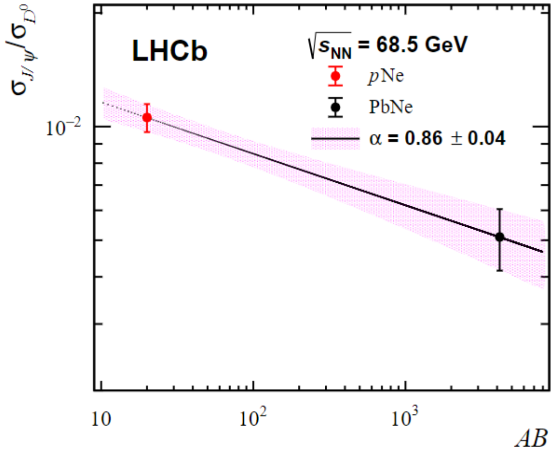
Eur. Phys. J. C83 (2023) 541



D^0- $\overline{D}^0$ cross-section and asymmetry in pNe

Suppression of charmonia in p / Pb-nucleus collisions

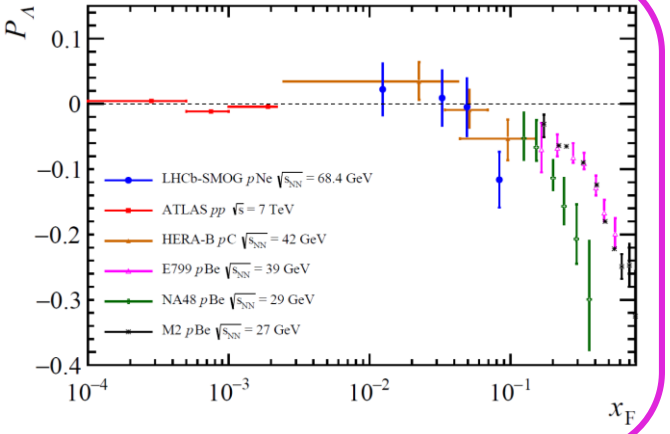
Eur. Phys. J. C83 (2023) 658



$J/\psi/\ D^0$ cross section ratio in pNe and PbNe collisions

Λ polarization in pNe collisions

JHEP 09 (2024) 082



Several publications

- Charm (hidden, open) production in proton-nucleons and Pb-Ne collisions
- Soft probes : Λ polarization in pNe, ϕ production in pNe JHEP 03 (2025) 151
- Astrophysics: prompt antiproton production PRL 121 (2018) 222001, antiproton from anti-hyperons decays EPJC 83 (2023) 543

Beginning of a large physics program ! But need more statistics

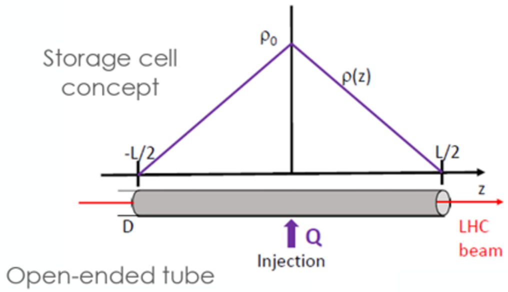
SMOG2

2009	2013	2015	2018	2022	2026	2030	2034	2036
Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5

SMOG

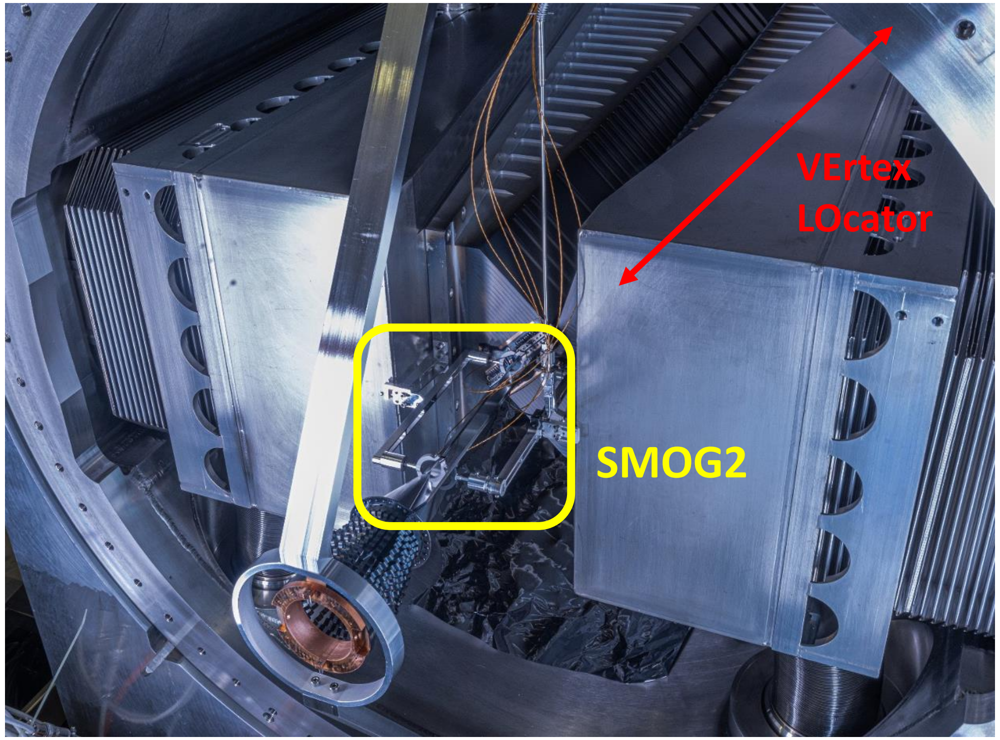
SMOG2

Since 2022: SMOG2 – System Measurement Overlap with Gas 2



- ❑ A storage cell with a physical aperture of 5 mm
  → Boost the gas density by a factor 8 – 35 for the same flow as in Run 2 with SMOG !

- ❑ SMOG2 interaction point within [-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*



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

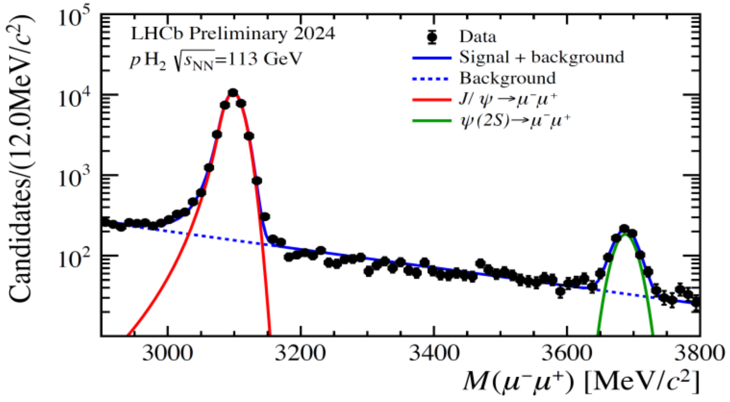
Significant improvement of the performances of the LHCb fixed-target system

SMOG2 is in place for Run 3, Run 4 and above !

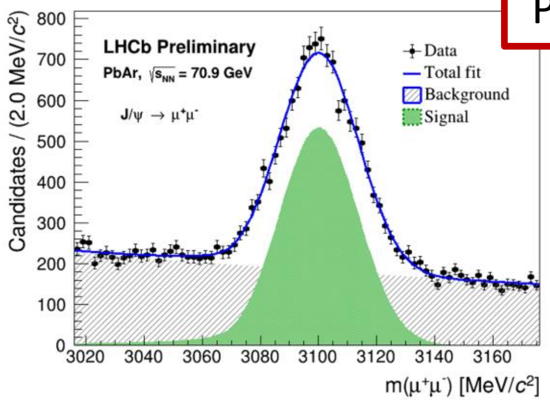
SMOG2 operations

SMOG2 is operating continuously since 2024

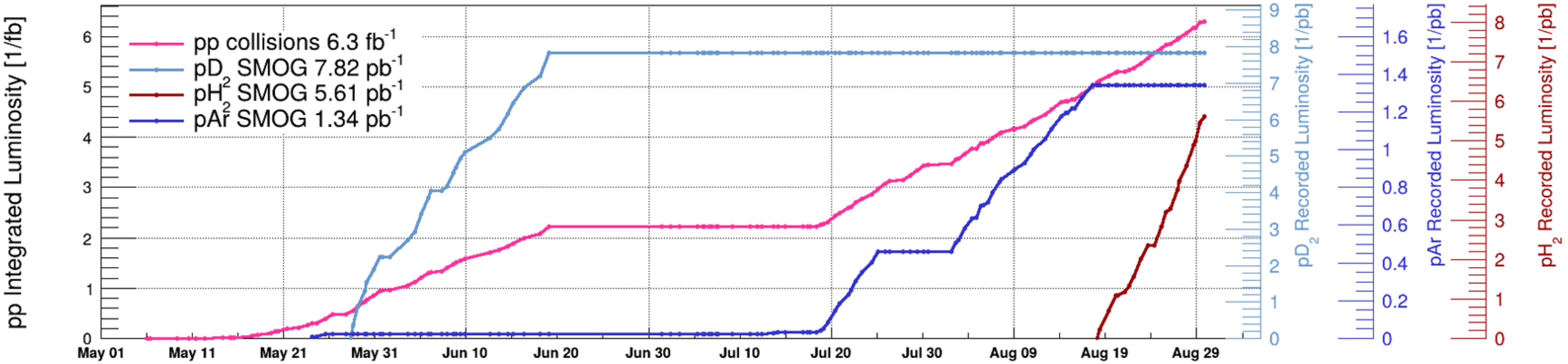
LHCb-FIGURE-2024-023



PbAr



Total Recorded Lumi vs Day - proton beams in 2025



LHCb can operate in collider and fixed-target modes simultaneously with the same excellent performances: Vertexing, tracking, Particle identification !

SMOG2 beyond Run 3

Run 4 objective: collect large statistics of

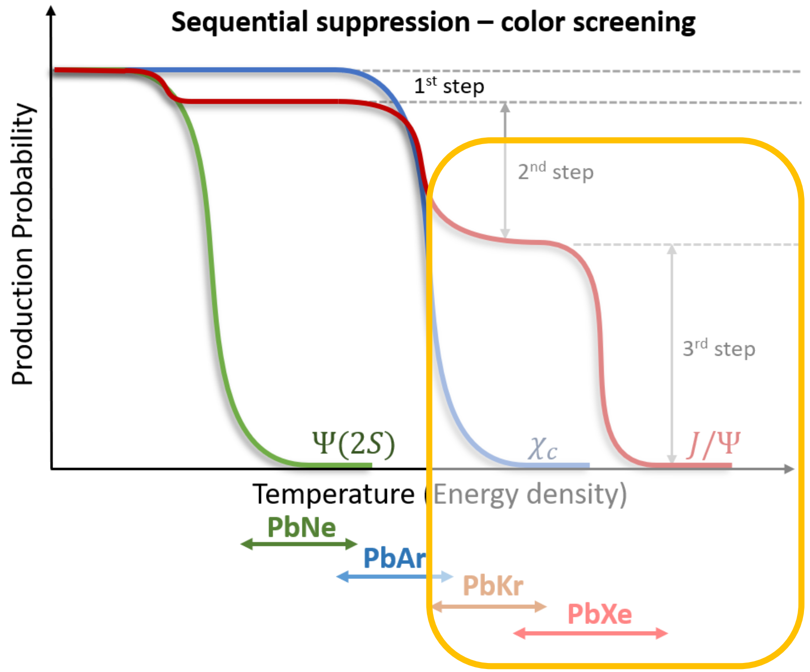
- **pH_2**, pD_2, pHe, **pNe, pAr**, pKr, pXe collisions
- PbH_2, PbHe, PbNe, **PbAr** collisions

(Large datasets already collected in Run 3)

LHCb was not designed for high-multiplicity events

→ LHCb tracking currently saturates in central PbPb collisions in collider mode (up to ~30%), corresponding to **PbAr collisions in fixed-target operation**

→ See Elisabeth's talk about LHCb upgrade



UP central part and Mighty Tracker are crucial for PbKr and PbXe collisions

→ Full access to the 2nd plateau of $c\bar{c}$ sequential suppression ?

→ Total suppression of J/ψ ?

Table 3: Estimated measured yields of quarkonia from PbXe collisions at $\sqrt{s_{NN}} = 71$ GeV in the Upgrade II scenario assuming $\mathcal{L}_{PbXe} = 1\,\mathrm{nb}^{-1}$ in different centrality intervals.

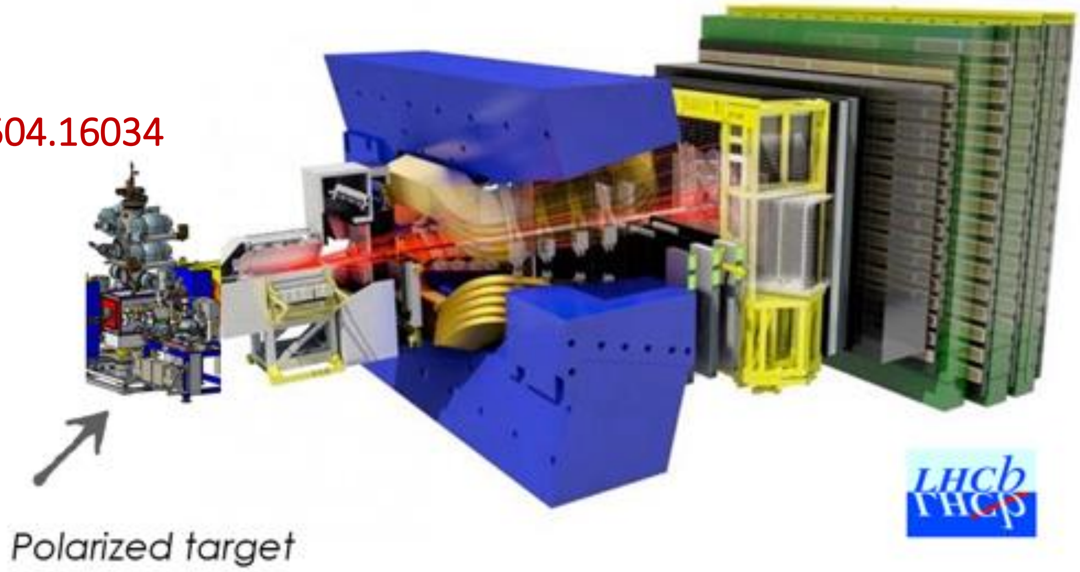
Centrality [%]	J/ψ	$\psi(2S)$	$\Upsilon(1S)$	$\chi_{c1}^{conv}(1P)$	$\chi_{c2}^{conv}(1P)$
100-90	7250	145	3	2	1
90-80	20770	207	8	5	3
80-70	37050	370	12	10	5
70-60	63300	633	18	17	10
60-50	106700	1219	35	29	16
50-40	170500	2273	65	47	27
40-30	300200	4002	115	83	47
30-20	493200	6580	151	137	78
20-10	786000	10480	180	219	125
10-0	1227000	16370	282	343	195
5-0	678000	9040	155	189	107
100-0	3213000	42280	872	898	510

Courtesy of O. Boente Garcia

With the upgraded tracking, assuming 2024 Pb data taking conditions, after 3 weeks, so $L_{PbXe} = L_{PbAr}^{2024} = 1\ nb^{-1}$, there would be 3M J/ψ

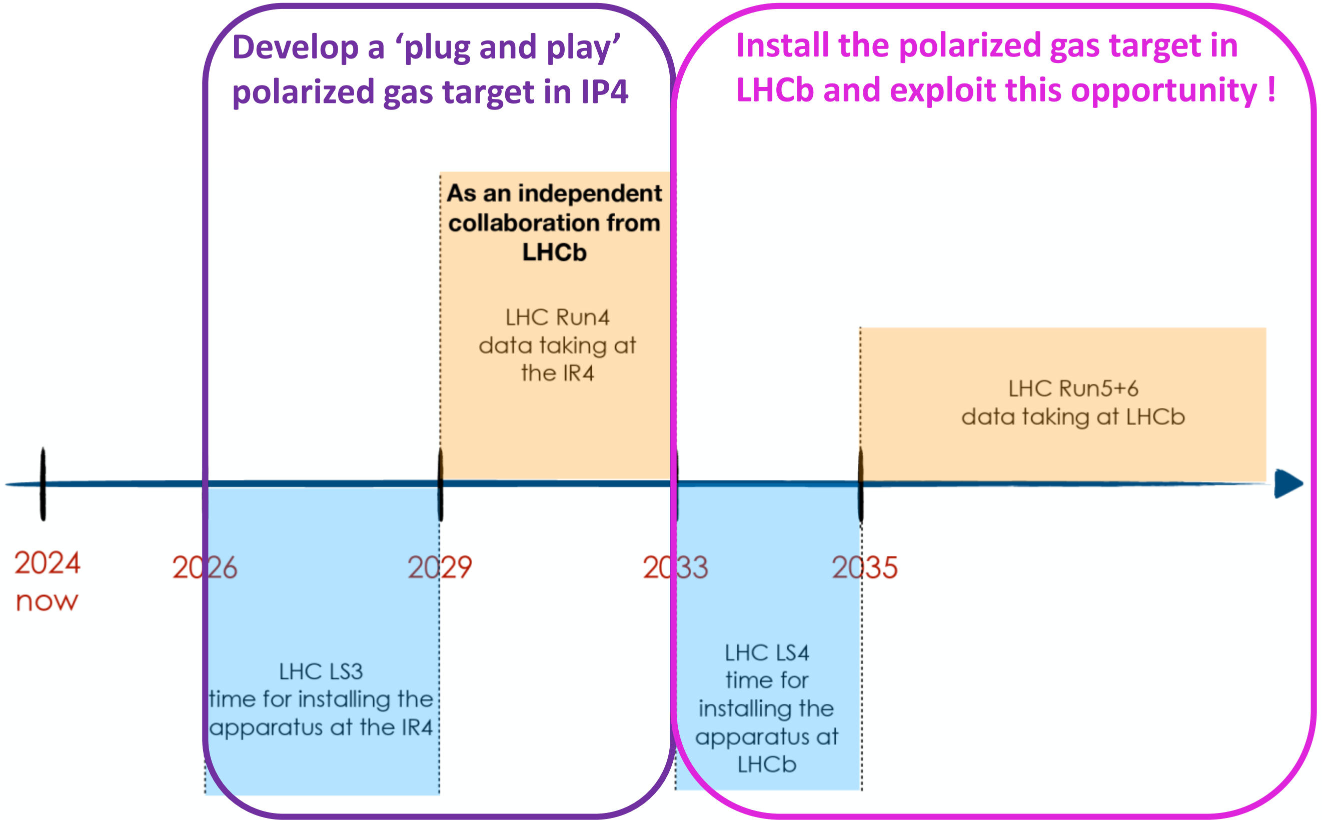
With LHCb Run 5, unique opportunity for a comprehensive QCD programme, up to very high multiplicities at $\sqrt{s_{NN}} \sim 100$ GeV

A polarized gas target: LHCspin https://arxiv.org/pdf/2504.16034



In addition to SMOG2, LHCspin aims to explore the **spin-related physics** by studying collisions between the LHC beam and the polarized gas targets, providing unique insights into the three-dimensional structure of the nucleon.

Ongoing extensive R&D based on the successful technology of HERA and COSY experiments



HERA polarized target

Conclusions

With its fixed-target mode, LHCb explores a nearly uncharted territory in QCD: cold matter, QGP, and spin physics

To fully unlock the QCD physics potential, it is essential to improve tracking for Run 5, enabling full access to central Pb–Xe collisions

SMOG2 development and installation have been successfully led by Pasquale Di Nezza (INFN)
LHCspin (also led by Pasquale – INFN) is an ambitious project seeking collaborators

French community

- **LLR, since 2015**: heavily involved in data taking (trigger, sprucing, shifts), Monte Carlo simulations, and defining the annual injection program. Leads charmonia and open-charm analyses in *p*-nucleus and Pb-nucleus collisions.

- **DPhN (CEA), since 2024,** highly involved in collider-mode measurements, may participate in future fixed-target measurements.

- **IJClab, back in 2025**: plan to measure vector meson photoproduction (UPC and PC) and elliptic flow, including trigger and MC associated development. Also interested in open and hidden heavy-flavor studies.

- **Subatech**, currently LHCb technical associate, plan to become LHCb full member in the coming years. Interested in collider-mode and fixed-target measurements.

The LHCb fixed-target program is still in its early stages, providing significant opportunities for new collaborators