Physics opportunities with SMOG2

a bridge between particle, nuclear and astroparticle physics

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on behalf of the LHCb Collaboration

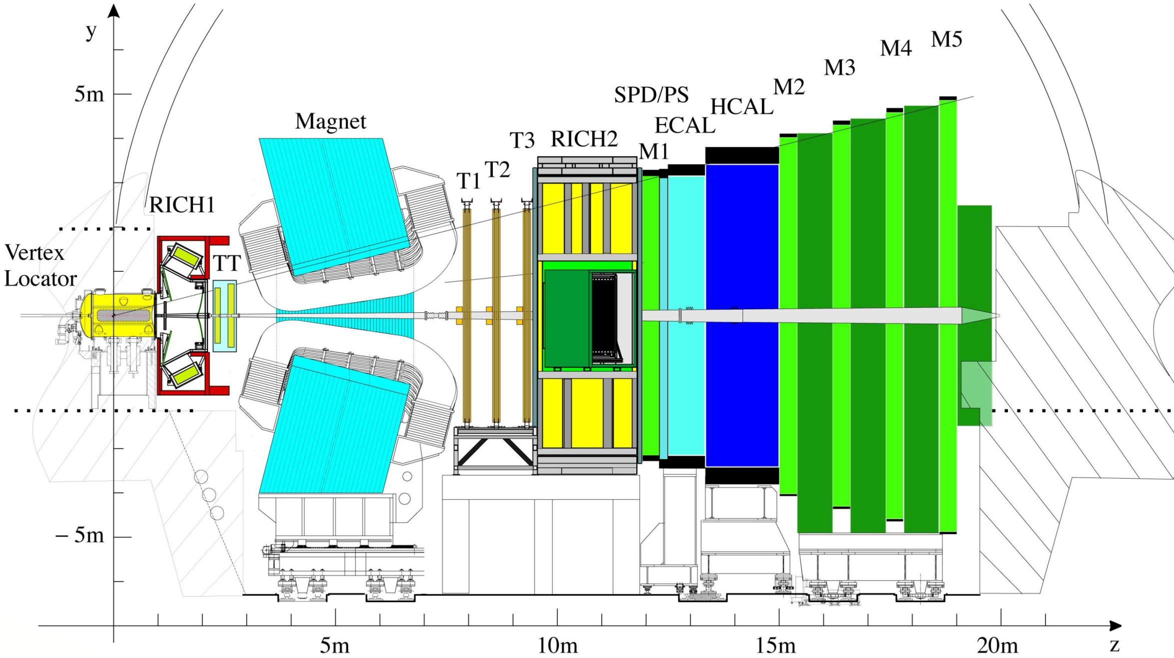
Exploring nuclear physics across energy scales 2024
Apr 26, 2024

The LHCb experiment

LHCb is the experiment devoted to heavy flavours at the LHC.

Detector requirements:

- **Forward geometry** to optimize acceptance for $b\bar{b}$ pairs: $2 < \eta < 5$
- **Tracking** : optimal resolution for proper time ($\sim$ 45 fs) and momentum ($< 1\%$ for $p < 200$ GeV/c)
- **Particle ID** : excellent capabilities to select exclusive decays
- **Trigger** : high flexibility and bandwidth (1 MHz at hardware level, up to 15 kHz to disk)



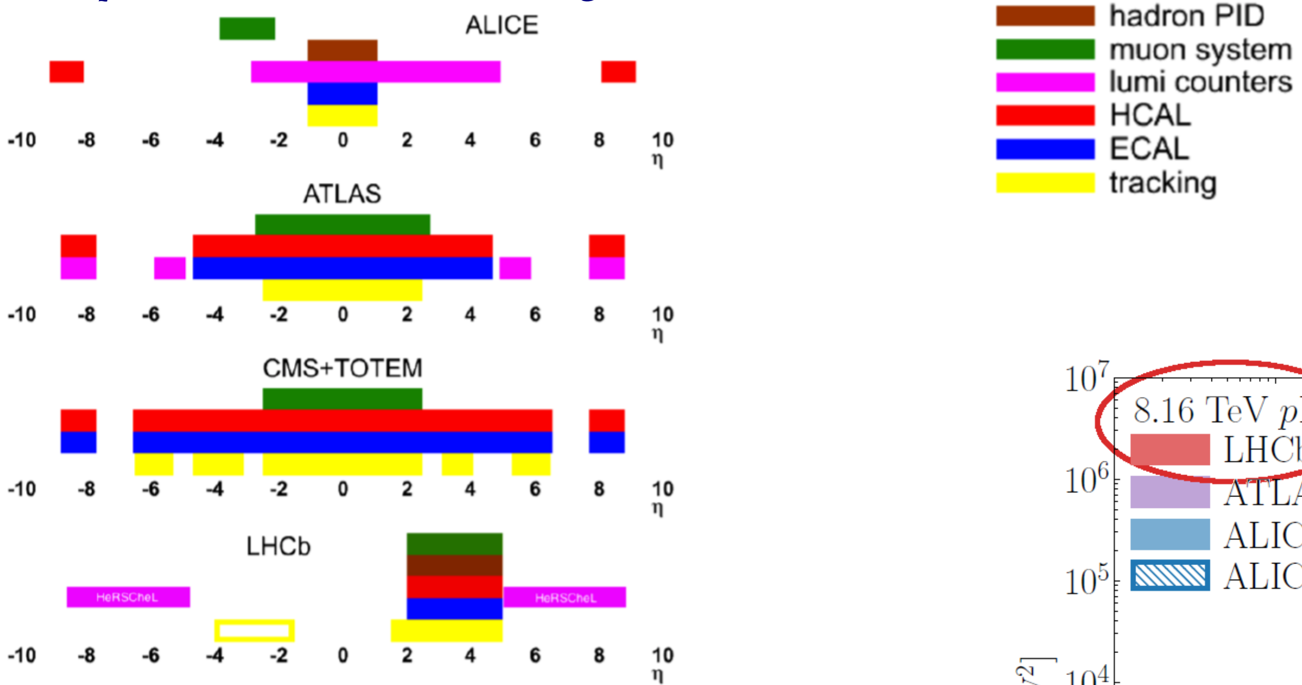
JINST 3, (2008) S08005
Int.J.Mod.Phys.A30 (2015) 1530022

Some unique features are also attractive for heavy ion physics:

- forward acceptance, complementary to other experiments at LHC
- excellent detector performance, notably for heavy flavours
- possibility to run in fixed-target mode

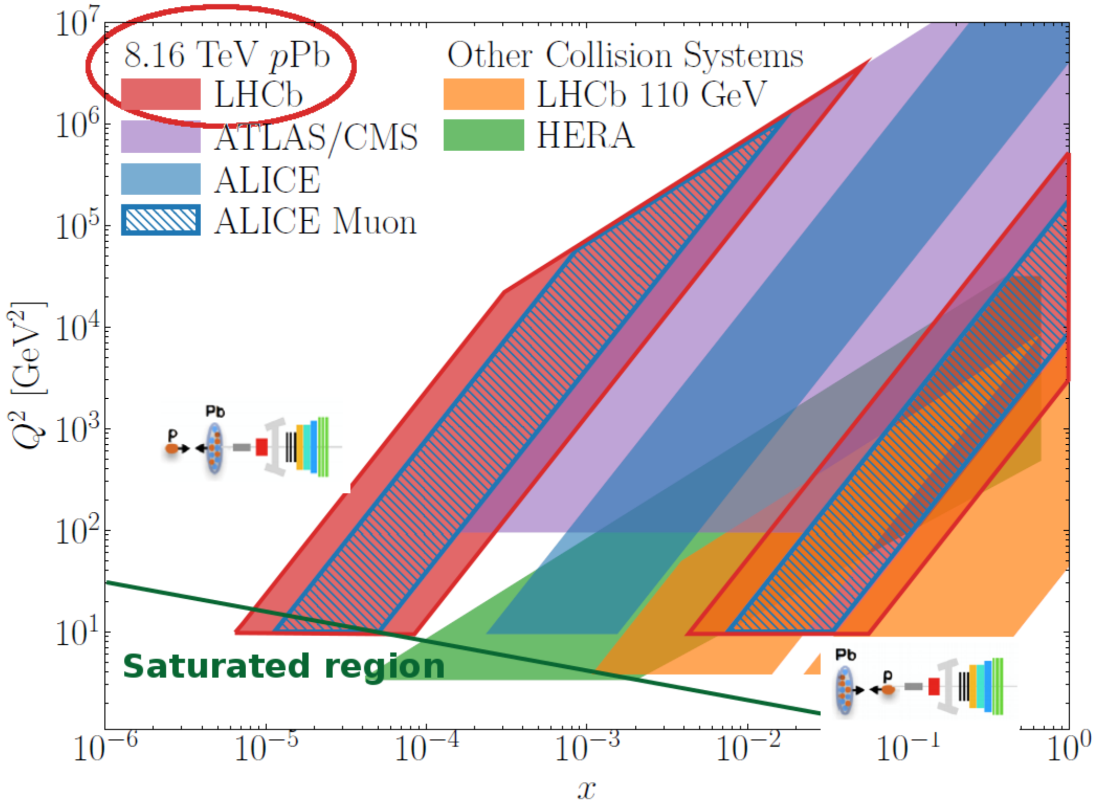
The LHCb experiment

- Unique forward coverage at LHC



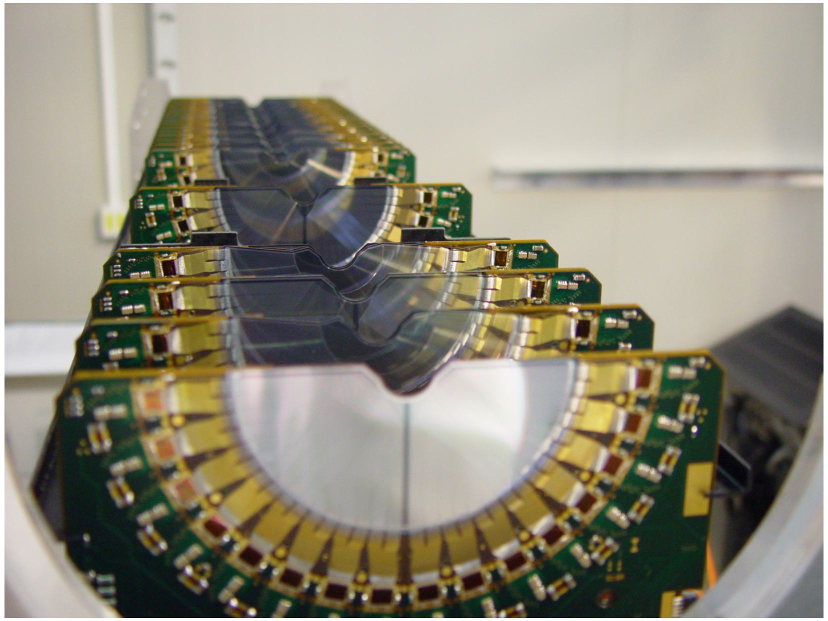
- Sensitivity to small x (down to $\sim 10^{-5}$) ➡ gluon saturation
- and to anti-shadowing region

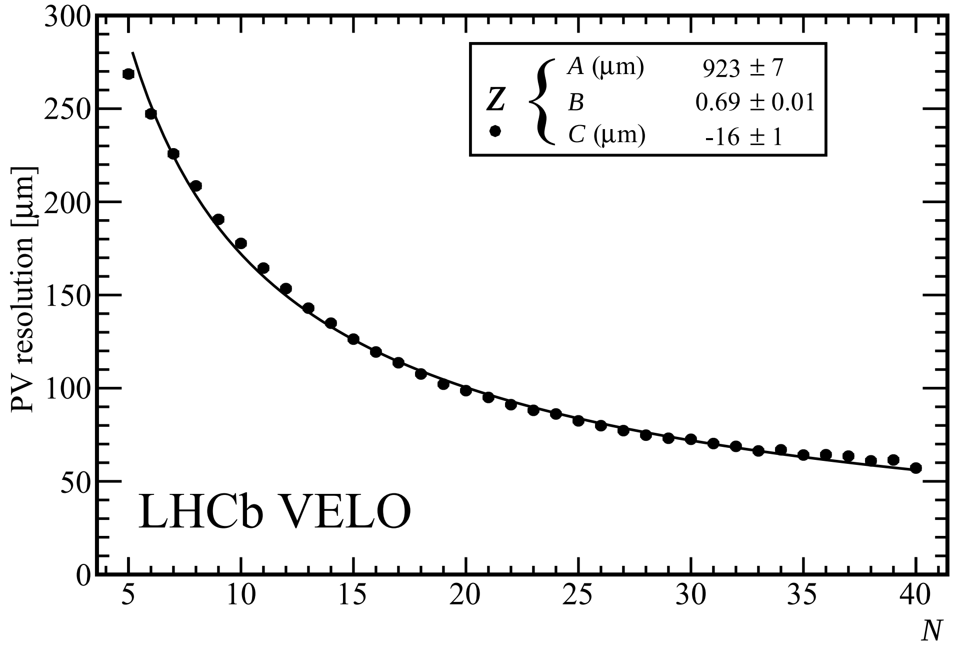
- Nicely complementing other LHC experiments (rapidity dependence can disentangle nuclear effects)

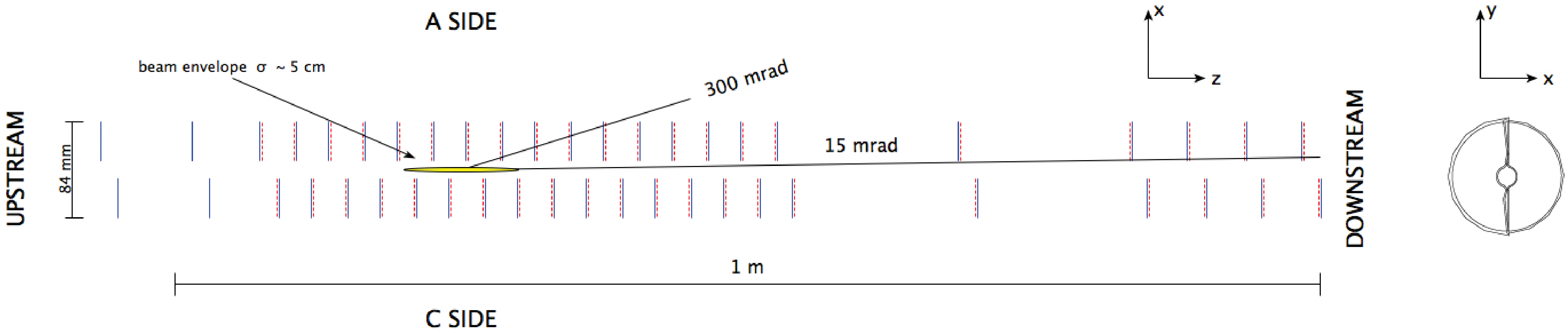


Key feature: the VErtex LOcator

- Optimized for forward particles and best proper time resolution of weak decays
- Sensors just 7 mm away from the LHC beams, mounted on two retractable halves





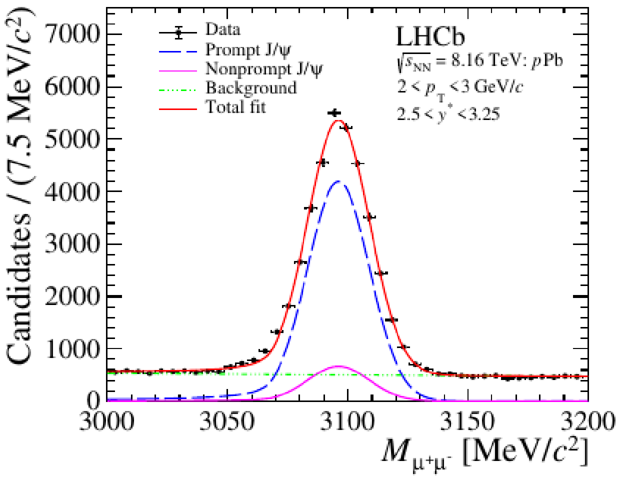


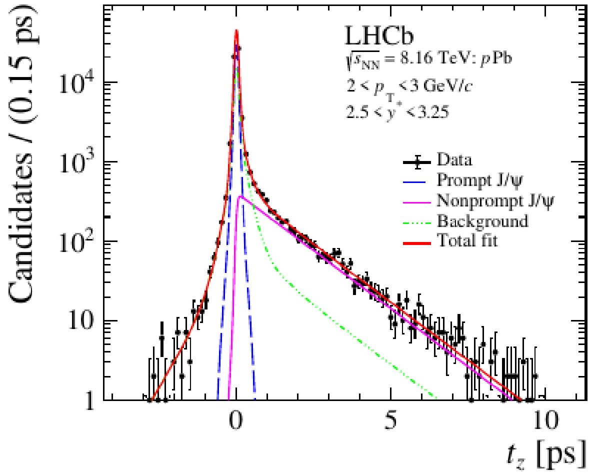
JINST 9 (2014) P09007

Key feature: detector performance

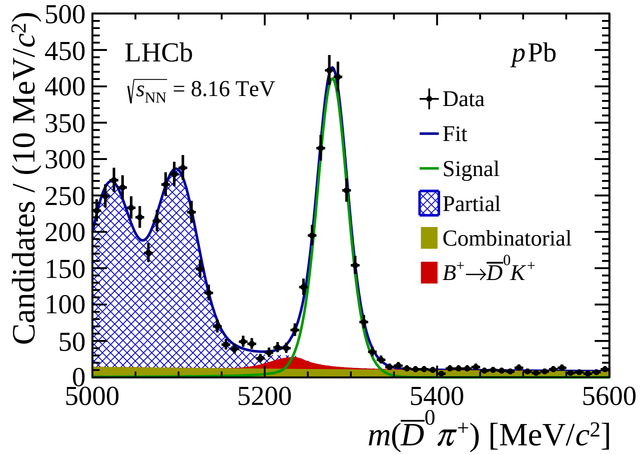
- Extreme vertexing performance and excellent PID: ideal for heavy flavour states, disentangling charm and beauty components

$J/\psi \to \mu^+\mu^-$ **JHEP 04 (2024) 111**





$B^+ \to \overline{D}^0\pi^+$ **PRD99 052011 (2019)**



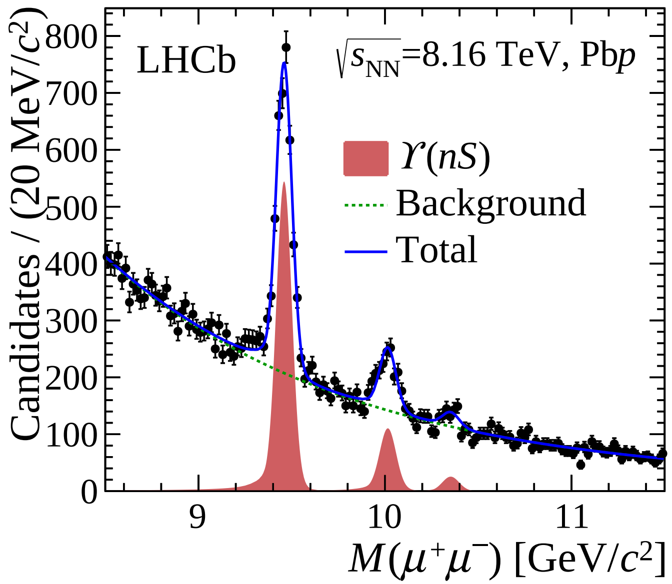
- No rate limitations from trigger and DAQ for heavy ion runs:
  - large samples of MB events
  - heavy flavour triggers with low p_T thresholds ($\sim$ 1 GeV)
- ⚠ tracking saturates for most central PbPb collisions
  ➡ LHCb more suited for small collision systems (pA collisions) crucial environment to understand cold nuclear matter effects and collectivity in small systems

Example: Bottomonia in pPb@8 TeV

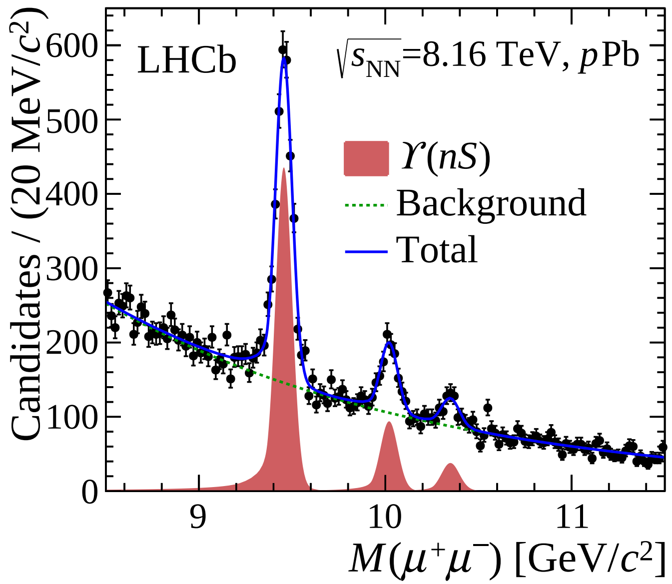
JHEP 11 (2018) 194

- Clean separation of three nS states

Backward



Forward

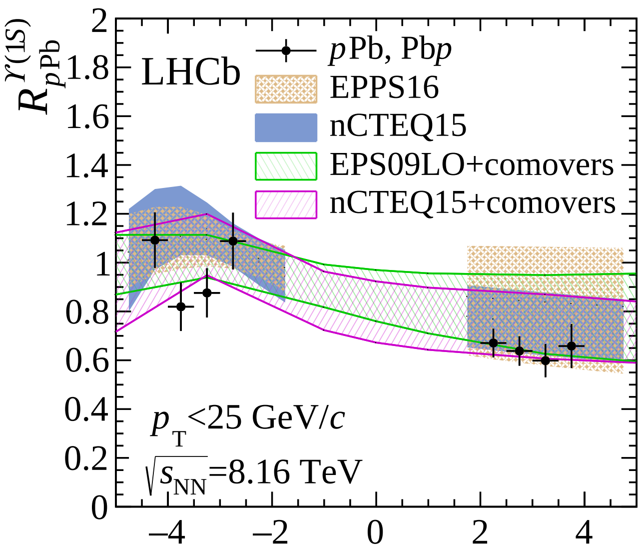


- "Comover" model predicts large final-state effects, larger for excited states and in backward direction

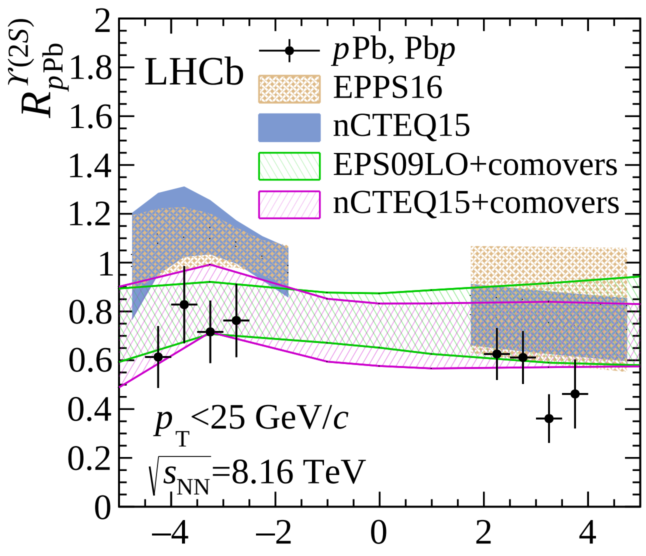
  Ferreiro and Lansberg, JHEP 10 (2018) 094

- Patterns observed in data support this picture…

R for $\Upsilon(1S)$

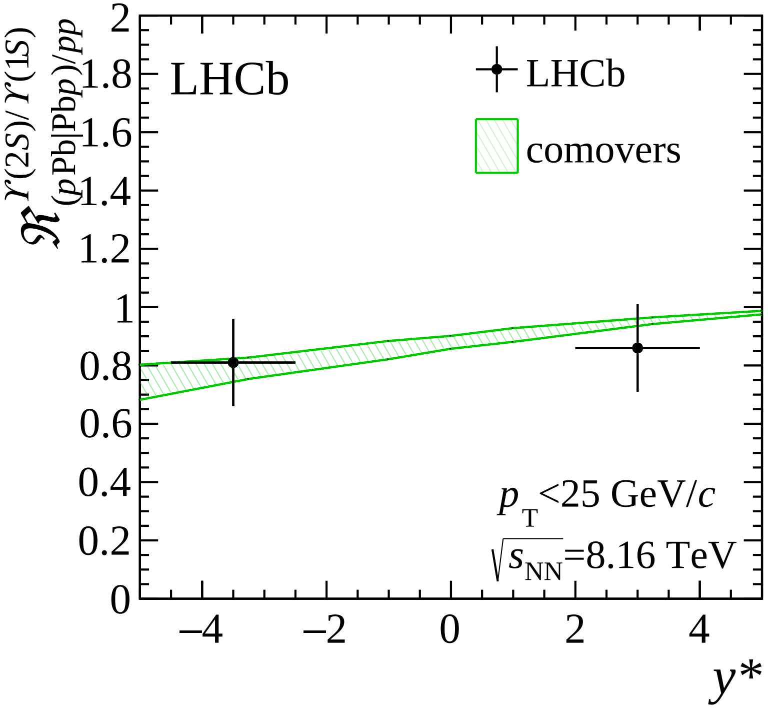


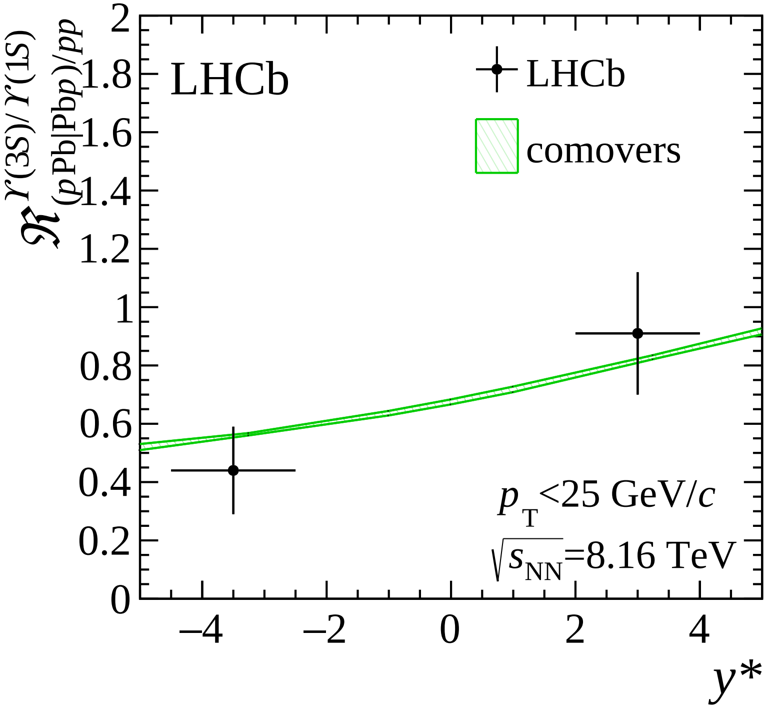
R for $\Upsilon(2S)$



$\mathbf{R}(\Upsilon(2S))/\mathbf{R}(\Upsilon(1S))$ $\quad$ $\mathbf{R}(\Upsilon(3S))/\mathbf{R}(\Upsilon(1S))$

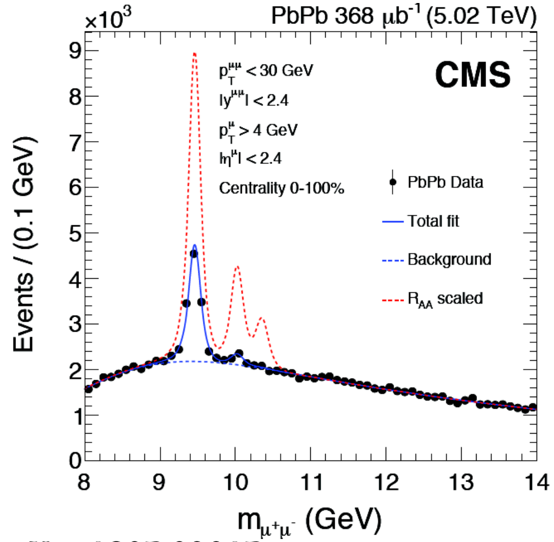
…notably for $\Upsilon(3S)$!





$$\Re^{\Upsilon(2S)/\Upsilon(1S)}_{p\mathrm{Pb}/pp} = 0.86 \pm 0.15,$$
$$\Re^{\Upsilon(3S)/\Upsilon(1S)}_{p\mathrm{Pb}/pp} = 0.81 \pm 0.15,$$
$$\Re^{\Upsilon(2S)/\Upsilon(1S)}_{\mathrm{Pb}p/pp} = 0.91 \pm 0.21,$$
$$\Re^{\Upsilon(3S)/\Upsilon(1S)}_{\mathrm{Pb}p/pp} = 0.44 \pm 0.15.$$

Understanding this effect is crucial to a correct interpretation of QGP-induced sequential quarkonia suppression observed in PbPb

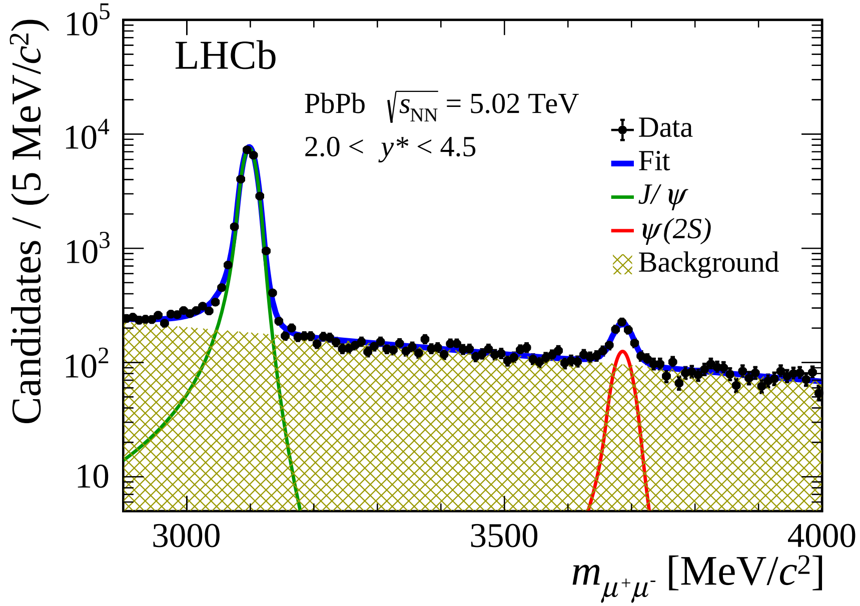


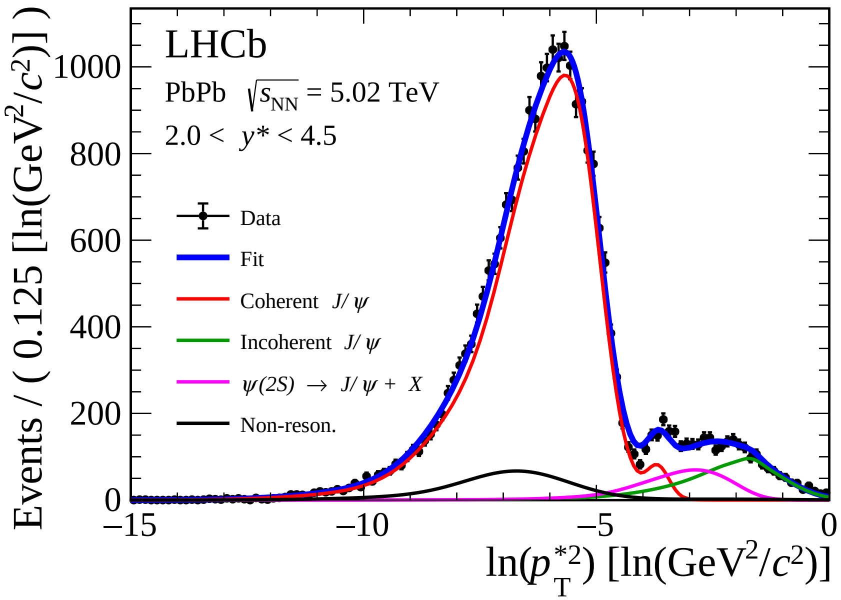
arXiv:1805.09215

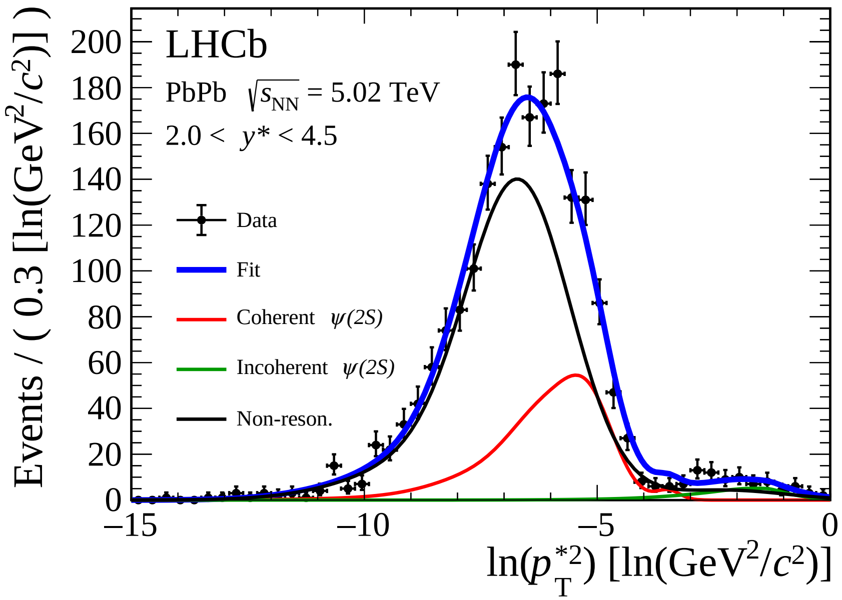
Example: UPC in PbPb @ 5 TeV

JHEP 06 (2023) 146

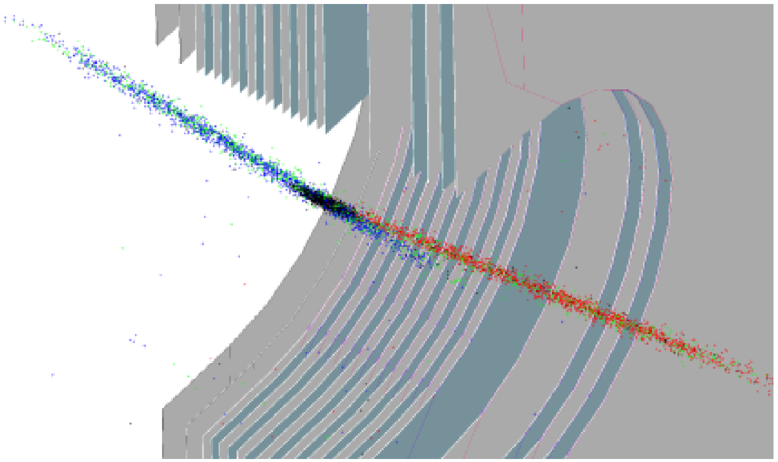
- hadron photo-production enhanced by photon flux ($\propto Z^2$) in PbPb
- sensitive to gluon distribution at x down to 10^{-5}, saturation region
- coherent and incoherent J/ψ photo-production can be distinguished from p_T shape
- 2018 data: 0.23/nb of PbPb @ $\sqrt{s_{NN}}$ =5 TeV





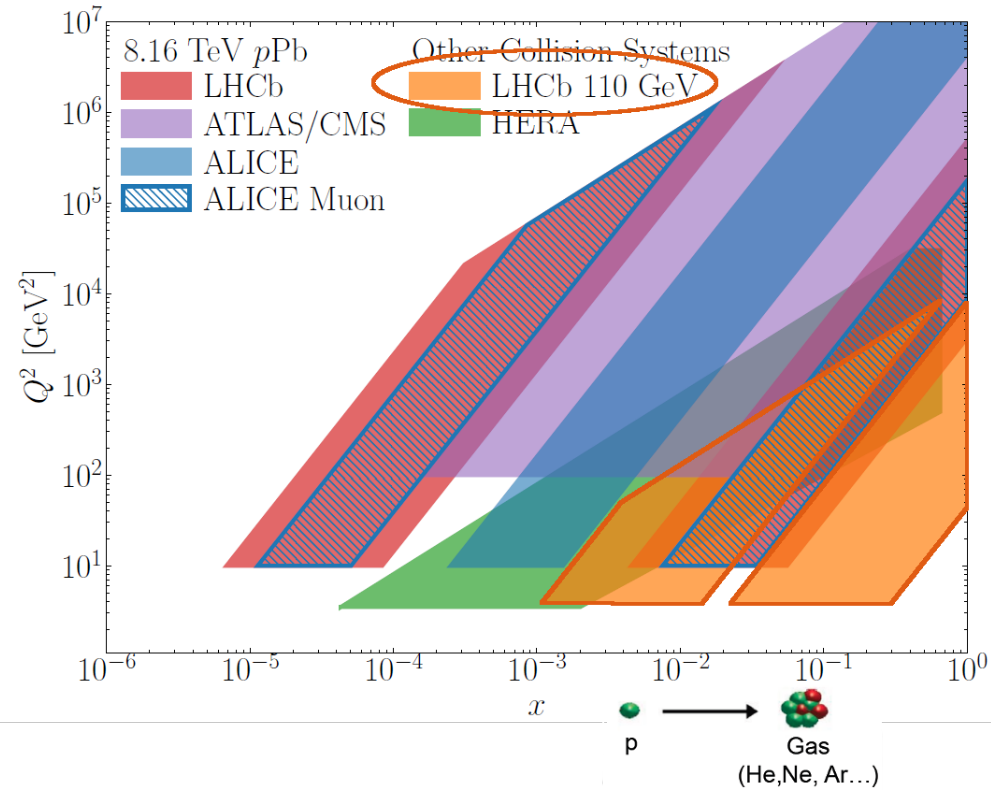


Key feature: the SMOG system

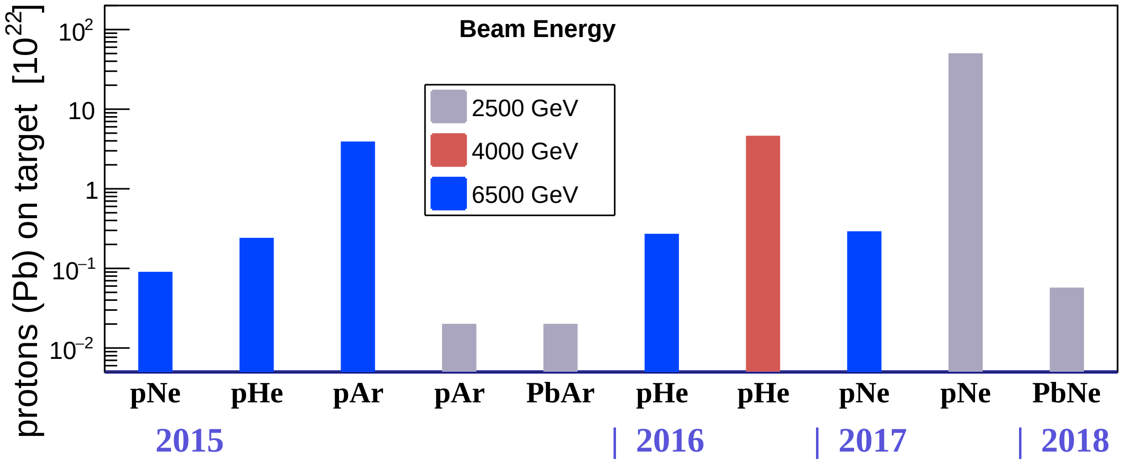


The System for Measuring Overlap with Gas (SMOG) allows to inject small amount of noble gas in the LHC beam pipe.
Turns LHCb into a fixed-target experiment!
Possible targets in Run 2: **He, Ne, Ar**
(more in the future...)
Typical pressure $\sim 2 \times 10^{-7}$ mbar
➡ luminosity up to $10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

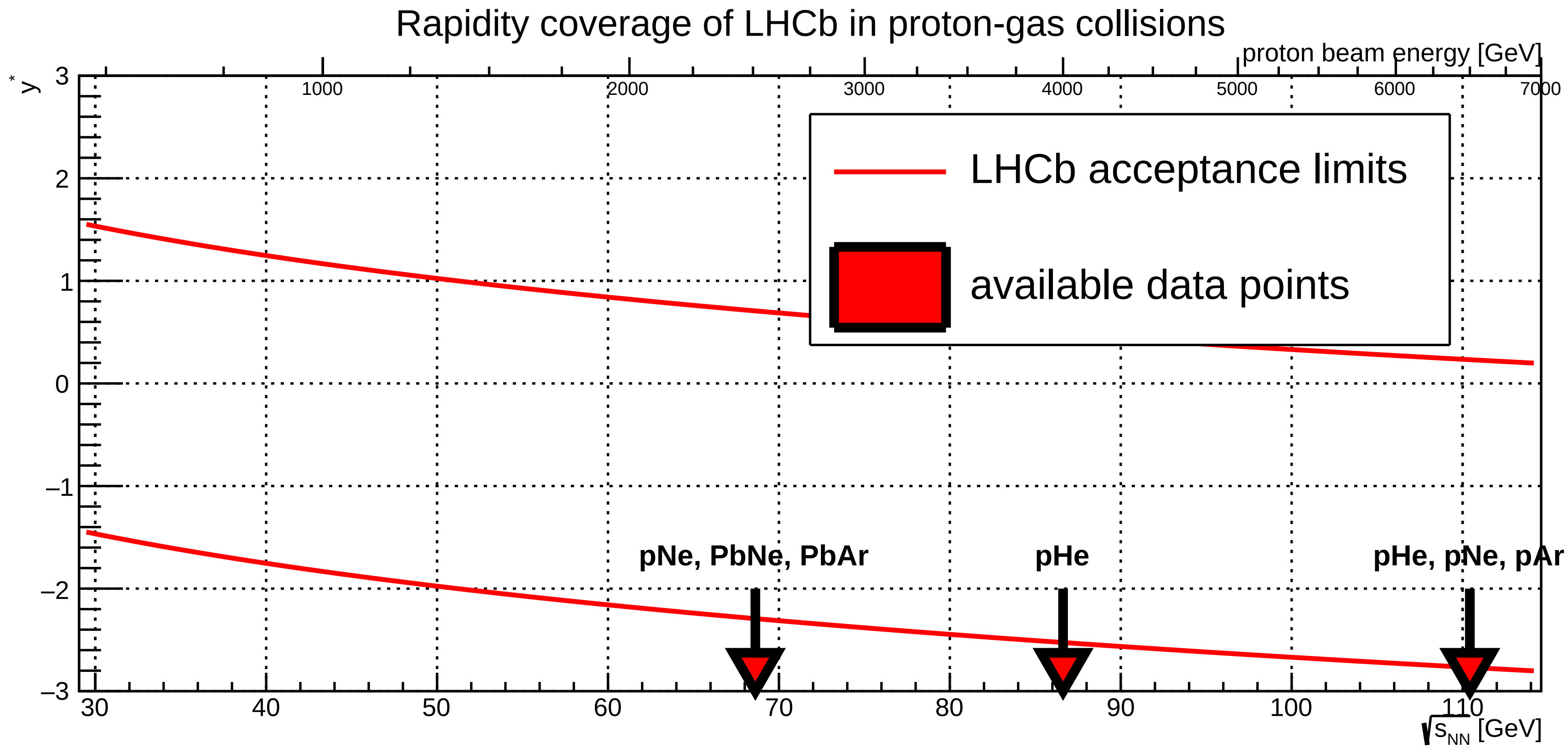
- Collisions at $\sqrt{s_{\mathrm{NN}}} = \sqrt{2E_{beam}M_p}$
  41-110 GeV for $E_{beam} = 0.9 - 6.5$ TeV
  ➡ relative unexplored energy scale between SPS and LHC experiments
- at $\sqrt{s_{\mathrm{NN}}} = 110$ GeV, c.m. rapidity is $-2.8 < y^* < 0.2$ backward detector with access to large x value in target nucleon, for different nuclear targets
  ➡ study nPDF in antishadowing/EMC region, possible intrinsic heavy quark content in nucleons



Fixed Target Samples (Run 2) and Acceptance



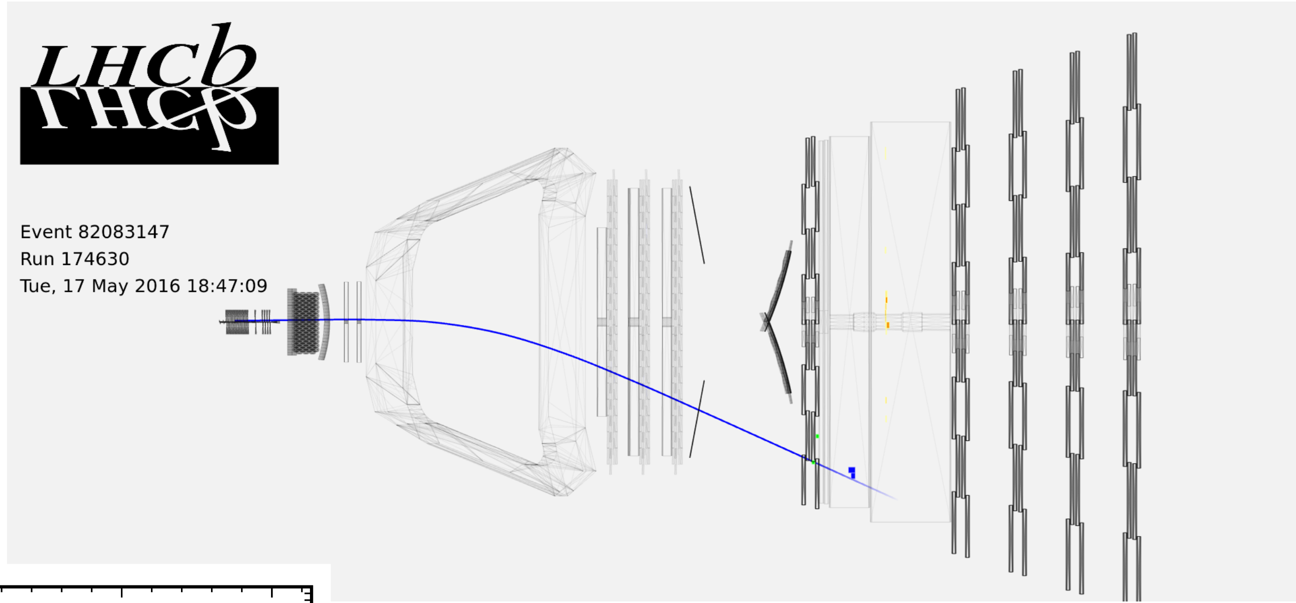
10^{22} POT ~ 5/nb per m of gas

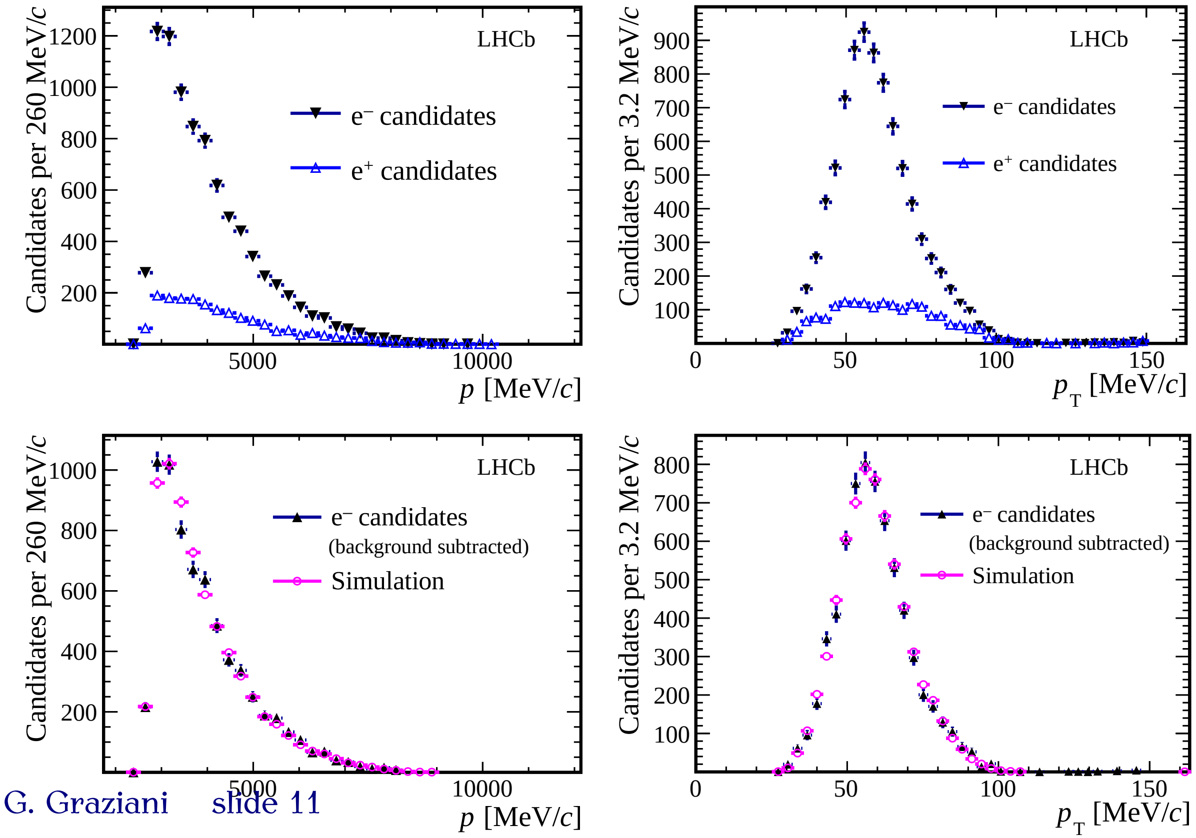


Fixed-target Luminosity

PRL 121 (2018), 222001

- SMOG gas pressure not precisely known. Absolute cross sections normalized to $p\,e^-$ elastic scattering





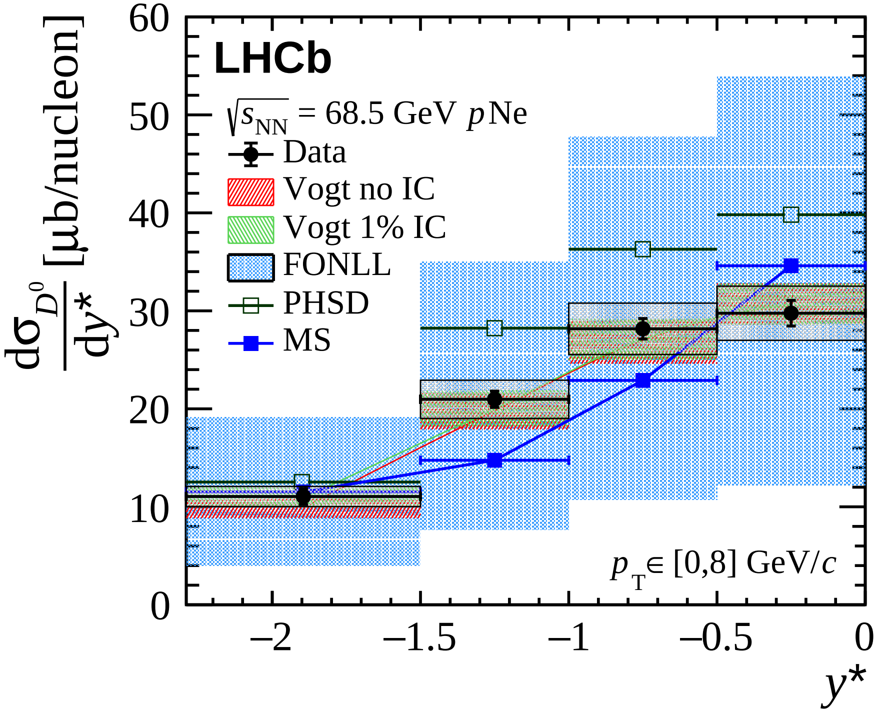
- Background measured from data, using events with single positive track
- Systematic uncertainty of 6%, due to low electron reconstruction efficiency (∼ 16%)

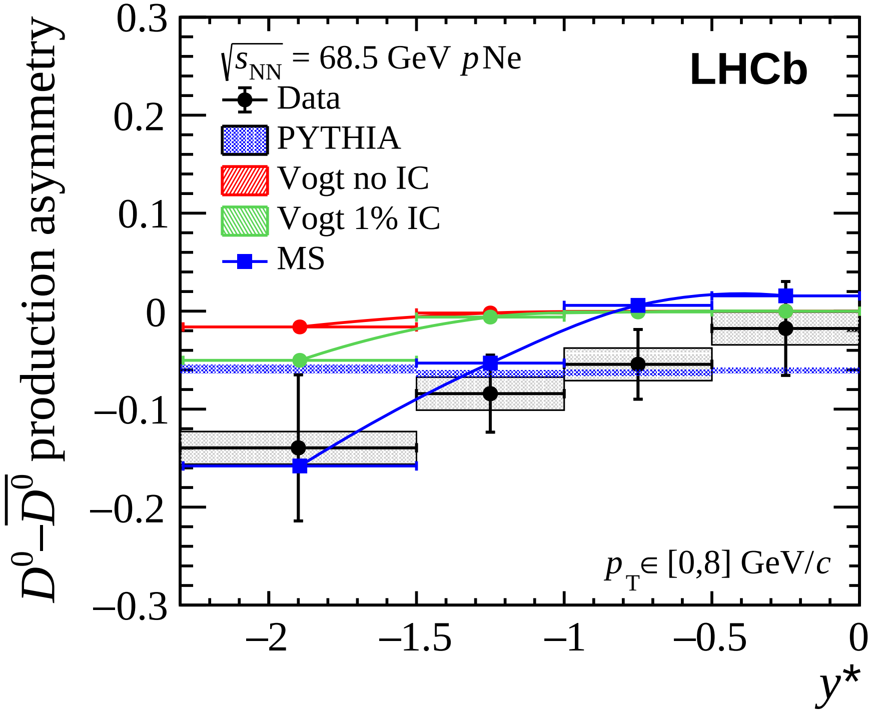
Charm production in fixed-target collisions

System	$\sqrt{s_{NN}}$	Measurement	Publication
p → He	86.6 GeV	• J/ψ and D^0 total and differential cross sections in y^* and p_T	PRL 122 (2019) 132002
p → Ne	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
p → Ar	110.4 GeV	• J/ψ and D^0 differential distributions in y^* and p_T	PRL 122 (2019) 132002
Pb → Ne	68.5 GeV	• J/ψ and D^0 cross section ratio	EPJC 83 (2023) 658

first fixed-target AB measurement at the LHC!

D^0 production



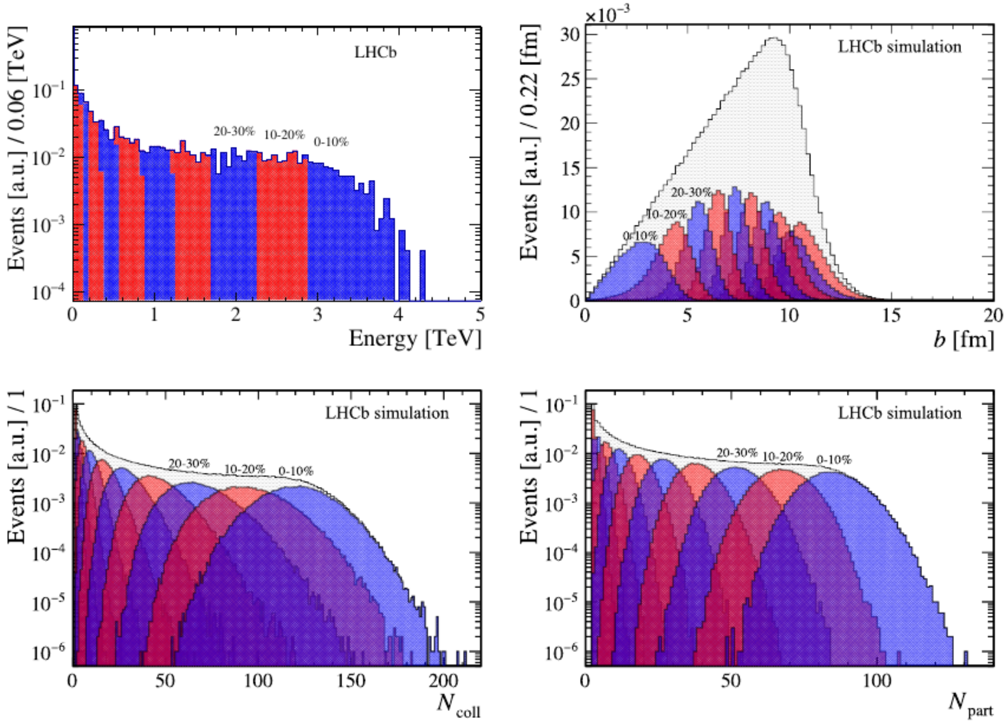


EPJC 83 (2023) 541

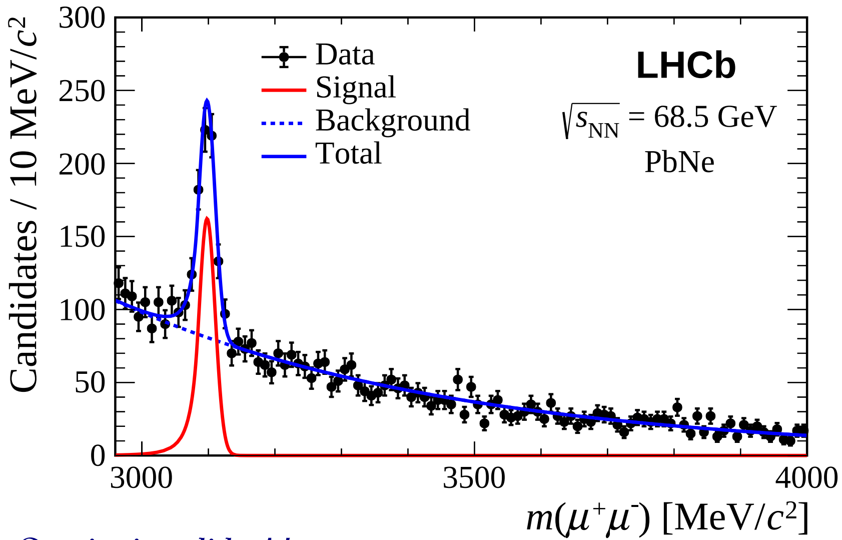
- most backward production sensitive to x up to ~ 0.4
- production better described by models including 1% of intrinsic charm (“Vogt ‘%” and “MS”), though no clear conclusion
- $(D^0\text{-}\overline{D}^0)/(D^0+\overline{D}^0)$ production asymmetry up to -15% observed in backward bin, likely hadronization with high-x valence quark (beam drag effect). Not reproduced in PYTHIA 8.

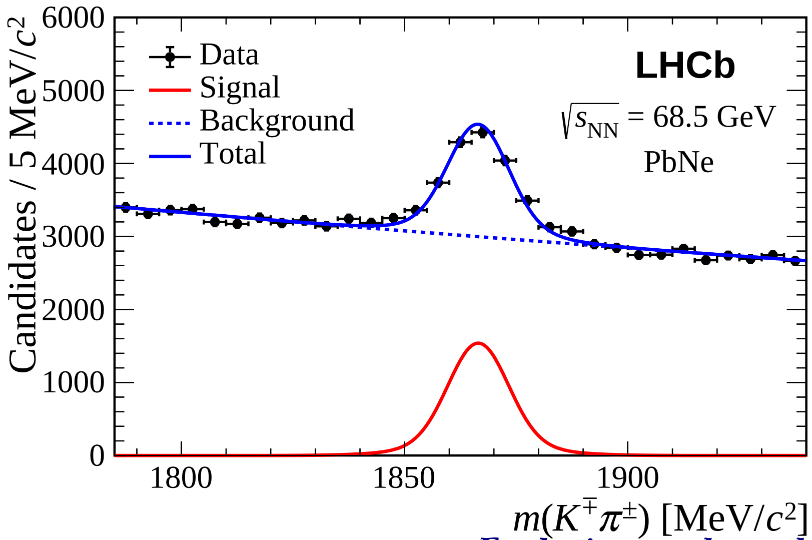
The PbNe sample

- 214 hours of recorded data with Ne injected during the LHCb 2018 PbPb run. Luminosity $O(0.1\,\mathrm{nb}^{-1})$, $\sqrt{s_{NN}}$ (PbNe) = 69 GeV
- $\sim$30M collisions recorded in 40 cm of gas in the VELO region
- fit to Glauber model of total energy in e.m. CAL (on MB triggered events) to get centrality, N_{coll}
- $\sim$ 550 J/ψ and 5700 D^0 candidates after background subtraction



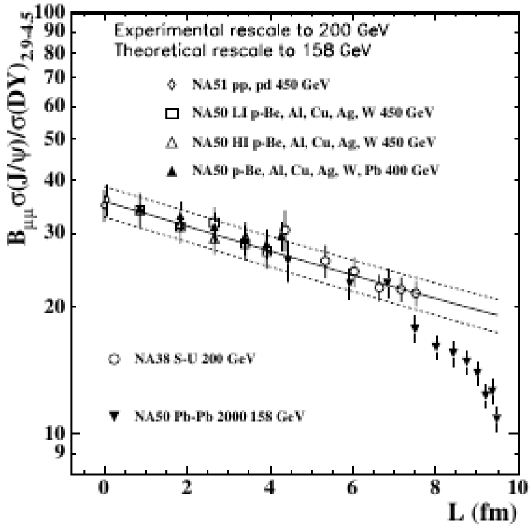
LHCb-DP-2021-002



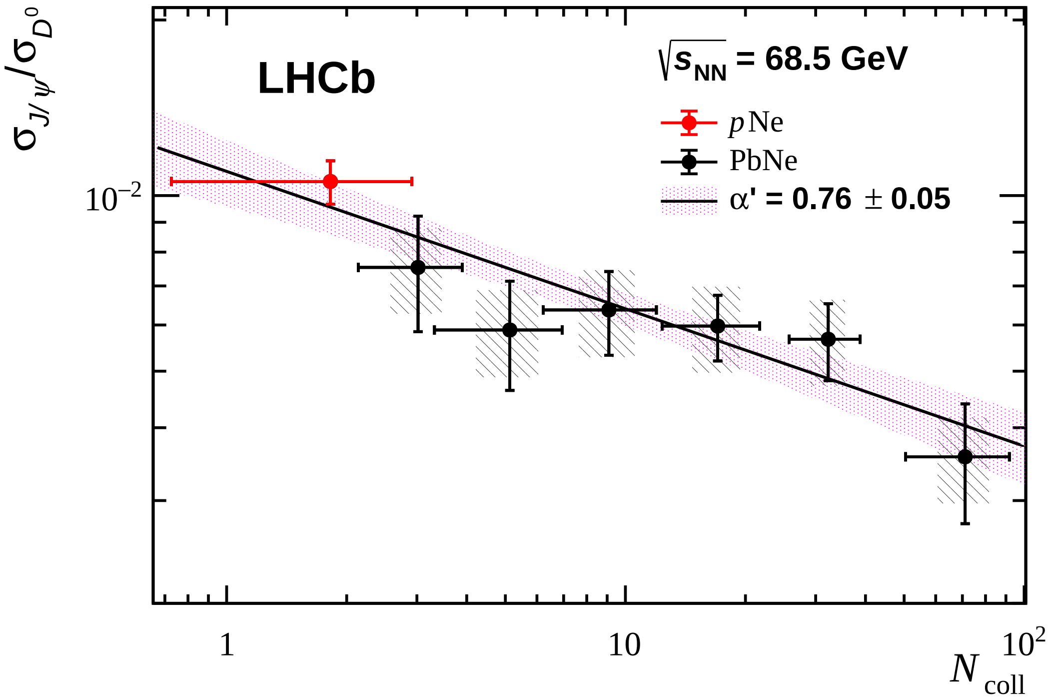


J/ψ suppression in PbNe collisions

- PbNe collisions at $\sqrt{s_{NN}} = 68.5$ GeV probe same energy density scale where NA50 observed anomalous J/ψ suppression in PbPb
- cold nuclear matter effects can be constrained by same measurement in pNe collisions at the same energy



NA50, EPJC 39 (2005) 335



EPJC 83 (2023) 658

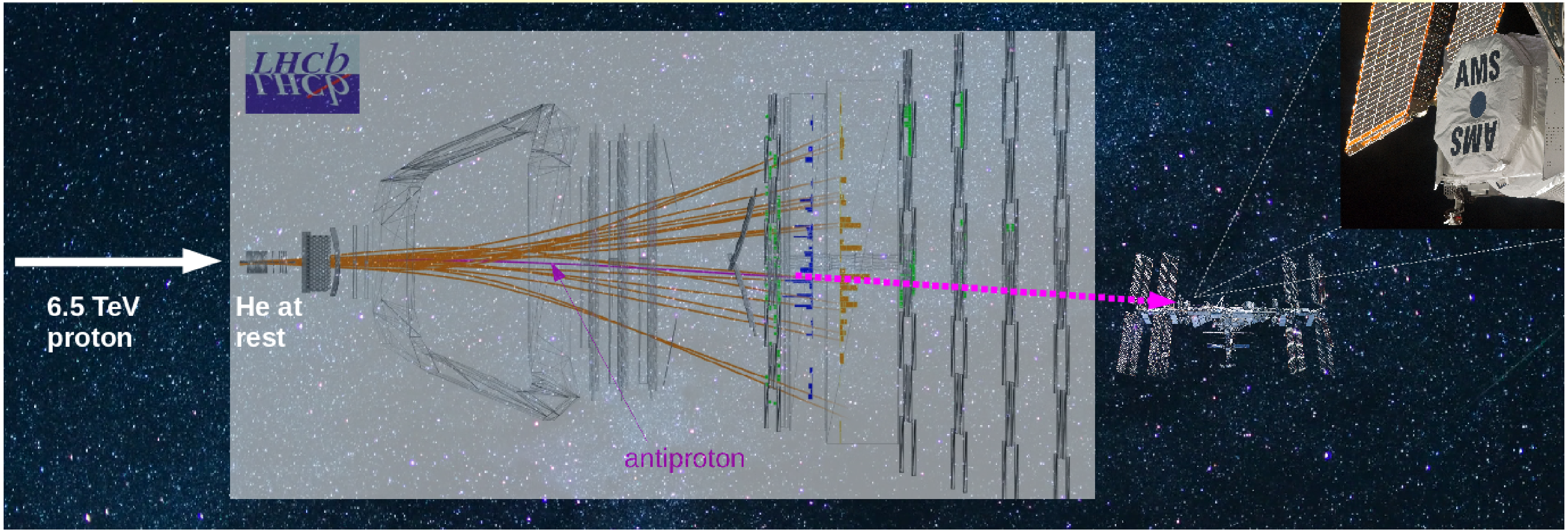
- expected multiplicity of $c\bar{c}$ pairs ~ 1
  ➡ no recombination effects
- $J/\psi/D^0$ ratio measured as a function of Ncoll using a Glauber model. Data compatible with

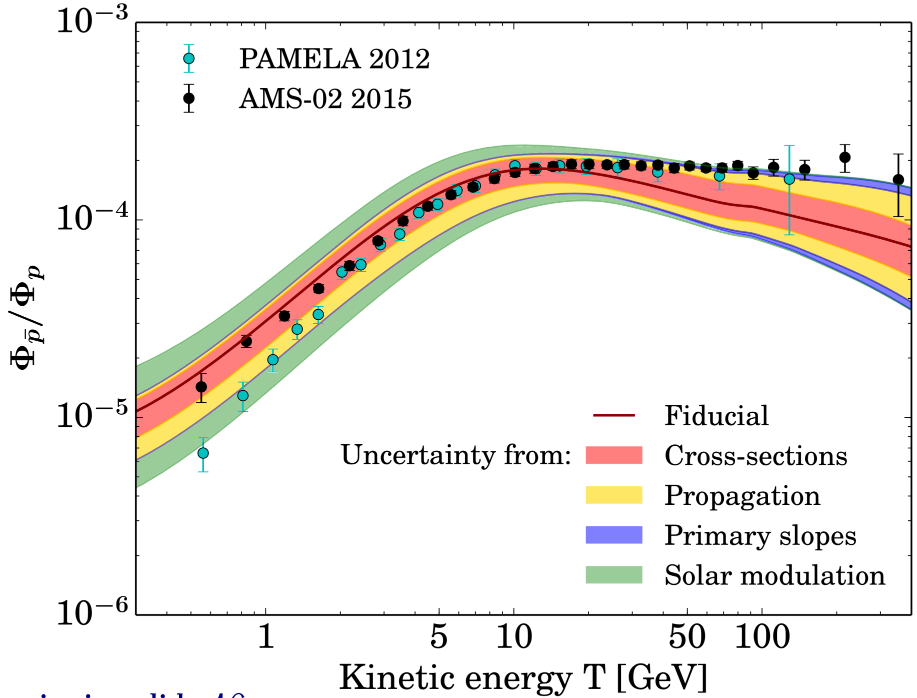
$$\sigma(J/\psi)/\sigma(D^0) \propto N_{coll}^{(\alpha'-1)}$$

with $\alpha' = 0.76 \pm 0.05$, in agreement with previous pA results PLB410 (1997) 337

➡ no hint for QGP-like anomalous J/ψ suppression

SMOG for astroparticle physics

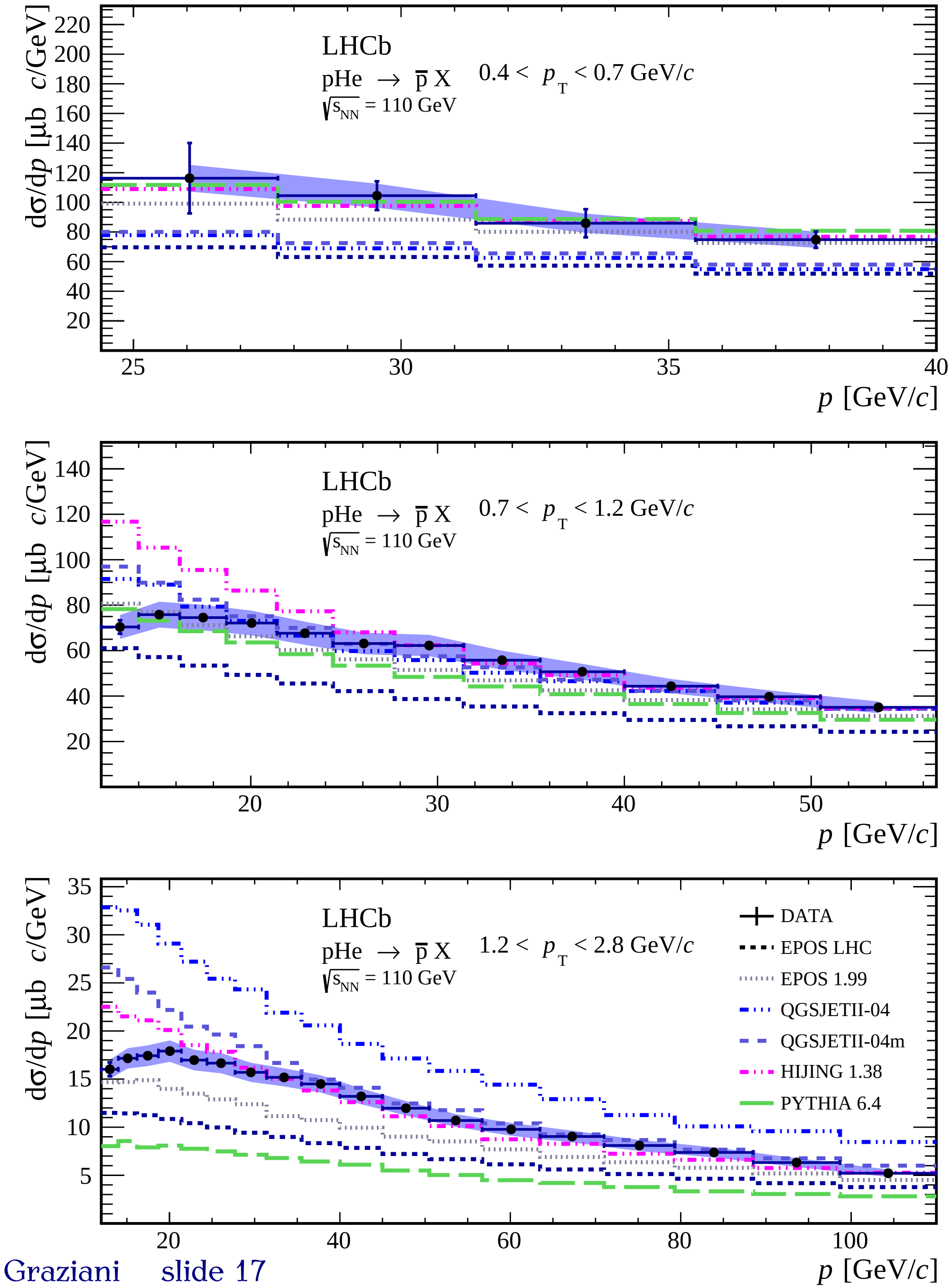




Giesen et al., JCAP 1509, 023

- pHe in SMOG reproduces collisions of cosmic rays on InterStellar medium
- provides key inputs to understanding antimatter production in the cosmos (powerful probe for dark matter)
- other unique measurements of interest to cosmic-ray physics (modeling of atmospheric showers, charm PDF for atmospheric UHE neutrinos)

Prompt antiproton production in pHe



PRL 121 (2018), 222001

Result for **prompt** production (excluding weak decays of hyperons), compared to

EPOS LHC PRC92 (2015) 034906
EPOS 1.99 Nucl.Phys.Proc.Suppl. 196 (2009) 102
QGSJETII-04 PRD83 (2011) 014018
QGSJETII-04m Astr. J. 803 (2015) 54
HIJING 1.38 Comp. Phys. Comm. 83 307
PYTHIA 6.4 (2pp + 2pn) JHEP 05 (2005) 026

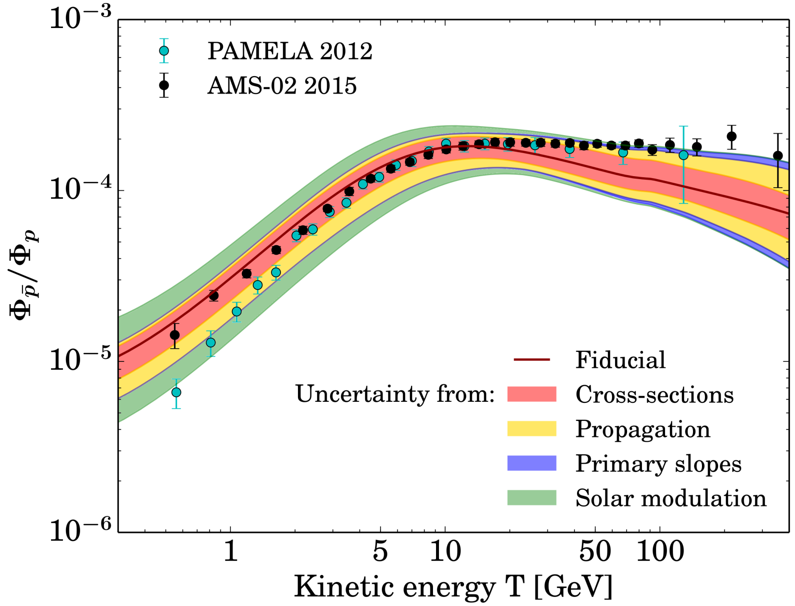
The "visible" inelastic cross section (yield of events reconstructible in LHCb) is compatible with simulation based on EPOS LHC:

$$\sigma_{vis}^{LHCb}/\sigma_{vis}^{EPOS-LHC} = 1.08 \pm 0.07 \pm 0.03$$

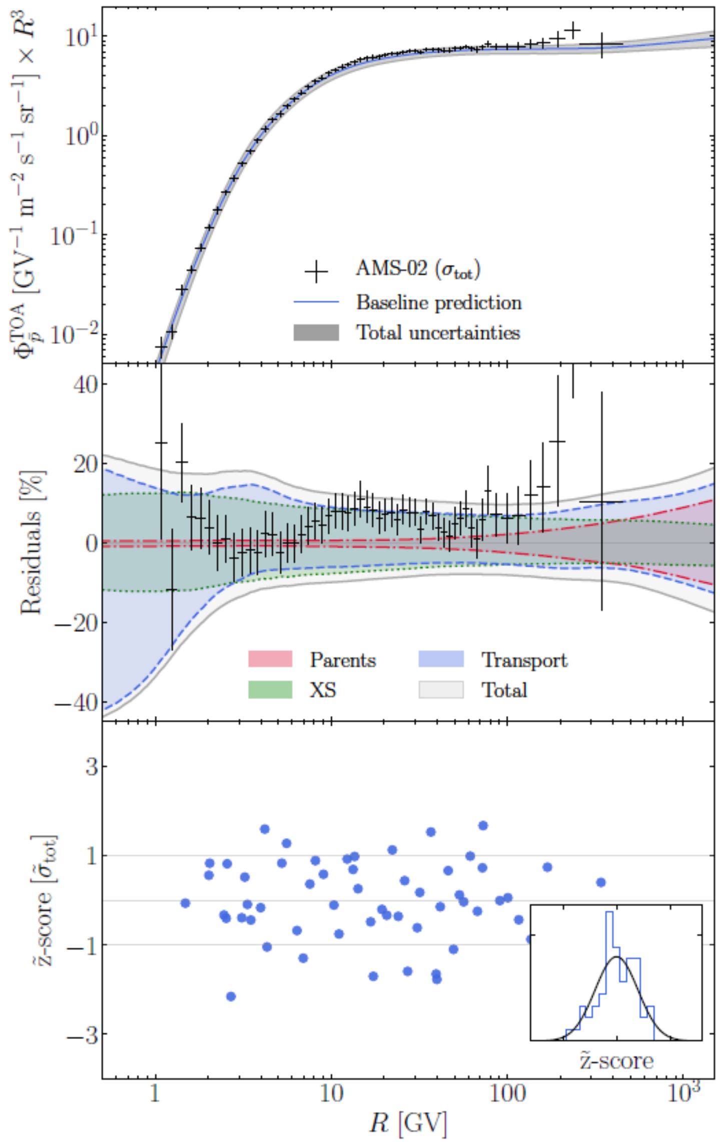
➡ excess of $\bar{p}$ yield over EPOS LHC (by factor ~ 1.5) mostly from $\bar{p}$ multiplicity

Impact on secondary cosmic $\overline{p}$ model

2015 Giesen et al., JCAP 1509, 023



2019 Boudad et al., arXiv:1906.07119



- Significant shrinking of uncertainty for the predicted secondary antiproton flux from the use of LHCb and NA61 (pp) new data (plus other improvements)
- LHCb results allowed to constrain scaling violation when extrapolating x-section toward high energy
- Models now in better agreement with AMS data, notably at high energy
- Cross-section uncertainty is still limiting model accuracy

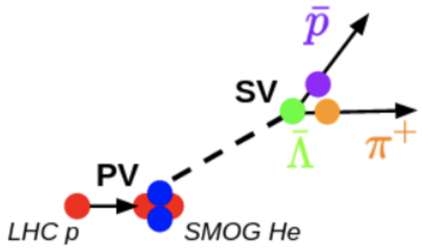
$\overline{p}$ from antihyperons in pHe @110 GeV

EPJC 83, 543 (2023)

- Analysis recently extended to detached $\overline{p}$ from anti-hyperon decays ($\sim$ 40% of $\overline{p}$ production)
- Two complementary approaches followed

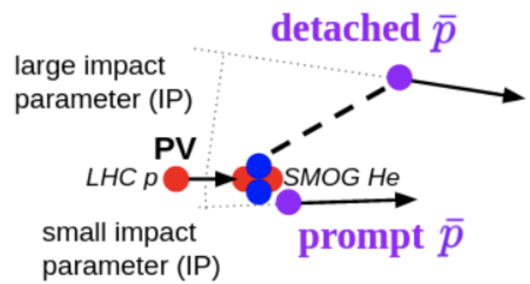
Exclusive approach

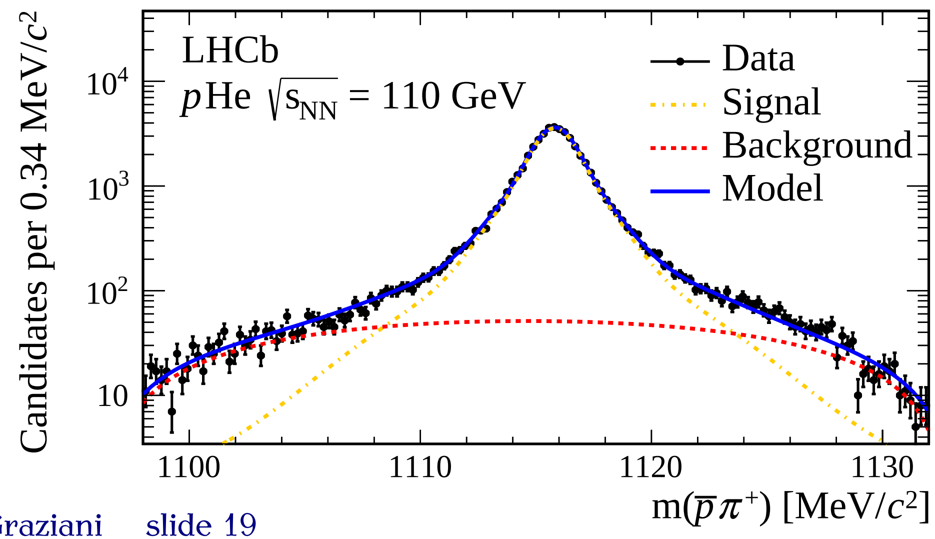
$$R_{\bar{\Lambda}} = \frac{\sigma(p\text{He} \to (\bar{\Lambda}_{\text{prompt}} \to \bar{p}\pi^+)X)}{\sigma(p\text{He} \to \bar{p}_{\text{prompt}} X)}$$

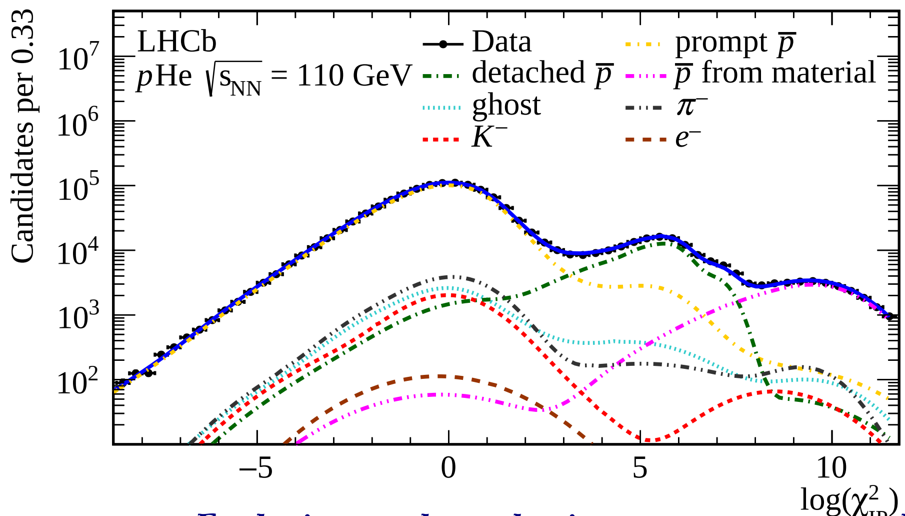


Inclusive approach

$$R_{\overline{H}} \equiv \frac{\sigma(p\text{He} \to \overline{H}X \to \bar{p}X)}{\sigma(p\text{He} \to \bar{p}_{\text{prompt}}X)} \qquad \bar{H} = \bar{\Lambda}, \bar{\Sigma}, \bar{\Xi}, \bar{\Omega}$$







Detached Antiprotons in pHe: results

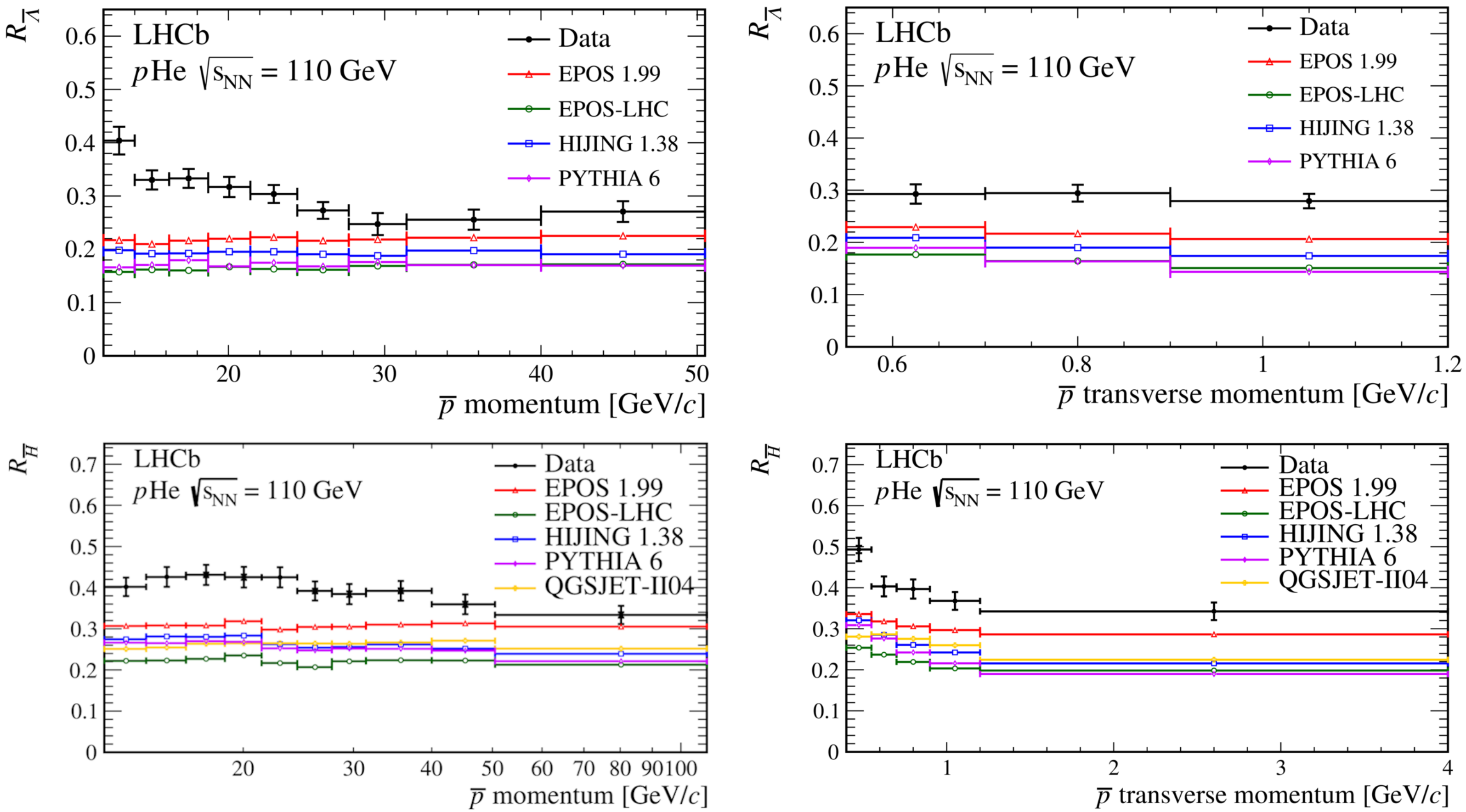
EPJC 83, 543 (2023)

Exclusive approach

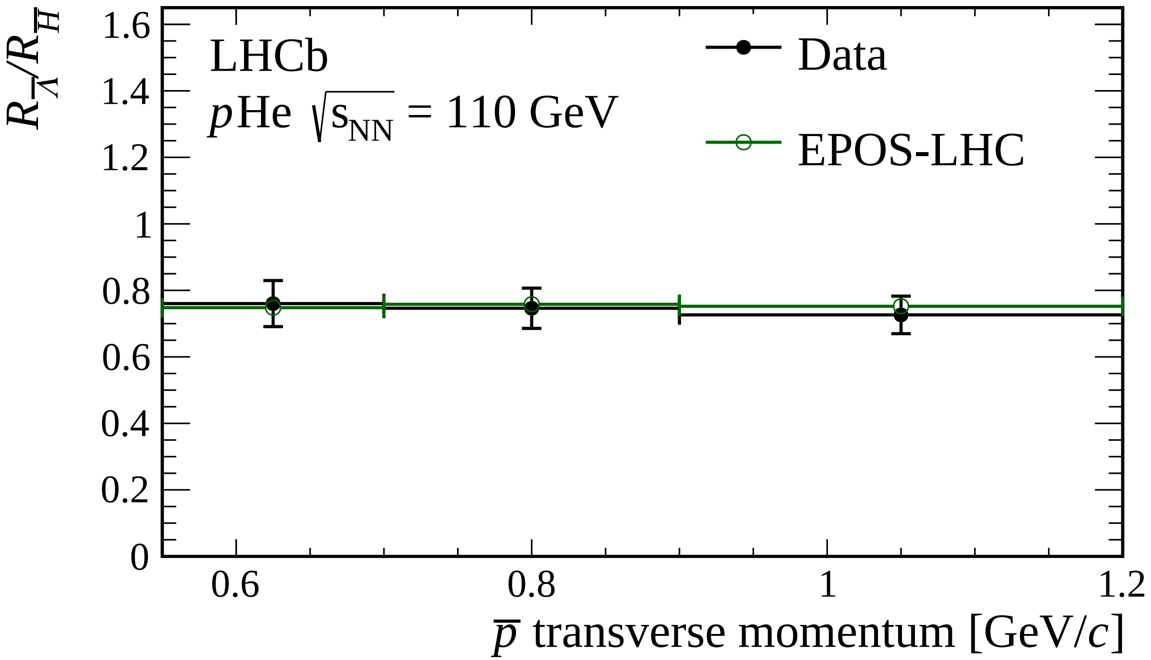
$$R_{\bar{\Lambda}} = \frac{\sigma(p\mathrm{He} \rightarrow (\bar{\Lambda}_{\mathrm{prompt}} \rightarrow \bar{p}\pi^+)X)}{\sigma(p\mathrm{He} \rightarrow \bar{p}_{\mathrm{prompt}} X)}$$

Inclusive approach

$$R_{\bar{H}} \equiv \frac{\sigma(p\mathrm{He} \rightarrow \bar{H}X \rightarrow \bar{p}X)}{\sigma(p\mathrm{He} \rightarrow \bar{p}_{\mathrm{prompt}} X)} \qquad \bar{H} = \bar{\Lambda}, \bar{\Sigma}, \bar{\Xi}, \bar{\Omega}$$

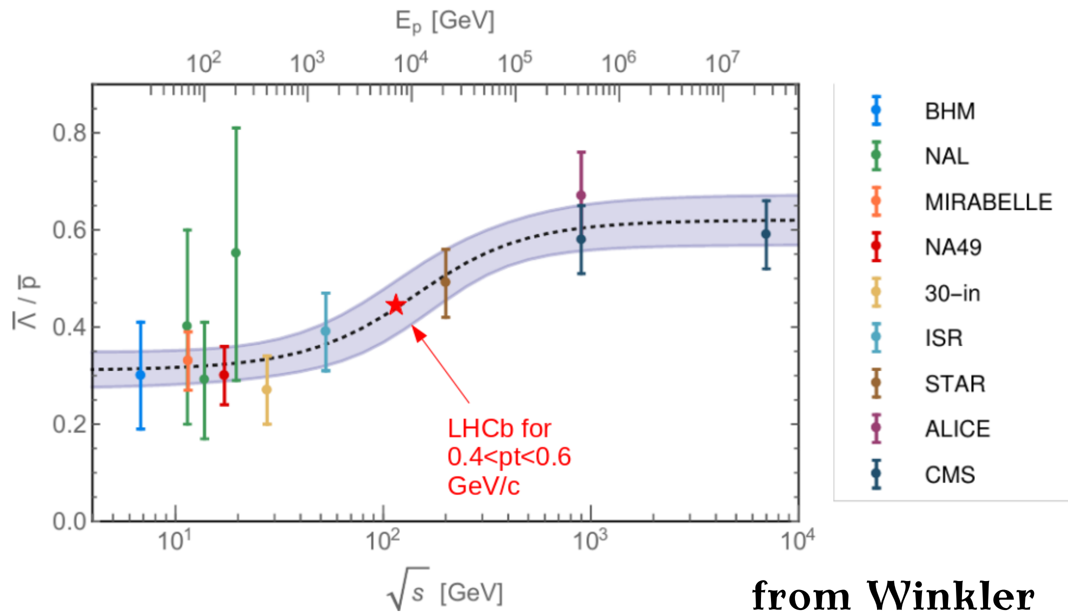


Both approaches indicate larger antihyperon production than predicted by most commonly used hadronic models



- Nice agreement of the excl.$\overline{\Lambda}$/incl.antihyperon ratio with (robust) theoretical expectations

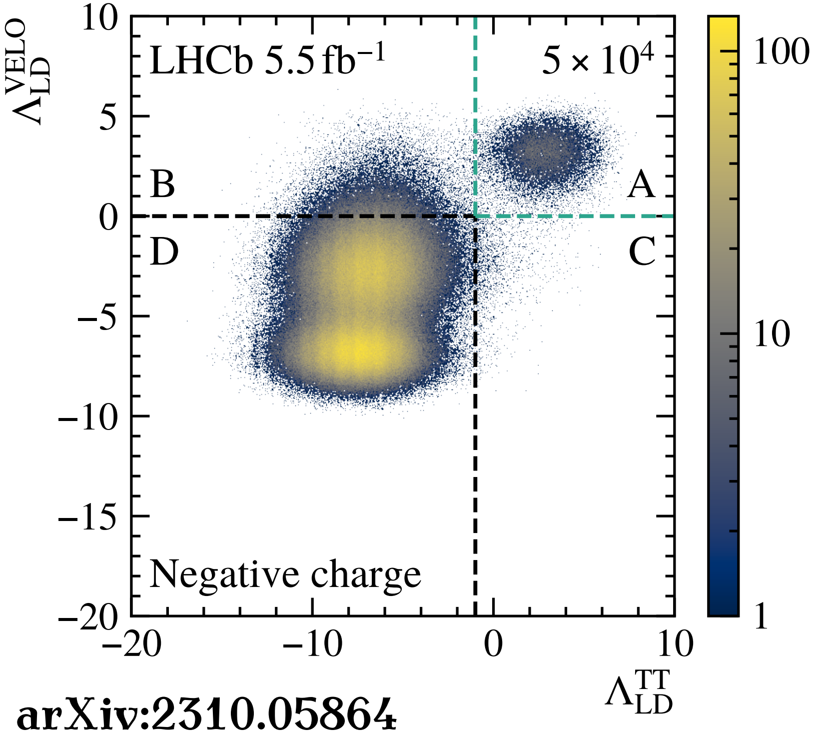
- Precise results at 100 GeV scale, at the onset of strangeness enhancement (observed at colliders)
- Significant dependence on kinematics observed (usually neglected in cosmic secondary $\overline{p}$ calculations)



from Winkler

Antinuclei in fixed target @ LHCb?

- LHCb was not designed for light nuclei identification
- However, recently the capability to isolate He/$\overline{\text{He}}$ candidates through dE/dx in the tracking system was demonstrated



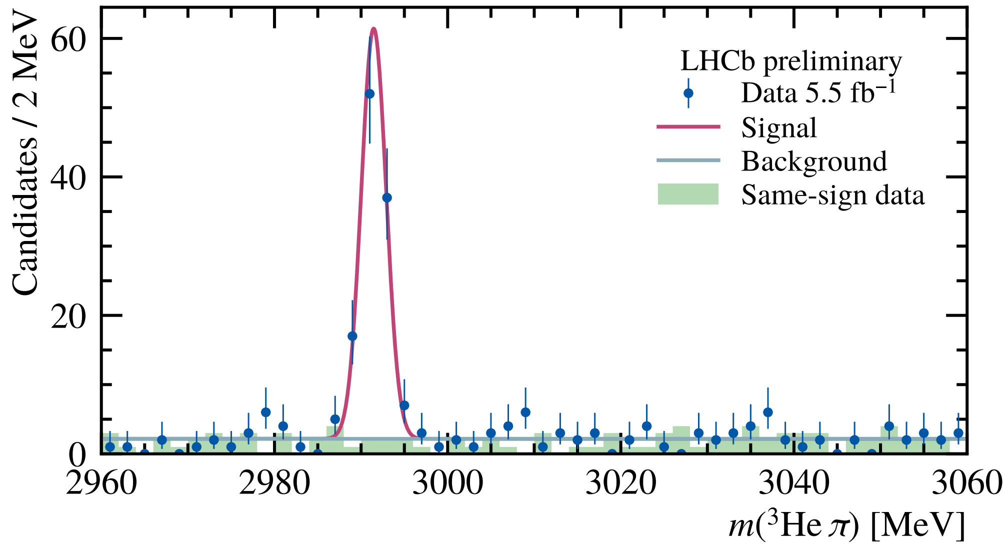
arXiv:2310.05864

Isolated $\overline{\text{He}}$ sample (region A) in LHCb *pp* data

- (anti)hypertriton decays

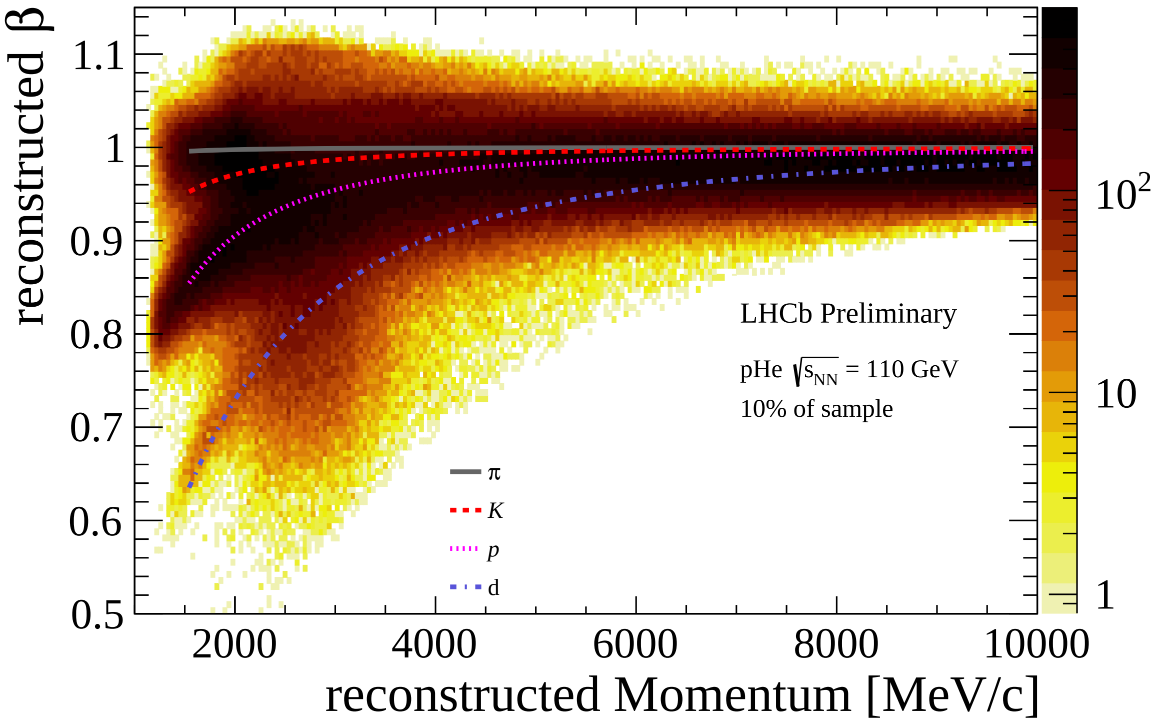
$$^{3}_{\Lambda}\text{H} \rightarrow {}^{3}\text{He}\pi^{-}$$

were seen in *pp* collisions at LHCb!



LHCb-CONF-2023-002

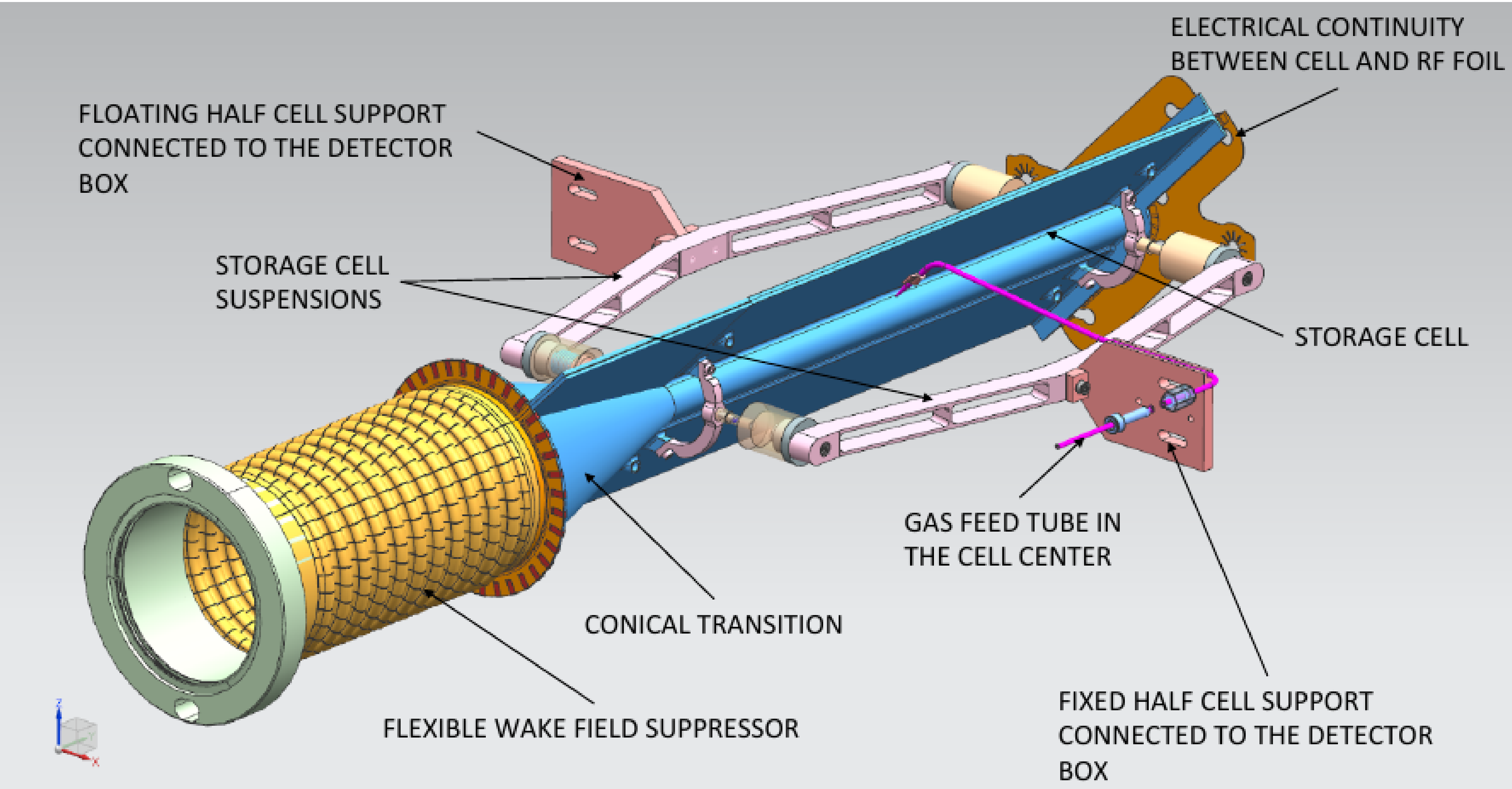
- low-momentum $d/\bar{d}$ can also be identified through TOF in outer tracker (work ongoing)
- Fragments of SMOG target nuclei can in principle be identified (down to $\eta^* = -3$)
- ⚠ unfortunately, ion identification capability not expected in the current upgraded detector



Velocity vs momentum for tracks reconstructed in LHCb pHe data

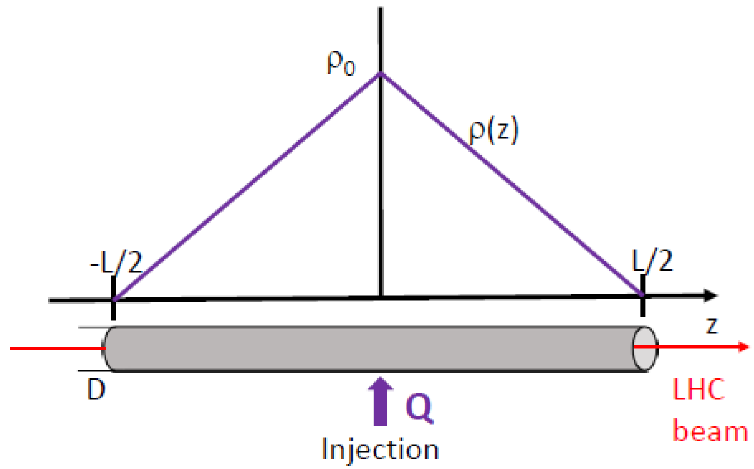
LHCb-FIGURE-2023-017

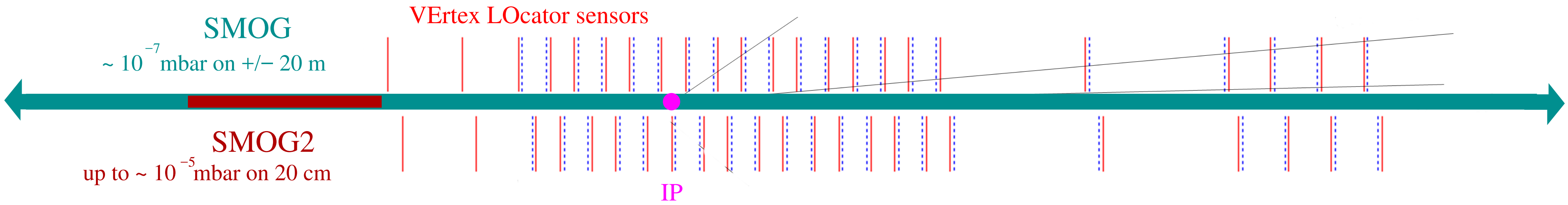
SMOG2
the next big step



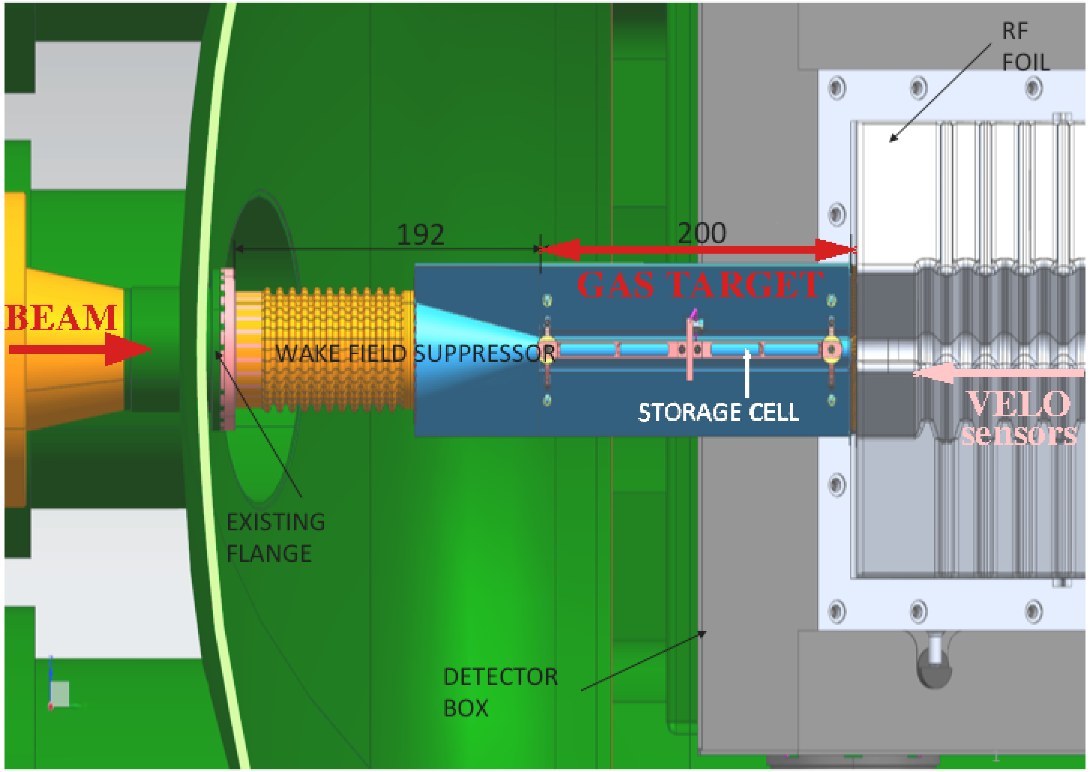
The gas target upgrade

- Major LHCb detector upgrade for the LHC Run 3, including upgraded VErtex LOcator (microstrip → pixel)
- The new VELO integrates a new fixed target device SMOG2, based on a storage cell:
  - increase effective luminosity with same gas flow
  - inject other gas species, as H, D, N, O, Kr, Xe
  - precise control of the gas density (improved accuracy on luminosity determination)
  - spatial separation between beam-gas and beam-beam collision regions
    ➡ easier **simultaneous data-taking**



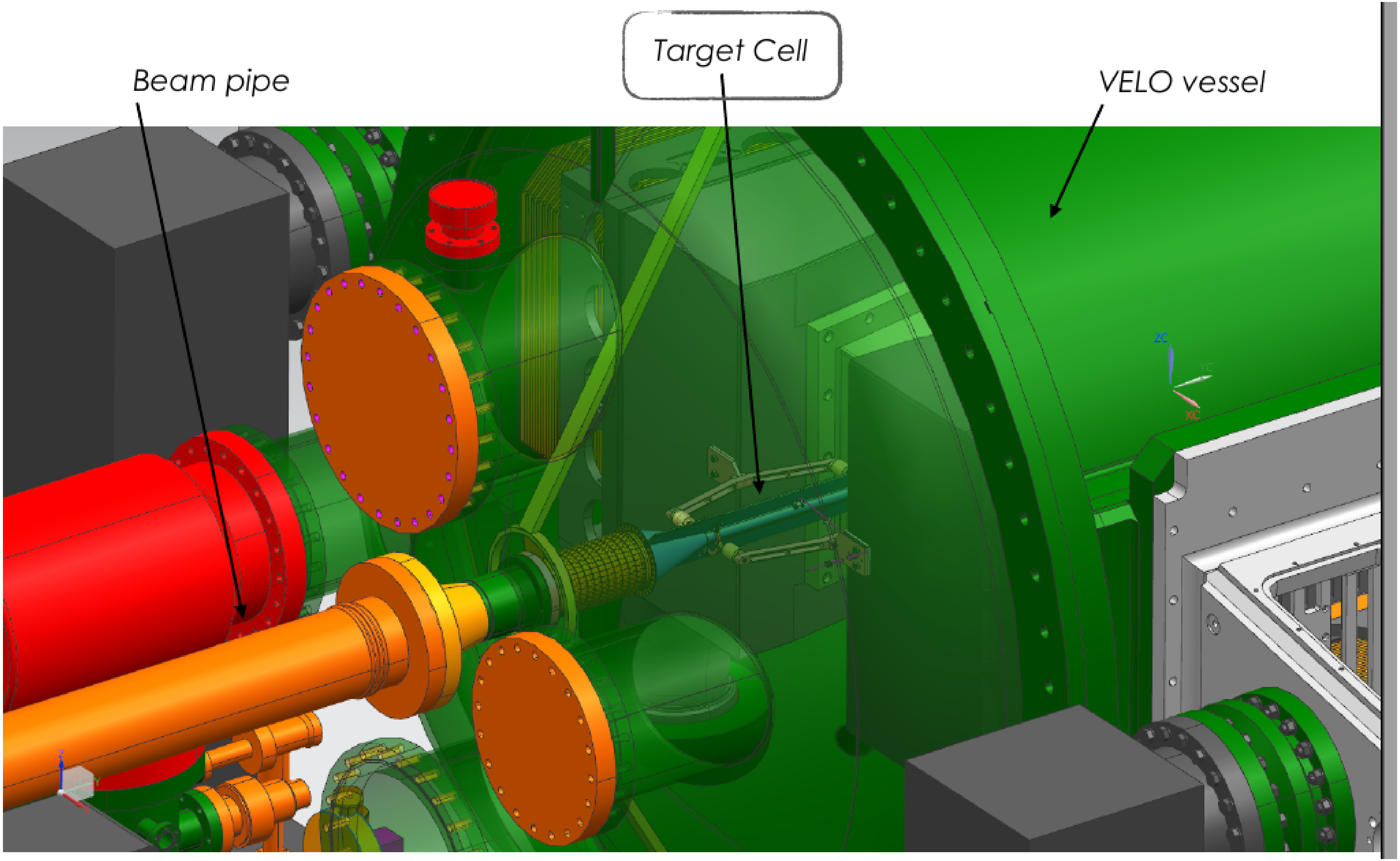


The SMOG2 gas target

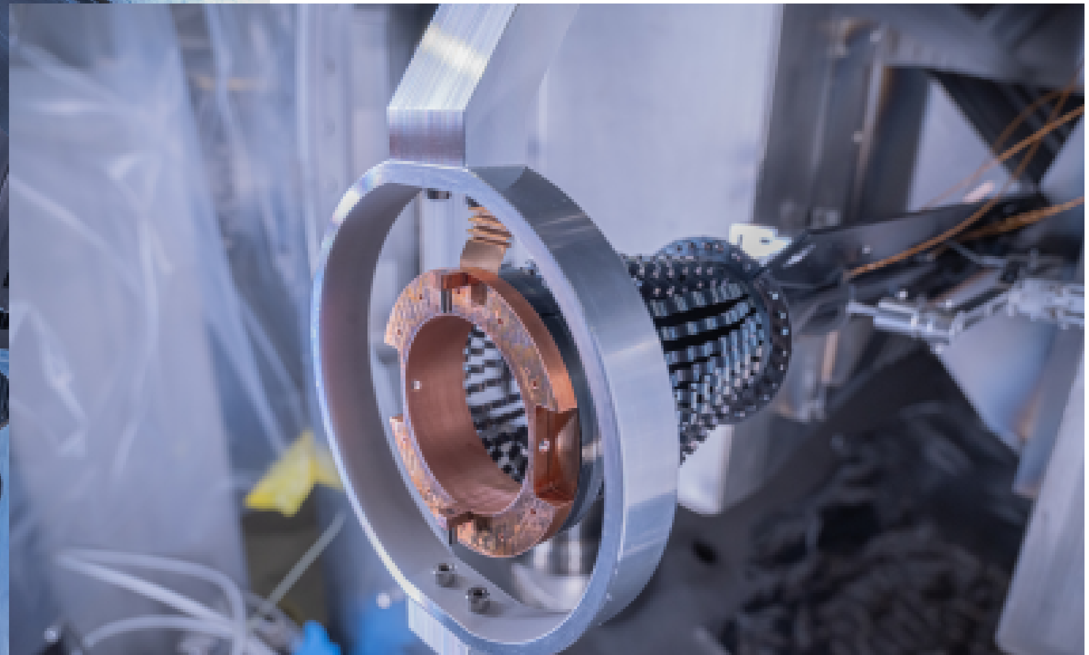


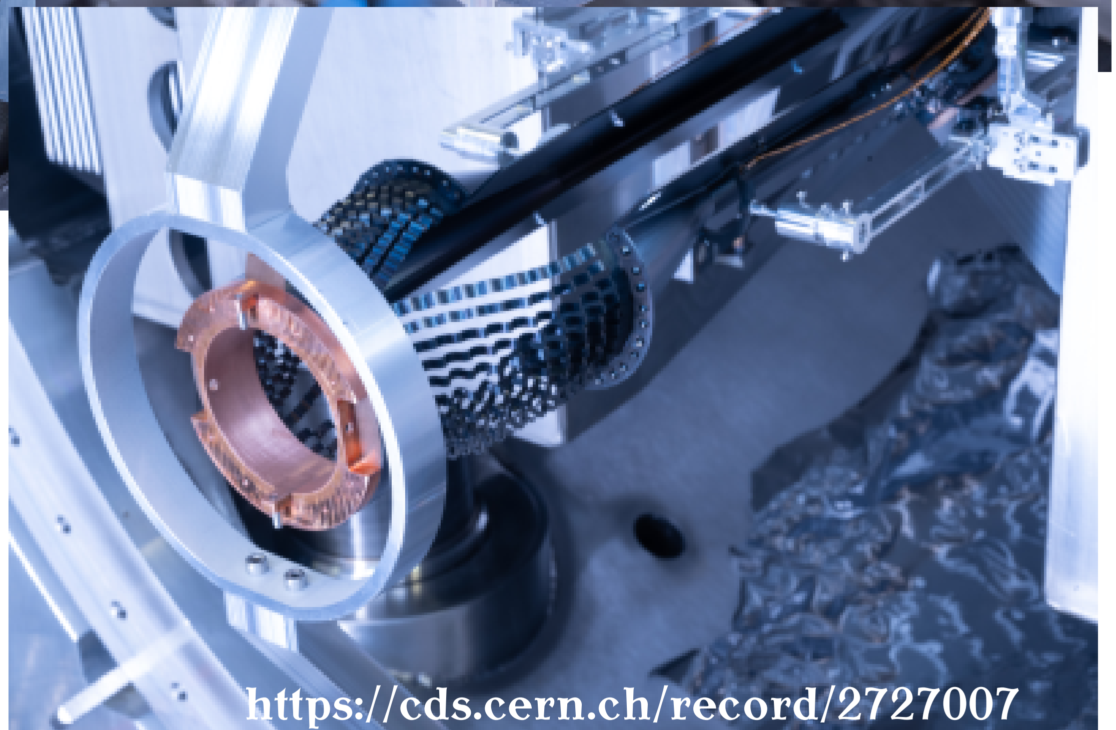
- 20-cm long storage cell, 5 mm radius around the beam, just upstream the LHCb VELO
- Made of two rectractable halves as the rest of VELO
- Up to x100 higher gas density with same gas flow of current SMOG
- Gas density measured with ~ 2% accuracy via Gas Feed System
- Fast switch between gas species

- TDR approved by LHCC in 2019 **CERN-LHCC-2019-005I**
- Installed in the LHCb cavern on august 2020


Beam pipe
Target Cell
VELO vessel

SMOG2 installation

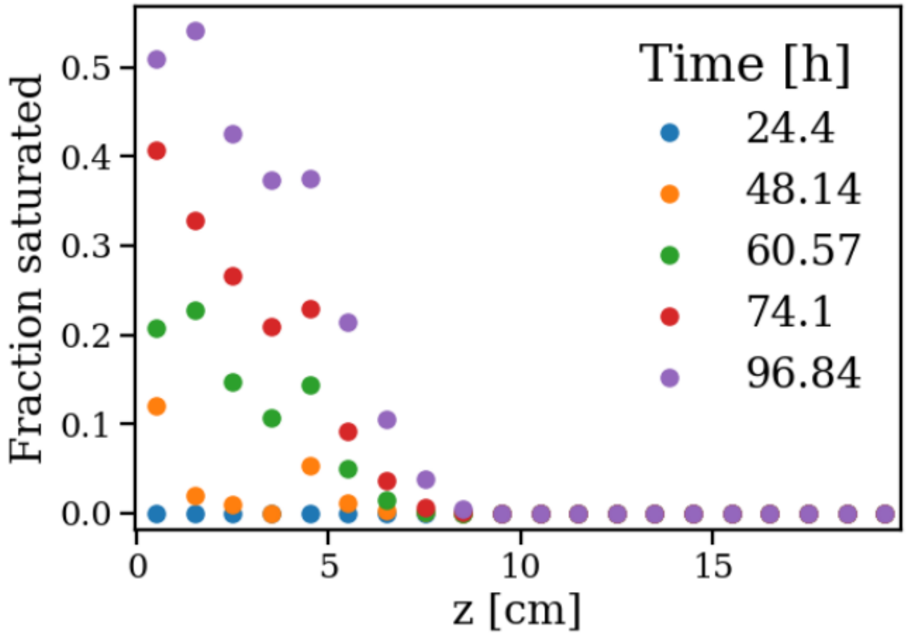




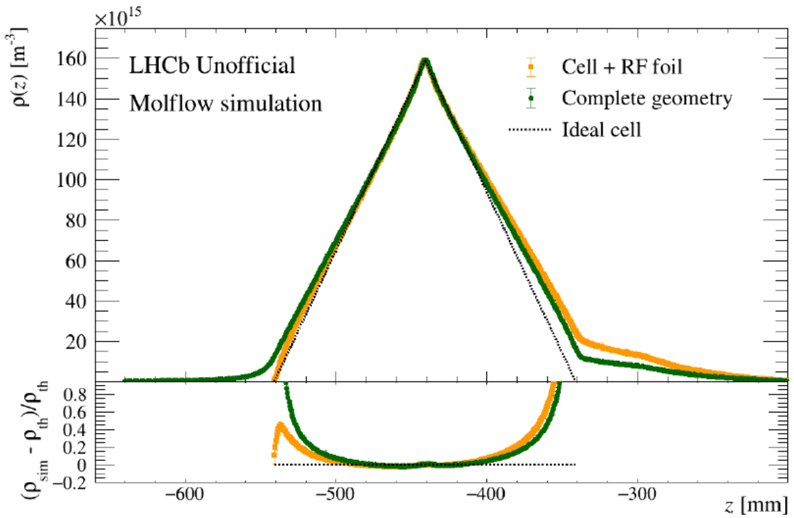
https://cds.cern.ch/record/2727007

Non-noble gas injection

- Injection of non-noble gas species can affect the beam elements, notably deteriorate the NEG coatings, increasing desorption and secondary electron emission, potentially harming the LHC beam operations.
- Hydrogen can also diffuse in the bulk and cause a peel-off of the coating (embrittlement)
- Detailed numerical simulations have been performed to estimate the time-dependent impact of the planned gas injection with H_2 and N_2, using a custom version of the Molflow+ molecular flow Monte Carlo simulator
- Simulation of 96 hours of H_2 gas flow and 10 hours of N_2 gas flow: the level of NEG saturation has been shown to be acceptable, limited in a region < 20 cm long



C.Lucarelli, CERN-PBC-Notes-2023-003



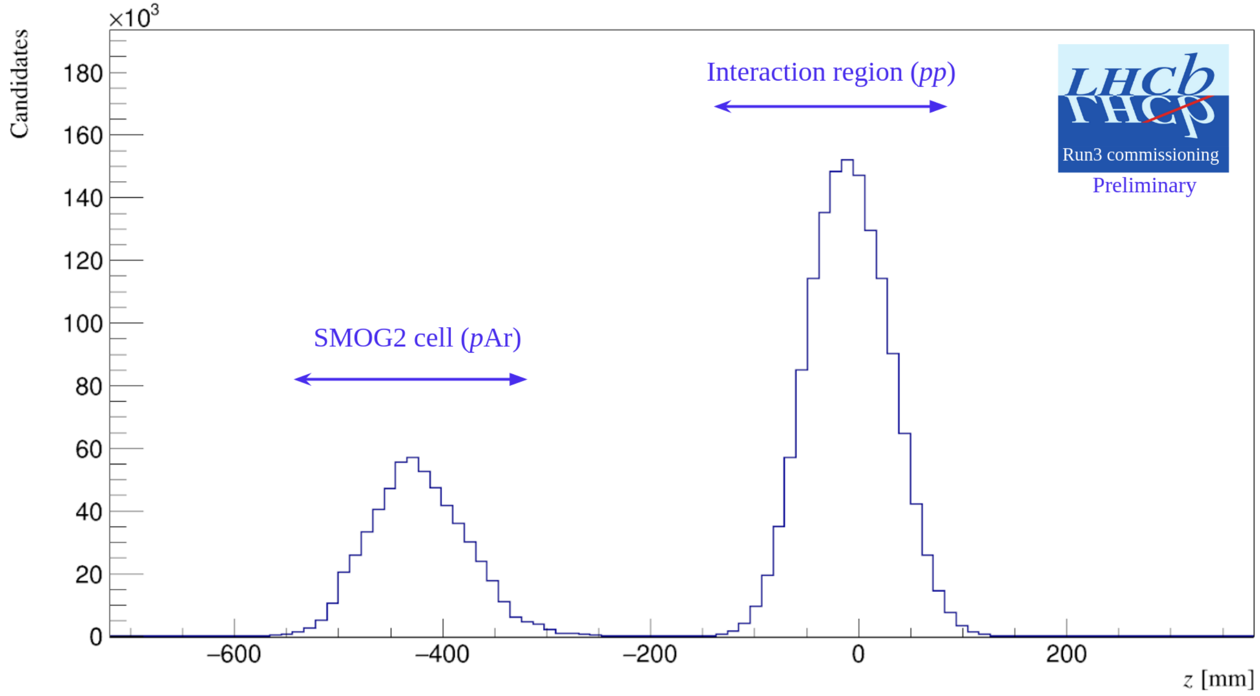
Simulated pressure profile with real geometry

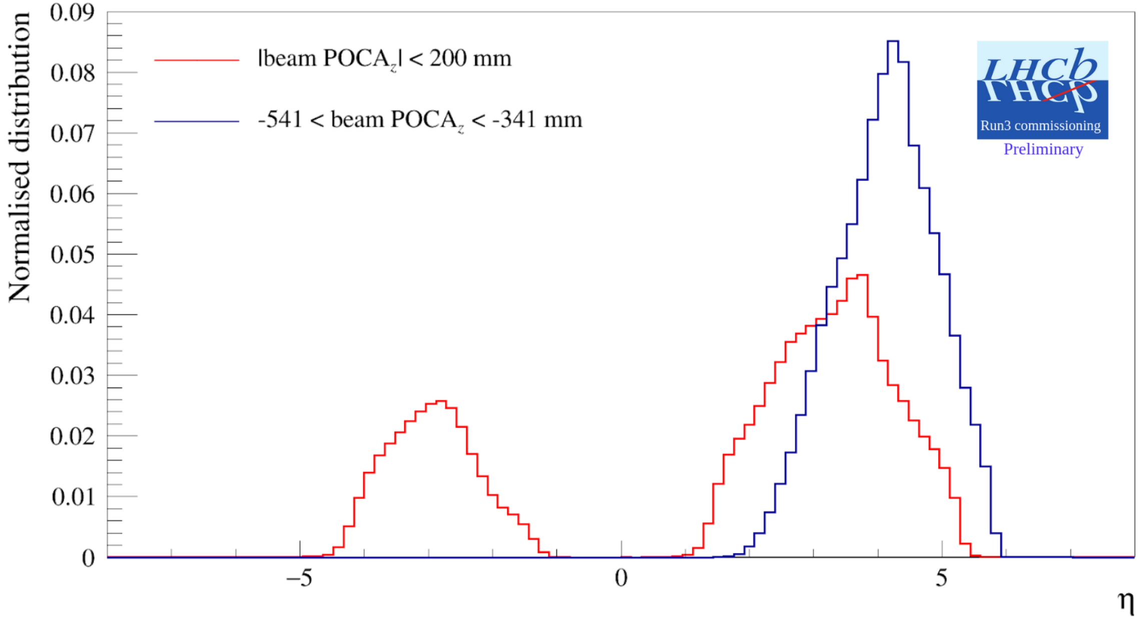
CERN-THESIS-2023-338

First SMOG2 operations in 2022

LHCb-FIGURE-2023-001

- 2022 has been a commisioning year for the upgraded LHCb detector
- SMOG2 has been succesfully tested with 4 gas species (**H**, He, Ne, Ar)
- first reconstructed primary vertices of simultaneous beam-gas and beam-beam collisions, obtained online through novel Real Time Reconstruction fully software trigger

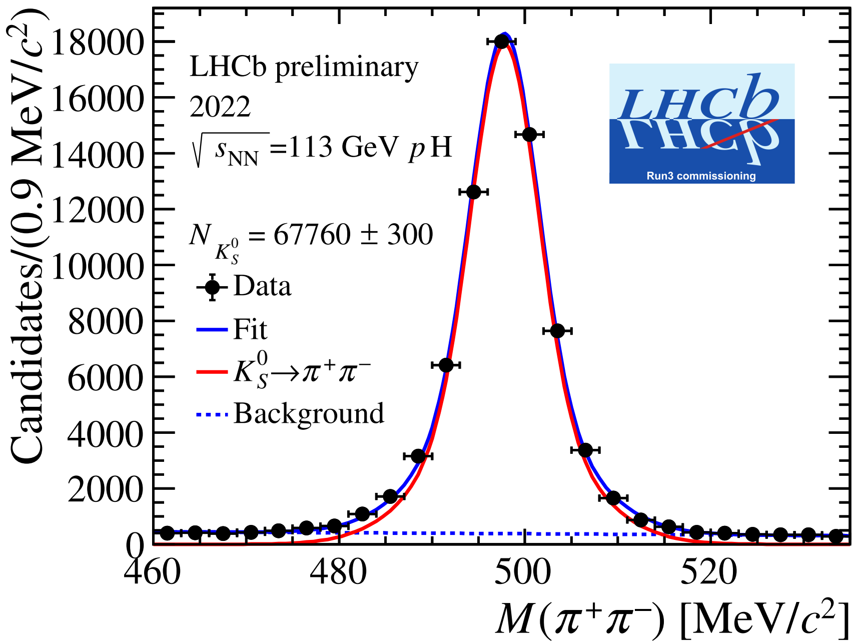


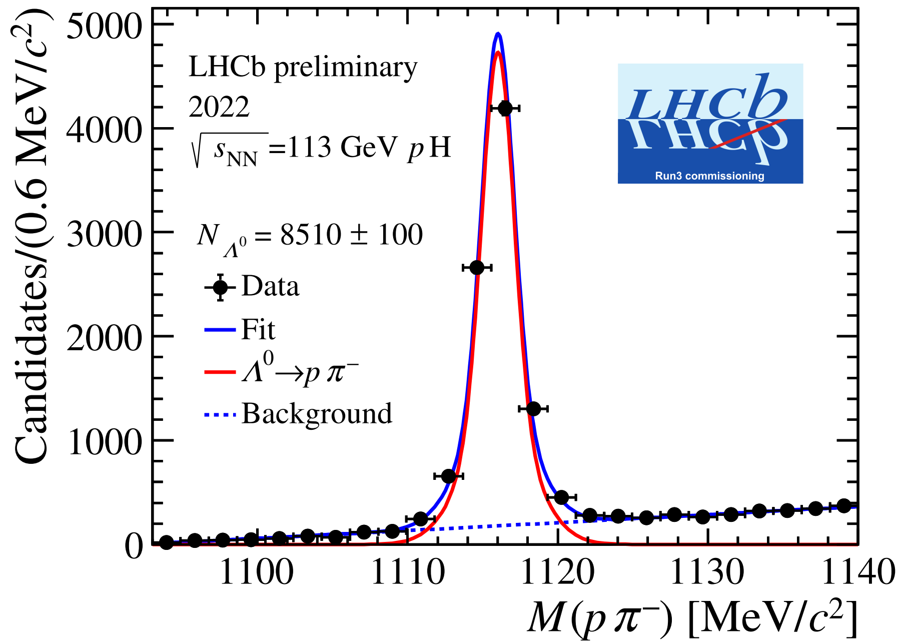


Physics in SMOG2 commissioning data!

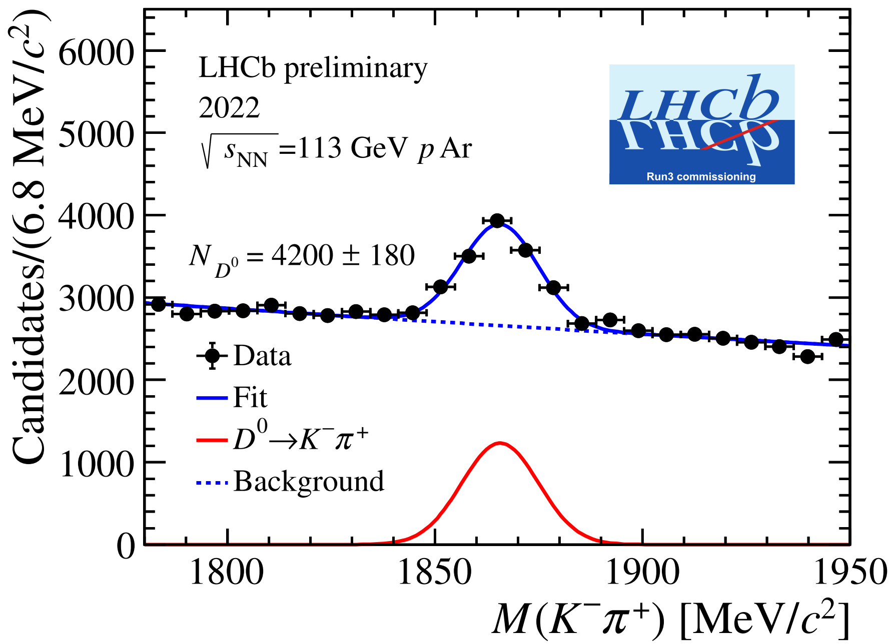
LHCb-FIGURE-2023-008

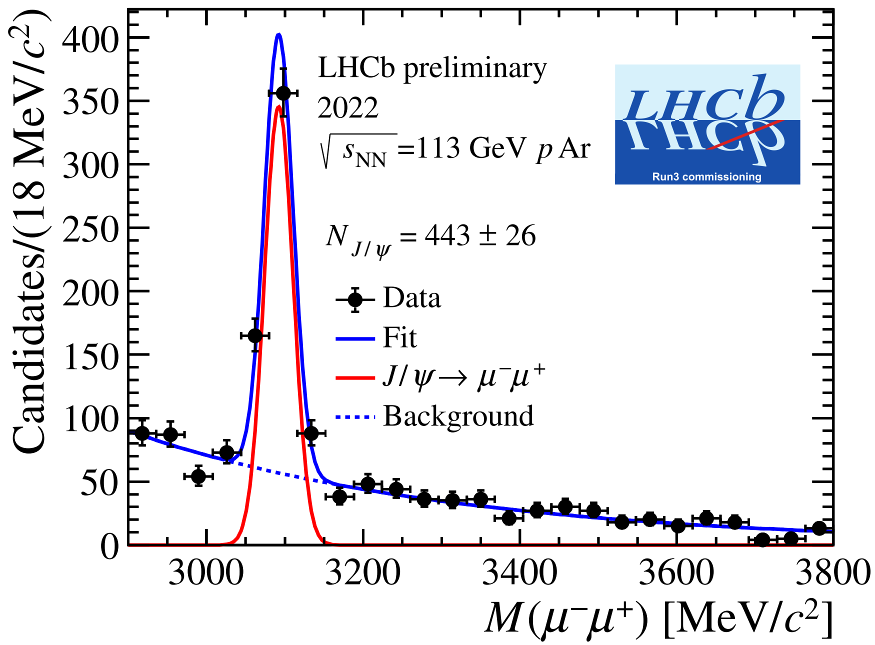
pH
20' run!





pAr
18' run!





Physics prospects with SMOG2

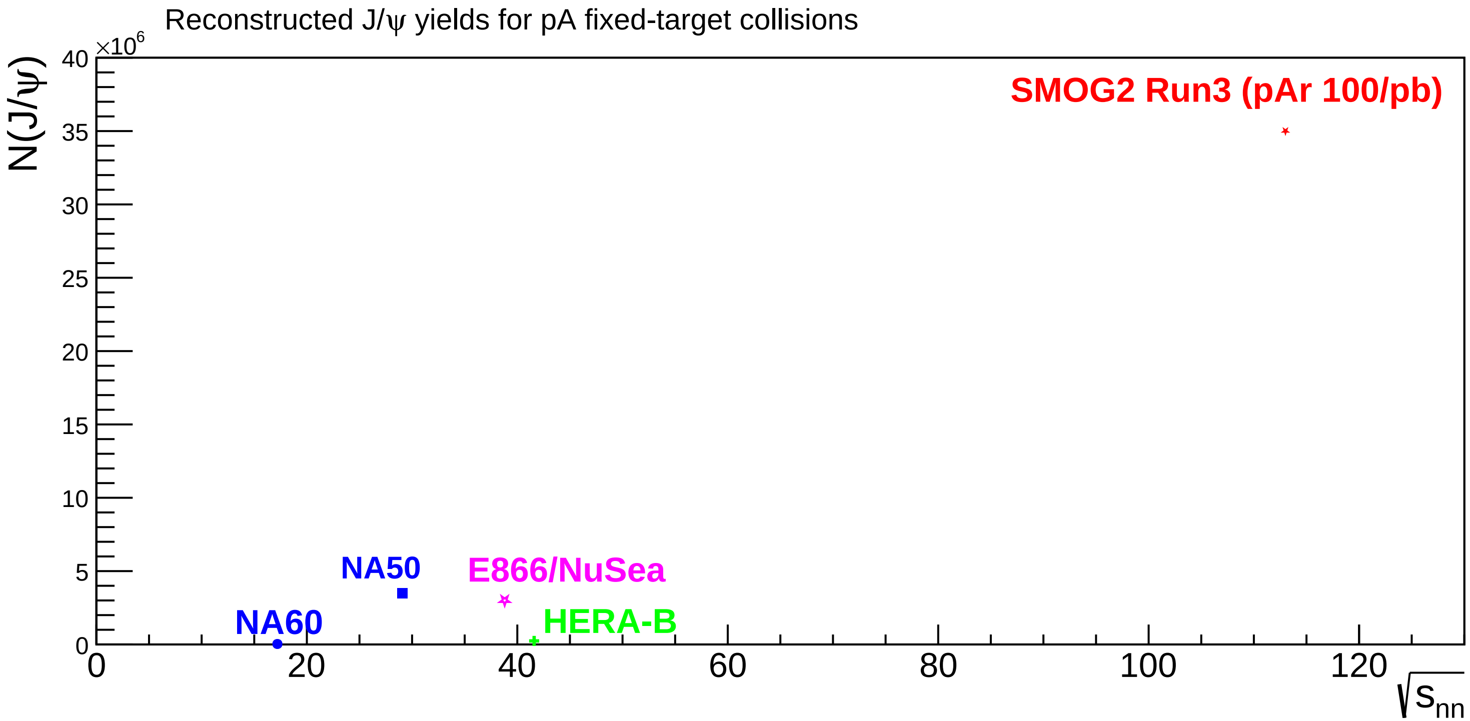
LHCB-PUB-2018-015

arXiv:1812.06772

- Expect data samples of order 100 pb^{-1} in Run3/4
- Precision charm production measurements, access *b* states, Drell-Yan, …

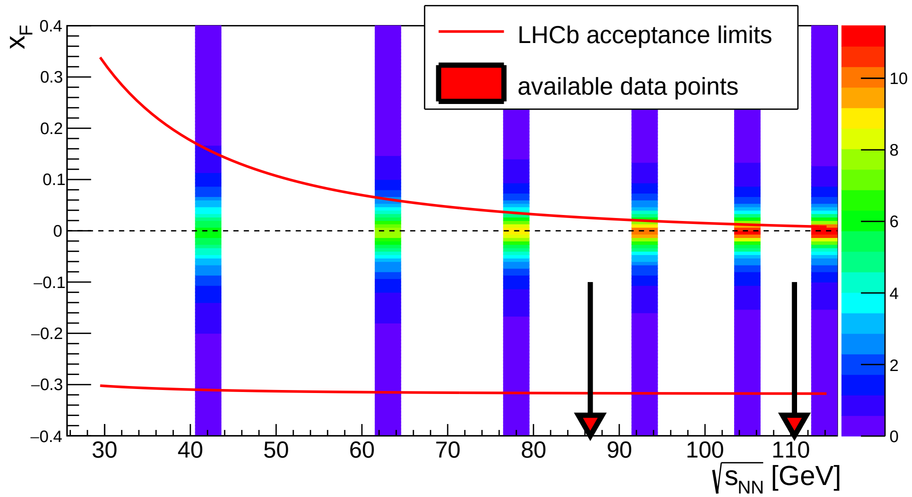
	SMOG largest sample p–Ne@68 GeV	SMOG2 example p–Ar@115 GeV
Integrated luminosity	$\sim 100\ nb^{-1}$	$100\ pb^{-1}$
syst. error on J/ψ x-sec.	6–7%	2–3 %
J/ψ yield	15k	35M
D^0 yield	100k	350M
Λ_c yield	1k	3.5M
$\psi(2S)$ yield	150	400k
$\Upsilon(1S)$ yield	4	15k
Low-mass ($5 < M_{\mu\mu} < 9\ GeV/c^2$) Drell-Yan yield	5	20k

- H and D targets to provide reference and study 3D structure functions



The ultimate $\overline{p}$ production cross-sections

- energy evolution of cross-sections (scaling violations, strangeness enhancement)



Expected Feynman-x distribution of $\overline{p}$ at different $\sqrt{s_{\rm NN}}$, and LHCb acceptance

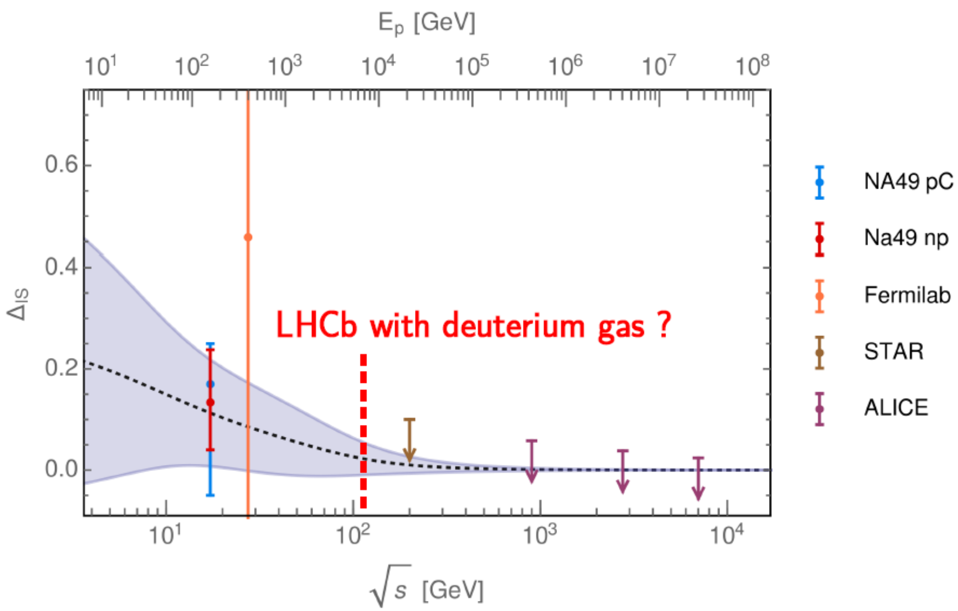
➡ Take **data at lower energy** (possibly also injection energy, this requires dedicated LHC optics). This also provides access to forward production in LHCb

- isospin effects (difference between $\overline{p}$ and $\overline{n}$ production)

$$\Delta_{IS} = \frac{\sigma(pp \to \overline{n}) - \sigma(pp \to \overline{p})}{\sigma(pp \to \overline{p})}$$

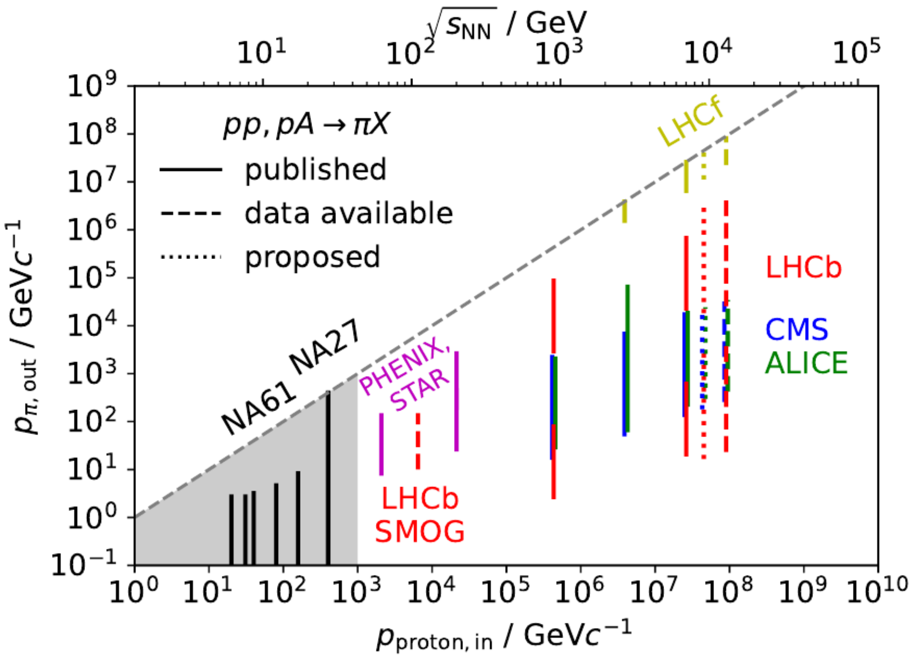
and nuclear effects in pHe vs pH (less important, note that He fraction in interstellar medium is not so precisely known)

➡ Collide protons with **hydrogen, deuterium and helium** targets in the same experiment



M.W.Winkler, JCAP02 (2017) 048

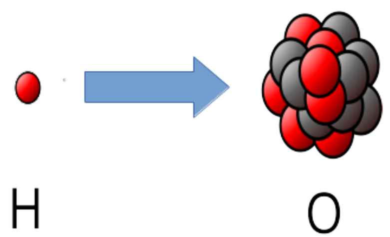
Expected inputs to UHE shower models

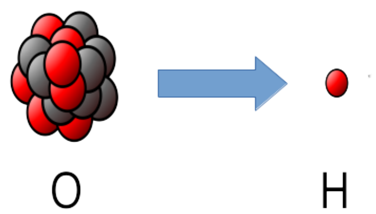


Ast.Sp.Sci. 367 (2022) 3, 27

- Modeling of UHE atmospheric showers requires knowledge of production cross-sections over some 10 orders of magnitude
- measurements of identified secondary particle spectra are needed

- Data from LHCb with O_2 and N_2 targets can provide useful inputs
- Additionally, during the oxygen beam run (scheduled in 2025) collisions of O beam on H target can be studied, providing a large phase space coverage for pO collisions at $\sqrt{s_{NN}} \sim 100$ GeV





More possibilities

- UPC physics : interesting cross-section for photoproduced J/ψ and η_c (sensitive to odderon) in LHCb-FT, can complement studies made/ongoing by LHCb in collisions (pp, pPb, $PbPb$)

  Lansberg et al., JHEP 1509 (2015) 087, Goncalves and Sauter PRD91 (2015) 870, Massacrier et al, arXiv:1709.09044, Goncalves and Jaime, arXiv:1802.04713

  Also interesting for nuclear structure?

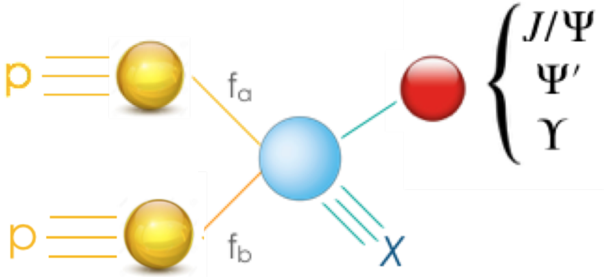
- Λ polarization induced by vorticity in HI collisions

  (see Becattini et al., PRC 88, 034905 (2013), STAR results on Nature 548, 62-65)

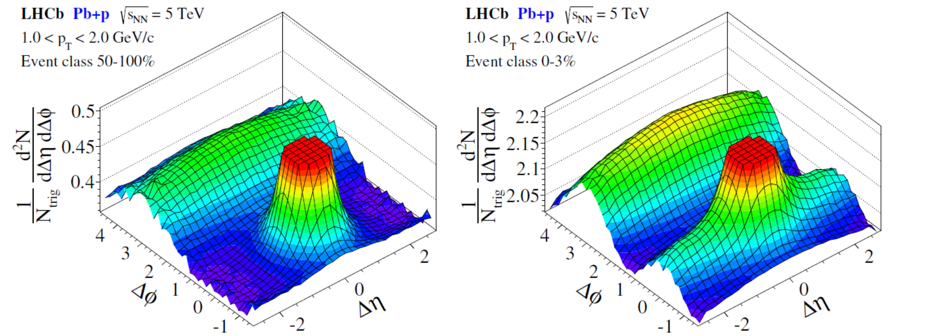
  Fixed target collisions have the correct energy scale (effect too small at TeV scale)

- Polarization measurements for Λ_c^+ and other heavy hadrons in pA are also a needed ingredient for the MDM/EDM proposed experiment

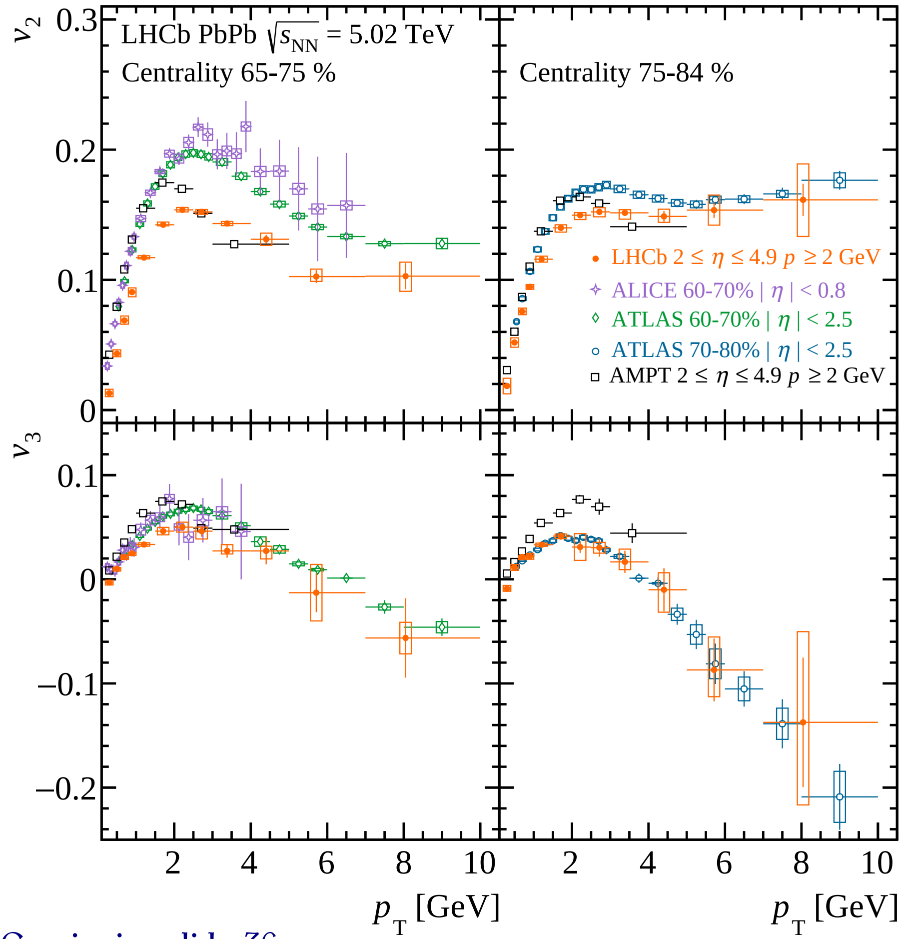
- Drell-Yan and heavy flavour channels with H_2 and D_2 targets will also give access to spin-independent nucleon TMDs as the Boer-Mulders functions in a novel kinematic range



- Hadronic flow can be studied over 3 units of pseudorapidity with full instrumentation at unique energy scale;
  - dihadron correlation studies already demonstrated by LHCb in pPb and PbPb
  - yields with SMOG2 could allow flow studies with charmed particles



Phys. Lett. B762 (2016) 473-483

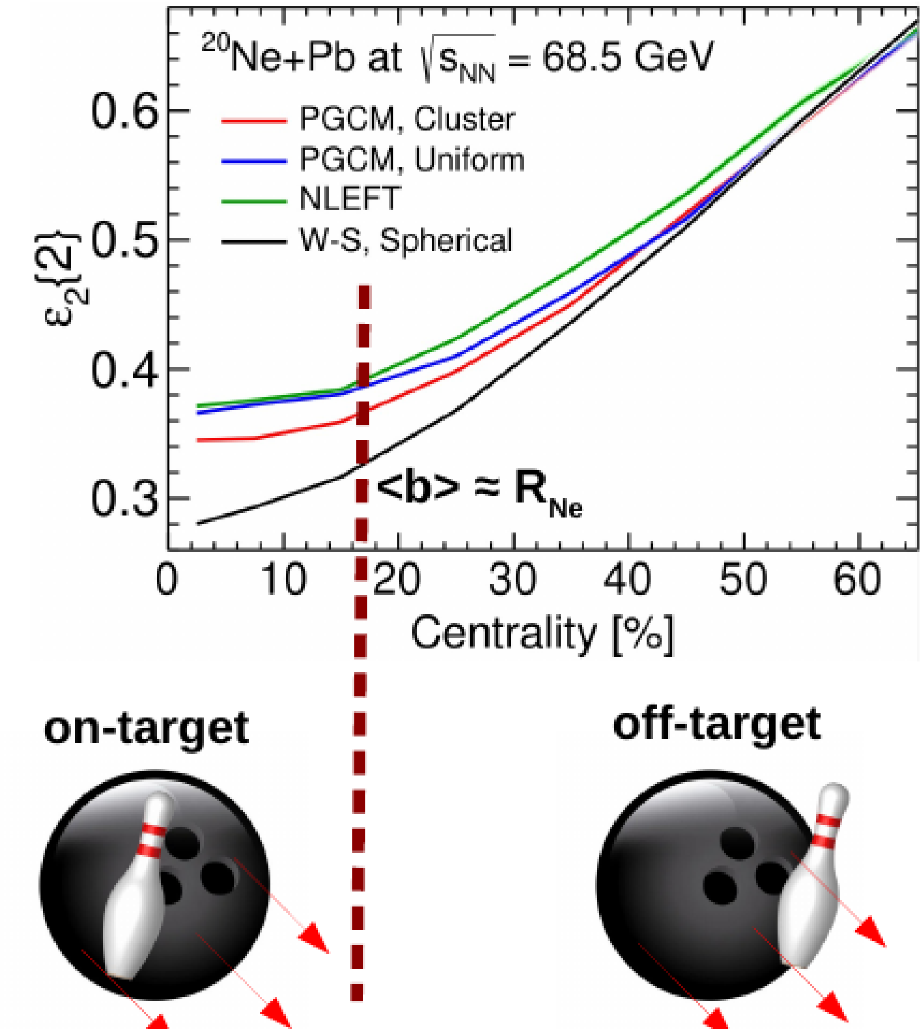


hadronic flow measured at forward rapidity $(2.0 < \eta < 4.9)$ in PbPb collisions at 5 TeV,
v_2 and v_3 obtained from 2-particle correlation analysis,
results compared to experiments at mid-rapidity and AMPT predictions

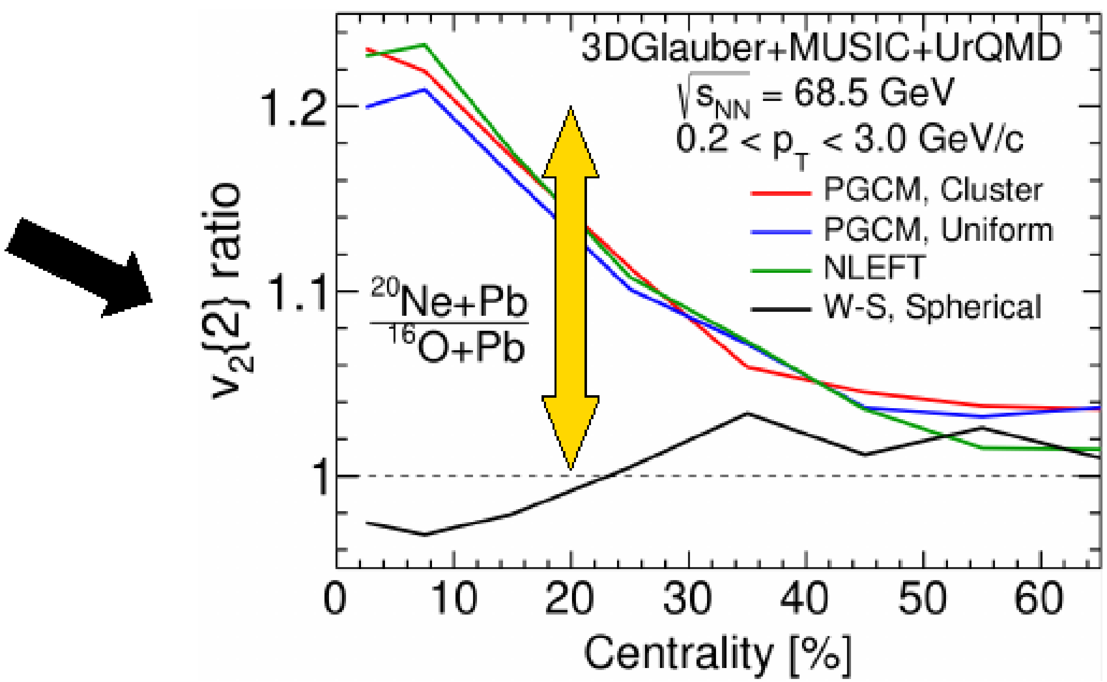
https://arxiv.org/abs/2311.09985

and of course, nuclear imaging

For deformed nuclei, flat eccentricity up to ~20% centrality



[W. Zhao et al., in preparation]



Signal is gigantic.

Unique potential of SMOG2 for imaging nuclei.

from Giuliano's talk

Available SMOG2 targets

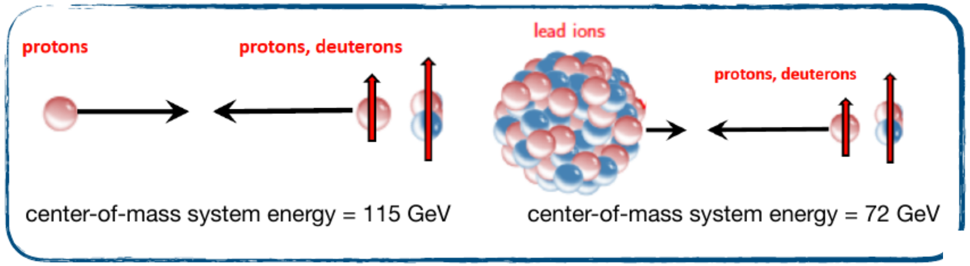
Summary of possible gas targets

✌	H	validated for O(100) h/year
~✌	D	as above (not tested yet)
✌	He	
~✌	N	not tested yet, but ok from simulations
☞	O	to be validated, should be possible at least for short runs
✌	Ne	
✌	Ar	
☞	Kr	to be validated, should be possible for short runs at end of data-taking
☞	Xe	to be validated, should be possible for short runs at end of data-taking

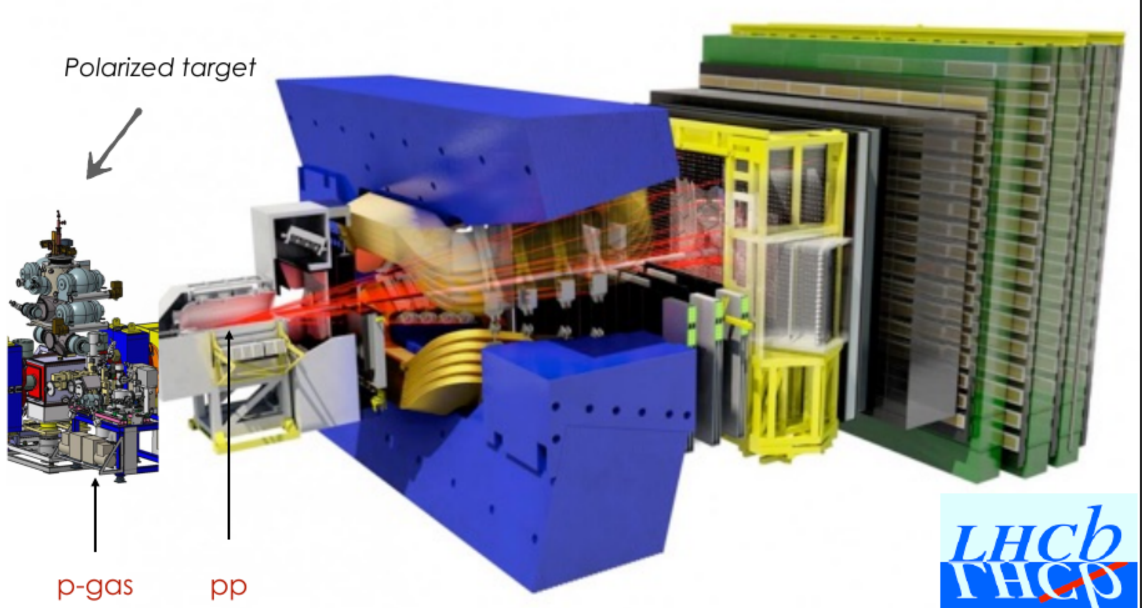
any isotope for approved gas should be ok

The future: Polarized Fixed target?

- The LHCSpin collaboration is proposing an upgrade to a polarised gas target
- Studies ongoing within the *Physics Beyond Colliders* forum at CERN
- Unprecedented potential for parton TMDS with transversely polarised Drell-Yan and other channels, complementary to EIC
- Unique opportunity for spin physics in heavy ion collisions!



- Currently planning an R&D phase at LHC IR4
- Then, proposed installation at LHCb



Conclusions

- LHCb successfully pioneered fixed-target physics at the LHC
- with the upgrade to the SMOG2 target LHCb becomes

the fixed-target experiment at the highest energy and the highest production rate ever

A novel QCD laboratory, extending the reach of the LHC complex, with strong connections with
heavy-ion HE physics
nuclear physics
astroparticle physics

from ESPP Update 2020

European Strategy Update

Physics Briefing Book

CERN-ESU-004
30 September 2019

Input for the European Strategy for Particle Physics Update 2020

The multi-TeV LHC proton- and ion-beams allow for the most energetic fixed-target (LHC-FT) experiments ever performed opening the way for unique studies of the nucleon and nuclear structure at high x, of the spin content of the nucleon and of the nuclear-matter phases from a new rapidity viewpoint at seldom explored energies [117, 118].

On the high-x frontier, the high-x gluon, antiquark and heavy-quark content (e.g. charm) of the nucleon and nucleus is poorly known (especially the gluon PDF for $x \gtrsim 0.5$). In the case of nuclei, the gluon EMC effect should be measured to understand that of the quarks. Such LHC-FT studies have strong connections to high-energy neutrino and cosmic-ray physics.

The physics reach of the LHC complex can greatly be extended at a very limited cost with the addition of an ambitious and long term LHC-FT research program. The efforts of the existing LHC experiments to implement such a programme, including specific R&D actions on the collider, deserve support.