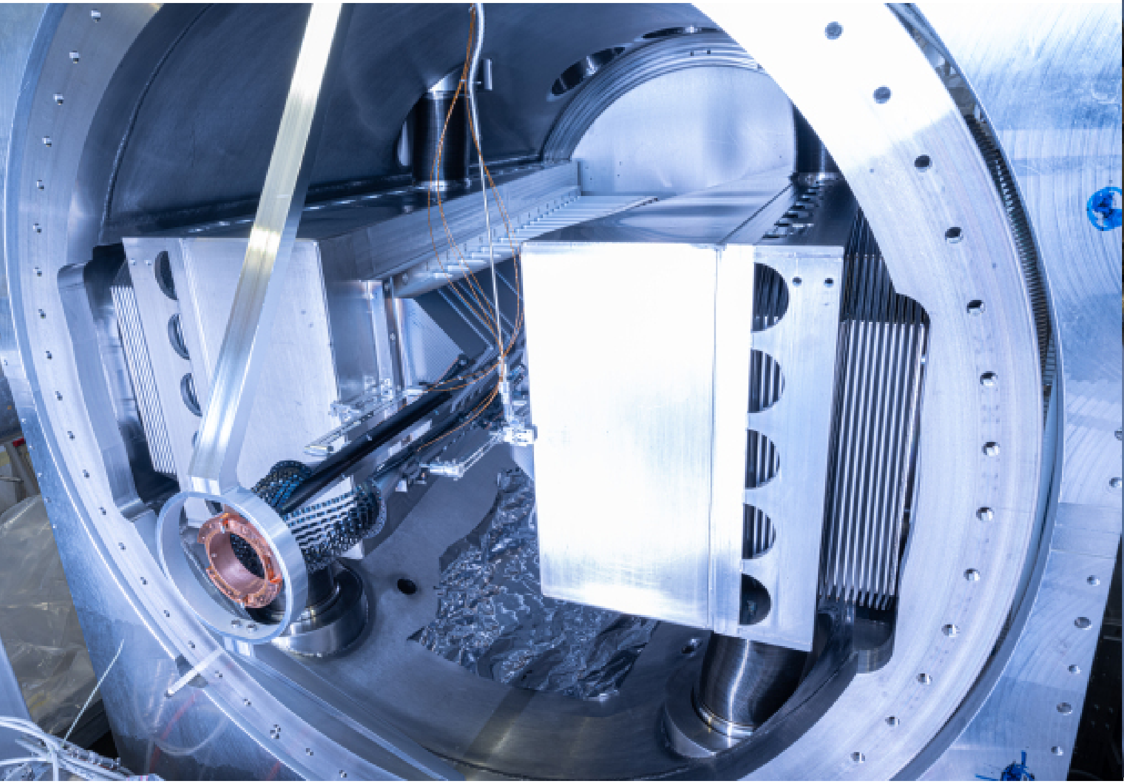
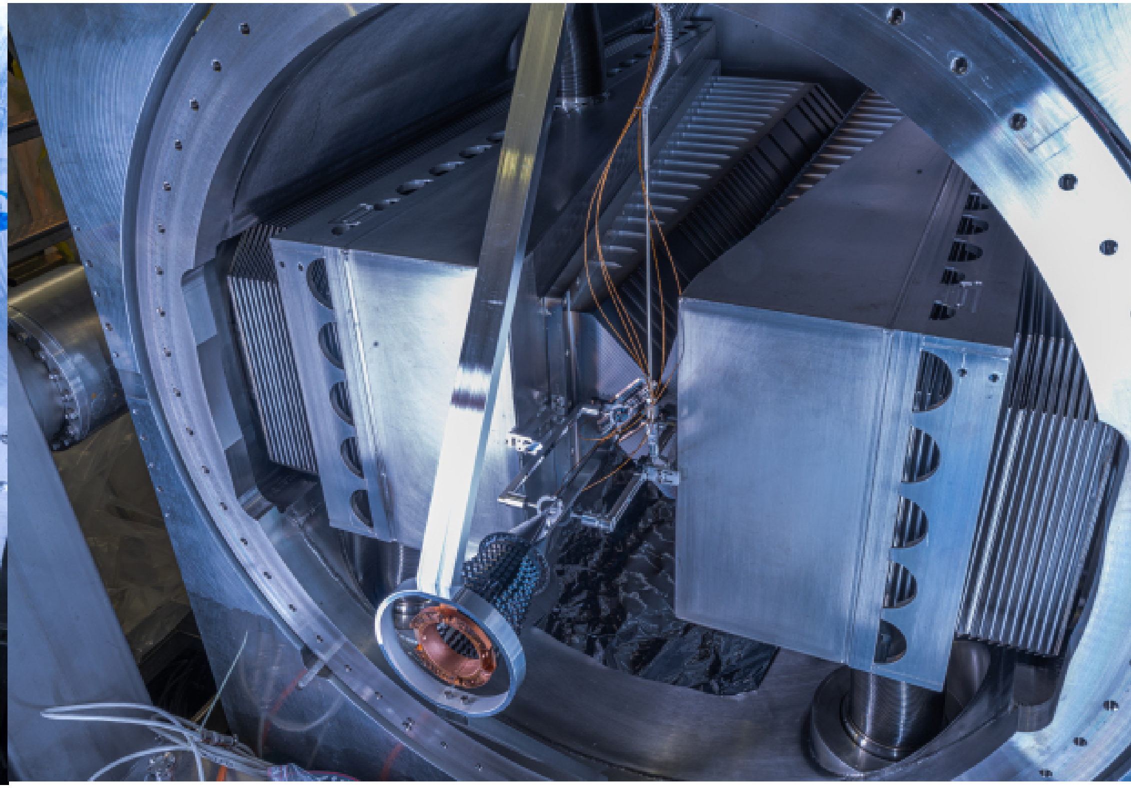
Fixed target experiments at the LHC: SMOG and SMOG2 at LHCb





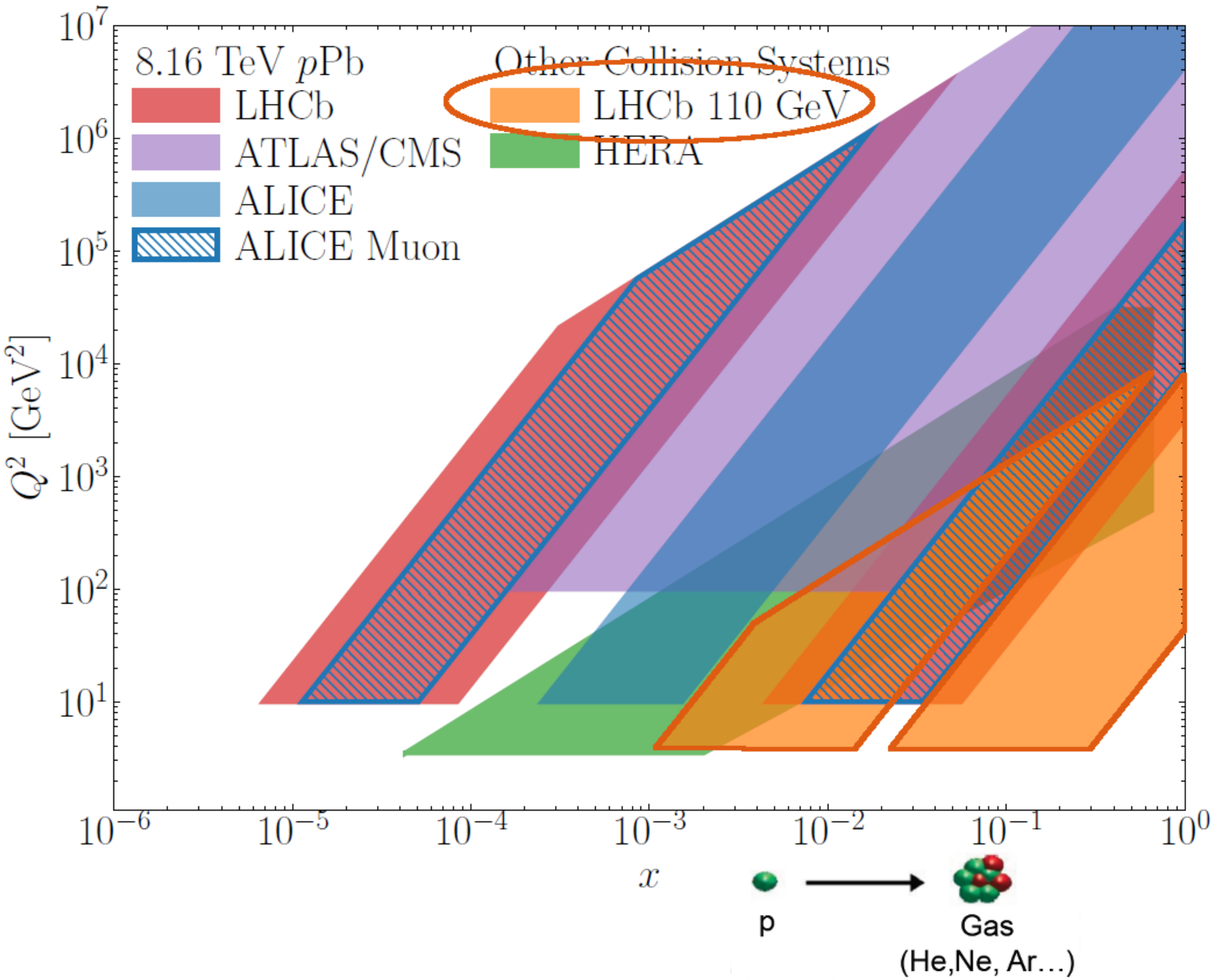
Giacomo Graziani (INFN Firenze)

Workshop on the tuning of hadronic interaction models
Wuppertal, Jan 24, 2024

Fixed-target Physics at the LHC

Fixed-target experiments at high-energy collider facilities offer unique possibilities:

- access to large x region
- variety of collision systems by changing the target
- access to intermediate energy between beam-beam collisions and past fixed-target



well recognised in the European Strategy for Particle Physics 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.

LHCb with the SMOG(2) gas target is currently
the only fixed-target experiment exploiting LHC beams

The LHCb experiment

LHCb is the experiment devoted to heavy flavours in pp collisions at the LHC.

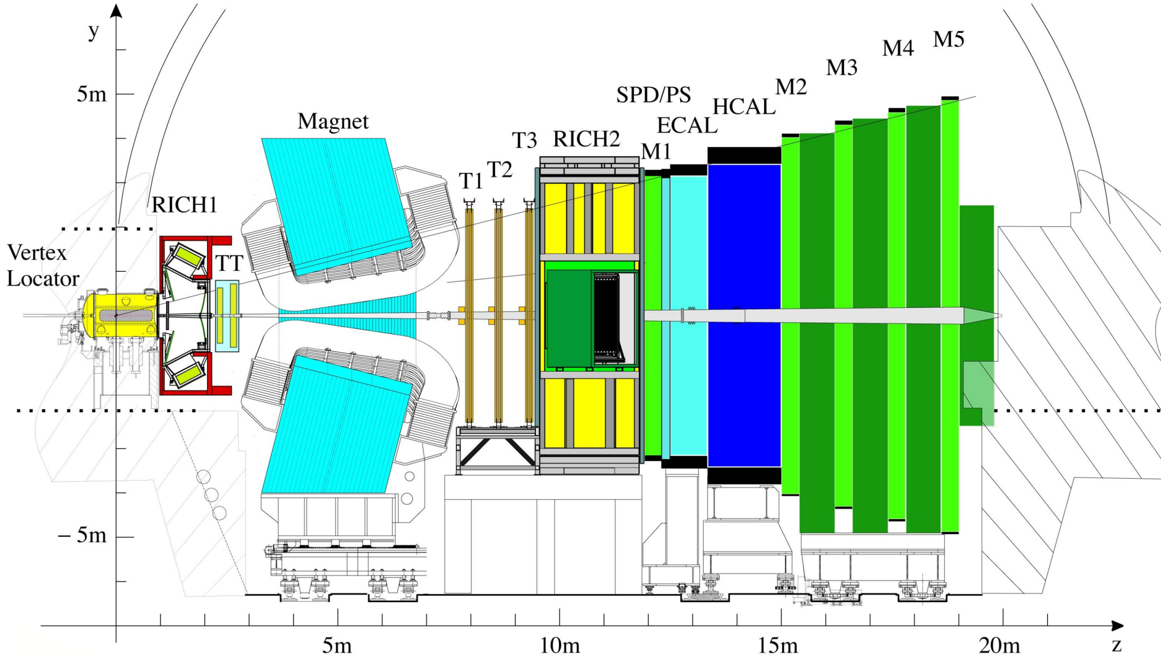
Detector requirements:

Forward geometry (pseudorap. $2 < \eta < 5$) optimises acceptance for $b\bar{b}$ pairs

Tracking : best possible proper time and momentum resolution

Particle ID : excellent capabilities to select exclusive decays

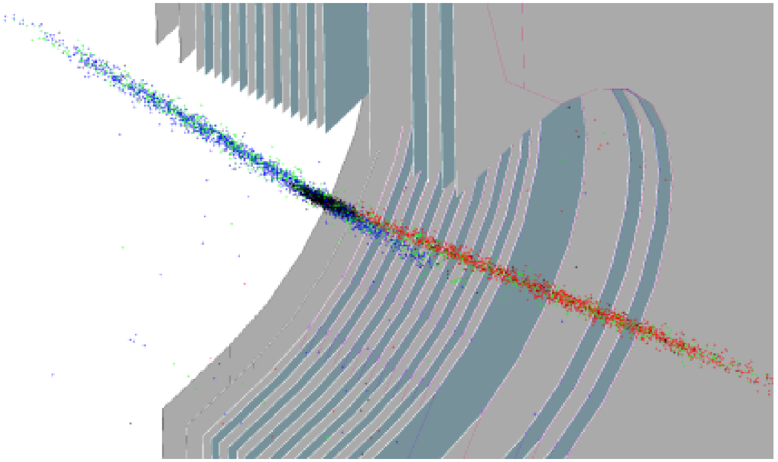
Trigger : high flexibility and bandwidth (up to 15 kHz to disk)



JINST 3, (2008) S08005

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

LHCb pioneered fixed-target physics@LHC during Run 2 thanks to SMOG



The System for Measuring Overlap with Gas

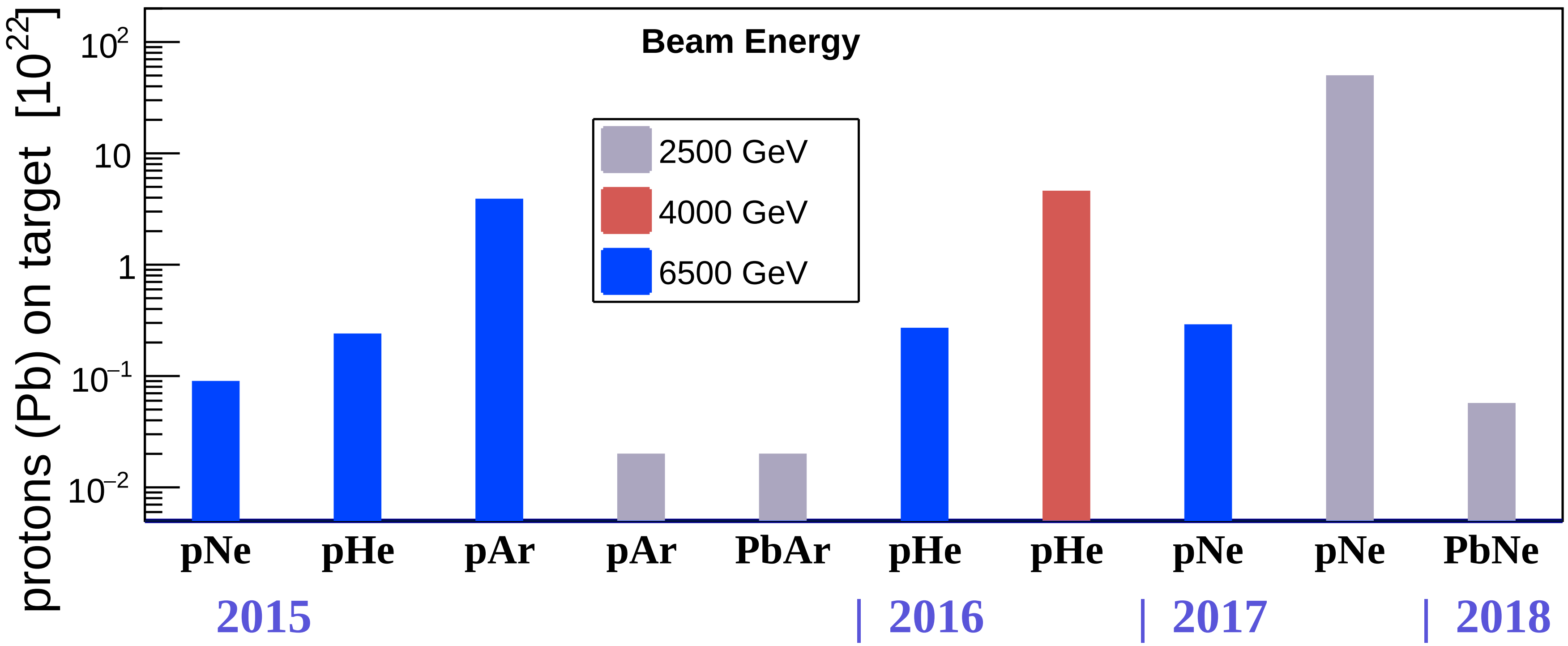
JINST 9 (2014) P12005

can inject small amount of noble gas in the LHC beam pipe around ($\sim \pm 20$ m) the LHCb collision region.

Possible targets: **He, Ne, Ar**, and more in the future

Gas pressure $\sim 2 \times 10^{-7}$ mbar ➡ $\mathcal{L} \lesssim 6 \times 10^{29} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

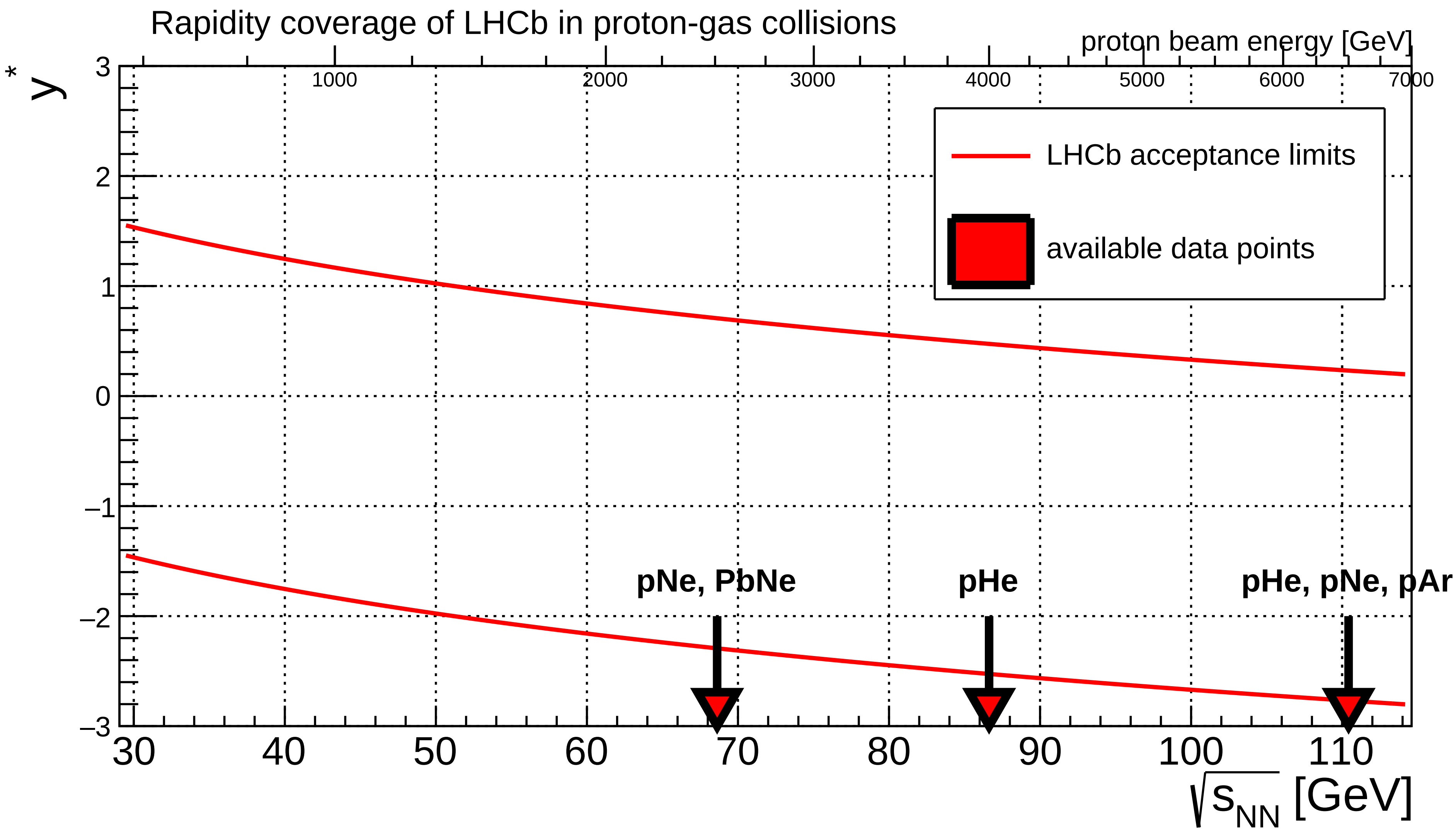
Fixed-target Run2 datasets



(at nominal SMOG pressure, 10^{22} POT correspond to 5/nb for 1 m of gas)

- First papers from first physics runs in 2015 and 2016
- Larger samples of pNe collisions ($\sim$ 100 nb^{-1}) and PbNe collisions at same energy collected in 2017 and 2018

Fixed Target Acceptance



Physics program

Measurements of identified particle production
(π, p and $\overline{p}$, K, hyperons, D^0, J/ψ, ...)
in this unique kinematic range can provide many insights:

- study of “cold” nuclear matter effects at the onset of QGP effects
- nuclear (and nucleon) PDFs at large x
- energy evolution of hadronization
  (strangeness enhancement, baryon/meson ratio, ...)

very relevant for cosmic ray physics:

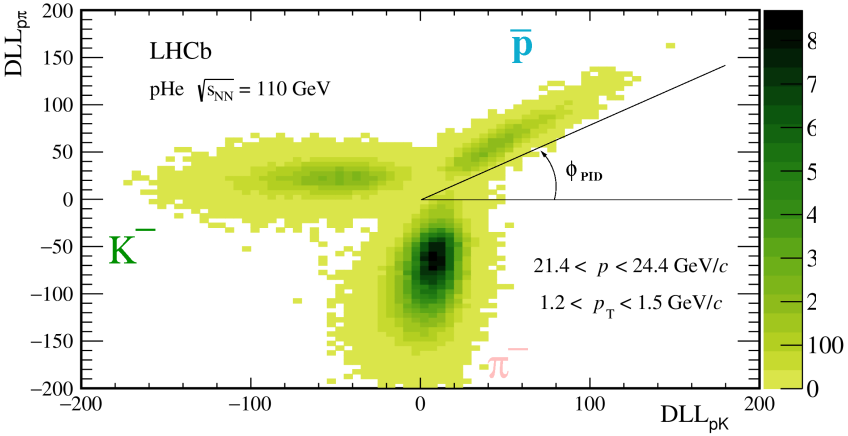
- pHe collisions reproduce interactions of primary cosmic rays on interstellar medium at a scale relevant for AMS-02 measurements, notably for DM searches via cosmic antimatter
- pNe, pAr data useful for atmospheric shower modeling (N_2 and O_2 targets in the future)
- charm PDF at large x (possible intrinsic charm) important for PeV atmopheric neutrinos (background to IceCube)

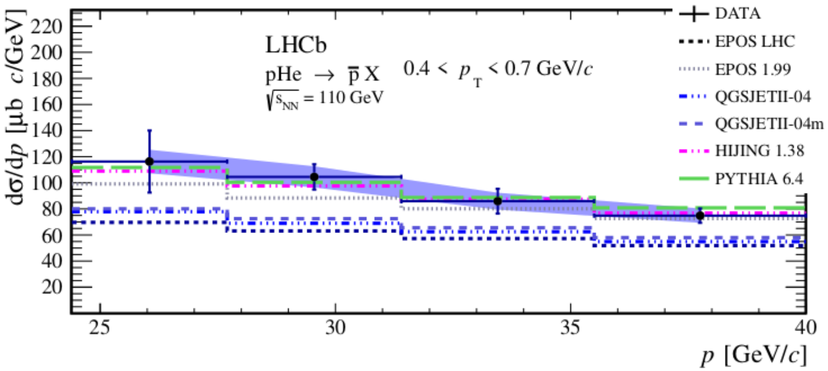
Antiprotons in pHe collisions

see next talk by Thomas Pöschl for a thorough discussion

Prompt production

Relying on $\overline{p}$ identification with RICH detectors



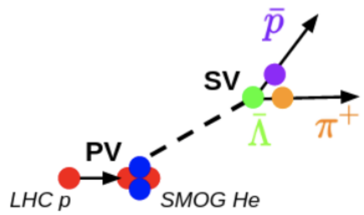


PRL 121 (2018), 222001

Detached $\overline{p}$ (from antihyperons)

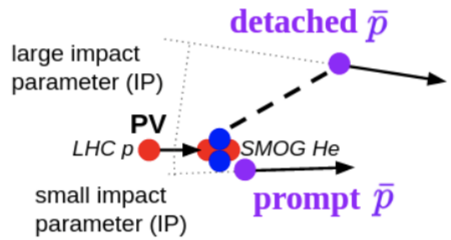
Exclusive approach

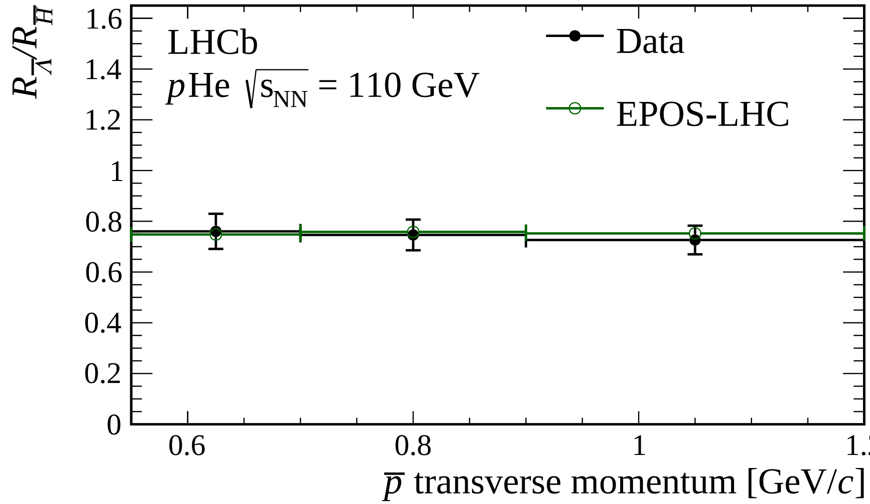
$$R_{\bar{\Lambda}} = \frac{\sigma(p\text{He} \to (\bar{\Lambda}_{\text{prompt}} \to \bar{p}\pi^+)X)}{\sigma(p\text{He} \to \bar{p}_{\text{prompt}}\, X)}$$



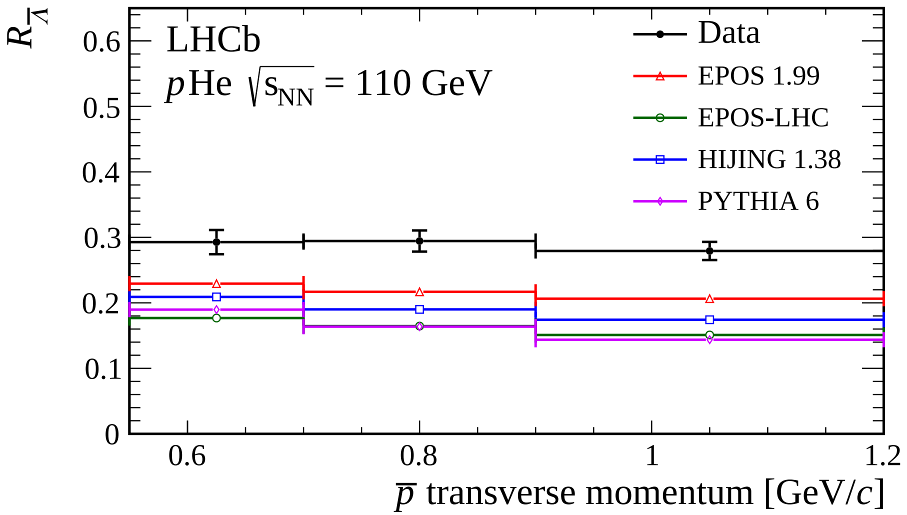
Inclusive approach

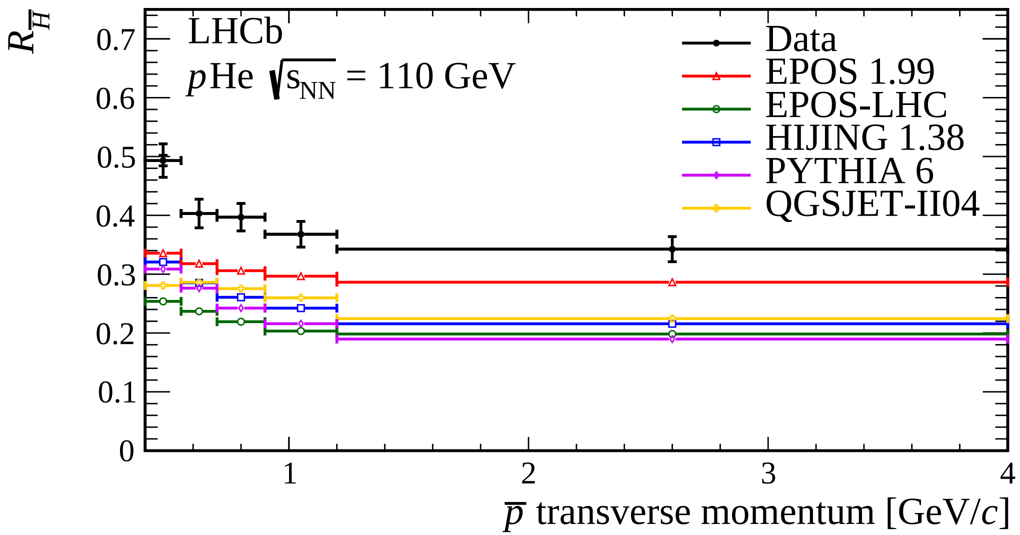
$$R_{\bar{H}} \equiv \frac{\sigma(p\text{He} \to \bar{H}X \to \bar{p}X)}{\sigma(p\text{He} \to \bar{p}_{\text{prompt}}X)} \qquad \bar{H} = \bar{\Lambda}, \bar{\Sigma}, \bar{\Xi}, \bar{\Omega}$$

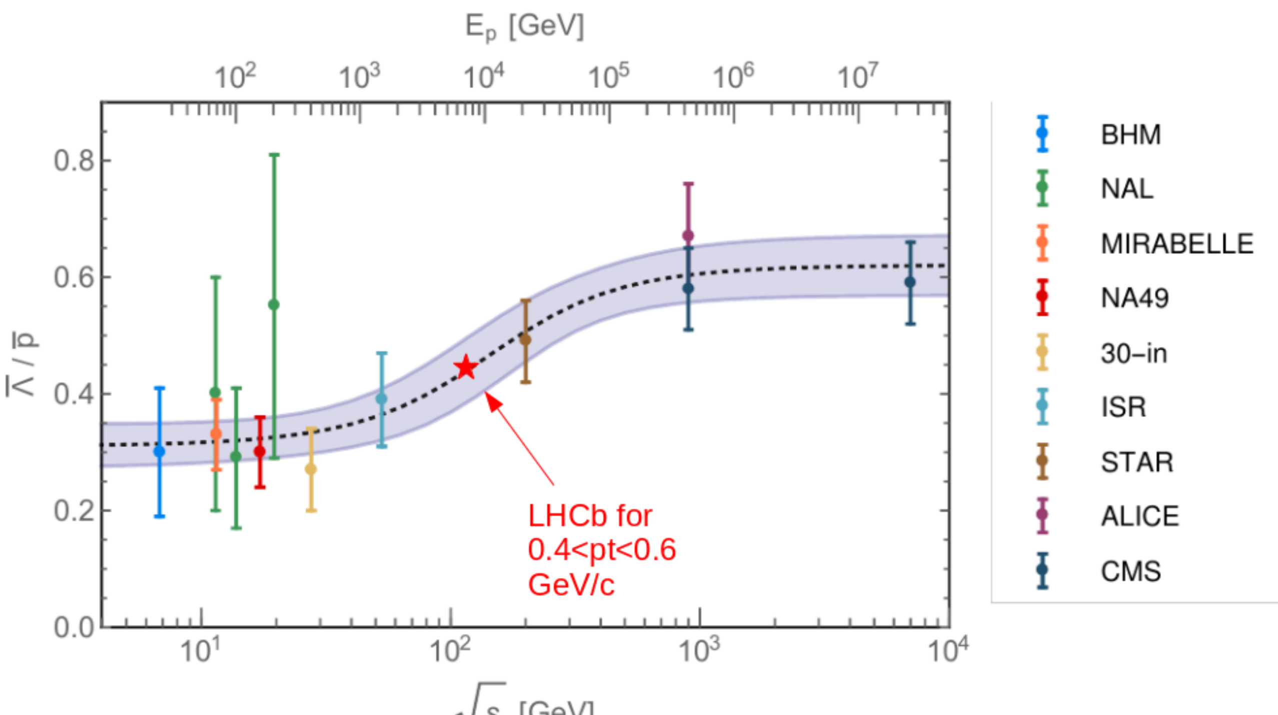




EPJC 83, 543 (2023)

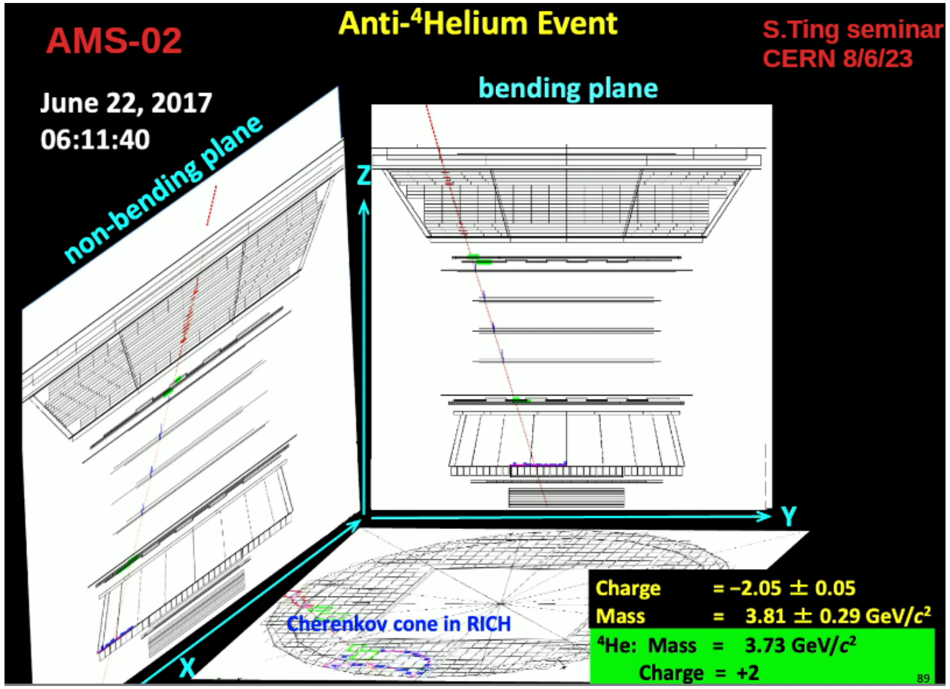






M.W.Winkler, JCAP02 (2017) 048

Light antinuclei: the challenge

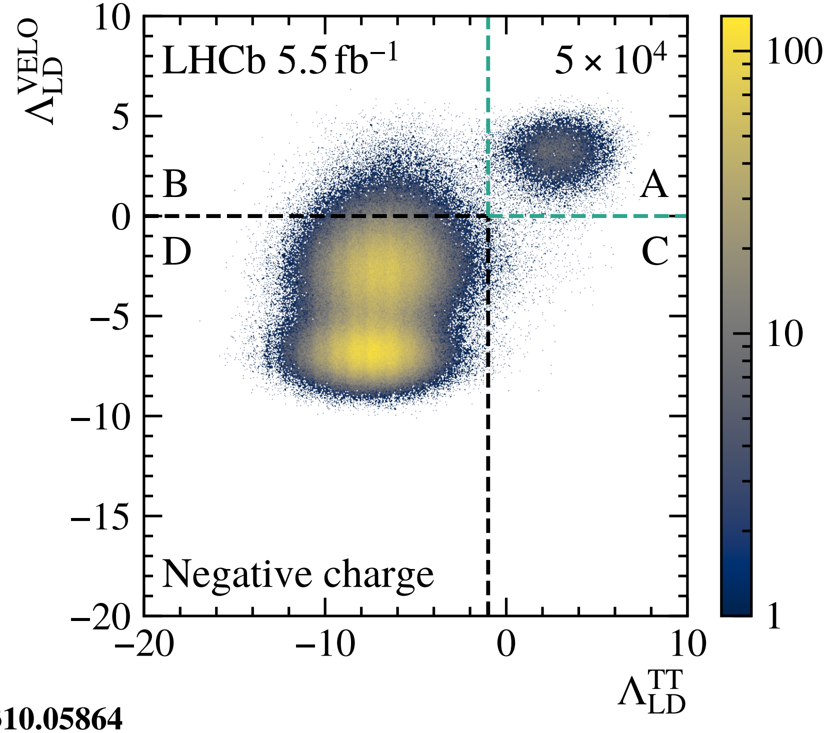


- detection of antideuteron or antihelium by AMS-02 and GAPS could be a smoking gun for dark matter signal
- intriguing events claimed by AMS-02

- still, large uncertainties on $\overline{d}$ and $\overline{\mathrm{He}}$ production, both in ISM and in the AMS-02 detector material
- predictions based on empirical production models (statistical or coalescence)
- sparse data exist, with large uncertainties, for $pp \to \overline{d}, \overline{\mathrm{He}}$ at $\sqrt{s_{\mathrm{NN}}} \sim 10$ GeV from the '70-'80
- precise measurements from ALICE in pp LHC collisions between 0.9 and 13 TeV
- Precision measurements at $\sqrt{s_{\mathrm{NN}}} \sim 10 - 100$ GeV scale are missing

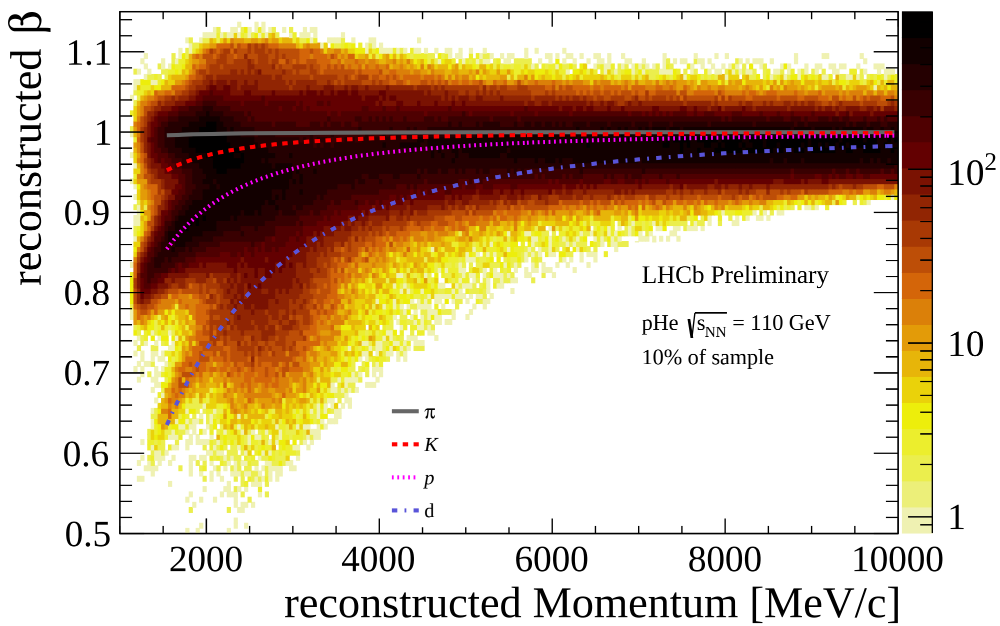
Antinuclei in fixed target @ LHCb?

- LHCb was not designed for light nuclei identification
- However, recently the capability to isolate $\mathrm{He}/\overline{\mathrm{He}}$ candidates through dE/dx in the tracking system was demonstrated
- low-momentum $d/\overline{d}$ can also be identified through TOF
- work ongoing…



arXiv:2310.05864

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



LHCb-FIGURE-2023-017

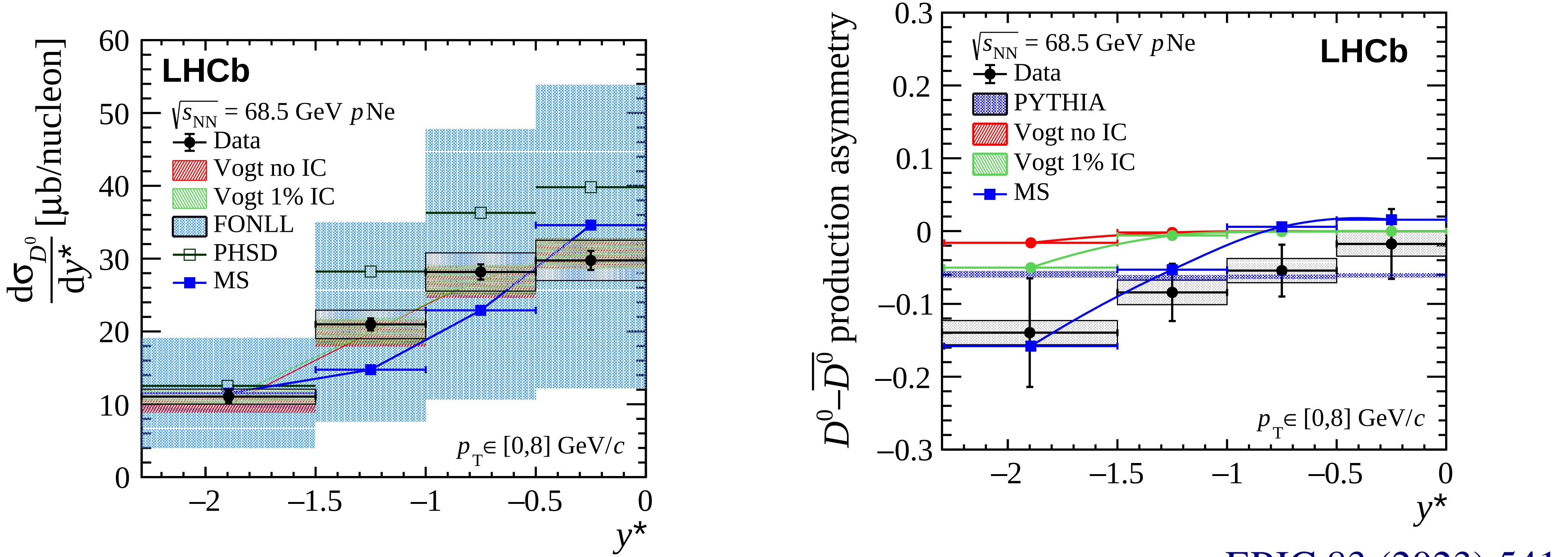
Velocity vs momentum for tracks reconstructed in LHCb pHe data

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	EPJC 83 (2023) 625
		• D^0 cross section and asymmetry	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

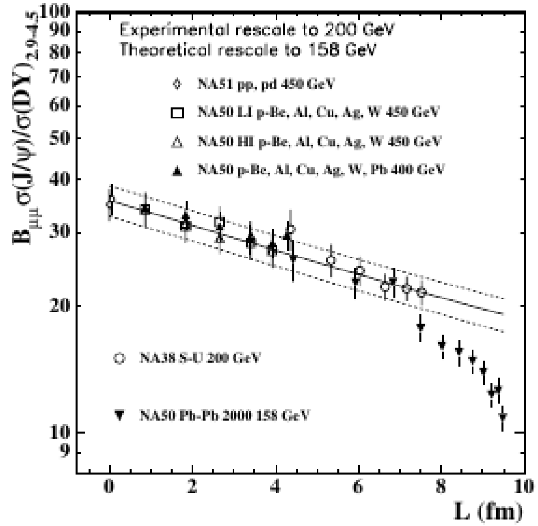


EPJC 83 (2023) 541

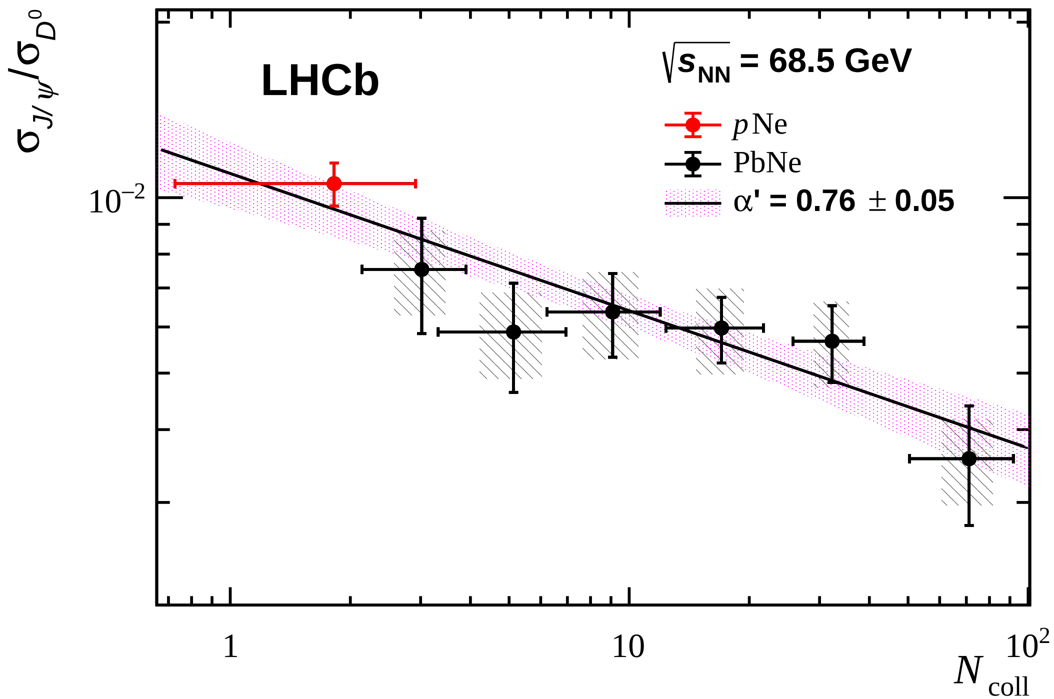
- most backward production sensitive to x up to ~ 0.4
- production better described by models including 1% of intrinsic charm (“Vogt ‘%” and “MS”), though no clear conclusion
- (D^0-$\overline{D}^0$)/(D^0 +$\overline{D}^0$) production asymmetry up to -15% observed in backward bin, likely hadronization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

J/ψ suppression in PbNe collisions

- PbNe collisions at $\sqrt{s_{\rm NN}} = 68.5$ GeV probe same energy density scale where NA50 observed anomalous J/ψ suppression in PbPb



NA50, EPJC 39 (2005) 335



EPJC 83 (2023) 658

- cold nuclear matter effects can be constrained by same measurement in pNe collisions at the same energy
- 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

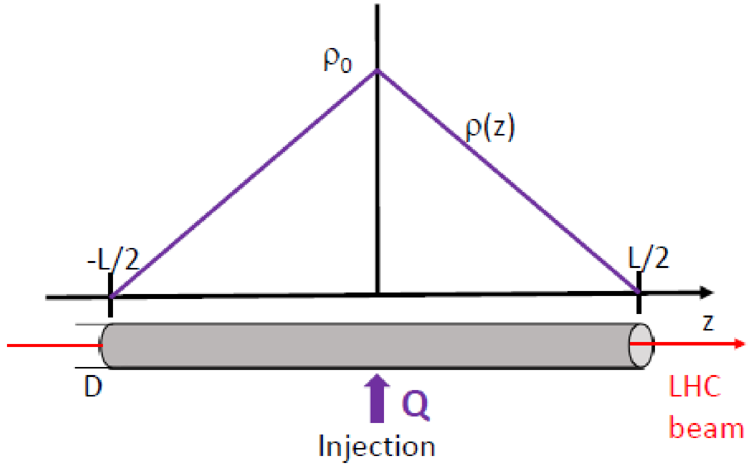
$$\sigma(J/\psi)/\sigma(D^0) \propto N_{\rm coll}^{(\alpha'-1)}$$

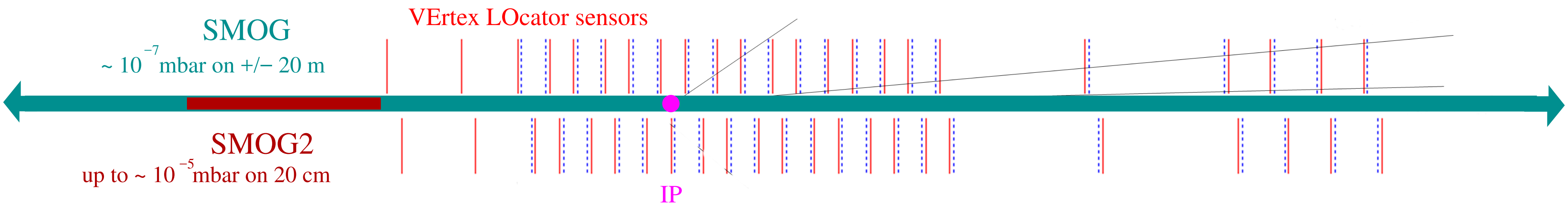
with $\alpha' = 0.76 \pm 0.05$, in agreement with previous pA results **PLB410 (1997) 337**

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

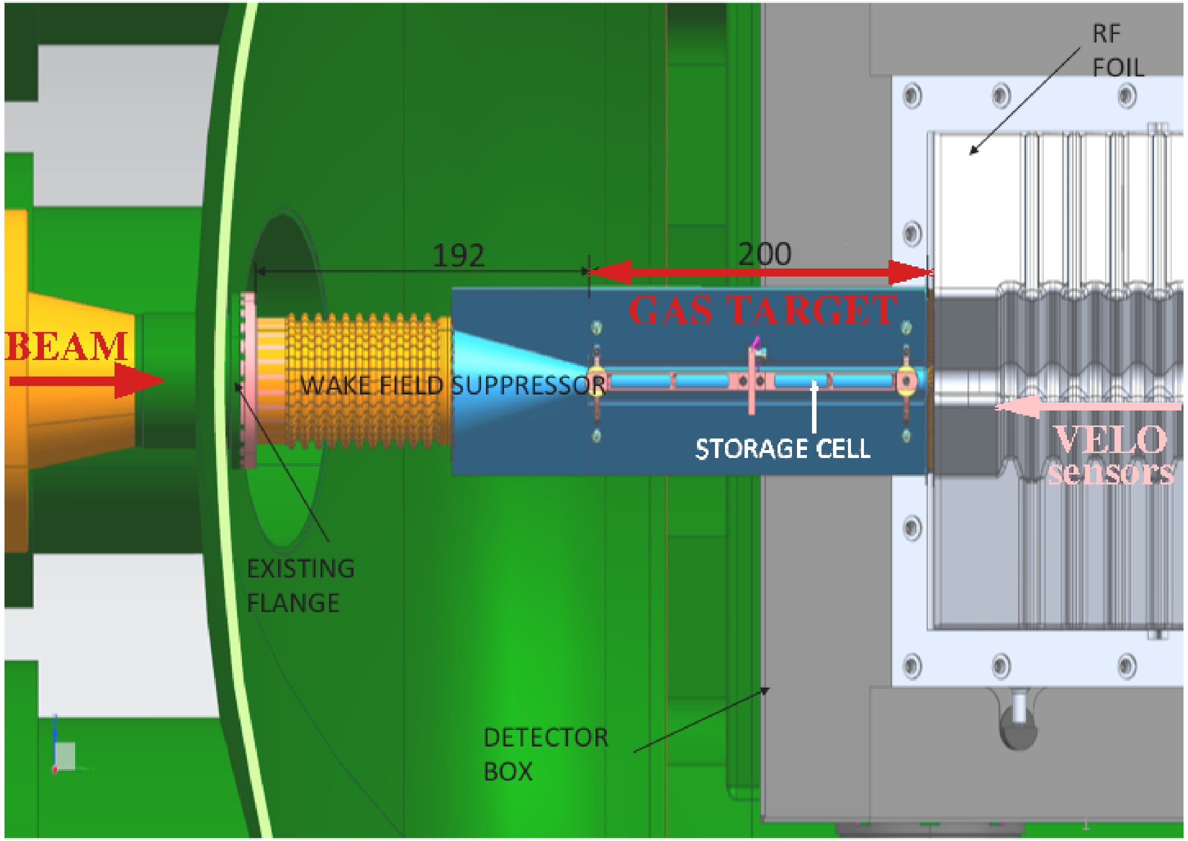
The gas target upgrade

- 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
  - possibly 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**





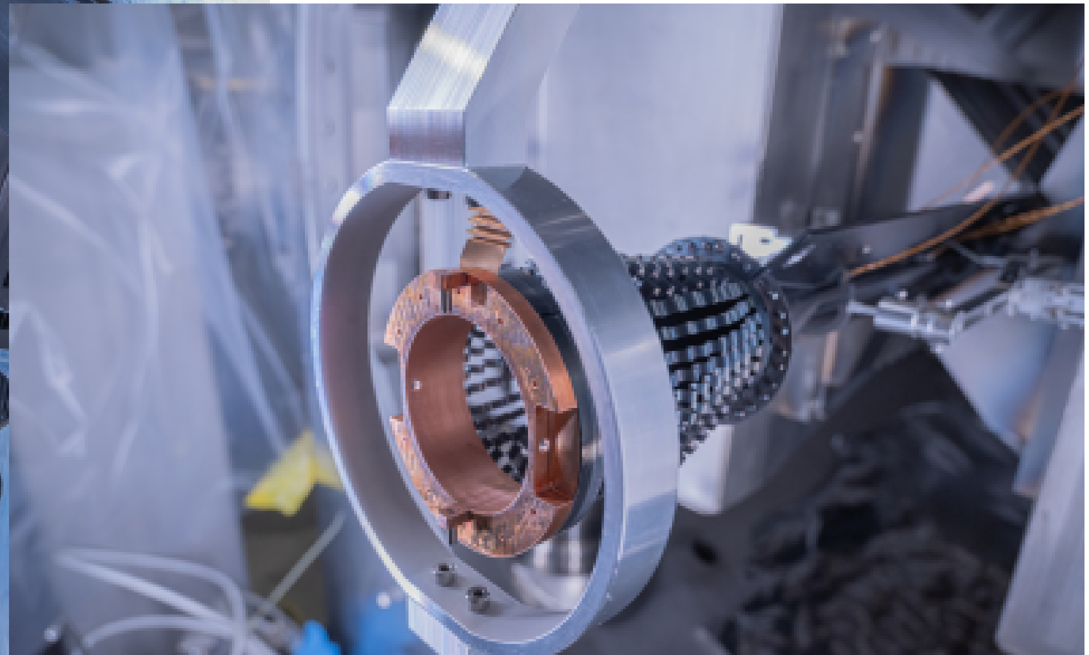
The SMOG2 gas target



- 20-cm long storage cell, 5 mm radius around the beam, just up-stream the LHCb VErtex LOcator
- 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 $\sim$ 2% accuracy via Gas Feed System
- Fast switch between gas species

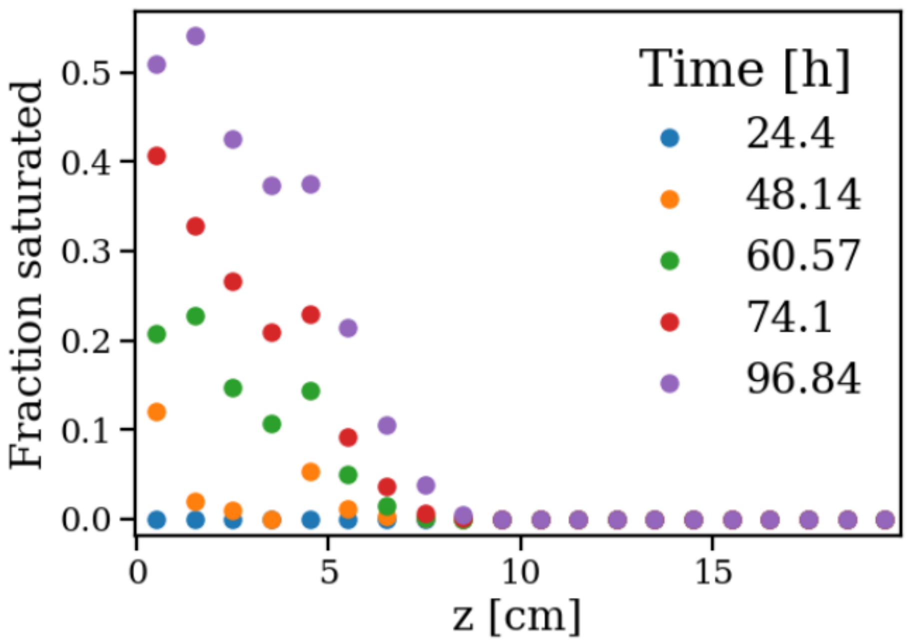
- TDR approved by LHCC in 2019
  CERN-LHCC-2019-005l
- Installed in the LHCb cavern on august 2020

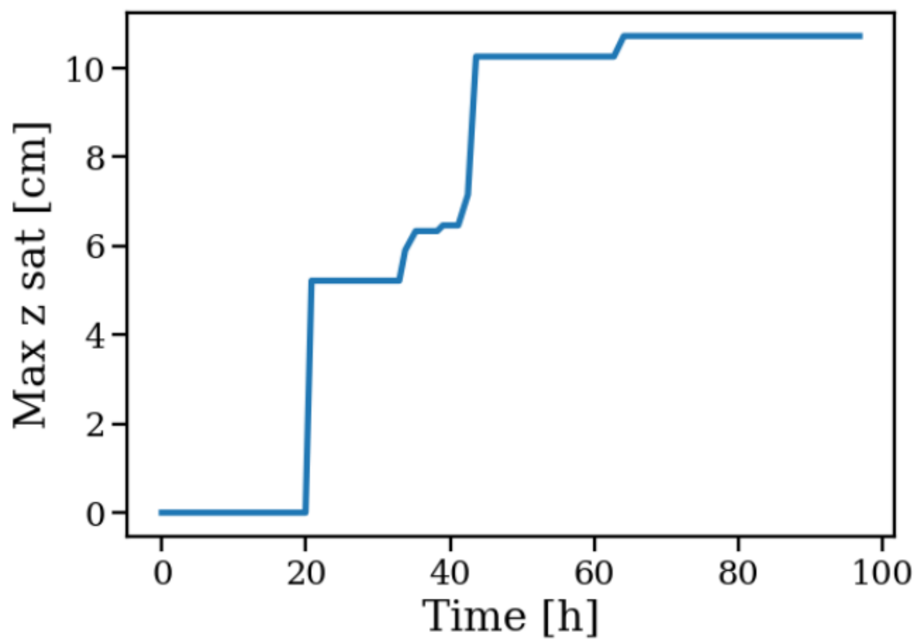
SMOG2 installation



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
- The level of NEG saturation has been shown to be acceptable, limited in a region $<$ 20 cm long, for at least 96 hours of H_2 gas flow and 10 hours of N_2 gas flow per year

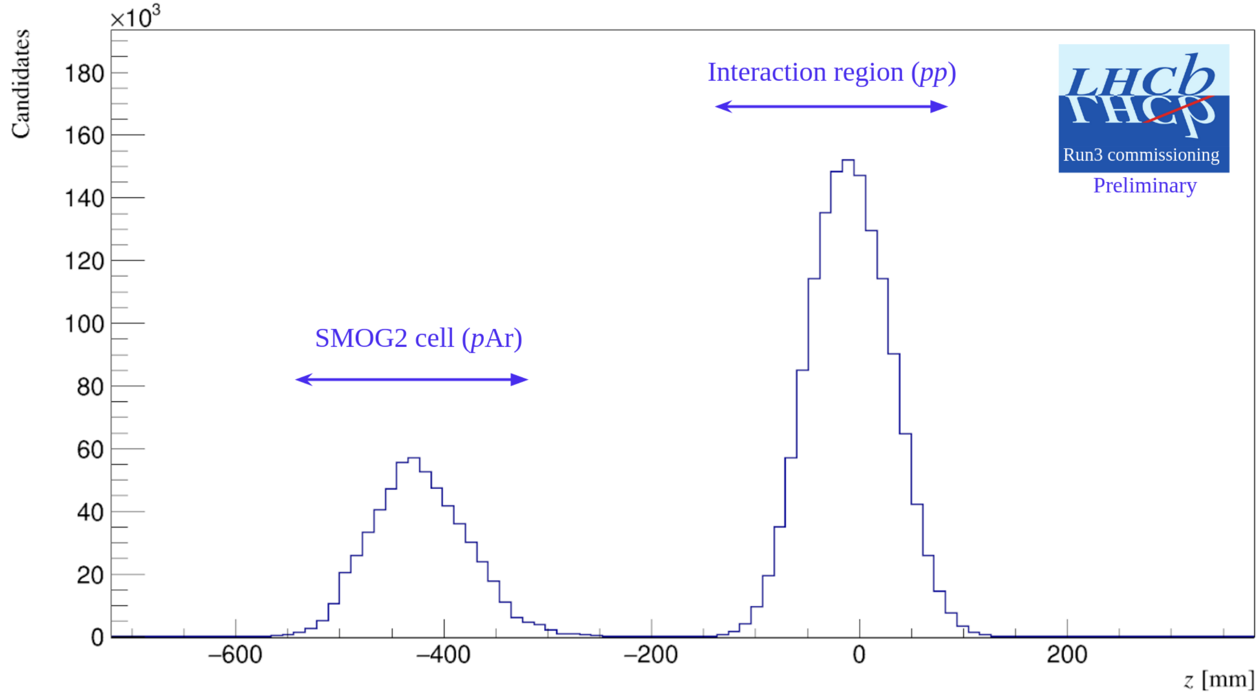


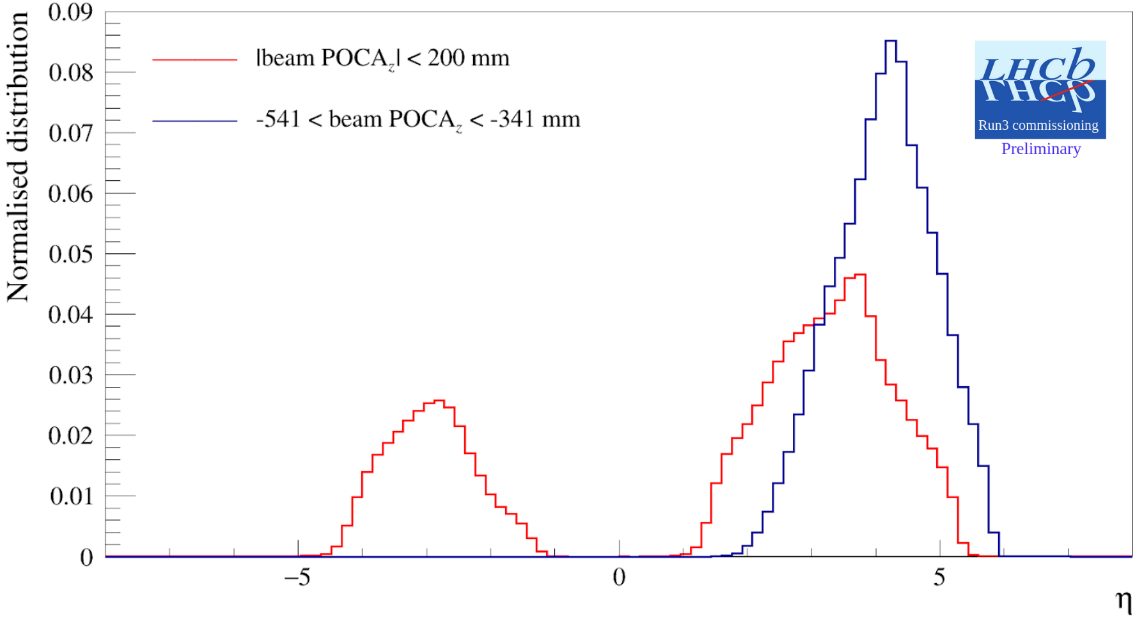


C.Lucarelli, CERN-PBC-Notes-2023-003

First SMOG2 operations in 2022

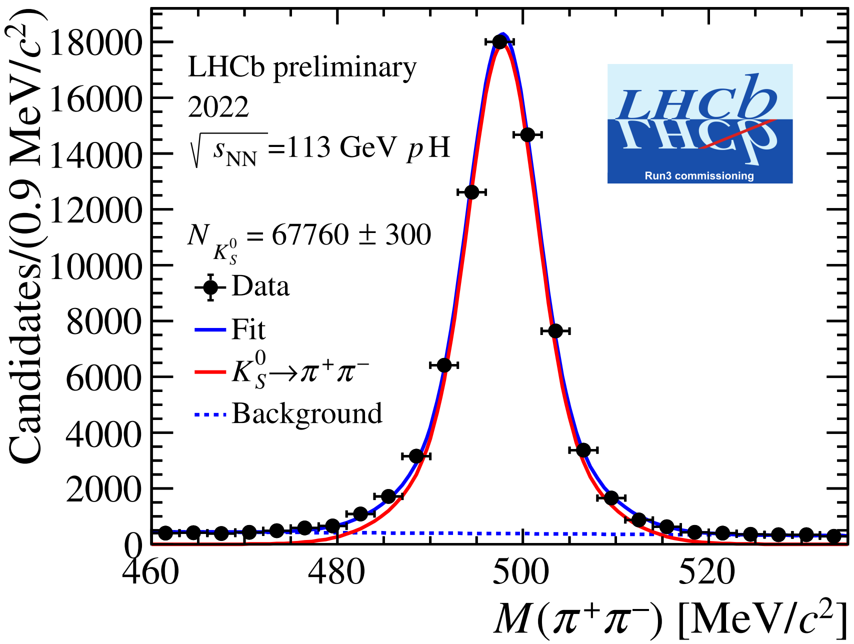
- 2022 has been a commisioning year for the upgraded LHCb detector
- SMOG2 has been succesfully tested with 4 gas species (**H**, He, Ne, Ar)
- first reconstructed primary vertices of simultaneous beam-gas and beam-beam collisions, obtained online through novel Real Time Reconstruction fully software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

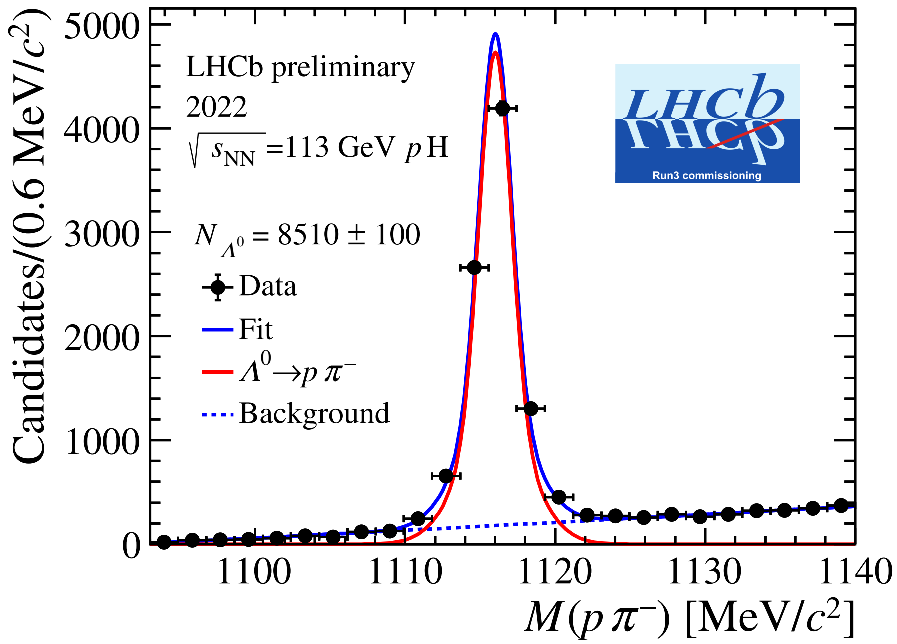




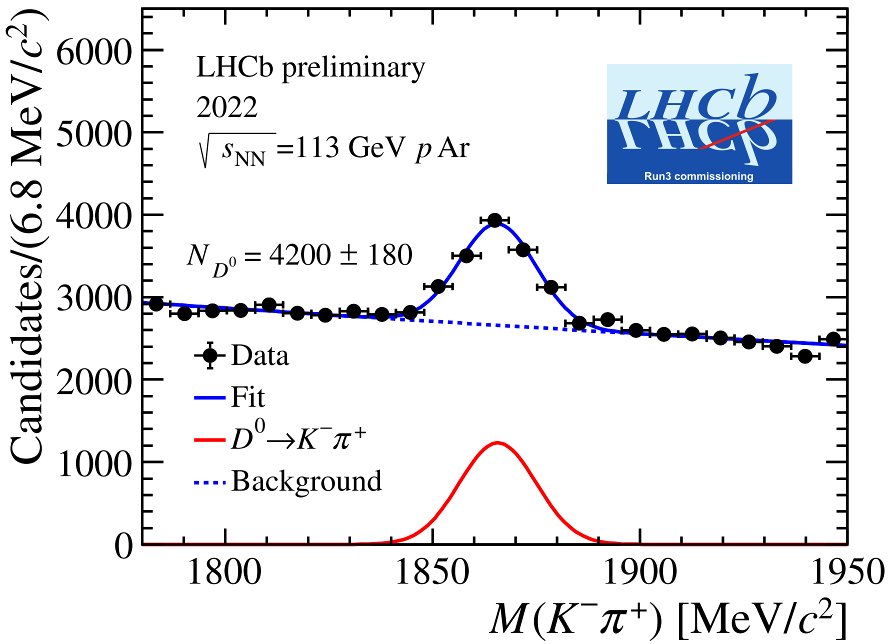
Physics signals in SMOG2 commissioning data!

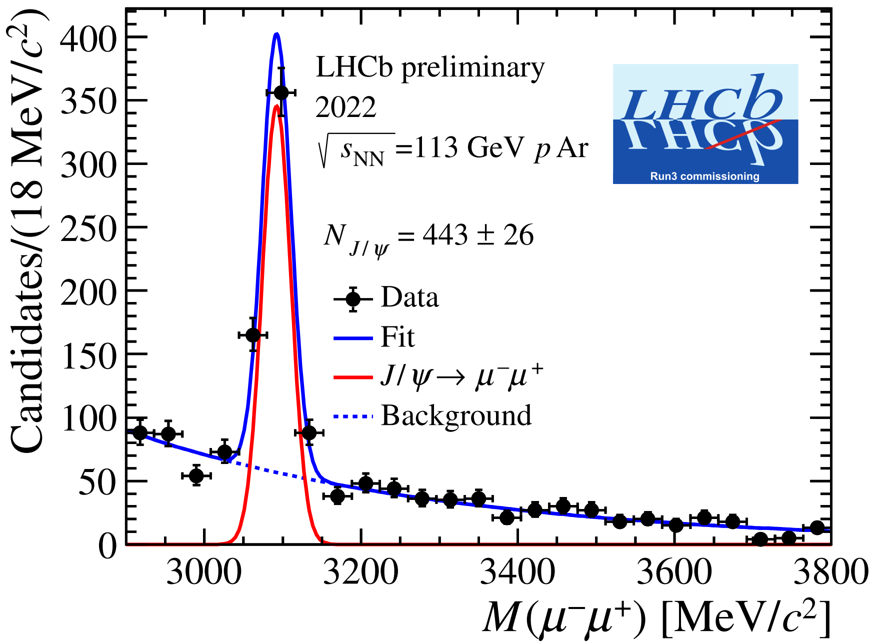
pH
20’ run!





pAr
18’ run!



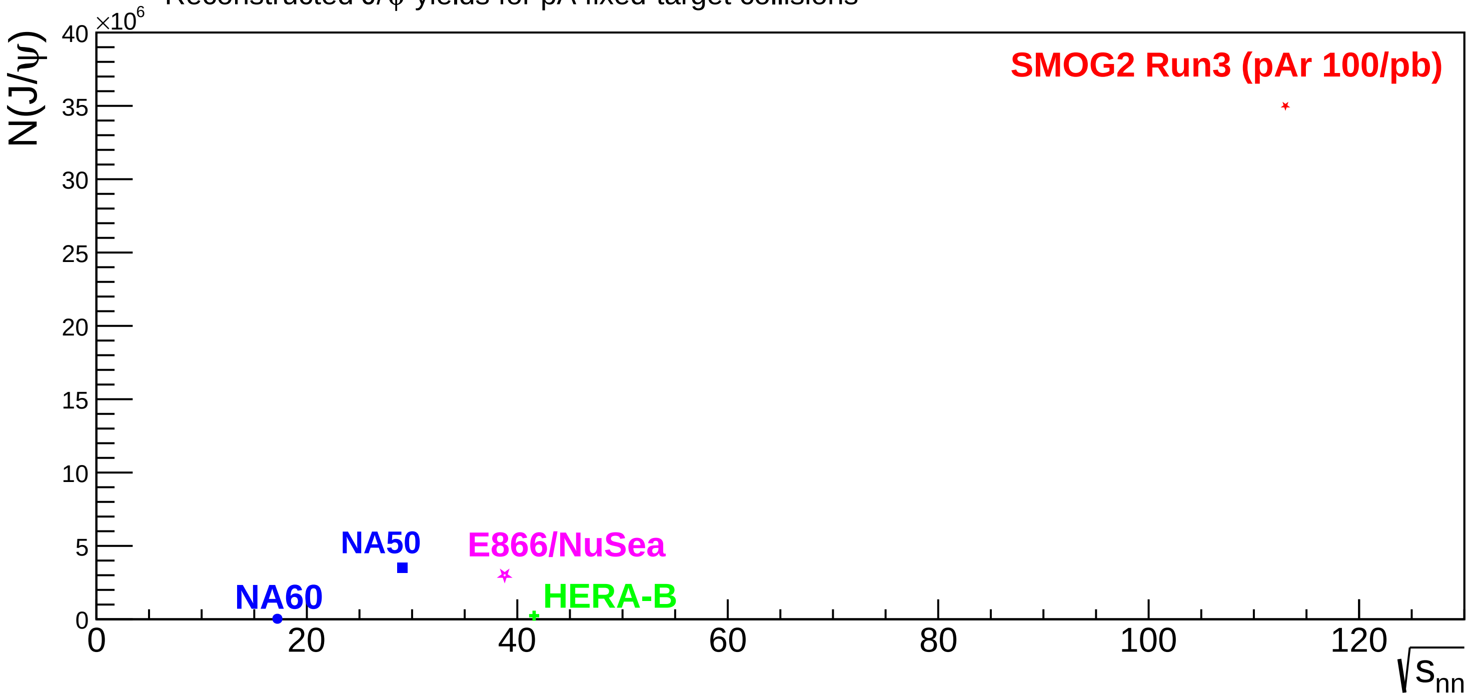


Physics prospects with SMOG2

LHCB-PUB-2018-015
arXiv:1812.06772

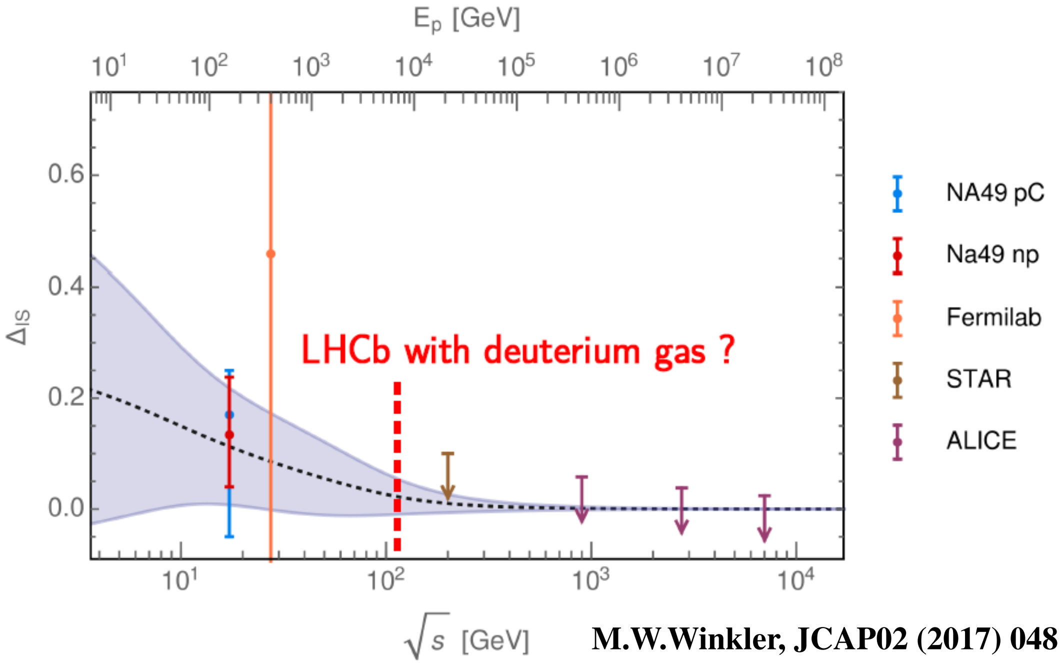
- Aiming at data samples up to 100 pb^{-1}
- Precision charm production measurements, access b states, Drell-Yan, . . .
- H and D targets to provide reference and study 3D structure functions

	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



Prospects for cosmic $\overline{p}$ with LHCb+SMOG2

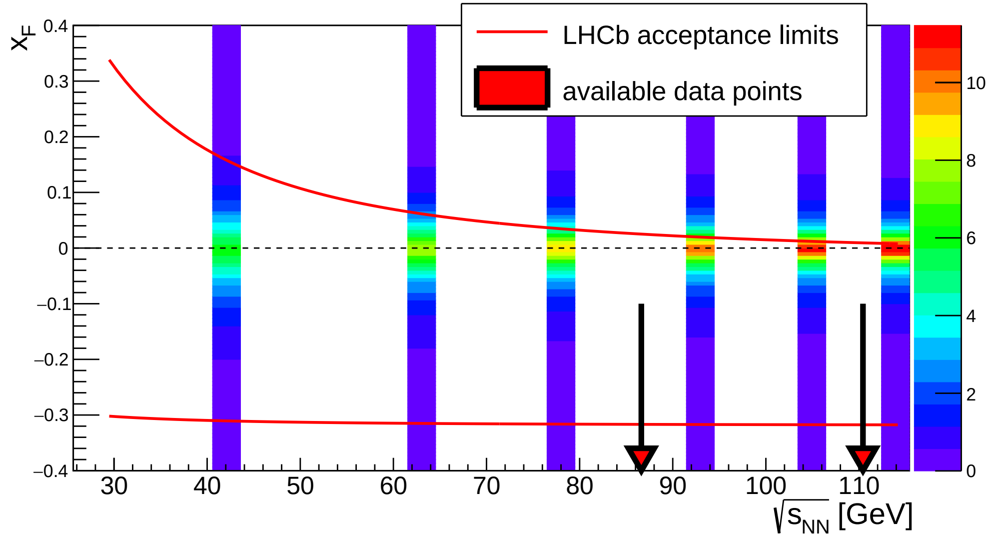
Thanks to the possibility to inject H_2, D_2 and He,
$\sigma(pp \to \overline{p}X)/\sigma(pn \to \overline{p}X)$
can be measured, providing constraints on
$\sigma(pp \to \overline{p}X)/\sigma(pp \to \overline{n}X)$



M.W.Winkler, JCAP02 (2017) 048

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

Data at different injection energy can constrain scaling violation and provide access to forward production in LHCb

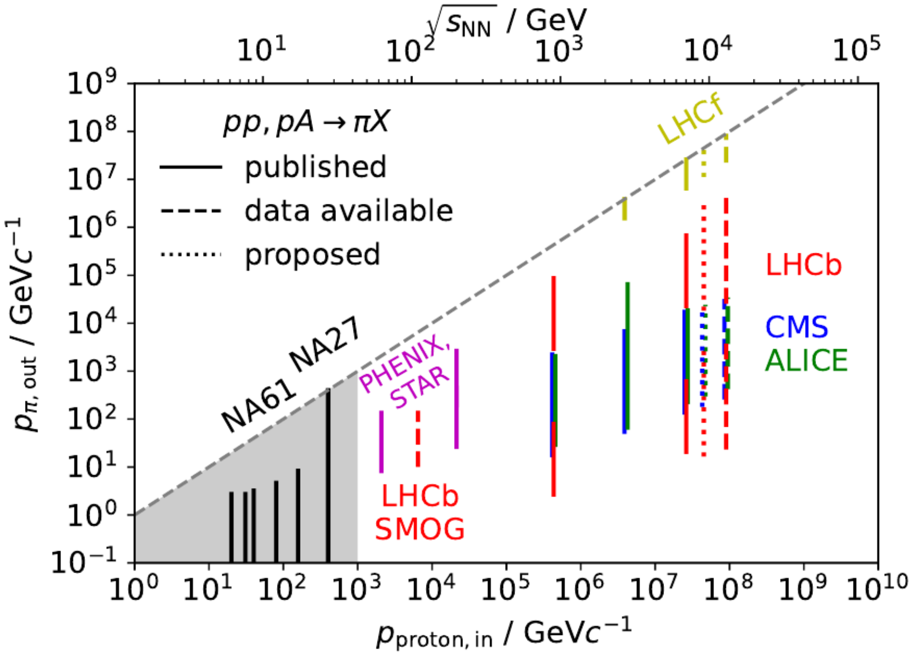


LHCB-PUB-2018-015

Feynman-x distribution for $\overline{p}$ vs $\sqrt{s_{NN}}$ and accessible region to LHCb

Uncertainties on secondary cosmic $\overline{p}$ from production x-sections are expected to become negligible after the SMOG2 program

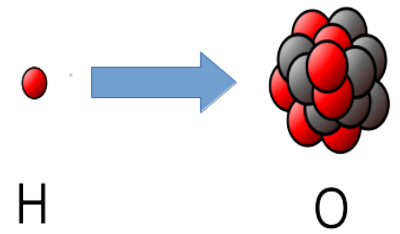
Expected inputs to UHE shower models

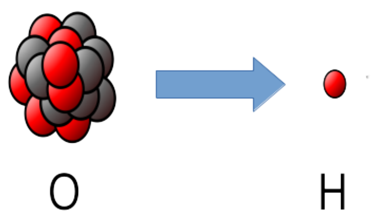


Ast.Sp.Sci. 367 (2022) 3, 27

- 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 $\sqrt{s_{\text{NN}}} \sim 100$ GeV

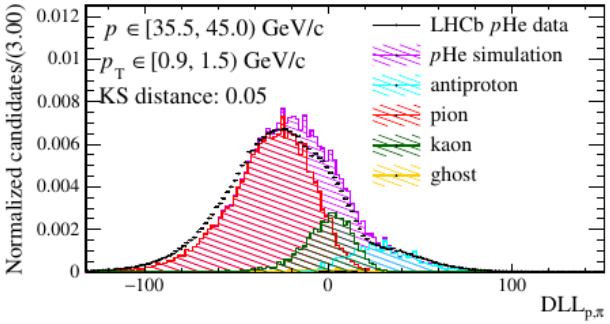




Conclusions

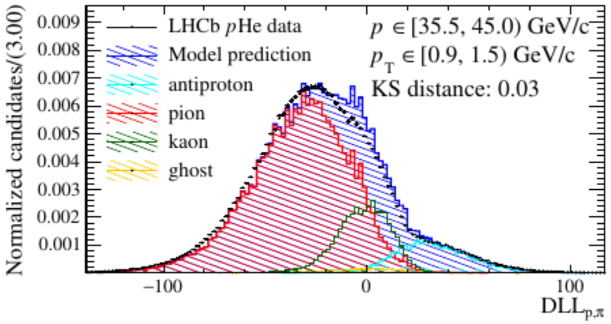
- Reach of Fixed-target physics at the LHC demonstrated with the SMOG gas target at LHCb in Run 2
- still many results to come from data on tape

MC-driven model



ongoing work to optimize particle identification performance for fixed-target samples

Data-driven model



JINST 17 P02018 (2021)

- exciting prospects from the incoming data-taking with SMOG2. First physics data-taking expected this year