Antiproton production from pHe collisions in LHCb

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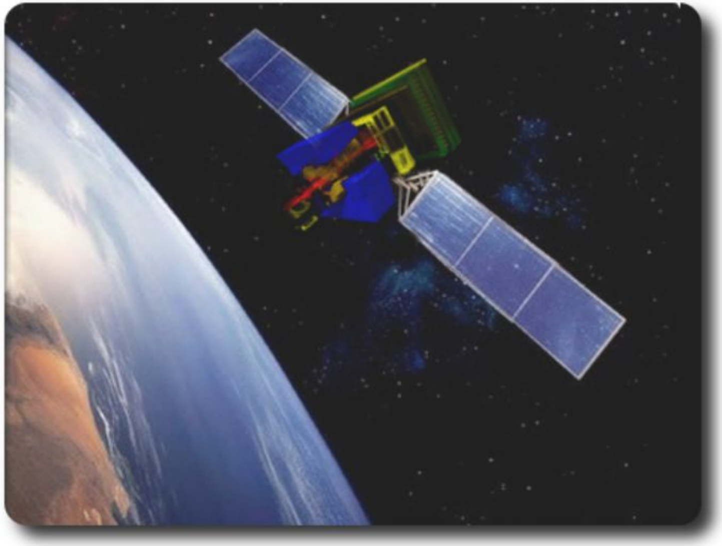
on behalf of the LHCb collaboration

STRONG 2020 meeting, 23/06/2022

Overview

- The interpretation of the antiproton (and more) flux measurements in space is currently **limited by the knowledge of its production processes** [See yesterday talk by Fiorenza Donato]
- **Cross-section measurements at the relevant energy scales are needed**



- Thanks its unique injection of noble gases in the LHC (e.g. He), **LHCb is contributing with its space mission** to improve the precision of models

- Introduction
- Measurements on Run2 data
- Prospects with SMOG2
- Conclusions

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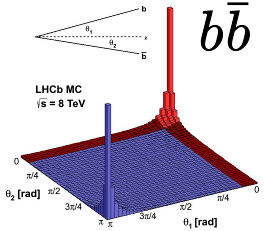
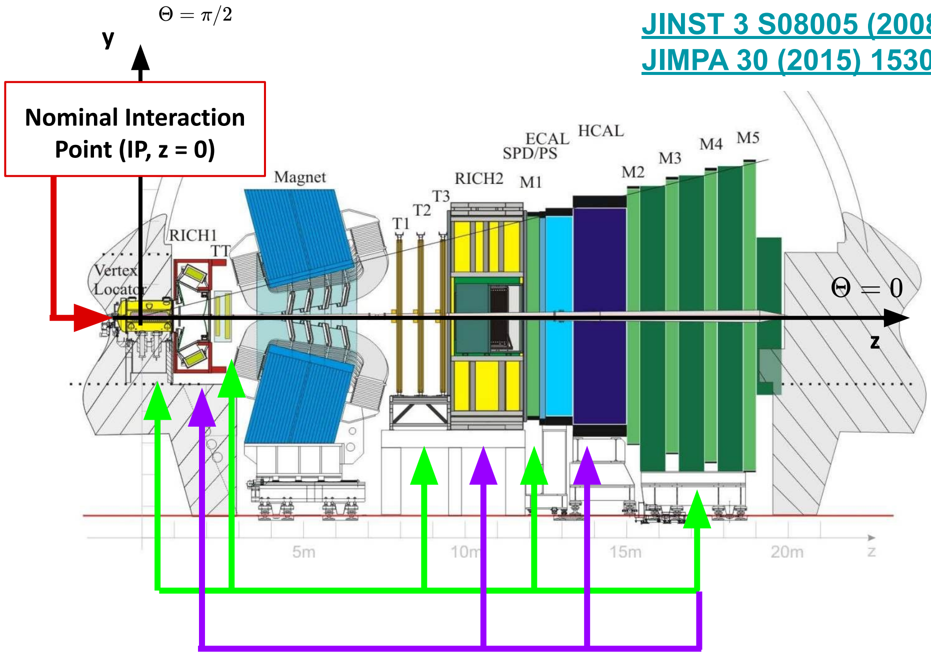
Introduction

The LHCb experiment

- Originally designed for **heavy flavour physics**, the instrumented region covers $\Theta \in [10, 250]$ mrad to balance costs and acceptance of $b\bar{b}$ pairs



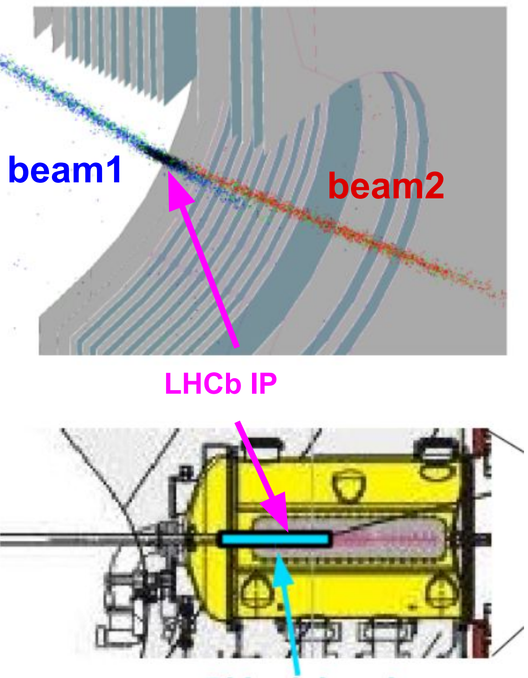
JINST 3 S08005 (2008)
JIMPA 30 (2015) 1530022



- **Complementary** wrt other LHC experiments
- Tracking system: **VErtex LOcator** + tracking stations and a dipole magnet
  - 0.5-1% *p* resolution for p < 300 GeV/c
  - 10-80 μm IP resolution
- Particle identification (PID): Two **Cherenkov detectors (RICH)** + calorimeters and muon
- **Flexible and versatile trigger**

The LHCb experiment in fixed-target mode

JINST 9, (2014) P12005



Fiducial region for p-He collisions (80 cm)

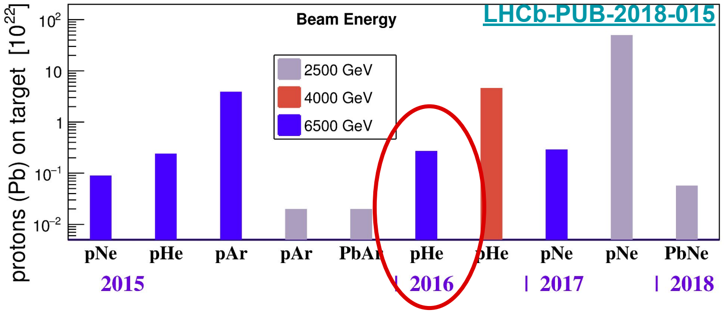
- From 2011, LHCb is equipped with a **System for Measuring Overlap with Gas (SMOG)**
  - Imaging applied to the LHC proton collisions with the small quantity of injected gas (10^{-7} mbar) used to reconstruct the **transverse profiles of the LHC beams**
  - **Lowest uncertainty** on the LHC luminosity measurement (1.2 -1.5%) among all LHC experiments

- In proximity of the LHCb IP, **the proton-nucleus interaction can be fully reconstructed**!

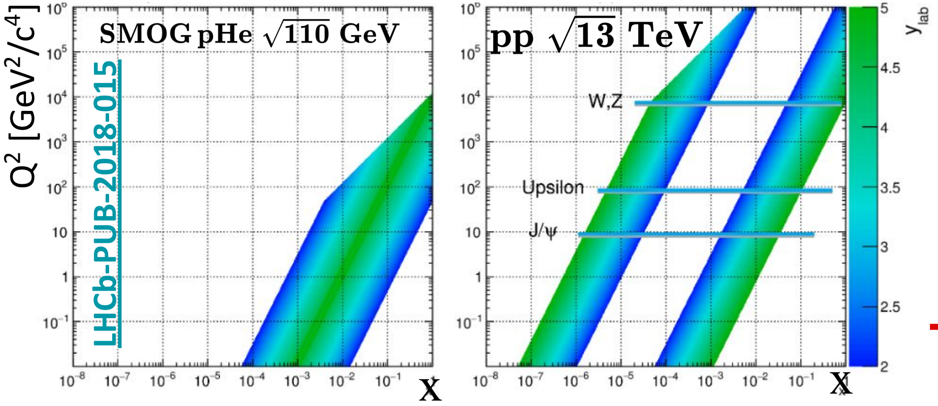
- Forward detector + gas target = **highest-energy fixed-target ever!**

Physics opportunities with SMOG

- pA and PbA fixed-target samples **collected during special runs in 2015-2018**

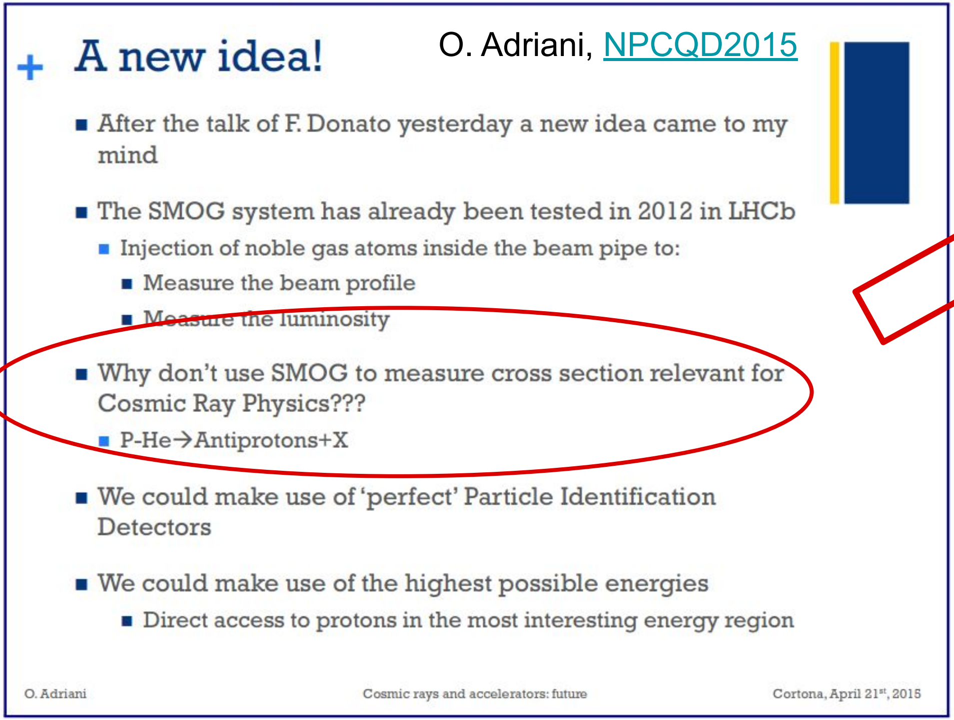


e.g. 6.5 TeV LHC protons on at-rest He correspond to a nucleon-nucleon centre-of-mass energy $\sqrt{s_{NN}}$ =110 GeV



- **Intermediate energy** to SpS and LHC
- Many collision systems (Z dependence)
- **Access to the moderate Q^2 and large target Bjorken-x** region

→ **Unique experimental inputs** to theoretical models, and, in particular…

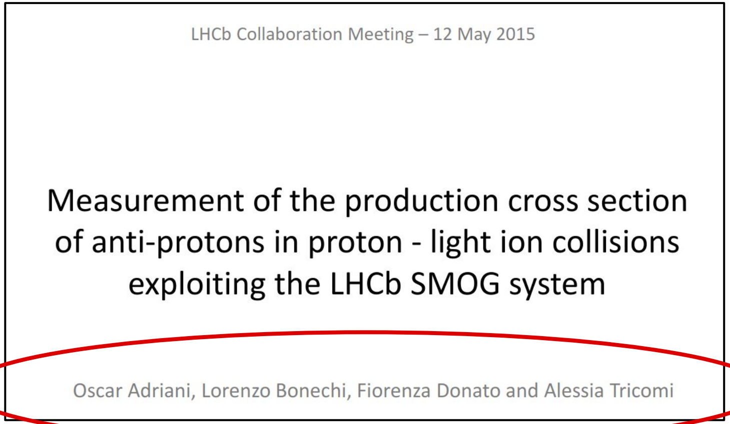


O. Adriani, NPCQD2015

A new idea!

- After the talk of F. Donato yesterday a new idea came to my mind
- The SMOG system has already been tested in 2012 in LHCb
  - Injection of noble gas atoms inside the beam pipe to:
    - Measure the beam profile
    - Measure the luminosity
- Why don't use SMOG to measure cross section relevant for Cosmic Ray Physics???
  - P-He→Antiprotons+X
- We could make use of 'perfect' Particle Identification Detectors
- We could make use of the highest possible energies
  - Direct access to protons in the most interesting energy region

O. Adriani | Cosmic rays and accelerators: future | Cortona, April 21st, 2015



LHCb Collaboration Meeting – 12 May 2015

Measurement of the production cross section of anti-protons in proton - light ion collisions exploiting the LHCb SMOG system

Oscar Adriani, Lorenzo Bonechi, Fiorenza Donato and Alessia Tricomi

- Proposal from the CR community to exploit **the LHCb SMOG system to measure for the first time** the antiproton production in *p*He collisions

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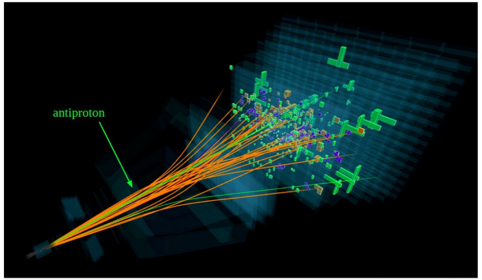
Run2 antiproton production measurements

ABOUT NEWS

LHCb reveals secret of antimatter creation in cosmic collisions

The finding may help determine whether or not any antimatter seen by experiments in space originates from dark matter

7 APRIL, 2022



Large Hadron Collider beauty experiment

LHCB NEWS | PHYSICS | DETECTOR | DATA COLLECTION | COLLABORATION | INSTALLATION | ACTIVITIES | GALLER

PHYSICS RESULTS

Measurement of antiproton production in p-He collisions

Can cosmic-ray antiprotons unveil dark matter collisions?

Large Hadron Collider beauty experiment

LHCB NEWS | PHYSICS | DETECTOR | DATA COLLECTION | COLLABORATION | INSTALLATION

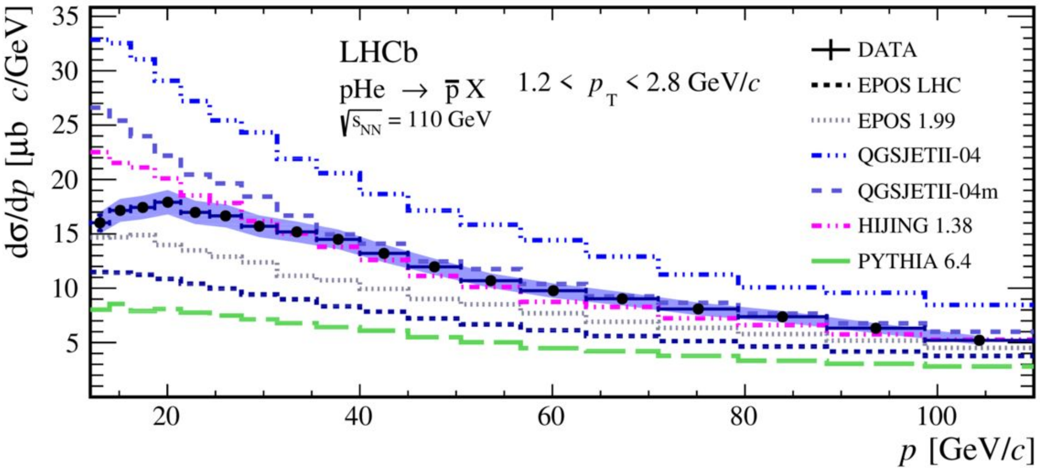
LATEST POSTS | PHYSICS RESULTS

LHCb measurements help to understand possible signatures of dark matter presence in the Universe

Prompt antiproton production measurement

PRL 121 (2018) 222001

- **First measurement ever** of $\sigma(p\mathrm{He} \to \bar{\mathrm{p}}_{\mathrm{prompt}}\mathrm{X})$ at $\sqrt{s_{\mathrm{NN}}} = 110$ GeV with 2016 *p*He data
- Only particles **produced promptly at the *p*He vertex** are selected within the fiducial region *p* є [12, 110] GeV/c; p_{T} є [0.4, 4] GeV/c
- Dominant uncertainties:
  - **Luminosity measurement** (injected gas pressure not precisely measured)
  - **Particle identification performance** (poor calibration statistics)



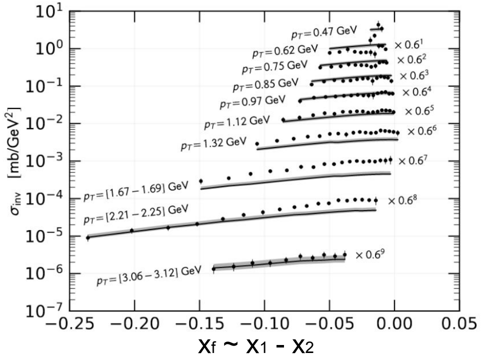
- Result uncertainties are **lower wrt to the spread of theoretical models**

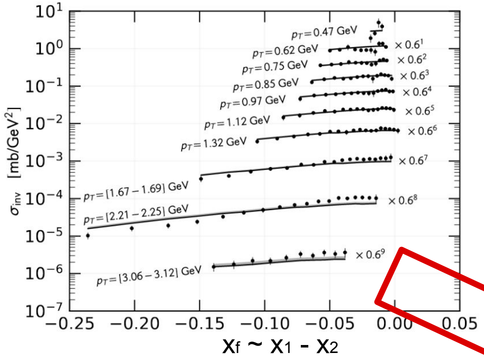
Impact of the measurement

PRL 121 (2018) 222001

Two models on the same LHCb data

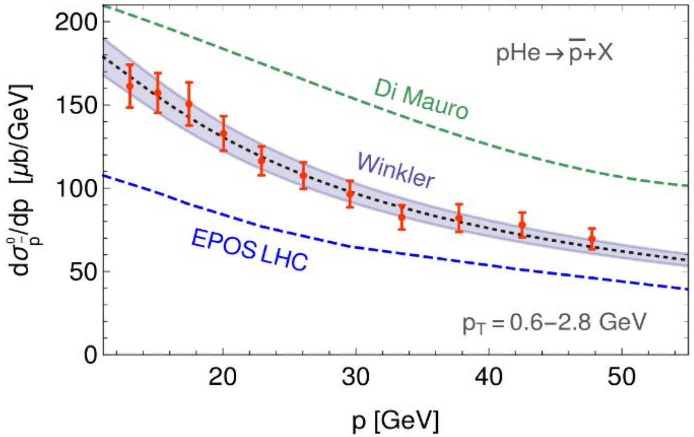
M. Korsmeier et. al., PRD97 (2018) 103019





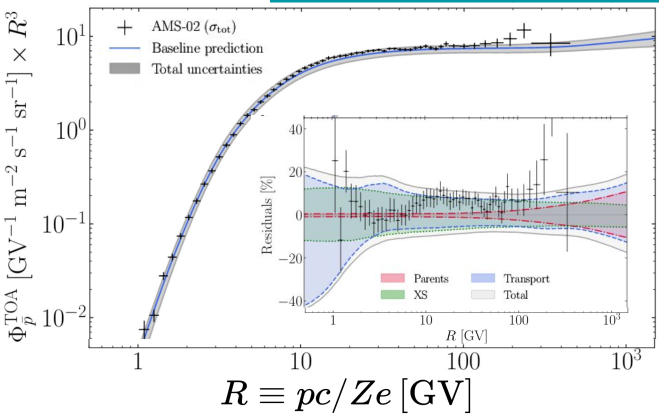
- **LHCb data** contributing to constrain:
  - the σ extrapolation **from H to He**
  - the σ evolution **with the energy**

A. Reinert, M. Winkler JCAP 1801 (2018) 055



+ other theo and exp results!

M. Boudaud et. al., PoS (ICRC2019) 038



- Room for exotic contribution **heavily reduced**!

Can we do more?

- LHCb SMOG wishlist:

1) $p\,He \rightarrow \bar{\Lambda}, \bar{\Sigma}$ from existing run
2) $p\,p\,(H_2) \rightarrow \bar{p}$ to test scaling violation in forward hemisphere
3) $p\,d \rightarrow \bar{p}$ to test isospin effects
4) $p\,p,\ p\,He \rightarrow \bar{d}, \bar{He}$ to determine coalescence momentum
5) $p\,p,\ p\,He \rightarrow \pi, K$ to model positron source term

Martin Winkler at 2nd LHCb Heavy Ion workshop

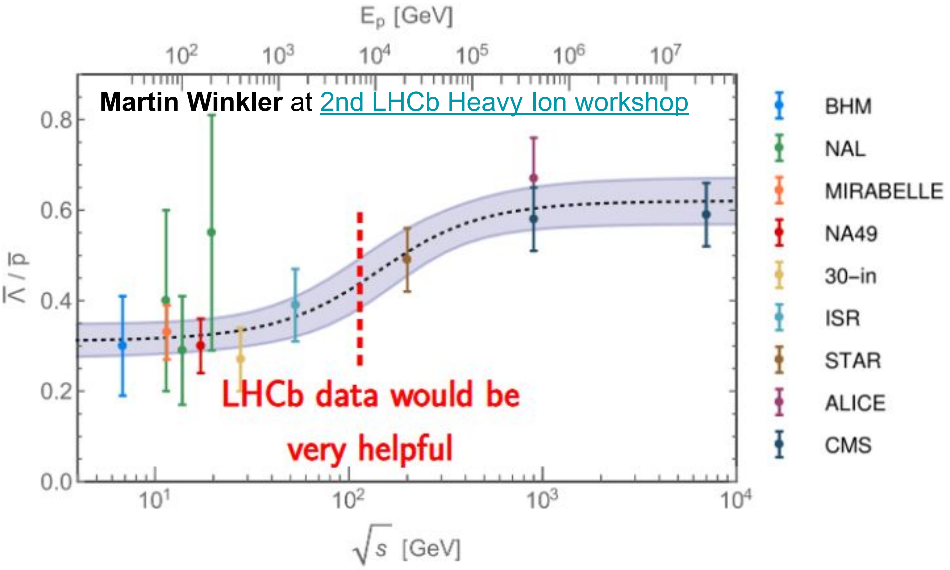
- **Feasible** with available SMOG or future SMOG2 data

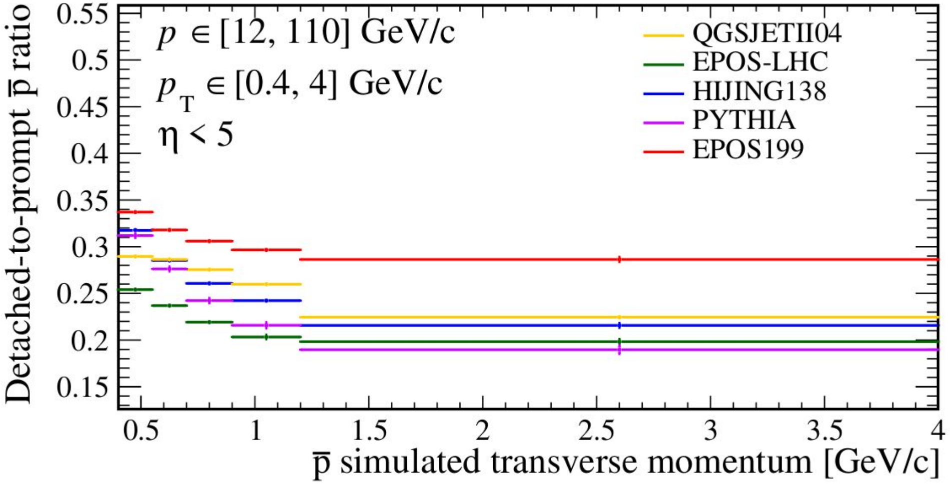
Predictions for antihyperon-produced antiprotons

- LHCb result only covered prompt $\bar{p}$, **excluding those from anti-hyperon decays** (detached)

$$\bar{\Lambda}^0_{\text{prompt}} \to \bar{p}\pi^+ \qquad \bar{\Sigma}^- \to \bar{p}\pi^0 \qquad \bar{\Xi}^+ \to \bar{\Lambda}\pi^+ \qquad \bar{\Xi}^0 \to \bar{\Lambda}\pi^0 \qquad \bar{\Omega}^+ \to \bar{\Lambda}K^+$$

- Scarce available data indicate a **strangeness enhancement** that **can be constrained** in a LHCb-SMOG measurement to reduce **the large spread among different theoretical models**

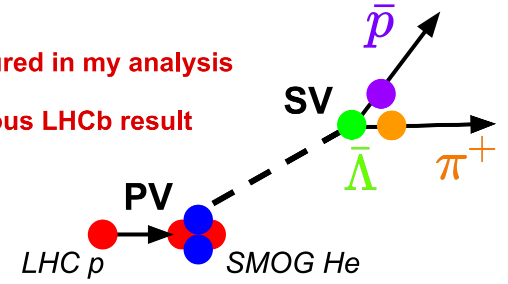




Approaches to the measurement

- **Two complementary approaches** to the measurement

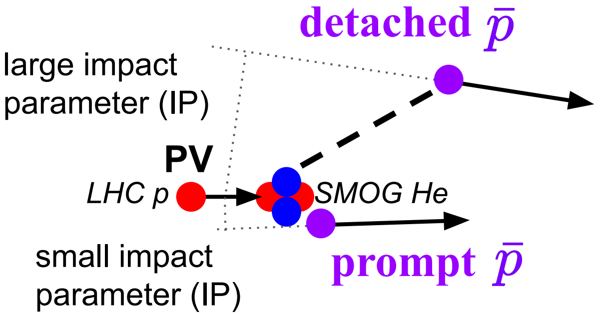
- **Exclusive approach**: $R_{\bar{\Lambda}} = \frac{\sigma(p\text{He} \to (\bar{\Lambda}_{\text{prompt}} \to \bar{p}\pi^+)X)}{\sigma(p\text{He} \to \bar{p}_{\text{prompt}}\, X)}$ → measured in my analysis (numerator) → previous LHCb result (denominator)
  - ➔ Focused on the **dominant detached component**
  - ➔ **Not using PID** information



- **Inclusive approach**: $R_{\bar{H}} \equiv \frac{\sigma(p\text{He} \to \bar{H}X \to \bar{p}X)}{\sigma(p\text{He} \to \bar{p}_{\text{prompt}} X)}$

$$\bar{H} = \bar{\Lambda}, \bar{\Sigma}, \bar{\Xi}, \bar{\Omega}$$

  - ➔ Focused on all **detached components**
  - ➔ **Selecting antiproton with PID** information and distinguishing between prompt and detached via the **excellent VELO IP resolution**

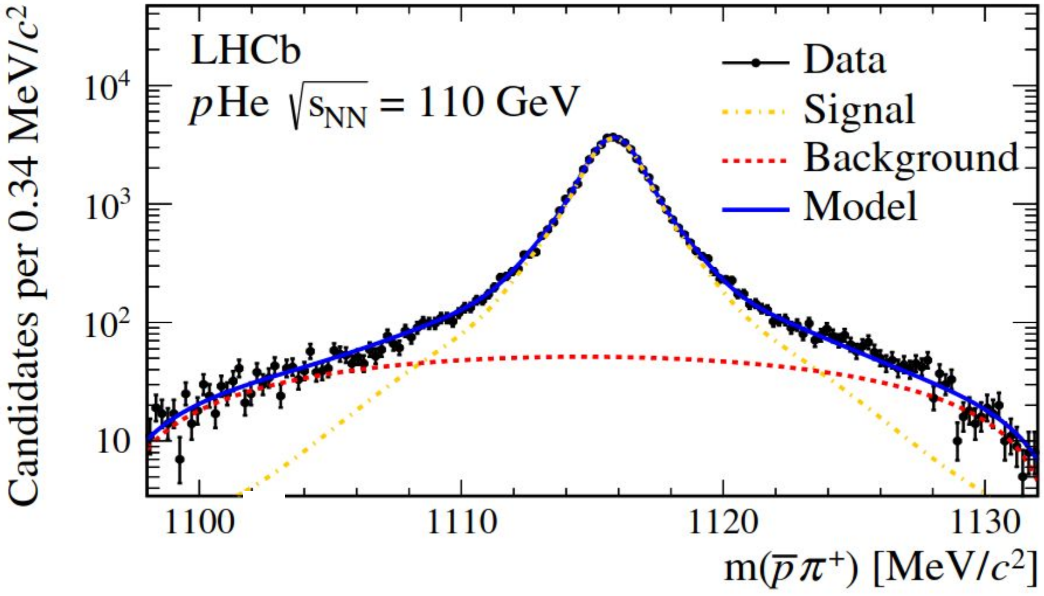


Exclusive approach: strategy

LHCb-PAPER-2022-006

- **Goal:** measure the antiprotons from $\bar{\Lambda}_{\rm prompt}$ decays, the **dominant detached component**

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



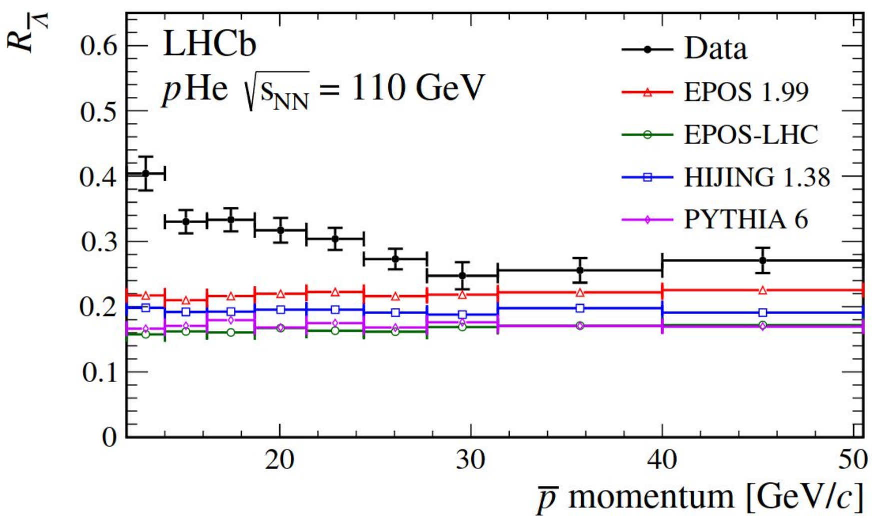
- Events selection only uses the **decay kinematic description in the Armenteros plot** and the **impact parameters** to select the signal decays
- Most systematic uncertainties (notably the lumi and the antiproton reco) **cancel in the ratio**

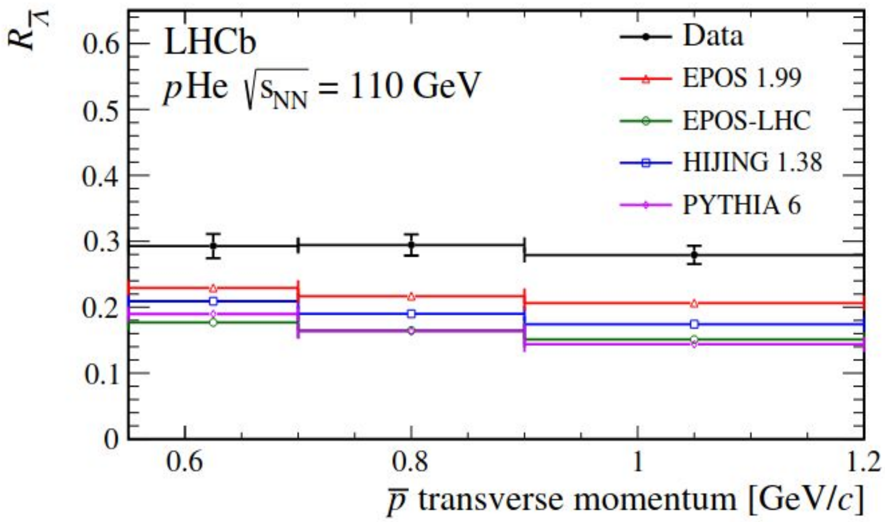
Exclusive approach: results

LHCb-PAPER-2022-006

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

- **Larger contribution measured wrt all most widely used theoretical models**





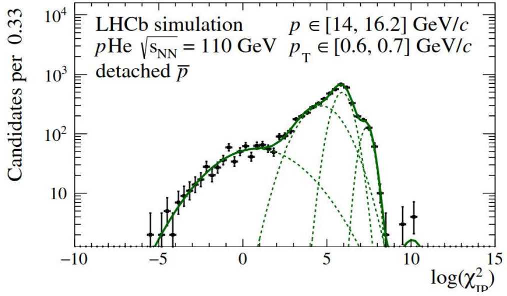
Inclusive approach: strategy

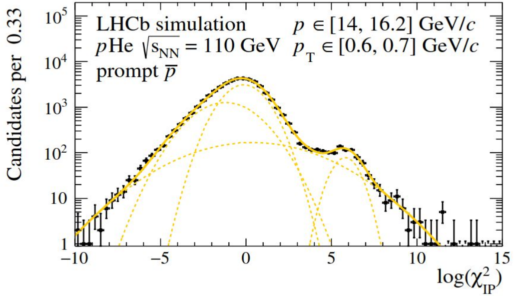
LHCb-PAPER-2022-006

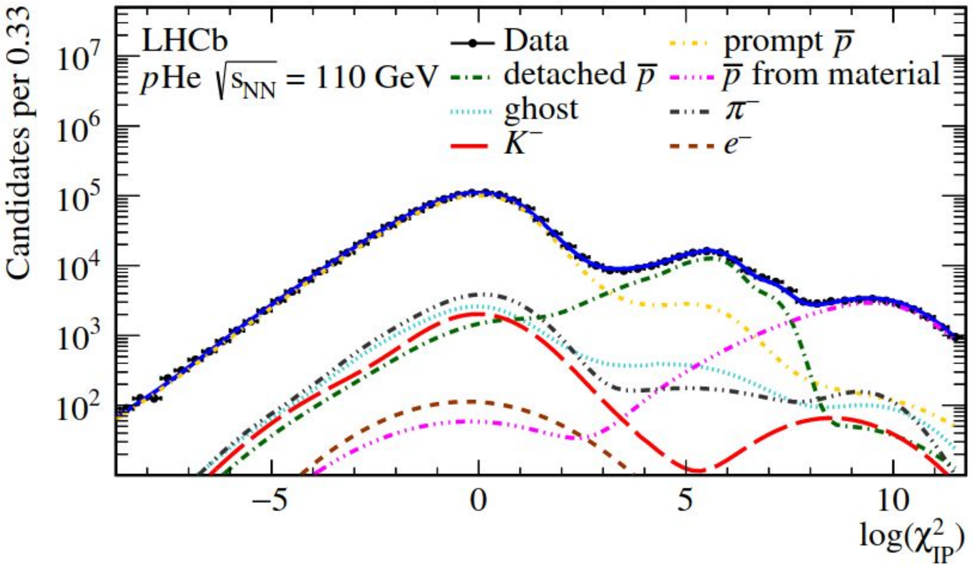
- **Goal:** measure all **detached contributions**

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

- Sample enriched with $\bar{p}$ selected with tight **PID cuts** and statistically separated as prompt, detached and secondary with a **fit to the pHe data impact parameter with the composition of templates** (Gaussian compositions applied to simulation)





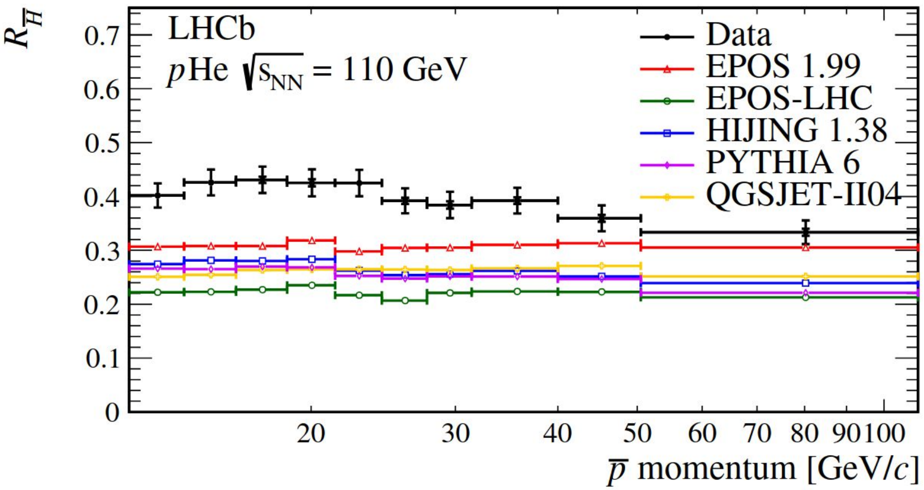


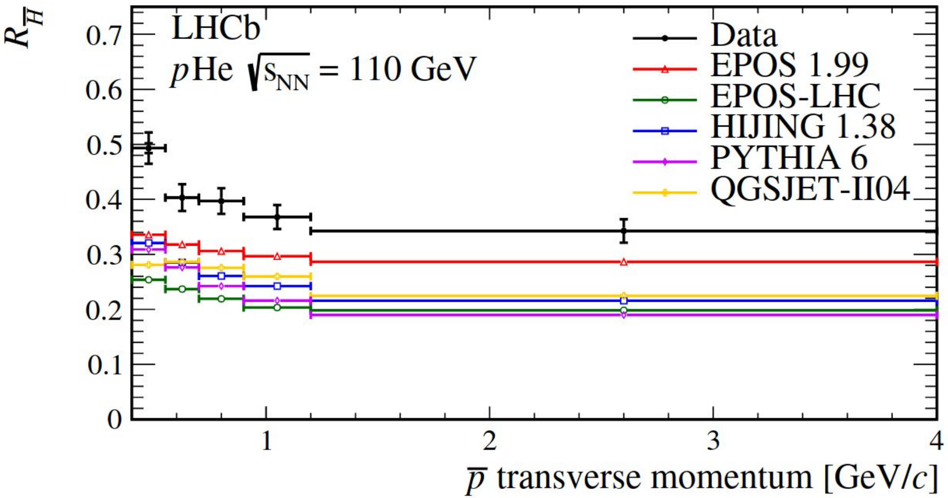
Inclusive approach: results

LHCb-PAPER-2022-006

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

- **Larger contribution measured wrt all most widely used theoretical models**

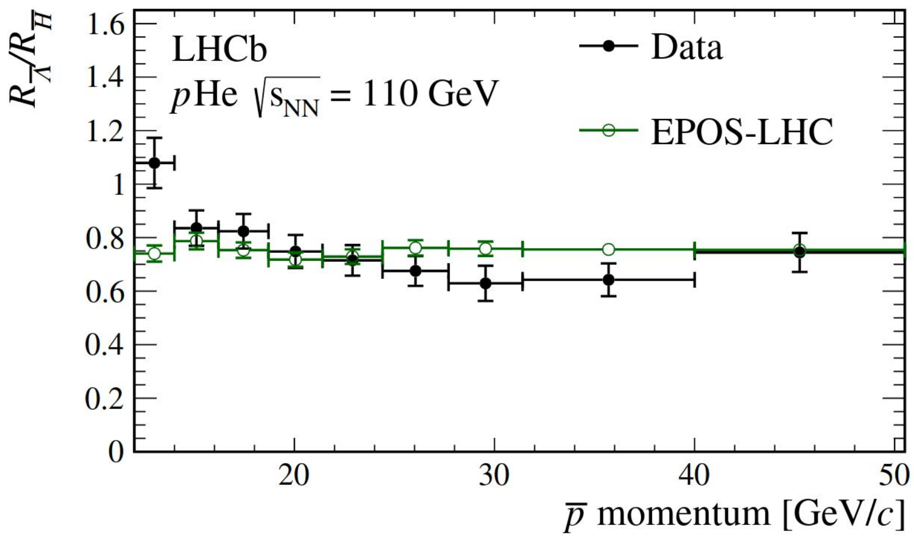


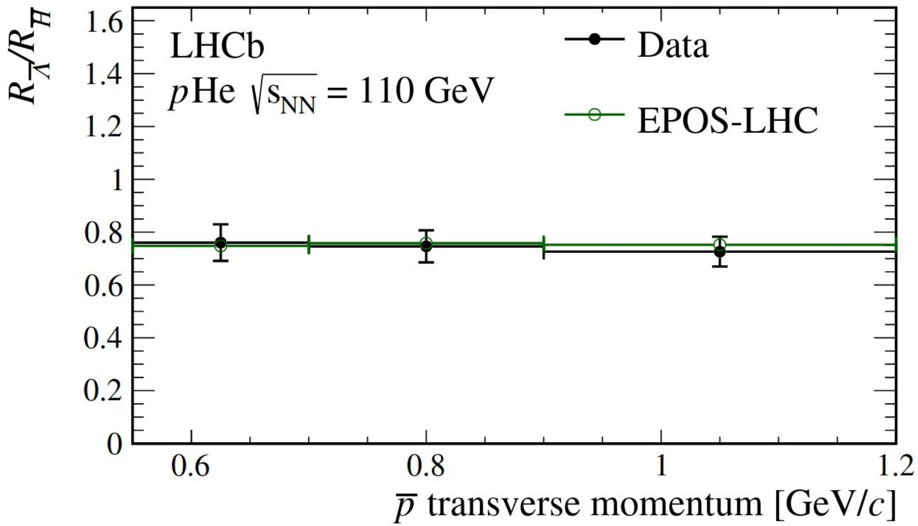


Comparison between the two approaches

LHCb-PAPER-2022-006

- Ratio of the results is expected to be **predicted more reliably** than the single terms (only depending on the hadronization)
- Results mutually cross-checked since found to be **consistent with EPOS-LHC prediction**

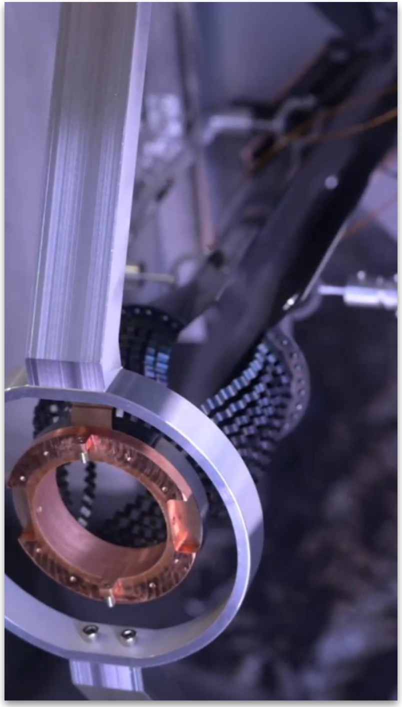




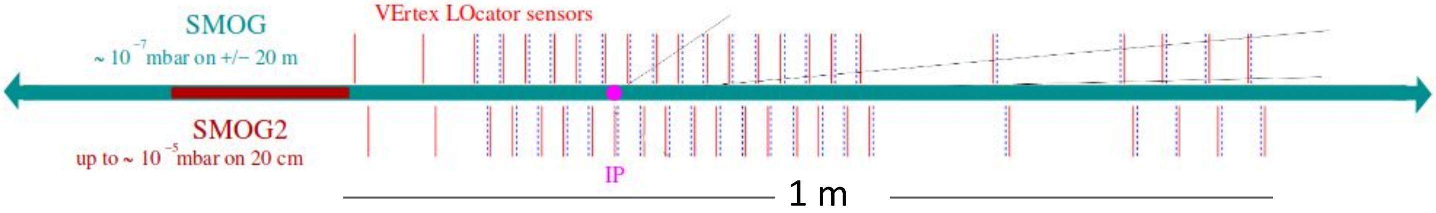
Prospects with SMOG2

SMOG2 in a nutshell

X10 speed wrt reality



LHCb-TDR-020



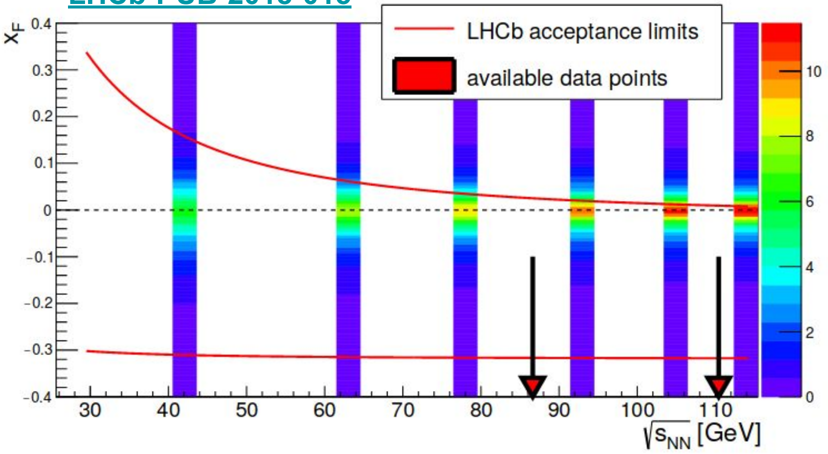
- **SMOG2: confinement of the gas in a cell made up of two movable halves upstream of the LHCb IP** (z є [-500, -300] mm)
  - Up to x100 gas **pressure wrt SMOG for the same gas flow**
  - **Simultaneous beam-beam beam-gas data-taking**
  - **Heavy noble (Kr, Xe) and non-noble gases (H_2, D_2, O_2, N_2 …)** can be injected → **a unique laboratory for QCD studies at LHC!**

LHCb-PUB-2018-015

- **New Gas Feed System**
  - Precise gas flow control → **direct luminosity measurement**
  - More gas recipients → **full switch with no intervention**

Prospects for antiproton production measurements

LHCb-PUB-2018-015



- Extension towards **lower energies**:
  - 2016 *p*He sample with $\sqrt{s_{NN}} = 87\ GeV$
  - Discussing **special runs with E_{beam} = 450 GeV** (requiring new optics to squeeze the beams)
- **Access to the positive Feynman-x regime**

- By injecting H_2, $\sigma(pHe \to \bar{p}X)/\sigma(pp \to \bar{p}X)$ measurement, less prone to systematic uncertainty, can **increase the accuracy**
- By injecting deuterium, the $\sigma(pD \to \bar{p}X)/\sigma(pp \to \bar{p}X)$ measurement can **constrain the isospin symmetry violation term** between the antiproton and antineutron production

Conclusions

[Reference]

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.

- Fixed-target physics acknowledged as a **key opportunity for the future** in the 2020 ESPPU

Conclusions

- Since 2015, LHCb is acting as the **highest energy ever fixed-target experiment** by injecting in the LHC accelerator **small quantities of noble gases**
- **Performed two antiproton production measurements in *p*He collisions**, crucial input to models of the antimatter production in space:
  - Prompt production, in 2018, **the first ever for the *p*He system**
  - Detached-to-prompt production, in 2022, showing **a large underestimation of all theoretical models for the antihyperon decay contributions**
- **The ongoing upgrade of the fixed-target programme,** with the increase of the gas target areal density and the injectable gas species, will improve the accuracy and will extend these measurements… **stay tuned!**

Thanks for your attention!

Want to follow up? saverio.mariani@cern.ch