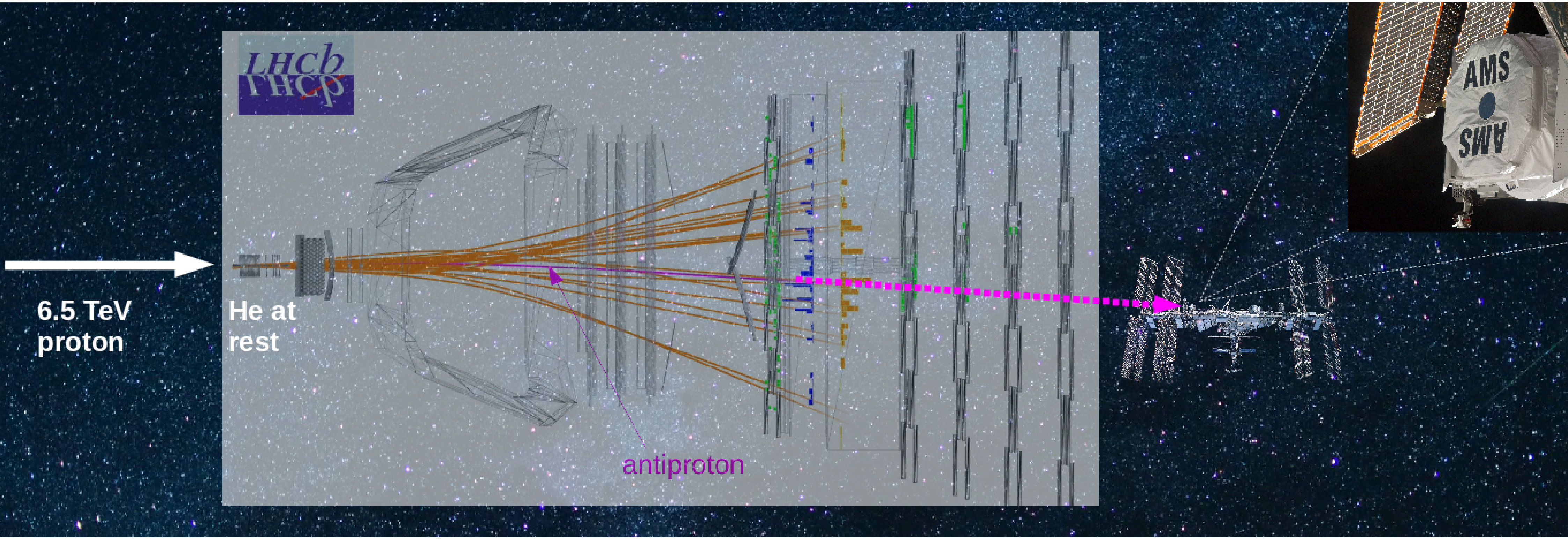
Measurements of Antiproton Production (and more) at LHCb



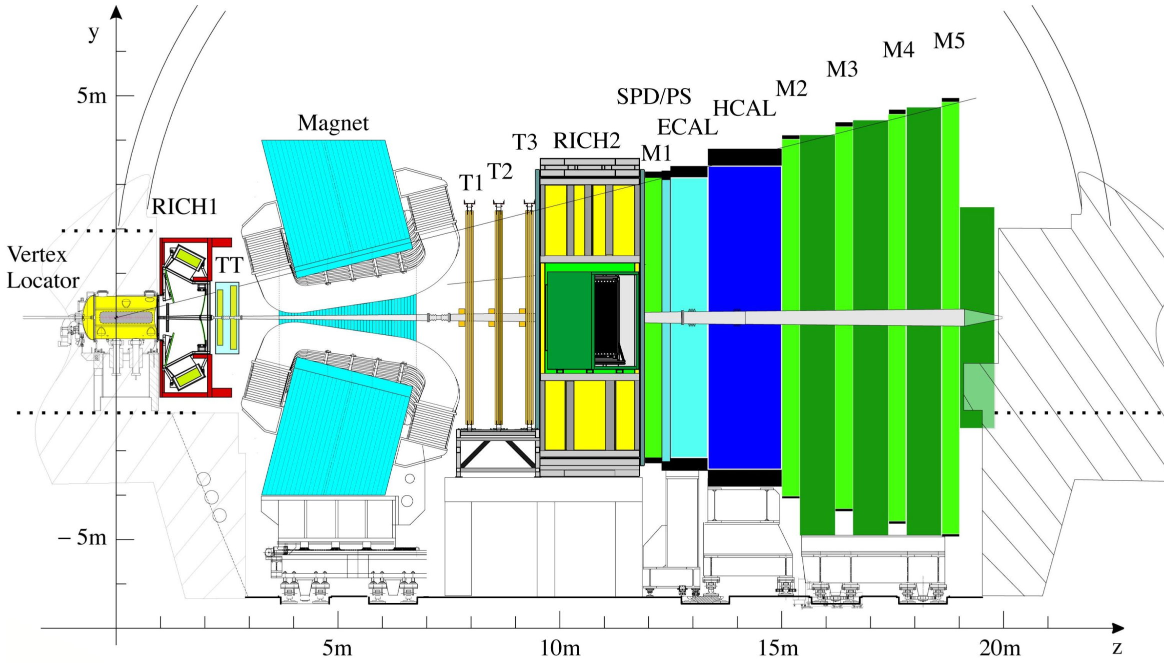
Giacomo Graziani (INFN Firenze)

PAW'24 - Physics at AMBER international Workshop 2024
March 18, 2024

LHCb as a fixed-target experiment

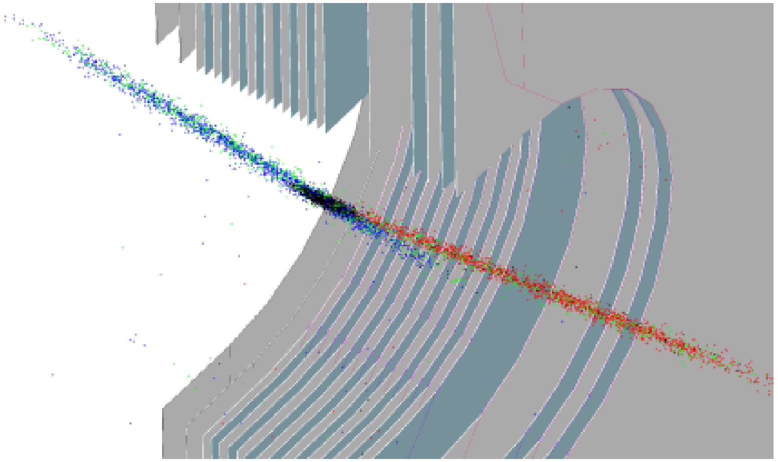
LHCb is the experiment devoted to heavy flavours in pp collisions at the LHC.

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

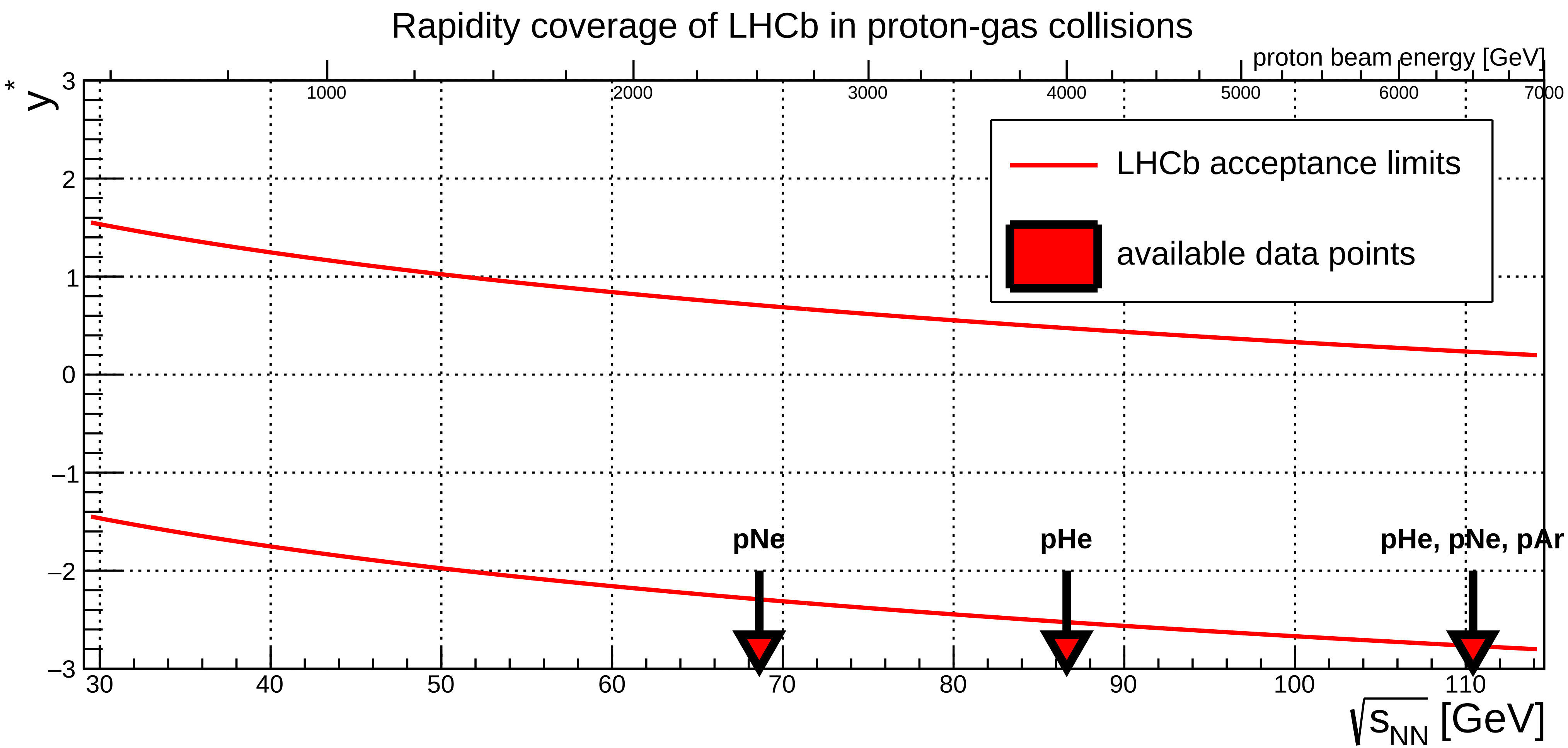
LHCb pioneered fixed-target physics@LHC during Run 2 thanks to SMOG



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**
(He suggested by cosmic ray community!)
Gas pressure $\sim 2 \times 10^{-7}$ mbar ➡ $\mathcal{L} \lesssim 6 \times 10^{29}\text{cm}^{-2}\text{s}^{-1}$

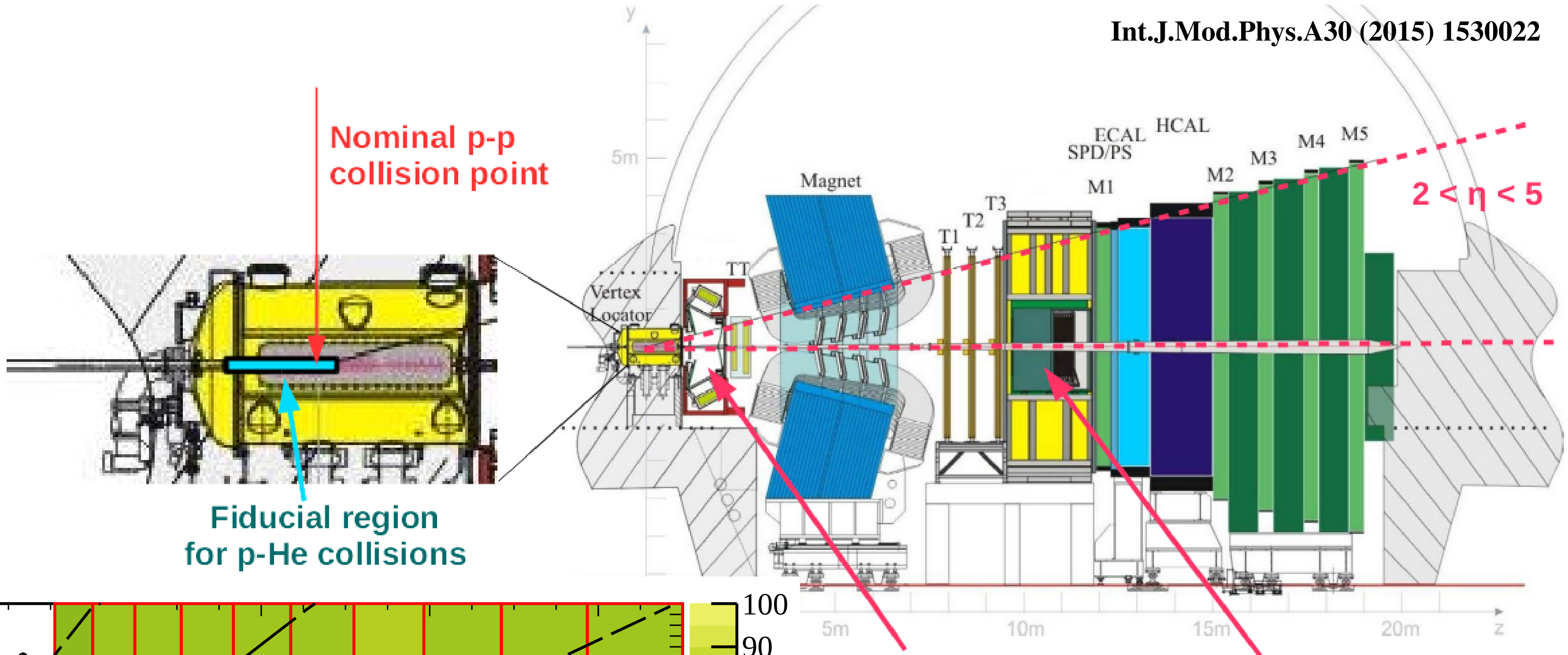
Fixed Target Acceptance

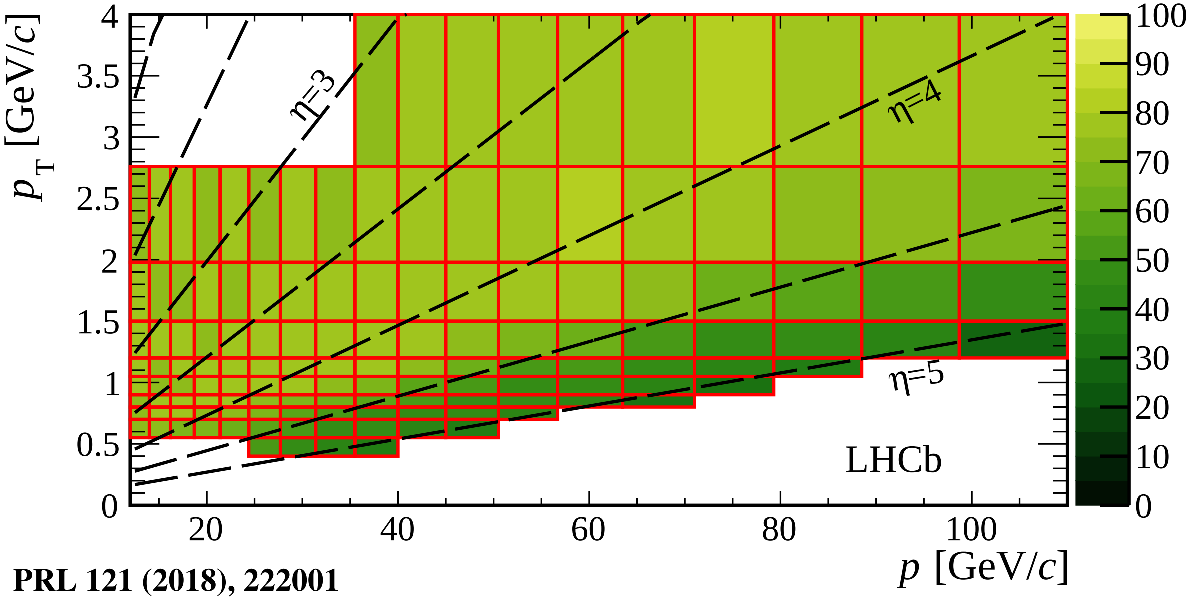


Acceptance for antiprotons in pHe collisions

JINST 3, (2008) S08005

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





PRL 121 (2018), 222001

Rapidity in c.m.s. system:

$$y^* \sim -2.8 \text{ - } 0.2$$

x-Feynman $$\frac{2p_L^*}{\sqrt{s_{NN}}} \sim -0.25 \text{ - } 0.$$

Acceptance × reconstruction efficiency for antiprotons

Antiprotons from pHe collisions

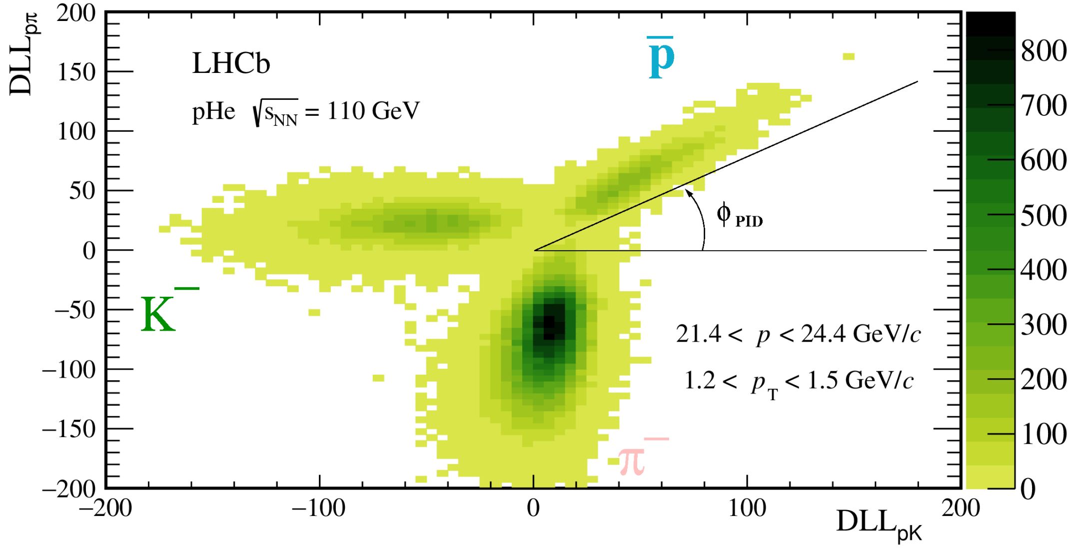
PRL 121 (2018), 222001

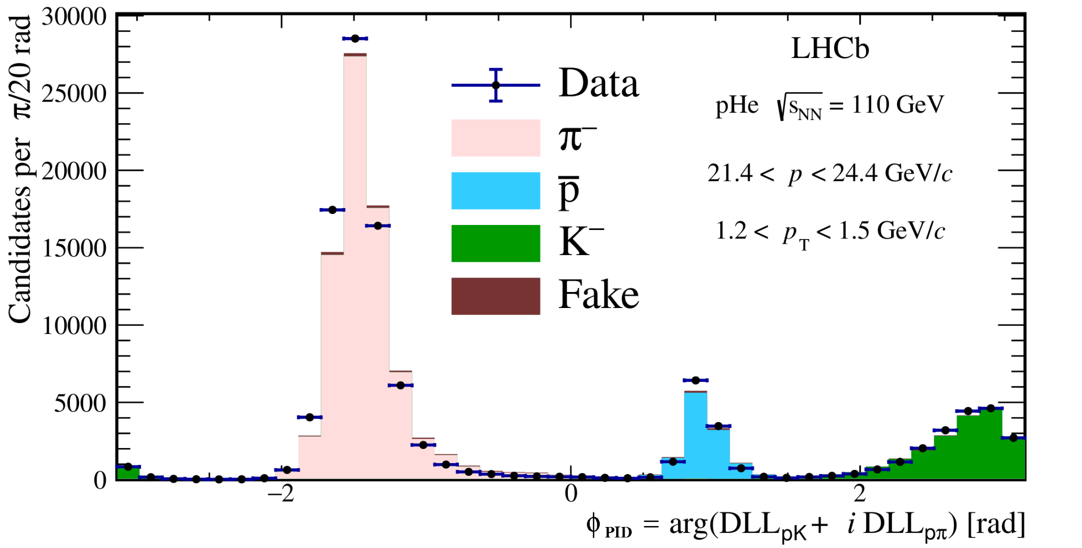
- First measurement of $p\text{He} \to \bar{p}X$ cross-section, the process accounts for $\sim 40\%$ of secondary cosmic $\bar{p}$
- Data collected in May 2016, with proton energy 6.5 TeV, $\sqrt{s_{\text{NN}}} = 110$ GeV, mostly from a single LHC fill (5 hours)
- Minimum bias trigger, fully efficient on candidate events
- Exploit **excellent particle identification** (PID) capabilities in LHCb to count antiprotons in $(p,\, p_{\text{T}})$ bins within the kinematic range

$$12 < p < 110\,\text{GeV}/c, \quad p_{\text{T}} > 0.4\,\text{GeV}/c$$

(good match with PAMELA/AMS-02 capabilities)

- Exploit excellent vertexing capabilities to select **prompt production**.
(anti-hyperon component measured in a dedicated analysis)

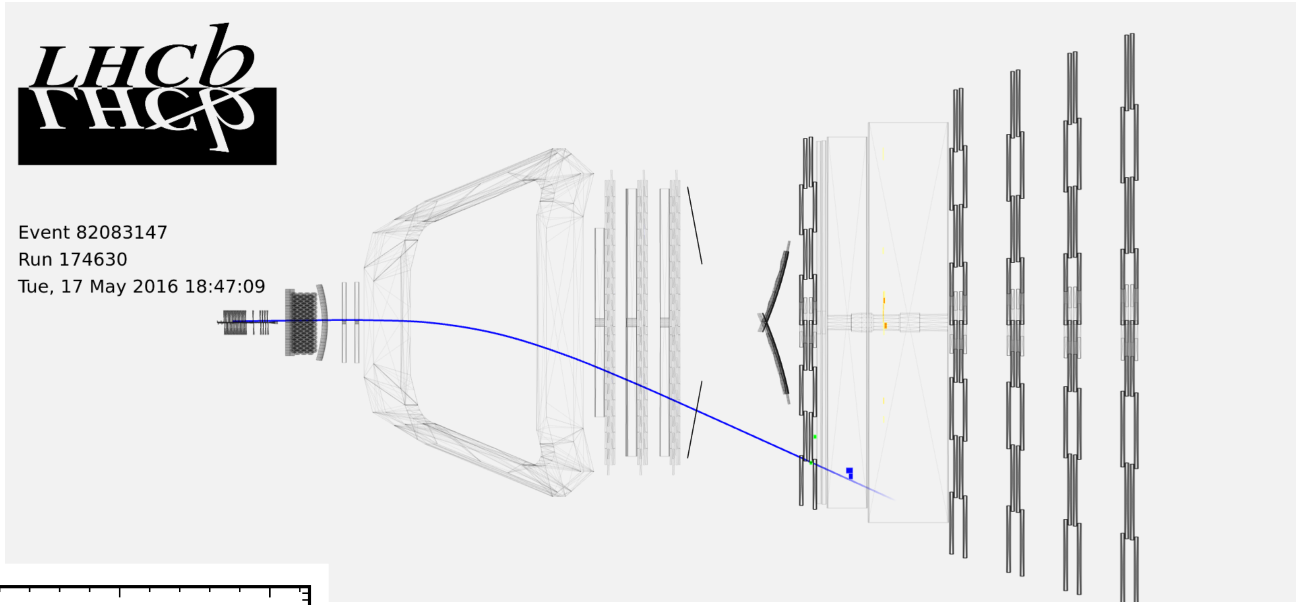


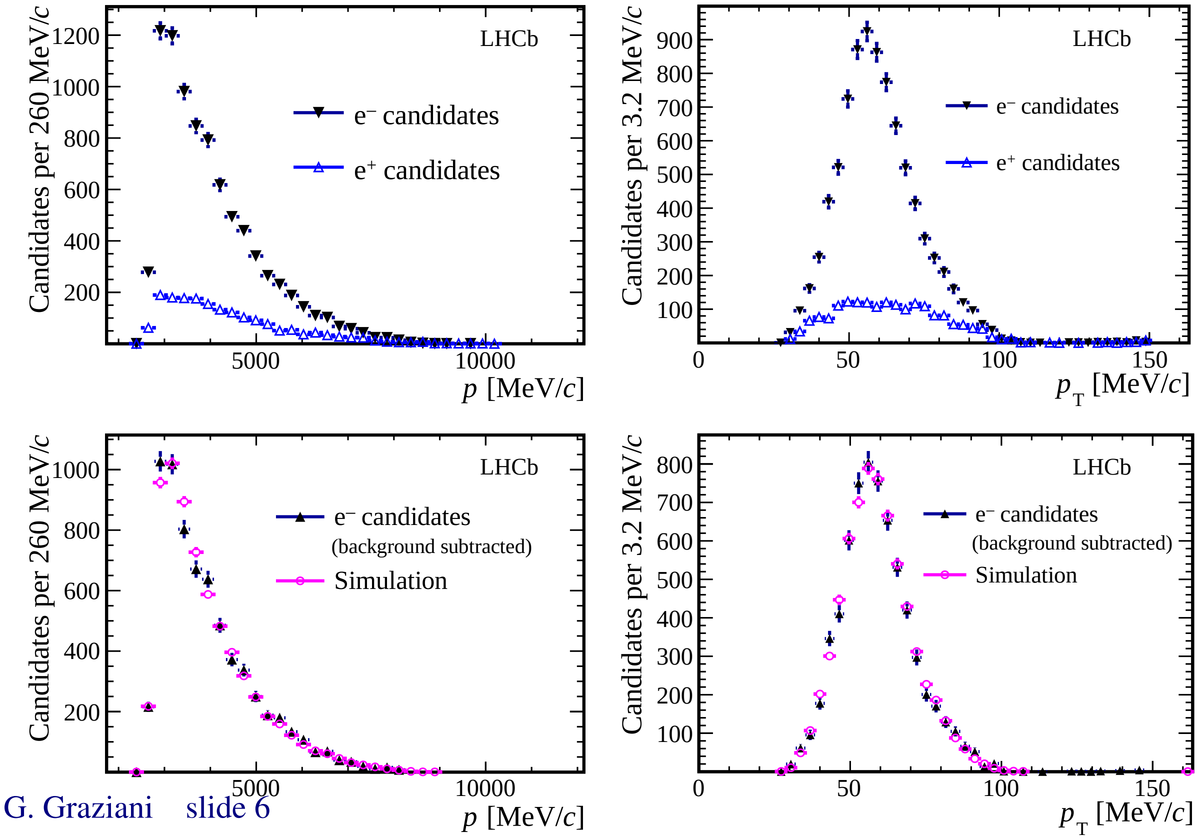


Fixed-target Luminosity

PRL 121 (2018), 222001

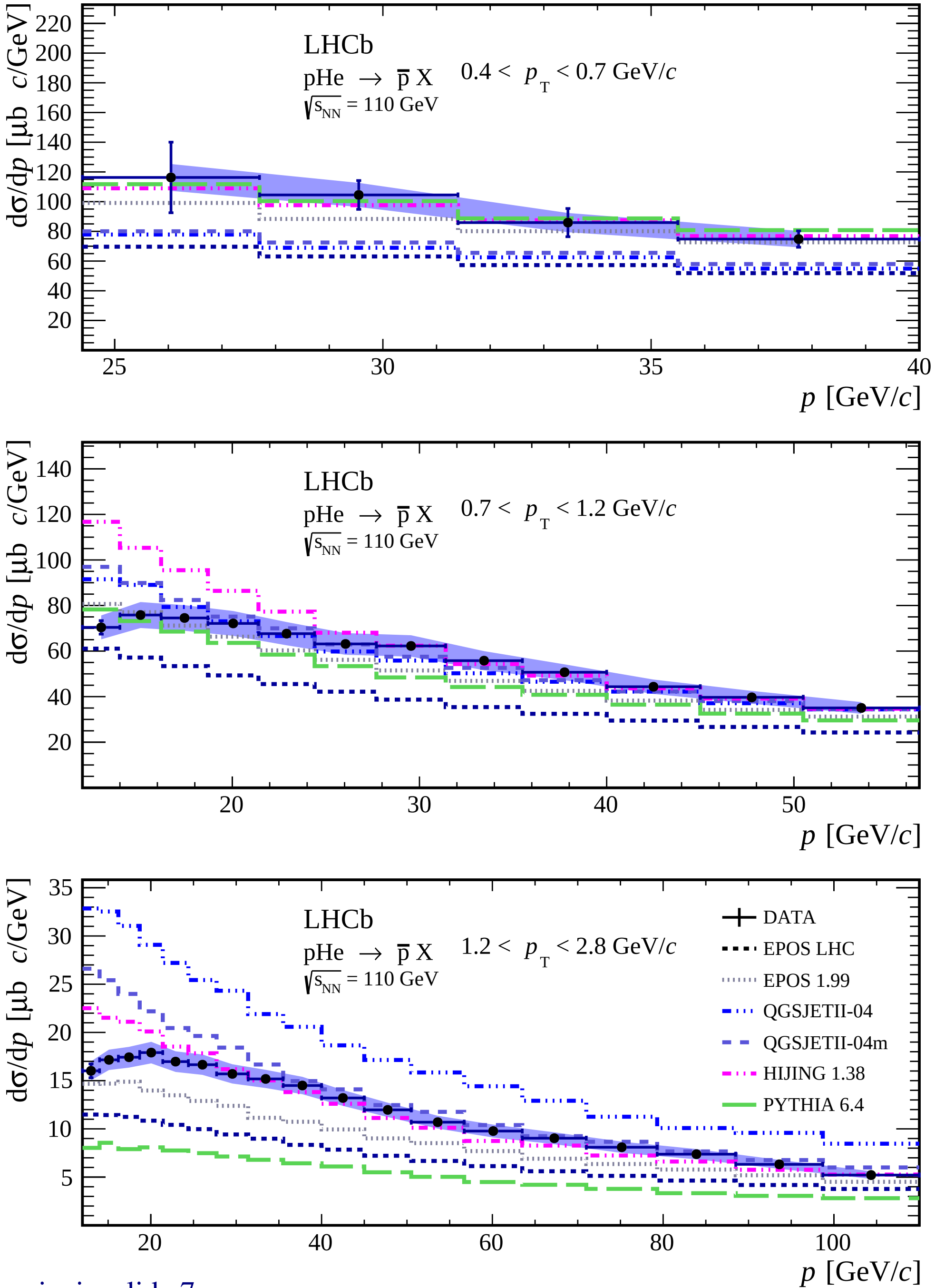
- SMOG gas pressure not precisely known. Absolute cross sections normalized to $p\,e^-$ elastic scattering





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

Results



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:

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

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

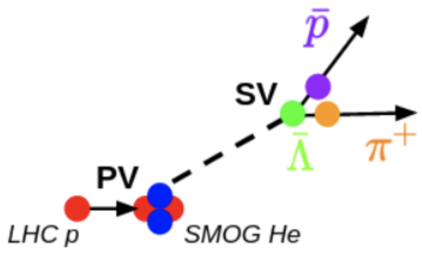
Antiprotons from antihyperons in pHe @110 GeV

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

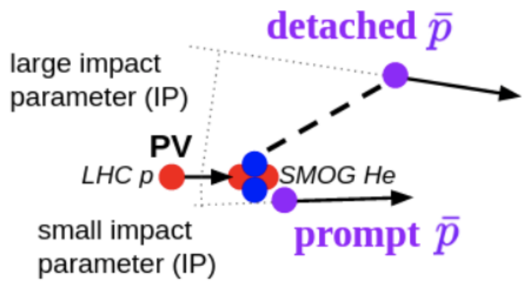
Exclusive approach

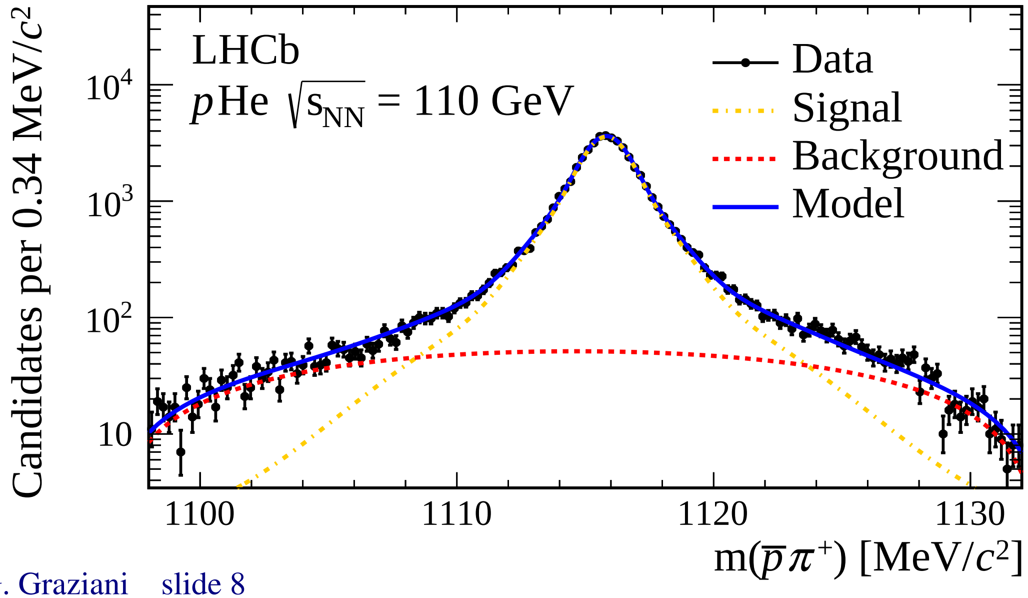
$$R_{\bar{\Lambda}} = \frac{\sigma(p\text{He} \to (\bar{\Lambda}_{\text{prompt}} \to \overline{p}\pi^+)X)}{\sigma(p\text{He} \to \overline{p}_{\text{prompt}} X)}$$

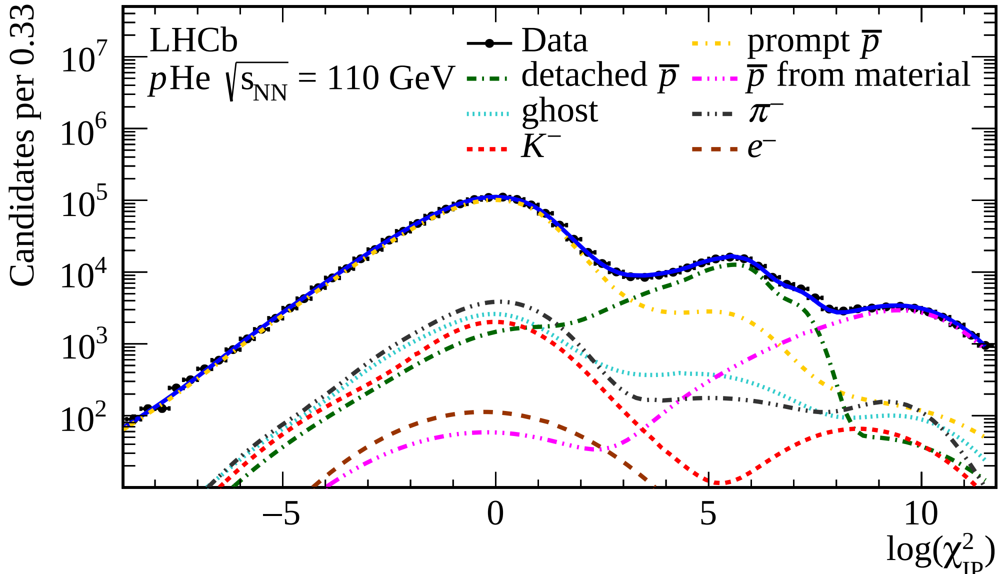


Inclusive approach

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







Detached Antiprotons in pHe: results

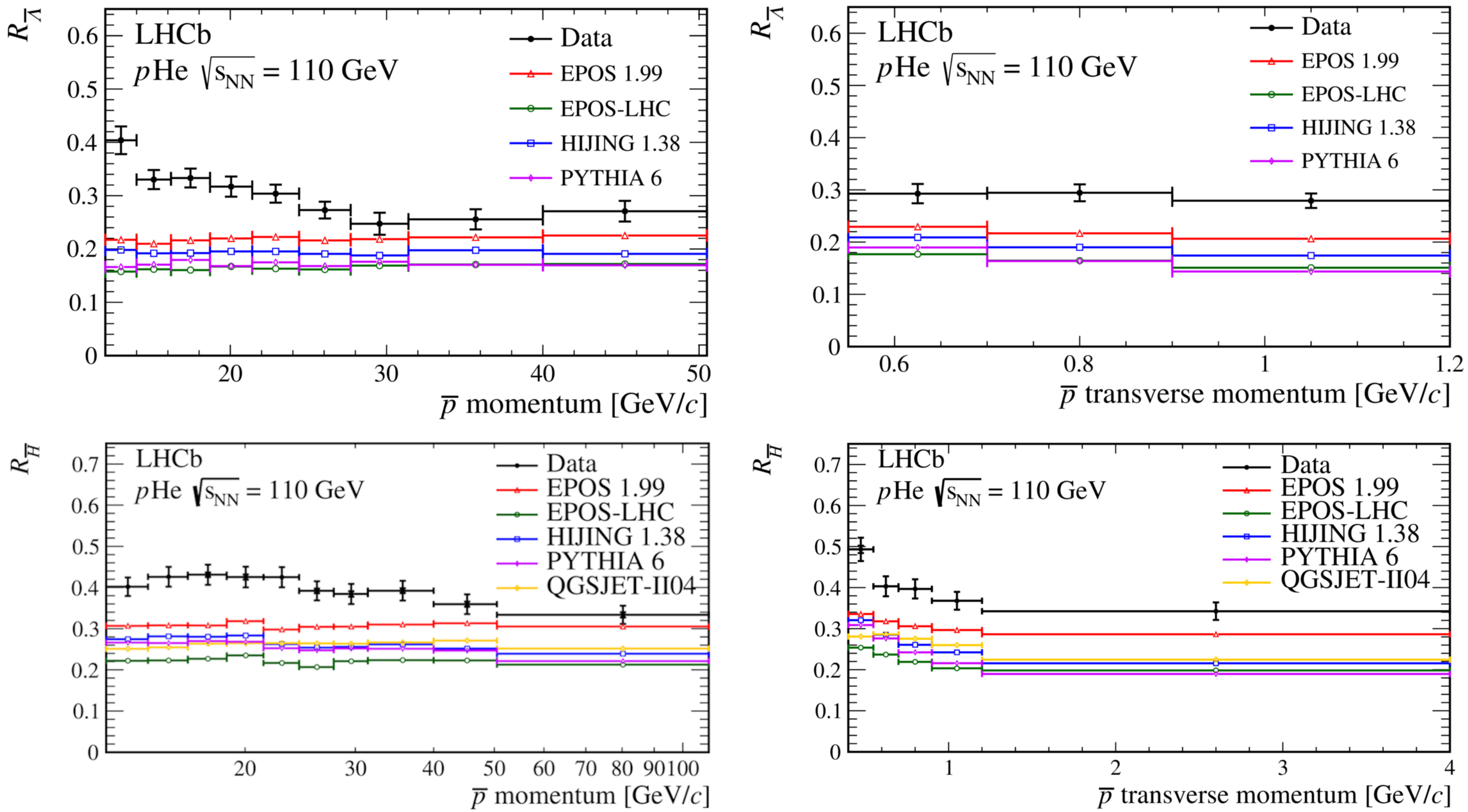
EPJC 83, 543 (2023)

Exclusive approach

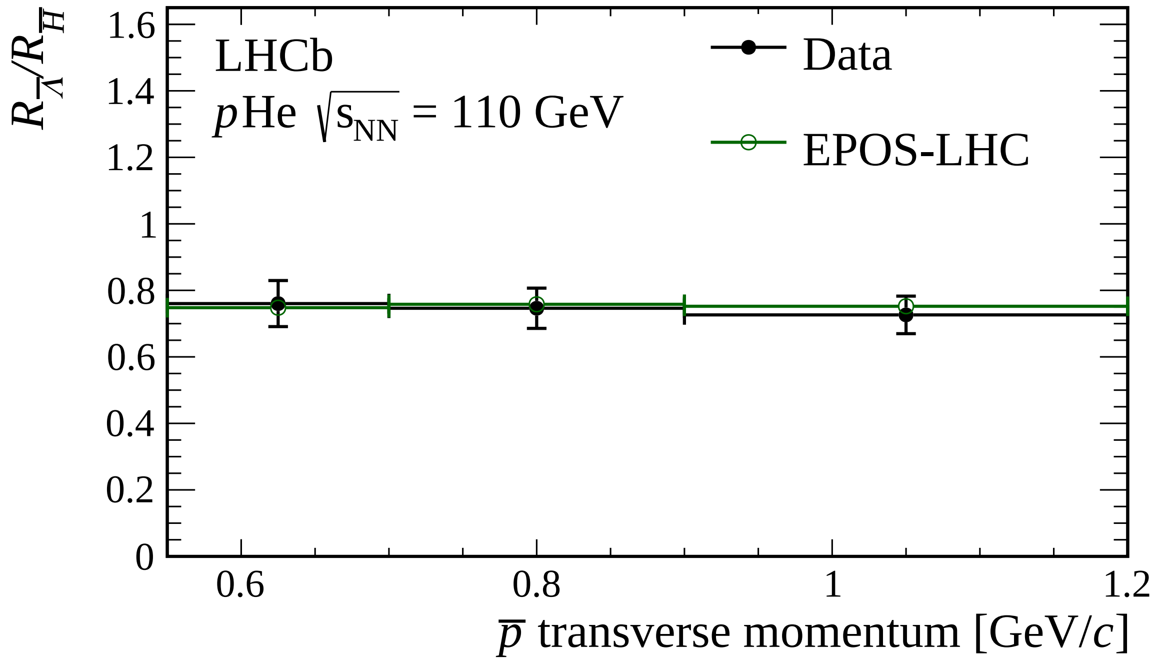
$$R_{\bar{\Lambda}} = \frac{\sigma(p\mathrm{He} \to (\bar{\Lambda}_{\mathrm{prompt}} \to \bar{p}\pi^{+})X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}}\, X)}$$

Inclusive approach

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

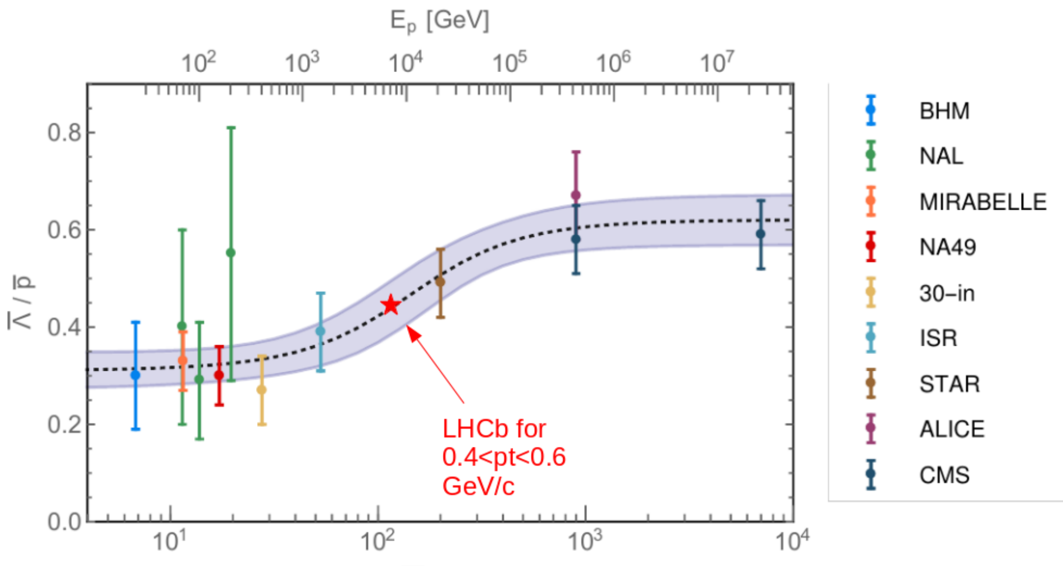


Both approaches indicate larger antihyperon production than predicted by most commonly used hadronic models



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

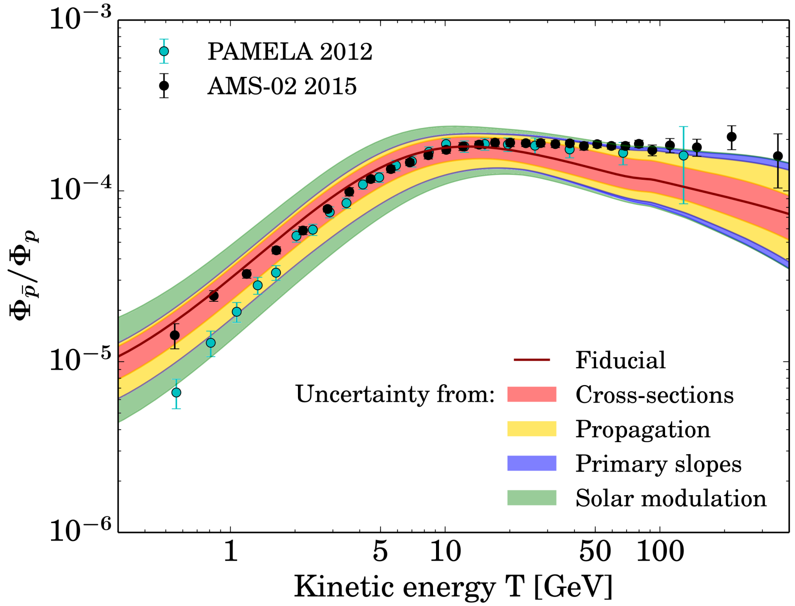
- Precise results at 100 GeV scale, at the onset of strangeness enhancement (observed at colliders)
- Significant dependence on kinematics observed (usually neglected in cosmic secondary $\overline{p}$ calculations)



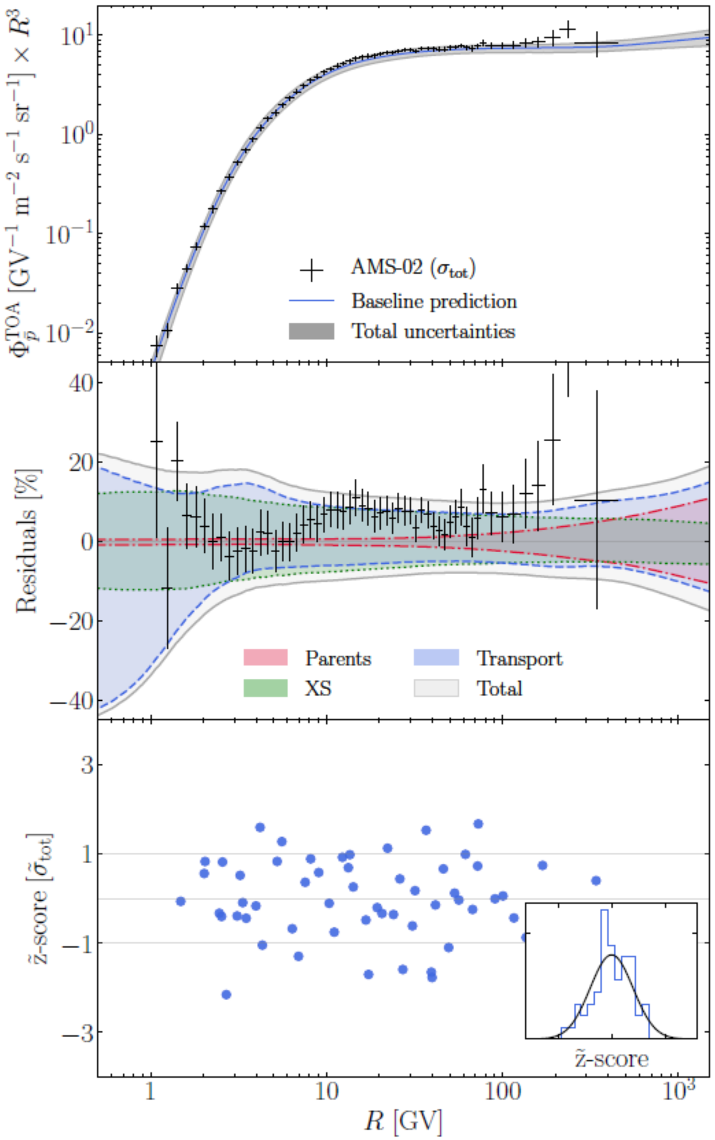
from Winkler

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

2015 Giesen et al., JCAP 1509, 023



2019 Boudad et al., arXiv:1906.07119

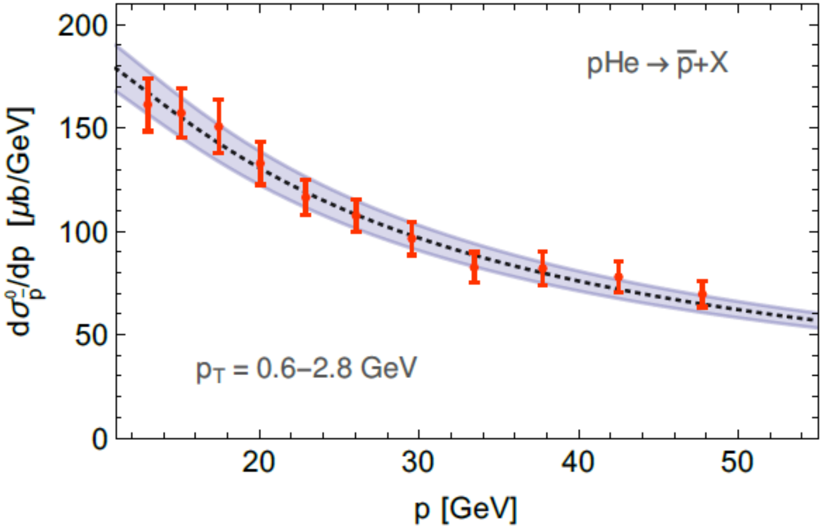


- Significant shrinking of uncertainty for the predicted secondary antiproton flux from the use of LHCb and NA61 (pp) new data (plus other improvements)
- LHCb results allowed to constrain scaling violation when extrapolating x-section toward high energy
- Models now in better agreement with AMS data,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

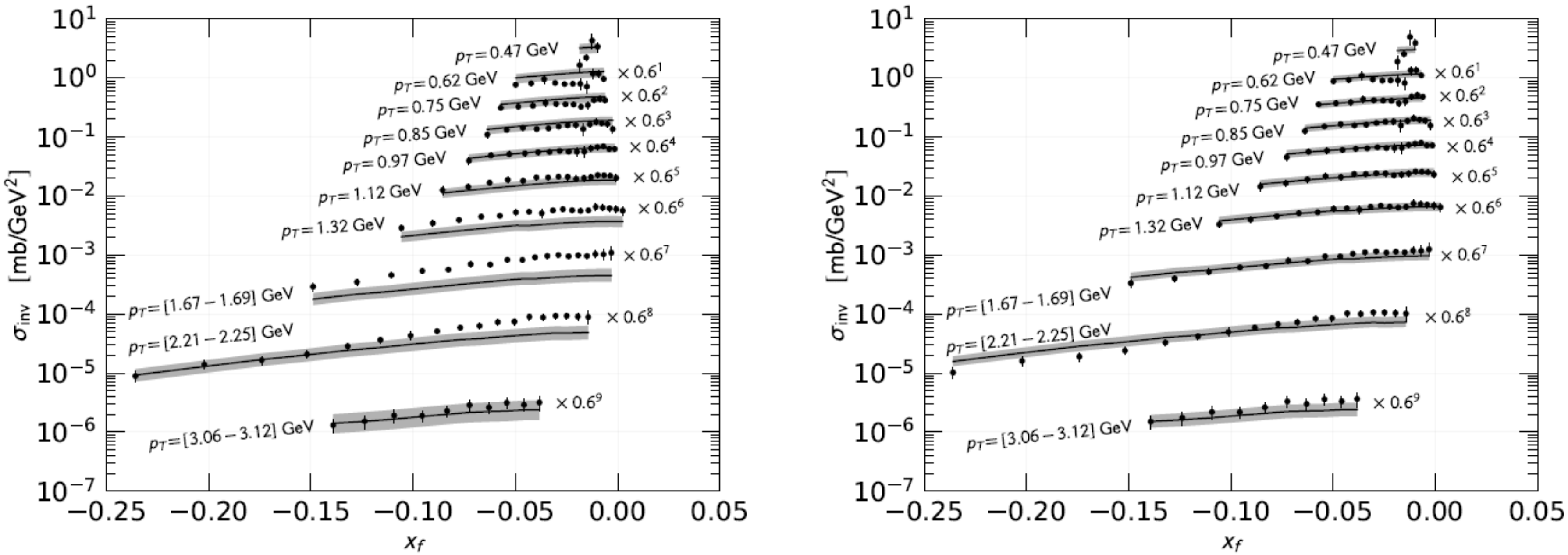
Models vs LHCb data (prompt $\overline{p}$)

LHCb prompt $\overline{p}$ results provided a testbench for parameterizations of the cross-section energy evolution (and extrapolations from pp to pHe collision system)

Reinert and Winkler, JCAP 1801 (2018) 055



Korsmeier, Donato, Di Mauro, PRD97 (2018) 103019

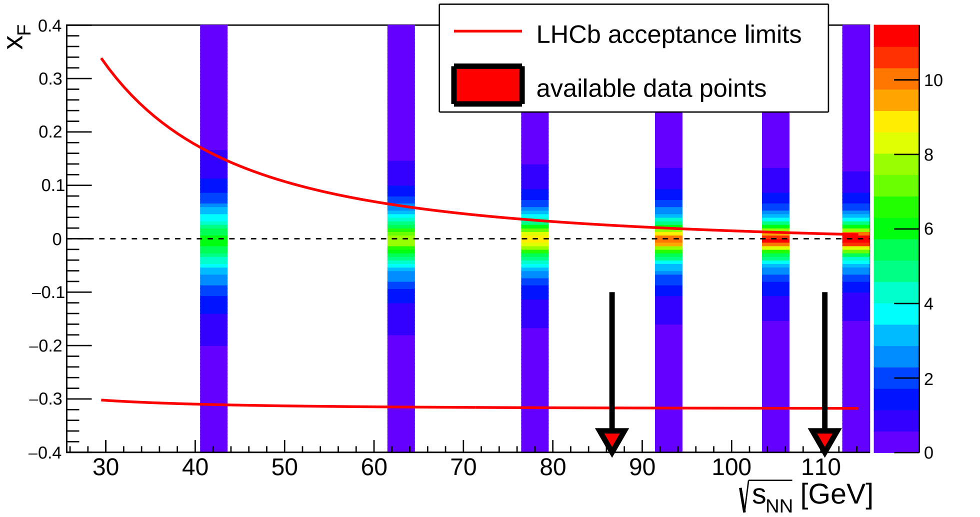


comparing LHCb $p\text{He} \to \overline{p}$ data with two different parameterizations

What is still needed for $\overline{p}$ production cross-sections?

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

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



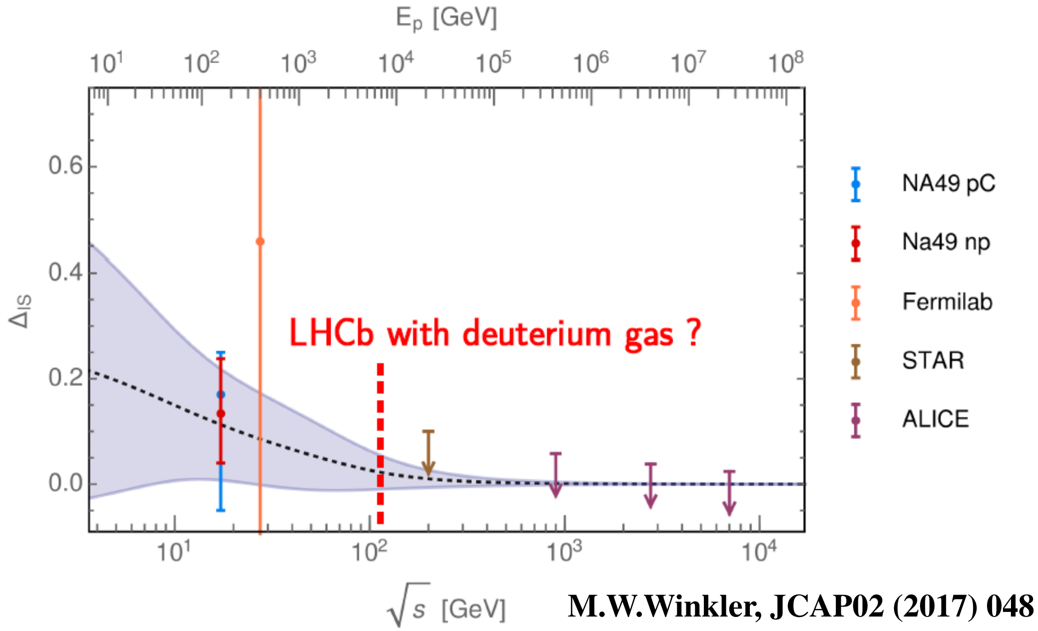
Expected Feynman-x distribution of $\overline{p}$ at different $\sqrt{s_{\rm NN}}$, and LHCb acceptance

- 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)

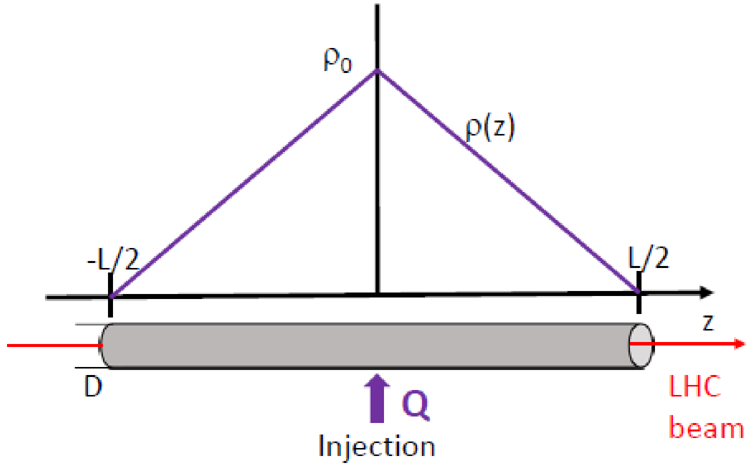
  ➡ Collide protons with **hydrogen, deuterium and helium** targets in the same experiment

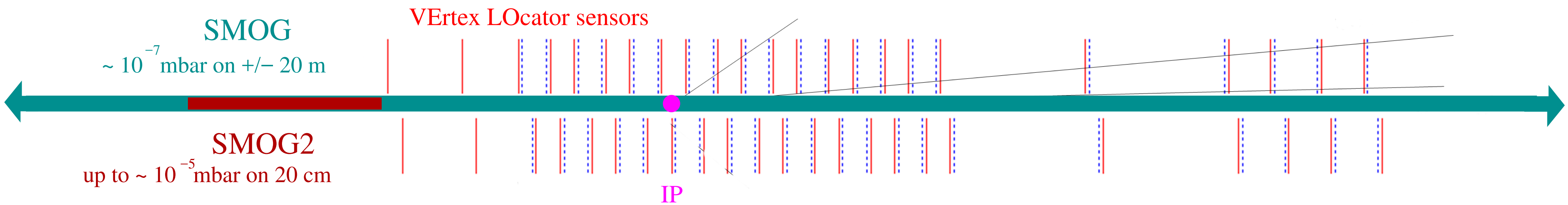


M.W.Winkler, JCAP02 (2017) 048

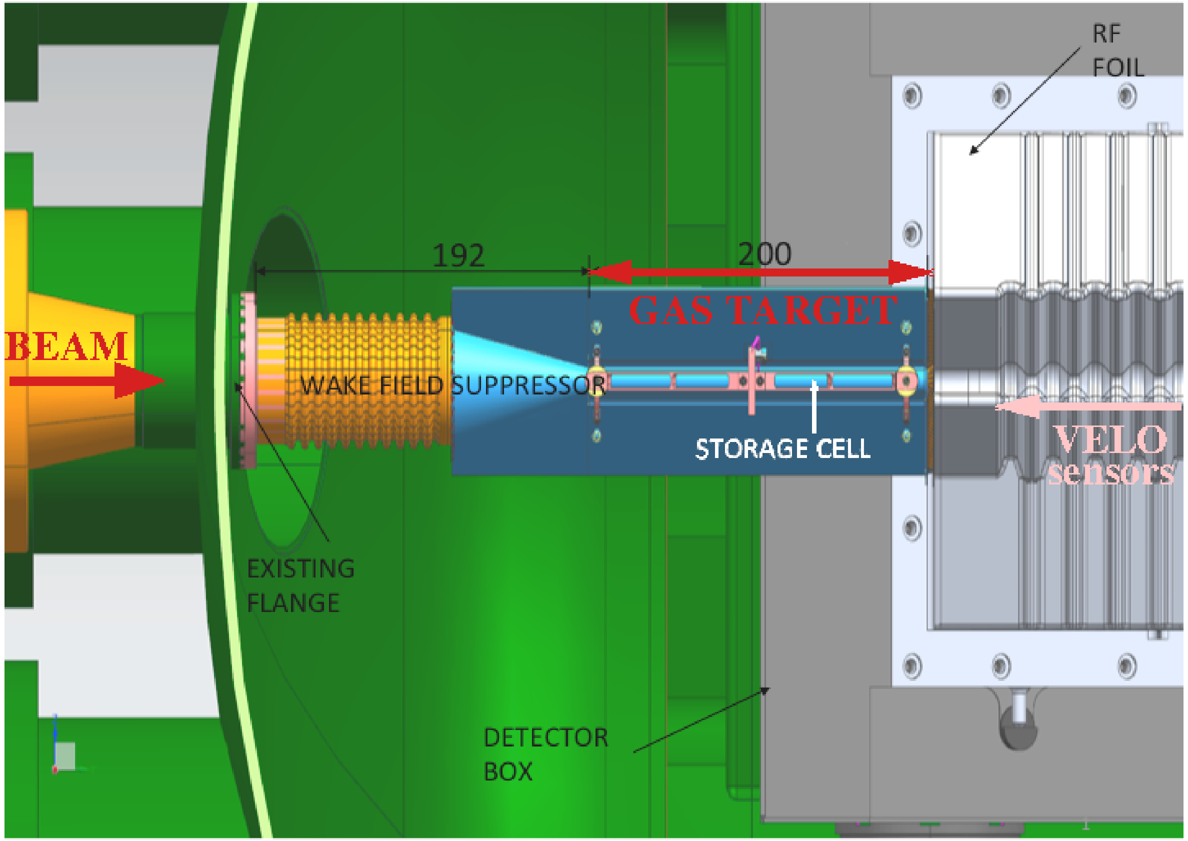
The gas target upgrade

- 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**





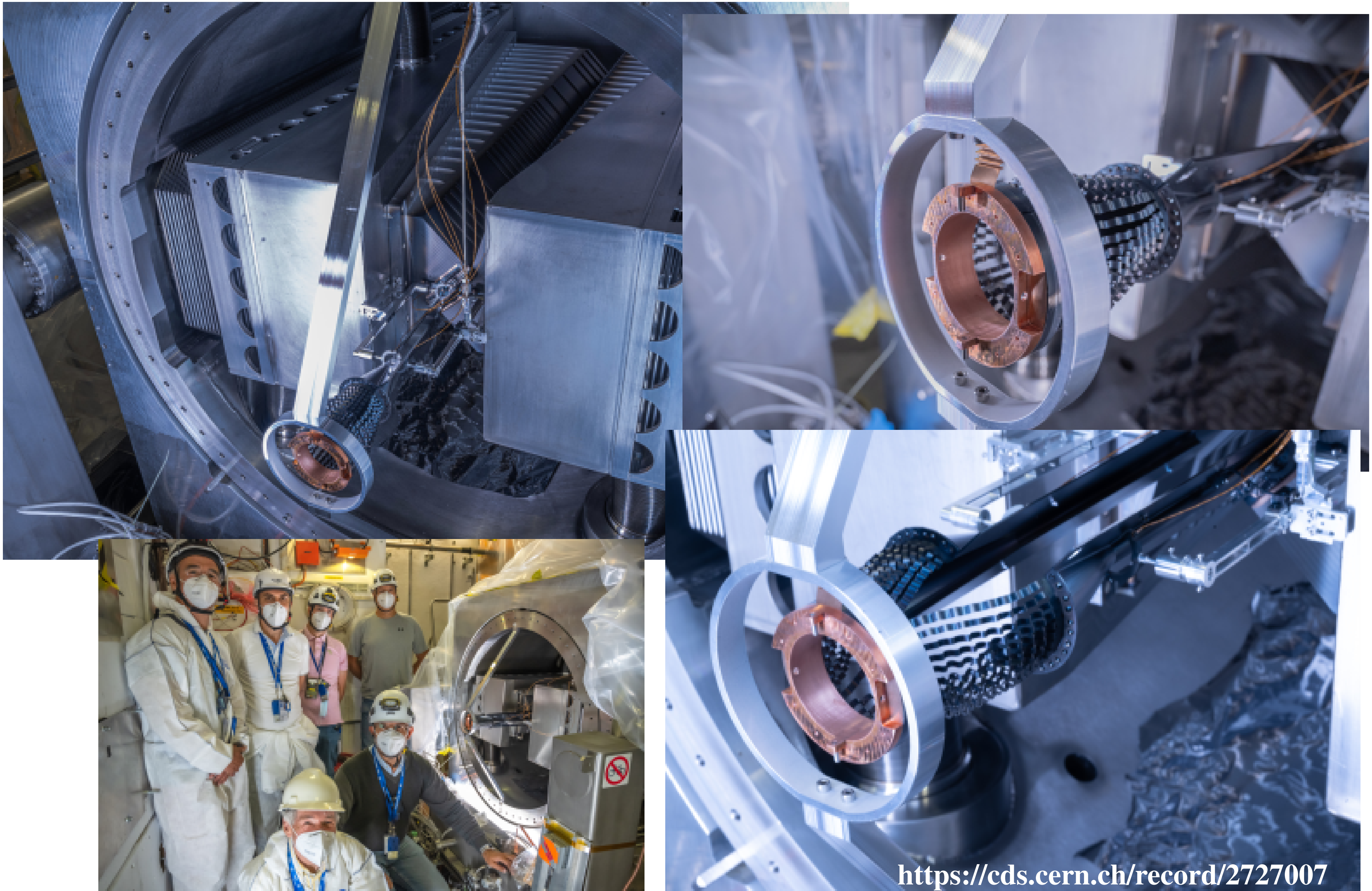
The SMOG2 gas target



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

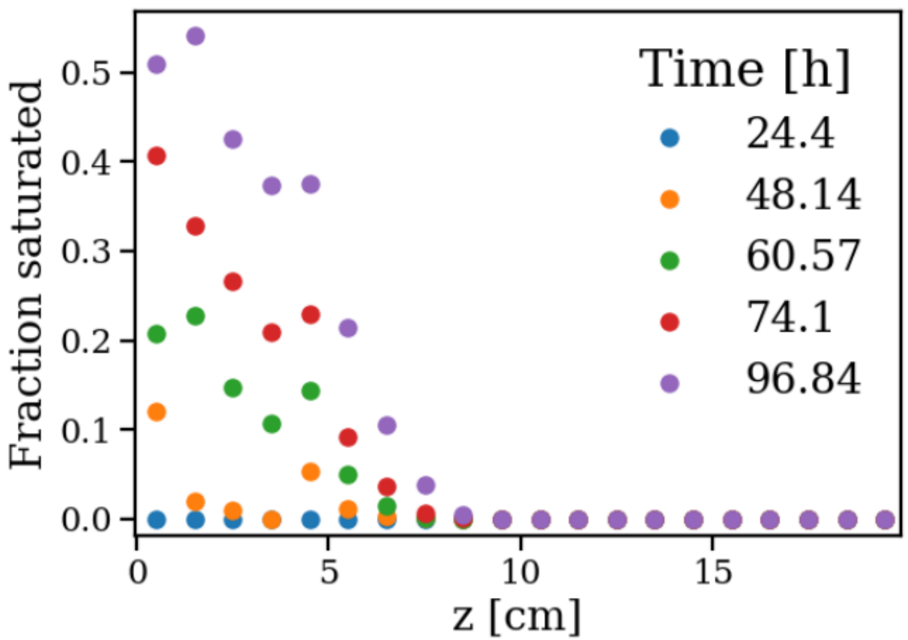
- 20-cm long storage cell, 5 mm radius around the beam, just up-stream the LHCb VErtex LOcator
- Made of two rectractable halves as the rest of VELO
- Up to x100 higher gas density with same gas flow of current SMOG
- Gas density measured with $\sim$ 2% accuracy via Gas Feed System
- Fast switch between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

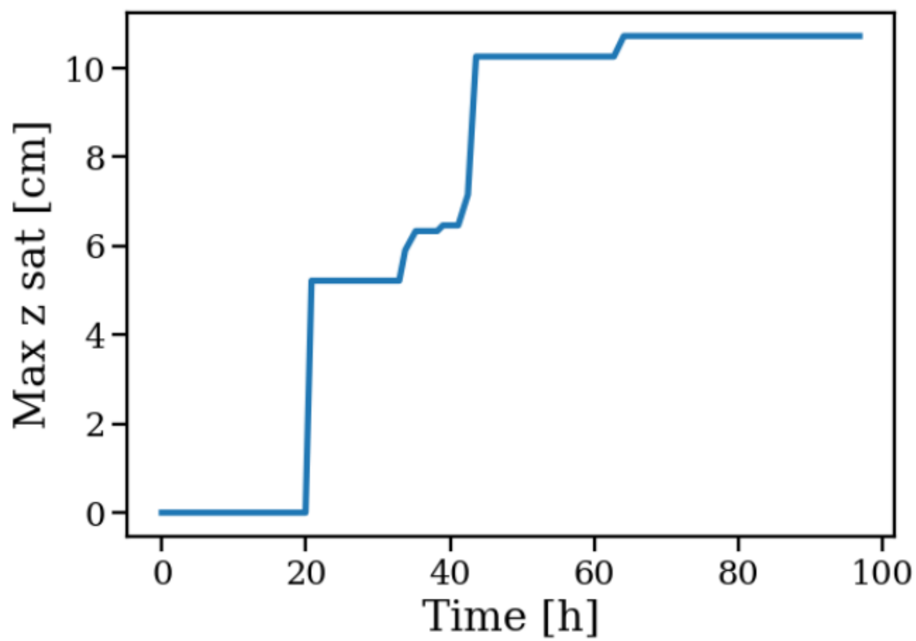
SMOG2 installation



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

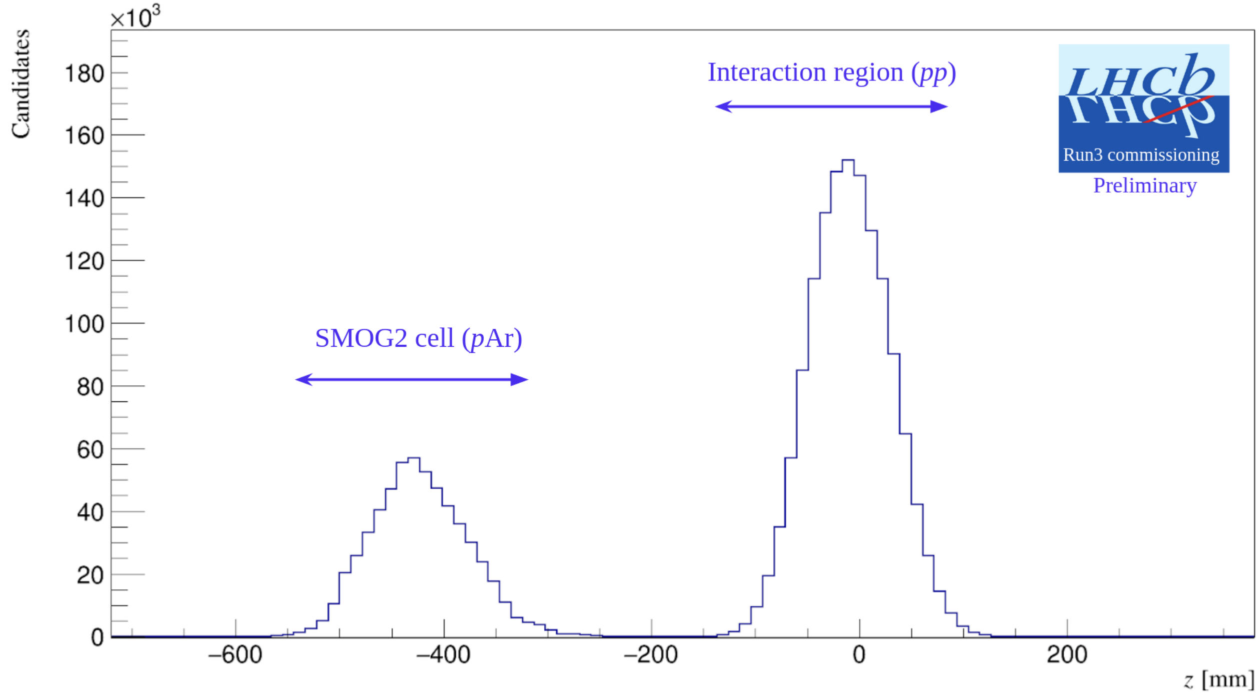


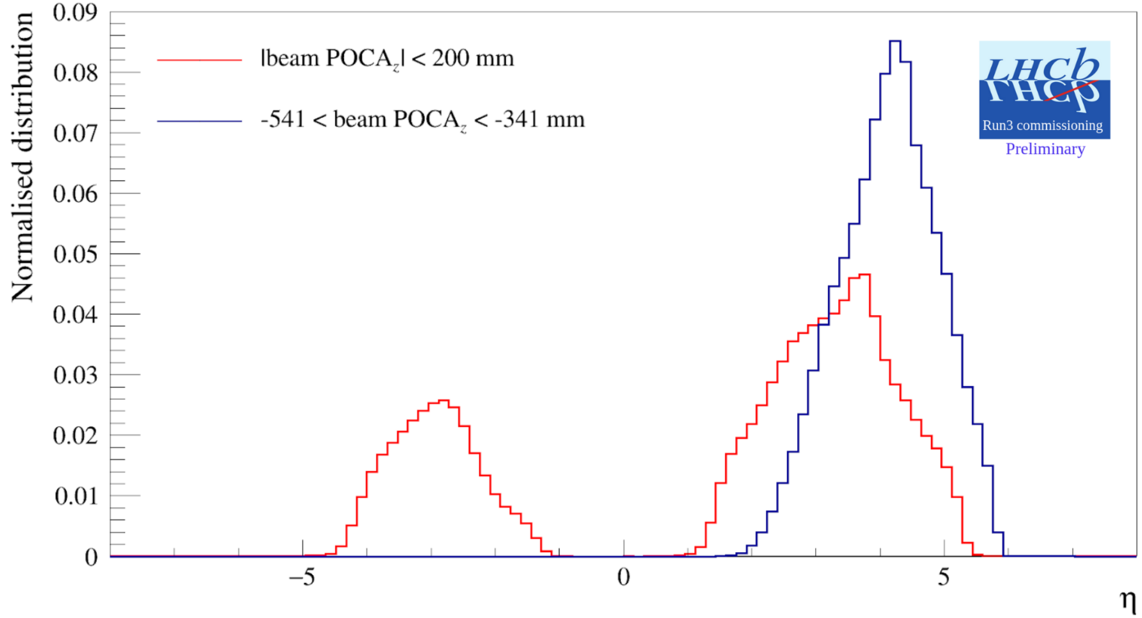


C.Lucarelli, CERN-PBC-Notes-2023-003

First SMOG2 operations in 2022

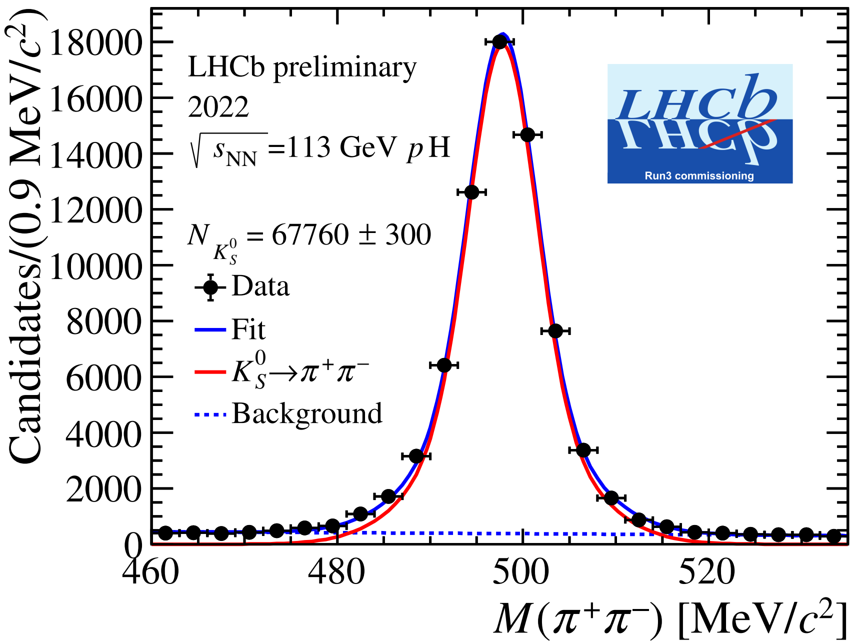
- 2022 has been a commisioning year for the upgraded LHCb detector
- SMOG2 has been succesfully tested with 4 gas species (**H**, He, Ne, Ar)
- first reconstructed primary vertices of simultaneous beam-gas and beam-beam collisions, obtained online through novel Real Time Reconstruction fully software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

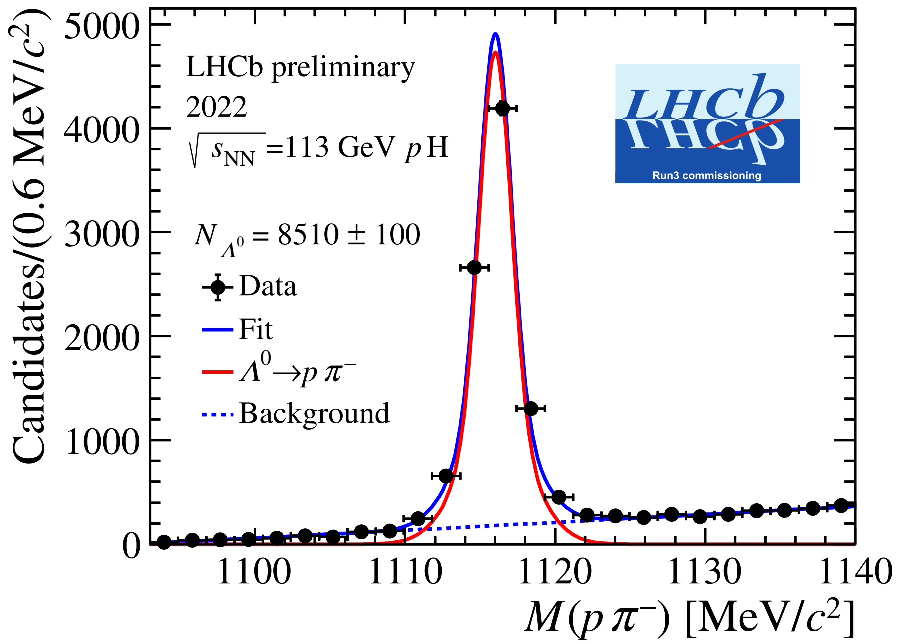




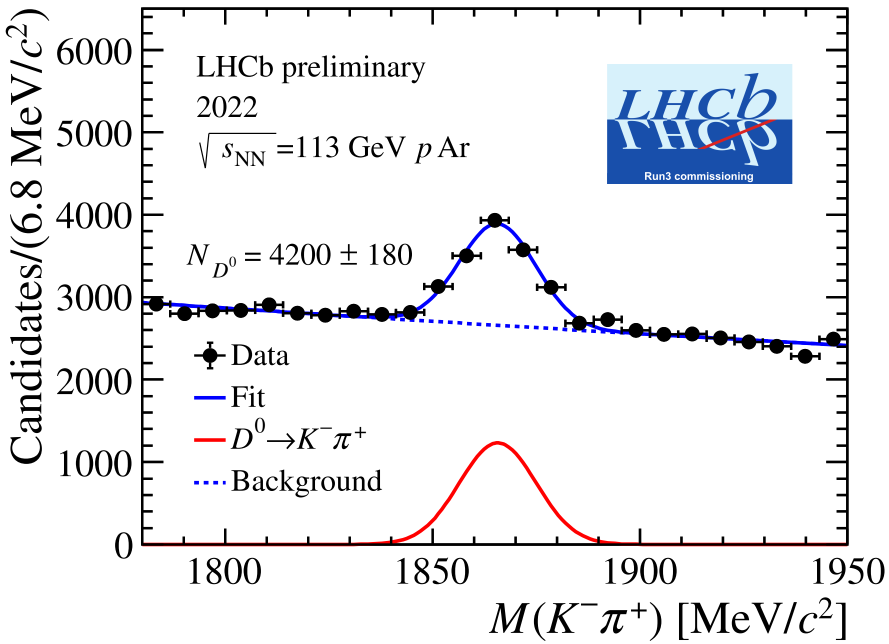
Physics signals in SMOG2 commissioning data!

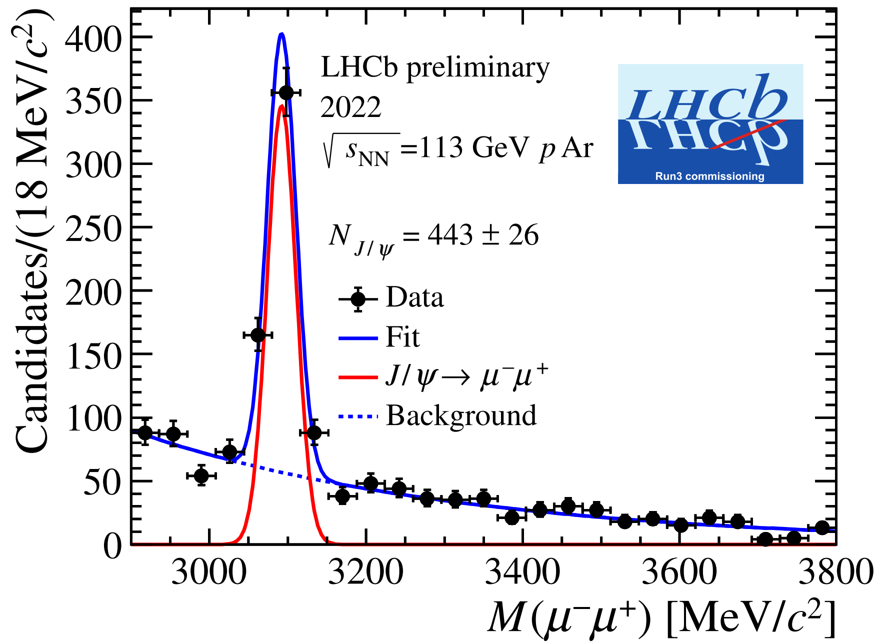
pH
20’ run!





pAr
18’ run!

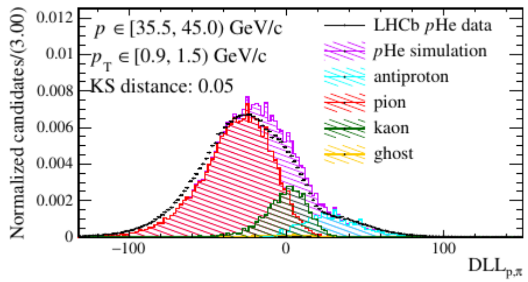




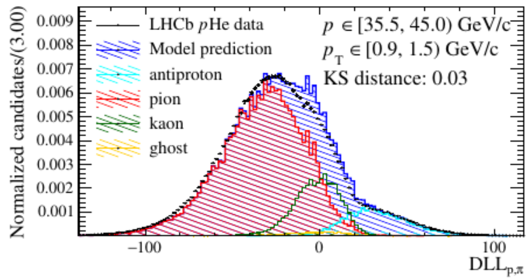
Plans with SMOG2 and more with SMOG

- First data-taking for pH, $pHe \to \overline{p}X$ expected in 2024
- deuterium target to be validated soon
- Major sources of systematics affecting SMOG measurements are expected to be reduced:
  - Luminosity: gas flow measured precisely ($\sim 2\%$) in SMOG2, proton-electron scattering can still be used for cross-check
  - Particle identification: specific ML-based tools have been developed to model the PID response in fixed-target data

MC-driven model



Data-driven model



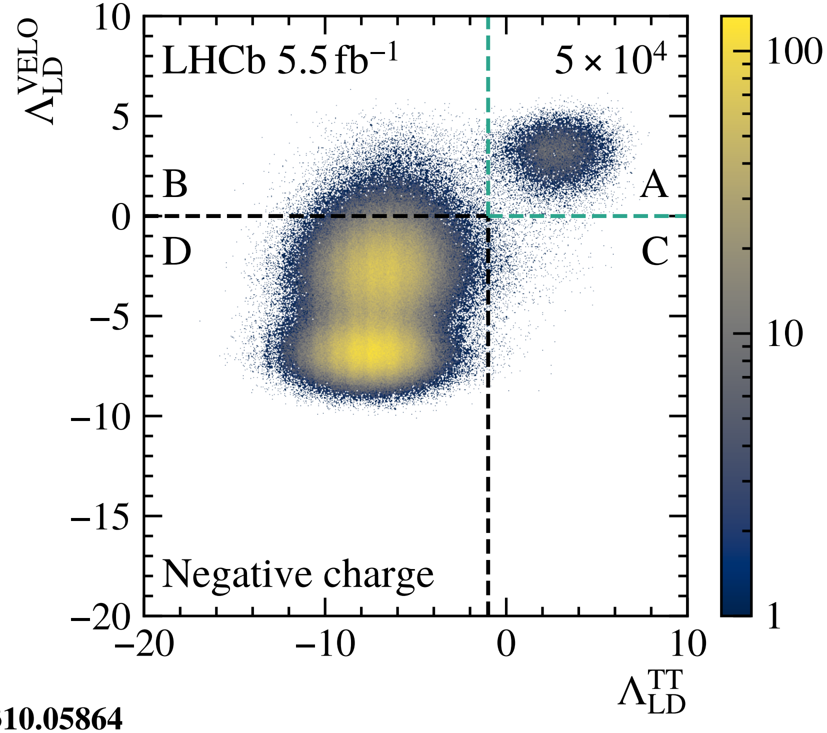
JINST 17 P02018 (2021)

- Possibility to acquire data at 2.5 TeV beam energy, and (probably next year) at injection energy (450 GeV)

- possibility to exploit past SMOG data also for anti-helium and anti-deuterium…

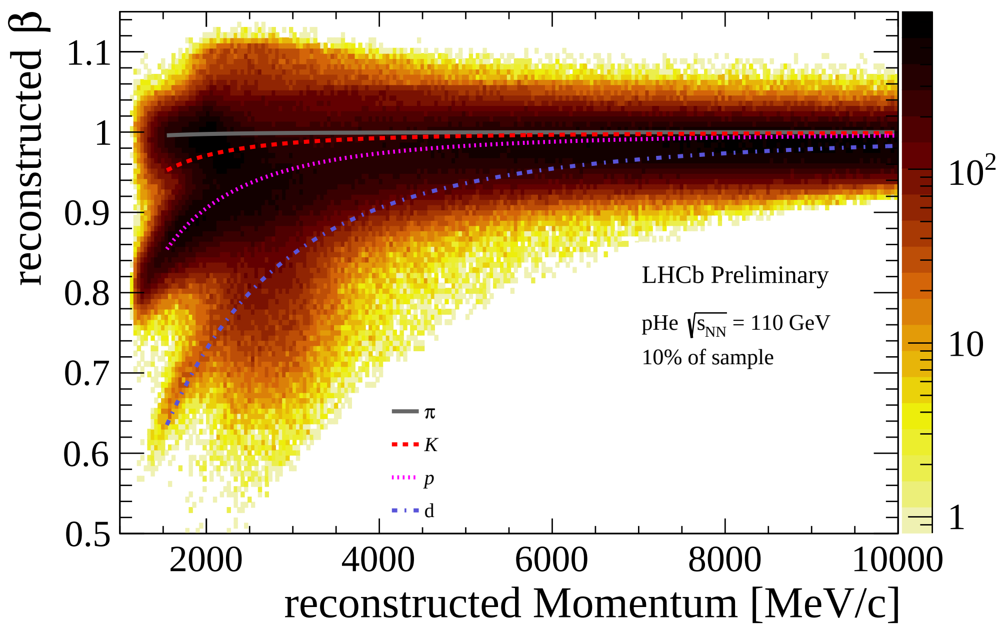
Antinuclei in fixed target @ LHCb?

- 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
- low-momentum $d/\overline{d}$ can also be identified through TOF in outer tracker drift tubes
- work ongoing…



arXiv:2310.05864

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



LHCb-FIGURE-2023-017

Velocity vs momentum for tracks reconstructed in LHCb pHe data

Conclusions

- LHCb pioneered fixed-target physics at the LHC, and provided the first measurements of $p\mathrm{He} \to \overline{p}\mathrm{X}$
- Program to be pursued with the new gas target SMOG2
- Repeating the measurement at SPS energy (450 GeV) would provide a direct cross-check between LHCb and AMBER measurements

Uncertainties on secondary cosmic $\overline{p}$ from production x-sections expected to become negligible after the SMOG2 and AMBER programs!

- Program not limited to antiprotons