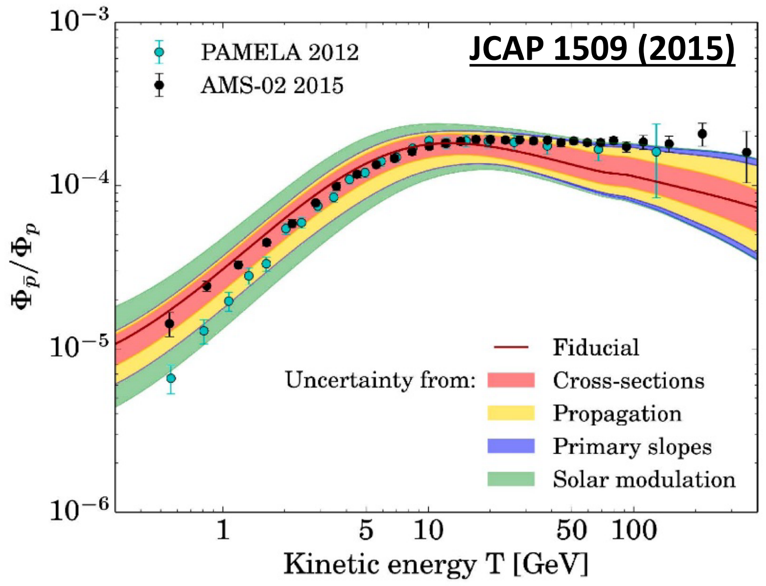
Fixed-target LHCb measurements for cosmic rays physics

Chiara Lucarelli, on behalf of the LHCb collaboration

XSCRC workshop 2024,
16-18 October 2024, CERN

Dark Matter and antimatter in space

Cosmic rays measurements are becoming increasingly precise → Improved understanding of CRs interactions during propagation required to interpret results.

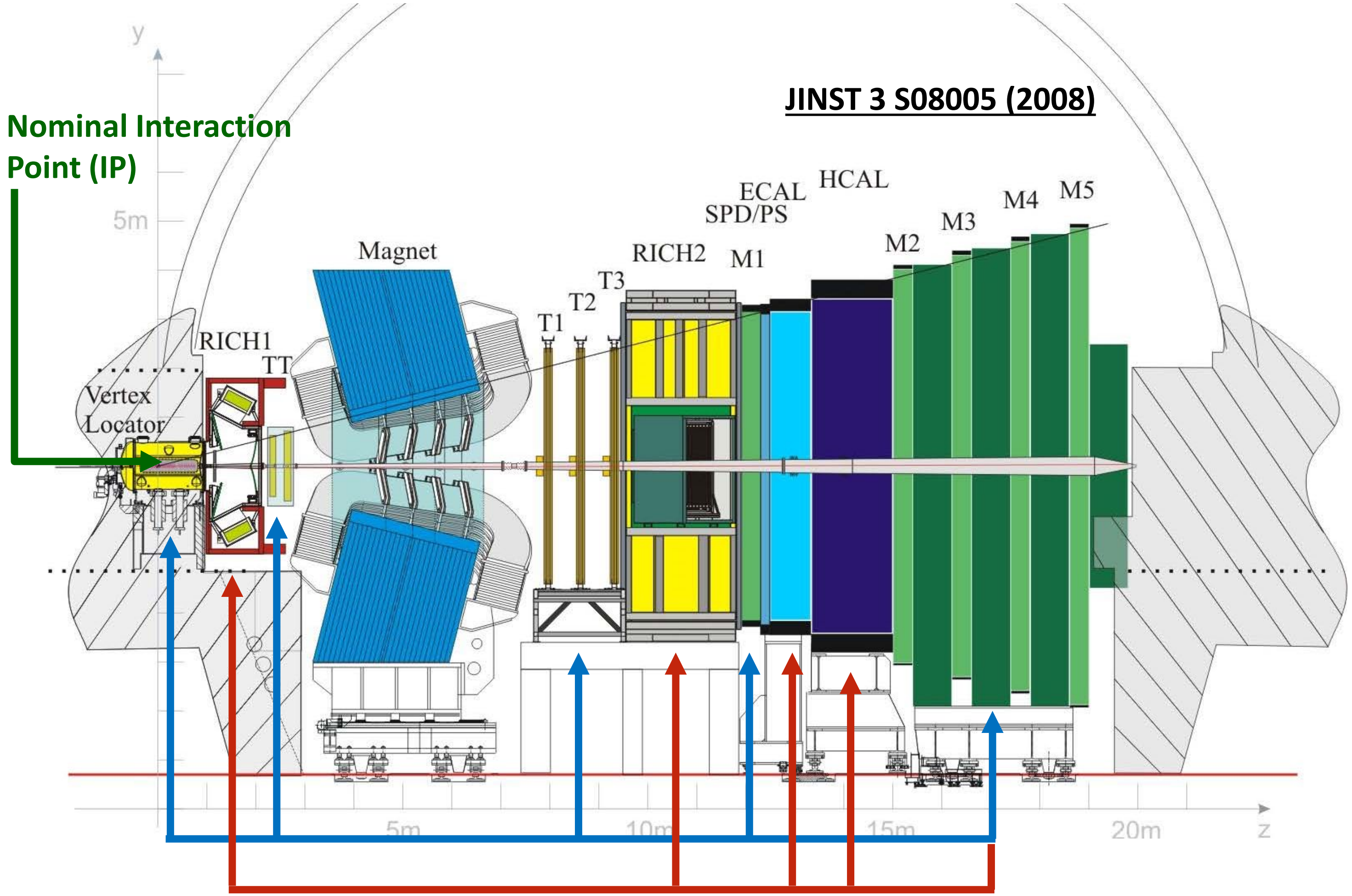


Accelerator experiments can complement Cosmic Rays investigations

Thanks to its unique forward geometry and possibility to inject gases in the LHC beampipe, **LHCb is contributing with its space mission to improve the precision of models**.

- **Antimatter production in the galaxy** → Improve modelling of secondary CR production in ISM through antimatter production studies in *pp* and fixed-target.
- **Neutrino astronomy** → Understanding background through charm production studies in *pp*, *p*Pb and fixed-target.
- **Atmospheric CRs propagation** → Help models of atmospheric showers through hadronic production studies in *pp*, *p*O and OO in collider and fixed-target.

The LHCb experiment

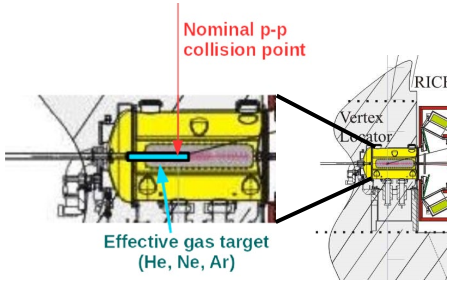


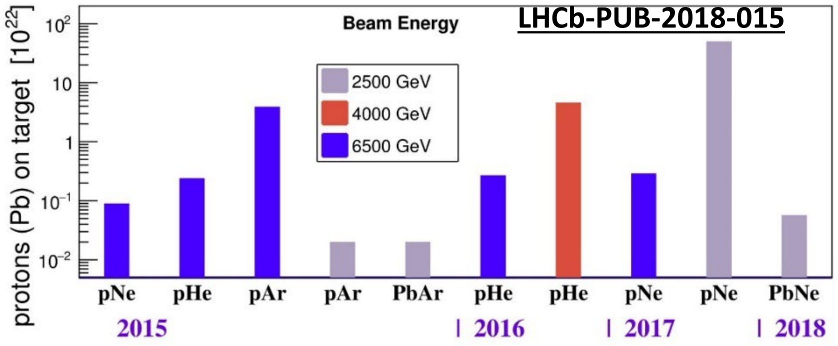
LHCb is a general-purpose experiment in the forward direction:

- **Single-arm forward spectrometer**: optimized for $b\bar{b}$ production, $2 < \eta < 5$, $\Theta \in [10, 250]$ mrad.
- **Tracking:** excellent vertexing, IP resolution: 15+29/p_T [GeV] μm, momentum resolution: $\Delta p/p = 0.5\% - 1.0\%$.
- **Particle Identification (PID):** excellent separation among π, K and p with momentum in [10, 110] GeV/c range.
- **Trigger:** flexible and versatile, bandwidth up to 15 kHz to disk.
- Its forward geometry is very well suited for **fixed-target physics.**

LHCb fixed-target apparatus

- The *System for Measuring Overlap with Gas* (**SMOG**) can inject gas in LHC beam pipe around (±20 m) the LHCb interaction point
  → Conceived for luminosity measurements, x100 nominal LHC vacuum
- Since 2015, exploited for LHCb fixed-target physics programme
  → Different targets and different centre of mass energies.





Forward geometry + gas target =
highest-energy ever fixed-target physics experiment

Unique physics opportunities at the LHC

- Unexplored **intermediate energy** to SpS and LHC
- **Large target Bjorken-*x* at low Q^2**
- Collisions with **targets of mass number A intermediate** between *p* and Pb

- **Cold nuclear-matter effects** for QGP studies
- **Nuclear PDFs at high-*x*** and nucleon intrinsic charm studies
- **Hadron production** and spectra measurements for Cosmic Rays physics

Antimatter production for Cosmic Rays physics

Dark Matter and antimatter in space

Antimatter fraction in Cosmic Rays (CR) is a sensitive **indirect probe for Dark Matter** (DM):

- Signatures of Dark Matter annihilation and decay processes
- Constrain space of Dark Matter candidates

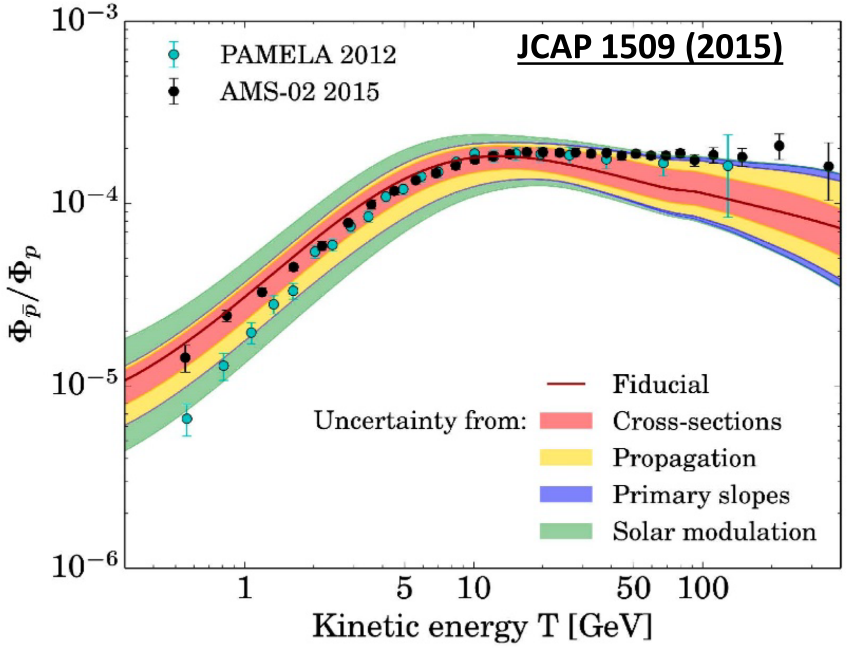
Space experiments (PAMELA, AMS) measured antimatter fluxes in CR

→ Inconclusive results due to **limited knowledge of production processes**.

E.g. **In 2015, new AMS-02 data for $\bar{p}$ abundance in CRs**:

Excess for T>10 GeV compared to expected $\bar{p}$ from collisions of primary CRs onto interstellar gas (90% H_2, 10% He).

→ **Improved theoretical modelling required** to be conclusive on the nature of this excess

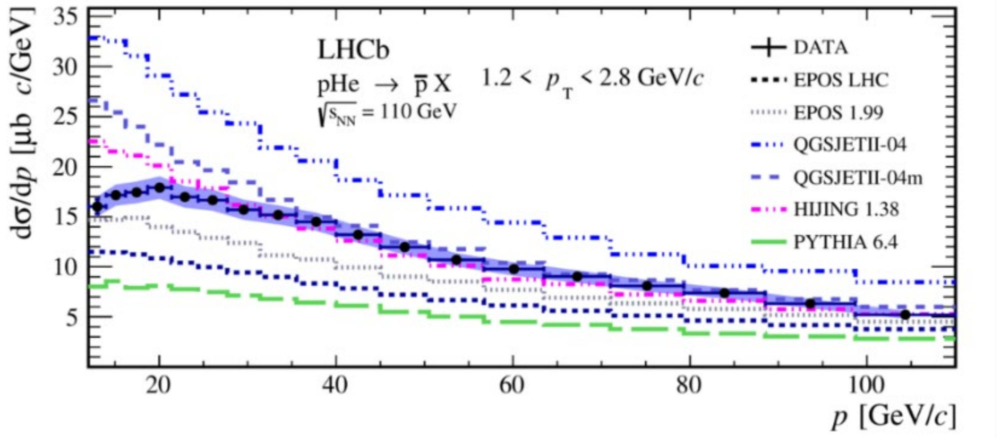


Prompt antiproton production

PRL 121 (2018) 222001

First measurement of $\boldsymbol{\sigma(pHe \longrightarrow \bar{p}_{prompt}X)}$ at $\sqrt{s_{NN}} = 110\ GeV$:

- Considered prompt $\bar{p}$ in the kinematic region ($p \in [12{,}110]\ GeV/c$, $p_{\mathrm{T}} \in [0.4, 4]\ GeV/c$) to optimize reconstruction and particle identification efficiencies.
- Uncertainty dominated by lack of direct luminosity measurement and poot calibration statistics for proton identification.
- Still, **experimental uncertainties (<10%) are lower than the spread among theoretical models**.

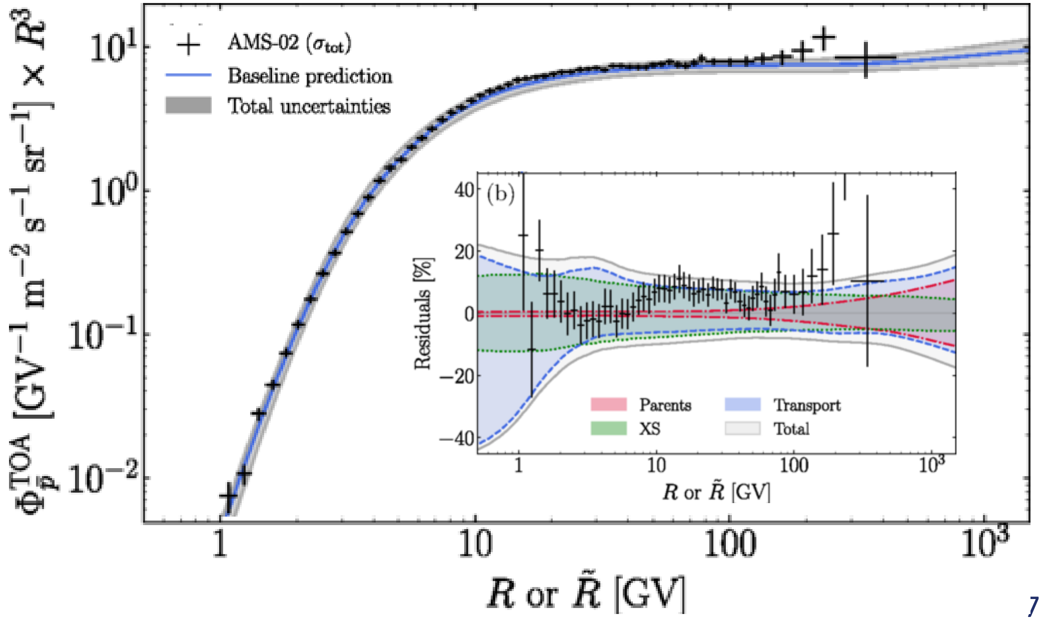


Important contribution to the improvement of the secondary $\bar{p}$ flux prediction:

→ Room for exotic contribution heavily reduced

→ Knowledge of **cross section still dominates uncertainties**

Phys.Rev.Res 2 (2019) 023022



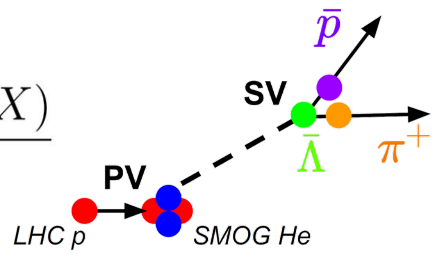
Detached antiproton production

Eur. Phys. J. C83 (2023) 543

- **Dedicated measurement to the component from anti-hyperon decays** (20-30% of $\bar{p}$ production) in pHe, extending first LHCb result only dealing with the prompt processes → Two complementary approaches

Exclusive

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

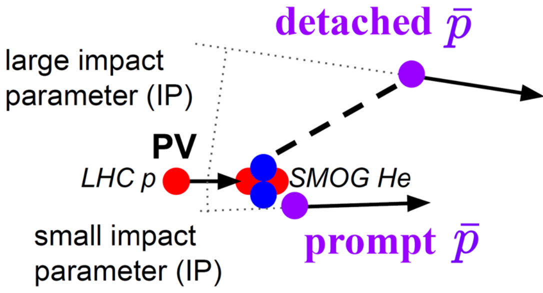


- Measure $\bar{\Lambda} \longrightarrow \bar{p}\pi^+$, dominant detached component.
- Identifying decay exploiting LHCb **excellent mass resolution** (no PID info).
- Most systematic uncertainties (luminosity, reco, …) **cancel in the ratio.**

Inclusive

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

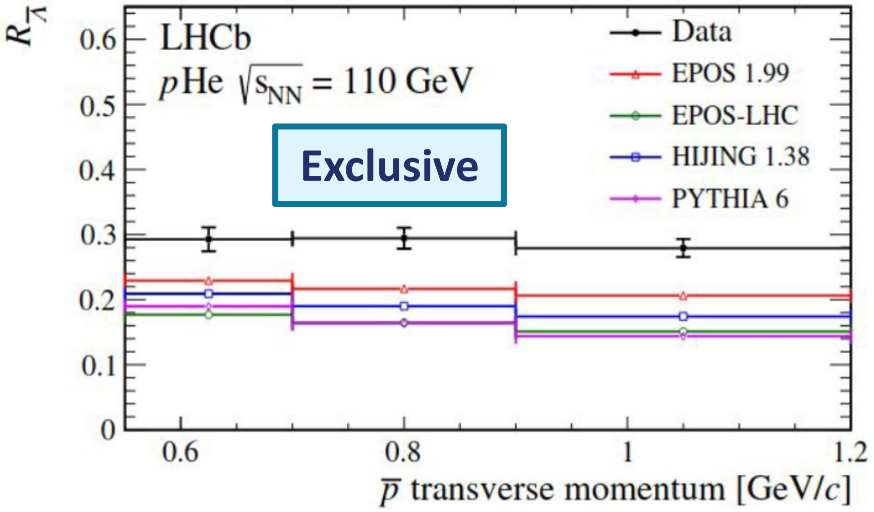
- Focused on **all detached components**.
- Selecting **antiproton with PID information** and distinguishing between prompt and detached $\bar{p}$ via excellent VELO IP resolution.

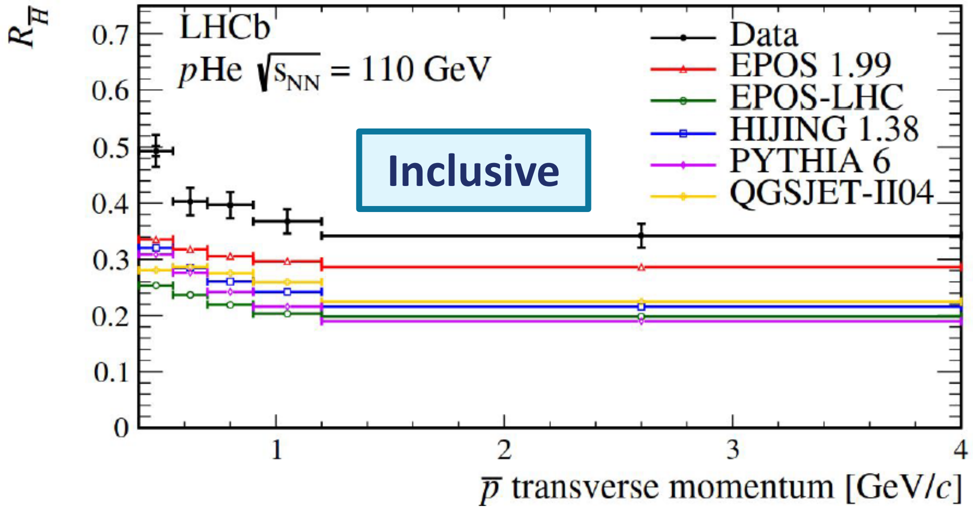


Results

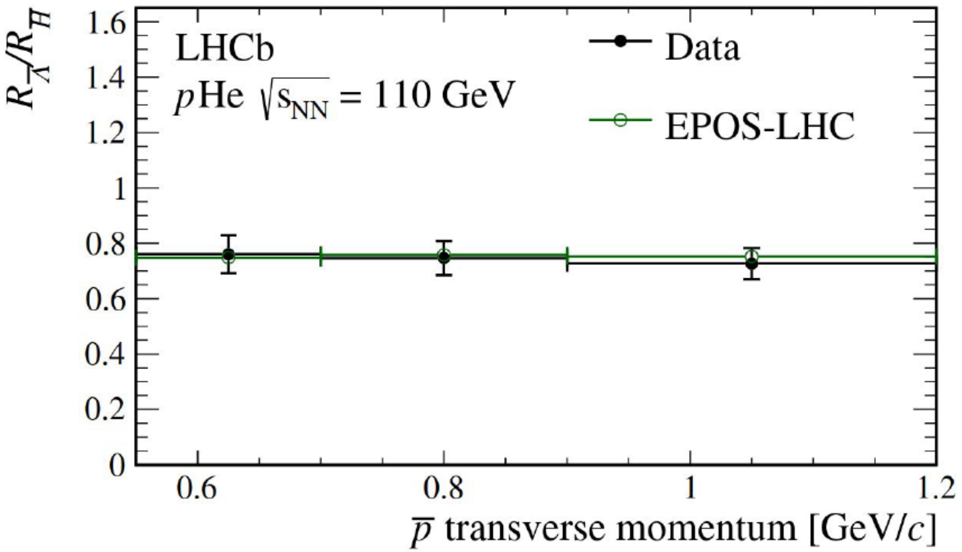
Eur. Phys. J. C83 (2023) 543

Larger contribution measured wrt all most widely used theoretical models





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



Light (anti-)nuclei identification

Talk by Valery this morning

Expand antimatter **production** measurements to **light anti-nuclei**:

- No known primary sources
- Low production cross-section in secondary collisions

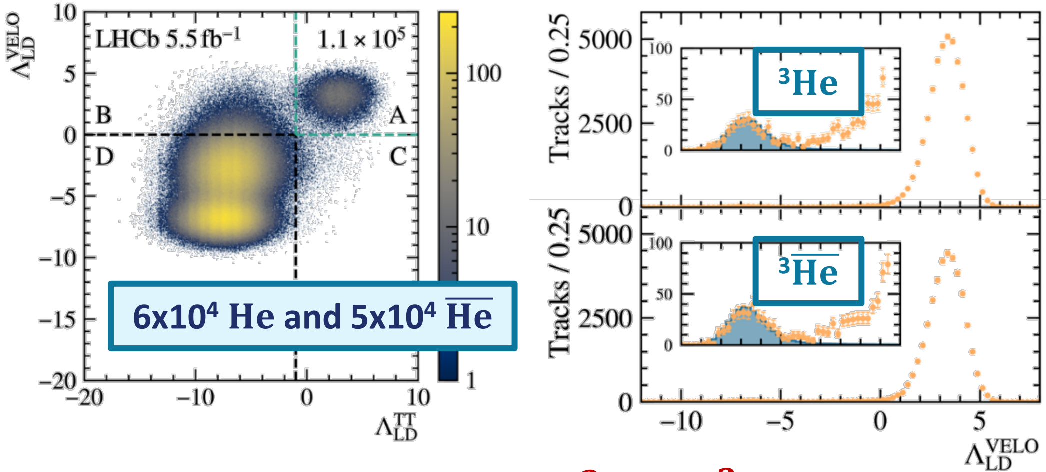
⇒ LHCb not designed to identify light (anti-)nuclei

→ **New techniques under development.**

LHCb-DP-2023-002

1 **Ionisation losses**: **Z^2 dependence** in Bethe-Bloch
→ dE/dx to **identify He**

$\boldsymbol{pp}$ **at $\sqrt{s} = 13$ TeV**, $\mathcal{L}_{int}$=5.5 fb^{-1}



6x10^4 He and 5x10^4 $\overline{\text{He}}$

Hypertriton pp collisions: ${}^3_\Lambda\text{H} \rightarrow {}^3\text{He}\,\pi^- + cc$

[LHCb-CONF-2023-002]

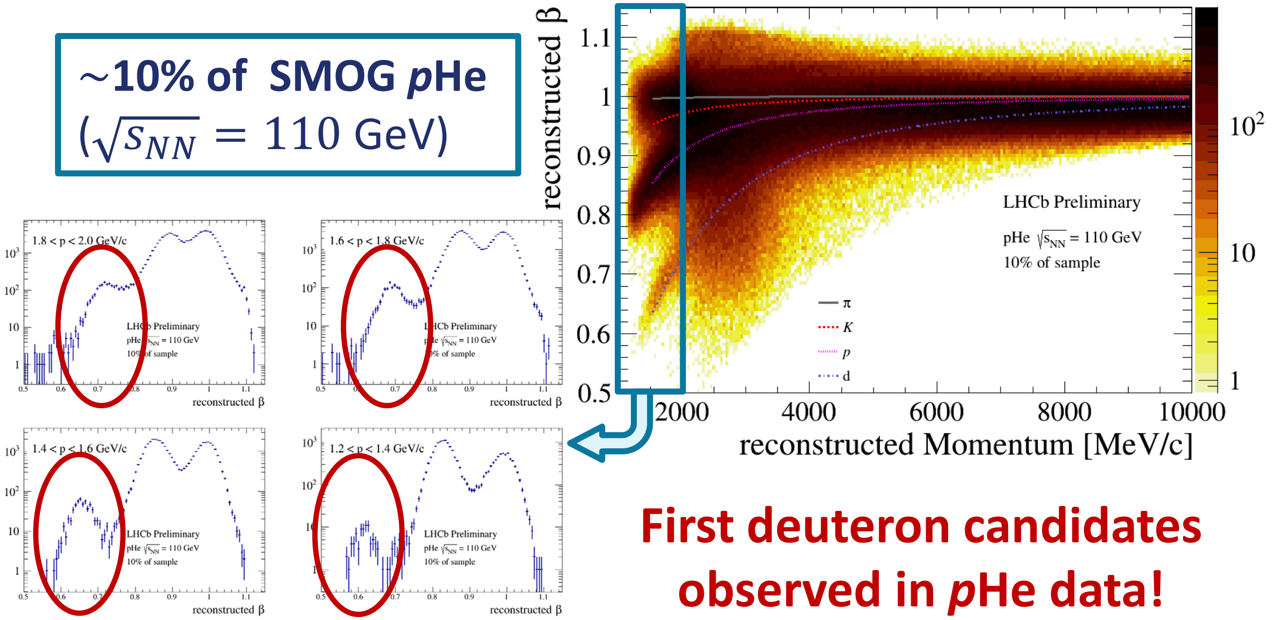
Anti-helium from $\overline{\Lambda}{}_b^0$ decay: $\overline{\Lambda}{}_b^0 \rightarrow {}^3\text{He}X$

[LHCb-CONF-2024-005]

LHCb-FIGURE-2023-017

2 Light nuclei much slower than c: **M dependence** of particle speed
→ **Time-of-flight** to **identify d, distinguish ^{3}He and ^{4}He**

~10% of SMOG pHe
($\sqrt{s_{NN}}$ = 110 GeV)

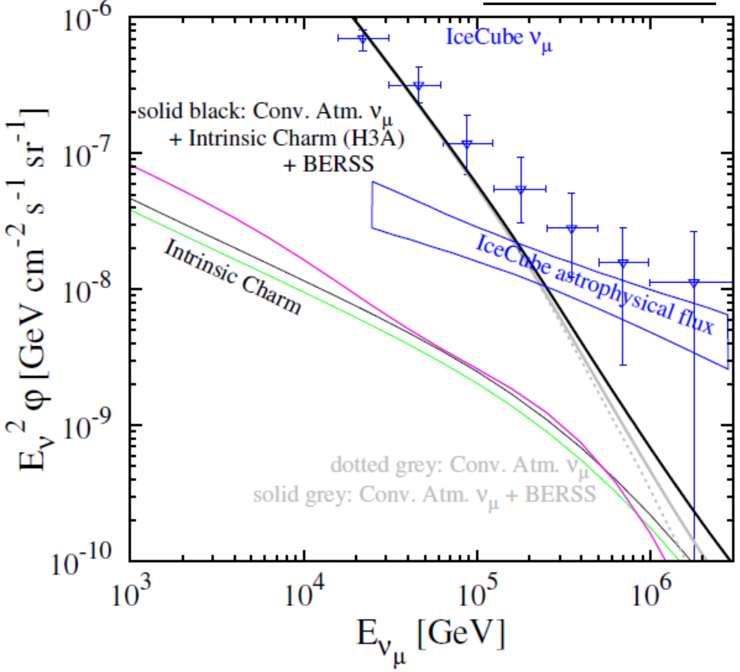


First deuteron candidates observed in pHe data!

Charm production in *p*Ne and PbNe

Charm production in fixed-target

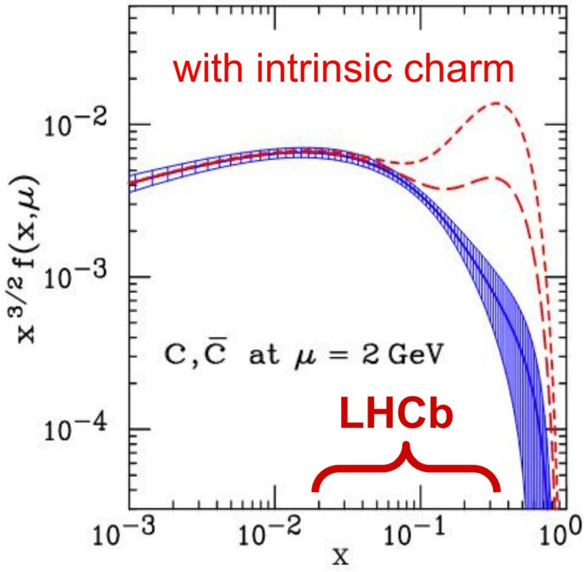
PRD 96 123002



Large volume neutrino telescopes (IceCube, KM3NET) are observing neutrinos up to PeV scale → Main background from neutrinos produced in **decays of charmed hadrons** in ultra high energy atmospheric showers.

Experimental data covering several orders of magnitude in energy are essential to be used in PDF fits and reduce QCD uncertainties

LHCb fixed-target (high-*x* at low Q^2) can give unique contribution.



Phys Rec D75 054029

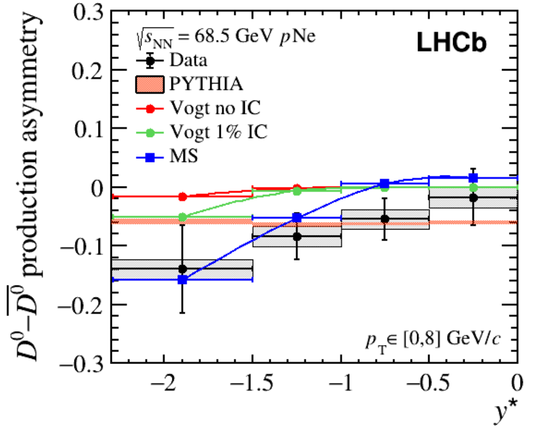
Measurement of D^0, J/ψ and ψ(2s) in *p*Ne at $\sqrt{s_{NN}}$=68 GeV

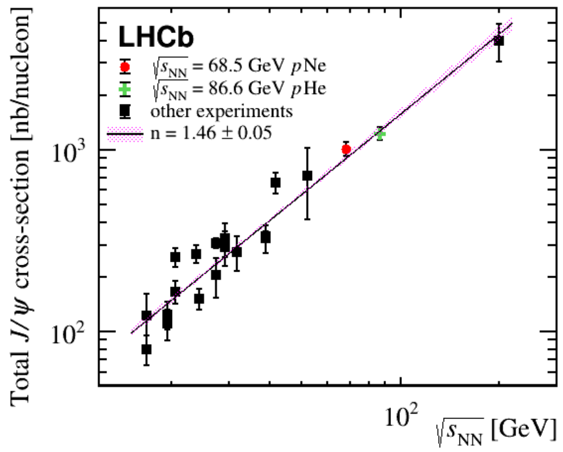
- Unique energy scale
- Sensitive to possible nucleon intrinsic charm (IC) content
- Extend previous D^0 and J/ψ measurements in *p*He (110 Gev) and *p*Ar (68 GeV) [PRL 122 (2019) 132002]

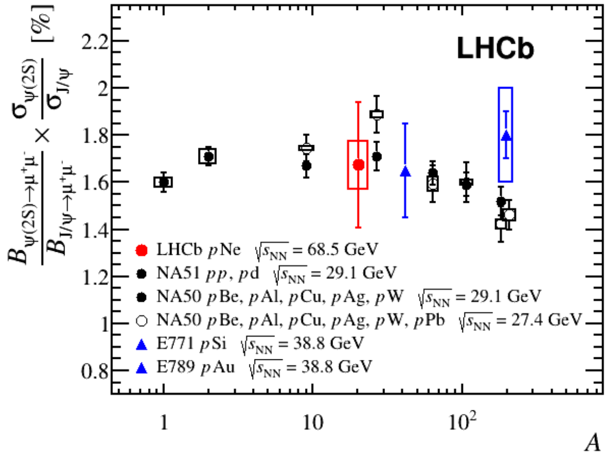
Results

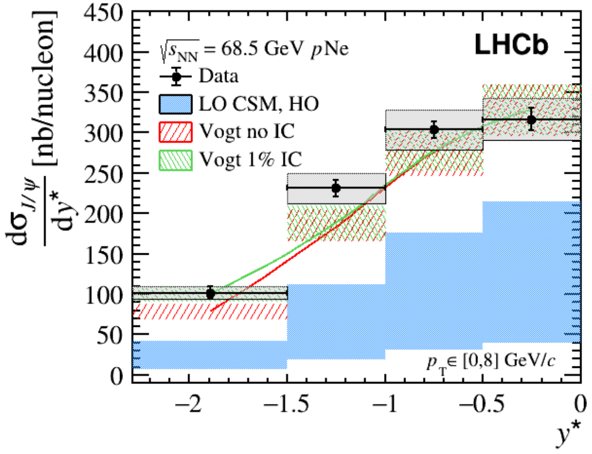
Eur. Phys. J. C83 (2023) 625
Eur. Phys. J. C83 (2023) 541

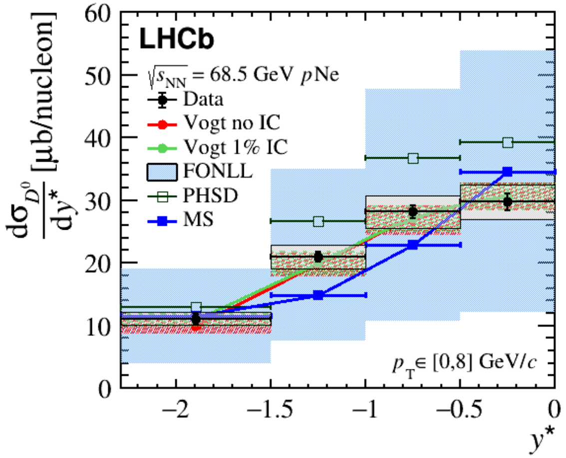
- **Filling a gap in energy**
- **J/ψ** cross-section **in agreement with previous experiments**
  - → **Power law dependence** on centre of mass energy
- ψ(2S)/ J/ψ ratio compatible with previous measurements with similar A.
- **Good agreement with Vogt** predictions (**no IC, 1% IC**)
- Statistically limited to distinguish between the two and to access heavier states.









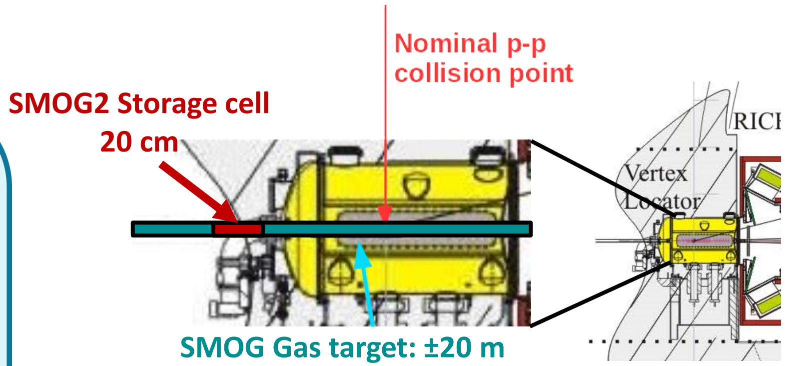


Fixed-target upgrade and prospects for Run 3

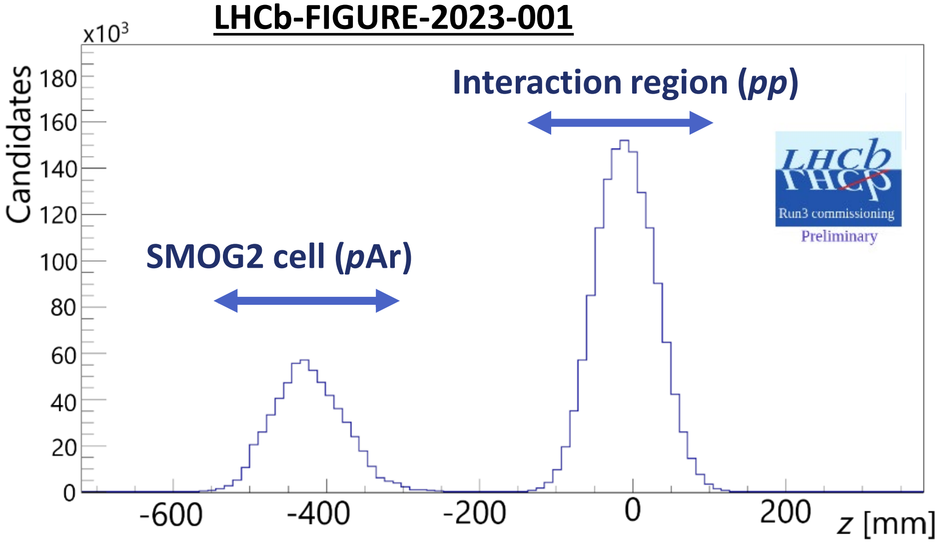
SMOG upgrade: SMOG2

SMOG2: gas confined in a 20 cm long storage cell upstream the interaction point:

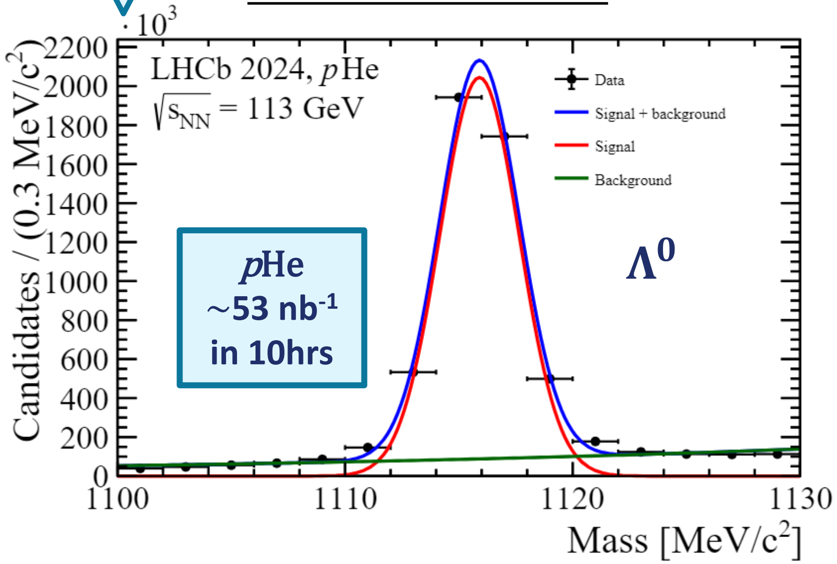
- **x100 average pressure** with same gas flow
- Direct and precise gas pressure and temperature measurement
- **Simultaneous *pp* + fixed-target data taking**
- Wider choice of injectable gases: $\mathbf{H_2}$, $\mathbf{D_2}$, $\mathbf{N_2}$, $\mathbf{O_2}$, Kr, Xe (+He, Ne, Ar)



LHCb-FIGURE-2023-001



LHCb-FIGURE-2024-005



Physics opportunities with SMOG2

Unique physics opportunities never explored at LHC:

- **Charmonium, bottomonia and exotica production** from H_2 to Kr.
- **Flow measurements** at low energy over wide pseudorapidity range.
- **Ultra-peripheral collisions** in *p*A and PbA.
- *p*H_2, *p*He, *p*D_2, *p*O_2 and OH_2 collisions to extend **modelling of productions of CR interest.**

SMOG (★) and SMOG2 (★)

★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

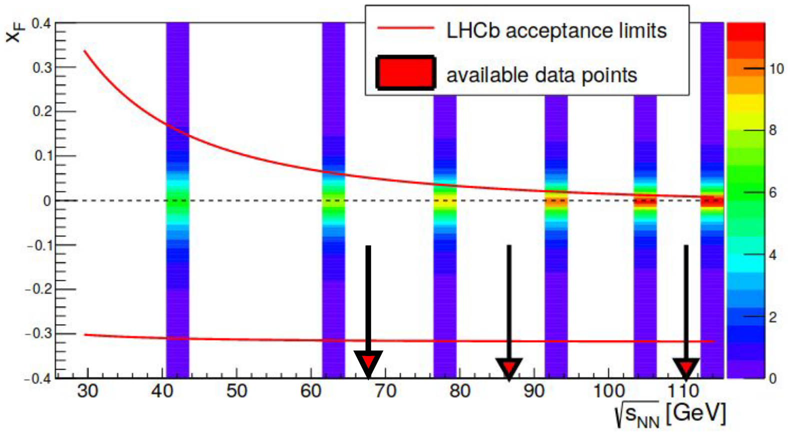
★4) $p\,p,\ p\,He \rightarrow \bar{d},\ \overline{He}$ to determine coalescence momentum

★5) $p\,p,\ p\,He \rightarrow \pi,\ K$ to model positron source term

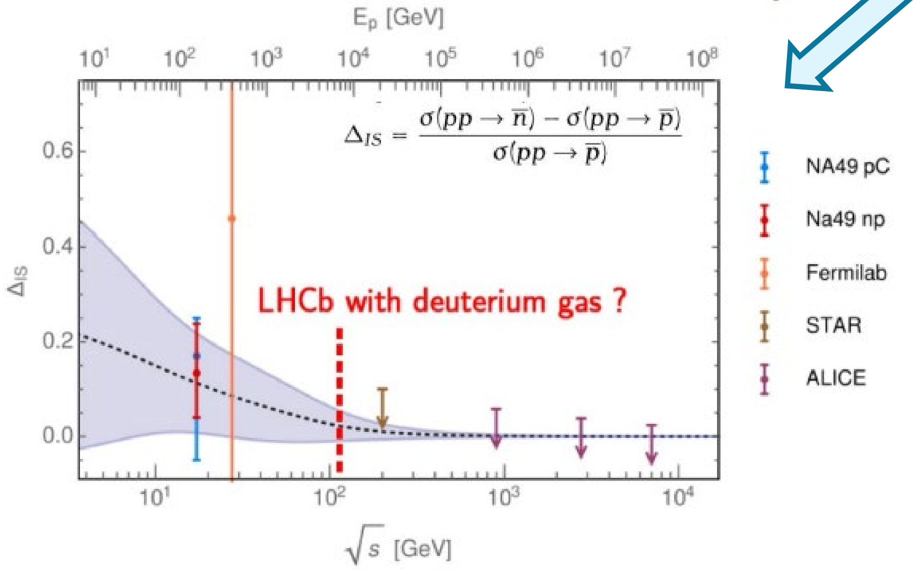
Martin Winkler at 2nd LHCb Heavy Ion workshop

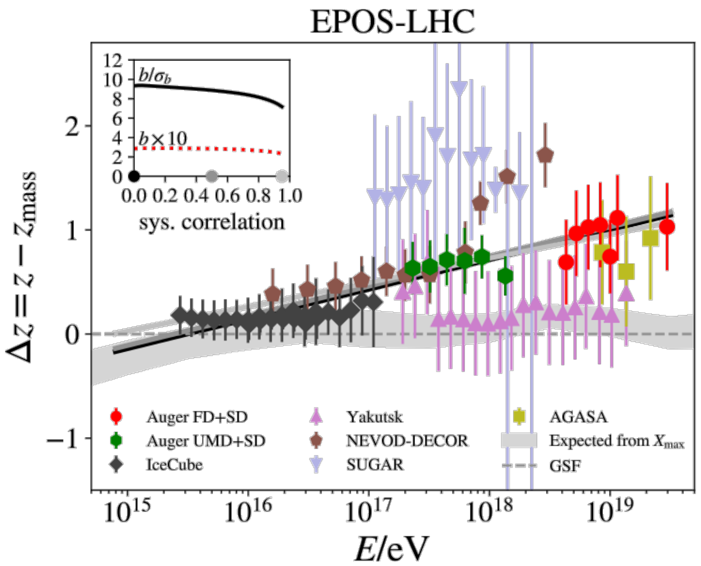
\+ ★ H_2, O_2, N_2 for atmospheric CRs physics

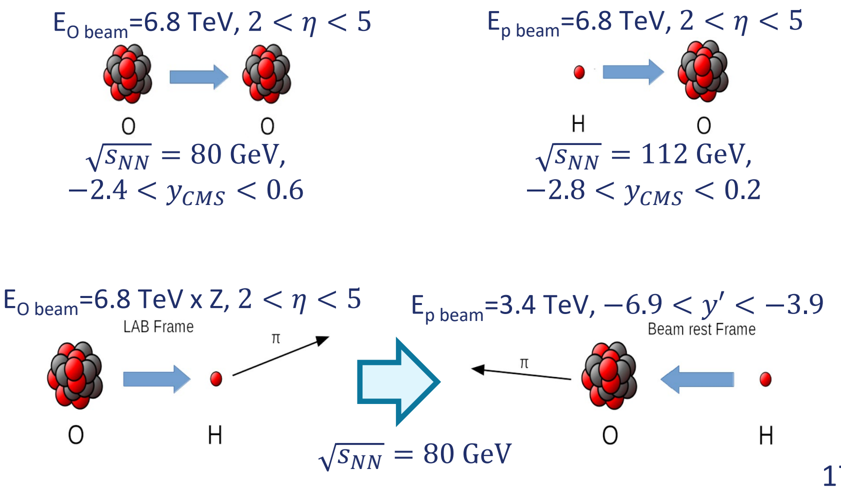
Physics opportunities with SMOG2



- At lower energies to test scaling violation in forward hemisphere → @87 GeV for SMOG *p*He, @68 GeV for SMOG2 during *pp* ref run
- With **H_2 injection**: $\boldsymbol{\sigma(pp \longrightarrow \bar{p}X)}$ and $\boldsymbol{\sigma(pHe \longrightarrow \bar{p}X)/\sigma(pp \longrightarrow \bar{p}X)}$ to constrain the production cross section.
- With **D_2 injection**: $\boldsymbol{\sigma(pD \longrightarrow \bar{p}X)/\sigma(pp \longrightarrow \bar{p}X)}$ to test for isospin violation and constrain the $\bar{n}$ production.
- With O_2 target and O beam: OO_2, pO_2 and OH_2 collisions to study **air showers and contribute to understand the muon puzzle**





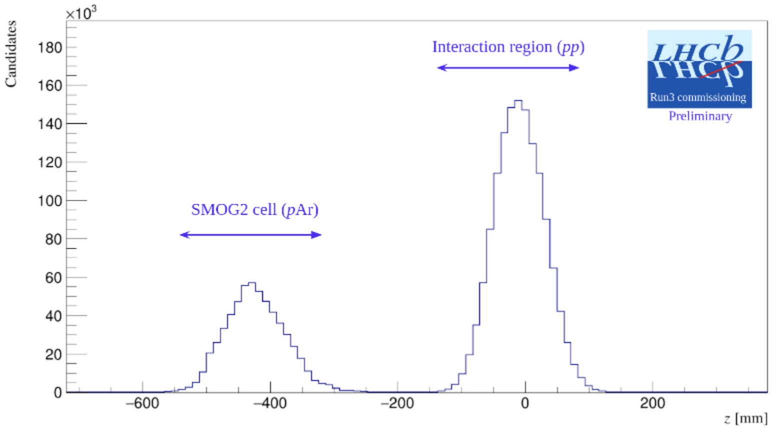


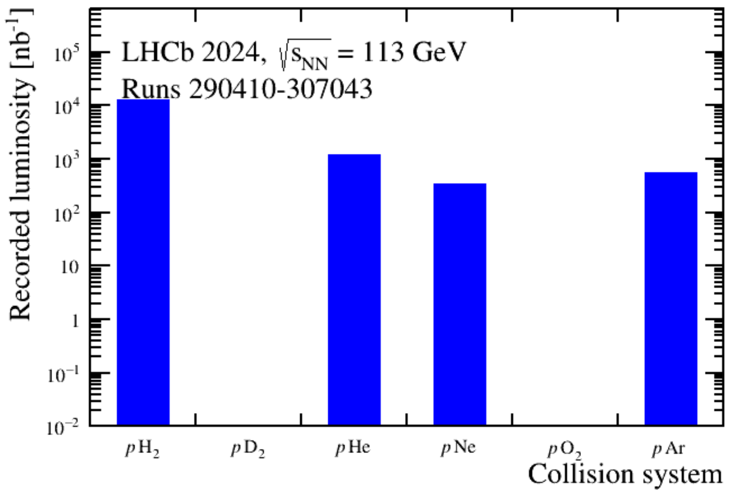
Some SMOG2 performance

Injections in SMOG2 as default since May 2024, already collected hundreds of hours for all available gases
→ **H_2 regularly injected in LHC!**

Efficient separation between *pp* and *p*Ar

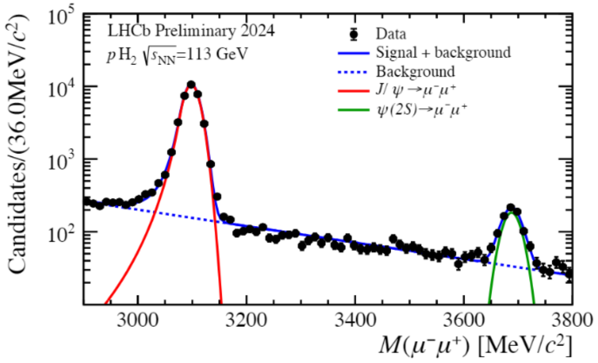
→ **Operating simultaneously in collider and fixed target mode with two colliding system and energies!**

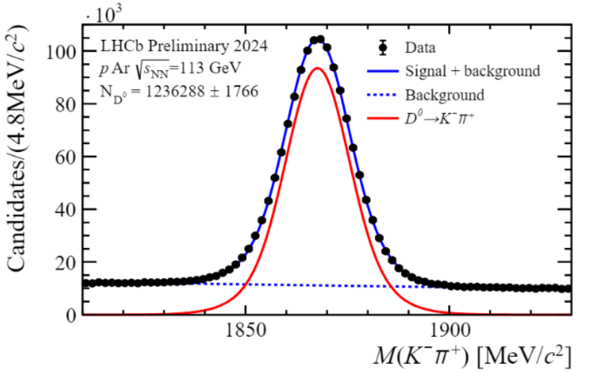




Already collected **more luminosity than the whole Run 2** datasample

Full analysis chain validated, first analysis on the way





Conclusions

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

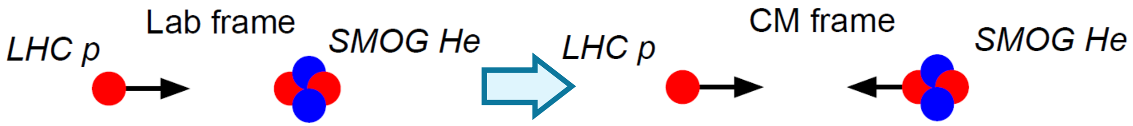
- LHCb is developing a **pioneering fixed-target programme in a mostly unexplored kinematic regime**
- It contributed to hadronic production measurements relevant for CR physics exploting Run2 datasamples:
  - The **antiproton measurement at fixed-target of $\sigma(p\mathrm{He} \longrightarrow \bar{p}X)$** with a 6.5 TeV proton beam helped to improve the secondary $\bar{p}$ flux predictions.
  - Its detached-to-prompt production ratio shows a large underestimation of all theoretical models for antihyperon decay contributions.
  - Charm production measurements contributed to constrain the main background for astro-neutrino observations
- The **analysis on the Run2 samples are still ongoing:** exploit lower energy datasamples and extension towards antinuclei measurements.
- The LHCb fixed-target programme **upgrade SMOG2** will improve the accuracy and extend these measurements, operating with up to x100 gas pressure and more gas species.

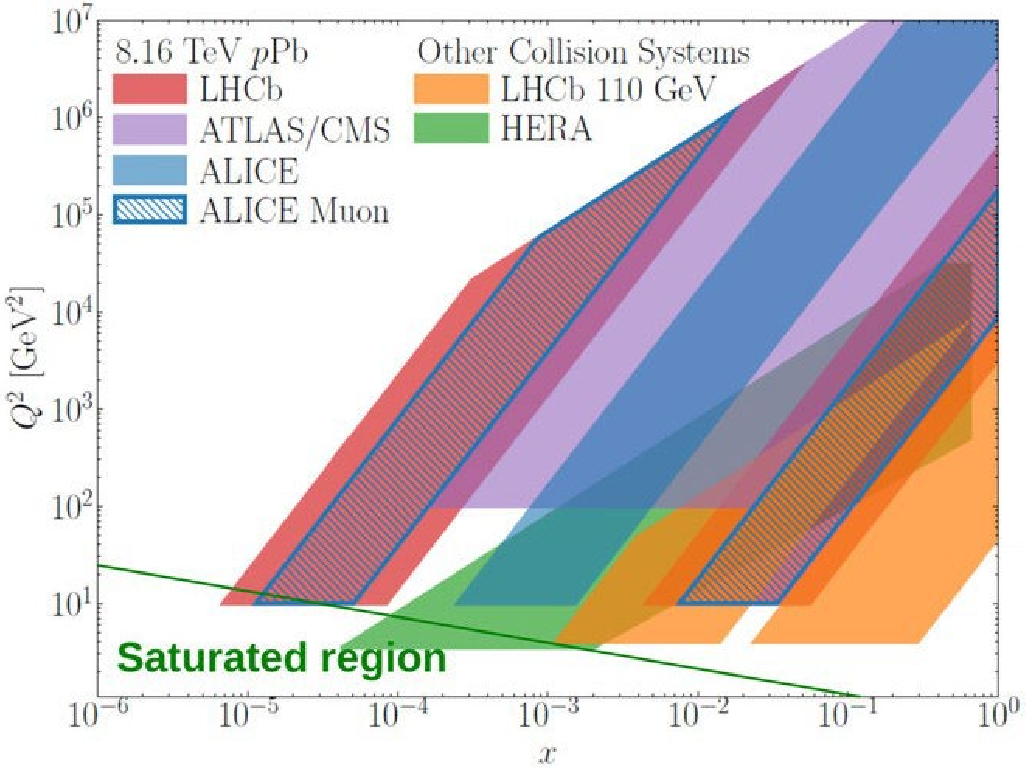
Thanks for the attention!

BACKUP

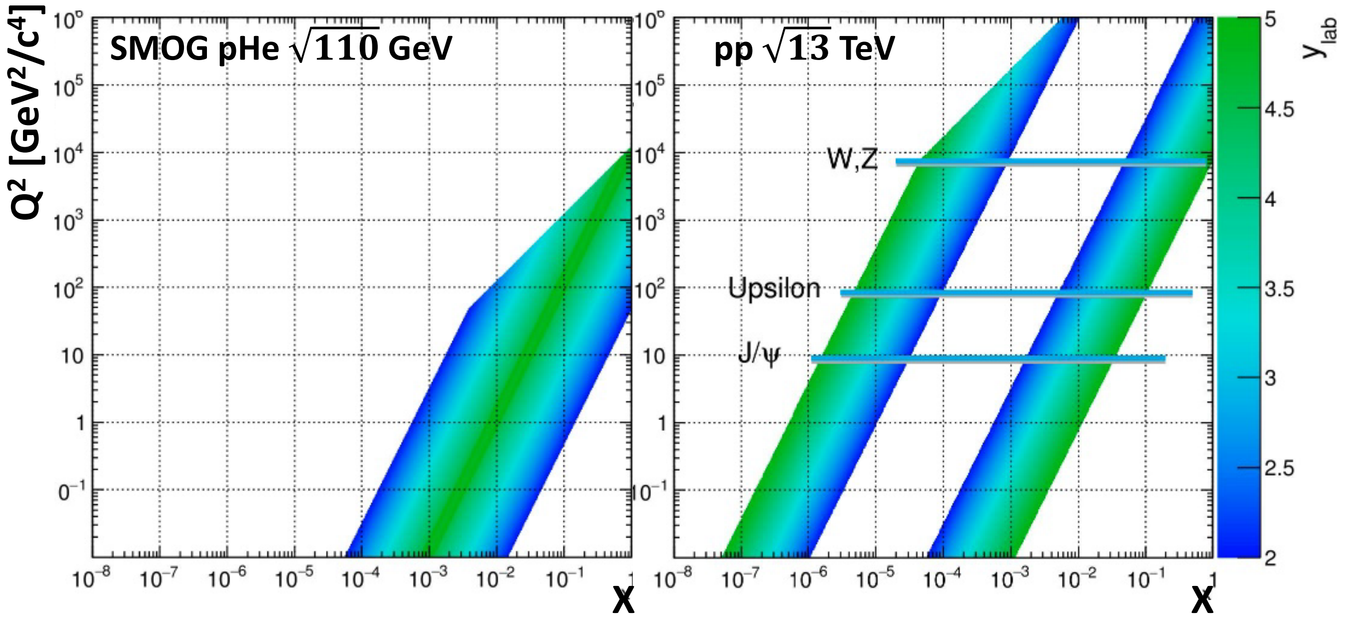
LHCb fixed-target apparatus

Unique physics opportunities at the LHC





LHCb-PUB-2018-015



Luminosity measurement in SMOG data samples

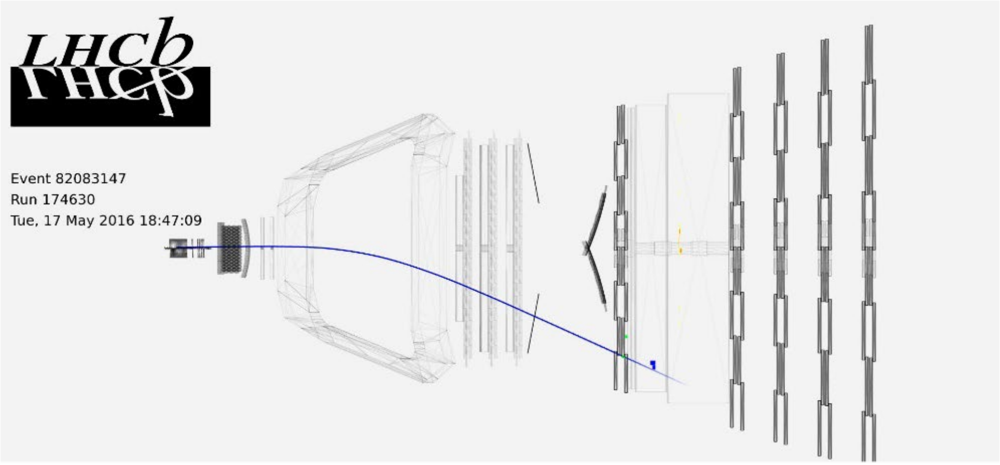
PRL 121 (2018) 222001

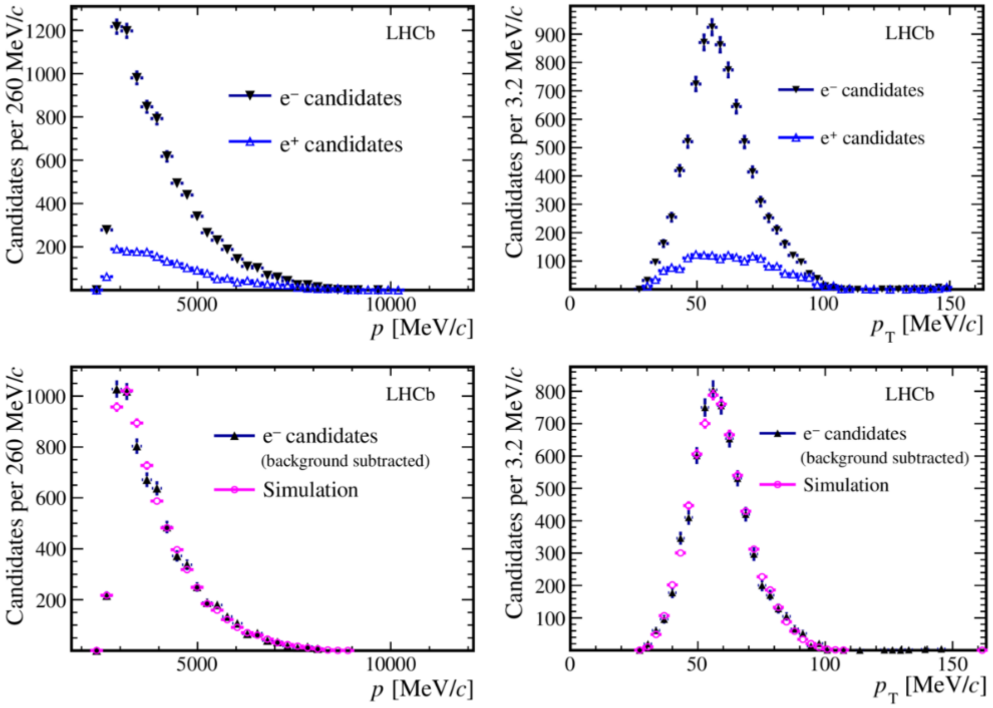
SMOG is not equipped with precise gauges for the gas pressure:

→ Luminosity is determined through ***pe* elastic scattering** with gas atomic electrons.

- pe events are identified as an isolated low-energy electron track.
- Charge symmetric background is evaluated through positron yield and subtracted from electron yield.
- Poor electron reconstruction efficiency (16%) → 6% uncertainty on luminosity

Dominant contribution to systematic uncertainty on σ!





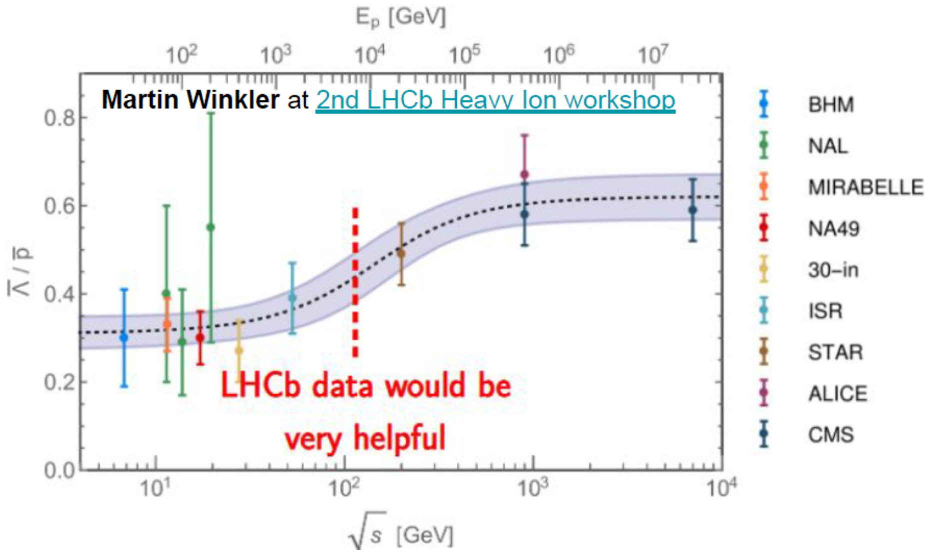
Detached antiproton production

- Around **20-30% of $\overline{p}$ production** comes from anti-hyperon decays → Dedicated measurement to the component from anti-hyperon decays in *p*He, extending first LHCb result only dealing with prompt processes

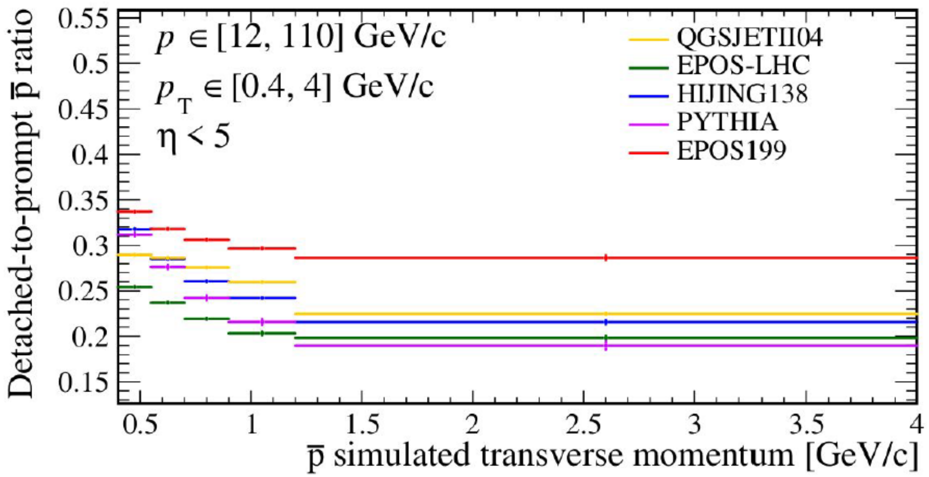
$$\bar{\Lambda}^0_{\rm prompt} \to \bar{p}\pi^+ \qquad \bar{\Sigma}^- \to \bar{p}\pi^0 \qquad \bar{\Xi}^+ \to \bar{\Lambda}\pi^+ \qquad \bar{\Xi}^0 \to \bar{\Lambda}\pi^0 \qquad \bar{\Omega}^+ \to \bar{\Lambda}K^+$$

- Available data indicate strangeness enhancement but **large spread among different theoretical models**

→ **LHCb SMOG measurement can constrain the models**



CERN-THESIS-2021-313

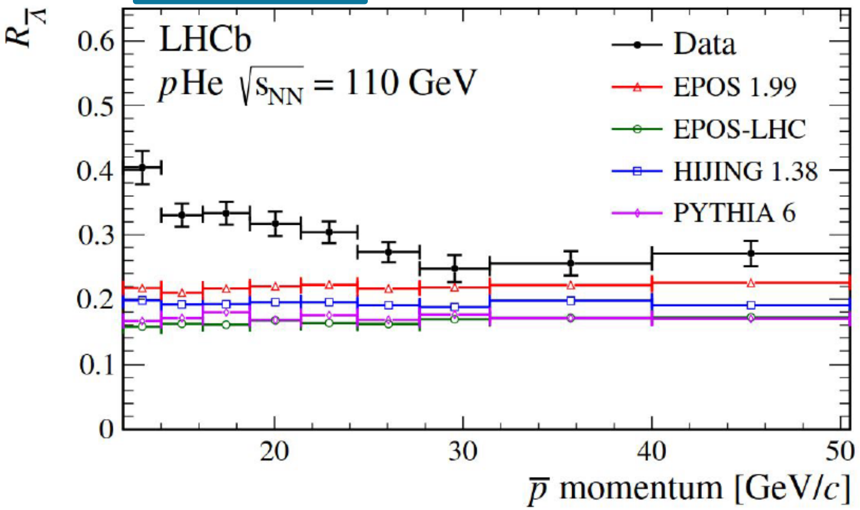


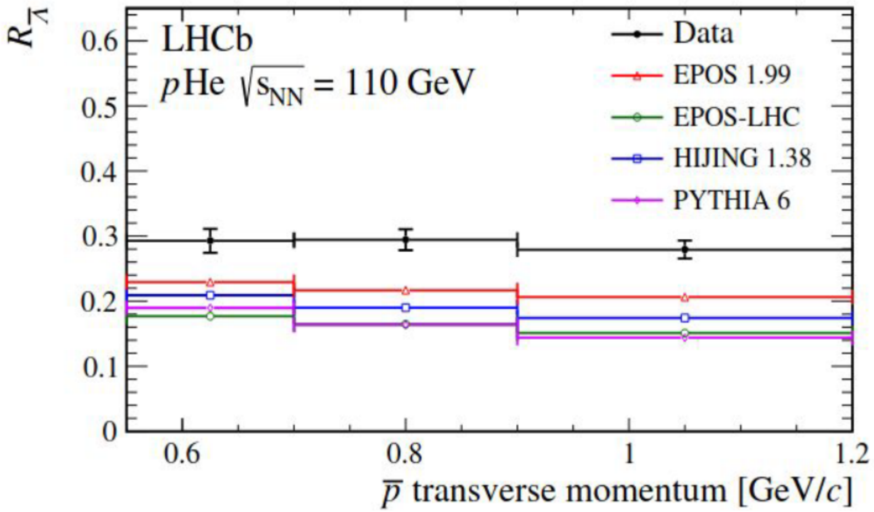
Results

Eur. Phys. J. C83 (2023) 543

Exclusive

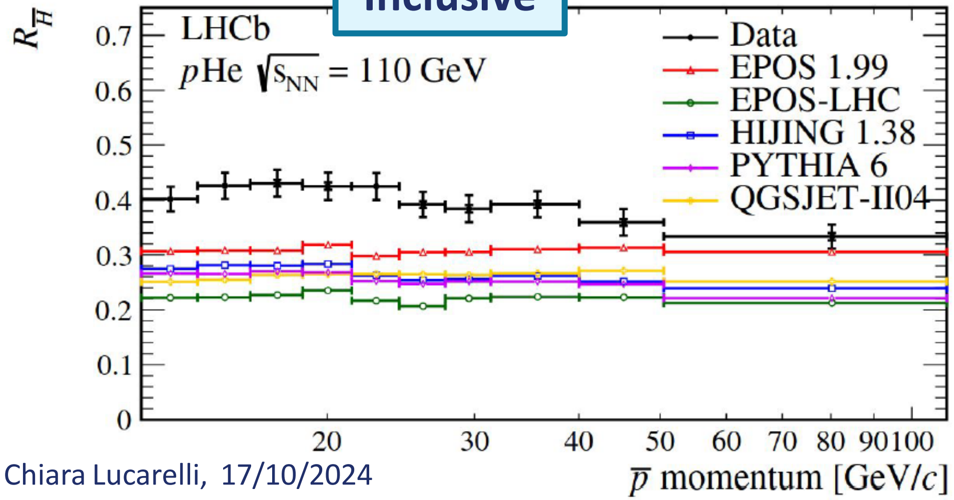
Larger contribution measured wrt all most widely used theoretical models

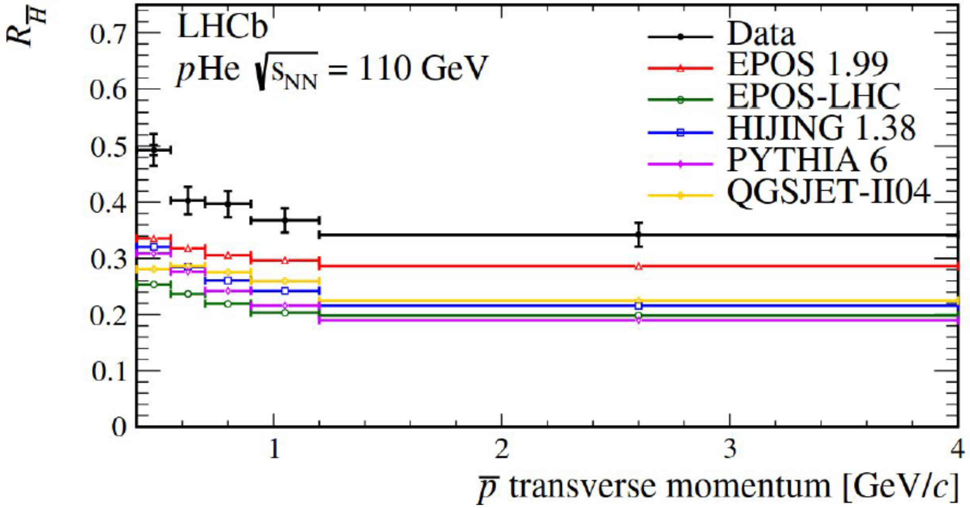




EPOS 1.99: Nuclear Physics B.2009.09.017
EPOS-LHC: Phys. Rev. C 92,034906
HIJING 1.38: Computer Physics Communications 83 (1994) 307-331
PYTHIA 6: JHEP 05 (2006) 026

Inclusive





Anti-nuclei production

- **No comprehensive theoretical model** to explain from first principles (anti-)nuclei production in hadronic interactions → **Phenomenological models tuned on data**

Coalescence model:

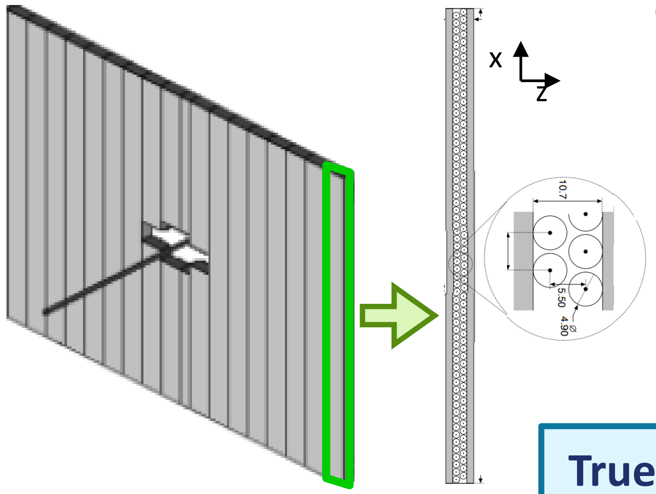
An anti-nucleus is produced if the nucleons are sufficiently close in phase space: $\boldsymbol{B_A}$ **coalescence probability**.

- Experimental data suggest that B_A depends on the **type of reaction** (*pp*, *p*A or AA) and on the **incident particle momentum** (p_{lab}).

- ALICE measures d and He production in *pp*, *p*Pb and PbPb interactions at $\sqrt{s} = 13$ TeV and central rapidity
- SpS fixed-target configuration covers $\sqrt{s_{NN}} < 27$ GeV and backward to central rapidity

Large uncertainties on extrapolation models to intermediate energy (E_{cr}~10-100 GeV)

Time-of-flight measurement at LHCb



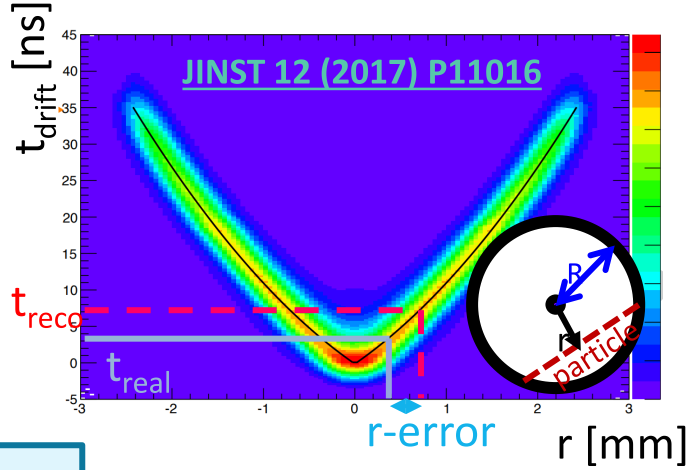
OT (Outer Tracker): largest area, straw-tube drift chambers

- Hit position from ionization cluster t_{drift}– r relation

$$t_{drift} = t_{TDC} - t_{TOF} - t_{prop}$$

- t_{TOF} calculated in the β=1 hypothesis. For β<1:

$$t_{TOF,reco} < t_{TOF,real} \implies t_{drift,reco} > t_{drift,real} \implies \text{r-error}$$



True β minimises the χ^2_{fit} → Particle ID through time measurement

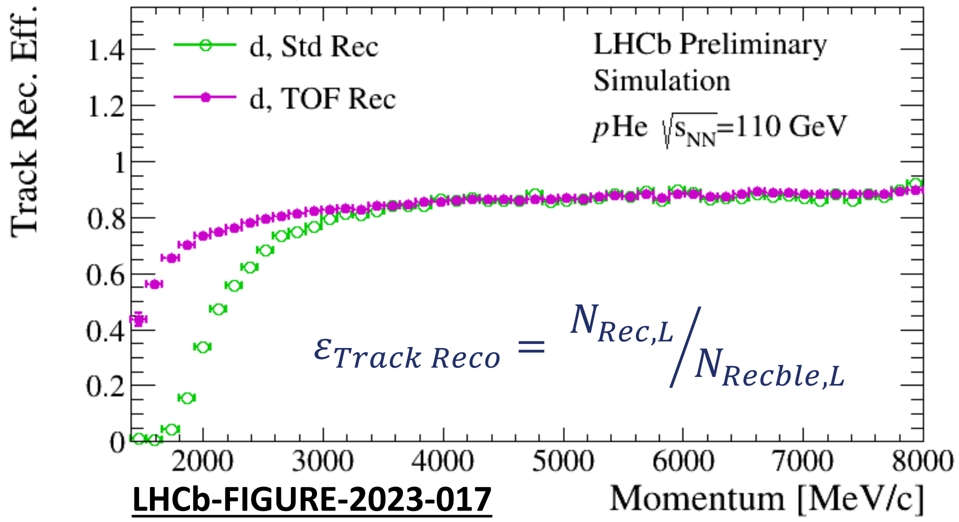
Standard LHCb reconstruction (β=1) inefficient for light nuclei
→ Modified pattern recognition algorithm

Correct hits position to recover reconstruction efficiency

- Loop on $\beta \in \left[1/\sqrt{1 + M^2_{max}/p^2}\,, 1\right]$
- For each β : hits position for β value and perform fit
- Select candidate with best χ^2_{fit}

MC sample:

QGSJET for *p*He + **coalescence afterburner** (1 coal x event)

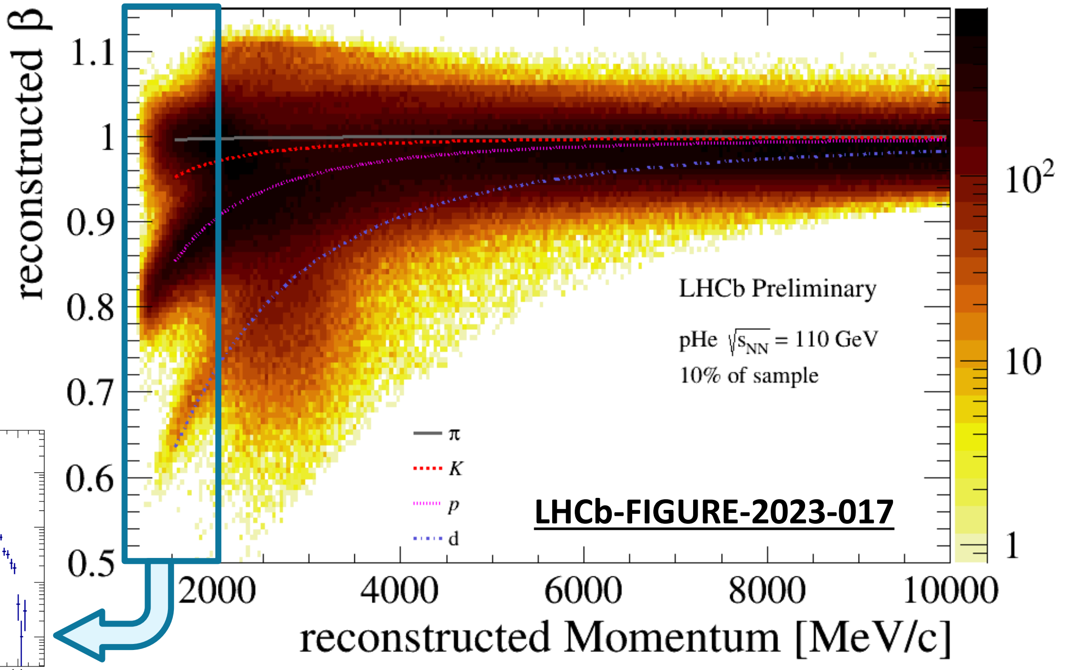


LHCb-FIGURE-2023-017

(Anti-)deuteron identification

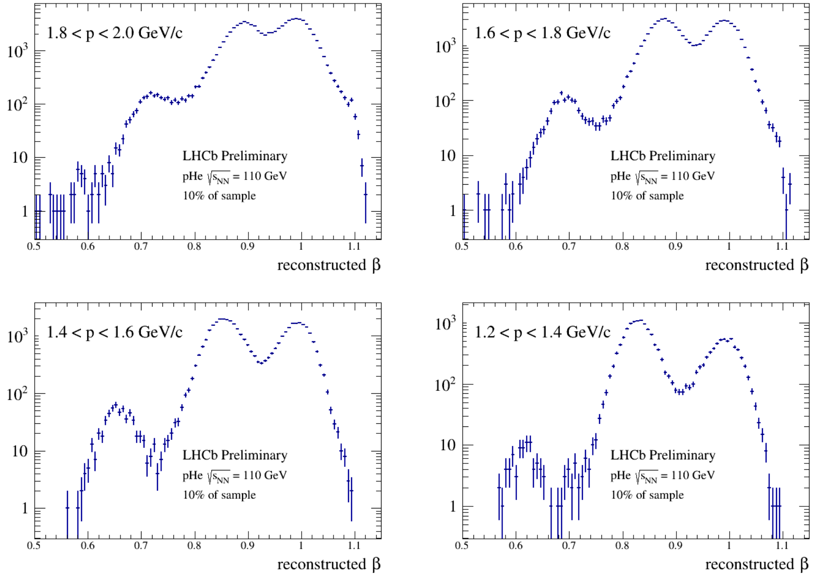
Reconstructed tracks refitted to determine β → Iterative procedure rerunning Kalman fit with different β hypotheses

1. At least 15 OT hits required on each track
2. Change β following χ^2_{fit} decrease (gradient descent) without outliers removal → $\chi^2_{\mathrm{fit}} = \chi^2_{\mathrm{track}} + [(t_{M1} - \langle M1 \rangle)/\sigma_{M1}]^2$
3. Fit around minimum to estimate β_{fit} and its uncertainty
4. If fit at minimum has outliers, removed and reiterate procedure



- ∼**10% of SMOG *p*He** ($\sqrt{s_{NN}}$ = 110 GeV) dataset
- **Background suppression**: σ(β) < 0.02 , χ^2_{OThits}/ndf <2

First deuteron candidates observed in *p*He data!



LHCb-FIGURE-2023-017

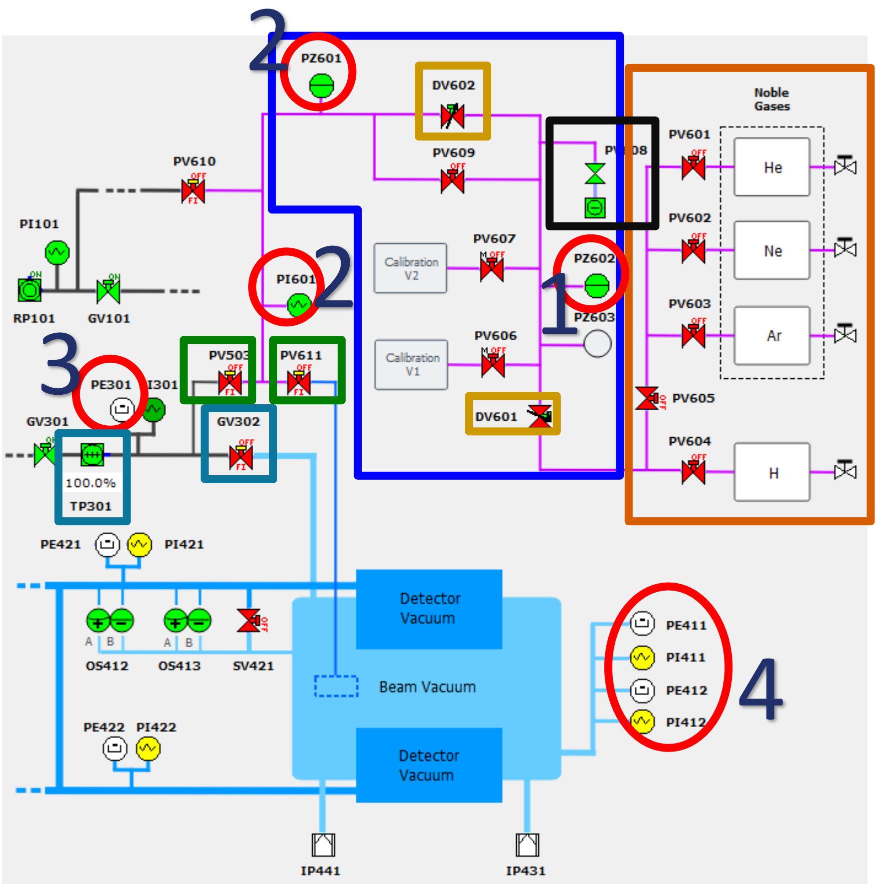
Under investigation:

- Some DATA/MC discrepancies in OT response
- Efficiencies and systematics studies
- Improve background suppression to expand momentum range where clean identification achievable

GFS and injection

Gas injected into cell or VELO tank through the Gas Feed System:

- Four gas reservoirs (3 noble gases + 1 non getterable line), used to fill the calibrated volumes V1 and V2, controlled by dosing valve DV601
- Table with calibrated volumes used during injection, pumping group to clean line and dosing valve DV602 to control injected flux.
- Gas feed line to feed either the VELO tank (PV503) or the cell (PV611)
- Turbo pump TP301 connected to VELO tank through GV302 (open during SMOG2 operations) to provide pumping when ion pumps off.



- Multiple gauges to measure pressure along the line and in the VELO tank:
  1. PZ602: pressure at calibration volumes, around 10 mbar when full.
  2. PZ601 and PI601: pressure at the beginning and end of GF line, O(0.01) mbar for SMOG2, O(0.001) mbar a-la-SMOG (PI601 under sensibility).
  3. PE301: pressure at the turbo pump TP301 (SMOG injection point), O(1e-8) mbar for SMOG2, O(1e-6) mbar a-la-SMOG.
  4. PE411 and PE412: pressure in the VELO tank in Ne equivalent, O(1e-8) mbar.