Antiproton results from SMOG at LHCb

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on behalf of the LHCb collaboration

JENAA workshop 2024,
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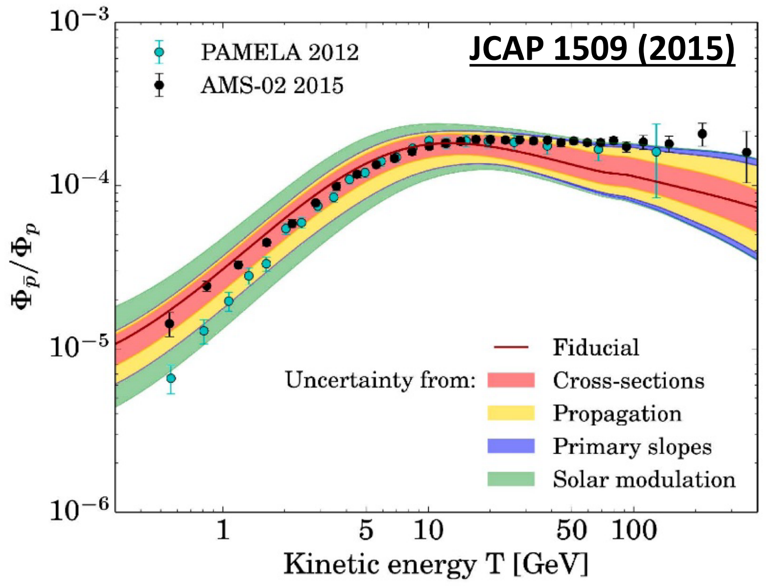
Dark Matter and antimatter in space

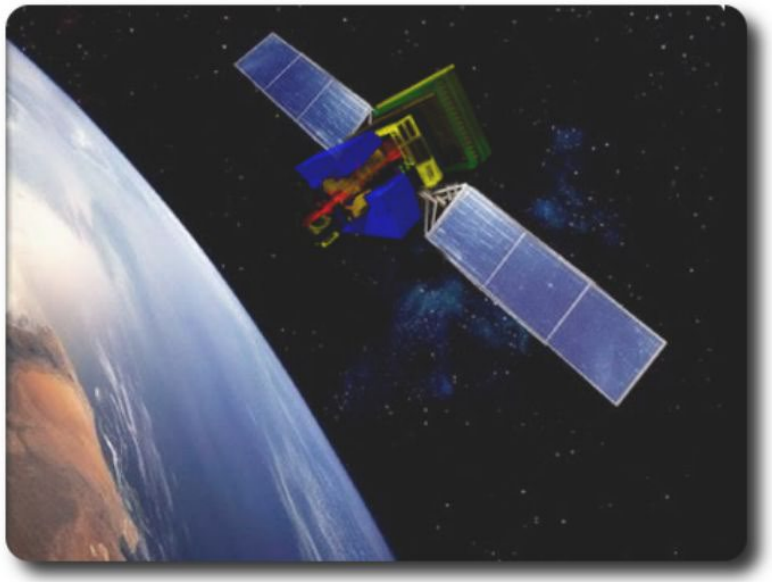
Antimatter fraction in Cosmic Rays is a sensitive **indirect probe** for Dark Matter:

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

Space experiments (PAMELA, AMS) measured antimatter fluxes in Cosmic Rays but conclusive interpretations curbed by **limited knowledge of production processes**.

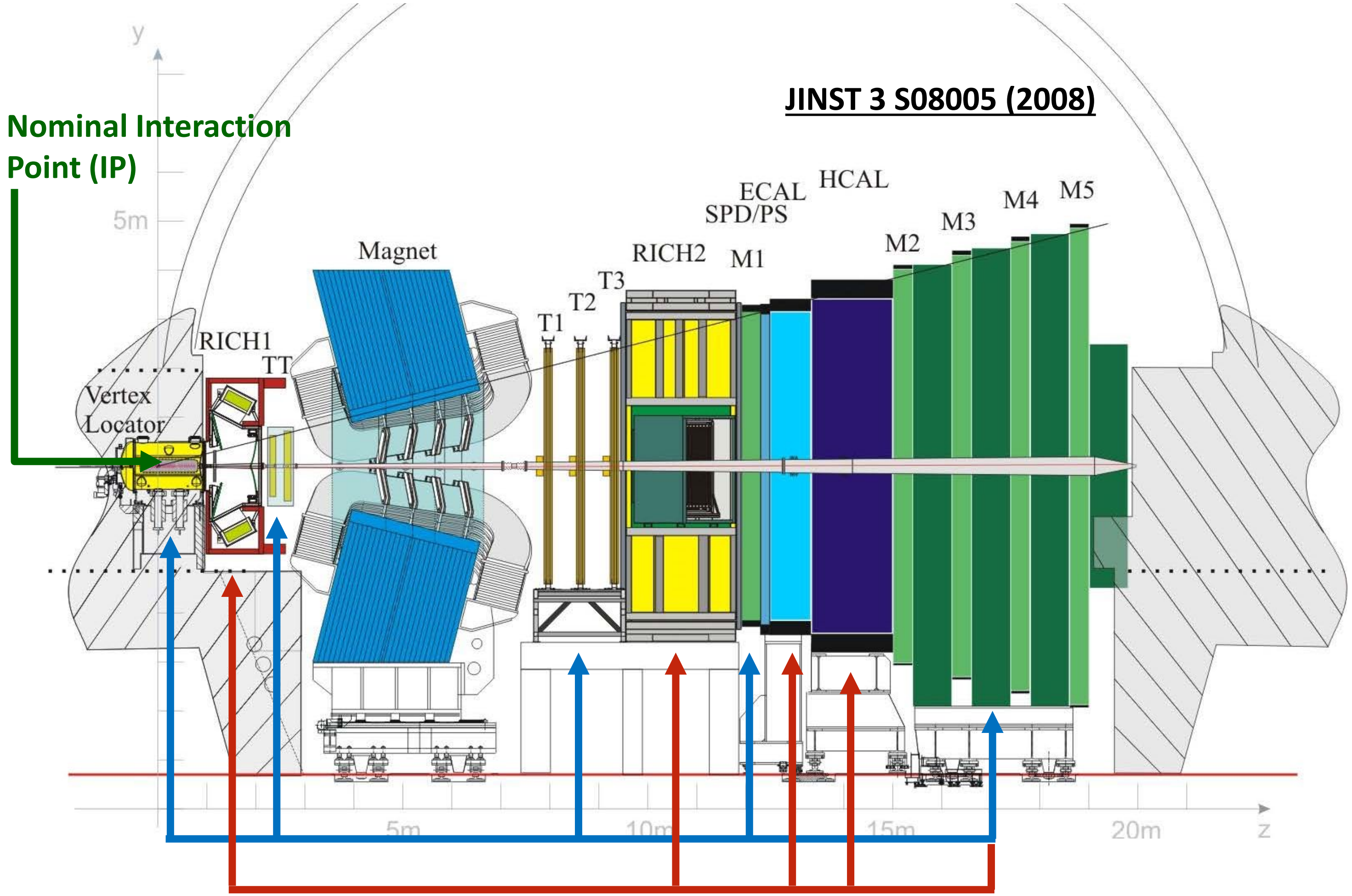


__Accelerator experiments can complement Cosmic Rays investigations__



Thanks to its unique injection of gases in the LHC (e.g. H_2, D_2, He), **LHCb is contributing with its space mission to improve the precision of models**.

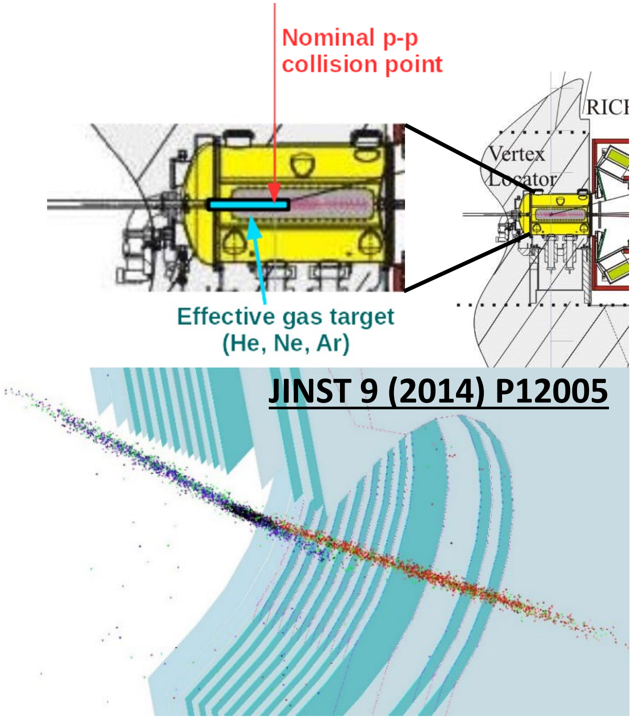
The LHCb experiment



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.**

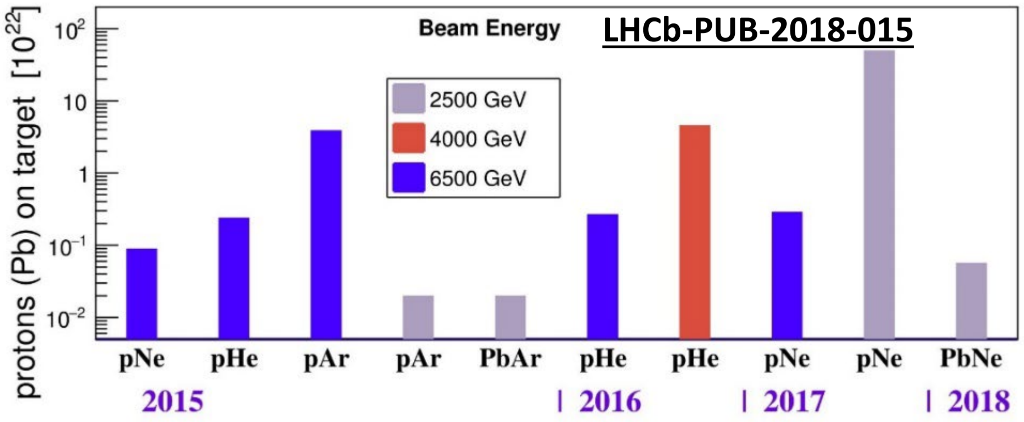
LHCb fixed-target apparatus



SMOG: The *System for Measuring Overlap with Gas* (2011-2018)

- Originally conceived for precise luminosity measurements through **Beam-Gas Imaging** (lowest uncertainty on the LHC luminosity measurement: 1.2-1.5%).
- Inject noble gases (He, Ne, Ar) in the LHC beam pipe around ±20 m of the LHCb IP
- Pressure of **2×10^{-7} mbar** (x100 nominal LHC vacuum)

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

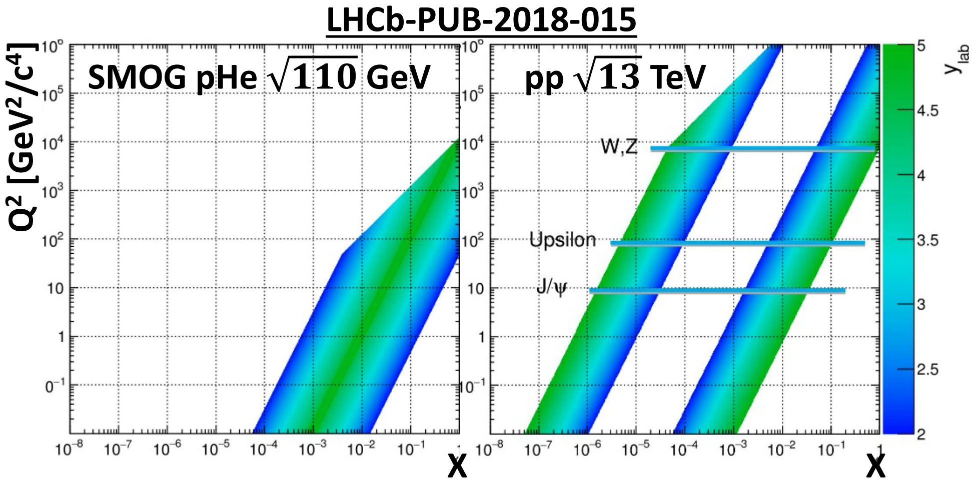


In 2015-2018, LHCb collected ***pA* and PbA physics samples in fixed-target configuration** with different targets and different centre of mass energies.

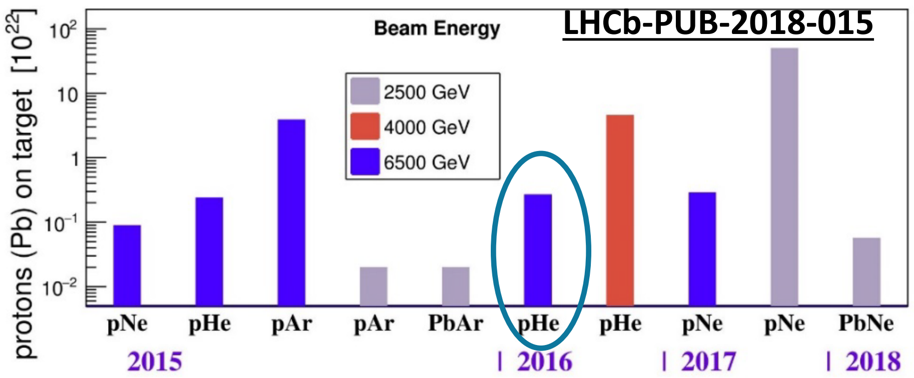
LHCb fixed-target apparatus

Unique physics opportunities at the LHC

- Unexplored **intermediate energy** to SpS and LHC: $\sqrt{s_{NN}} \in [30, 115]$ GeV
- **Large target Bjorken-*x* at intermediate Q^2**
- Collisions with **targets of mass number A intermediate** between *p* and Pb



- **Cold nuclear-matter effects (CNM)** for QGP studies
- **Nuclear PDFs at high-*x*** and strange hadronization process
- **Polarization studies** in baryon production
- **Hadron production** and spectra measurements for CRs physics



e.g. **6.5 TeV LHC *p* on at-rest He ($\sqrt{s_{NN}} = 110\ GeV$)**

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

Prompt antiproton production in *p*He collisions

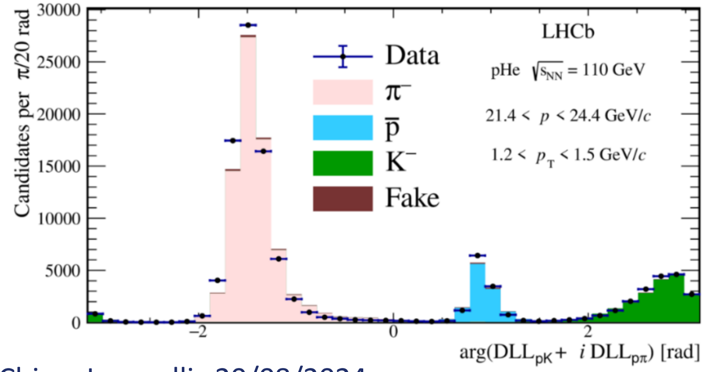
Prompt antiproton production

PRL 121 (2018) 222001

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

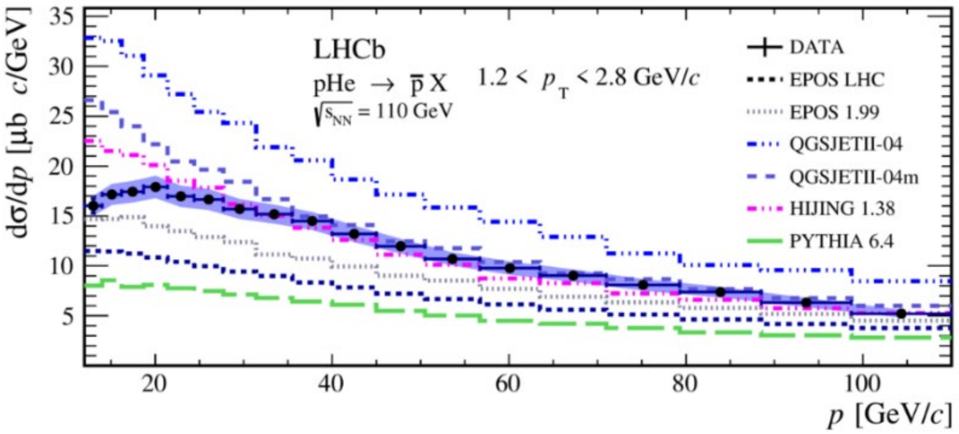
- $\bar{p}$ reconstructed in the kinematic region ($p \in [12,110]\ GeV/c$, $p_T \in [0.4, 4]\ GeV/c$) to optimize reconstruction and particle identification efficiencies.
- **Only $\bar{p}$ promptly produced** considered
  → detached component reduced cutting on the impact parameter wrt the primary vertex.
- $\bar{p}$ number from simultaneous fit to PID variables in (p, p_T) bins.
- Luminosity from ***pe*** **elastic scattering** with gas atomic electrons.

  → **Dominant contribution to systematic:**



- **Luminosity measurement:** injected gas pressure not precisely measured.
- **Particle identification performance:** poor calibration statistics.

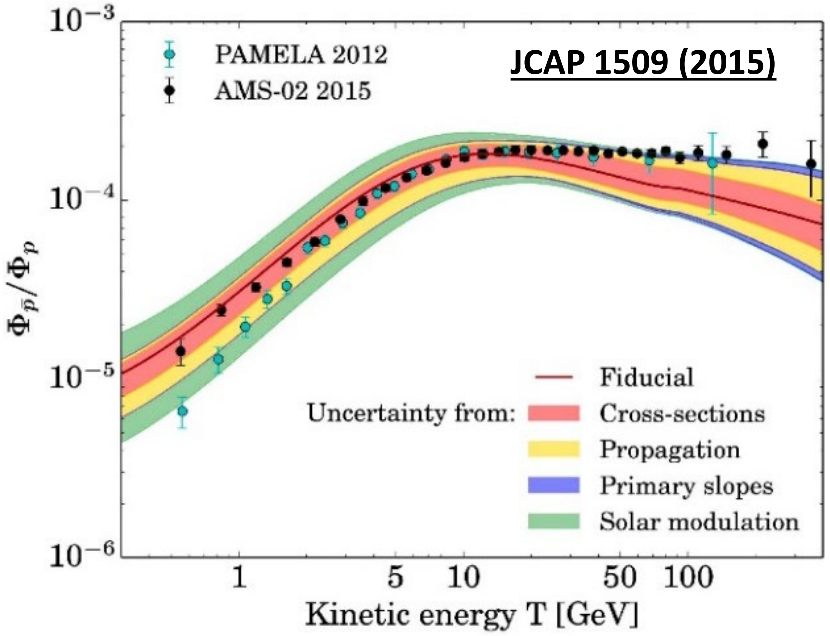
- Result on XS is compared to different MC event generator.
- **Experimental uncertainties (<10%) are lower than the spread among theoretical models.**

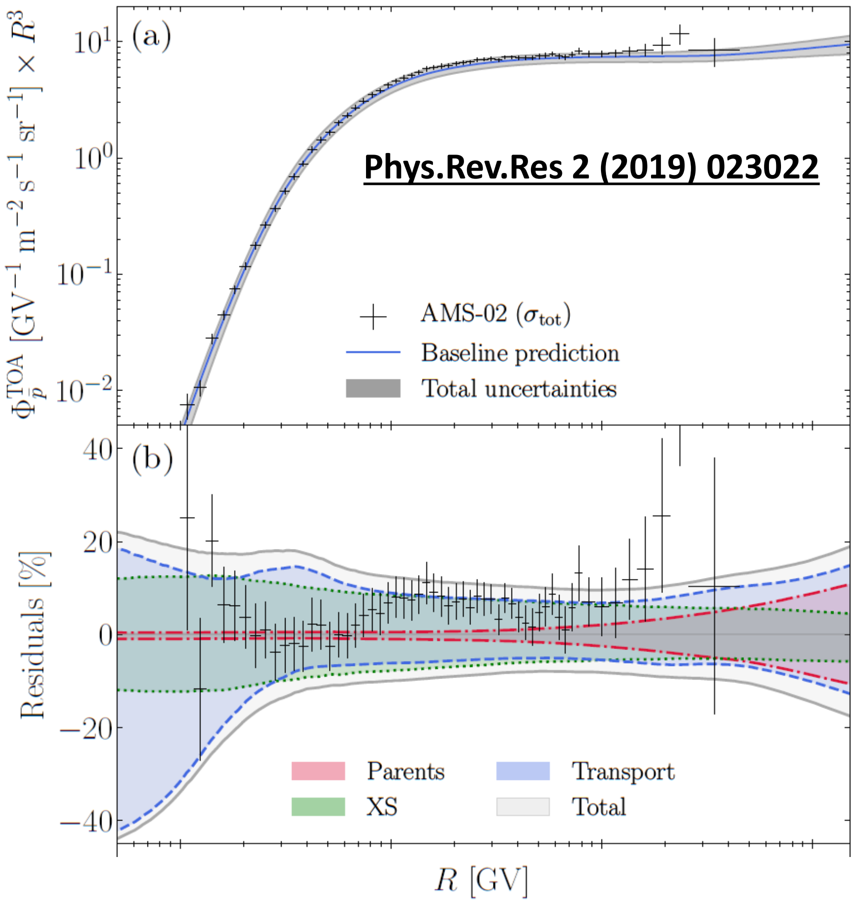


Impact of the measurement

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

- Validation of the extrapolation of the cross section from pH to pHe.
- Validate models for the cross section energy evolution (violation of Feynman scaling above 50 GeV).





- **The uncertainty on the predicted secondary $\overline{p}$ flux is reduced but cross section uncertainties are still dominating.**
- **Room for exotic contribution heavily reduced**

Antiproton production from antihyperon decays

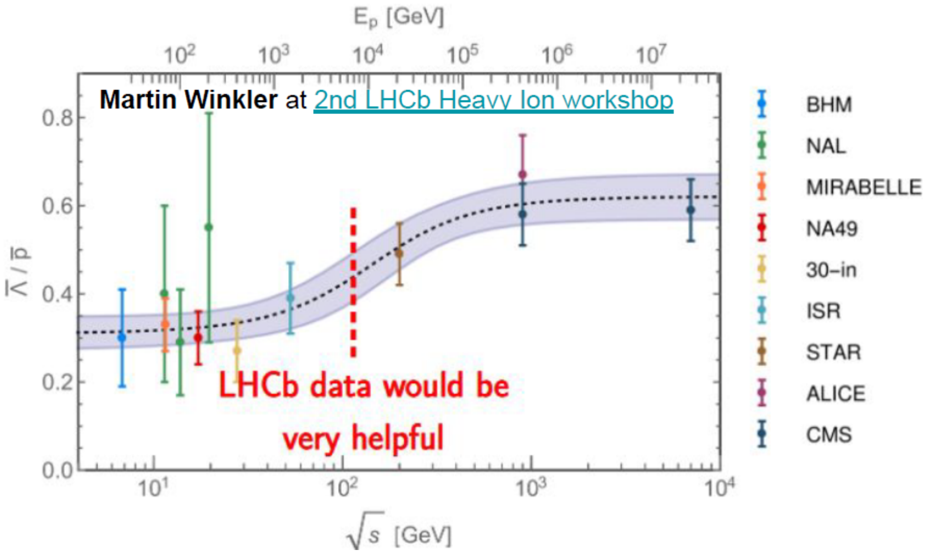
Detached antiproton production

- 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

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

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

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



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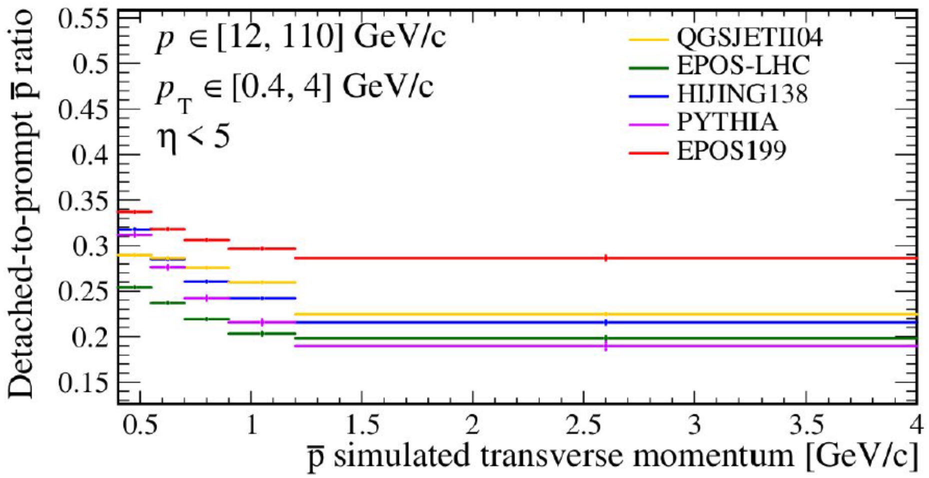

Analysis strategy

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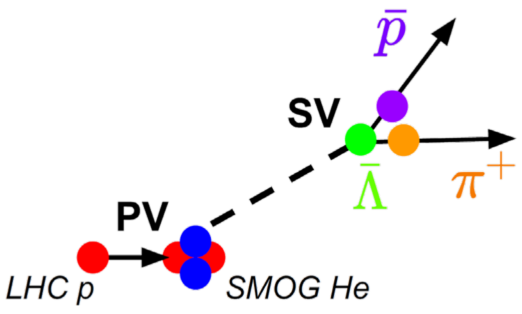
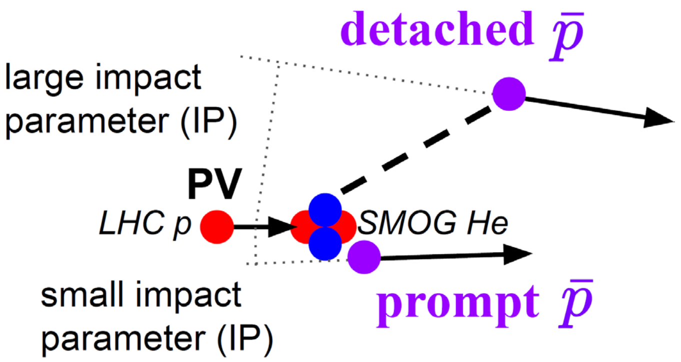
Analysis for secondary-to-primary $\bar{p}$ ratio $\boldsymbol{R = \sigma_{sec}/\sigma_{prim}}$ following **two complementary approaches**:

- **Exclusive approach:** $$R_{\bar{\Lambda}} = \frac{\sigma(p\mathrm{He} \to (\bar{\Lambda}_{\mathrm{prompt}} \to \bar{p}\pi^+)X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}} X)}$$
  - Measure $\boldsymbol{\bar{\Lambda} \longrightarrow \bar{p}\pi^+}$, dominant detached component.
  - Identifying decay exploiting LHCb **excellent mass resolution** (no PID info).



- **Inclusive approach:** $$R_{\bar{H}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{H}X \to \bar{p}X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}} X)}, \bar{H} = \bar{\Lambda}, \bar{\Sigma}, \bar{\Xi}, \bar{\Omega}$$
  - Focused on **all detached components.**
  - Selecting **antiproton with PID information** and distinguishing between prompt and detached $\bar{p}$ via excellent VELO IP resolution.



Exclusive approach

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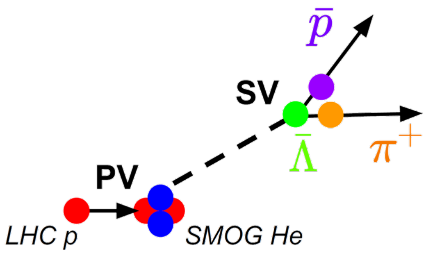
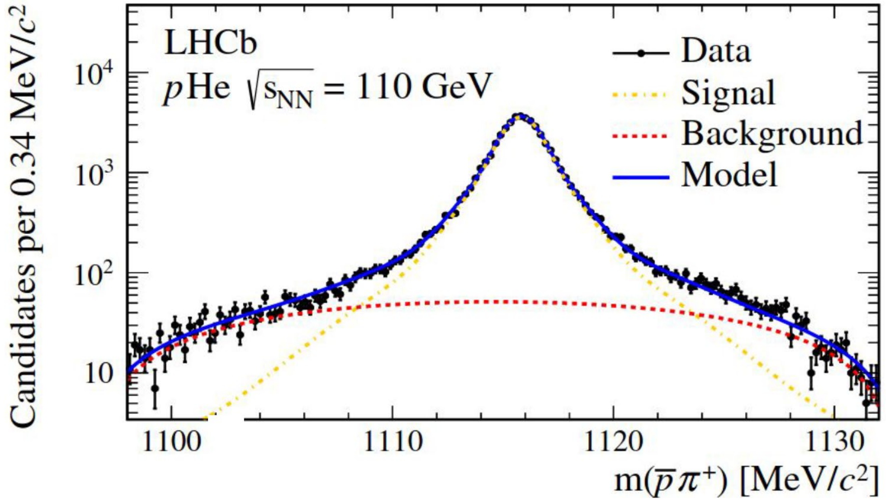
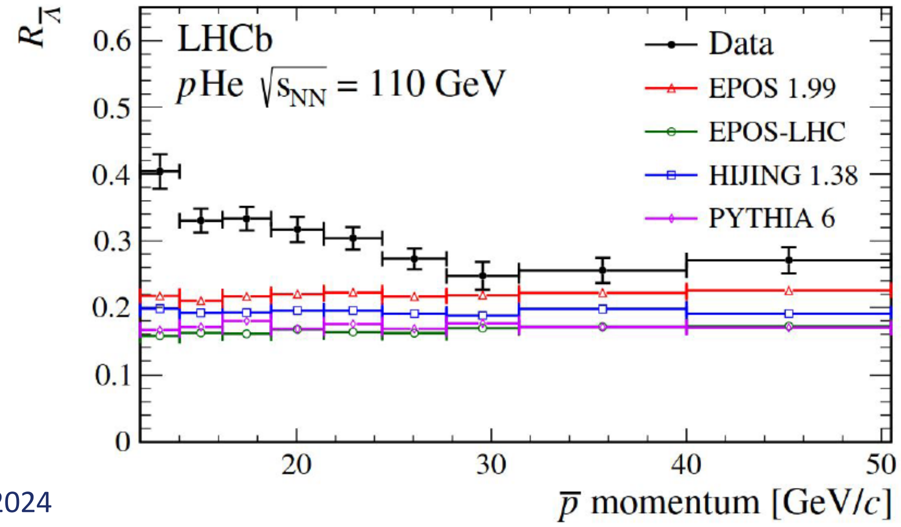
Measure antiprotons from $\bar{\Lambda}_{prompt}$: $$R_{\bar{\Lambda}} = \frac{\sigma(p\mathrm{He} \to (\bar{\Lambda}_{\mathrm{prompt}} \to \bar{p}\pi^+)X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}}\, X)}$$

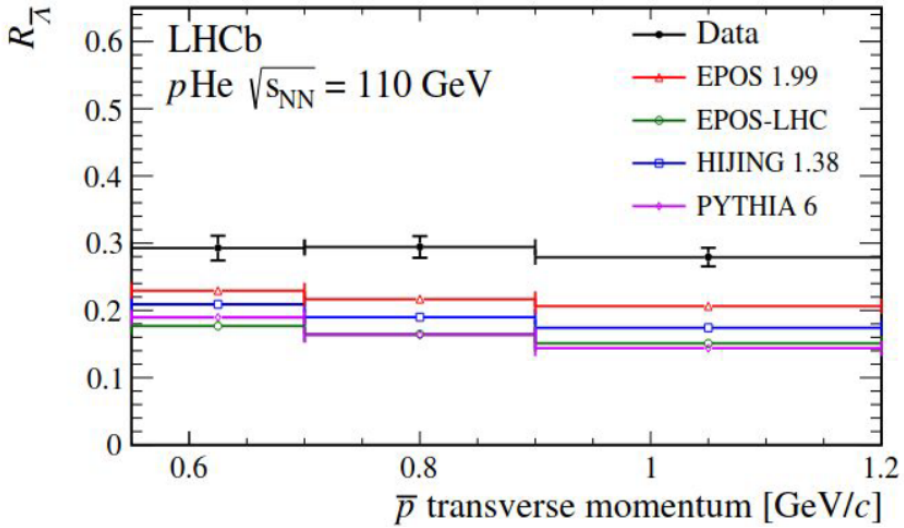
- Event selection via **kinematic description in the Armenteros plot** and **impact parameters to select signal decays**.
- Most systematic uncertainties (luminosity, reco, …) **cancel in the ratio**.





Larger contribution measured wrt all most widely used theoretical models





Inclusive approach

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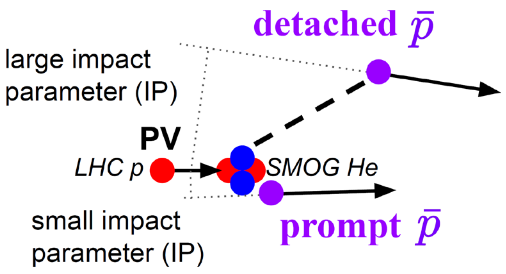
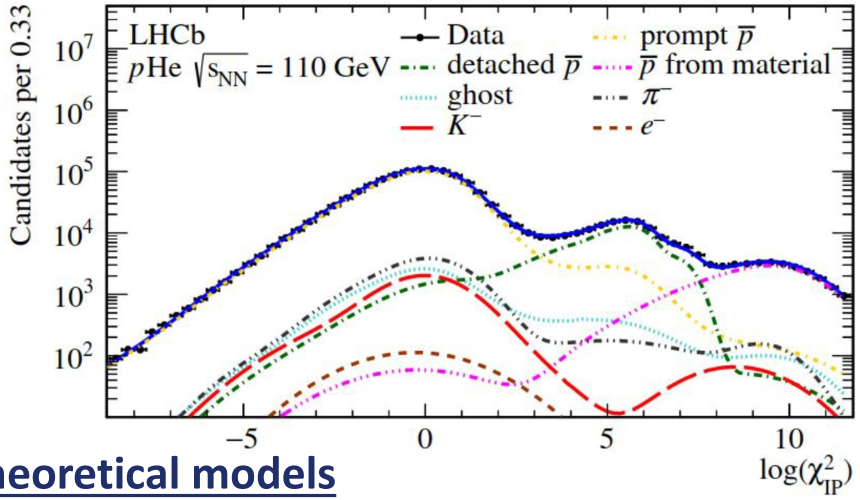
Measure antiprotons from all detached components: $R_{\bar{H}} \equiv \frac{\sigma(p\text{He} \to \bar{H}X \to \bar{p}X)}{\sigma(p\text{He} \to \bar{p}_{\text{prompt}}X)}$, $\bar{H} = \bar{\Lambda}, \bar{\Sigma}, \bar{\Xi}, \bar{\Omega}$

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





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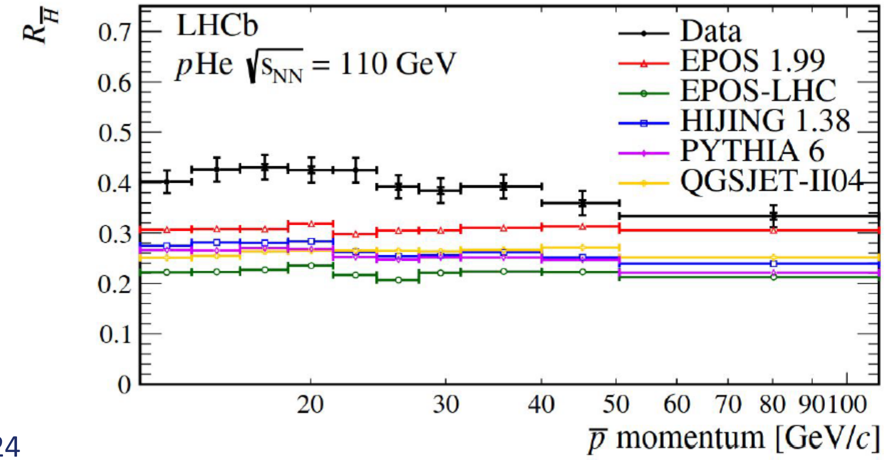

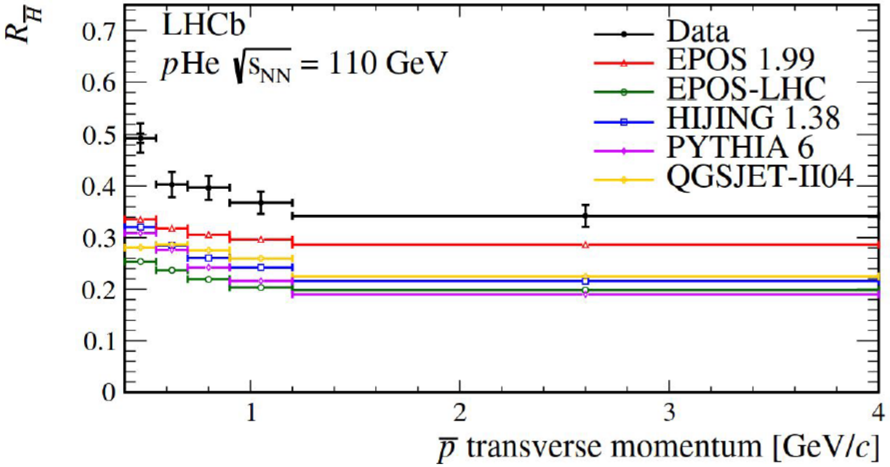

Comparison between the approaches

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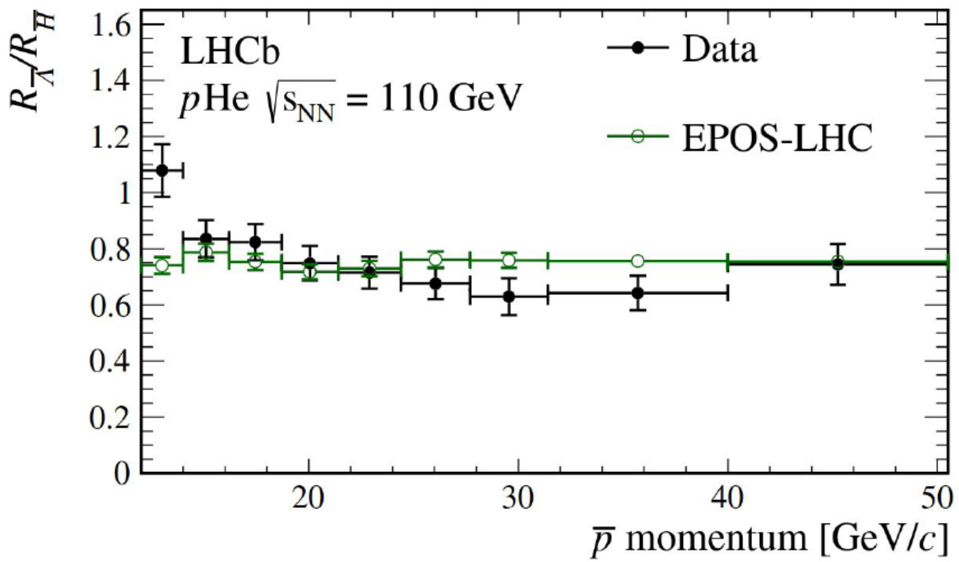
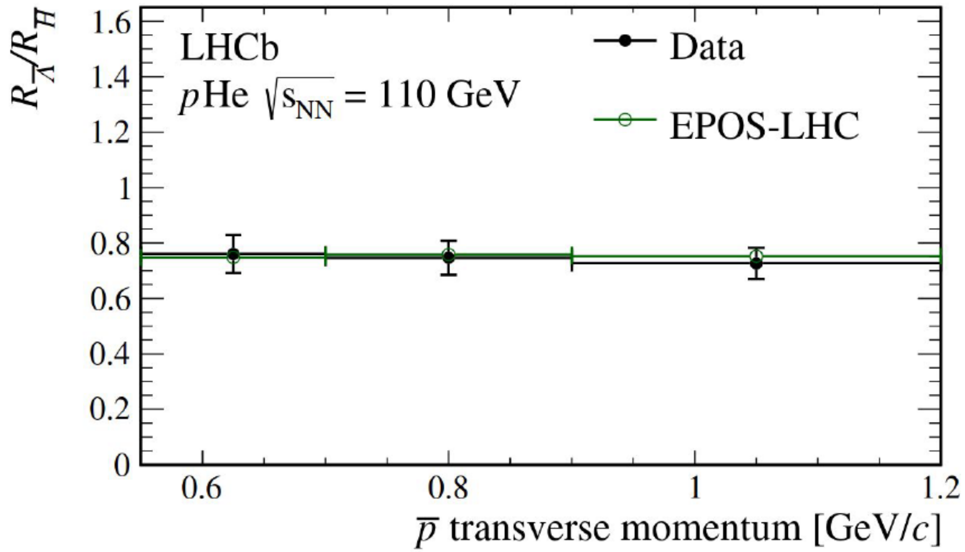
- Ratio of the results is expected to be **predicted more reliably** than the single terms (depends only on the hadronization).
- Results mutually cross-checked since found to be **consistent with EPOS-LHC prediction.**





Extension of Run 2 analysis and prospects for Run 3

Light (anti-)nuclei identification

[Talk by Thomas on monday]

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

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

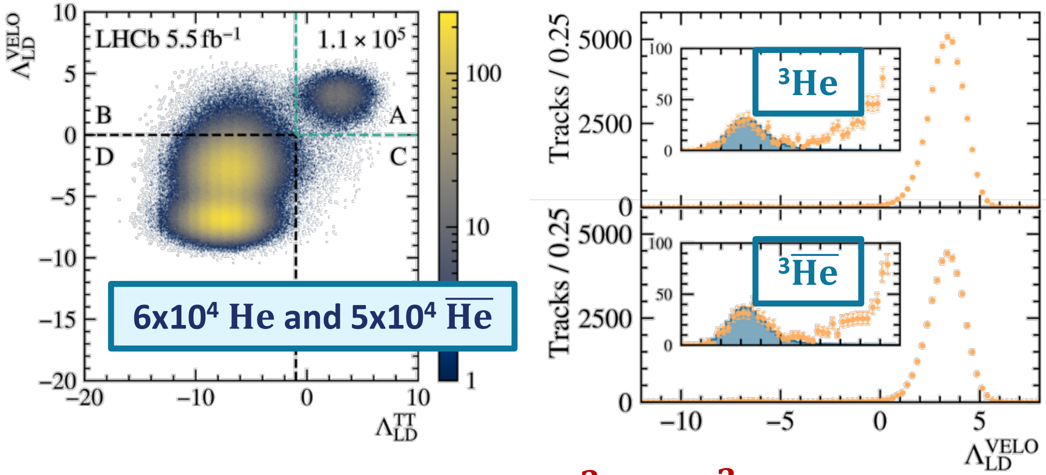
LHCb not designed to identify light (anti-)nuclei

→ **New techniques under development.**

1 [LHCb-DP-2023-002]

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

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



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: $\overline{\Lambda}_b^0 \rightarrow\ ^3\text{He}X$

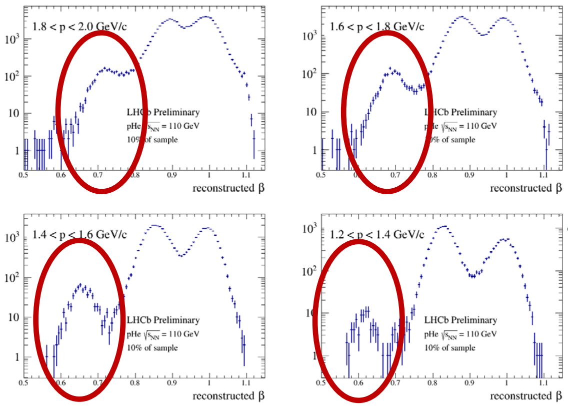
[LHCb-CONF-2024-005]

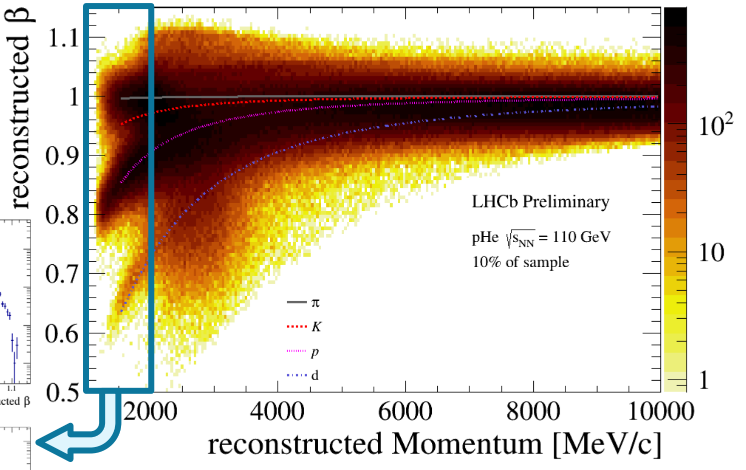
2 [LHCb-FIGURE-2023-017]

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 *p*He ($\sqrt{s_{NN}} = 110$ GeV)



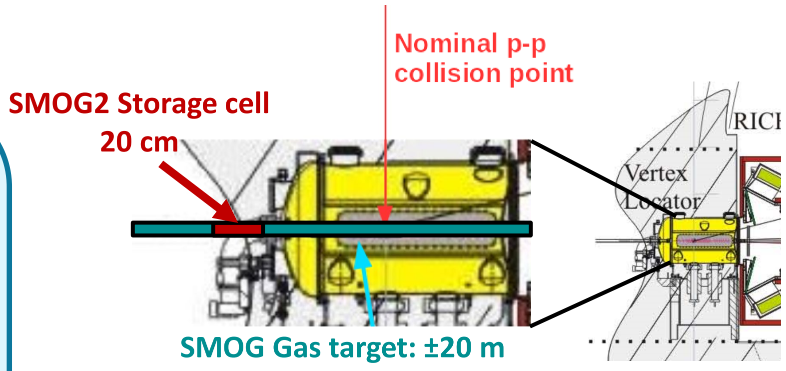


First deuteron candidates observed in *p*He data!

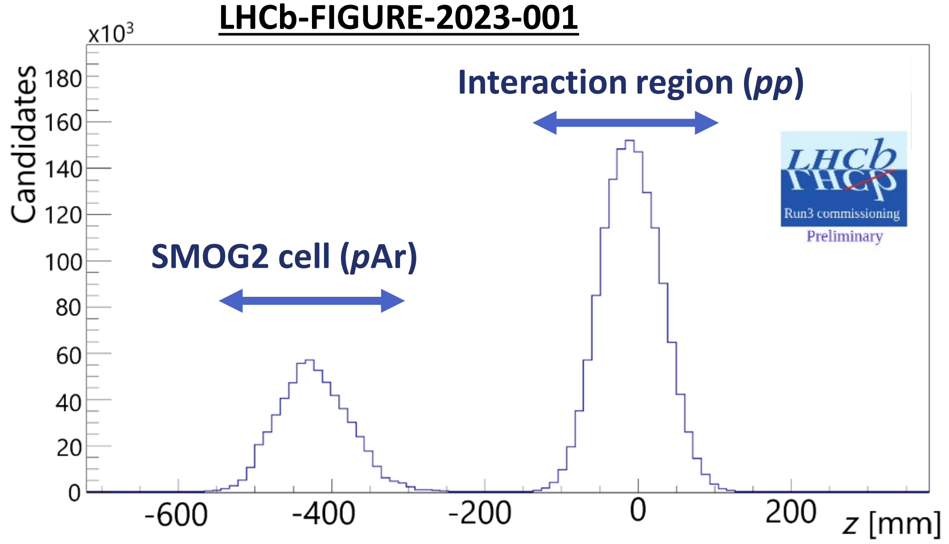
SMOG upgrade: SMOG2

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

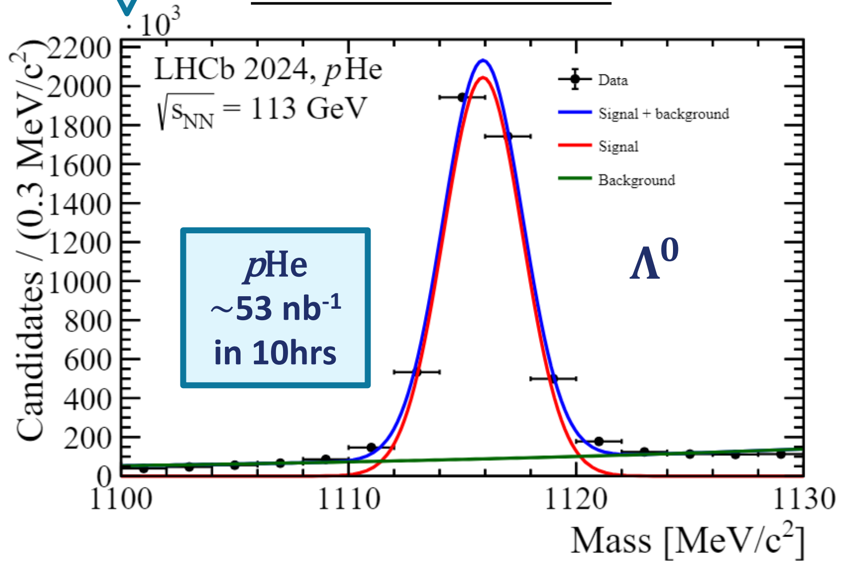
- **x100 average pressure** with same gas flow
- Direct and precise gas pressure and temperature measurement
- **Simultaneous *pp* + fixed-target data taking**
- Wider choice of injectable gases: $\mathbf{H_2}$, $\mathbf{D_2}$, $\mathbf{N_2}$, $\mathbf{O_2}$, Kr, Xe (+He, Ne, Ar)



LHCb-FIGURE-2023-001



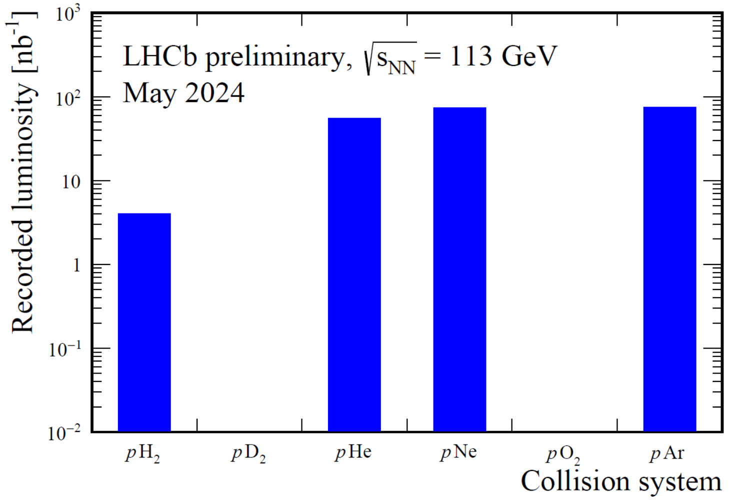
LHCb-FIGURE-2024-005

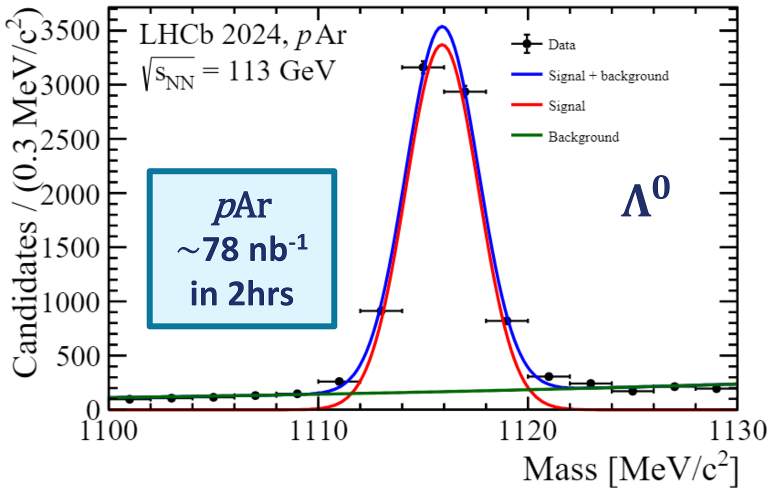


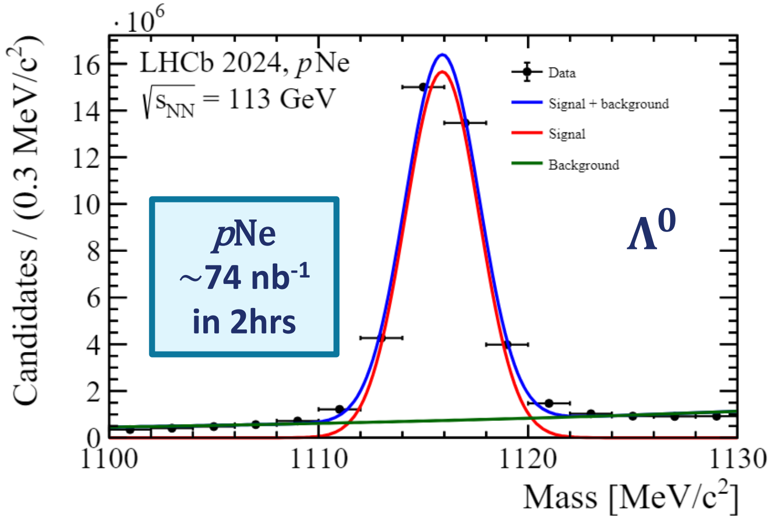
SMOG upgrade: SMOG2

LHCb-FIGURE-2024-005

Data samples collected during April and May 2024 with all available gases!

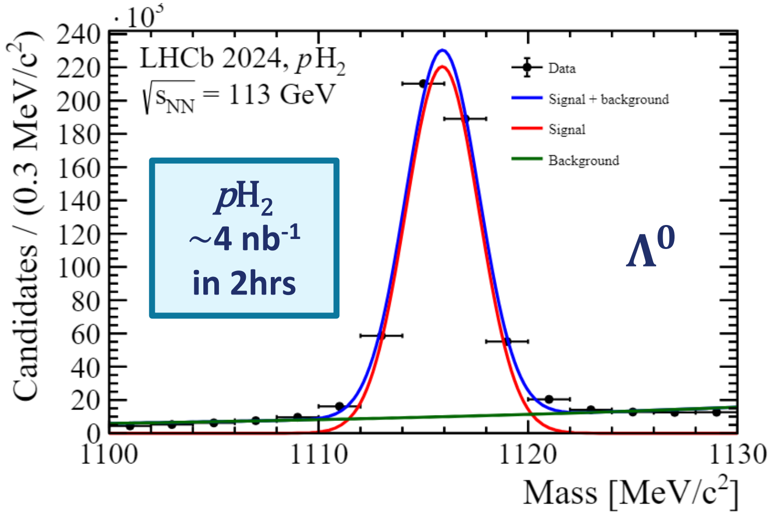






Unique physics opportunities never explored at LHC:

- **Charmonium, bottomonia and exotica production** from H_2 to Kr.
- **Flow measurements** at low energy over wide pseudorapidity range.
- **Ultra-peripheral collisions** in pA and PbA.
- pH_2, pHe, pD_2, pO_2 and OH_2 collisions to extend **modelling of productions of CR interest.**



LHCb cosmic programme

Many open possibilities to be explored with LHCb fixed-target programme, both with SMOG (★) and SMOG2 (★) data samples:

★2) $p\,p\ (H_2)\ \to \bar{p}$ to test scaling violation in forward hemisphere

★3) $p\,d\ \to \bar{p}$ to test isospin effects

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

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

Martin Winkler at 2nd LHCb Heavy Ion workshop

+

★ H_2, O_2, N_2 for atmospheric CRs physics

- 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: pO_2 and OH_2 ($\eta\sim7.6$ in the pO system) collisions to study **air showers**

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 performed two antiproton production measurements in *p*He collisions, crucial input to models of antimatter production in space:
  - The **measurement at fixed-target of $\boldsymbol{\sigma(p\mathrm{He} \longrightarrow \overline{p}X)}$** with a 6.5 TeV proton beam helped to improve the secondary $\bar{p}$ flux predictions.
  - Detached-to-prompt production shows a large underestimation of all theoretical models for antihyperon decay contributions.
- 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

Luminosity measurement in SMOG data samples

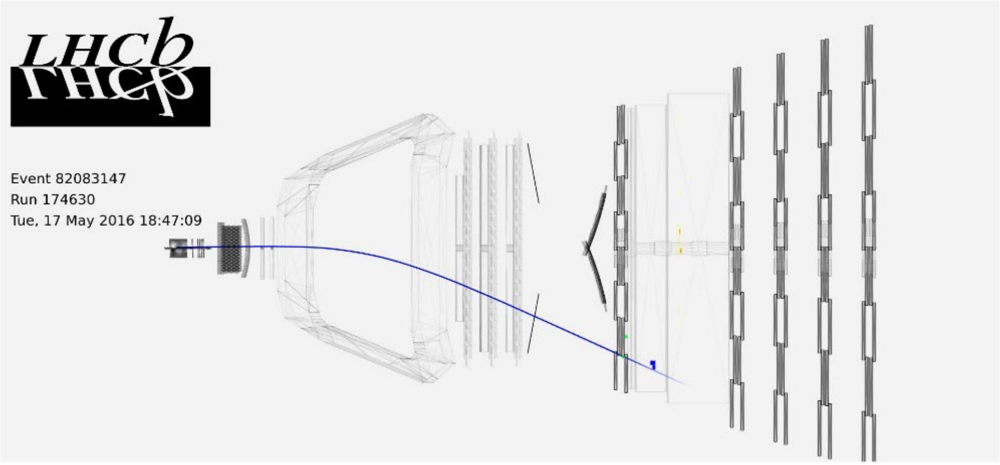
PRL 121 (2018) 222001

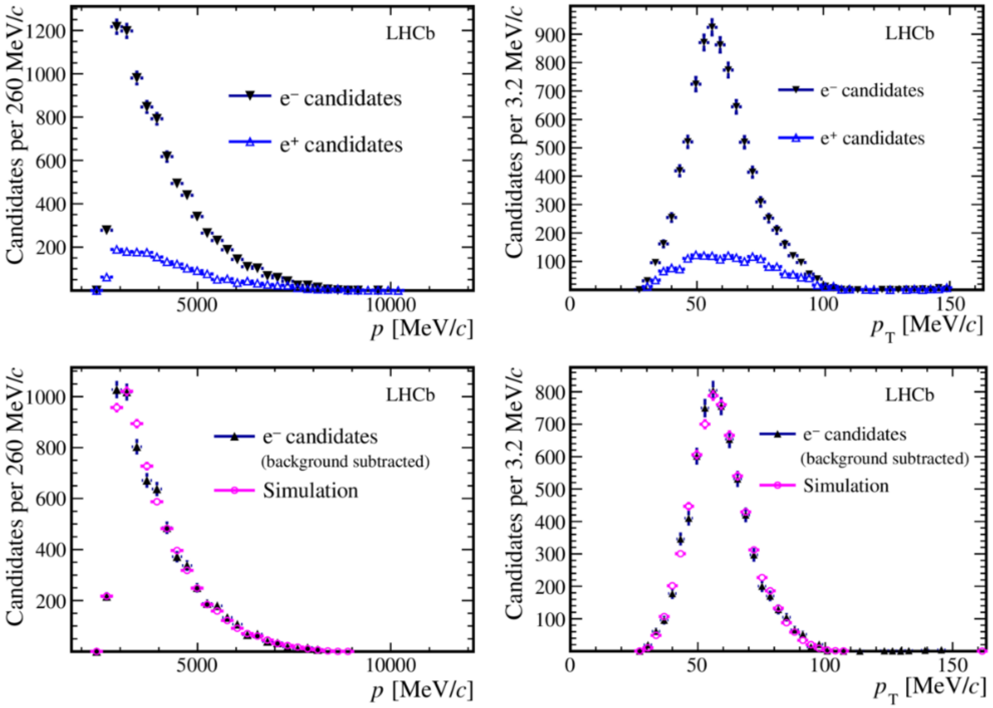
SMOG is not equipped with precise gauges for the gas pressure:

→ 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!





Results

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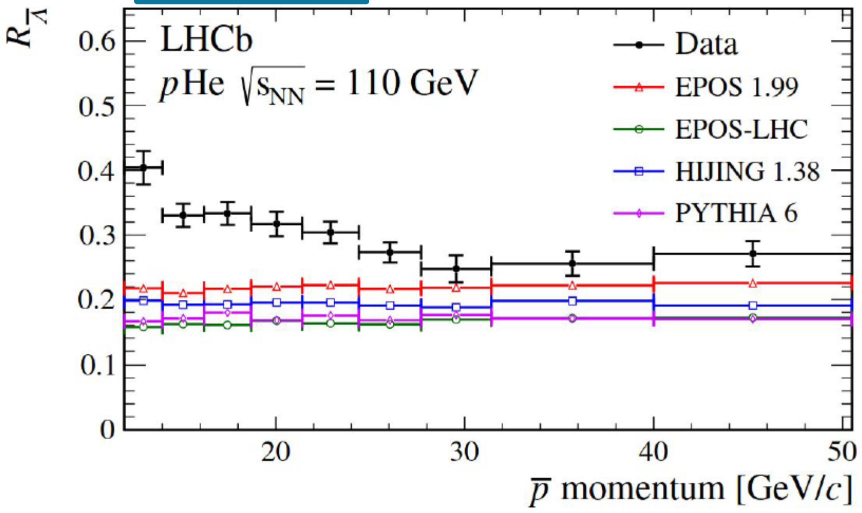
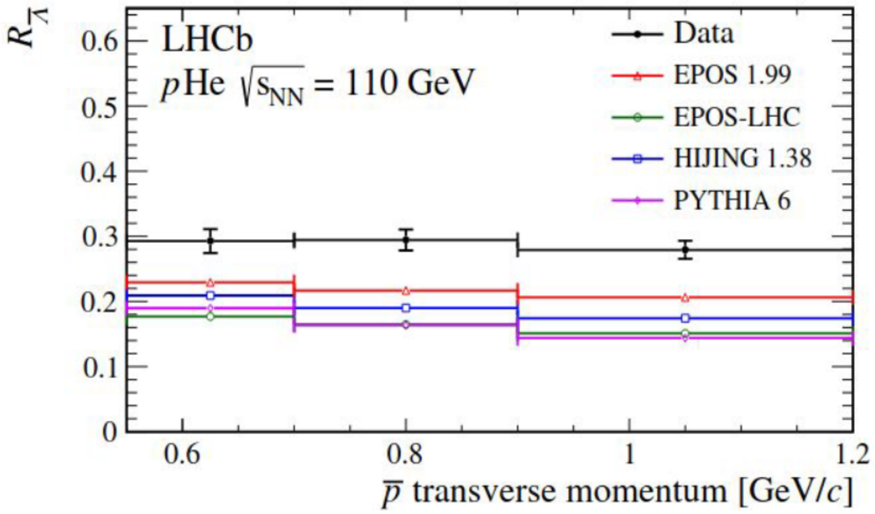
Larger contribution measured wrt all most widely used theoretical models

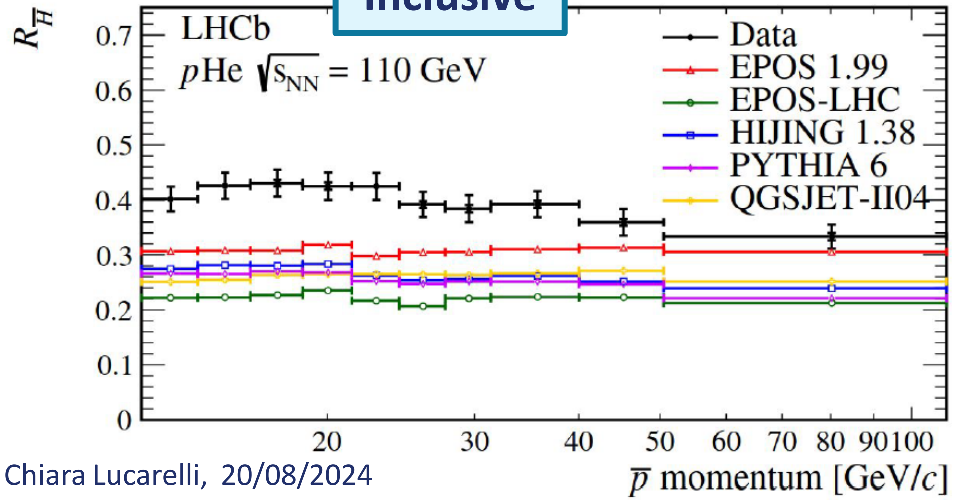
Exclusive

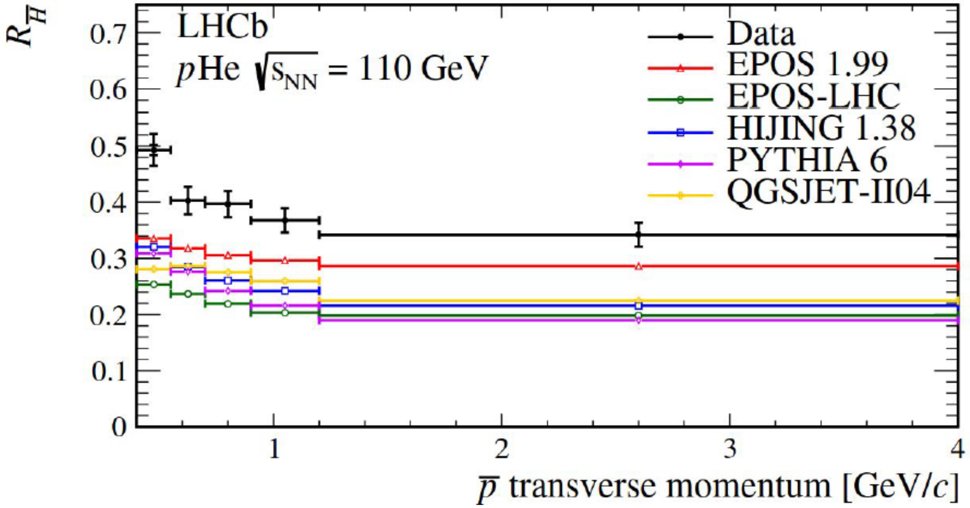




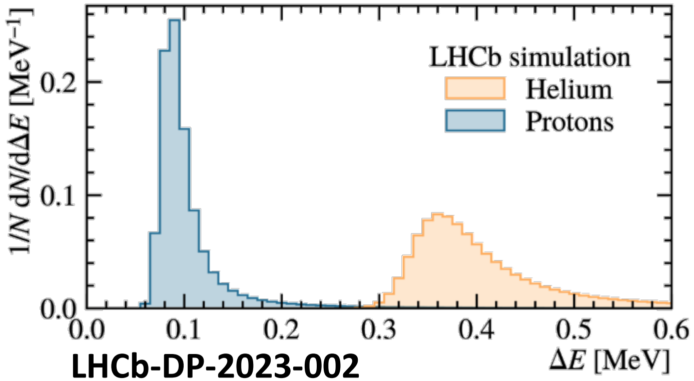
EPOS 1.99: Nuclear Physics B.2009.09.017
EPOS-LHC: Phys. Rev. C 92,034906
HIJING 1.38: Computer Physics Communications 83 (1994) 307-331
PYTHIA 6: JHEP 05 (2006) 026

Inclusive





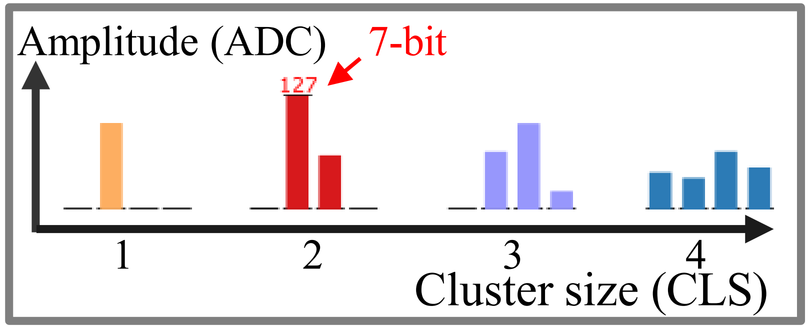
(Anti-)Helium identification



LHCb-DP-2023-002

Bethe-Bloch: Z=2 particles deposits ~4 times the energy of Z=1 particles

→ **He: higher ADC counts and wider cluster size**



Define Likelihood discriminators based on cluster size and ADC counts:

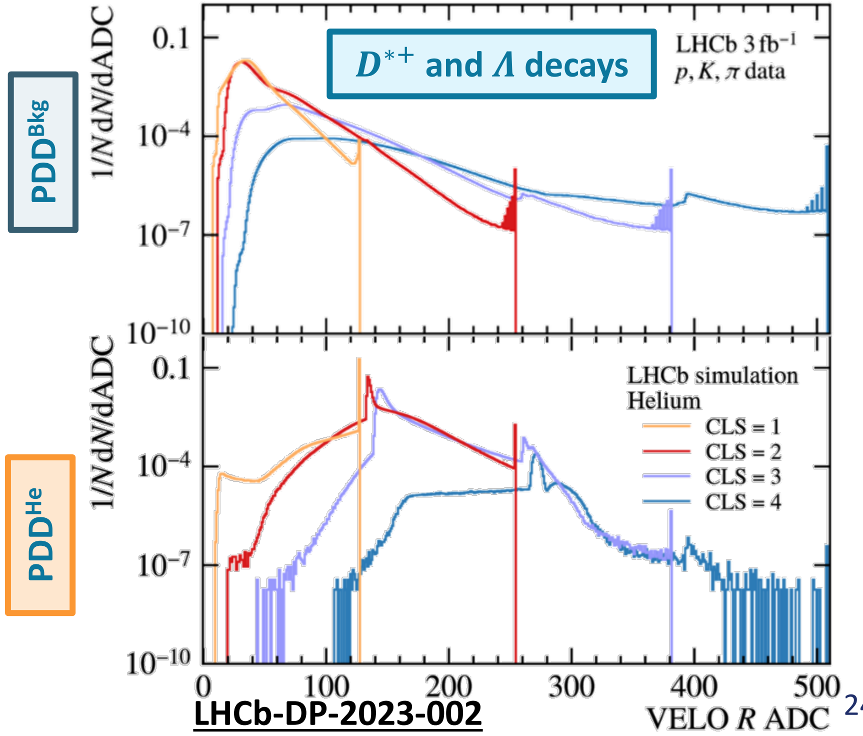
$$\mathcal{L}^X = \left(\prod_{i=1}^{n} \mathrm{PDD}_i^X\right)^{1/n} , X = \{\mathrm{He}, \mathrm{Bkg}\}$$

$$\Lambda_{\mathrm{LD}} = \log\mathcal{L}^{\mathrm{He}} - \log\mathcal{L}^{\mathrm{Bkg}}$$

One discriminator for each subdetector:

- $\Lambda_{\mathrm{LD}}^{\mathrm{VELO}}$
- $\Lambda_{\mathrm{LD}}^{\mathrm{TT}}$
- $\Lambda_{\mathrm{LD}}^{\mathrm{IT}}$

Probability Density Distributions (PDD)



LHCb-DP-2023-002

Prompt (anti-)Helium at LHCb

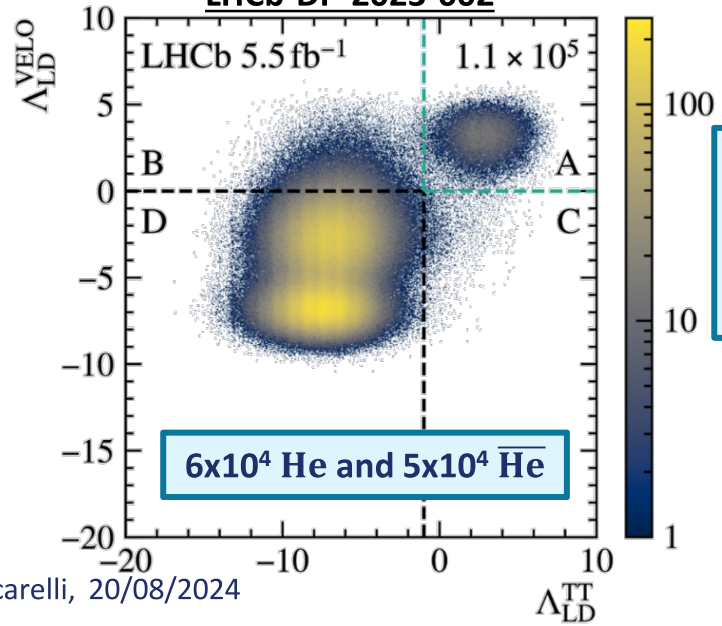
Selection:

Run2 data: ***pp* collisions at $\sqrt{s} = 13$ TeV**, $\mathcal{L}_{int}$=5.5 fb^{-1}

- All trigger lines
- Prompt tracks (compatible with PV) passing through VELO, TT, and T1->T3
- Good quality tracks ($\chi^2_{track} < 3$, $N_{clusters\ X\ Si\ station}$ >2)
- $p/|Z|$>2.5 GV and $p_T/|Z|$>0.3 GV
- Λ_{LD}^{VELO}>0 and Λ_{LD}^{TT}>-1; Λ_{LD}^{IT}>-1 for IT tracks
- Rejection of photon conversions

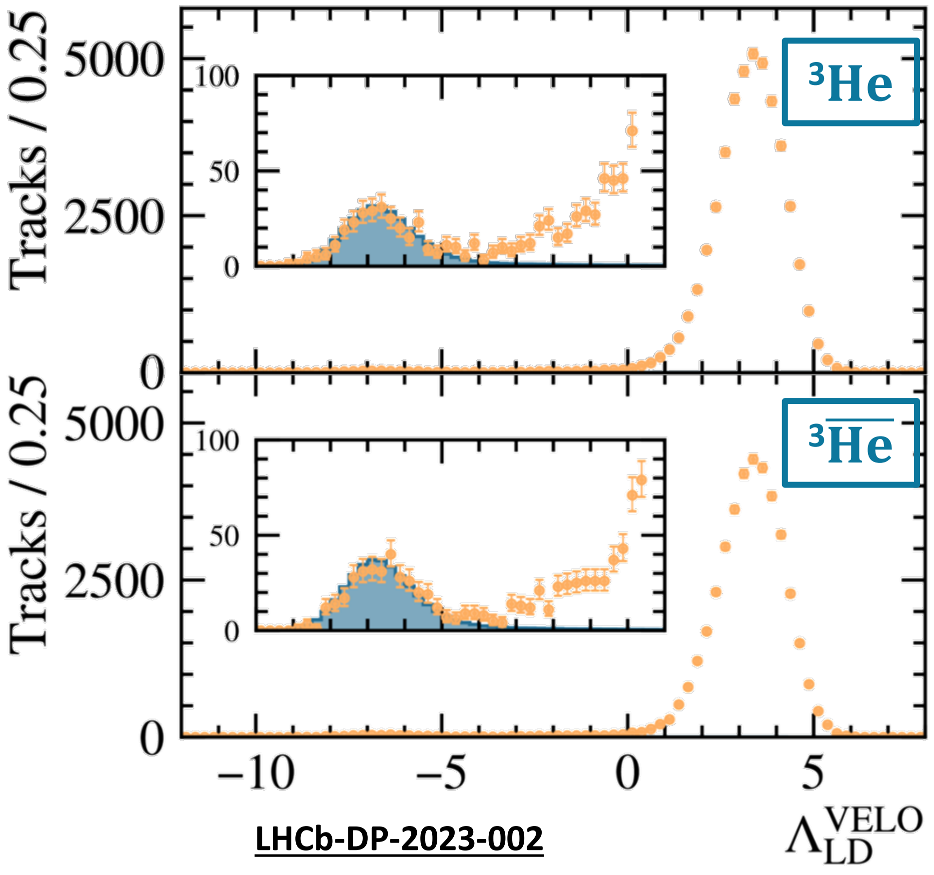
First (anti-)Helium candidates observed in *pp* in LHCb data!

LHCb-DP-2023-002



Performance:

- **MisID** probability: $\mathcal{O}(10^{-12})$
- **Signal efficiency**: $\sim 50\%$



LHCb-DP-2023-002

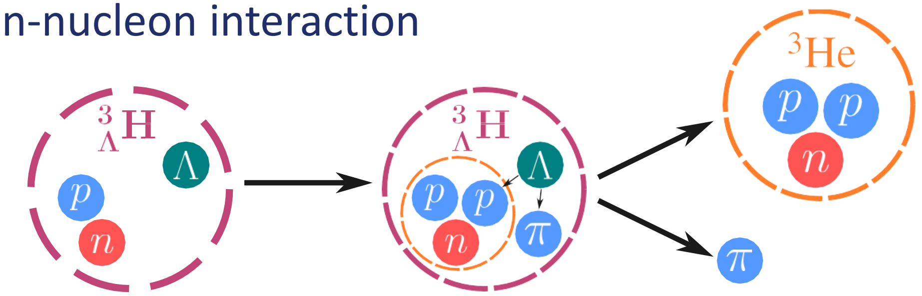
Application: Hypertriton

- Hypertriton life-time and binding energy gives access to hyperon-nucleon interaction

  → **Constrains on maximum mass of neutron stars**

Search for 2-body decay into He:

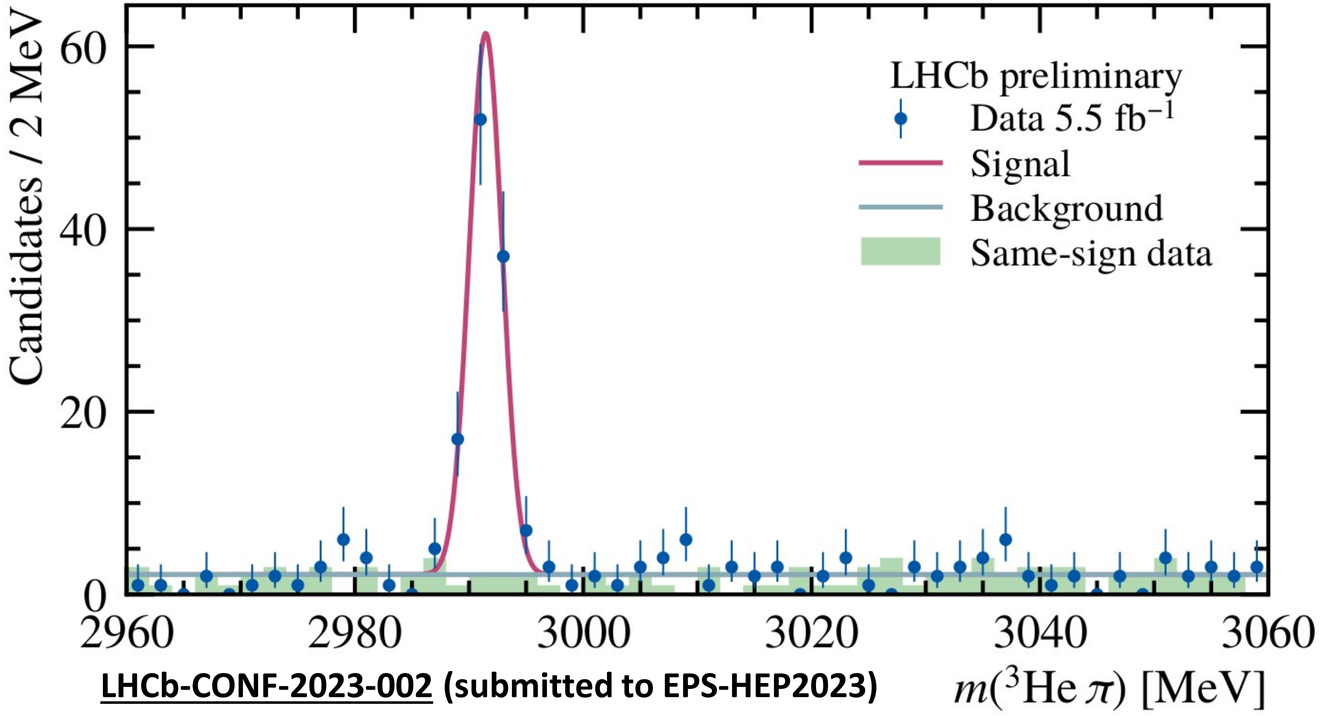
$${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He}\,\pi^{-} + cc$$



Results:

(Run2 *pp* collisions at $\sqrt{s} = 13$ TeV)

- **Yields**:
  - 61 ± 8 Hypertriton
  - 46 ± 7 anti-Hypertriton
- Statistical **mass precision**: 0.16 MeV

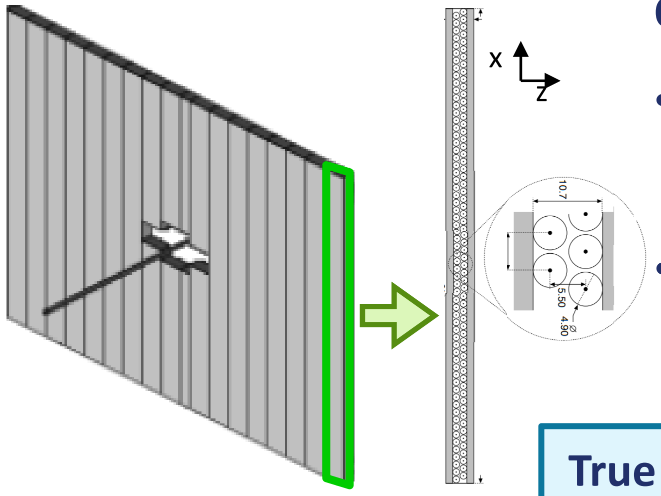


LHCb-CONF-2023-002 (submitted to EPS-HEP2023)

Under investigation:

- Systematic corrections on mass scale:
  - Charge-sign dependent energy-loss
  - Tracking corrections for Z=2
- Efficiency and acceptance corrections

Time-of-flight measurement at LHCb



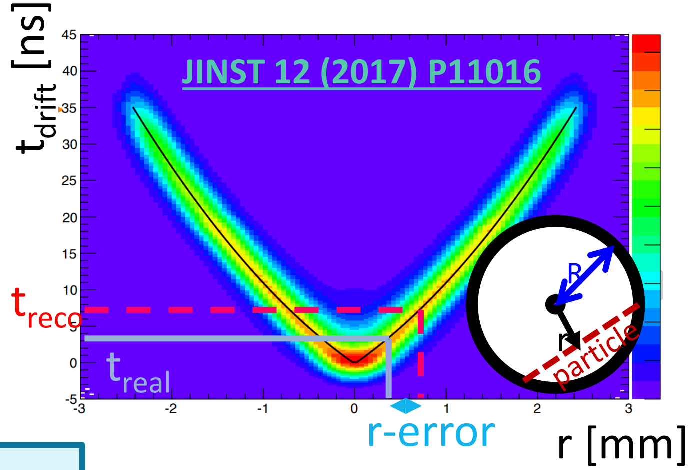
OT (Outer Tracker): largest area, straw-tube drift chambers

- 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

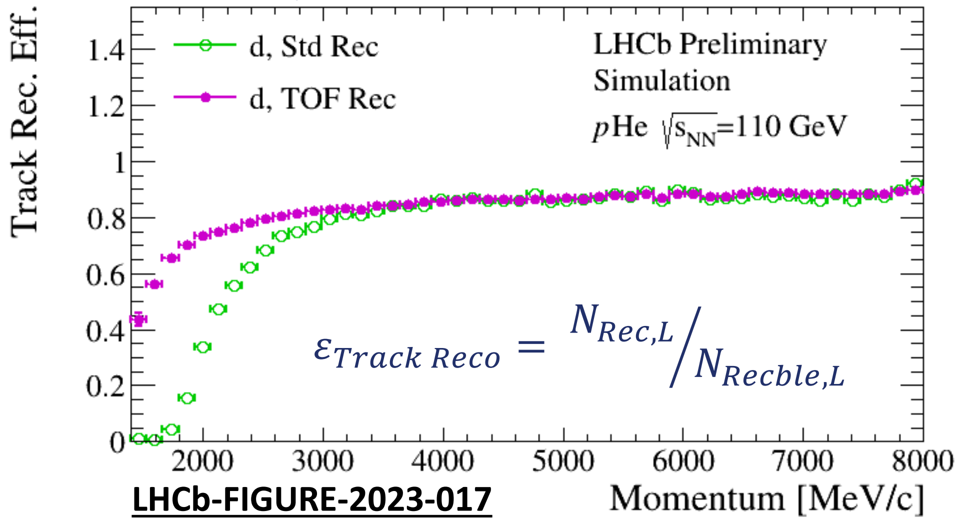
Standard LHCb reconstruction (β=1) inefficient for light nuclei
→ Modified pattern recognition algorithm

Correct hits position to recover reconstruction efficiency

- Loop on β ∈ $\left[1/\sqrt{1 + M^2_{max}/p^2}\,, 1\right]$
- 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)

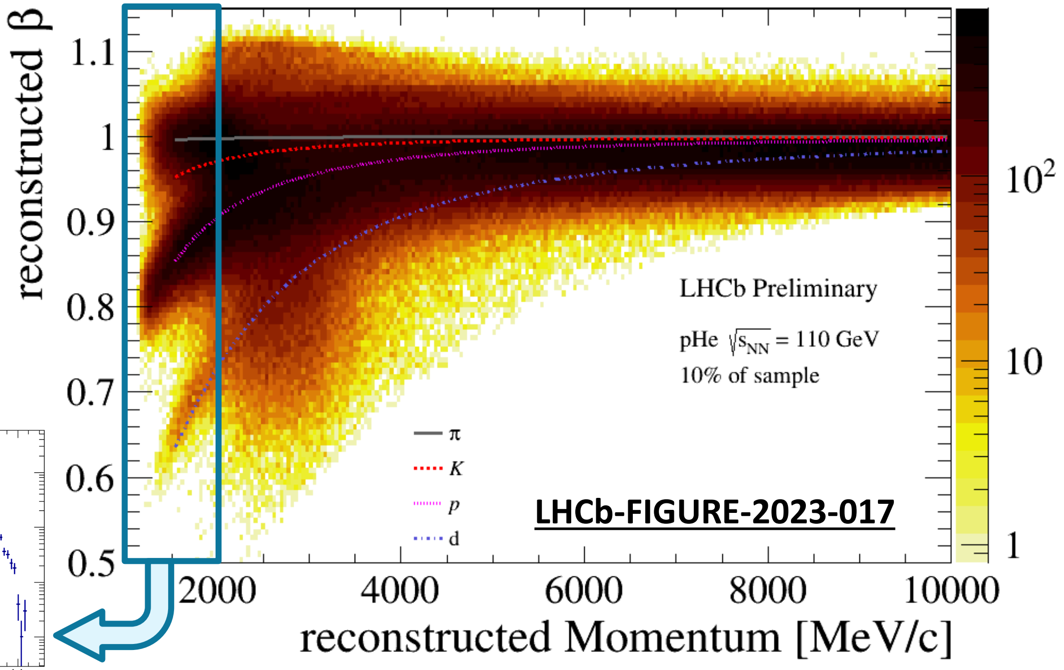


LHCb-FIGURE-2023-017

(Anti-)deuteron identification

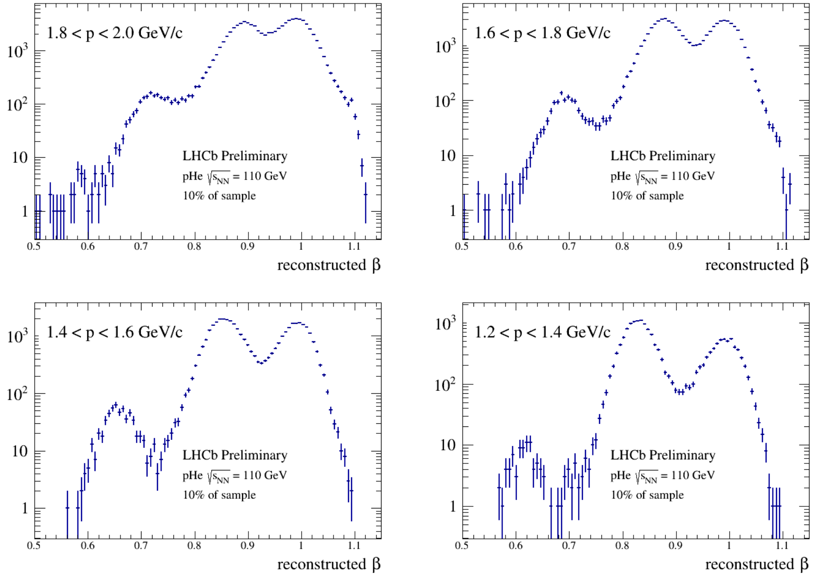
Reconstructed tracks refitted to determine β → Iterative procedure rerunning Kalman fit with different β hypotheses

1. At least 15 OT hits required on each track
2. Change β following χ^2_{fit} decrease (gradient descent) without outliers removal → $\chi^2_{\text{fit}} = \chi^2_{\text{track}} + \left[(t_{M1} - \langle M1 \rangle)/\sigma_{M1}\right]^2$
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

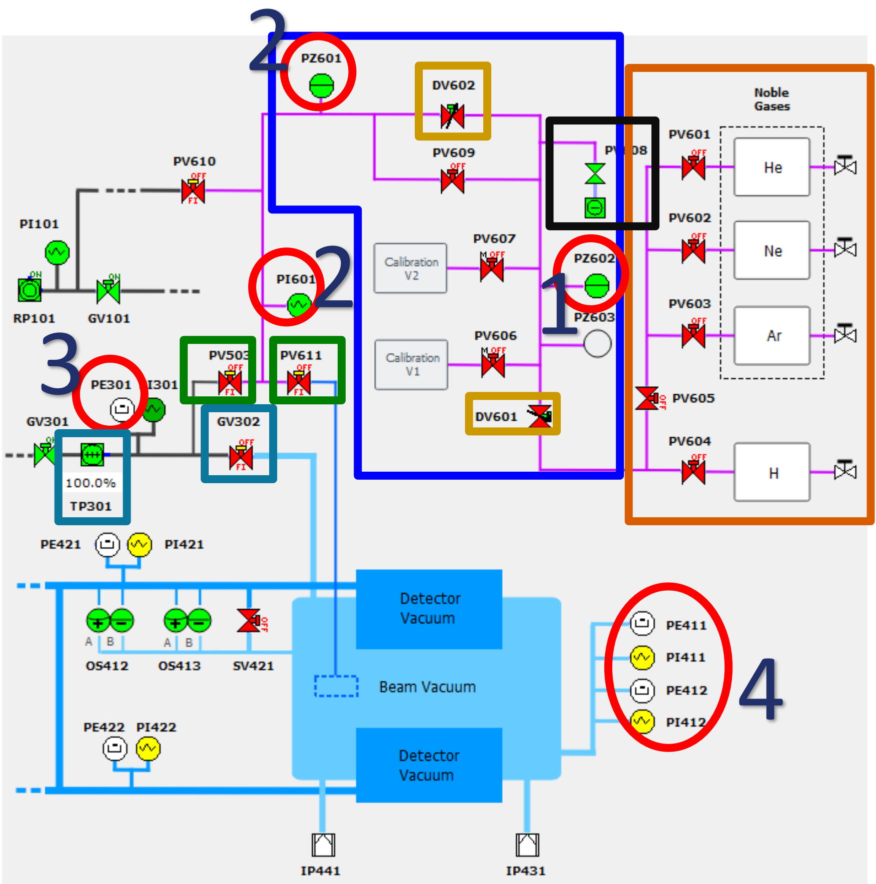
Under investigation:

- 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.