Light-nuclei identification in LHCb for cosmic rays physics

Chiara Lucarelli
on behalf of the LHCb collaboration

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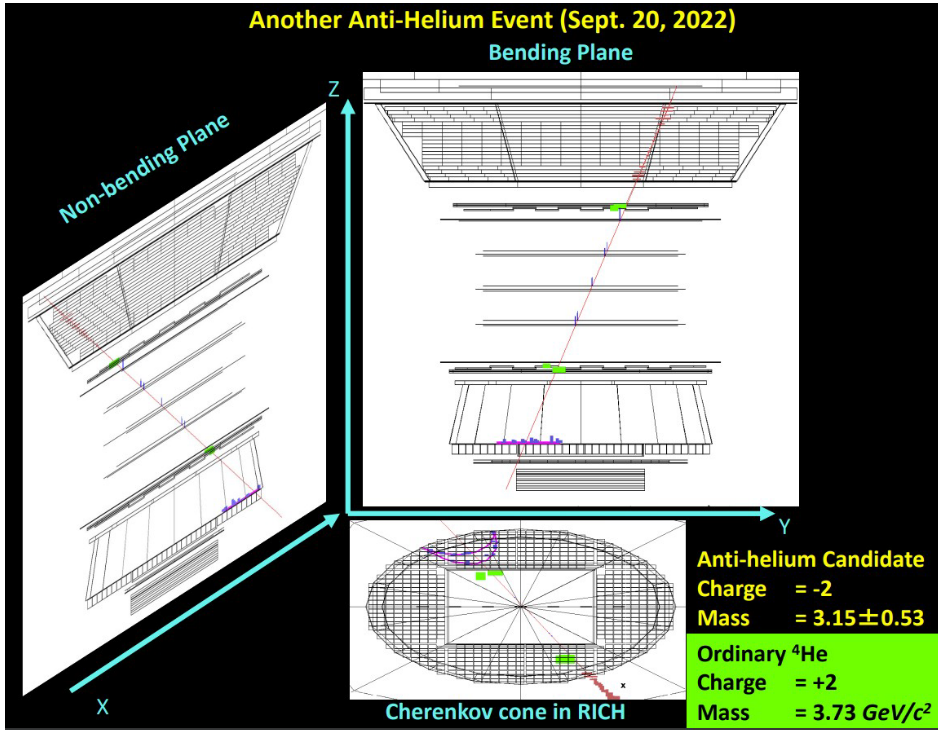
Light anti-nuclei in space

Antimatter fraction in Cosmic Rays is a sensitive indirect probe for Dark Matter or exotic sources.

- AMS-02 observed anti-Helium and anti-Deuteron candidates in CRs
- $\mathcal{O}(10)\ \overline{\mathrm{He}}$ candidates, $\mathcal{O}(1)\ \bar{\mathrm{d}}$ candidates, expected $\bar{\mathrm{d}}/\ {}^{3}\overline{\mathrm{He}}$ around 10^3

→ Needed **knowledge of production processes.**



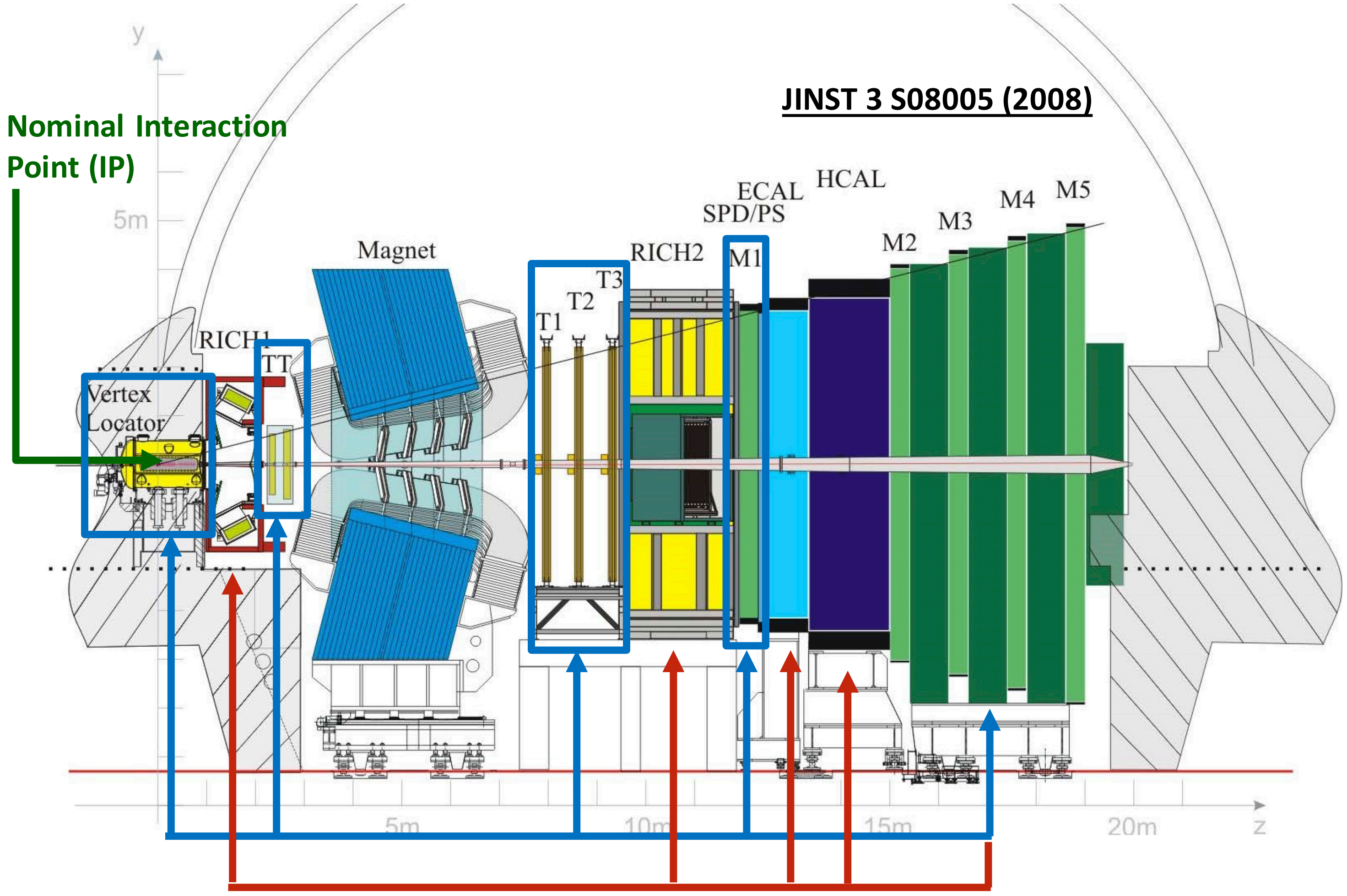
CERN Colloquium 08/06/23

Accelerator experiments can complement CRs investigations

- ALICE measures d and He production in *pp* 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)

The LHCb experiment

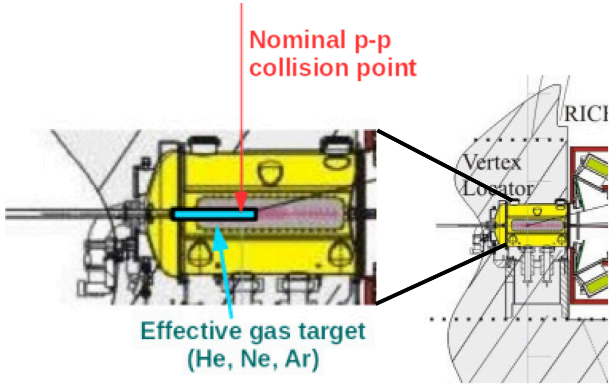


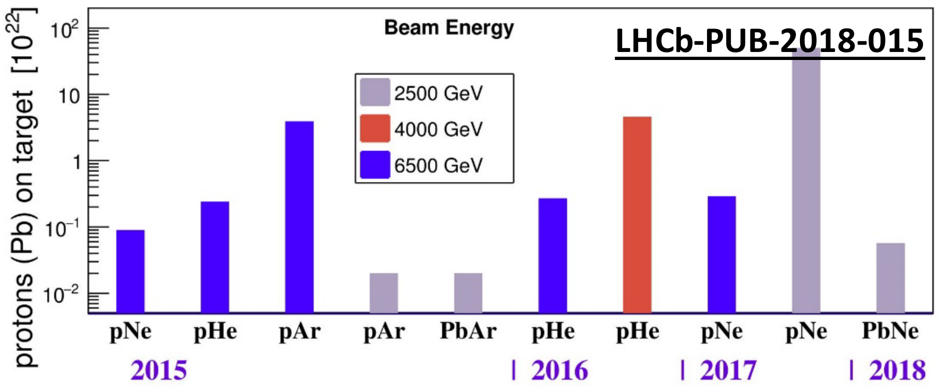
The LHCb is a general-purpose experiment in the forward direction:

- **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 K, π 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 programme

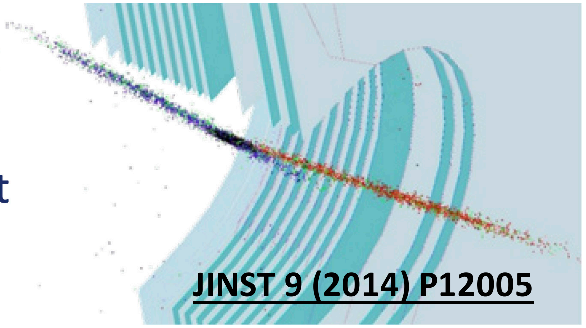
- The *System for Measuring Overlap with Gas* (**SMOG**) can inject gas in LHC beam pipe around (±20 m) the LHCb IP.
- Originally conceived for precise luminosity measurements through **Beam-Gas Imaging**.
- For machine safety, **only noble gases** with a maximum pressure of **2x10^{-7} mbar** (x100 nominal LHC vacuum) can be injected → Luminosity: $\mathcal{L}\sim\mathcal{O}\left(10^{29}\ cm^{-2}s^{-1}\right)$.





Since 2015, exploited for LHCb fixed-target physics programme

→ Collected physics samples with different targets and different centre of mass energies.

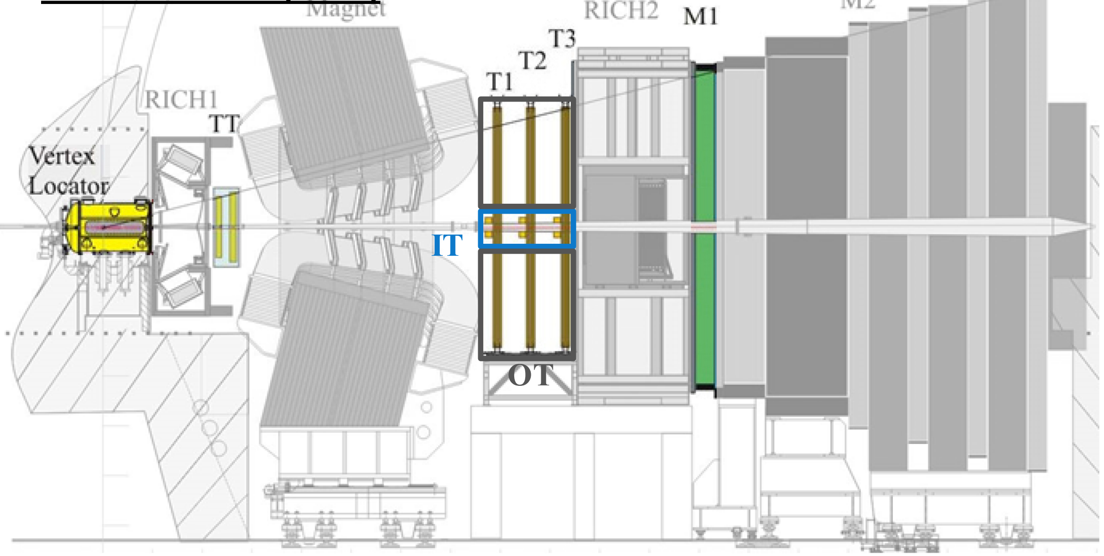


Unique opportunities at the LHC:

- Collisions with **targets of mass number A intermediate** between p and Pb → **Reproduce CR interactions (*pp*, *p*He)**
- **Energy range** $\sqrt{s_{NN}} \in [30, 115]$ GeV for beam energy in $[0.45, 7]$ TeV → **Unexplored gap** between SpS and LHC/RHIC.

Light nuclei identification technique

JINST 3 S08005 (2008)

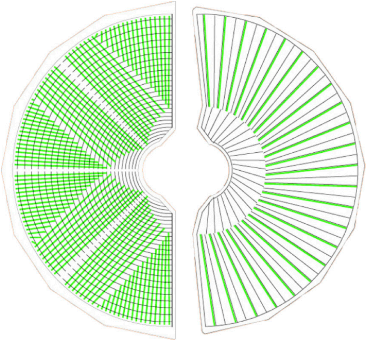


LHCb detector not designed to identify light (anti-)nuclei

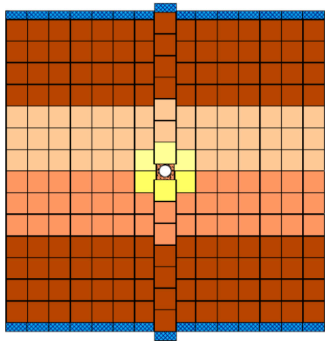
Use information from the tracking system

1 **Ionisation losses** in silicon sensors: **Z^2 dependence** in Bethe-Bloch

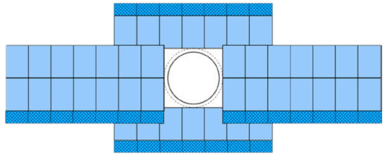
→ dE/dx in VELO, TT, IT to **identify He**



VELO: 2 x 21 layers



TT: 4 layers

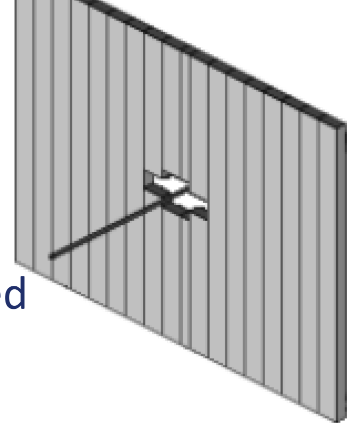


IT: 12 layers

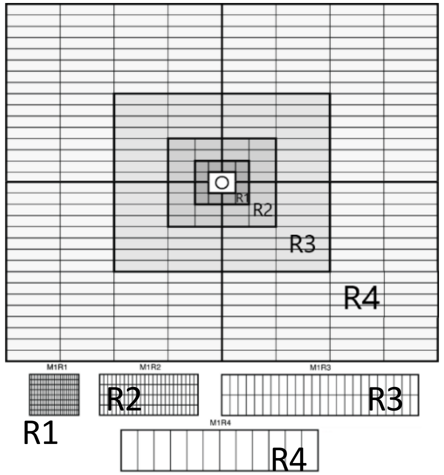
2 Light nuclei slower than c: **M dependence** of particle speed

→ **Time-of-flight** in OT and M1 to **identify d, distinguish ^{3}He and ^{4}He**

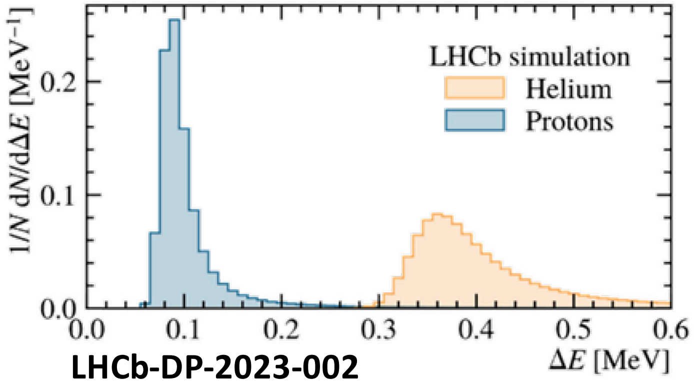
OT: 2.4 ns σ_t



M1: 3-4 ns σ_t



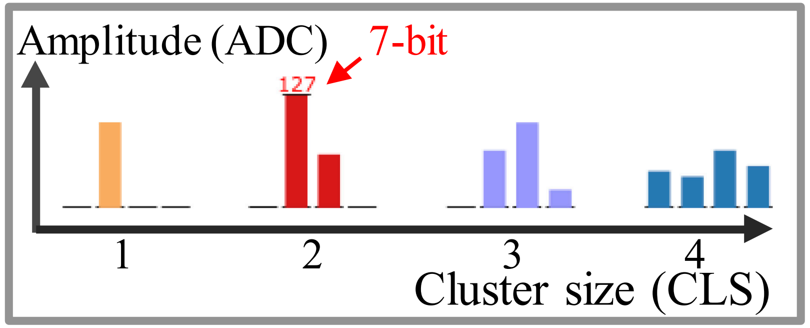
(Anti-)Helium identification



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:

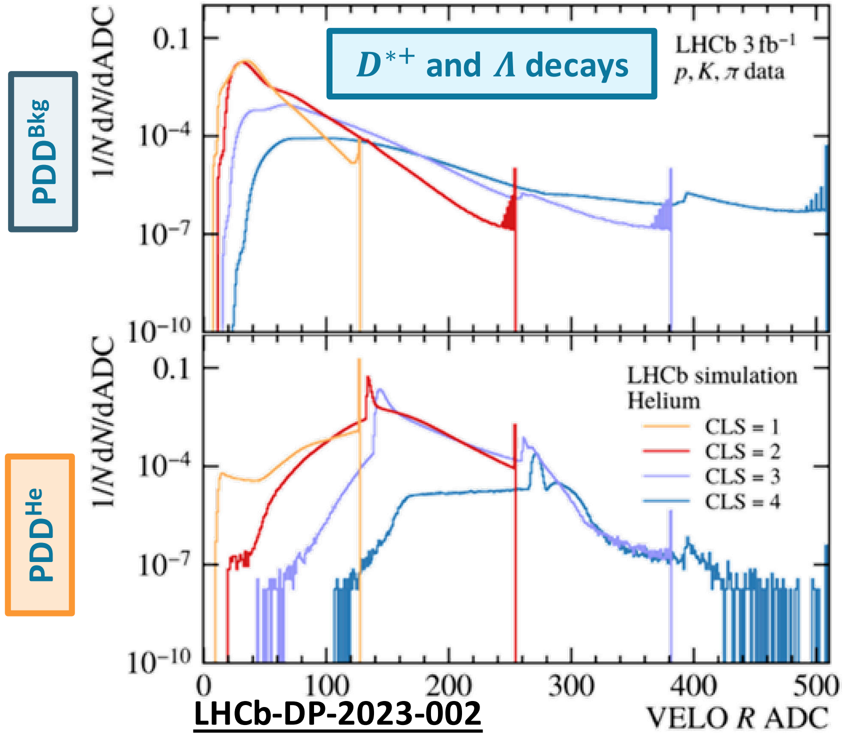
$$\mathcal{L}^X = \left(\prod_{i=1}^{n} \mathrm{PDD}_i^X\right)^{1/n}, X = \{\mathrm{He}, \mathrm{Bkg}\}$$

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

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

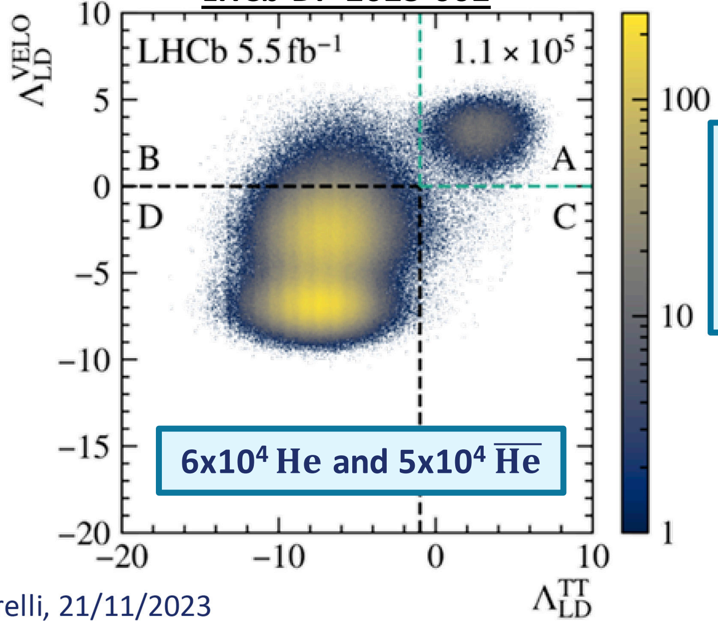
Selection:

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

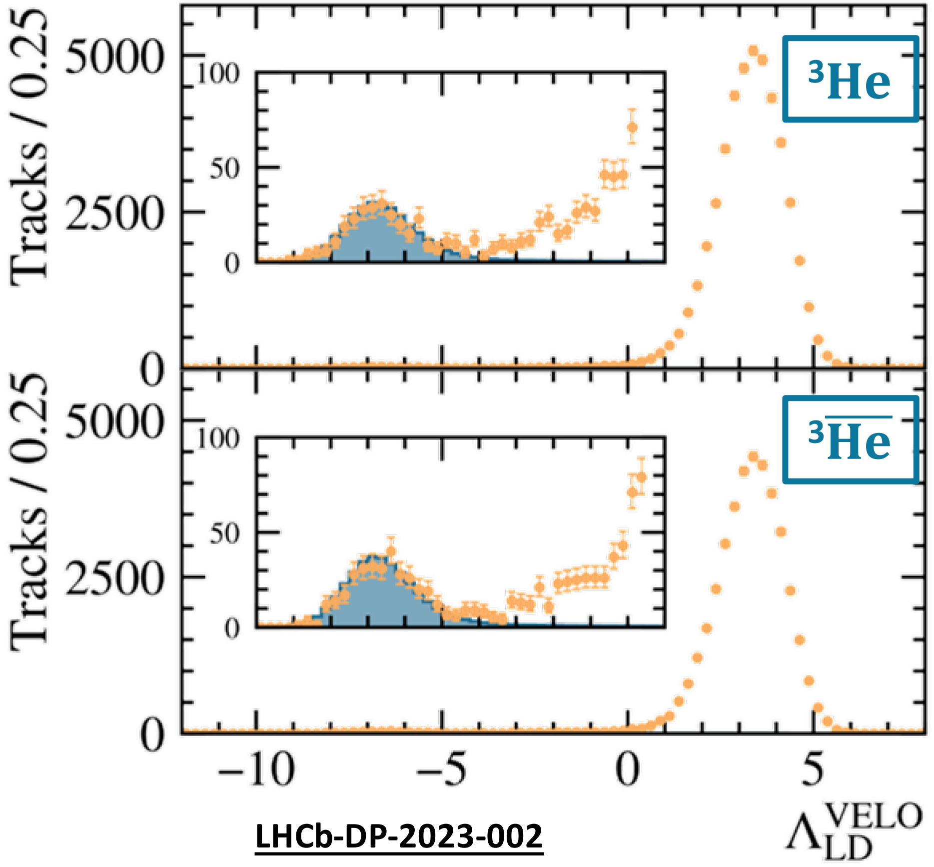
First (anti-)Helium candidates observed in *pp* in LHCb data!

LHCb-DP-2023-002



Performance:

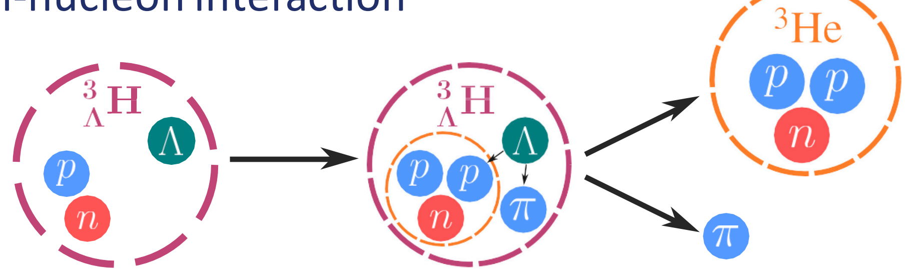
- **MisID** probability: $\mathcal{O}(10^{-12})$
- **Signal efficiency**: ~ 50%



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:

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

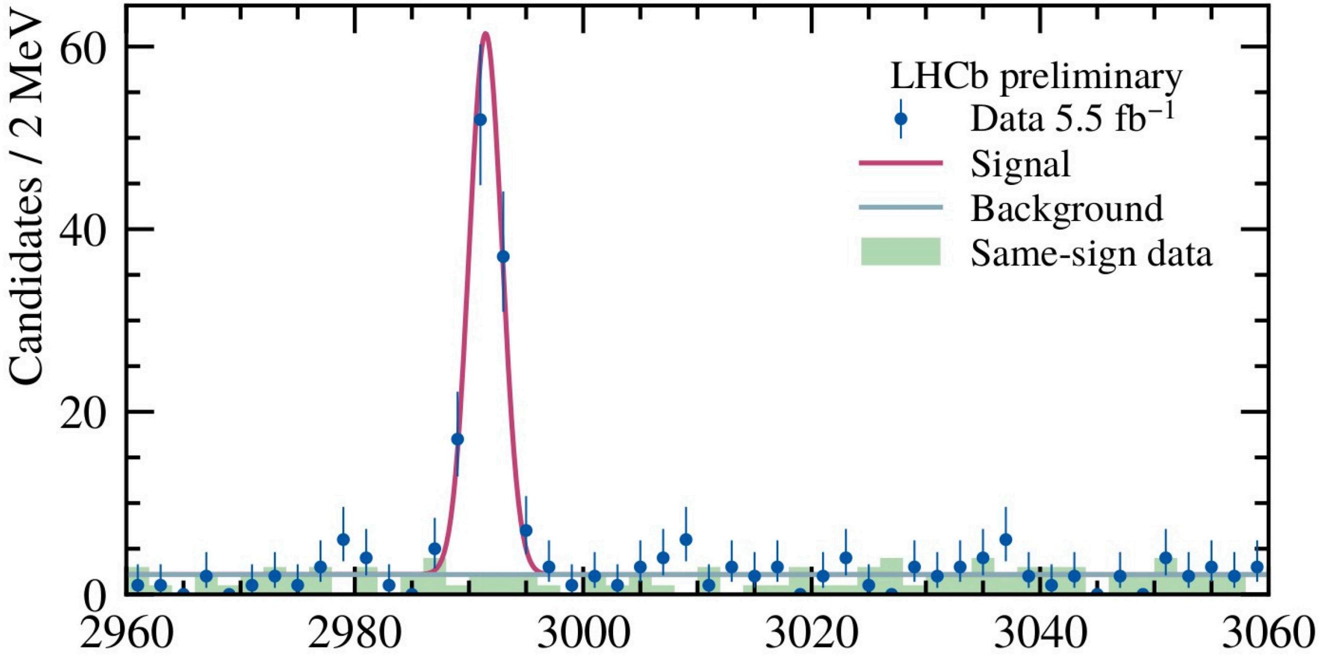
Results:

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

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

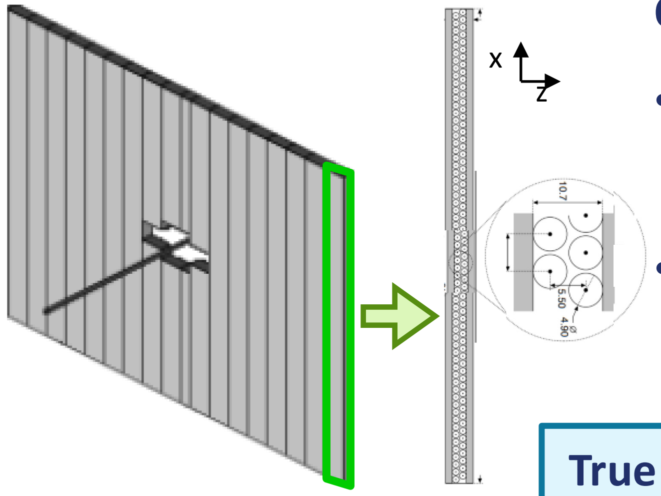
Under investigation:

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



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

Time-of-flight measurement at LHCb



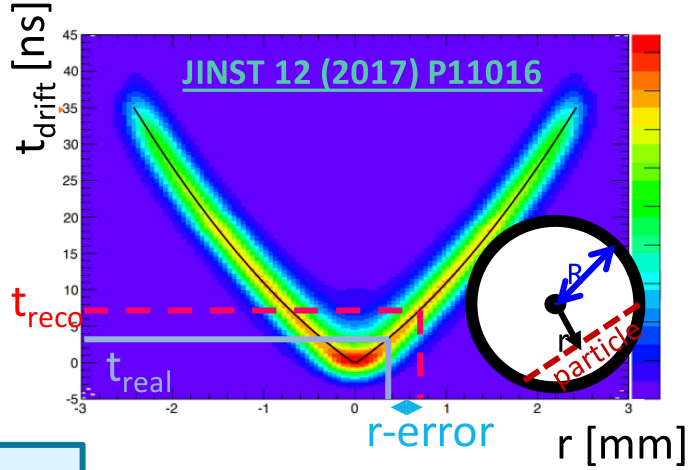
OT (Outer Tracker): largest area, straw-tube drift chambers

- 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:

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



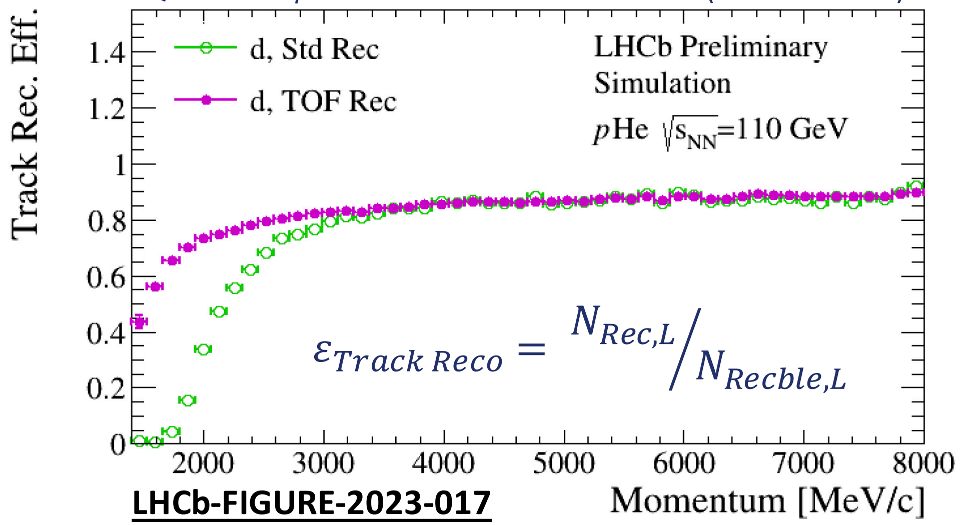
True β minimises the χ^2_{fit} → Particle ID through time measurement

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)

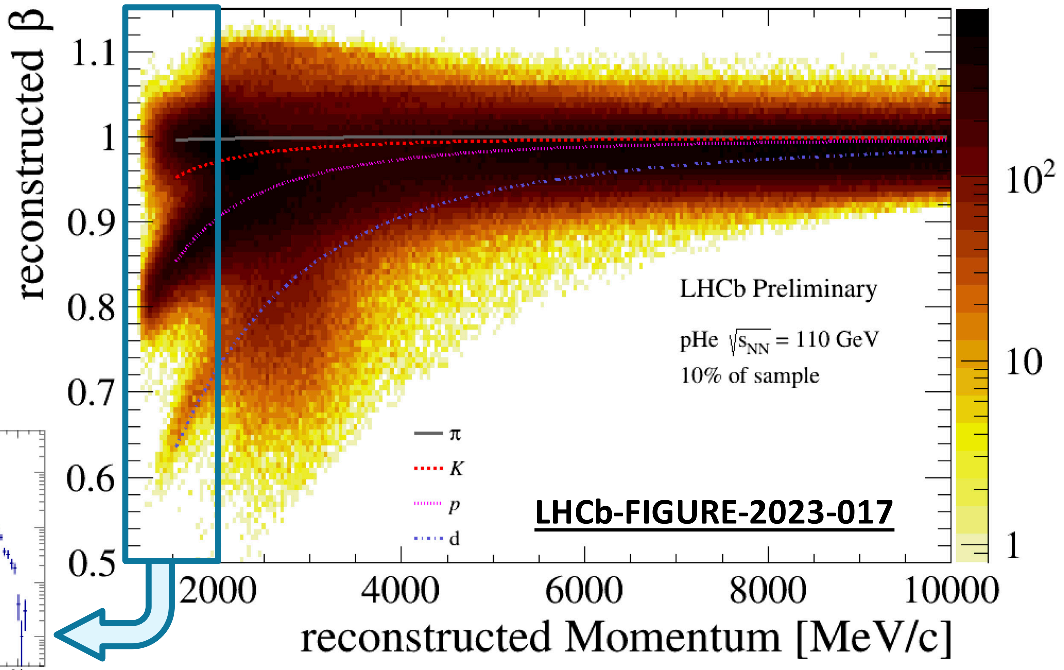


LHCb-FIGURE-2023-017

(Anti-)deuteron identification

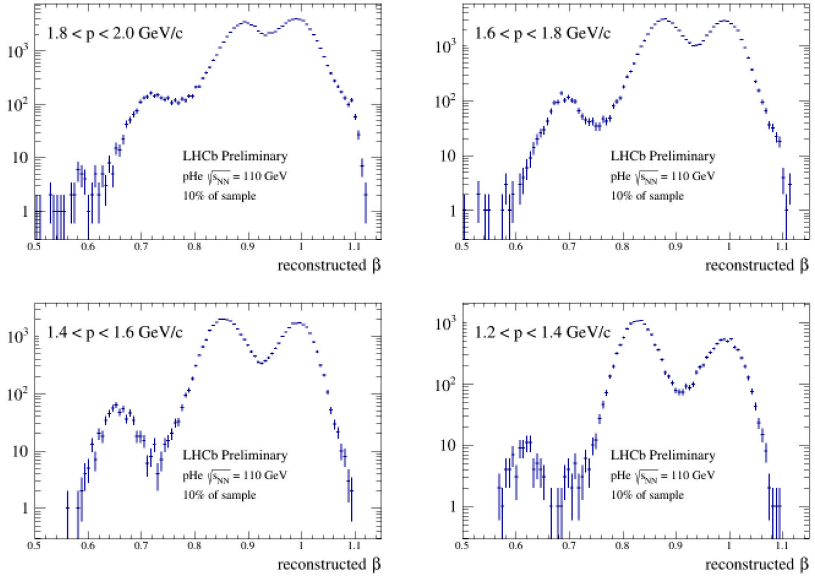
Reconstructed tracks refitted to determine β → Iterative procedure rerunning Kalman fit with different β hypotheses

1. At least 15 OT hits required on each track
2. Change β following $\chi^2_{\rm fit}$ decrease (gradient descent) without outliers removal → $\chi^2_{\rm fit} = \chi^2_{\rm track} + [(t_{\rm M1} - \langle {\rm M1} \rangle)/\sigma_{\rm M1}]^2$
3. Fit around minimum to estimate $\beta_{\rm fit}$ 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 , $\chi^2_{\rm OThits}$/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

Conclusions

LHCb is now able to identify light nuclei in Run2 datasample

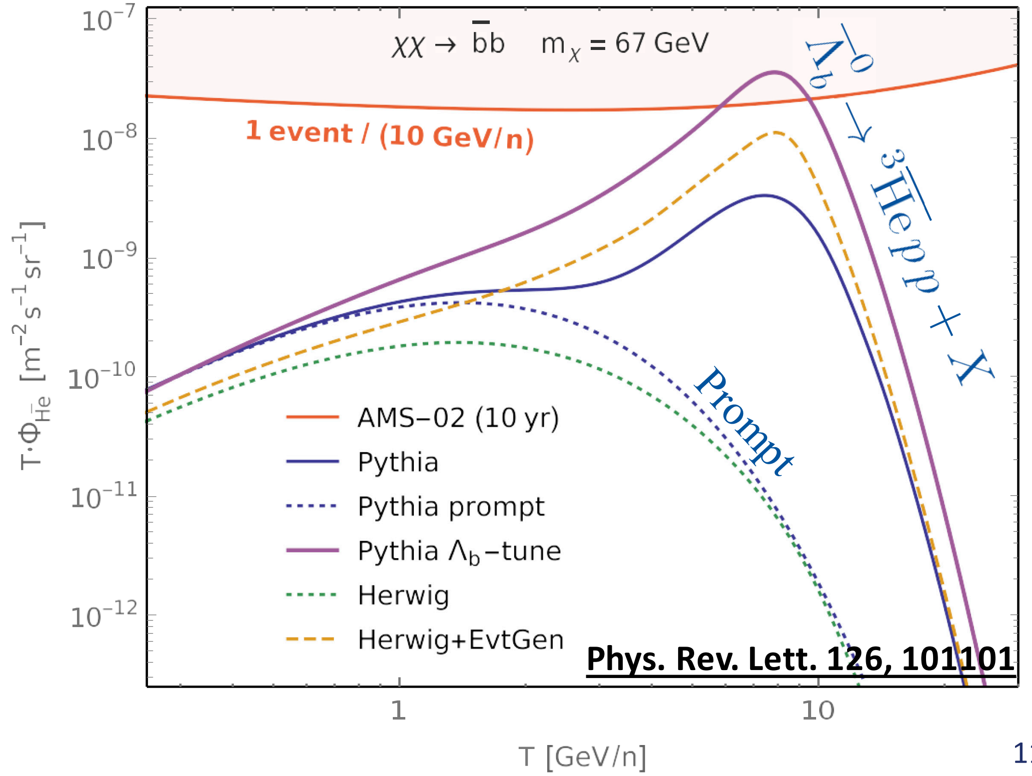
- (Anti-)Helium identified via dE/dx
- Time-of-flight based technique to identify (anti-)Deuteron

First (anti-)Helium and (anti-)Deuterons candidates observed in *pp* and SMOG *p*He data in LHCb!

Promising start! Many interesting results in future:

- Measure properties of Hypertriton (binding energy and life-time)
- Measure prompt (anti-)Deuteron and (anti-)Helium production in fixed-target datasample
- Measure anti-helium production from $\bar{\Lambda}_b^0$ decay

Thanks for the attention!



Phys. Rev. Lett. 126, 101101

BACKUP

Anti-nuclei production

- Main channels for indirect DM measurements are e^+ and $\bar{p}$ but limited in accuracy by the knowledge of background from secondary production (e^+, $\bar{p}$) and standard primary sources (e^+).
- Anti-nuclei production cross section (SM) scales with mass number A: $\sigma_{anti\text{-}N}/\sigma_{anti\text{-}p} = (10^{-3})^{A-1}$

  → $\bar{d}$ and $\overline{^3He}$ are ideal channels but it's necessary to predict with high precision the secondary flux.

⇩

Coalescence model:

An anti-nucleus is produced if the nucleons relative momenta in the center of mass frame are $(k_{Ni}-k_{Nj})/2 < p_0$, **coalescence momentum**.

- Experimental data suggest that p_0 depends on the **type of reaction** (*pp*, *p*A or AA) and on the **incident particle momentum** (p_{lab}).
- **No comprehensive theoretical model** that describes p_0 dependences
  → Different parametrizations possible (p_0 constant, $p_0(p_{lab})$, p_0(reaction), …).

⇨ **More direct measurements in the interesting system and energy range are needed.**

Coalescence model

$\bar{d}$ formation is described via the coalescence of a $\bar{p}$-$\bar{n}$ pair:

$$\gamma_{\bar{d}} \frac{d^3 N_{\bar{d}}}{d^3 k_{\bar{d}}}(\vec{k}_{\bar{d}}) = \frac{4}{3}\pi p_0^3 \cdot \gamma_{\bar{p}} \gamma_{\bar{n}} \frac{d^3 N_{\bar{p}} d^3 N_{\bar{n}}}{d^3 k_{\bar{p}} d^3 k_{\bar{n}}} \left(\frac{\vec{k}_{\bar{d}}}{2}, \frac{\vec{k}_{\bar{d}}}{2}\right) \quad (1)$$

Factorization hypothesis and *isospin invariance* hypothesis:

$$\gamma_{\bar{d}} \frac{\mathrm{d}N_{\bar{d}}}{\mathrm{d}^3 k_{\bar{d}}}(\vec{k}_{\bar{d}}) = R_n(\sqrt{s + m_{\bar{d}}^2 - 2\sqrt{s}E_{\bar{d}}}) \cdot \frac{4}{3}\pi p_0^3 \cdot \left[\gamma_{\bar{p}} \frac{\mathrm{d}N_{\bar{p}}}{\mathrm{d}^3 k_{\bar{p}}}\left(\frac{\vec{k}_{\bar{d}}}{2}\right)\right]^2 \quad (2)$$

where R_n is associated to the reduction of the phase space after the production of the first nucleon.

For an anti-nucleon with mass number A, under the same hypotesis:

$$\gamma_A \frac{\mathrm{d}N_A}{\mathrm{d}^3 k_A}(\vec{k}_A) = R_n(\sqrt{s + m_A^2 - 2\sqrt{s}E_A}) \cdot \left(\frac{4\pi}{3} p_0^3\right)^{(A-1)} \cdot \left[\gamma_{\bar{p}} \frac{\mathrm{d}N_{\bar{p}}}{\mathrm{d}^3 k_{\bar{p}}}\left(\frac{\vec{k}_A}{A}\right)\right]^A \quad (3)$$

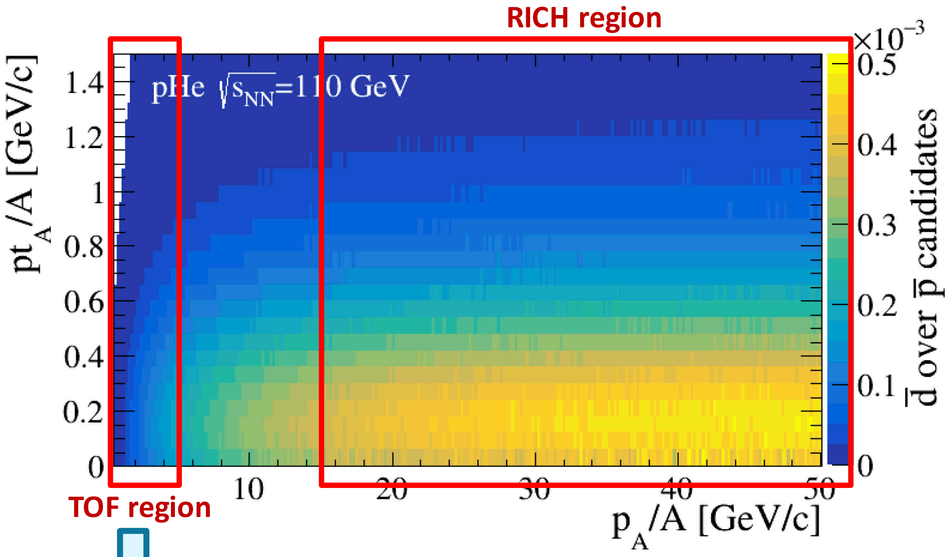
Alternative parameter: $B_A = \frac{A}{m_p^{A-1}} \left(\frac{4\pi}{3} p_0^3\right)^{A-1}$

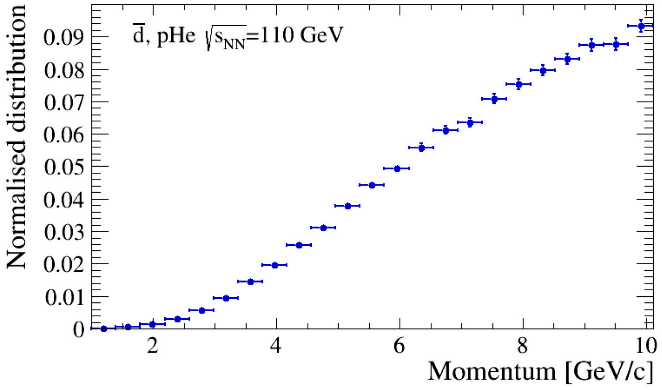
Expected anti-nuclei in SMOG dataset

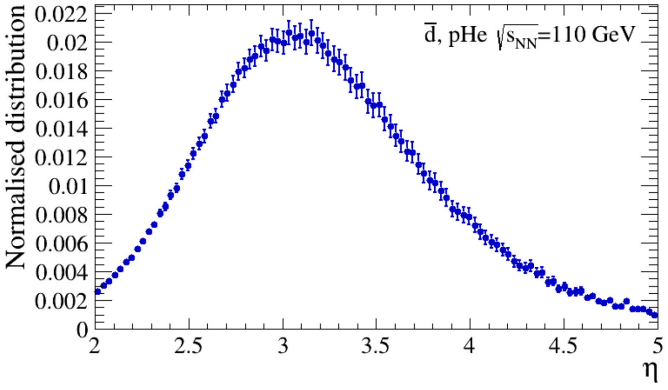
EPOS-LHC for pHe ($\sqrt{s_{NN}}$= 110 GeV) + afterburner based on simplified analytic coalescence model (constant p_0) to obtain $\bar{d}$ and $\overline{^3He}$ distribution for (1<p_p<100) GeV/c, p_T<3 GeV/c, 2<η<5.

- In the whole kinematic region, **anti-He/anti-*p* ratio expected is around 2x10^{-6}** ~ 5 candidates expected → Challenging ☹

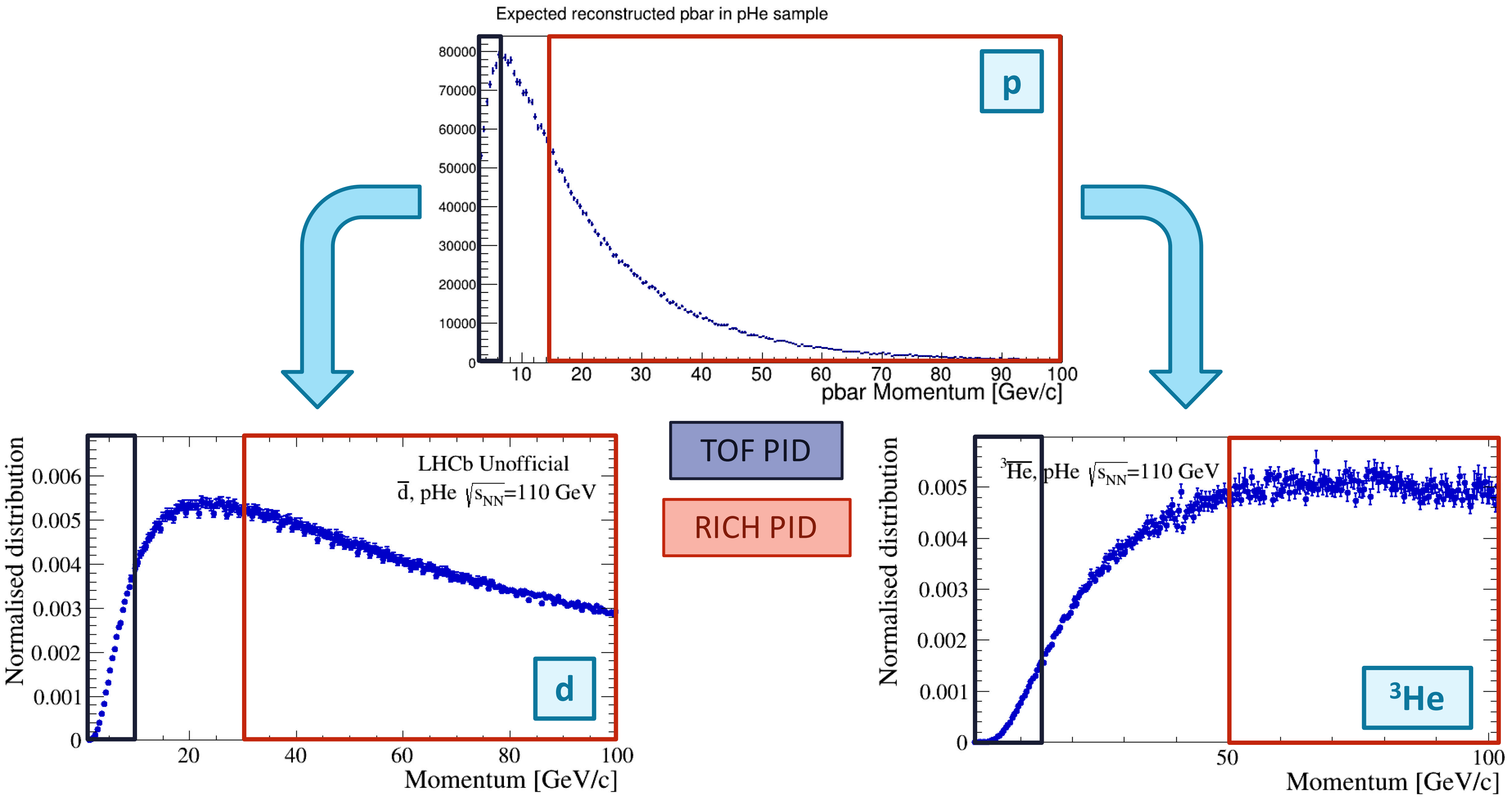
- In the whole kinematic region, **anti-d/anti-*p* ratio expected is around 0.9x10^{-3}** = 4500 candidates
- In TOF the kinematic region (2<p<10) GeV/c, **anti-d/anti-*p* ratio reduces to 0.3x10^{-3}** = 300 candidates



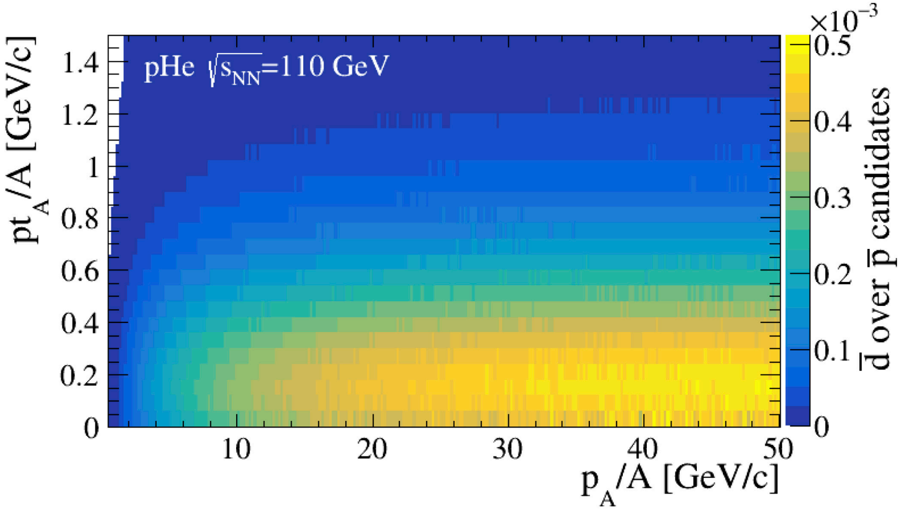


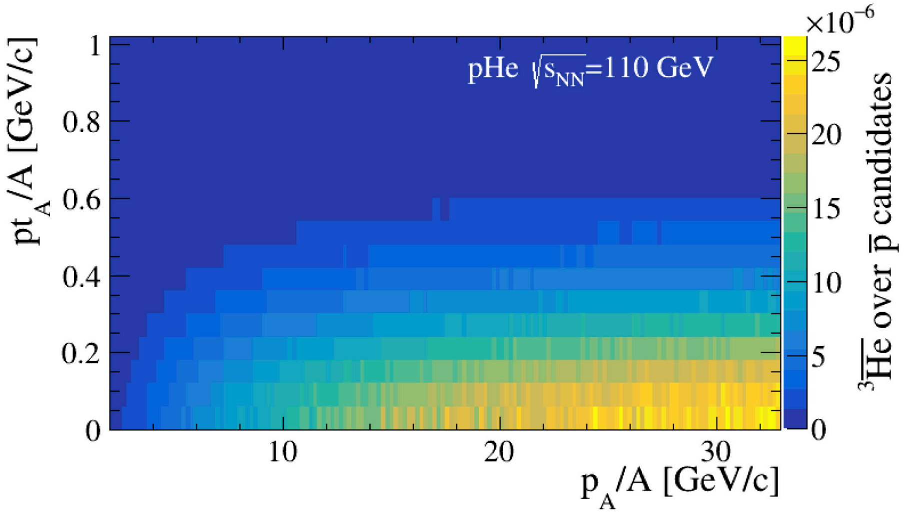


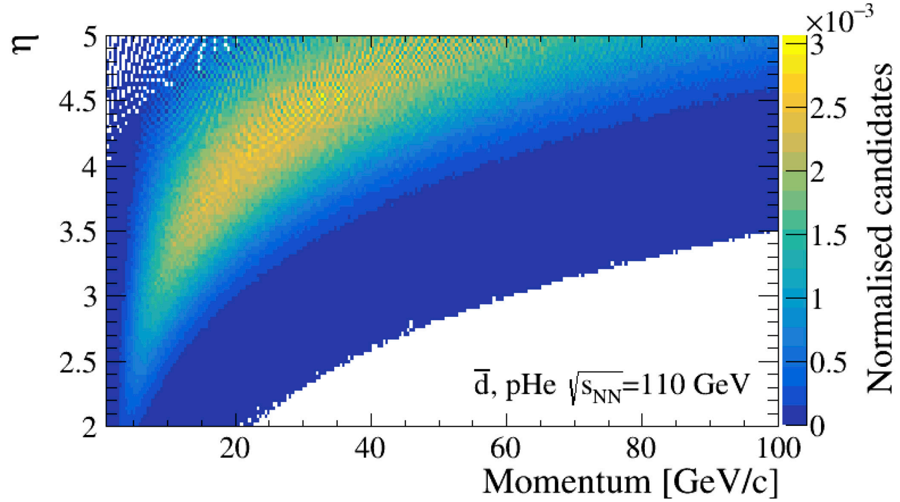
Expected anti-nuclei in SMOG dataset

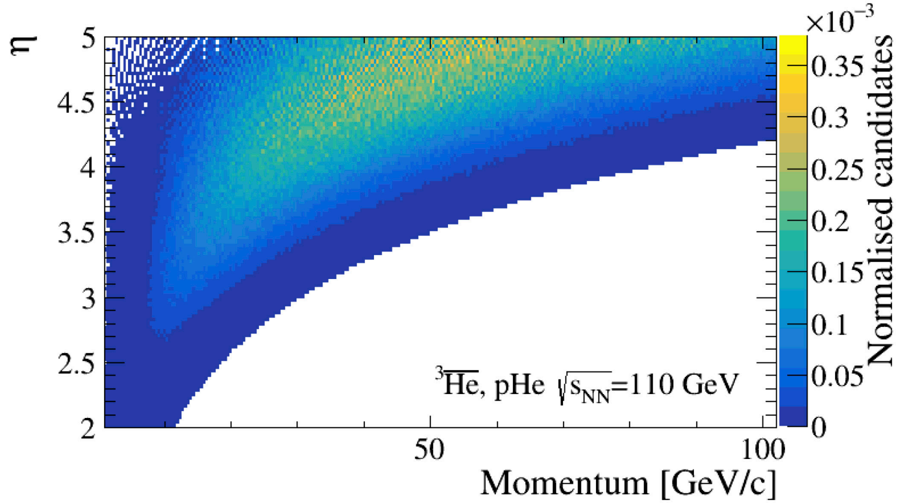


Anti-nuclei distributions









Minimum bias (anti-)Helium

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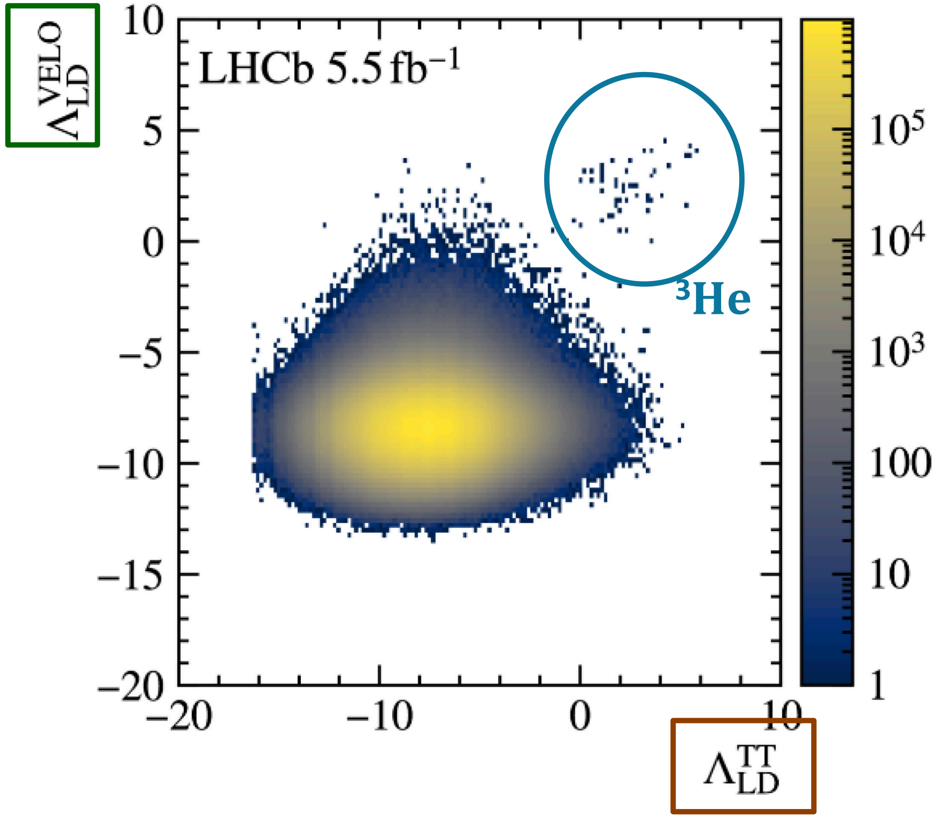

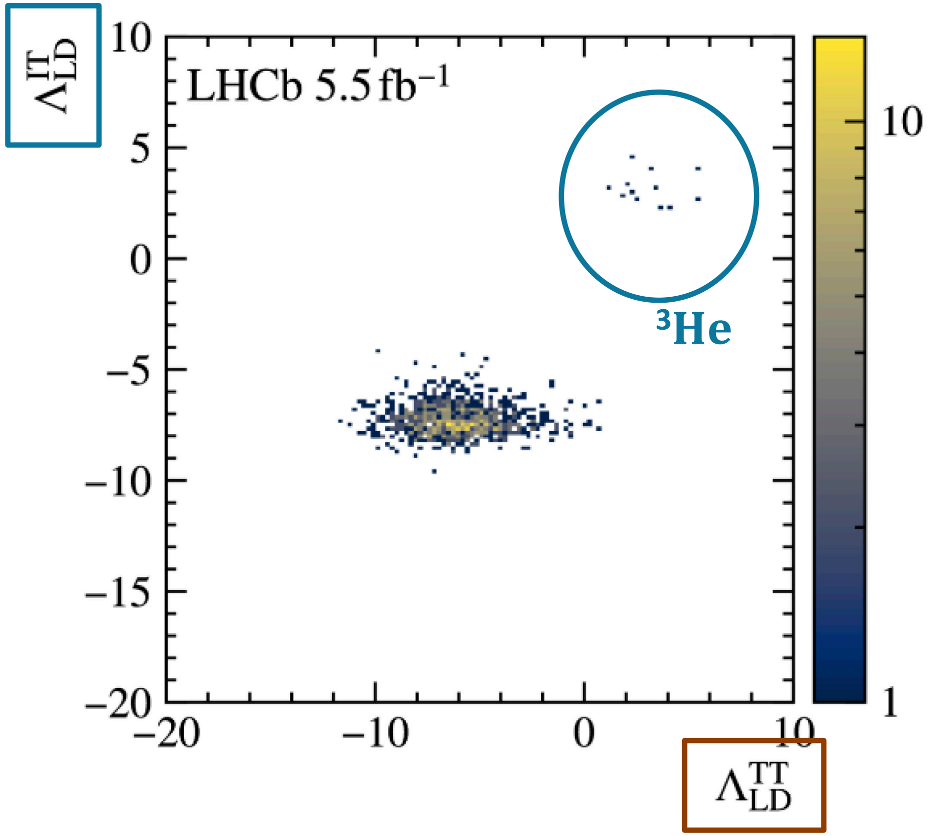

Candidates in IT acceptance

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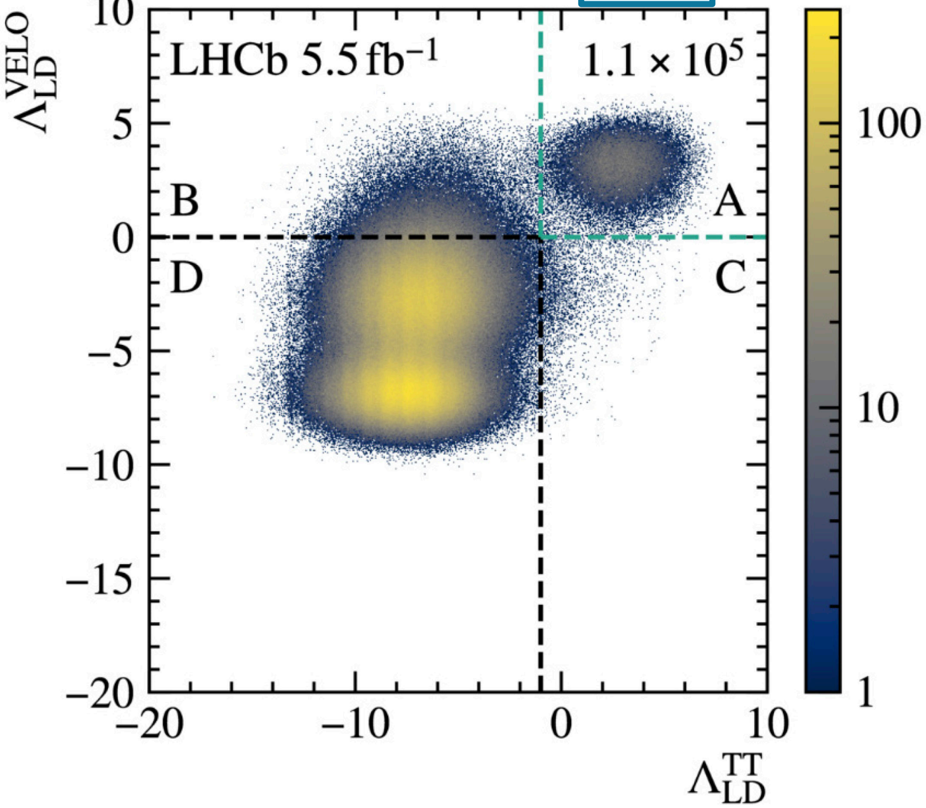
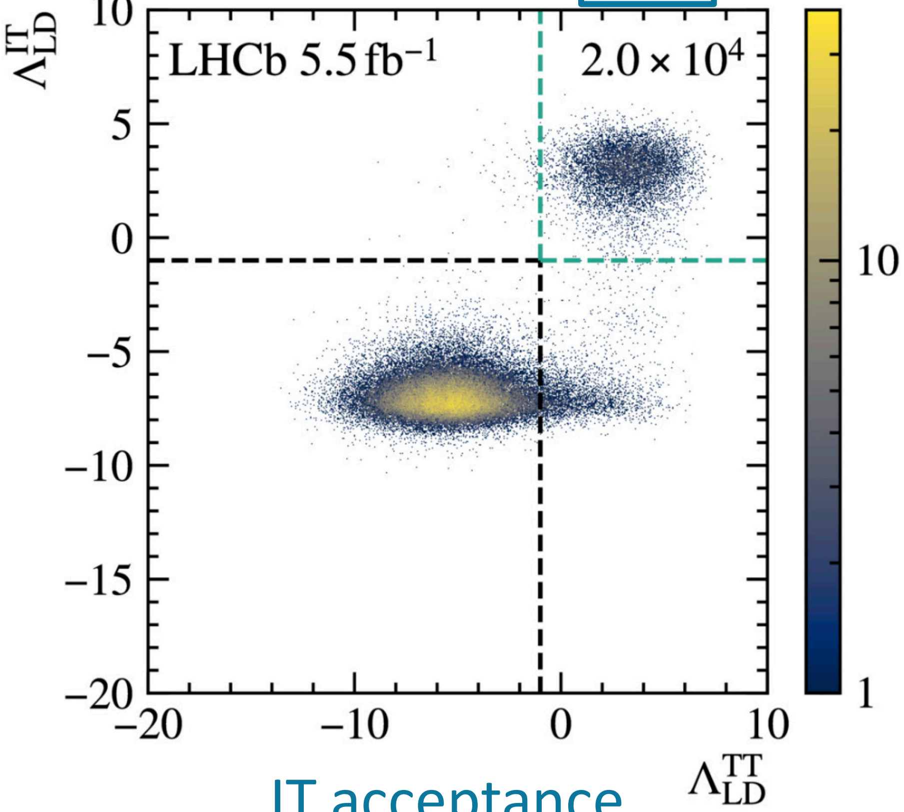
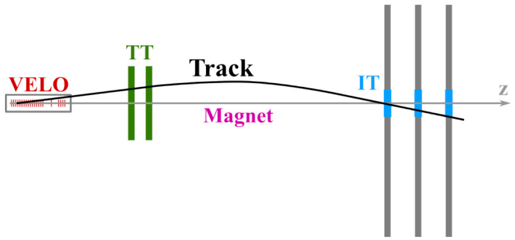
^{3}He



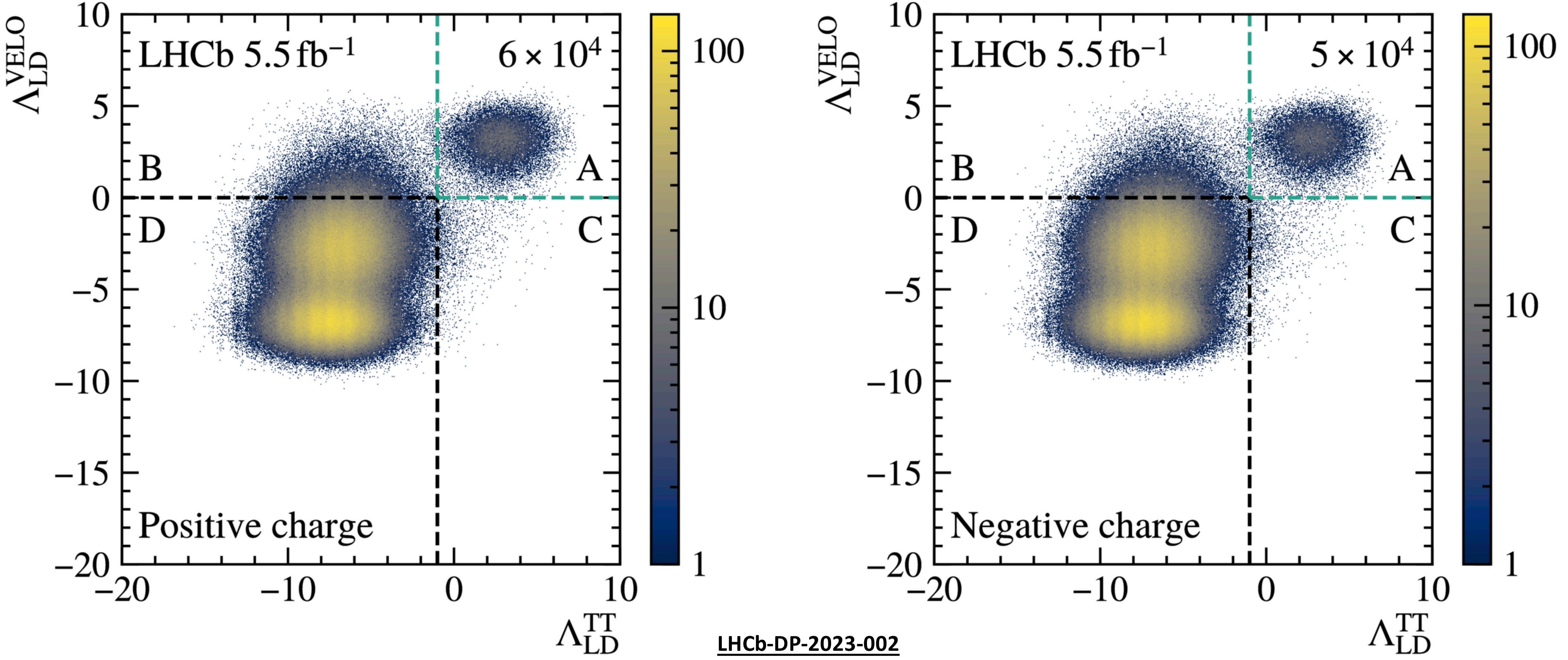
^{3}He



IT acceptance



Prompt Helium and anti-Helium

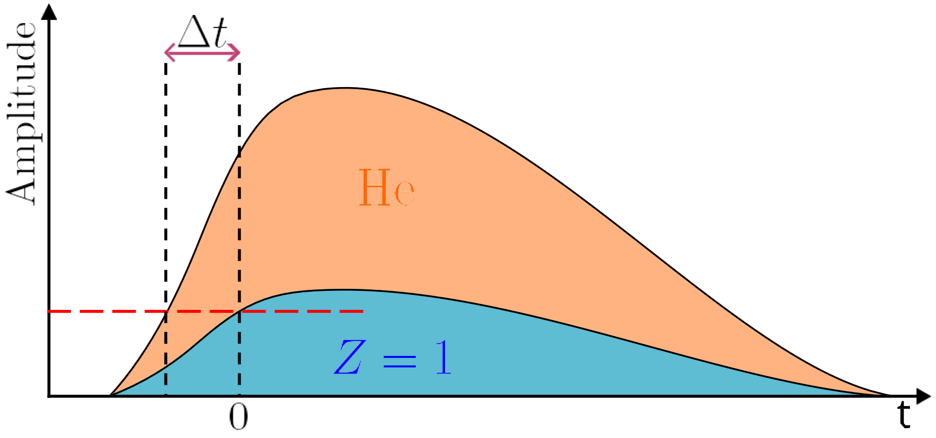


LHCb-DP-2023-002

Timing information from OT

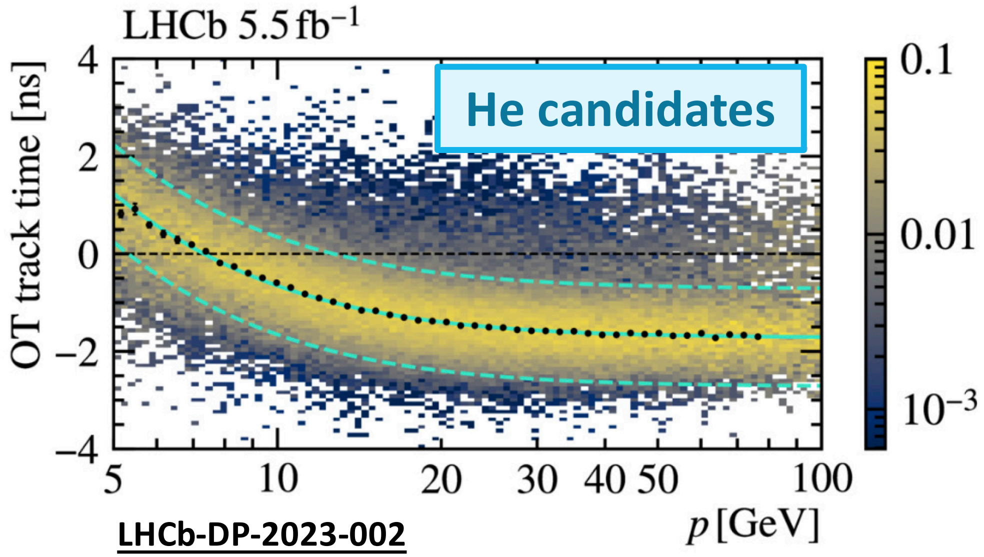
Tracks with no IT info: OT information

- OT: straw-tube drift chambers detector
  → Hit position from ionization cluster t_{drift}
- TDC time measurement with constant threshold
  → No dE/dx information
  → Time walk effect: **Z=2 crosses threshold earlier**



OT track time: delay of ionization cluster t_{drift} wrt t(r) from reconstructed track

- Expected **negative** track time for Z=2 particles
  → **Helium ID in full acceptance**



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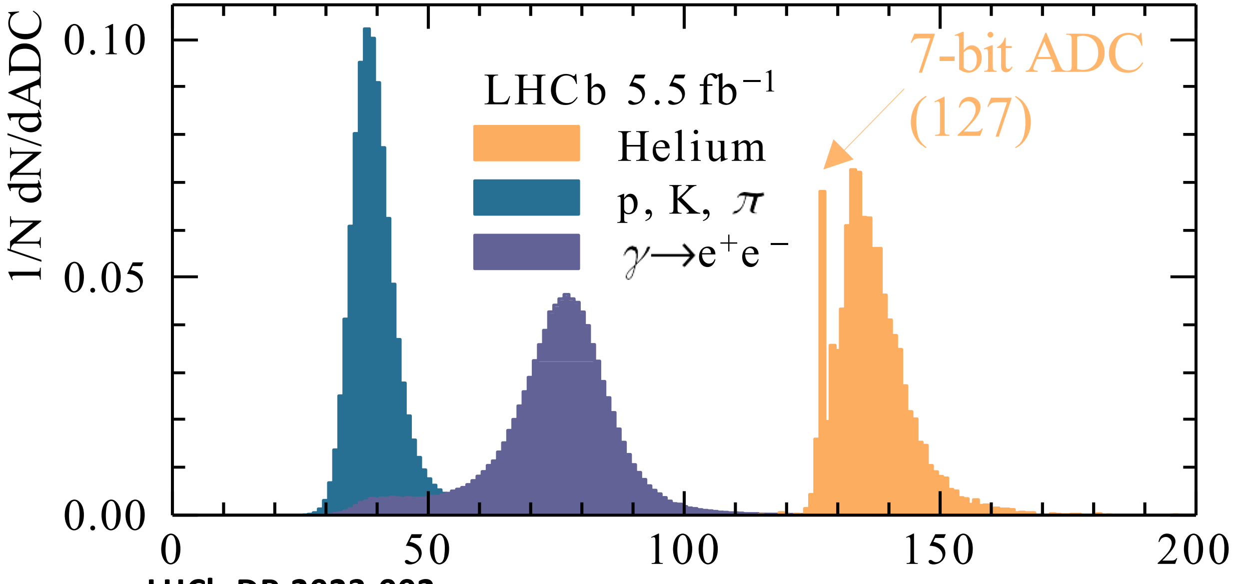
Converted photons



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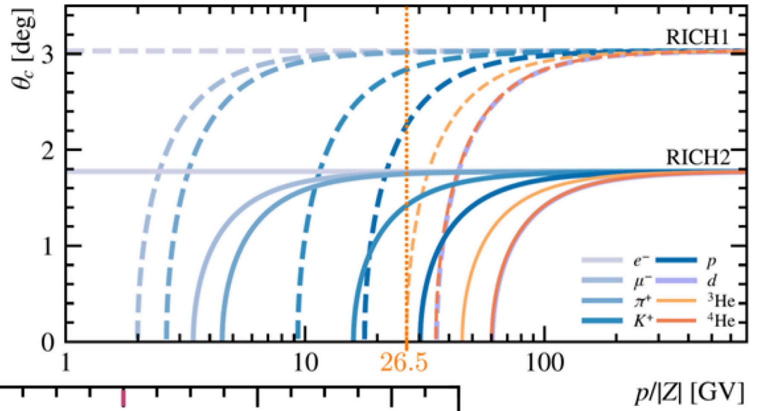
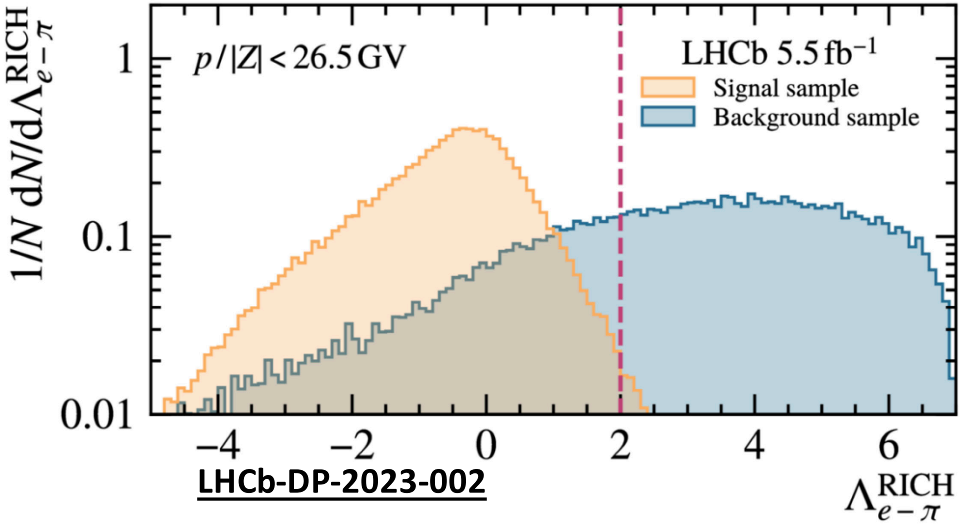


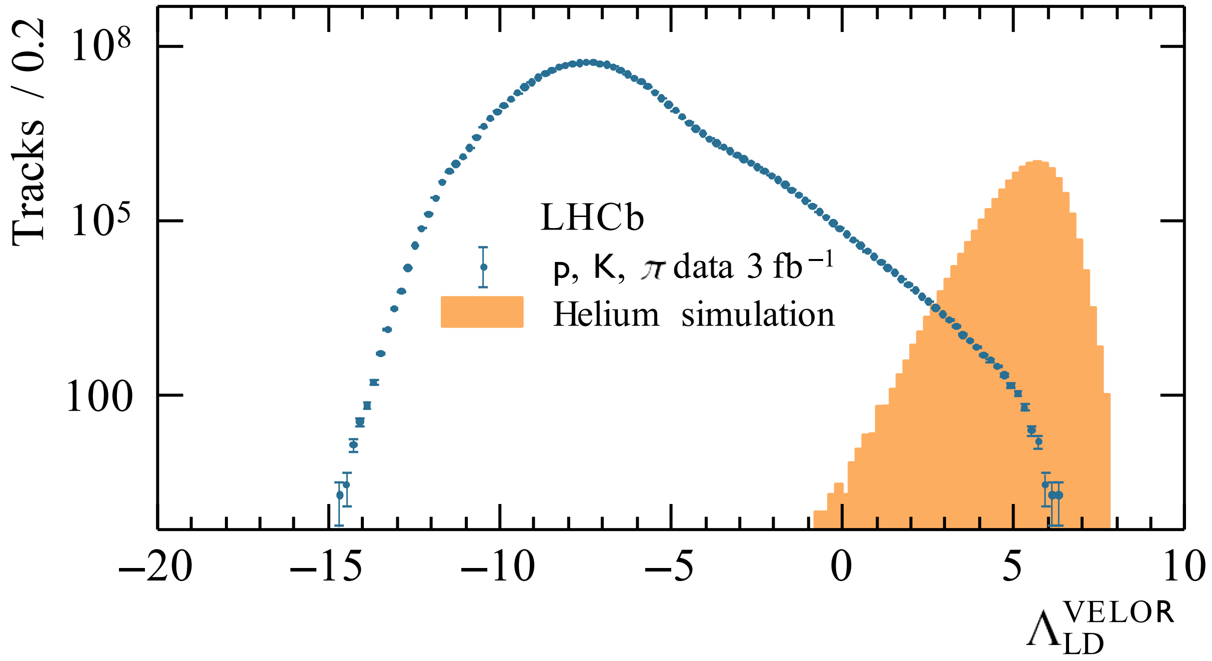


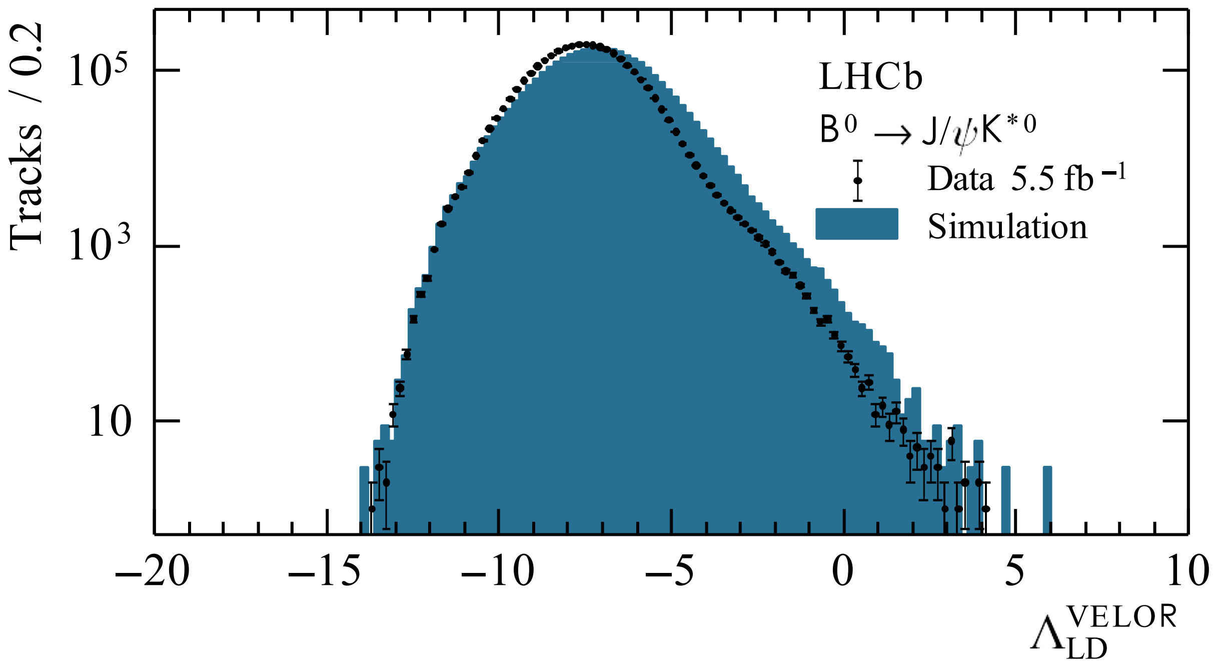
LHCb-DP-2023-002

- Conversion signature:
  e^+ and e^- contribute to same cluster
  ⇒ Closer to Helium than Z=1

Converted photons below ^{3}He Cherenkov threshold rejected ($\mathcal{O}(10^2)$)

Data and simulation comparison

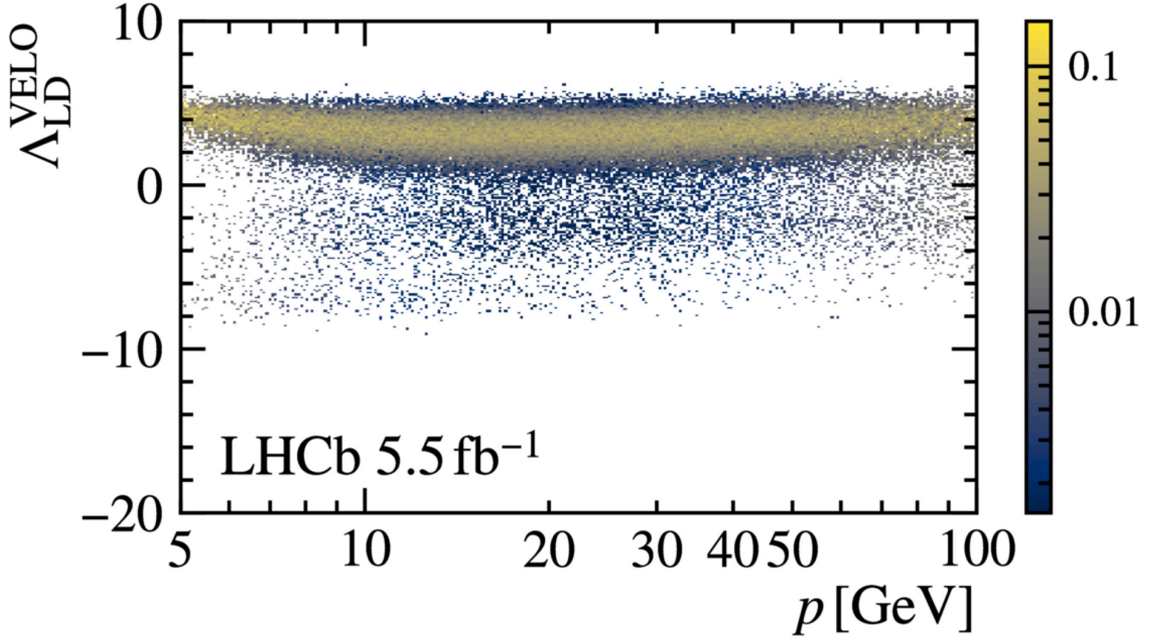


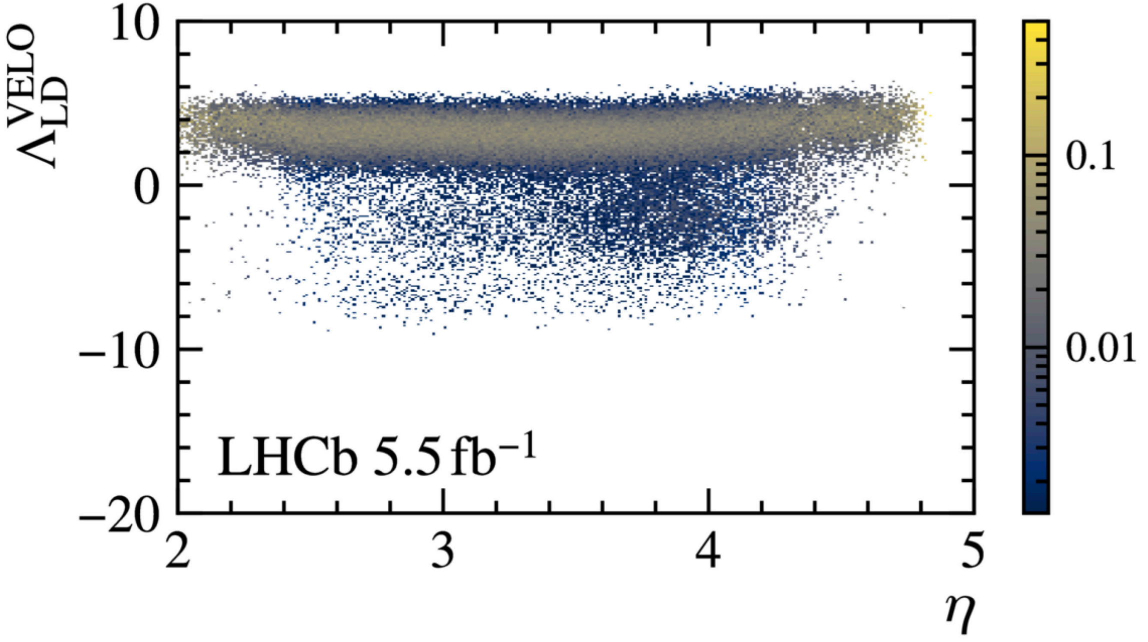


LHCb-DP-2023-002

Kinematic dependence

LHCb-DP-2023-002



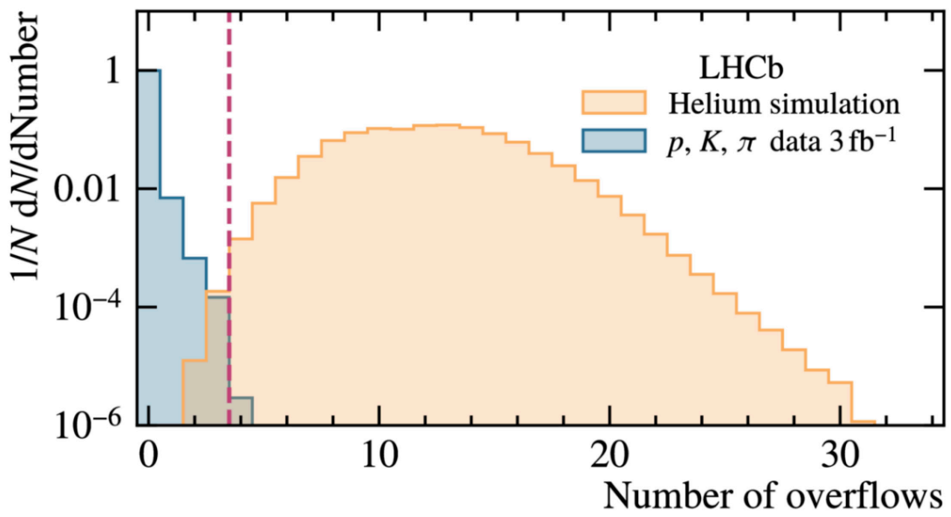


No strong dependence on kinematics for Λ_{LD}

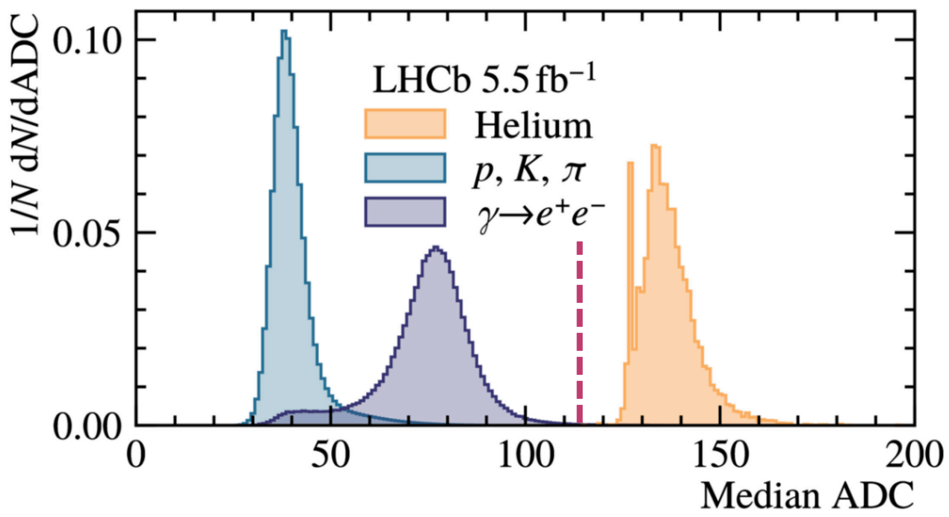
Data preselection

Two independent preselections, each with ~50% efficiency (estimated on ~50 minimum bias candidates).

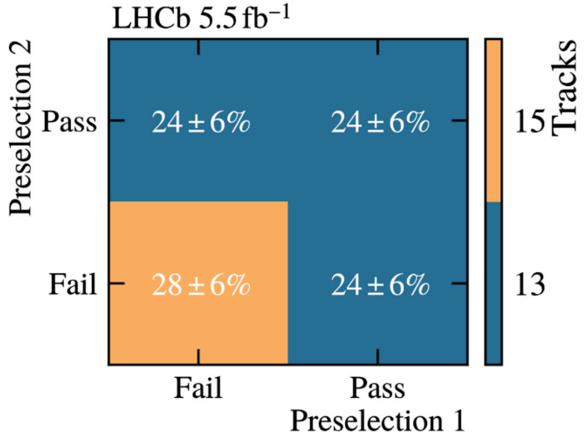
Preselection 1



Preselection 2

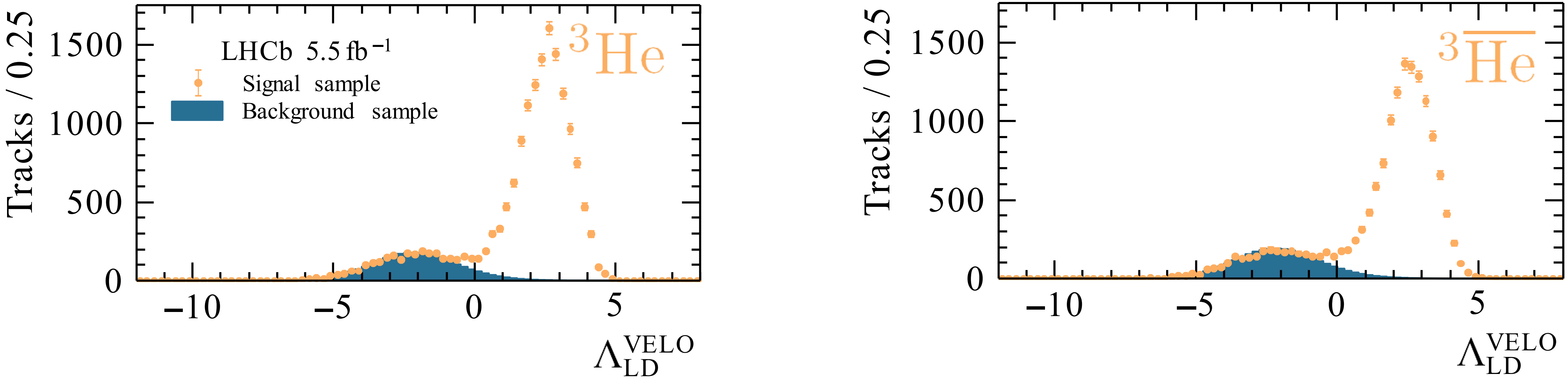


LHCb-DP-2023-002



Prompt (anti-)Helium at LHCb

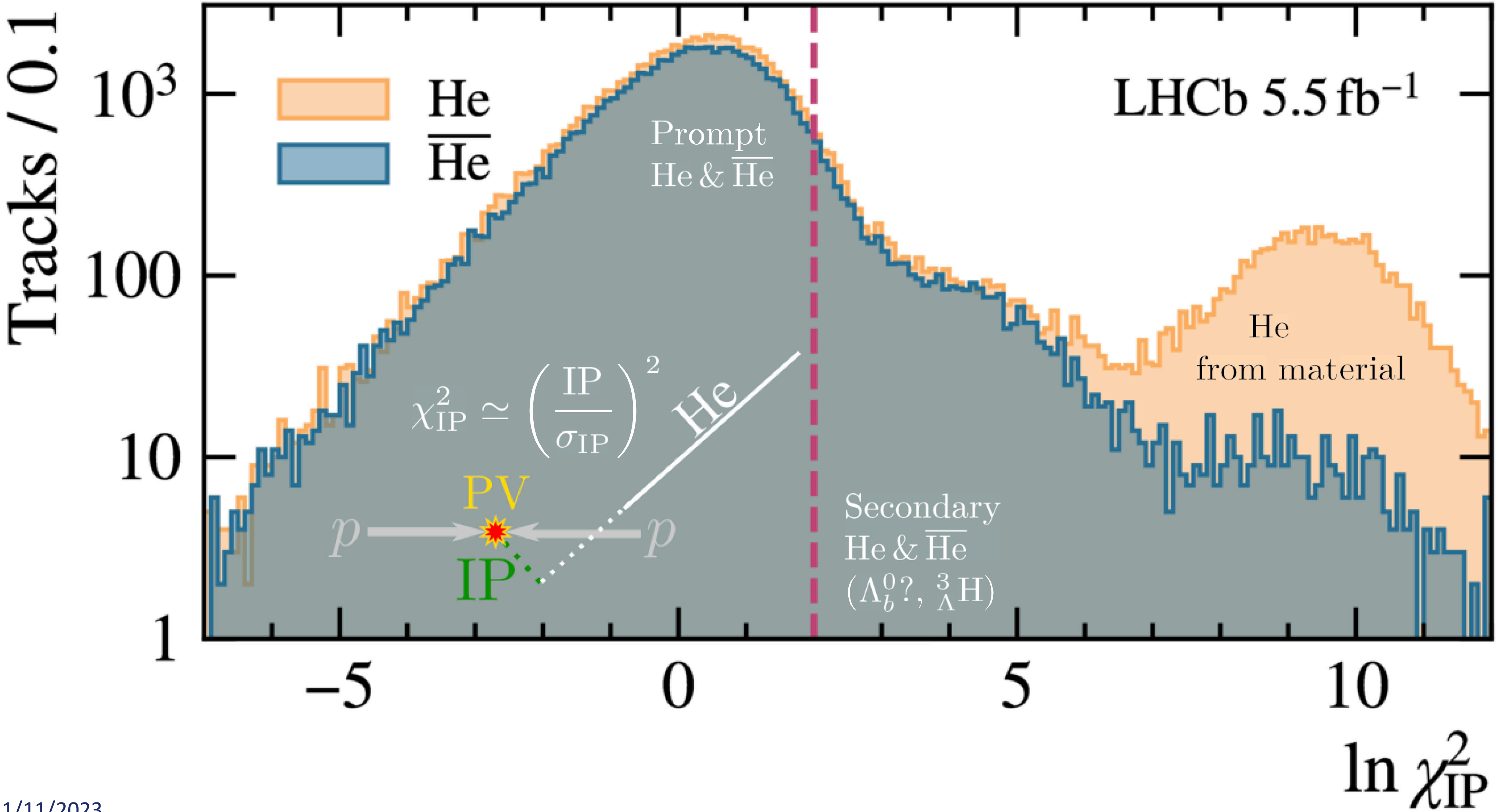
Preselection 2



LHCb-DP-2023-002

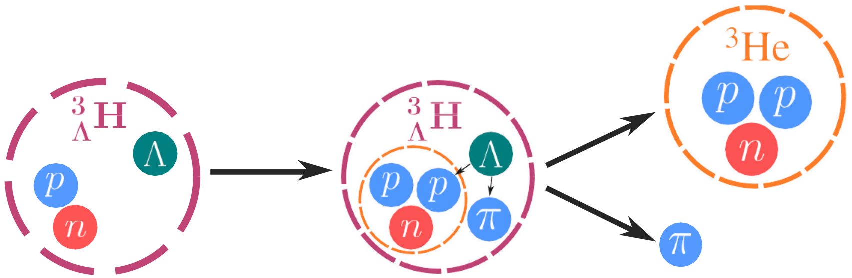
Sources of helium

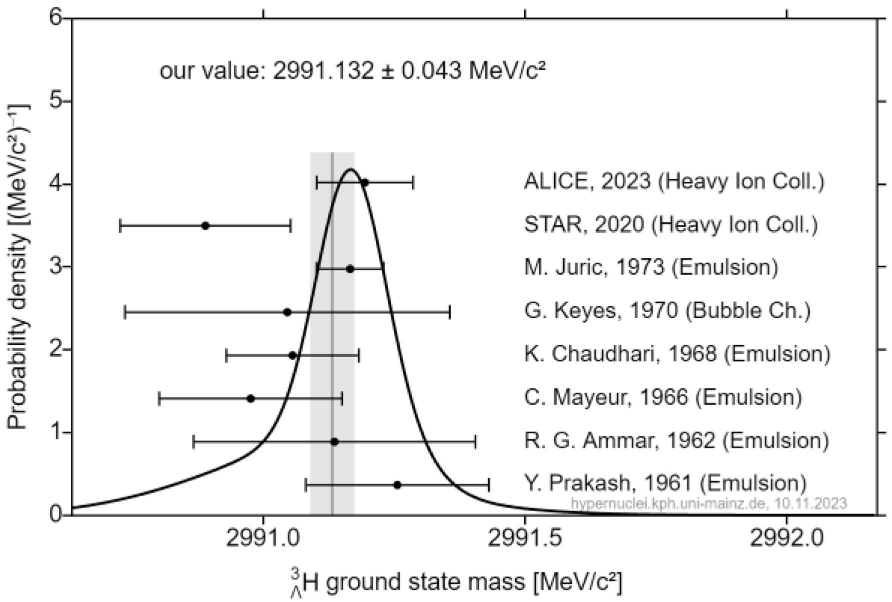
LHCb-DP-2023-002

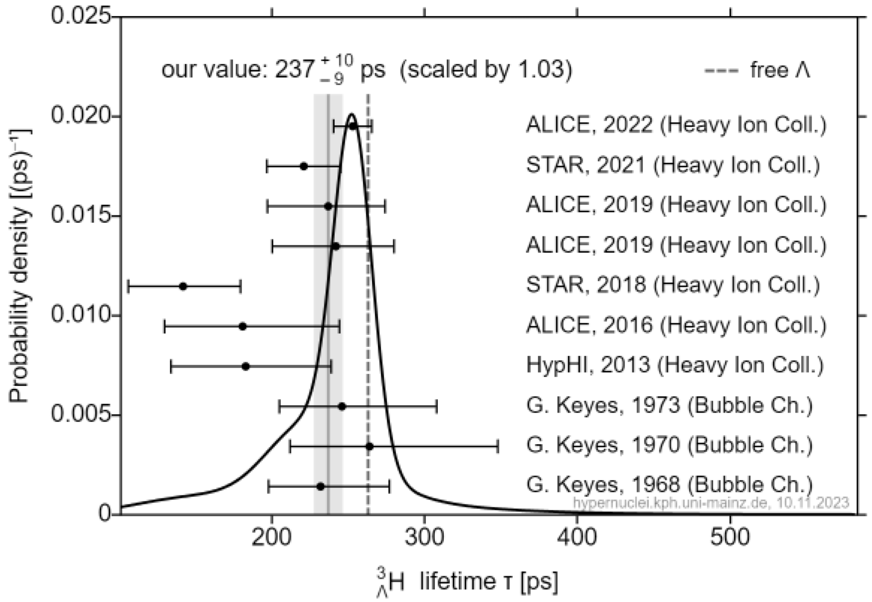


Hypertriton life-time puzzle

- Tension between STAR and ALICE results
  - → **Hypertriton life-time puzzle**





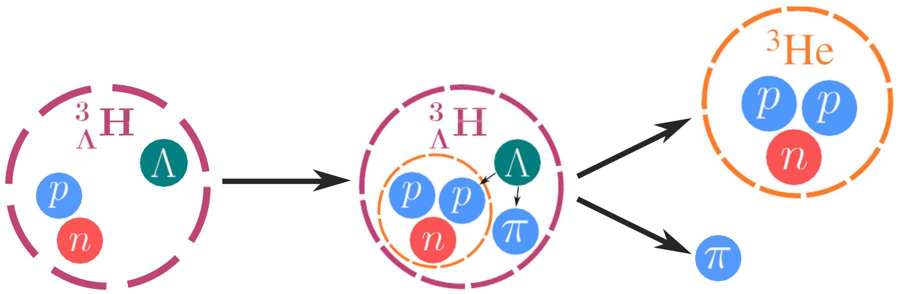


hypernuclei.kph.uni-mainz.de/

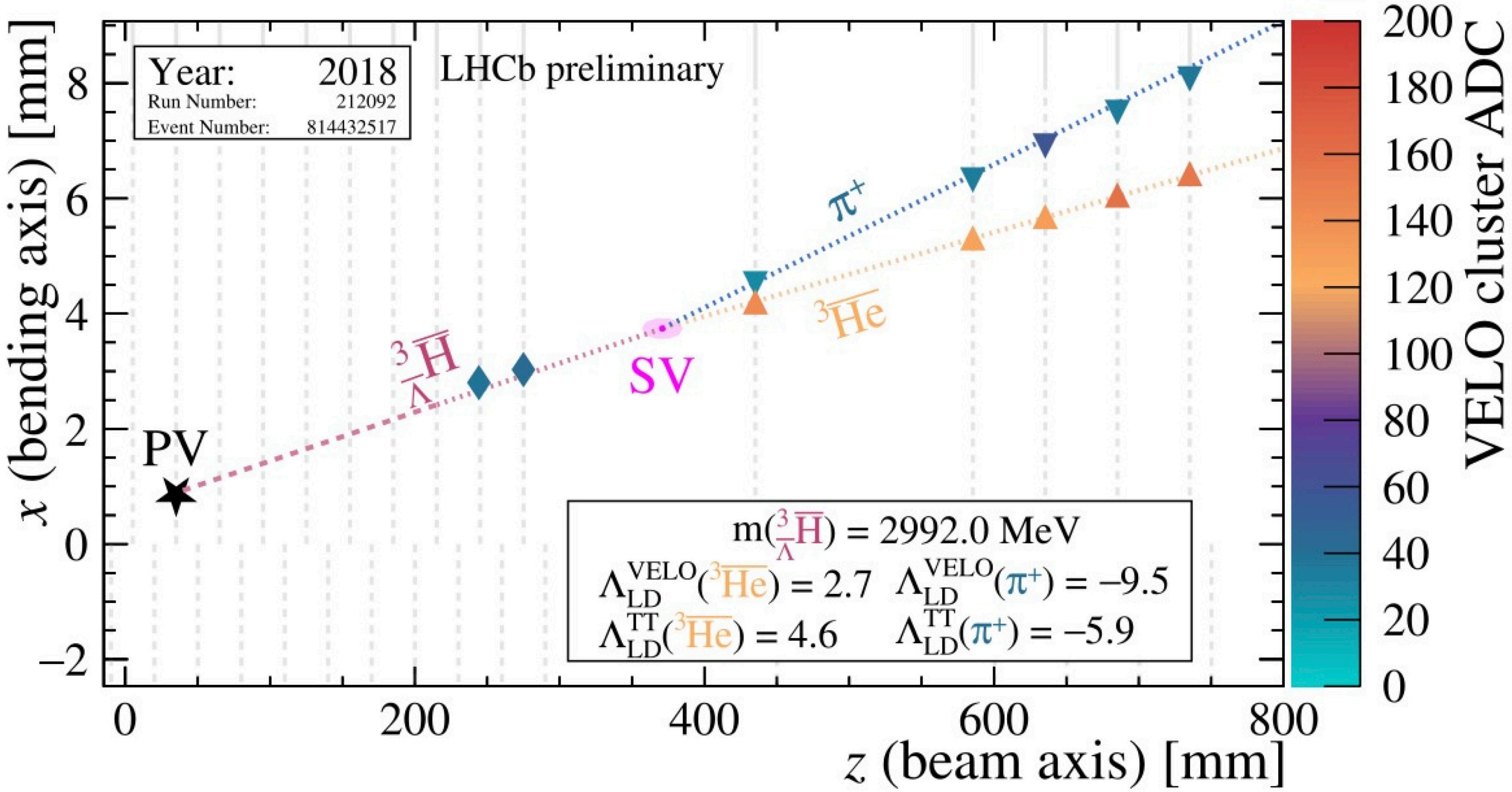
Application: Hypertriton

Candidates selection:

- Secondary $^{3}\mathrm{He}$ track, not compatible with PV: $\log(\chi^2_{\mathrm{IP}})>2$
- Matching π track
- Well reconstructed secondary vertex: $\log(\chi^2_{\mathrm{vtx}})<2$
- Prompt $^{3}_{\Lambda}\mathrm{H}$ track: $\log(\chi^2_{\mathrm{IP}})<2$

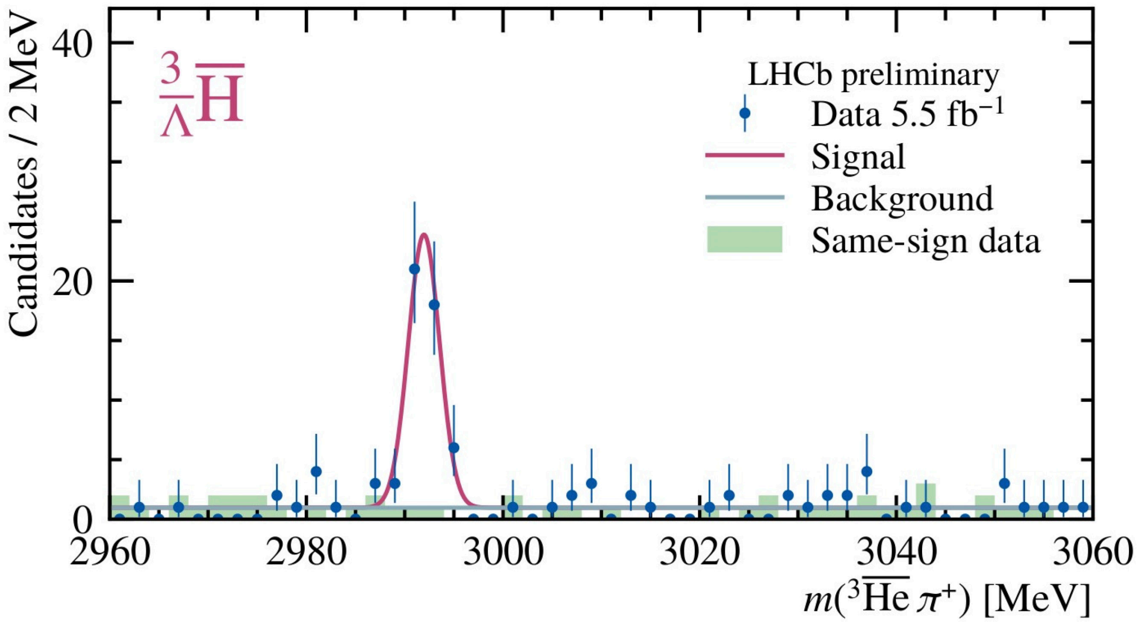


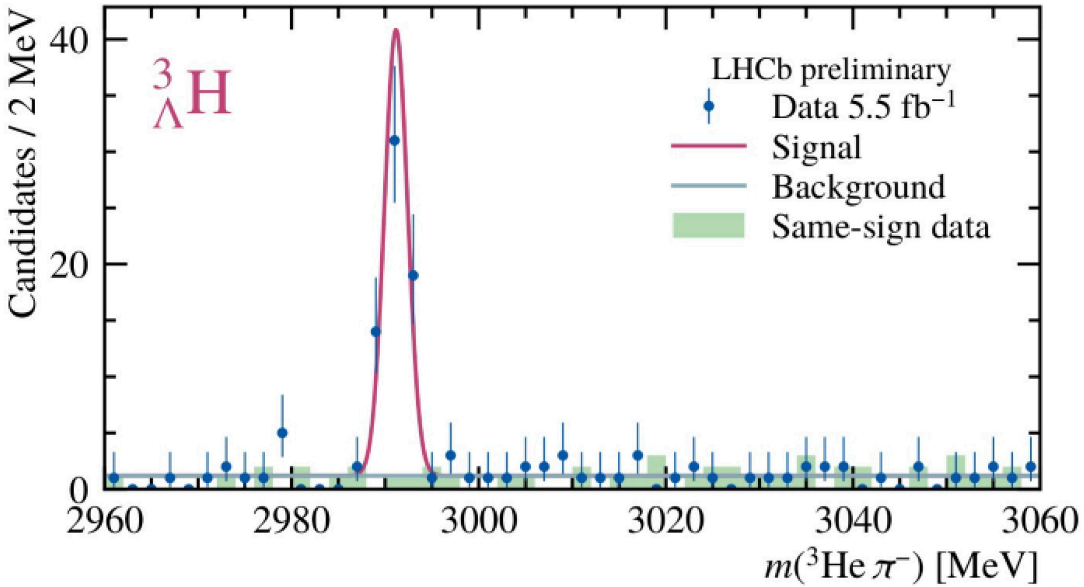
LHCb-CONF-2023-002
(submitted to EPS-HEP2023)



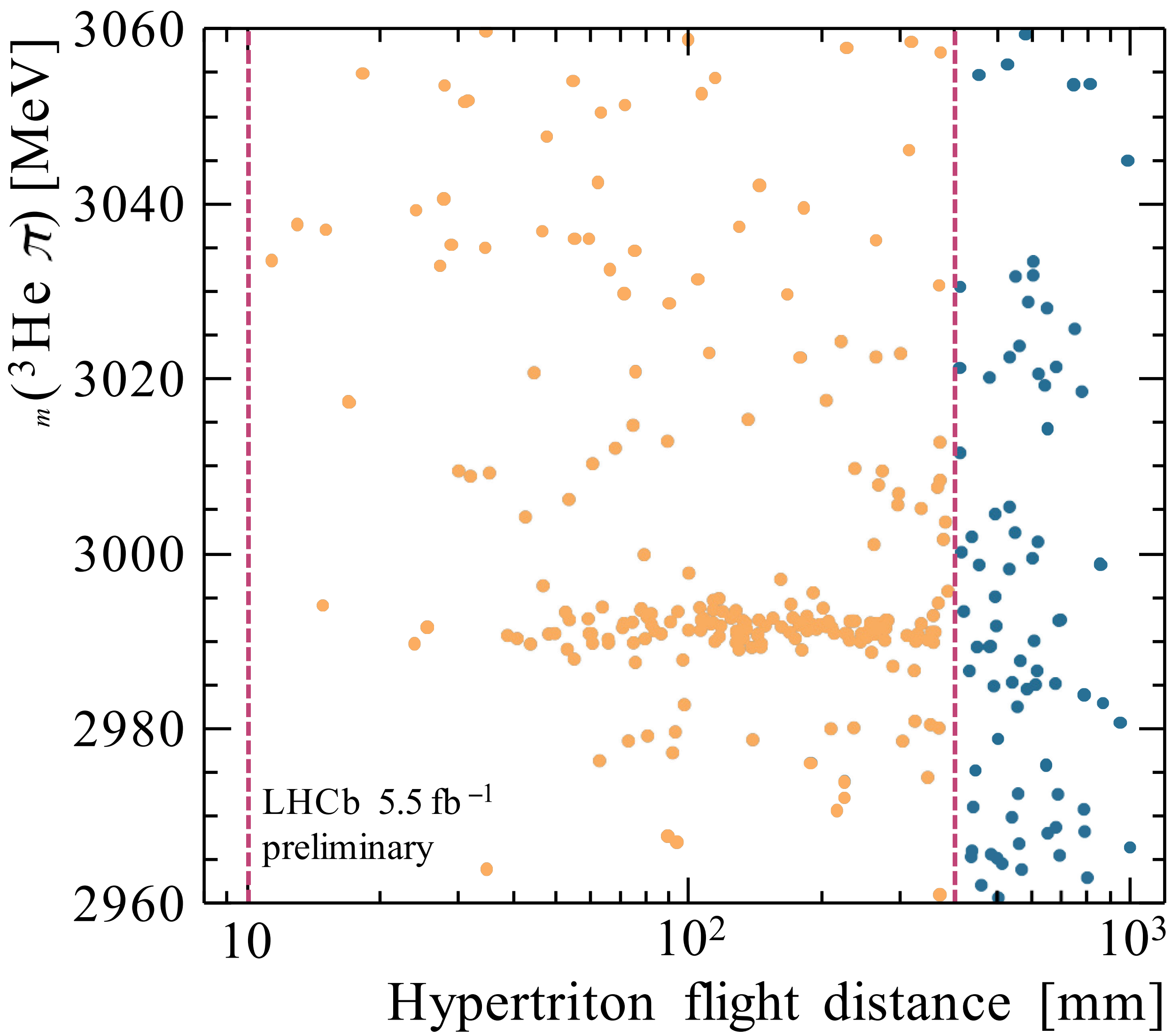
(Anti-)Hypertriton results

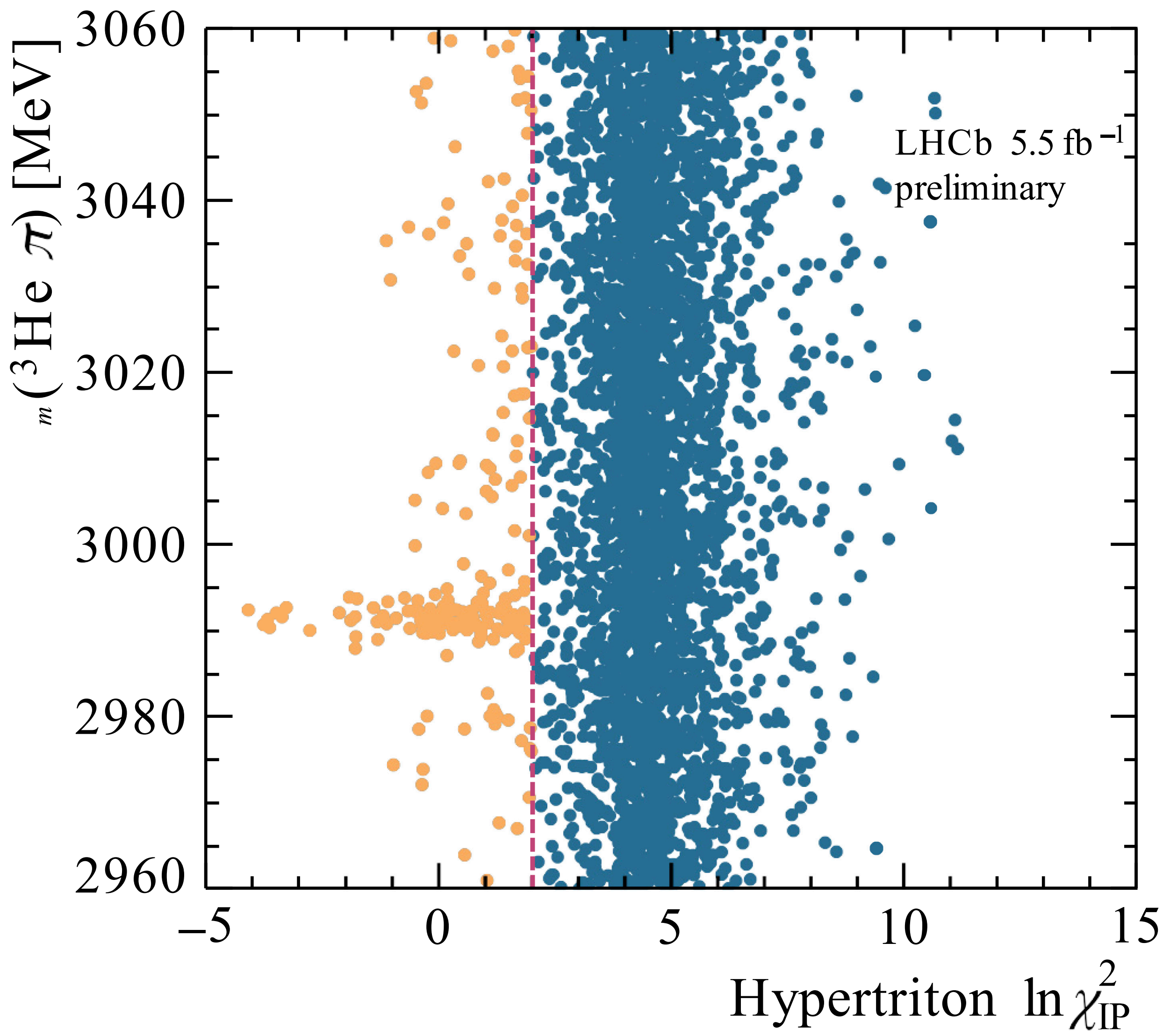
LHCb-CONF-2023-002 (submitted to EPS-HEP2023)





Hypertriton selection





<u>LHCb-CONF-2023-002</u> **(submitted to EPS-HEP2023)**

OT Reconstruction with TOF

Modify the reconstruction algorithm to take into account β

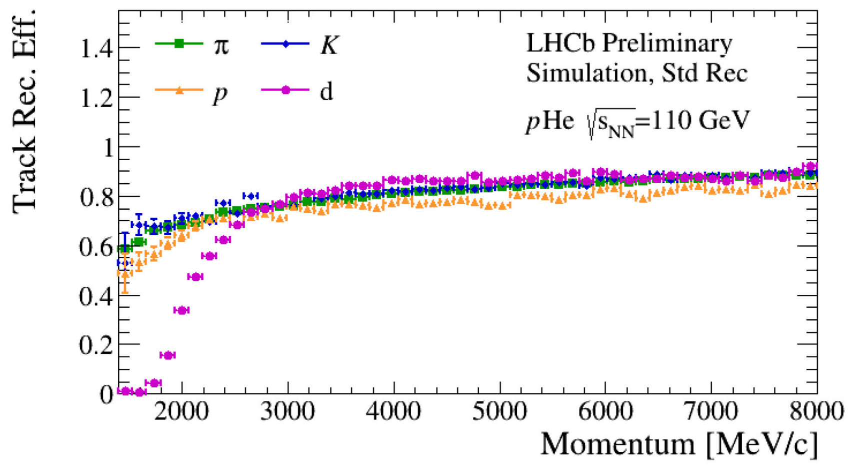
***Target*: Correct hits position** with right β to i**nclude all possible hits and** improve χ^2

Add loop on possible β values and save track with best χ^2

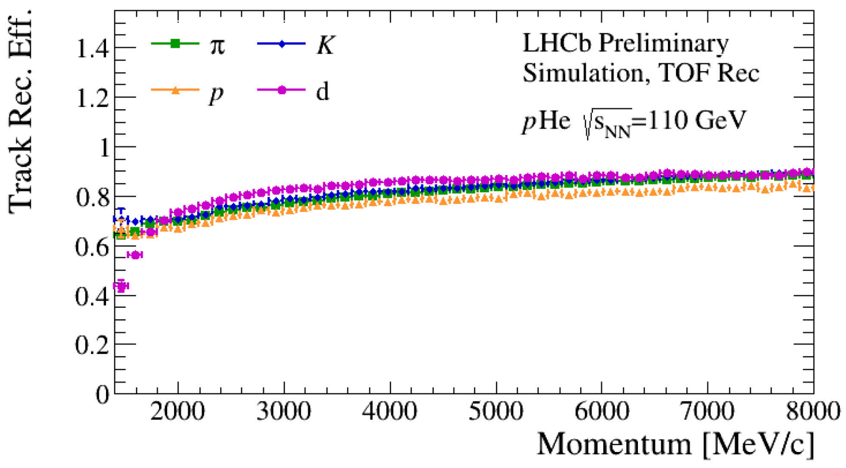
- Add **PreLoop with no OT drift time**: hit position at center of straw, σ_{hit} = 2.5 mm
  1. If no candidate track, stop algorithm
  2. If no OT hit, run regular reconstruction
  3. If track with OT hit, use track momentum to set β range for loop:
     $\beta_{min} = 1/\sqrt{(1+M_{max}^2/p^2)}$, M_{max} = maximum mass for candidate particle
- For each step in loop, correct hits position for beta value and perform fit
- Select candidate track with best χ^2
- If χ^2 doesn't improve for two consecutive steps, stop loop

Reconstruction efficiency

MC sample:
crmc qgsjet for *p*He + **coalescence afterburner**



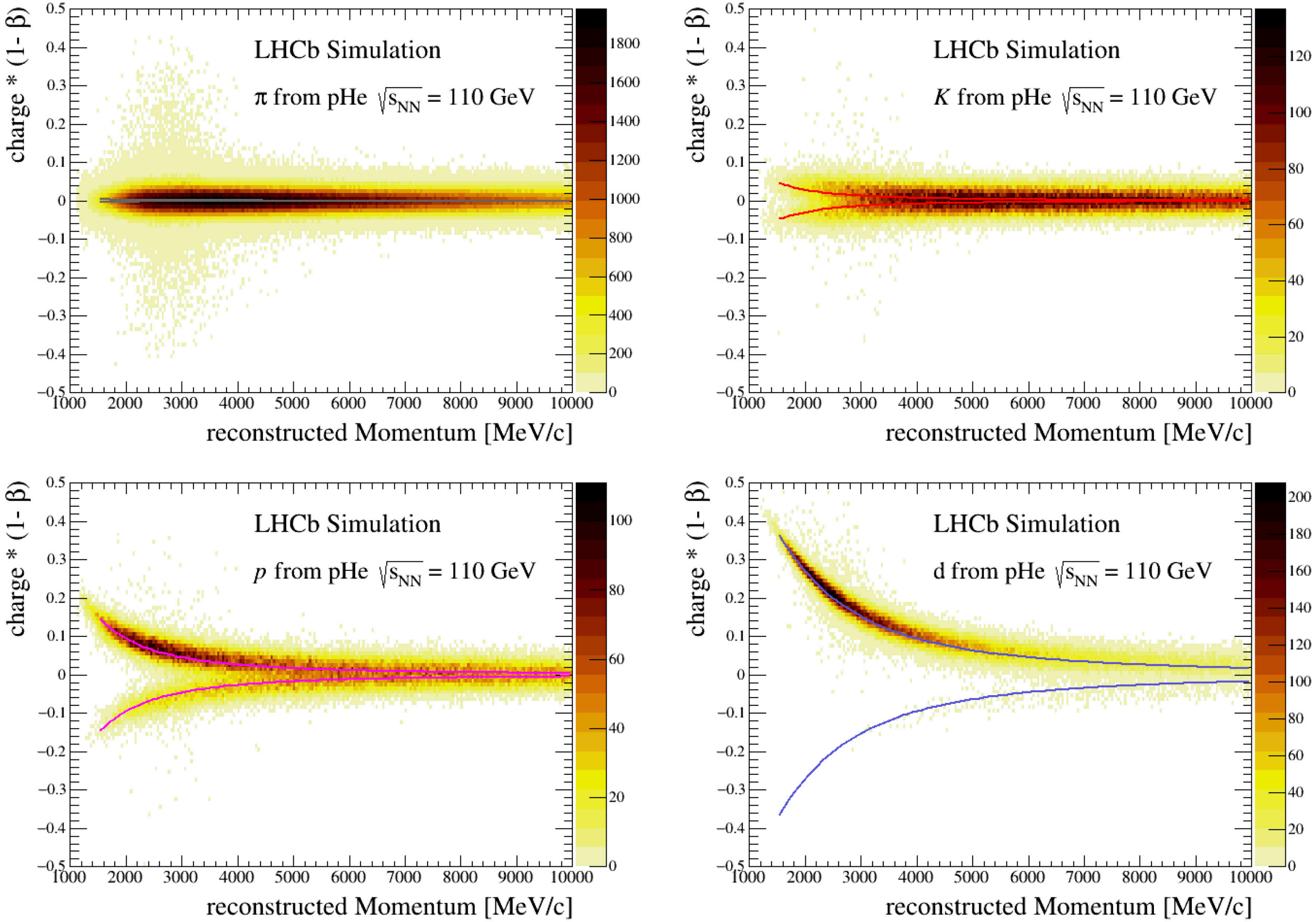
$$\varepsilon_{Track\ Reco} = {N_{Rec,L}}\Big/{N_{Recble,L}}$$



LHCb-FIGURE-2023-017

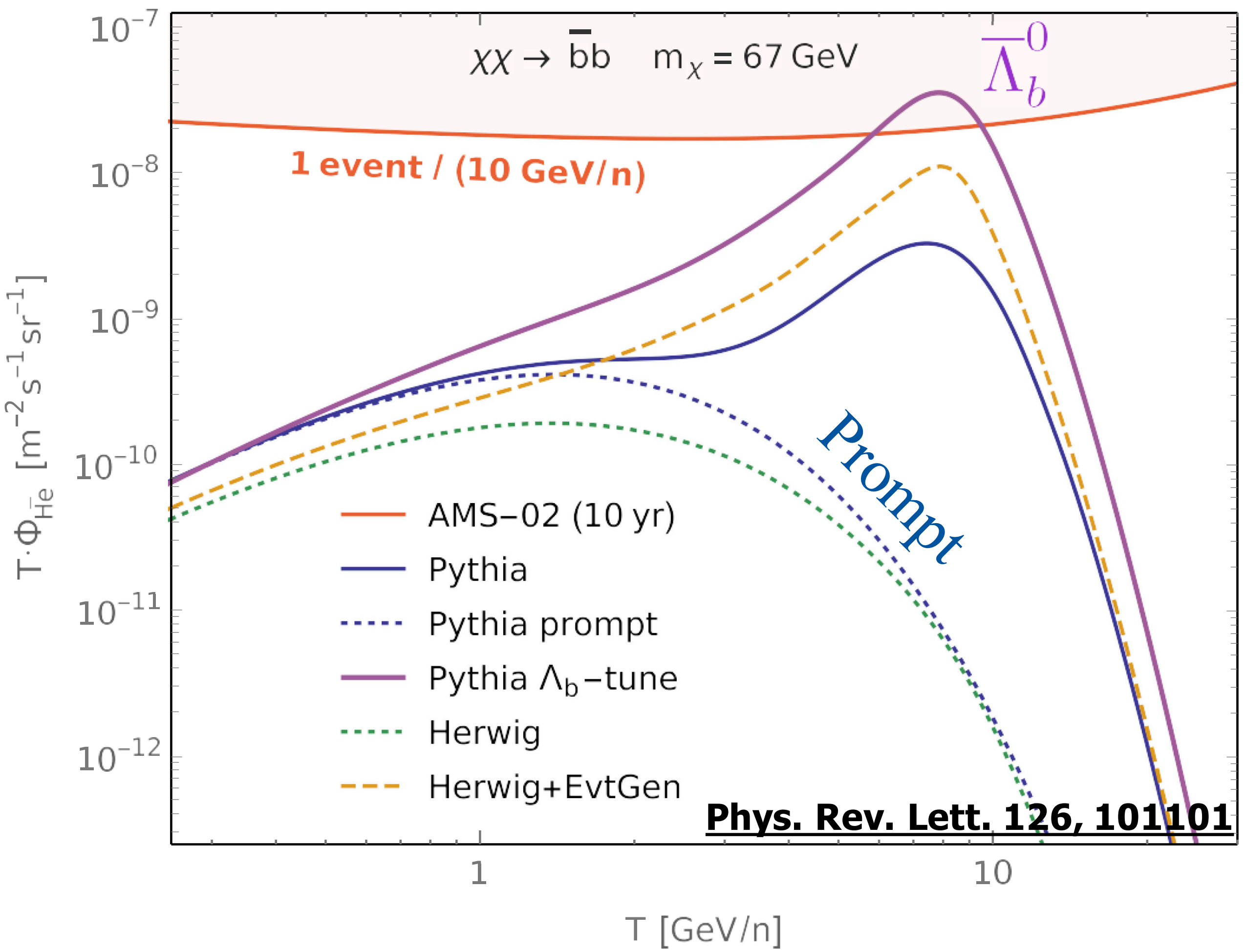
(Anti-)deuteron identification

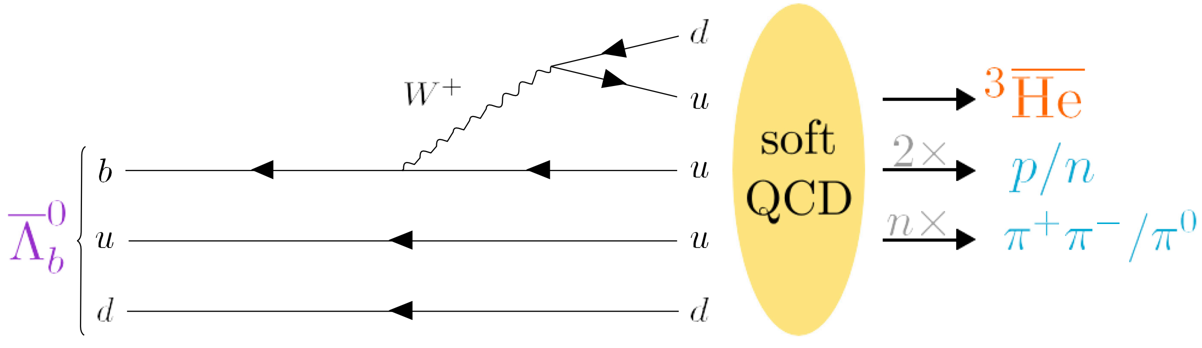
LHCb-FIGURE-2023-017



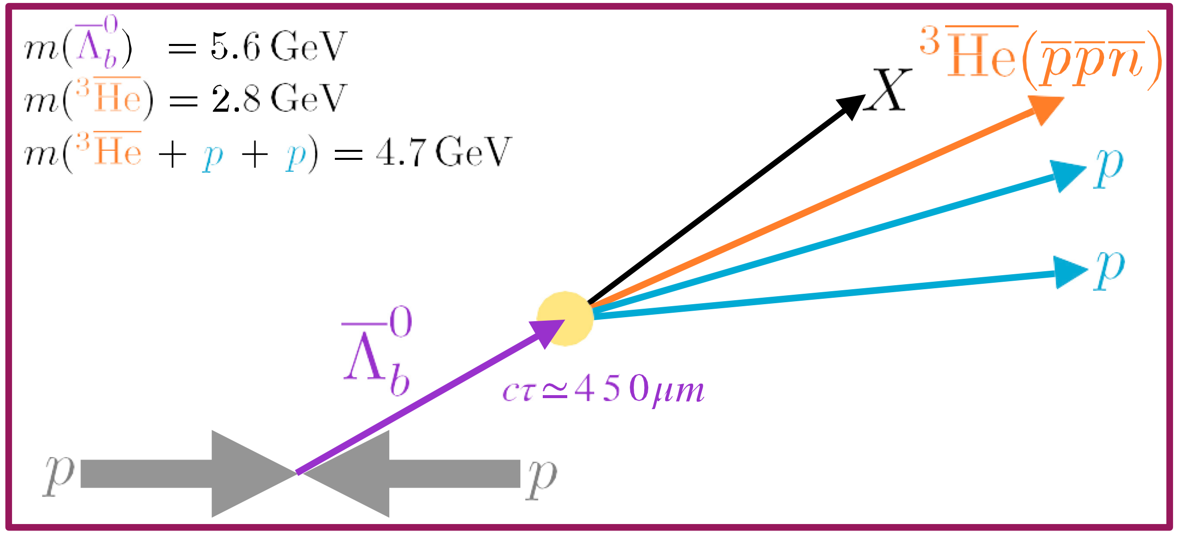
MC sample:
qgsjet for *p*He + **coalescence afterburner** (1 coal x event)

Anti-Helium production via $\overline{\Lambda}_b^0$





Experimentally cleanest: $\overline{\Lambda}_b^0 \to {}^3\overline{He}\, p\, p + X$



- $\overline{\Lambda}_b^0$ decays: $^3\overline{He}$ production enhanced with respect to $\overline{d}$