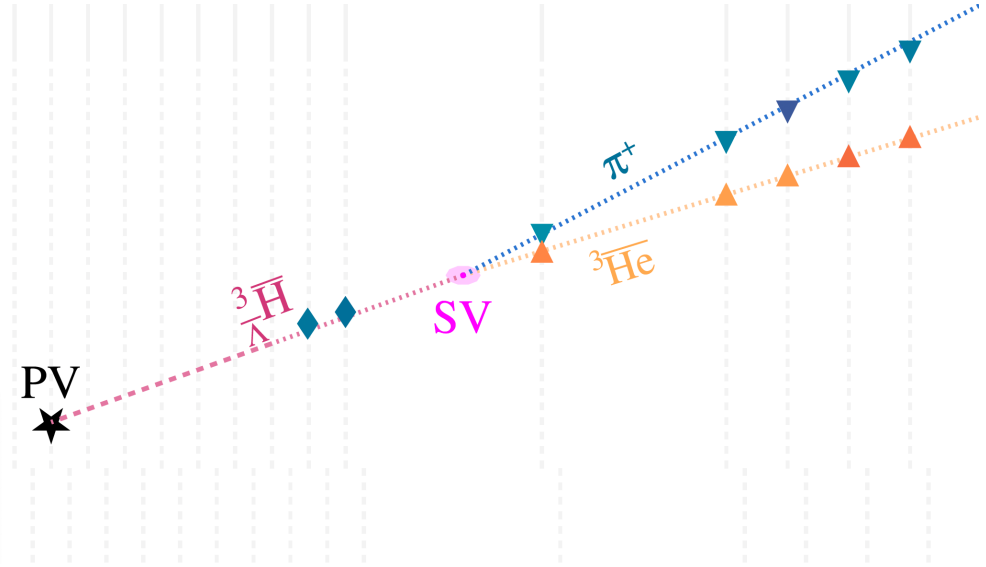
Measurements of (anti)nuclei at LHCb

Thomas Pöschl (CERN) on behalf of the LHCb collaboration

JENAA workshop on nuclear physics at the LHC and connections to astrophysics

19.08.2024



Inputs on (anti)nuclei for astrophysics from colliders

(Anti)nuclei formation

Required input for models of cosmic rays and indirect dark matter search

NA44, Nucl. Phys. A 590, 483C-486C (1995)
ALICE, Phys. Rev. C 93, 024917 (2016)
…

(Anti)nuclei absorption

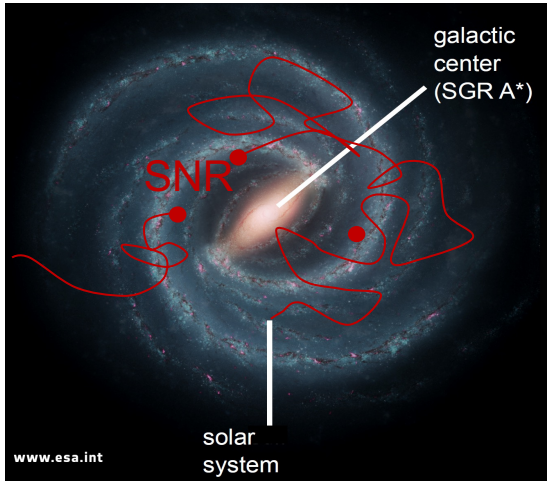
Modification of cosmic-ray (anti)nuclei fluxes during propagation in the Galaxy

ALICE, Phys. Rev. Lett 125, 162001 (2020),
ALICE, Nat. Phys. 19, 61-71 (2023)
…

Hyperon-nucleon interactions

Understanding hyperon content of neutron stars

STAR, Phys. Rev. C 97, 054909 (2018)
ALICE, Phys. Rev. Lett 131, 102302 (2023)
…



Cosmic rays

Credit: ESA

Neutron stars

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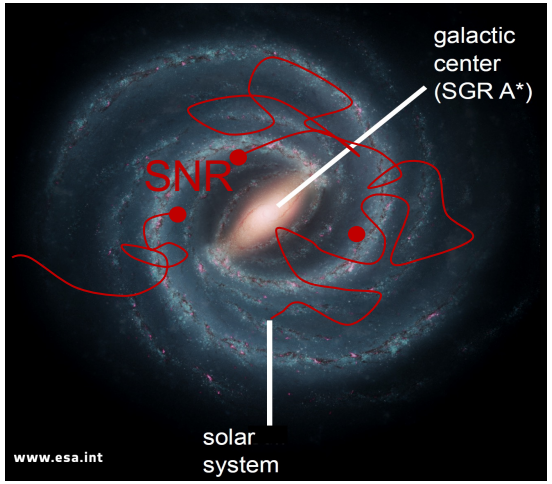
New input on (anti)nuclei by LHCb on its way!



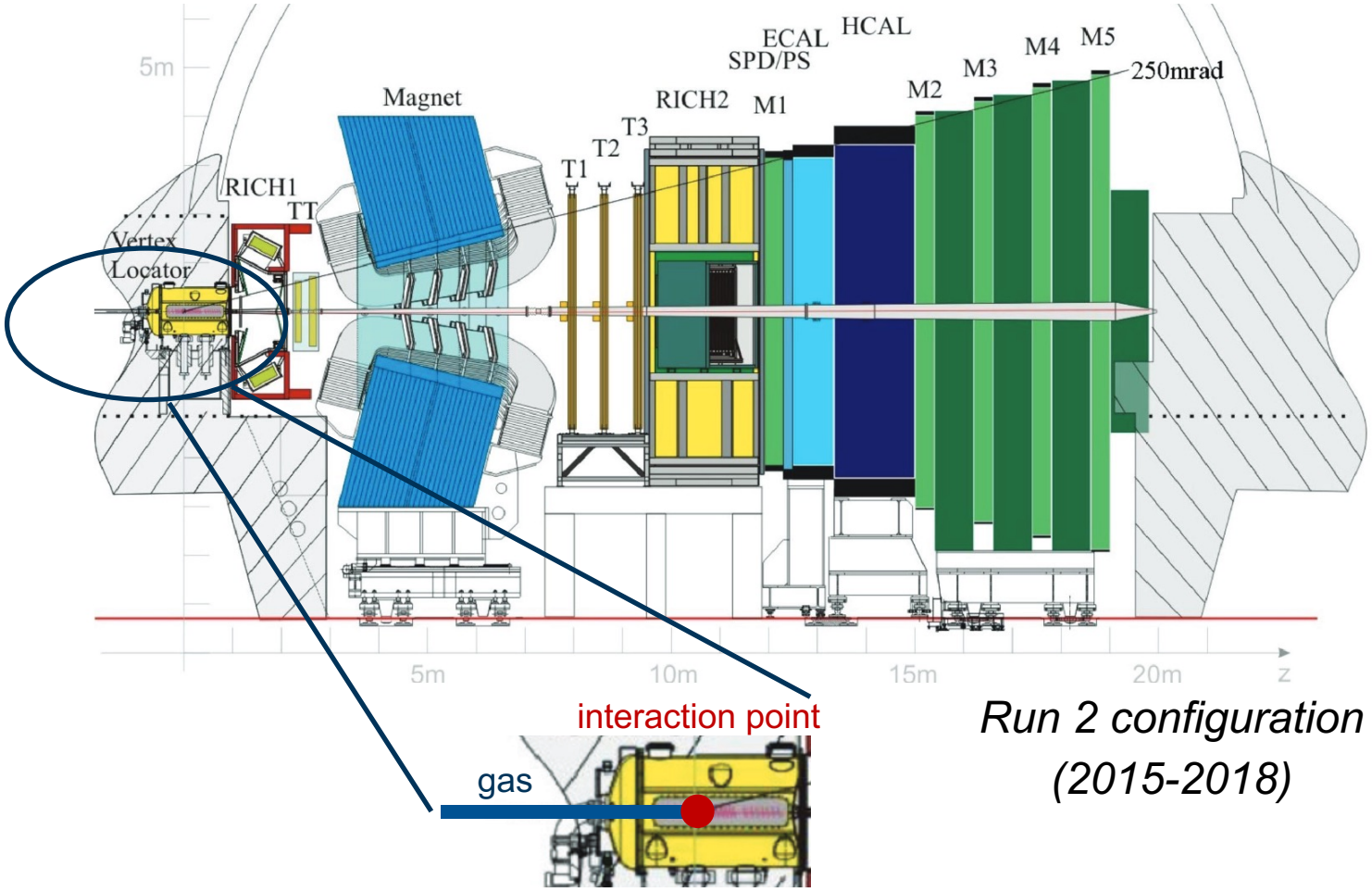
Cosmic rays

Credit: ESA

Neutron stars

LHCb: Unique opportunities for (anti)nuclei studies at the LHC

IJMPA 30 (2015) 1530022



Run 2 configuration (2015-2018)

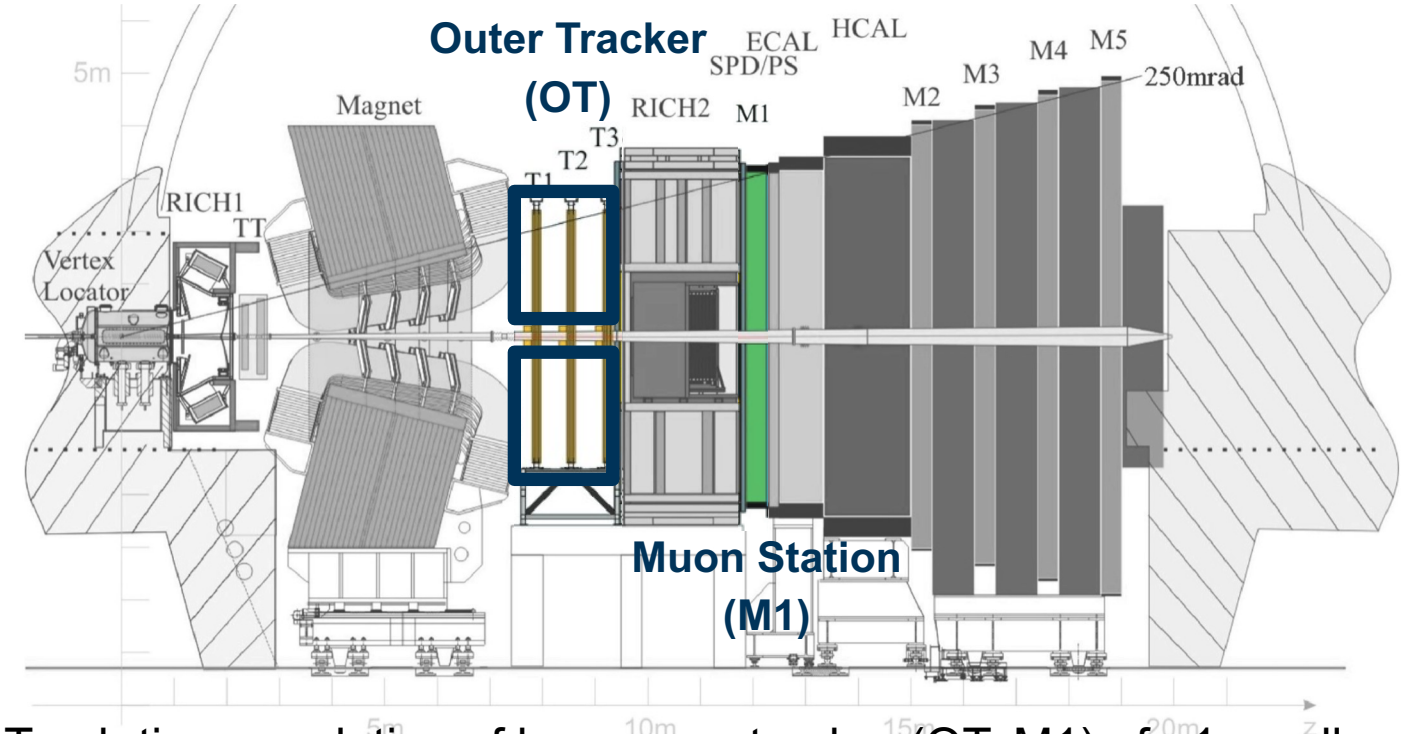
SMOG system

- Forward spectrometer at the LHC $(2 < \eta < 5)$
  → *Complementary to central rapidity measurements*
- Fixed target system (SMOG) to study (anti)nuclei production at lower collision energies and with different targets simultaneously to beam-beam collisions

  E.g. antiproton production in p-He collisions, see talk by C. Lucarelli tomorrow
- However, measurement of (anti)nuclei initially not considered and required PID currently under development

Identification of (anti)deuterons: Time-of-flight measurement

IJMPA 30 (2015) 1530022



- Track-time resolution of large-area tracker (OT, M1) of ~1 ns allows to perform ToF measurements of light (anti)nuclei at low momenta (e.g. for deuterons below around 2 GeV/c)

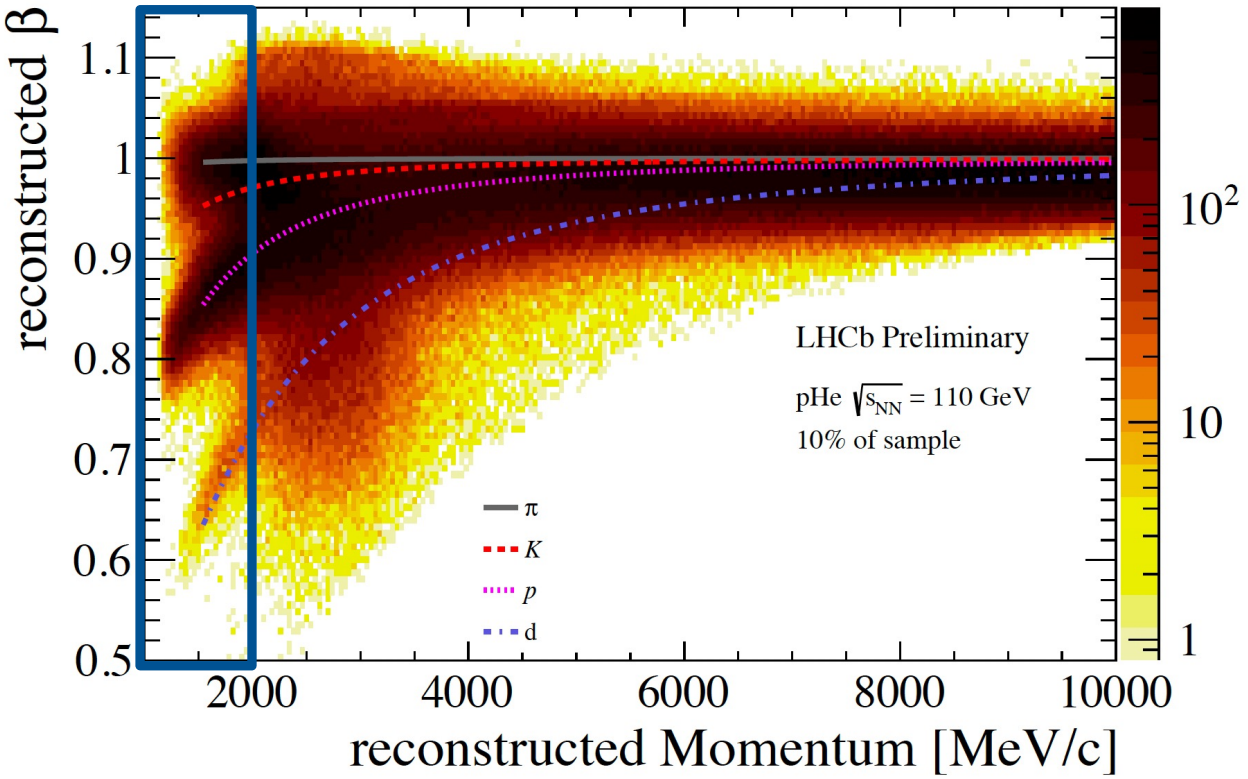
- Standard LHCb reconstruction assumes (β=1): Requires modified track-reconstruction
  → *extensive efficiency studies necessary*

Identification of (anti)deuterons: Time-of-flight measurement

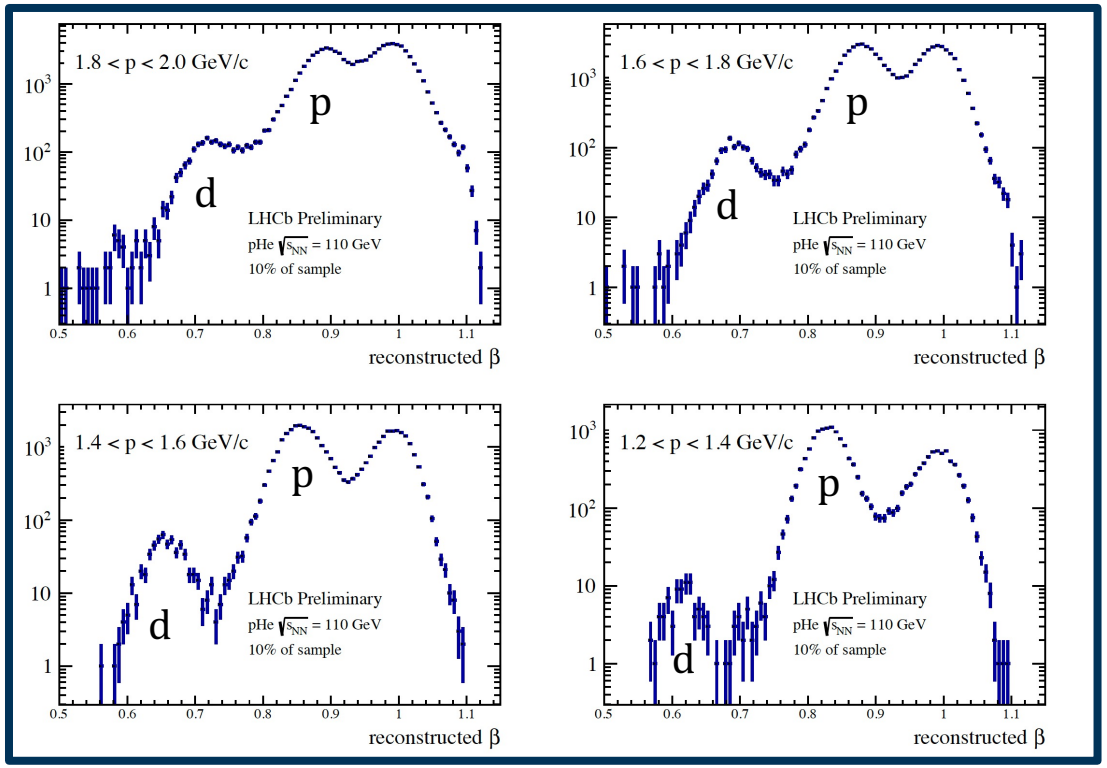
Current status

- Proof-of-concept using 10% of 2016 *p*He SMOG data ($\sqrt{s_{NN}} = 110$ GeV)
- Visible separation of deuterons from protons in momentum-velocity distribution

LHCb-FIGURE-2023-017



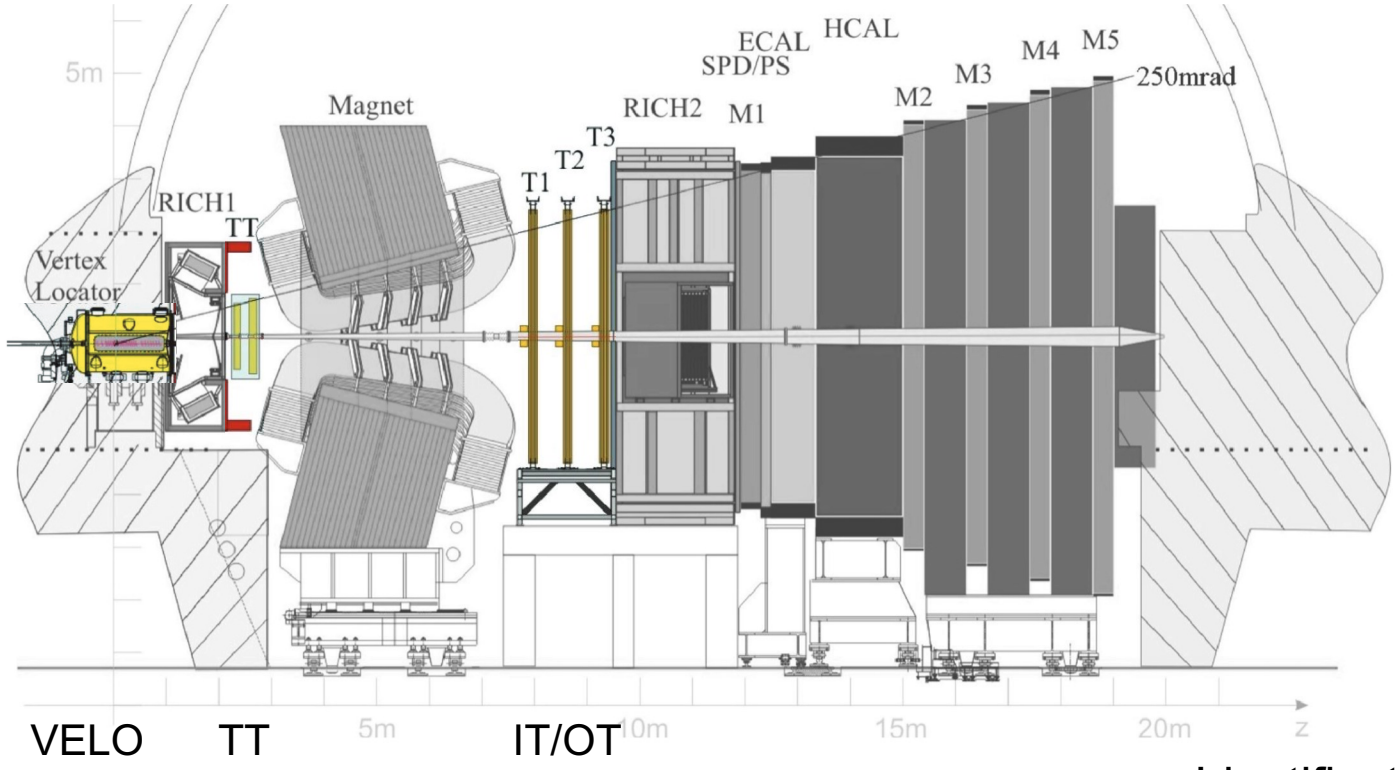
LHCb-FIGURE-2023-017



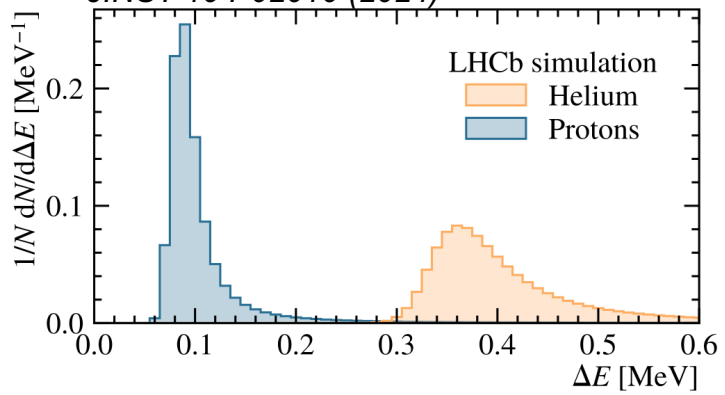
work in progress

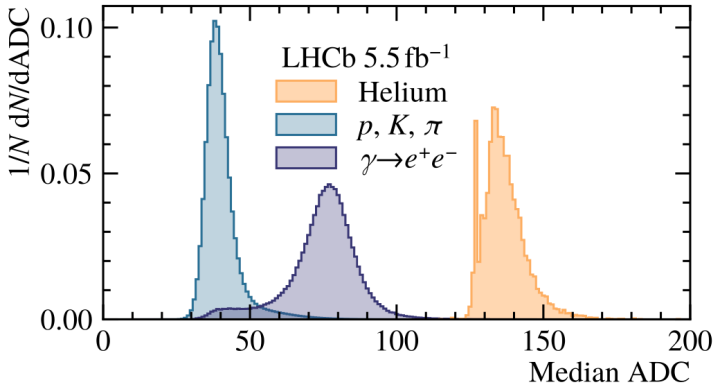
Identification of (anti)helium: Ionization-loss measurement

IJMPA 30 (2015) 1530022

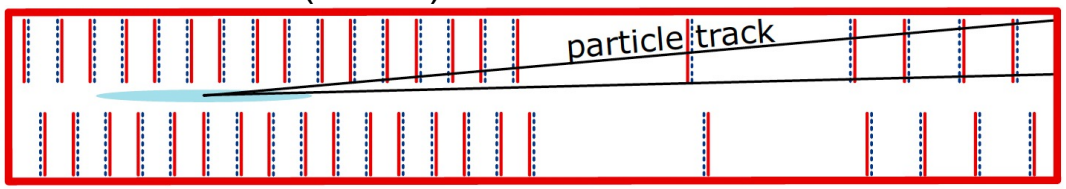


JINST 19 P02010 (2024)





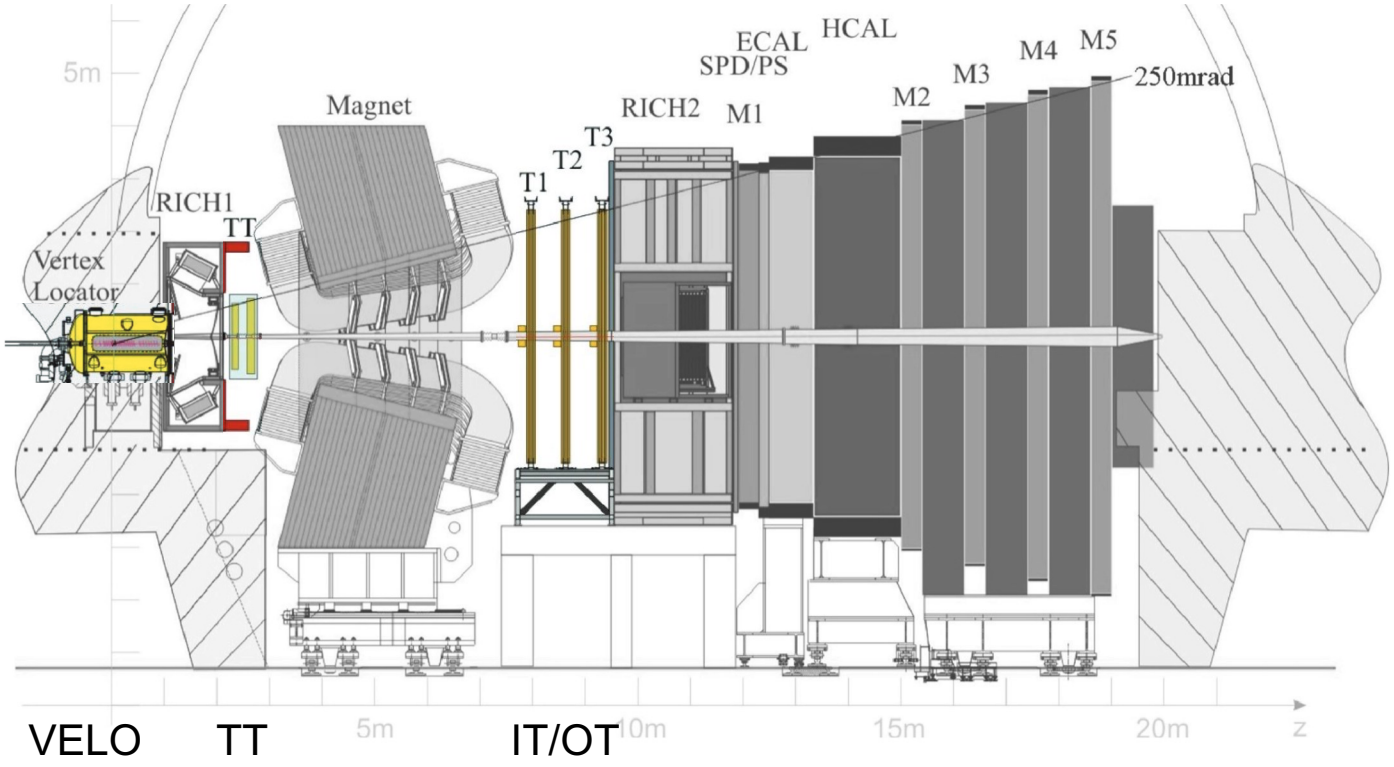
Vertex Locator (VELO)



- Identification of He (Z = 2) via energy deposition in tracking detectors ($\mathrm{d}E/\mathrm{d}x \propto Z^2$), especially in silicon sensors (VELO, TT, IT)
- Additional information from downstream tracker (OT), RICH, and Calorimeter to improve identification

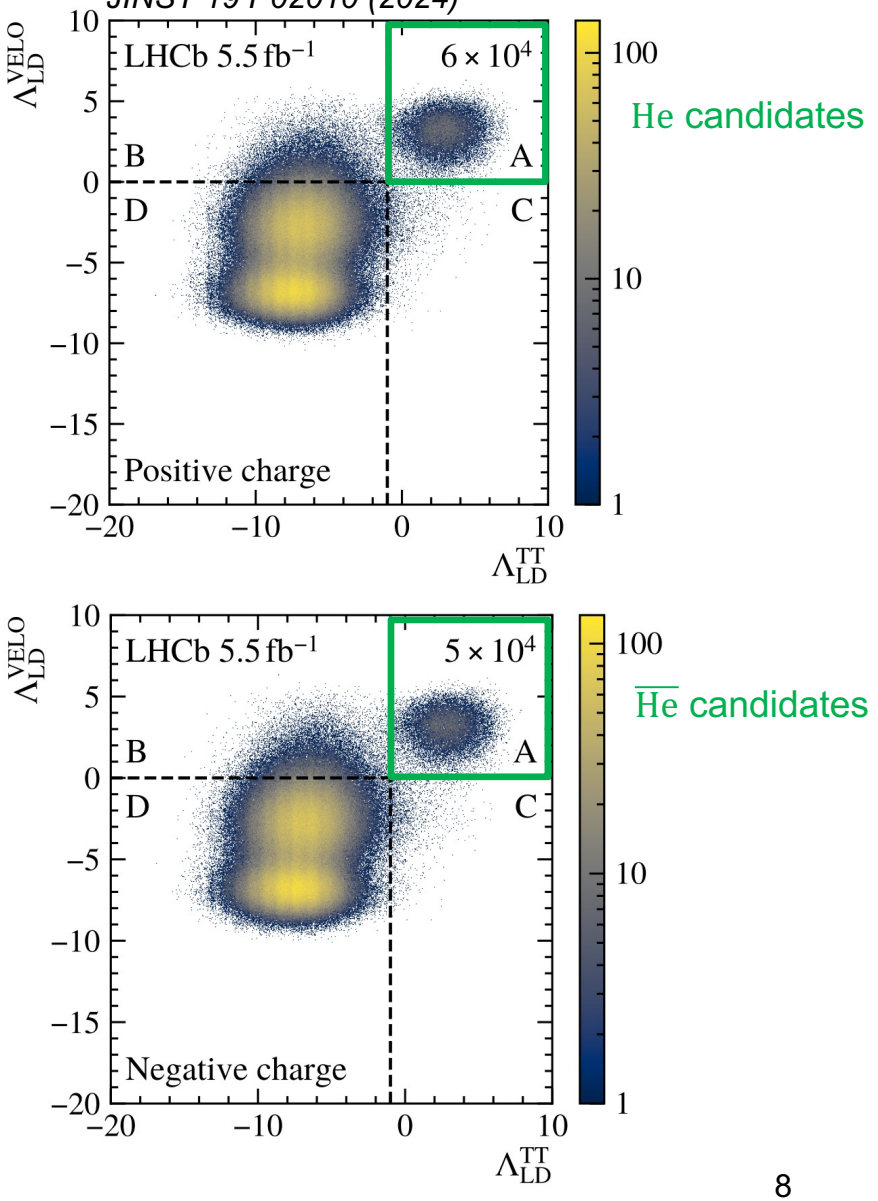
Identification of (anti)helium: Ionization-loss measurement

IJMPA 30 (2015) 1530022

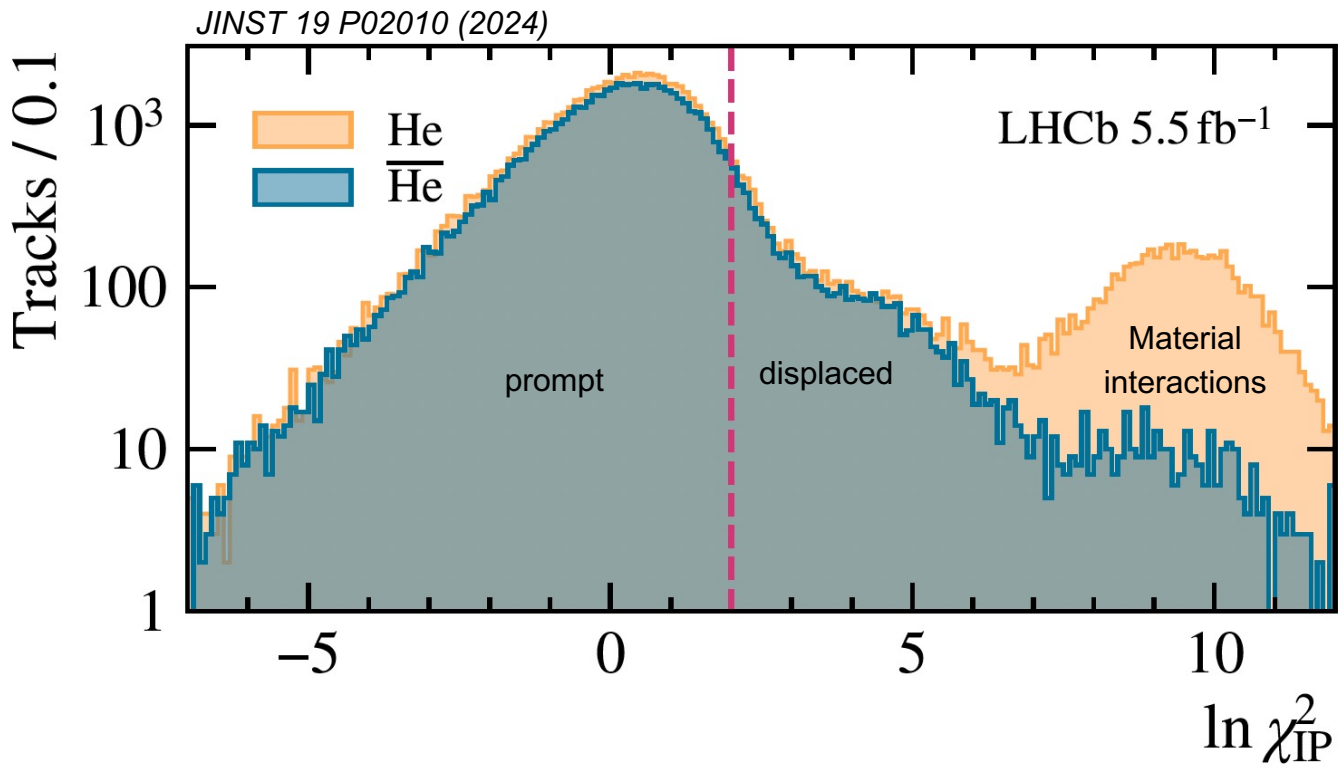


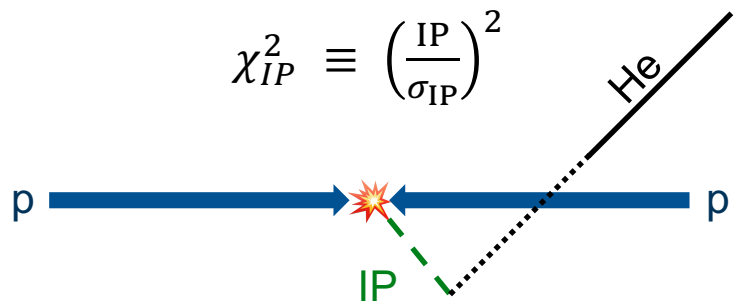
- Likelihood estimators ($\Lambda_{\mathrm{LD}}^{X}$) for VELO, TT, and IT to identify $Z = \pm 2$ candidates from energy depositions
- Background rejection rate of $\mathcal{O}(10^{12})$

JINST 19 P02010 (2024)



Current analyses with (anti)helium identification





Ongoing (anti)helium analyses with Run2 data

- Prompt production of (anti)helium in pp@13 TeV, SMOG pX(He,Ne,…)
- Displaced (anti)helium from (anti)hypertriton decays
- Antihelium from $\overline{\Lambda}_b^0$ decays

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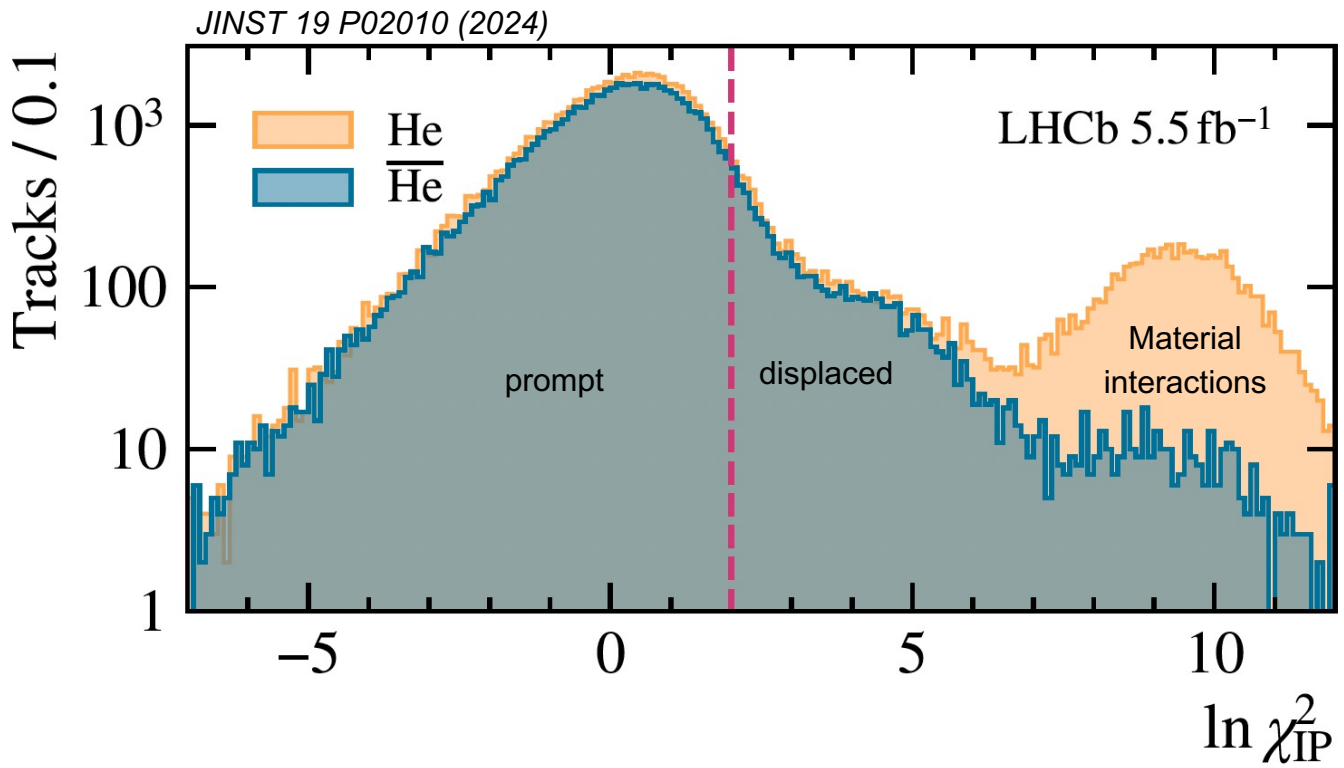

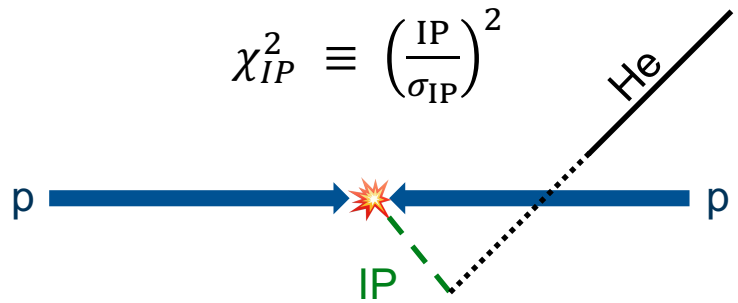

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- Antihelium from $\overline{\Lambda}_b^0$ decays

Measurement of (anti)hypertriton

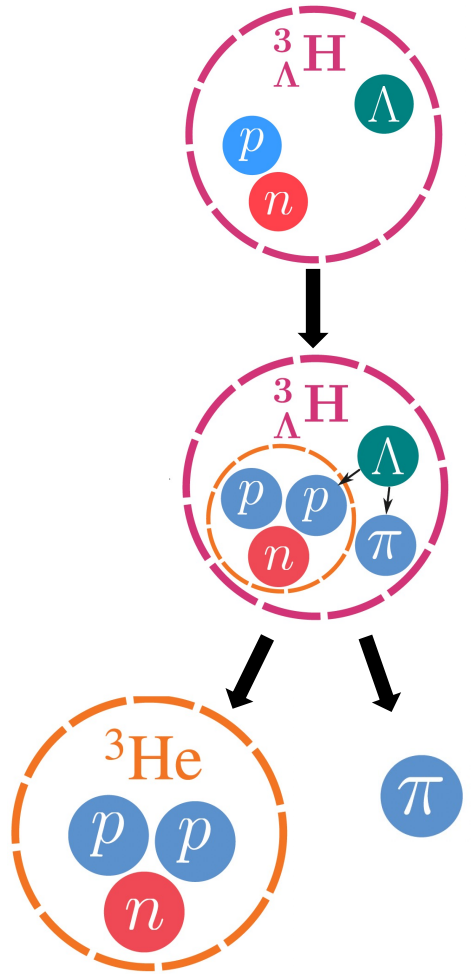
Motivation

- Ideal system to study hyperon-nucleon interactions

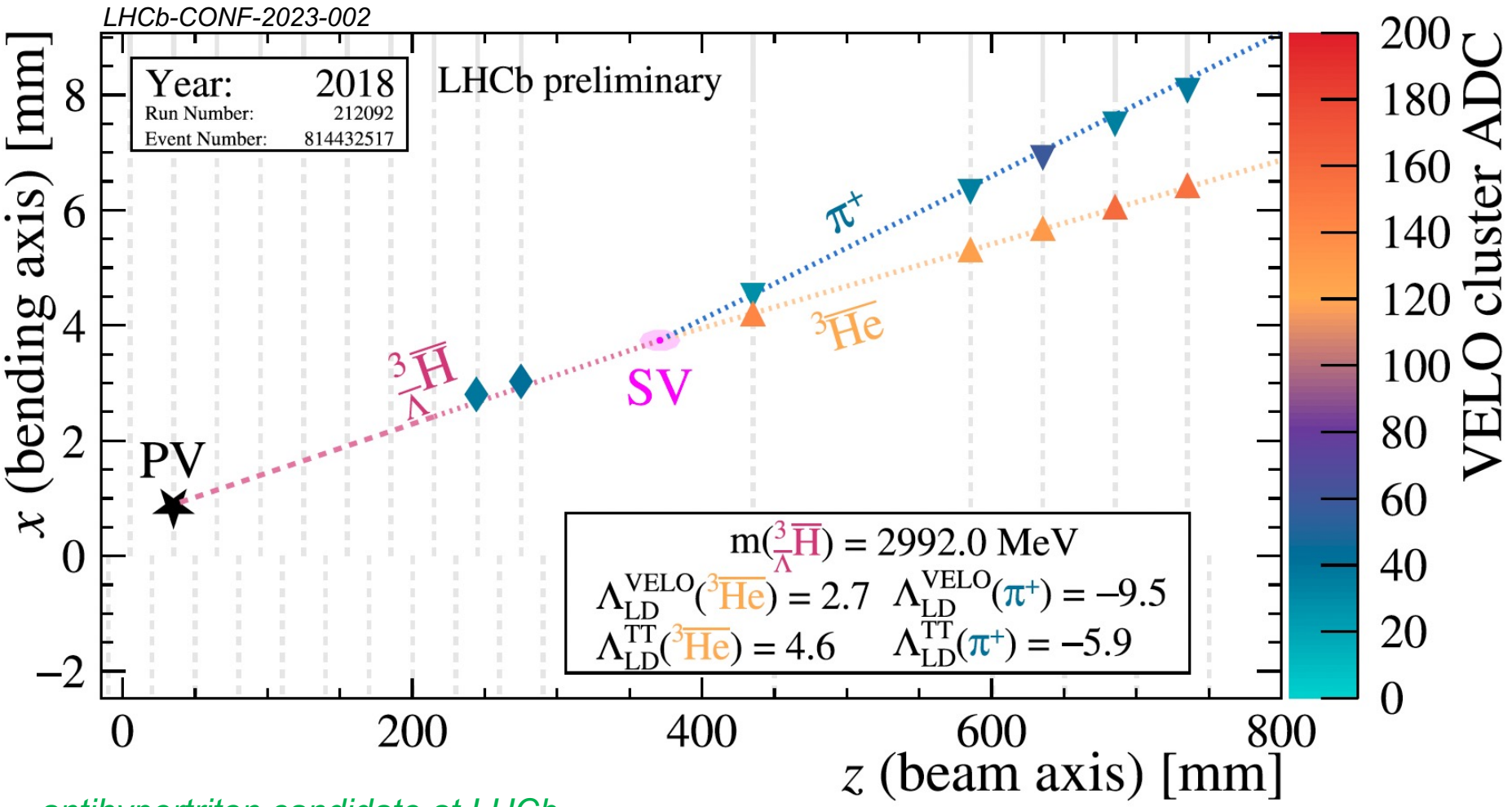
more details in next talk by F. Mazzaschi

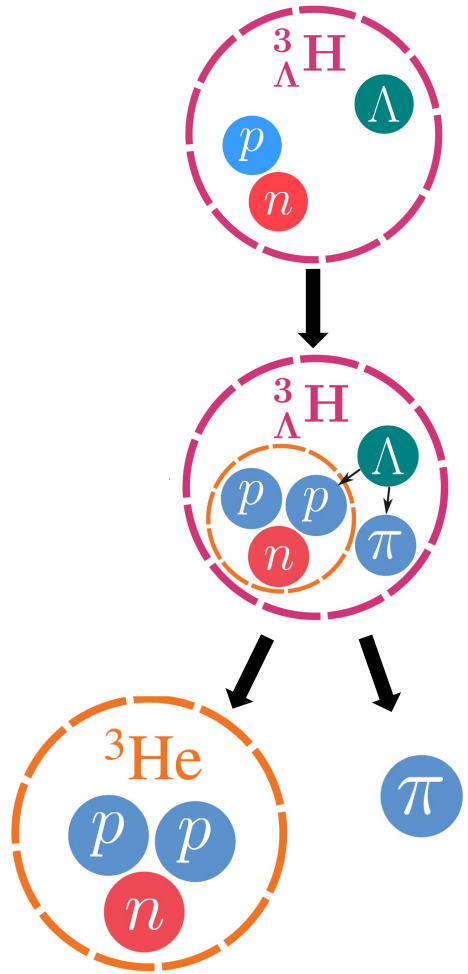
Identification

- Reconstruction via 2-body decay ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$
- Helium candidate from a displaced secondary vertex: $\chi^2_{\mathrm{IP}}({}^{3}\mathrm{He}) > 2$
- Well reconstructed secondary vertex with charged pion



Measurement of (anti)hypertriton

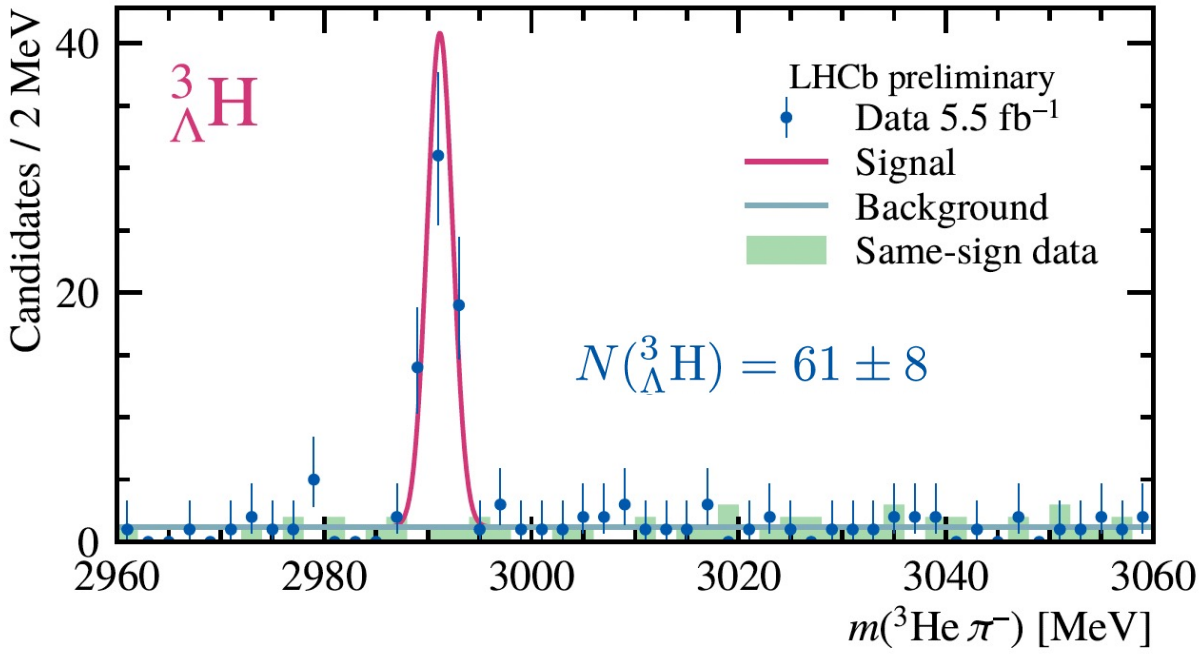


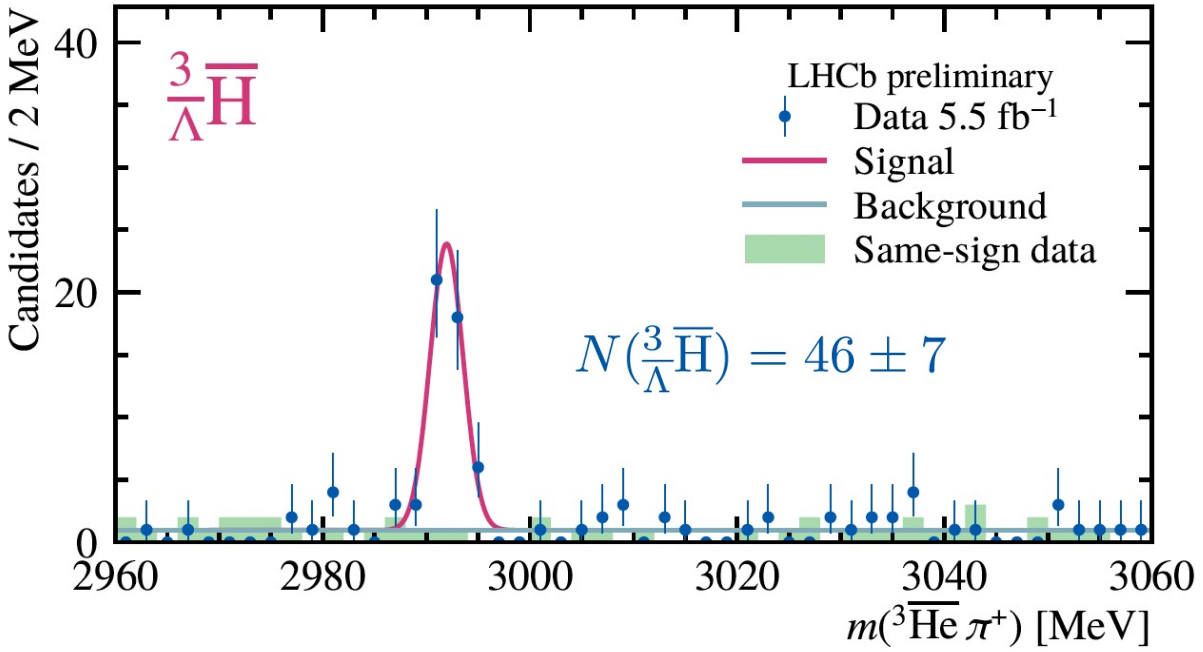


antihypertriton candidate at LHCb

Invariant-mass distribution of (anti)hypertriton candidates

LHCb-CONF-2023-002





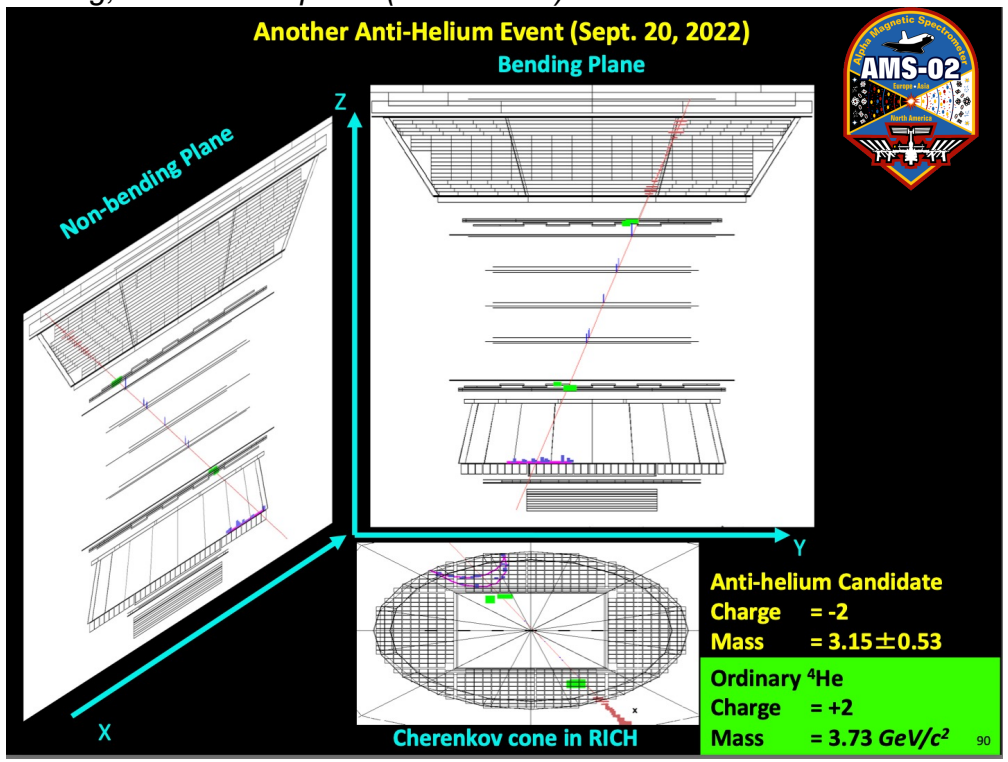
107 ± 11 (anti)hypertriton candidates in Run2 pp@13TeV (5.5 fb^{-1})

Ongoing work:

- Further optimization of signal selection (improvements in He identification)
- Systematic corrections on mass scale: charge-sign dependent tracking and energy-loss corrections
- Efficiency and acceptance corrections

Search for antihelium from $\overline{\Lambda}_b^0$ decays: Motivation

S. Ting, CERN colloquium (08.06.2023)

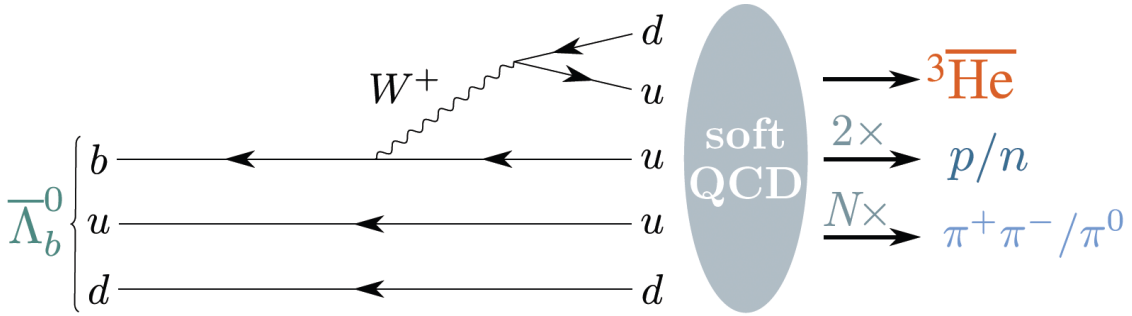


- Several antihelium candidates found in CR by AMS-02
- Flux magnitude hard to explain by conventional production models and even for most DM models due to constraints from cosmic antiproton flux

Dark Matter Annihilation Can Produce a Detectable Antihelium Flux through $\bar{\Lambda}_b$ Decays

Martin Wolfgang Winkler[1,*] and Tim Linden[1,†]

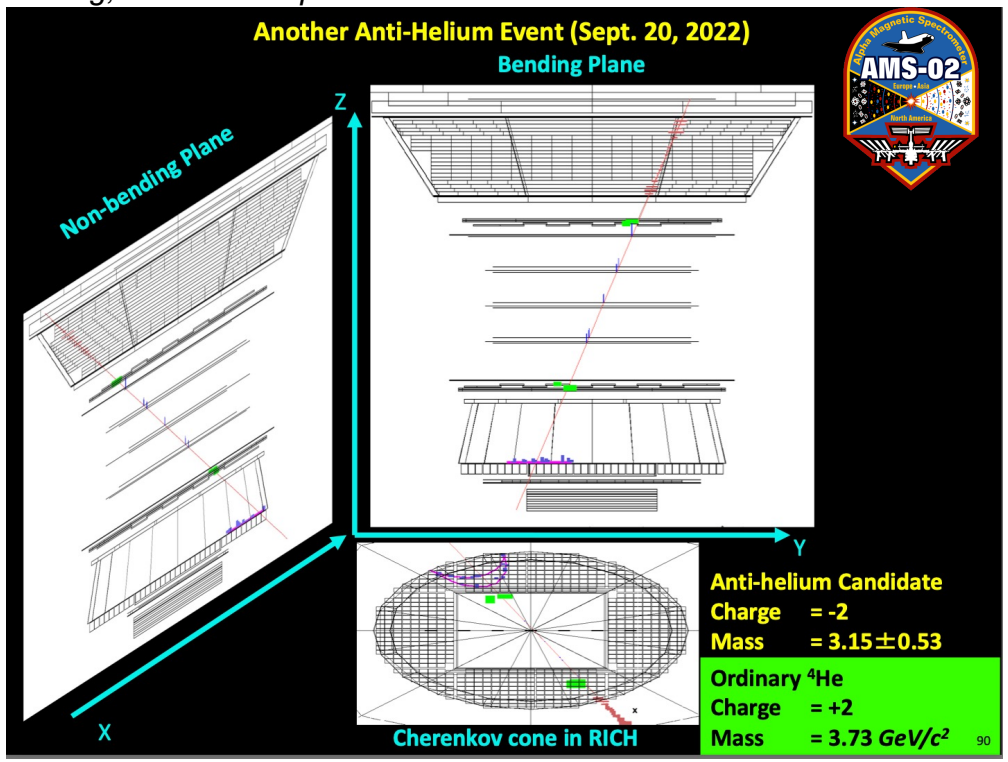
[1]*Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*



- $\overline{\Lambda}_b^0$ expected to be generically produced in DM annihilations involving b quarks
- Rest mass slightly above $5\times m_{\mathrm{p,n}}$
  → Small relative momentum between (anti)nuclei to increase chance of coalescence to $^3\overline{\mathrm{He}}$

Search for antihelium from $\overline{\Lambda}_b^0$ decays: Motivation

S. Ting, CERN colloquium



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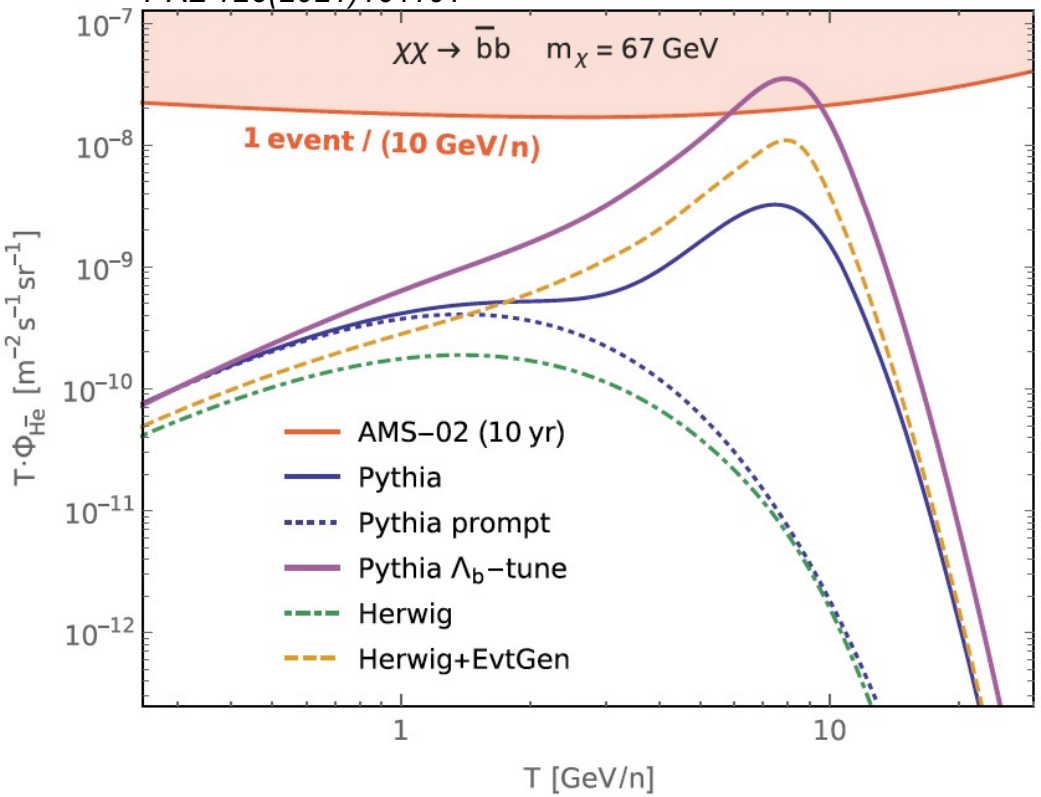
PRL 126(2021)101101



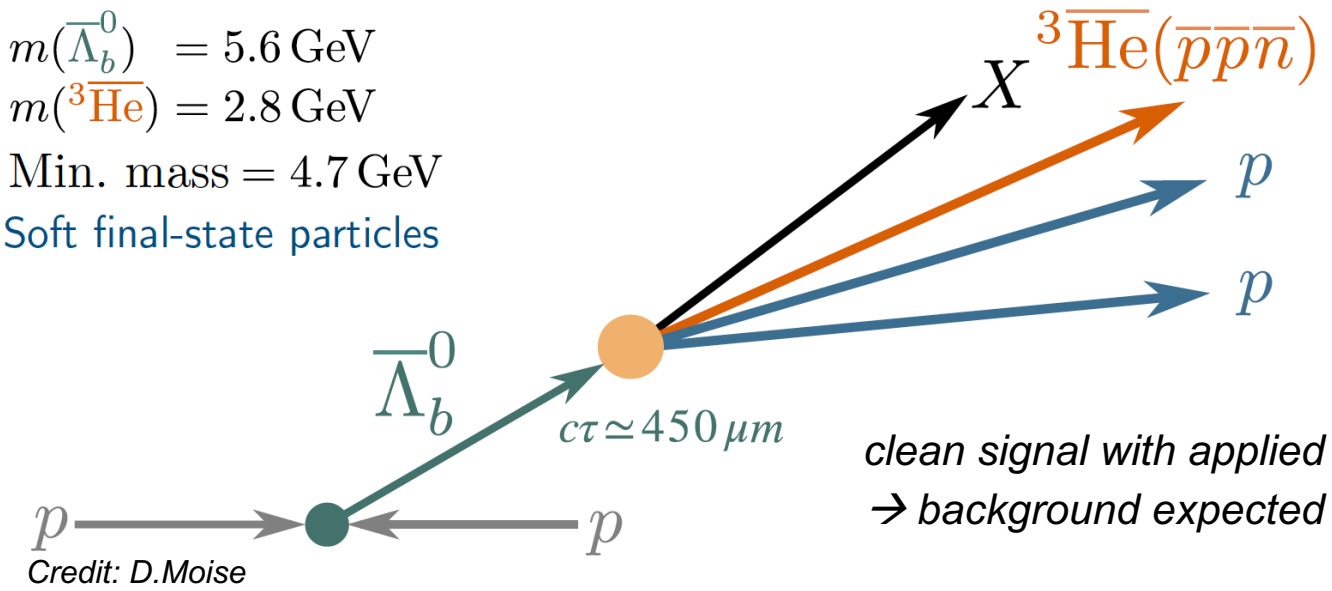
measureable flux for AMS-02 with tuned Pythia for $\mathcal{B}(\overline{\Lambda}_b^0 \to \overline{\mathrm{He}} + X) \approx \mathcal{O}(10^{-6})$

Search for antihelium from $\overline{\Lambda}_b^0$ decays: Search strategy

Run 2 pp@13 TeV (5.5 fb^{-1})

LHCb-CONF-2024-005

$m(\overline{\Lambda}_b^0) = 5.6\,\text{GeV}$
$m(^3\overline{\text{He}}) = 2.8\,\text{GeV}$
$\text{Min. mass} = 4.7\,\text{GeV}$
Soft final-state particles



Credit: D.Moise

clean signal with applied He and p PID
→ background expected only from combinatorics

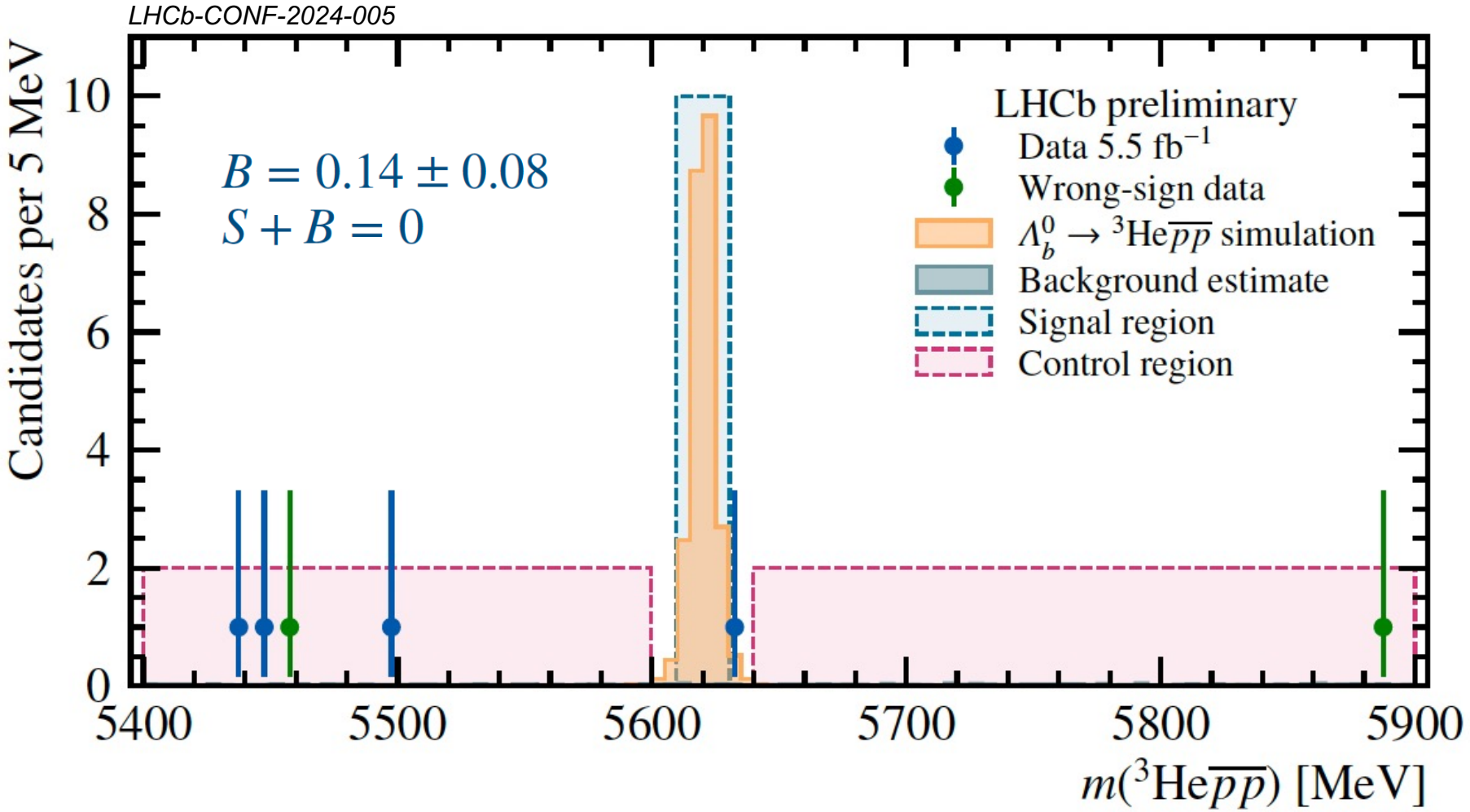
Measure:

$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\text{He}} + \text{p} + \text{p})$ **(exclusive mode)**
$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\text{He}} + \text{p} + \text{p} + \text{X})$ **(inclusive mode)**
$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\text{He}} + p + \text{X})$ **(inclusive mode)**

→ use decay models to extrapolate to $\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\text{He}} + \text{X})$

Search for antihelium from $\overline{\Lambda}_b^0$ decays: Invariant-mass spectra

$\overline{\Lambda}_b^0 \rightarrow {}^3\overline{\mathrm{He}} + \mathrm{p} + \mathrm{p}$ (exclusive mode)



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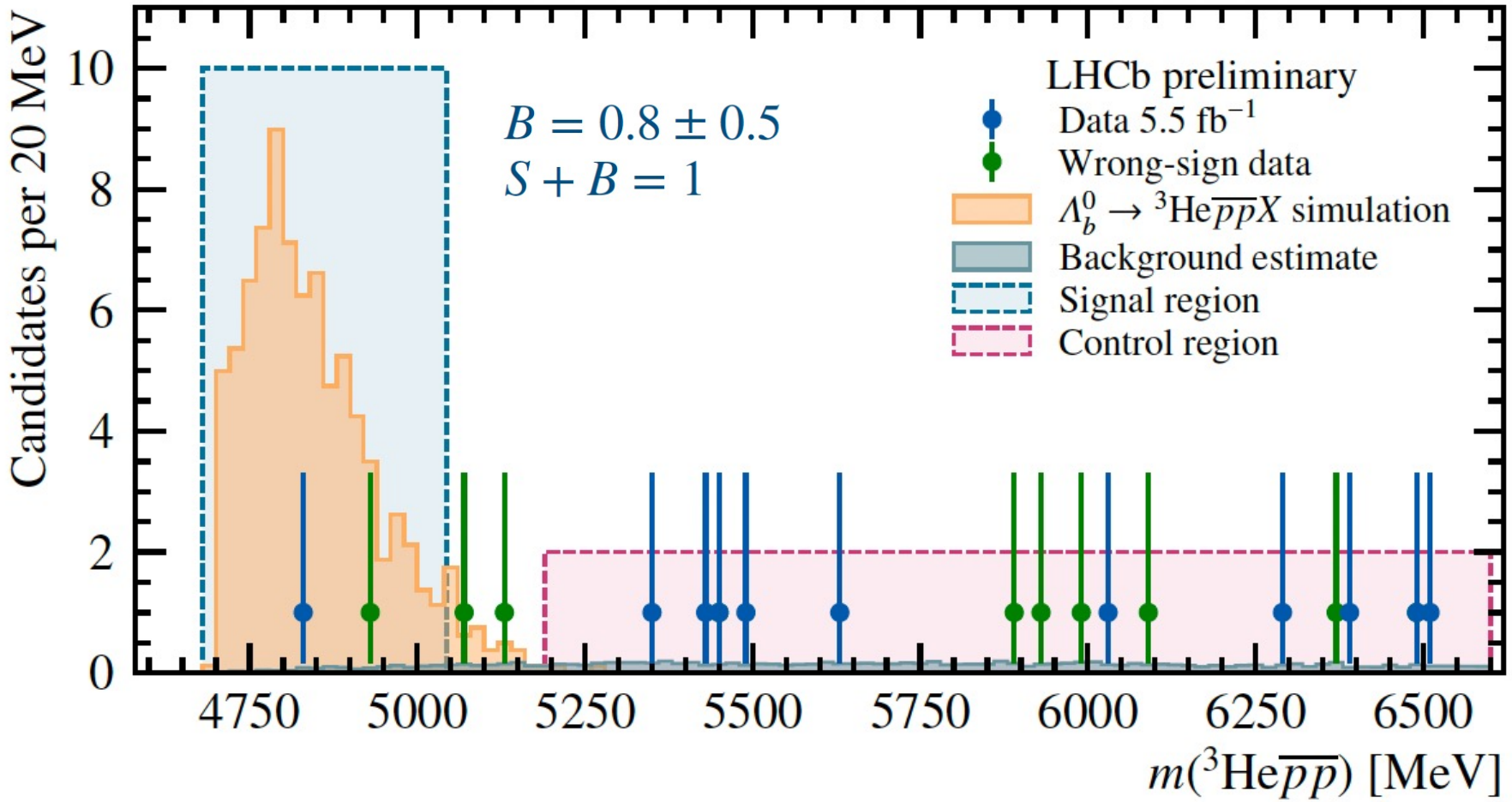

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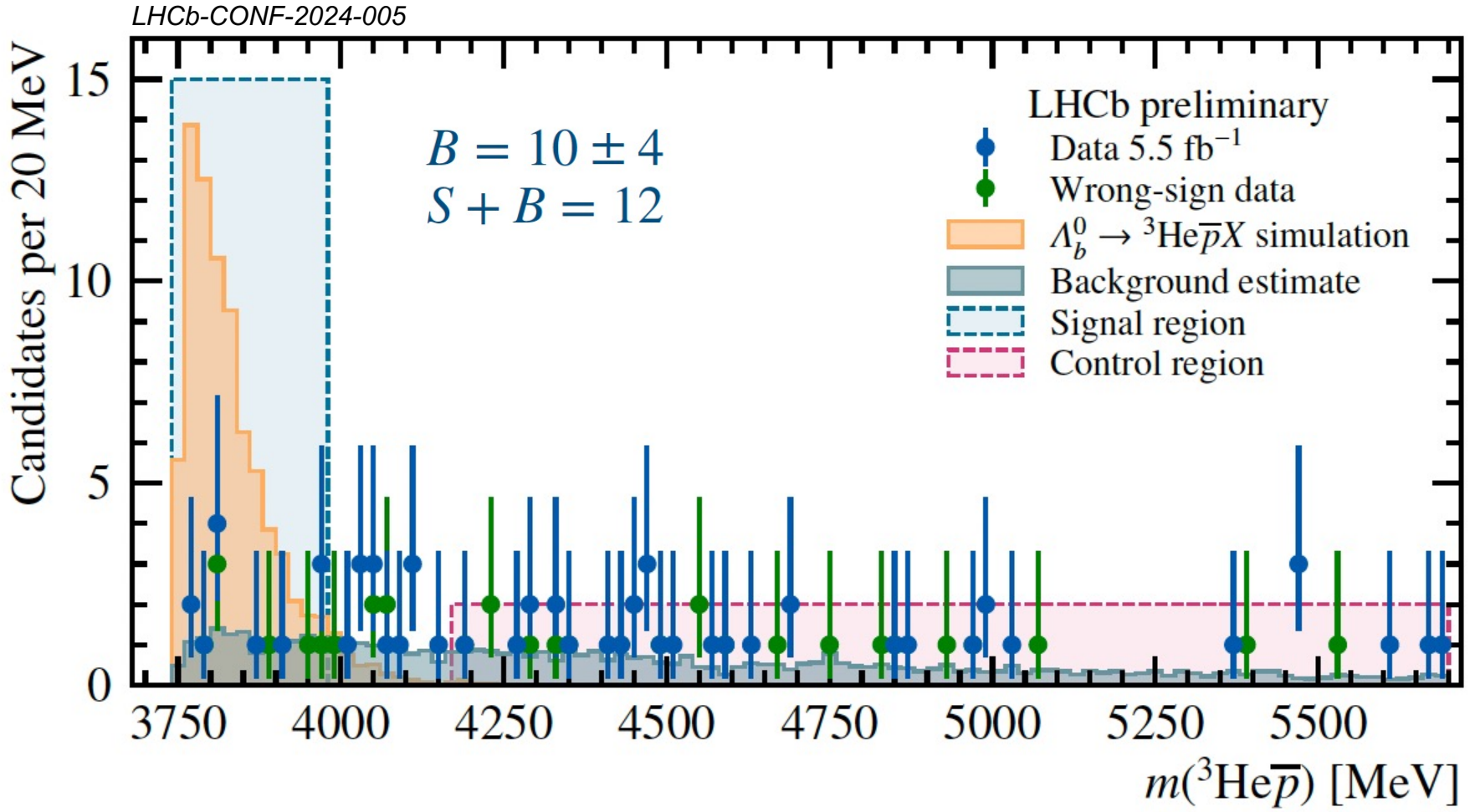

No significant signal found for any of the decay modes

Search for antihelium from $\overline{\Lambda}_b^0$ decays: Measured upper limits

- Upper limit for $\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}} + \mathrm{p} + \mathrm{p})$ with no signal candidate using profile-likelihood method *NIM A, Vol.458,3,745 (2001)*
- For inclusive modes, limits via $\mathrm{CL_s}$ method *J. Phys. G28, 2693 (2002)*
- *Including systematic uncertainties (dominating is the background estimate)*

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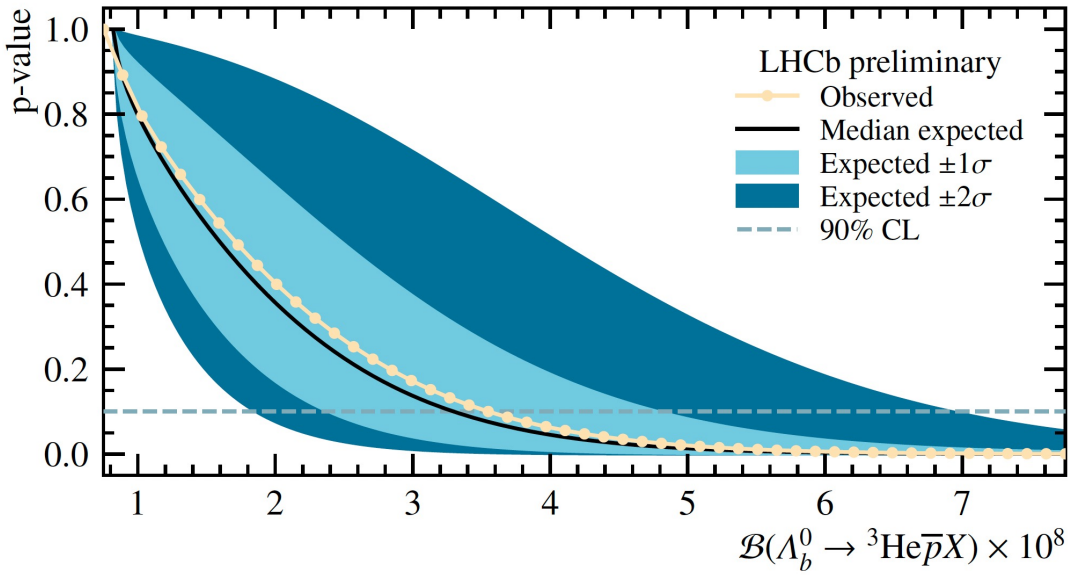
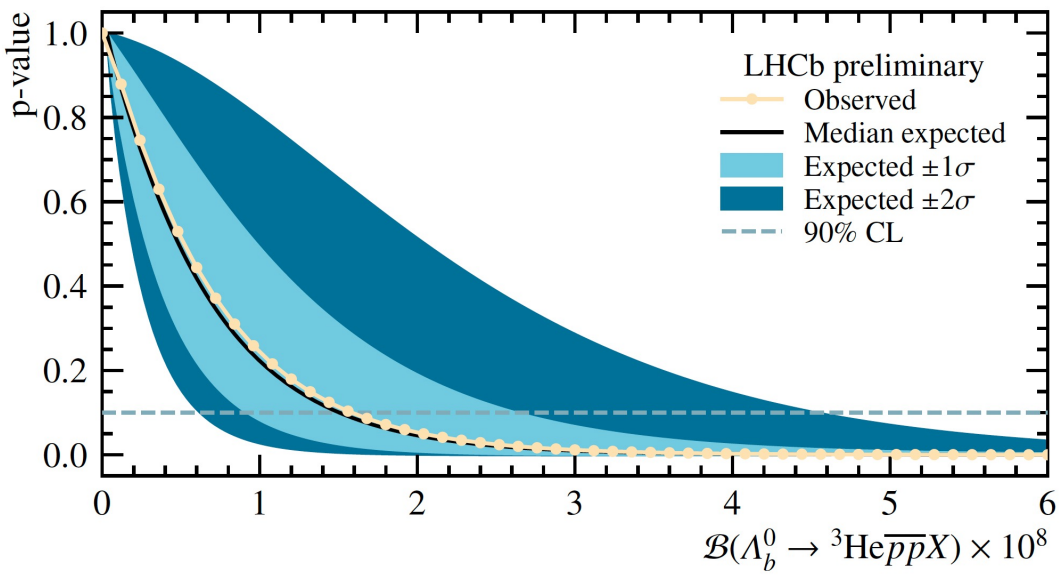




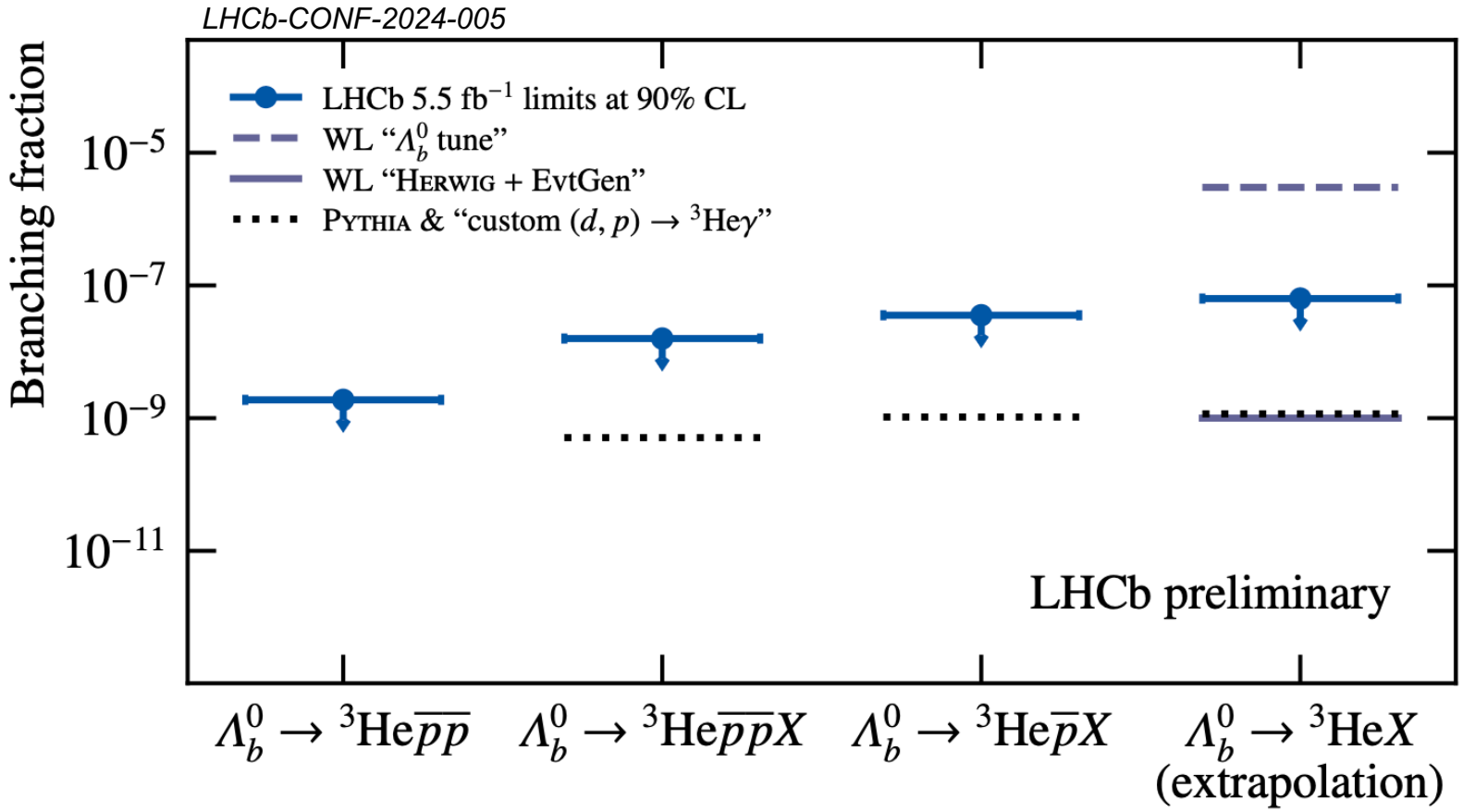
$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}pp) < 1.9 \times 10^{-9} \text{ at } 90\% \text{ CL}$$

$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}ppX) < 1.6 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}pX) < 3.6 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

Search for antihelium from $\overline{\Lambda}_b^0$ decays: Extrapolation to $\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}X)$

Conservative extrapolation assuming isospin symmetric production of nucleons



$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}X) < 6.3 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

Summary and Outlook

New techniques under development for (anti)nuclei PID in Run 2 open a new field of research for LHCb and provide new input for astroparticle physics

- First limit on (Anti)helium production from $\overline{\Lambda}_b^0$ decays

$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}X) < 6.3 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

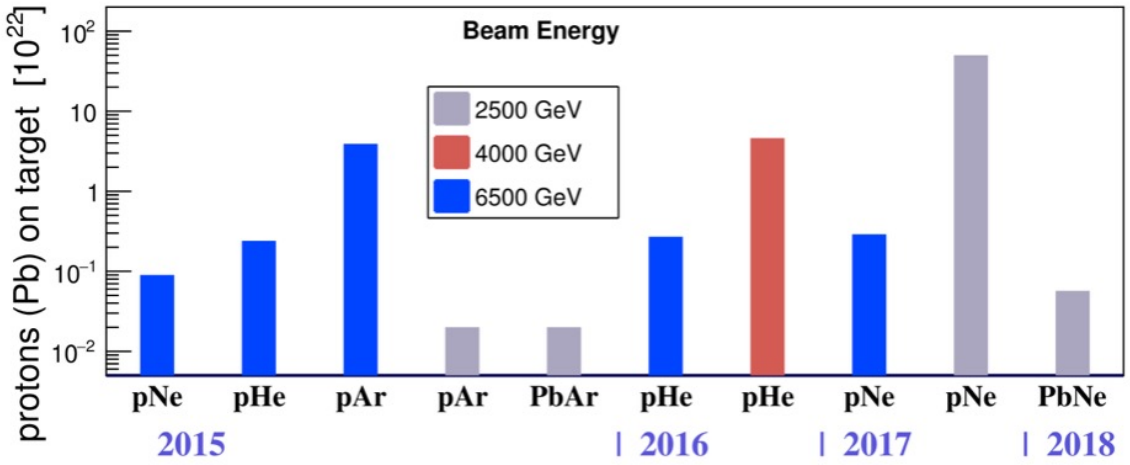
- Observation of around 110 (anti)hypertriton candidates (*characteristics to be extracted*)

- Further analyses ongoing on SMOG data: Production of antideuerons and antihelium (*work in progress*)

Long-term perspective: LHCb Upgrade II

- Enhanced nuclei PID due to new TORCH detector (Run 5&6) *Nim. A 1048, 167991 (2023)*

LHCb-PUB-2018-015



Thank you for your attention!

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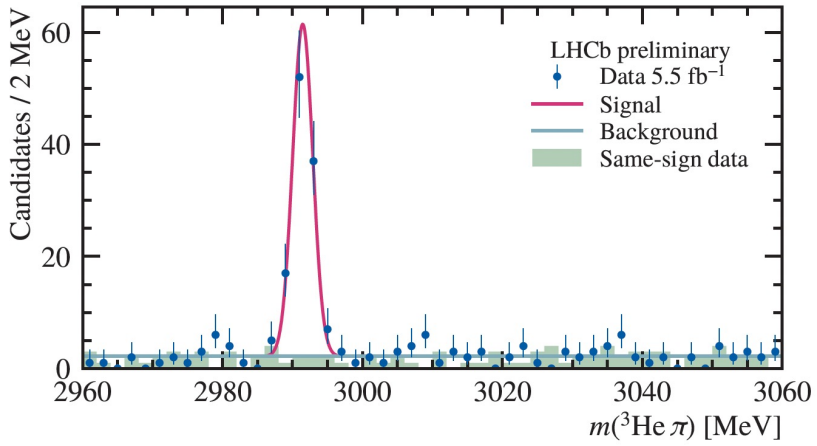

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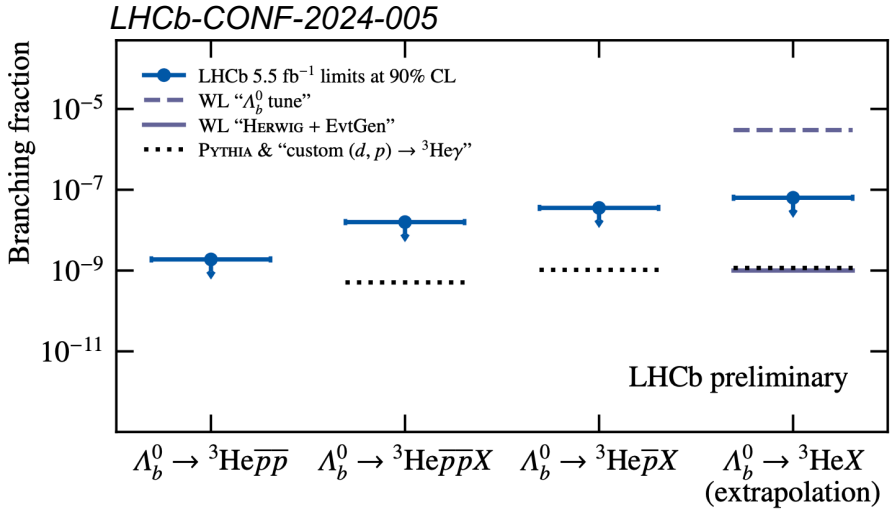
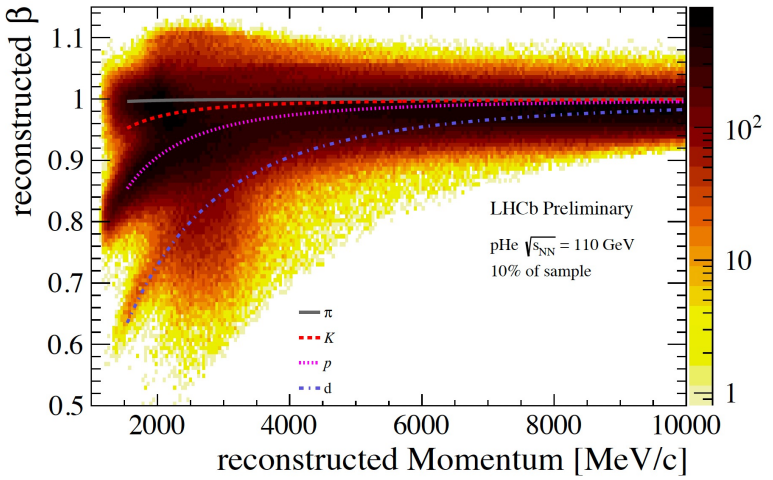


LHCb-FIGURE-2023-017



Any Questions?

Backup