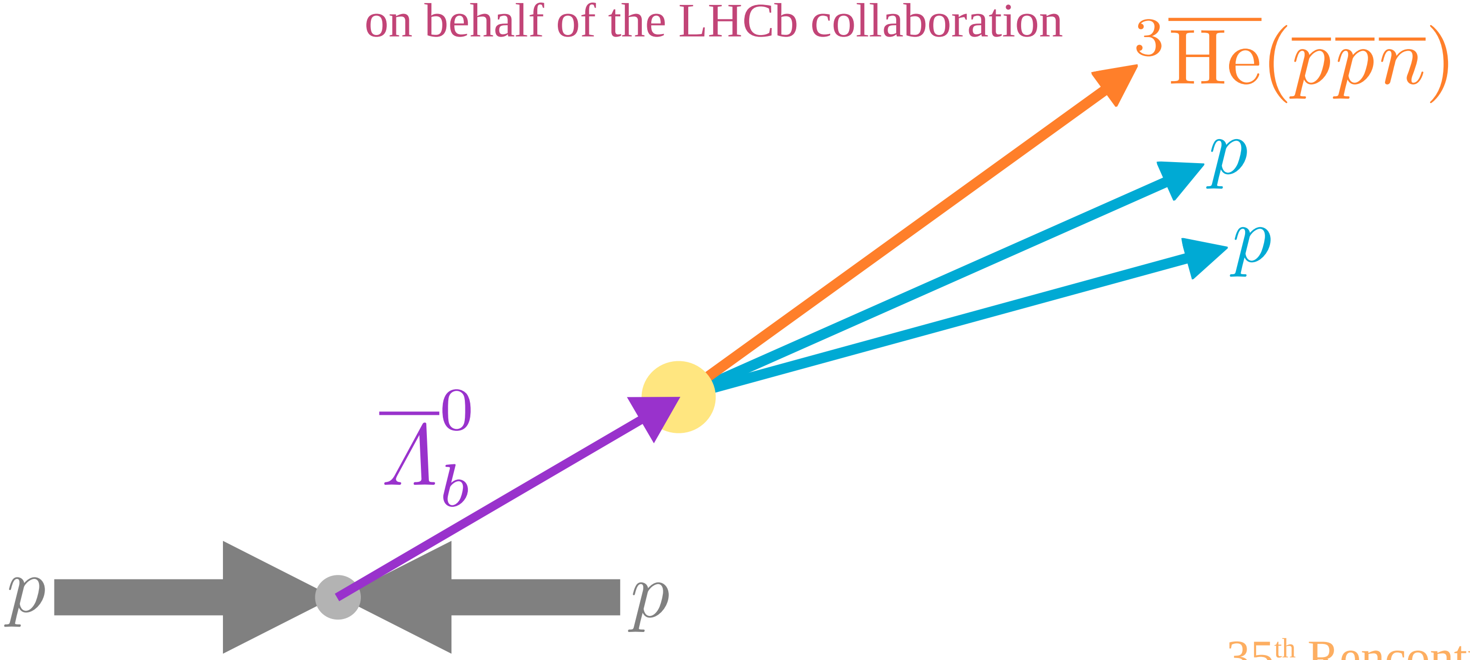
Antihelium production in $\overline{\Lambda}_b^0$ decays

Hendrik Jage

on behalf of the LHCb collaboration



35th Rencontres de Blois

23rd October 2024

Bundesministerium für Bildung und Forschung

FSP LHCb Erforschung von Universum und Materie

I.PI I. Physikalisches Institut

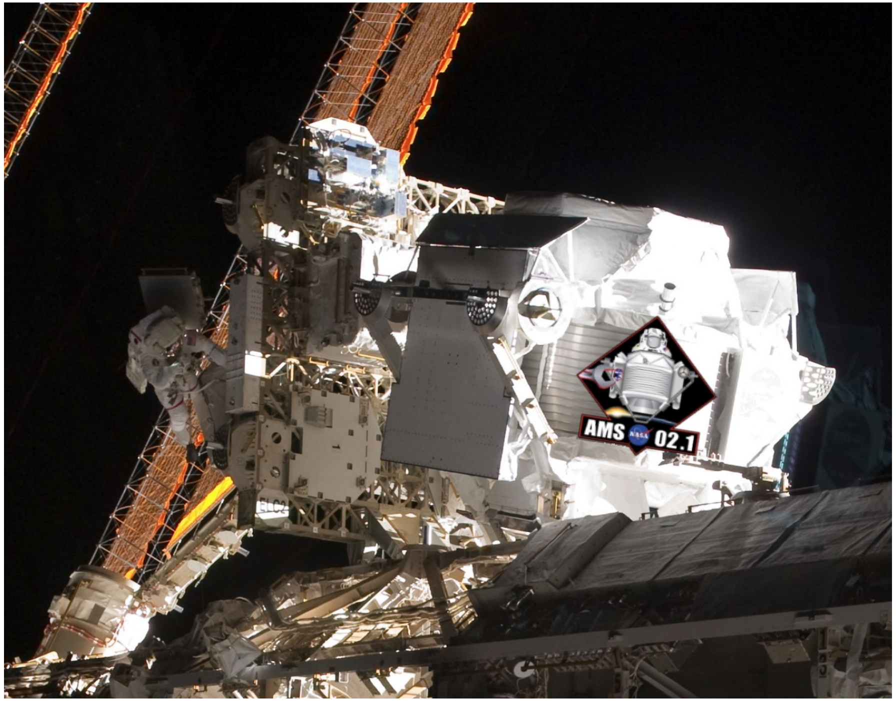
RWTH AACHEN UNIVERSITY

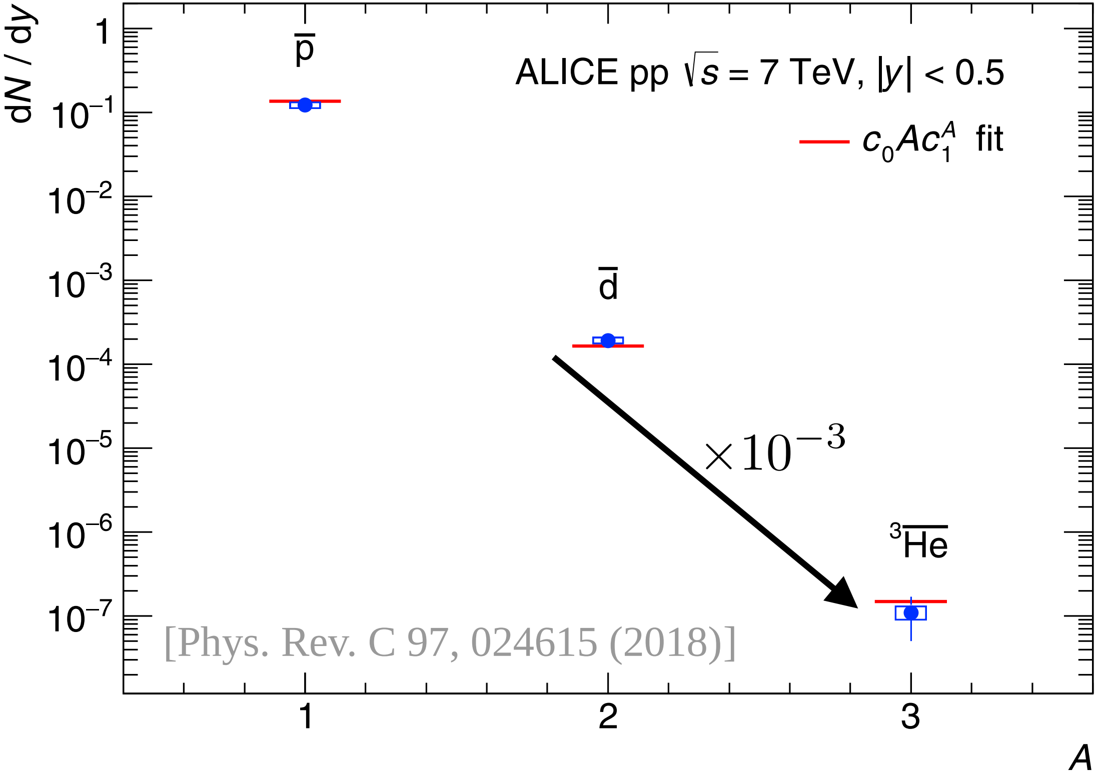
LHCb

AMS-02: Antihelium in space

[COSPAR 2022]

- Reported $\mathcal{O}(10)$ $\overline{\mathrm{He}}$ candidates in cosmic rays at conferences
- Origin is unclear: AMS never reported $\overline{\mathrm{d}}$ observation





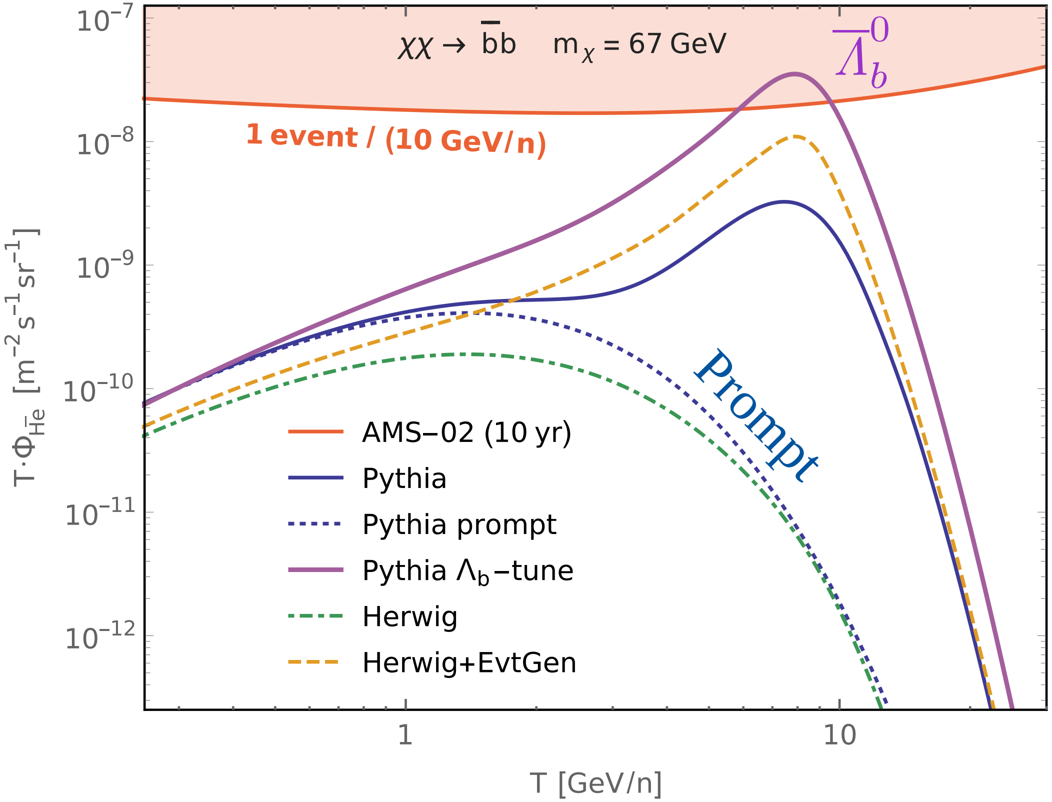
$\Rightarrow$ Expected $\overline{\mathrm{d}}/{}^3\overline{\mathrm{He}}$ ratio is 10^3

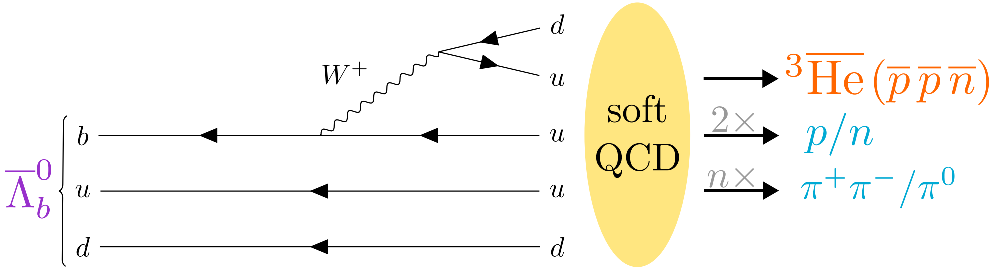
- If AMS-02 results are confirmed: **New source** of $\overline{\mathrm{He}}$ required

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

Martin Wolfgang Winkler* and Tim Linden†

[PRL 126(2021)101101]





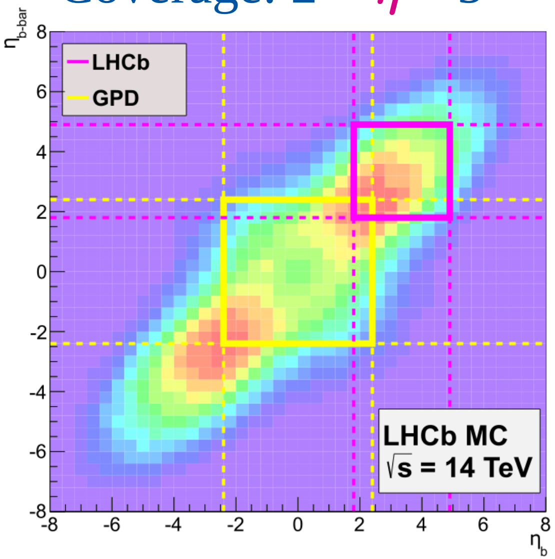
- $^3\overline{\mathrm{He}}$ production enhanced w.r.t. $\bar{\mathrm{d}}$
- Large **variations** depending on model:
  - Herwig+EvtGen:
    $\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}\,X) < 10^{-9}$
  - Pythia Λ_b-tune*:
    $\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}\,X) \simeq 1.5 \times 10^{-6}$
    *increased baryon production

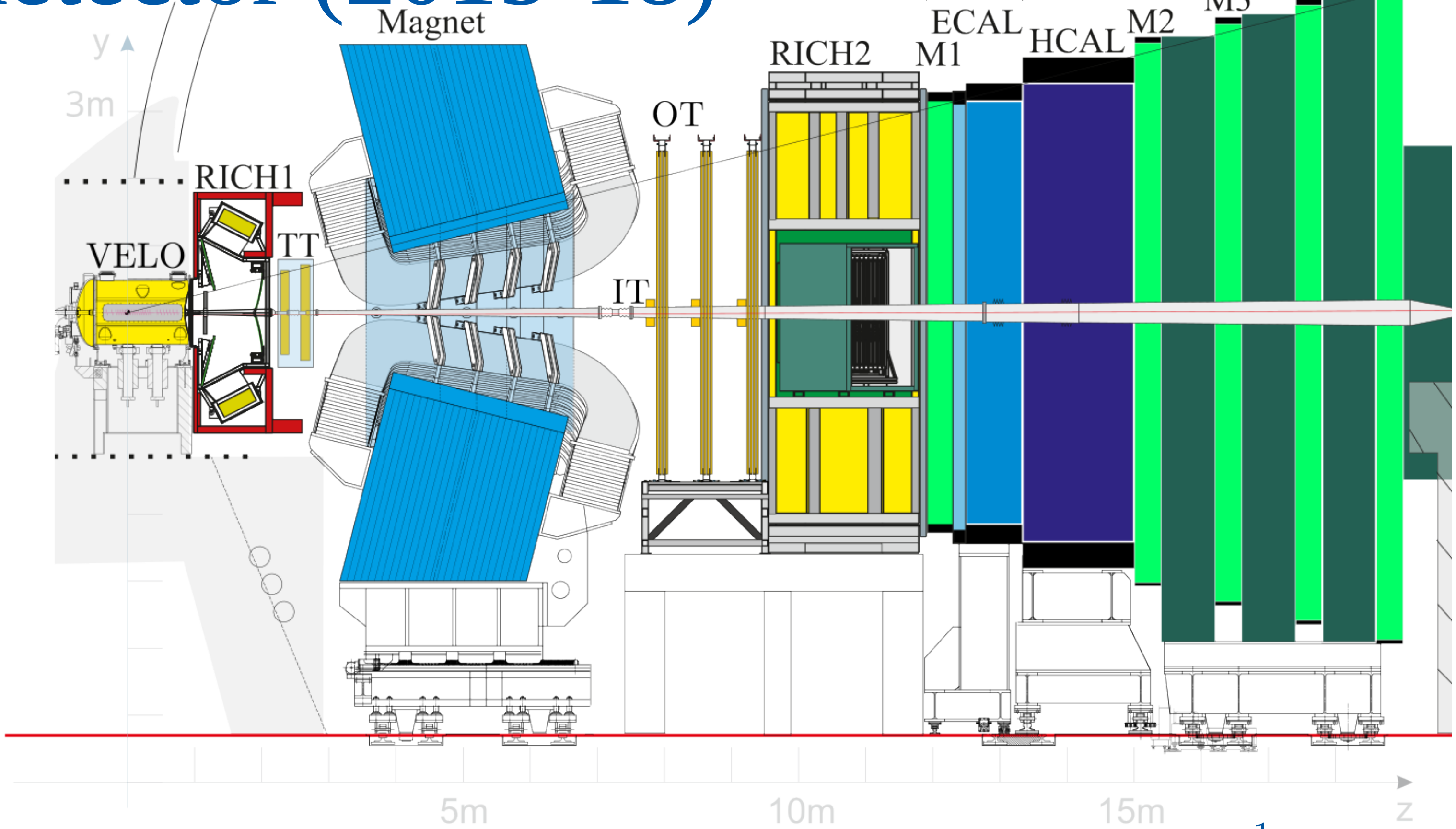
NB: discussion ongoing, e.g. [PRC 1018(2023) 024903]

The LHCb detector (2015-18)

[IJMPA 30 (2015) 1530022]
[JINST 3 (2008) S08005]

- Coverage: $2 < \eta < 5$





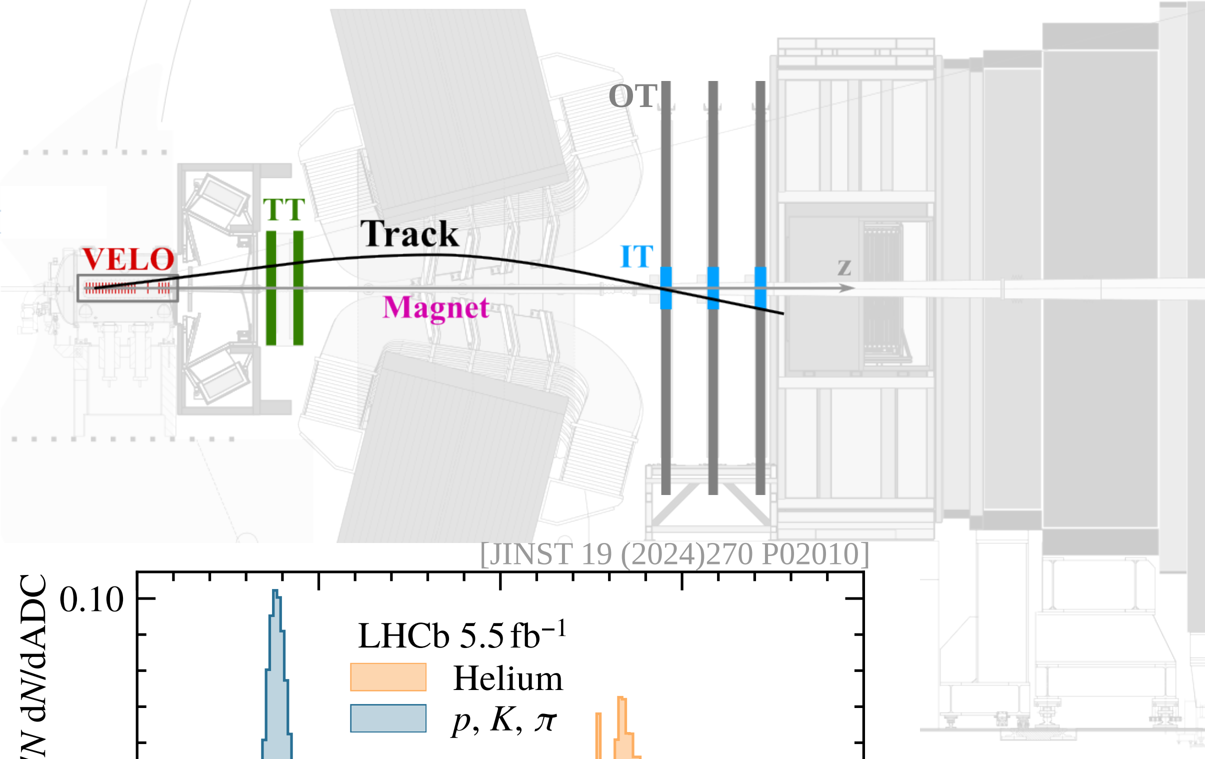
- About $10^{11}\,\Lambda_b^0$ have been produced in LHCb acceptance in Run 2 ($\mathcal{L}_{\rm int} = 5.5\,{\rm fb}^{-1}$)
- LHCb has measured $\mathcal{B}(\Lambda_b^0 \to p\,\pi^-\mu^+\mu^-) = (6.9 \pm 2.5) \times 10^{-8}$ [JHEP 04 (2017) 029]
  $\Rightarrow \mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\rm He}\,X) \simeq 1.5 \times 10^{-6}$ **well within reach**

Helium ID: dE/dx

- Ionization losses in VELO, TT and IT
  $\rightarrow$ amplitude digitized with ADC
- Encoded with log-Likelihood Discrimi
  $\rightarrow$ one for each sub-detector: $\Lambda^{X}_{\mathrm{LD}}$

[JINST 19 (2024)270 P02010]

[JINST 3 (2008) S08005]



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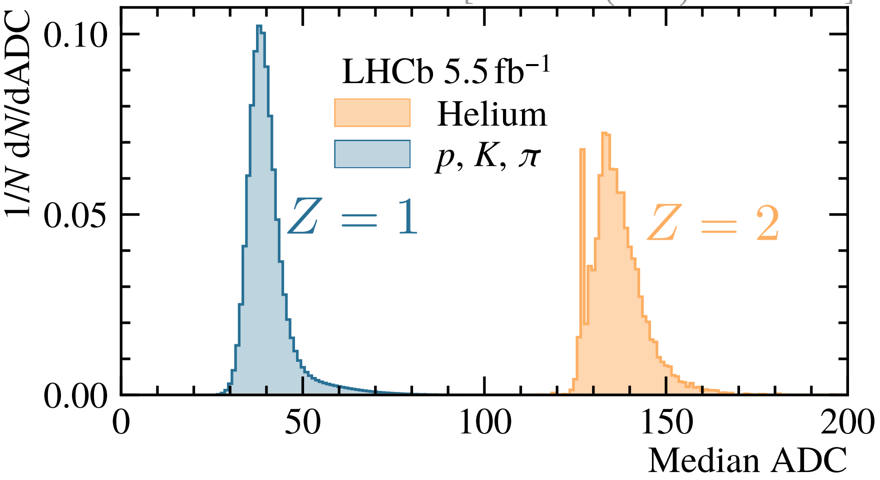

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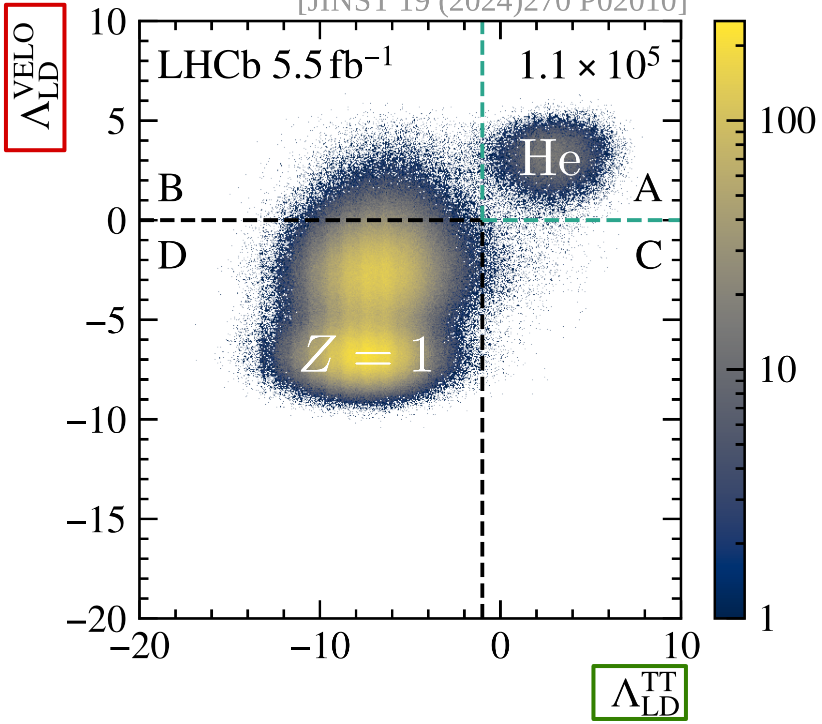
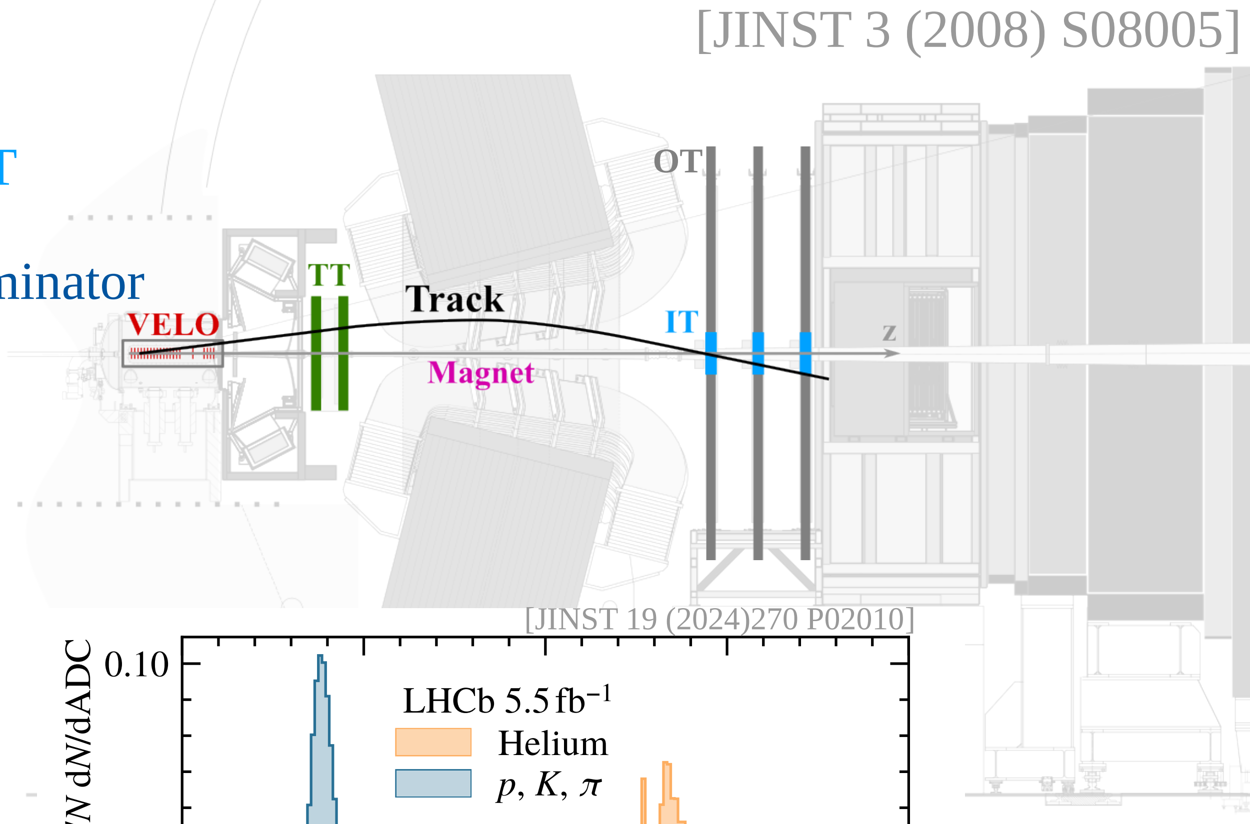
[JINST 19 (2024)270 P02010]



[JINST 3 (2008) S08005]



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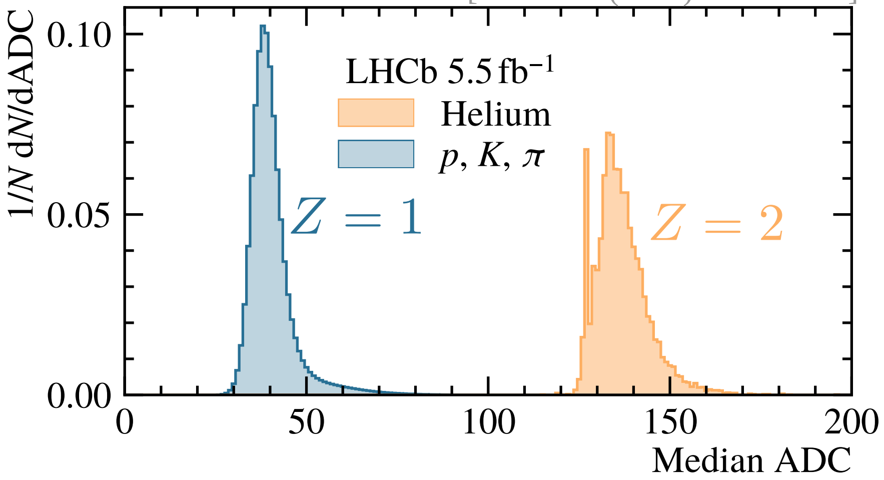

$\Rightarrow$ Excellent separation between helium and Z=1 particles

[JINST 3 (2008) S08005]

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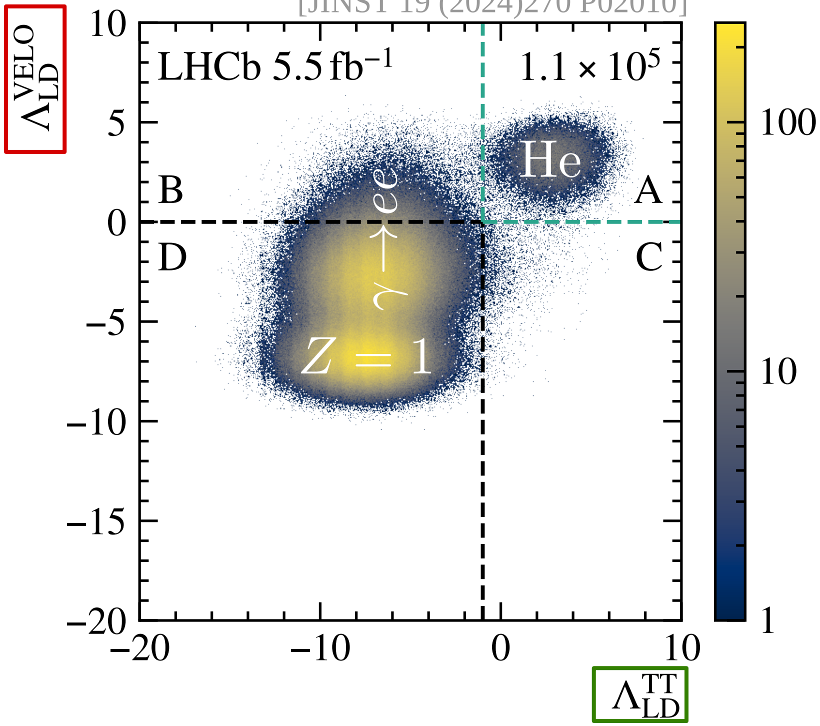
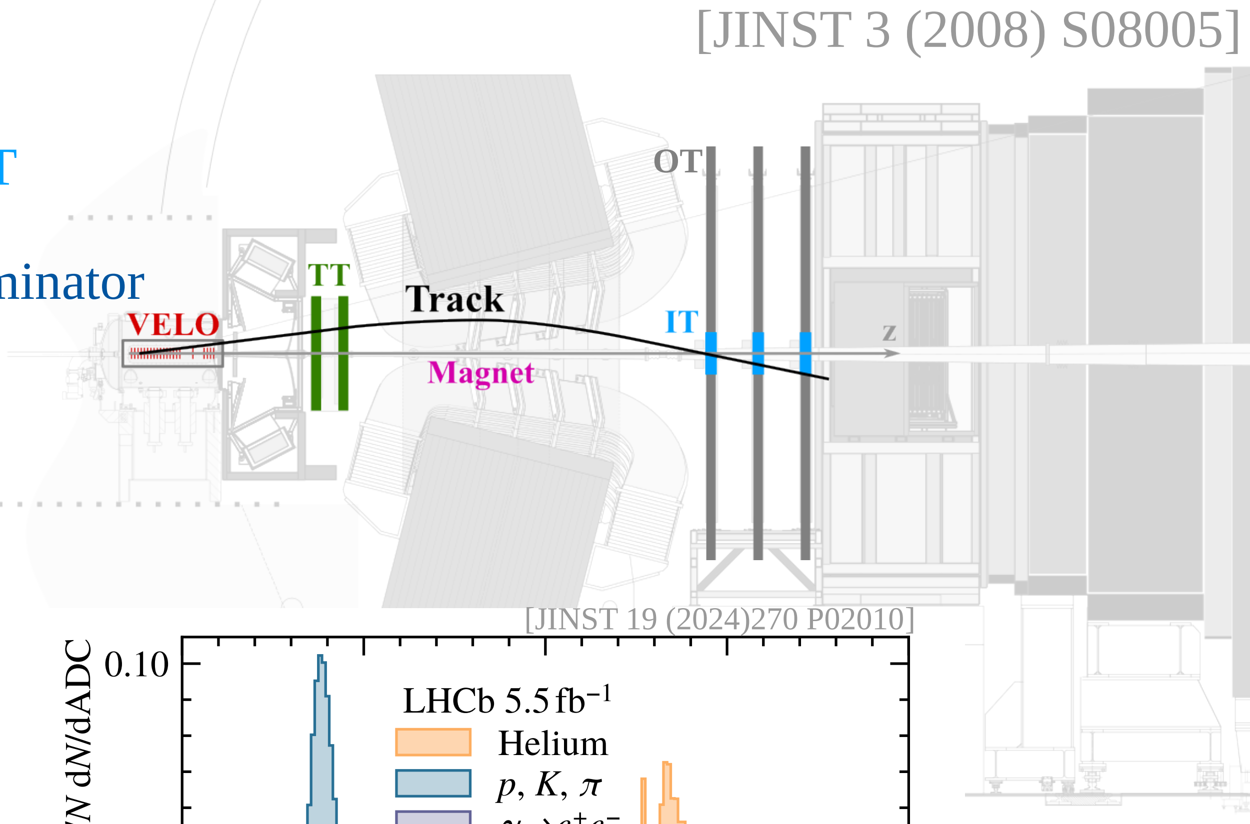
[JINST 19 (2024)270 P02010]





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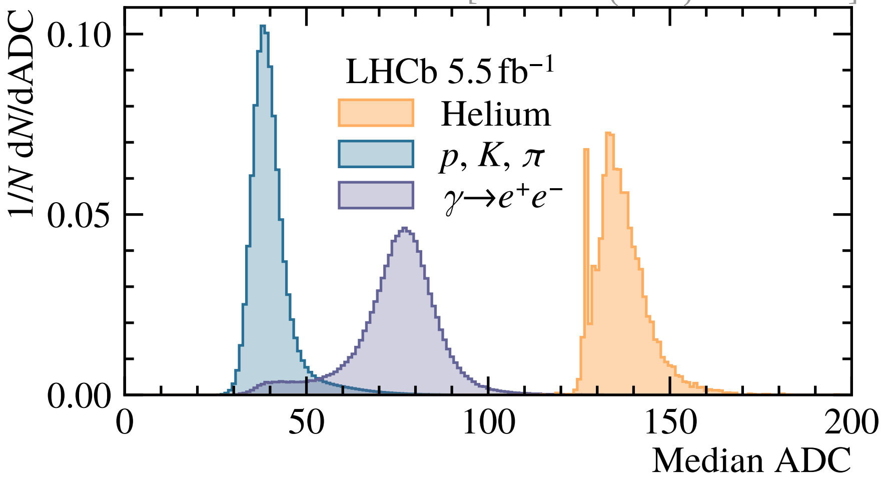
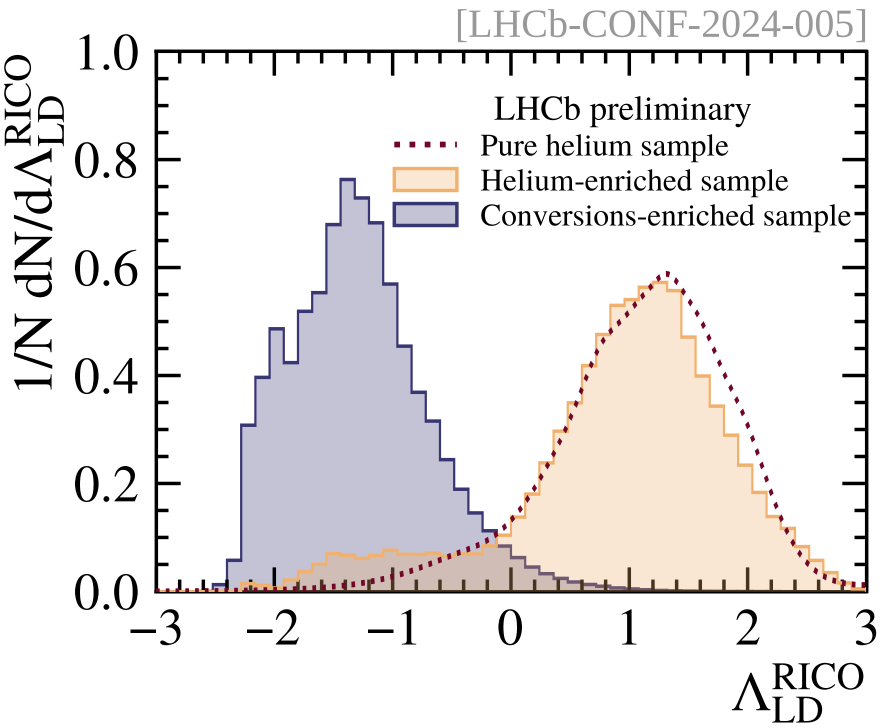
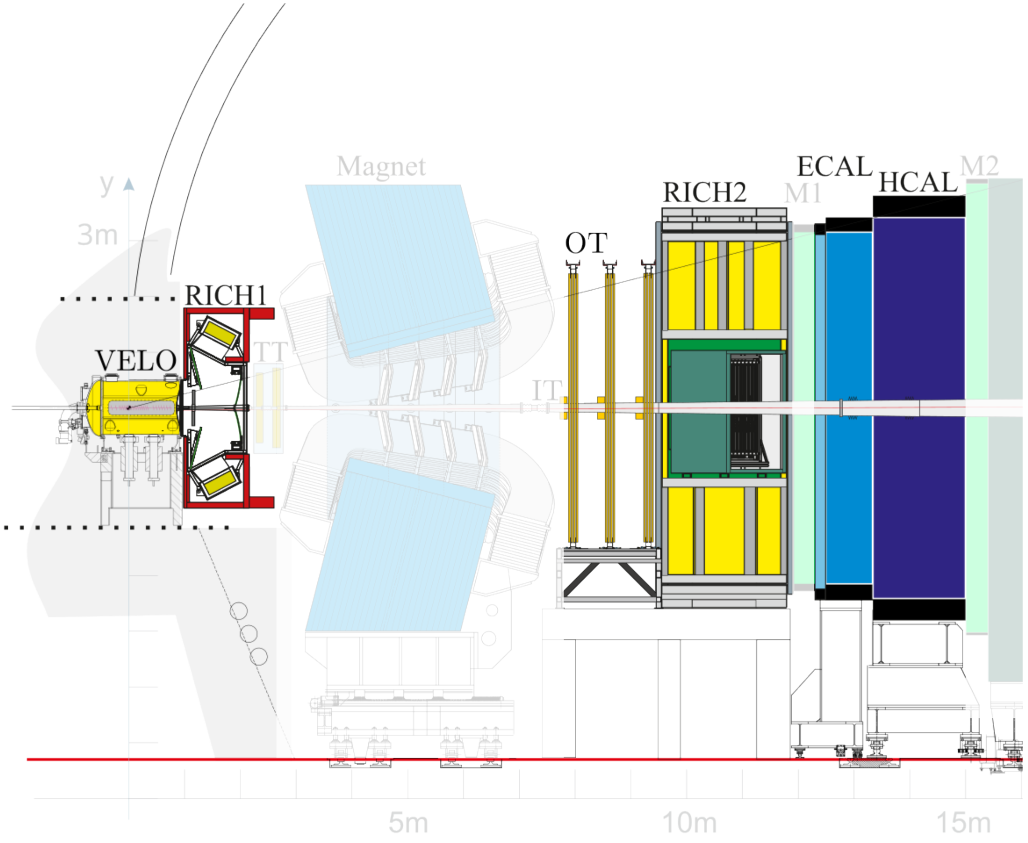


Helium ID: conversion rejection

- Combine **R**ICH, track **I**solation, **C**alorimetry and **O**T timing information:
  $\rightarrow$ dedicated log-likelihood estimator: $\Lambda_{\mathrm{LD}}^{\mathrm{RICO}}$

[LHCb-CONF-2024-005]

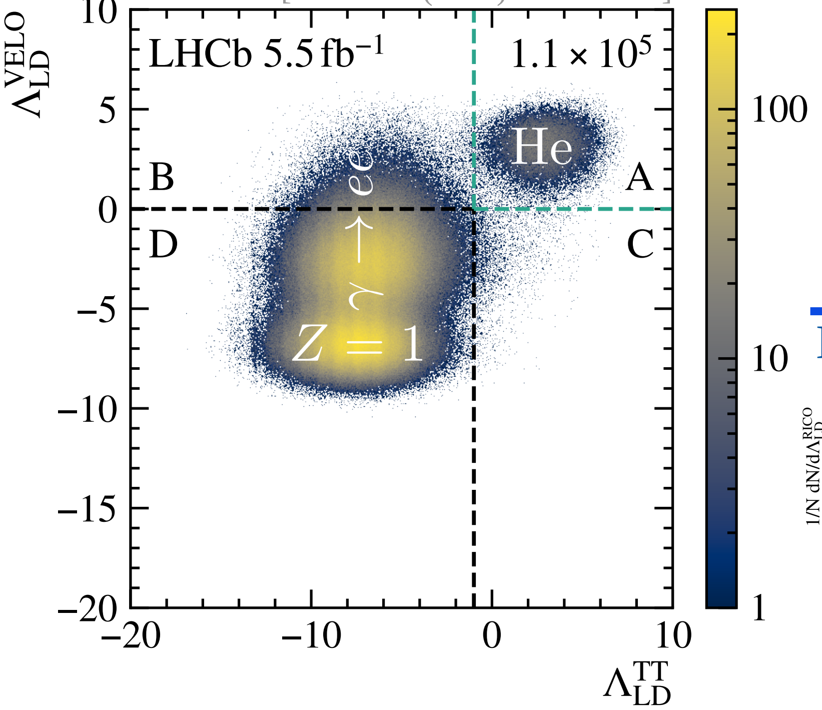




Helium ID: conversion rejection

- Combine **R**ICH, track **I**solation, **C**alorimetry and **O**T timing information: $\rightarrow$ dedicated log-likelihood estimator: $\Lambda_{\mathrm{LD}}^{\mathrm{RICO}}$
- Removes residual background from conversions

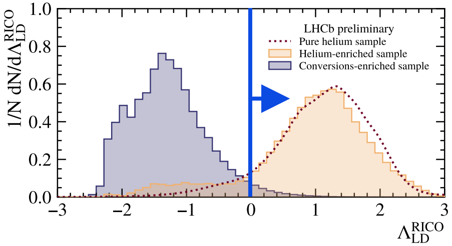
[JINST 19 (2024)270 P02010]



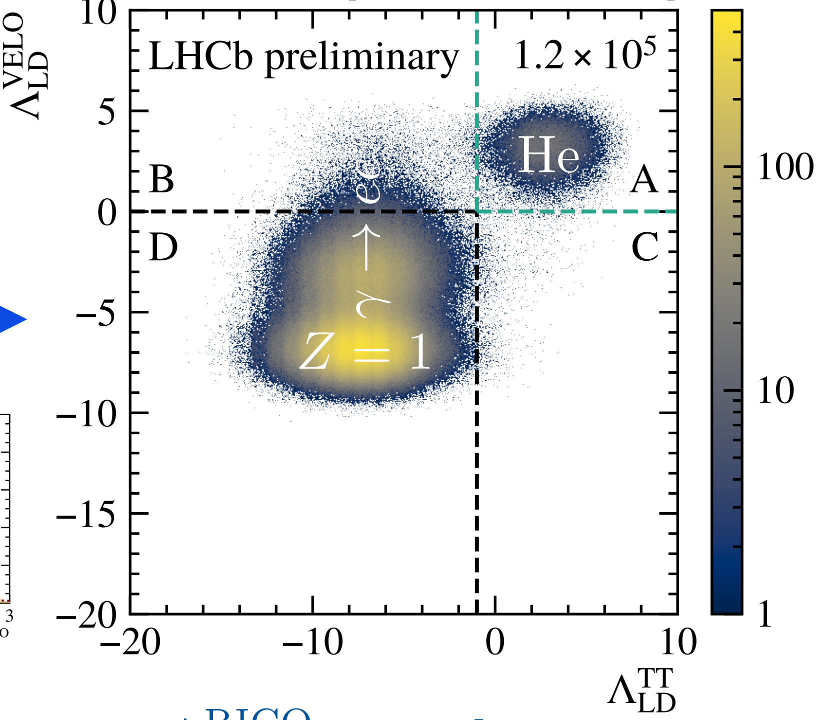
$\rightarrow$ cut base OT+RICH selection

Signal $\nearrow$ 10%

Background $\searrow \times 3$



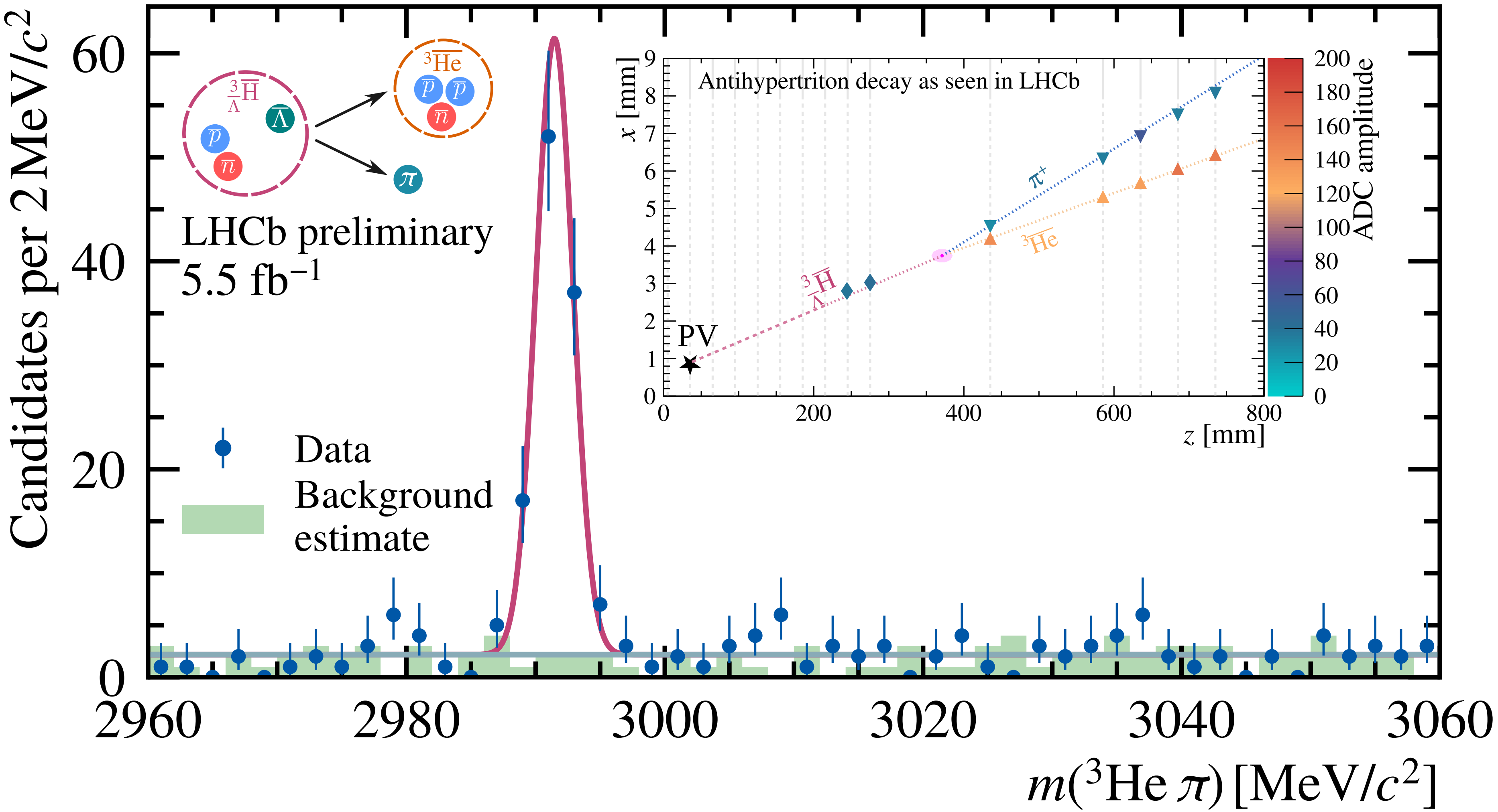
[LHCb-CONF-2024-005]



$\rightarrow \Lambda_{LD}^{\mathrm{RICO}} > 0$ selection

Observation of **hypertriton** at LHCb

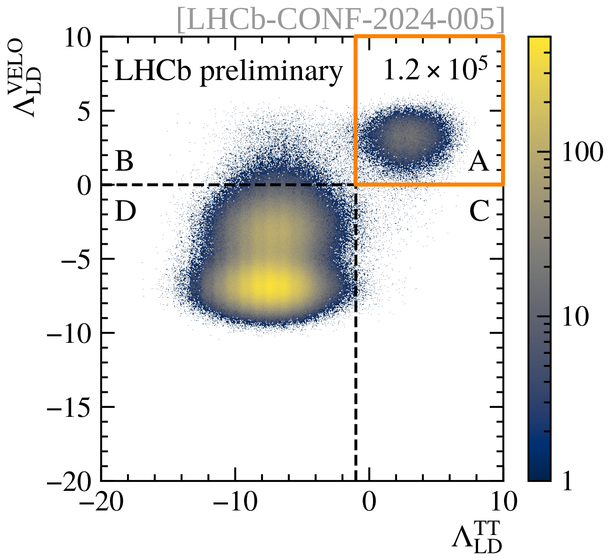
[LHCb-CONF-2023-002]

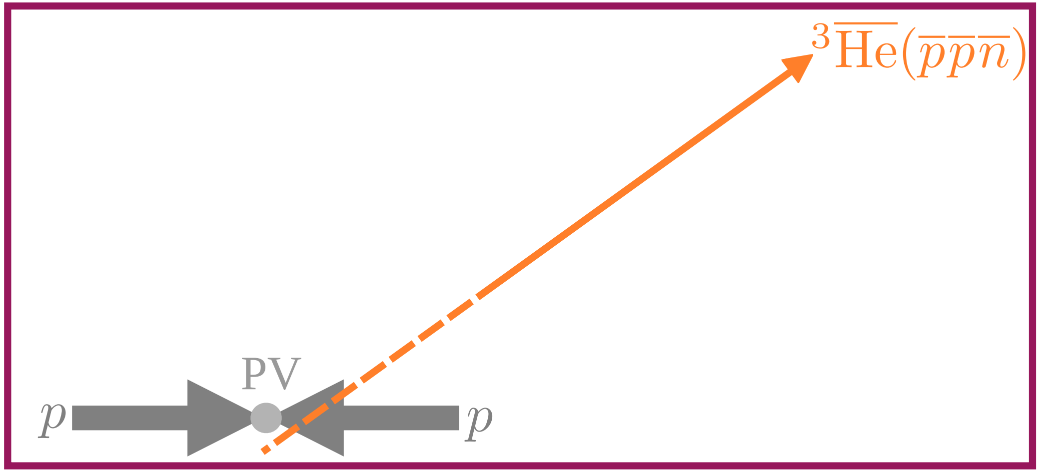


$\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}\, X$ analysis strategy

- Dataset
  - Proton-proton collisions
  - Run 2 data (2016-18, $\sqrt{s} = 13\,\mathrm{TeV}$)
  - $\mathcal{L}_{\mathrm{int}} = 5.5\,\mathrm{fb}^{-1}$

- Selection
  - Helium displaced from **P**rimary **V**ertex
  - Good **SV** with proton
  - SV well separated from PV





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- Selection
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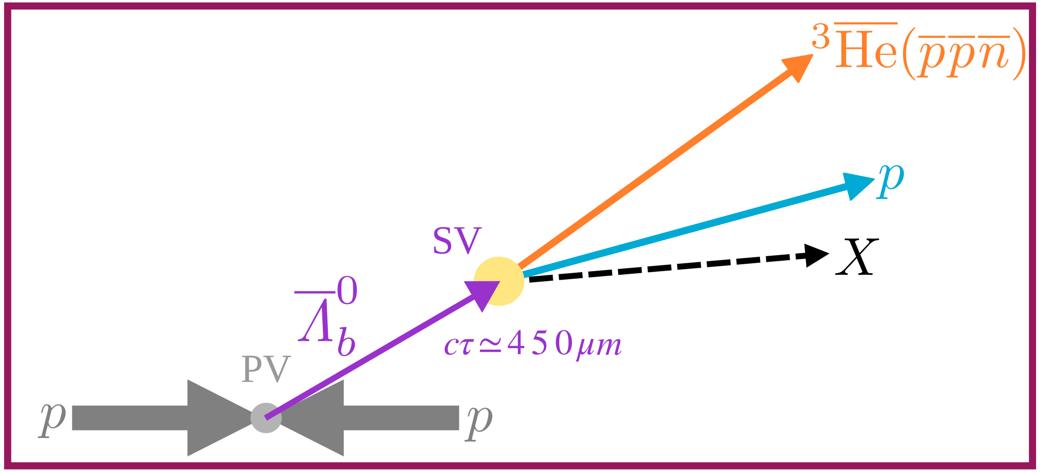
After proton PID:
Only **combinatorial** background expected



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- Selection
  - Helium displaced from PV
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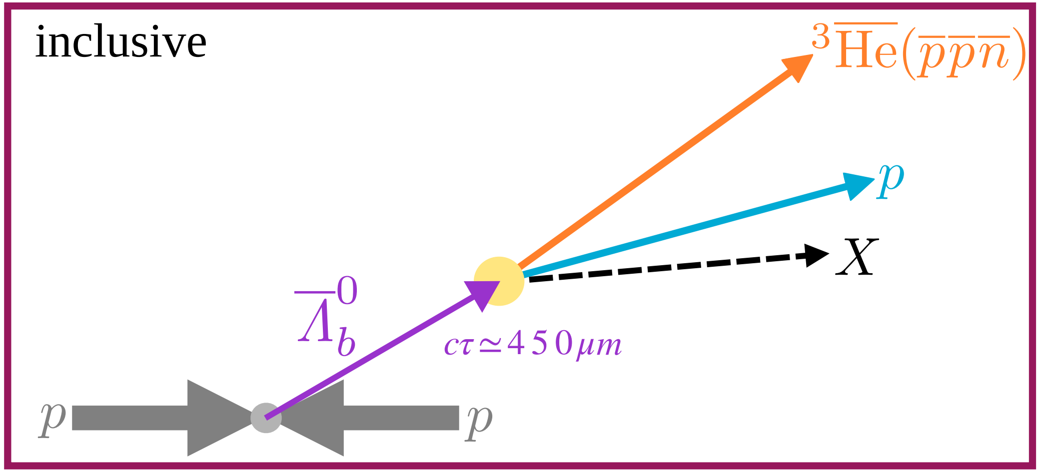
- Three signal channels:
  1. $\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}\, p\, X$
  2. $\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}\, p\, p\, X$
  3. $\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}\, p\, p$

Signal: $m({}^3\overline{\mathrm{He}}\, p)$ peaks at kinematic **threshold**



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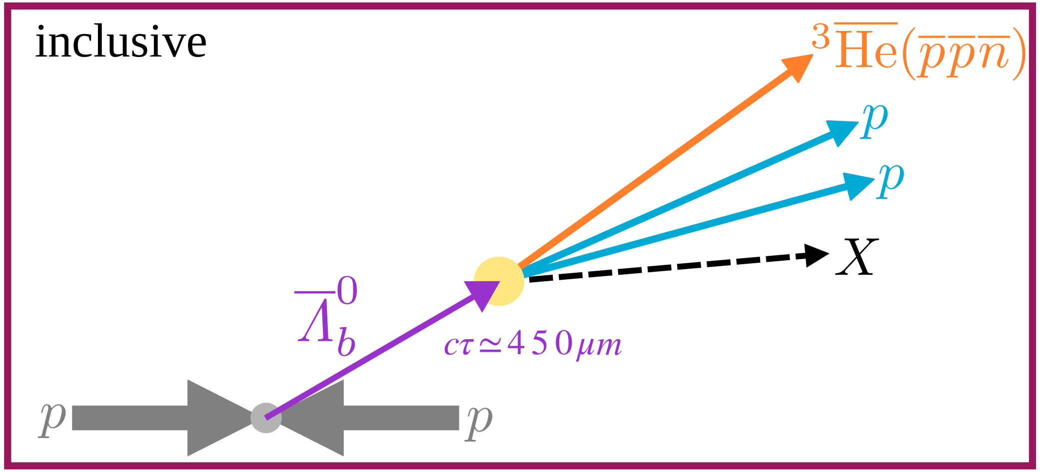

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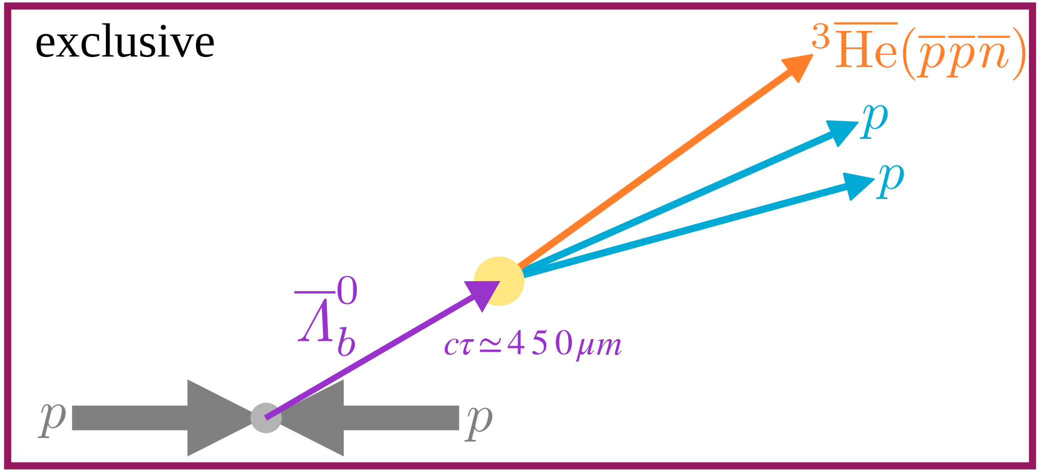
  3. $\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}\,p\,p$

Purity ↓ Yield ↑

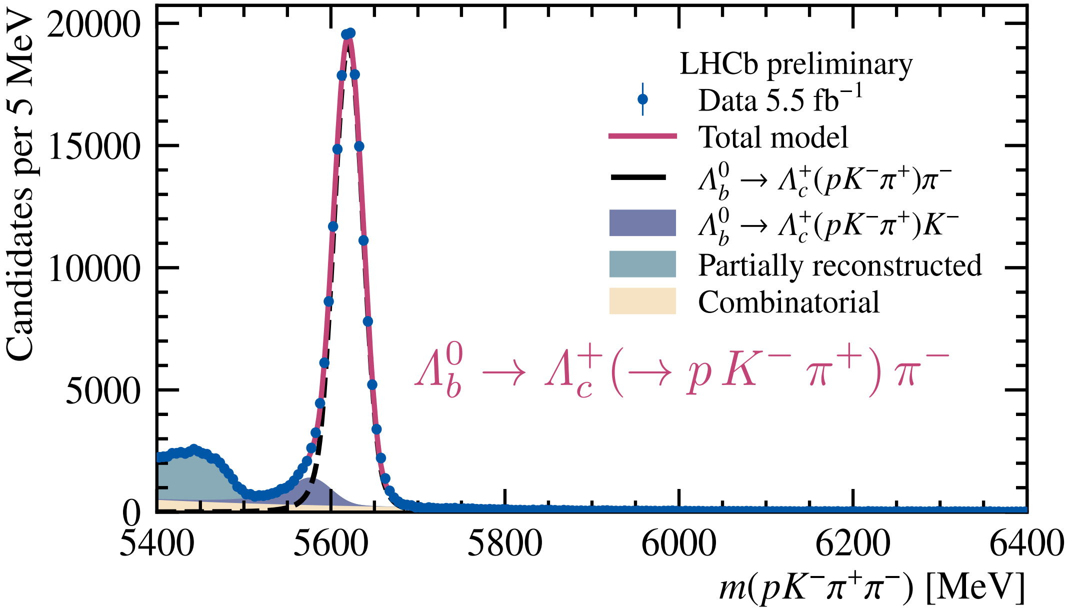
Signal: $m({}^3\overline{\mathrm{He}}\,p\,p)$ **peaking** at $m(\Lambda_b^0)$



Analysis strategy: Normalization channel

- $\Lambda_b^0 \to \Lambda_c^+(\to p\, K^-\, \pi^+)\, \pi^-$
  - **topology** comparable to signal
- Selection
  - similar vertex and proton PID requirements as signal
- Yields:
  - ext. unbinned max. likelihood fit
  - shapes from simulation
  - $S^{\text{norm}} \approx 1.7 \times 10^5$

[LHCb-CONF-2024-005]

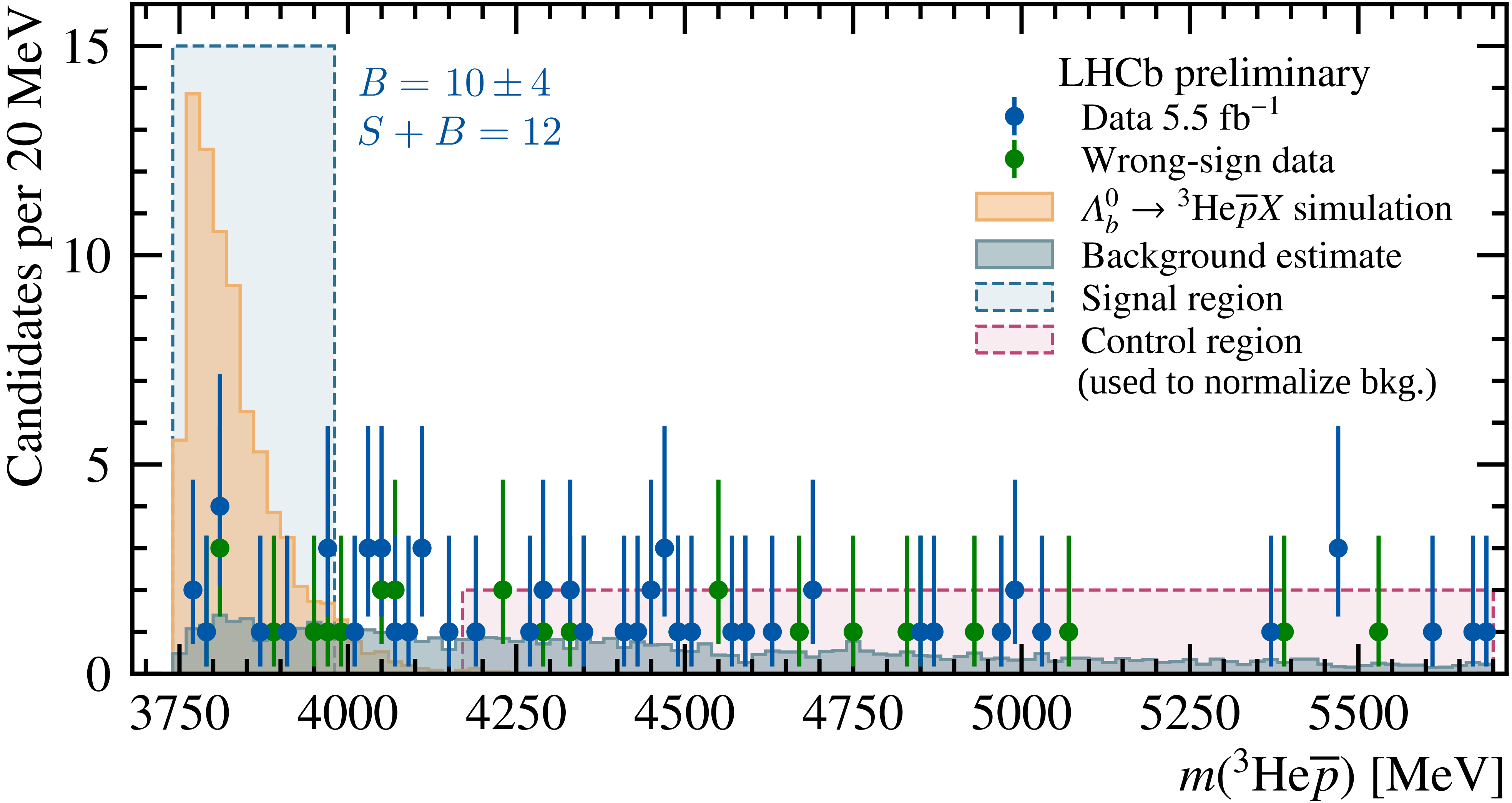


$$\mathcal{B}(\Lambda_b^0 \to {}^3\text{He}\,\overline{p}\,\overline{p}) = \frac{S^{\text{He}\,\overline{p}\,\overline{p}}}{\varepsilon^{\text{He}\,\overline{p}\,\overline{p}}}\,\frac{\varepsilon^{\text{norm}}}{S^{\text{norm}}}\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\,\pi^-)\mathcal{B}(\Lambda_c^+ \to p\,K^-\,\pi^+)$$

$\Rightarrow$ Systematic uncertainties on $\mathcal{L}_{\text{int}}$, $\sigma_{b\bar{b}}$ and $f_{\Lambda_b^0}$ **cancel** in ratio

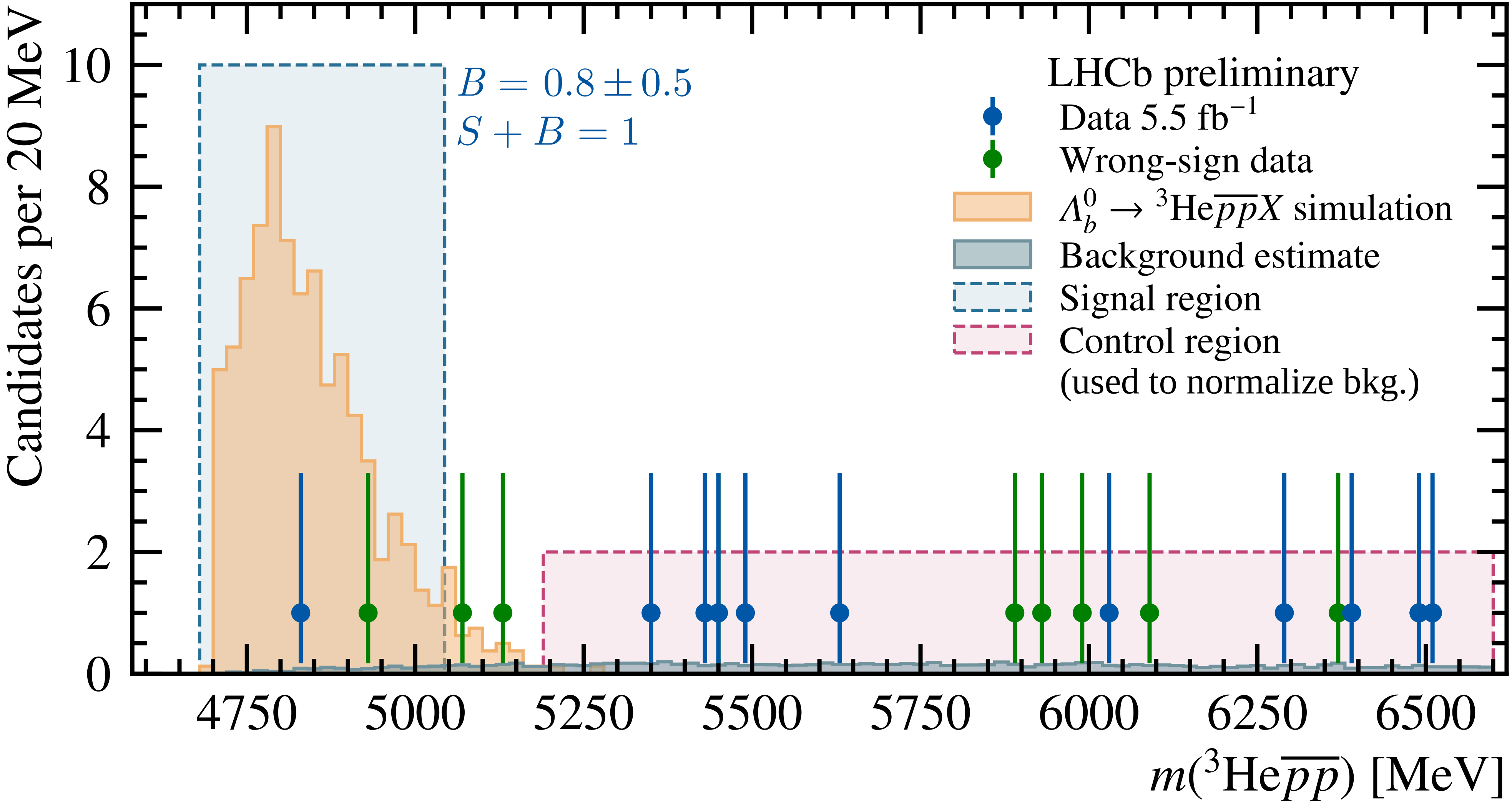
1. $\Lambda_b^0 \to {}^3\mathrm{He}\,\overline{p}\,X$ candidates

[LHCb-CONF-2024-005]



2. $\Lambda_b^0 \to {}^3\mathrm{He}\,\overline{p}\,\overline{p}\,X$ candidates

[LHCb-CONF-2024-005]



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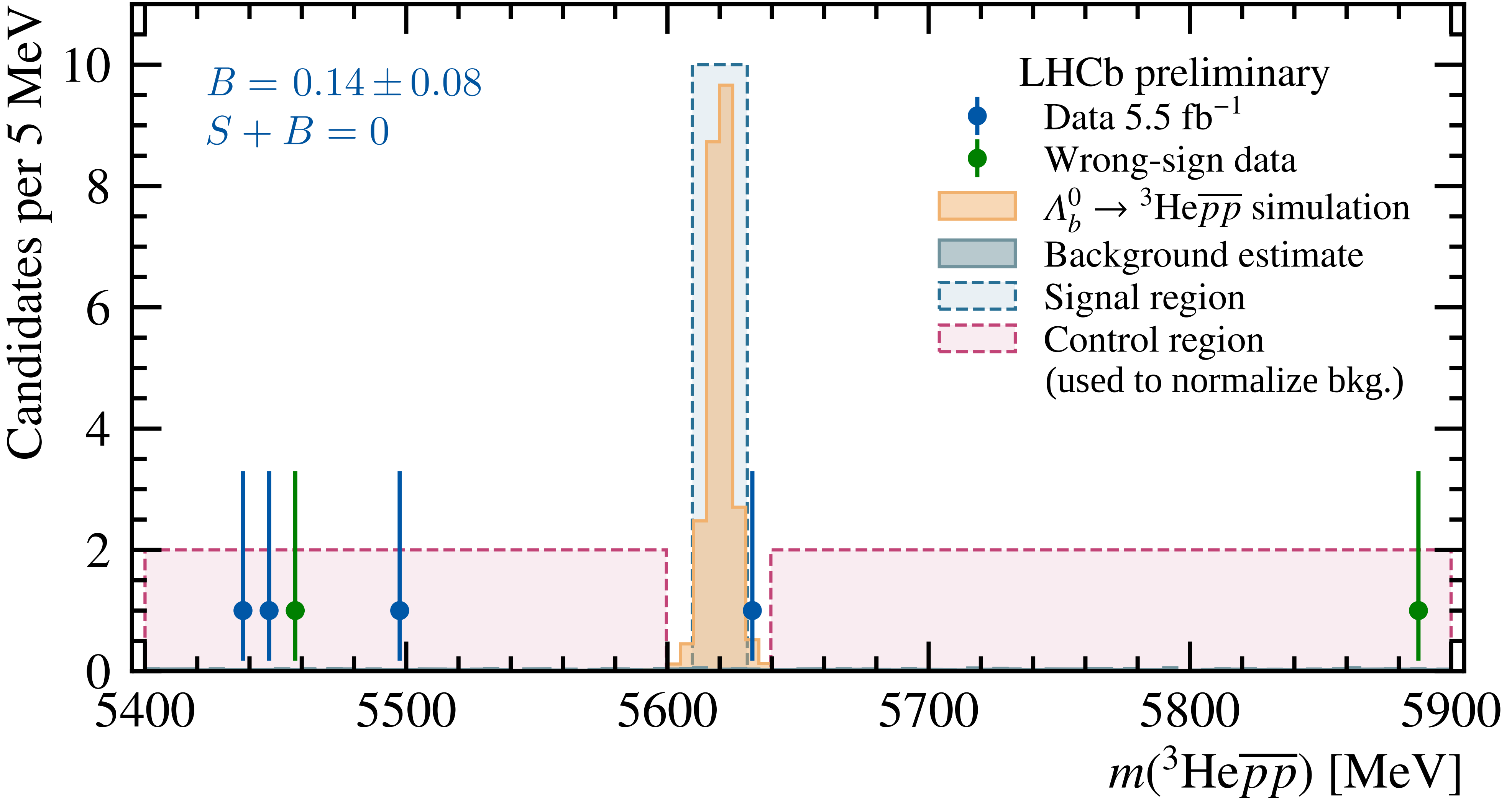
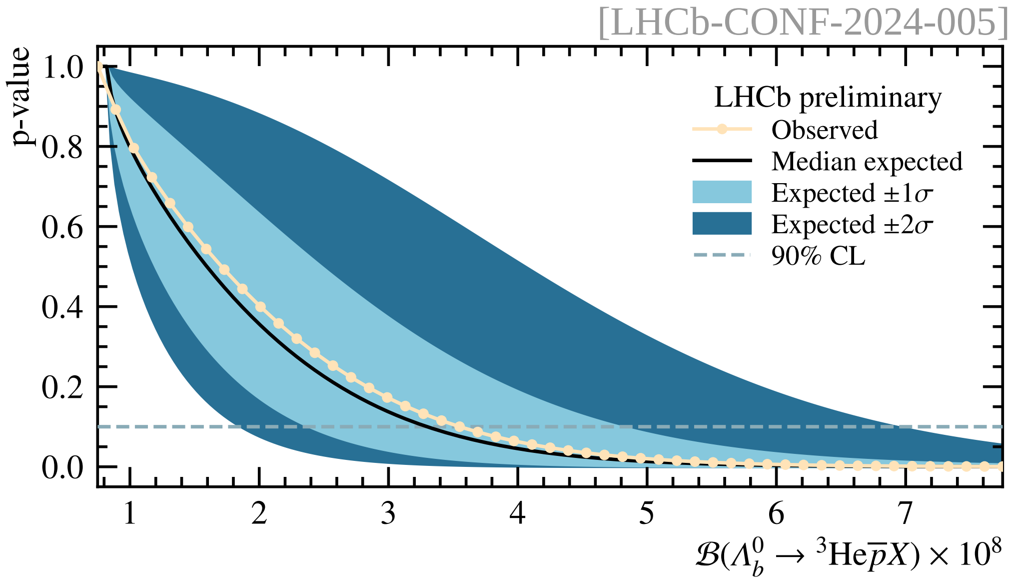


Upper limits at 90% CL (preliminary)

- No significant signal observed ⇒ set upper limits at 90% CL



$$\mathcal{B}(\Lambda_b^0 \to {}^3\mathrm{He}\,\overline{p}\,X) < 3.6 \times 10^{-8}$$

$$\mathcal{B}(\Lambda_b^0 \to {}^3\mathrm{He}\,\overline{p}\,\overline{p}\,X) < 1.6 \times 10^{-8}$$

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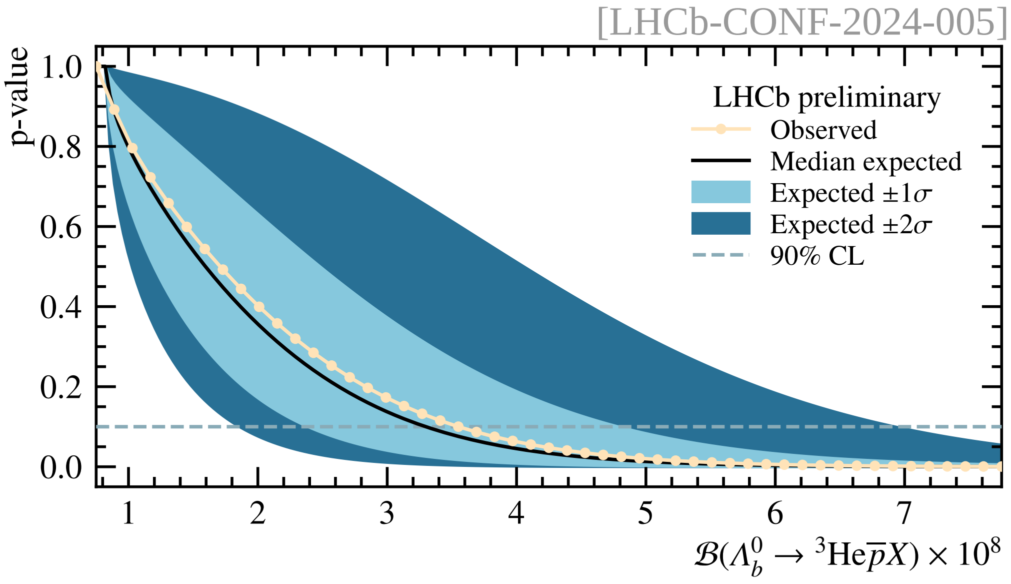

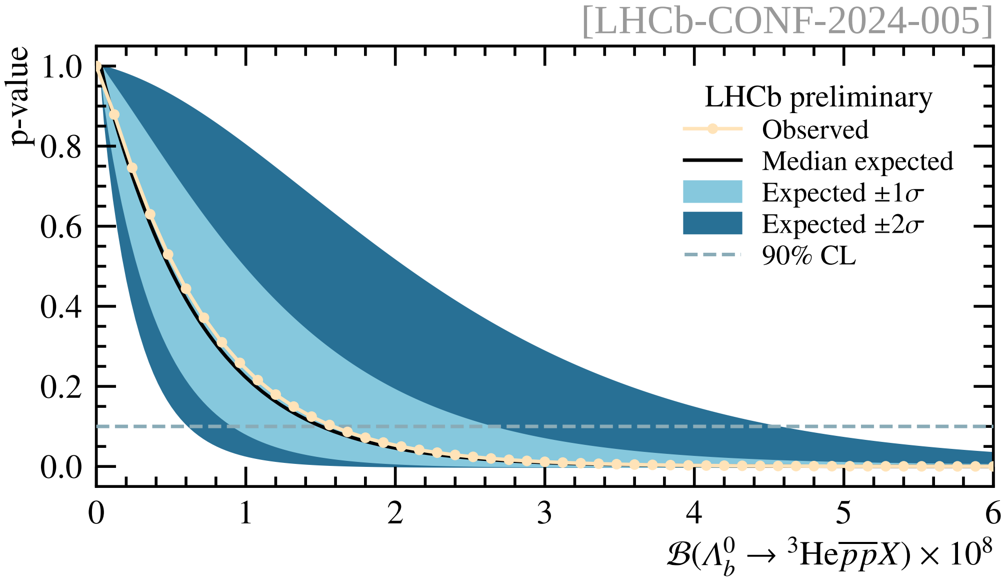

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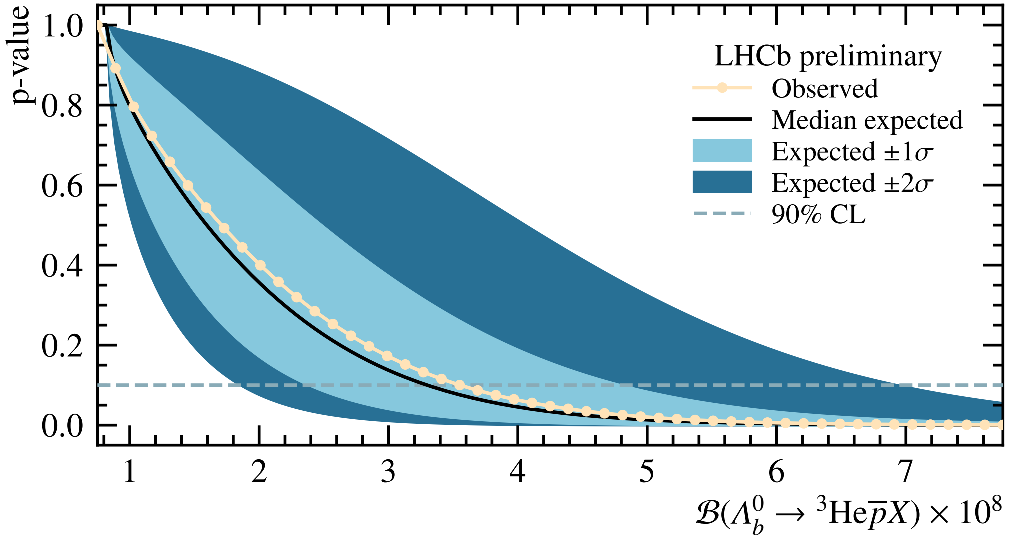

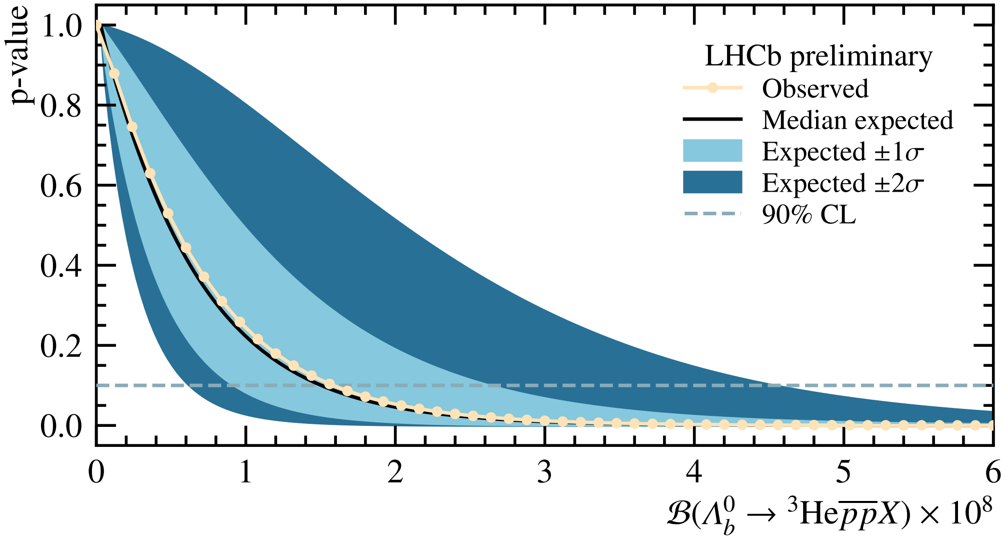

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$$\mathcal{B}(\Lambda_b^0 \to {}^3\mathrm{He}\,\overline{p}\,\overline{p}) < 1.9 \times 10^{-9}$$

Extrapolation to $\mathcal{B}(\Lambda_b^0 \to {}^3\mathrm{He}\,X)$ (preliminary)

[LHCb-CONF-2024-005]

- Model assumption required
  - Considered two Pythia coalescence configurations

1. $\Lambda_b^0 \to {}^3\mathrm{He}\,\overline{p}\,X$

Sensitive to production of additional deuterons: $(p, n) \to d$

2. $\Lambda_b^0 \to {}^3\mathrm{He}\,\overline{p}\,\overline{p}\,X$

Pythia models:

$$\frac{\mathcal{B}(\Lambda_b^0 \to {}^3\mathrm{He}\,\overline{p}\,\overline{p}\,X)}{\mathcal{B}(\Lambda_b^0 \to {}^3\mathrm{He}\,X)} \approx 40\%$$

3. $\Lambda_b^0 \to {}^3\mathrm{He}\,\overline{p}\,\overline{p}$

Too rare, mostly there are additional **pions** in Pythia

$$\mathcal{B}(\Lambda_b^0 \to {}^3\mathrm{He}\,X)$$

Extrapolation to $\mathcal{B}(\Lambda_b^0 \to {}^3\mathrm{He}\,X)$ (preliminary)

[LHCb-CONF-2024-005]

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  - Considered two PYTHIA coalescence configurations

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PYTHIA models:

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Extrapolation to $\mathcal{B}(\Lambda_b^0 \to {}^3\mathrm{He}\, X)$ (preliminary) [LHCb-CONF-2024-005]

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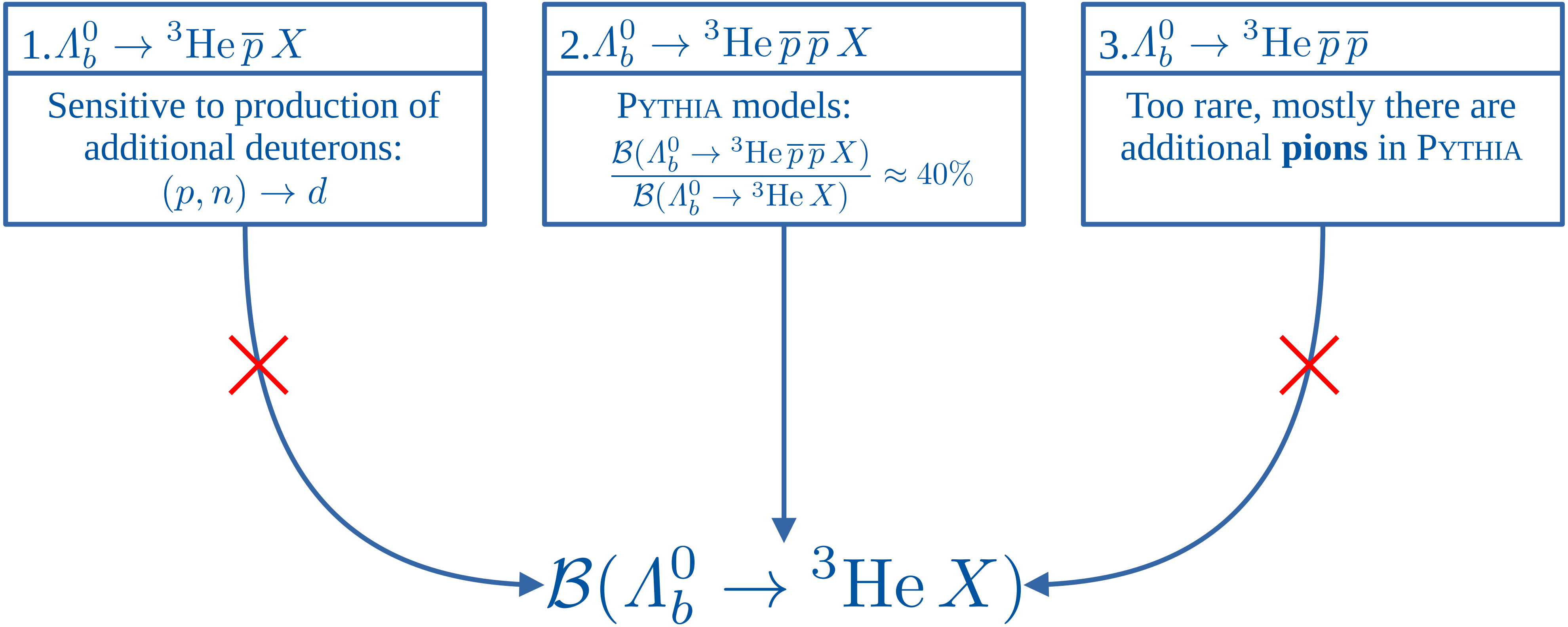

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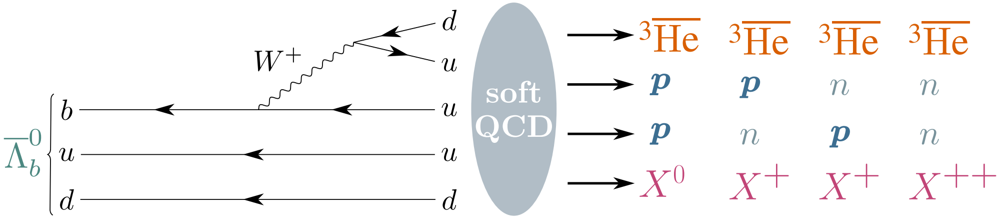
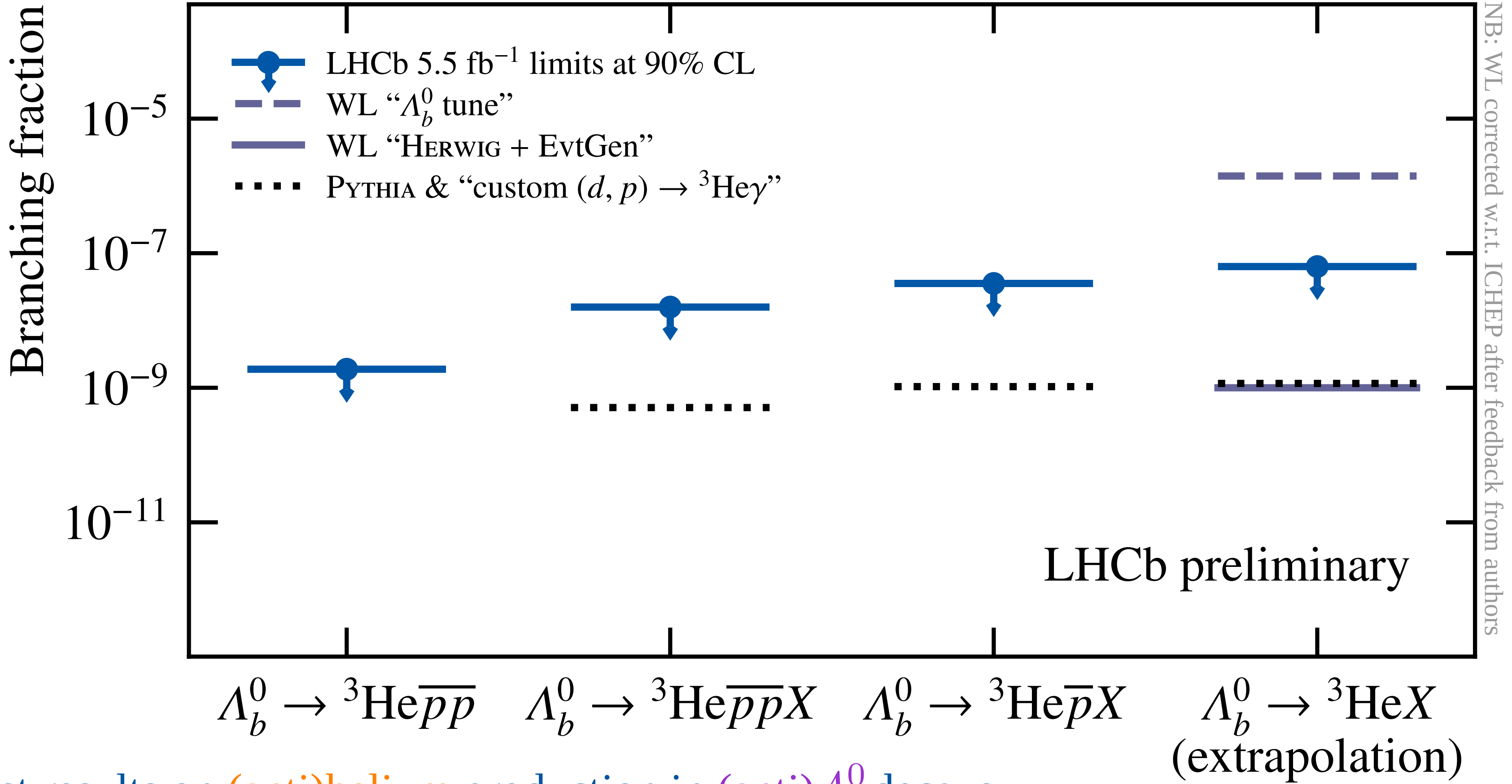


Assuming strong **isospin**: 1 : 1 : 1 : 1

$$\Rightarrow \frac{\mathcal{B}(\Lambda_b^0 \to {}^3\mathrm{He}\,\overline{p}\,\overline{p}\, X)}{1/4} = \mathcal{B}(\Lambda_b^0 \to {}^3\mathrm{He}\, X) < 6.3 \times 10^{-8}$$

Summary

[LHCb-CONF-2024-005]

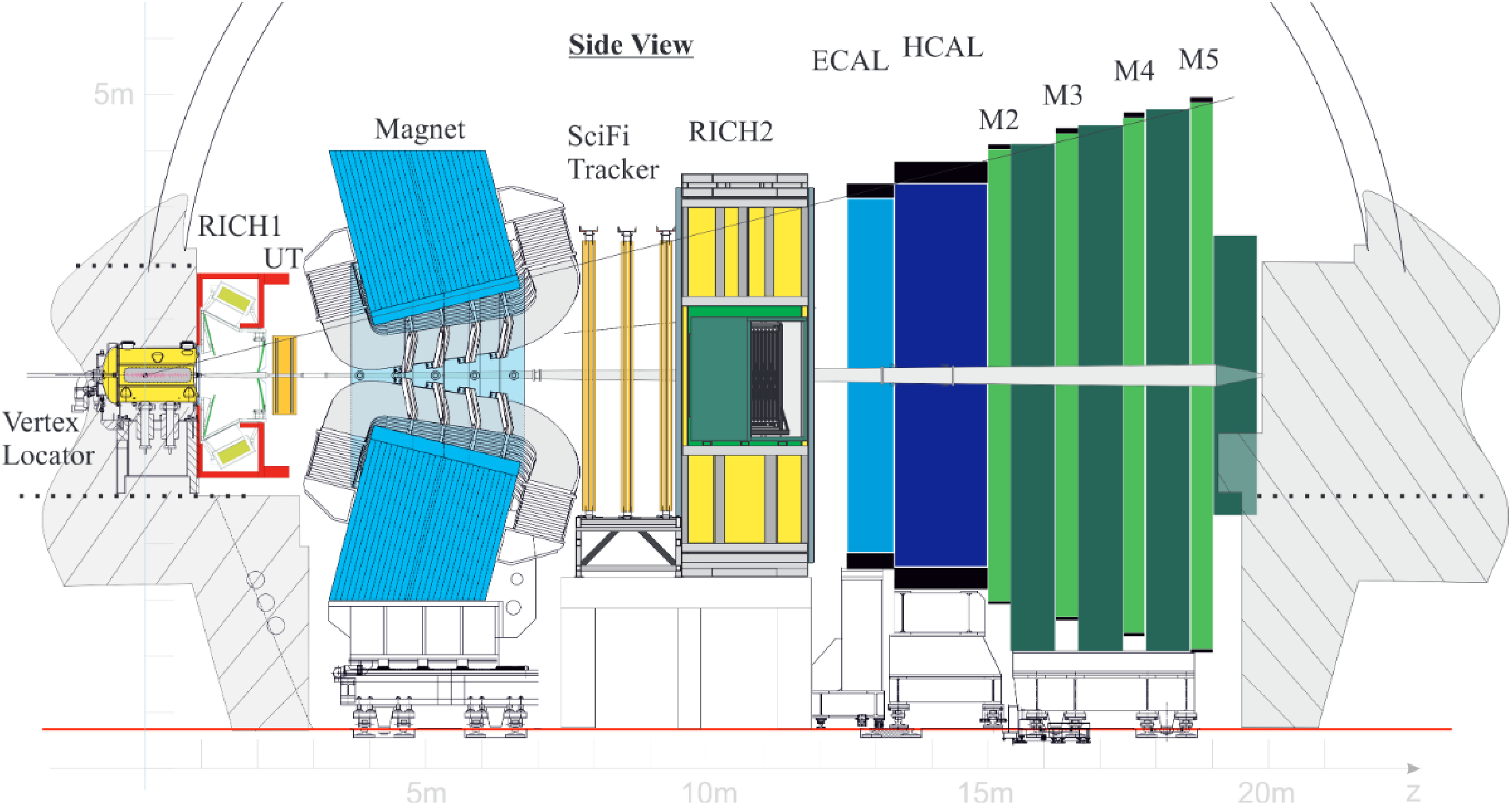


- First results on (anti)helium production in (anti)Λ_b^0 decays
- Abundance of $^3\overline{\mathrm{He}}$ from potential Dark Matter significantly **restricted**
- LHCb **Upgrade II** offers potential to cover current estimates

Backup

LHCb detector Run 3

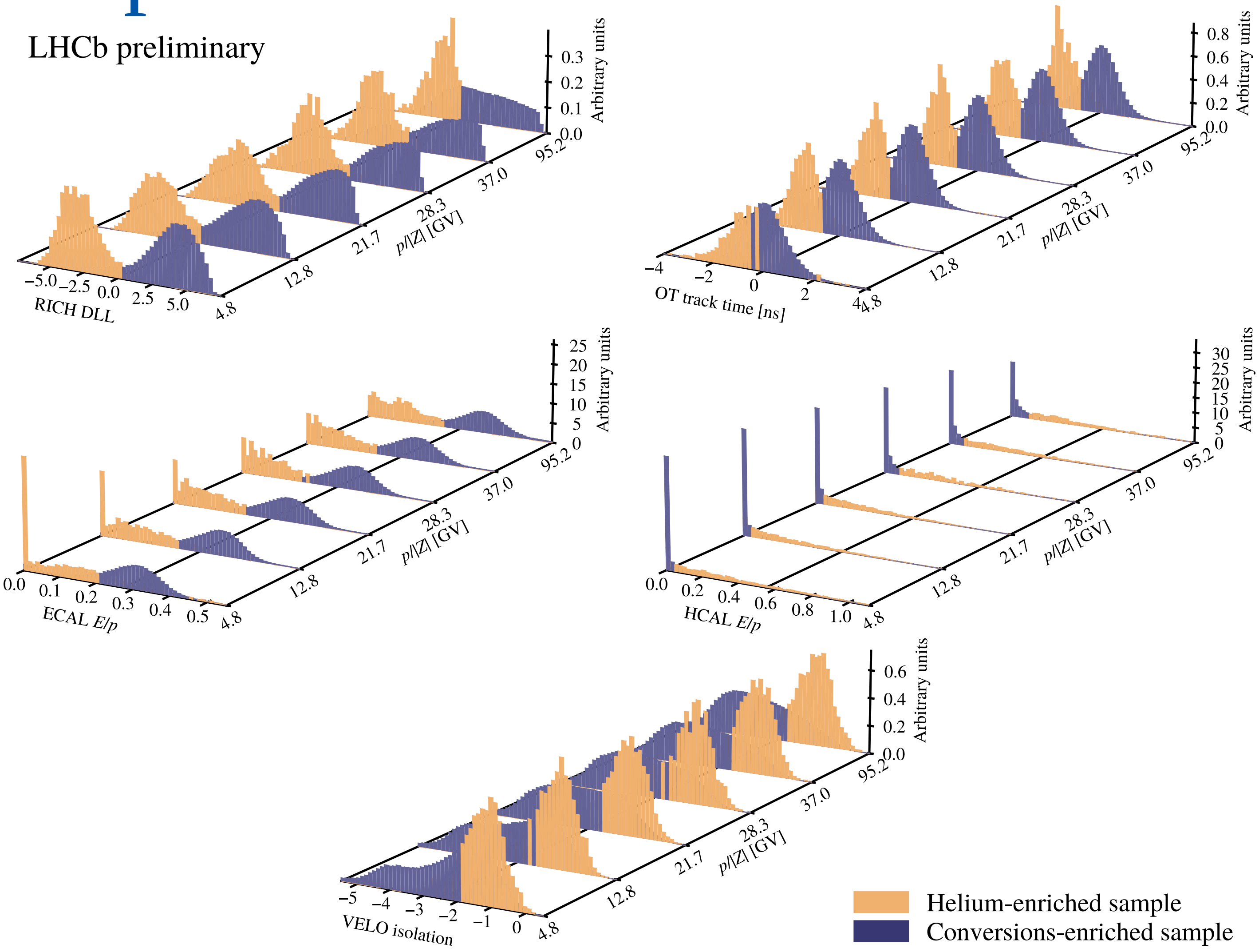
[CERN-LHCC-2014-001]



Less amplitude information available in Run3

RICO inputs

[LHCb-CONF-2024-005]



Systematic uncertainties

[LHCb-CONF-2024-005]

Table 1: Relative systematic uncertainties and bias corrections, in percent, affecting the signal branching fractions. Bias corrections and their uncertainties are also listed where applicable. Simulation is denoted by "MC" where applicable. The impact of the composition of the simulated $\Lambda_b^0 \to {}^3\mathrm{He}X$ decays is denoted by "$\Lambda_b^0 \to {}^3\mathrm{He}X$ MC". The uncertainty on the normalisation-mode branching fraction product is denoted by "normalisation BR".

Uncertainty [%]	$\Lambda_b^0 \to {}^3\mathrm{He}\overline{p}\overline{p}$	$\Lambda_b^0 \to {}^3\mathrm{He}\overline{p}\overline{p}X$	$\Lambda_b^0 \to {}^3\mathrm{He}\overline{p}X$
Background estimate	58.1	59.1	38.3
Normalisation (total)	14.5	19.0	14.8
Normalisation BR	9.4	9.4	9.4
Size of MC and calib. samples	8.7	9.2	9.0
Software trigger	-8.0 ± 4.0	-8.0 ± 4.0	-6.8 ± 3.4
Proton PID	8.0 ± 6.0	10.9 ± 14.2	3.6 ± 5.6
Hardware trigger	5.6 ± 1.4	5.6 ± 1.4	5.6 ± 1.4
$\Lambda_b^0 \to {}^3\mathrm{He}X$ MC	N/A	3.0	3.0
$\Lambda_b^0 \to \Lambda_c^+(pK^-\pi^+)\pi^-$ yield	0.5	0.5	0.6

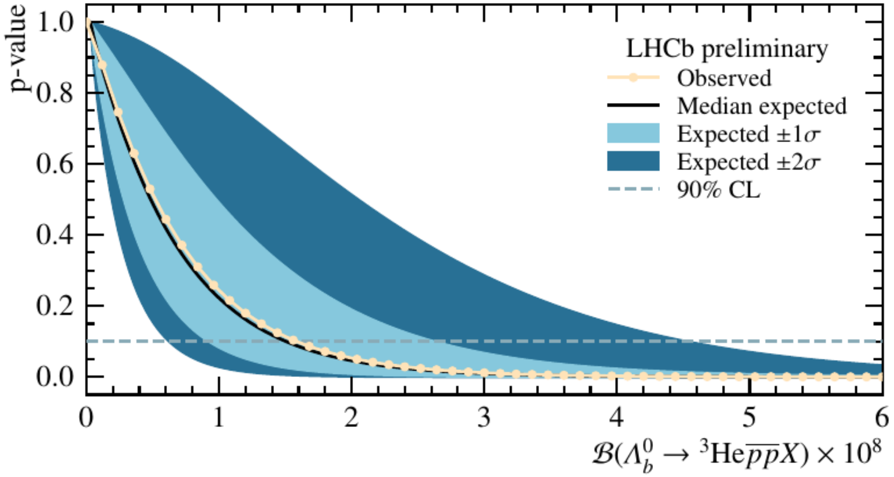
Upper limits

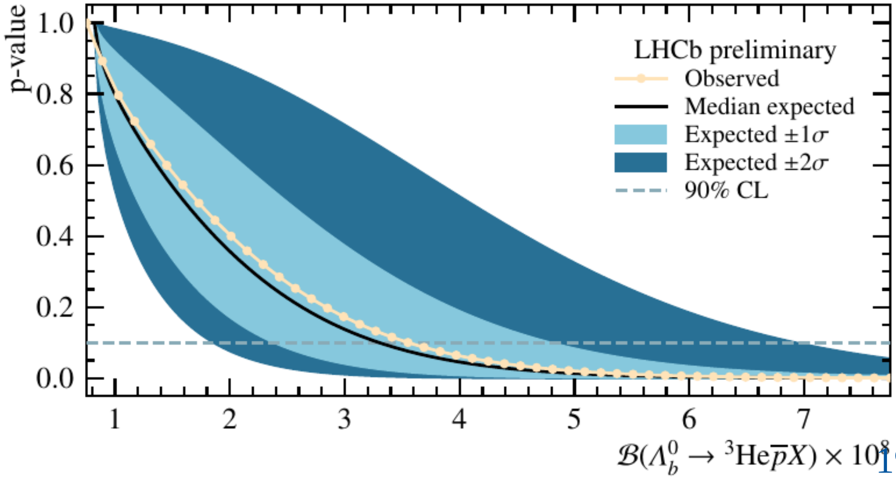
values & uncertainties of normalisation & expected bkg.

$$\mathcal{L}(\mathcal{B}_{\text{sig}}, c_{\text{norm}}, B) = \mathcal{P}(\mathcal{B}_{\text{sig}}/c_{\text{norm}} + B) \cdot \mathcal{G}(c_{\text{norm}}|\mu_{\text{norm}}, \sigma_{\text{norm}}) \cdot \mathcal{G}(B|\mu_B, \sigma_B)$$

- CLs method based on Poisson likelihood
  - $\mathcal{B}(\Lambda_b^0 \to {}^3\text{He}\overline{p}\overline{p}X) < 1.6 \times 10^{-8}$
  - $\mathcal{B}(\Lambda_b^0 \to {}^3\text{He}\overline{p}X) < 3.6 \times 10^{-8}$
- similar results from invariant-mass fit, and from the Rolke method NIMA458(2001)745-758
- fit impractical for exclusive mode, Rolke used
  - $\mathcal{B}(\Lambda_b^0 \to {}^3\text{He}\overline{p}\overline{p}) < 1.9 \times 10^{-9}$
- conservative extrapolation assuming isospin:

  $\Rightarrow \mathcal{B}(\Lambda_b^0 \to {}^3\text{He}X) < 6.3 \times 10^{-8}$

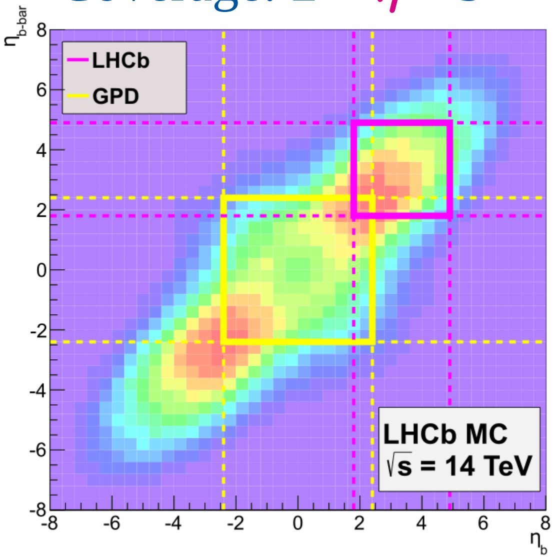


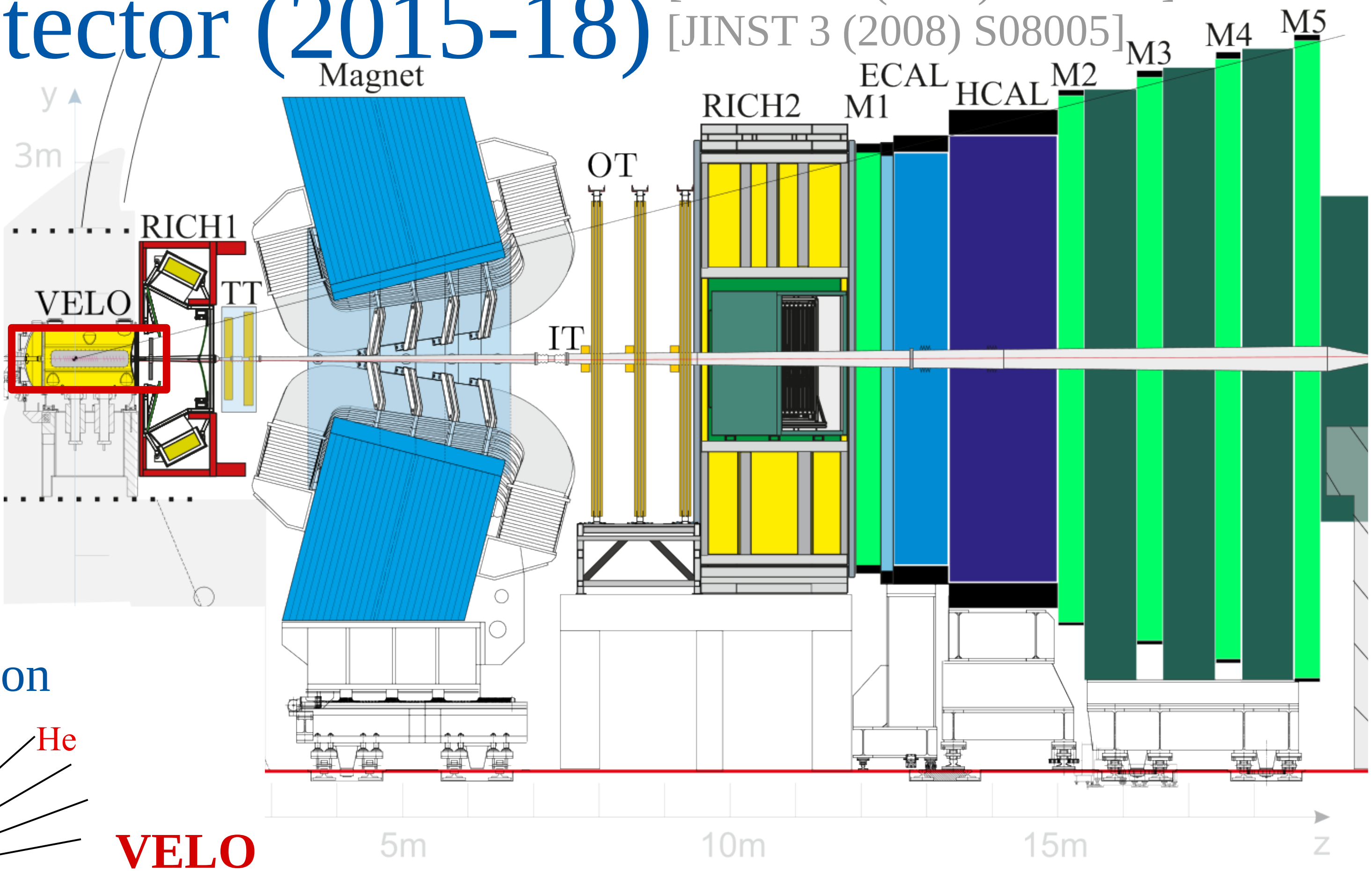


The LHCb detector (2015-18)

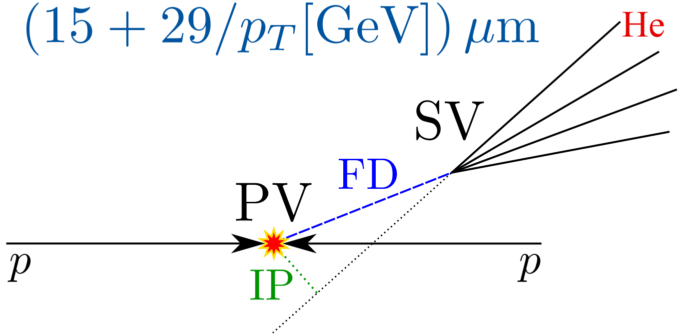
[IJMPA 30 (2015) 1530022]
[JINST 3 (2008) S08005]

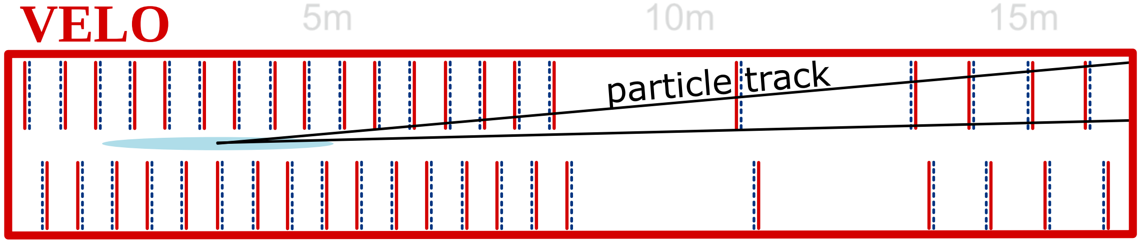
- Coverage: $2 < \eta < 5$





- **I**mpact **P**arameter resolution
  $(15 + 29/p_T[\mathrm{GeV}])\ \mu\mathrm{m}$





Helium selection

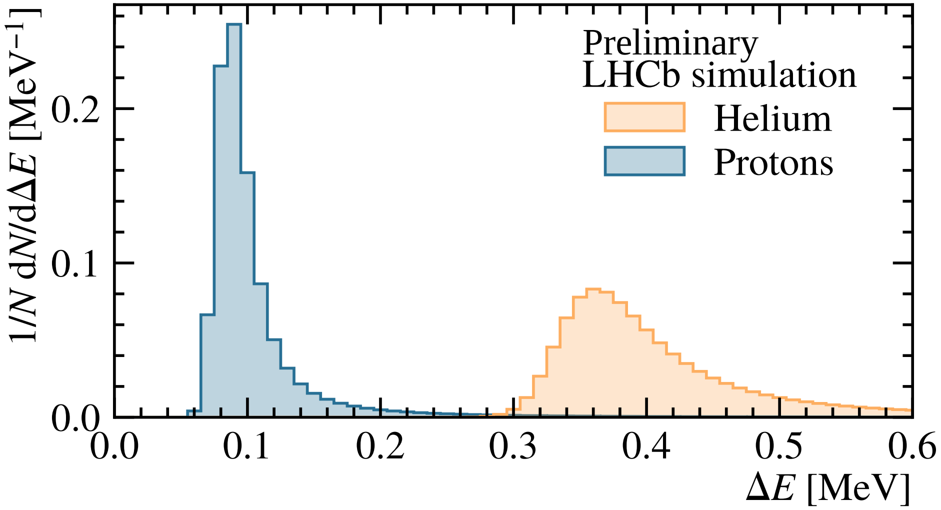
[JINST 19 (2024)270 P02010]

Table 1. Helium selection criteria quantified throughout this paper. The logical or is required between the two preselection criteria. Given the complementary acceptances of OT and IT, the logical or is also required between the downstream requirements.

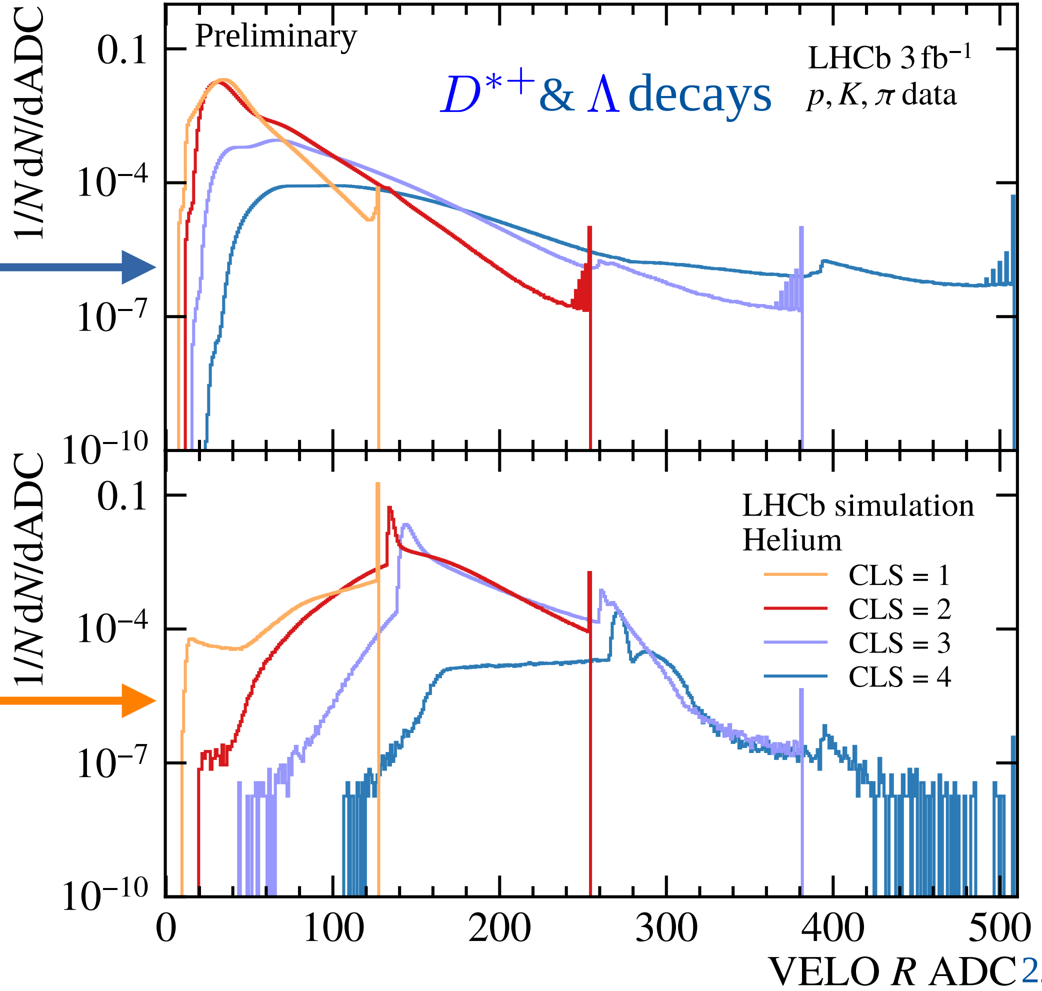
Type	Track property	Selection
Acceptance, kinematics	η	$\in (2, 5)$
	$p/\lvert Z\rvert$	> 2.5 GV
	$p_{\mathrm{T}}/\lvert Z\rvert$	> 0.3 GV
Preselection	Number of overflows	> 3
	Median ADC	> 115
Downstream	Δt_{OT}	< 1 ns
	$\Lambda_{\mathrm{LD}}^{\mathrm{IT}}$	> -1
Conversion rejection	Unique VELO segment	Yes
	$\Lambda_{e-\pi}^{\mathrm{RICH}}$	< 2
PV origin	$\ln \chi^2_{\mathrm{IP}}$	< 2

dE/dx measurements

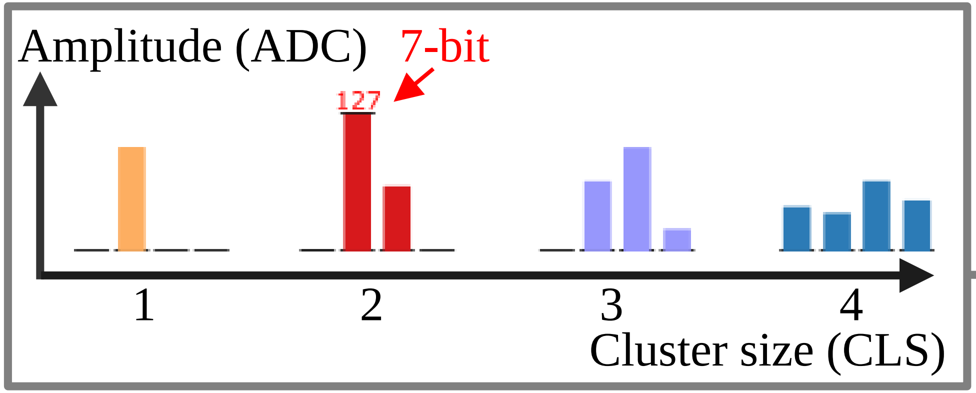
[JINST 19 (2024)270 P02010]



- Helium induces **higher ADC** counts and **wider clusters**



- Digitization & clustering:



Likelihood Discriminators

[JINST 19 (2024)270 P02010]

- Combine n measurements:

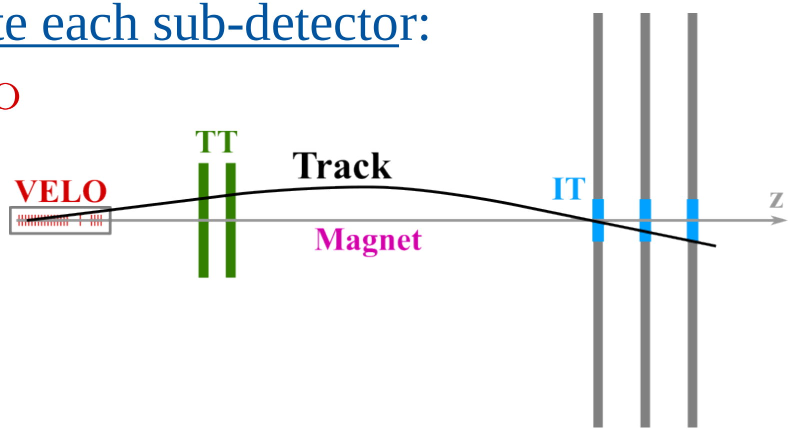
$$\mathcal{L}^X = \left(\prod_{i=1}^{n} \mathrm{PDD}_i^X(\mathrm{CLS}, \mathrm{ADC}) \right)^{\frac{1}{n}}$$

with $X = \{\mathrm{bkg}, \mathrm{He}\}$

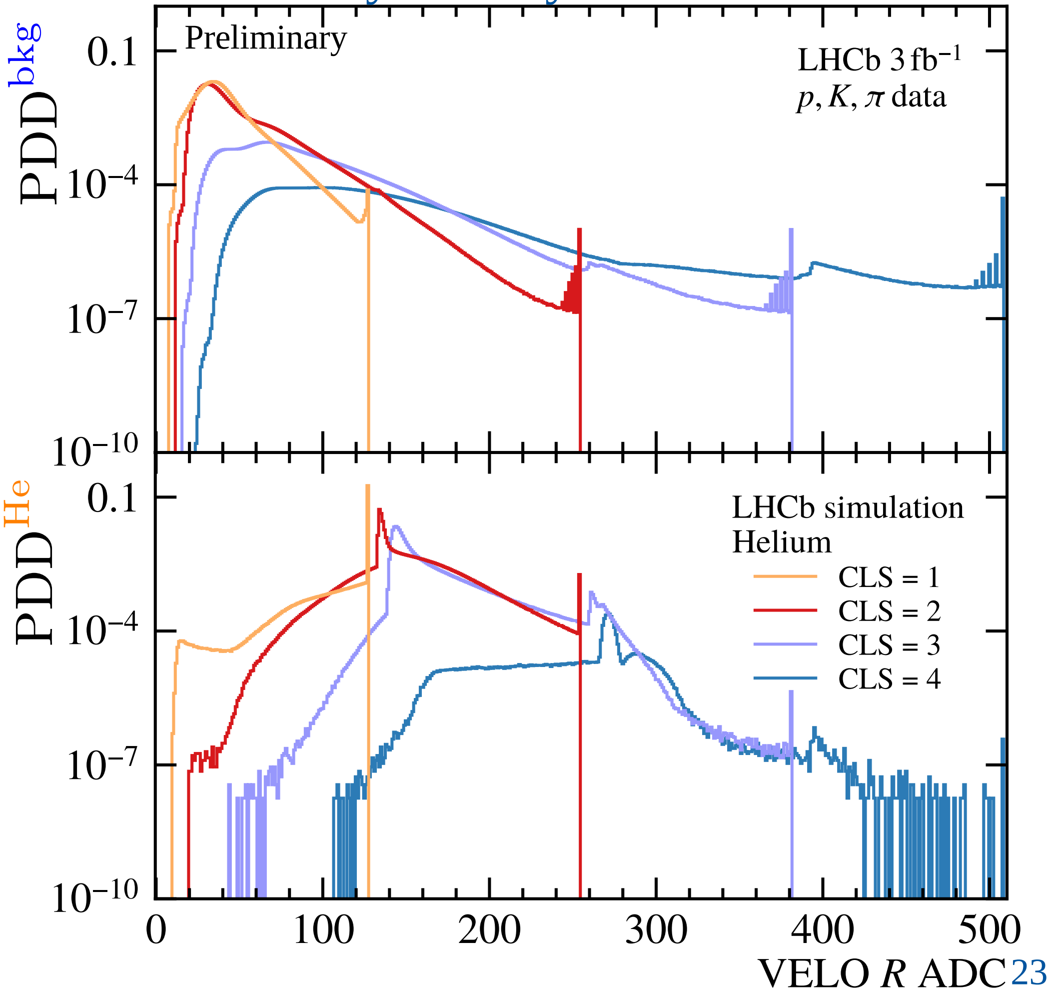
$$\mathbf{\Lambda_{LD}} = \log \mathcal{L}^{\mathrm{He}} - \log \mathcal{L}^{\mathrm{bkg}}$$

- Separate each sub-detector:

1. $\Lambda_{\mathrm{LD}}^{\mathrm{VELO}}$
2. $\Lambda_{\mathrm{LD}}^{\mathrm{TT}}$
3. $\Lambda_{\mathrm{LD}}^{\mathrm{IT}}$

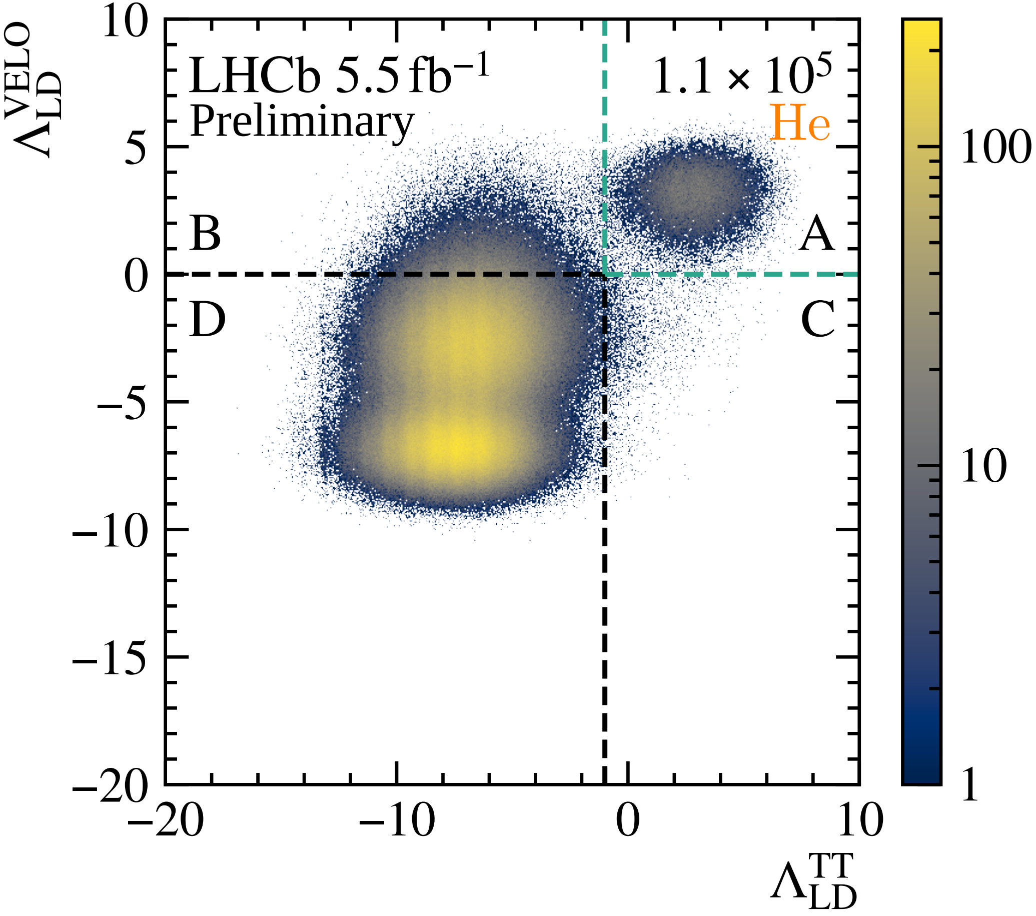


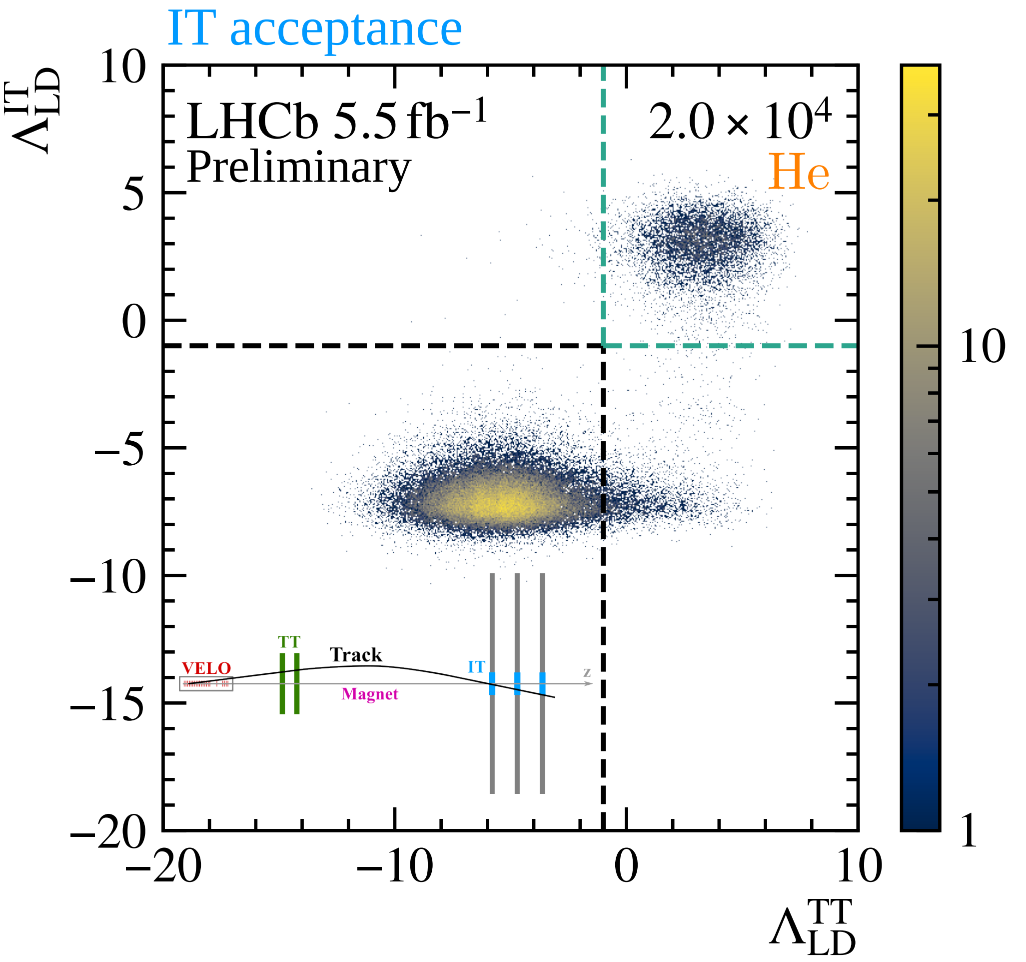
- **P**robability **D**ensity **D**istributions



Prompt helium at LHCb

[JINST 19 (2024)270 P02010]

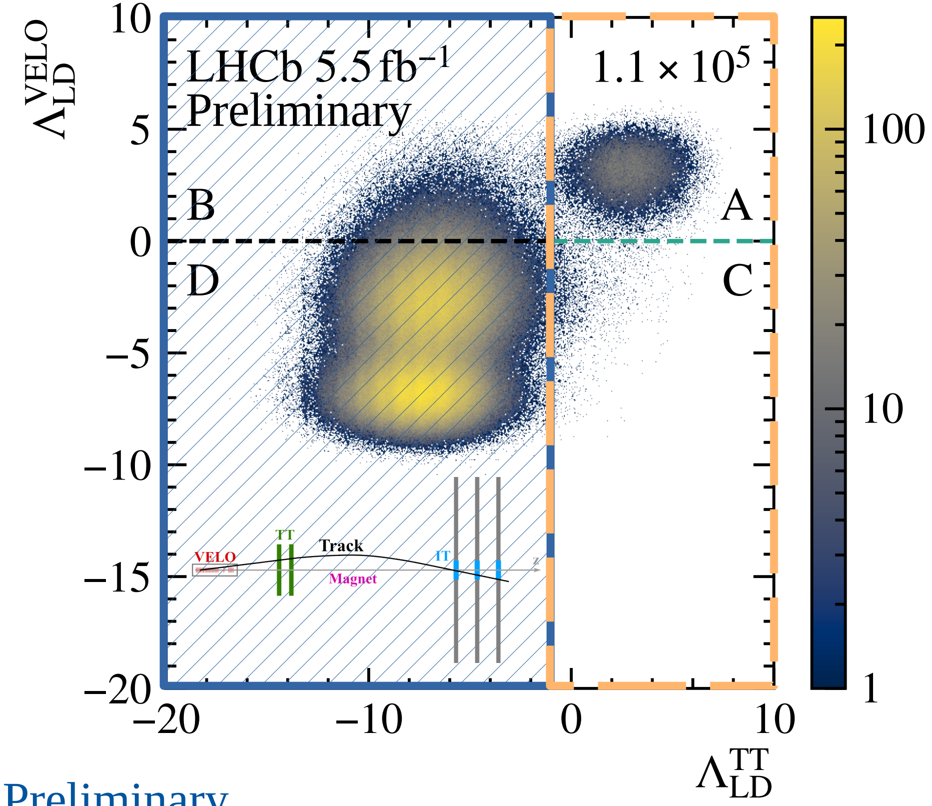


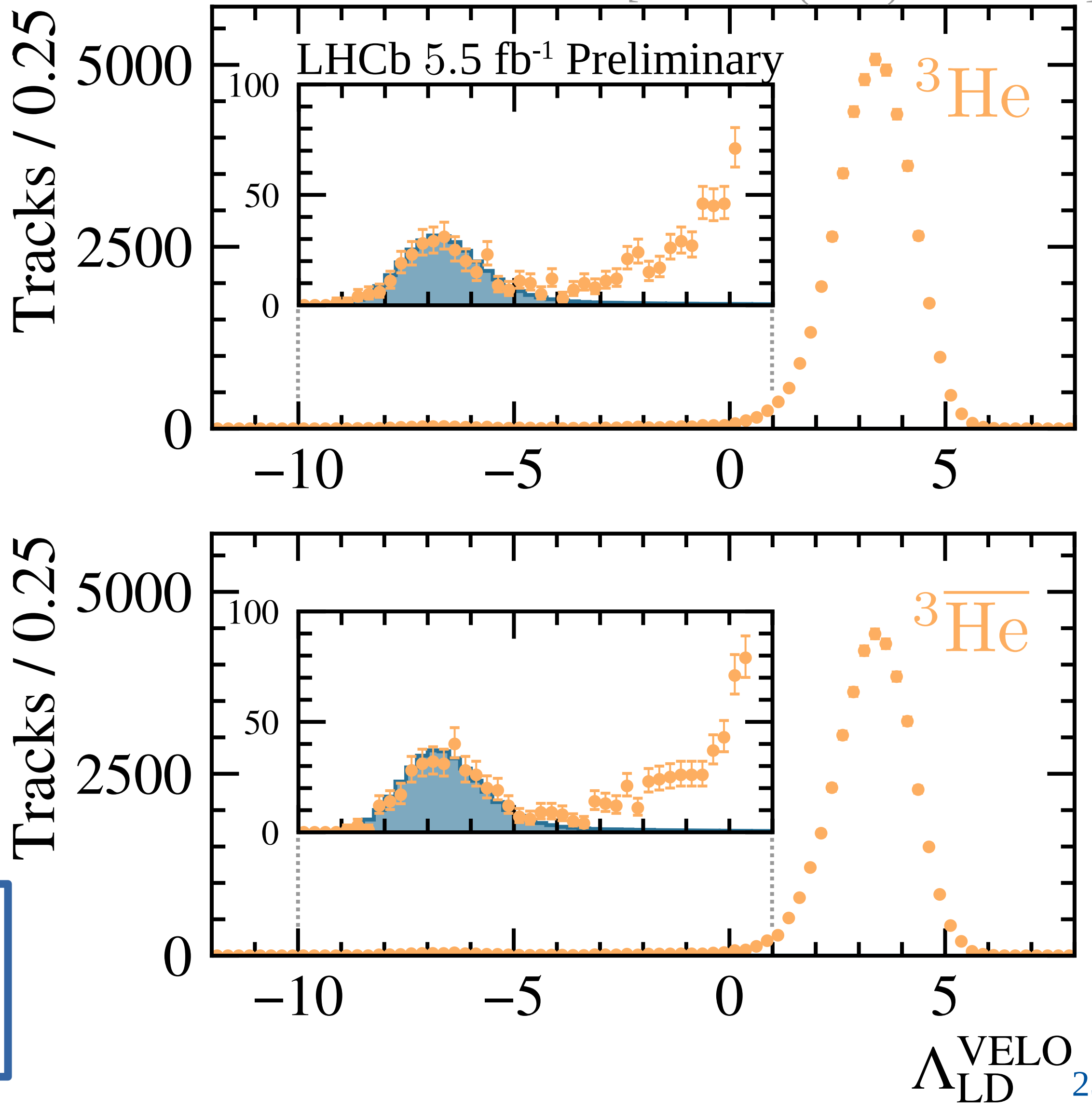


First helium identification at LHCb!

[JINST 19 (2024)270 P02010]

Separation power:



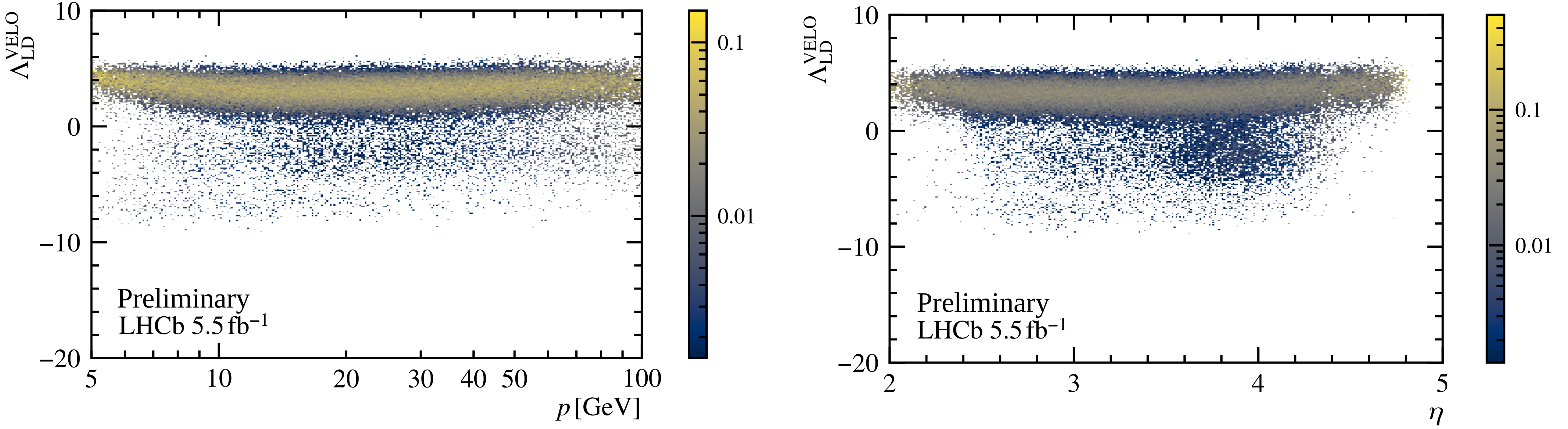


Preliminary

Performance for well-reconstructed tracks:

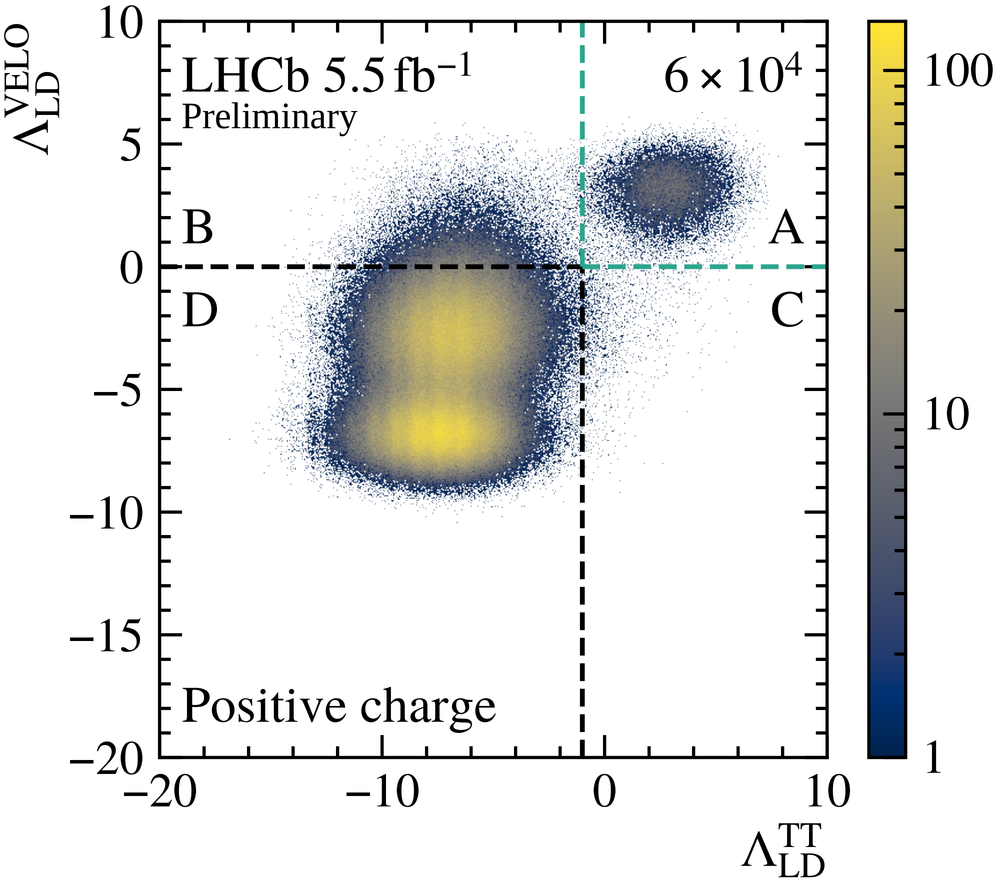
- Mis-ID probabiltiy (bkg $\rightarrow$ He): $\mathcal{O}(10^{-12})$
- Signal (He) efficieny: ~50%

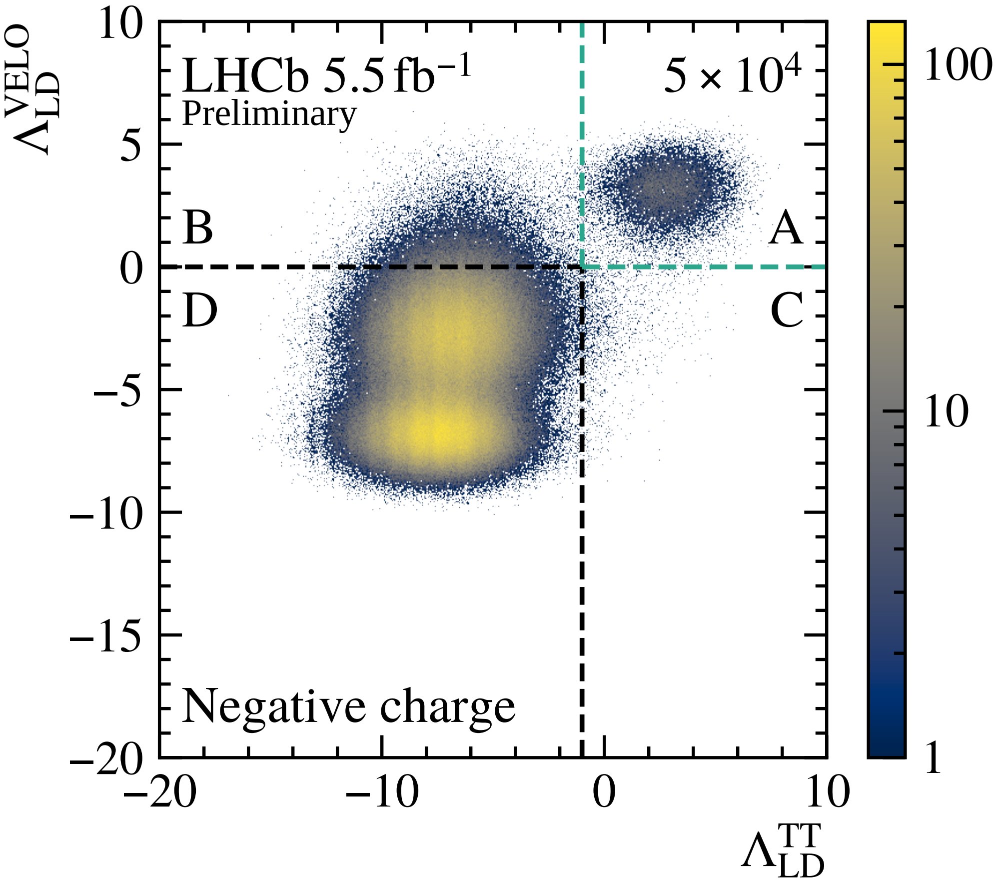
Λ_{LD}: No strong dependence on kinematics



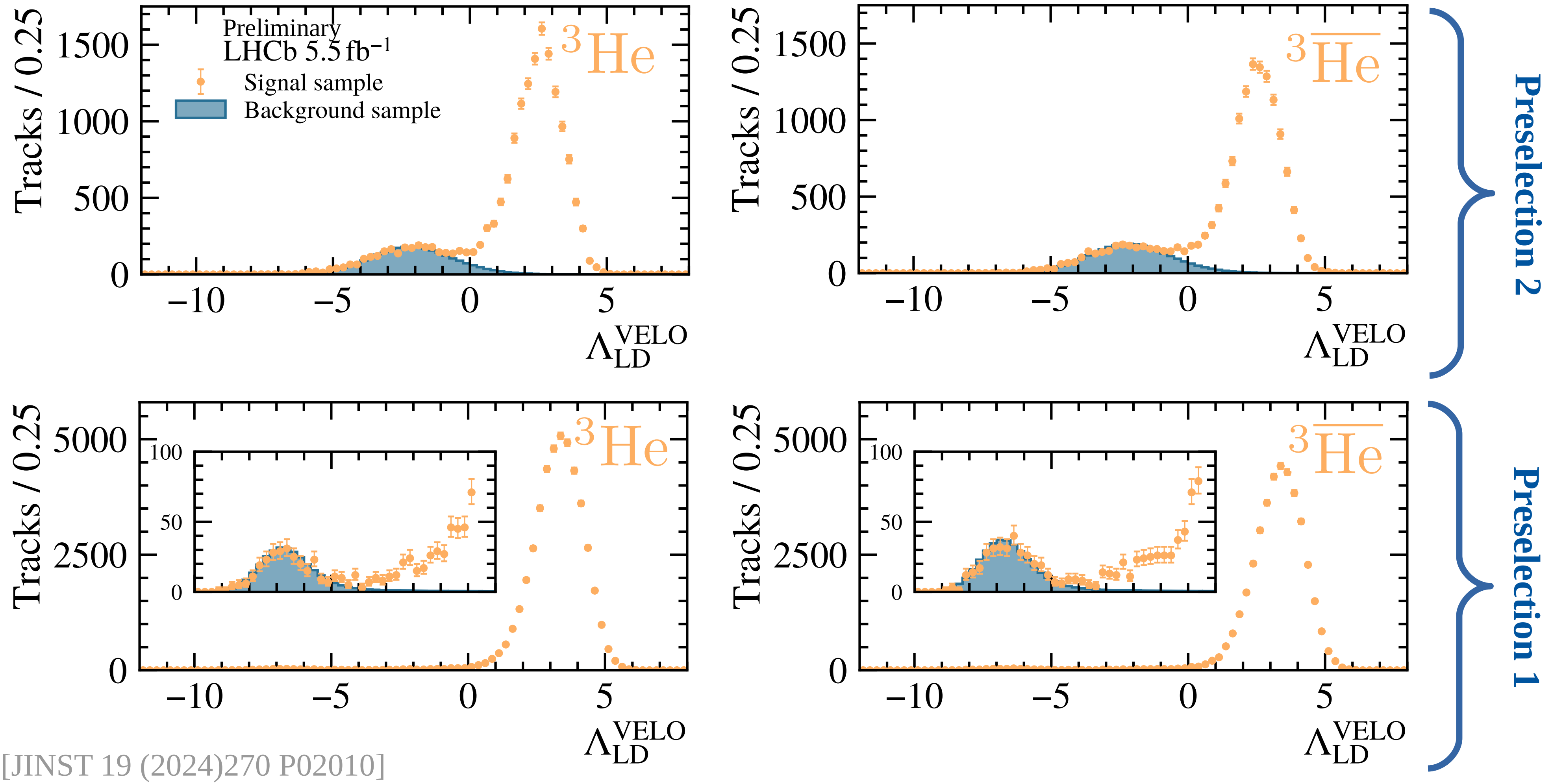
Prompt helium and antihelium

[JINST 19 (2024)270 P02010]





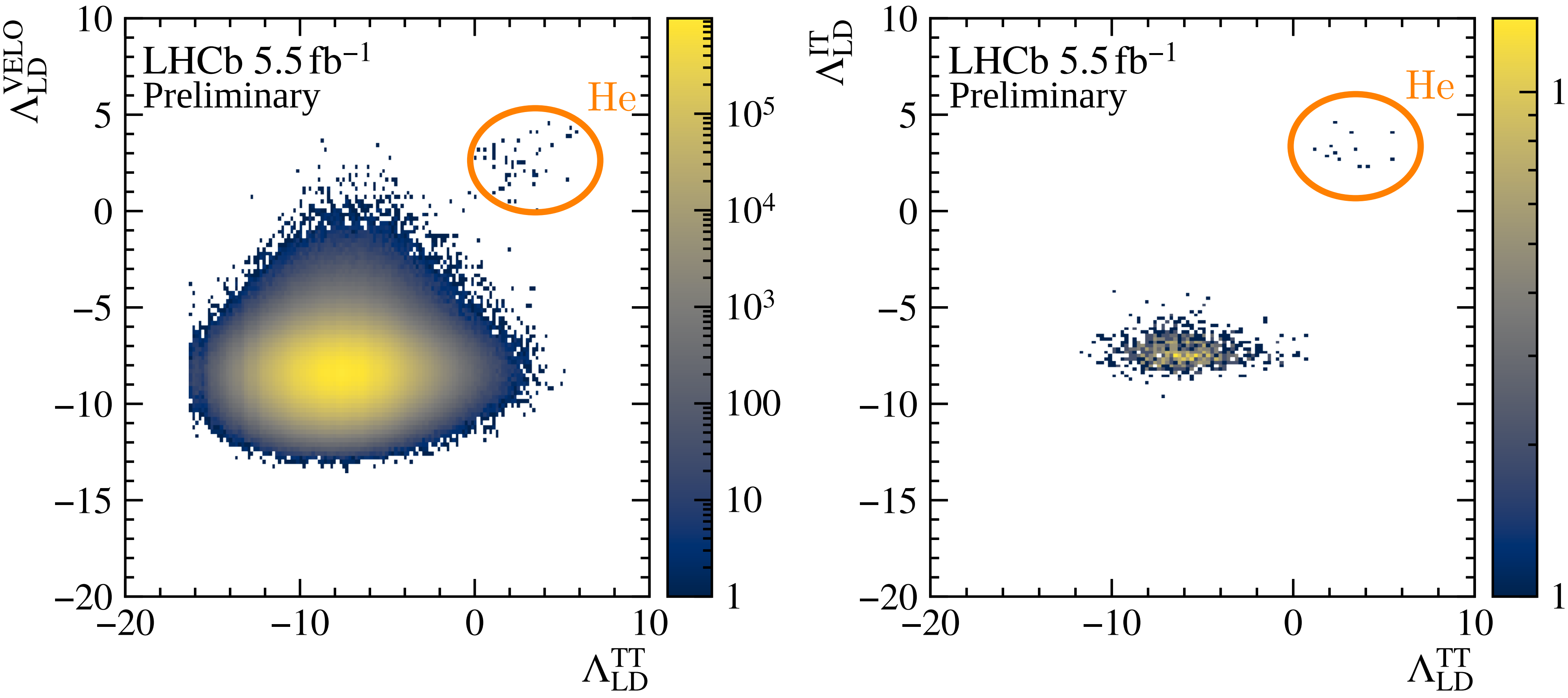
Λ_{LD}^{VELO} separated by charge and preselection



[JINST 19 (2024)270 P02010]

Helium in minimum bias data

[JINST 19 (2024)270 P02010]



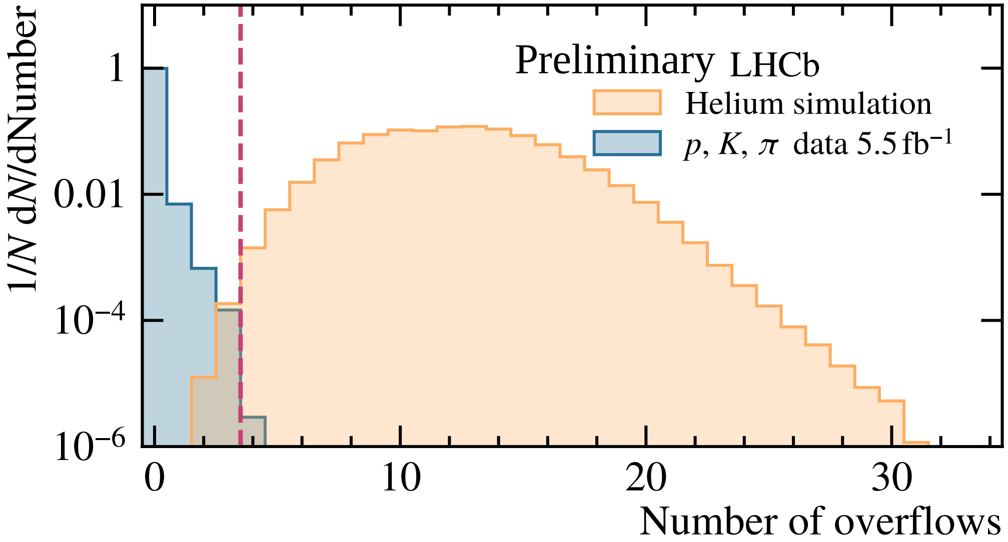
Observe in 2×10^9 tracks a displaced population of 54 at large Λ_{LD}

LHCb skimming stage

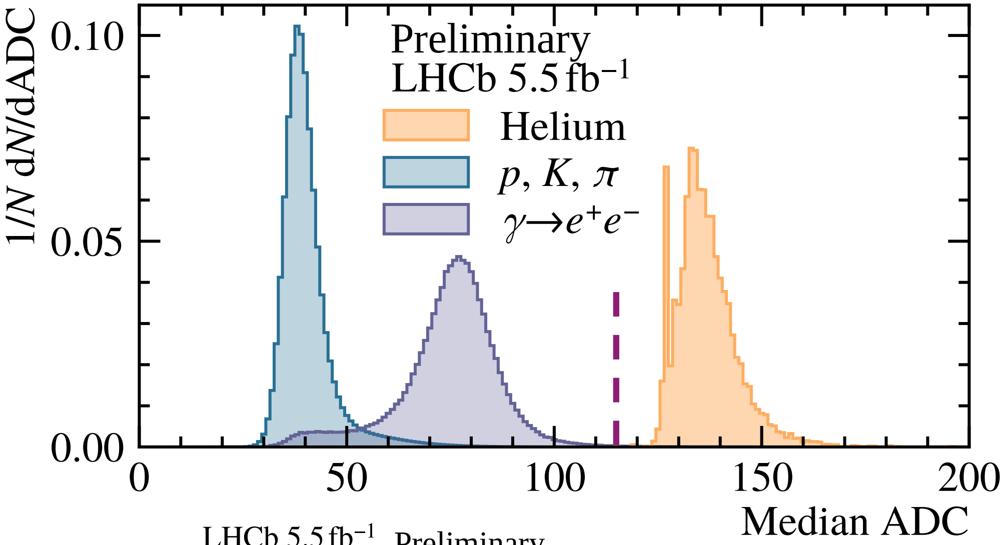
[JINST 19 (2024)270 P02010]

- Run2 pp data from two different preselections

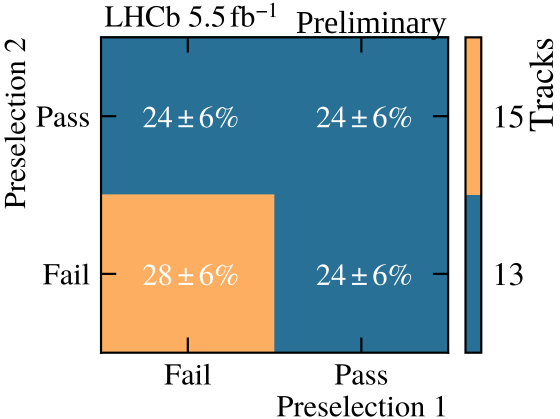
Preselection 1



Preselection 2

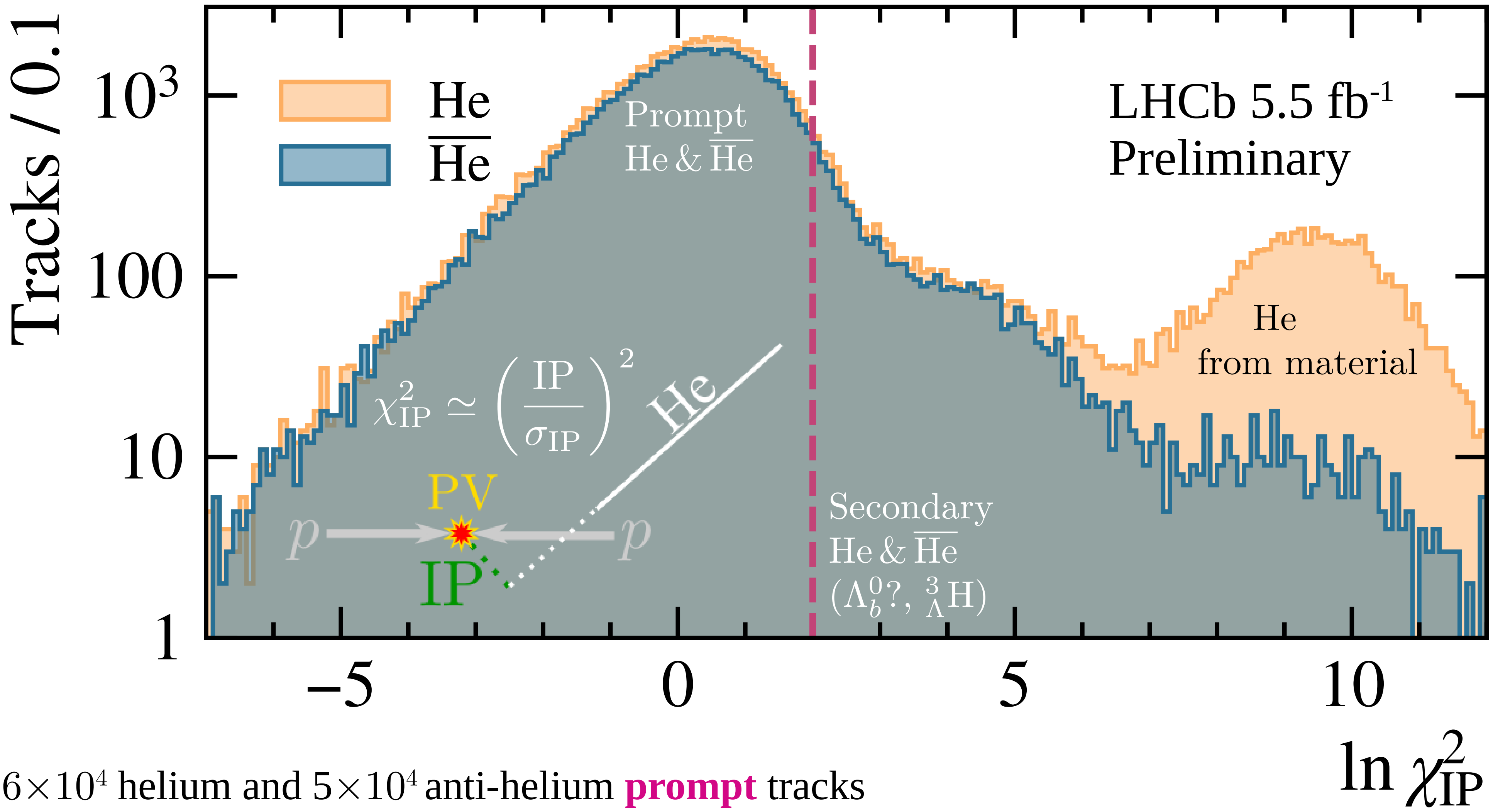


Efficiencies estimated from minimum bias candidates:



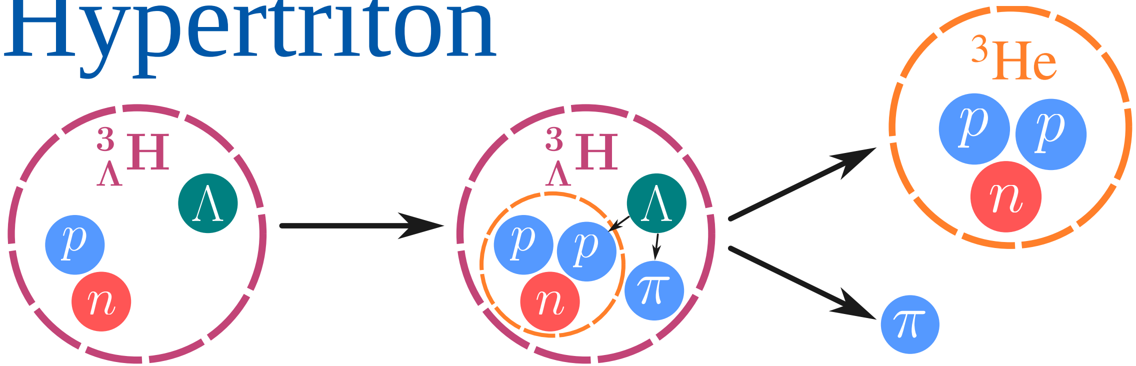
Sources of helium

[JINST 19 (2024)270 P02010]



6×10^4 helium and 5×10^4 anti-helium **prompt** tracks

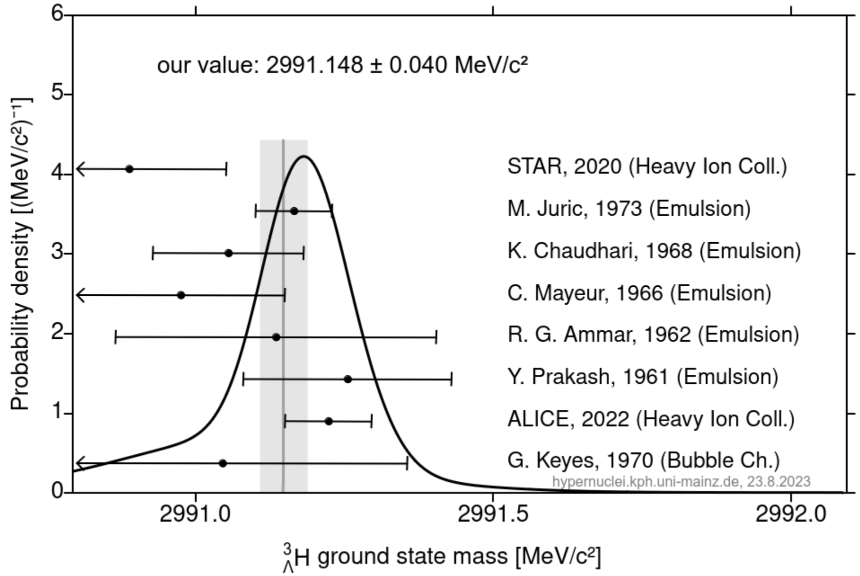
Hypertriton

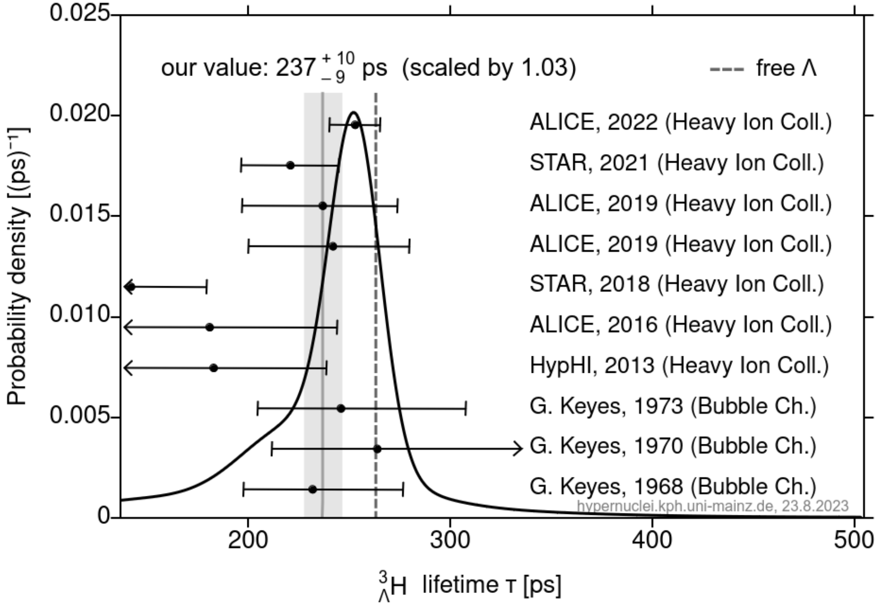


- Access to hyperon-nucleon interaction
  $\Rightarrow$ Implications for **neutron stars**
- Hypertriton "life-time puzzle":
  - Tension between STAR and ALICE

Selection

- 2-body decay into helium:
  $^3_\Lambda\mathrm{H} \to {}^3\mathrm{He}\,\pi^-$
- Secondary helium candidates (not from PV):
  $\ln \chi^2_{\mathrm{IP}}(^3\mathrm{He}) > 2$
- Combine with charged pion
- Well reconstructed secondary vertex





[hypernuclei.kph.uni-mainz.de]