Antihelium production at LHC(b) and in Space

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on behalf of the LHCb

XSCRC2024 16-18 October, CERN

Antihelium in Space

Motivation:

Relic $\overline{He}$ from antimatter domains — PHYSICS REPORT, VOLUME 222, 6, 309 (1992)

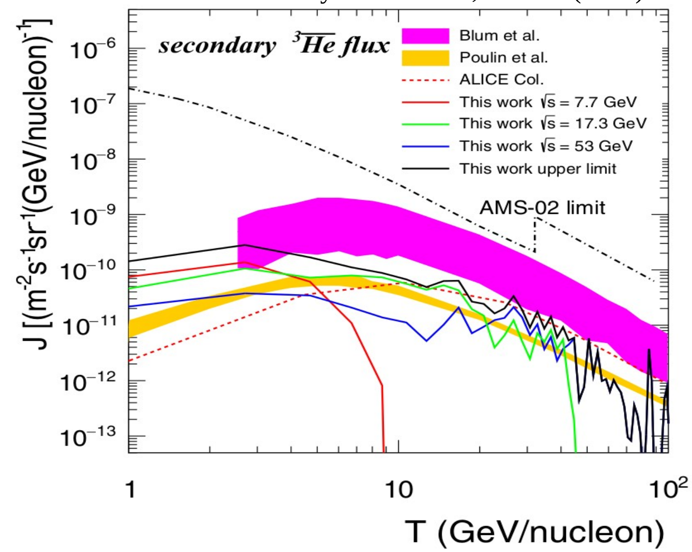
DM annihilation, eg. : $\chi + \chi \rightarrow b\bar{b} \rightarrow {}^3\overline{He} + X$ — PHYSICAL REVIEW D, VOLUME 62, 043003 (2000)

Background:

Cosmic Rays(CR): *p,He,O,C,N,etc* interacting with
- Interstellar Gas: *H, He, etc.*
- Detector material: *C, Al, Fe, etc.*

production of $\overline{He}$ via 'coalescence' of $\bar{p}, \bar{n}, \bar{\Lambda}$,..

Phys.Rev. C 105, 065801 (2022)



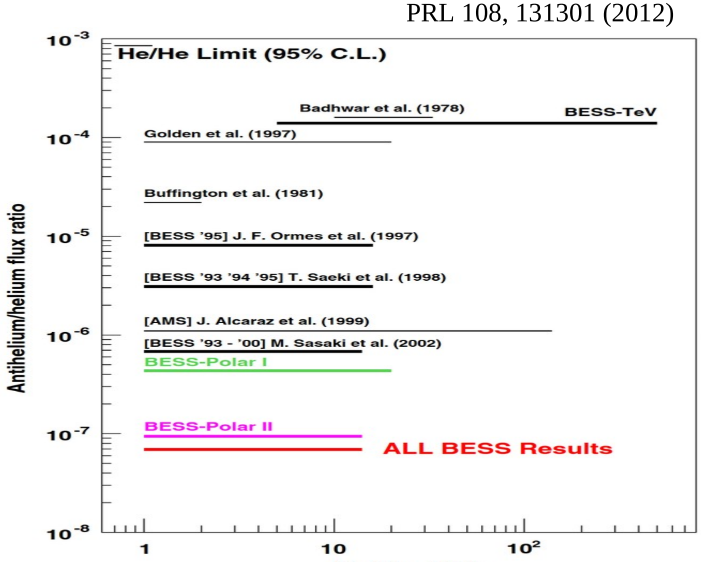
Observations:

No published observed $\overline{He}$, hence upper limit

Best published is from BESS2 polar: $\overline{He}/He < 1.\ 10^{-7}$ 95% C.L.

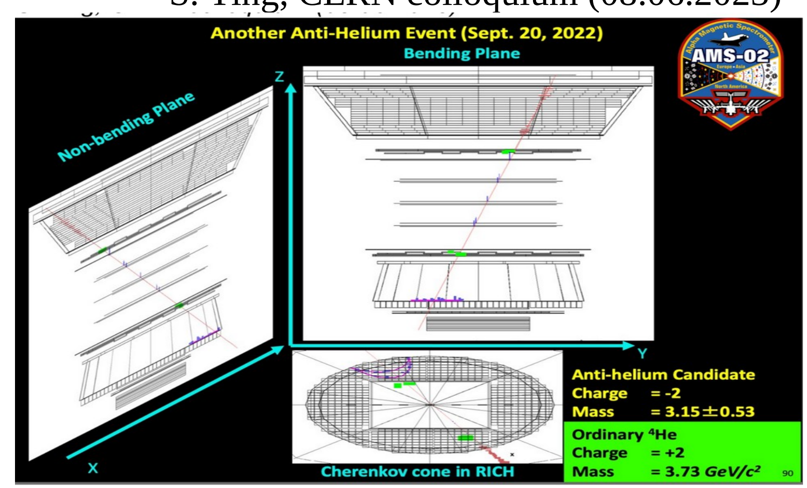
AMS02 has measured by now ~2. 10^9 He, i.e. without observation of $\overline{He}$ this would correspond to the limit $\overline{He}/He < 1.5\ 10^{-9}$ 95%C.L.

PRL 108, 131301 (2012)



AMS02 observed a few $\overline{He}$-like candidates ?

S. Ting, CERN colloquium (08.06.2023)

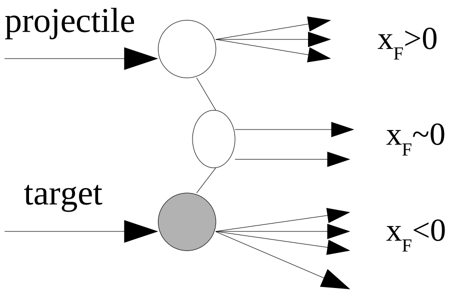


Antihelium in Accelerators

Many $^3\overline{\text{He}}$ registered in central collisions, where $\overline{\text{He}}$/He ~ 1:
STAR(RIHC) AuAu, arxiv nucl-ex0104007 , nucl-ex/0108022, PRL 87, 262301 (2001)
ALICE(LHC) pp,pPb arxiv2109.13026, arxiv2212.04777, arxiv1709.08522, arxiv1907.06906 (2019)

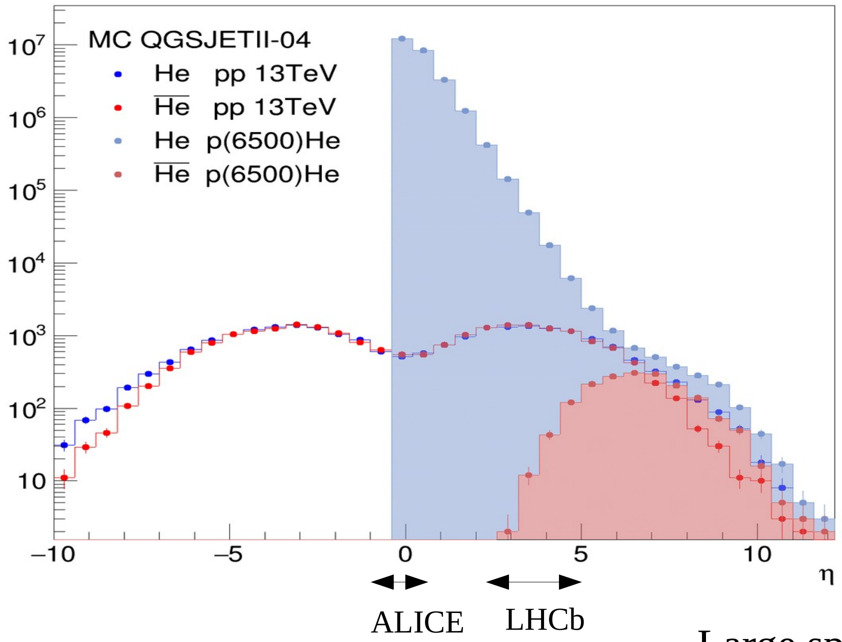
But CR interactions are rather similar to the fixed target(FT), where $\overline{\text{He}}$/He<<1
very few $^3\overline{\text{He}}$ observed so far:
p(76 GeV/c)+Al ***5*** *$^3\overline{\text{He}}$ (and 4 $\overline{\text{T}}$) Serpukhov70, Phys.Lett.(1971) 164*
p(20 GeV/c)+Al ***10*** *$^3\overline{\text{He}}$ SPS WA33. Nuclear Physics B144(1978) 317*
Pb(158A GeV/c)+Pb ***1*** *$^3\overline{\text{He}}$ SPS NA52, Nuclear Physics A661(1999) 177*

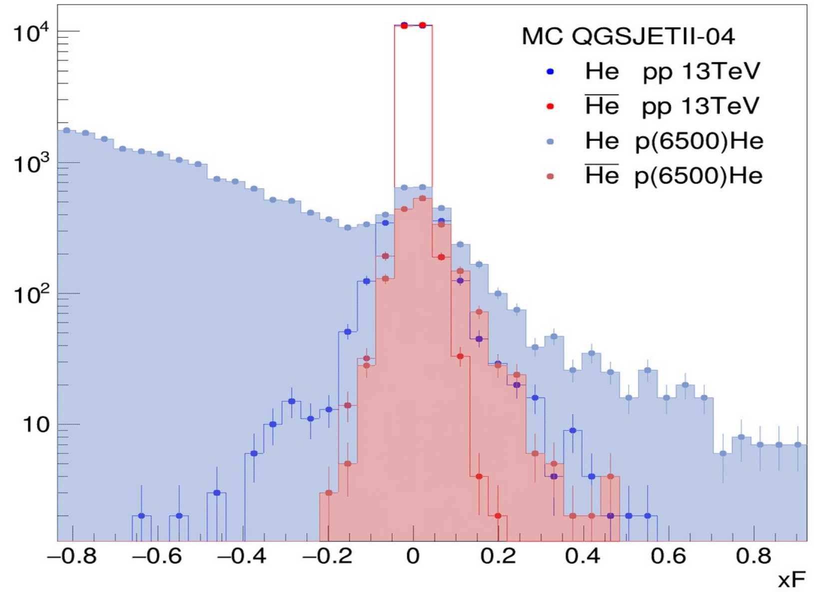
$x_F = 2\, p^*_{\parallel} / \sqrt{s_{NN}}$



At fixed target ^{3}He and $^3\overline{\text{He}}$ are produced in different kinematic regions

CRMC QGSJETII-04 + coalescence





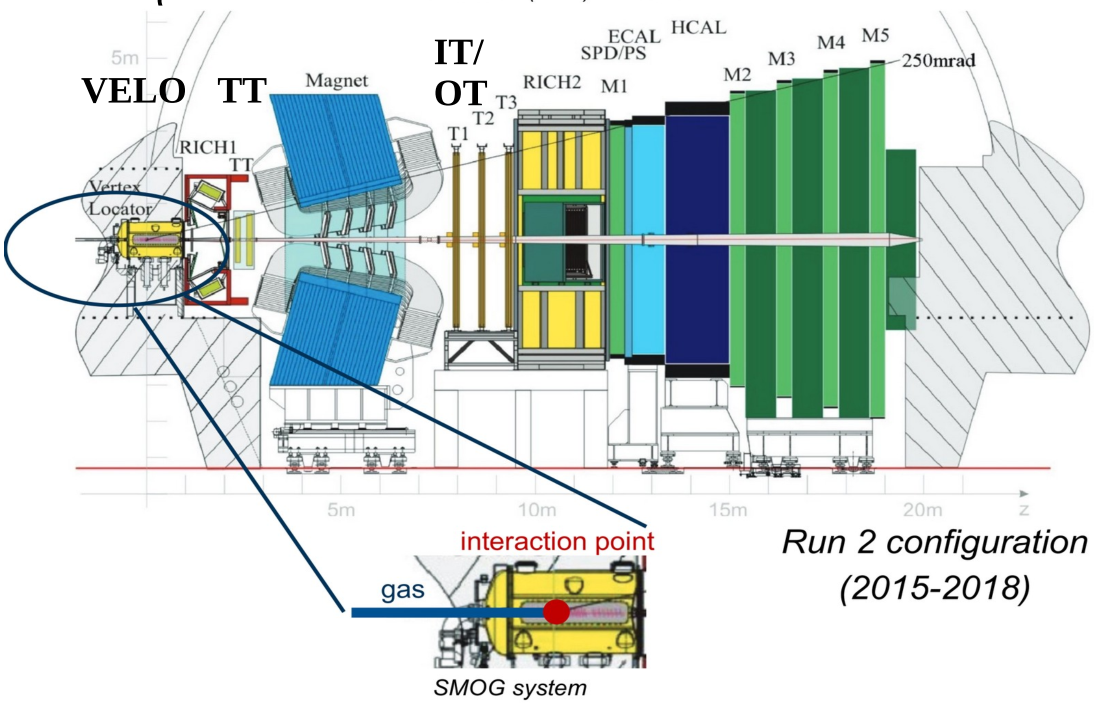
Large spread in different simulations for $\overline{\text{He}}$ predictions in FT
Same emitting source for $\overline{\text{He}}$ in central and FT interactions?

LHCb in Run 2

Designed for B decays, not for ions. Particle identification with RICH, but for ^{3}He θ_c>0 at p>50 GeV/c

2<η<5

IJMPA 30 (2015) 1530022



Run 2 configuration (2015-2018)

In Run2 LHCb had silicon strip tracking detectors, which are readout by 7-bit ADC → dEdx~Z^2

- **VELO** vertex locator 42 layers
- **TT** trigger tracker 4 layers
- **IT** inner tracker (after magnet) 12 layers
  only central ~20% of acceptance, outer are
- **OT** straw drift tubes that measure time delay with respect to interaction using fixed threshold discriminator. For He this delay has negative offset with respect to mips(*π,K,p,..*)

Also used RICH as a veto and E/HCAL signal to improve He identification

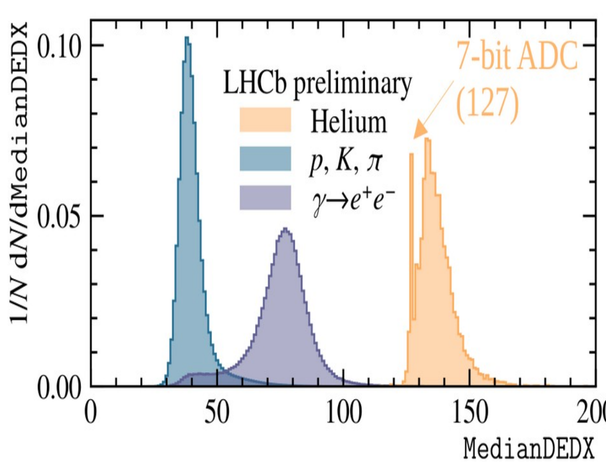
Major upgrade for Run3 (2021-):
lost most of dEdx measurements!

LHCb can operate in:

- **collisions mode**:
  pp, PbPb, pPb

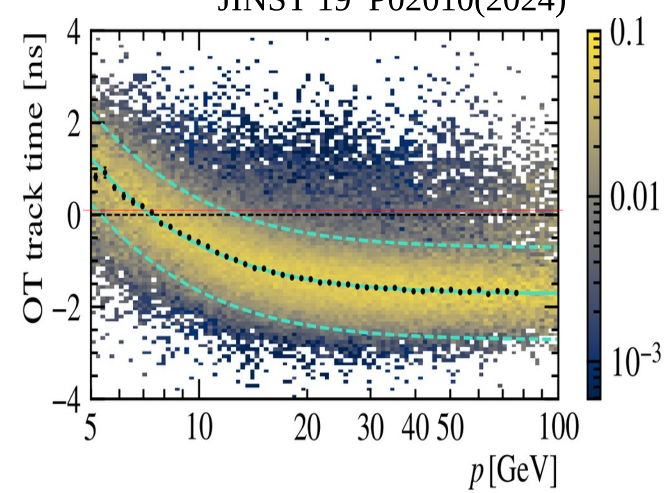
- **fixed target mode** (SMOG) when the gas is injected inside beam pipe and only one downstream *p,Pb* beam:
  pNe, pHe, pAr,...

Response in VELO



OT time for He with respect to mips

JINST 19 P02010(2024)

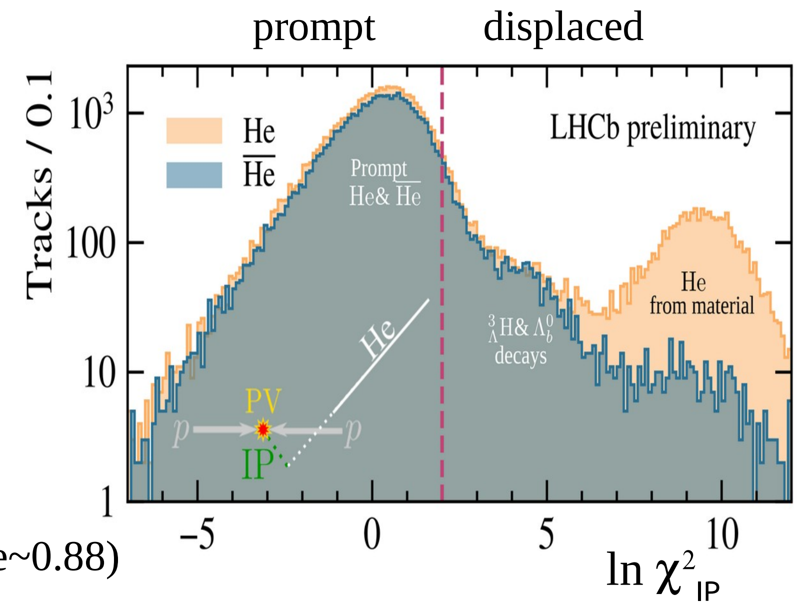


Prompt $^3\overline{\mathrm{He}}$ at LHCb in pp13 TeV

Run2 pp 13 TeV L_{int}=5.5 fb^{-1}

- Select good tracks and identify He using LogLikelihood(LD) from different subdetectors: $\Lambda^{VELO}, \Lambda^{TT}, \Lambda^{IT}$ and OT time
- Select prompt track using PV Impact Parameter(IP) χ^2

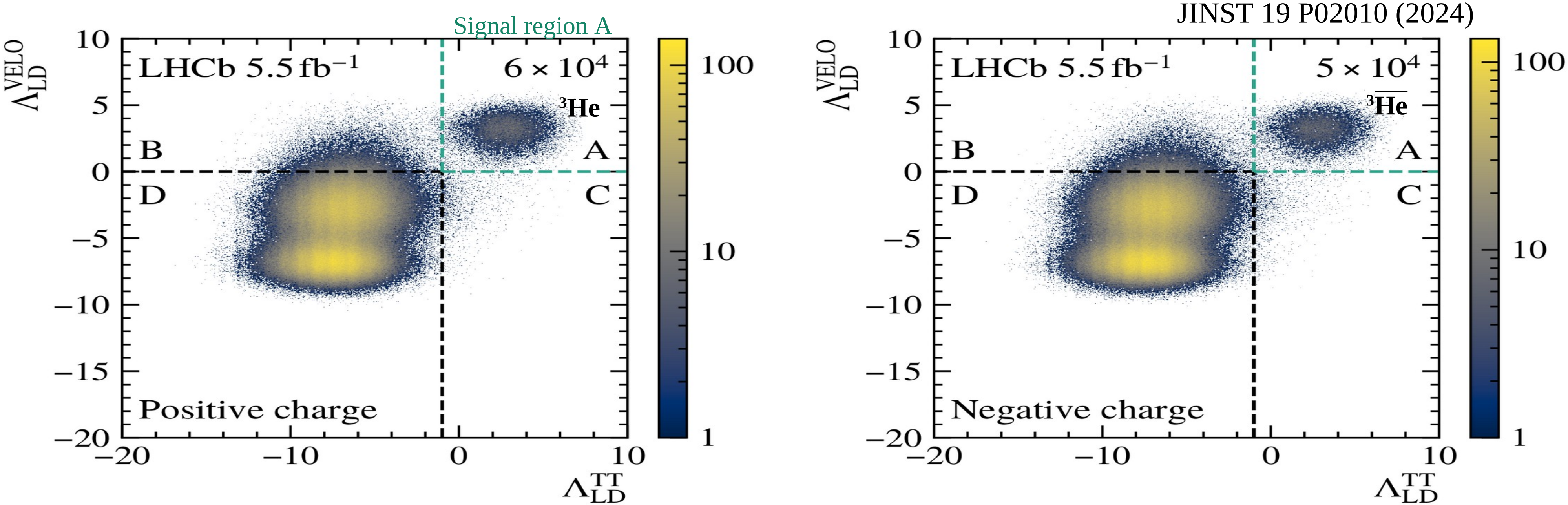
  displaced tracks can be from:
  - interactions with detector material (mostly He)
  - hypertriton $^3\overline{\mathrm{H}}_\Lambda \rightarrow {}^3\overline{\mathrm{He}} + \pi^+$
  - $\overline{\Lambda}_b \rightarrow {}^3\overline{\mathrm{He}}$ +X PRL 126, 101101 (2021)



Overall ~**1.1 10^5** $^3\overline{\mathrm{He}}$+^{3}He with **~ 5 10^4 $^3\overline{\mathrm{He}}$** candidates($^3\overline{\mathrm{He}}$/^{3}He~0.88)

Population of selected tracks in the Lhood plane of VELO-TT

JINST 19 P02010 (2024)



Ongoing analysis of efficiencies, cs and coalescence factors...

Displaced $^3\overline{\mathrm{He}}$ in pp13 TeV: Hypertriton

Displaced $^3\overline{\mathrm{He}}$ from hypertriton :

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

m=2991.148±0.040 MeV
cτ~7.9 cm

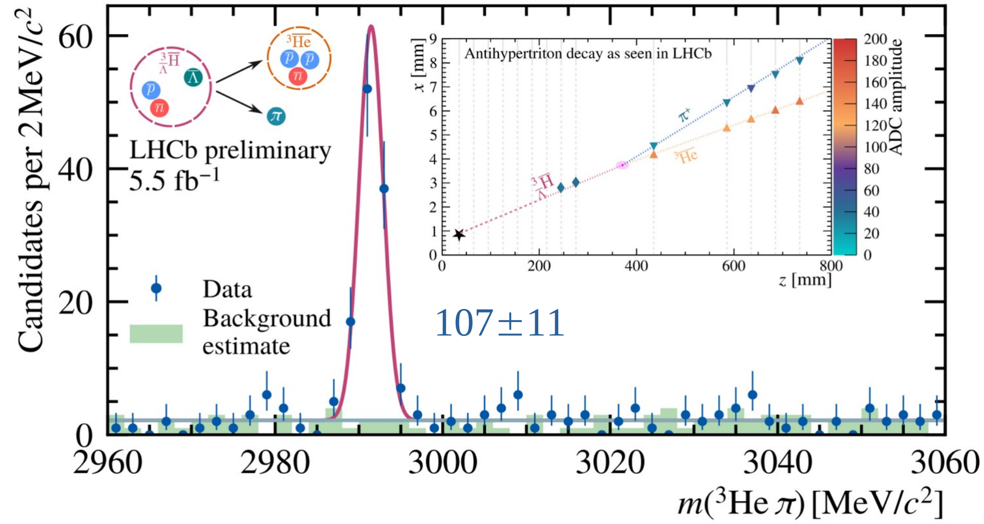
- Identify displaced He and construct Minv(^{3}Heπ) at secondary vertex

Observed **107** candidates in total; **46 $^3\overline{\mathrm{He}}$** from $^3\overline{\mathrm{H}}_{\Lambda}$

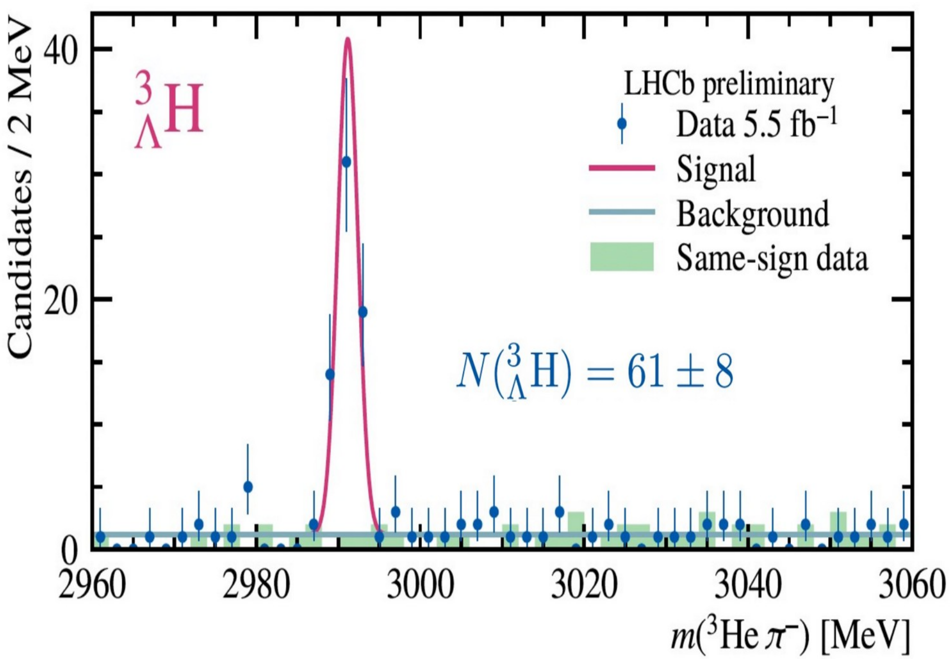
For the same data, observed 1.1 10^5 prompt (^{3}He+$^3\overline{\mathrm{He}}$), i.e $^3\mathrm{H}_{\Lambda}/^3\overline{\mathrm{He}}$ <0.001, but $^3\mathrm{H}_{\Lambda}/^3$He >0.1 from PbPb(ALICE) and AuAu(STAR) arXiv:2310.12674.

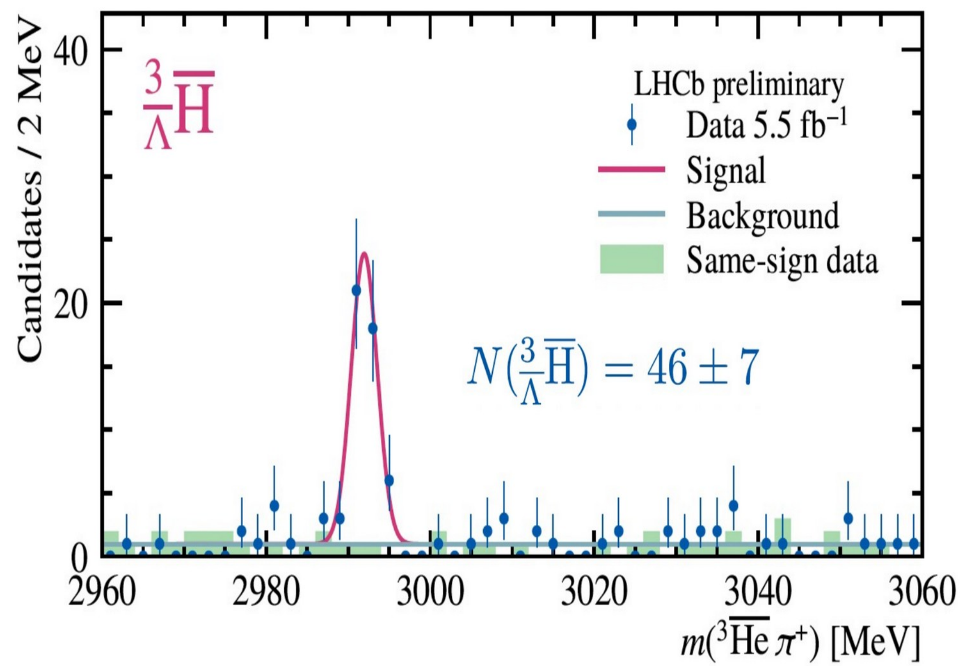
Lower efficiency of $^3\mathrm{H}_{\Lambda}$ and $^3\overline{\mathrm{H}}_{\overline{\Lambda}}$ is due to soft pion that can escape reconstruction.

CERN Courier 11.2023



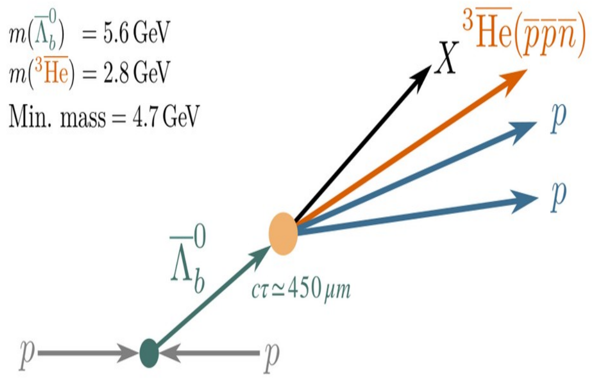
LHCb-CONF-2023-002





Ongoing analysis of efficiencies and systematics

Displaced $^3\overline{He}$ in pp13 TeV: from $\overline{\Lambda}_b$ decays



Coalescence of Λ_b decay products boosted for He comparing to prompt production, and can be a source of $^3\overline{He}$ from eg. DM annihilation with Br($\overline{\Lambda}_b \to {}^3\overline{He}X$~ 3. 10^{-6}) Phys. Rev. Lett. 126, 101101 (2021).

About 10^{11} Λ_b should be produced at LHCb during Run 2!

- Identify He and construct the exact(exclusive) or incomplete(inclusive) invariant masses for search channels. Signal regions are from simulations.
- Background is all combinatorial, investigated and normalized using reference channel: $\Lambda_b \to \Lambda_c(pK\pi)\pi$, and $\Lambda_b \to pK\pi\pi$, $B \to K\pi\pi\pi$

LHCb-CONF-2024-005

Consider 3 channels:

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

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

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

Using Pythia8.3 + coalescence

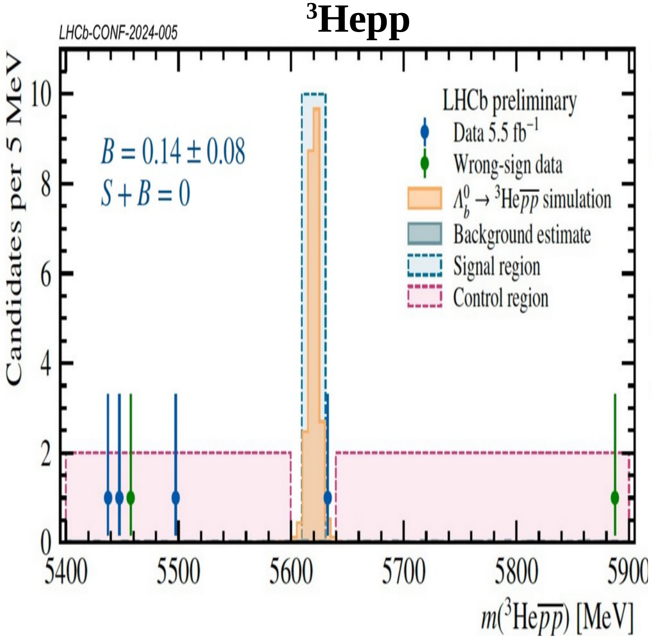
$\mathcal{B}(^3\overline{He}pp)/\mathcal{B}(^3\overline{He}X)$ $<10^{-6}$

$\mathcal{B}(^3\overline{He}ppX)/\mathcal{B}(^3\overline{He}X)$ ~0.38

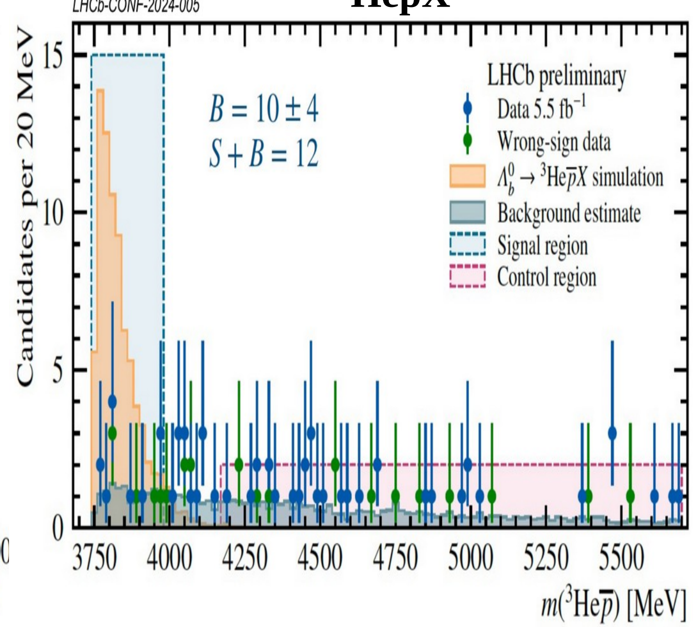
$\mathcal{B}(^3\overline{He}pX)/\mathcal{B}(^3\overline{He}X)$ ~0.42

No visible excess observed in signal regions, derive limits

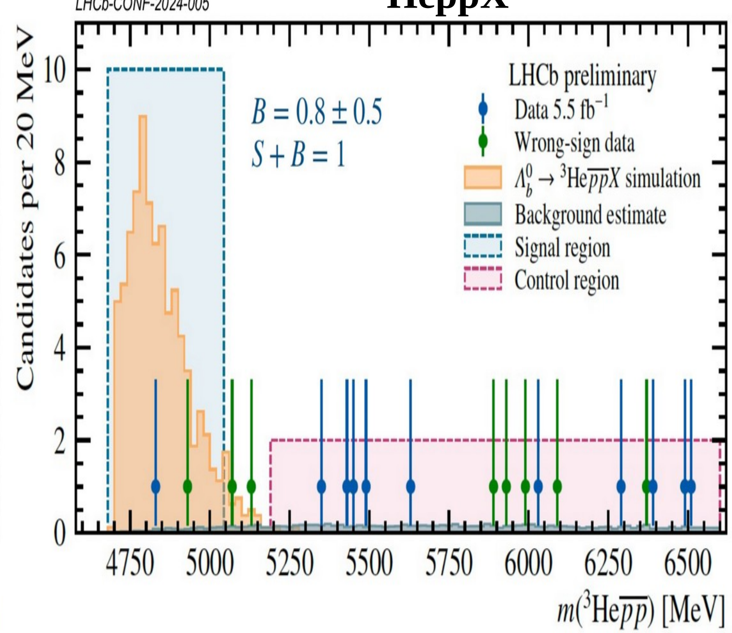
$^3\overline{He}pp$



$^3\overline{He}pX$



$^3\overline{He}ppX$



Limit $\overline{\Lambda}_b \to {}^3\overline{\text{He}}X$

CLs Upper Limits, including systematic:

$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\text{He}}pp) < 1.9 \times 10^{-9} \text{ at } 90\% \text{ CL}$$
$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\text{He}}ppX) < 1.6 \times 10^{-8} \text{ at } 90\% \text{ CL}$$
$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\text{He}}pX) < 3.6 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

Extrapolation to inclusive $\overline{\Lambda}_b \to {}^3\overline{\text{He}}X$ require some model assumptions:

• Using Pythia8.3+coalescence.
$^3\overline{\text{He}}pX$ has largest fraction, but is sensitive to the deuterons production $\overline{\Lambda}_b \to {}^3\overline{\text{He}}dX$, while the $\overline{\Lambda}_b \to {}^3\overline{\text{He}}pp$ is not visible.
Therefore use the $\overline{\Lambda}_b \to {}^3\overline{\text{He}}ppX$ channel and get:

$B(\overline{\Lambda}_b \to {}^3\overline{\text{He}}X) < 4.2\ 10^{-8}$ (90%CL)

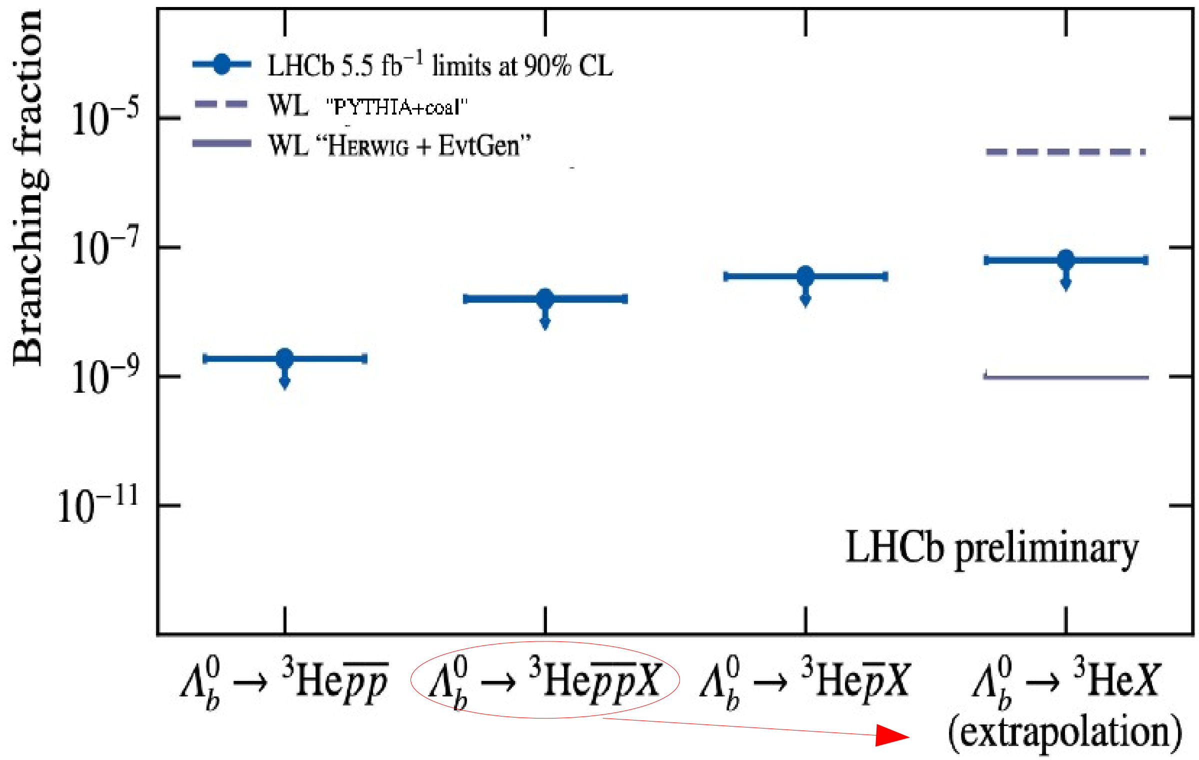
• Using strong isospin factors.
will give $\mathcal{B}({}^3\overline{\text{He}}ppX)/\mathcal{B}({}^3\overline{\text{He}}X) = 1/4$ and get:

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

Note that isospin is broken in $\overline{\Lambda}_b$ decay, suppressing $^3\overline{\text{He}}nnX^{++}$ states, hence this limit is conservative.

On the other hand $^3\overline{\text{He}}nnX$ can be enhanced due to absence of coulomb barrier (WL), but measured $^3\text{H}/^3\text{He}\sim 1$, i.e coulomb effects are not large.

LHCb-CONF-2024-005



WL
M. Winkler T.Linden Phys. Rev. Lett. 126, 101101 (2021)
$\overline{\Lambda}_b \to {}^3\overline{\text{He}}X$ and $\overline{\Lambda}_b \to {}^3\overline{\text{H}}({}^3\overline{\text{He}}+\nu+e)X$ total Br~3.10^{-6} i.e $\overline{\Lambda}_b \to {}^3\overline{\text{He}}X$ Br~$1.5\ 10^{-6}$
Used PYTHIA probQQtoQ to match the bb$\to\Lambda_b$ fragmentation fractions (PhysRev D100, 031102 (2019), but this doesnt affect the Λ_b decays, see arXiv 2105.00799, arXiv2404.13114 for discussion.
The coalescence of He from Λ_b depends upon baryonic form factors that are not well modeled in Pythia hadronization, regardless tunes.
These factors can be measured, eg in charmless decays, like $\Lambda_b \to \Lambda p\overline{p}$ (Br~$3.2\ 10^{-6}$) or others. Scientific Reports 9, 1358 (2019)

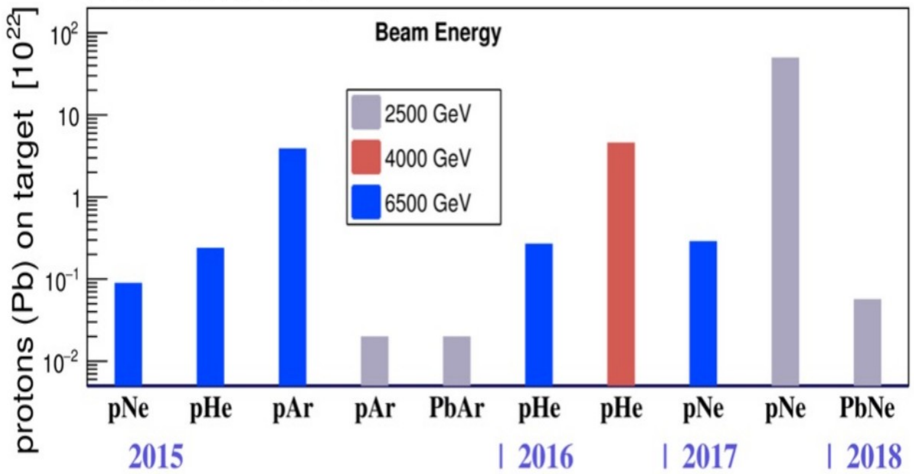
Fixed Target measurements at LHCb

In Run2 many FT data samples and analysis, eg:

Antiproton in pHe s=110GeV.   Phys. Rev. Lett. 121 (2018) 222001
Antiprotons from Λ in pHe Eur.Phys.J C83 (2023) 543
Charmonium in pNe s=68.5 GeV   Eur. Phys. J. C83 (2023) 625…...

see Chiara Lucarelli talk

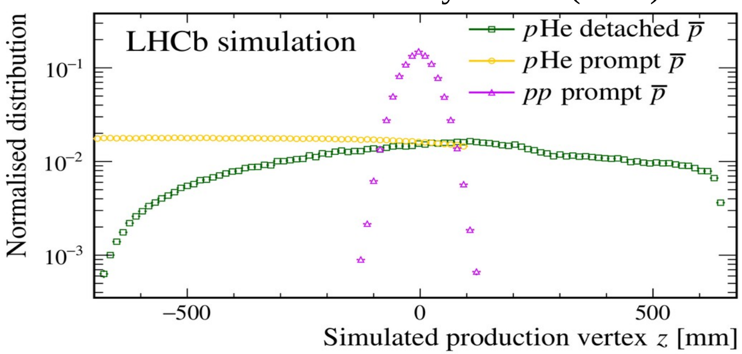
LHCb-PUB-2018-015



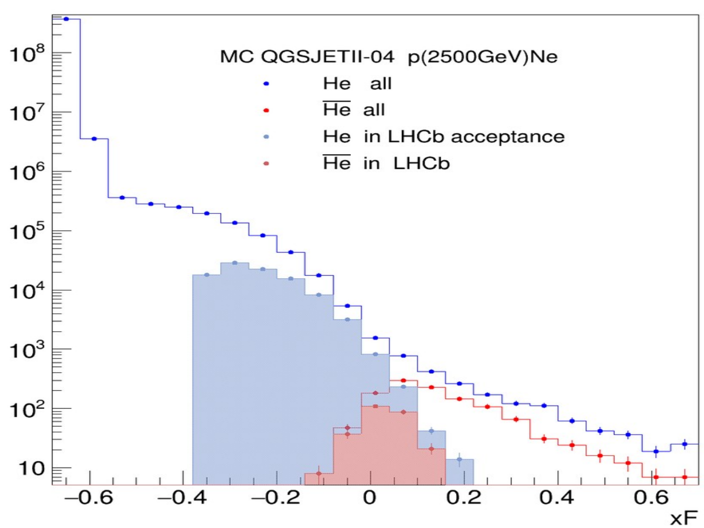
Largest samples $pNe(\sqrt{s_{NN}}$=68.5 GeV)
and $pHe(\sqrt{s_{NN}}$=110 GeV) have been ana;yzed

Analysis is similar to pp collisions, but with distributed primary vertex and contamination from pp

Eur.Phys.J C83 (2023) 543



MC QGSJET xF of *pNe* in LHCb acceptance



Plenty ^{3}He and only a few $^3\overline{He}$ are expected in the LHCb acceptance:
(η[2-5], p/z >1GeV/c)

pNe results are in the approval process...

Summary

• Many He,$\overline{\mathrm{He}}$ analysis of Run2 data are ongoing at LHCb and publications are pending.

• LHCb detector has some advantages over others: good vertexing, forward η[2-5], fixed target facilities provide unique measurements relevant to antihelium production in Space.

• Unfortunately the Run3-4 will hardly contribute to the He studies, some He identification can be developed for the Run 5, after 2034.

Backup: Coalescence

Pythia8.3+coalescence
default settings

- 3 body event-by-event coalescence (ppn/Λ)

dp<p_c and dr<r_c , p_c=125 GeV r_c=2fm

$\mathcal{B}(\Lambda_b \to {}^3\overline{\mathrm{He}}X)$ ~2. 10^{-6}
$^3\overline{\mathrm{He}}pp+X^0$ ~38.3%
$^3\overline{\mathrm{He}}nn+X^{--}$ ~11.1%
$^3\overline{\mathrm{He}}pn+X^-$ ~4.2%
$^3\overline{\mathrm{He}}d+X^-$ ~46.5%

$\mathcal{B}(\Lambda_b \to {}^3\overline{\mathrm{H}}X)$ ~1.4 10^{-6}
$^3\overline{\mathrm{H}}pp+X^+$ ~25%
$^3\overline{\mathrm{H}}nn+X^-$ ~21.3%
$^3\overline{\mathrm{H}}pn+X^0$ ~4.6%
$^3\overline{\mathrm{H}}d+X^0$ ~49.2%

- 2 body coalescence. Using deuterons produced in Pythia (Phys.Rev. D92,069903, 2015) and add an antiproton in (dp,dr)
its not a really consistent procedure.
$\mathcal{B}(\Lambda_b \to {}^3\overline{\mathrm{He}}X)$ ~1.2 10^{-9}

isospin in the Λ_b decays

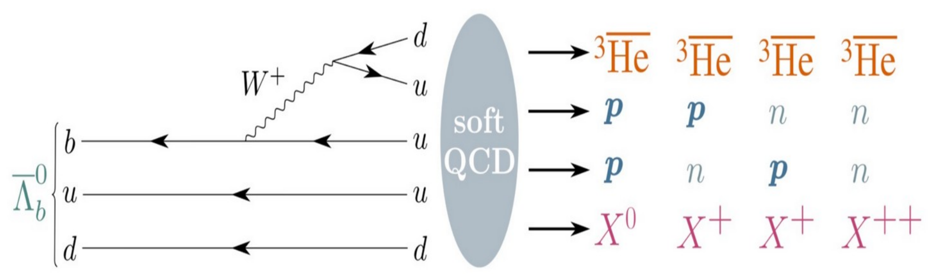
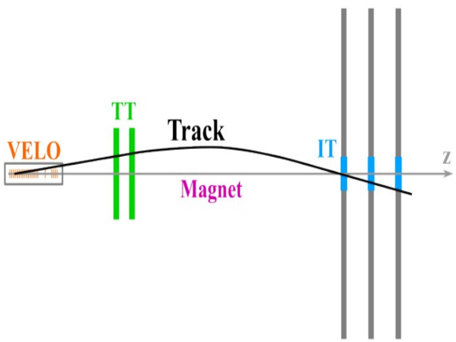
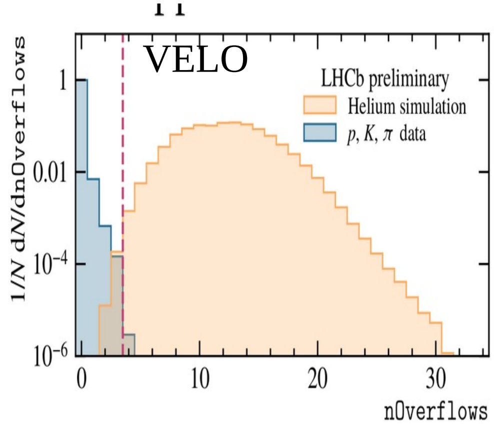


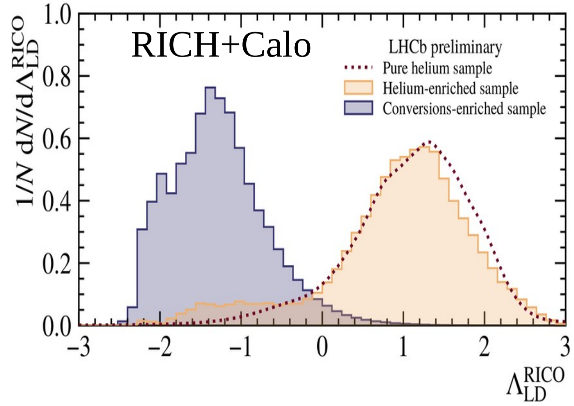
Table 14: Composition of the $\Lambda_b^0 \to {}^3\mathrm{He}X$ simulation samples.

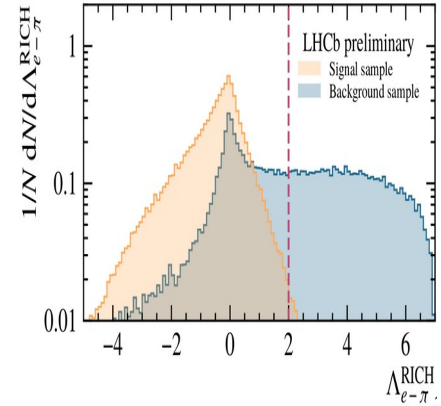
Rate [%]	Decay	Rate [%]	Decay
14.366000	$^3\mathrm{He}\bar{d}\pi^+\pi^-\pi^-\pi^0$	0.192555	$^3\mathrm{He}\overline{pp}K^+\pi^-\pi^0$
10.666000	$^3\mathrm{He}\overline{pp}\pi^+\pi^-\pi^0\pi^0$	0.192555	$^3\mathrm{He}\overline{pp}K^-\pi^+\pi^0$
9.760510	$^3\mathrm{He}\overline{pp}\pi^+\pi^-\pi^0$	0.190800	$^3\mathrm{He}\overline{pp}\pi^0\pi^0$
6.550000	$^3\mathrm{He}\bar{d}\pi^-\pi^0\pi^0$	0.186510	$^3\mathrm{He}\overline{pp}K^0_{\mathrm{L}}\pi^+\pi^-$
6.258540	$^3\mathrm{He}\bar{d}\pi^+\pi^-\pi^-\pi^0\pi^0$	0.186000	$^3\mathrm{He}\overline{pn}\pi^+\pi^+\pi^-\pi^-\pi^-$
4.905030	$^3\mathrm{He}\bar{d}\pi^+\pi^-\pi^-\pi^0\pi^0\pi^0$	0.176000	$^3\mathrm{He}\overline{pp}\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$
4.610000	$^3\mathrm{He}\bar{d}\pi^+\pi^-\pi^-$	0.170800	$^3\mathrm{He}\overline{pn}\pi^-\pi^0\pi^0\pi^0\pi^0$
3.982510	$^3\mathrm{He}\overline{pp}\pi^+\pi^+\pi^-\pi^-\pi^0$	0.121000	$^3\mathrm{He}\overline{nn}K^0_{\mathrm{L}}\pi^-\pi^-$
3.334510	$^3\mathrm{He}\overline{pp}\pi^+\pi^-\pi^0\pi^0\pi^0$	0.111000	$^3\mathrm{He}\bar{d}K^0_{\mathrm{L}}\pi^-\pi^0\pi^0$
2.935200	$^3\mathrm{He}\overline{nn}\pi^-\pi^-\pi^0$	0.108000	$^3\mathrm{He}\overline{nn}K^-\pi^-\pi^0$
2.797540	$^3\mathrm{He}\overline{pp}\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$	0.103510	$^3\mathrm{He}\bar{d}K^-\pi^0\pi^0$
2.391000	$^3\mathrm{He}\overline{nn}\pi^+\pi^-\pi^-\pi^-\pi^0$	0.095500	$^3\mathrm{He}\overline{nn}\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-$
2.000000	$^3\mathrm{He}\bar{d}\pi^+\pi^+\pi^-\pi^-\pi^-$	0.093040	$^3\mathrm{He}\overline{pp}K^0_{\mathrm{L}}\pi^0\pi^0$
1.795100	$^3\mathrm{He}\bar{d}\pi^-\pi^0$	0.088000	$^3\mathrm{He}\overline{pp}K^+\pi^-\pi^0\pi^0$
1.699000	$^3\mathrm{He}\bar{d}\pi^-\pi^0\pi^0\pi^0\pi^0$	0.088000	$^3\mathrm{He}\overline{pp}K^-\pi^+\pi^0\pi^0$
1.662510	$^3\mathrm{He}\overline{pp}\pi^+\pi^+\pi^-\pi^-$	0.080500	$^3\mathrm{He}\overline{pp}K^0_{\mathrm{L}}\pi^+\pi^-\pi^0$
1.577000	$^3\mathrm{He}\overline{pp}\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$	0.075500	$^3\mathrm{He}\bar{d}K^+\pi^-\pi^-\pi^0$
1.312700	$^3\mathrm{He}\overline{pn}\pi^+\pi^-\pi^-\pi^0$	0.075500	$^3\mathrm{He}\bar{d}K^-\pi^+\pi^-\pi^0$
1.291000	$^3\mathrm{He}\overline{nn}\pi^-\pi^-\pi^0\pi^0\pi^0$	0.060330	$^3\mathrm{He}\overline{pp}\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0$
1.277000	$^3\mathrm{He}\overline{nn}\pi^+\pi^-\pi^-\pi^-\pi^0\pi^0$	0.057800	$^3\mathrm{He}\bar{d}K^-\pi^0\pi^0\pi^0$
1.250000	$^3\mathrm{He}\overline{pp}\pi^+\pi^-$	0.042710	$^3\mathrm{He}\overline{pn}K^0_{\mathrm{L}}\pi^-\pi^0$
1.222000	$^3\mathrm{He}\bar{d}\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0$	0.035200	$^3\mathrm{He}\overline{pn}K^-\pi^0\pi^0$
1.161000	$^3\mathrm{He}\overline{pp}\pi^0\pi^0\pi^0$	0.027700	$^3\mathrm{He}\overline{nn}K^0_{\mathrm{L}}\pi^-\pi^-\pi^0$
0.960000	$^3\mathrm{He}\overline{nn}\pi^-\pi^-\pi^0\pi^0\pi^0\pi^0$	0.023900	$^3\mathrm{He}\overline{pp}K^+\pi^-$
0.953200	$^3\mathrm{He}\overline{nn}\pi^-\pi^-\pi^0\pi^0$	0.023900	$^3\mathrm{He}\overline{pp}K^-\pi^+$
0.940800	$^3\mathrm{He}\bar{d}\pi^-\pi^0\pi^0\pi^0$	0.022600	$^3\mathrm{He}\overline{nn}K^-\pi^-\pi^0\pi^0$
0.930510	$^3\mathrm{He}\overline{nn}\pi^+\pi^-\pi^-\pi^-$	0.020100	$^3\mathrm{He}\overline{pn}K^+\pi^-\pi^-$
0.714000	$^3\mathrm{He}\bar{d}\pi^-\pi^0\pi^0\pi^0\pi^0\pi^0$	0.020100	$^3\mathrm{He}\overline{pn}K^-\pi^+\pi^-$
0.682000	$^3\mathrm{He}\overline{pn}\pi^+\pi^-\pi^-\pi^0\pi^0$	0.017600	$^3\mathrm{He}\overline{pn}\pi^+\pi^-\pi^-\pi^0\pi^0\pi^0$
0.568000	$^3\mathrm{He}\overline{pn}\pi^+\pi^-\pi^-$	0.010100	$^3\mathrm{He}\overline{pp}\pi^0$
0.407600	$^3\mathrm{He}\overline{pn}\pi^-\pi^0\pi^0$	0.010100	$^3\mathrm{He}\bar{d}\pi^-$
0.404700	$^3\mathrm{He}\overline{pp}\pi^0\pi^0\pi^0\pi^0\pi^0$	0.007540	$^3\mathrm{He}\bar{d}K^0_{\mathrm{L}}\pi^-$
0.374700	$^3\mathrm{He}\overline{pn}\pi^-\pi^0\pi^0\pi^0$	0.005030	$^3\mathrm{He}\overline{pp}K^0_{\mathrm{L}}\pi^0$
0.342000	$^3\mathrm{He}\bar{d}K^+\pi^-\pi^-$	0.005030	$^3\mathrm{He}\bar{d}K^-\pi^0$
0.342000	$^3\mathrm{He}\bar{d}K^-\pi^+\pi^-$	0.005030	$^3\mathrm{He}\overline{pn}K^0_{\mathrm{L}}\pi^-$
0.329510	$^3\mathrm{He}\bar{d}K^0_{\mathrm{L}}\pi^-\pi^0$	0.005030	$^3\mathrm{He}\overline{pn}\pi^-$
0.304600	$^3\mathrm{He}\overline{pn}\pi^-\pi^0$	0.005030	$^3\mathrm{He}\overline{nn}\pi^-\pi^-$
0.259100	$^3\mathrm{He}\overline{pp}\pi^0\pi^0\pi^0\pi^0$	0.002510	$^3\mathrm{He}\overline{pn}\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0$

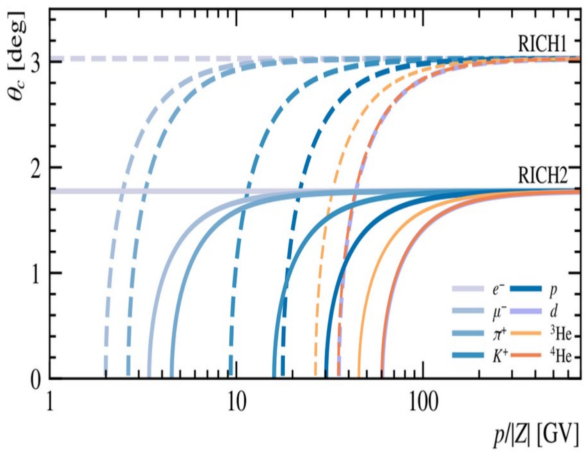
Backup: He identification in LHCb



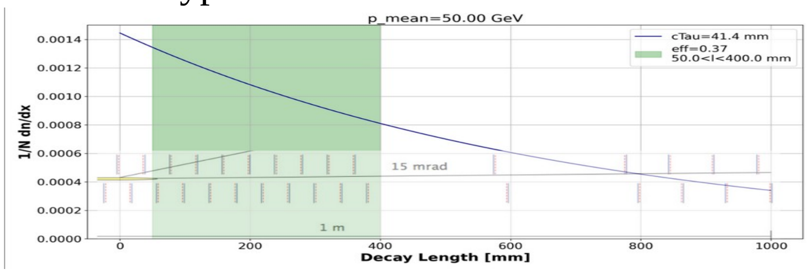


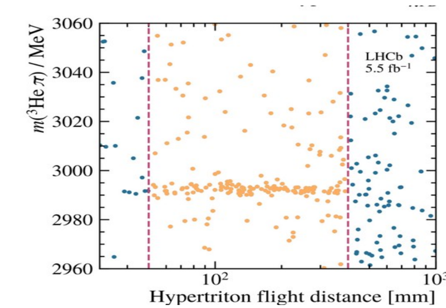


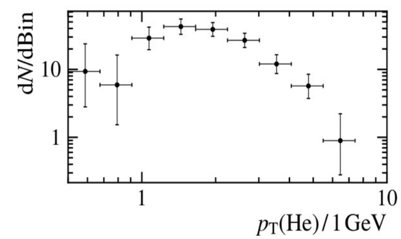


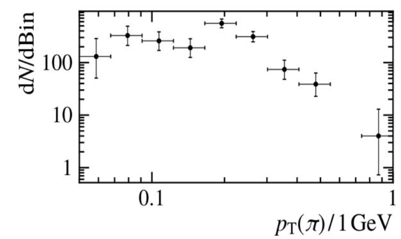


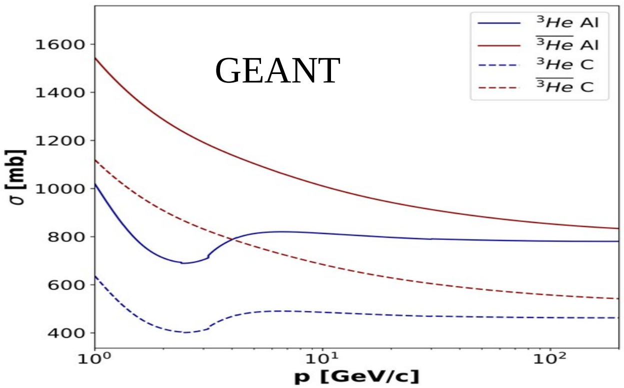
Hypertriton











- He PID efficiency can be estimated from data using different subdetector: PID(He)>80% and contamination <1%
- Overall efficiency depends upon trigger, event and track selections, can be low
- In Run 3 the VELO and OT/IT are replaced by detectors with digital readouts
- In Run 5&6(>2034) expecting TORCH detector with TOF measurements allowing He identification up to 20 GeV/c