TeV Particle Astrophysics
TeVPA
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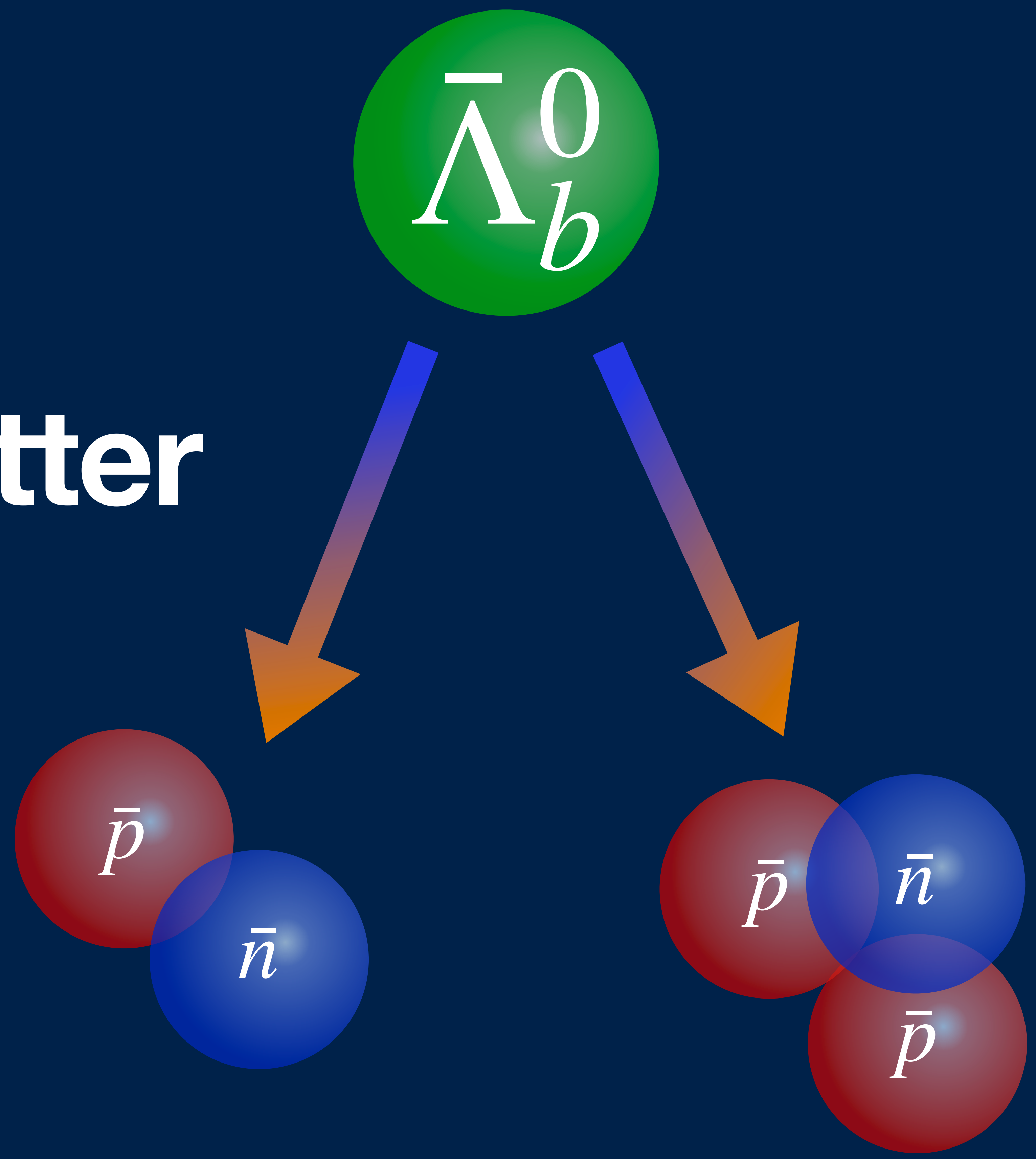
Antinuclei production from dark matter via weakly decaying b-hadrons

In collaboration with M. Di Mauro, A. Jueid, and R. Ruiz de Austri

Phys.Rev.D 112 (2025) 8, 083017 [2504.07172]



Jordan Koechler (INFN Turin)

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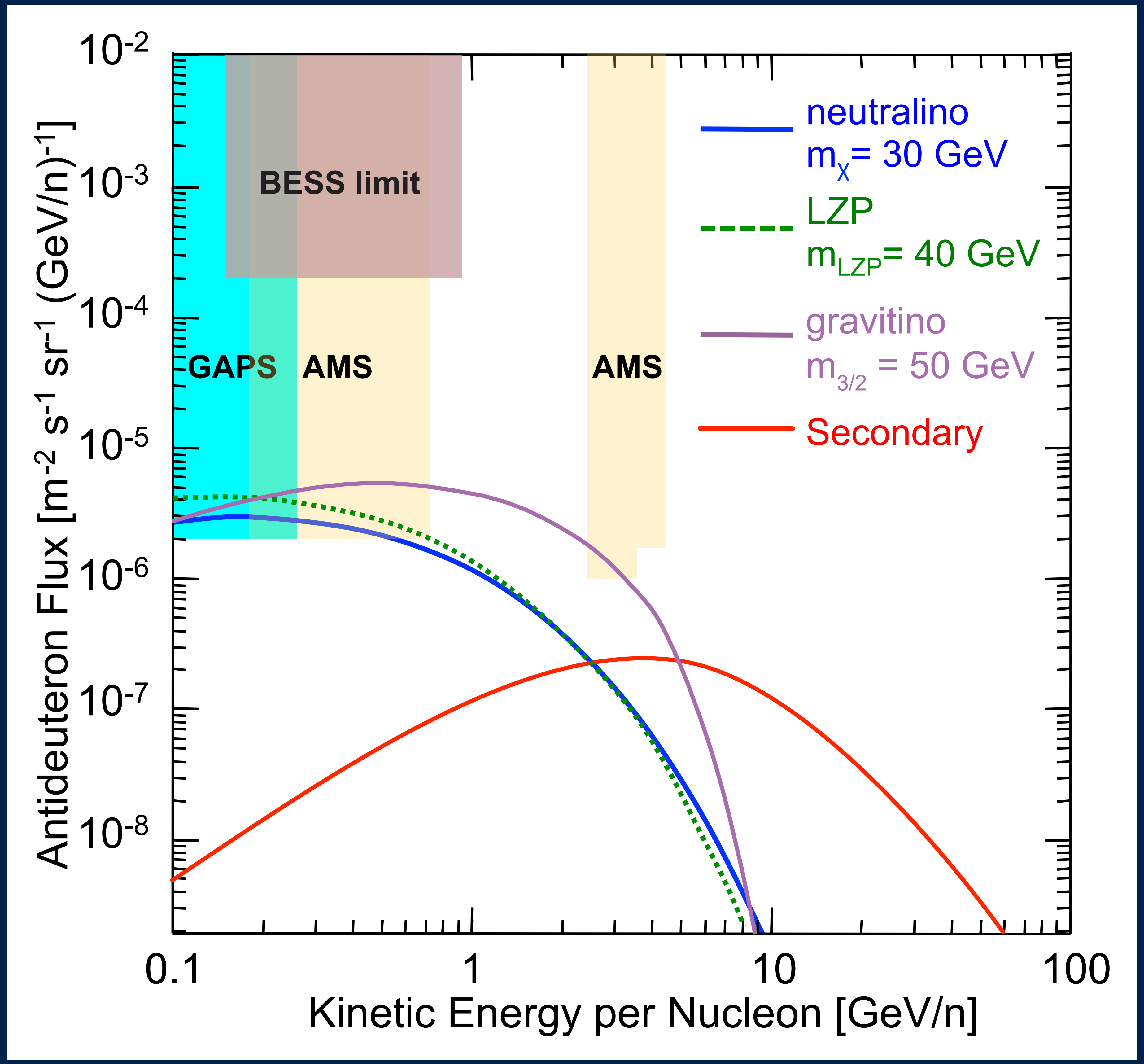
INFN TORINO

The antinuclei problem

Antinuclei ($\overline{\mathrm{D}}$, $\overline{\mathrm{He}}$, . . .) less likely to be produced by astrophysics below ~1 GeV/n

⬇

Strong dark matter probe



GAPS collab., *Astropart.Phys.* 74 (2016) 6-13

The antinuclei problem

For $m_{DM} = 50$ GeV

$$\overline{p} : \overline{\mathrm{D}} : {}^{3}\overline{\mathrm{He}} \sim 1 : 10^{-4} : 10^{-8}$$

BUT

AMS-02 detected $\overline{\mathrm{D}}$ and $\overline{\mathrm{He}}$ ‘candidates’

$\sim 7\,\overline{\mathrm{D}}$ $\sim 5\,{}^{3}\overline{\mathrm{He}}$ $\sim 4\,{}^{4}\overline{\mathrm{He}}$ **???**

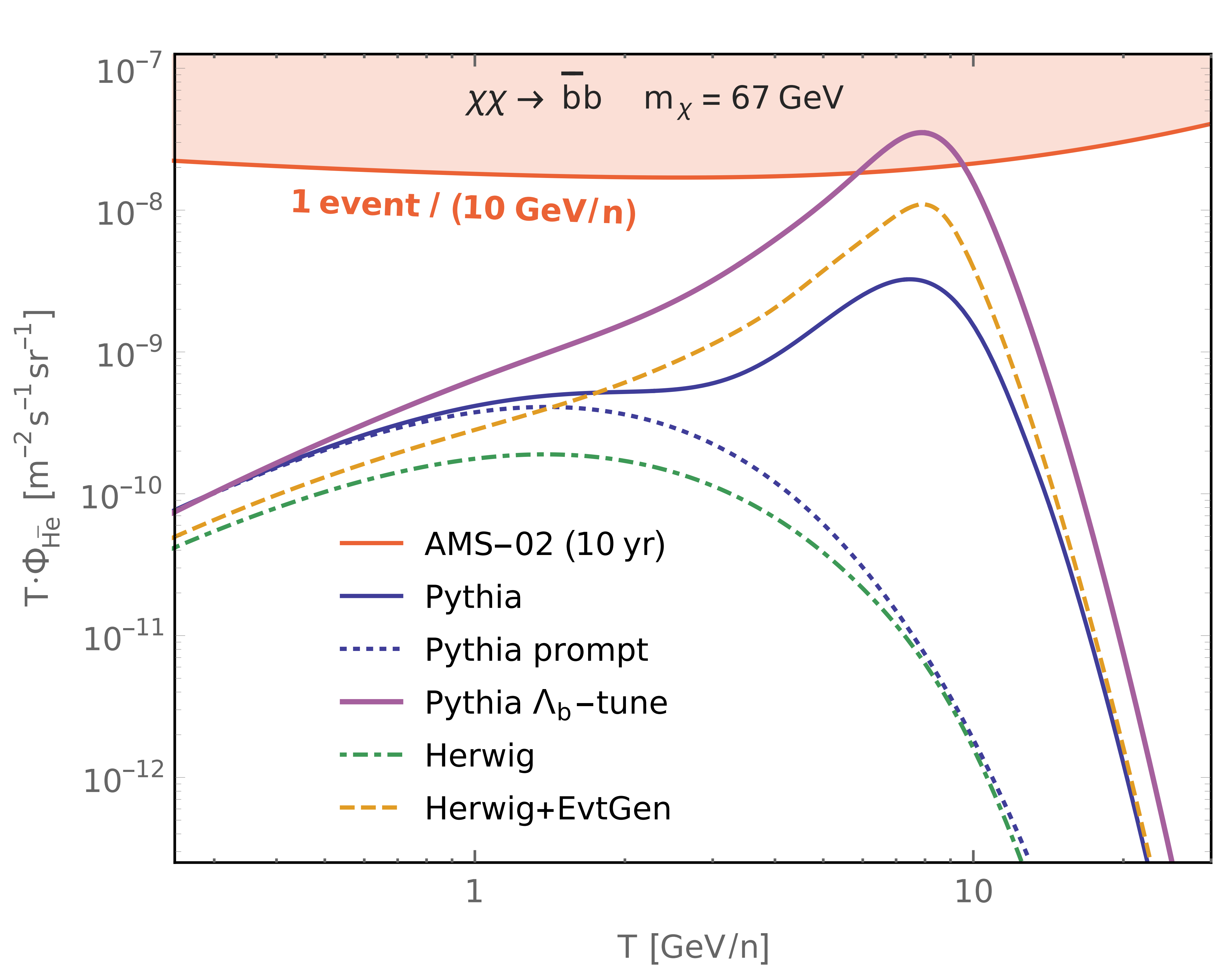
P. Zuccon, Talk at MIAPbP 2022

The antinuclei problem

Solution? An excess of $\overline{\text{He}}$ could come from the decay of DM-produced weakly decaying b-baryons (e.g., $\overline{\Lambda}_b^0$)

Λ_b	Content	Mass
Λ_b^0	uds	5619.57 ± 0.16 MeV
Σ_b^0	udb	Not measured
Σ_b^+	uub	5810.56 ± 0.25 MeV
Σ_b^-	ddb	5815.64 ± 0.27 MeV
Ξ_b^0	usb	5791.7 ± 0.4 MeV
Ξ_b^-	dsb	5797.0 ± 0.4 MeV
Ω_b^-	ssb	6045.8 ± 0.8 MeV

At least 10 times less produced in e^+e^- and pp collisions than Λ_b^0



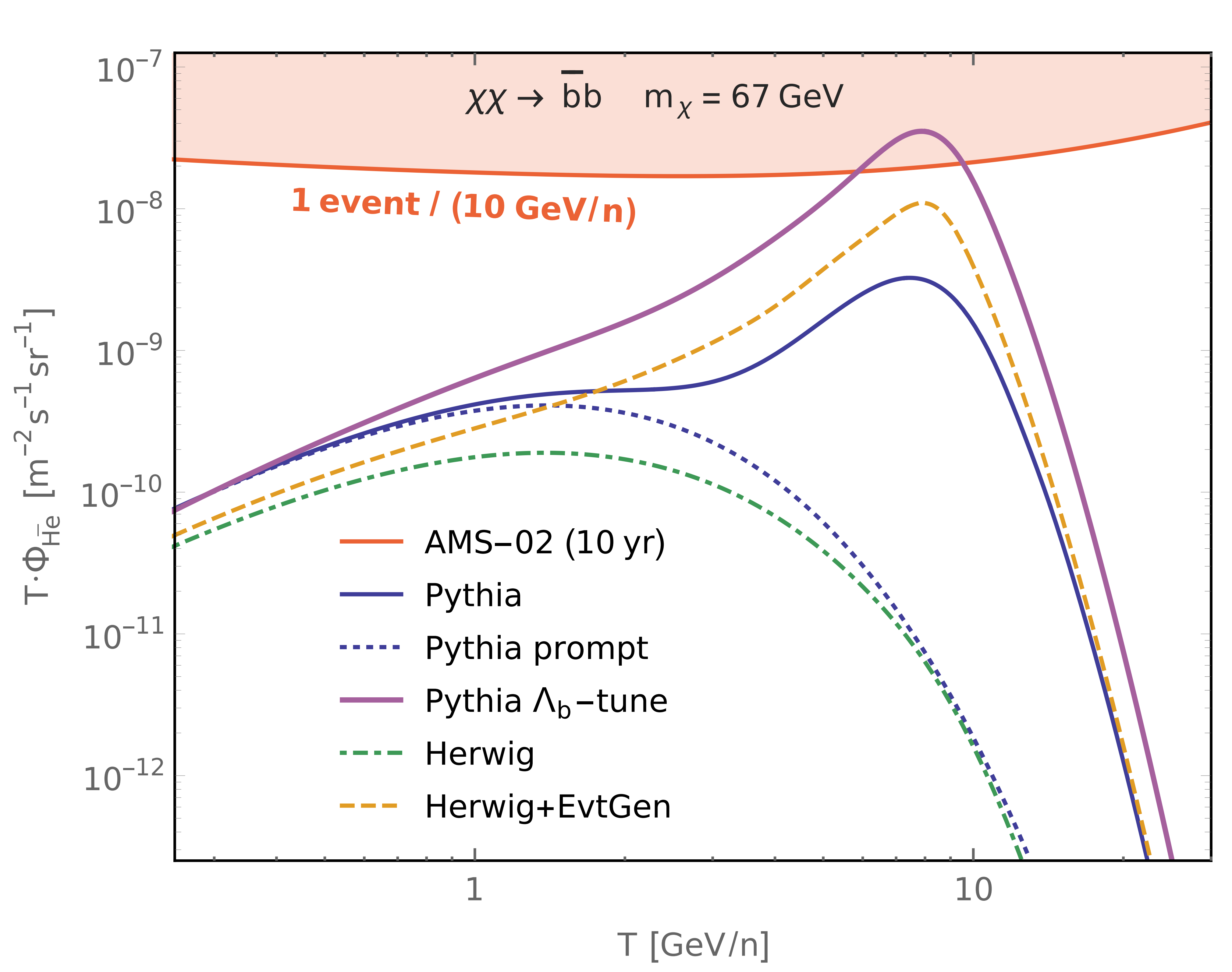
M. Winkler & T. Linden, *Phys.Rev.Lett.* 126 (2021) 10, 101101

The antinuclei problem

Solution? An excess of $\overline{\text{He}}$ could come from the decay of DM-produced weakly decaying b-baryons (e.g., $\overline{\Lambda}_b^0$)

Using PYTHIA, the baryon/meson ratio can be controlled with probQQtoQ

BUT trying to match the measured $f(b \to \Lambda_b)$ leads to $p/\overline{p}$ multiplicities exceeding by 40σ LEP data



M. Winkler & T. Linden, *Phys.Rev.Lett.* 126 (2021) 10, 101101

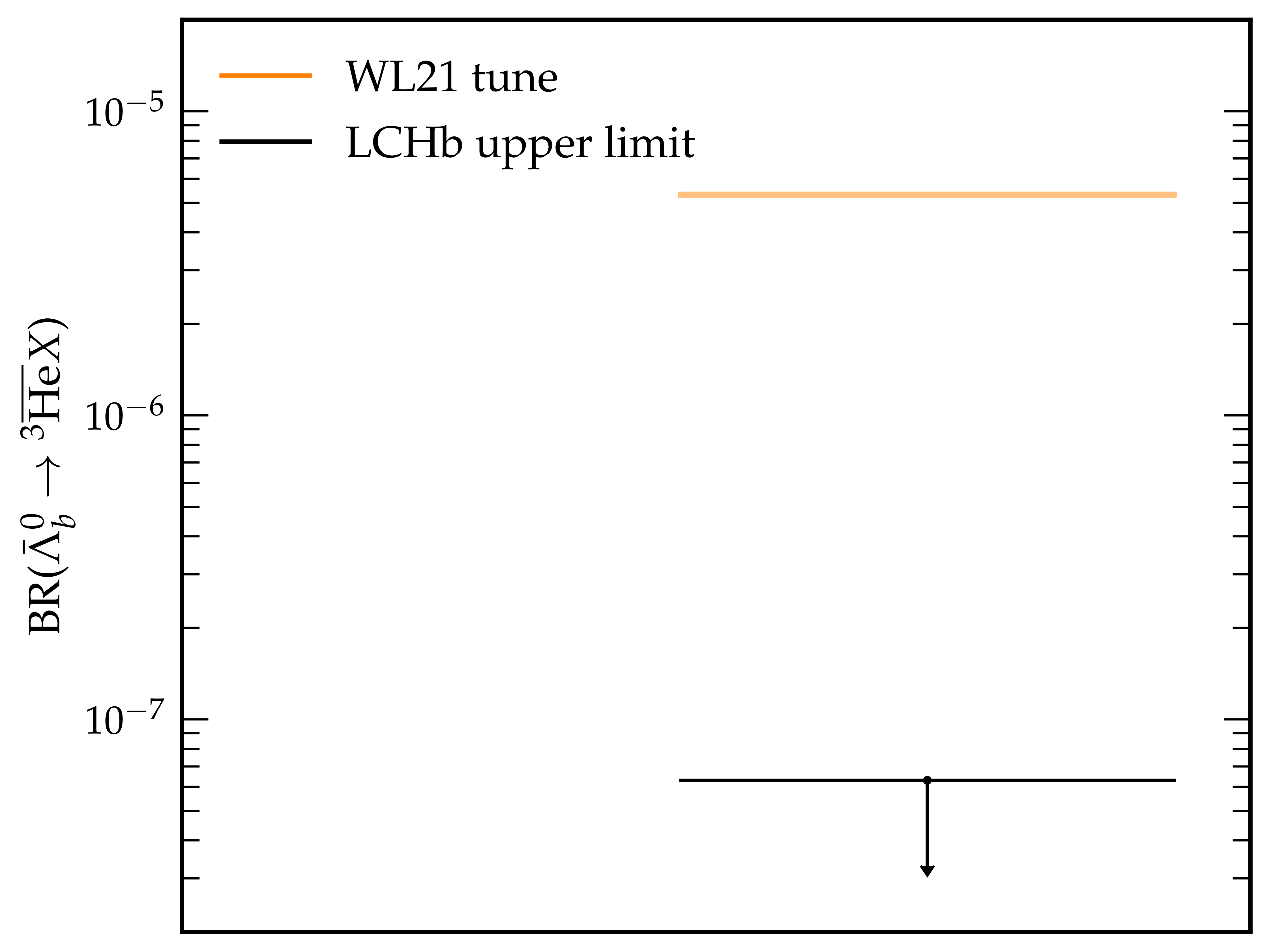
The antinuclei problem

Also: Recently, LHCb released the first experimental upper limit on the inclusive branching ratio of $\overline{\Lambda}_b^0$ to $^3\overline{\text{He}}$

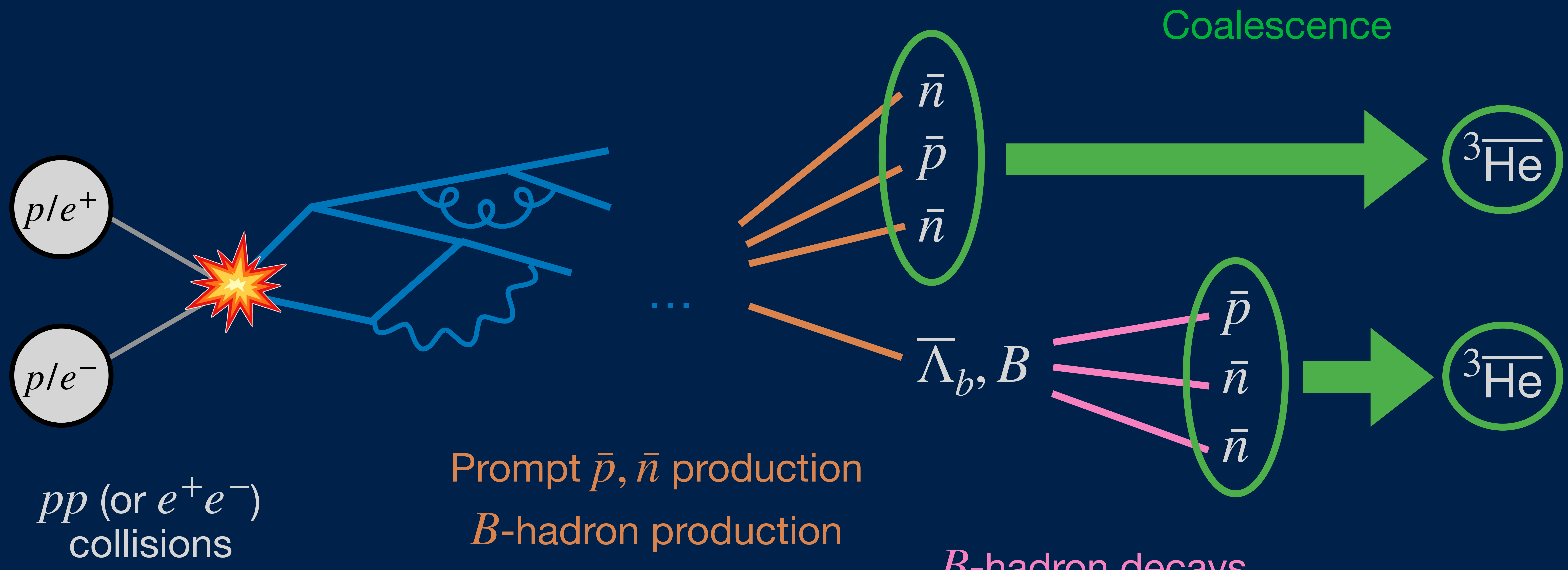
$$\text{BR}(\overline{\Lambda}_b^0 \to {}^3\overline{\text{He}}\, X) < 6.3 \times 10^{-8}$$

R.-D. Moise, *PoS* ICHEP2024 (2025) 676

Goal: Provide a new and robust computation of antinuclei production from dark matter using PYTHIA

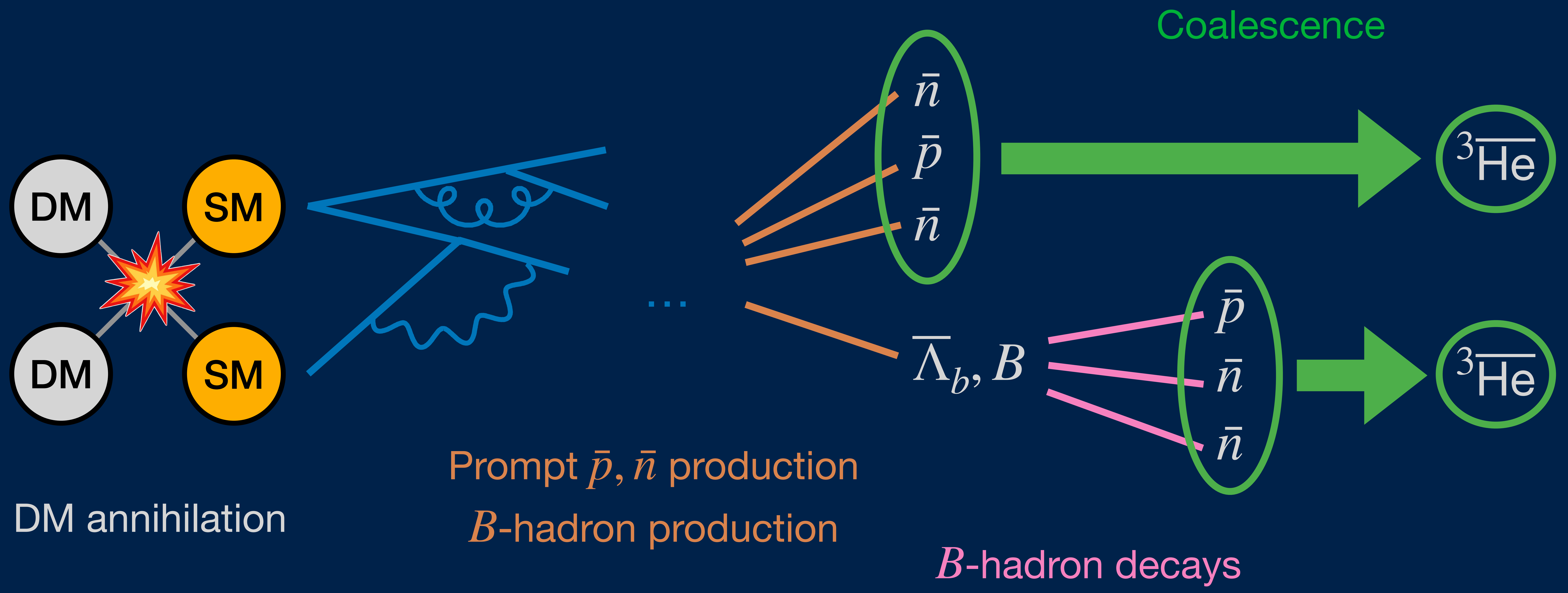


Outline



Coalescence
$\bar{n}$
$\bar{p}$
$\bar{n}$
$^3\overline{\text{He}}$
p/e^+
p/e^-
...
$\overline{\Lambda}_b, B$
$\bar{p}$
$\bar{n}$
$\bar{n}$
$^3\overline{\text{He}}$
pp (or e^+e^-) collisions
Prompt $\bar{p}, \bar{n}$ production
B-hadron production
B-hadron decays

Outline



Coalescence
DM
SM
DM
SM
$\bar{n}$
$\bar{p}$
$\bar{n}$
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...
$\overline{\Lambda}_b, B$
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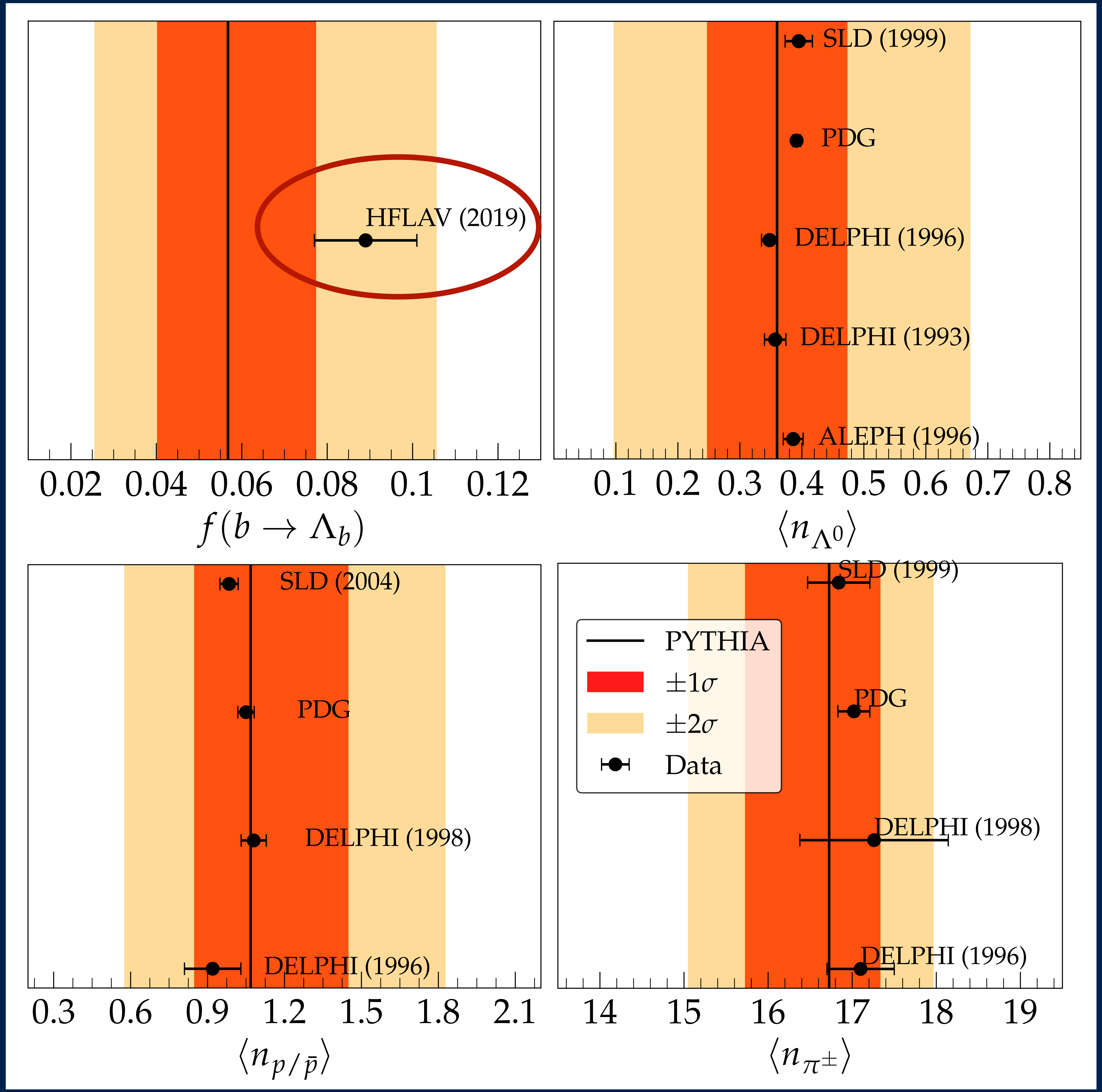
$^3\overline{\text{He}}$
DM annihilation
Prompt $\bar{p}, \bar{n}$ production
B-hadron production
B-hadron decays

I Tuning the PYTHIA hadronisation model

Using 4185 collider measurements, we perform tuning of 14 PYTHIA parameters related to flavor selection and hadronisation

Parameter	Range	Monash	Had. tune
StringZ:aLund	0.0 – 2.0	0.68	0.7832 ± 0.0123
StringZ:bLund	0.2 – 2.0	0.98	1.1729 ± 0.0100
StringZ:aExtraDiquark	0.0 – 2.0	0.97	0.9251 ± 0.0175
StringFlav:ProbStoUD	0.0 – 1.0	0.217	0.2265 ± 0.0016
StringFlav:mesonUDvector	0.0 – 3.0	0.50	0.6655 ± 0.0152
StringFlav:mesonSvector	0.0 – 3.0	0.55	0.5842 ± 0.0177
StringFlav:etaSup	0.0 – 1.0	0.60	0.6499 ± 0.0005
StringFlav:etaPrimeSup	0.0 – 1.0	0.12	0.1778 ± 0.0037
StringFlav:probQQtoQ	0.0 – 1.0	0.081	0.1112 ± 0.0008
StringFlav:probSQtoQQ	0.0 – 1.0	0.915	0.9791 ± 0.0061
StringFlav:probQQ1toQQ0	0.0 – 1.0	0.0275	0.8761 ± 0.0171
StringFlav:popcornSpair	0.0 – 1.0	0.50	0.6108 ± 0.0241
StringFlav:popcornSmeson	0.0 – 1.0	0.90	0.8306 ± 0.0231
StringFlav:popcornRate	0.0 – 1.0	0.50	0.4117 ± 0.0055

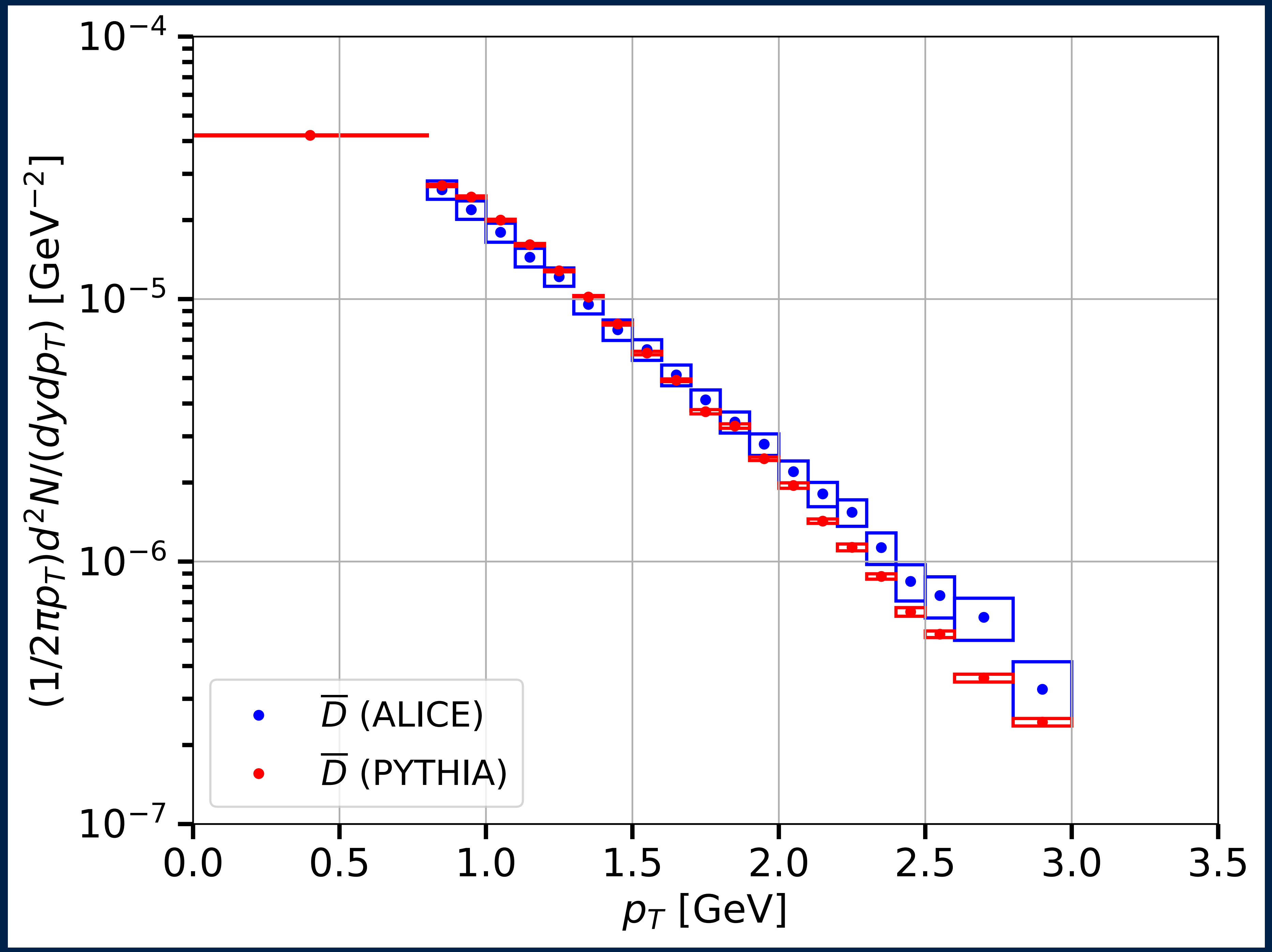


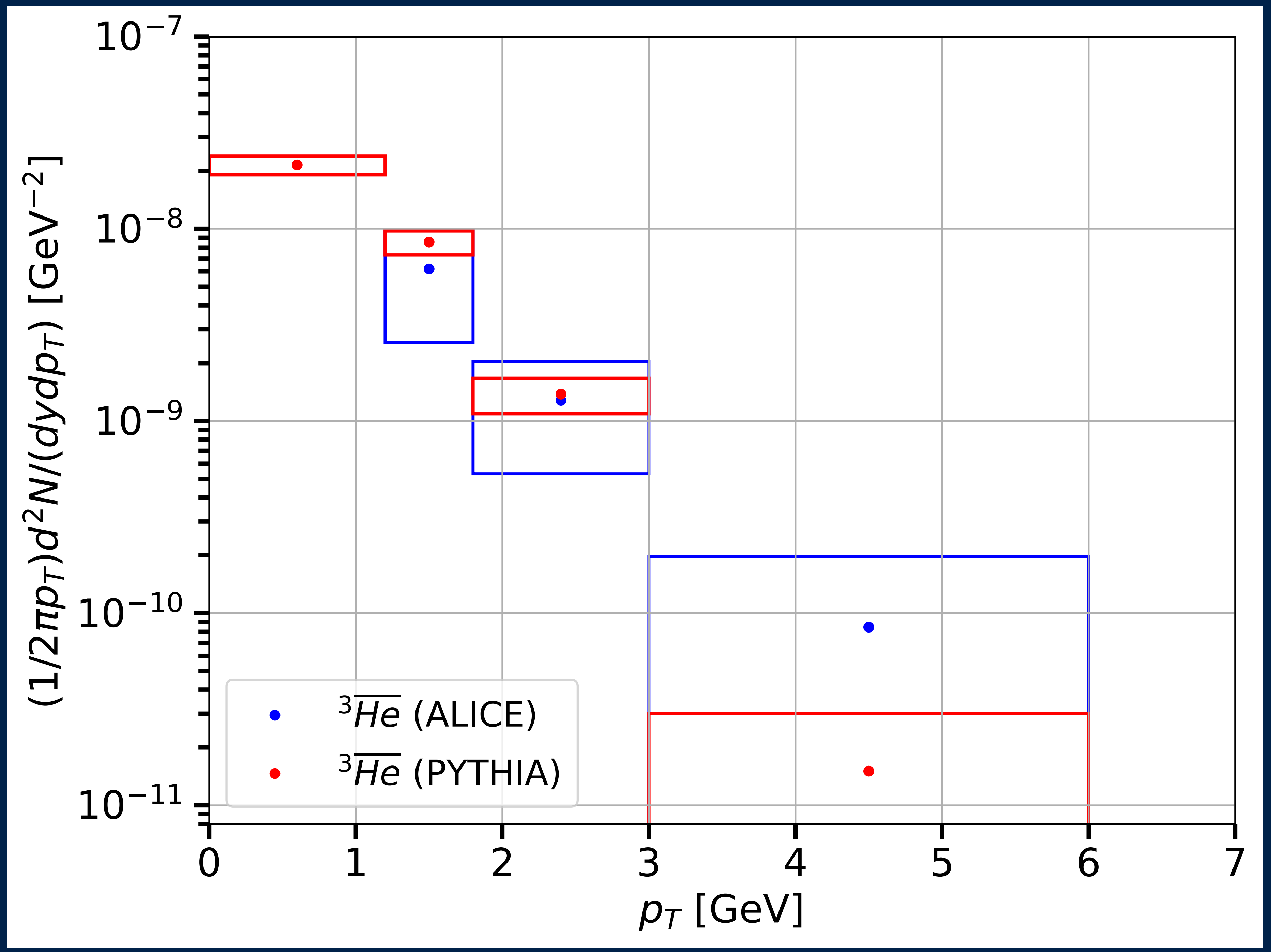
II Setting the coalescence model

We choose a simple coalescence with distance cutoff ($\Delta p < p_{coal}$ and $\Delta r < 3$ fm)

We find $p_{coal} = 0.20 \pm 0.01$ GeV

ALICE data at $\sqrt{s} = 7$ TeV





I.bis Tuning the PYTHIA hadronisation model

Now we can assess

$\mathrm{BR}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}\, X)$

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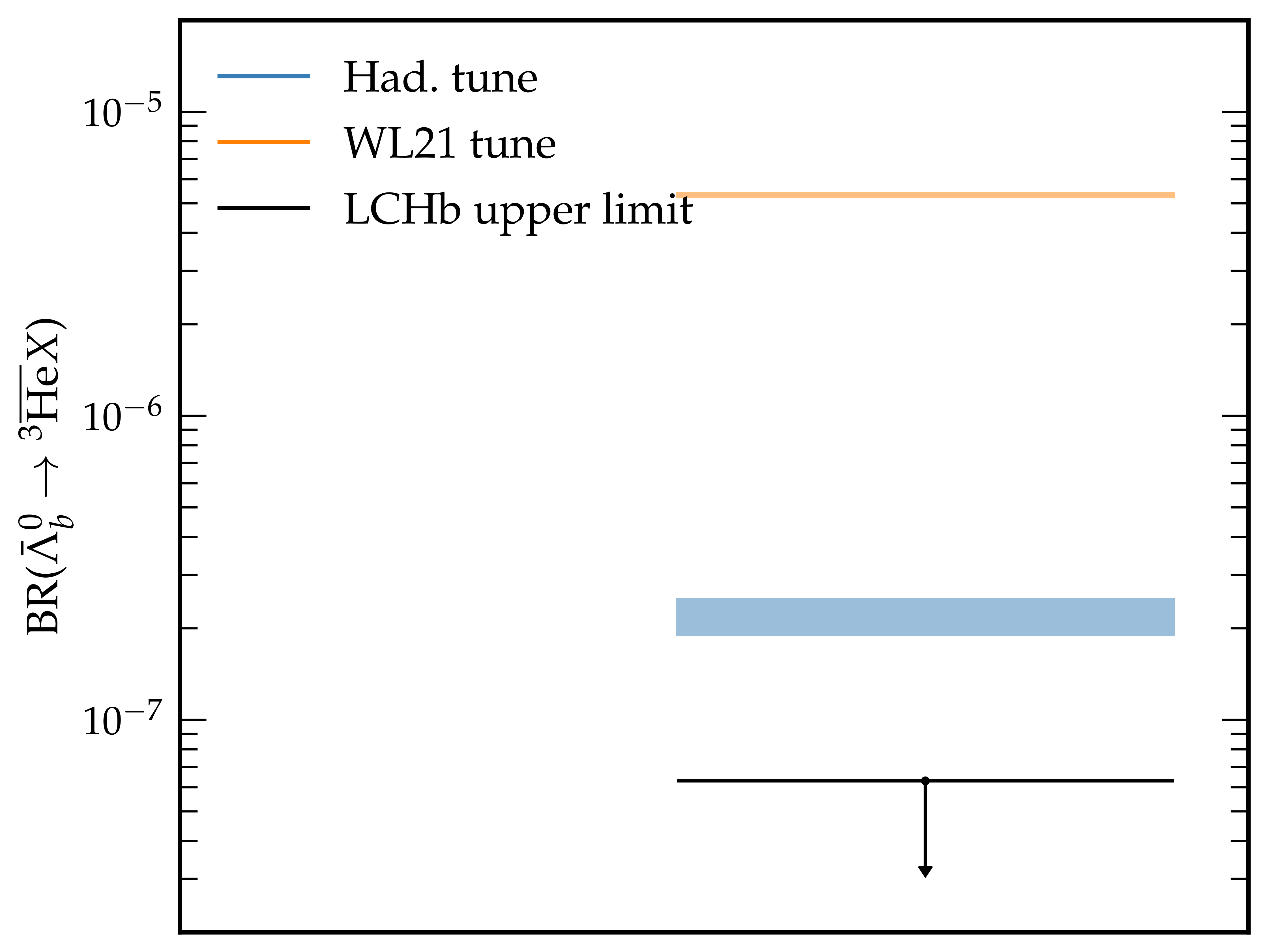

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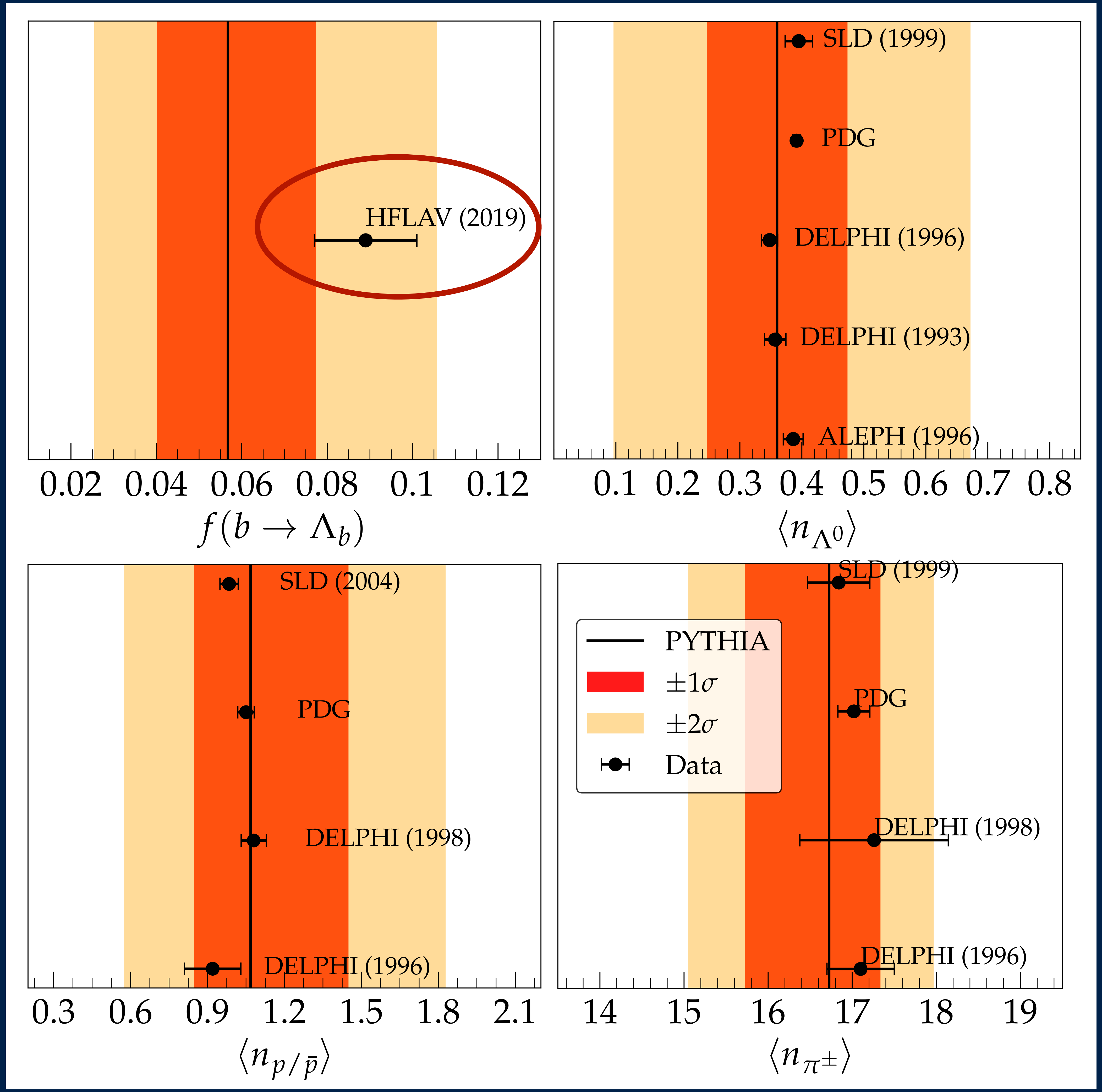
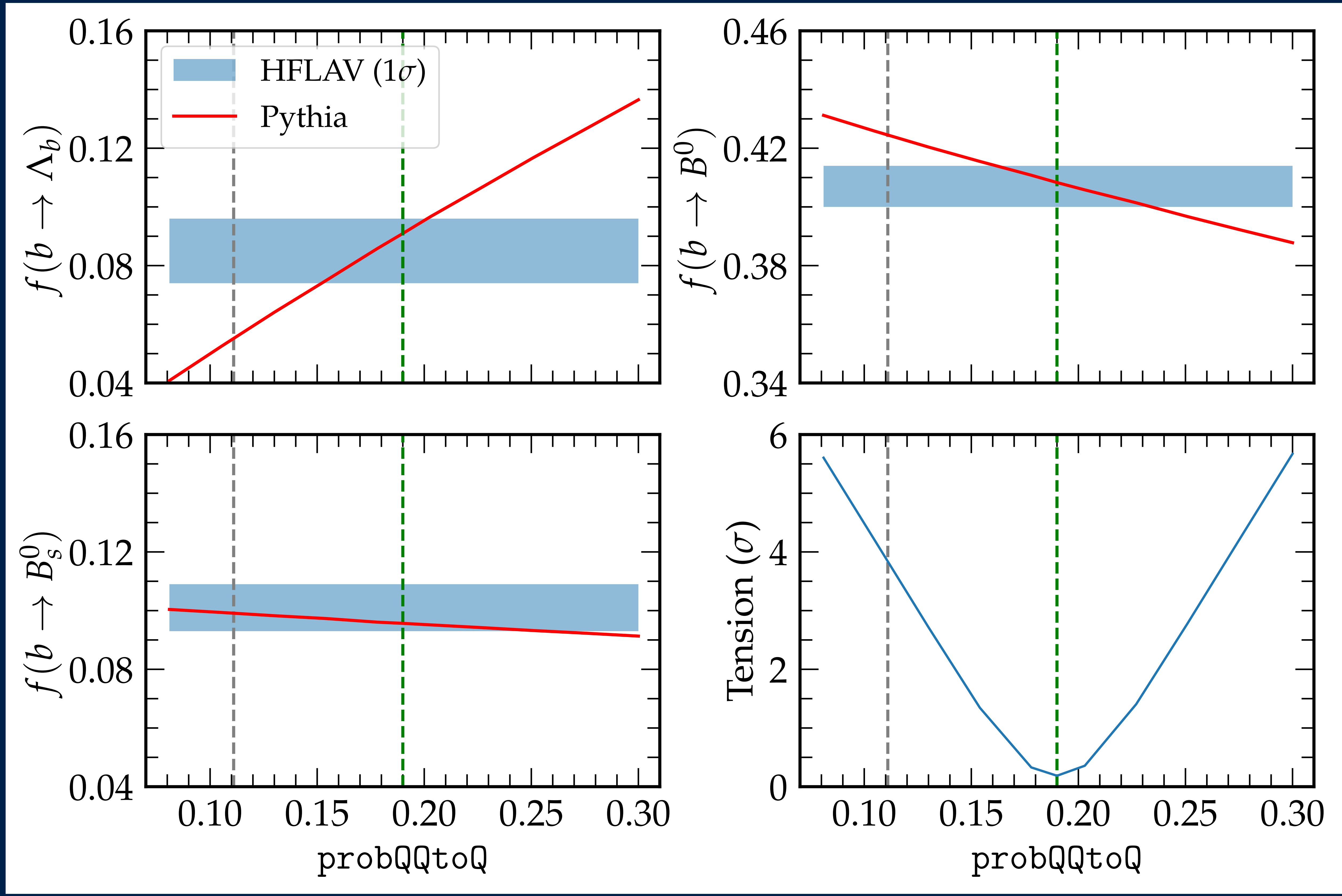


III Fixing $f(b \to \Lambda_b^0, B^0, B_s^0)$

We correct the fragmentation functions into B-hadrons by tuning probQQtoQ

New value to be used solely for the $\overline{p}$ and $\overline{n}$ production from B-hadrons decays:

probQQtoQ $= 0.19 \pm 0.03$



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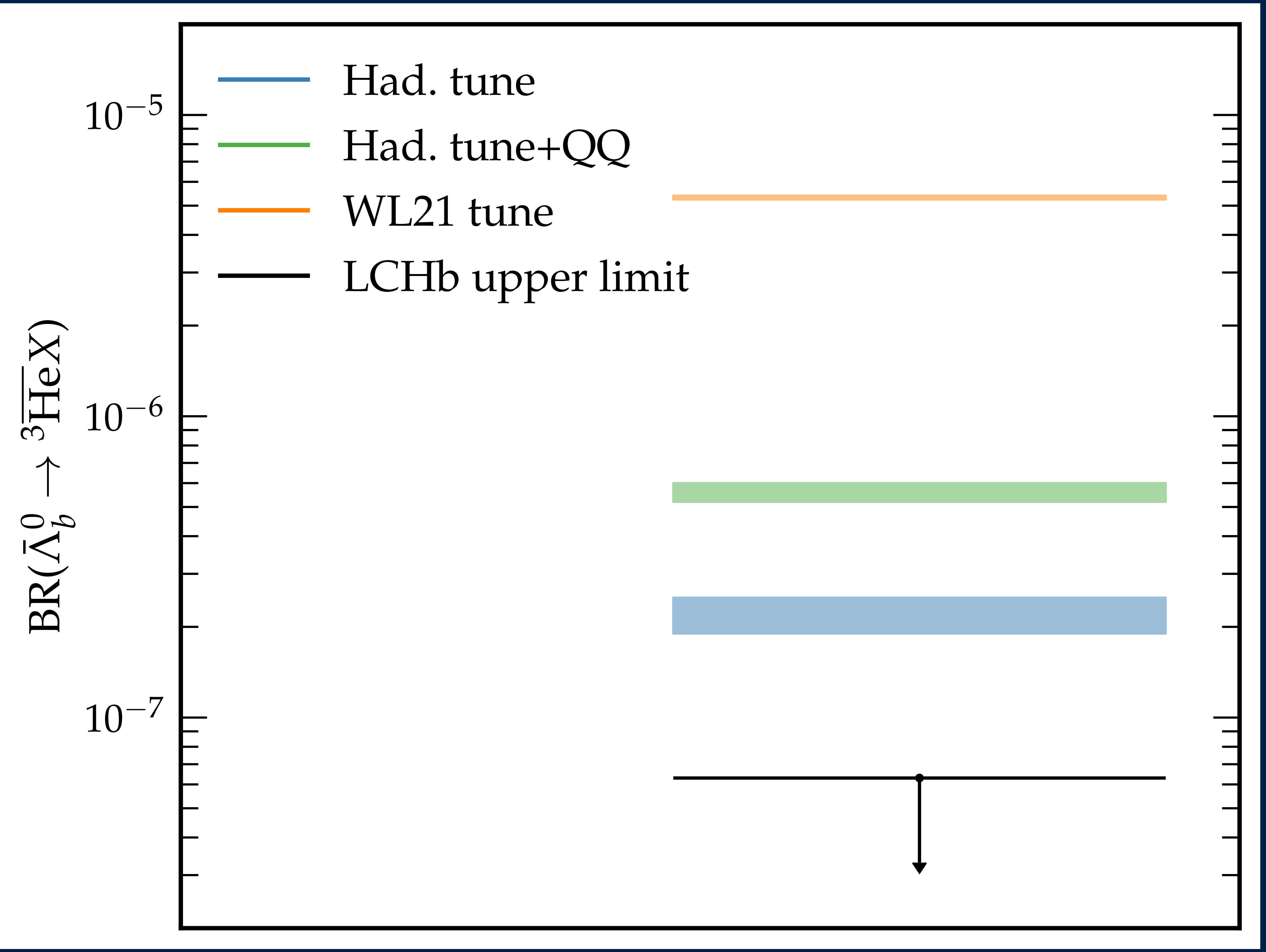
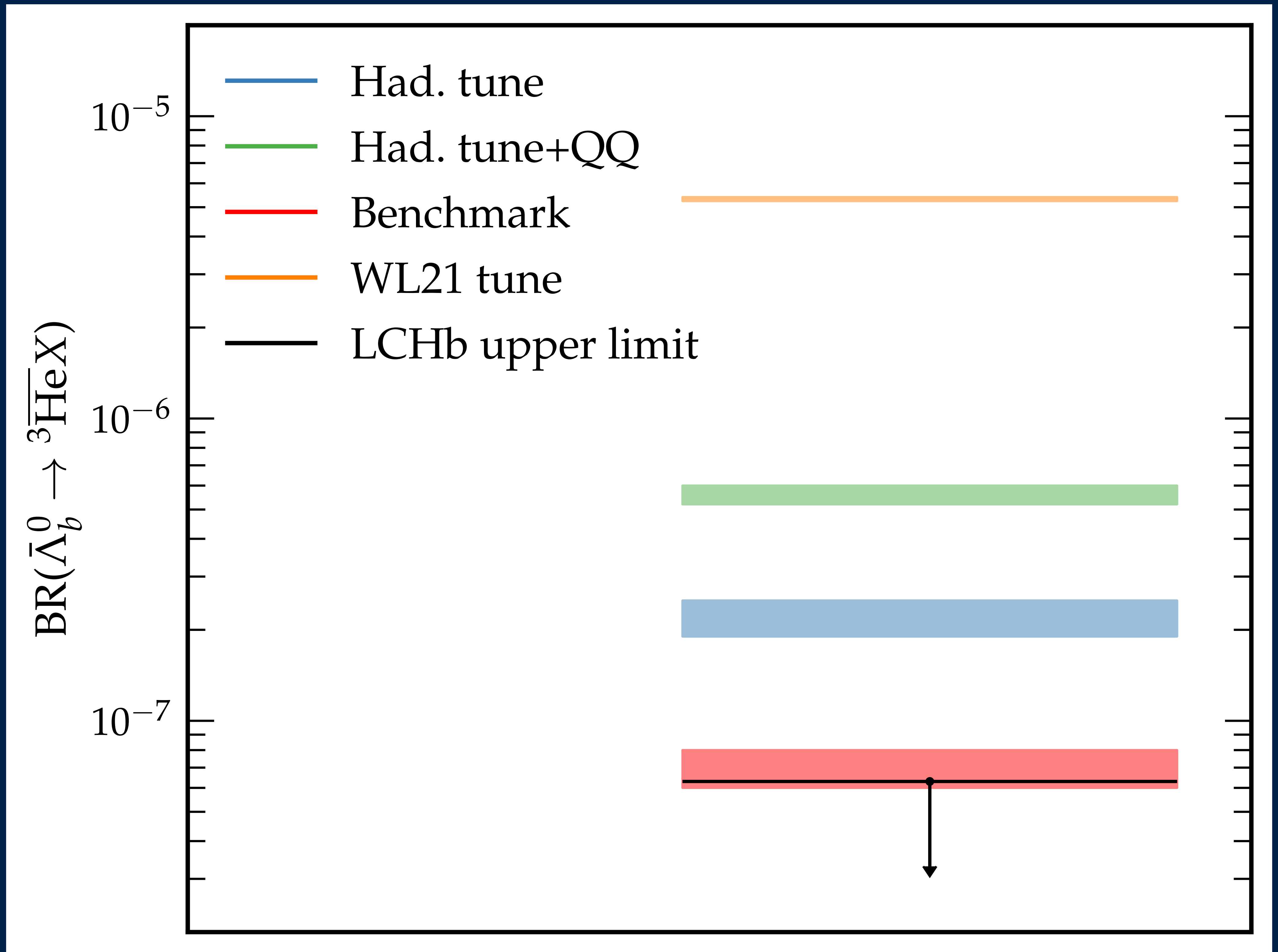


IV Fixing $\mathrm{BR}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}\,X)$

We fix branching ratios of Λ_b^0 to di-quark modes to match the LHCb upper limit on $\mathrm{BR}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}\,X)$ and the PDG values for other hadronic modes

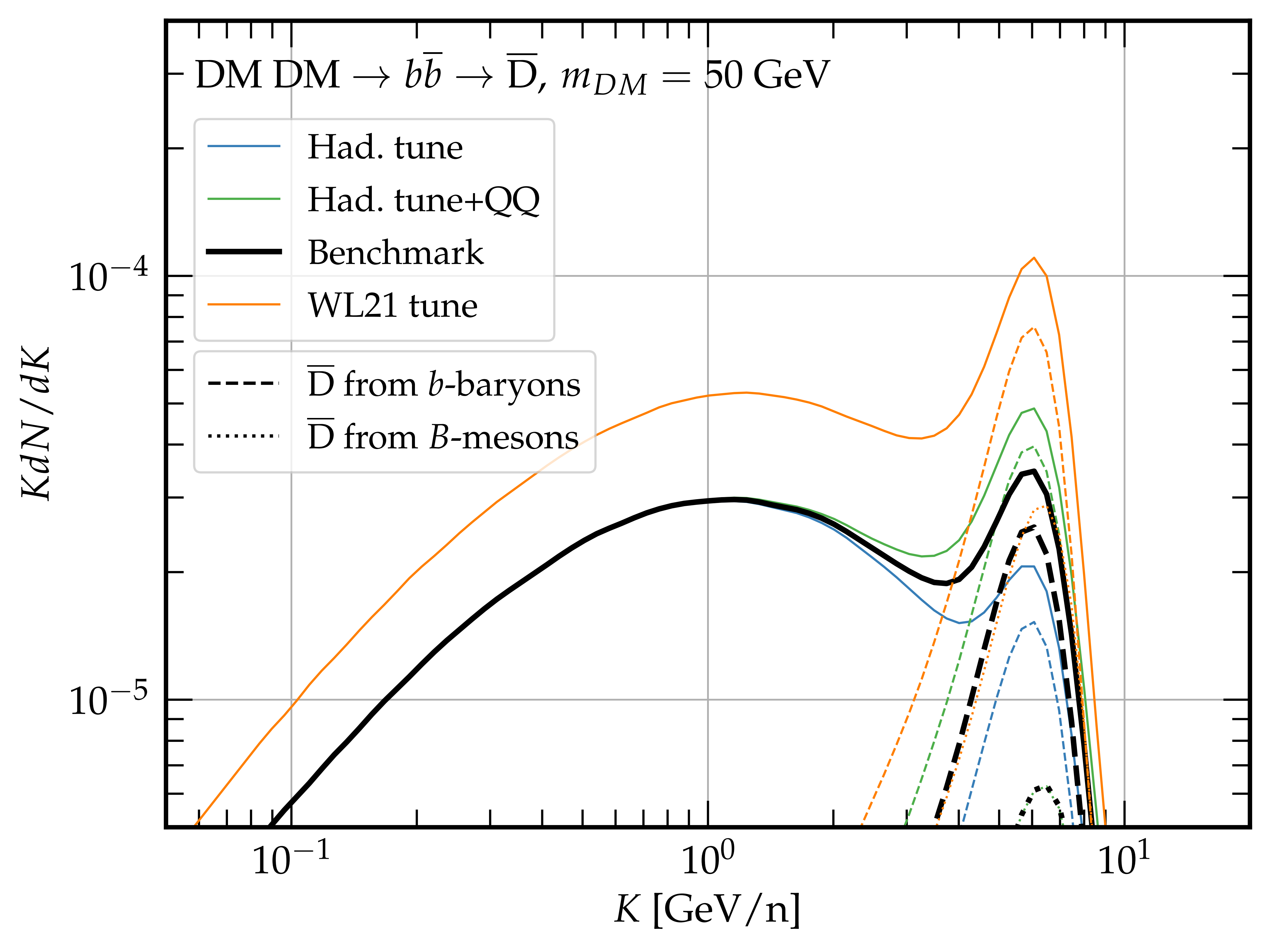
Λ_b^0 decay mode	Default Pythia	Tuned Pythia
$\overline{u}du(ud)_0$	0.012	0.001
$\overline{u}dc(ud)_0$	0.5321147	0.5321147
$\overline{c}su(ud)_0$	0.012	0
$\overline{c}sc(ud)_0$	0.08	0.103

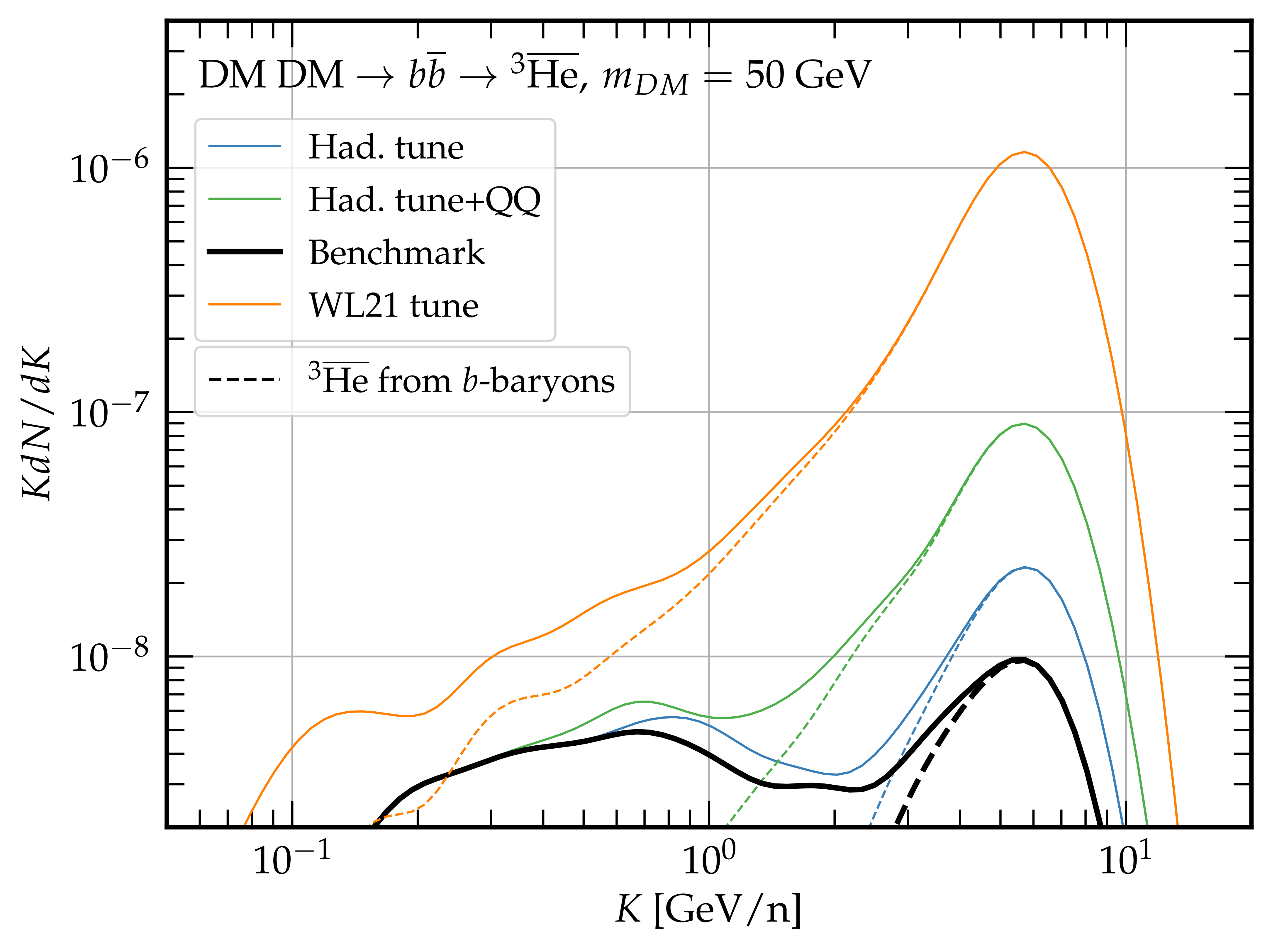
$\bar{\Lambda}_b^0$ decay mode	Measured BR	WL21 tune	Had. tune	Benchmark
$\Lambda_c^- \ell^+ \nu_\ell$	$(6.2^{+1.4}_{-1.3})\%$	$(5.9569 \pm 0.0009)\%$	$(5.956 \pm 0.002)\%$	$(5.957 \pm 0.001)\%$
$\bar{p}\bar{D}^0\pi^+$	$(6.2 \pm 0.6) \times 10^{-4}$	$(7.13 \pm 0.01) \times 10^{-4}$	$(6.11 \pm 0.02) \times 10^{-4}$	$(6.64 \pm 0.01) \times 10^{-4}$
$\bar{p}D^-\pi^-\pi^+$	$(2.7 \pm 0.4) \times 10^{-4}$	$(2.544 \pm 0.006) \times 10^{-4}$	$(2.154 \pm 0.008) \times 10^{-4}$	$(2.215 \pm 0.006) \times 10^{-4}$
$\bar{p}\pi^+$	$(4.6 \pm 0.8) \times 10^{-6}$	$(1.219 \pm 0.005) \times 10^{-4}$	$(1.035 \pm 0.006) \times 10^{-5}$	$(1.41 \pm 0.02) \times 10^{-5}$
$\Lambda_c^- K^+ K^- \pi^+$	$(1.02 \pm 0.11) \times 10^{-3}$	$(1.342 \pm 0.002) \times 10^{-3}$	$(1.391 \pm 0.003) \times 10^{-3}$	$(1.354 \pm 0.002) \times 10^{-3}$
$\Lambda_c^- p\bar{p}\pi^+$	$(2.63 \pm 0.23) \times 10^{-4}$	$(3.285 \pm 0.003) \times 10^{-3}$	$(2.677 \pm 0.009) \times 10^{-3}$	$(4.615 \pm 0.009) \times 10^{-4}$
$\bar{p}\bar{n}X$	–	$(5.337 \pm 0.003) \times 10^{-3}$	$(7.32 \pm 0.02) \times 10^{-4}$	$(6.56 \pm 0.01) \times 10^{-4}$
$\bar{p}\bar{p}\bar{n}X$	–	$(7.64 \pm 0.04) \times 10^{-5}$	$(1.04 \pm 0.06) \times 10^{-6}$	$(2.4 \pm 0.3) \times 10^{-7}$
${}^3\overline{\mathrm{He}}X$	$< 6.8 \times 10^{-8}$	$(5.32 \pm 0.08) \times 10^{-6}$	$(2.2 \pm 0.3) \times 10^{-7}$	$(7 \pm 1) \times 10^{-8}$



Results

In the end, the contribution from b-hadrons is negligible!





Summary

- We performed a full tuning of PYTHIA and determination of the coalescence model in order to match different collider observables in order to correctly assess the production of light antinuclei ($\overline{\mathrm{D}}$, $^3\overline{\mathrm{He}}$) arising from DM annihilation

- We now expect the production of light antinuclei from weakly decaying b-baryons to be negligible compared to the prompt production

- If the $\overline{\mathrm{D}}$, $^3\overline{\mathrm{He}}$ and $^4\overline{\mathrm{He}}$ candidates detected by AMS-02 were confirmed, we need to come up with new production mechanisms to explain these events

Thank you for your attention!

Questions?