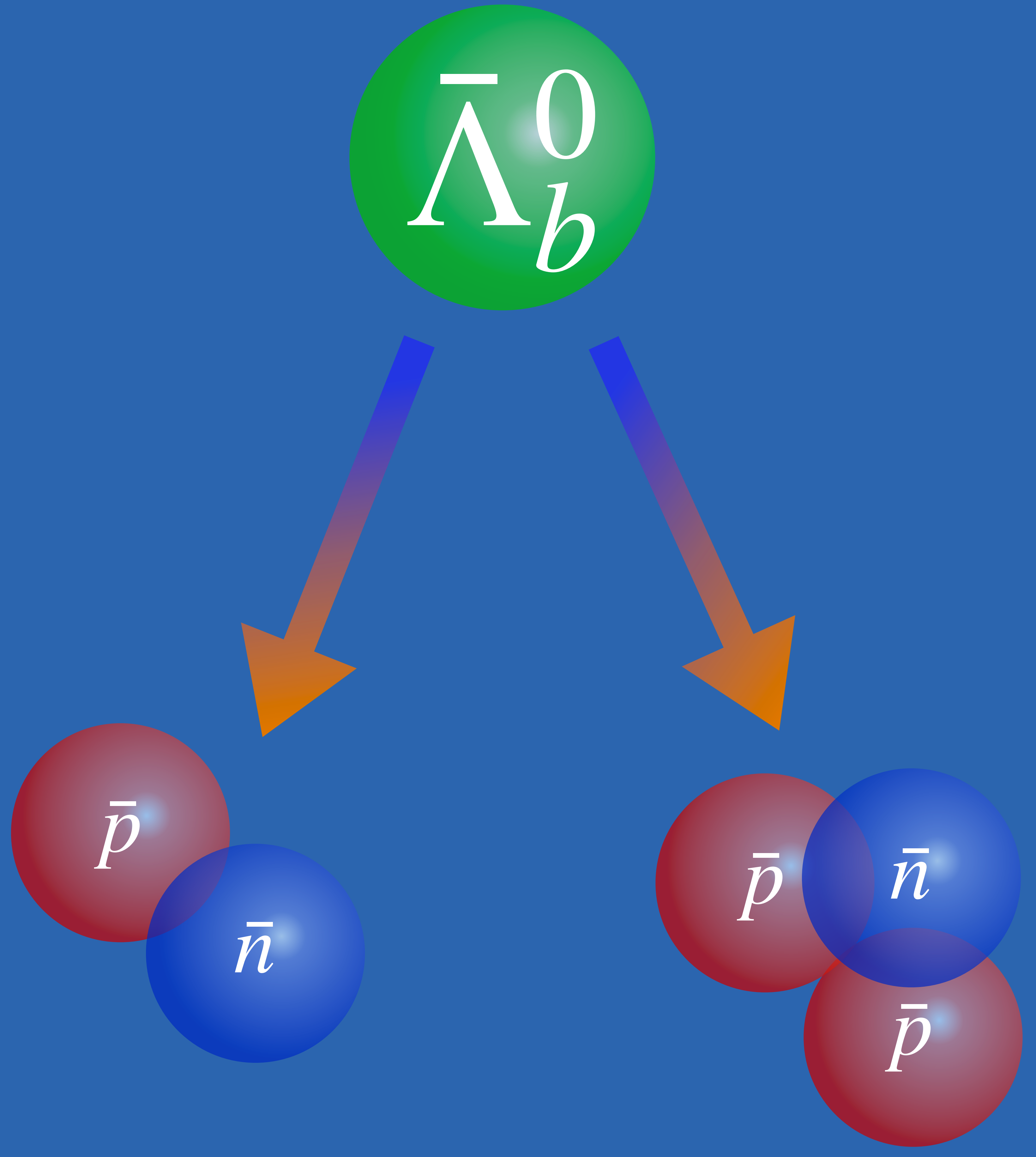
Antinuclei production from weakly-decaying b-baryons

Jordan Koechler (INFN Turin)

Dark Tools 2025



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PIANO NAZIONALE DI RIPRESA E RESILIENZA

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TORINO

Introduction

AMS-02 detected $\overline{\text{D}}$ and $\overline{\text{He}}$ ‘candidates’ though. In fact:

$\sim 7\,\overline{\text{D}}$ $\qquad \sim 5\,{}^{3}\overline{\text{He}}$ $\qquad \sim 4\,{}^{4}\overline{\text{He}}$

P. Zuccon, Talk at MIAPbP 2022

Why did we detect almost as many $\overline{\text{D}}$ than $\overline{\text{He}}$, while the multiplicity of a given nucleus is suppressed by more than 10^3 for each additional nucleon?

Introduction

M. Winkler & T. Linden proposed a solution:

DM-produced weakly-decaying b-baryons (Λ_b) can enhance the production of $^3\overline{\text{He}}$

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

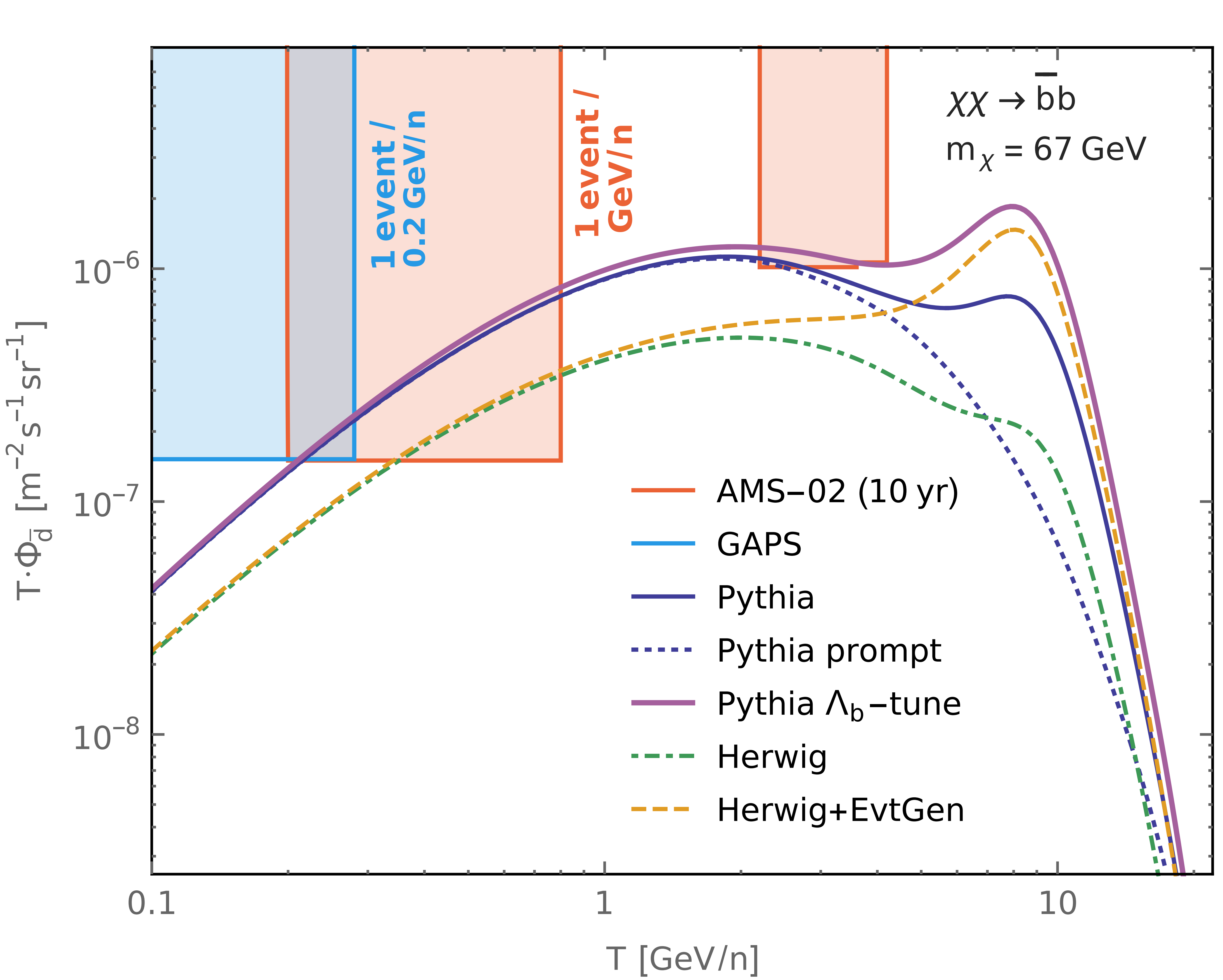
Λ_b	Content	Mass
Λ_b^0	uds	5619.57 ± 0.16 MeV
Σ_b^0	udb	Not measured
Σ_b^+	uub	5810.56 ± 0.25 MeV
Σ_b^-	ddb	5815.64 ± 0.27 MeV
Ξ_b^0	usb	5791.7 ± 0.4 MeV
Ξ_b^-	dsb	5797.0 ± 0.4 MeV
Ω_b^-	ssb	6045.8 ± 0.8 MeV

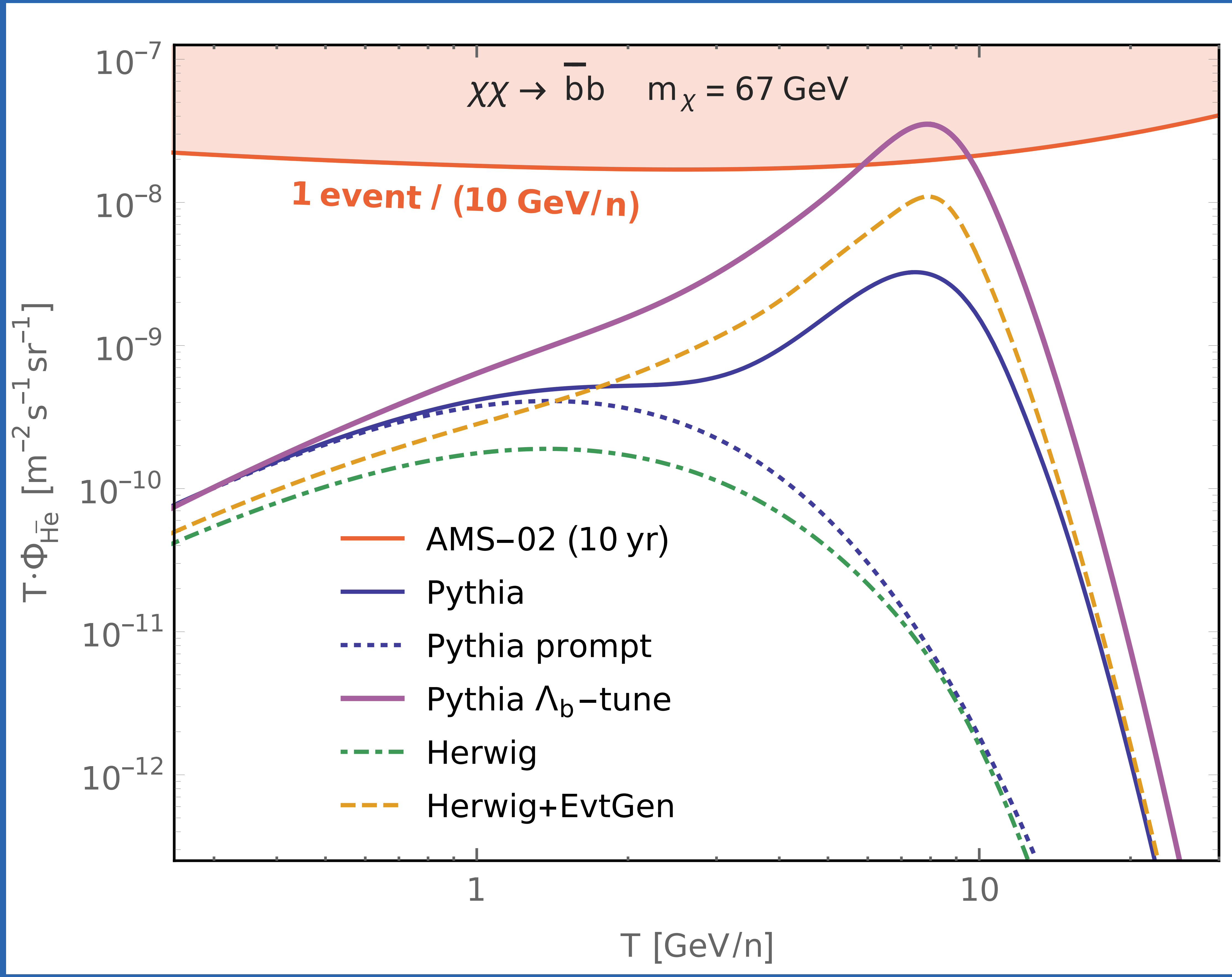
S. Navas et al. (Particle Data Group), *Phys.Rev.D* 110, 030001 (2024) and 2025 update

B	Content	Mass
B^0	u$\bar{\text{b}}$	5279.63 ± 0.20 MeV
B^+	d$\bar{\text{b}}$	5279.41 ± 0.07 MeV
B_s^0	s$\bar{\text{b}}$	5366.91 ± 0.11 MeV

B-mesons decays can be an important contribution to the production of $\overline{\text{D}}$

Introduction





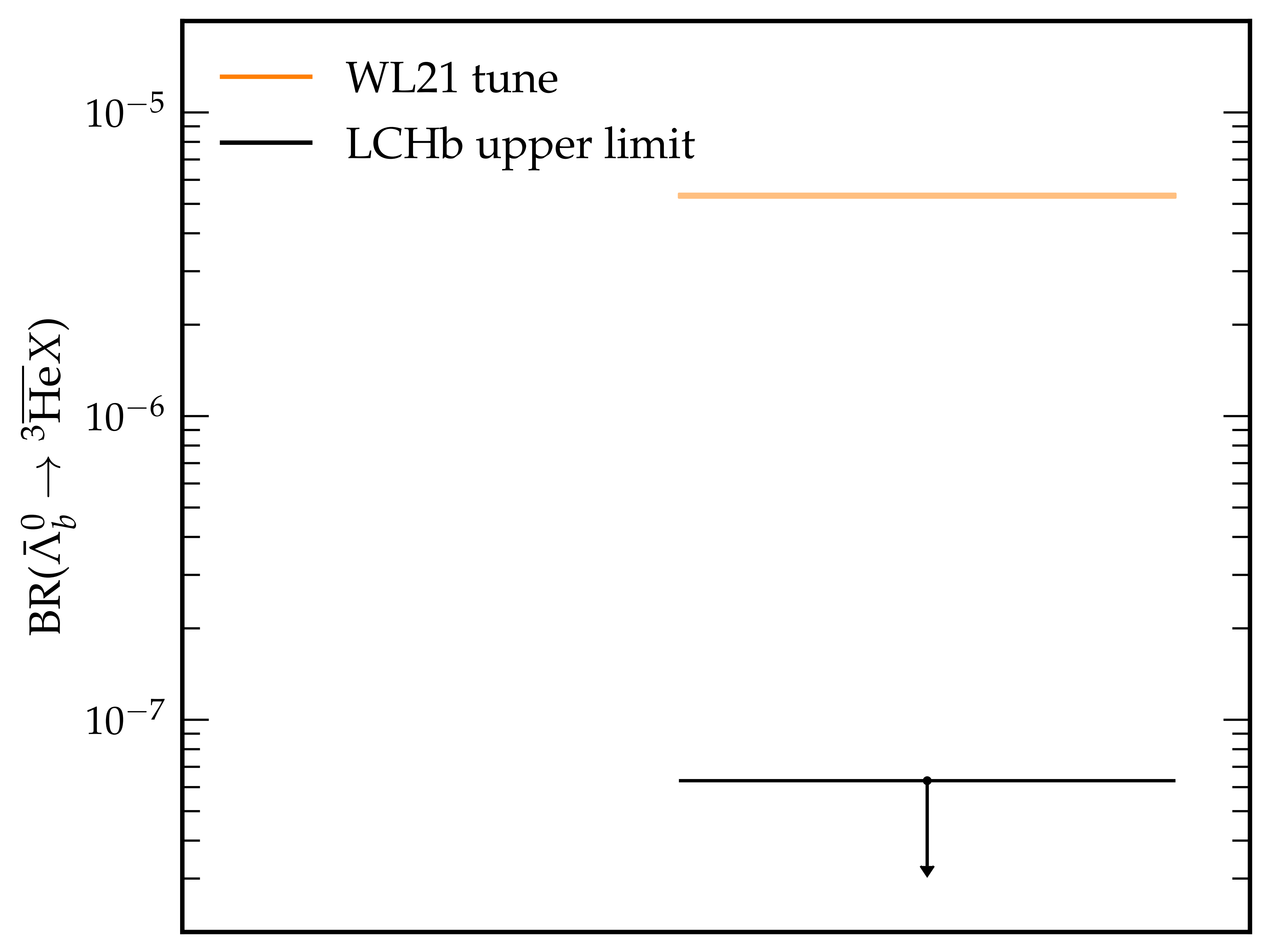
M. Winkler & T. Linden, *Phys.Rev.Lett.* 126 (2021) 10, 101101

Introduction

- Using PYTHIA, we can set the ratio between baryon and meson production with the parameter probQQtoQ
- probQQtoQ is set to match the measured fragmentation function $f(b \to \Lambda_b) = 0.1^{+0.04}_{-0.03}$ (PDG, 1998), obtaining 0.243 $(3 \times$ the default$)$
- One issue: the $p/\overline{p}$ multiplicities exceeds by 40σ the LEP measurement at the Z-pole → the coalescence momentum had to be decreased to match $\overline{\text{D}}$ ($\overline{^3\text{He}}$) data at ALEPH (ALICE)

Introduction

Another issue:



LHCb's first experimental limits on the inclusive branching ratio of Λ_b^0 to ^{3}He

$\mathrm{BR}(\Lambda_b^0 \to {}^3\mathrm{He}) < 6.3 \times 10^{-8}$

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

Our work

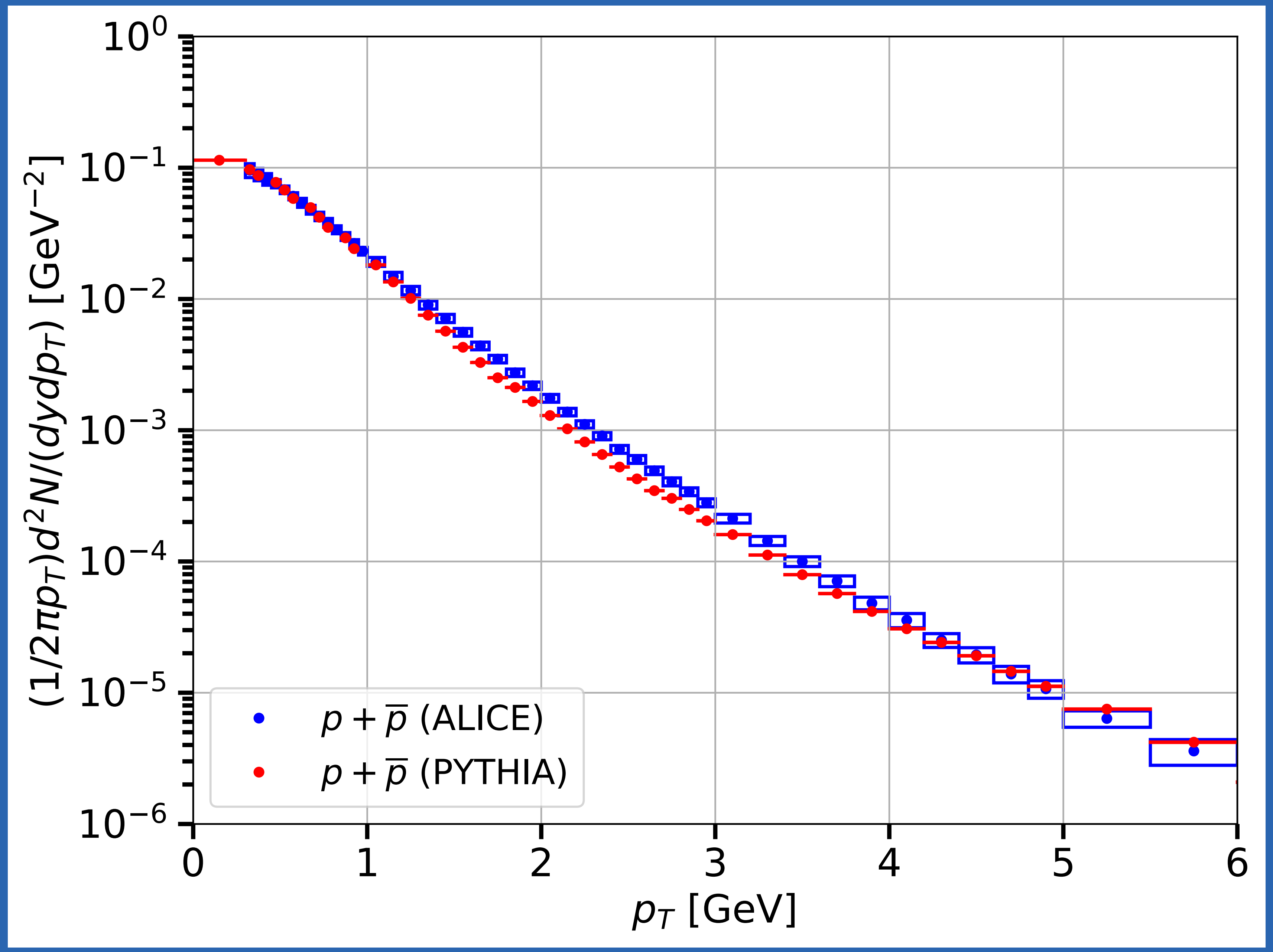
M. Di Mauro, A. Jueid, **JK**, R. Ruiz de Austri, 2504.07172

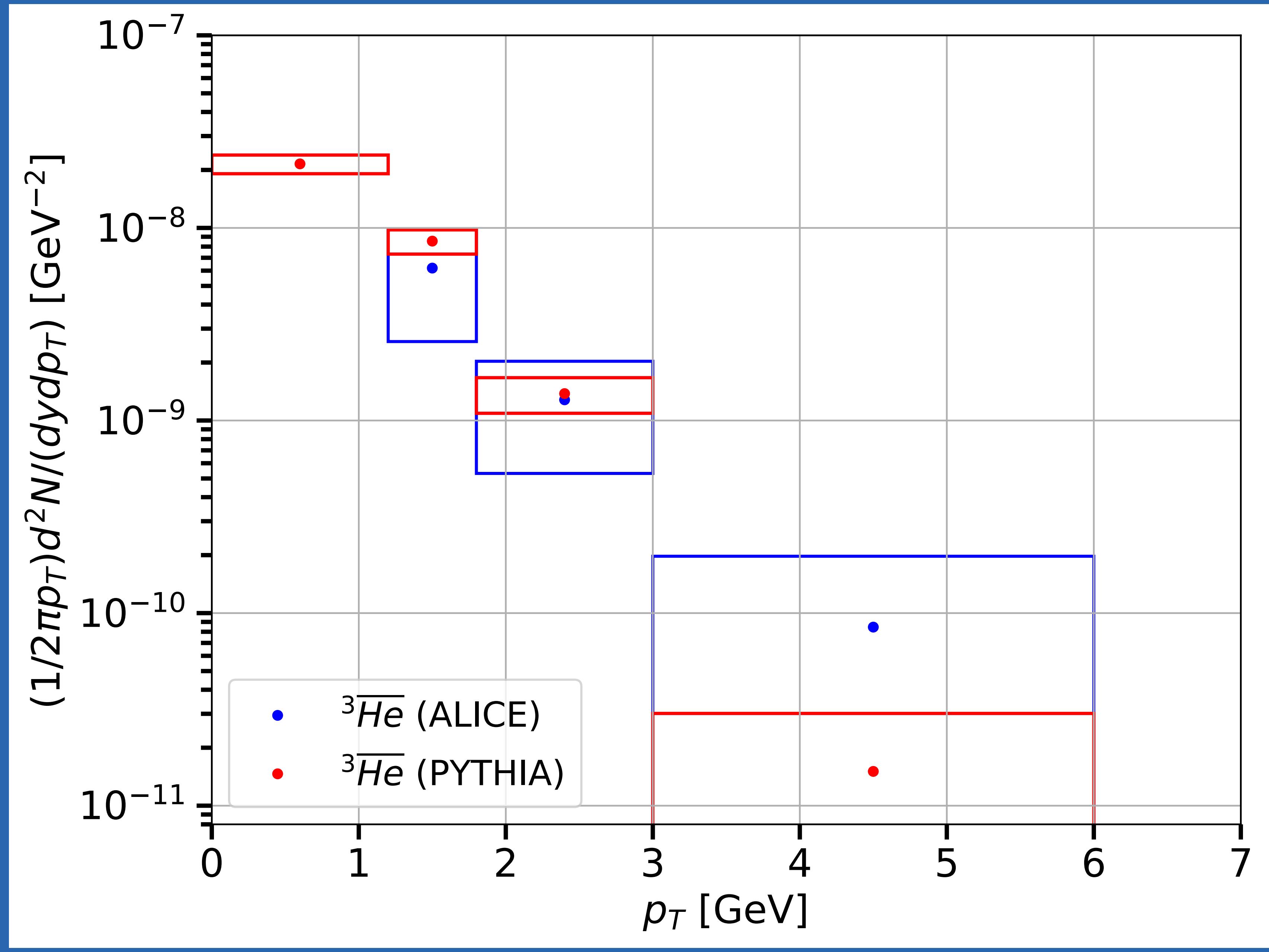
- Setting the coalescence model using ALICE data
- New tuning of PYTHIA to match:
  - $p/\overline{p}$, Λ^0 and $\pi^{\pm}$ multiplicities measured at LEP
  - The most recent value of the fragmentation function $f(b \to \Lambda_b) = 0.089 \pm 0.012$ (HFLAV, 2021)
  - The new LHCb limit for BR($\Lambda_b^0 \to {}^3$He)

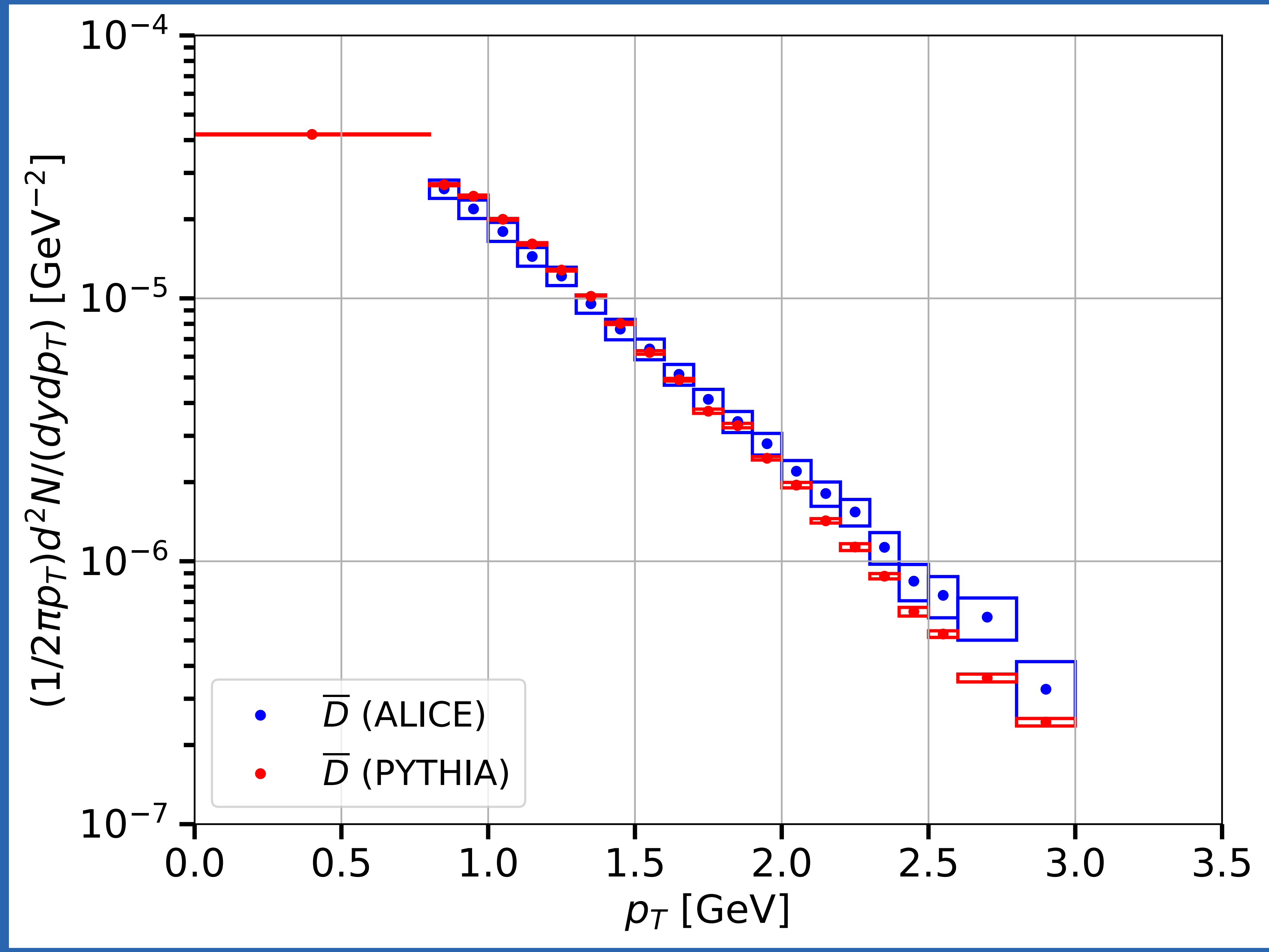
Coalescence model

Choosing a simple coalescence with distance cutoff ($\Delta p < p_{coal}$ and $\Delta r < 3$fm) and we obtain $p_{coal} = 0.20 \pm 0.01$ GeV

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





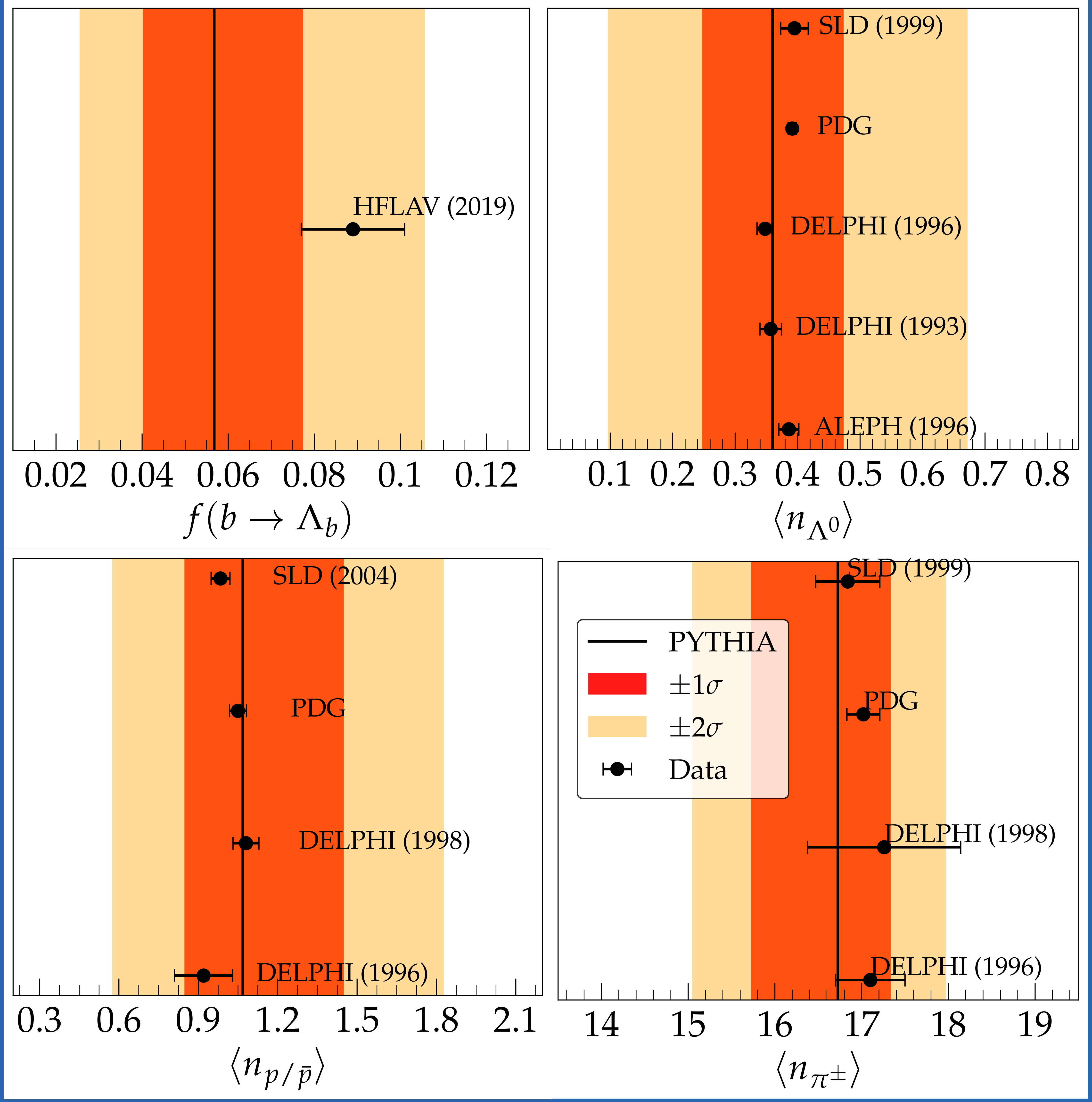


PYTHIA tuning

Hadronisation tune

We performed 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



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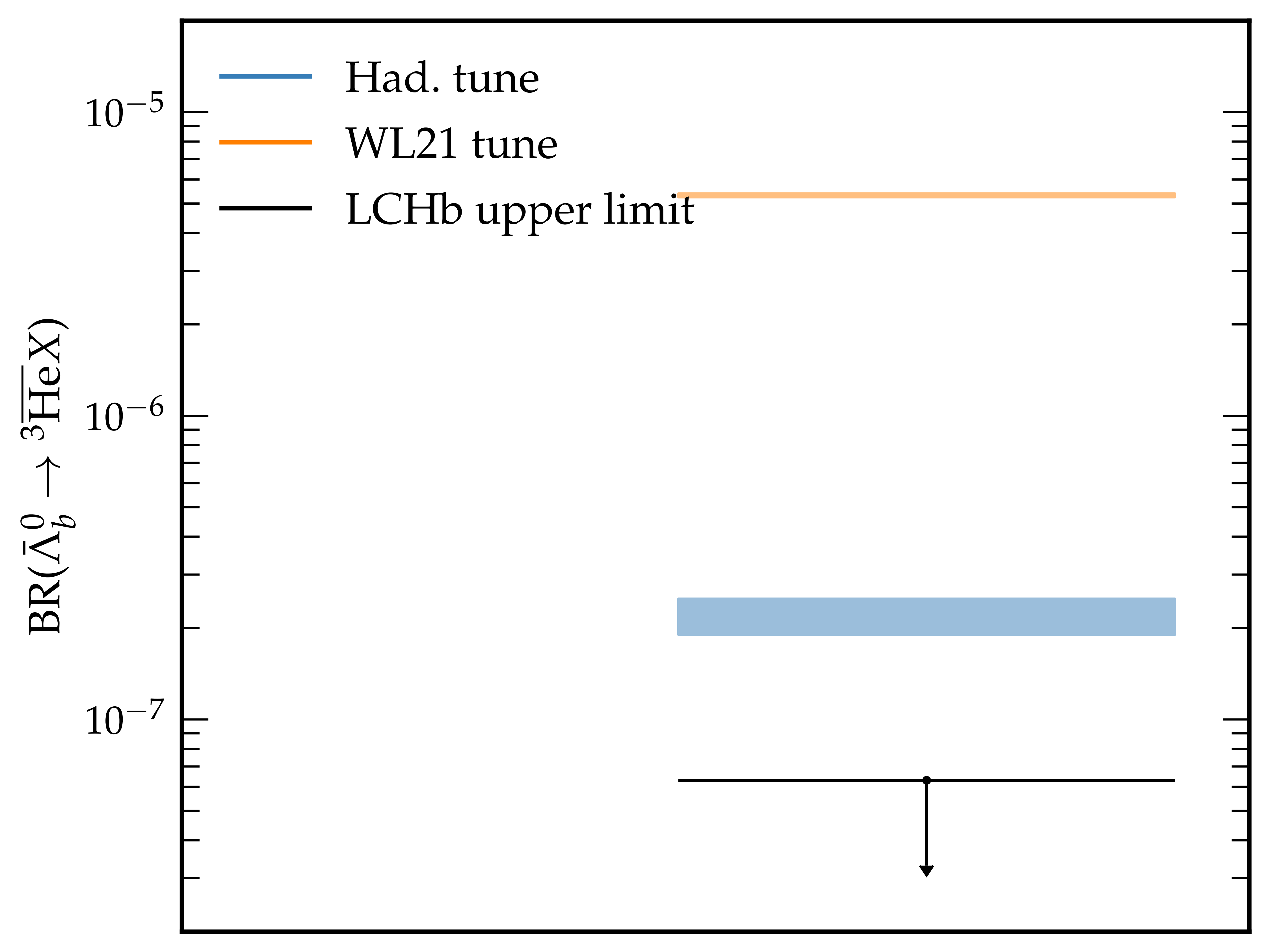
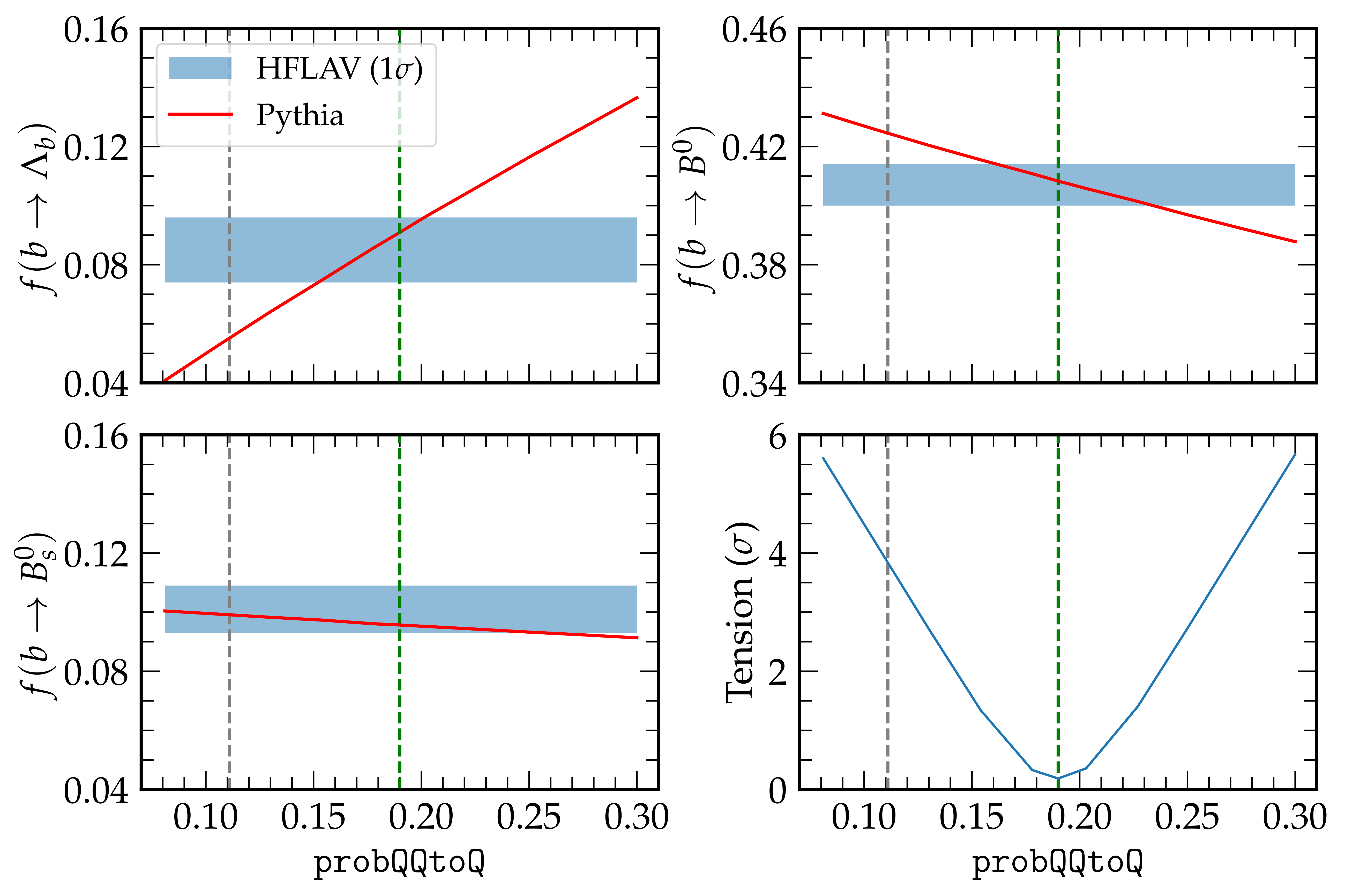


PYTHIA tuning

Fragmentation functions

Extra tuning of the probQQtoQ parameter, to be used solely for the production of $\overline{p}$ and $\overline{n}$ from $\overline{\Lambda}_b$ and B-meson decay:

$$\text{probQQtoQ} = 0.19 \pm 0.03$$



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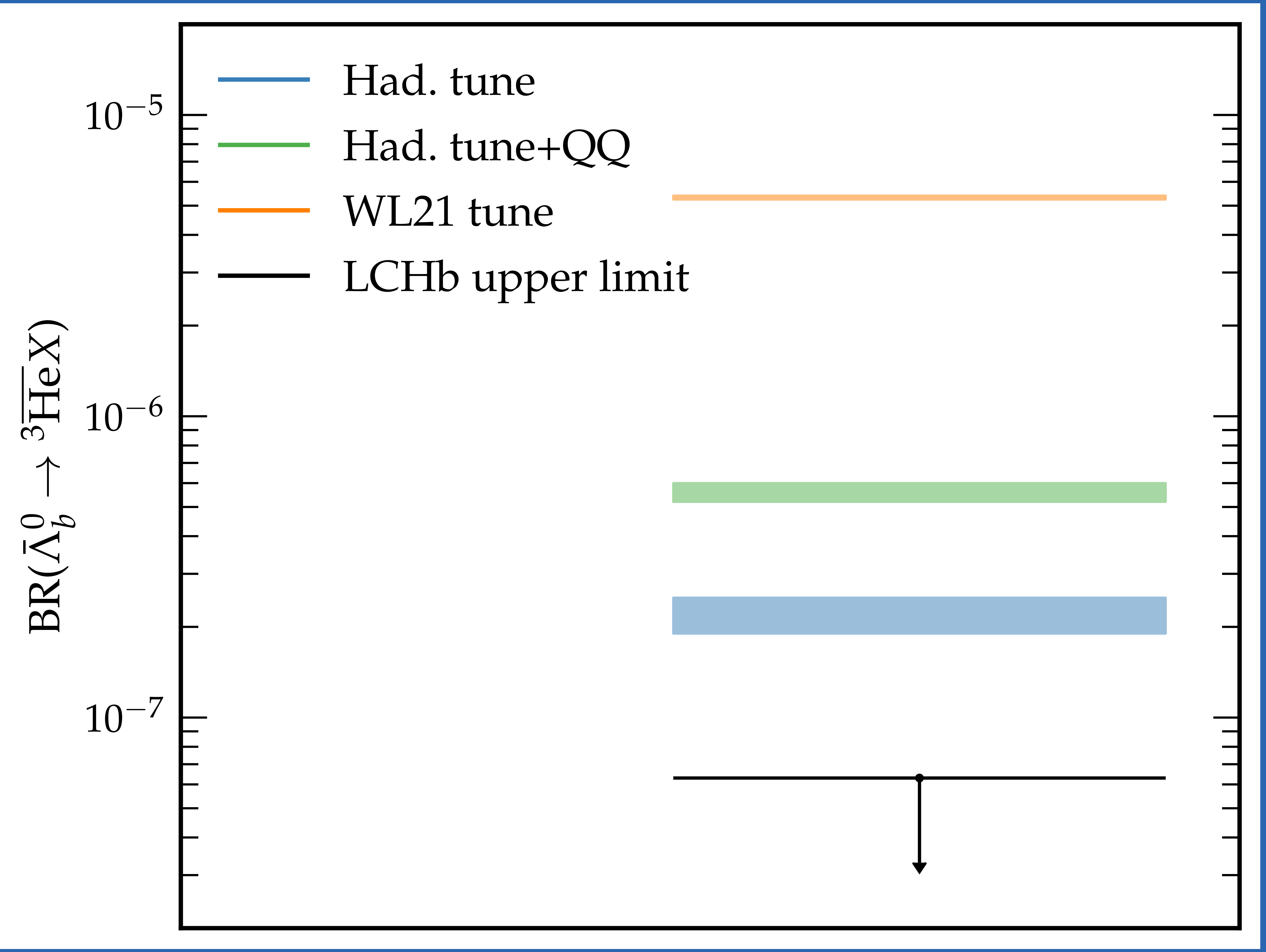


PYTHIA tuning

Branching ratios into di-quark modes

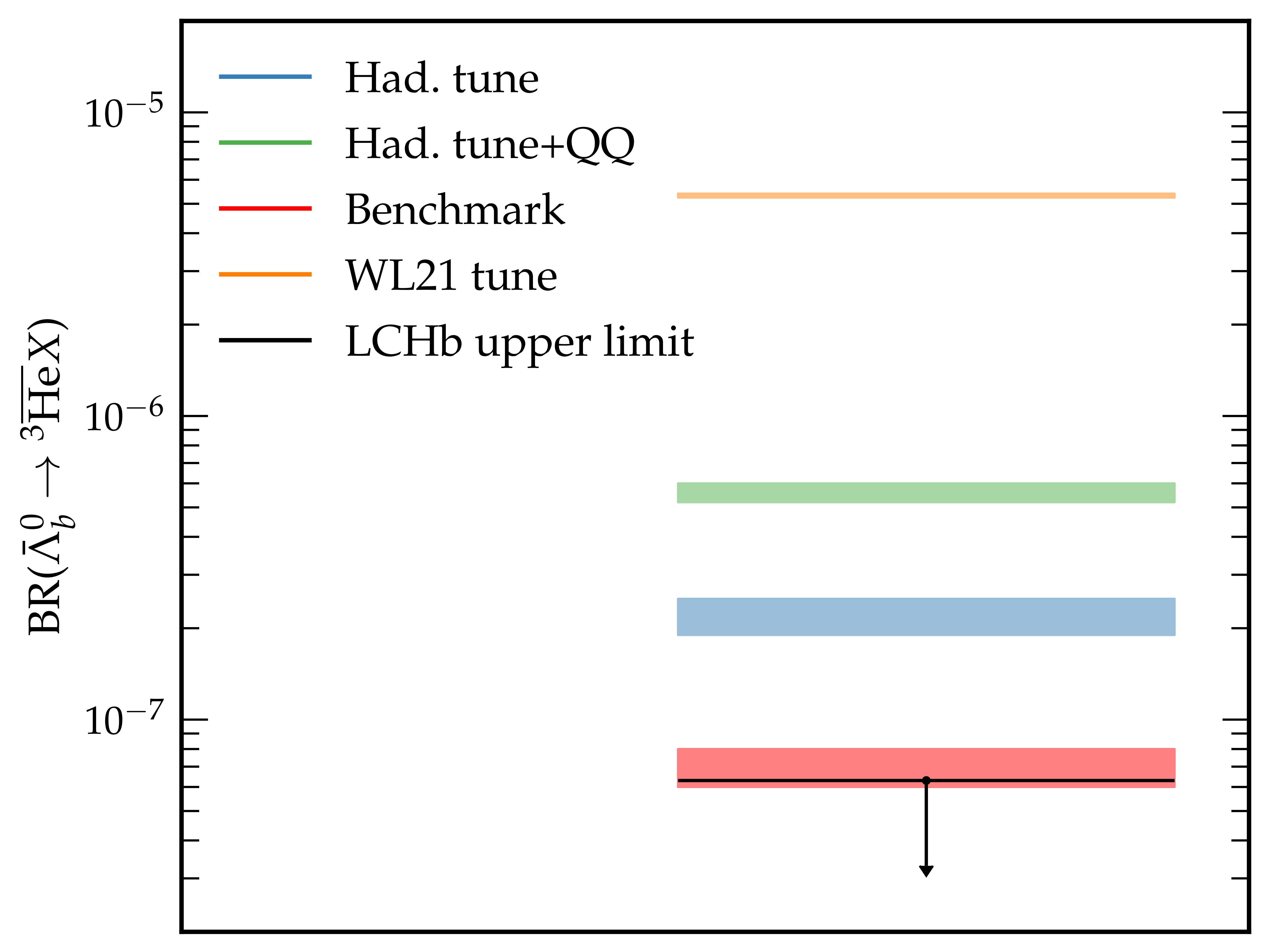
$\bar{\Lambda}_b^0$ decay mode	Measured BR	WL21 tune	Had. tune	Benchmark
$\Lambda_c^- \ell^+ \nu_\ell$	$(6.2^{+1.4}_{-1.3})\%$	$(5.9569 \pm 0.0009)\%$	$(5.956 \pm 0.002)\%$	$(5.957 \pm 0.001)\%$
$\bar{p}\overline{D}^0\pi^+$	$(6.2 \pm 0.6) \times 10^{-4}$	$(7.13 \pm 0.01) \times 10^{-4}$	$(6.11 \pm 0.02)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

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

We also modify some branching ratios of the Λ_b^0 to di-quark modes to match the LHCb upper limit on BR$(\Lambda_b^0 \to {}^3\overline{\mathrm{He}}\,X)$

PYTHIA tuning

Branching ratios into di-quark modes



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PYTHIA tuning

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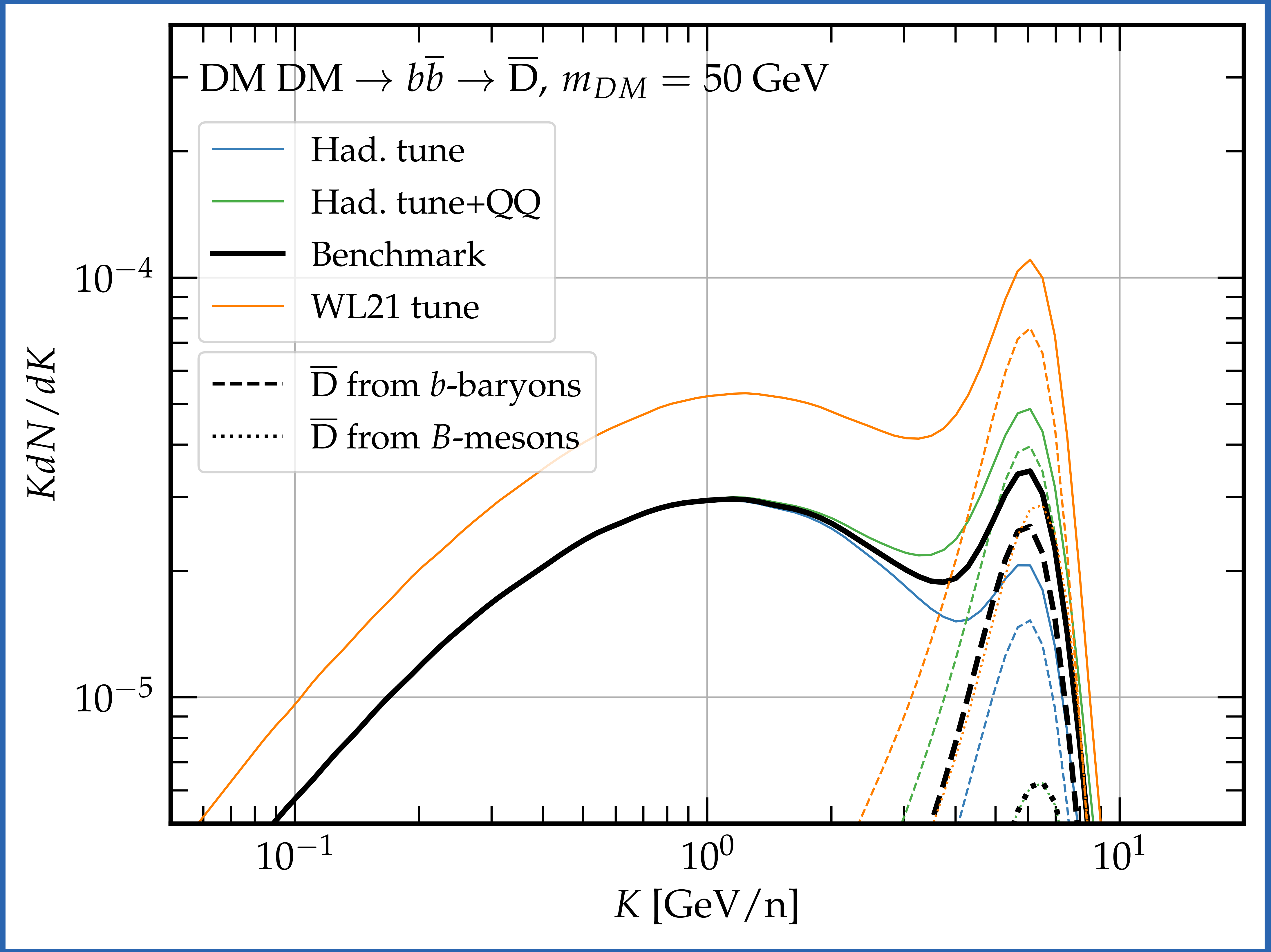
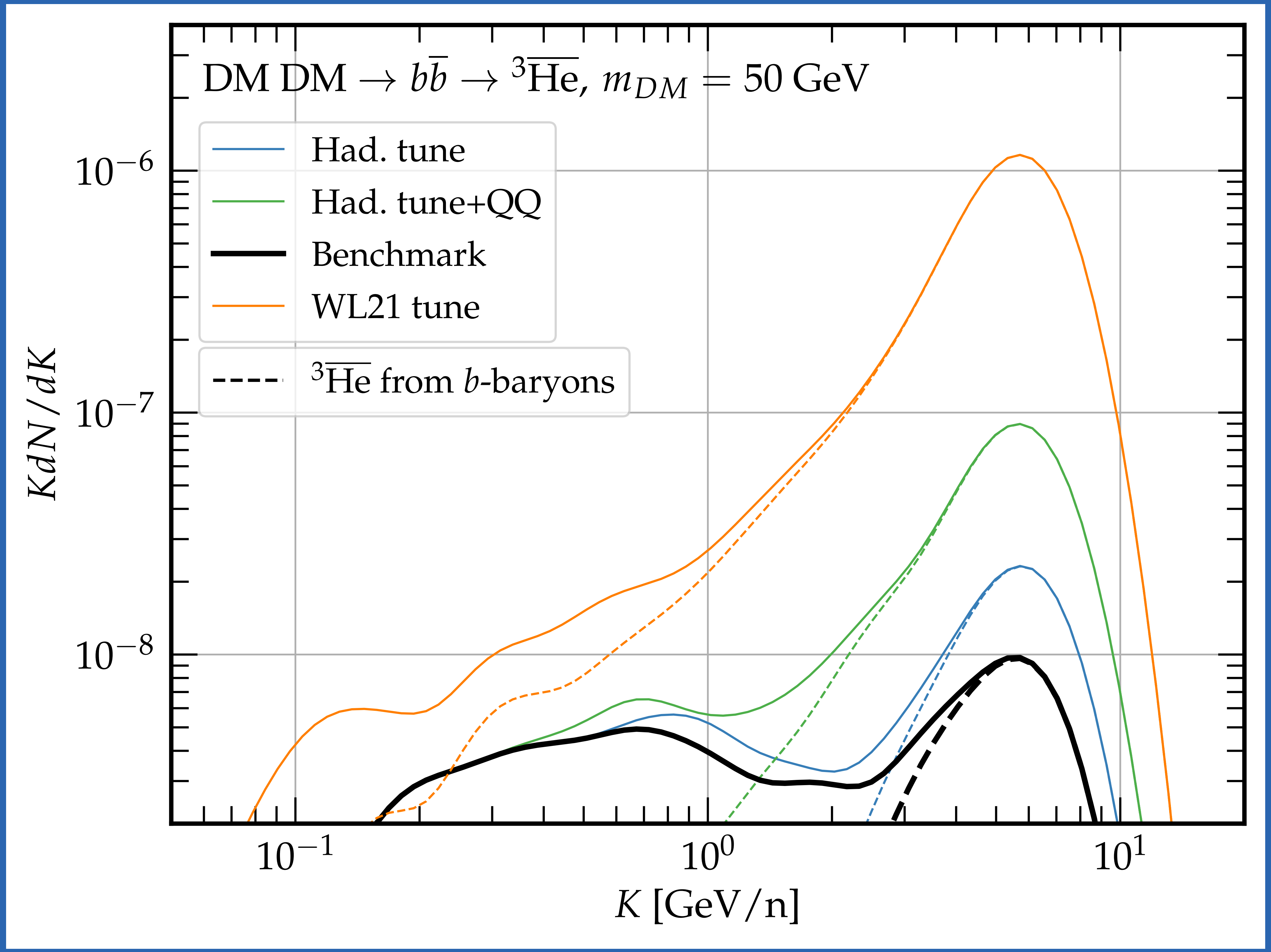




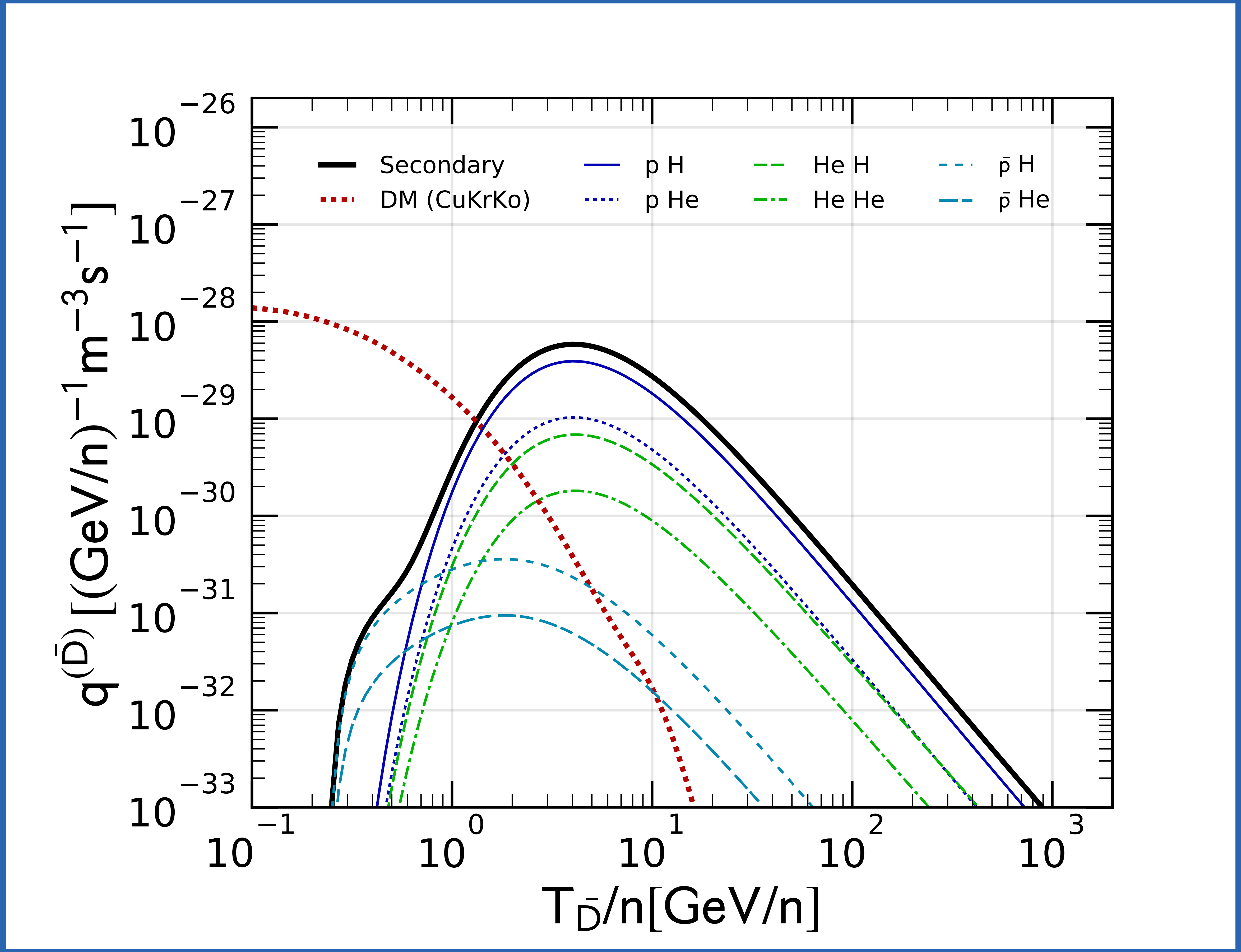
Summary

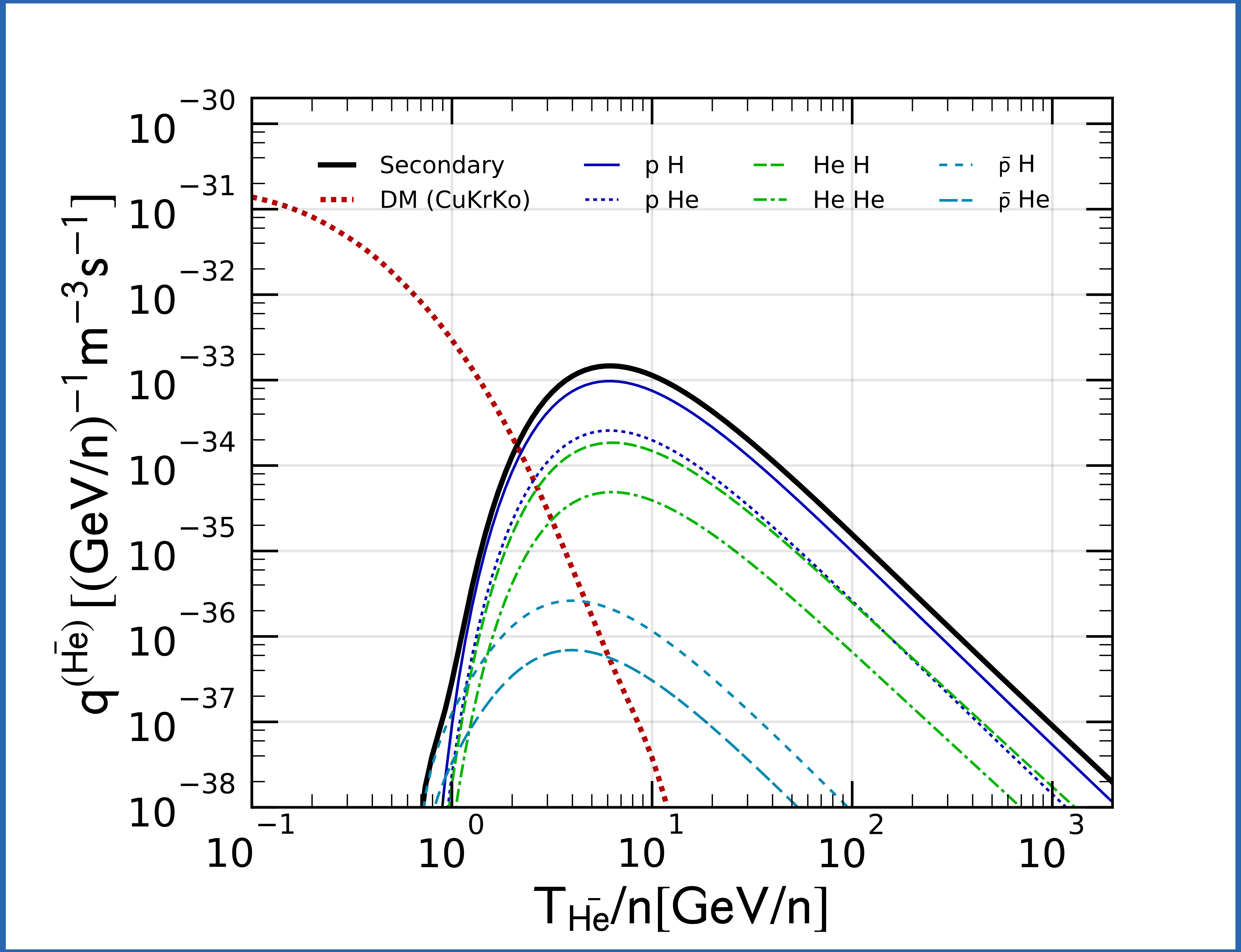
- We performed a full tuning of PYTHIA and determination of the coalescence model in order to match different collider observables in order to correctly assess the production of light antinuclei ($\overline{\mathrm{D}}$, $^3\overline{\mathrm{He}}$) arising from DM annihilation
- We now expect the production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

Light antinuclei as a strong DM signal





M. Korsmeier, F. Donato, N. Fornengo, *Phys.Rev.D* 97 (2018) 10, 103011

CuKrKo = A. Cuoco, M. Krämer, M. Korsmeier, *Phys.Rev.Lett.* 118 (2017) 19, 191102

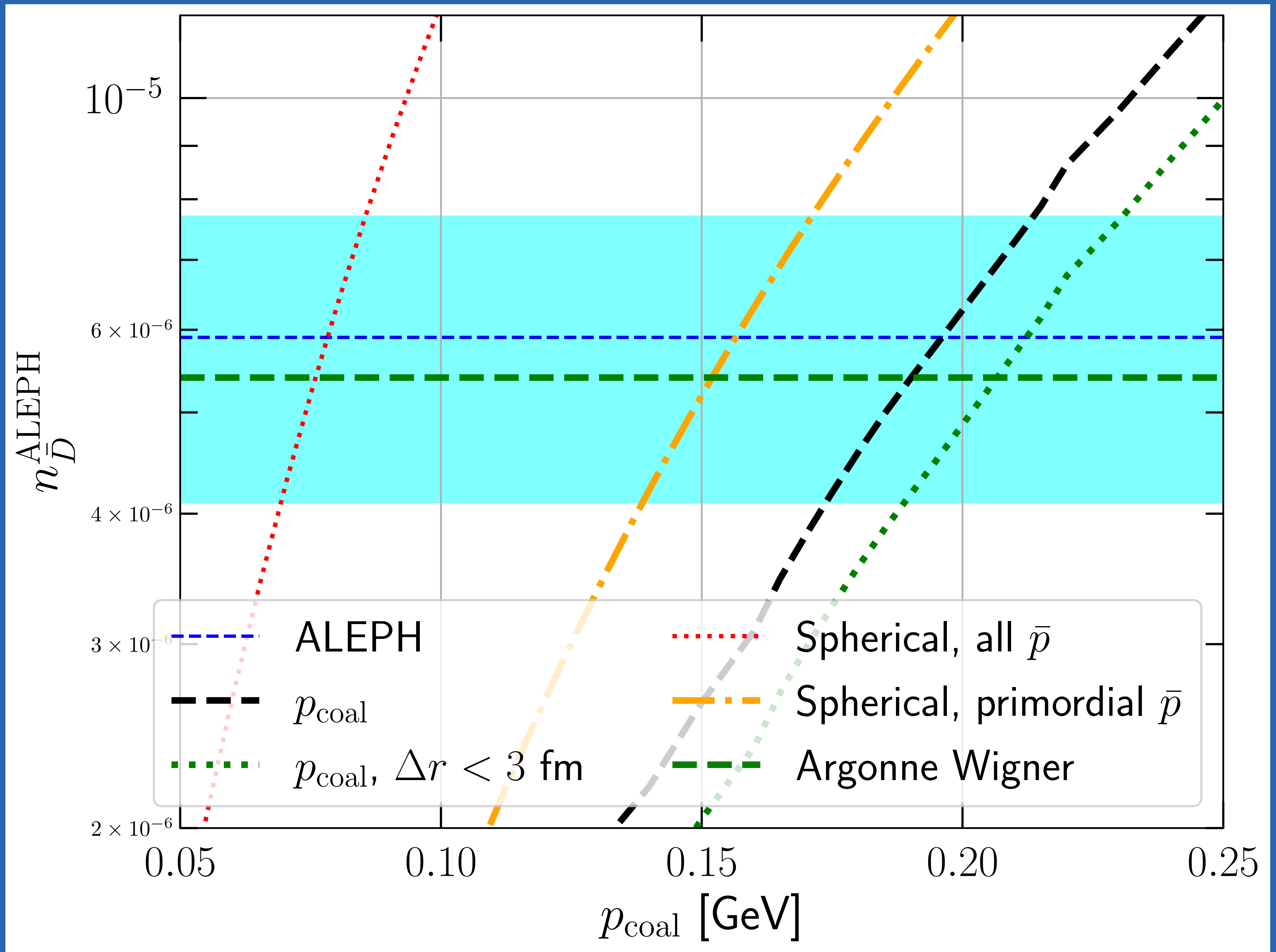
Coalescence models

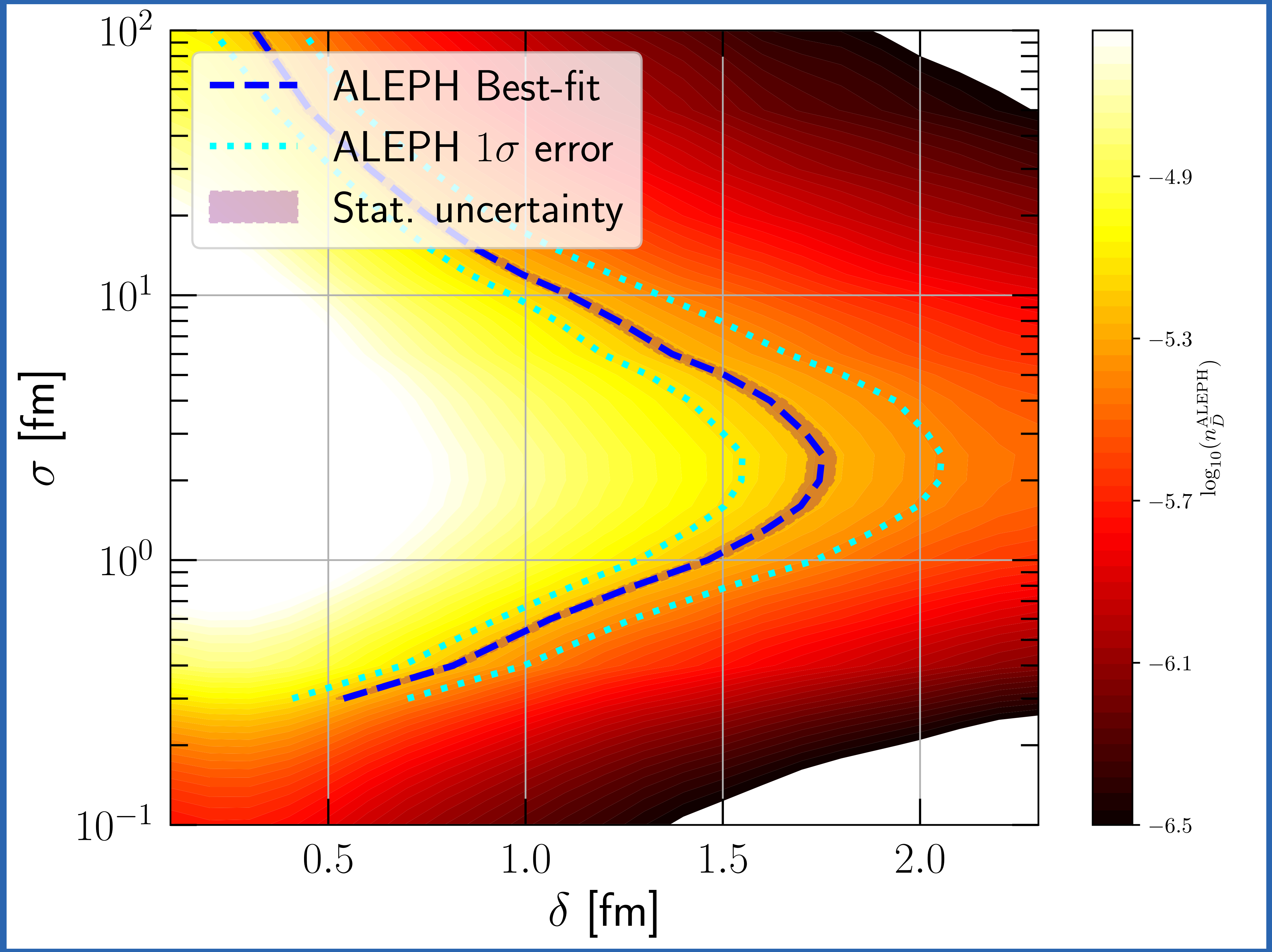
Some coalescence models:

- Simple coalescence: $\Delta p < p_{coal}$
- Simple coalescence with distance cutoff: $\Delta p < p_{coal}$ and $\Delta r < 3$ fm
- Gauss Wigner: $\mathscr{D}(\Delta r, \Delta p) \propto e^{-\Delta r^2/(2\sigma^2)} e^{-\Delta p^2 \delta^2/2}$ 
- Argonne Wigner: $\mathscr{D}(\Delta r, \Delta p) = \frac{1}{8\pi}\left(T_1 + T_2 + T_3 + T_4 + T_5 + T_6\right)$ 

Coalescence models

ALEPH data (e^+e^- collisions at the Z-pole)





M. Di Mauro, N. Fornengo, A. Jueid, R. Ruiz de Austri, F. Bellini, 2411.04815

Coalescence models

$$T_1 = (2\pi f)^{3/2} N_3^2 e^{-\frac{f^2 q^2 + 4r^2}{2f}}$$

$$T_2 = \frac{16a^2 N_1^2}{\pi q r} \int_0^\infty d\xi \frac{\sin(q\xi)}{4a^2 + 4r^2 + \xi^2} \log\left[\frac{4a^2 + (\xi + 2r)^2}{4a^2 + (\xi - 2r)^2}\right]$$

$$T_3 = \frac{8aN_1N_3}{qr} \int_0^\infty d\xi \sin(q\xi) e^{-\frac{2a^2 + 4r^2 + \xi^2}{2f}} \left[\mathrm{Ei}\left(\frac{4a^2 + (2r + \xi)^2}{4f}\right) - \mathrm{Ei}\left(\frac{4a^2 + (\xi - 2r)^2}{4f}\right)\right]$$

Coalescence models

$$T_4 = \frac{4bN_2N_3}{q}\int_0^\infty\int_{-1}^{1} d\xi d\gamma \sin(q\xi)\xi\left(\frac{e^{-\frac{4r^2+4\gamma r\xi+\xi^2}{4f}}}{b^2+c^2-c\sqrt{4r^2-4\gamma r\xi+\xi^2}+r^2-\gamma r\xi+\frac{\xi^2}{4}}+\frac{e^{-\frac{4r^2-4\gamma r\xi+\xi^2}{4f}}}{b^2+c^2-c\sqrt{4r^2+4\gamma r\xi+\xi^2}+r^2+\gamma r\xi+\frac{\xi^2}{4}}\right)$$

$$T_5 = \frac{4abN_1N_2}{\pi q}\int_0^\infty\int_{-1}^{1} d\xi d\gamma \sin(q\xi)\xi\left[\frac{\left(a^2+r^2+\gamma r\xi+\frac{\xi^2}{4}\right)^{-1}}{b^2+\left(c-\frac{1}{2}\sqrt{4r(r-\gamma\xi)+\xi^2}\right)^2}+\frac{\left(a^2+r^2-\gamma r\xi+\frac{\xi^2}{4}\right)^{-1}}{b^2+\left(c-\frac{1}{2}\sqrt{4r(r+\gamma\xi)+\xi^2}\right)^2}\right]$$

$$T_6 = \frac{4N_2^2b^2}{\pi q}\int_0^\infty\int_{-1}^{1} d\xi d\gamma \sin(q\xi)\xi\left[\frac{1}{b^2+\left(c-\frac{1}{2}\sqrt{4r(r+\gamma\xi)+\xi^2}\right)^2}\times\frac{1}{b^2+\left(c-\frac{1}{2}\sqrt{4r(r-\gamma\xi)+\xi^2}\right)^2}\right]$$