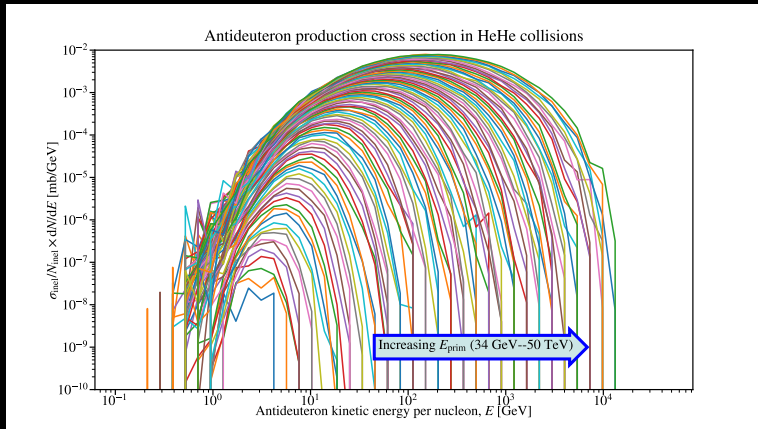


Antinuclei in the Milky Way

Michael Kachelrieß (NTNU, Trondheim)



with Jonas Tjemsland and Sergey Ostapchenko

Formation of light nuclei

interested in various types of reactions:

- $DM + DM \rightarrow X\bar{d}$
- $e^+e^- \rightarrow X\bar{d}$
- $pp \rightarrow X\bar{d}$
- $Ap \rightarrow X\bar{d}$
- $AA \rightarrow X\bar{d}$

different systems: point-like, hadronic, nuclear

General picture of coalescence mechanism:

- separation of scales:

- ▶ $B_d \simeq 2 \text{ MeV} \ll \Lambda_{\text{QCD}}, T_{\text{QCD}}$
- ▶ $p_0 \simeq 100 \text{ MeV} \ll m_p$

⇒ coalescence happens after hadronisation

- semiclassical picture: $\bar{p}(\mathbf{x}, \mathbf{p})$ and $\bar{n}(\mathbf{x}', \mathbf{p}')$ form an antideuteron, if “close” in phase-space

- approximations:

- ▶ coalescence in momentum space: $V \ll 4\pi R_d^3/3$
⇒ $f_{\bar{p}}(\mathbf{x}, \mathbf{p}) \simeq \delta(\mathbf{x} - \mathbf{x}_0) f_{\bar{p}}(\mathbf{p})$
- ▶ coalescence in coordinate space: $V \gg 4\pi R_d^3/3$
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“Old” coalescence model in momentum space

- nucleons with cms momentum difference $\Delta p < p_0$ form a nucleus
- for pp and pA collisions: “fireball” **isotropic** distribution d^3N/dp^3
- **antideuteron** $\sim$ **antiproton**²

$$\frac{dN_{\bar{d}}}{dT} = \frac{p_0^3}{6} \frac{m_d}{m_N^2} \frac{1}{\sqrt{T_d^2 + 2m_d T_d}} \left(\frac{dN_{\bar{N}}}{dT} \Big|_{T_d = T_{\bar{N}}/2} \right)^2$$

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- more general: antinuclei $A \sim B_A$ antiprotons^A with

$$B_A = A \left(\frac{4\pi}{3} \frac{p_0^3}{m_N} \right)^{A-1}$$

$\Rightarrow$ strong hierarchy $\bar{p} \gg \bar{d} \gg \overline{{}^3\text{He}} \gg \overline{{}^4\text{He}}$

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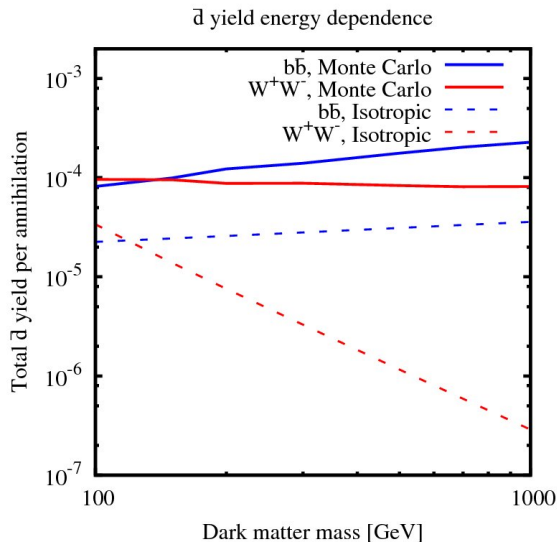
- consider e.g. **DM annihilation** $XX \rightarrow W^+ W^-$:

$$\frac{dN_{\bar{d}}}{dx} \propto \frac{1}{M_X^2} \frac{dN_{\bar{n}}}{dx} \frac{dN_{\bar{p}}}{dx}$$

- $1/M_X^2$ suppression in **contradiction to Lorentz invariance**:
- **decay products** of W are **boosted** in cone with $\vartheta \sim m_W/m_X$

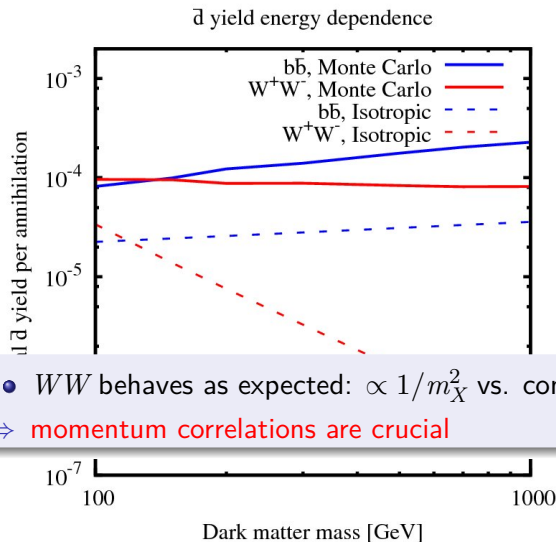
Deuteron yield: “Isotropic” vs. event-by-event:

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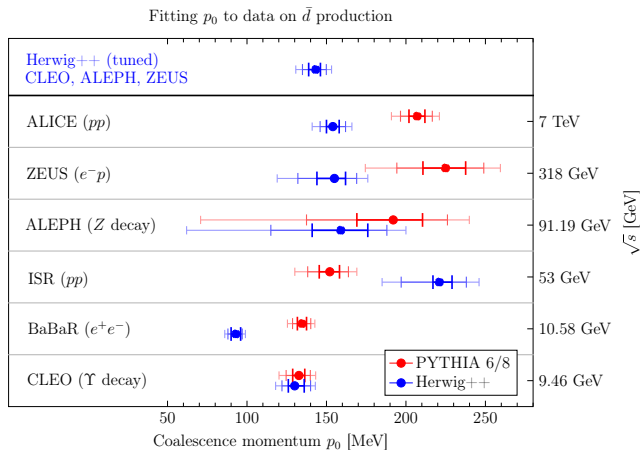


- WW behaves as expected: $\propto 1/m_X^2$ vs. const.

$\Rightarrow$ momentum correlations are crucial

Problems of MC coalescence in momentum space:

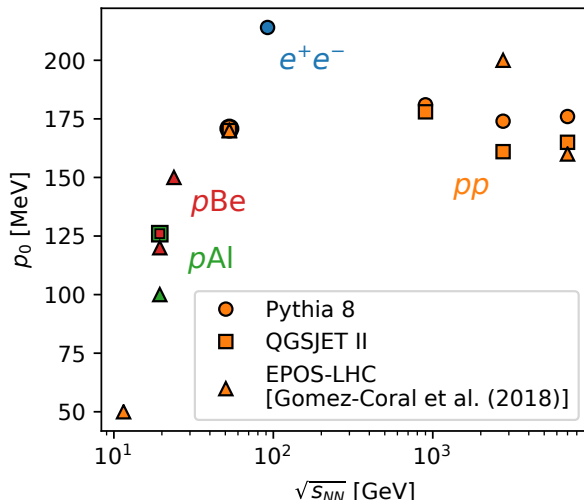
- discrepancies in p_0 between e^+e^- , pp and $A p$



[Aramki et al, 1505.07785]

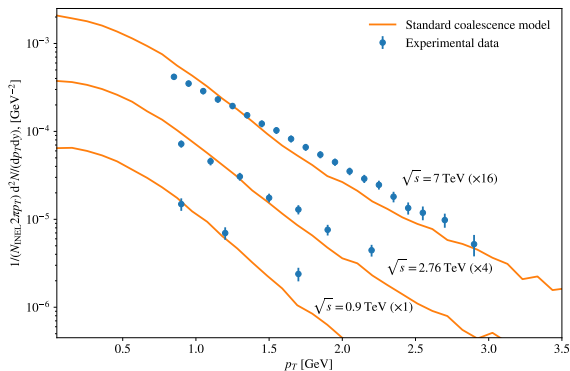
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- discrepancies in p_0 between e^+e^- , pp and $A p$
- energy dependence of p_0 – different for d and $\bar{d}$:
- **bad fit of ALICE data** at large $p_\perp$



Solution: use Wigner functions with momentum correlation

- two-body **Wigner function** $W(x, p)$ contains **full quantum mechanical information** of a system
- probability distributions follow as

$$\int dx W(x, p) = \phi^*(p) \phi(p), \quad \int \frac{dp}{2\pi} W(x, p) = \psi^*(x) \psi(x)$$

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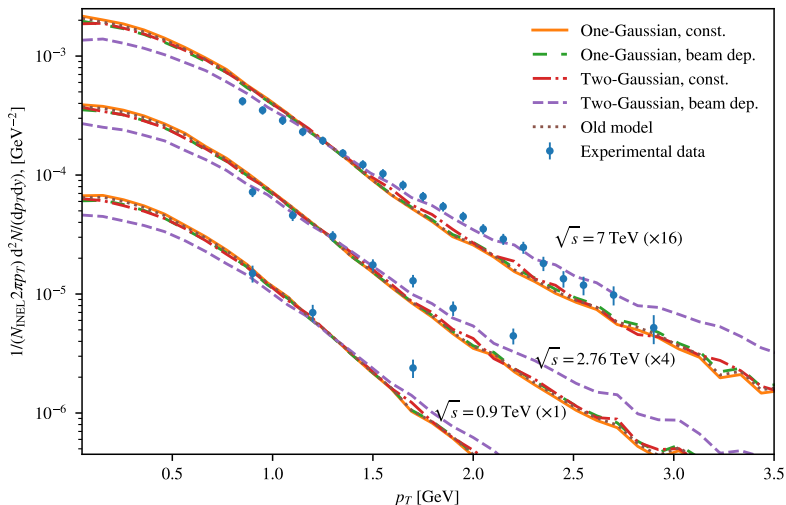
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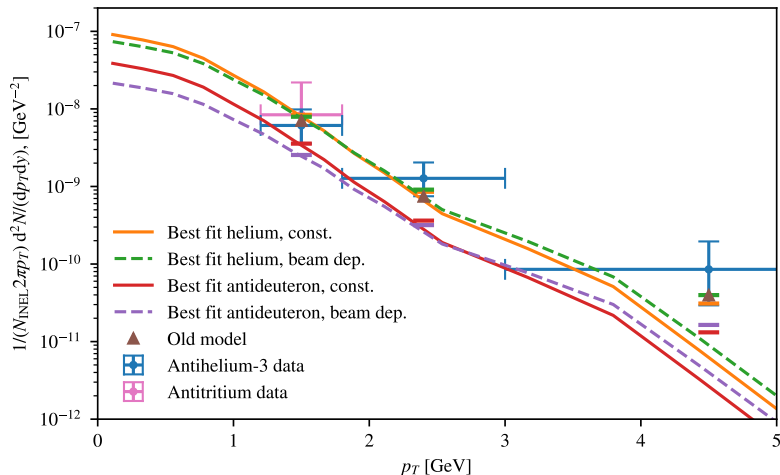
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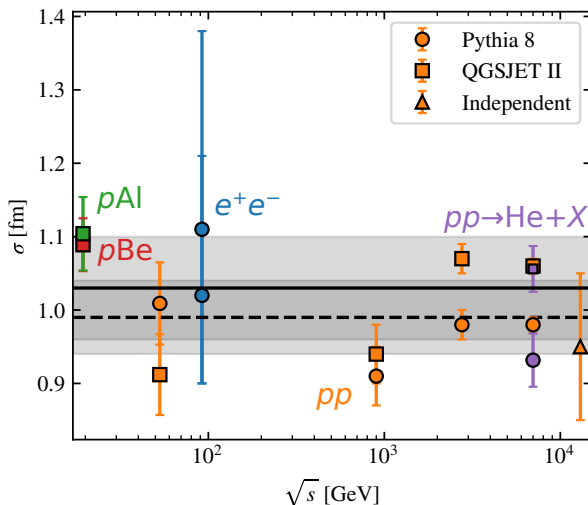


Comparison with experimental data on pp and Ap:

- assume $R_A \simeq a_0 A^{1/3}$ with $\sigma^{pp} \simeq a_0$ as fit parameter

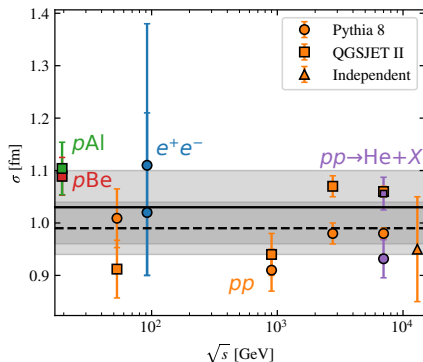
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- good agreement with expectation $\sigma^{pp} \sim 1$ fm
- independent of energy and reaction type

Determination of σ from femtoscopy:

- ALICE measured **size of baryon emitting source** in pp collisions

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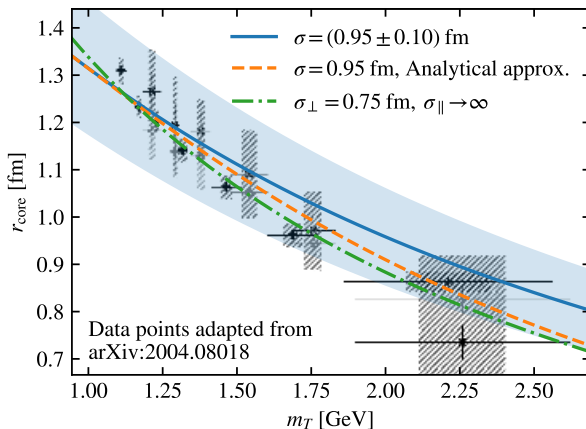
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- evidence for **collective flow?**

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Misuse of B_2 :

- **model-independent** determination of $\bar{d}$ yield, based on exp. data ?

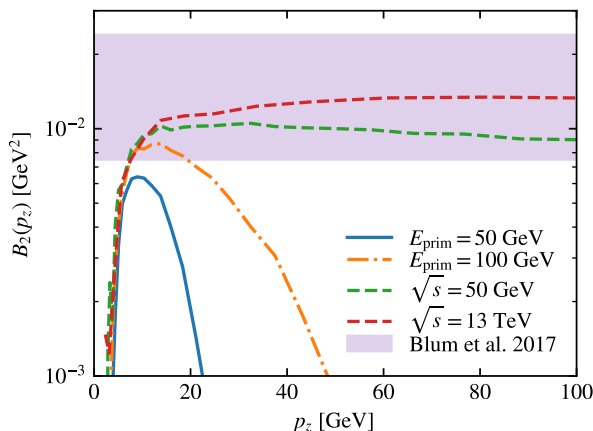
[Blum '18,'19,...]

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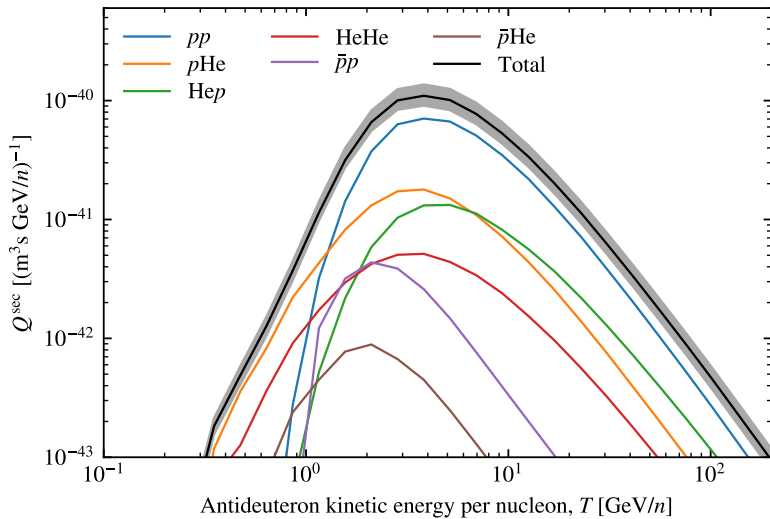
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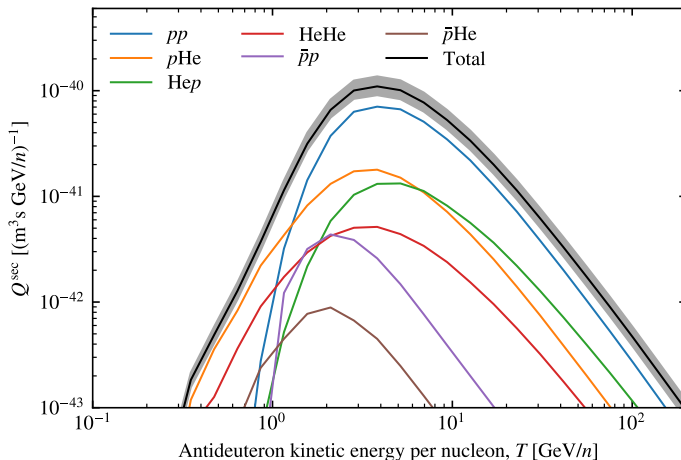
- not possible: B_2 is not a constant



Source term Q^{sec} for secondary production of $\bar{d}$:

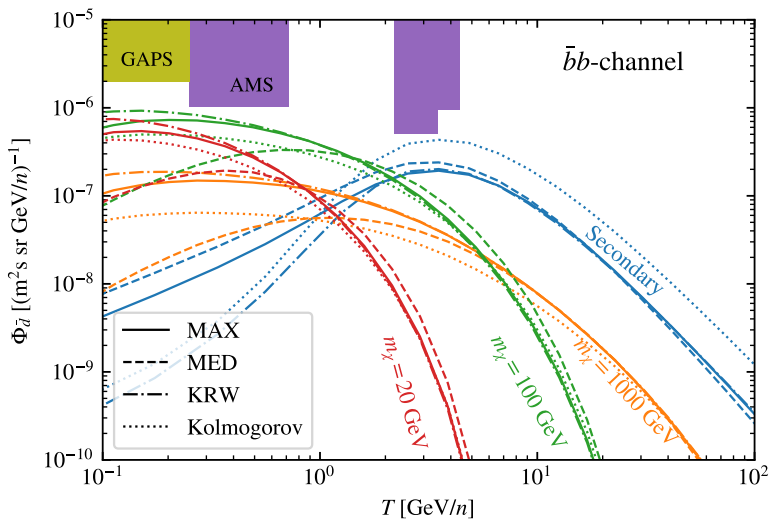


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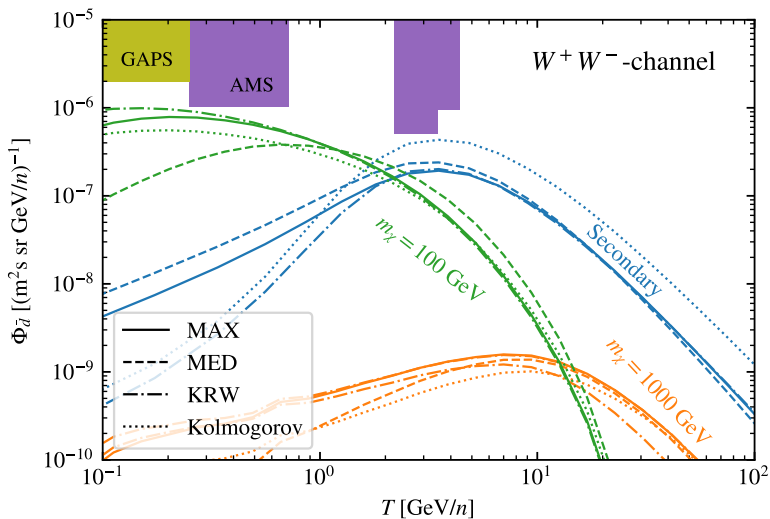


- lower threshold in pA reactions $\Rightarrow$ dominate at low T
- use of “nuclear enhancement factors” fails

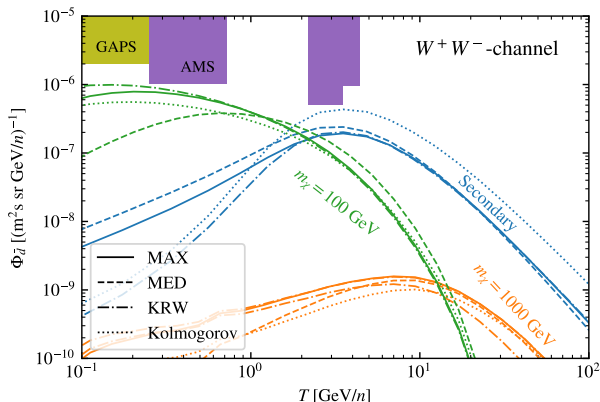
Antideuteron flux: secondaries plus $\bar{b}b$ channel



Antideuteron flux: secondaries plus WW channel

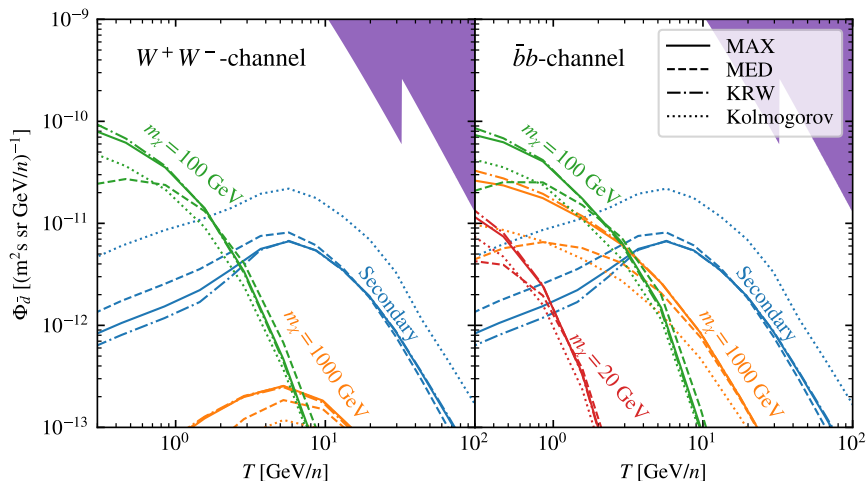


Antideuteron flux: secondaries plus WW channel



- DM signal at low-energies background-free
- $\bar{d}$ flux limited by $\bar{p}$

Antihelium-3 flux:



Conclusions

- ① Formation of light antinuclei is interesting in itself:
 - ▶ inclusion of two-particle momentum correlations necessary
 - ▶ reaction-dependent size of source is important
- ② Coalescence in phasespace – WiFunC model:
 - ▶ consistent description of various reactions
- ③ Antinuclei are a useful tool searching for new physics
 - ▶ antideuteron as signal for DM
 - ▶ simulations of pA , AA reactions needed at low energies
 - ▶ strong hierarchy of fluxes as function of A
 - ▶ antihelium-3 and especially antihelium-4 would challenge cosmology

Can $\bar{\Lambda}_b$ decays boost $\overline{{}^3\text{He}}$ from DM?

[Winkler, Linden '21]

- **Majorana** DM: $\sigma_{\text{ann}} \propto m_f^2 \Rightarrow$ couples mainly to **b quarks** for $m_X < m_Z$

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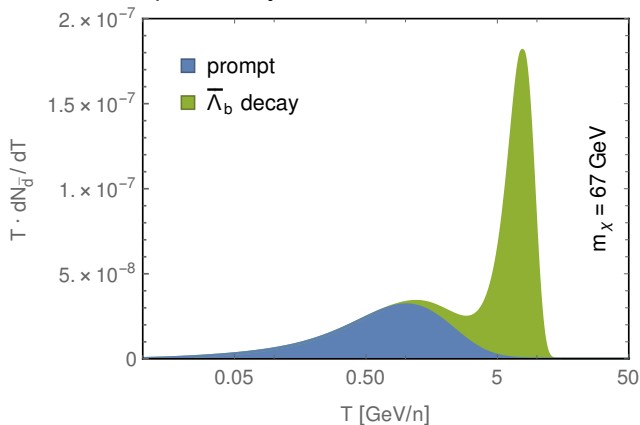
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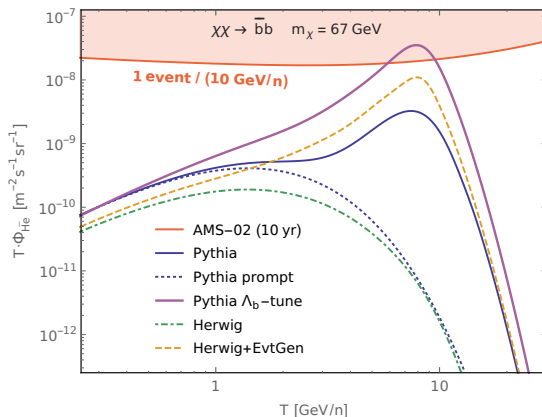
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- **no:**
 - ▶ Λ_b tune of Pythia is excluded
 - ▶ Pythia overestimates $\text{BR}(\Lambda_b \rightarrow \bar{u}du(ud_0))$