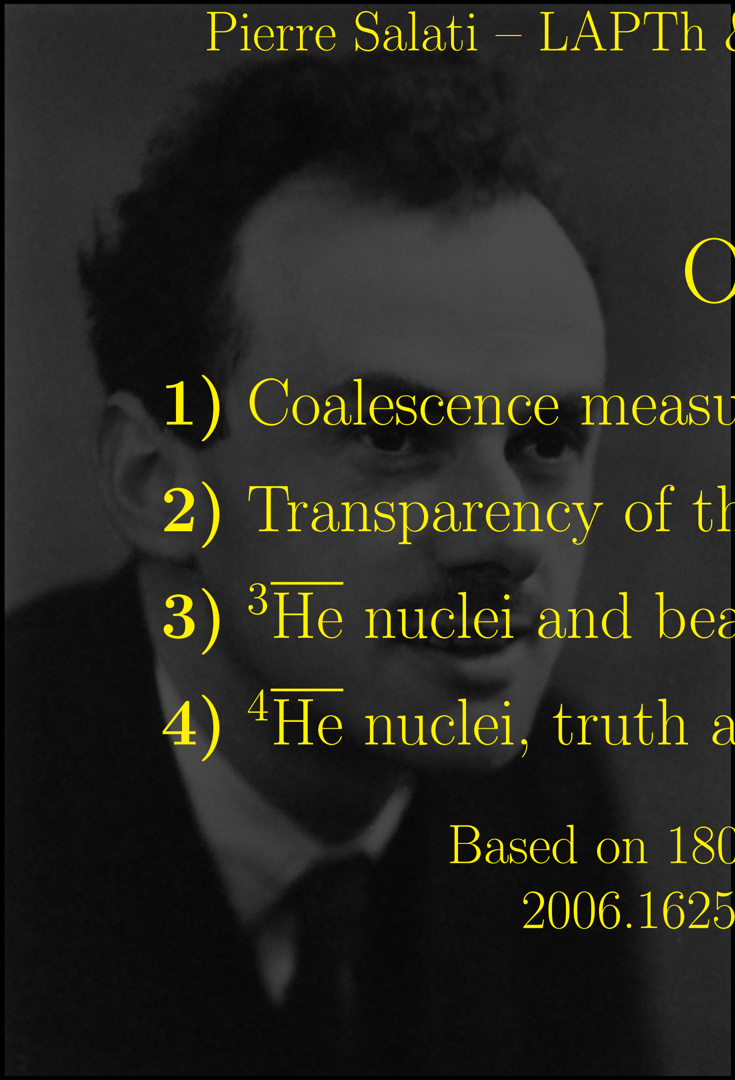
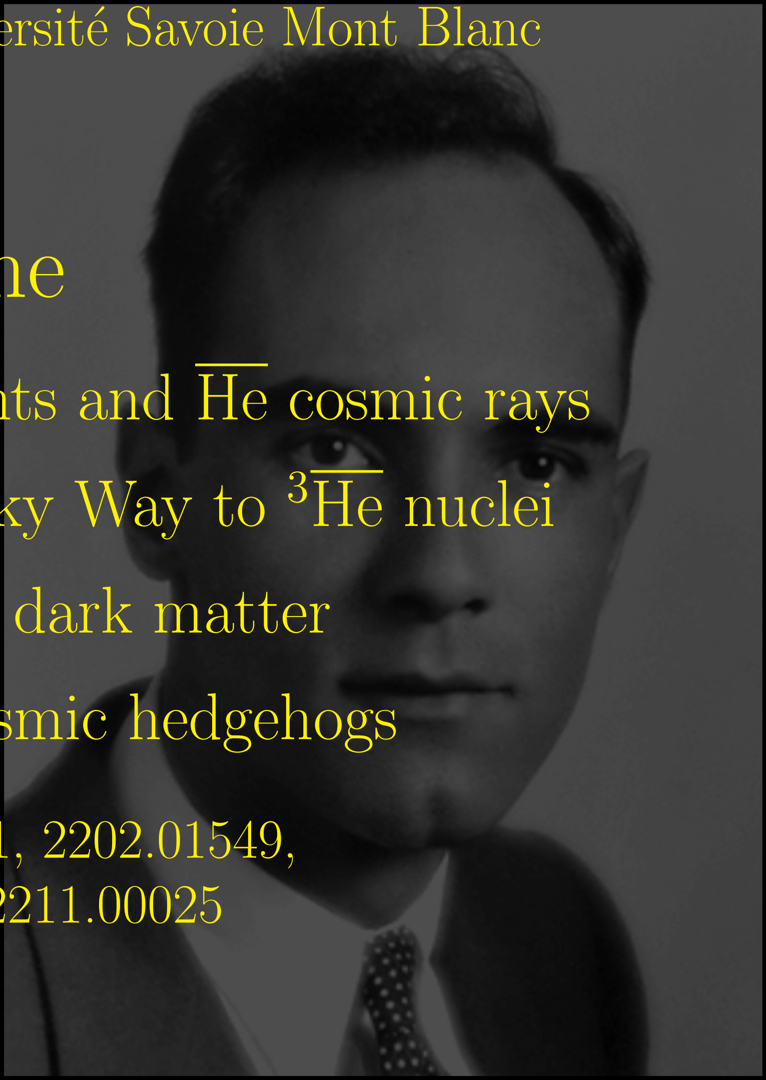
Valuable measurements for cosmic ray anti-nuclei

Pierre Salati – LAPTh & Université Savoie Mont Blanc





Outline

1) Coalescence measurements and $\overline{\mathrm{He}}$ cosmic rays

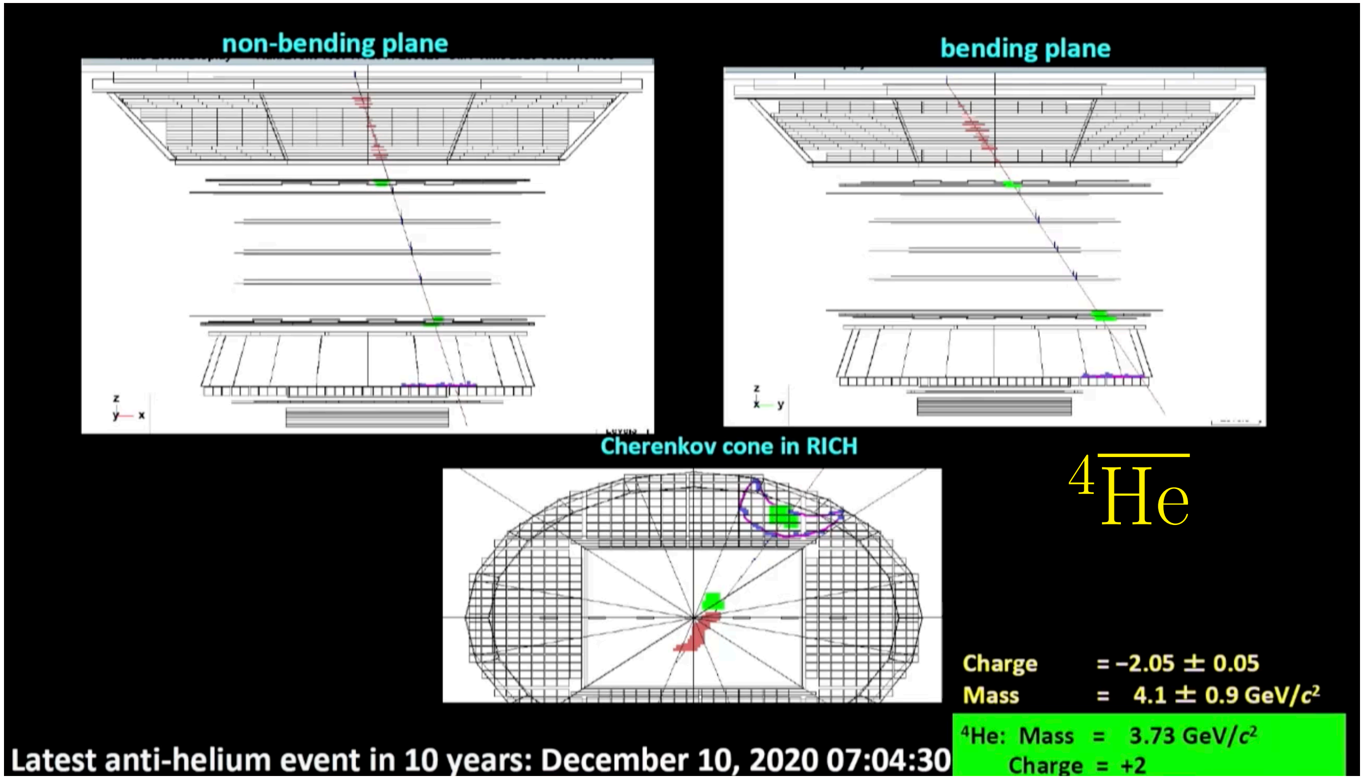
2) Transparency of the Milky Way to $^3\overline{\mathrm{He}}$ nuclei

3) $^3\overline{\mathrm{He}}$ nuclei and beautiful dark matter

4) $^4\overline{\mathrm{He}}$ nuclei, truth and cosmic hedgehogs

Based on 1808.08961, 2202.01549,
2006.16251 and 2211.00025

AMS-02 and possible anti-He events



V. Choutko, Cosmic Heavy Anti-Matter, COSPAR E1.3-05-22, July 17th 2022

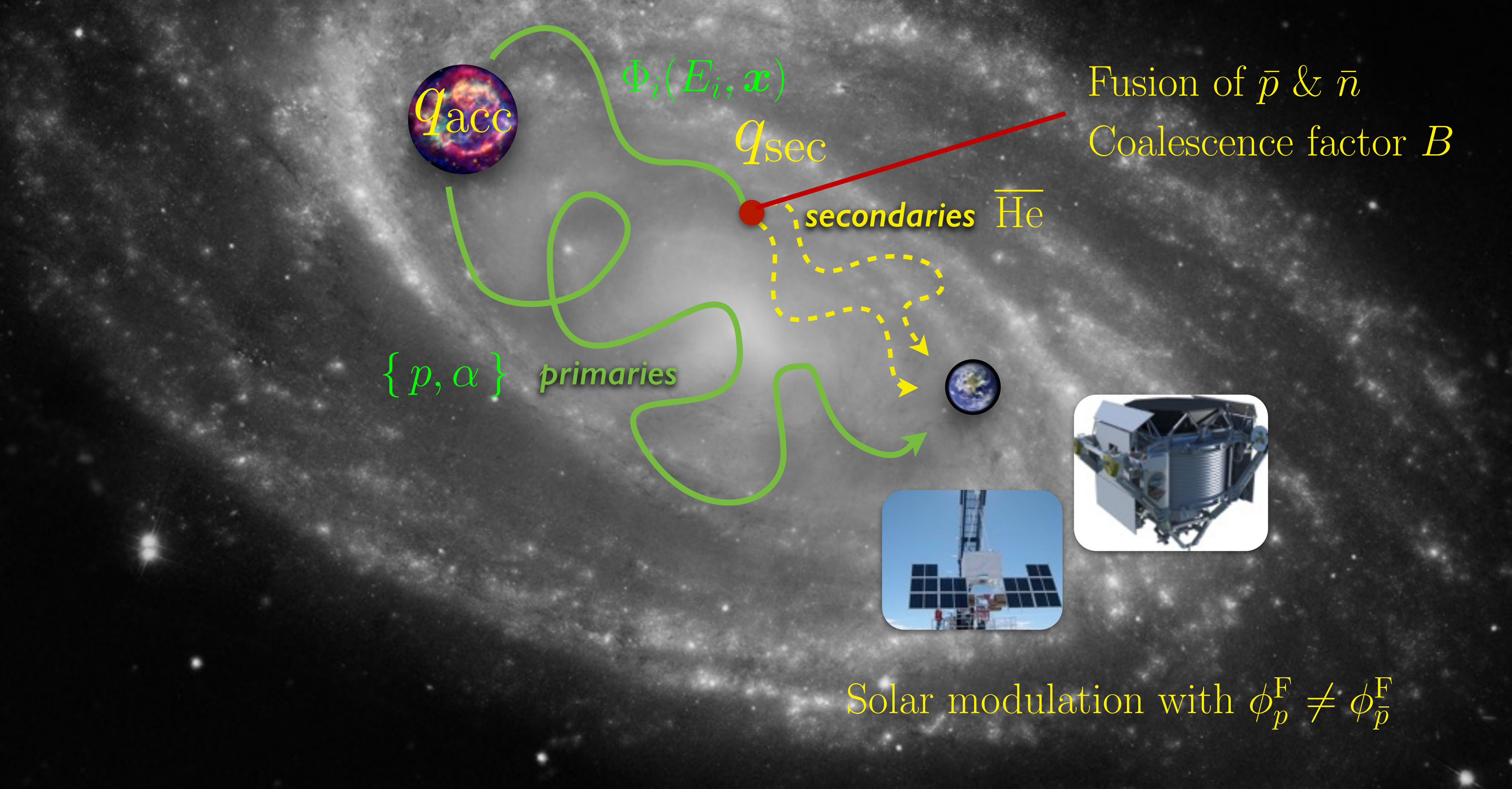
• AMS-02 has observed few events in the mass region from 0 to 10 GeV with charge $Z = -2$ and rigidity $\mathcal{R} < 50$ GV. The masses of all events are in the $^3\overline{\text{He}}$ and $^4\overline{\text{He}}$ mass region. As of 2018, 6 events $^3\overline{\text{He}}$ and 2 events $^4\overline{\text{He}}$.

• The event rate is 1 anti-helium in $\sim$ 100 million helium.

• Massive MC background simulations are carried out to evaluate significance. So far 35 billion He events simulated vs 6.8 billion He event triggers for 10 years. AMS-02 did not find background to the anti-helium events. At this level, the MC simulations are difficult to validate.

1) Coalescence measurements and $\overline{\mathrm{He}}$ cosmic rays

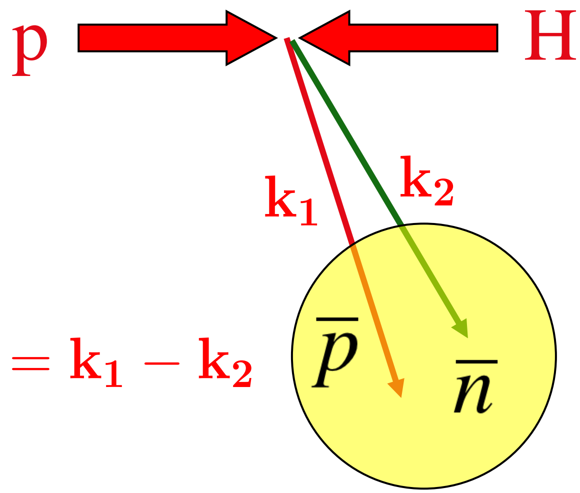
$$q_{\mathrm{sec}}(\overline{\mathrm{He}}\,|\,E_{\overline{\mathrm{He}}},\boldsymbol{x}) = \sum_{i\in \mathrm{p},\alpha}\ \sum_{j\in \mathrm{H},\mathrm{He}} 4\,\pi \int dE_i\ \Phi_i(E_i,\boldsymbol{x})\, n_j(\boldsymbol{x})\ \frac{d\sigma_{ij\to\overline{\mathrm{He}}}}{dE_{\overline{\mathrm{He}}}}(E_i,E_{\overline{\mathrm{He}}})$$



Courtesy Antje Putze, TeVPA 2015

Anti-helium production and the coalescence factor

coalescence $\equiv$ fusion of $\bar{p}$ & $\bar{n}$ into $\bar{d}$, $\overline{^3\mathrm{He}}$ or $\overline{^4\mathrm{He}}$



$2\boldsymbol{\Delta} = \mathbf{k_1} - \mathbf{k_2}$ $\quad$ $||\boldsymbol{\Delta}|| \leq p_0$

coalescence momentum $p_0 = p_{\rm coal}/2$

$$d^3\mathcal{N}_{\bar{d}}(\mathbf{K}) = \int d^6\mathcal{N}_{\bar{p},\bar{n}}\left\{\mathbf{k_1},\mathbf{k_2}\right\} \times \mathcal{C}(\boldsymbol{\Delta}) \;\; \text{where } \mathbf{K} = \mathbf{k_1} + \mathbf{k_2}$$

$$B_2 = \frac{E_{\bar{d}}}{E_{\bar{p}}\,E_{\bar{n}}} \int d^3\boldsymbol{\Delta}\; \mathcal{C}(\boldsymbol{\Delta}) \simeq \frac{m_{\bar{d}}}{m_{\bar{p}}\,m_{\bar{n}}} \left\{ \frac{4}{3}\pi\, p_0^3 \equiv \frac{\pi}{6}\, p_{\rm coal}^3 \right\}$$

Coalescence factor B_2

$$\frac{E_{\bar{d}}}{\sigma_{\rm in}}\frac{d^3\sigma_{\bar{d}}}{d^3\mathbf{K}} = B_2 \left\{ \frac{E_{\bar{p}}}{\sigma_{\rm in}}\frac{d^3\sigma_{\bar{p}}}{d^3\mathbf{k_1}} \right\} \left\{ \frac{E_{\bar{n}}}{\sigma_{\rm in}}\frac{d^3\sigma_{\bar{n}}}{d^3\mathbf{k_2}} \right\}$$

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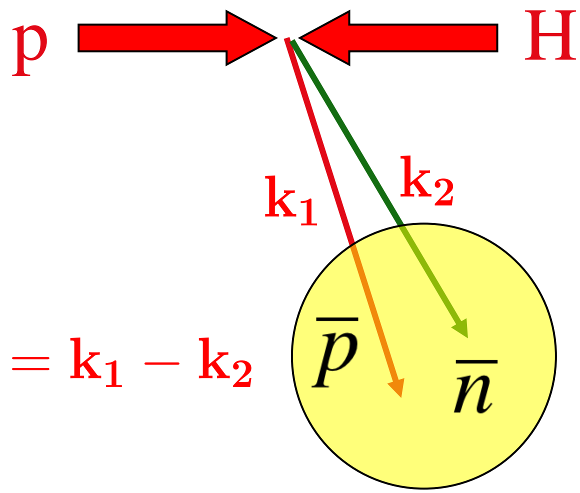


$$2\boldsymbol{\Delta} = \mathbf{k_1} - \mathbf{k_2} \qquad ||\boldsymbol{\Delta}|| \leq p_0$$

coalescence momentum $p_0 = p_{\mathrm{coal}}/2$

Production on anti-nuclei with mass A

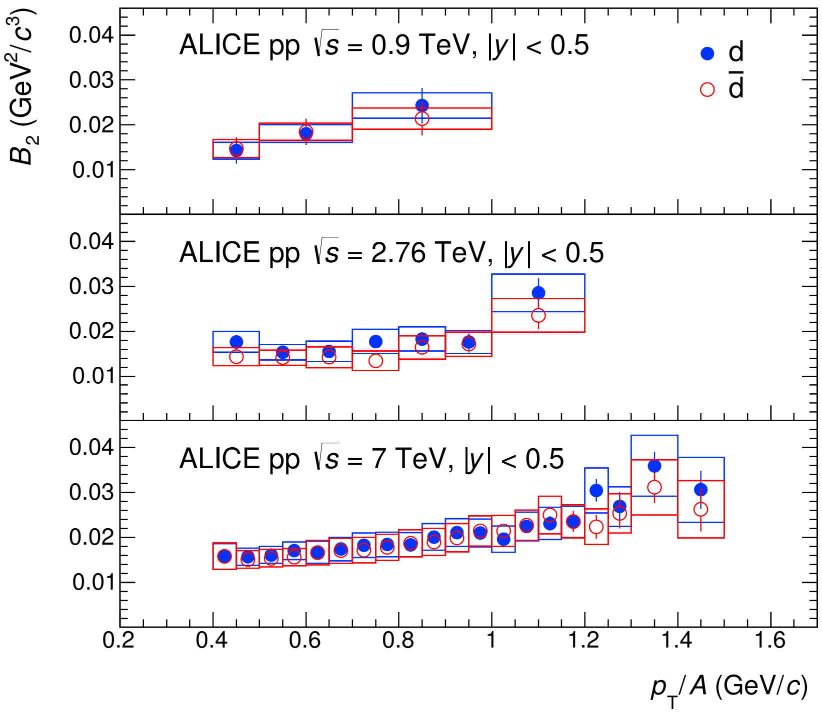
$$\frac{E_{\bar{A}}}{\sigma_{\mathrm{in}}} \frac{d^3\sigma_{\bar{A}}}{d^3\boldsymbol{k}_{\bar{A}}} = B_A \left\{ \frac{E_{\bar{p}}}{\sigma_{\mathrm{in}}} \frac{d^3\sigma_{\bar{p}}}{d^3\boldsymbol{k}_{\bar{p}}} \right\}^Z \left\{ \frac{E_{\bar{n}}}{\sigma_{\mathrm{in}}} \frac{d^3\sigma_{\bar{n}}}{d^3\boldsymbol{k}_{\bar{n}}} \right\}^{A-Z} \quad \text{with} \quad \boldsymbol{k}_{\bar{p}} = \boldsymbol{k}_{\bar{n}} = \boldsymbol{k}_{\bar{A}}/A$$

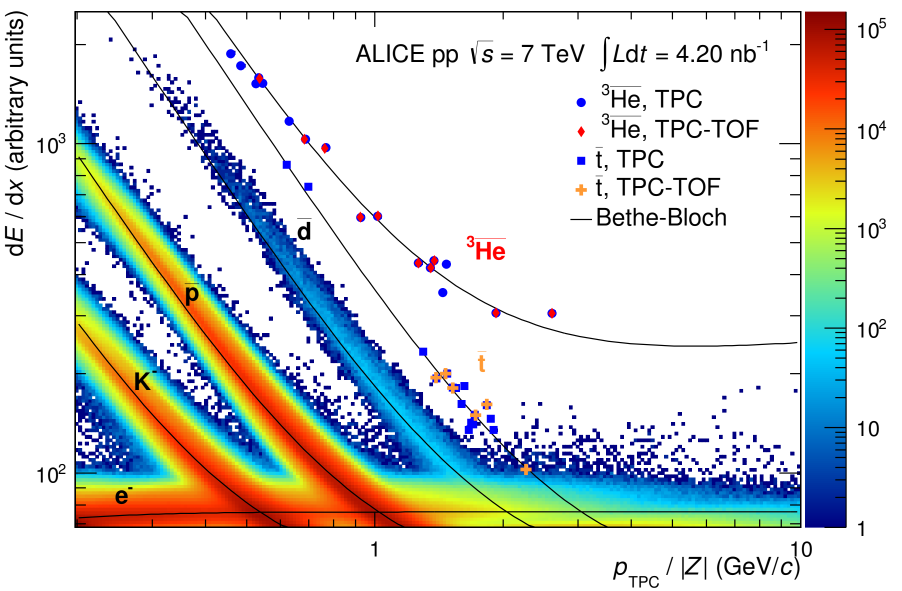
Coalescence factor B_A

$$B_A = \frac{m_A}{m_p^Z m_n^{A-Z}} \left\{ \frac{\pi}{6} p_{\mathrm{coal}}^3 \right\}^{A-1}$$

Determination of the coalescence momentum

- ALICE provides an **experimental** determination of B_2 and B_3.
  $\bar{p}$ production cross-section is **measured**.
  Approximately the same value for p_0 from $\bar{d}$, $\bar{t}$ and $^3\overline{\mathrm{He}}$.





S. Acharya et al., Phys. Rev. **C97** (2018) 024615

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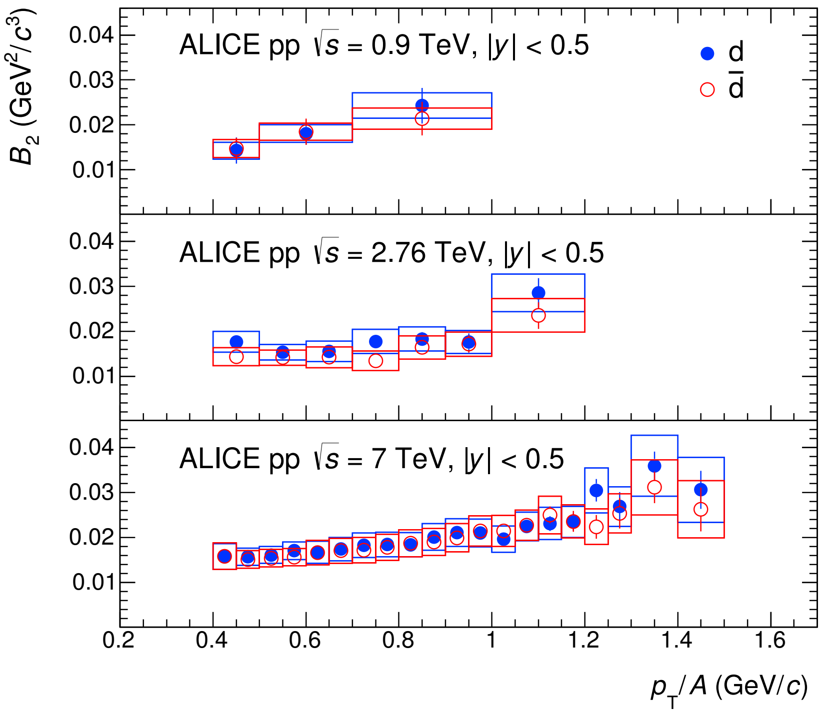
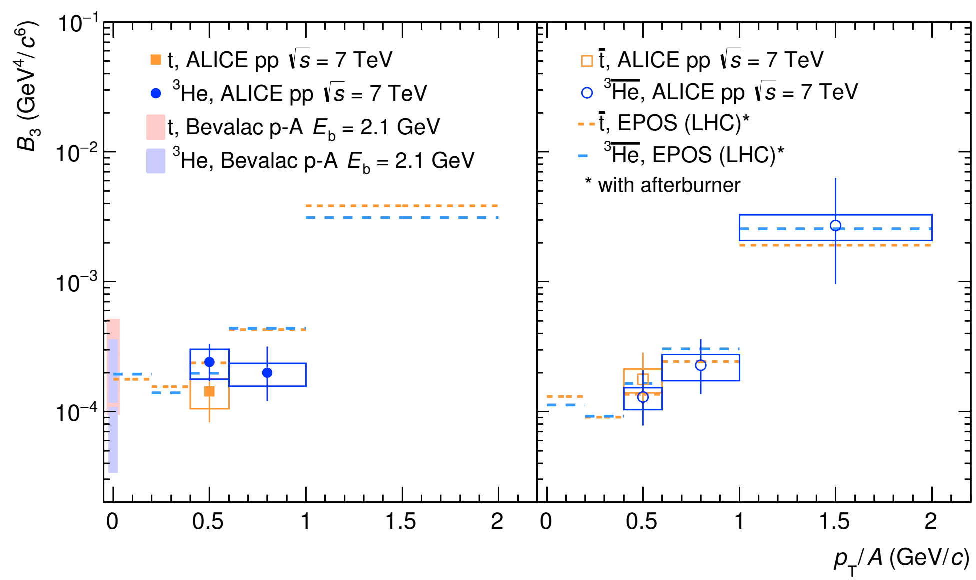


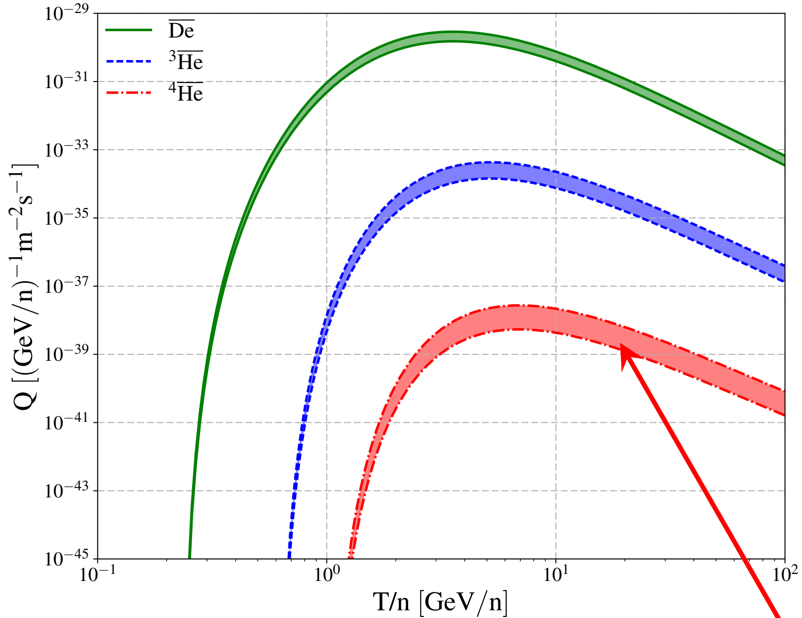


$208\ \mathrm{MeV} \leq p_{\mathrm{coal}} \leq 262\ \mathrm{MeV}$ $\qquad$ $218\ \mathrm{MeV} \leq p_{\mathrm{coal}} \leq 262\ \mathrm{MeV}$

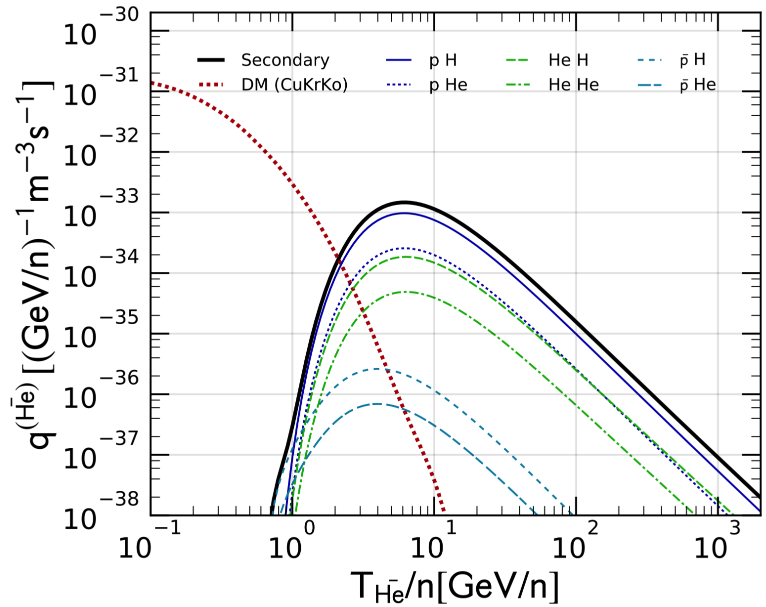
S. Acharya et al., Phys. Rev. **C97** (2018) 024615

Local source term for anti-nuclei production in cosmic-rays

$$q_{\rm sec}(\overline{\rm He}\,|\,E_{\overline{\rm He}},\boldsymbol{x}) = \sum_{i\in {\rm p},\alpha}\;\sum_{j\in {\rm H,He}} 4\pi\int dE_i\;\Phi_i(E_i,\boldsymbol{x})\,n_j(\boldsymbol{x})\,\frac{d\sigma_{ij\to\overline{\rm He}}}{dE_{\overline{\rm He}}}(E_i,E_{\overline{\rm He}})$$



V. Poulin et al., Phys. Rev. **D99** (2019) 023016

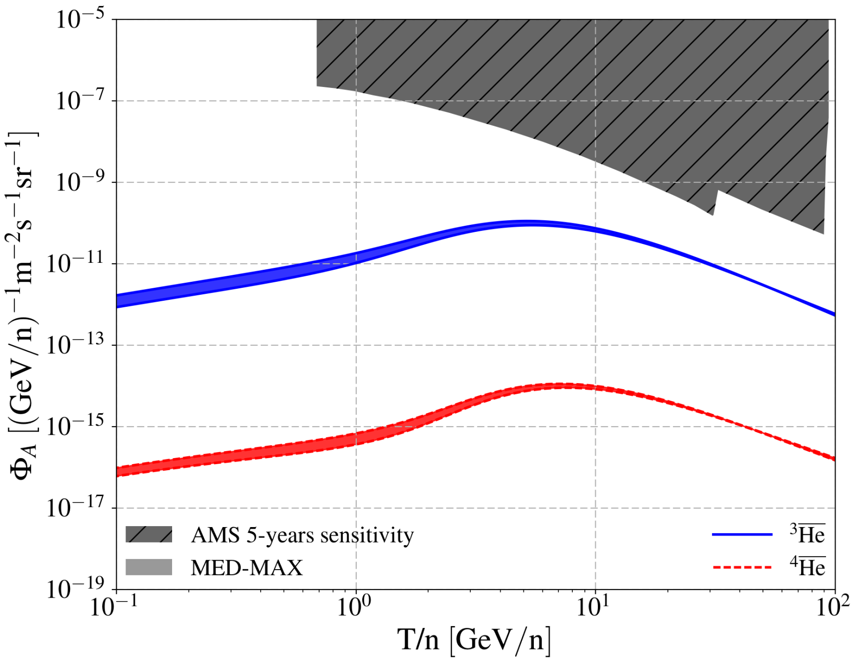


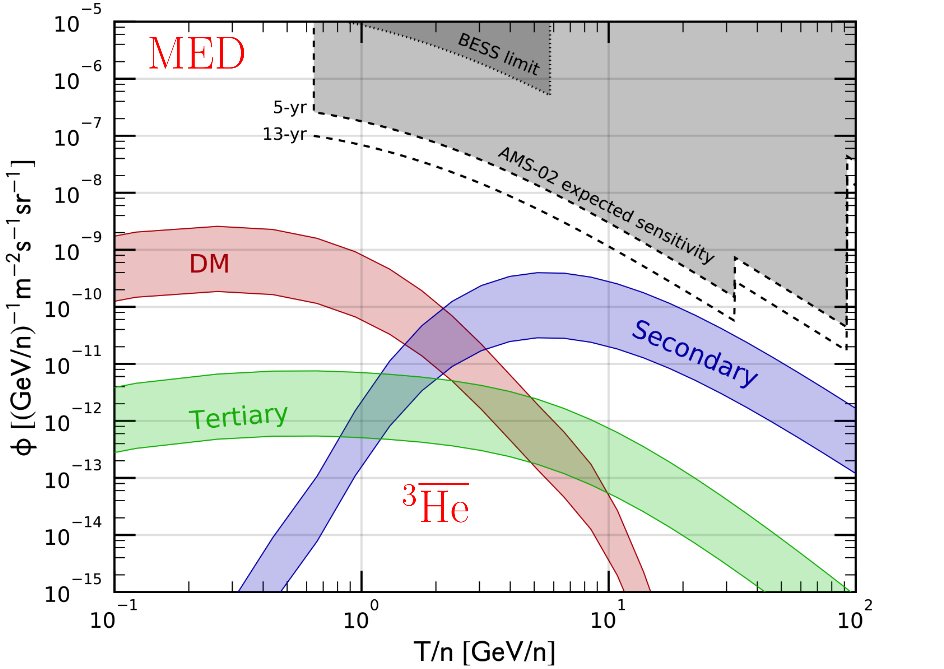
M. Korsmeier et al., Phys. Rev. **D97** (2018) 103011

$$7.7\times10^{-7} \leq \frac{B_4}{\rm GeV^6} \leq 3.9\times10^{-6}$$

$\bar{p}$ production modeled as in
M. di Mauro et al., Phys. Rev. **D90** (2014) 085017

Secondary anti-helium fluxes





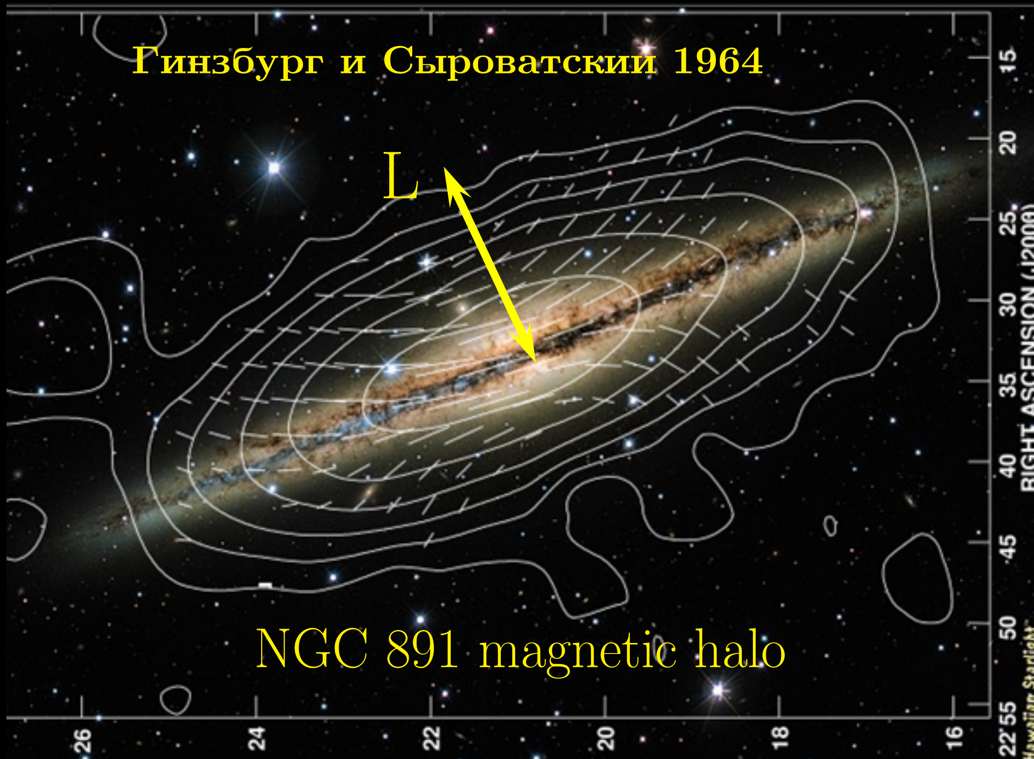
V. Poulin et al., Phys. Rev. **D99** (2019) 023016 M. Korsmeier et al., Phys. Rev. **D97** (2018) 103011

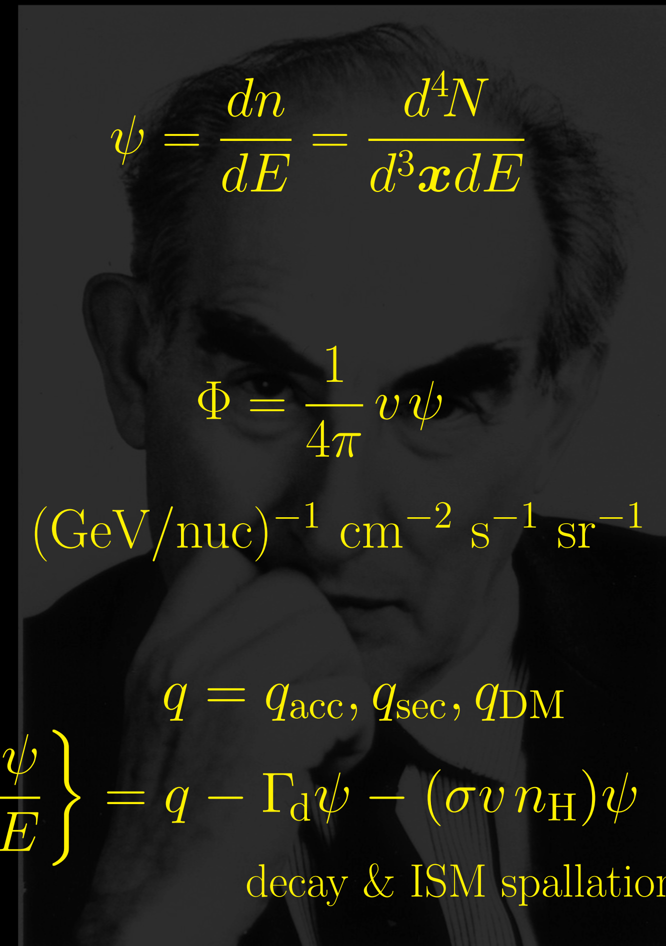
- Interactions of high-energy cosmic-ray protons and helium nuclei on the ISM yield a **secondary anti-He flux** well below AMS-02 sensitivity.

- The same conclusion holds for DM decays or annihilations although M. Winkler and T. Linden have proposed a nice counter-example based on $\bar{\Lambda}_b$ production if pure $^3\overline{\mathrm{He}}$ events – Winkler+[2006.16251].

- Very recently, M. Winkler, P. De La Torre Luque and T. Linden have proposed a scenario where DM is coupled to a dark QCD sector where dark pions decay into t-quarks – Winkler+[2211.00025]

2) Transparency of the Milky Way to $^3\overline{\mathrm{He}}$ nuclei





$$\psi = \frac{dn}{dE} = \frac{d^4N}{d^3\boldsymbol{x}\,dE}$$

$$\Phi = \frac{1}{4\pi} v\psi$$

$$(\mathrm{GeV/nuc})^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

$$q = q_{\mathrm{acc}}, q_{\mathrm{sec}}, q_{\mathrm{DM}}$$

$$\dot{\psi} + \boldsymbol{\nabla}\cdot\{-K\,\boldsymbol{\nabla}\psi + \psi\boldsymbol{V}_C\} + \frac{\partial}{\partial E}\left\{b\,\psi - D_{EE}\frac{\partial\psi}{\partial E}\right\} = q - \Gamma_{\mathrm{d}}\psi - (\sigma v\, n_{\mathrm{H}})\psi$$

convection

E losses

decay & ISM spallation

$\boldsymbol{x}$ diffusion

E diffusion

$$K = \beta^{\eta} K_0 \left\{1 + \left(\frac{R_{\mathrm{l}}}{R}\right)^{\frac{\delta-\delta_{\mathrm{l}}}{s_{\mathrm{l}}}}\right\}^{s_{\mathrm{l}}} \left(\frac{R}{1\,\mathrm{GV}}\right)^{\delta} \left\{1 + \left(\frac{R}{R_{\mathrm{h}}}\right)^{\frac{\delta-\delta_{\mathrm{h}}}{s_{\mathrm{h}}}}\right\}^{-s_{\mathrm{h}}}$$

$$D_{EE} = \frac{4}{3}\frac{\beta^2}{\delta(4-\delta^2)(4-\delta)}\frac{{V_a}^2 p^2}{K}$$

Typical timescales for Galactic CR propagation

- From $\tau_{\rm inel} = (\sigma_{\rm ine} v_{\rm CR} n_{\rm ISM})^{-1}$, $\tau_{\rm diff} = hL/K$ and $\tau_{\rm conv} = h/V_C$, we build the typical timescale for the disk

$$\frac{1}{\tau_{\rm disk}} = \frac{1}{\tau_{\rm inel}} + \frac{1}{\tau_{\rm conv}\left\{1 - e^{-\tau_{\rm diff}/\tau_{\rm conv}}\right\}}$$

- Energy losses and diffusive reacceleration are respectively associated to the timescales $\tau_{\rm loss} = T/|b|$ and $\tau_{\rm DR} = T^2/D_{\rm EE}$.

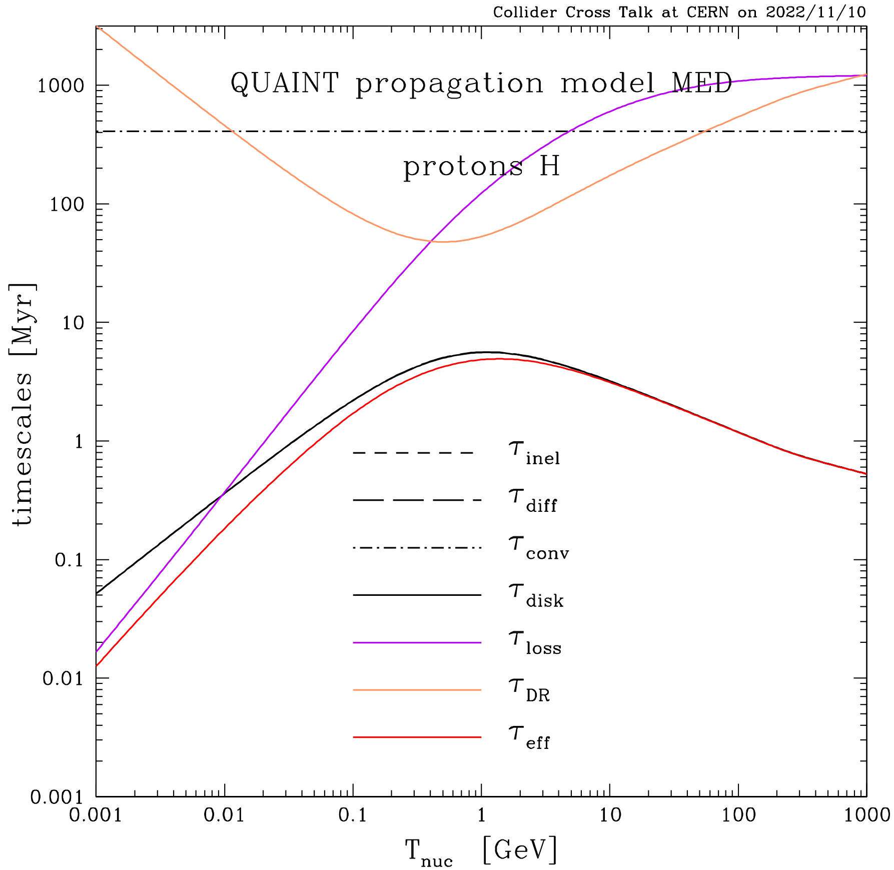


TABLE VI: Propagation parameters for the MIN, MED, and MAX configurations of the QUAINT models.

QUAINT	L [kpc]	δ	$\log_{10} K_0$ [kpc^2/Myr]	V_a [km/s]	V_c [km/s]	η
MAX	6.840	0.504	-1.092	83.929	0.469	-1.001
MED	4.080	0.451	-1.367	52.066	0.239	-2.156
MIN	2.630	0.403	-1.643	18.389	0.151	-3.412

Y. Génolini et al., Phys. Rev. **D104** (2021) 083005

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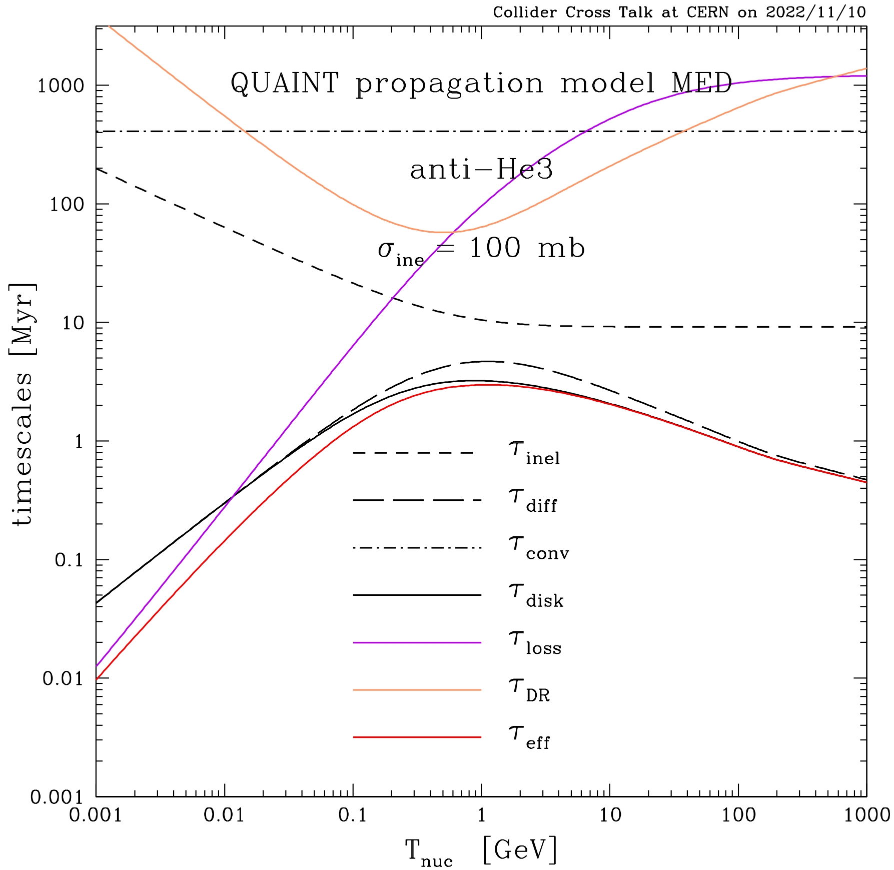

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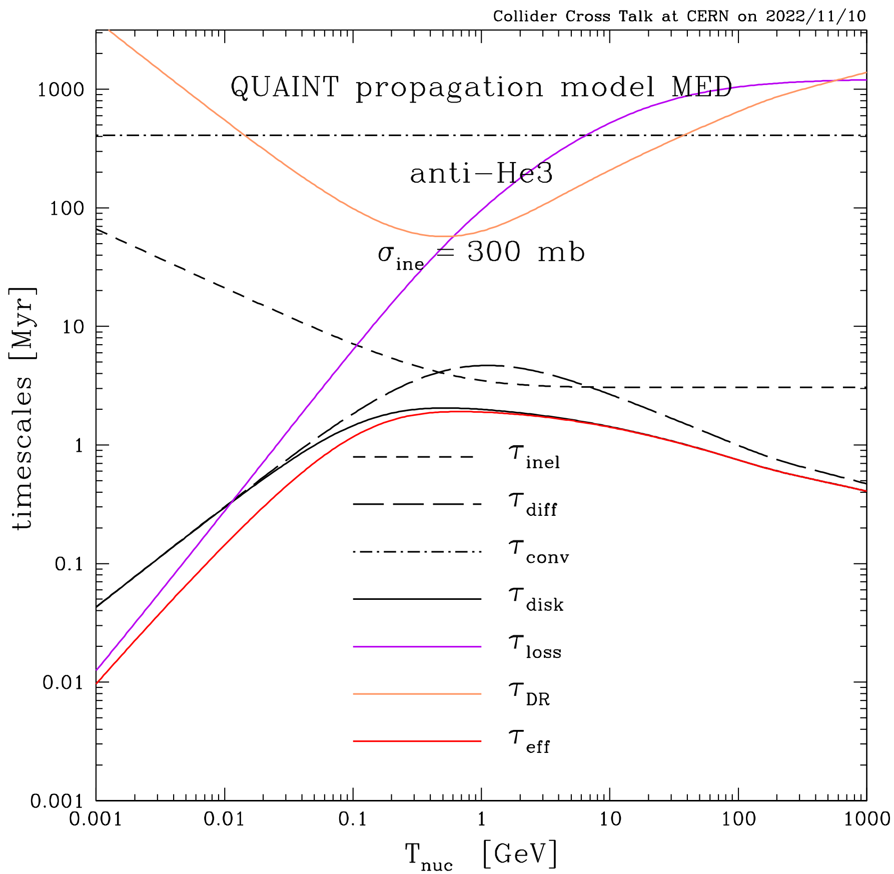

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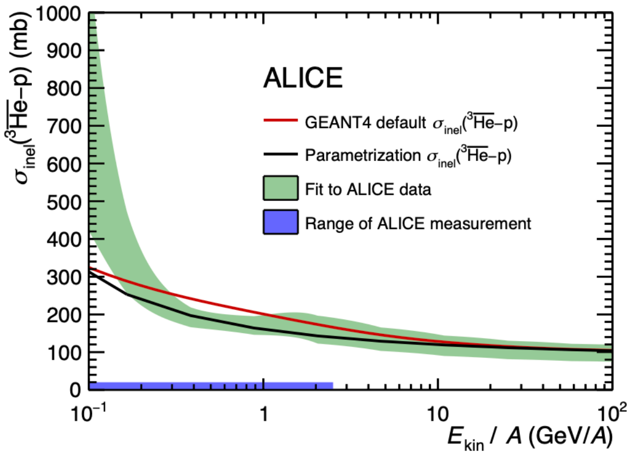
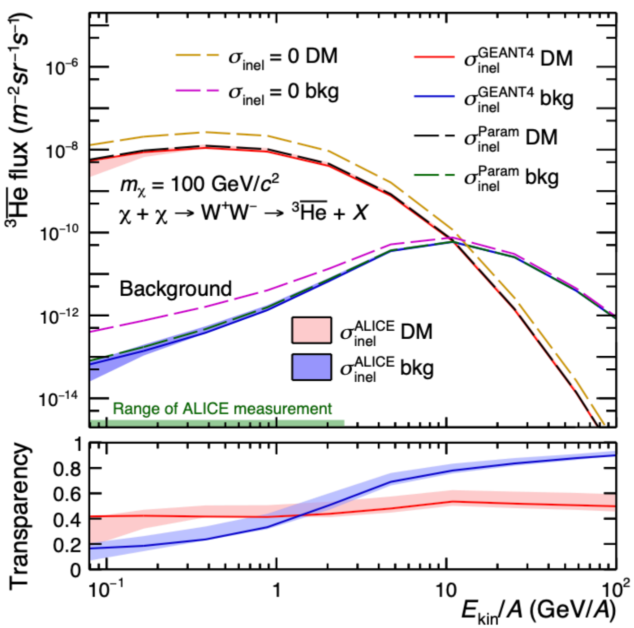
Y. Génolini et al., Phys. Rev. **D104** (2021) 083005

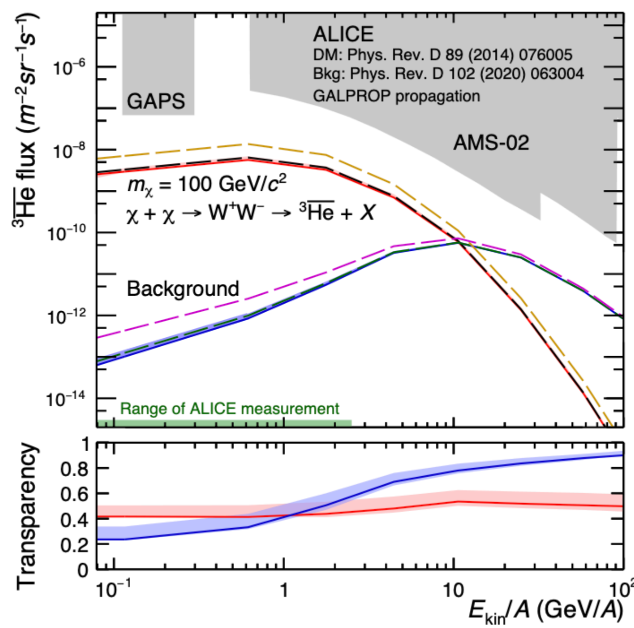
First measurement of the absorption of $^{3}\overline{\text{He}}$ nuclei in matter and impact on their propagation in the galaxy

arXiv:2202.01549 – ALICE Collaboration



$$\mathcal{T}_{\mathrm{MW}} = \frac{\tau_{\mathrm{disk}}(\sigma_{\mathrm{ine}} \neq 0)}{\tau_{\mathrm{disk}}(\sigma_{\mathrm{ine}} = 0)}$$



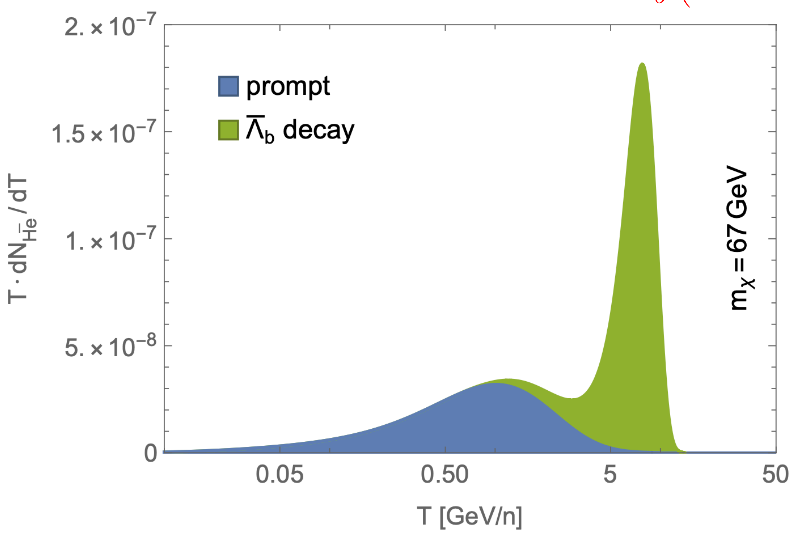


3) $^3\overline{\mathrm{He}}$ nuclei and beautiful dark matter

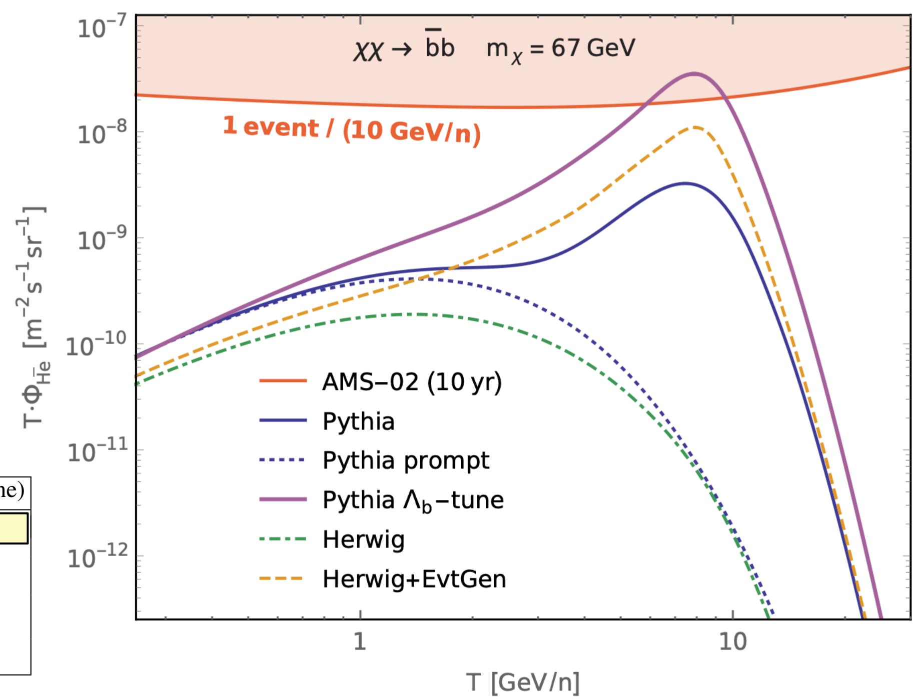
- In general, DM species annihilations do not produce a detectable amount of antihelium nuclei $^3\overline{\mathrm{He}}$.
- Since DM is at rest, the spectrum peaks at low energy $\neq \mathcal{O}(10)$ GeV/n.
- Recently, a new proposal based on DM coupling to b quarks.

$$\chi + \chi \to b + \bar{b} \qquad \bar{b} \to \bar{\Lambda}_b \text{ baryon } (\bar{b}\bar{u}\bar{d})$$

$$\bar{\Lambda}_b\,(5.6\ \text{GeV}) \to {}^3\overline{\mathrm{He}} + 2p\,(4.7\ \text{GeV})$$



experiment	channel	measurement	Pythia (default)	Pythia (Λ_b-tune)
LEP [4, 5]	$f(b \to \Lambda_b)$	$0.101^{+0.039}_{-0.031}$	0.037	0.101
LEP [6]	$f(b \to \Lambda_b, \Xi_b, \Omega_b)$	0.117 ± 0.021	0.047	0.127
Tevatron CDF [7]	$\frac{f(b\to\Lambda_b)}{f(b\to B)}$	$0.281^{+0.141}_{-0.103}$	0.046	0.135
LHCb [8]	$\frac{f(b\to\Lambda_b)}{f(b\to B)}$	0.259 ± 0.018	0.048	0.134



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

Counterarguments – Kachelriess+[2105.00799]

- To get the value of $f(b \to \Lambda_b)$ measured at LEP, WL21 have increased the probability `probQQtoQ` for diquark formation in hadronization from 0.09 to 0.24, playing havoc with other processes.

- This implies:
(i) an over production of protons and antiprotons at LEP by a factor of 2,
(ii) an increase in proton yield with respect to kaon and pion yields $dN/dy|_{|y|<0.5}$ measured by ALICE at LHC.

- In default Pythia, $\mathrm{Br}(\bar{\Lambda}_b \to \overline{^3\mathrm{He}}) \simeq 3 \times 10^{-6}$ may already be too large. Default Pythia overestimates branching ratios for several Λ_b decay channels. Mismodeling of diquark formation.

$\sqrt{s}$	≈ 10 GeV	29–35 GeV	91 GeV	130–200 GeV
Obs.	0.266 ± 0.008	0.640 ± 0.050	1.050 ± 0.032	1.41 ± 0.18
WL21	0.640	1.161	2.102	2.33

p and $\bar{p}$ multiplicity in e^+e^- annihilations

Particle	proton	kaon	pion
dN/dy, LHC	0.124 ± 0.009	0.286 ± 0.016	2.26 ± 0.10
dN/dy, Λ_b tune	0.328	0.231	1.90

dN/dy at mid-rapidity $|y| < 0.5$
at LHC at $\sqrt{s} = 7$ TeV for p, K^+ and π^+

Branching ratio	PDG	Pythia
$\Lambda_b \to \Lambda_c^+ p\bar{p}\pi^-$	2.65×10^{-4}	1.5×10^{-3}
$\Lambda_b \to \Lambda_c^+ \pi^+\pi^-\pi^-$	7.7×10^{-3}	0.047
$\Lambda_b \to \Lambda\pi^+\pi^-$	4.7×10^{-6}	2.0×10^{-5}
$\Lambda_b \to p\pi^-\pi^+\pi^-$	2.11×10^{-5}	9.6×10^{-5}
$\Lambda_b \to pK^-K^+\pi^-$	4.1×10^{-6}	1.7×10^{-5}
$B^0 \to p\bar{p}K^0$	2.66×10^{-6}	6.1×10^{-6}
$B^0 \to p\bar{p}\pi^+\pi^-$	2.87×10^{-6}	5.6×10^{-6}
$B^0 \to \Lambda_c^- p\pi^+\pi^-$	1.02×10^{-3}	2.1×10^{-3}
$\Lambda_c \to p\pi^+\pi^-$	4.61×10^{-3}	0.012
$\Lambda_c \to p\pi^0$	$< 2.7 \times 10^{-4}$	2.0×10^{-3}
$\Lambda_c \to \Lambda K^+\pi^+\pi^-$	$< 5 \times 10^{-4}$	2.1×10^{-3}

Let us measure $\mathrm{Br}(\bar{\Lambda}_b \to \overline{^3\mathrm{He}})$ and see!

4) $^4\overline{\mathrm{He}}$ nuclei, truth and cosmic hedgehogs

Production on anti-nuclei with mass A

$$\frac{E_{\bar{A}}}{\sigma_{\rm in}}\frac{d^3\sigma_{\bar{A}}}{d^3\boldsymbol{k}_{\bar{A}}} = B_A \left\{\frac{E_{\bar{p}}}{\sigma_{\rm in}}\frac{d^3\sigma_{\bar{p}}}{d^3\boldsymbol{k}_{\bar{p}}}\right\}^Z \left\{\frac{E_{\bar{n}}}{\sigma_{\rm in}}\frac{d^3\sigma_{\bar{n}}}{d^3\boldsymbol{k}_{\bar{n}}}\right\}^{A-Z} \quad \text{with} \quad \boldsymbol{k}_{\bar{p}} = \boldsymbol{k}_{\bar{n}} = \boldsymbol{k}_{\bar{A}}/A$$

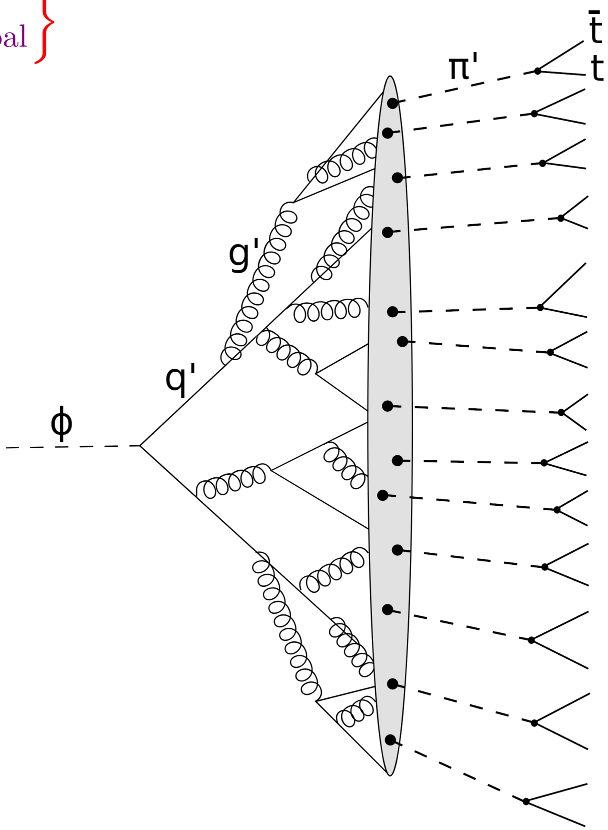
Coalescence factor B_A

$$B_A = \frac{m_A}{m_p^Z m_n^{A-Z}} \left\{\frac{\pi}{6}\, p_{\rm coal}^3\right\}^{A-1}$$

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{\bar{\rm p}} \frac{d^3 N_{\bar{\rm p}}}{dp_{\bar{\rm p}}^3}\right)^Z \left(E_{\bar{\rm n}} \frac{d^3 N_{\bar{\rm n}}}{dp_{\bar{\rm n}}^3}\right)^{A-Z}$$

$$\chi\chi \to hh \to 2\bar{b}b \to \mathcal{O}(100)\ \pi$$

$$\chi\chi \to \phi\phi \to 2\bar{q}' q' \to N_{\pi'}\ \pi' \to N_{\pi'}\ \bar{t}t$$



M. Winkler, P. De La Torre Luque and T. Linden, arXiv:2211.00025

4) ${}^{4}\overline{\mathrm{He}}$ nuclei, truth and cosmic hedgehogs

Production on anti-nuclei with mass A

$$\frac{E_{\bar{A}}}{\sigma_{\rm in}} \frac{d^3\sigma_{\bar{A}}}{d^3\boldsymbol{k}_{\bar{A}}} = B_A \left\{ \frac{E_{\bar{p}}}{\sigma_{\rm in}} \frac{d^3\sigma_{\bar{p}}}{d^3\boldsymbol{k}_{\bar{p}}} \right\}^{Z} \left\{ \frac{E_{\bar{n}}}{\sigma_{\rm in}} \frac{d^3\sigma_{\bar{n}}}{d^3\boldsymbol{k}_{\bar{n}}} \right\}^{A-Z} \quad \text{with} \quad \boldsymbol{k}_{\bar{p}} = \boldsymbol{k}_{\bar{n}} = \boldsymbol{k}_{\bar{A}}/A$$

Coalescence factor B_A

$$B_A = \frac{m_A}{m_p^Z m_n^{A-Z}} \left\{ \frac{\pi}{6} \, p_{\rm coal}^3 \right\}^{A-1}$$

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{\bar{\rm p}} \frac{d^3 N_{\bar{\rm p}}}{dp_{\bar{\rm p}}^3} \right)^{Z} \left(E_{\bar{\rm n}} \frac{d^3 N_{\bar{\rm n}}}{dp_{\bar{\rm n}}^3} \right)^{A-Z}$$

$$\chi\chi \to hh \to 2\bar{b}b \to \mathcal{O}(100)\,\pi$$

$$\chi\chi \to \phi\phi \to 2\bar{q}'q' \to N_{\pi'}\,\pi' \to N_{\pi'}\,\bar{t}t$$

$$\phi \to 2\varphi_1 \to 4\varphi_2 \to \ldots 2^n\varphi_n \to 2^{n+1}\pi' \to 2^{n+1}\bar{t}t$$

M. Winkler, P. De La Torre Luque and T. Linden, arXiv:2211.00025

Benchmark models for enhanced $^4\overline{\text{He}}$ production

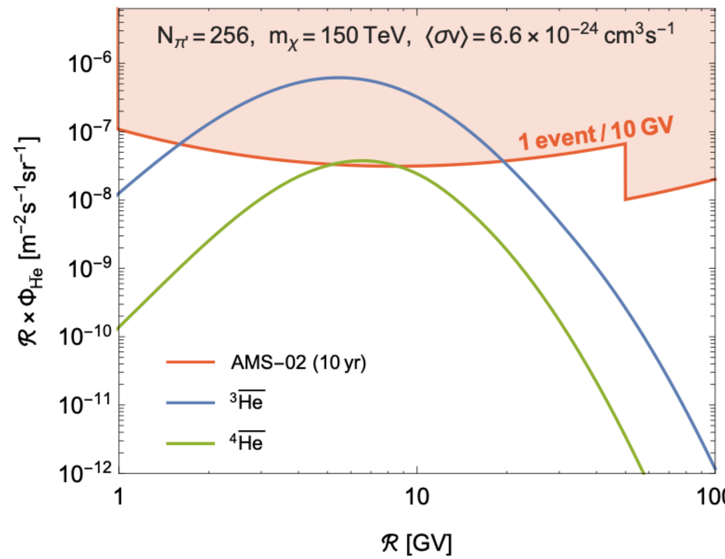
DM type	Annihilating	Decaying
Input Parameters		
m_χ [TeV]	150	5000
m_ϕ [TeV]	50.4	375
$m_{\pi'}$ [GeV]	380	700
$N_{\pi'}$	256	1024
$\langle\sigma v\rangle$ [cm^{3}s^{-1}]	6.6×10^{-24}	–
Γ [s^{-1}]	–	9×10^{-30}
Antinuclei Events at AMS-02		
$^3\overline{\text{He}}$	15.6	20.3
$^4\overline{\text{He}}$	1.0	3.1
$\bar{\text{d}}$	19.3	1.2
Antinuclei Events at GAPS		
$\bar{\text{d}}$	0.7	0

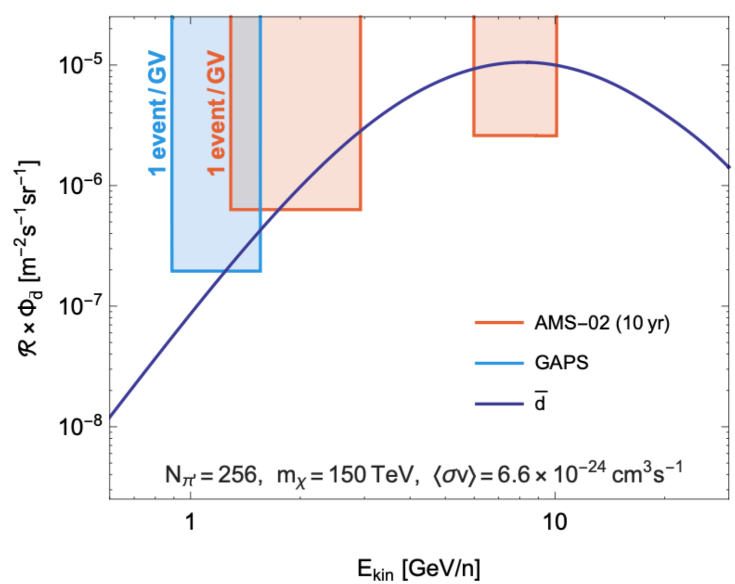
TABLE I. Input parameters of one annihilating and one decaying DM benchmark scenario. Also given are the predicted antihelium and antideuteron event numbers at AMS-02 (per ten years) and GAPS.

$$\bar{\text{p}} : \bar{\text{d}} : {}^3\overline{\text{He}} : {}^4\overline{\text{He}} = 3\times10^4 : 3\times10^2 : 18 : 1$$

instead of the conventional ratios

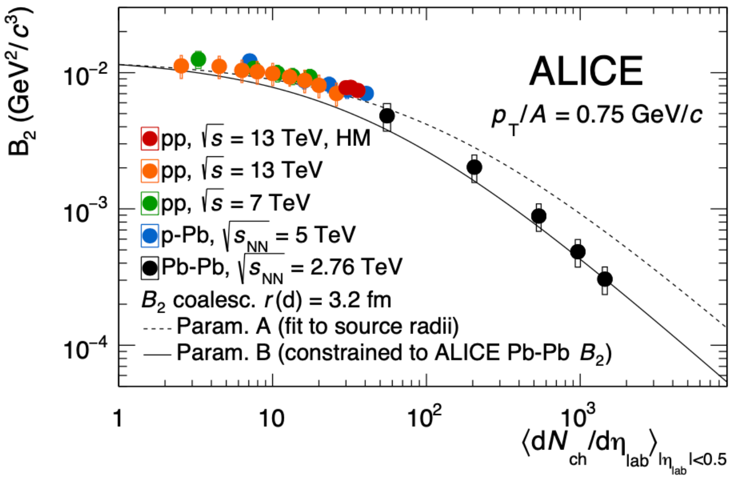
$$\bar{\text{p}} : \bar{\text{d}} : {}^3\overline{\text{He}} : {}^4\overline{\text{He}} = 10^{10} : 10^7 : 10^4 : 1$$



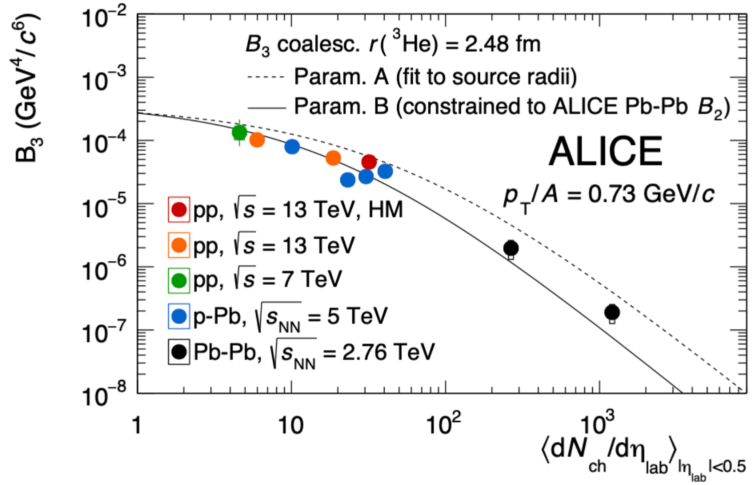


M. Winkler, P. De La Torre Luque and T. Linden, arXiv:2211.00025

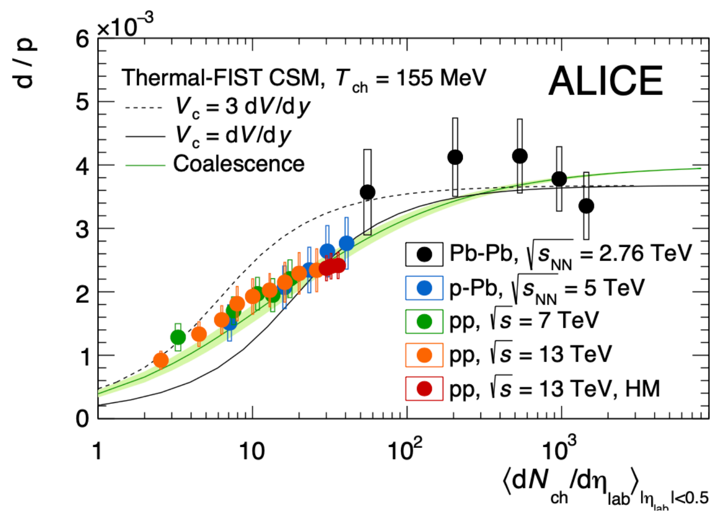
The message from heavy ion collisions



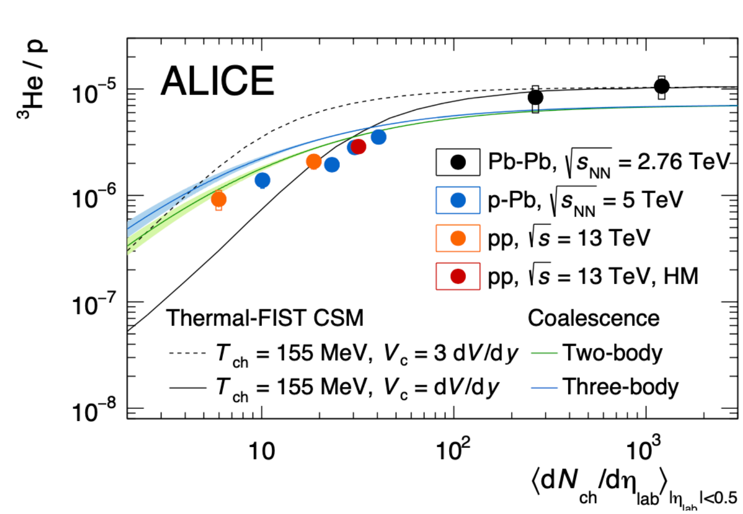
(a) (Anti)deuterons



(b) (Anti)helions



(a) (Anti)deuterons



(b) (Anti)helions

The conventional hierarchy is not much modified when the multiplicity increases

S. Acharya et al., JHEP **01** (2022) 106

Takeaway

- Anti-helium-3 and anti-helium-4 candidates may have been identified by AMS-02.
  Massive background simulations are carried out to evaluate significance.
  No $\overline{\mathrm{He}}$ found but MC simulations are difficult to validate.

- $^3\overline{\mathrm{He}}$ events
  Unless CR propagation and coalescence are very different from expected,
  AMS-02 should **not** see secondary CR $^3\overline{\mathrm{He}}$.
  Interesting possibility from DM annihilating into $\bar{\Lambda}_b$ baryons.
  The branching ratio $\mathrm{Br}(\bar{\Lambda}_b \to \overline{^3\mathrm{He}})$ is a measurement of great importance.

- $^4\overline{\mathrm{He}}$ events
  There is no hope to detect a single event from CR spallation.
  Heavy ion collisions jeopardize Winkler et al. proposal of a dark QCD sector.
  If confirmed, a single $^4\overline{\mathrm{He}}$ would be a major discovery.

- Observation of $^3\overline{\mathrm{He}}$ and $^4\overline{\mathrm{He}}$ events would imply a drastic revision of cosmology and would request a more fundamental theory than the standard model of particle physics. A few routes have already been explored.

Thanks for your attention