Antinuclei as a signature of dark matter

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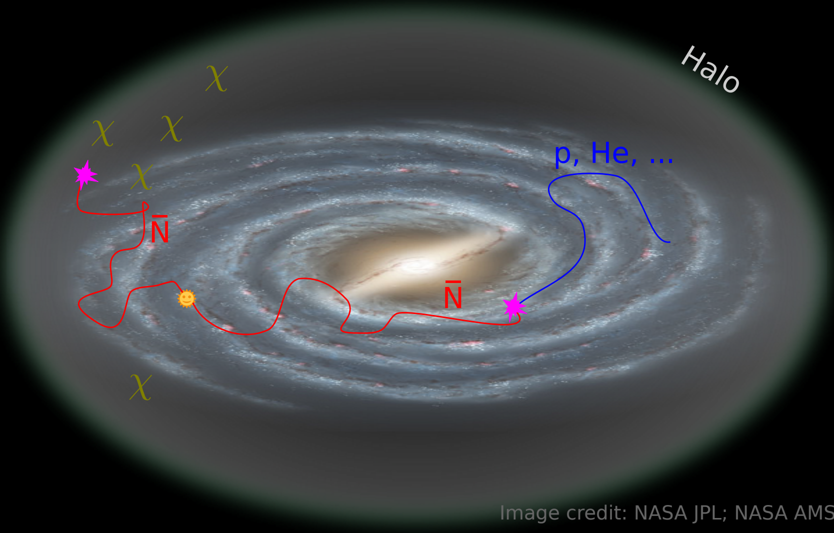
Content

Antinuclei as a signature of dark matter



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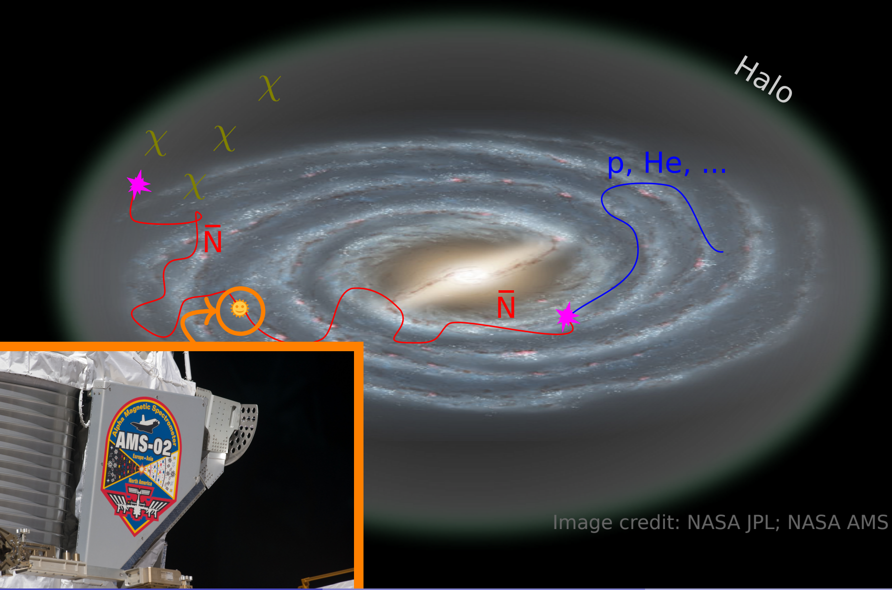
Antinuclei as a signature of dark matter



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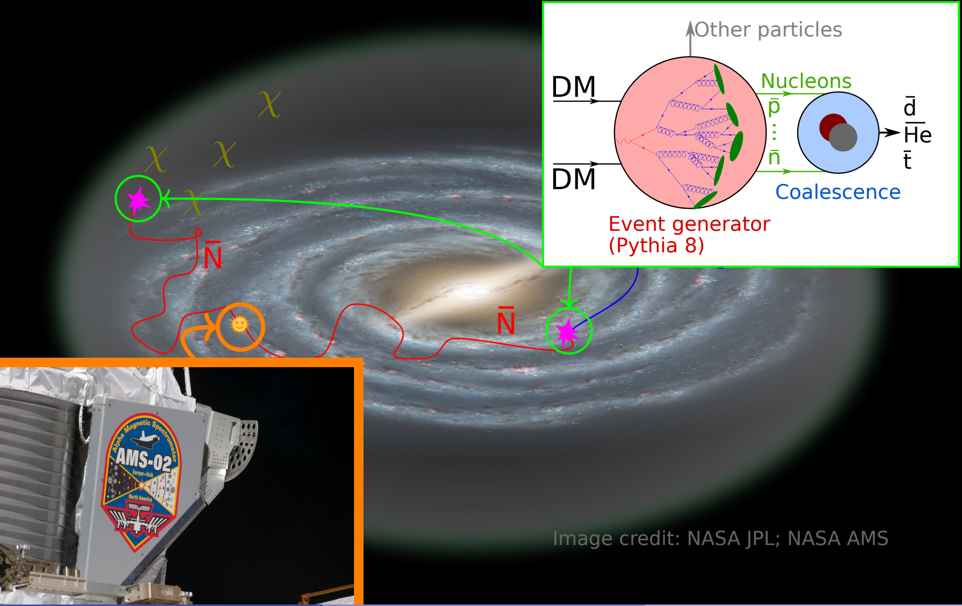

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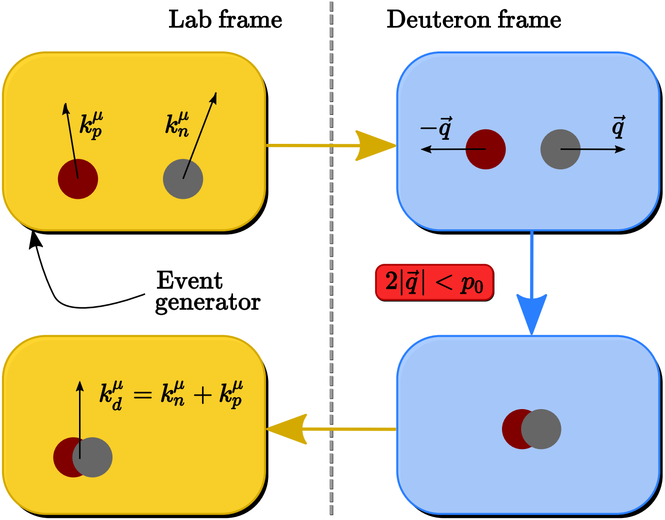
The coalescence model in momentum space



The new coalescence model

Based on M. Kachelriess, S. Ostapchenko & J. Tjemsland (2019) [arXiv:1905.01192]

Deuteron formation model (yield in lab frame)

$$\frac{\mathrm{d}^3 N_d}{\mathrm{d}P_d^3} = \frac{1}{\gamma}\frac{3\zeta}{(2\pi)^3}\int \frac{\mathrm{d}^3 q}{(2\pi)^3}\mathrm{e}^{-q^2 d^2} G_{np}(\vec{q}, -\vec{q}),$$

$$\zeta \equiv \left(\frac{d^2}{d^2 + 4\sigma^2}\right)^{3/2} \leq 1.$$

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- Spatial distribution of the hadronisation $\sigma \sim 5\ \mathrm{GeV}^{-1}$ process dependent
- Size of the deuteron $d = 3.2\ \mathrm{fm} = 16\ \mathrm{GeV}^{-1}$ (Zhaba 2017)
- Two-nucleon momentum distribution from the event generator

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$$\boxed{\zeta \equiv \left(\frac{d^2}{d^2+4\sigma^2}\right)^{3/2}} \leq 1.$$

connected to the hadronisation process

$$\Rightarrow \zeta = \frac{d^2}{d^2+4\sigma^2/(\cos^2\theta+\gamma^2\sin^2\theta)}\sqrt{\frac{d^2}{d^2+4\sigma^2}};$$

$$\sigma_{pp} = 7\ \mathrm{GeV}^{-1} = \sqrt{2}\sigma_{e^\pm}$$

Comparison with experimental data

We have considered mainly two experiments:

- pp collisions at $\sqrt{s} = 0.9, 2.76$ and $7\ \mathrm{TeV}$ (Acharya 2018).
- e^+e^- annihilations at the Z resonance (Schael 2006).

Results

- $\sigma_{pp} = (7.6 \pm 0.1)\ \mathrm{GeV}^{-1} = \sqrt{2}(5.4 \pm 0.1)\ \mathrm{GeV}^{-1}$
- $\sigma_{e^\pm} = 5.3^{+1.0}_{-0.6}\ \mathrm{GeV}^{-1}$

Comparison with experimental data

We have cons

- pp collisi
- e^+e^- an

Agrees well with the physical interpretation:

$$\sigma_{pp} \sim 7\ \mathrm{GeV}^{-1}$$
$$\sigma_{e^\pm} \sim 5\ \mathrm{GeV}^{-1}$$

Results

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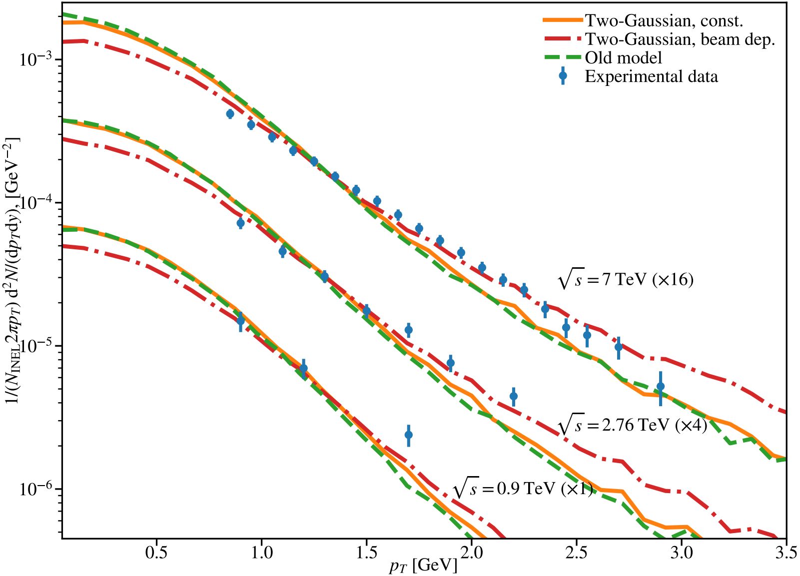
Best fits to the antideuteron production in *pp* collisions



Work in progress

Proton-nucleus collisions

$$\sigma_\perp^2 = \sigma_{e^\pm}^2 + \frac{2R_A^2 R_p^2}{R_A^2 + R_p^2}; \qquad \sigma_\parallel^2 = \sigma_{e^\pm}^2 + R_A^2$$

$$\sigma_{e^\pm} \sim a_0; \qquad R_A \sim a_0 A^{1/3}; \qquad R_p \sim a_0$$

$a_0 \sim 1\ \mathrm{fm}$ free parameter

Work in progress

Proto

$a_0 \sim$

Experiment	a_0 [fm]	$\chi^2/(N-1)$	Ref.
pBe 200 GeV	1.14	2.2/4	Bozzoli et al. 1978
pAl 200 GeV	1.02	2.3/2	Bozzoli et al. 1978
pp 7 TeV	1.10	34/19	Acharya 2018
pp 2.76 TeV	1.31	5.6/6	Acharya 2018
pp 900 GeV	1.19	0.3/2	Acharya 2018
e^+e^- 91 GeV*	$1.15^{+0.27}_{-0.22}$	-	Schael 2006; Akers 1995

Event generator:
QGSJET II-04m (Ostapchenko 2011; Kachelriess et al. 2015)
*Pythia 8.230 (Sjöstrand et al. 2015; Sjostrand et al. 2006)

Propagation

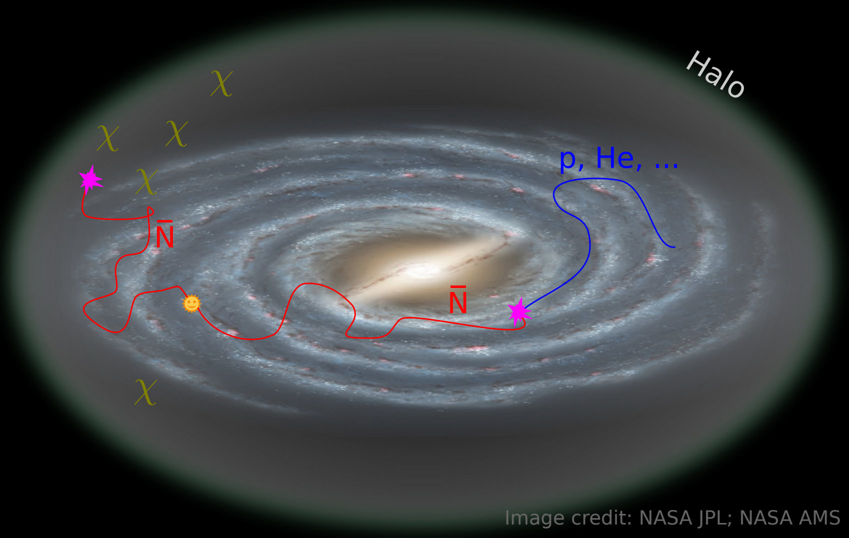
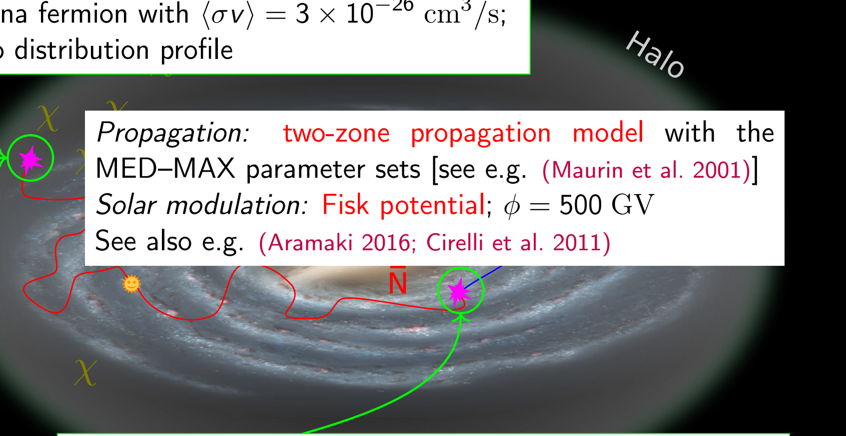


Image credit: NASA JPL; NASA AMS



$$Q(\vec{r}, T) = \frac{1}{2} \frac{\rho^2(\vec{r})}{m_\chi^2} \langle \sigma v \rangle \frac{\mathrm{d}N_{\bar{N}}}{\mathrm{d}T_{\bar{N}}};$$

Majorana fermion with $\langle \sigma v \rangle = 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$;

Einasto distribution profile

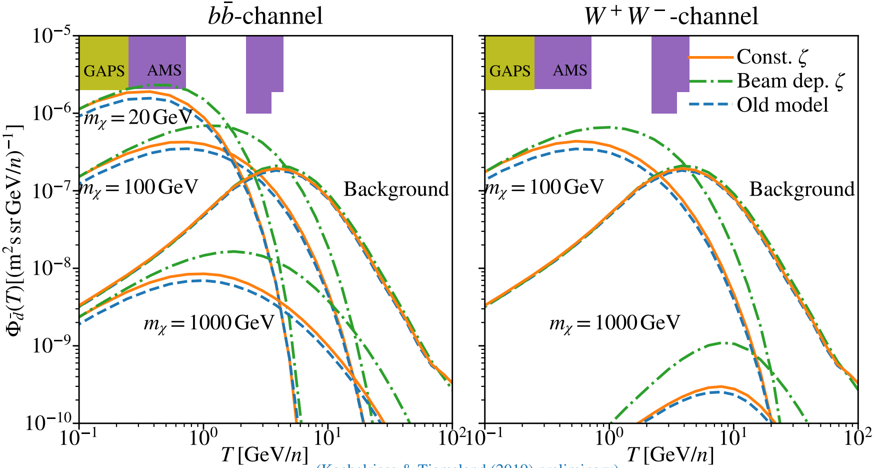
Propagation: two-zone propagation model with the MED–MAX parameter sets [see e.g. (Maurin et al. 2001)]

Solar modulation: Fisk potential; $\phi = 500\ \mathrm{GV}$

See also e.g. (Aramaki 2016; Cirelli et al. 2011)

$$Q^{\mathrm{sec}}(T_{\bar{N}}, \vec{r}) = 4\pi n_p(\vec{r}) \int_{T_{\mathrm{min}}^{(p,p)}}^{\infty} \mathrm{d}T_p \frac{\mathrm{d}\sigma_{p,p}(T_p, T_{\bar{N}})}{\mathrm{d}T_{\bar{N}}} \Phi_p(T_p, \vec{r})$$

Detection prospects for antideuterons



(Kachelriess & Tjemsland (2019) preliminary)

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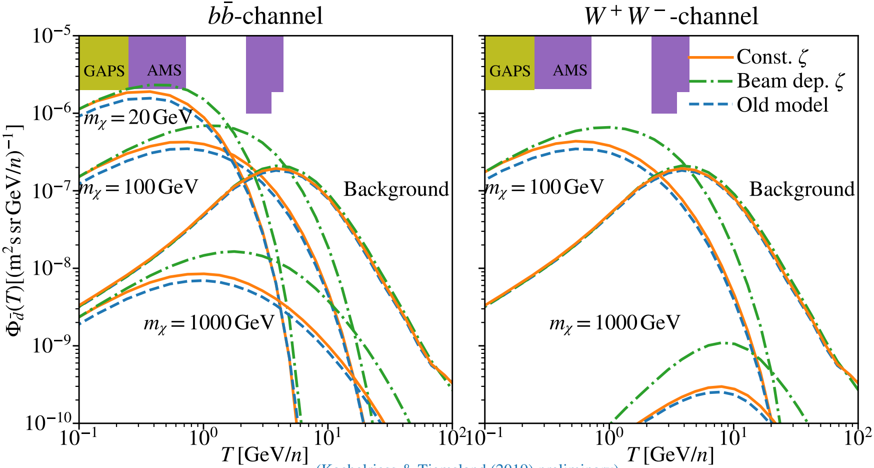

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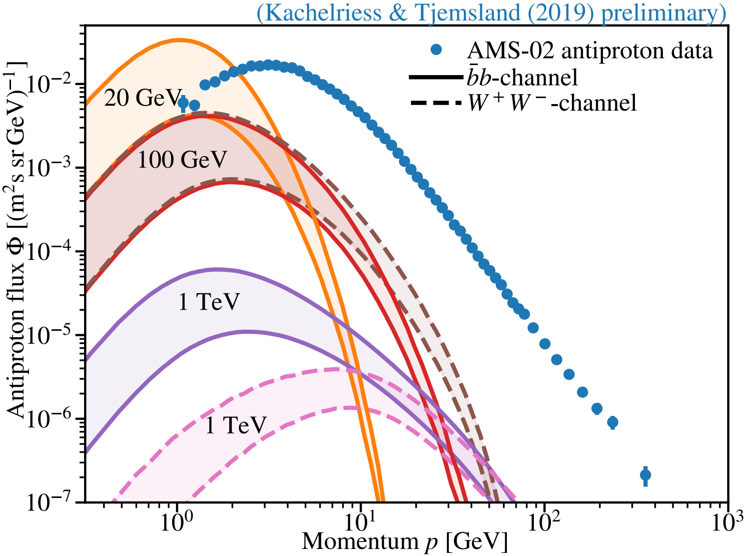
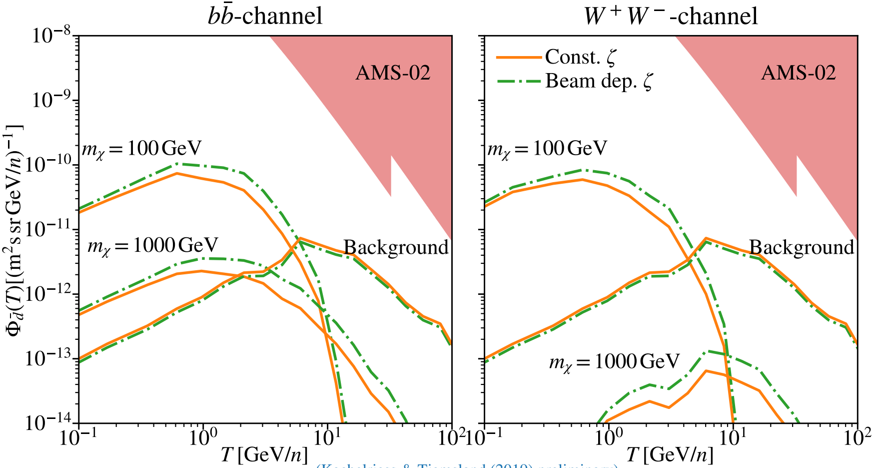
A quick consistency check

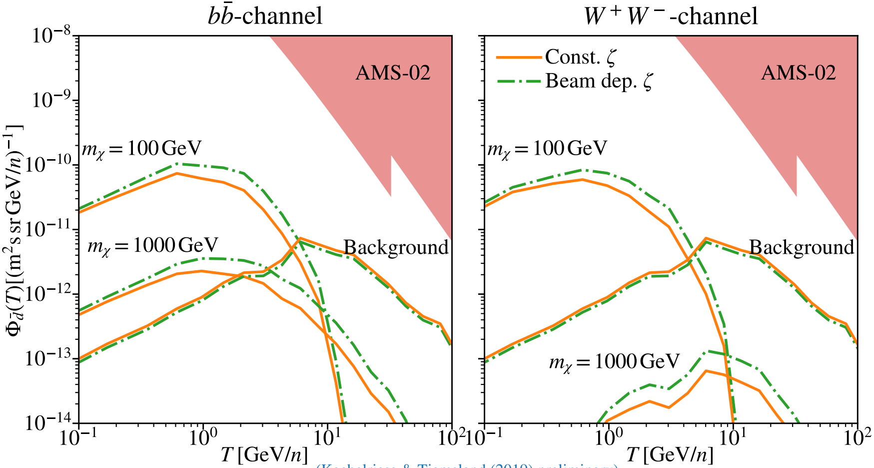


Detection prospects for antihelium-3



(Kachelriess & Tjemsland (2019) preliminary)

Detection prospects for antihelium-3



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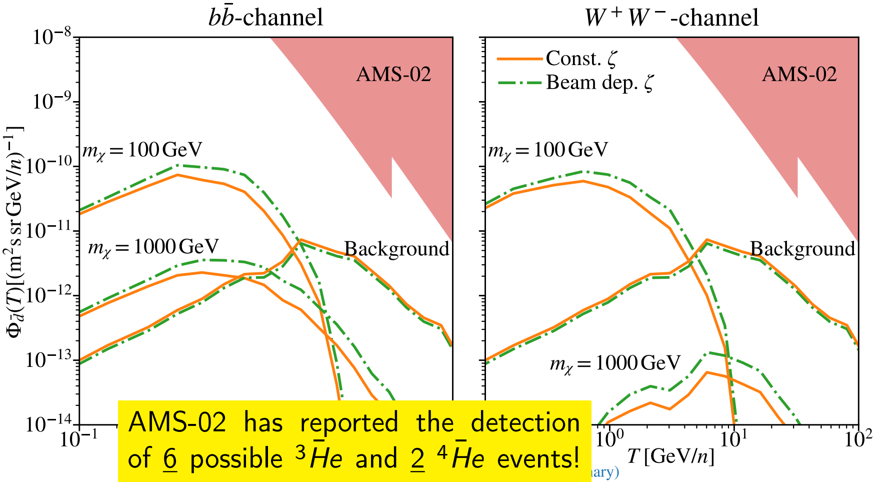


AMS-02 has reported the detection of <u>6</u> possible $^3\overline{He}$ and <u>2</u> $^4\overline{He}$ events! (Ting 2018)

Summary

- Antinuclei offers a potential method of identifying the nature of dark matter
- The existing coalescence model is phenomenological
- Wigner function based coalecence model:

$$\boxed{\frac{\mathrm{d}^3 N_d}{\mathrm{d}P_d^3} = \frac{1}{\gamma}\frac{3\zeta}{(2\pi)^3}\int \frac{\mathrm{d}^3 q}{(2\pi)^3}\mathrm{e}^{-q^2 d^2} G_{np}(-\vec{q},\vec{q})}$$

- It includes constraints on both momentum and space variables, has a semi-classical treatment and a microphysical picture
- The new model does not change the detection prospects significantly

Extra: Helium-3 and tritium

Helium-3 and tritium formation model (yield in lab frame)

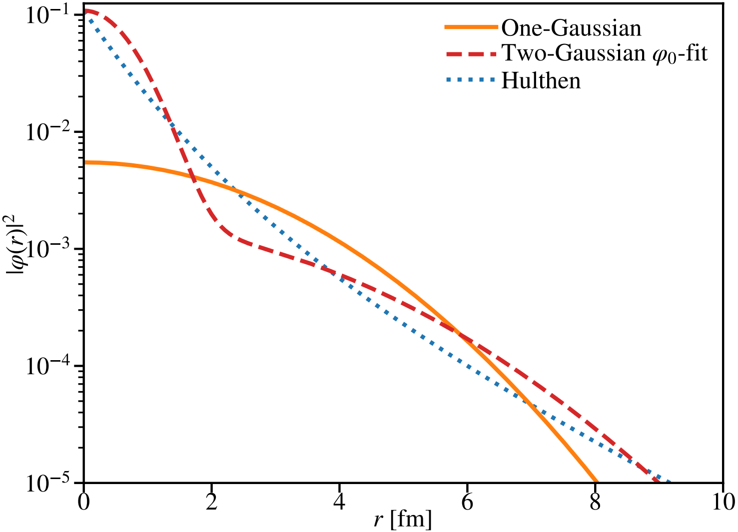
$$\frac{\mathrm{d}^3 N_{\mathrm{He}}}{\mathrm{d}P_{\mathrm{He}}^3} = \frac{64 s\zeta}{\gamma(2\pi)^3}\int \frac{\mathrm{d}^3 p_1}{(2\pi)^3}\frac{\mathrm{d}^3 p_2}{(2\pi)^3} G_{N_1 N_2 N_3}(-\vec{p}_2 - \vec{p}_3, \vec{p}_2, \vec{p}_3)\mathrm{e}^{-b^2 P^2},$$

$$\zeta = \left(\frac{2b^2}{2b^2 + 4\sigma^2}\right)^3,$$

$$P^2 = \frac{1}{3}\left[(\vec{p}_1 - \vec{p}_2)^2 + (\vec{p}_2 - \vec{p}_3)^2 + (\vec{p}_2 - \vec{p}_3)^2\right] = \frac{2}{3}\left[\vec{p}_2^2 + \vec{p}_3^2 + \vec{p}_1 \cdot \vec{p}_2\right].$$

$b_{^3\mathrm{He}} = 1.96\ \mathrm{fm}$; $b_t = 1.76\ \mathrm{fm}$; $s = 1/12$

Extra: Improving the deuteron wave function I



Extra: Improving the deuteron wave function II

The ground state of the deuteron is well described by the Hulthen wave function,

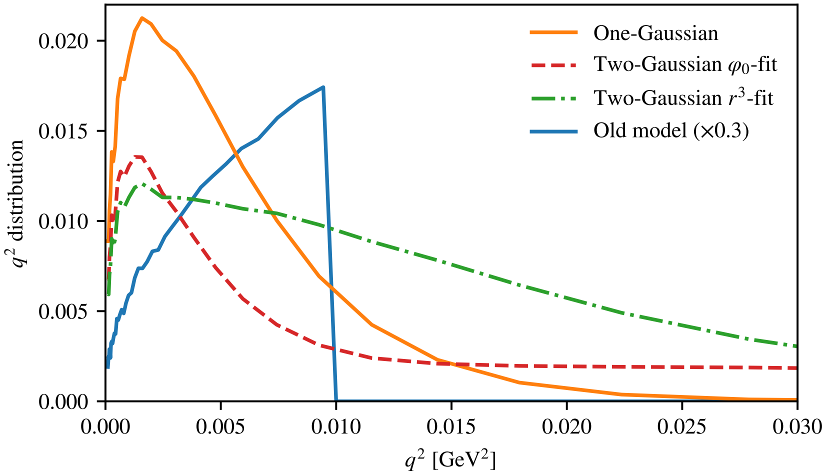
$$\varphi_d(\vec{r}) = \sqrt{\frac{\alpha\beta(\alpha+\beta)}{2\pi(\alpha-\beta)^2}}\,\frac{\mathrm{e}^{-\alpha r} - \mathrm{e}^{-\beta r}}{r},$$

with $\alpha = 0.23\mathrm{fm}^{-1}$ and $\beta = 1.61\mathrm{fm}^{-1}$ (Zhaba 2017).

Two-Gaussian wave function:

$$\varphi_d(\vec{r}) = \pi^{-3/4}\left(\mathrm{i}\sqrt{\frac{\Delta}{d_1^3}}\mathrm{e}^{-r^2/2d_1^2} + \sqrt{\frac{1-\Delta}{d_2^3}}\mathrm{e}^{-r^2/2d_2^2}\right).$$

Extra: Improving the deuteron wave function III



pp collisions at $\sqrt{s} = 7$ TeV with $\sigma = 7\ \mathrm{GeV}^{-1}$ and $p_0 = 0.2$ GeV.

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