Antinuclei as a signature for dark matter

Spaatind 2020

Jonas Tjemsland

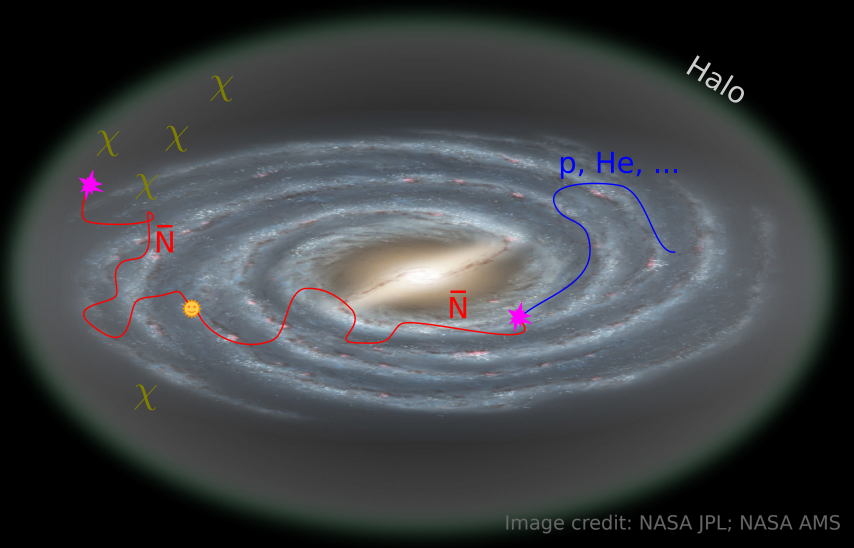
PhD candidate
Department of Physics
Norwegian University of Science and Technology

Supervisor: Michael Kachelrieß

Table of Contents

Table of Contents

Antinuclei as a signature for dark matter



Antinuclei as a signature for dark matter

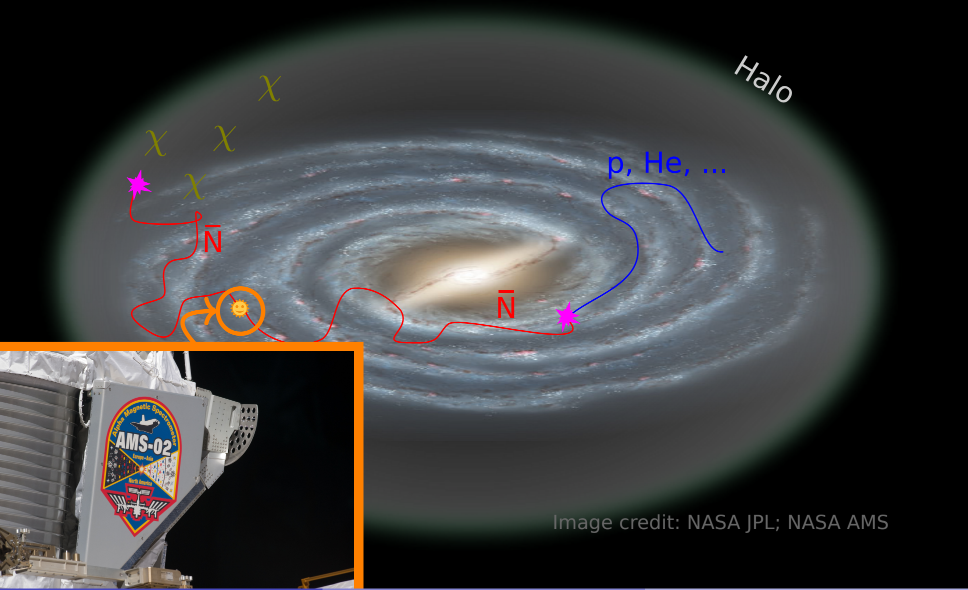


Image credit: NASA JPL; NASA AMS

Antinuclei as a signature for dark matter

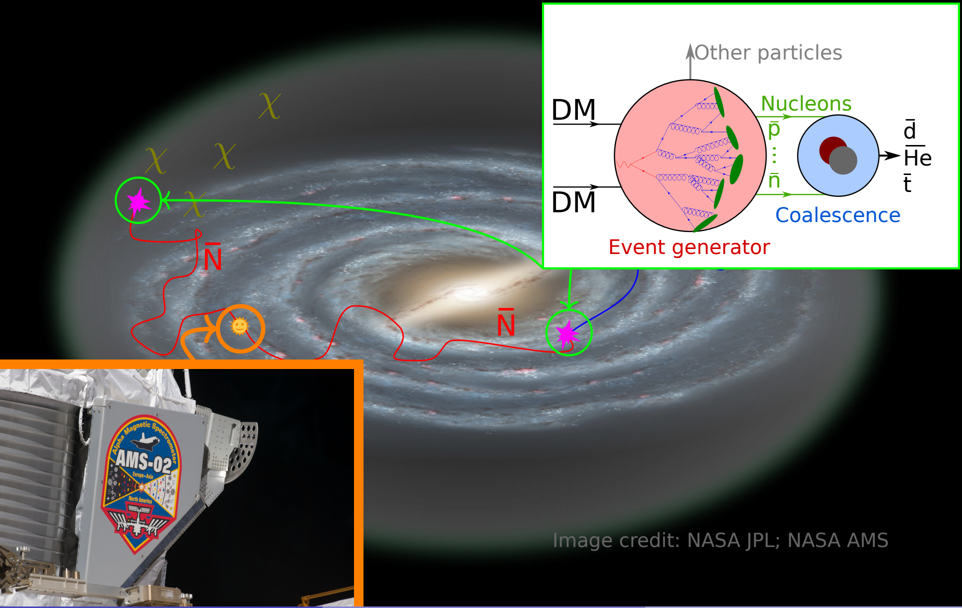
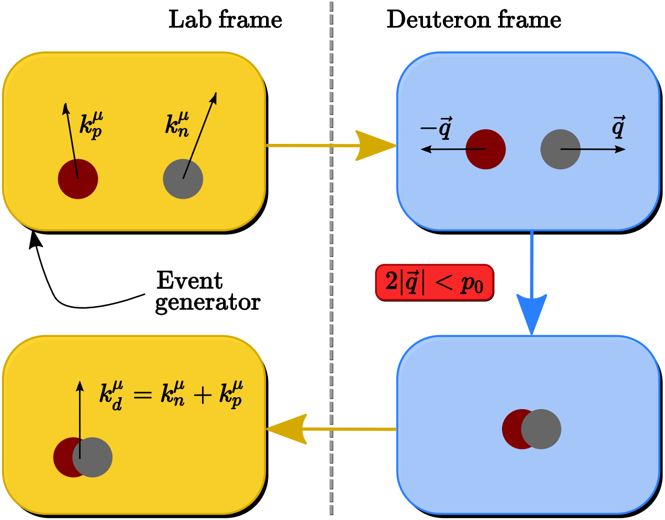


Image credit: NASA JPL; NASA AMS

Table of Contents

The coalescence model in momentum space



The new coalescence model

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

Deuteron formation model

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

$$\zeta \equiv \frac{d^2}{d^2 + 4\sigma_\perp^2}\sqrt{\frac{d^2}{d^2 + 4\sigma_\parallel^2}} \leq 1$$

The new coalescence model

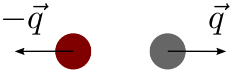
(M. Kachelriess, S. Ostapchenko & J. Tjemsland (2019) [arXiv:1905.01192])

Deuteron formation model

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

$$\zeta \equiv \frac{d^2}{d^2+4\sigma_\perp^2}\sqrt{\frac{d^2}{d^2+4\sigma_\parallel^2}} \leq 1$$

- Two-nucleon momentum distribution
- Size of the deuteron
  $d = 3.2\ \mathrm{fm}$
- Spatial distribution factor
  $\sigma \sim 1\ \mathrm{fm}$ free parameter



Standard coalescence model

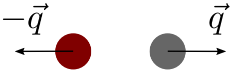
$$w = \Theta(p_0 - 2q)$$

- Phenomenological with constraints in momentum space
- Free parameter p_0

New model

$$w = 3\zeta(\sigma)\exp\left\{-q^2 d^2\right\}$$

- Semi-classical
- Free parameter σ
- Physical interpretation: Size of the formation region



Standard coalescence model

$$w = \Theta(p_0 - 2q)$$

- Phenomenological with constraints in momentum space
- Free parameter p_0

New model

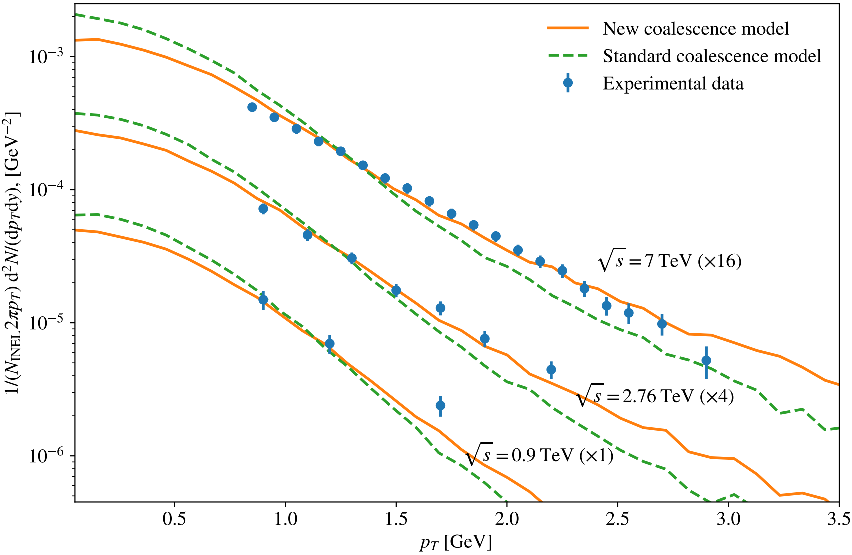
$$w = 3\zeta(\sigma)\exp\left\{-q^2 d^2\right\}$$

- Semi-classical
- Free parameter σ
- Physical interpretation: Size of the formation region

Example

Electron-positron and DM:	$\sigma_{e^\pm} \sim 1\ \mathrm{fm}$
Proton-proton:	$\sigma_{pp} = \sqrt{2}\sigma_{e^\pm}$
Proton-nucleus:	Utilise $R_A = a_0 A^{1/3}$, $a_0 \approx 1\ \mathrm{fm}$

Comparison to experimental data (Pythia 8)



Comparison to experimental data (Pythia 8)

Experiment	a_0 [fm]	$\chi^2/(N-1)$	Ref.
pp 7 TeV	1.07	34/19	Acharya 2018
pp 2.76 TeV	1.05	5.6/6	Acharya 2018
pp 900 GeV	0.97	0.3/2	Acharya 2018
pp 53 GeV	1.22	0.3/2	Henning 1978; Alper 1
e^+e^- 91 GeV	$1.0^{+0.2}_{-0.1}$	-	Schael 2006
pBe $E_{\rm prim} = 200\ {\rm GeV}$ $(A = 9)^*$	1.00	2.2/4	**Bozzoli:1978ud**
pAl $E_{\rm prim} = 200\ {\rm GeV}$ $(A = 27)^*$	0.88	2.3/2	**Bozzoli:1978ud**

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

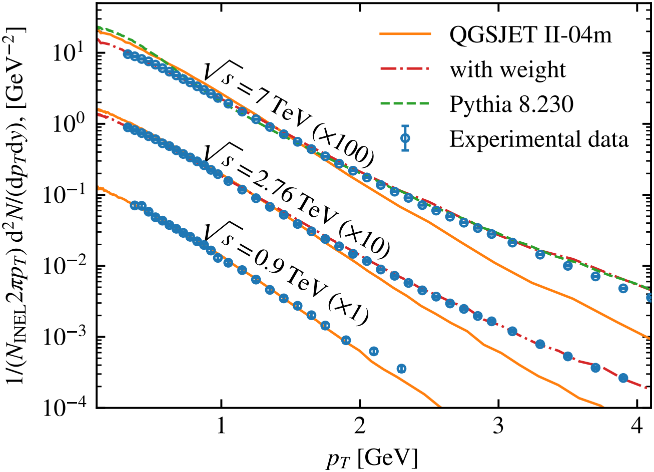
Determining the coalescence parameter a_0

The value of a_0 varies quite a bit for different experiments and event generators

- Uncertainties in the coalescence model
- Experimental uncertainties
- Current event generators are not tuned to two-particle correlations
- One cannot expect the model to represent the antideuteron data better than the corresponding antiproton data

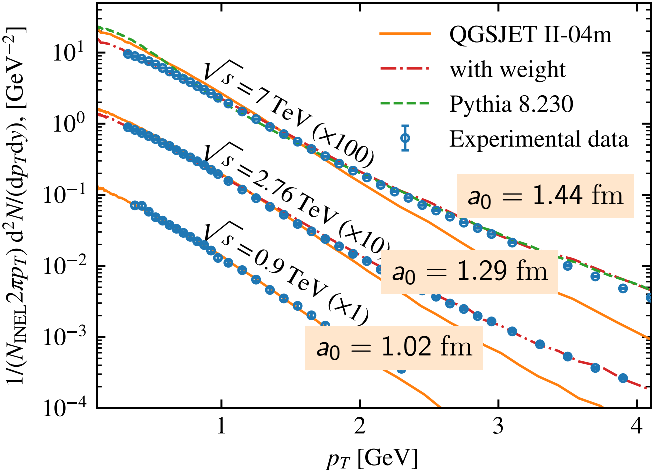
Determining the coalescence parameter a_0

Example: antiproton+proton data masured by ALICE (Aguilar 2016) compared to QGSJET II-04m



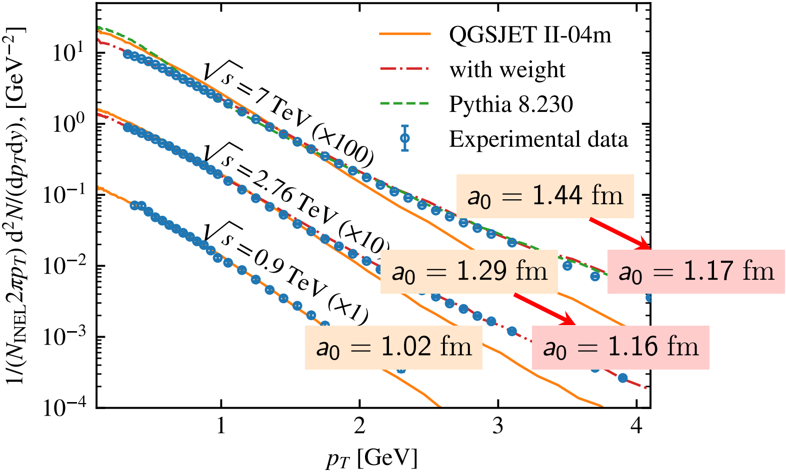
Determining the coalescence parameter a_0

Example: antiproton+proton data masured by ALICE (Aguilar 2016) compared to QGSJET II-04m



Determining the coalescence parameter a_0

Example: antiproton+proton data masured by ALICE (Aguilar 2016) compared to QGSJET II-04m



Determining the coalescence parameter a_0

The value of a_0 varies quite a bit for different experiments and event generators

- Uncertainties in the coalescence model
- Experimental uncertainties
- Current event generators are not tuned to two-particle correlations
- One cannot expect the model to represent the antideuteron data better than the corresponding antiproton data

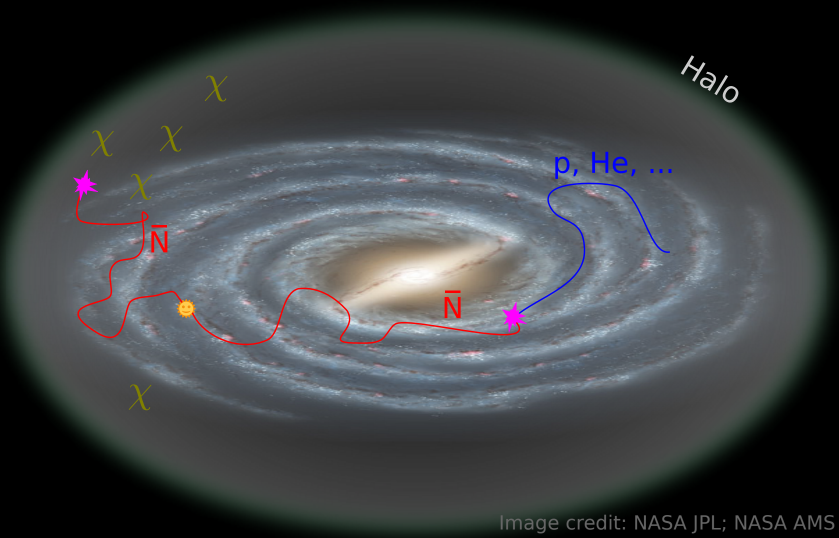
Conclusion

$$a_0 = (1.0 \pm 0.1)\ \mathrm{fm}$$

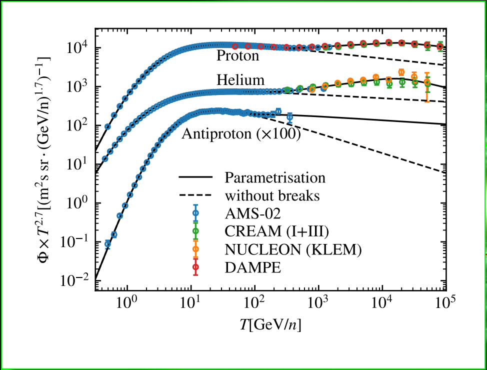
Should hold for all interactions in which coalescence is the dominant production mechanism for antinuclei

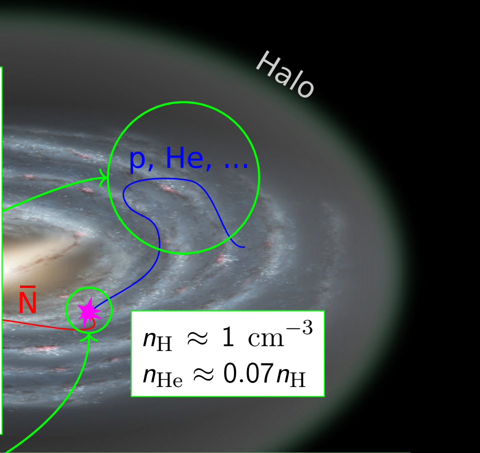
Table of Contents

Secondary source



Secondary source



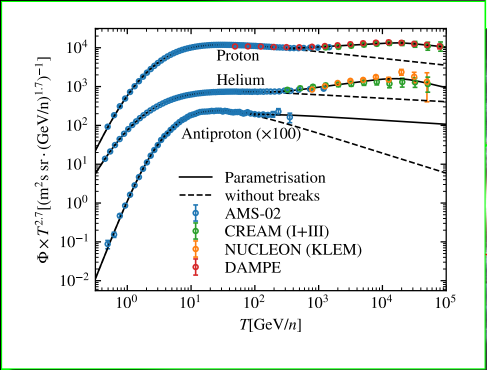


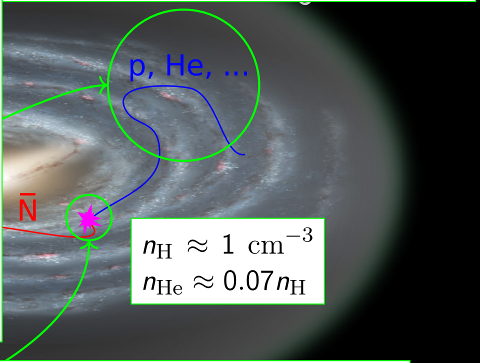
$n_{\mathrm{H}} \approx 1\ \mathrm{cm}^{-3}$
$n_{\mathrm{He}} \approx 0.07 n_{\mathrm{H}}$

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

Secondary source

Propagation: two-zone diffusion model Maurin et al. 2001; Donato et al. 2001; Maurin et al. 2002; Donato et al. 2004



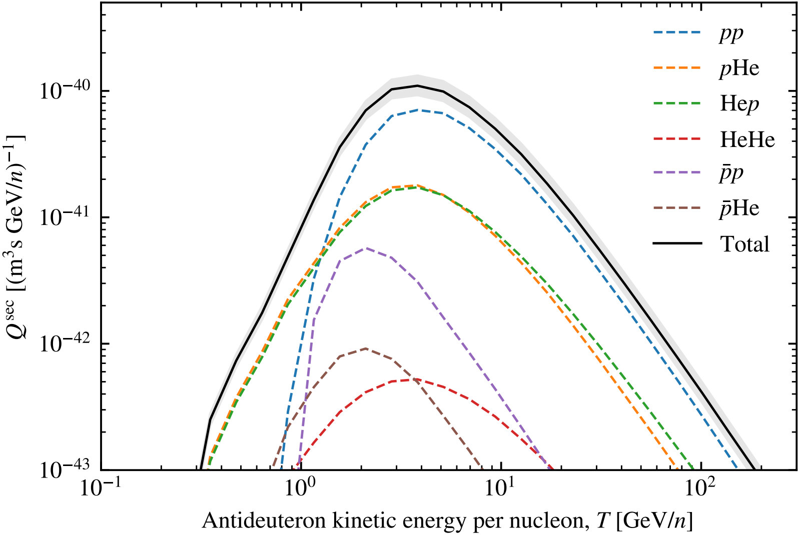


$n_{\mathrm{H}} \approx 1\ \mathrm{cm}^{-3}$

$n_{\mathrm{He}} \approx 0.07 n_{\mathrm{H}}$

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

Secondary source: results (QGSJET II-04m)

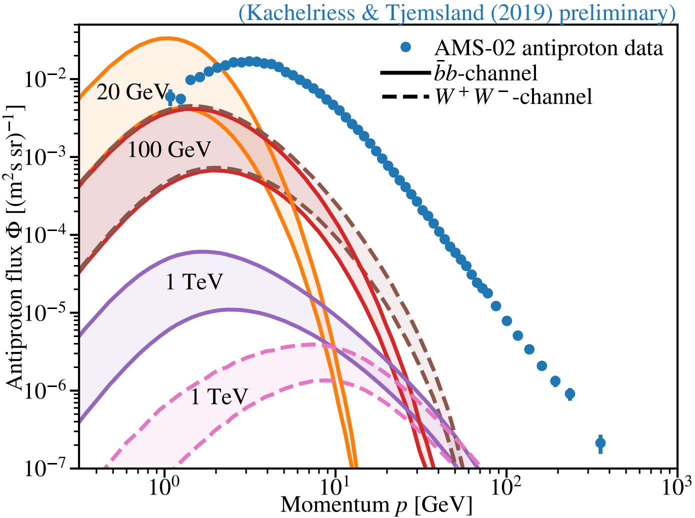


Primary source: dark matter annihilations

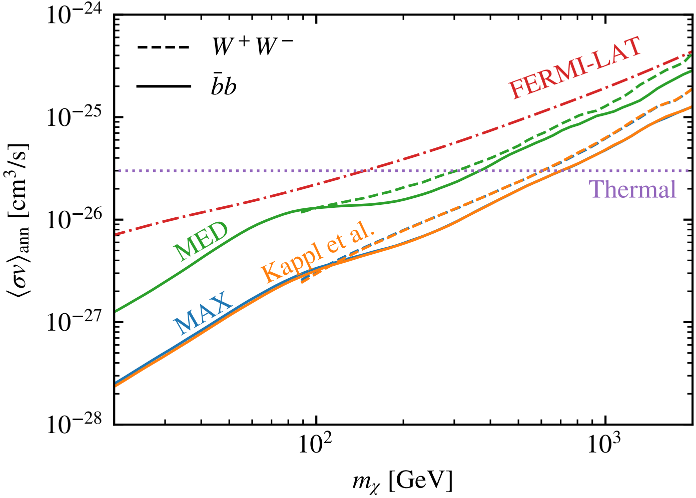
$$Q(\vec{r}, T) = \frac{1}{2}\frac{\rho^2(\vec{r})}{m_\chi^2}\langle\sigma v\rangle\frac{\mathrm{d}N_{\bar{N}}}{\mathrm{d}T_{\bar{N}}}$$

- Generic annihilating dark matter into $\bar{b}b$ and W^+W^-
- Fermionic WIMP, modelled as non-radiating e^+e^- annihilation using Pythia 8.230
- Particle physics parameters: $(m_\chi, \langle\sigma v\rangle_{\mathrm{ann}})$
- Dark matter distribution $\rho(\vec{r}_\odot) \approx 0.3\ \mathrm{GeV/cm^3}$
- Large uncertainties related to propagation

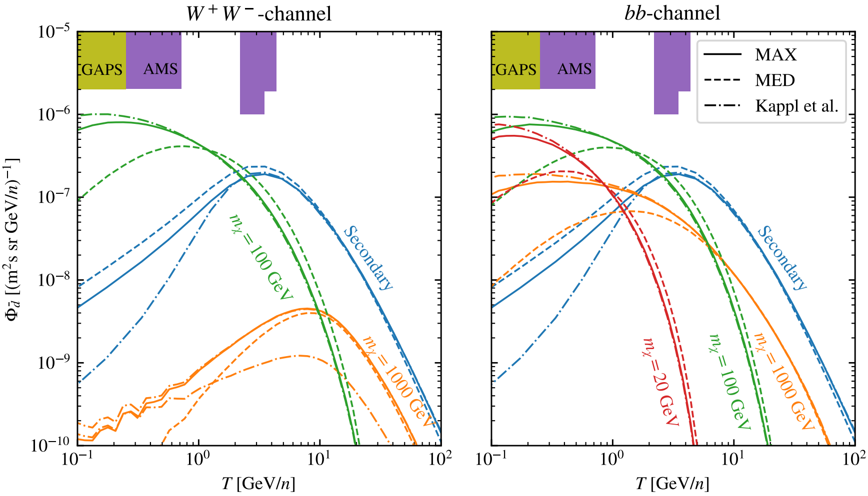
Primary source: upper limit on annihilation cross section



Primary source: upper limit on annihilation cross section



Detection prospects for antideuterons



Detection prospects for antihelium

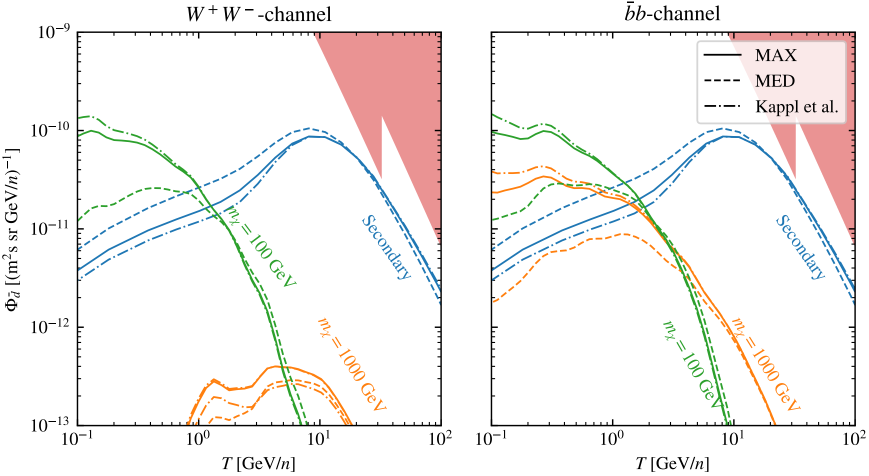


Table of Contents

Experimental status of antinucleus

- The AMS-02 (The Alpha Magnetic Spectrometer) Experiment (Battiston 2008)

Current hints for exotic physics

- Antiproton: Small exess at rigidities 10–20 GV
  $\Rightarrow \langle \sigma_{\rm ann} v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s};\ m_\chi \sim 80\ \mathrm{GeV}$ (Cuoco et al. 2017)
- Antideuteron: No detection
- Antihelium: 8 possible antihelium events, 2 of which are possible $^4\overline{\mathrm{He}}$ events (Ting 2018)

- GAPS (General AntiParticle Spectrometer) is being launched during the next Solar minimum in 2021(Aramaki et al. 2016a)

Summary

- Antinuclei offers a potential method of identifying the nature of dark matter
- New coalecence model:

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

- It includes constraints on both momentum and space variables, has a semi-classical treatment and a microphysical picture
- Can now describe all prosesses relevant for secondary production and DM annihilation with a single free parameter
- The new model does not change current detection prospects significantly
- The AMS-02 collaboration have detected 8 possible antihelium events, of which 2 are possible antihelium-4 events

References I

Acharya, Shreyasi, et al. 2018. "Production of deuterons, tritons, ^{3}He nuclei and their antinuclei in pp collisions at $\sqrt{s} = 0.9$, 2.76 and 7 TeV." *Phys. Rev.* C97 (2): 024615. doi:10.1103/PhysRevC.97.024615. arXiv: 1709.08522 [nucl-ex].

Aguilar, M., et al. 2016. "Antiproton Flux, Antiproton-to-Proton Flux Ratio, and Properties of Elementary Particle Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station." *Phys. Rev. Lett.* 117 (9): 091103. doi:10.1103/PhysRevLett.117.091103.

Alper, B., et al. 1973. "Large angle production of stable particles heavier than the proton and a search for quarks at the cern intersecting storage rings." *Phys. Lett.* 46B:265–268. doi:10.1016/0370-2693(73)90700-4.

Aramaki, T., C. J. Hailey, S. E. Boggs, P. von Doetinchem, H. Fuke, S. I. Mognet, R. A. Ong, K. Perez, and J. Zweerink. 2016a. "Antideuteron Sensitivity for the GAPS Experiment." *Astropart. Phys.* 74:6–13. doi:10.1016/j.astropartphys.2015.09.001. arXiv: 1506.02513 [astro-ph.HE].

Aramaki, T., et al. 2016b. "Review of the theoretical and experimental status of dark matter identification with cosmic-ray antideuterons." *Phys. Rept.* 618:1–37. doi:10.1016/j.physrep.2016.01.002. arXiv: 1505.07785 [hep-ph].

Battiston, Roberto. 2008. "The Antimatter Spectrometer (AMS-02): A Particle Physics Detector in Space." Proceedings of the First International Conference on Astroparticle Physics, *Nucl. Instrum. Meth.* 588, no. 1 (April): 227–234. ISSN: 01689002. doi:10.1016/j.nima.2008.01.044.

References II

Cuoco, Alessandro, Michael Krämer, and Michael Korsmeier. 2017. "Novel Dark Matter Constraints from Antiprotons in Light of AMS-02." *Phys. Rev. Lett.* 118 (19): 191102. doi:10.1103/PhysRevLett.118.191102. arXiv: 1610.03071 [astro-ph.HE].

Donato, F., D. Maurin, P. Salati, A. Barrau, G. Boudoul, and R. Taillet. 2001. "Anti-protons from spallations of cosmic rays on interstellar matter." *Astrophys. J.* 563:172–184. doi:10.1086/323684. arXiv: astro-ph/0103150 [astro-ph].

Donato, F., Nicolao Fornengo, D. Maurin, and P. Salati. 2004. "Antiprotons in cosmic rays from neutralino annihilation." *Phys. Rev.* D69:063501. doi:10.1103/PhysRevD.69.063501. arXiv: astro-ph/0306207 [astro-ph].

Henning, S., et al. 1978. "Production of Deuterons and anti-Deuterons in Proton Proton Collisions at the CERN ISR." *Lett. Nuovo Cim.* 21:189. doi:10.1007/BF02822248.

Kachelriess, M., S. Ostapchenko, and J. Tjemsland. 2019. "Alternative coalescence model for deuteron, tritium, helium-3 and their antinuclei." *Submitted to JHEP.* arXiv: 1905.01192 [hep-ph].

Kachelriess, Michael, Igor V. Moskalenko, and Sergey S. Ostapchenko. 2015. "New calculation of antiproton production by cosmic ray protons and nuclei." *Astrophys. J.* 803 (2): 54. doi:10.1088/0004-637X/803/2/54. arXiv: 1502.04158 [astro-ph.HE].

Maurin, D., F. Donato, R. Taillet, and P. Salati. 2001. "Cosmic rays below z=30 in a diffusion model: new constraints on propagation parameters." *Astrophys. J.* 555:585–596. doi:10.1086/321496. arXiv: astro-ph/0101231 [astro-ph].

References III

Maurin, David, Richard Taillet, and Fiorenza Donato. 2002. "New results on source and diffusion spectral features of galactic cosmic rays: I- B/C ratio." *Astron. Astrophys.* 394:1039–1056. doi:10.1051/0004-6361:20021176. arXiv: astro-ph/0206286 [astro-ph].

Ostapchenko, Sergey. 2011. "Monte Carlo treatment of hadronic interactions in enhanced Pomeron scheme: I. QGSJET-II model." *Phys. Rev.* D83:014018. doi:10.1103/PhysRevD.83.014018. arXiv: 1010.1869 [hep-ph].

Schael, S., et al. 2006. "Deuteron and anti-deuteron production in e+ e- collisions at the Z resonance." *Phys. Lett.* B639:192–201. doi:10.1016/j.physletb.2006.06.043. arXiv: hep-ex/0604023 [hep-ex].

Schwarzschild, A., and Č. Zupančič. 1963. "Production of Tritons, Deuterons, Nucleons, and Mesons by 30-GeV Protons on A1, Be, and Fe Targets." *Phys. Rev.* 129, no. 2 (January): 854–862. ISSN: 0031-899X. doi:10.1103/PhysRev.129.854.

Sjostrand, Torbjorn, Stephen Mrenna, and Peter Z. Skands. 2006. "PYTHIA 6.4 Physics and Manual." *JHEP* 05:026. doi:10.1088/1126-6708/2006/05/026. arXiv: hep-ph/0603175 [hep-ph].

Sjöstrand, Torbjörn, Stefan Ask, Jesper R. Christiansen, Richard Corke, Nishita Desai, Philip Ilten, Stephen Mrenna, Stefan Prestel, Christine O. Rasmussen, and Peter Z. Skands. 2015. "An Introduction to PYTHIA 8.2." *Comput. Phys. Commun.* 191:159–177. doi:10.1016/j.cpc.2015.01.024. arXiv: 1410.3012 [hep-ph].

Ting, Samuel. 2018. *Latest Results from the AMS Experiment on the International Space Station.* Talk at CERN Colloquium, May. https://cds.cern.ch/record/2320166.

References IV

Zhaba, V. I. 2017. "Deuteron: properties and analytical forms of wave function in coordinate space." *arXiv e-prints.* arXiv: 1706.08306 [nucl-th].

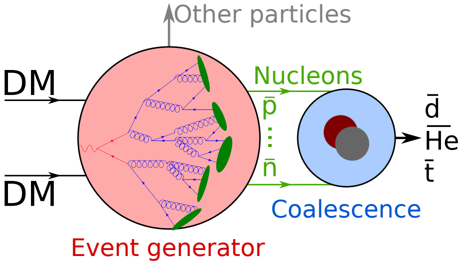
Extra: Process dependence

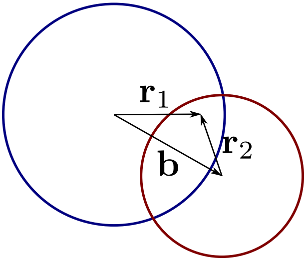
- e^+e^- and dark matter annihilations:

$$\sigma_{\perp(e^\pm)} \sim \Lambda_{\mathrm{QCD}} \sim 1\ \mathrm{fm} \qquad \sigma_{\parallel(e^\pm)} \sim L_{\mathrm{had}} \sim 1\ \mathrm{fm}$$

- Hadron-hadron and hadron-nucleus collisions will obtain an additional contribution from multiparton interactions:

$$\sigma^2_{\perp(\mathrm{geom})} \sim \frac{2R_1^2R_2^2}{R_1^2+R_2^2} \qquad \sigma^2_{\parallel(\mathrm{geom})} \sim \max\{R_1, R_2\}$$





-

Extra: Process dependence

- e^+e^- and dark matter annihilations:

$$\sigma_{\perp(e^\pm)} \sim \Lambda_{\mathrm{QCD}} \sim 1\ \mathrm{fm} \qquad \sigma_{\parallel(e^\pm)} \sim L_{\mathrm{had}} \sim 1\ \mathrm{fm}$$

- Hadron-hadron and hadron-nucleus collisions will obtain an additional contribution from multiparton interactions:

$$\sigma^2_{\perp(\mathrm{geom})} \sim \frac{2R_1^2R_2^2}{R_1^2+R_2^2} \qquad \sigma^2_{\parallel(\mathrm{geom})} \sim \max\{R_1, R_2\}$$

-

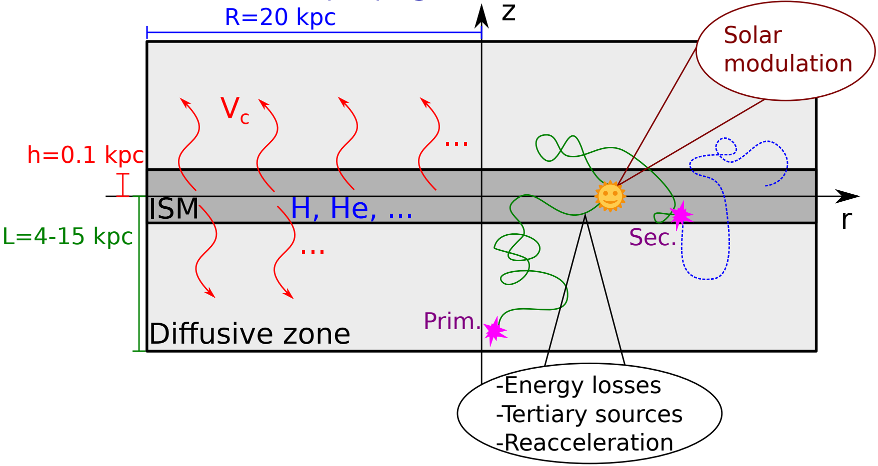
Example (proton-proton collisions, $R_1 = R_2 = 1\ \mathrm{fm}$)

$$\sigma^2_{\perp(pp)} \sim \sigma^2_{\perp(e^\pm)} + \sigma^2_{\perp(\mathrm{geom})} \sim 2\sigma^2_{\perp(e^\pm)} \sim (\sqrt{2}\ \mathrm{fm})^2$$
$$\sigma^2_{\parallel(pp)} \sim \sigma^2_{\perp(e^\pm)} + \sigma^2_{\perp(\mathrm{geom})} \sim 2\sigma^2_{\perp(e^\pm)} \sim (\sqrt{2}\ \mathrm{fm})^2$$

- Nuclear radius: $R_A = a_0 A^{1/3}$, $a_0 \approx 1\ \mathrm{fm}$ ($A \lesssim 10$)

$\Rightarrow$ Set $a_0 \sim 1\ \mathrm{fm}$ as a free parameter

Extra: The two-zone propagation model



- Semi-analytical solution (Maurin et al. 2001)
- Parameters are constrained using e.g. a B/C study (Aramaki 2016b); MED–MAX parameters

Extra: Helium-3 and tritium

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

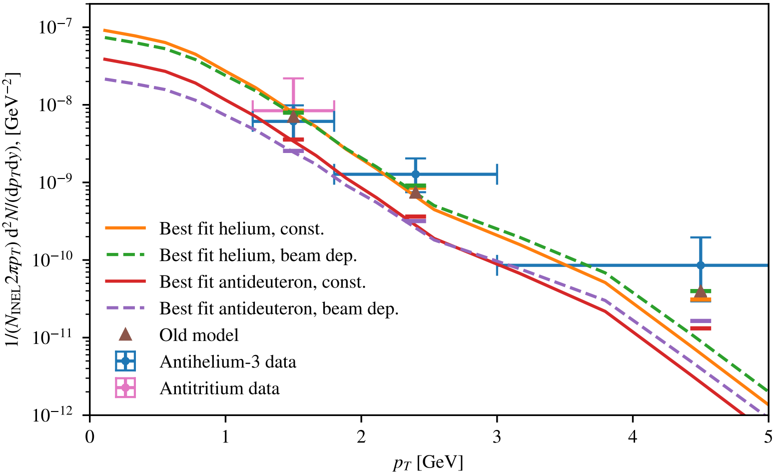
$$\frac{\mathrm{d}^3 N_{\mathrm{He}}}{\mathrm{d}P^3_{\mathrm{He}}} = \frac{64 s\zeta}{\gamma(2\pi)^3} \int \frac{\mathrm{d}^3 p_1}{(2\pi)^3} \frac{\mathrm{d}^3 p_2}{(2\pi)^3} G_{N_1 N_2 N_3}(-\vec{p}_2 - \vec{p}_3, \vec{p}_2, \vec{p}_3) \mathrm{e}^{-b^2 P^2},$$

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

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

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

Extra: Best fit to the ALICE helium-3 data



Extra: The coalescence model

The formation of a nucleon ${}^A_Z N$ can be described by the coalescence model (Schwarzschild and Zupančič 1963)

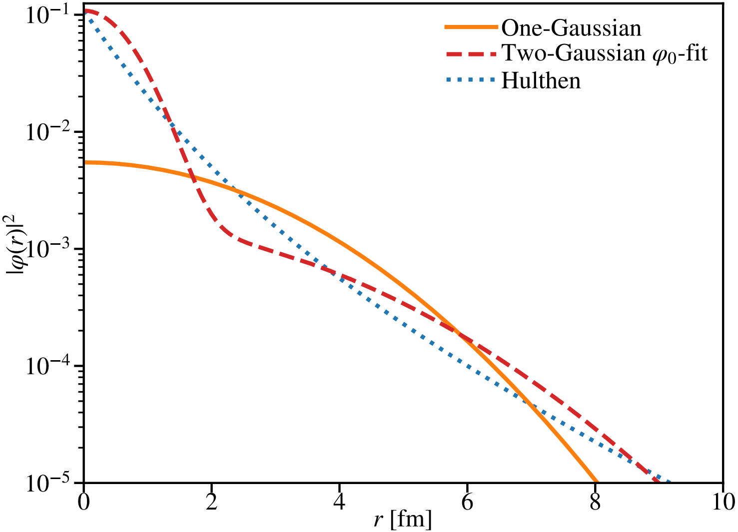
$$E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}P_A^3} = B_A \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}P_p^3} \right)^Z \left(E_n \frac{\mathrm{d}^3 N_n}{\mathrm{d}P_n^3} \right)^N \Bigg|_{P_p = P_n = P_A/A},$$

where B_A is the coalescence parameter.

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

$$B_A \propto V^{A-1}$$

Improving the deuteron wave function



Extra: Improving the deuteron wave function II

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

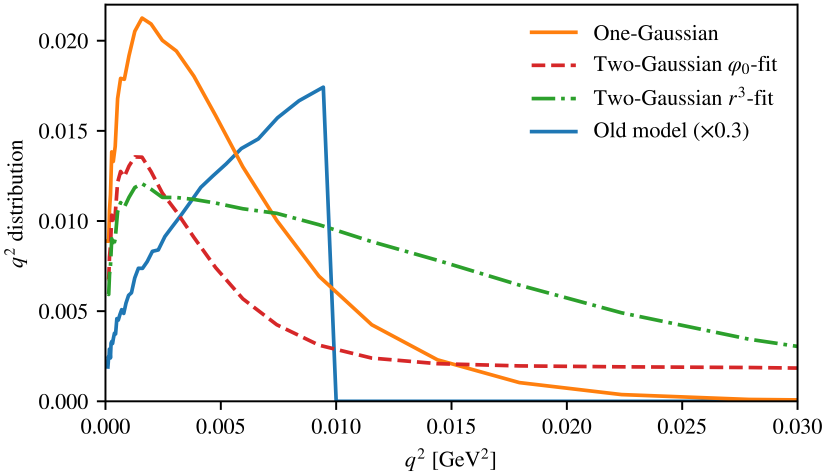
$$\varphi_d(\vec{r}) = \sqrt{\frac{\alpha\beta(\alpha+\beta)}{2\pi(\alpha-\beta)^2}}\frac{\mathrm{e}^{-\alpha r} - \mathrm{e}^{-\beta r}}{r},$$

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 $\sqrt{s} = 0.9$ TeV with $\sigma = 7$ GeV^{-1} and $p_0 = 0.2$ GeV.

Extra: Wigner Functions

1. $f^{\mathrm{W}}(p,x) = \int \rho(x+y/2, x-y/2) e^{-\mathrm{i}py} \, \mathrm{d}y$
2. $\int f^{\mathrm{W}}(p,x) \frac{\mathrm{d}p}{2\pi} = \rho(x,x) = P(x)$
3. $\int f^{\mathrm{W}}(p,x) \, \mathrm{d}x = \rho(p,p) = P(p)$

Deuteron Wigner function:

$$\mathcal{D}(\vec{r},\vec{q}) = \int \mathrm{d}^3\xi \exp\left\{-\mathrm{i}\vec{q}\cdot\vec{\xi}\right\} \varphi_d(\vec{r}+\vec{\xi}/2)\varphi_d^*(\vec{r}-\vec{\xi}/2)$$