FORMATION OF COSMIC RAY ANTINUCLEI

Based on M. Kachelrieß, S. Ostapchenko and J. Tjemsland
arXiv:[1905.01192, 2002.10481]

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Content

Motivation

The microphysics of coalescence

Antinuclei detection prospects

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Note: The discussions on coalescence apply equally well to particles and antiparticles. Moreover, only the deuteron production will be discussed, but the same description has been applied to antihelium and antitritium as well.

Antinuclei as a signature

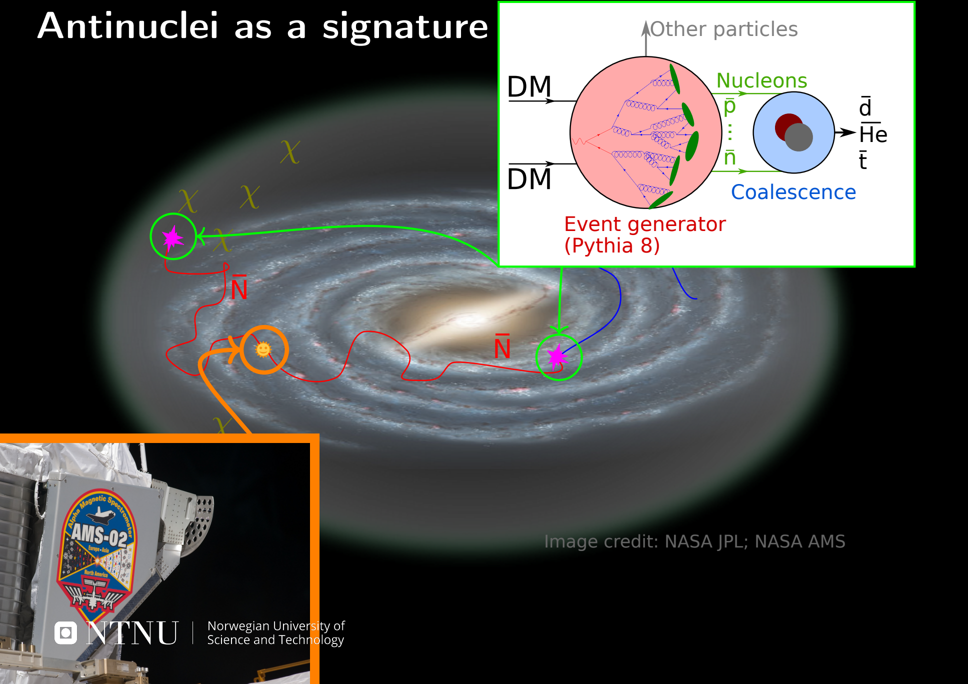
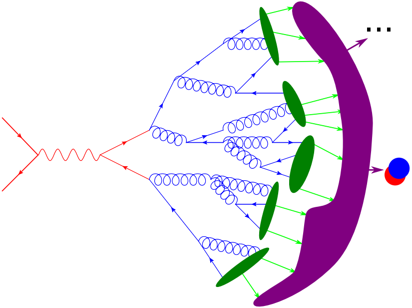


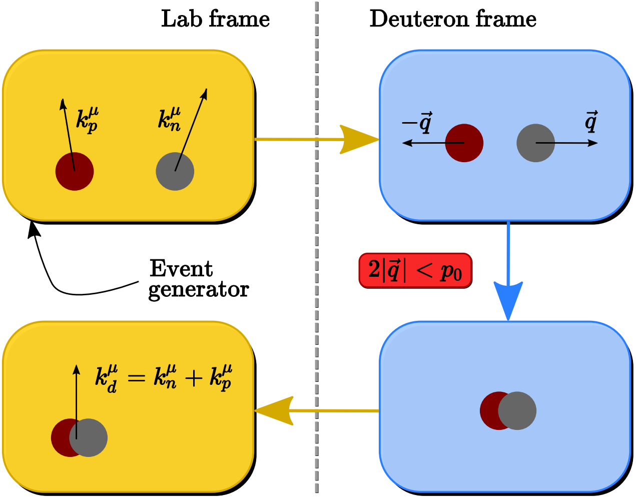
Image credit: NASA JPL; NASA AMS

Timescales

- Hard process: $t_{\mathrm{ann}} \sim 1/\sqrt{s}$
- Perturbative cascade:
  $\Lambda^2_{\mathrm{QCD}} \ll |q^2| \ll s$
- Hadronisation:
  $L_{\mathrm{had}} \sim \gamma L_0,\ L_0 \sim R_p \sim 1\ \mathrm{fm}$
- Coalescence:
  merging of nucleons that have nearly completed their formation



The coalescence model in momentum space



The new coalescence model

M. Kachelrieß, S. Ostapchenko and JT [1905.01192]

Goals

- Include constraints on both momentum and space variables
- Include a quantum mechanical treatment
- Have microphysical picture
- Include momentum correlations

Starting points

- Nucleon capture process: $p + n \to d^*$
- Wigner functions

The quantum mechanics of coalescence

Starting point (Scheibl and Heinz [nucl-th/9809092])

$$\frac{\mathrm{d}^3 N_d}{\mathrm{d}p_d^3} = \mathrm{tr}\,\rho_d \rho_{\mathrm{nucl}}$$

$$\rho_d = |\phi_d\rangle \langle\phi_d|$$

$$\rho_{\mathrm{nucl}} = |\psi_p \psi_n\rangle \langle\psi_p \psi_n|$$

Detour: 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. $\int f^{\mathrm{W}}(p, x) \, \mathrm{d}x = \rho(p, p) = P(p)$

An expression for the deuteron yield

$$\frac{\mathrm{d}^3 N_d}{\mathrm{d}P_d^3} = \frac{3}{8(2\pi)^3}\int \mathrm{d}^3 r_d \int \frac{\mathrm{d}^3 q\, \mathrm{d}^3 r}{(2\pi)^3} \mathcal{D}(\vec{r},\vec{q})\, W_{np}(\vec{p}_p,\vec{p}_n,\vec{r}_p,\vec{r}_n)$$

- Internal deuteron Wigner function

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

$$\varphi_d(\vec{r}) = (\pi d^2)^{-3/4}\exp\left\{-\frac{r^2}{2d^2}\right\}$$

- Two-nucleon Wigner function

$$W_{np} = H_{np}(\vec{r}_n,\vec{r}_p)G_{np}(\vec{p}_n,\vec{p}_p)$$

$$H_{np}(\vec{r}_n,\vec{r}_p) = h(\vec{r}_n)h(\vec{r}_p) \qquad h(\vec{r}) = (2\pi\sigma^2)^{-3/2}\exp\left\{-\frac{r^2}{2\sigma^2}\right\}$$

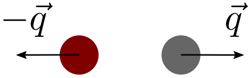
The new coalescence model

Deuteron formation model

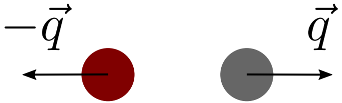
$$\frac{\mathrm{d}^3 N_d}{\mathrm{d}P_d^3} = \frac{1}{\gamma}\frac{3\zeta}{(2\pi)^3}\int \frac{\mathrm{d}^3 q}{(2\pi)^3} G_{np}(\vec{q}, -\vec{q})\ \mathrm{e}^{-q^2 d^2}$$

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

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



1. Momentum correlations

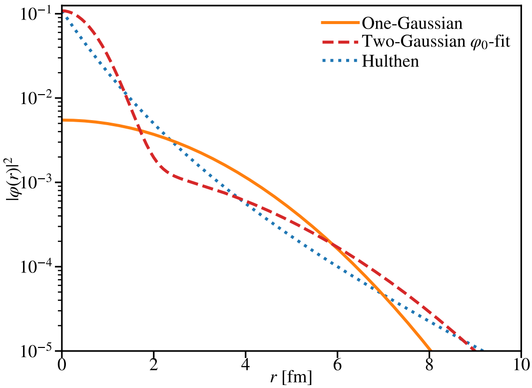


- QCD inspired event generators (Here: Pythia 8.2, QGSJET II)

Coalescence probability

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

2. Deuteron wave function



$$w = 3\Delta\zeta(d_1)\exp\{-q^2 d_1^2\} + 3(1-\Delta)\zeta(d_2)\exp\{-q^2 d_2^2\}$$

3. Process dependence of σ

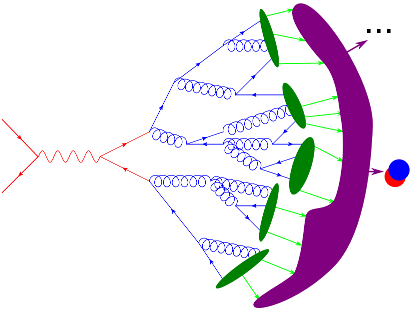
Point-like processes

Longitudinal spread

- Relevant lengthscale: $L_{\mathrm{had}} \sim \gamma L_0 \sim \gamma R_p$
- Formation size: $\sigma_{\parallel(e^+e^-)} \sim L_{\mathrm{had}}/\gamma \sim R_p \sim 1\ \mathrm{fm}$

Transverse spread

- Relevant lengthscale: $\Lambda_{\mathrm{QCD}}^{-1}$
- Formation size: $\sigma_{\perp(e^+e^-)} \sim \Lambda_{\mathrm{QCD}}^{-1} \sim 1\ \mathrm{fm}$



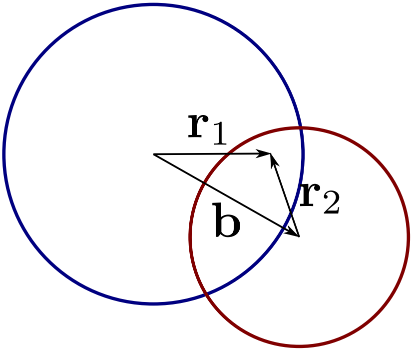
3. Process dependence of σ
Geometrical contribution (proton-proton)

Longitudinal spread

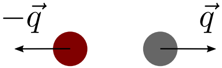
- Relevant lengthscale: γR_p
- Formation size:
  $\sigma_{\parallel(\mathrm{geom})} \sim R_p \sim 1\ \mathrm{fm}$

Transverse spread

- Relevant lengthscale: Spread in overlapping parton clouds, $\rho = (\pi R^2)\exp\{-r^2/R^2\}$
- Formation size: $\sigma^2_{\perp(\mathrm{geom})} \sim \langle r_1^2 \rangle_O - \langle \vec{r}_1^2 \rangle_O = R_p = 1\ \mathrm{fm}$



Summary of the coalescence models



Standard coalescence model

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

- Phenomenological
- Free parameter p_0

New model

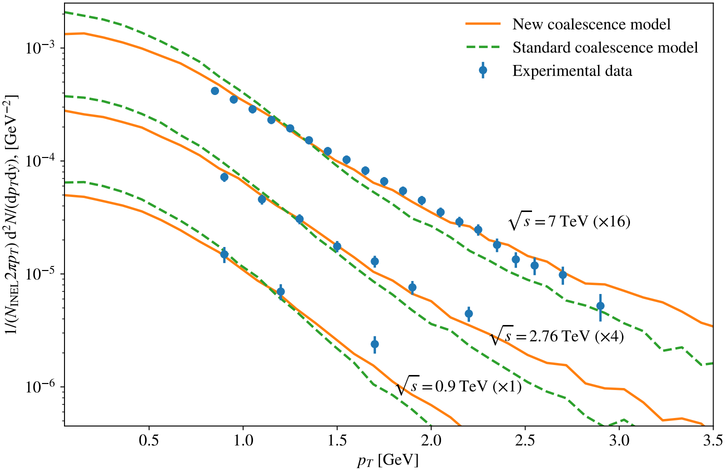
$$w = 3\zeta(\sigma)\exp\{-q^2 d^2\}$$

$$\zeta = \frac{d^2}{d^2 + 4\tilde{\sigma}_\perp^2}\sqrt{\frac{d^2}{d^2 + 4\sigma_\parallel^2}}$$

$$\tilde{\sigma}_\perp^2 = \sigma_\perp^2 / (\cos^2\theta + \gamma^2 \sin^2\theta)$$

- Semi-classical
- Free parameter $\sigma \equiv \sigma_{(e^+e^-)} \simeq \sigma_{pp}/\sqrt{2} \simeq 1\ \mathrm{fm}$

Experimental data: antideuteron spectrum



Proton-proton collisions, ALICE [1709.08522] MC: Pythia 8.2

Comparison to experimental data

Experiment	σ [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	1.03	3.3/7	(Alper 1975)
e^+e^- 91 GeV	$1.0^{+0.2}_{-0.1}$	-	(Schael 2006)
pBe* $E_{\mathrm{prim}} = 200\ \mathrm{GeV}$	1.00	2.2/4	(Bozzoli et al. 1978)
pAl* $E_{\mathrm{prim}} = 200\ \mathrm{GeV}$	0.88	2.3/2	(Bozzoli et al. 1978)

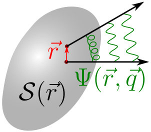
Event generators:

Pythia 8.2 and *QGSJET II

Femtoscopy experiments

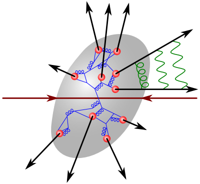
- Measurable quantity:

$$\mathcal{C}(\vec{q}) = \int \mathrm{d}^3 r \, \mathcal{S}(\vec{r}) |\Psi(\vec{r}, \vec{q})|^2$$



- A Gaussian source if often assumed in experiments

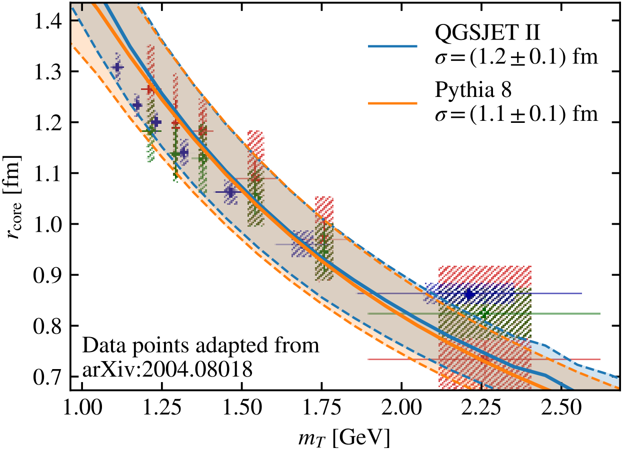
$$\mathcal{S}(\vec{r}) \propto \exp\left\{ -\frac{r^2}{4 r_0^2} \right\}$$



- The nucleon Wigner functions predict the baryon source

$$W_{np} \propto \exp\left\{ -\frac{r_\parallel^2}{4\sigma_\parallel^2} - \frac{r_\perp^2 \cos^2\theta + \gamma^2 r_\perp \sin^2\theta}{4\sigma_\perp^2} \right\}$$

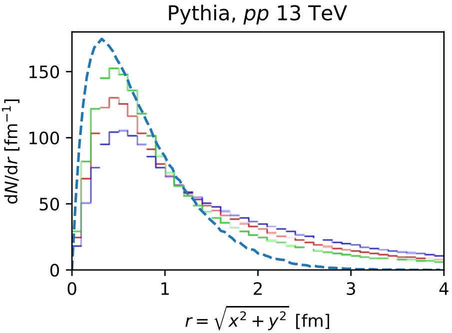
Experimental data: baryon emission source



Preliminary

Sidenote: Space-time structure in Pythia 8.2

Pythia 8.2 includes now a description of the spacetime structure of a cascade (Ferreres-Solé and Sjöstrand 2018)



Can instead use:

$$w = 3\exp\left\{-\frac{r^2}{d^2} - q^2 d^2\right\}$$

Detection prospects for cosmic ray antinuclei

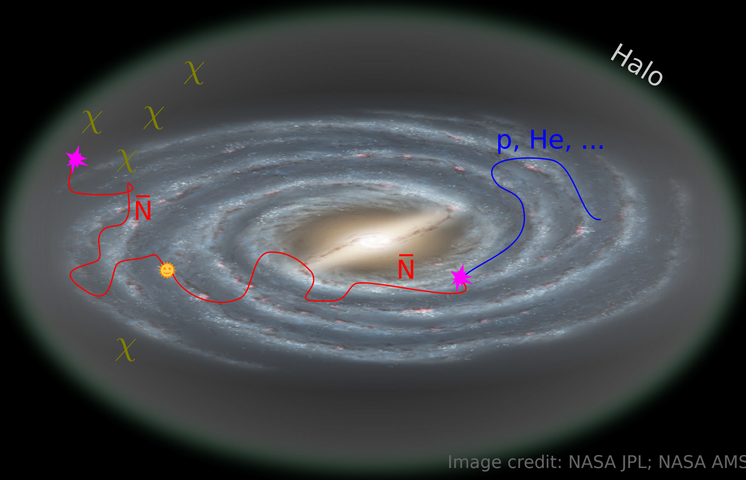
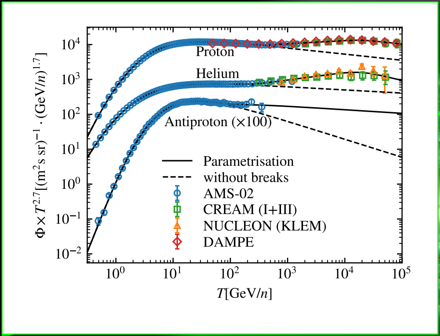
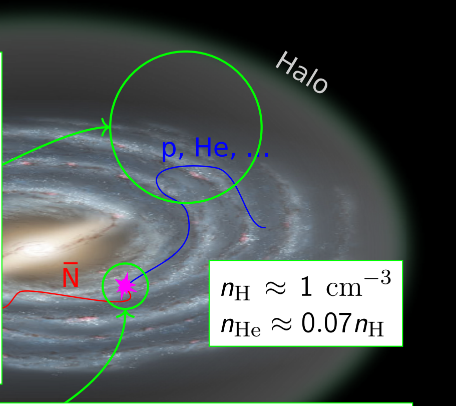


Image credit: NASA JPL; NASA AMS

Secondary source

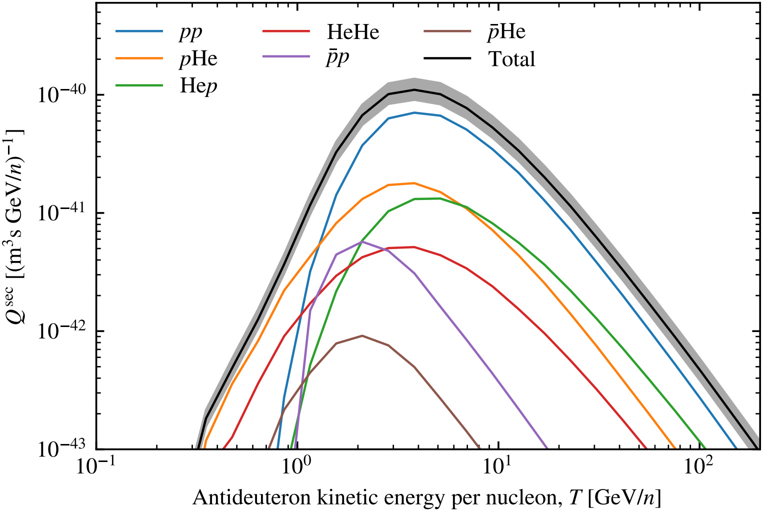




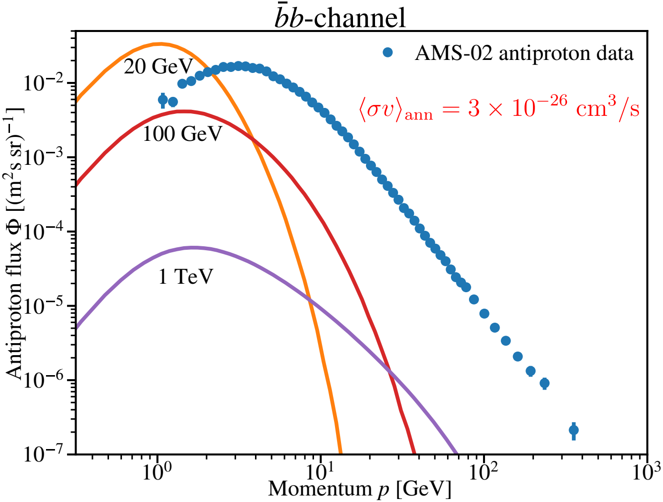
$n_{\mathrm{H}} \approx 1\ \mathrm{cm}^{-3}$
$n_{\mathrm{He}} \approx 0.07\, n_{\mathrm{H}}$

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

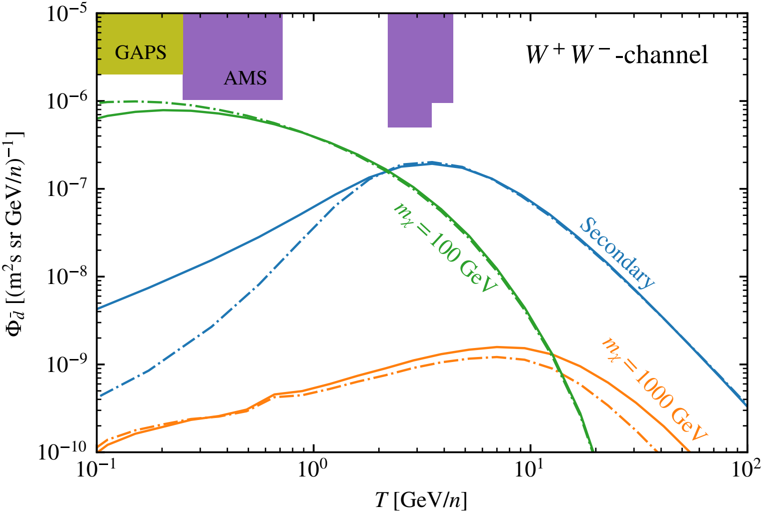
Secondary source



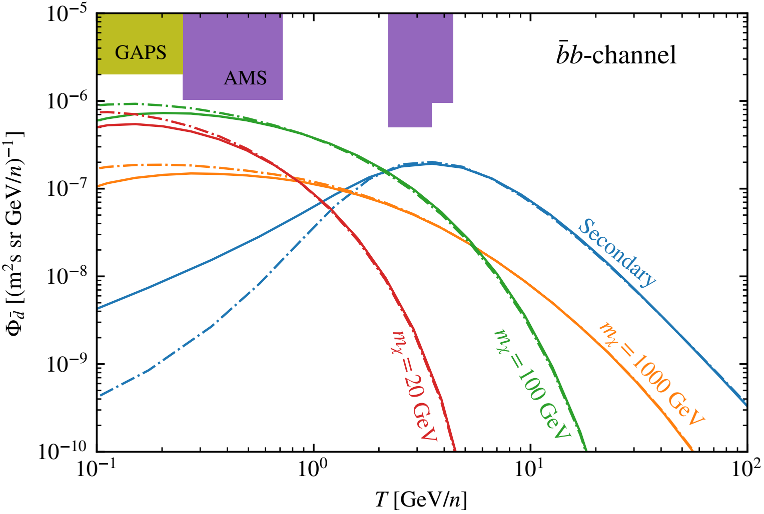
Primary source cannot exceed the antiproton spectrum



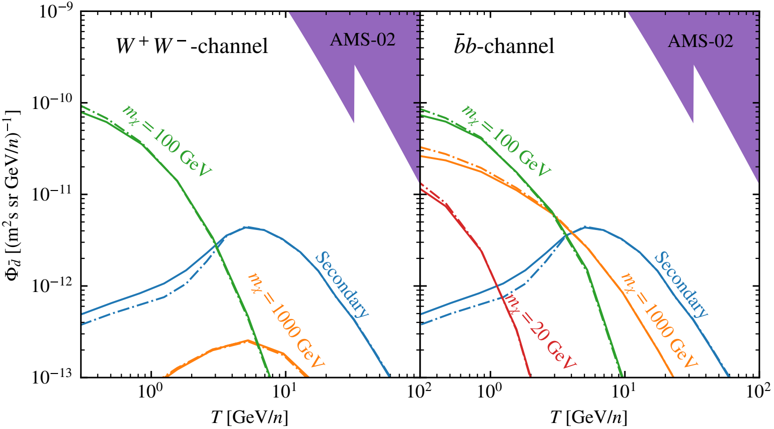
Detection prospects for antideuteron



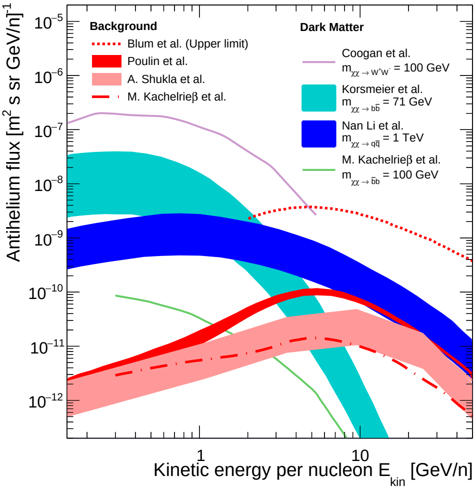
Detection prospects for antideuteron



Detection prospects for antihelium-3

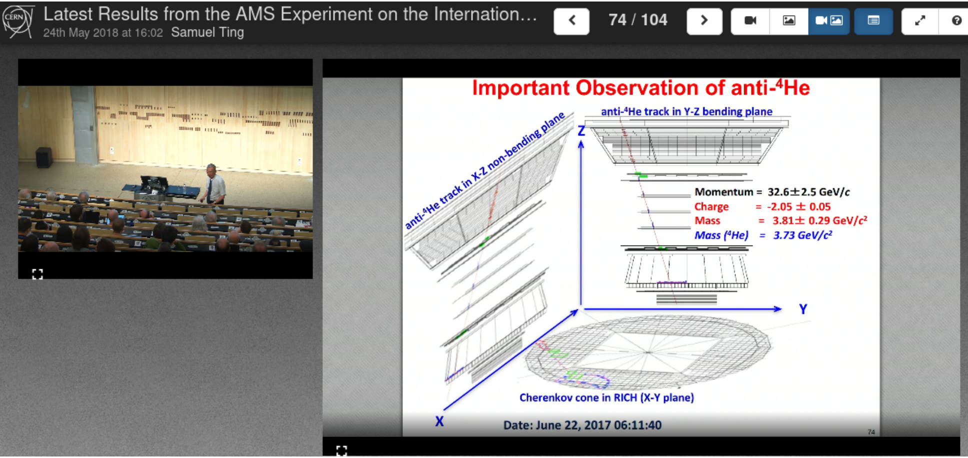


Detection prospects for antihelium-3



(Doetinchem [2002.04163])

The puzzling AMS-02 antihelium events



(S. Ting: CERN Colloquium 24 May 2018)

Summary

- Antinuclei offers a promising method of identifying the nature of exotic physics
- 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, has a microphysical picture and includes momentum correlations
- The new model does not change the detection prospects significantly
- The detection of cosmic ray antinuclei may be just around the corner

BACKUP SLIDES

Thermal state in heavy ion collisions

$$W^{\mathrm{th}}_{p,n}(\vec{p}_{p,n}, \vec{r}_{p,n}) = \frac{3}{4(mT_{\mathrm{k}}\sigma^2_{\mathrm{th}})^{3/2}} \exp\left\{ -\frac{p^2_{p,n}}{2mT_{\mathrm{k}}} - \frac{r^2_{p,n}}{2\sigma^2_{\mathrm{th}}} \right\}$$

$$N_d \sim N_n N_p \left(\frac{d^2}{d^2 + 4\sigma^2_{\mathrm{th}}} \right)^{3/2} \left(\frac{1}{mT_{\mathrm{k}} d^2 + 1} \right)^{3/2}$$

The traditional 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:

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

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

Coalescence of helium-3 and tritium

Helium-3 and tritium formation model

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

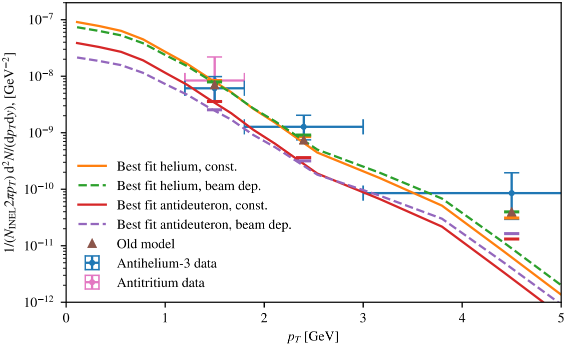
$$\zeta = \left(\frac{2b^2}{2b^2 + 4\sigma^2} \right)^3,$$

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

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

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

Best fit to the ALICE helium-3 data



Improving the deuteron wave function I

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

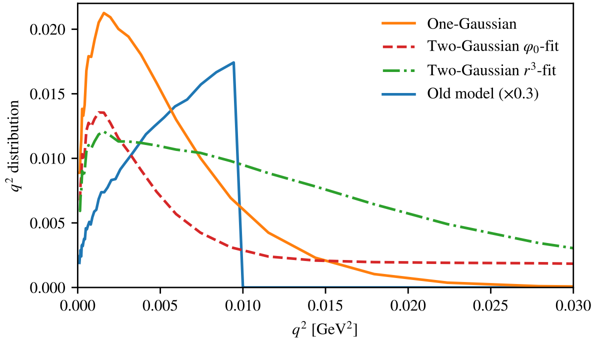
$$\varphi_d(\vec{r}) = \sqrt{\frac{\alpha\beta(\alpha+\beta)}{2\pi(\alpha-\beta)^2}}\,\frac{\mathrm{e}^{-\alpha r} - \mathrm{e}^{-\beta r}}{r},$$

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

Two-Gaussian wave function:

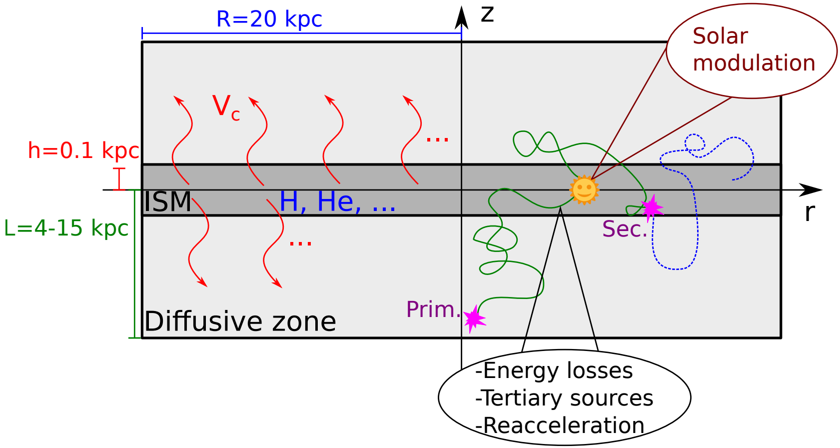
$$\varphi_d(\vec{r}) = \pi^{-3/4}\left(\mathrm{i}\sqrt{\frac{\Delta}{d_1^3}}\mathrm{e}^{-r^2/2d_1^2} + \sqrt{\frac{1-\Delta}{d_2^3}}\mathrm{e}^{-r^2/2d_2^2}\right).$$

Improving the deuteron wave function II



Pythia, *pp* collisions at $\sqrt{s} = 7\ \mathrm{TeV}$

The two-zone propagation model



- Semi-analytical solution (Maurin et al. [astro-ph/0101231])
- Parameters are constrained using e.g. a B/C study (Aramaki [1505.07785]); MED–MAX parameters