

COSMIC RAY ANTINUCLEI



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Summary

- ▶ M. Kachelrieß, S. Ostapchenko and JT [1905.01192, 2002.10481, and work in progress]
- ▶ Recent Review: P. von Doetinchem et al. (2020) [2002.04163]

Motivation

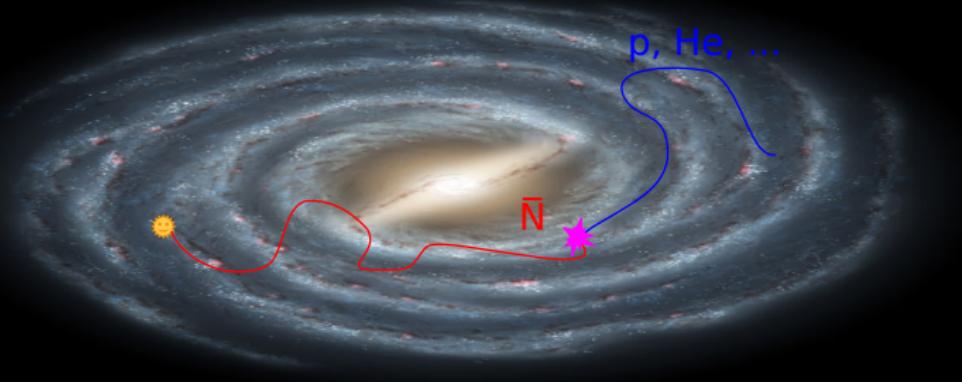


Image credit: NASA JPL; NASA AMS

Motivation

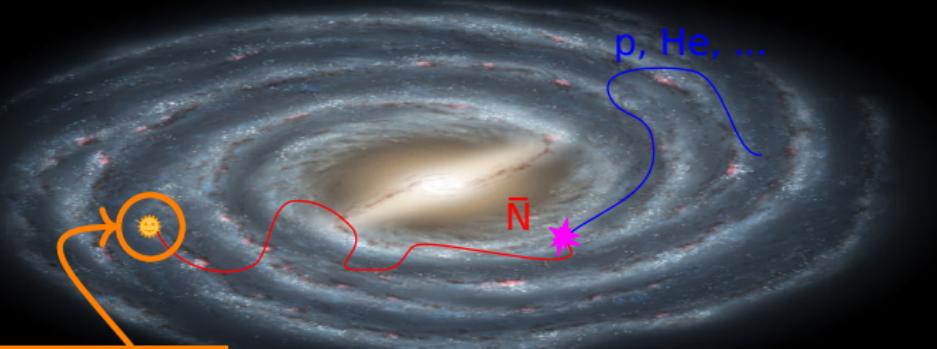


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Motivation

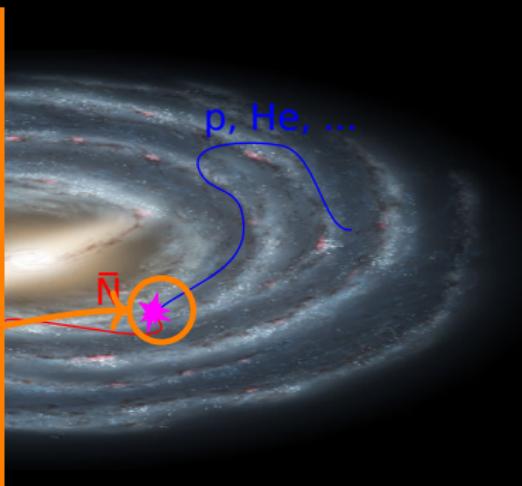
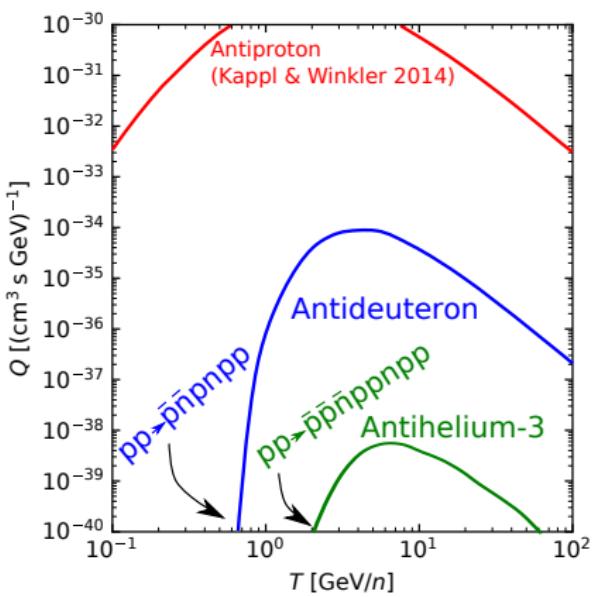


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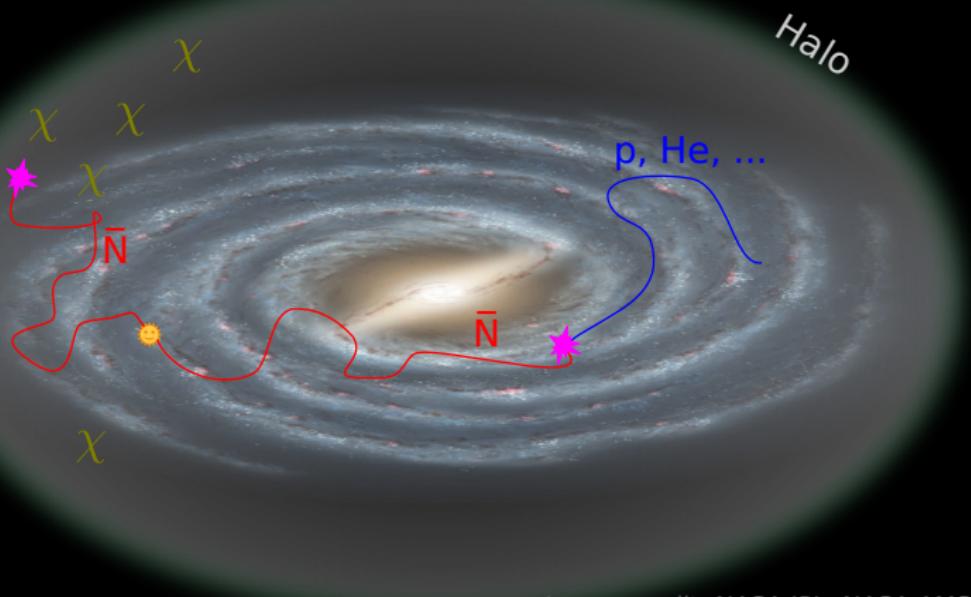
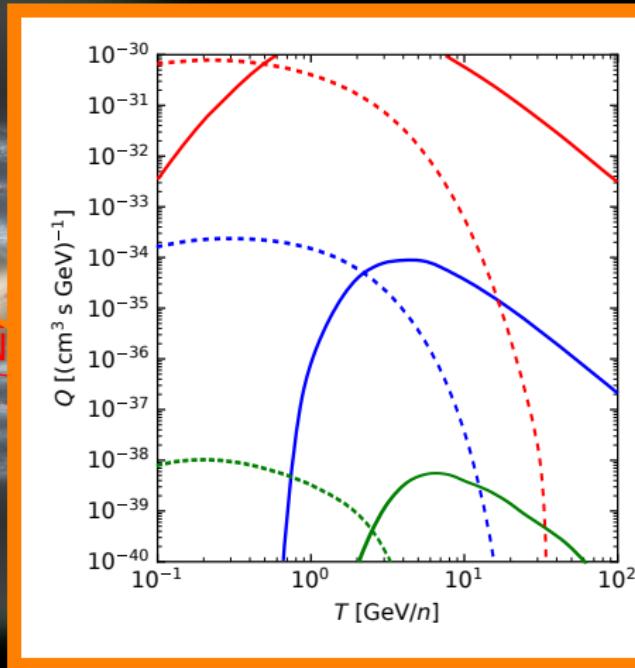
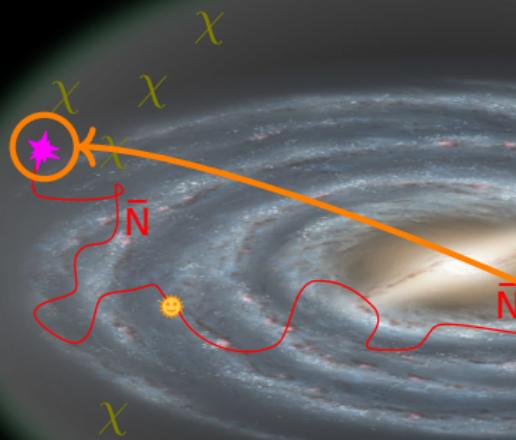
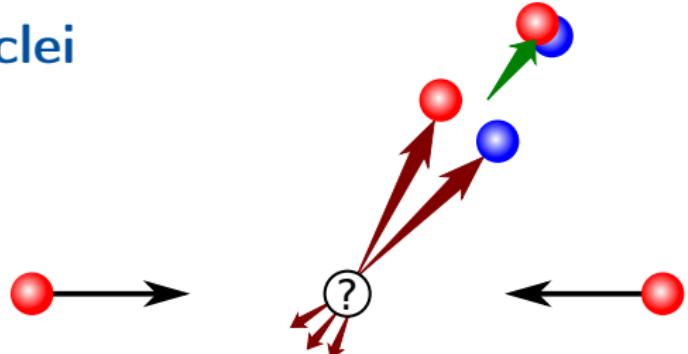


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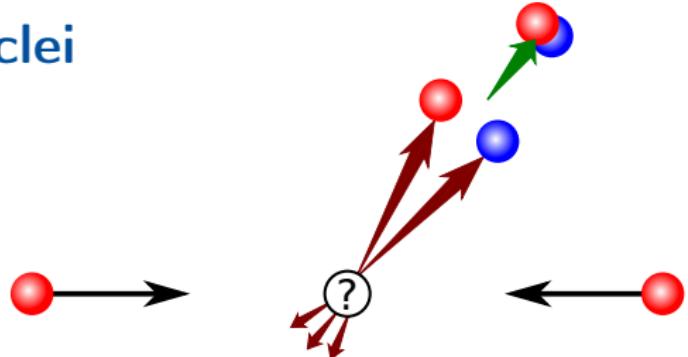


Formation of antinuclei



- ▶ $E_A \frac{d^3 N_A}{dP_A^3} = B_A \left(E_p \frac{d^3 N_p}{dP_p^3} \right)^Z \left(E_n \frac{d^3 N_n}{dP_n^3} \right)^N \Big|_{P_p = P_n = P_A/A}$
- ▶ Nucleon capture process $p + n \rightarrow d^*$

Formation of antinuclei

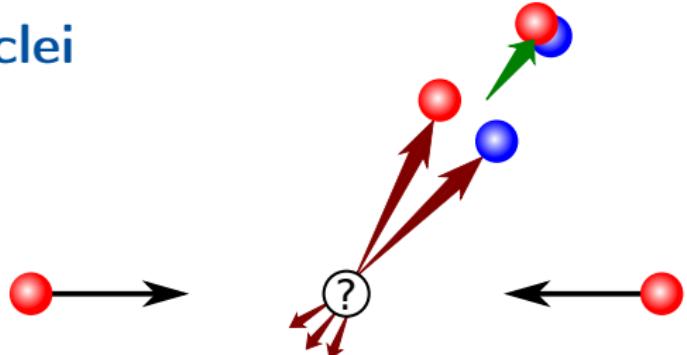


$$\blacktriangleright E_A \frac{d^3 N_A}{dP_A^3} = B_A \left(E_p \frac{d^3 N_p}{dP_p^3} \right)^Z \left(E_n \frac{d^3 N_n}{dP_n^3} \right)^N \Big|_{P_p = P_n = P_A/A}$$

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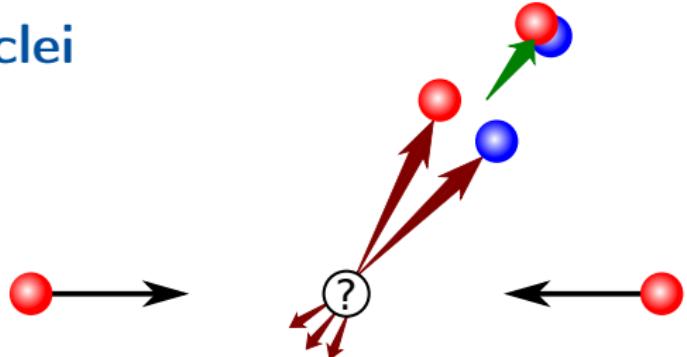
Nucleus	Constituents	Mass [GeV]	Binding energy [MeV]
Deuteron	pn	1.876	2.22
Triton	pnn	2.809	8.48
Helion	ppn	2.808	8.83

Formation of antinuclei



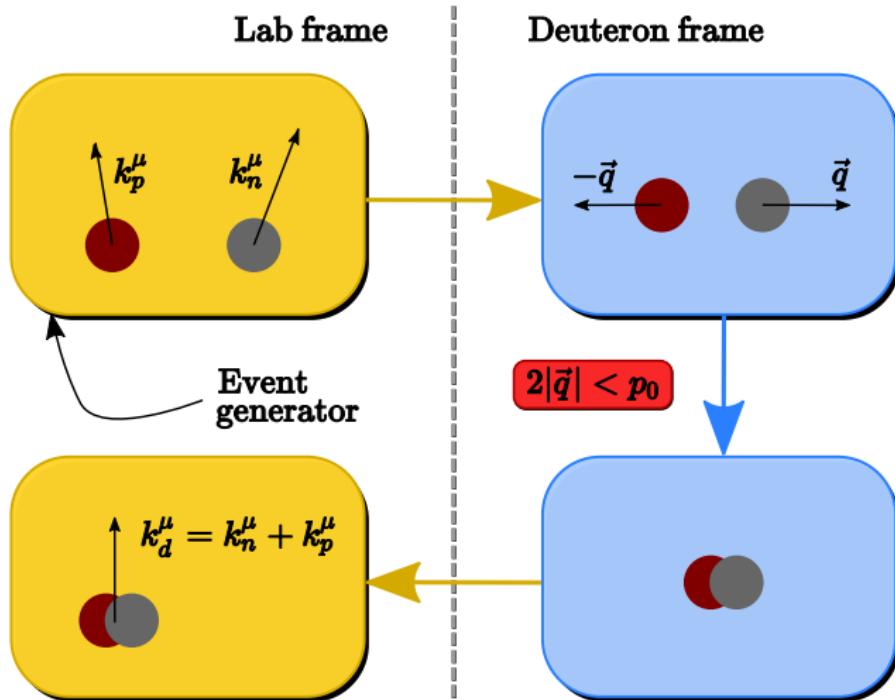
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- ▶ Nucleon capture process $p + n \rightarrow d^*$
- ▶ The particles must be close in momentum space: $2|\vec{q}| < p_0$

Formation of antinuclei

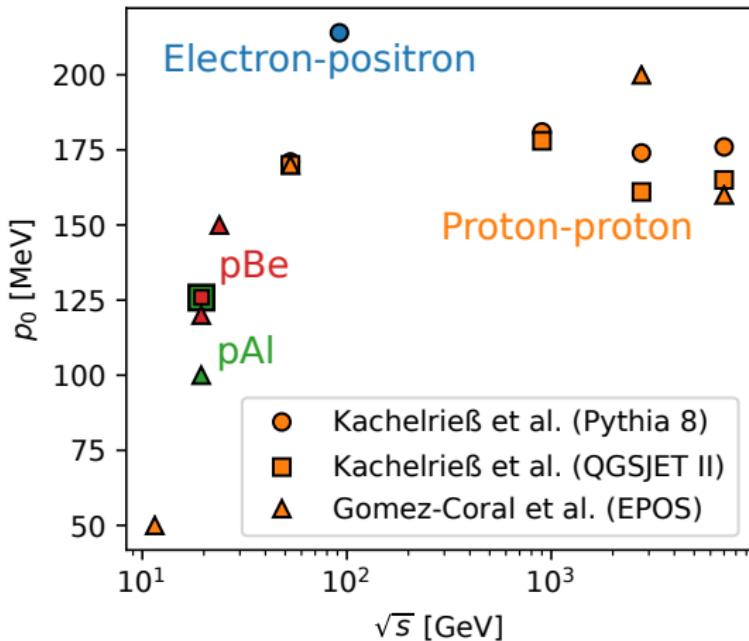


- ▶ $E_A \frac{d^3 N_A}{dP_A^3} = B_A \left(E_p \frac{d^3 N_p}{dP_p^3} \right)^Z \left(E_n \frac{d^3 N_n}{dP_n^3} \right)^N \Big|_{P_p = P_n = P_A/A}$
- ▶ Nucleon capture process $p + n \rightarrow d^*$
- ▶ The particles must be close in momentum space: $2|\vec{q}| < p_0$
- ▶ Isotropic nucleon yields $\Rightarrow B_A \propto p_0^{3(A-1)}$

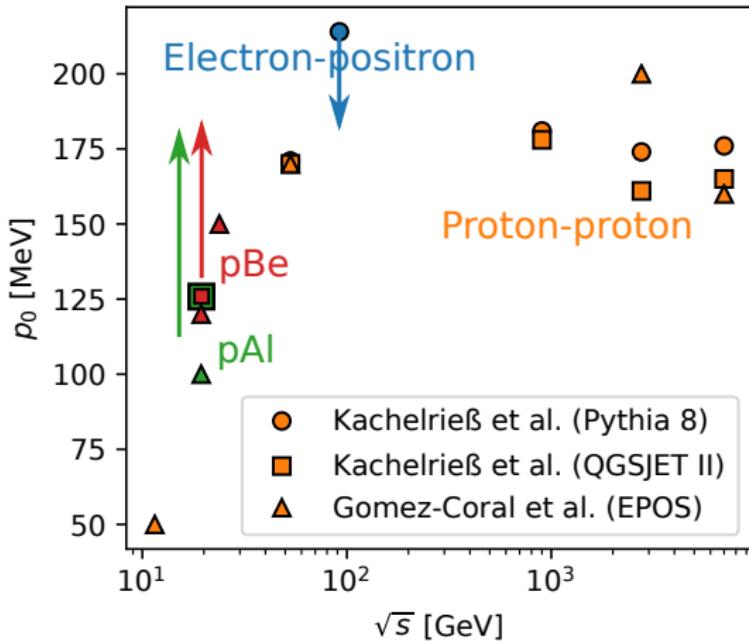
The coalescence model in momentum space



The coalescence model in momentum space



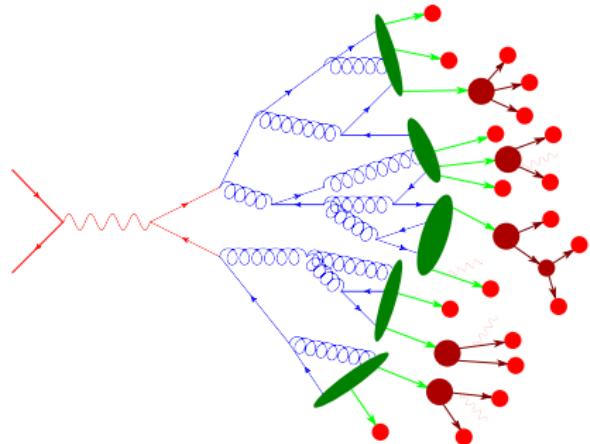
The coalescence model in momentum space



We should take into account also the process dependence!

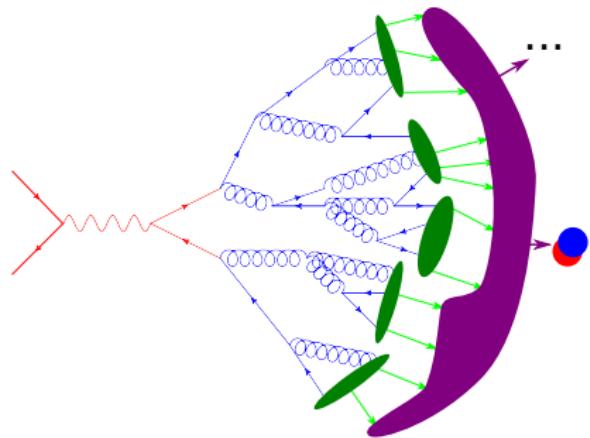
Timescales

- ▶ Hard process: $t_{\text{ann}} \sim 1/\sqrt{s}$
- ▶ Perturbative cascade:
 $\Lambda_{\text{QCD}}^2 \ll |q^2| \ll s$
- ▶ Hadronisation:
 $L_{\text{had}} \simeq \gamma L_0, L_0 \sim R_p \simeq 1 \text{ fm}$



Timescales

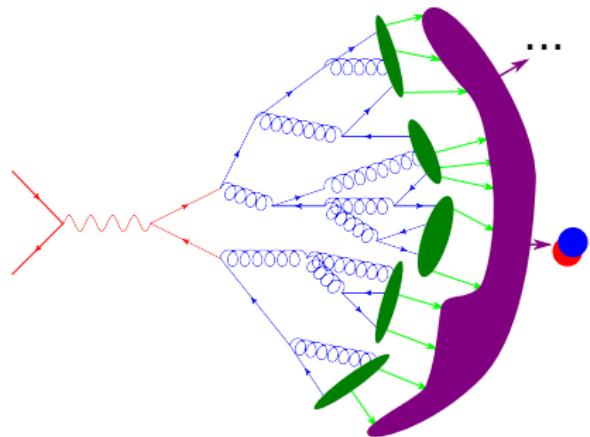
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- ▶ Coalescence:
merging of nucleons that have nearly completed their formation



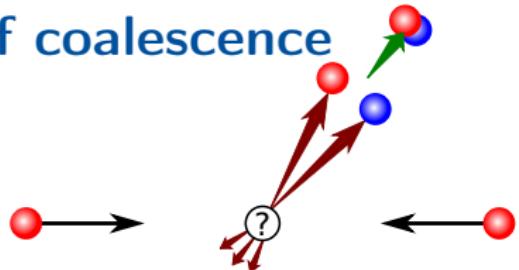
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merging of nucleons that have nearly completed their formation

$r_{\text{rms}}^d \sim 2 \text{ fm} \sim L_0 \implies$ The size of the formation region must be taken into account!



The quantum mechanics of coalescence



► $\frac{d^3 N_d}{dp_d^3} = \text{tr } \rho_d \rho_{\text{nucl}}$ (Scheibl and Heinz [nucl-th/9809092])

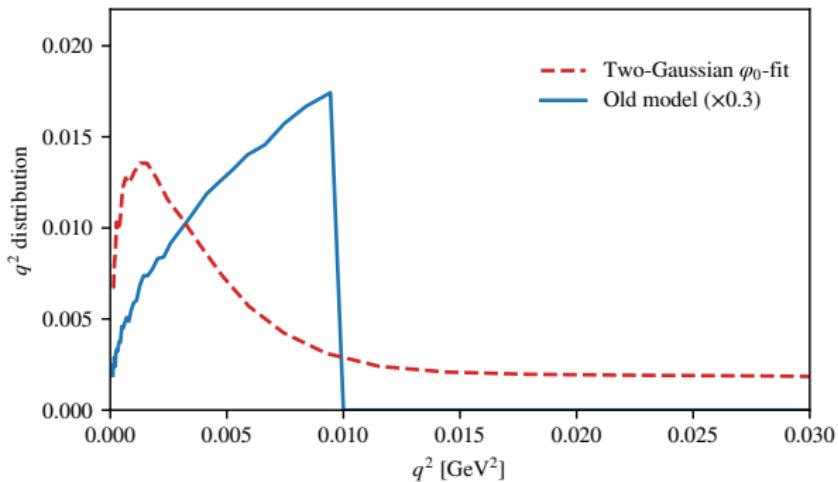
Coalescence probability (Kachelriess et al. [1905.01192])

$$w = 3\zeta(\sigma) \exp\{-q^2 d^2\}; \quad d \simeq 3.2 \text{ fm}$$

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

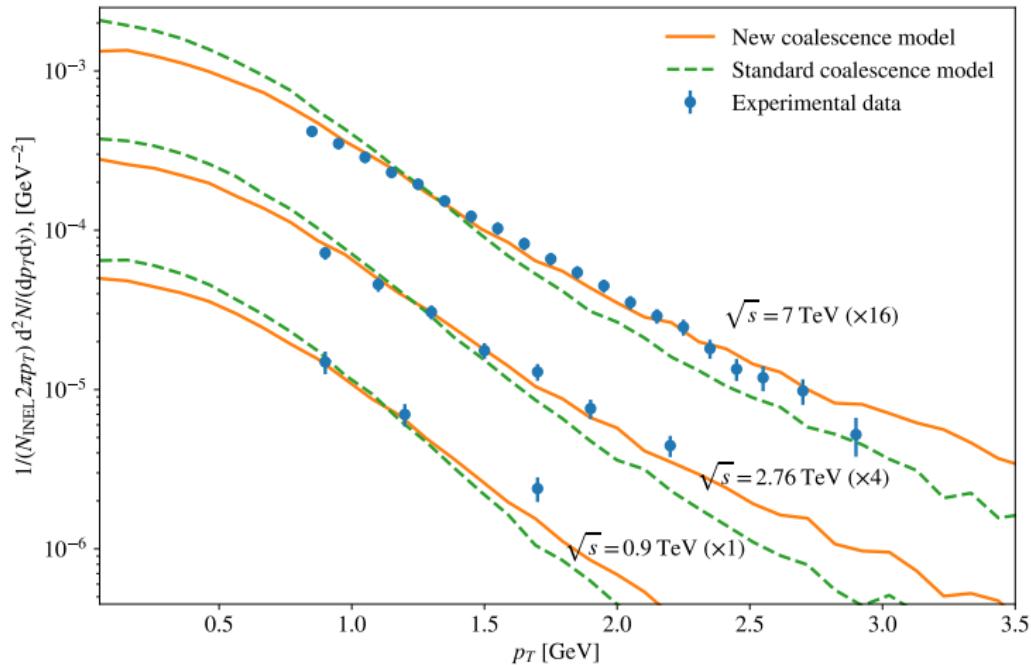
$$\sigma \equiv \sigma_{(e^+ e^-)} \simeq \sigma_{pp}/\sqrt{2} \simeq 1 \text{ fm}$$

Momentum distributions in the coalescence models



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

Experimental data: antideuteron spectrum



Proton-proton collisions, ALICE [1709.08522]

MC: Pythia 8.2

Detection prospects for cosmic ray antinuclei

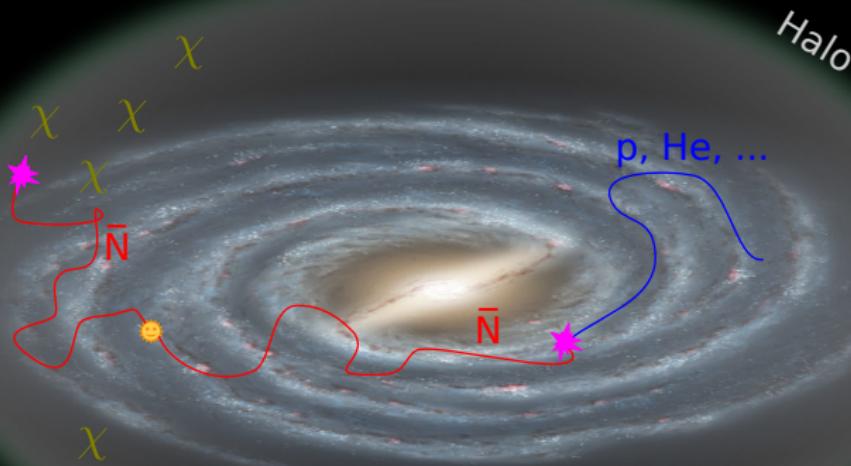
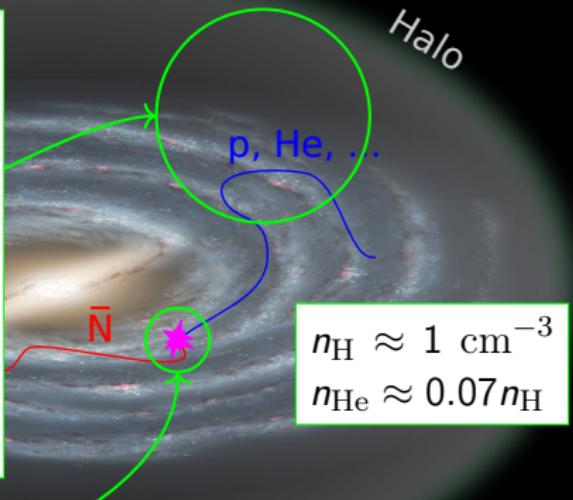
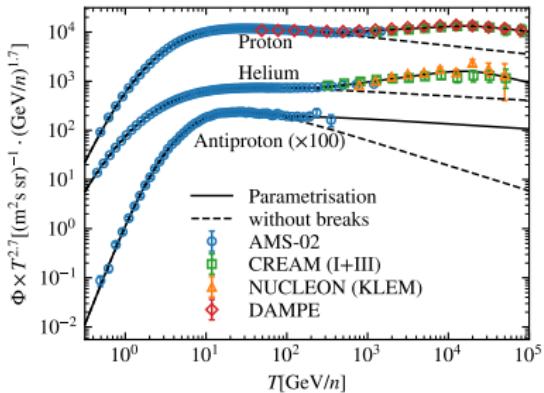


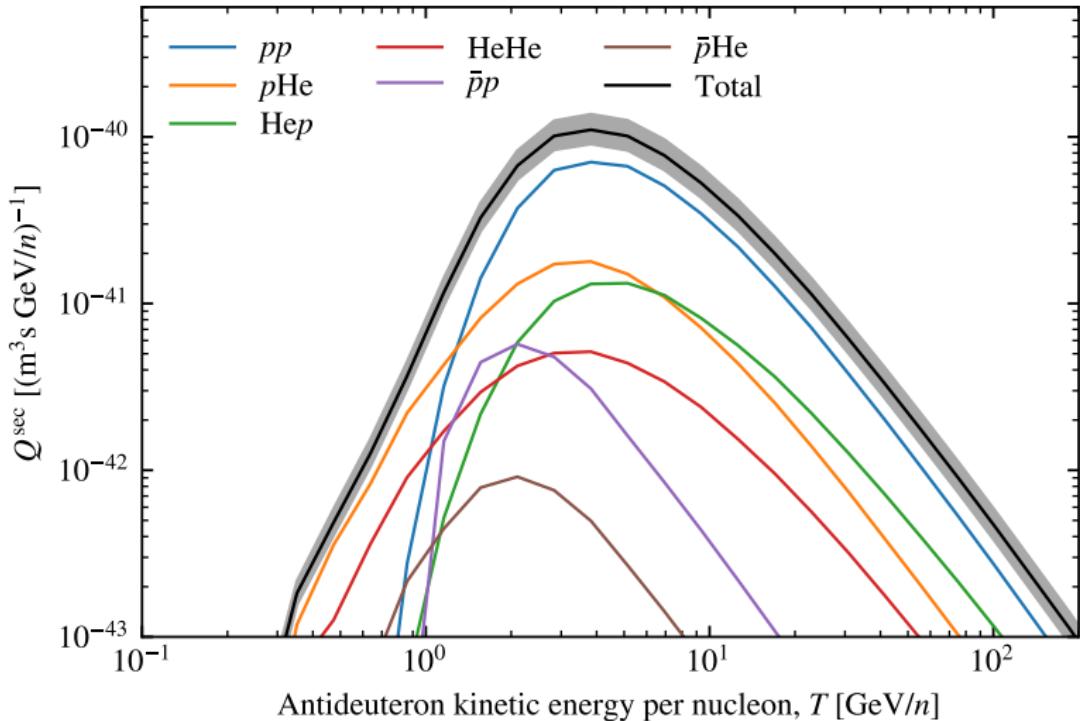
Image credit: NASA JPL; NASA AMS

Secondary source

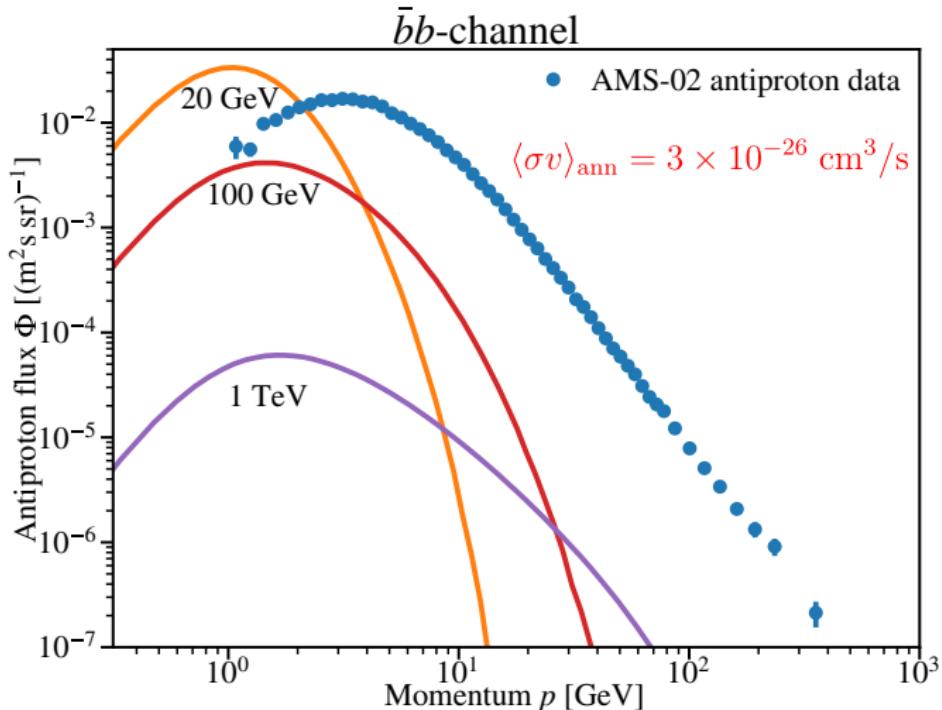


$$Q_{pp}^{\text{sec}}(T_{\bar{N}}, \vec{r}) = 4\pi n_p(\vec{r}) \int_{T_{\min}^{(p,p)}}^{\infty} dT_p \frac{d\sigma_{p,p}(T_p, T_{\bar{N}})}{dT_{\bar{N}}} \Phi_p(T_p, \vec{r})$$

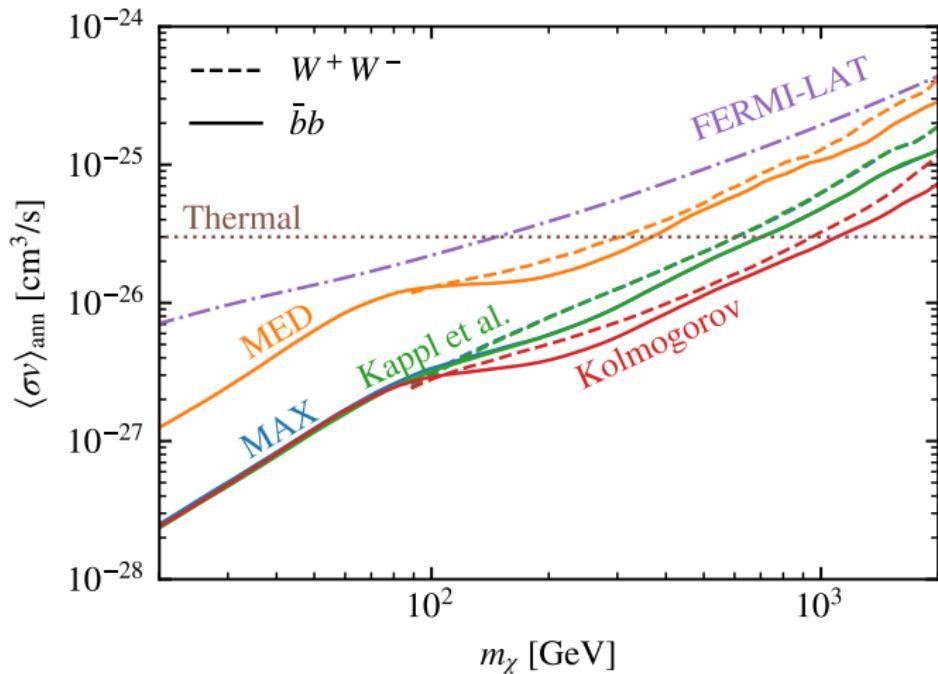
Secondary source



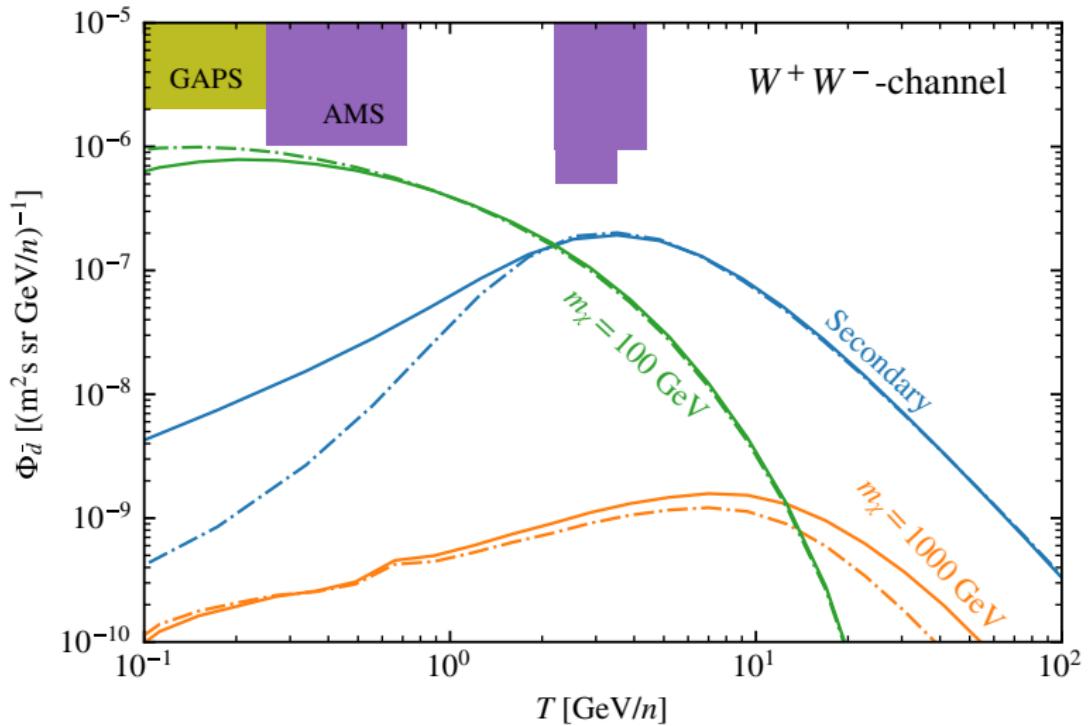
Primary source cannot exceed the antiproton spectrum



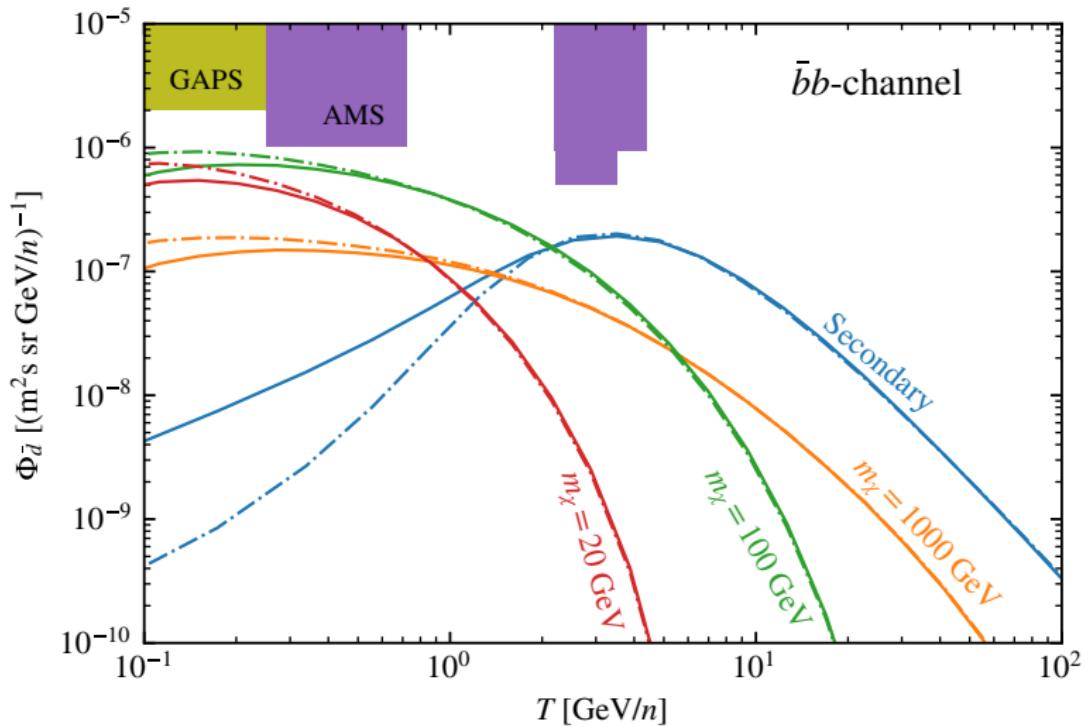
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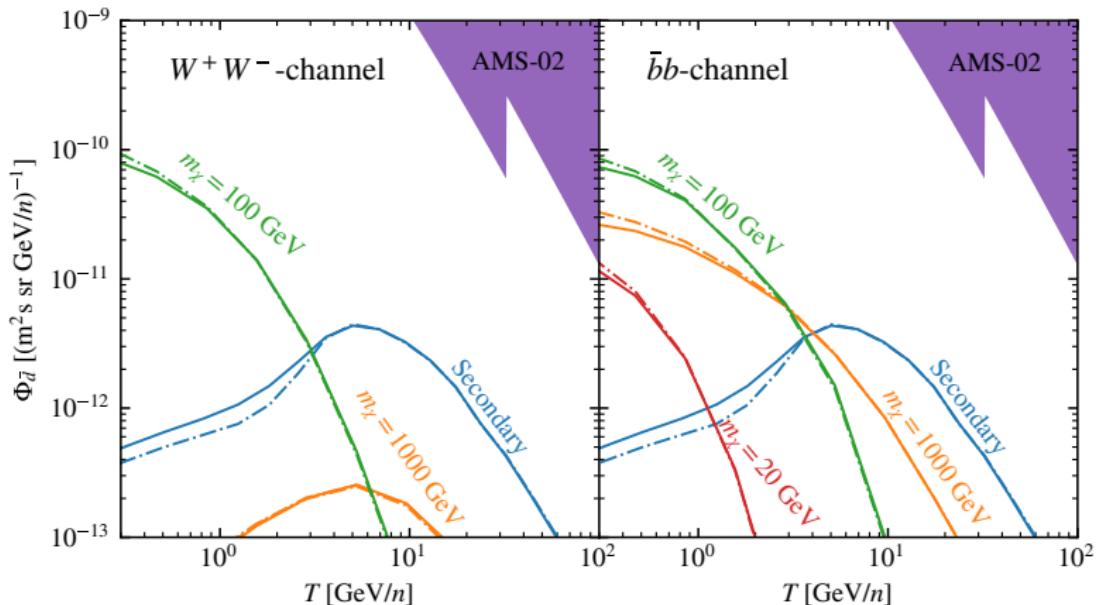
Detection prospects for antideuteron



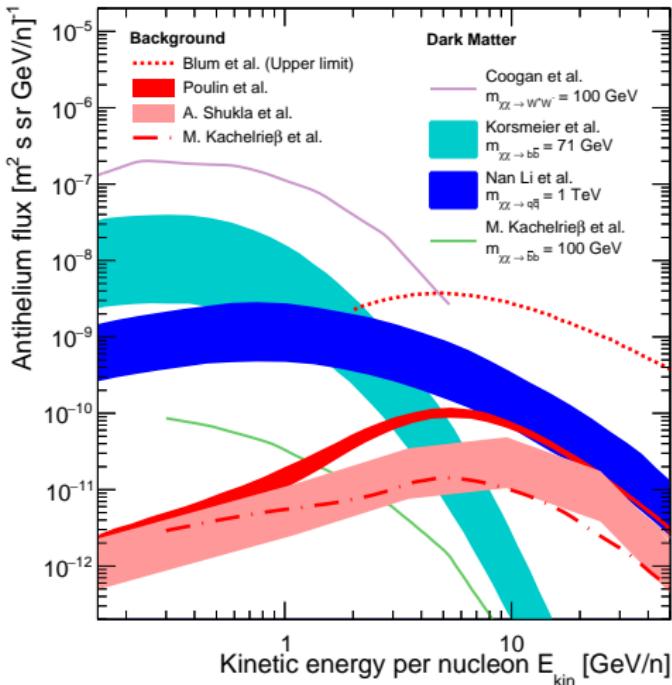
Detection prospects for antideuteron



Detection prospects for antihelium-3



Detection prospects for antihelium-3



(Doetinchem [2002.04163])

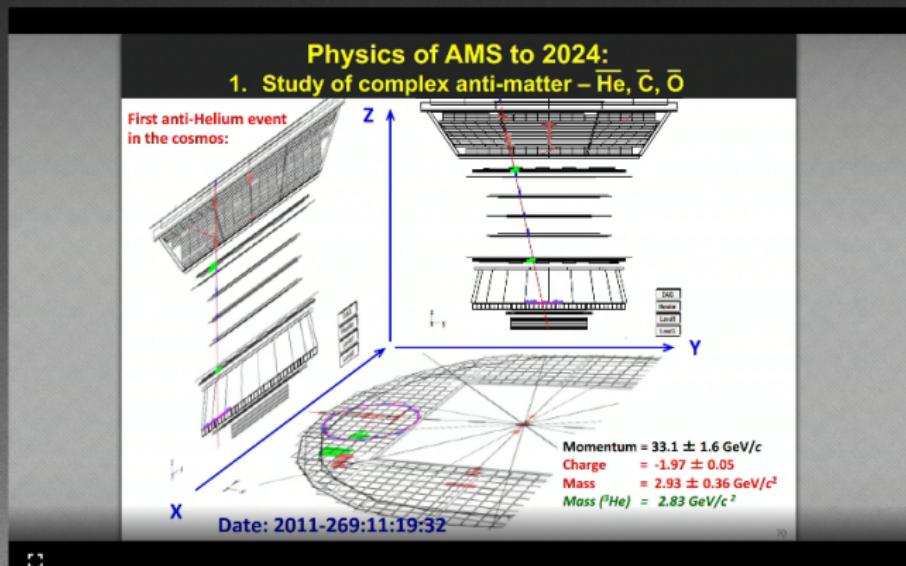
The puzzling AMS-02 antihelium events



Latest Results from the AMS Experiment on the Internation...

24th May 2018 at 16:02 Samuel Ting

70 / 104



(S. Ting: CERN Colloquium 24 May 2018)

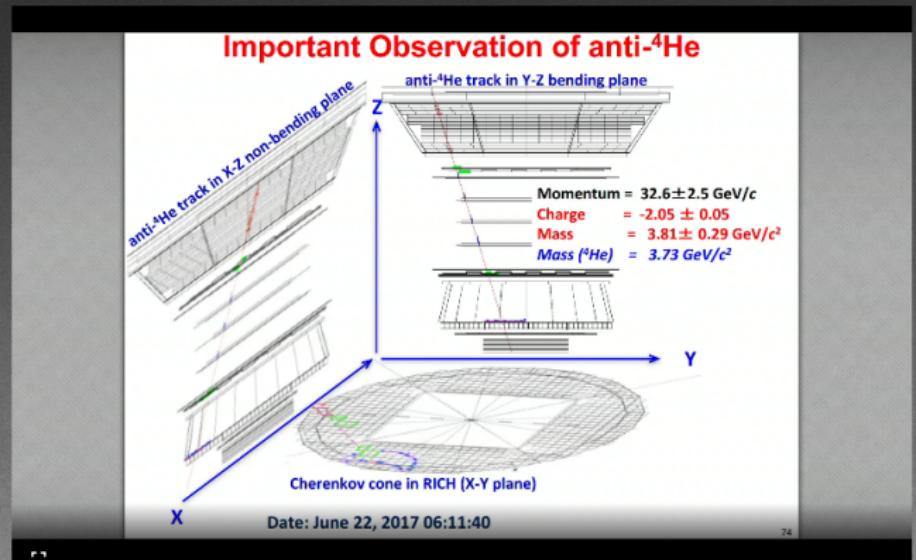
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74

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The puzzling AMS-02 antihelium events



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24th May 2018 at 16:02 Samuel Ting

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Observations on ${}^4\bar{\text{He}}$

1. We have two ${}^4\bar{\text{He}}$ events with a background probability of 3×10^{-3} .
2. Continuing to take data through 2024 the background probability for ${}^4\bar{\text{He}}$ would be 2×10^{-7} , i.e., greater than 5-sigma significance.
3. The ${}^3\text{He}/{}^4\text{He}$ ratio is 10-20% yet ${}^3\bar{\text{He}}/{}^4\bar{\text{He}}$ ratio is 300%. More data will resolve this mystery.

(S. Ting: CERN Colloquium 24 May 2018)

Summary

- ▶ Cosmic ray antinuclei offer a promising probe for identifying the nature of exotic physics
- ▶ Theoretical estimations has large uncertainties induced mainly by propagation and productino models
- ▶ One should include both **momentum correlations** and the **size of the formation region** when estimating the production in astrophysical processes
- ▶ *The detection of cosmic ray antinuclei may be just around the corner!*

BACKUP SLIDES

The new coalescence model

Deuteron formation model

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

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

1. Two-nucleon momentum distribution

2. Size of the deuteron

$$d = 3.2 \text{ fm}$$

3. Spatial distribution factor

$$\sigma \sim 1 \text{ fm free parameter}$$



Coalescence of helium-3 and tritium

Helium-3 and tritium formation model

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

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

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

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

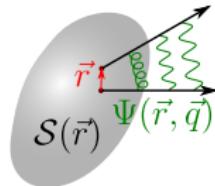
Femtoscopy experiments

- ▶ Measurable quantity:

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

- ▶ A Gaussian source is often assumed in experiments

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



Femtoscopy experiments

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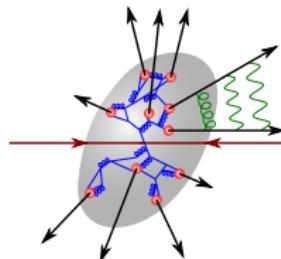
$$\mathcal{C}(\vec{q}) = \int d^3r S(\vec{r}) |\Psi(\vec{r}, \vec{q})|^2$$

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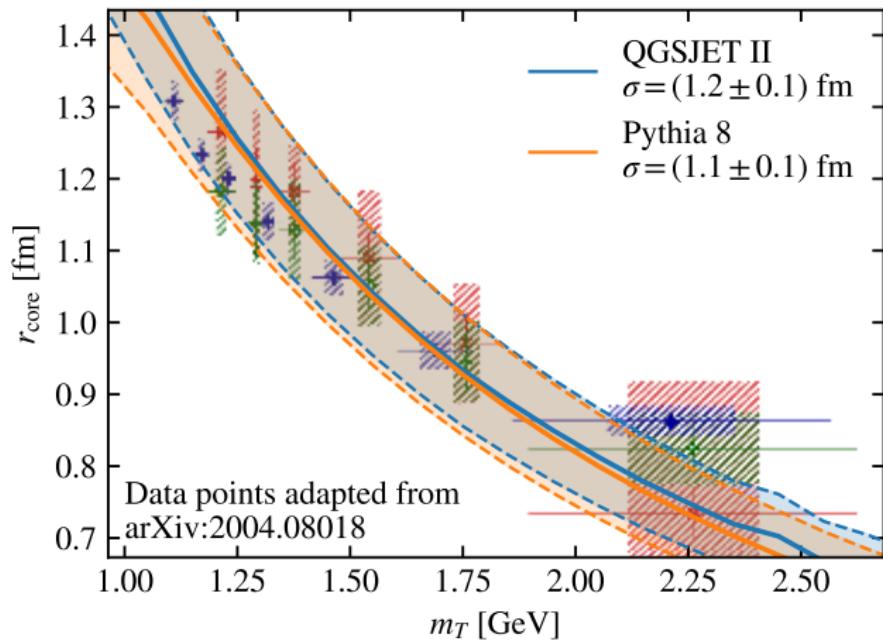
$$S(\vec{r}) \propto \exp\left\{-\frac{r^2}{4r_0^2}\right\}$$

- ▶ The nucleon Wigner functions predict the baryon source

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

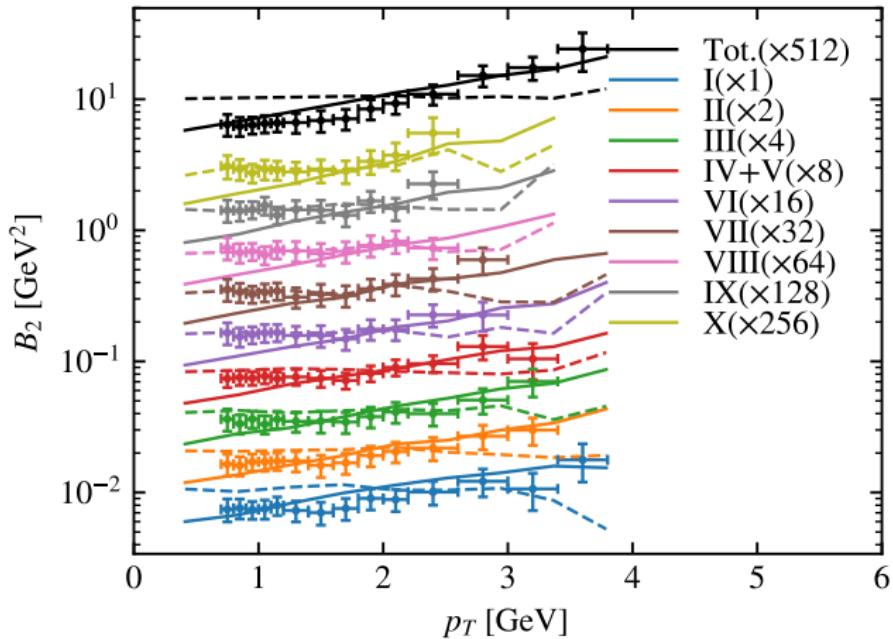


Experimental data: baryon emission source



Preliminary

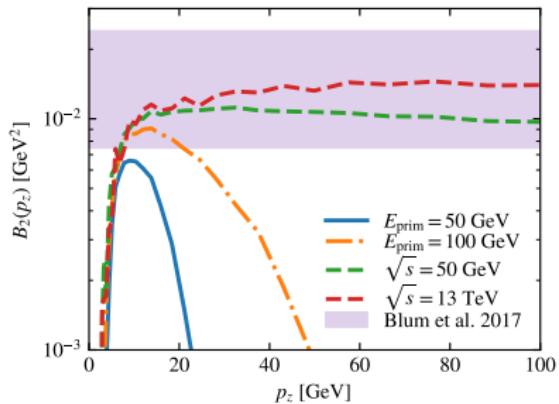
Coalescence parameter, $B_2(p_z)$



pp 13 TeV (Acharya [2003.03184])

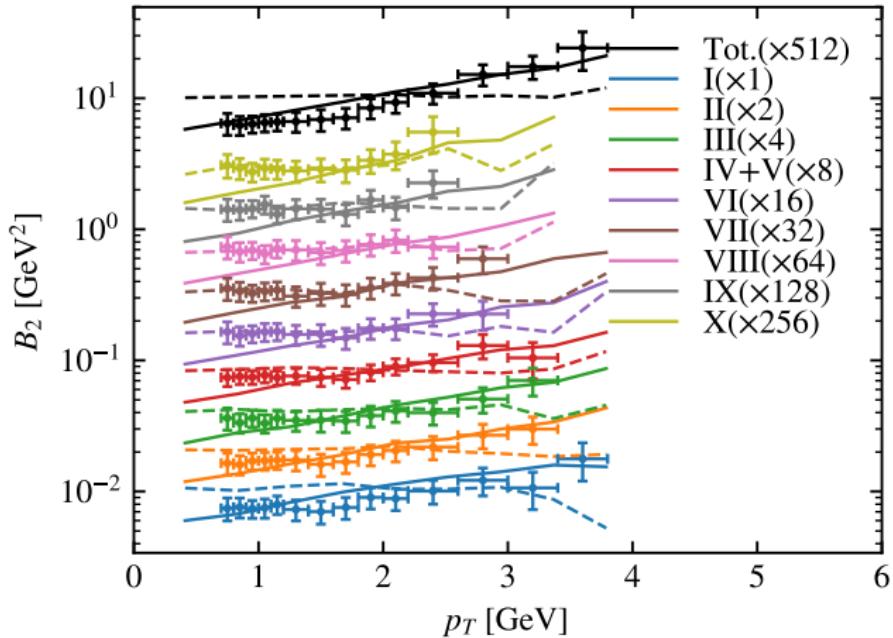
Preliminary

Coalescence parameter, $B_2(p_z)$



Preliminary

Coalescence parameter, $B_2(p_T)$



pp 13 TeV (Acharya [2003.03184])

Preliminary

Improving the deuteron wave function

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

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

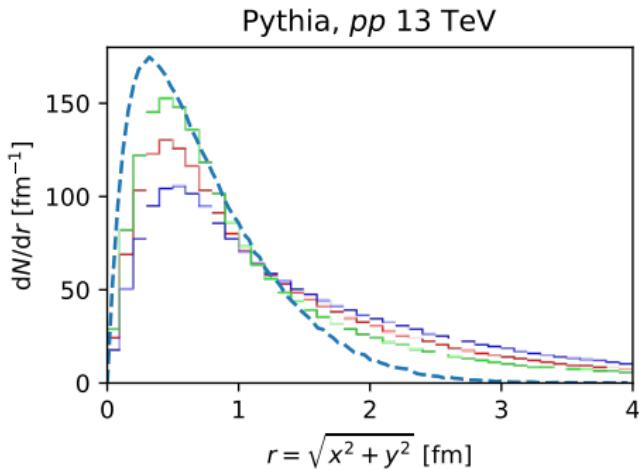
with $\alpha = 0.23\text{fm}^{-1}$ and $\beta = 1.61\text{fm}^{-1}$ (**Zhaba 2017**).

Two-Gaussian wave function:

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

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:

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

Thermal model for nucleus production

$$W_{p,n}^{\text{th}}(\vec{p}_{p,n}, \vec{r}_{p,n}) = \frac{3}{4(mT_k\sigma_{\text{th}}^2)^{3/2}} \exp\left\{-\frac{p_{p,n}^2}{2mT_k} - \frac{r_{p,n}^2}{2\sigma_{\text{th}}^2}\right\}$$
$$N_d \sim N_n N_p \left(\frac{d^2}{d^2 + 4\sigma_{\text{th}}^2}\right)^{3/2} \left(\frac{1}{mT_k d^2 + 1}\right)^{3/2}$$