FORMATION OF LIGHT (ANTI)NUCLEI

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

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Tools 2020

Content

Motivation: Cosmic ray antinuclei

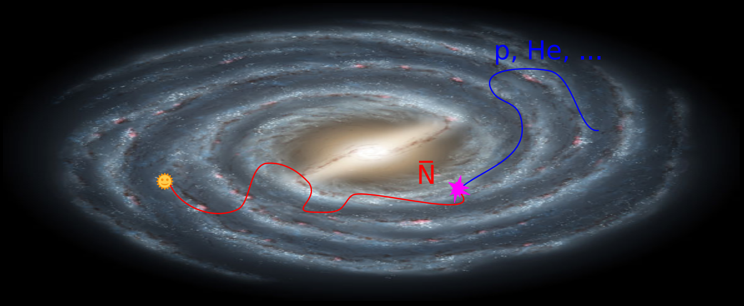

Image credit: NASA JPL; NASA AMS

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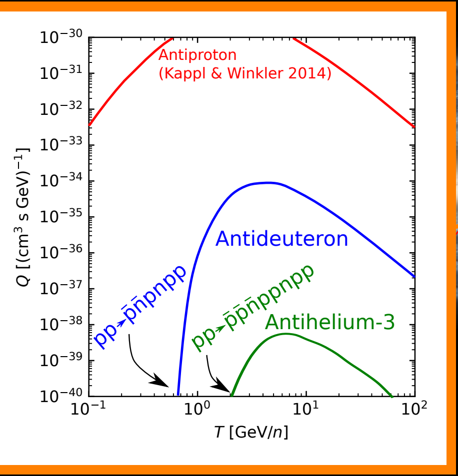


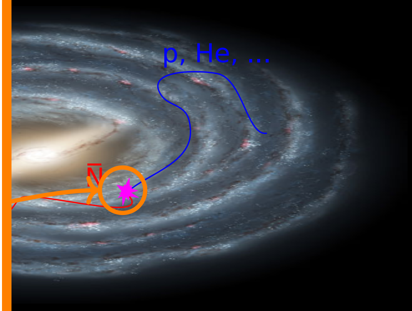
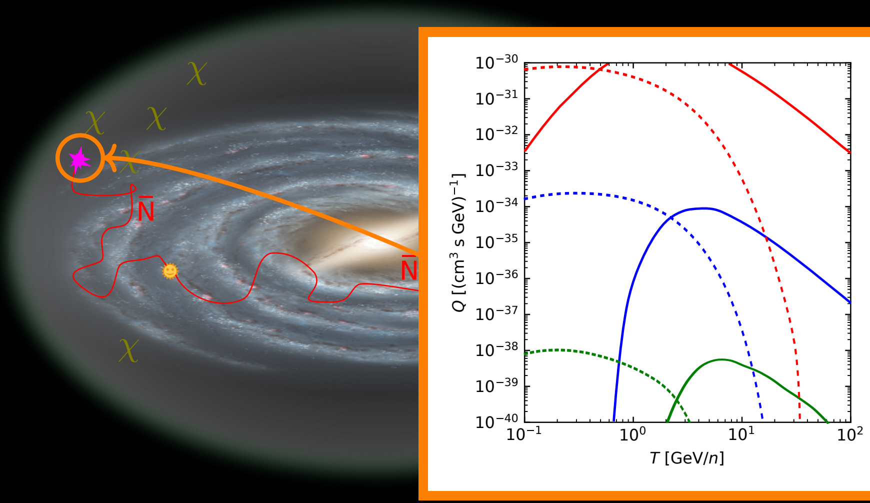
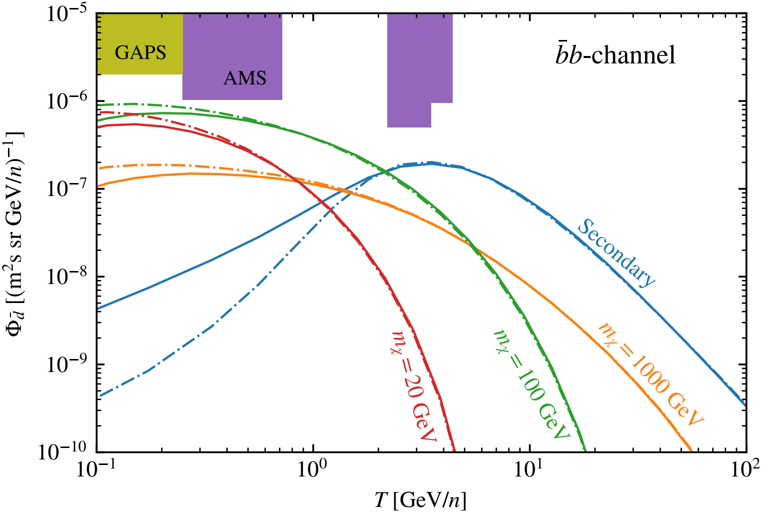


Image credit: NASA JPL; NASA AMS

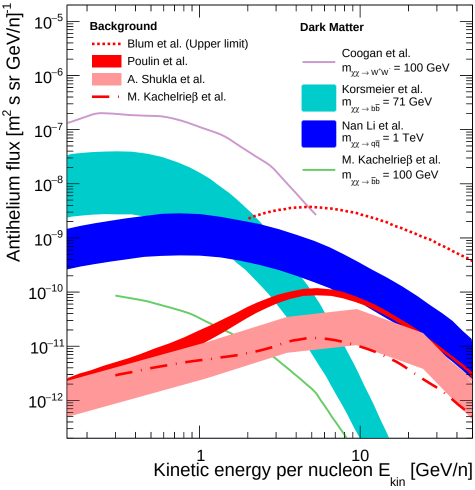
Motivation


χ
χ
χ
χ
χ
N̄
N̄
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
Q [(cm^3 s GeV)$^{-1}$]
10^{-1}
10^{0}
10^{1}
10^{2}
T [GeV/n]

Detection prospects for antideuteron

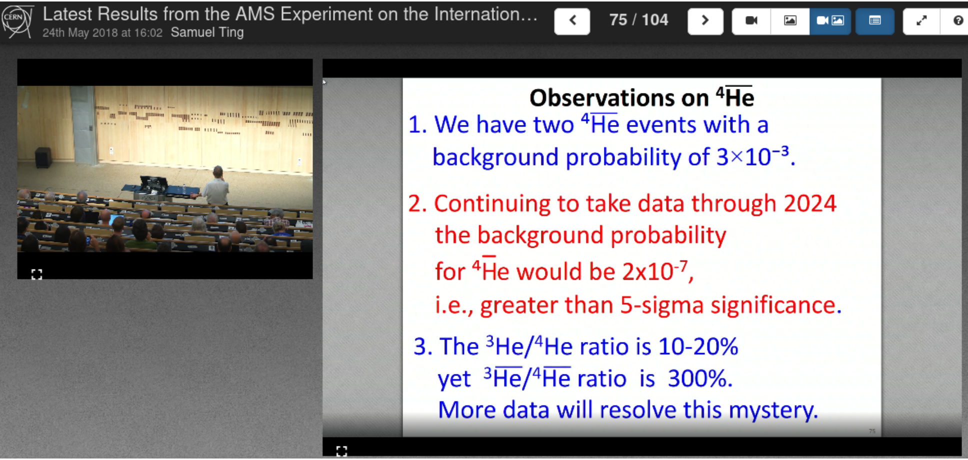


Detection prospects for antihelium-3



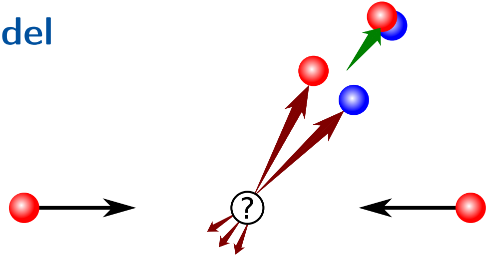
(Doetinchem [2002.04163])

The puzzling AMS-02 antihelium events



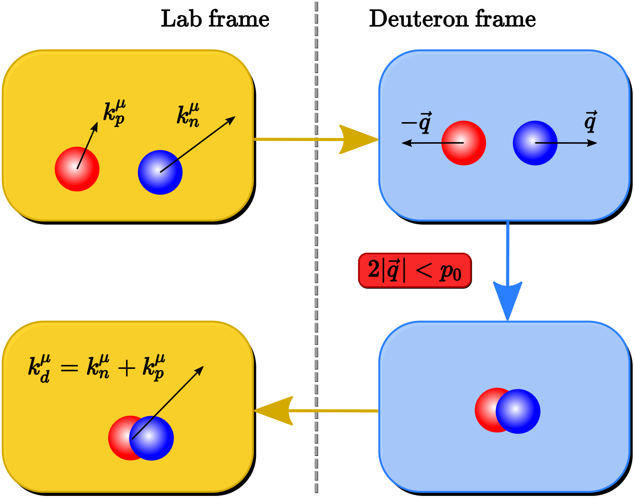
(S. Ting: CERN Colloquium 24 May 2018)

The coalescence model



- Nucleon capture process $p + n \to d^*$
- $E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}P_A^3} = B_A \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}P_p^3} \right)^Z \left(E_n \frac{\mathrm{d}^3 N_n}{\mathrm{d}P_n^3} \right)^N \Bigg|_{P_p = P_n = P_A/A}$
- Small interacting systems: $B_A \propto p_0^{3(A-1)}$

The coalescence model in momentum space



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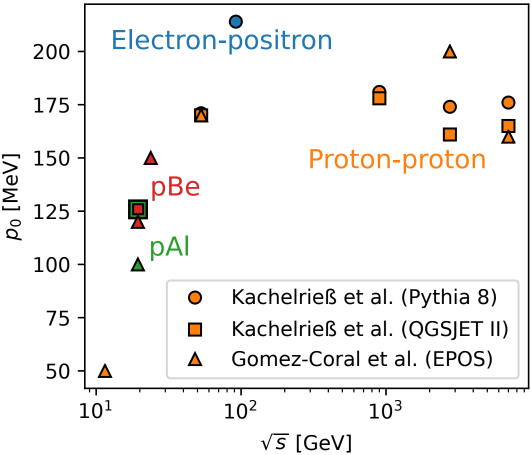

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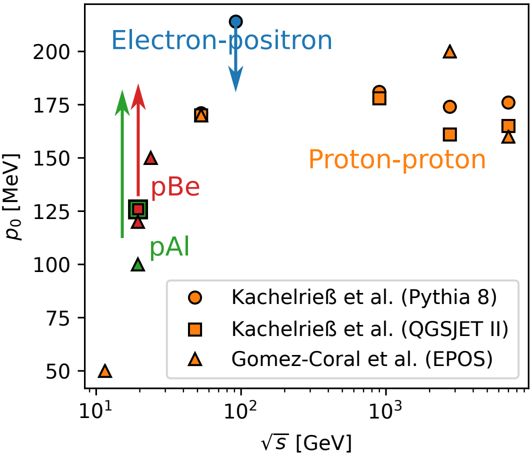
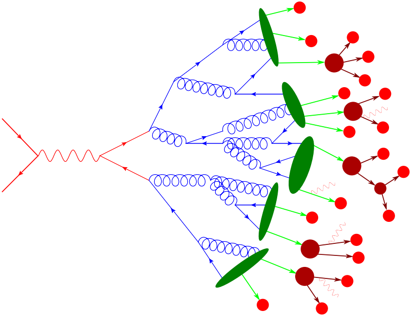


We should take into account also the process dependence!

Comment: Timescales

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



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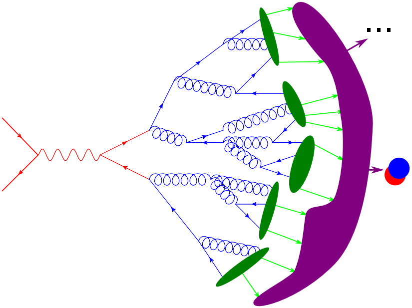
  merging of nucleons that have nearly completed their formation



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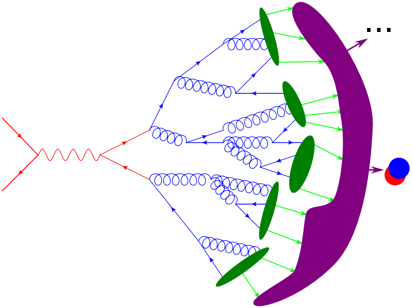

$r^d_{\mathrm{rms}} \sim 2\ \mathrm{fm} \sim L_0 \Longrightarrow$ The size of the formation region must be taken into account!

The quantum mechanics of coalescence

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

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

  - Internal deuteron Wigner function
  - Two-nucleon Wigner function

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  - Internal deuteron Wigner function → $\mathcal{D}(\vec{r}, \vec{q})$
  - Two-nucleon Wigner function → $W_{np}(\vec{p}_p, \vec{p}_n, \vec{r}_p, \vec{r}_n)$

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

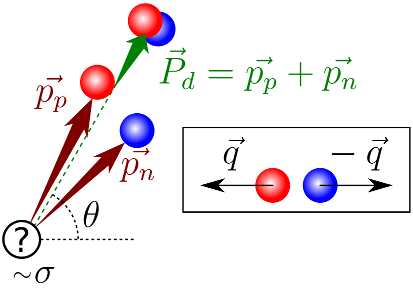
$$H_{np}(\vec{r}_n, \vec{r}_p) = h(\vec{r}_n) h(\vec{r}_p) \qquad h(\vec{r}) = (2\pi\sigma^2)^{-3/2} \exp\left\{-\frac{r^2}{2\sigma^2}\right\}$$

The new coalescence model for (anti)deuteron

(Kachelriess et al. [1905.01192])

Coalescence probability

$$w = 3\Delta\zeta_1 \mathrm{e}^{-d_1^2 q^2} + 3(1-\Delta)\zeta_2 \mathrm{e}^{-d_2^2 q^2}$$



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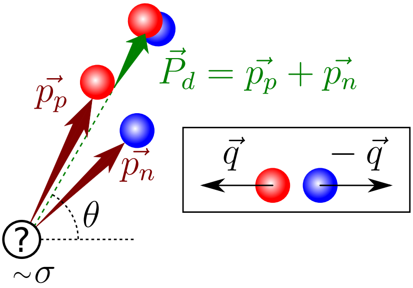
$$\zeta_i = \frac{d_i^2}{d_i^2 + 4\tilde{\sigma}^2}\sqrt{\frac{d_i^2}{d_i^2 + 4\sigma^2}}$$

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

$\Delta = 0.581$, $d_1 = 3.979$ fm, $d_2 = 0.890$ fm



$$\sigma \equiv \sigma_{e^\pm} \simeq \sigma_{pp}/\sqrt{2} \simeq 1 \text{ fm}$$

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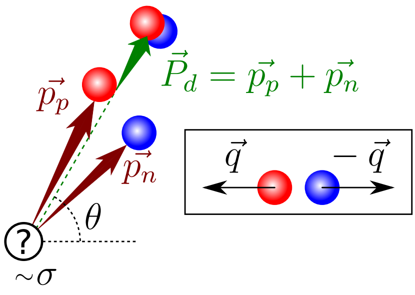
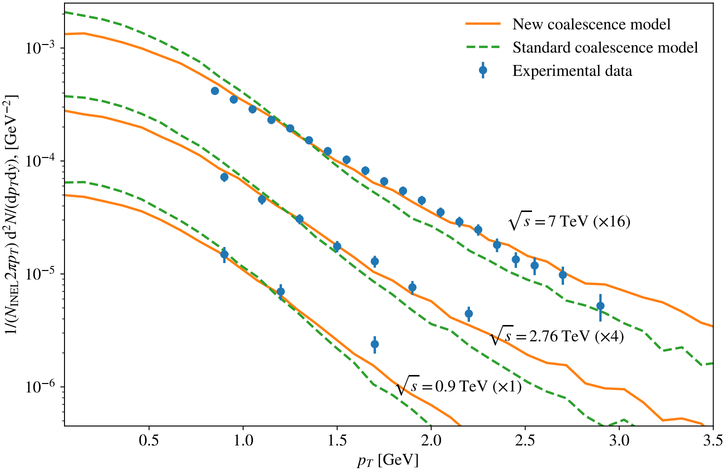


$$\sigma \equiv \sigma_{e^\pm} \simeq \sigma_{pp}/\sqrt{2} \simeq 1 \text{ fm}$$

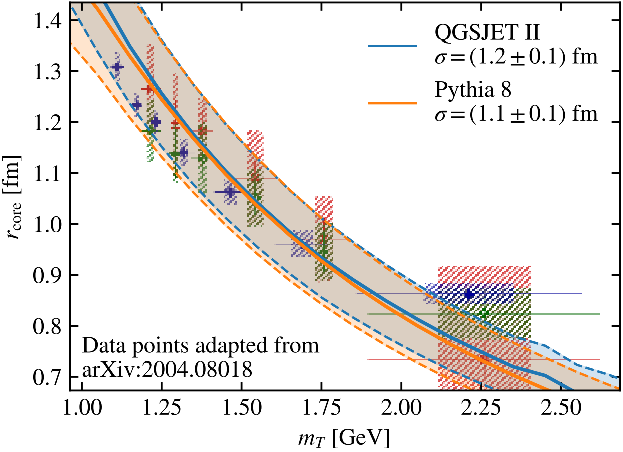
Can be added to nearly any event generator to describe the production of light (anti)nuclei in small interacting systems

Experimental data: antideuteron spectrum



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

Experimental data: baryon emission source



Preliminary

Comment: Alternative description of the emission volumes

Some event generators have implemented a description of the space-time structure:

- Pythia 8 (Ferreres-Solé and Sjöstrand [1808.04619])
- UrQMD (Bleicher [hep-ph/9909407])

Simple coalescence model (UrQMD):
$\Delta p < p_0$ and $\Delta r < r_0$ (Sombun et al. 2019)

Can instead use:

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

Summary

- *The detection of cosmic ray antinuclei may be just around the corner!*
- A good description of the antinucleus production in the processes e^+e^-, pp, pHe, Hep, HeHe, $\bar{p}p$, $\bar{p}He$ is needed
- One should include both momentum correlations and the size of the formation region when estimating the production in small interacting systems
- An improved coalescence model for (anti)deuteron Kachelrieß et al. [1905.01192; 2002.10481]

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

BACKUP SLIDES

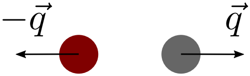
The new coalescence model

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



Coalescence of helium-3 and tritium

Helium-3 and tritium formation model

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

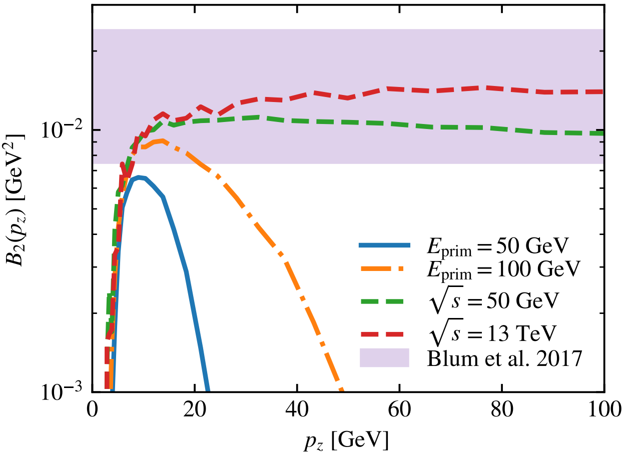
$$\zeta = \left(\frac{2b^2}{2b^2 + 4\sigma^2} \right)^3,$$

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

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

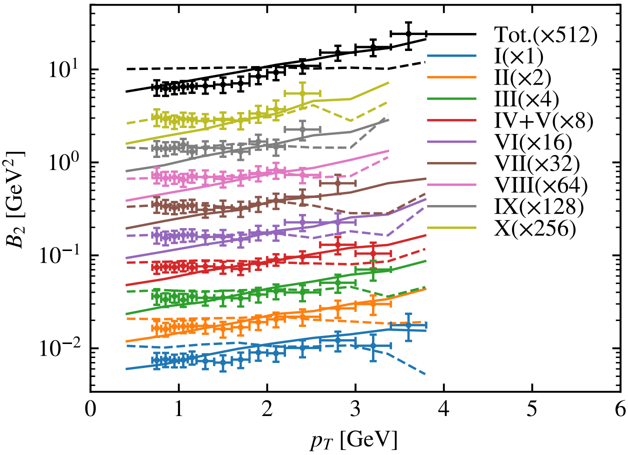
$b_{^3\mathrm{He}} = 1.96\ \mathrm{fm}$; $b_t = 1.76\ \mathrm{fm}$; $s = 1/12$

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,

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

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

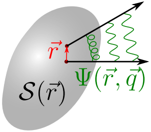
Two-Gaussian wave function:

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

Femtoscopy experiments

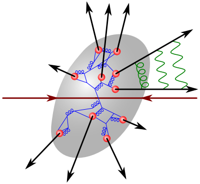
- Measurable quantity:

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



- A Gaussian source if often assumed in experiments

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



- The nucleon Wigner functions predict the baryon source

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

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

Secondary source