An alternative coalescence model

J. Tjemsland

In collaboration with M. Kachelriess and S. Ostapchenko

Department of Physics
Norwegian University of Science and Technology

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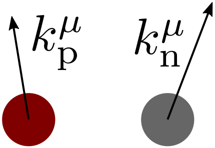
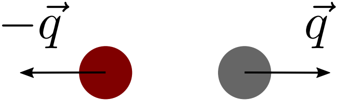
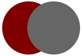
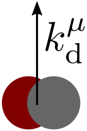
Overview

The coalescence model in momentum space

1. From event generator: 

2. In center of mass frame: 

3. Any nucleons with $2|\vec{q}| < p_0$ merge to form a nucleon: 
4. In lab frame:  $k_\mathrm{d}^\mu = k_\mathrm{n}^\mu + k_\mathrm{p}^\mu$

A Wigner function based coalescence model

Goals

- Include constraints on both momentum and space variables
- Include a quantum mechanical treatment
- Microphysical picture
- Evaluated per-event within the Monte Carlo

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Starting points

- Nucleon capture process: $p + n \rightarrow d$
- Wigner function representation of the deuteron and nucleons

Wigner function properties

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:

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

An expression for the deuteron yield

Antideuteron spectrum in the d frame (Scheibl and Heinz 1999)

$$\frac{\mathrm{d}^3 N_d}{\mathrm{d}P_d^3} = \frac{s}{(2\pi)^3} \int \mathrm{d}^3 r_d \int \frac{\mathrm{d}^3 q \, \mathrm{d}^3 r}{(2\pi)^3} \mathcal{D}(\vec{r}, \vec{q}) f_p^{\mathrm{W}}(\vec{q}, \vec{r}_+) f_n^{\mathrm{W}}(-\vec{q}, \vec{r}_-),$$

All combinations that are allowed from the Pauli exclusion principle are given equal weights, (Mattiello et al. 1997).

$$s_d = \frac{3}{8}; \qquad s_{^3\mathrm{He}} = s_t = \frac{1}{12}.$$

$f_p^{\mathrm{W}}(\vec{q}, \vec{r}_+)$: Proton Wigner function
$f_n^{\mathrm{W}}(-\vec{q}, \vec{r}_-)$: Neutron Wigner function
$\mathcal{D}(\vec{r}, \vec{q})$: Deuteron Wigner function

A new coalescence model I

Ansatz for nuleon Wigner functions:

$$f_p^{\mathrm{W}}(\vec{q},\vec{r}) = f_n^{\mathrm{W}}(\vec{q},\vec{r}) = \left(2\pi\sigma^2\right)^{-3/2} g(\vec{q}) \exp\left\{-\frac{r^2}{2\sigma^2}\right\}$$

$g(\vec{q})$: taken from the event generator
σ: free parameter

Ansatz for deuteron wave function:

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

$r_{\mathrm{rms},d} = 1.96\ \mathrm{fm}$ (Zhaba 2017) $\quad\Rightarrow d = 3.2\ \mathrm{fm} = 16\ \mathrm{GeV}^{-1}$

A new coalescence model II

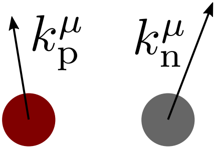
Antideuteron formation model (yield in lab frame)

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

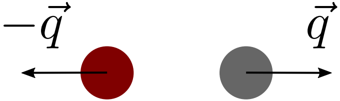
$$\zeta \equiv \left(\frac{d^2}{d^2+4\sigma^2}\right)^{3/2} \leq 1.$$

A new coalescence model III

1. From event generator:



2. In center of mass frame:



3. The two nucleons merges with a probability

$$w = 3\zeta e^{-q^2 d^2},$$

where

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

A new coalescence model IV

Antihelium-3 and antitritium formation model (yield in lab frame)

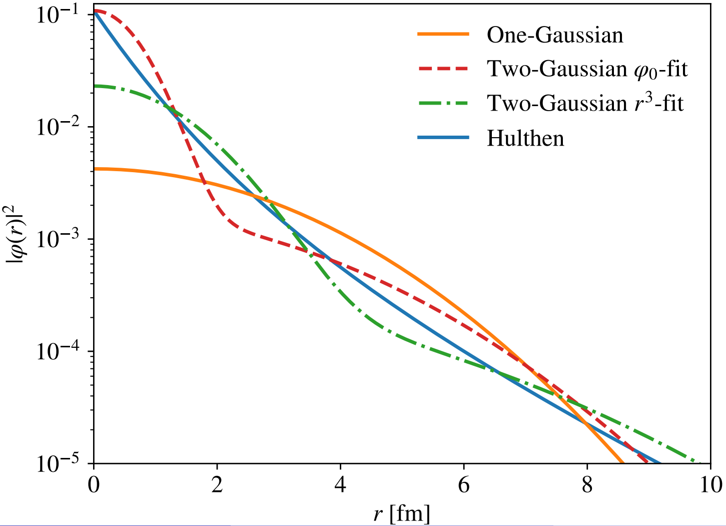
$$\frac{\mathrm{d}^3 N_{\mathrm{He}}}{\mathrm{d}P^3_{\mathrm{He}}} = \frac{64 s\zeta}{\gamma(2\pi)^3} \int \frac{\mathrm{d}^3 p_1}{(2\pi)^3} \frac{\mathrm{d}^3 p_2}{(2\pi)^3} g(-\vec{p}_2 - \vec{p}_3) g(\vec{p}_2) g(\vec{p}_3) \mathrm{e}^{-b^2 P^2},$$

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

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

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

Improving the deuteron wave function



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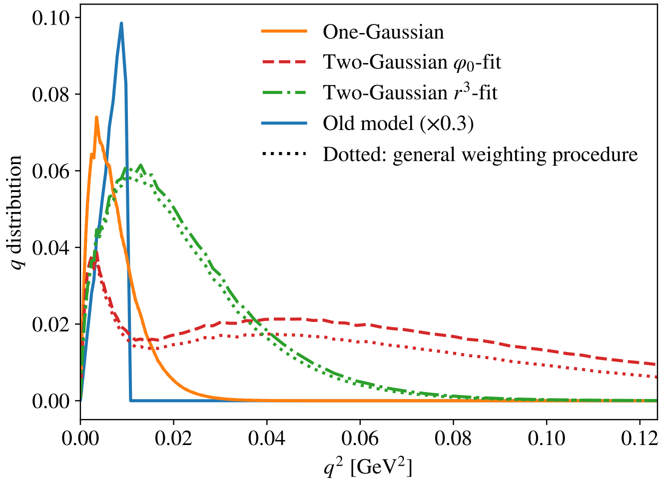
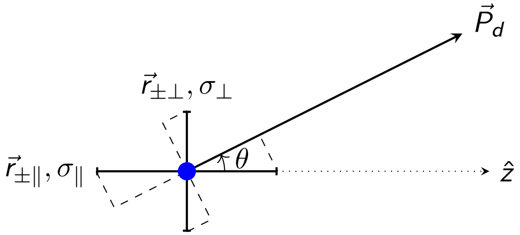


pp collisions at $\sqrt{s} = 0.9$ TeV with $\sigma = 7$ GeV^{-1} and $p_0 = 0.2$ GeV.

Parameter estimation

- One can try to capture the hadronisation length L_N by defining the nucleon Wigner functions in the lab frame.
- $L_N \sim \gamma L_0$
- $\sigma_{\parallel(e^{\pm})} \sim L_0 \sim R_p \sim 5\ \mathrm{GeV}^{-1}$
- $\sigma_{\perp(e^{\pm})} \sim \Lambda_{\mathrm{QCD}} \sim \sigma_{\parallel(e^{\pm})}$
- $\sigma^2_{(pp)} = \sigma^2_{(e^{\pm})} + \sigma^2_{(\mathrm{geom})}$

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



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

$$\Rightarrow \zeta = \frac{d^2}{d^2 + 4\tilde{\sigma}_\perp^2}\sqrt{\frac{d^2}{d^2 + 4\sigma_\parallel^2}} \quad \text{where} \quad \tilde{\sigma}_\perp = \frac{\sigma_\perp}{\sqrt{\cos^2\theta + \gamma^2 \sin^2\theta}}.$$

Comparison with experimental data

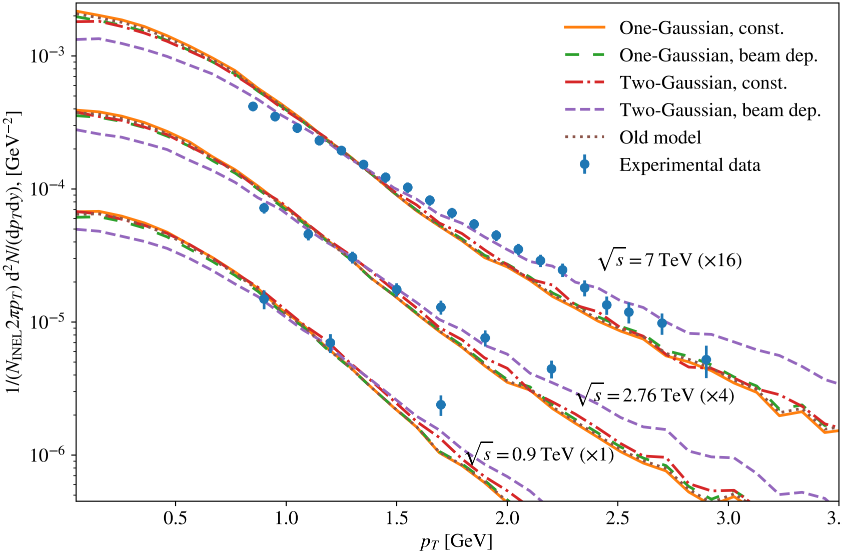
We have considered mainly two experiments:

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

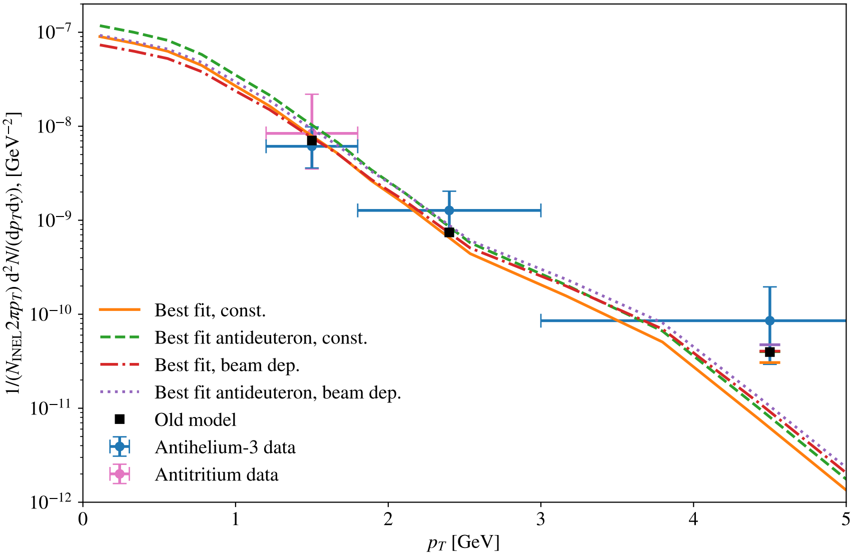
Results

- Two-Gaussian wave function, constant ζ
  - $\sigma_{pp} = (6.4 \pm 0.2)\ \mathrm{GeV}^{-1} = \sqrt{2}(4.5 \pm 0.2)\ \mathrm{GeV}^{-1}$
  - $\sigma_{e^\pm} = 5.0^{+1.2}_{-0.9}\ \mathrm{GeV}^{-1}$
- Two-Gaussian wave function, beam dependent ζ
  - $\sigma_{pp} = (7.0 \pm 0.1)\ \mathrm{GeV}^{-1} = \sqrt{2}(4.9 \pm 0.1)\ \mathrm{GeV}^{-1}$
  - $\sigma_{e^\pm} = 5.2^{+0.9}_{-0.6}\ \mathrm{GeV}^{-1}$

Best combined fit to the ALICE antideuteron data

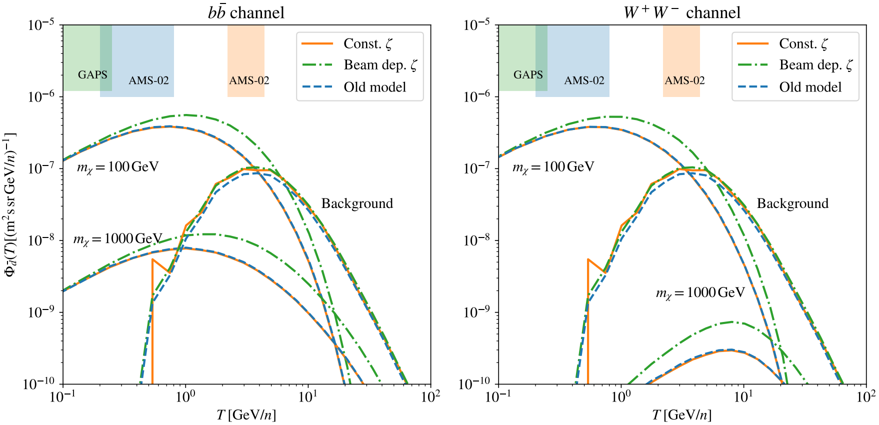


Best fit to the ALICE helium-3 data



Detection prospects for antideuterons from DM annihilations

- Two-zone propagation model with MED parameters, Einasto profile and $\langle \sigma v \rangle = 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$ neglecting energy loss (Fornengo et al. 2013)



Summary

- The existing state of the art coalescence model is purely phenomenological
- Wigner function based coalecence model:

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

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

References I

- Scheibl, Ruediger and Ulrich Heinz (1999). "Coalescence and Flow in Ultra-Relativistic Heavy Ion Collisions". In: *Physical Review C* 59.3, pp. 1585–1602.
- Mattiello, R. et al. (1997). "Nuclear Clusters as a Probe for Expansion Flow in Heavy Ion Reactions at 10-15AGeV". In: *Physical Review C* 55.3, pp. 1443–1454.
- Zhaba, V. I. (2017). "Deuteron: properties and analytical forms of wave function in coordinate space". In: arXiv: 1706.08306 [nucl-th].
- Collaboration, ALICE (2018). "Production of Deuterons, Tritons, ^{3}He Nuclei and Their Anti-Nuclei in Pp Collisions at $\sqrt{s} = 0.9, 2.76$ and 7 TeV". In: *Physical Review C* 97.2.
- Collaboration, ALEPH (2006). "Deuteron and Anti-Deuteron Production in e+e- Collisions at the Z Resonance". In: *Physics Letters B* 639.3-4, pp. 192–201.

References II

Fornengo, N. et al. (2013). "Dark Matter Searches with Cosmic Antideuterons: Status and Perspectives". In: *Journal of Cosmology and Astroparticle Physics* 2013.09, pp. 031–031.