Deuteron (and cluster) production

Radka Sochorová

FNSPE CTU in Prague
Zimányi School '19, Budapest

3rd December 2019

Get introduced: the deuteron

Wave functions

- spherical harmonic oscillator ($d = 3.2\ \mathrm{fm}$)

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

- Hulthen form ($\alpha = 0.23\ \mathrm{fm}^{-1}$, $\beta = 1.61\ \mathrm{fm}^{-1}$)

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

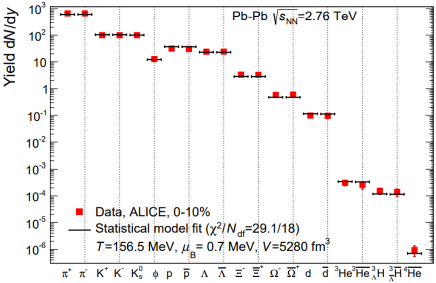
r ... distance between proton and neutron
rms radius: $1.96\ \mathrm{fm}$
binding energy: $2.2\ \mathrm{MeV}$

Clusters and statistical model

Universal description with the statistical model ⟵⟵⟵

Is this well-known feature, or is this a result of fine-tuning (transport model)?

What does it actually tell us?



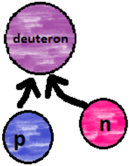
[A. Andronic *et al.*, J. Phys: Conf. Ser 779 (2017) 012012]

Clusters actually carry femtoscopic information about the freeze-out ⟶ motivation for studying clusters

Thermal model vs. coalescence model

- **Thermal model**
  - at T_{ch} $\longrightarrow$ chemical equilibrium, inelastic collisions are ineffective to change abundances of individual species
  - below T_{ch} $\longrightarrow$ yields unchanged, elastic scattering until kinetic freeze-out

- **Coalescence model**
  - light nuclei $\longrightarrow$ formed only after the breakup of the fireball $\longrightarrow$ by recombination of protons and neutrons



Thermal model vs. coalescence model

- for Pb-Pb collisions at the LHC - thermal model describes yields of all hadron species with $T \approx 156 \text{ MeV}$
- light nuclei seem to behave like ALL other hadrons
- VERY SURPRISING - it is hard to imagine that loosely bound sizeable nuclei can exist in the HOT and DENSE hadron gas
- both models $\longrightarrow$ similar deuteron yields
- possible difference for elliptic flow

Production mechanism: coalescence

[R. Scheibl, U. Heinz, Phys. Rev. C 59 (1999) 1585]

Projection of the deuteron density matrix onto two-nucleon density matrix
Deuteron spectrum:

$$E_d \frac{dN_d}{d^3P_d} = \frac{3}{8(2\pi)^3} \int_{\Sigma_f} P_d \cdot d\Sigma_f(R_d) f_p\left(R_d, \frac{P_d}{2}\right) f_n\left(R_d, \frac{P_d}{2}\right) \mathcal{C}_d(R_d, P_d)$$

QM correction factor

$$\mathcal{C}_d(R_d, P_d) \approx \int d^3r \frac{f(R_+, P_d/2) f(R_-, P_d/2)}{f^2(R_d, P_d/2)} |\varphi_d(\vec{r})|^2$$

r ... relative position
R_+, R_- ... positions of nucleons
approximation: narrow width of deuteron Wigner function in momentum

DRAGON - Monte Carlo generator

- blast-wave model
- 277 particles included - stable and resonances
- used for the ALICE data description ([I. Melo, B. Tomášik, J. Phys. G. 43 (2016) 015102], [I. Melo, B. Tomášik, arXiv:1908.03023])
- Cooper-Frye formula (p_T spectrum):

$$E_p \frac{d^3N}{dp^3} = \frac{d^3N}{p_T dp_T dy d\phi} = \int d\Sigma_\mu(x) \cdot p^\mu f_{eq}(p^\alpha \cdot u_\alpha(x))$$

$$f_{eq}(p^\alpha \cdot u_\alpha) = \frac{1}{(2\pi)^3} \left[\exp\left(\frac{p^\alpha \cdot u_\alpha - \mu}{T} \right) - \epsilon \right]^{-1}$$

transverse expansion

$$v_t = \tanh(\eta_t)$$

- p_t spectrum can be developed into Fourier expansion

$$E\frac{d^3}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Theta_n))\right) \tag{1}$$

where anisotropic flow v_n

$$v_n = \frac{\int_0^{2\pi} d\phi \cos(n(\phi - \Theta_n)) \frac{d^3N_d}{p_T dp_T dy d\phi}}{\int_0^{2\pi} d\phi \frac{d^3N_d}{p_T dp_T dy d\phi}} \tag{2}$$

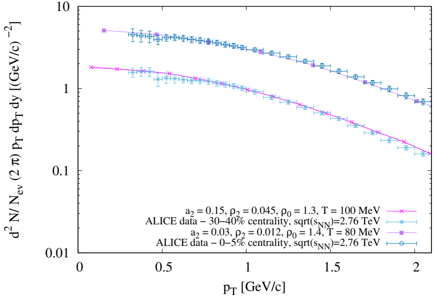
- v_1 ... directed flow coefficient
- v_2 ... elliptic flow coefficient
- expansion anisotropy $\rho(\bar{r}, \Theta_b) = \bar{r}\eta_f \left(1 + \sum_{n=2}^{\infty} 2\rho_2 \cos(2(\Theta_b - \Theta_2))\right)$
- spatial anisotropy $R(\Theta) = R_0 \left(1 - \sum_{n=2}^{\infty} a_2 \cos(2(\Theta - \Theta_2))\right)$

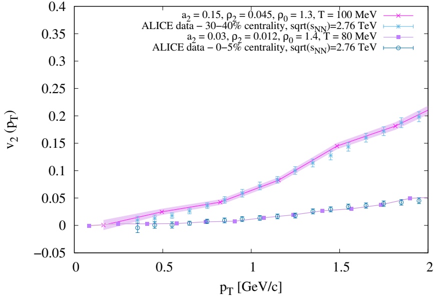
DRAGON with coalescence

- protons and neutrons generated by Monte Carlo generator
- each p-n pair $\longrightarrow$ momentum and position of p and n boosted to the 2-particle rest-frame
- particle that decoupled earlier $\longrightarrow$ propagated to the later time of the other particle
- relative momenta $\Delta p = |\vec{p_1} - \vec{p_2}|$ and relative distances $\Delta r = |\vec{x_1} - \vec{x_2}|$
- spin-isospin factor $3/8$

DRAGON - protons

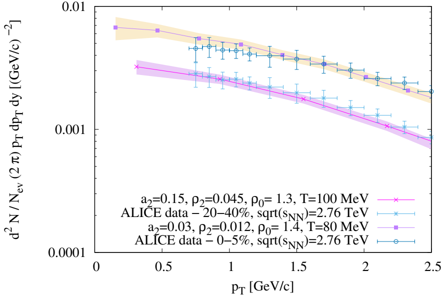
Firstly, we fitted proton spectra and elliptic flow - then we used these parameters for describing deuterons spectra and v_2

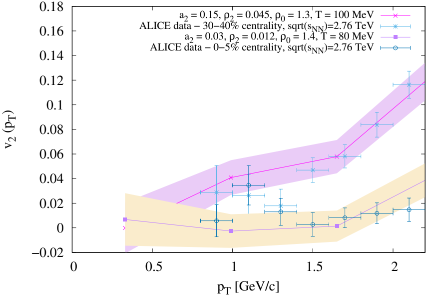




- $0 - 5\%$ centrality: $T = 80$ MeV, $\eta_f = 1.4$
- $30 - 40\%$ centrality: $T = 100$ MeV, $\eta_f = 1.3$

DRAGON with coalescence - deuterons





- $0-5\%$ centrality: $T = 80$ MeV, $\eta_f = 1.4$, $R_b = 10$ fm, $\Delta p \leq 0.200$ GeV/c, $\Delta r \leq 2.1$ fm
- $30-40\%$ centrality: $T = 100$ MeV, $\eta_f = 1.3$, $R_b = 6$ fm, $\Delta p \leq 0.200$ GeV/c, $\Delta r \leq 2.1$ fm

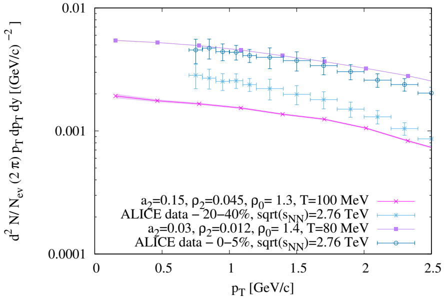
Conclusions

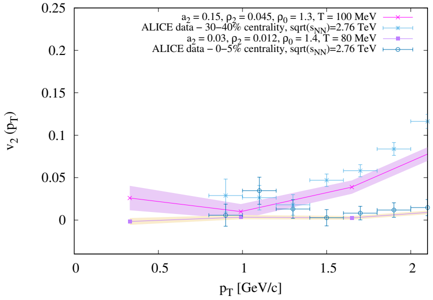
- we added coalescence to Monte Carlo generator DRAGON (blast-wave model) - this is only pilot study
- we found that this model is not very good (problems with fitting v_2) $\longrightarrow$ it needs improvements

- OUTLOOK:
  - v_2 for other types of particles, for other clusters, ...
  - comparison with direct deuteron production
  - we could add also other parameters: baryochemical potentials, ...

Backup slides

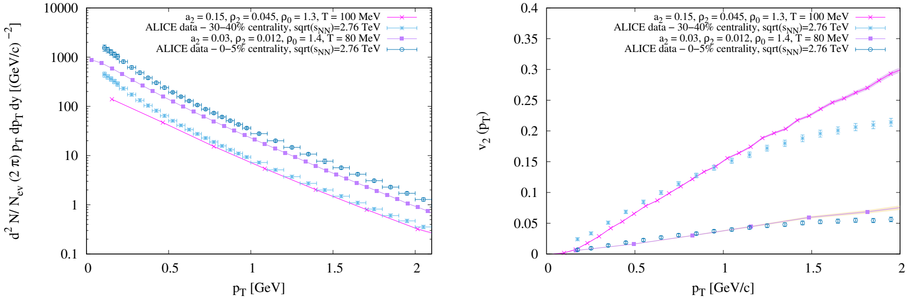
DRAGON - direct deuterons





- $0 - 5\%$ centrality: $T = 80$ MeV, $\eta_f = 1.4$, $R_b = 10$ fm
- $30 - 40\%$ centrality: $T = 100$ MeV, $\eta_f = 1.3$, $R_b = 6$ fm

DRAGON - pions



- $0-5\%$ centrality: $T = 80$ MeV, $\eta_f = 1.4$, $R_b = 10$ fm
- $30-40\%$ centrality: $T = 100$ MeV, $\eta_f = 1.3$, $R_b = 6$ fm