Deuteron and cluster production in heavy ion collisions

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Support: project CAAS CZ.02.1.01/0.0/0.0/16_019/0000778

1. Motivation

- In this figure, the yield of different types of particles is plotted, including pions, kaons, protons but also deuterons, antideuterons and other clusters.
- They are all fitted by the statistical model.
- It seems that the statistical model is universal.
- The question is if this is well-known feature or the result of fine tuning? And what does it actually tell us?

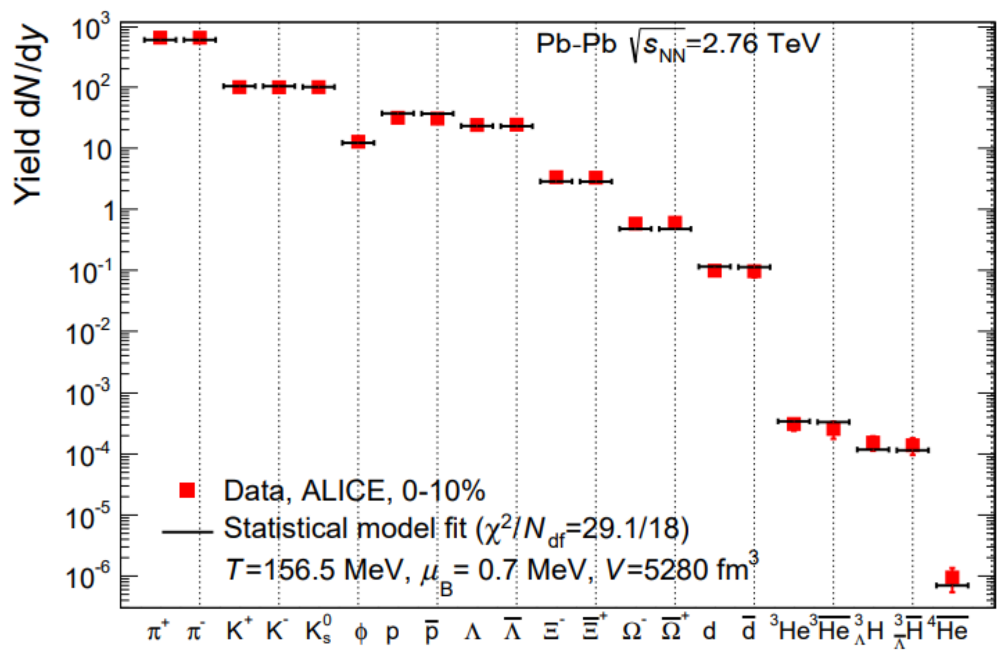


Figure: Particle yields and statistical hadronization model predictions are plotted for different hadrons including light nuclei for central Pb+Pb collisions. The data are from the ALICE Collaboration [2]

- Motivation for studying deuterons and other clusters is answering these questions and fact, that clusters actually carry femtoscopic information about freeze out.

2. Thermal model vs. coalescence

- The production of light nuclei and their antiparticles in relativistic heavy ion collisions is described by a variety of mechanisms.
- These mechanisms include for example thermal statistical model and coalescence model.
- **THERMAL MODEL –** particle yields are given by the temperature and chemical potential for the conserved charges.
- In this model, at the LHC chemical freeze-out at chemical freeze-out temperature T_{ch} = 156 MeV is assumed.
- At this temperature chemical equilibrium occurs.
- Below this temperature the yields are unchanged, but particles can scatter elastically until the system reaches the kinetic freeze-out temperature.

- On the other hand, **COALESCENCE MODEL** postulates that light nuclei are formed only after the breakup of the fireball by recombination of protons and neutrons with close positions and velocities on the kinetic freeze-out surface.
- This model predicts momentum spectra of nuclei with number of proton Z and number od neutrons A-Z.

- It is very surprising that the thermal model is able to describe also light nuclei, as it is hard to imagine that loosely bound (binding energy of deuterons is around 2.2 MeV) sizable nuclei can exist in the hot and dense hadron gas.
- In this case the temperature exceeds by two orders of magnitude the deuteron binding energy and the inter-hadron spacing in the gas is much smaller than the radii of nuclear fragments.

- The results show that both the thermal model and the coalescence model predict similar deuteron yields.
- However, using a blast-wave model for proton transverse momentum spectra and flow with simply replacing the proton mass by those of light nuclei, the model failed to describe the experimental data on the elliptic flows of these light nuclei [3].

3. DRAGON – coalescence production

COALESCENCE MODEL

- Coalescence model is used for describing the formation of composite objects.
- The number of created deuterons with momentum P_d is given by the projection of the deuteron density matrix onto two-nucleon density matrix.
- Deuteron spectrum has then the form

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

QM correction factor: $C_d(R_d, P_d) \sim \int d^3r \frac{f\left(R_+, \frac{P_d}{2}\right) f\left(R_-, \frac{P_d}{2}\right)}{f^2\left(R_d, \frac{P_d}{2}\right)} |\varphi_d(\vec{r})|^2$

where

- **r** is relative position of the nucleons in the deuteron rest frame. In this frame the relative motion of the two nucleons and their coalescence into a bound state is described (quantum mechanics).
- R_+, R_- are positions of nucleons in the fireball rest frame. In this frame motion of the deuterons, it means motion of the centre of mass of the nucleon pair (we use relativistic formulation) is described.
- φ_d is internal deuteron wave function.
- Σ_f describes the freeze-out hypersurface, $d\Sigma_f$ is normal four-vector.
- **f-functions** are the equilibrium distributions of proton and neutron.
- **3/8** is a spin-isospin factor.

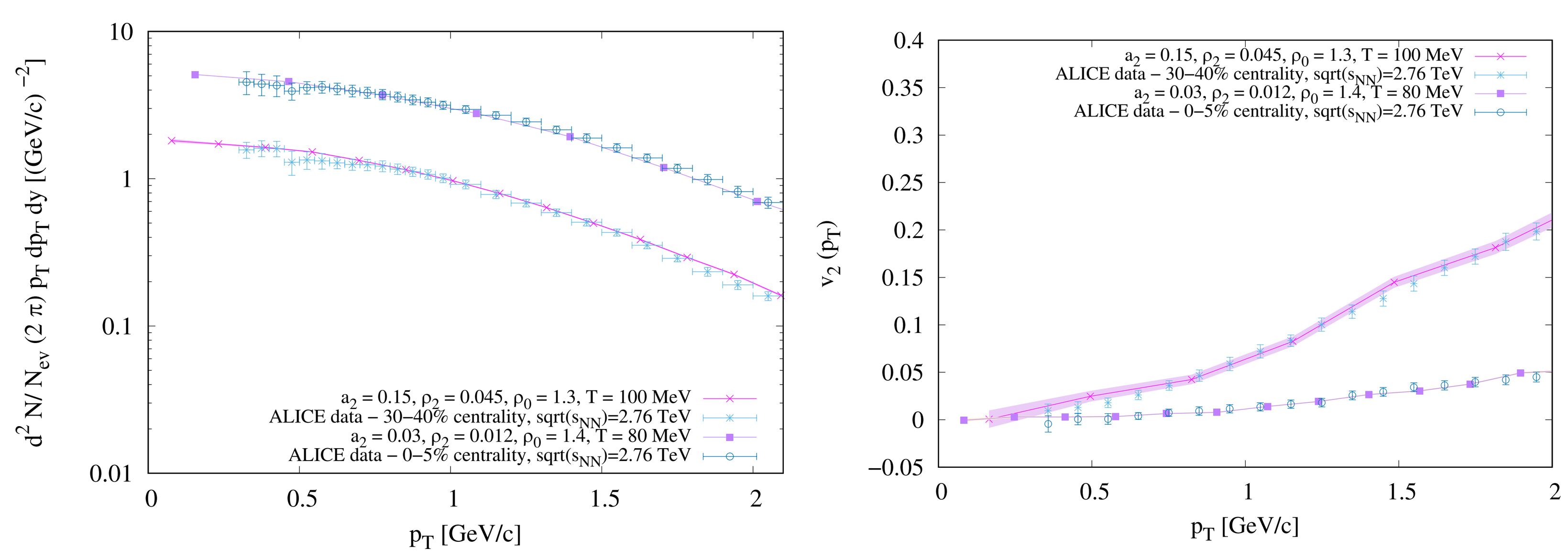
DRAGON – Monte Carlo Generator

- Used for the generation of protons and neutrons.
- Phase-space distribution based on the blast-wave model.
- It includes 277 species both stable and resonances.
- <u>Coalescence in DRAGON:</u>

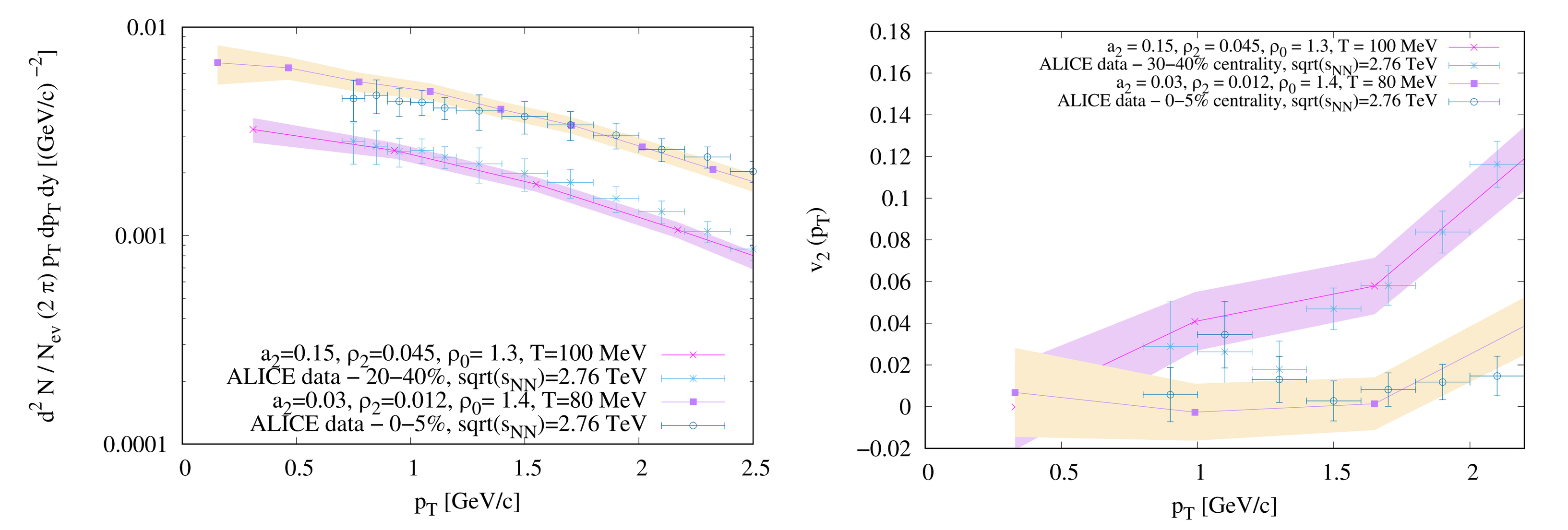
1. For each p-n pair → momentum and position of p and n boosted to the 2-particle rest-frame
2. Particle that decoupled earlier → propagated to the decoupling time of the other particle
3. Deuteron candidate given by the conditions of $\Delta p \leq 0.200$ GeV/c and $\Delta r \leq 2.1$ fm
1. For each deuteron candidate - spin-isospin factor 3/8

4. Results

- First, we fitted proton spectra and the elliptic flow and then we used the gained parameters for describing deuterons spectra and elliptic flow.
- In these two figures you can see results for protons. The left figure shows transverse momentum spectra for two centralities, 0-5 % and 30-40 % centrality. We fitted ALICE data for energy 2.76 TeV. The right panel shows $v_2(p_T)$ of protons for the same two centralities.
- 0−5% centrality: T =80 MeV, $\langle v_t \rangle$=0.99
- 30−40% centrality: T = 100 MeV, $\langle v_t \rangle$=0.83



- We used the same parameters for the deuteron's description.
- Here are the conditions for deuteron production by coalescence.
- 0−5% centrality: T =80 MeV, $\langle v_t \rangle$ =0.99, R_b =10 fm
- 30−40% centrality: T =100 MeV, $\langle v_t \rangle$=0.83, R_b =6 fm



5. Conclusions

- We added coalescence to Monte Carlo generator DRAGON.
- It seems that our model is able to describe the transverse momentum spectra and elliptic flow of protons and deuterons with the same parameters.
- BUT we found that this model is not very good for fitting elliptic flow of pions with the same parameters that works for protons and deuterons.
- The solution could be to try another freeze-out hypersurface.
- The next step will be to add coalescence into the THERMINATOR, which allows the setting of the general freeze-out hypersurface.

References

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