Resolving deuteron production in ultra-relativistic heavy-ion collisions with the help of elliptic flow [1]

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1. Motivation

- The yields of deuterons and larger clusters is well reproduced by the statistical model, which is fitted to the yields of hadrons [2]
- It seems that the statistical model is universal.
- The temperature is higher that the binding energy by two orders of magnitude – clusters cannot exist under such conditions
- Natural model to describe cluster production is provided by coalescence, which also leads to good description of the yields
- Coalescence is sensitive to the distance between the merging nucleons. Thus, it is sensitive to the space-time structure of the emitting fireball – it is a femtoscopic probe!
- Elliptic flow is influenced by the azimuthal variation of the producing homogeneity regions
- (Deuteron) coalescence should be sensitive to elliptic anisotropy of the fireball
- Distinguish thermal production and coalescence by the elliptic flow!

2. Coalescence vs. thermal 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, a temperature T_{ch} = 156 MeV [2] is obtained from fits to data on hadron abundances.
- 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.
- 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.
- 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) sizeable nuclei can exist in the hot and dense hadron gas.

Coalescence model

- The 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 small nuclei (clusters)

- 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 and 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. The model – formalism

Coalescence formalism

- 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 [4]

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

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

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).
- $\boldsymbol{R_+, R_-}$ are positions of nucleons in the fireball rest frame. In this frame motion of the deuterons, i.e. motion of the centre of mass of the nucleon pair (we use relativistic formulation) is described.
- $\boldsymbol{\varphi_d}$ is internal deuteron wave function.
- $\boldsymbol{\Sigma_f}$ describes the freeze-out hypersurface, $\mathbf{d\Sigma_f}$ is normal four-vector.
- **f**-functions are the equilibrium distributions of proton and neutron.
- **3/8** is a spin-isospin factor.

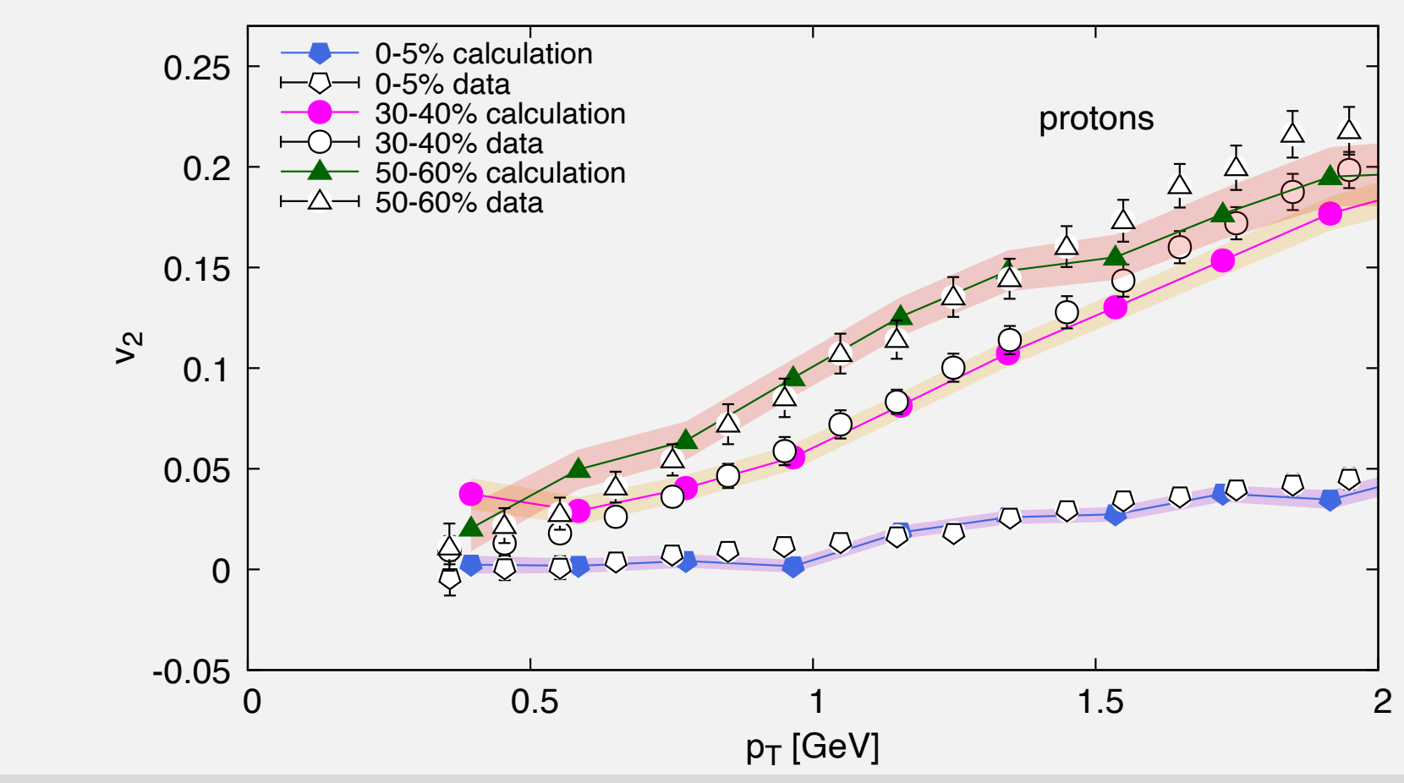
4. The model – implementation

Monte Carlo implementation

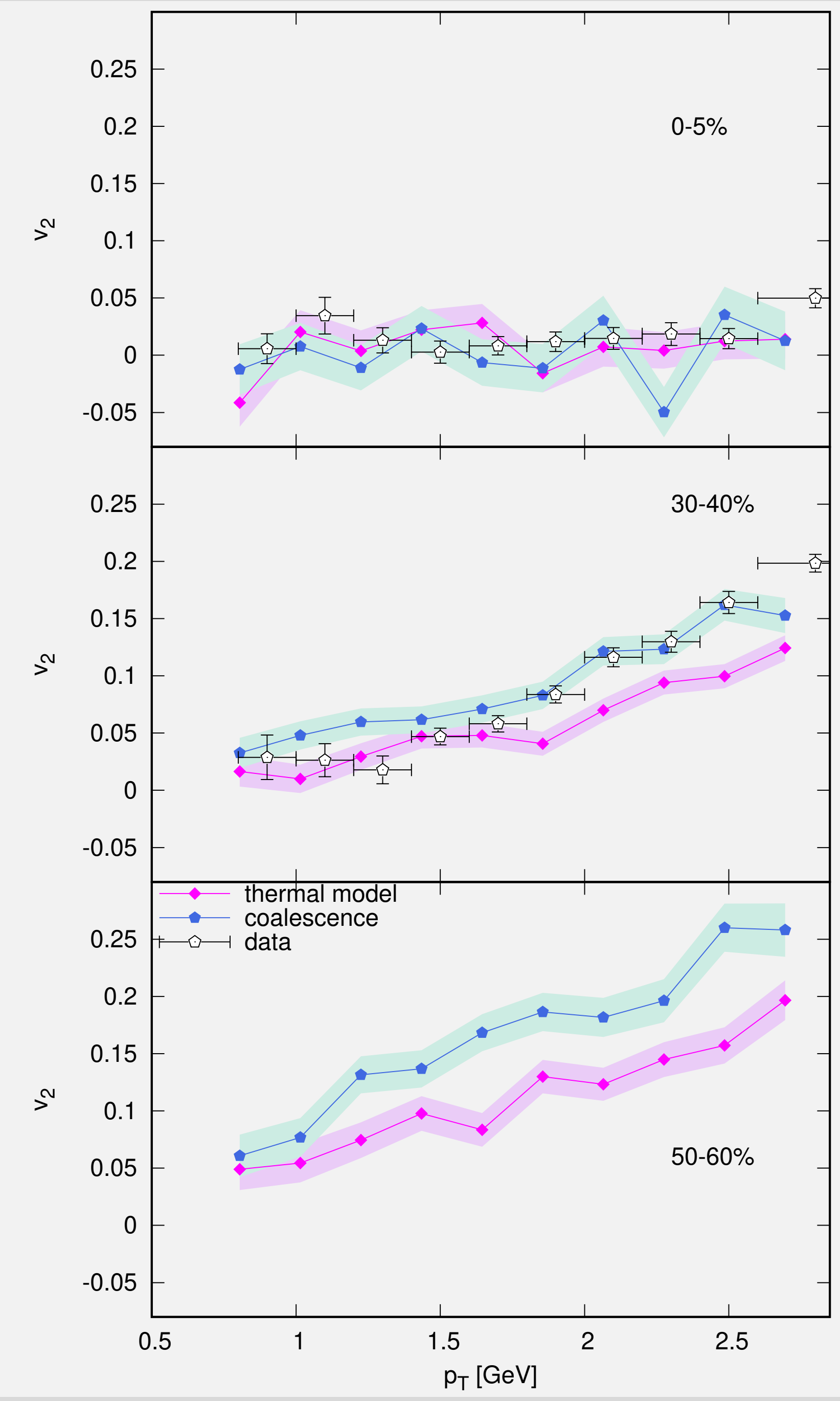
- MC used for generation of protons and neutrons.
- Phase-space distribution based on the (extended) blast-wave model – modified FO hypersurface and implemented spatial anisotropy and flow anisotropy
- Includes resonances - decays simulated by SMASH [5], no rescattering
- Viscous corrections here are adopted from [6]
- Coalescence:
  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 $\Delta p \leq 0.260$ GeV/c and $\Delta r \leq 3.5$ fm
  4. For each deuteron candidate - spin-isospin factor 3/8

5. Results

- Proton and pion spectra and the elliptic flow fitted, in order to tune the parameters



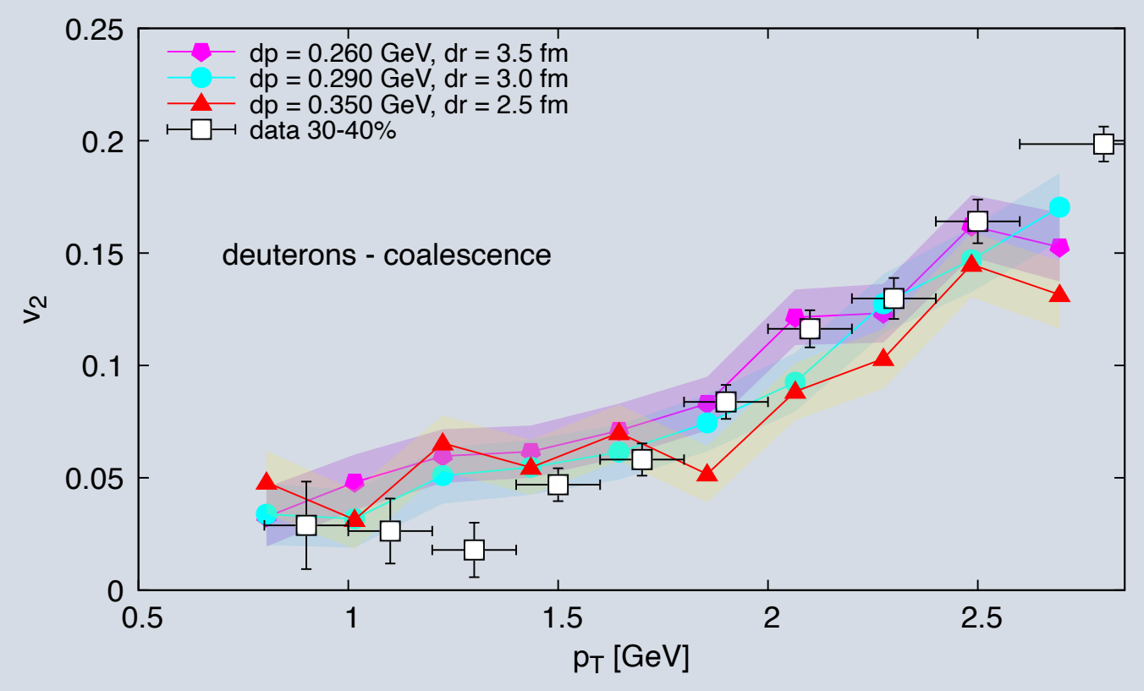
Elliptic flow of protons for three centralities, 0-5 %, 30-40 % and 50-60% centrality. We fitted ALICE data for energy 2.76 TeV.



- v_2 of deuterons calculated for thermal production and from coalescence
- As we wanted to confirm our hypothesis that in more peripheral collisions coalescence may be more sensitive to the azimuthal variation of the homogeneity region, we also looked at the 50-60% centrality class.

$v_2(p_T)$ of deuterons from coalescence for different values of Δr and Δp compared to the same experimental data for centrality 30-40 %.

For smaller Δr the anisotropy of the deuteron distribution—measured by v_2—decreases. With the current variation of Δr, simulated v_2 stay close to experimental data



6. Conclusions

- The elliptic flow v_2 is larger in case of coalescence than it is for the direct statistical production of deuterons.
- Our simulations include the decay of resonances, details of source shape and flow, both anisotropic shape of the fireball and the anisotropy of its expansion.
- Deuterons modelled by the ’box’ coalescence
- Outlook:
  - try other models for the deuteron wave function with this approach
  - calculate larger clusters

References

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