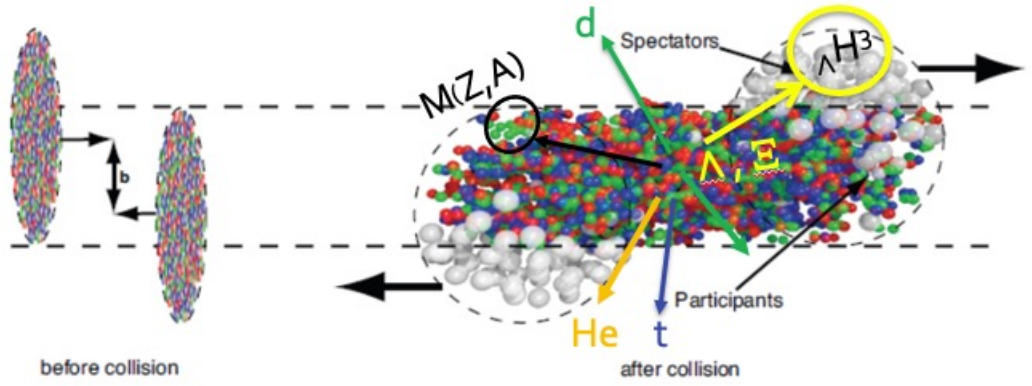
Kinetic versus potential mechanism for deuteron production in HICs from SIS to RHIC energies.

Gabriele Coci

In collaboration with the PHQMD group:
S. Gläßel , V. Kireyeu , V. Voronyuk , J. Aichelin ,
C. Blume , E. Bratkovskaya , V. Kolesnikov , M. Winn

SQM2022
The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

Poster session: Resonances and Hypernuclei | 14 June 2022



➢ Clusters are abundantly formed.
(at √s ≤ 3 GeV about 50% of protons are bound).

➢ Light nuclei (d, t, ^{3}He, ^{4}He) are fragile objects.
(E_B(d) ≈ 2 MeV << T_f ≈ 150 MeV).
How can “ice cubes” survive in the fireball ?

Parton-Hadron Quantum Molecular Dynamics

PHQMD

- Model: A **unified n-body microscopic transport approach** for the description of HICs and **dynamical cluster formation** from low to ultra-relativistic energies.

[J. Aichelin et al. PRC 101 (2020) 044905]

- Realization: (**PHSD** + **QMD**) & **MST/SACA**.

Quantum Molecular Dynamics (QMD)
Initialization & Propagation of baryons

Parton-Hadron-String-Dynamics (PHSD)
Propagation and interaction of partons and mesons
QGP phase by Dynamical Quasi-Particle Model (DQPM)

Cluster Identification
Minimum Spanning Tree (MST)
Simulated Annealing Clusterization Algorithm (SACA)

Baryons described by *n*-body Wigner functions, preserve many-body correlations.
J. Aichelin Phys. Rep. 202, (1991) 233
C. Hartnack, Puri, Aichelin et al. EPJ A 1, (1998)

Collision Integral → reactions of partons and hadrons (also **deuterons**: this work!)
W. Cassing, E. Bratkovskaya, NPA 831, (2009)
P. Moreau, O. Soloveva, et al. PRC 100 (2019)

Bound baryons which are close in coordinate space (PHQMD + MST).
S. Gläßel et al. PRC 105, (2022) 01498.
V. Kireyeu et al. PRC 105, (2022) 04909

Deuteron production by multi-particle reactions

d+N ⟷ p+n+N , d+π ⟷ N+N , **d+π ⟷ N+N+π** , d+X elastic

[J. Staudenmaier et al., PRC 104 (2021) 3, 034908]
[D. Oliinychenko PRC 99 (2019) 4, 044907]

- Cross sections parametrized according to exp. data [PDG PRD 98 (2018)].
- Numerically realized in static "box". Compared to analytic solutions.
- 2 ⟶ 3 either by geometric or stochastic collision criterium.

$$d_T < \sqrt{\frac{\sigma_{tot}^{2,3}(\sqrt{s})}{\pi}} \qquad P_{2.3}\left(\sqrt{s}\right) = \sigma_{tot}^{2,3}(\sqrt{s}) v_{rel} \frac{\Delta t}{\Delta V_{cell}}$$

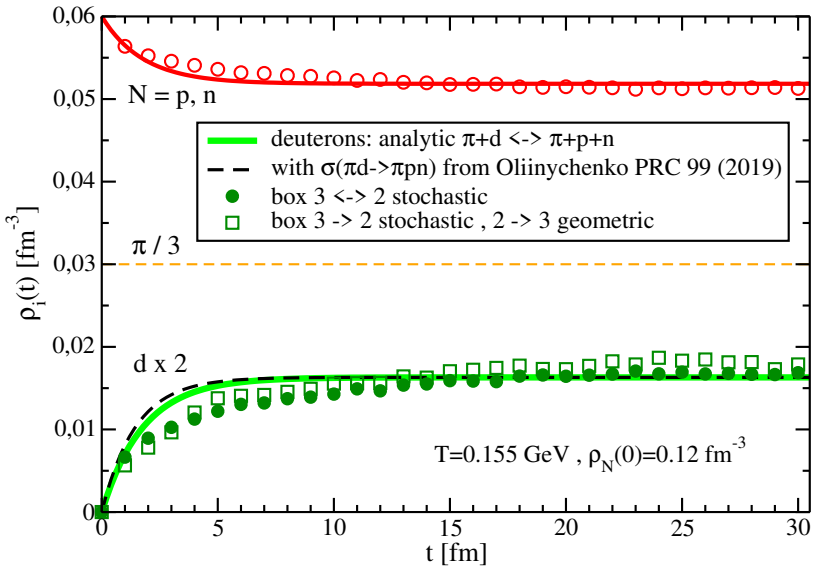
- 2 ⟵ 3 realized via **covariant rate formalism** [W. Cassing NPA 700 (2000)].

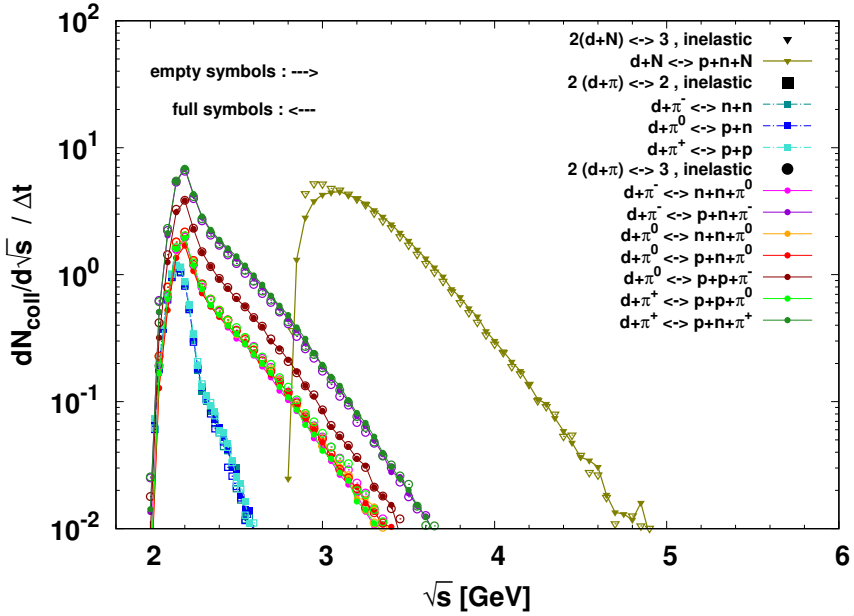
$$P_{3,2}(\sqrt{s}) = F_{iso} \times P_{2,3}(\sqrt{s}) \frac{E_1^f E_2^f}{2E_3E_4E_5} \frac{R_2(\sqrt{s}, m_1, m_2)}{R_3(\sqrt{s}, m_3, m_4, m_5)} \frac{1}{\Delta V_{cell}}$$

✓ **d+π ⟷ N+N+π inclusion of all possible channels allowed by total isospin T conservation:**

$$F_{iso} = |\langle N, N, \pi | T(d+\pi) = 1, T_3 \rangle|^2$$

- Verification of detailed balance condition.





Modelling kinetic deuterons in PHQMD

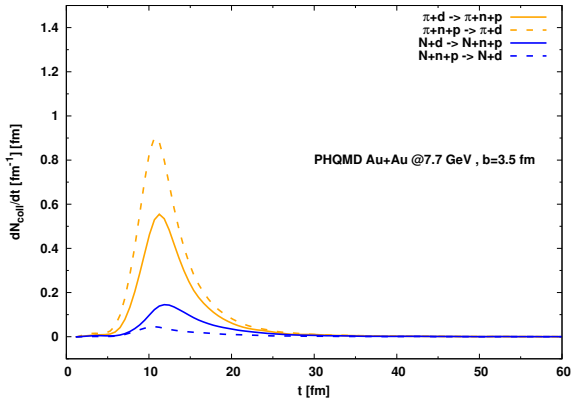
RHIC-BES energy √s = 7.7 GeV:

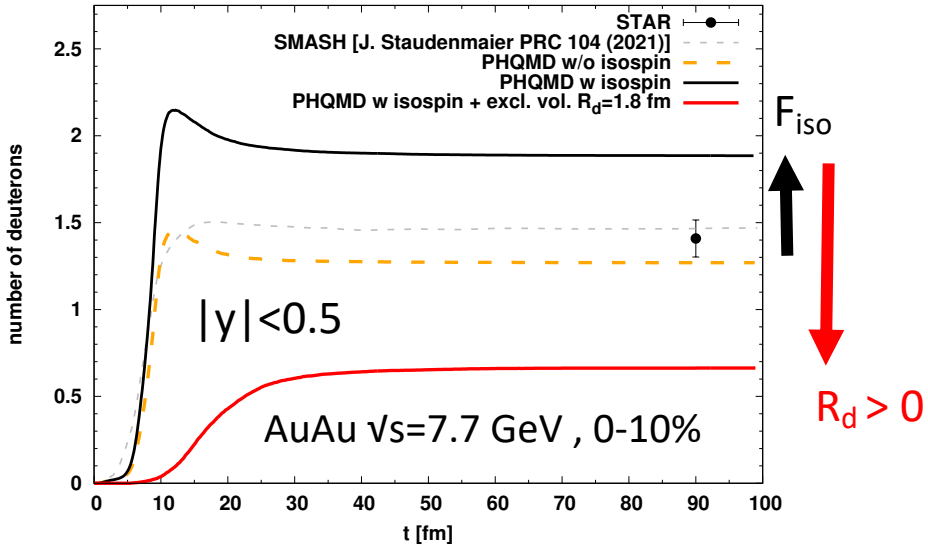
- Hierarchy due to large π abundance
  π+p+n→π+d >> N+p+n→N+d

- Comparison of $N_d(t)$ and p_T spectra at mid-rapidity with other models.

  [J. Staudenmaier et al., PRC 104 (2021) 3, 034908]

Time evolution of collision rate





- In the fireball (π N N) >> (π p n)

→ **Include all channel reactions enhances yield ~ 50%.**
(same at RHIC √s = 200 GeV)

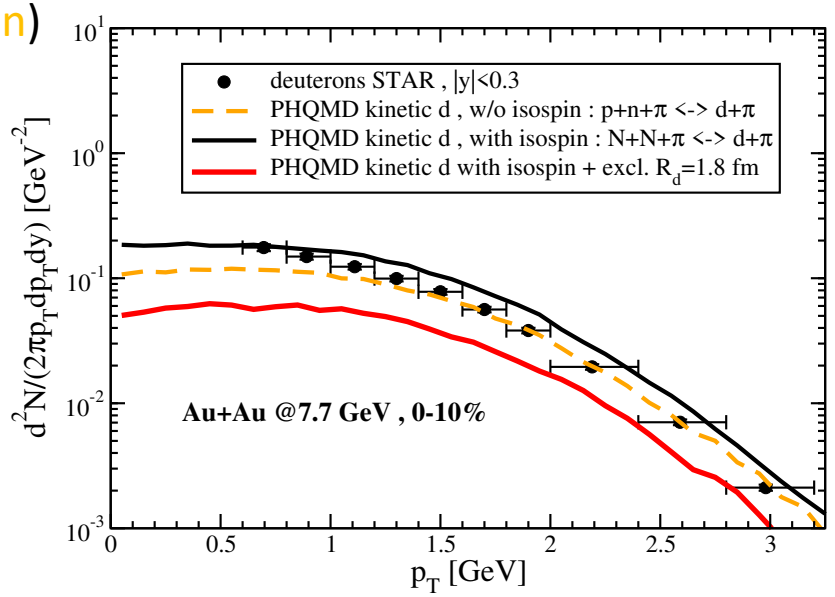
→ p_T slope is not affected.

- Account for deuteron size:

$$\langle r_d^2 \rangle = \int_0^\infty r^2 |\phi_d(r)|^2 dr \sim 1.8\, fm$$

→ **Suppression + time delay**

→ p_T slope is not affected.

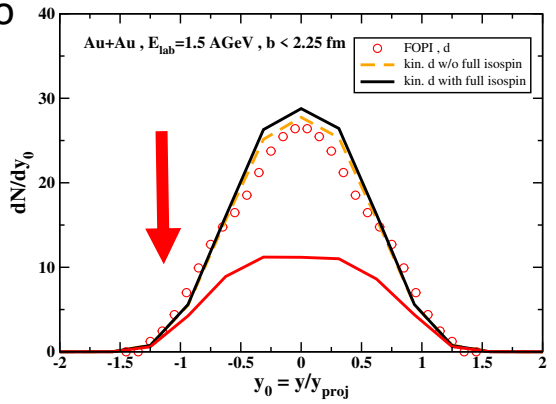


Exp. data J.Adam (STAR) PRC 99, (2019) 064905.

low energy:

p+n+N → d+N >> N+N+π → d+π

- Difference due to isospin channels is negligible.
- Suppression by finite size effect.
- More deuterons formed due to potential binding.



FOPI W.Reisdorf NPA 848, (2010) 246.

PHQMD results: “combined” deuterons

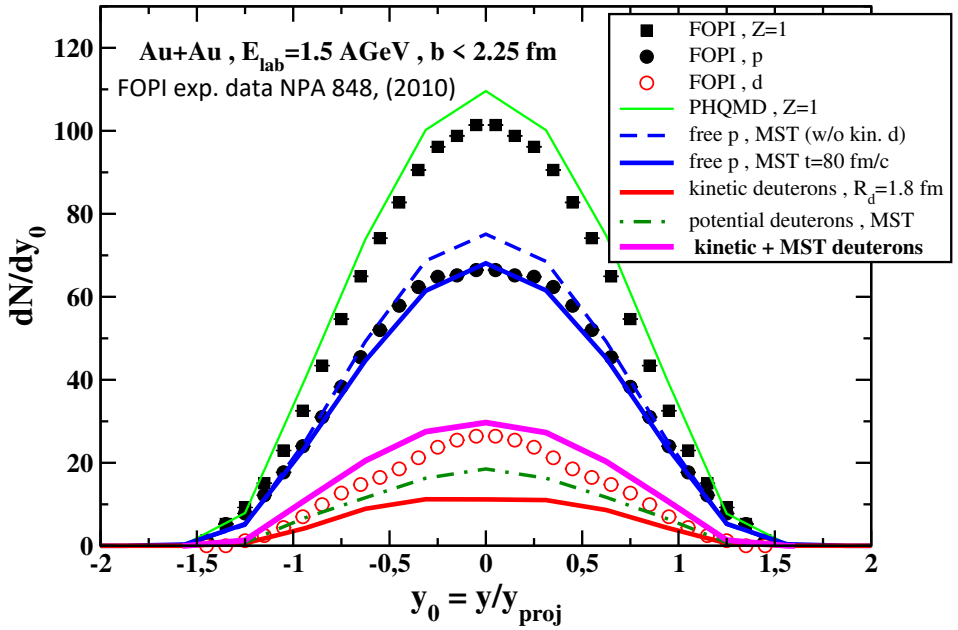
Coupling two dynamical process for deuteron formation:

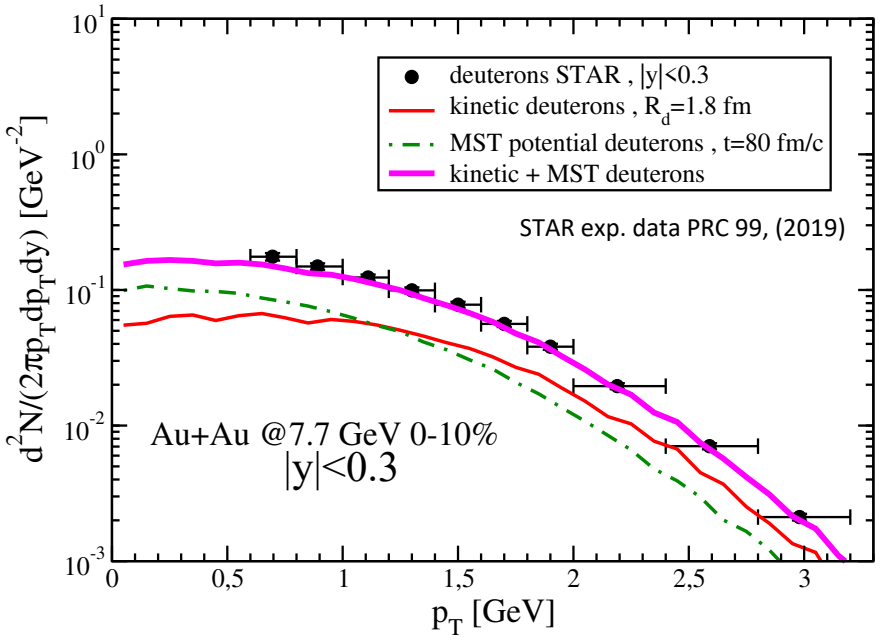
- kinetic mechanism: (πNN→ πd , NNN→ Nd , NN→ dπ)
  with finite-size effect by Excluded-Volume: $|\vec{r}(i)^* - \vec{r}(d)^*| < R_d$

No d formation!

* positions in cms of candidate deuteron

- potential interaction: p-n pairs can be bound as “deuteron” by MST. [S. Gläßel et al. PRC 105, (2022) 01498.]
  → kinetic deuterons are excluded from MST (no double counting!) .





Summary:

- We studied deuteron reactions in PHQMD by N- & π-catalysis including full isospin channels and finite-size effects.
- “Combine” kinetic (PHSD-like) plus potential (QMD-like) produced deuterons provides good agreement with measured y and p_T spectra. [G.Coci, J. Aichelin, E. Bratkovskaya et al. in preparation]