Mechanisms for deuteron production in heavy-ion collisions

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&
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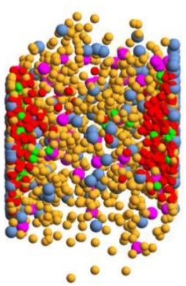
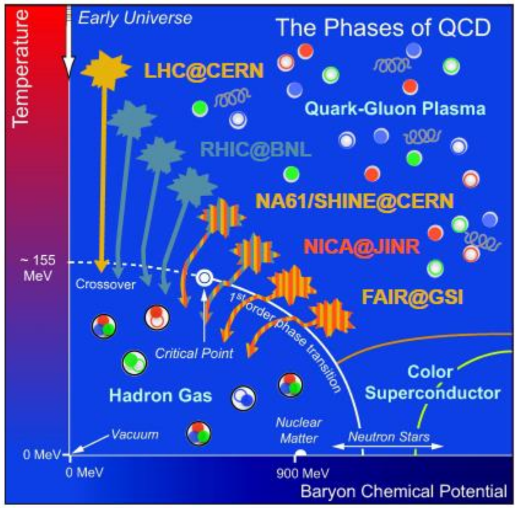
EMMI Workshop "4th Workshop on Anti-Matter, Hyper-Matter and Exotica Production at the LHC",
University of Bologna, Italy, 13-17 February 2023



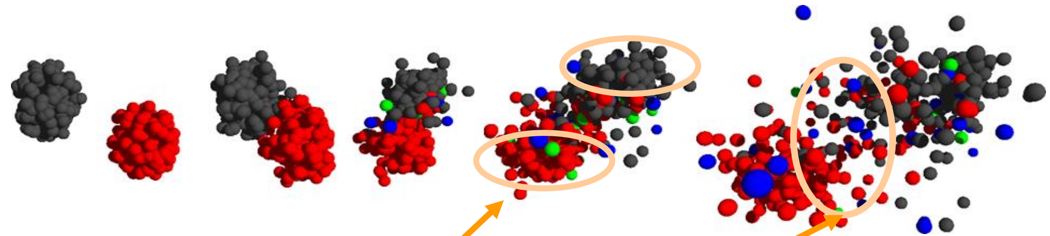
The ‚holy grail‘ of heavy-ion physics:

The phase diagram of QCD



Experimental observables:

... Clusters and (anti-) hypernuclei

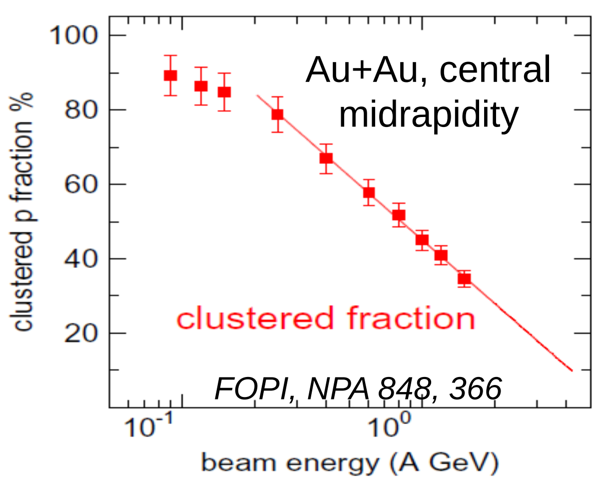


IQMD: Ch. Hartnack

- projectile/target spectators➔ heavy cluster formation
- midrapidity➔ light clusters

! Hyperons are created in participant zone

- Clusters are very **abundant at low energy**

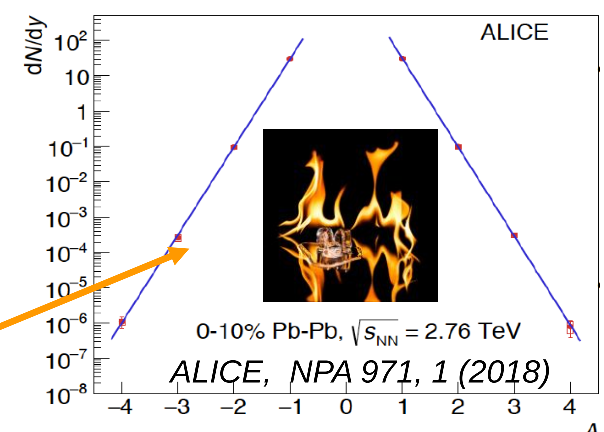


(Anti-) hypernuclei production:

- at mid-rapidity by coalescence of Λ with nucleons during expansion
- at projectile/target rapidity by rescattering/absorption of Λ by spectators

High energy HIC:

‚Ice in a fire‘ puzzle:
how the weakly bound objects can be formed and survive in a hot enviroment ?!



Modeling of cluster and hypernuclei formation

Existing models for cluster formation:

- **statistical model:**
  - assumption of thermal equilibrium
- **coalescence model:**
  - determination of clusters at a freeze-out time by coalescence radii in coordinate and momentum space

➔ don't provide information on the dynamical origin of cluster formation

➔ cf. talk by Tom Reichert

In order to understand the microscopic origin of cluster formation one needs a realistic model for the dynamical time evolution of the HIC

→ transport models:
dynamical modeling of cluster formation based on interactions:

– via potential interaction – 'potential' mechanism ➔ cf. talk by Susanne Glässel

-- by scattering – 'kinetic' mechanism

PHQMD

PHQMD

PHQMD: a **unified n-body microscopic transport approach** for the description of heavy-ion collisions and **dynamical cluster formation** from low to ultra-relativistic energies

Realization: combined model **PHQMD = (PHSD & QMD) & (MST/SACA)**

Parton-Hadron-Quantum-Molecular Dynamics

↓

Initialization → propagation of baryons:
QMD (Quantum-Molecular Dynamics)

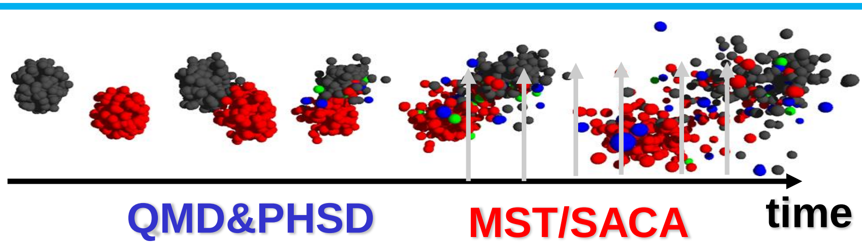
↓

Propagation of partons (quarks, gluons) and mesons
+ collision integral = interactions of hadrons and partons (QGP)
from PHSD (Parton-Hadron-String Dynamics)

↓

Cluster recognition:
SACA (Simulated Annealing Clusterization Algorithm)
or MST (Minimum Spanning Tree)

➔ cf. talk by Susanne Glässel



J. Aichelin et al., PRC 101 (2020) 044905;
S. Gläßel et al., PRC 105 (2022) 1

PHQMD

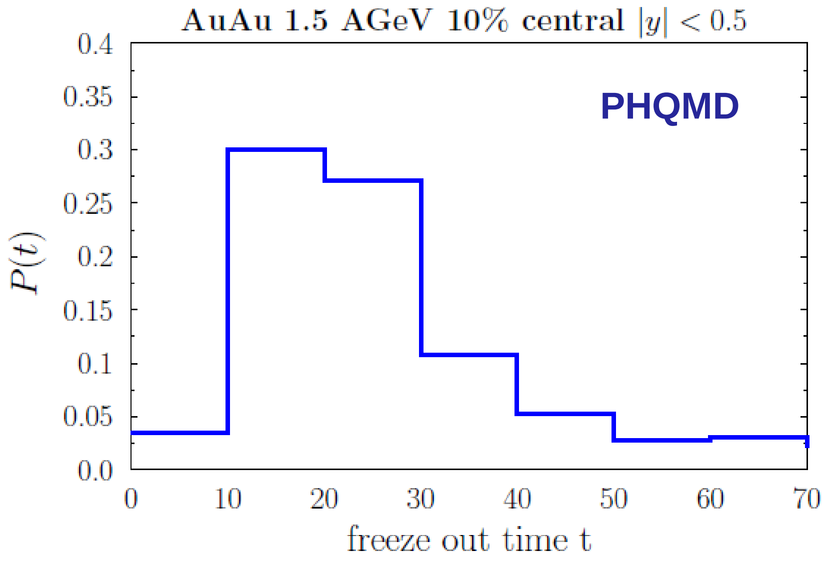
Where are the clusters formed during heavy-ion collisions?

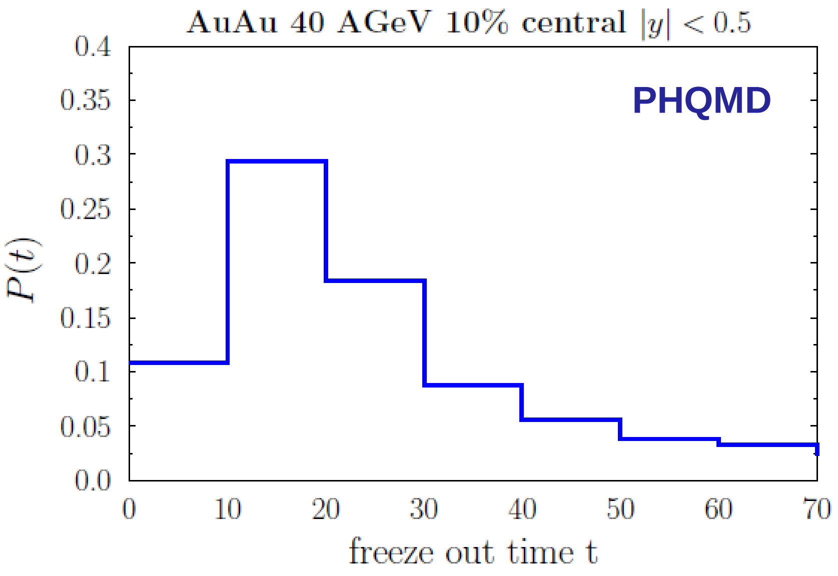
MST vs. coalescence in PHQMD and UrQMD

PHQMD: When does the system freeze out?

- The normalized distribution of the freeze-out time of baryons (nucleons and hyperons) which are finally observed at mid-rapidity |y|<0.5

  * Here freeze-out time as defined by the last elastic or inelastic collision, after that only potential interaction between baryons occurs





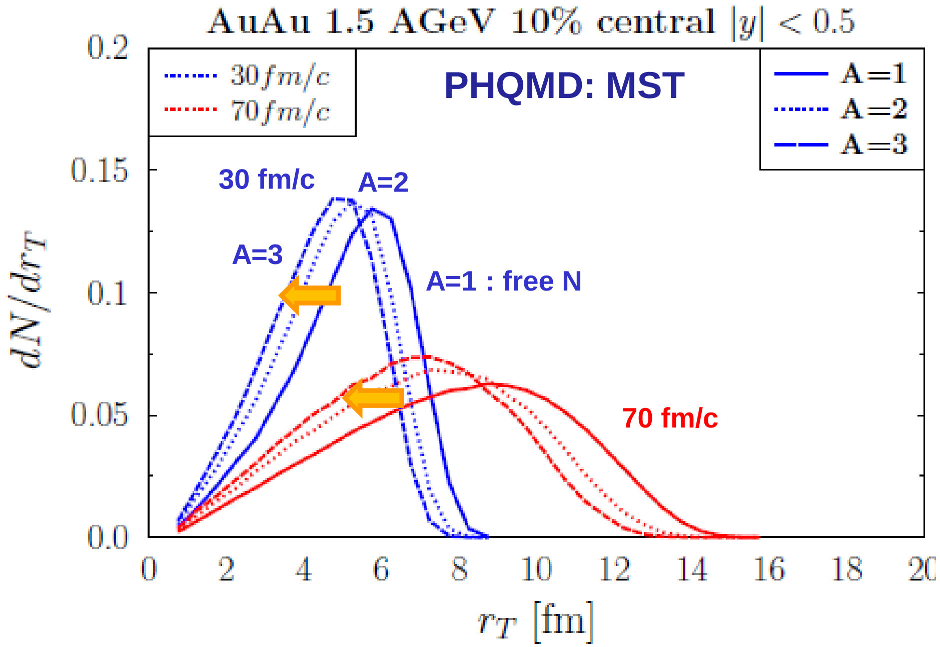
➔ **Freeze-out time of baryons in Au+Au at 1.5 AGeV and 40 AGeV:**

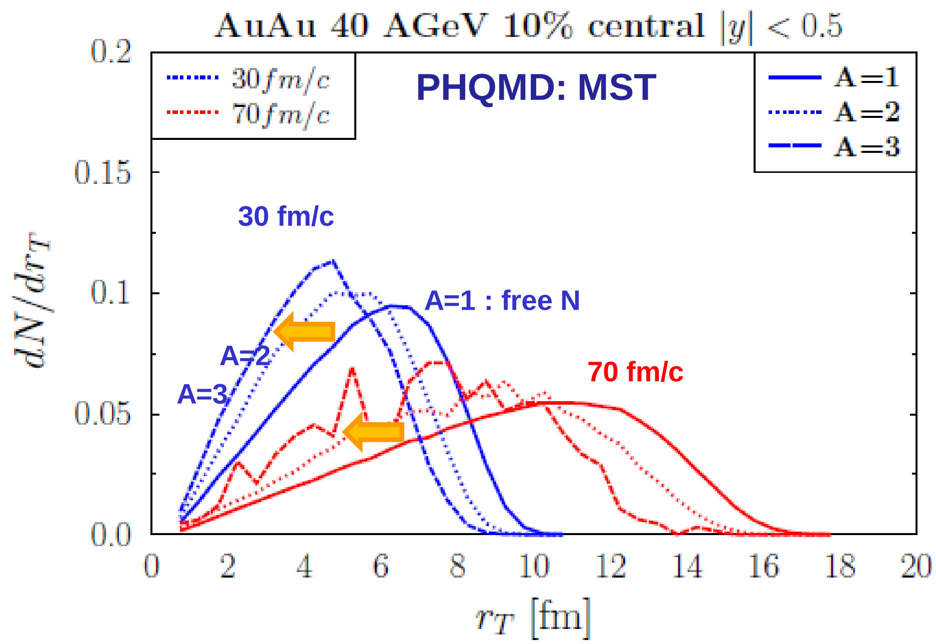
- **similar profile since expansion velocity of mid-rapidity fireball is roughly independent of the beam energy**

S. Gläßel et al., Phys. Rev. C 105 (2022) 1

PHQMD: Where are the clusters formed?

- The MST snapshot (taken at time 30 and 70 fm/c) of the **normalized distribution of the transverse distance r_T of the nucleons** to the center of the fireball.
- It is shown for A=1 (free nucleons) and for the nucleons in A=2 and A=3 clusters



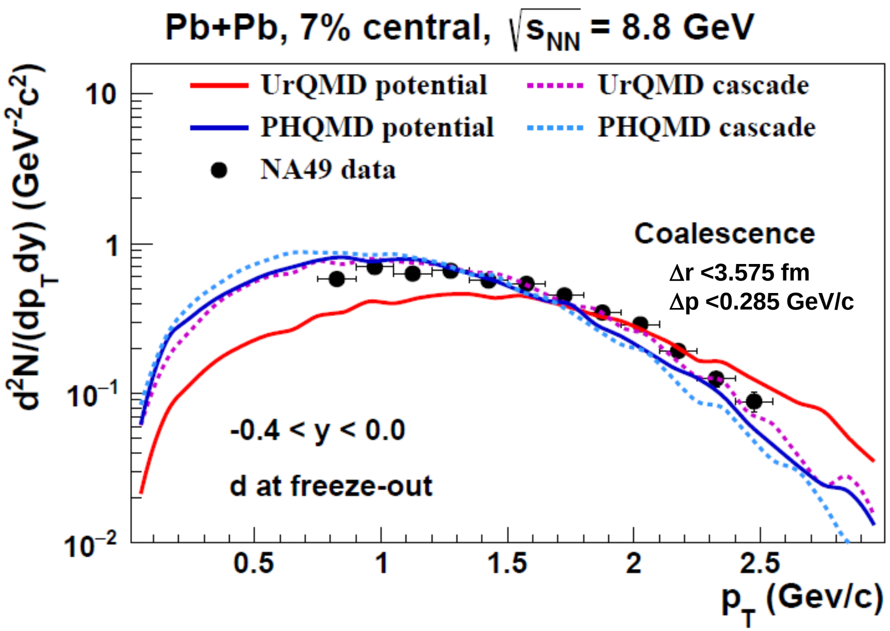


➔ **Transverse distance profile** of free nucleons and clusters are different!
➔ Clusters are mainly formed **behind the 'front' of free nucleons** of expanding fireball
➔ **'ice' is behind the 'fire'** ➔ cluster can survive

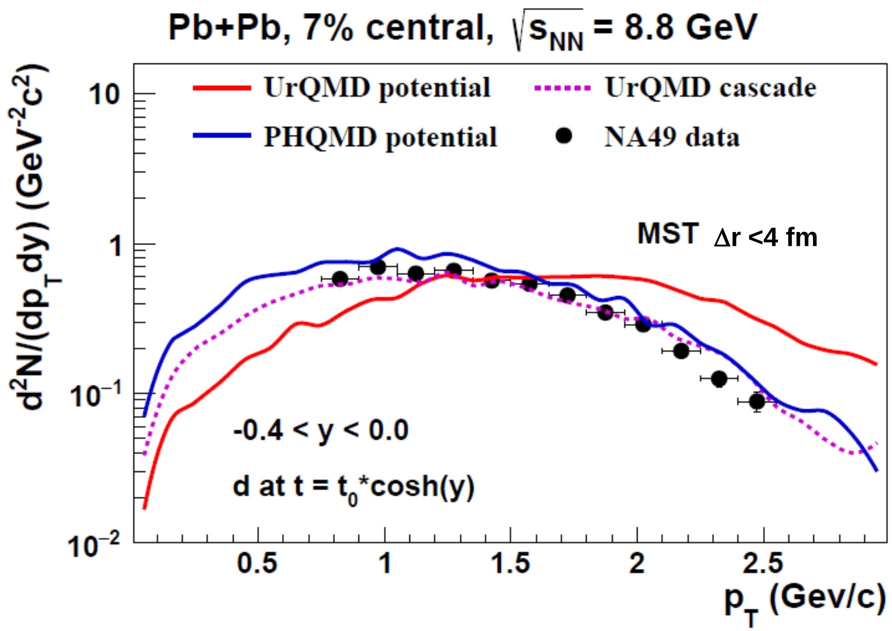
S. Gläßel et al., Phys. Rev. C 105 (2022) 1

Comparison of the coalescence and MST for d applied to PHQMD and UrQMD

Coalescence applied to PHQMD and UrQMD



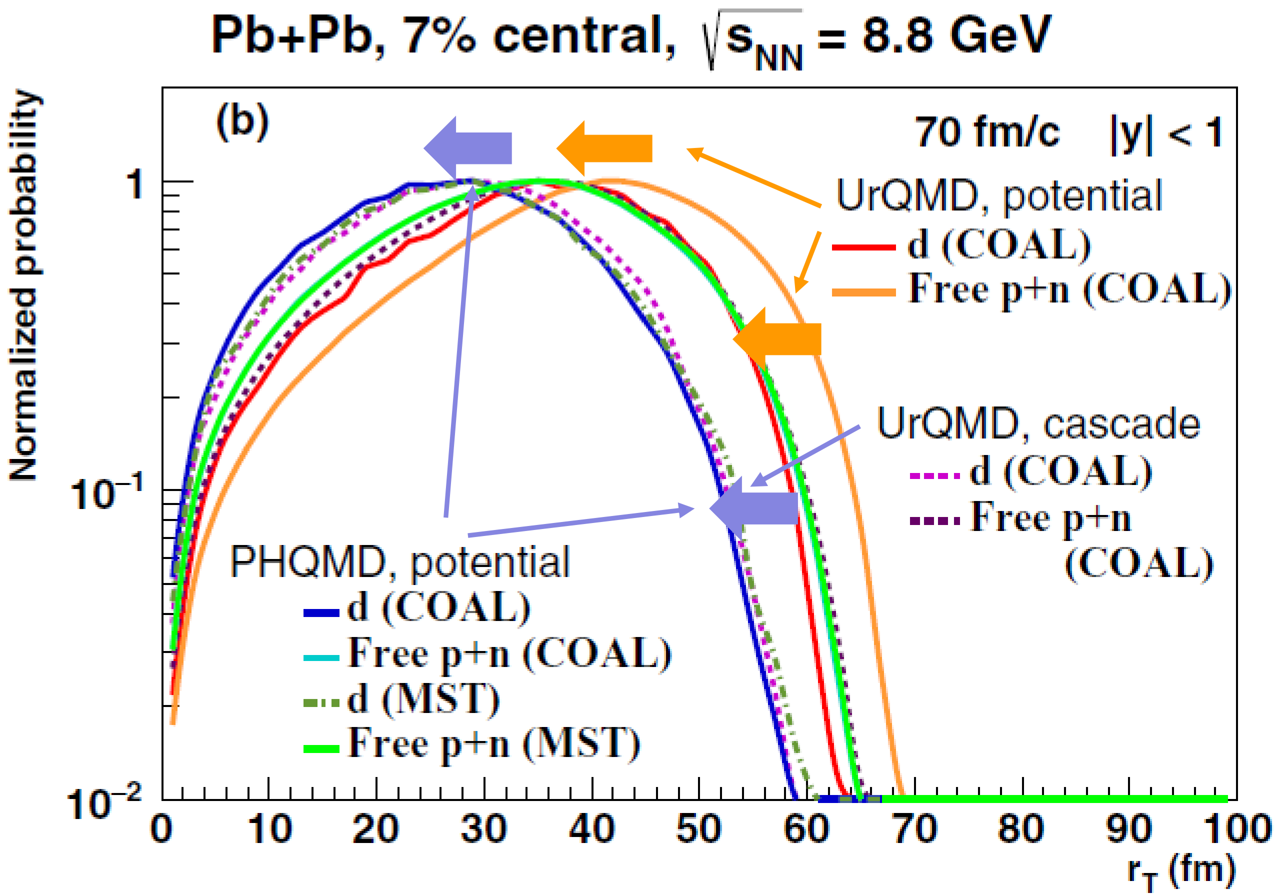
MST applied to PHQMD and UrQMD



- ➔ **Coalescence and MST give very similar multiplicities and y- and p_T –distributions**
- ➔ **PHQMD and UrQMD results in the cascade mode are very similar**
- ➔ **Deuteron production is sensitive to the realization of potential in transport approaches**

V. Kireyeu, J. Steinheimer, M. Bleicher, J. Aichelin, E.B., Phys. Rev. C 105 (2022) 044909

PHQMD & UrQMD: Comparison of the coalescence and MST for d



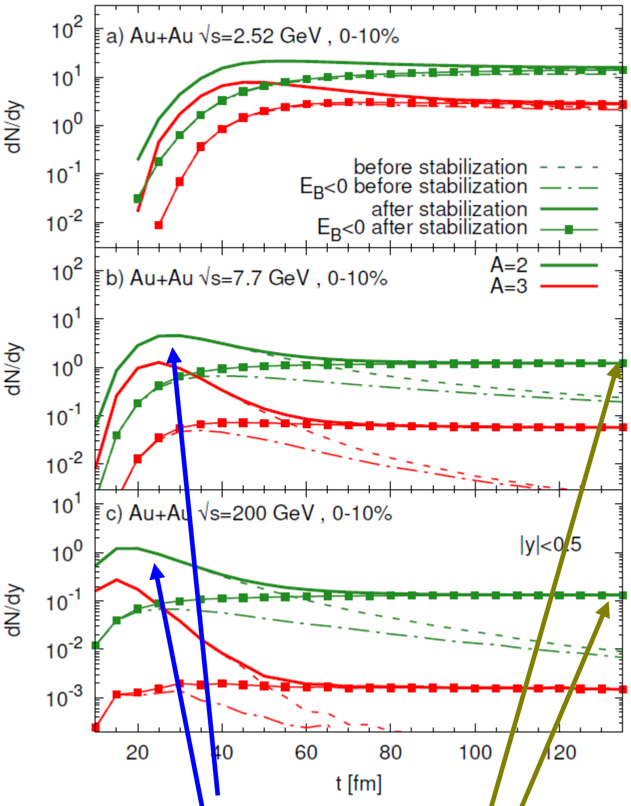
➔ Coalescence as well as the MST procedure show that the deuterons remain in transverse direction closer to the center of the heavy-ion collision than free nucleons

➔ deuterons are behind the fast nucleons (and pion wind)

V. Kireyeu, J. Steinheimer, M. Bleicher, J. Aichelin, E.B., Phys. Rev. C 105 (2022) 044909

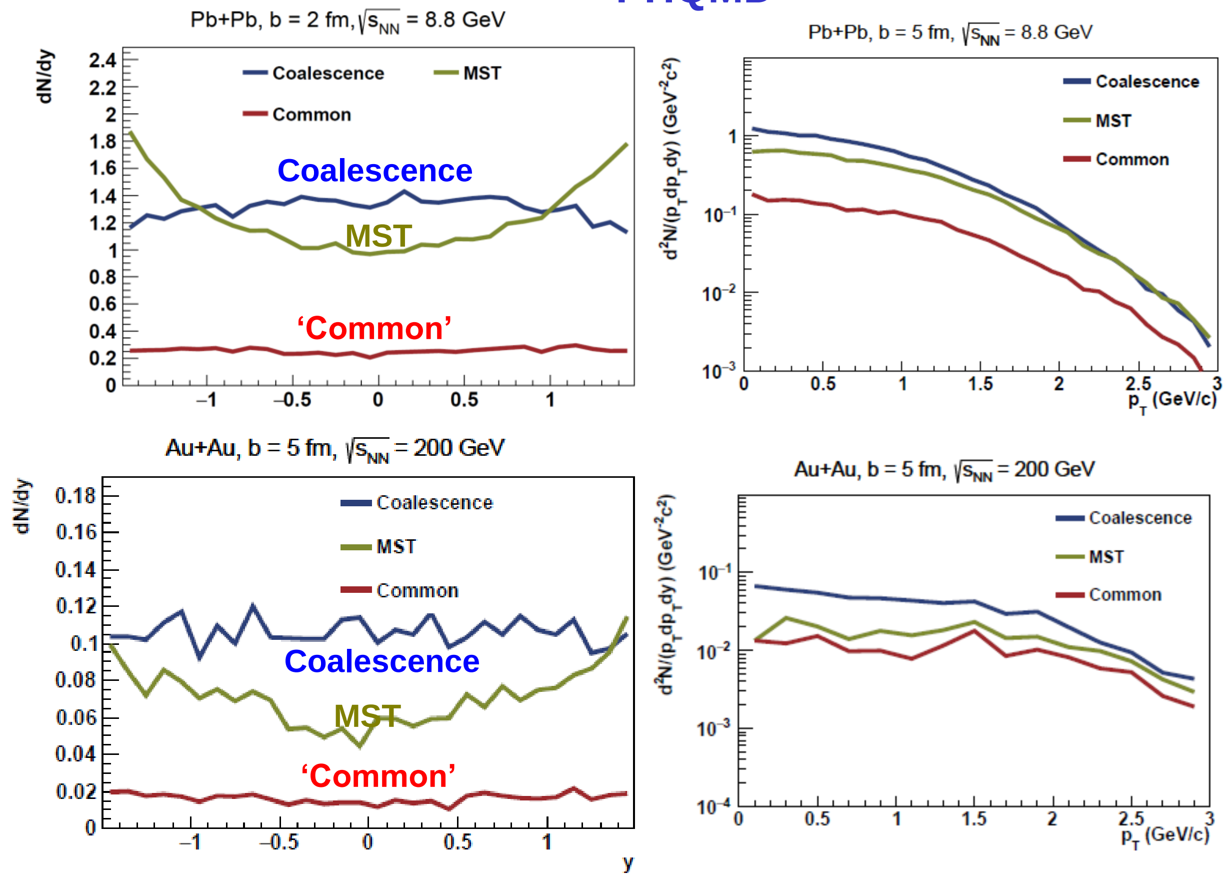
PHQMD: Comparison of the coalescence and MST for d

MST



time: freeze-out → asymptotic

PHQMD



- At mid-rapidity **only 20% of coalescence deuterons (at freeze-out)** are found by **MST (asymptotically)**
- Rapidity and p_T distributions from MST and coalescence have a different shape
  ➔ **make it possible to be distinguishable in experiments!**

Viktar Kireyeu, in progress

Kinetic mechanism for deuteron production in PHQMD

PHQMD

Gabriele Coci et al., in preparation

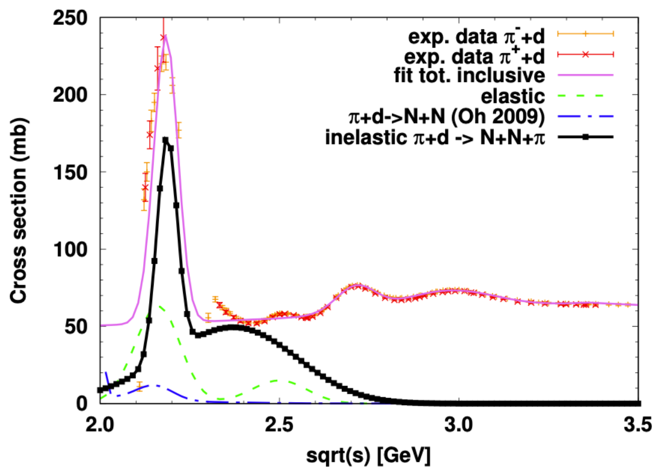
Deuteron production by hadronic reactions

"Kinetic mechanism"

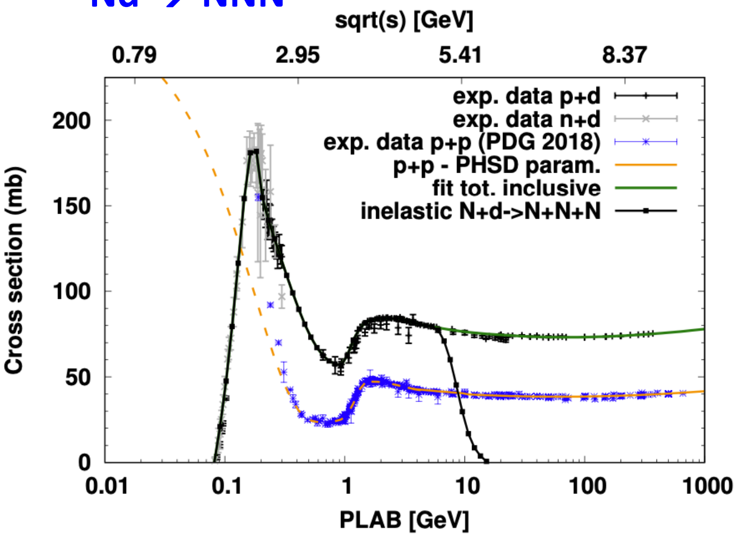
1) hadronic inelastic reactions NN ⟷ dπ , πNN ⟷ dπ , NNN ⟷ dN
2) hadronic elastic π+d, N+d reactions

❑ Hadronic reactions for d+π and d+N scattering have very large cross sections $\sigma_{peak} \approx 200$ mb

πd → πNN



Nd → NNN



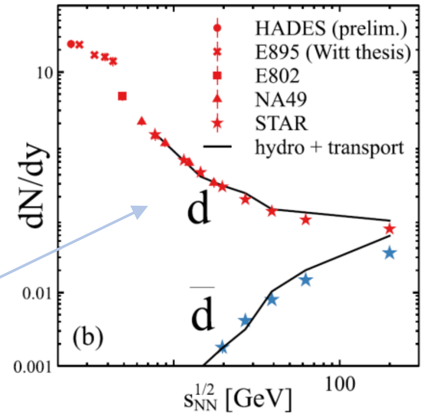
❑ the rates for the inverse processes pNN →pd, NNN→dN in hadronic matter are large due to the time-reversal symmetry

* Kinetic production by inverse reaction N + p + n → N + d first studied in HICs at E_{Lab} ∽ 1 AGeV
by P.J. Siemens, J. Kapusta PRL 43 (1979) 1486

Models for deuteron production by hadronic reactions

- SMASH, AMPT: Inverse reactions X+N+N → X+d (X=π,N with X catalyzer) important for d formation in HICs
- at RHIC and LHC energies: large π abundance
  → deuterons form by π-catalysis: π+p+n → π+d

  at SIS energies: large N abundance
  → deuterons form by N-catalysis: N+p+n → N+d



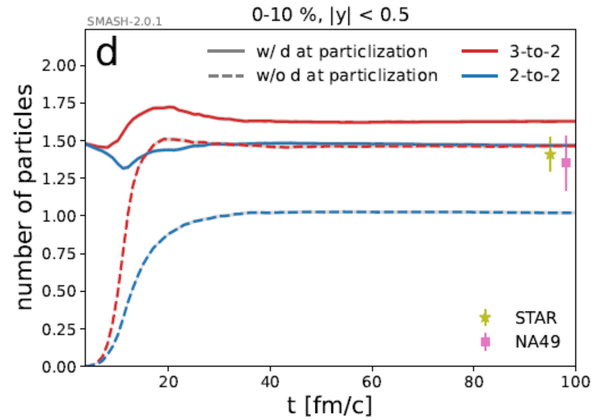
- SMASH (hydro + kinetic): πNN ↔ dπ , NNN ↔ dN are realized

1) via fictitious dibaryon resonance d' as two-step processes of N+N → d' and π + d' → π + d

   D. Oliinychenko PRC 99 (2019) 4, 044907

2) via 3 ↔ 2 transition rates

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



- AMPT: πNN ↔ dπ via impulse approximation:

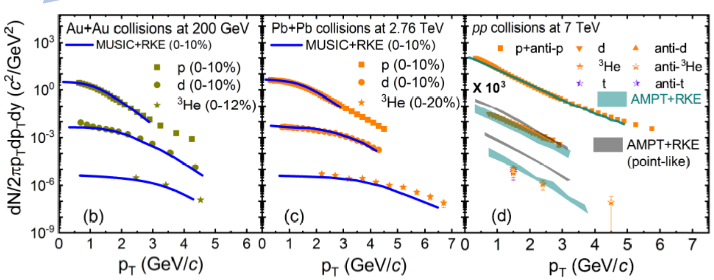
$$\mathcal{M}_{\pi d\to\pi NN} \rightarrow \langle\tilde{p}_N|\phi_d\rangle\mathcal{M}_{\pi N\to\pi N}$$

+ accounting of the finite size of deuterons via Wigner function

$$|\phi_d(\tilde{\mathbf{p}})|^2 = \int d^3\mathbf{r}\gamma_d W_d = (4\pi\sigma_d^2)^{3/2}e^{-\tilde{\mathbf{p}}^2\sigma_d^2}$$

leads to the suppression of d production in pp

K.-J. Sun, R. Wang, C.-M. Ko et al., 2106.12742



cf. talk by Kai Sun

Collision Integral: covariant rate formalism

PHQMD

- **Covariant collision rate for deuteron production for 3→2 reactions is the number of reactions in the covariant volume $d^4x = dt*dV$:**

W. Cassing, NPA 700 (2002) 618
E. Seifert, W. Cassing, PRC 97 (2018) 024913, (2018) 044907

PHSD: Multi-meson fusion reactions
$m_1+m_2+...+m_n \leftrightarrow B+Bbar$
m=π,ρ,ω,.. B=p,Λ,Σ,Ξ,Ω, (>2000 channels)

$$\frac{dN_{coll}[3+4+5\to 1(d)+2]}{dtdV} = \int \left(\prod_{k=3}^{5} \frac{d^3p_k}{(2\pi)^3 2E_k} f_k(x,p_k)\right) \times$$

$$\int \frac{d^3p_1}{(2\pi)^3 2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} W_{3,2}(p_3,p_4,p_5;p_1,p_2)(2\pi)^4\,\delta(p_1+p_2-p_3-p_4-p_5)$$

- **Using the assumption that the transition amplitude depends only on invariant energy : $W(\sqrt{s})$ and using a detailed balance, the covariant collision rate can be expressed in terms of the reaction probability $P_{2,3}$ which is proportional to 2→3 total cross sections**
With test particle ansatz the transition rate for 3→2 reactions in cells of volume ΔV_{cell} is:

$$\frac{\Delta N_{coll}[3+4+5\to 1(d)+2]}{\Delta N_3 \Delta N_4 \Delta N_5} = P_{3,2}(\sqrt{s})$$

Energy and momentum of final particles

2,3-body phase space integrals [Byckling, Kajantie]

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

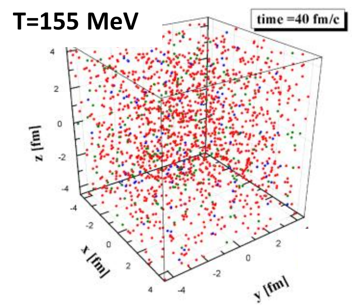
$$P_{2,3}(\sqrt{s}) = \sigma_{tot}^{2,3}(\sqrt{s}) v_{rel} \frac{\Delta t}{\Delta V_{cell}}$$

Reaction probability 2→3 ~ total cross sections for 2→3 reaction

PHQMD

PHQMD: deuteron reactions in the box

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



- **2 ⟶ 2 and 2 ⟶ 3 either by geometric criterium or stochastic method**

Kodama et al. Phys. Rev. C 29 (1984)

W. Cassing NPA 700 (2002) 618

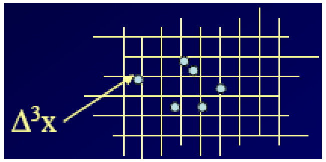
$$d_T < \sqrt{\frac{\sigma_{tot}^{2,3}(\sqrt{s})}{\pi}}$$

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

- **3 ⟶ 2 realized via covariant rate formalism by stochastic method**

W. Cassing NPA 700 (2002) 618

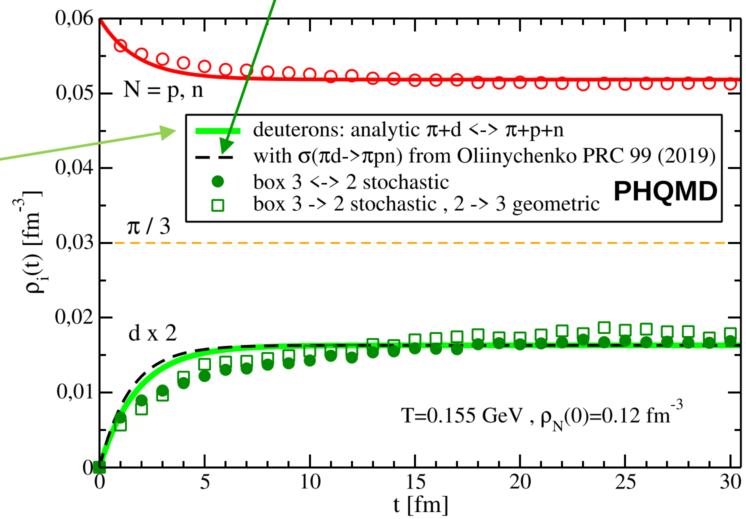
- **Numerically tested in "static" box**



- **PHQMD provides a good agreement with analytic solutions from rate equations**

Comparison to SMASH cross sections: $F_{iso} = 1$

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



$$\begin{cases} \dot{\lambda}_d = \sum < v_{rel}\sigma_{\pi d} > \left(\frac{g_d g_\pi}{g_N^2 g_\pi}\lambda_N^2 - \lambda_d\right) n_\pi^{eq}\lambda_\pi \\ \dot{\lambda}_N = -\sum < v_{rel}\sigma_{\pi d} > \left(\frac{g_d g_\pi}{g_N^2 g_\pi}\lambda_N^2 - \lambda_d\right) n_\pi^{eq}\lambda_\pi \\ \dot{\lambda}_\pi = 0 \end{cases}$$

+ initial conditions

[Y. Pan S. Pratt, PRC 89 (2014), 044911]

Density inside the box at temperature T: $\rho_i = n^{eq}(T)*\lambda_i(t)$

Isospin deuteron reactions in the box

π+N+N$\leftrightarrow$ d+π , d+N $\leftrightarrow$ p+n+N , N+N $\leftrightarrow$ d+π , d+X elastic

$$\pi^{\pm,0} + p + n \leftrightarrow \pi^{\pm,0} + d$$

$$\pi^- + p + p \leftrightarrow \pi^0 + d$$

$$\pi^+ + n + n \leftrightarrow \pi^0 + d$$

$$\pi^0 + p + p \leftrightarrow \pi^+ + d$$

$$\pi^0 + n + n \leftrightarrow \pi^- + d$$

Novel aspects in PHQMD:

N+N+π inclusion of all possible channels allowed by total isospin T conservation:

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

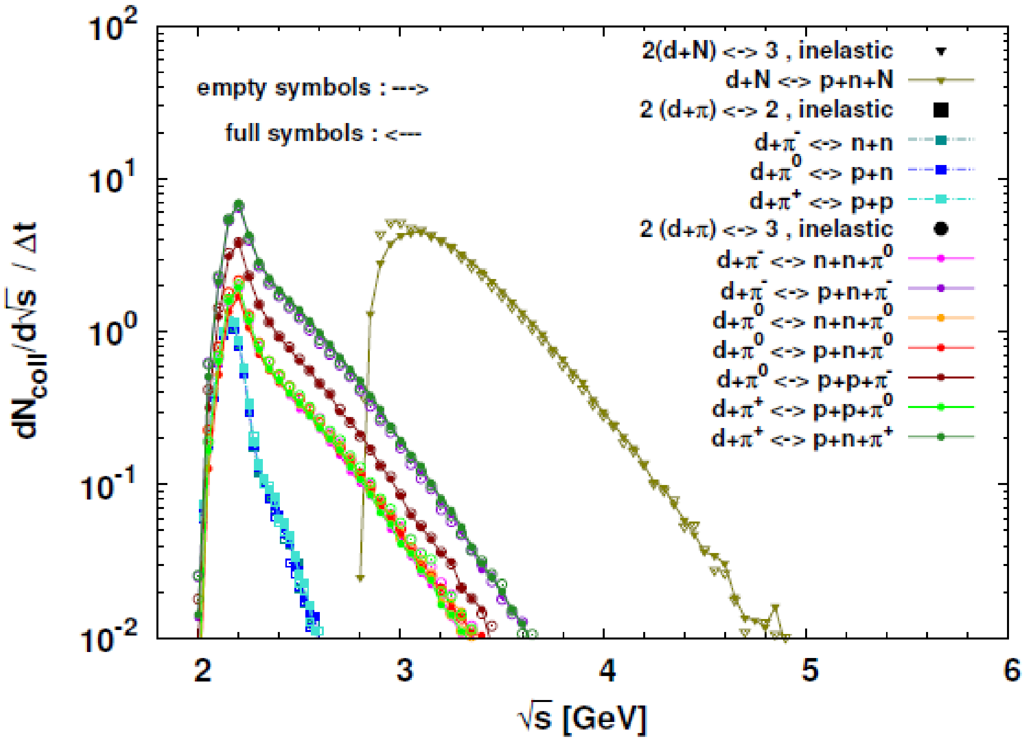
- **NNπ expanded as superposition of eigenstates of total isospin T**

$$|N, N, \pi\rangle = \sum_T \sum_{T_3=-T}^{-T} \langle T, T_3 | N, N, \pi\rangle \, |T, T_3\rangle$$

- **Fourier coefficient of eigenstate of total isospin 1 (= T(d π)=T(π))**

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

➔ For the realistic description of HICs: Important to account for all possible isospin channels !

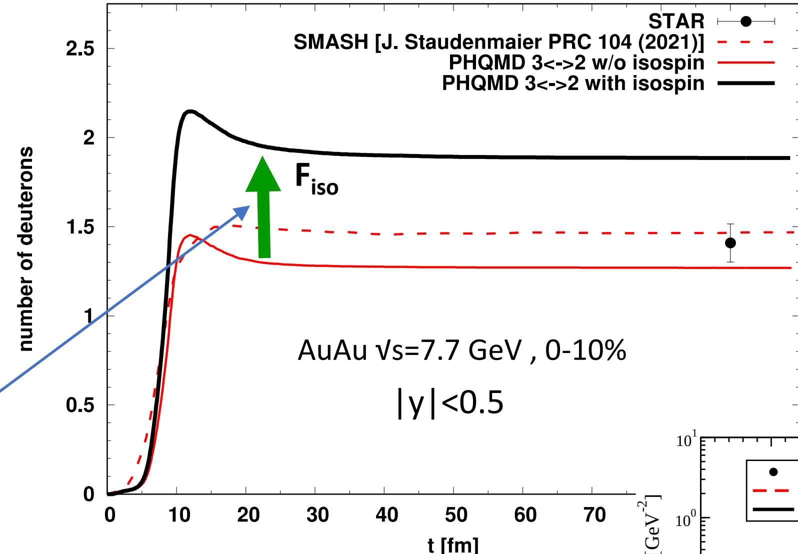


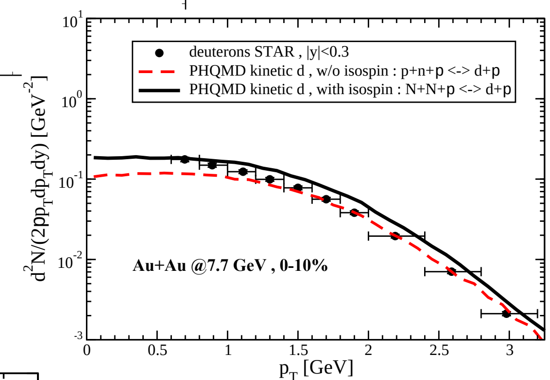
→ **Detailed balance condition fulfilled**

Kinetic deuterons in PHQMD – isospin effects

RHIC BES energy √s = 7.7 GeV:

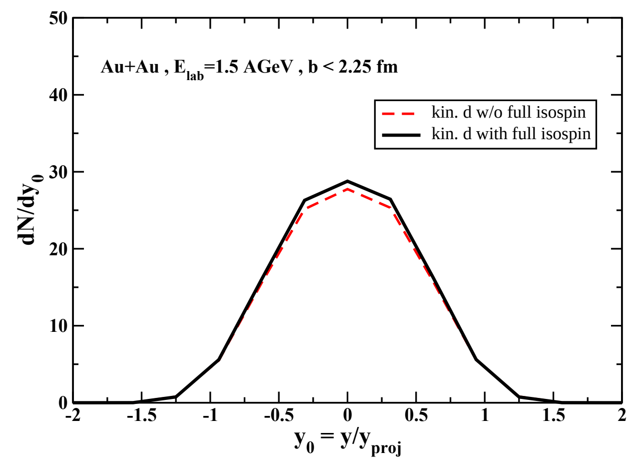
- Hierarchy due to large π abundance
  π+N+N→π+d >> N+p+n→N+d
- **Inclusion of all isospin channels enhances deuteron yield ~ 50%.**
- p_T slope is not affected





GSI SIS energy √s < 3GeV :

- Baryon dominated matter
- Enhancement due to inclusion of isospin π+N+N channels is negligible



Modelling of deuteron finite-size effects in kinetic mechanism

How to account for the **quantum nature of deuteron**, i.e. for

1) the finite-size of *d* in **coordinate space** (*d* is not a point-like particle) – for in-medium d production
2) the **momentum correlations** of *p* and *n* inside *d*

Realization 1) assume that a deuteron can not be formed in a high density region, i.e. if there are other particles (hadrons or partons) inside the 'excluded volume':

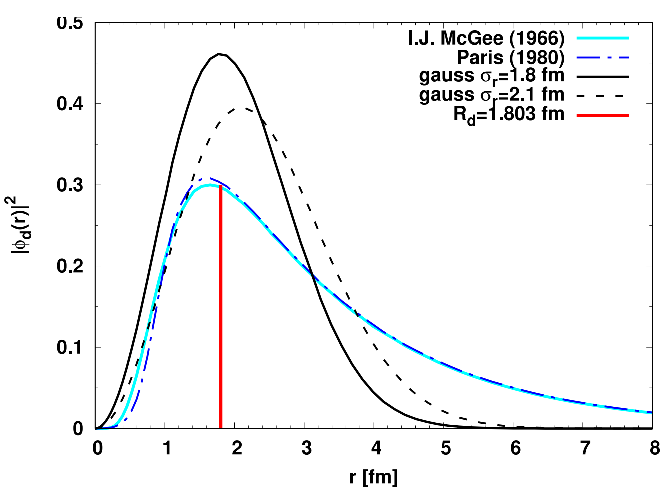
Excluded-Volume Condition:

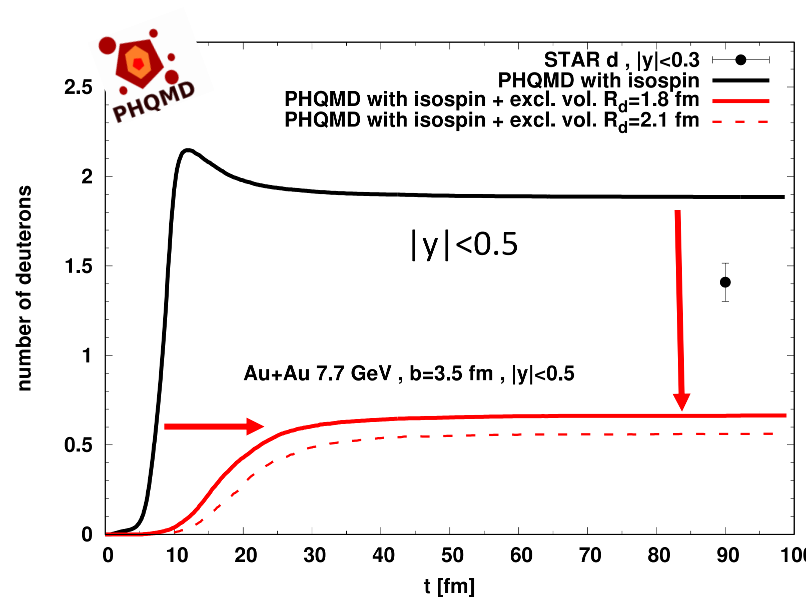
$$|\vec{r}(i)^* - \vec{r}(d)^*| < R_d$$

"i" is any particle not participating in
$\pi NN \rightarrow \pi d$, $NNN \rightarrow Nd$, $NN \rightarrow d\pi$
* means that positions are in the cms of pre-calculated "candidate" deuteron

The exclusion parameter R_d is tuned to the physical radius

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

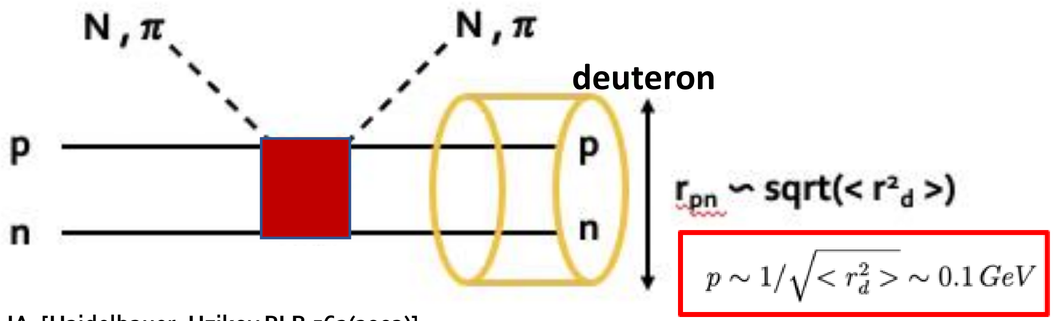




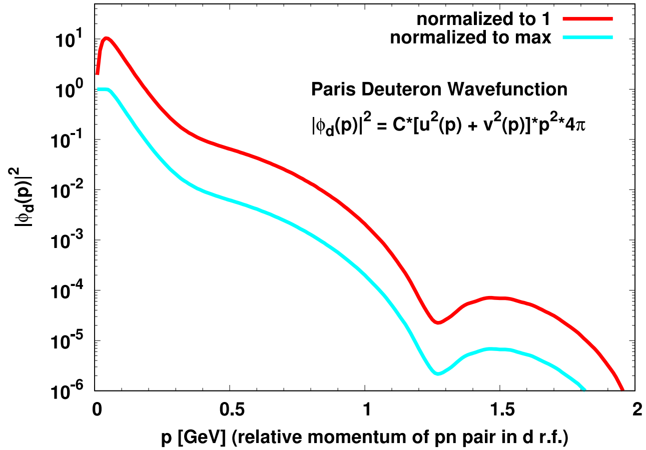
- **Strong reduction of d production!**
- **p_T slope is not affected by excluded volume condition**

Modelling of deuteron finite-size effects in kinetic mechanism

2) QM properties of deuteron must be also in momentum space
→ **momentum correlations of pn-pair**

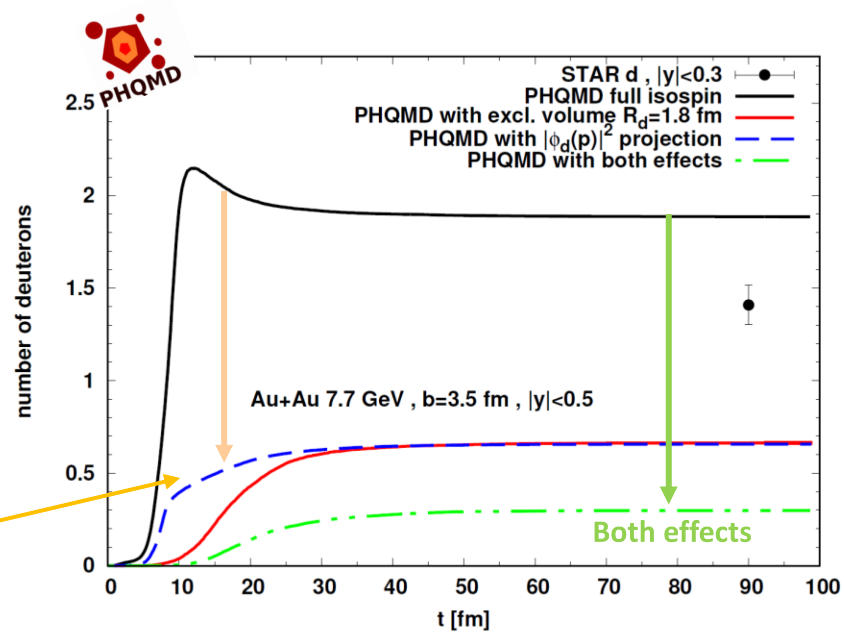


IA: [Haidelbauer, Uzikov PLB 562(2003)]
[Hoftiezer et al. PRC23 (1981)]
Same spirit - IA in AMPT [K.-J. Sun, R. Wang, C.-M. Ko et al., 2106.12742]



[Lacombe et al. PL (1981)]

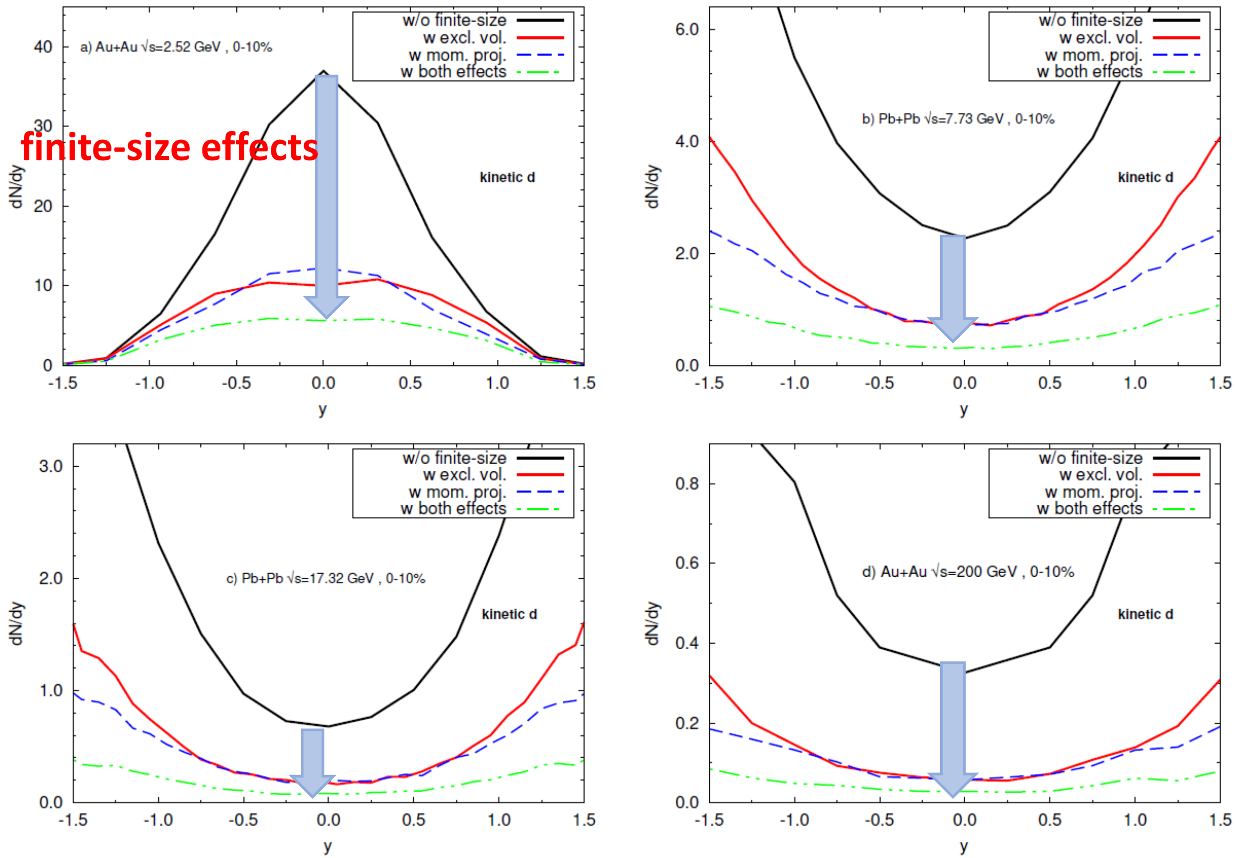
- **For a "candidate" deuteron calculate the relative momentum p of the interacting pn-pair in the deuteron rest frame**
- **The probability of the pn-pair to bind into a final deuteron with momentum p is given by the DWF $|\Phi_d(p)|^2$**
- **Bound pn-pairs are selected by projection on DWF $|\Phi_d(p)|^2$**



❑ **Strong reduction of d production by projection on DWF $|\Phi_d(p)|^2$**

Kinetic vs. potential deuteron production

Total deuteron production = Kinetic mechanism with finite-size effects
+ MST (with stabilization) identification of deuterons (“stable” bound (E_B<0) A=2, Z=1 clusters)



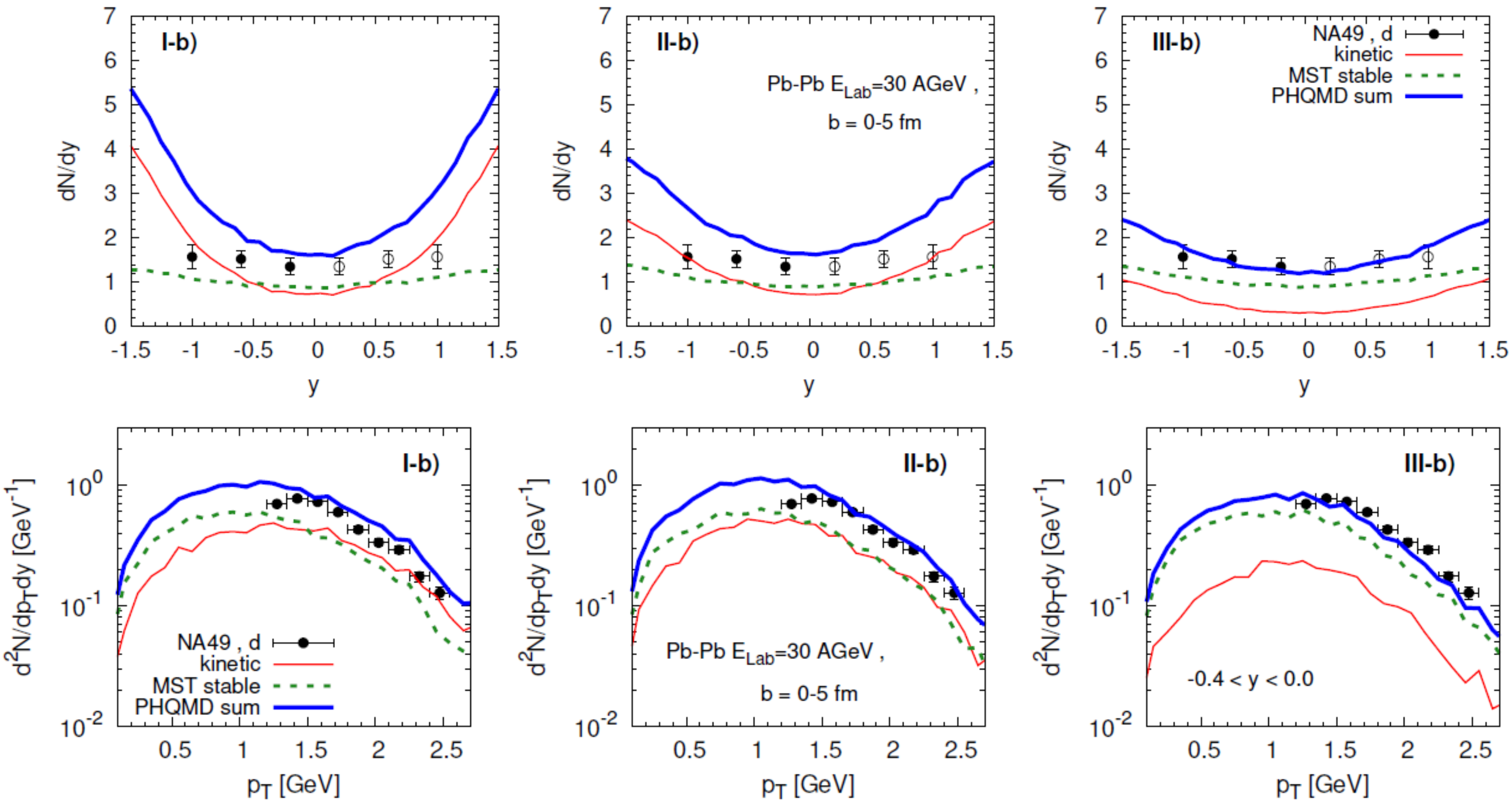
- Kinetic deuterons: finite-size effects (momentum projection + excluded volume) lead to a strong suppression of deuteron production at all energies
- Shape of y-distribution is different for different mechanisms of d production!

Kinetic vs. potential deuteron production

Total deuteron production = Kinetic mechanism with finite-size effects
+ MST (with stabilization) identification of deuterons ("stable" bound (E_B<0) A=2, Z=1 clusters)

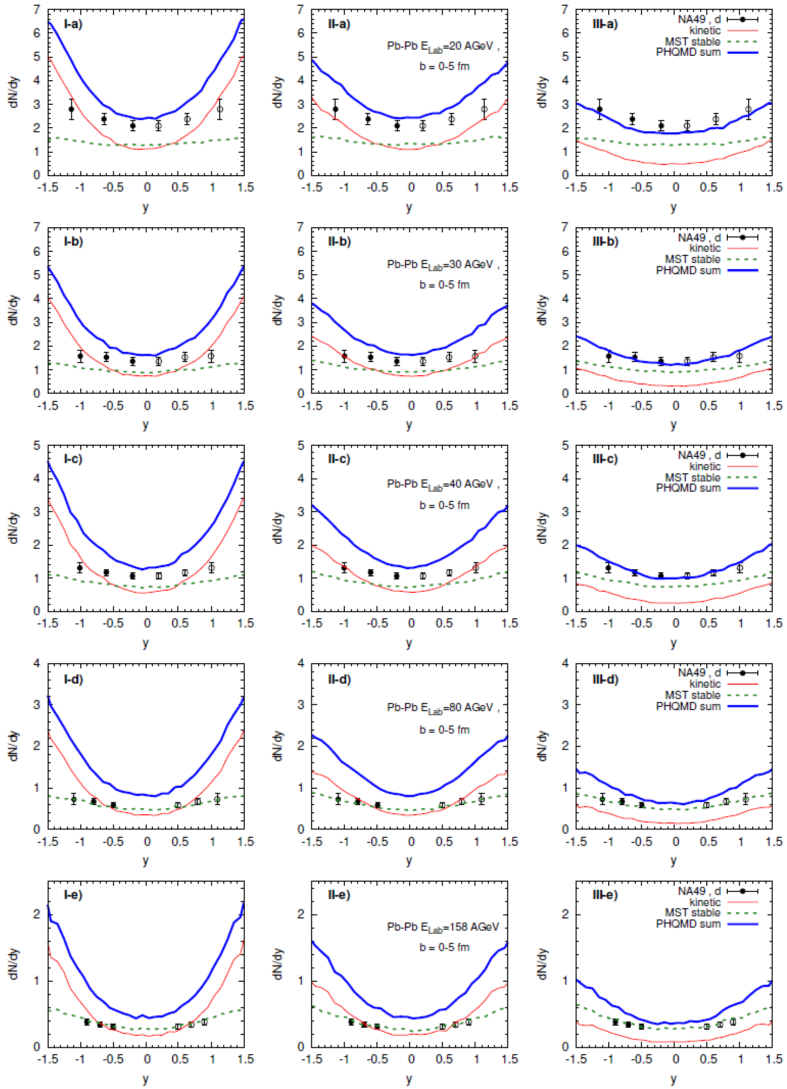
Finite-size effects for kinetic deuterons:

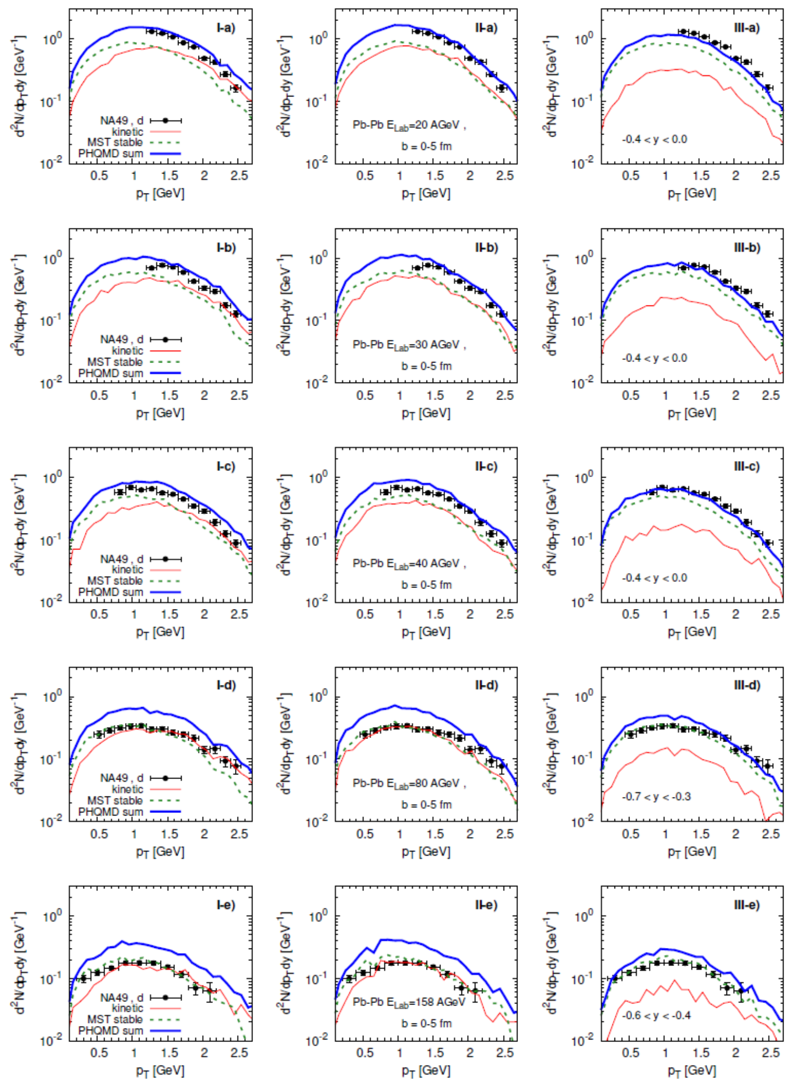
1) excluded-volume **2) Momentum projection** **3) both effects**



- **Good description of mid-rapidity NA49 data** [PRC 94 (2016) 04490699]

Kinetic vs. potential deuteron production



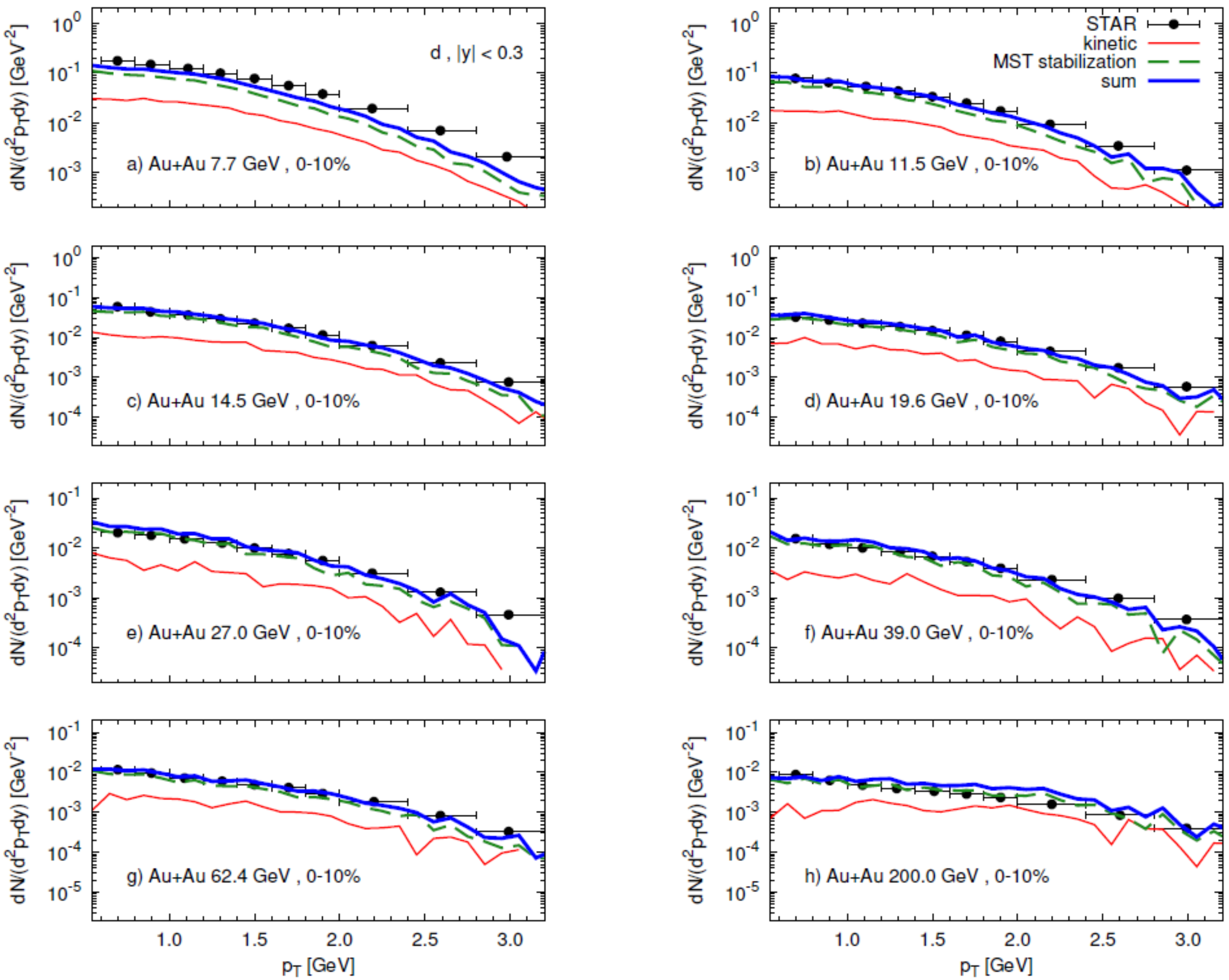


Total deuteron production = Kinetic mechanism with finite-size effects

+ MST (with stabilization) identification of deuterons ("stable" bound (E_B<0) A=2 , Z=1 clusters)

Kinetic vs. potential deuteron production

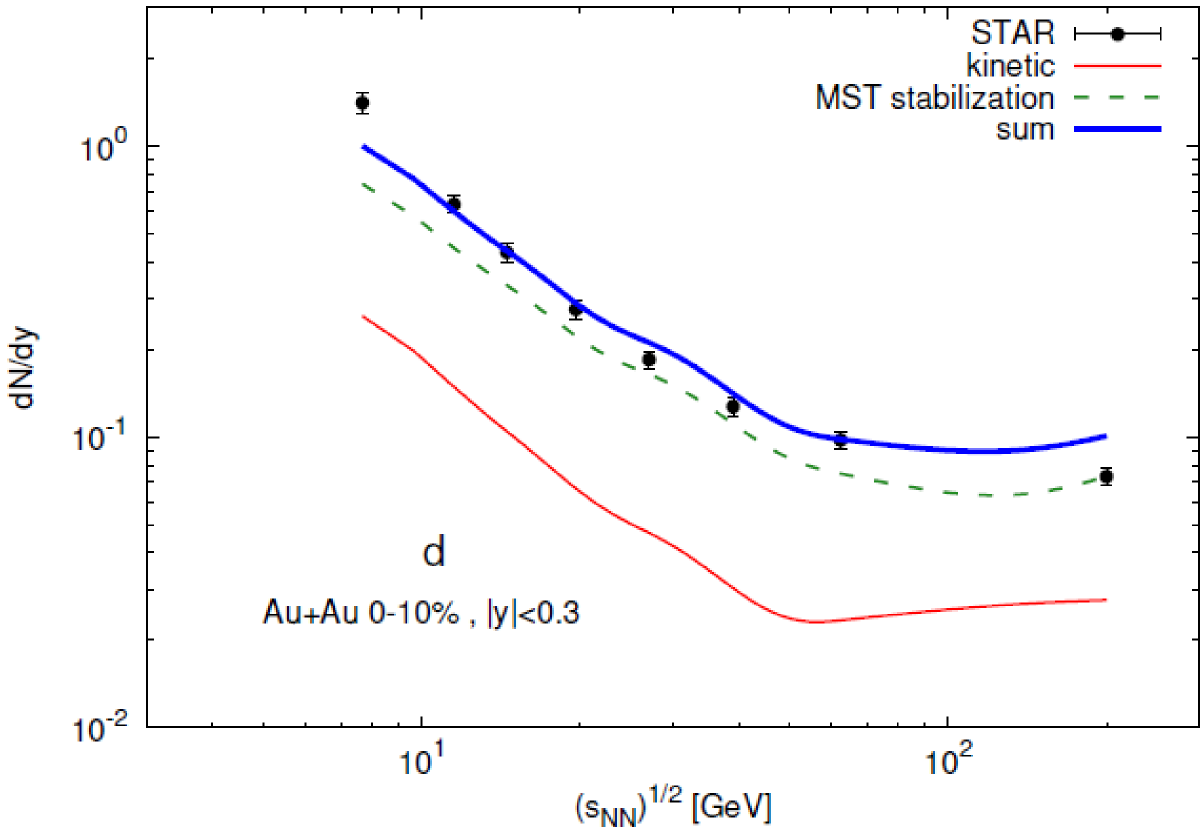
Total d = Kinetic mechanism with finite-size effects + MST (with stabilization) identification of d



➔ **Good description of mid-rapidity STAR data** [PRC 99, (2019)]

Kinetic vs. potential deuteron production

Excitation function dN/dy of deuterons at midrapidity



- **PHQMD provides a good description of STAR data on d yield at midrapidity**
- **The potential mechanism is dominant for d production at all energies!**

PHQMD

Summary

- The PHQMD is a microscopic n-body transport approach for the description of heavy-ion dynamics and cluster and hypernuclei formation

combined model PHQMD = (PHSD & QMD) & (MST | SACA)

- Clusters are formed dynamically by potential interactions among nucleons and hyperons and identified by Minimum Spanning Tree model

- Kinetic mechanism for deuteron production is implemented in the PHQMD with inclusion of full isospin decomposition for hadronic reactions which enhances d production
- However, accounting for the quantum properties of the deuteron, modelled by the finite-size excluded volume effect in coordinate space and projection of relative momentum of the interacting pair of nucleons on the deuteron wave-function in momentum space, leads to a strong reduction of d production, especially at target/projectile rapidities

- The PHQMD reproduces cluster and hypernuclei data on dN/dy and dN/dp_T as well as ratios d/p and $\bar{d}/\bar{p}$ for heavy-ion collisions from AGS to top RHIC energies (cf. talk by Susanne Glässel)

A detailed analysis reveals that stable clusters are formed

- shortly after elastic and inelastic collisions have ceased
- behind the front of the expanding energetic hadrons
- since the 'fire' is not at the same place as the 'ice', cluster can survive

- PHQMD and UrQMD give very similar coalescence and MST distributions of deuterons

- Shape of y-and p_T- distributions depends on a production mechanism ➔ possibility to distinguish between production mechanisms experimentally!

Thank you for your attention !

Thanks to the Organizers !

PHQMD

https://phqmd.gitlab.io/

(under construction)