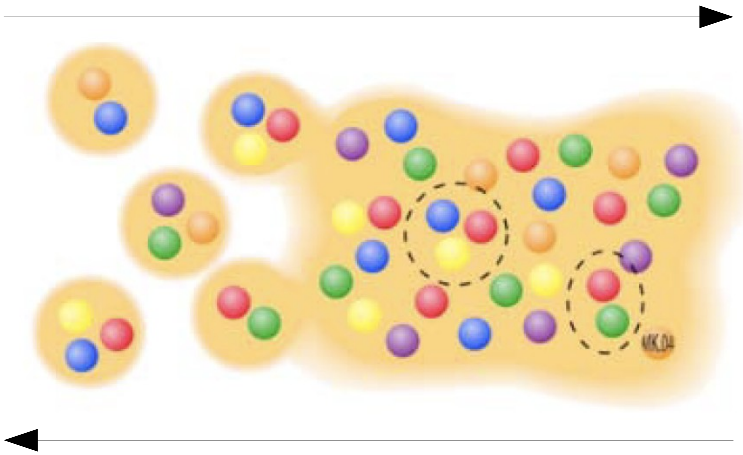
Production of hadrons and nuclei at chemical freezeout

David Blaschke
University of Wroclaw, Poland & JINR Dubna & MEPhI Moscow, Russia

Mott delocalization = dissociation, deconfinement

Hadrons

Nuclei



Quark-Gluon Plasma

Mott localization = hadronization, confinement

Non-**e**quilibrium **D**ynamics, Castiglione della Pescaia, 18.06.2019

Grant No. 17-12-01427

Production of hadrons and nuclei at chemical freezeout

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1. **Bound states in a plasma**
   Generalized Beth-Uhlenbeck approach
2. **Freeze-out vs. Mott effect in the Phase diagram**
3. **Justification of sudden freeze-out by localization**
4. **Applications of the sudden freeze-out scheme**
   Light clusters in THESEUS
   K+/pi+ horn from the generalized Beth-Uhlenbeck approach

Non-**e**quilibrium **D**ynamics, Castiglione della Pescaia, 18.06.2019

JINR DUBNA
MEPhI
NARODOWE CENTRUM NAUKI
cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
Uniwersytet Wrocławski
RSF Russian Science Foundation

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

Light clusters in nuclei and nuclear matter: Nuclear structure and decay, heavy ion collisions, and astrophysics

From Monday, 2 September, 2019 - 08:00 to Friday, 6 September, 2019 - 14:00

Location: ECT* meeting room

Abstract:
Nuclear systems are important examples for strongly interacting quantum liquids. New experiments in nuclear physics and observations of compact astrophysical objects require an adequate description of correlations, in particular the formation of clusters and the occurrence of quantum condensates in low-density nuclear systems. Alpha clustering is an important phenomenon in light 4-n self-conjugated nuclei (Hoyle state). New results have been obtained for such nuclei with additional nucleons (e.g. the 9B and (9-11)Be nuclei). Collective excitations show also effects of α-like clustering. In addition, clustering is of relevance for radioactive decay, alpha preformation and the life-time of heavy nuclei. Cluster formation is essential to investigate nuclear systems in heavy ion collisions. Transport codes have to be worked out to describe the time evolution of correlations and bound states for expanding hot and dense matter. An interesting issue is the BEC-BCS transition in nuclear systems.

Registration period: 16 May 2019 to 12 Aug 2019

Website: https://indico.ectstar.eu/event/52/

http://www.ectstar.eu/node/4447

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The first compact star merger event – Implications for nuclear and particle physics

From Monday, 14 October, 2019 - 08:00 to Friday, 18 October, 2019 - 14:00

Location: ECT* meeting room

Abstract:
Multimessenger observation of compact stars (CSs) mergers have the potential to revolutionize nuclear astrophysics. Data from the first detection, now called GW170817, has already provided strong hints that heavy elements are produced in CS mergers and first constrains the properties of dense matter. It is expected that the Advanced LIGO & Virgo detector network will discover several new events in the first months of the new observing run, which should start in the early 2019 after a series of upgrades to the detectors that should boost their sensitivities by a factor ~3. A vibrant collaborative efforts involving nuclear physicists, computational astrophysicists, and GW and EM observers will be key for the interpretation of past and future observations. This workshop will bring together prominent members of these communities with the aim of maximizing the scientific impact of CS merger observations in nuclear astrophysics.

Registration period: 29 Jul 2019 to 23 Sep 2019

ENSAR2

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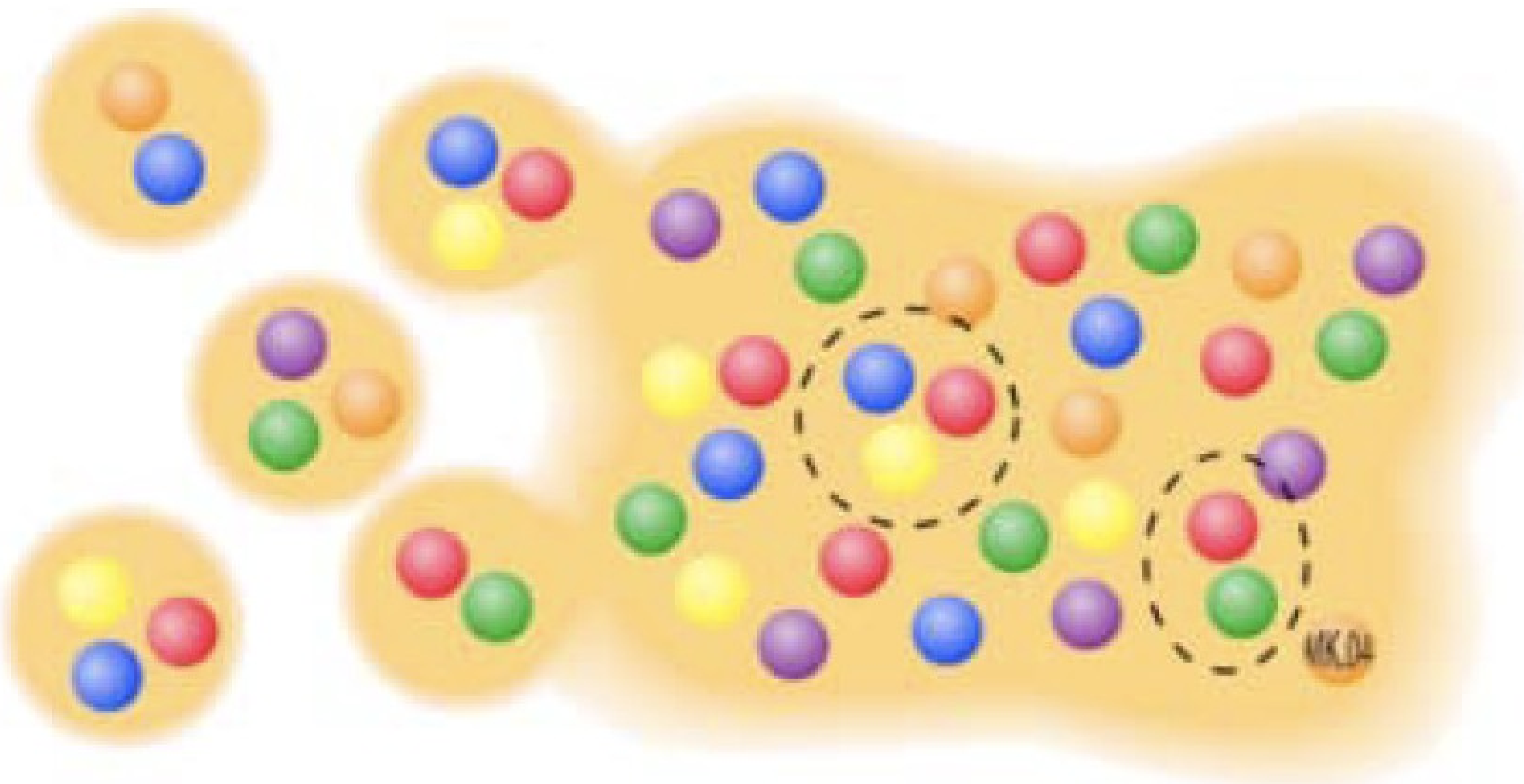
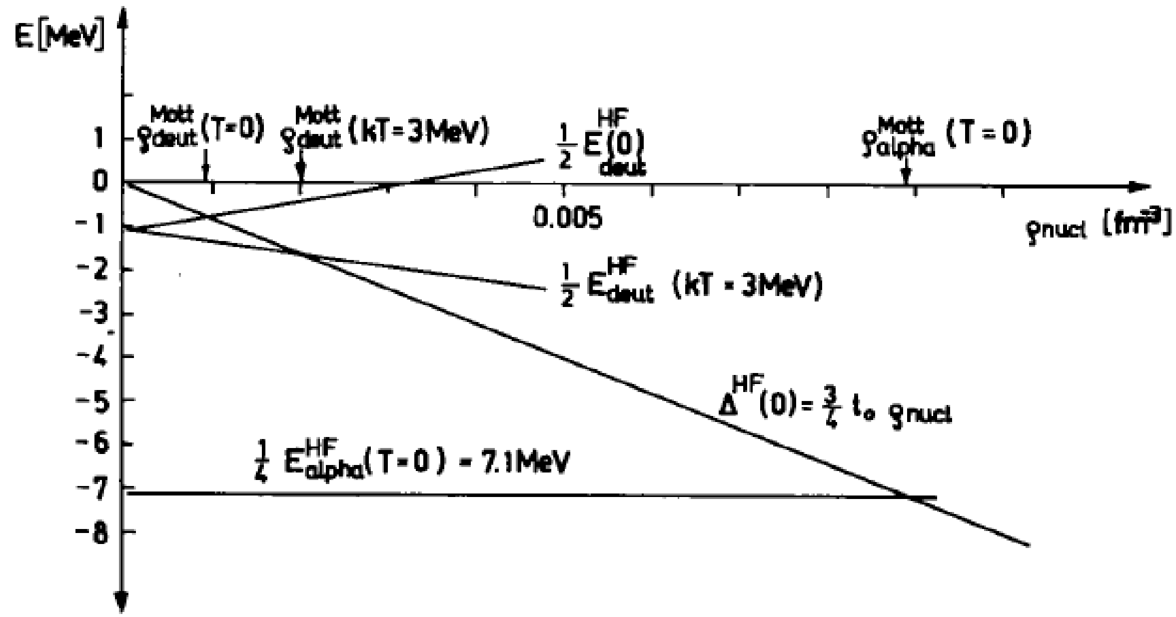
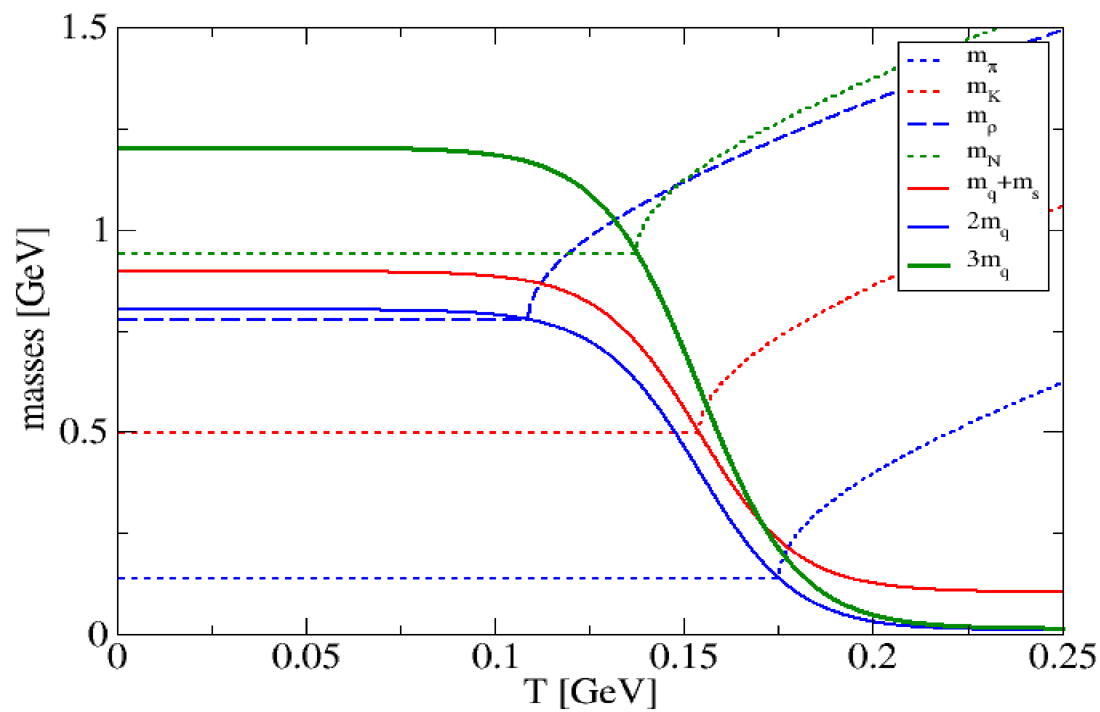


Mott Effect:

Nuclei in Nuclear Matter

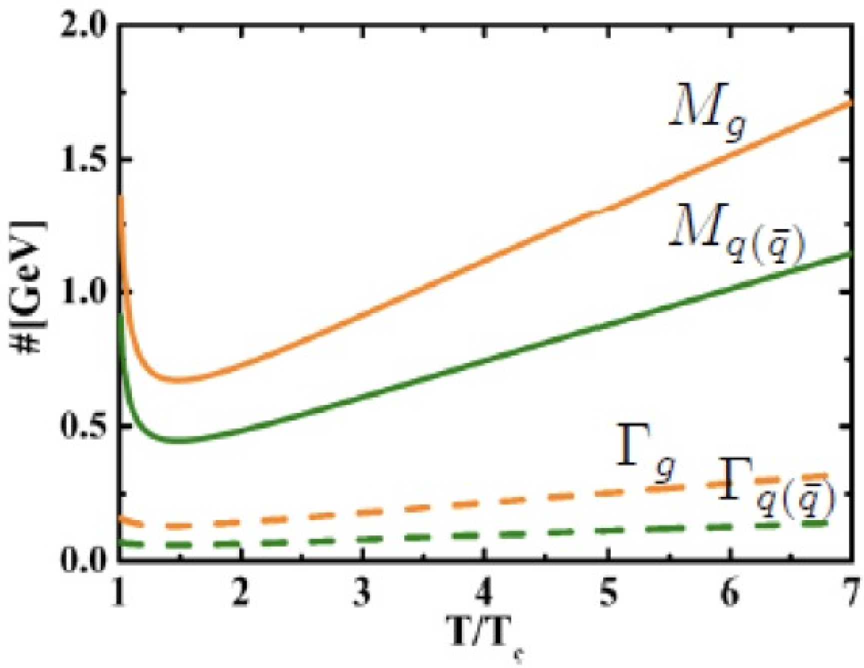


Hadrons in Quark Matter

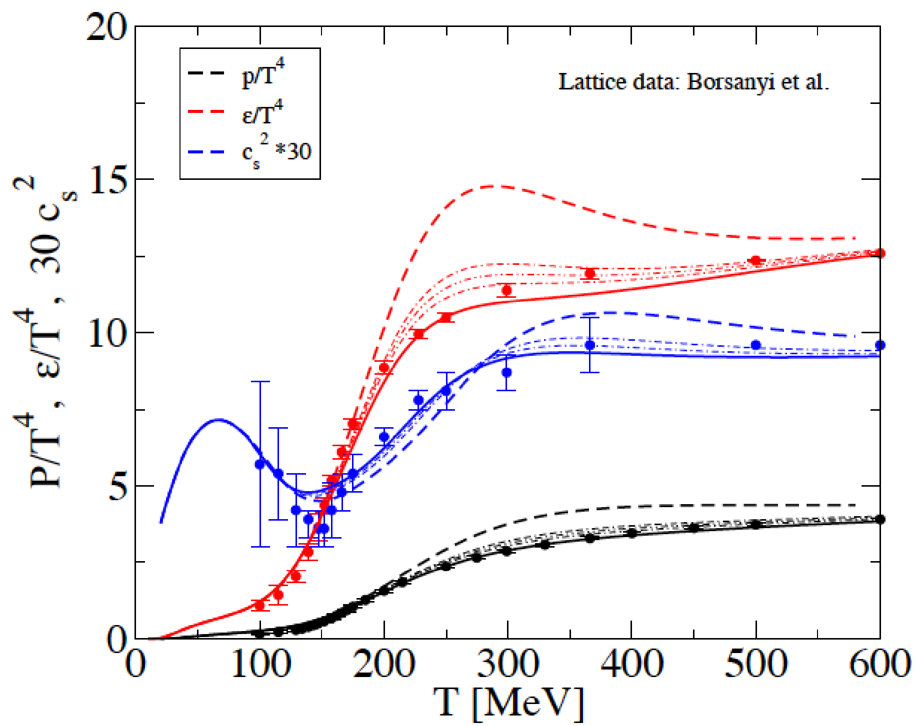


A Teaser:

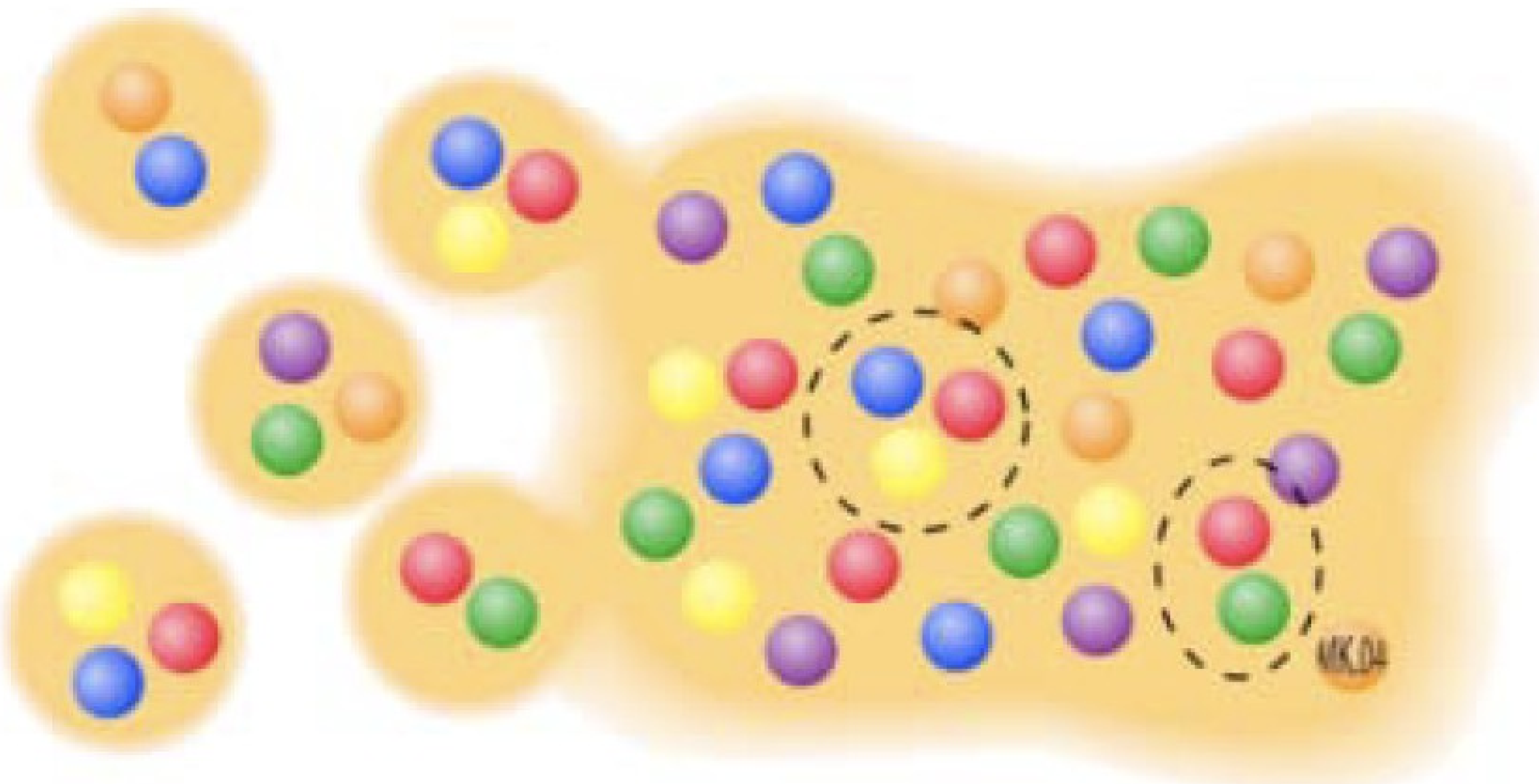
If quark masses have a
Minimum at ~400 MeV,
Then all mesons with
M<800 MeV
And baryons with
M<1200 MeV
Would not undergo
Mott dissociation!



Lattice QCD thermodynamics
Explained by hadrons only!



L. Turko et al.
JPCS 455, 012056 (2013)
Arxiv:1307.1732

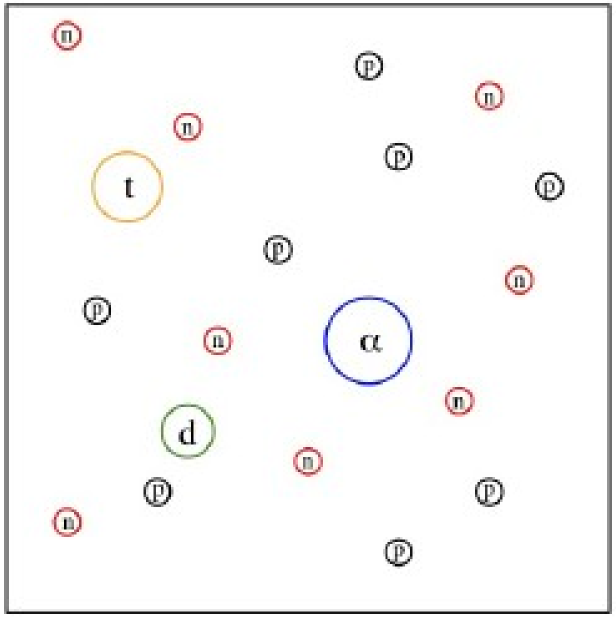


Bound states in a plasma – Clusters in nuclear matter

Chemical picture:

Ideal mixture of reacting components

Mass action law

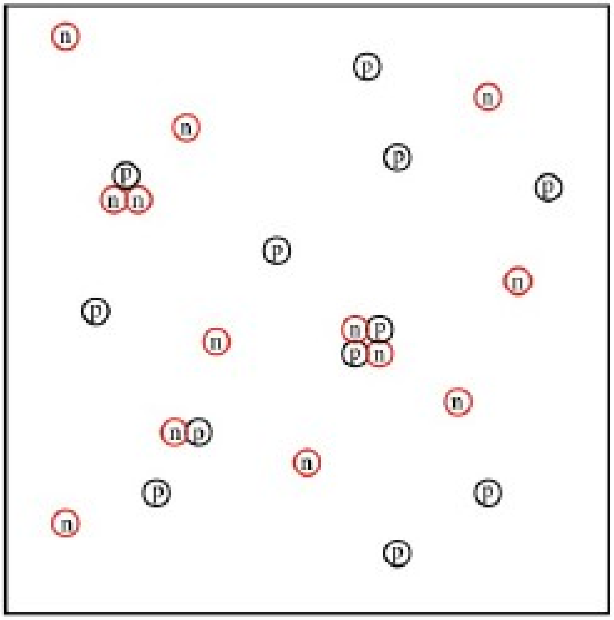


Interaction between the components
internal structure: Pauli principle

Physical picture:

"elementary" constituents

and their interaction



Quantum statistical (QS) approach,
quasiparticle concept, virial expansion

Bound states in a plasma – Clusters in nuclear matter

Effective wave equation for deuterons in nuclear matter

In-medium two-particle wave equation in mean-field approximation

$$\left(\frac{p_1^2}{2m_1}+\Delta_1+\frac{p_2^2}{2m_2}+\Delta_2\right)\Psi_{d,P}(p_1,p_2)+\sum_{p_1',p_2'}(1-f_{p_1}-f_{p_2})V(p_1,p_2;p_1',p_2')\Psi_{d,P}(p_1',p_2')$$

$$= E_{d,P}\Psi_{d,P}(p_1,p_2)$$

Add self-energy

Pauli-blocking

Thouless criterion

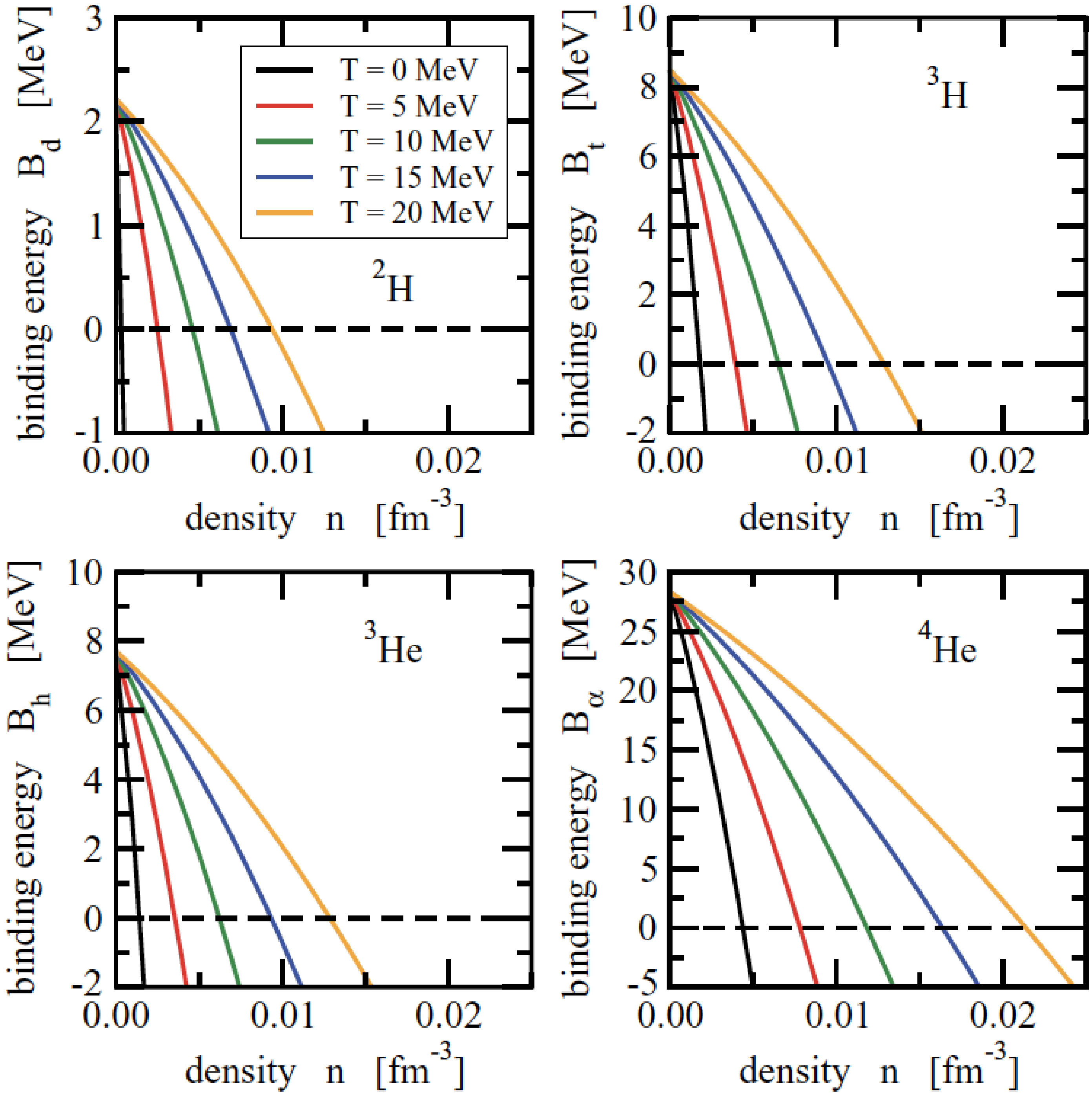
$$E_d(T,\mu)=2\mu$$

Fermi distribution function

$$f_p=\left[e^{(p^2/2m-\mu)/k_BT}+1\right]^{-1}$$

BEC-BCS crossover:
Alm et al.,1993

Binding energies for light clusters in the QCD phase diagram



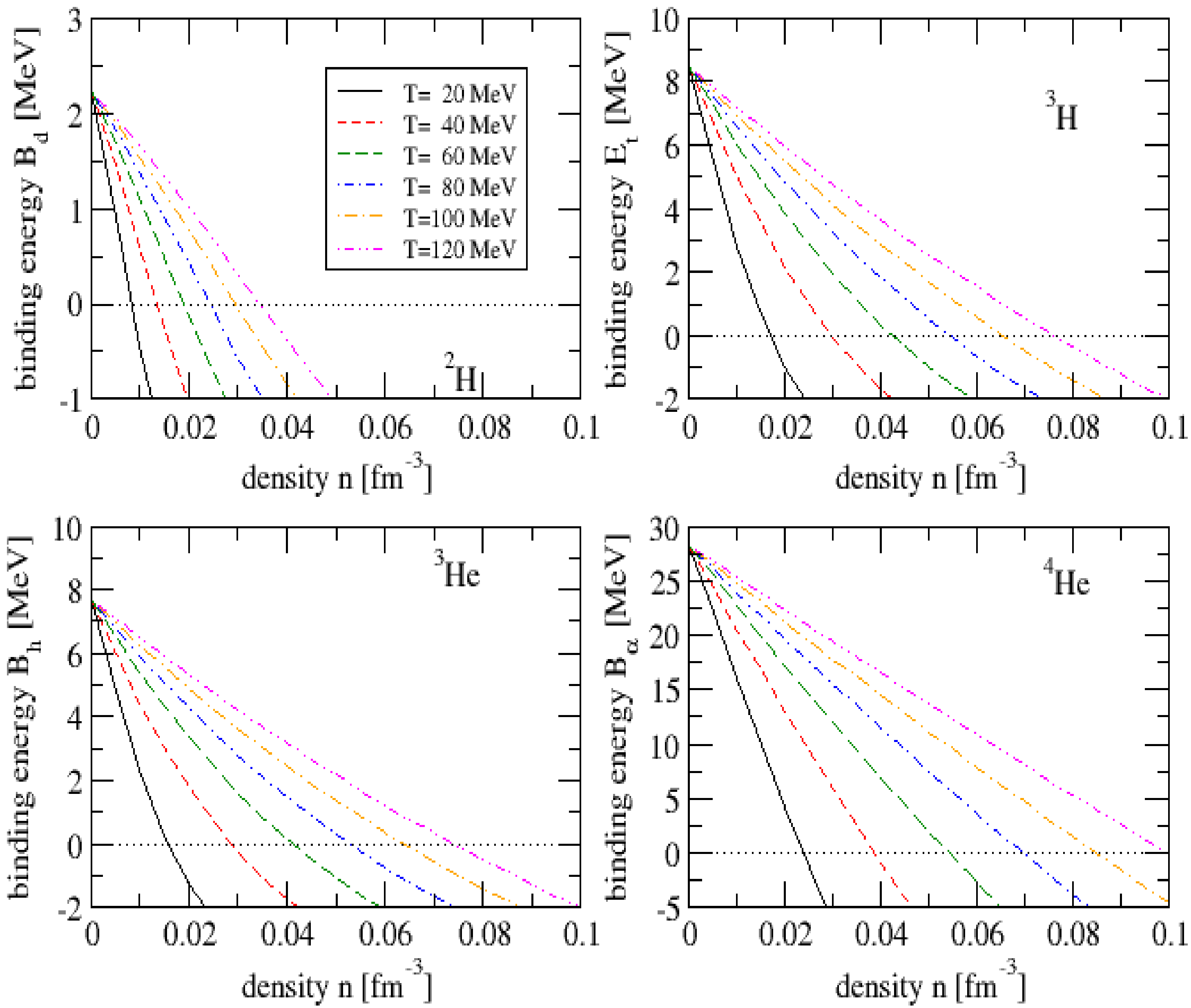
Vanishing binding energies
Indicate Mott effect for the
Light clusters!

Mott-lines in the T-μ plane
can be extracted, where the
Binding energy vanishes

Here lower temperatures:
0 < T[MeV] < 20

S. Typel et al., PRC 81, 015803 (2010)

Binding energies for light clusters in the QCD phase diagram



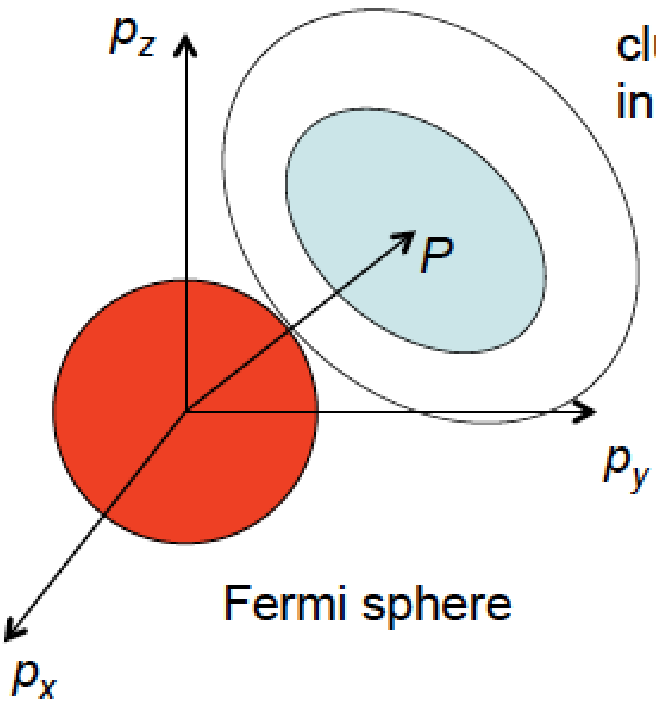
Mott-lines in the T-μ plane can be extracted, where The binding energy vanishes

Here higher temperatures:

20 < T[MeV] < 120

Courtesy: G. Roepke

Pauli blocking – phase space occupation



cluster wave function (deuteron, alpha,…)
in momentum space

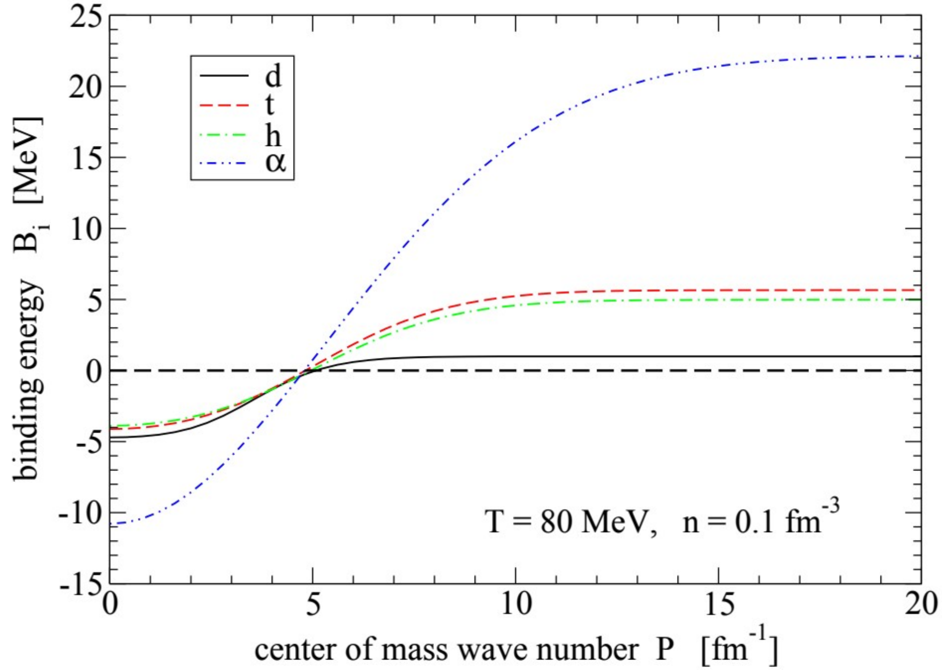
P - center of mass momentum

The Fermi sphere is forbidden,
deformation of the cluster wave function
in dependence on the c.o.m. momentum *P*

momentum space

The deformation is maximal at $P = 0$.
It leads to the weakening of the interaction
(disintegration of the bound state).

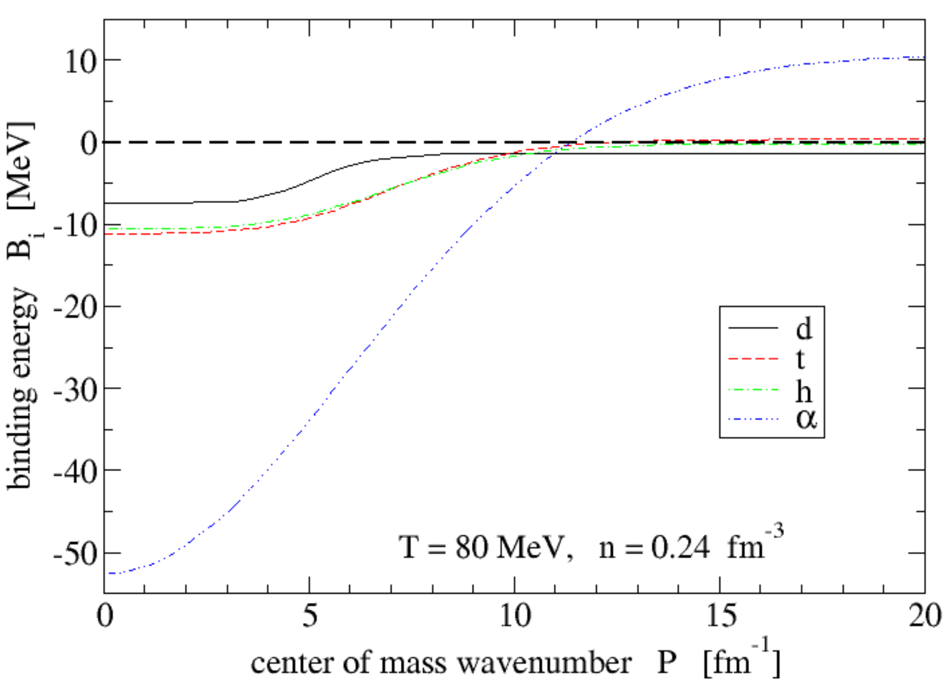
Momentum dependence of binding energies for light clusters

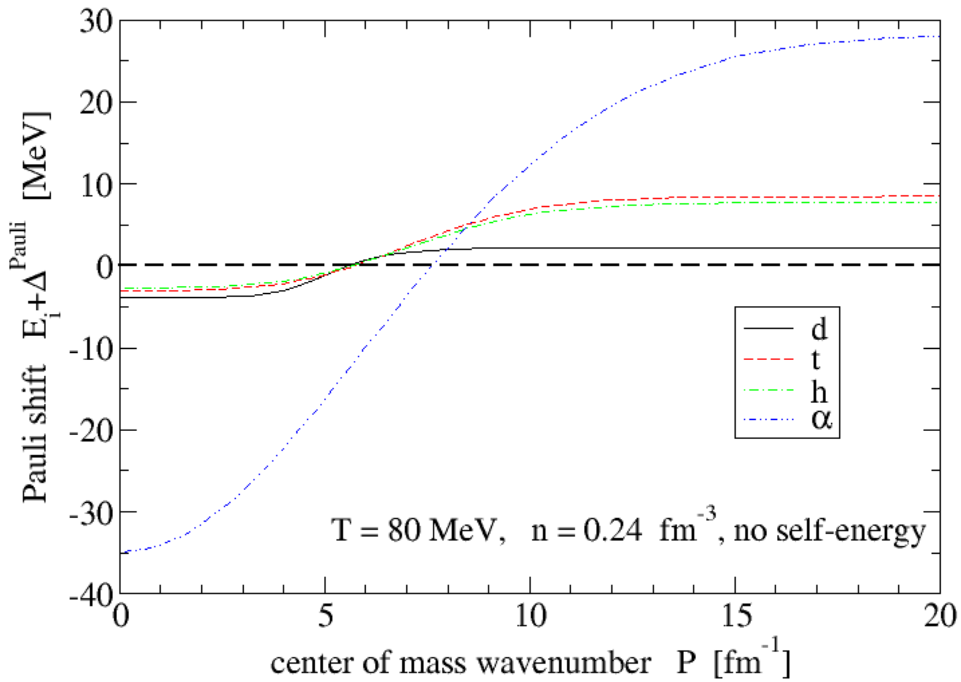


The light clusters that underwent a Mott Dissociation for low momenta become “resurrected” at high momenta relative to the medium !

The minimal momentum where this Occurs is called “Mott momentum”;
It depends on temperature and density

Binding energies without selfenergy shift,
Only Pauli blocking shift accounted for

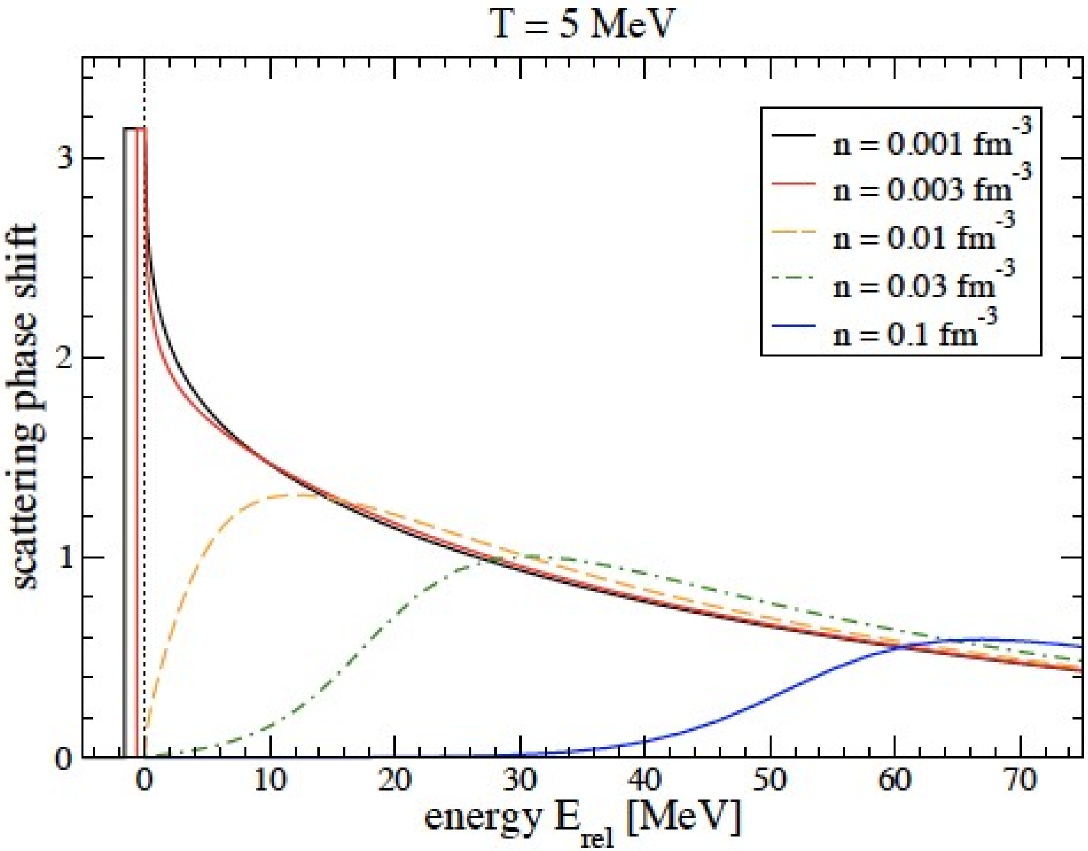




Bound states in a plasma – Clusters in nuclear matter

Deuteron-like scattering phase shifts

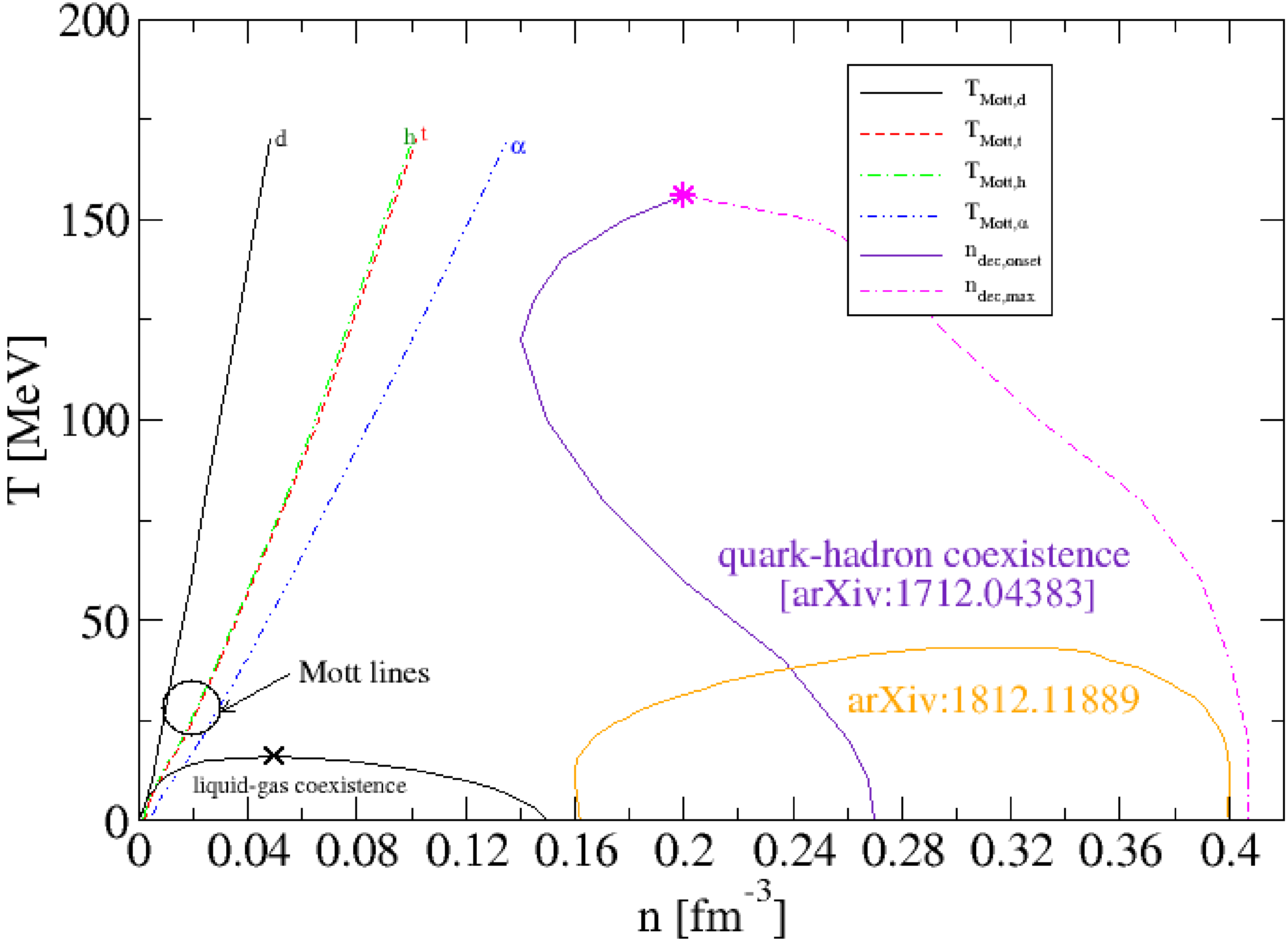
Virial coeff. $\propto e^{-E_d^0/T} - 1 + \frac{1}{\pi T}\int_0^\infty dE\, e^{-E/T}\left\{\delta_c(E) - \frac{1}{2}\sin[2\delta_c(E)]\right\}$



deuteron bound state -2.2 MeV

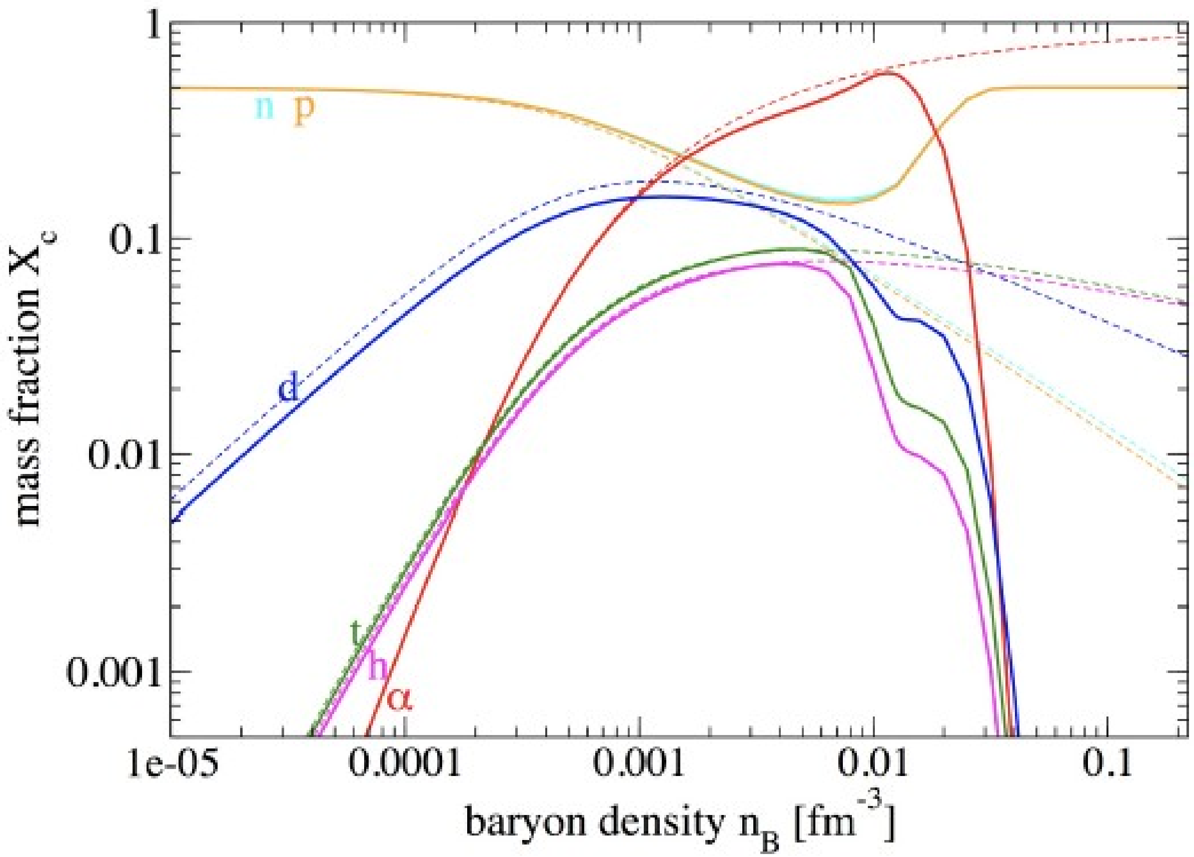
G. Roepke, J. Phys.: Conf. Series 569, 012031 (2014).

Mott lines in the QCD phase diagram



Bound states in a plasma – Clusters in nuclear matter

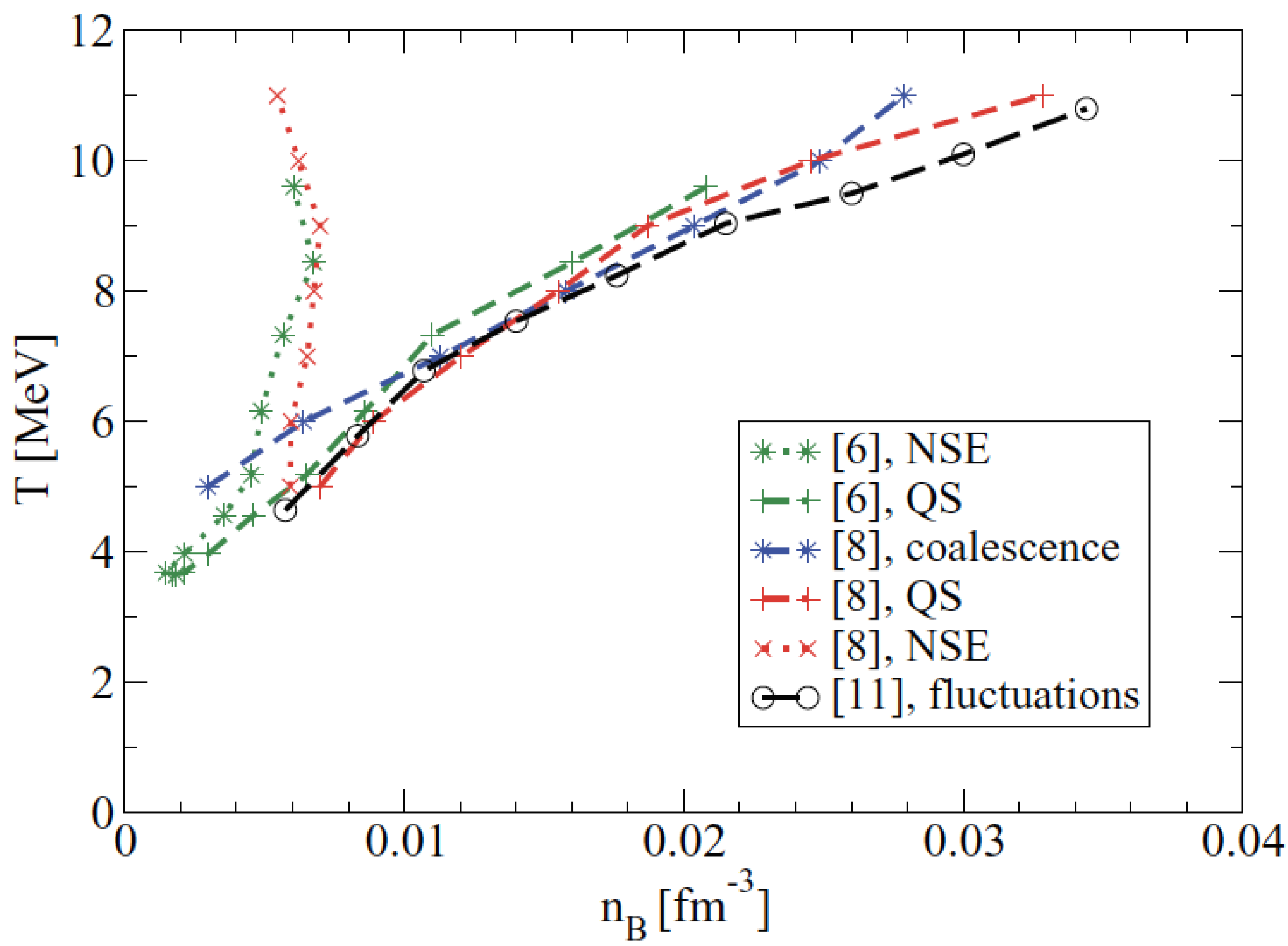
Light Cluster Abundances

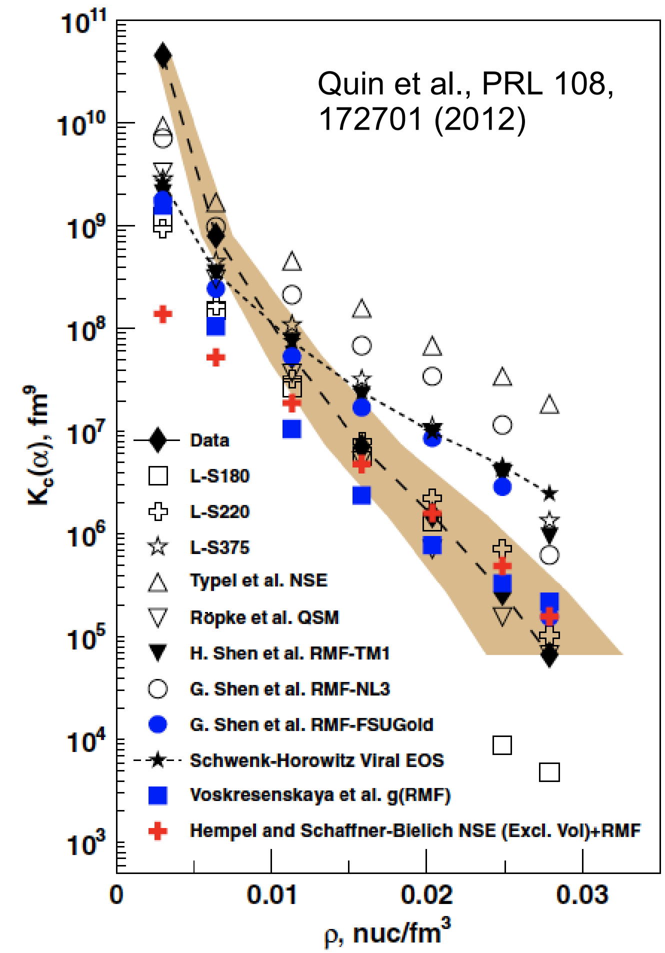


Composition of symmetric matter in dependence on the baryon density n_B, T = 5 MeV. Quantum statistical calculation (full) compared with NSE (dotted).

G. Roepke, Phys. Rev. C 92, 054001 (2015)

Mott lines and chemical freeze-out in the QCD phase diagram



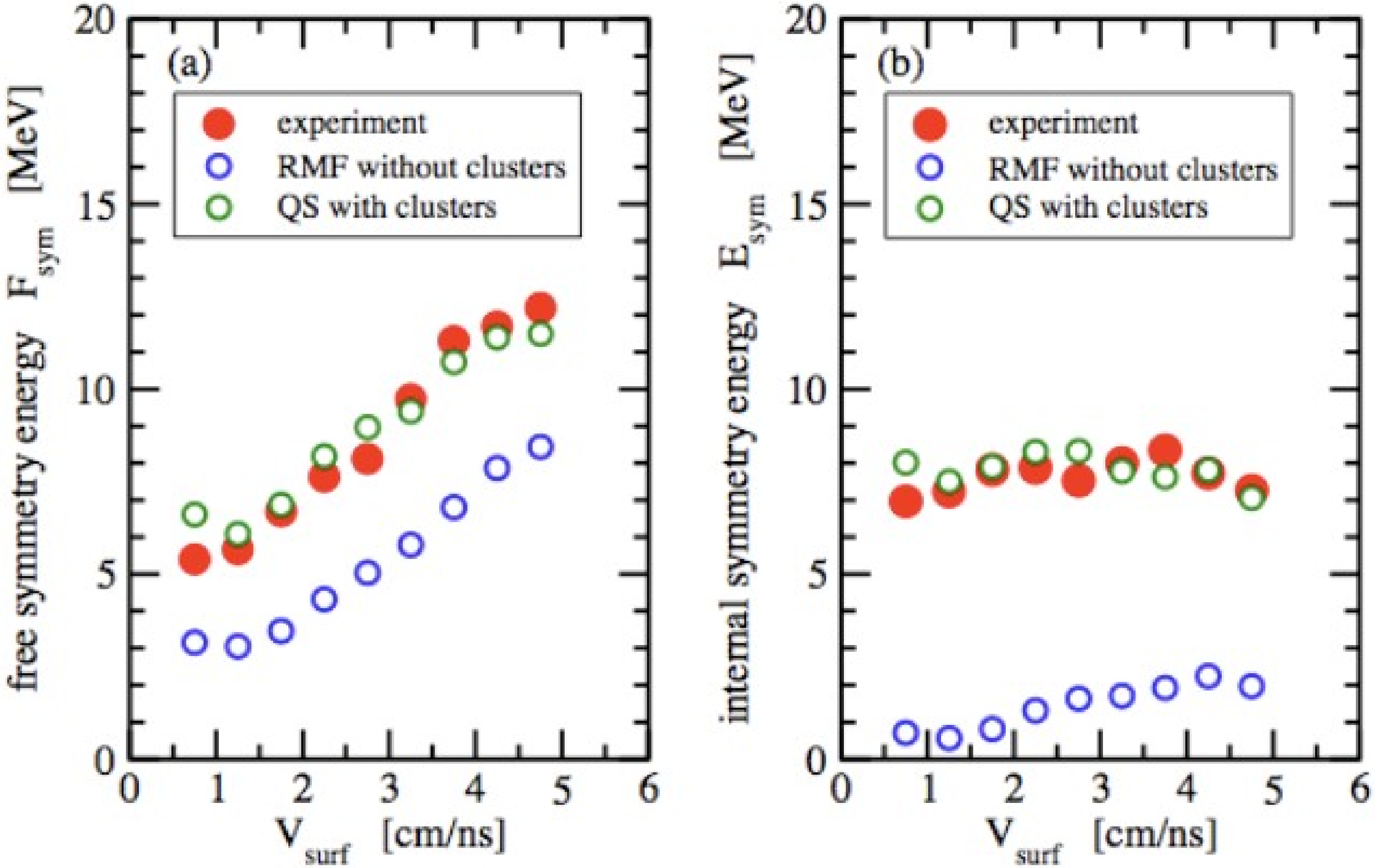


Baryon density derived from yields of light elements. Data according to refs. [6,8,11] are compared with results of the analysis of yields using NSE and QS calculations for the chemical equilibrium constant of alpha particles Kα From G. Roepke et al., Phys. Rev. C88, 024609 (2013).

$$K_c(A,Z) = \frac{n_{A,Z}}{n_p^Z n_n^{(A-Z)}}$$

Bound states in a plasma – Clusters in nuclear matter

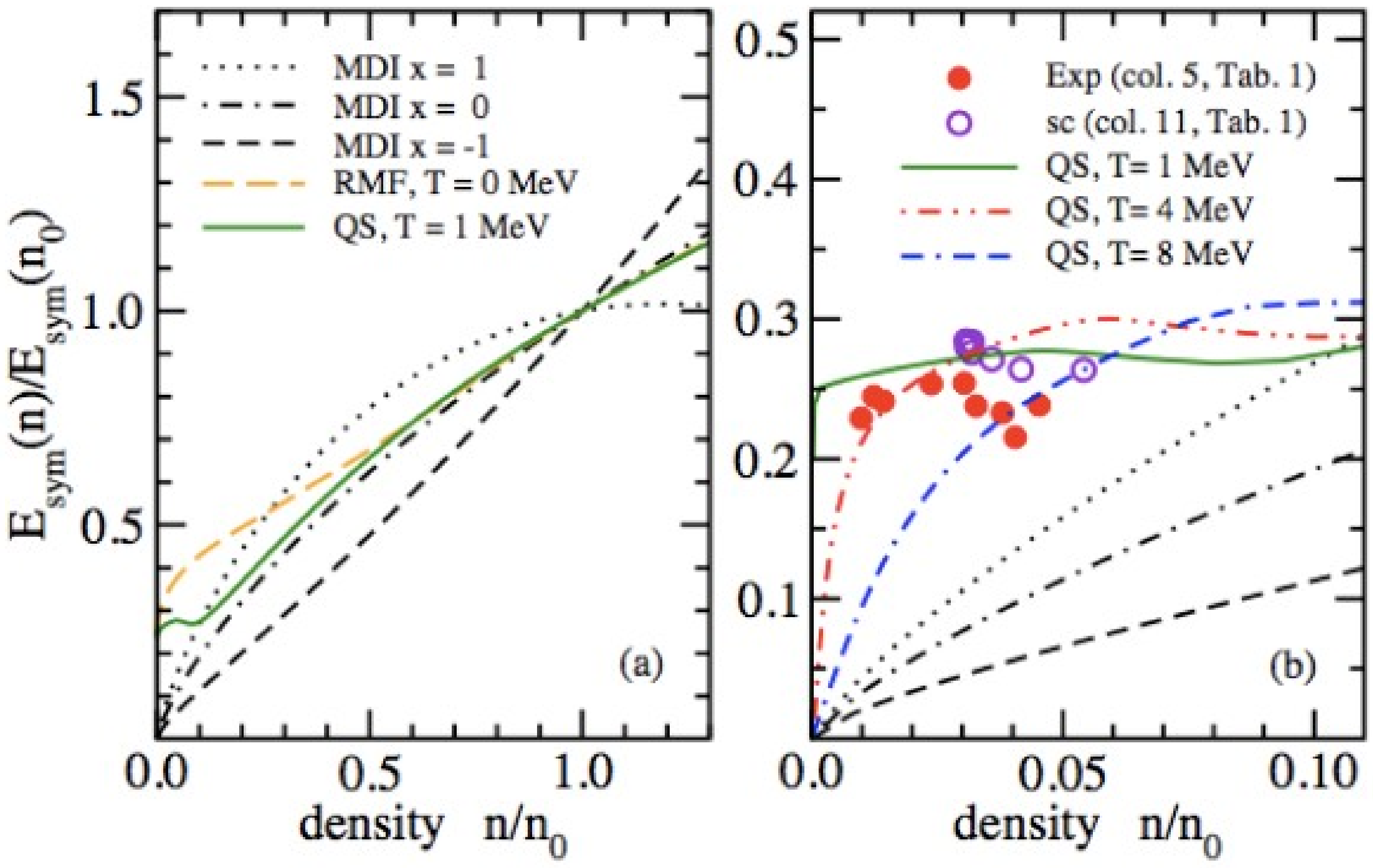
Symmetry energy, comparison experiment with theories



J. Natowitz et al., Phys. Rev. Lett. 104, 202501 (2010)

Bound states in a plasma – Clusters in nuclear matter

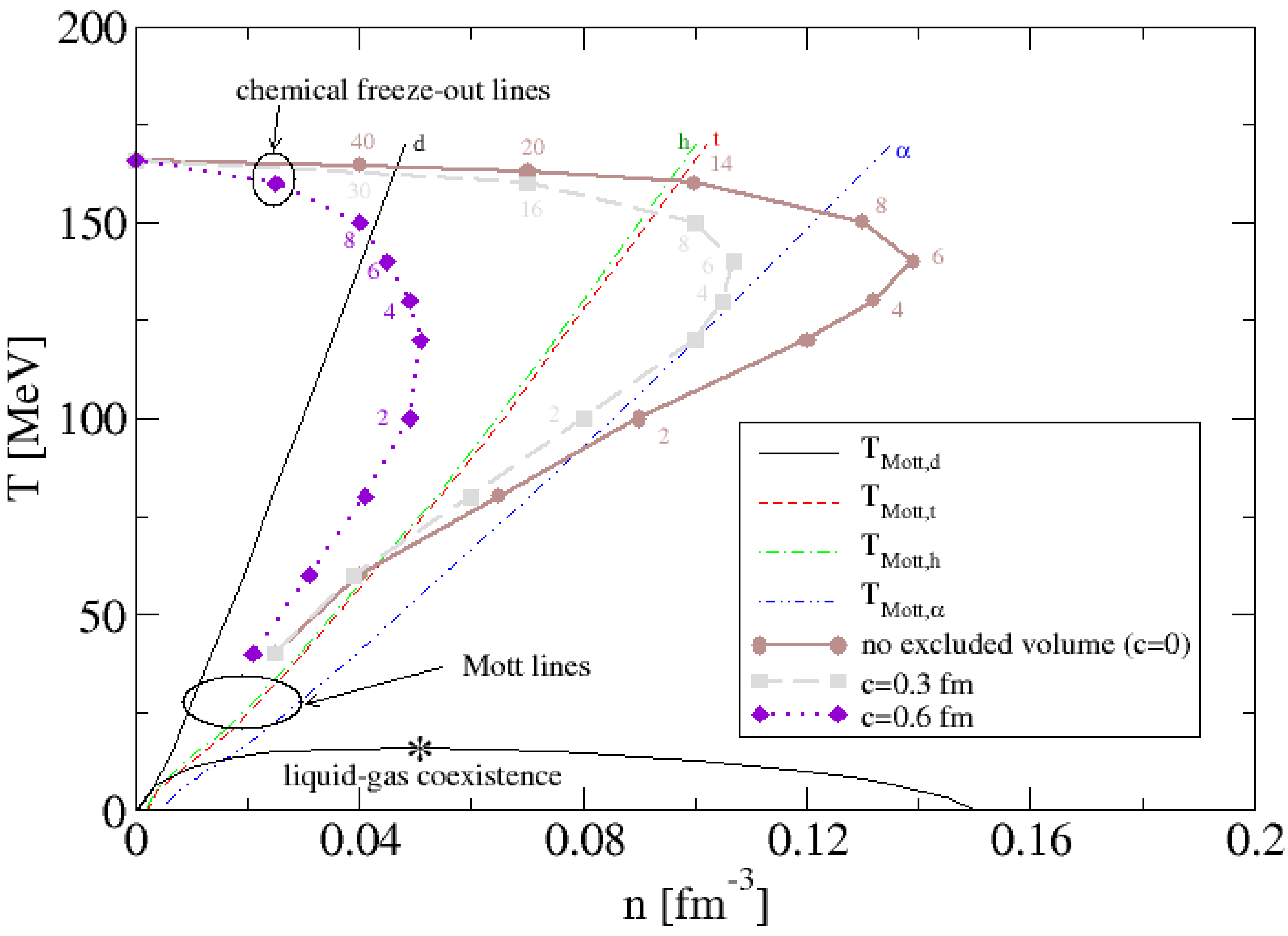
Symmetry Energy



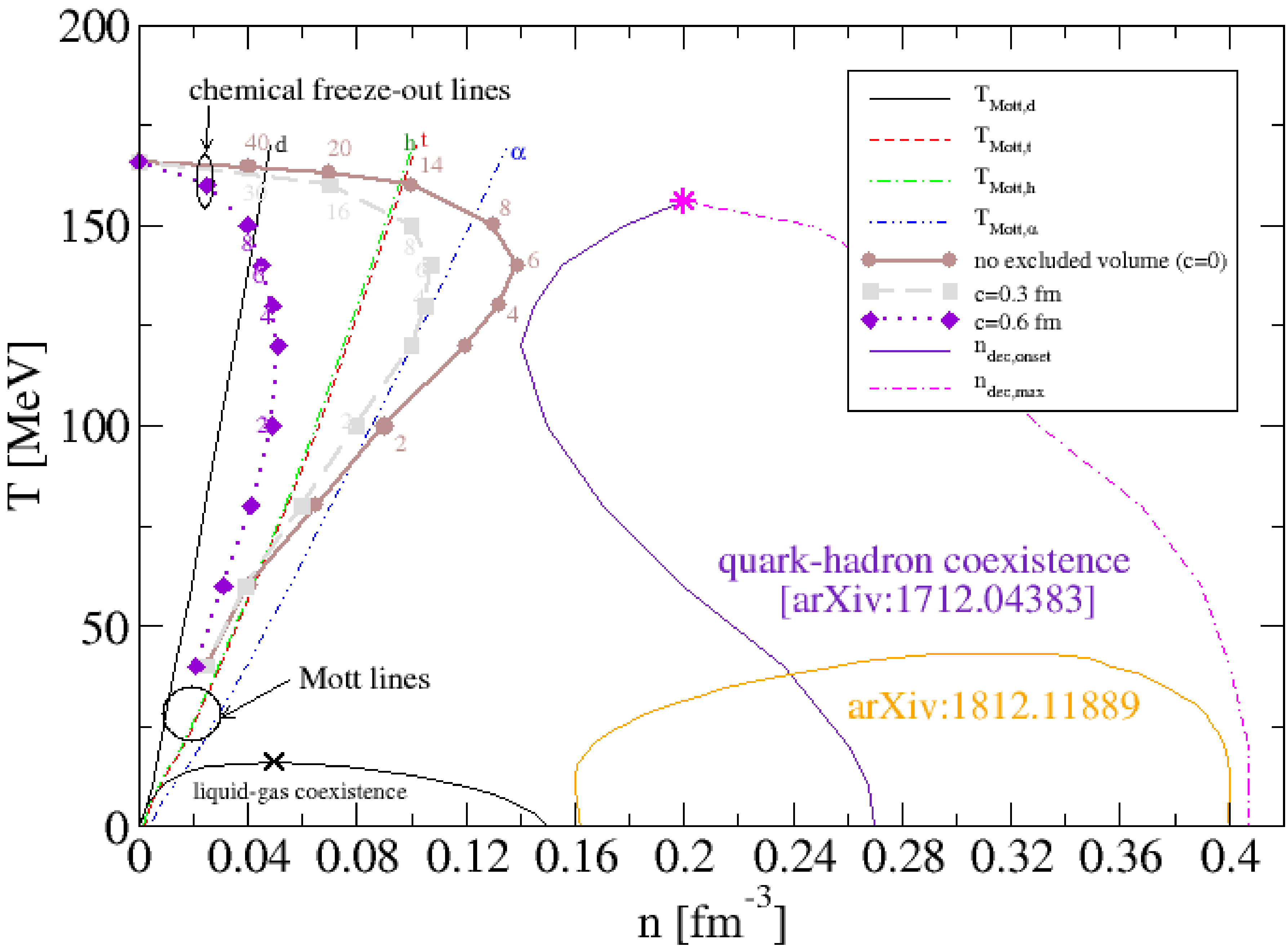
Scaled internal symmetry energy as a function of the scaled total density.
MDI: Chen et al., QS: quantum statistical, Exp: experiment at TAMU

J. Natowitz et al., Phys. Rev. Lett. 104, 202501 (2010)

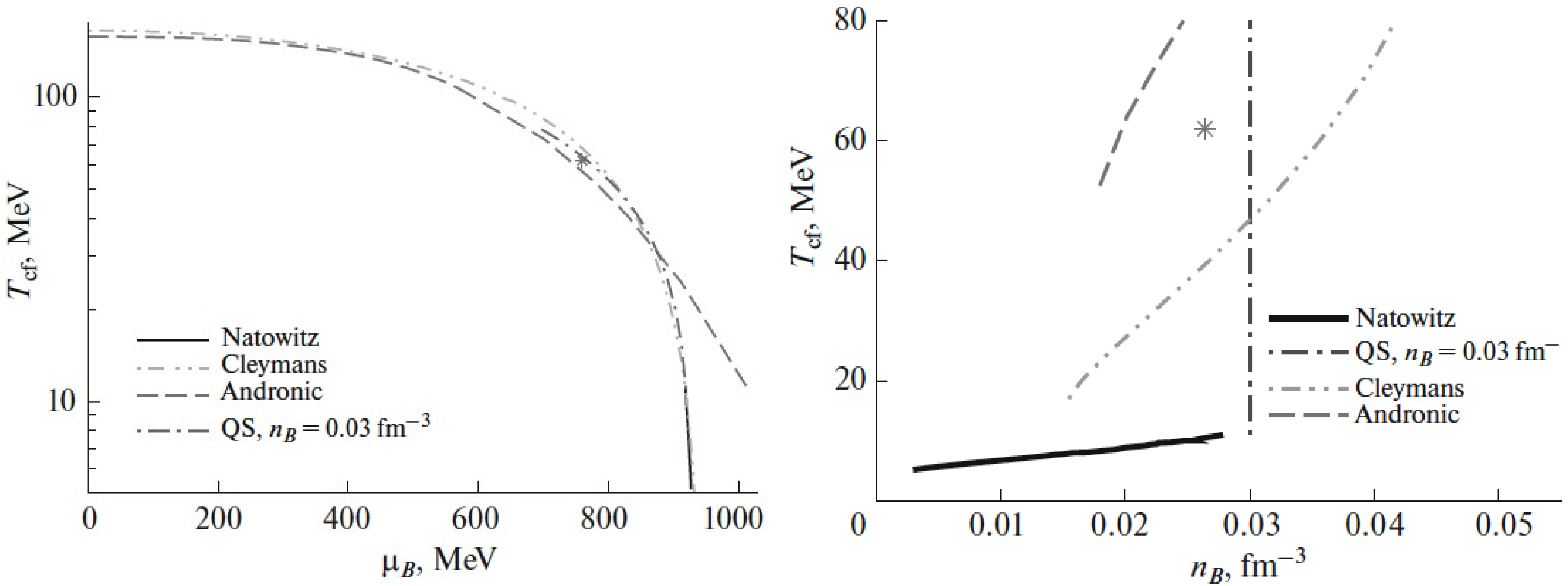
Mott lines and chemical freeze-out in the QCD phase diagram



Mott lines and chemical freeze-out in the QCD phase diagram



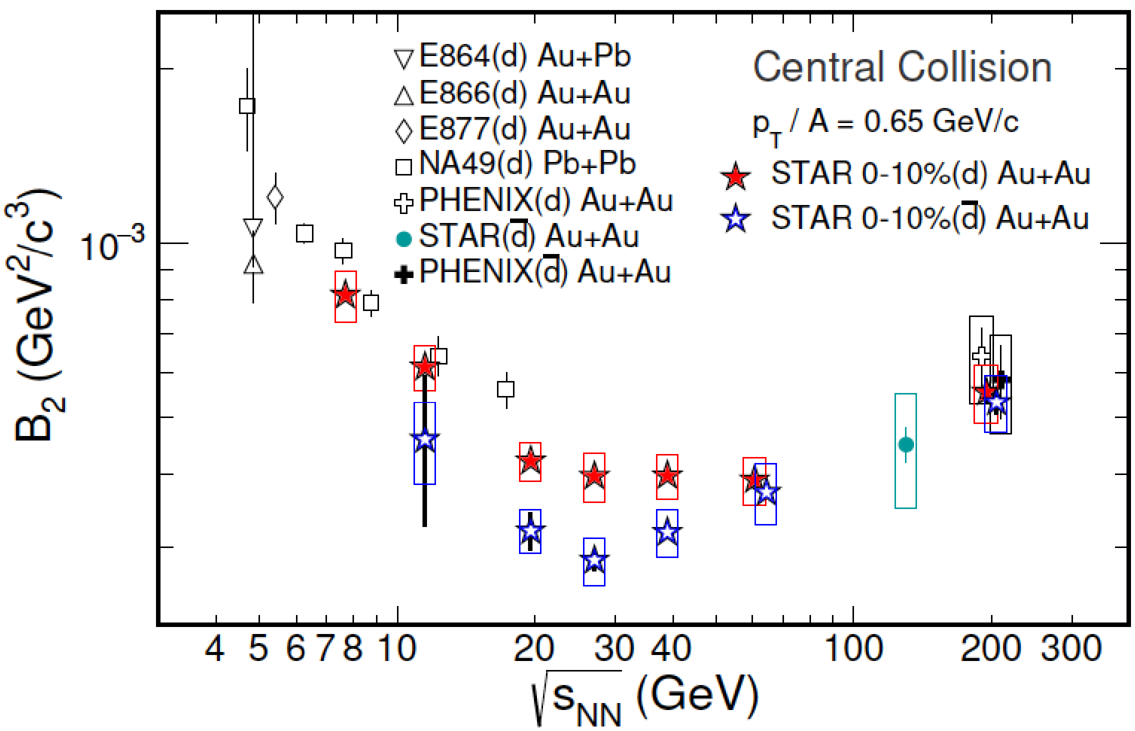
Mott lines and chemical freeze-out in the QCD phase diagram

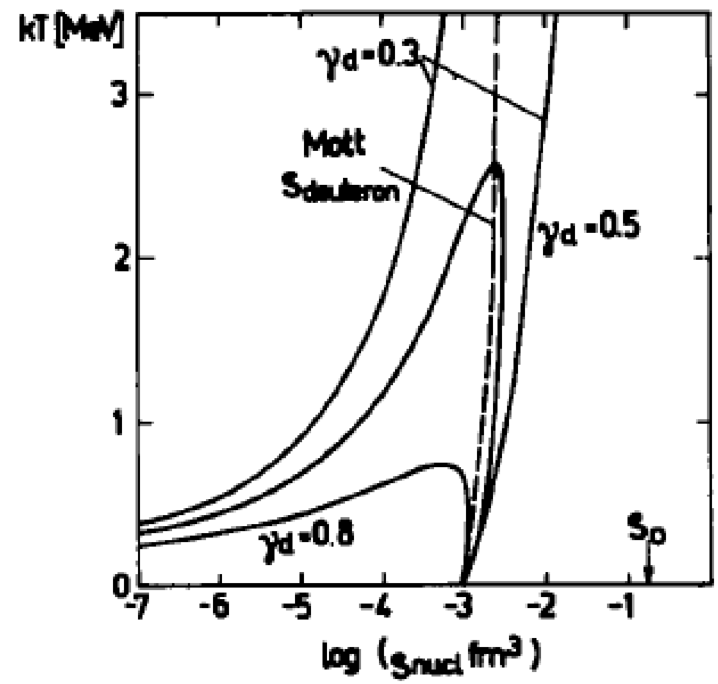


G. Roepke, D. B., Yu. Ivanov, Iu. Karpenko, O. Rogachevsky, H. Wolter, Phys. Part. Nucl. Lett. 15 (3), 225 (2018)

Natowitz et al.: 47 AMeV asymmetric ion collisions at Texas A&M Univ.

Mott lines and chemical freeze-out in the QCD phase diagram

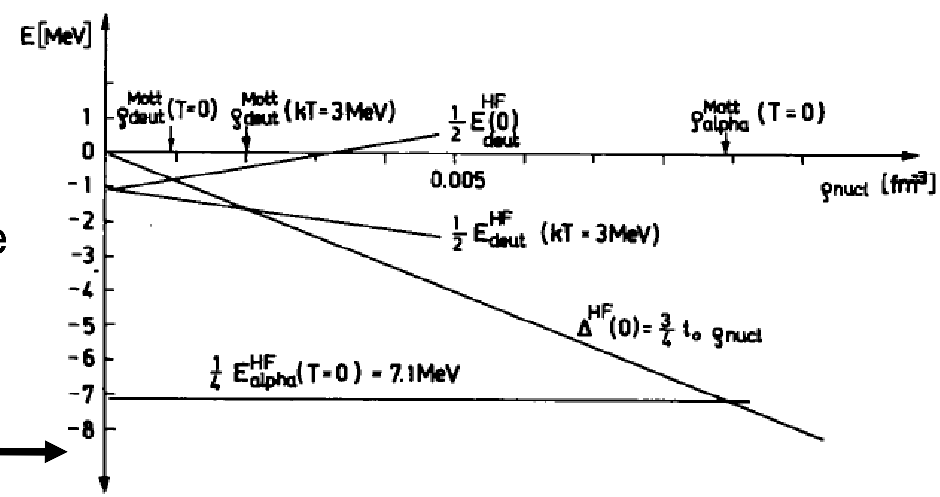




Energy dependence of coalescence parameter B_2(d)

J. Adam et al. (STAR Collab), arXiv:1903.11778

Association degree $\gamma_d=2\rho_d/\rho_n$



<u>Minimum:</u>

Nonmonotonous behaviour of association degree (coalescence factor) along the freeze-out line ?

G. Roepke et al., Nucl. Phys. A379, 536 (1982) →

Hydrodynamic modelling for NICA / FAIR

More complicated for lower energies:
→ baryon stopping effects,
→ finite baryon chemical potential,
→ EoS unknown from first principles
We want to simulate the effects of, and ultimately discriminate different EoS/PT types
The model has to be coupled to a detector response code to simulate detector events

Initial state → hydrodynamic evolution → particlization → hadronic cascade → detector response

3-fluid hydro, (Yu. Ivanov)

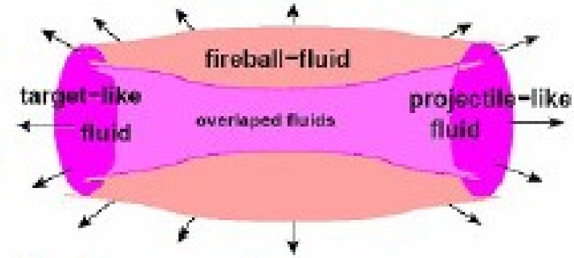
adapt the procedure from existing hybrid model (Iu. Karpenko)

(optionally) UrQMD, etc (Iu. Karpenko, H. Elfner)

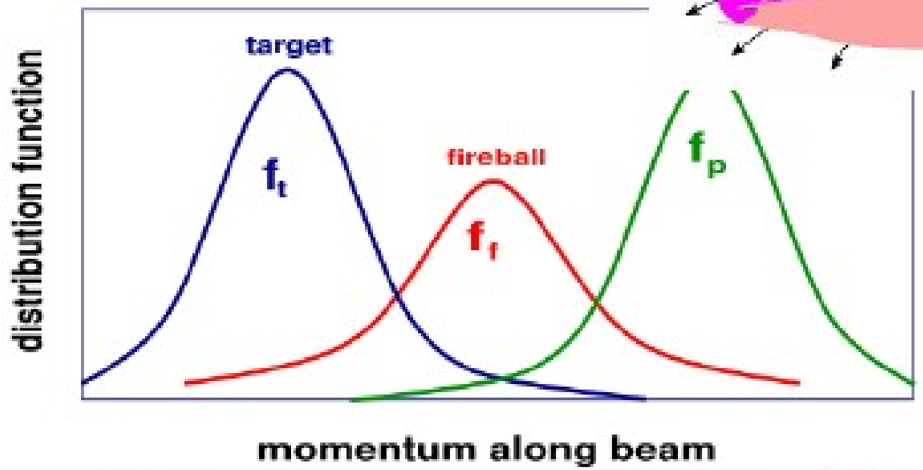
GEANT MPD, BM @N (O. Rogachevsky, P. Batyuk, S. Merts, et al.)

P. Batyuk et al., Phys. Rev. C 94, 044917 (2016) [THESEUS project]

3-Fluid Dynamics



Produced particles populate mid-rapidity
$\Rightarrow$ fireball fluid



Target-like fluid: $\partial_\mu J_t^\mu = 0$ $\quad \partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$

Leading particles carry bar. charge exchange/emission

Projectile-like fluid: $\partial_\mu J_p^\mu = 0,$ $\quad \partial_\mu T_p^{\mu\nu} = -F_{pt}^\nu + F_{fp}^\nu$

Fireball fluid: $J_f^\mu = 0,$ $\quad \partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$

Baryon-free fluid Source term Exchange

The source term is delayed due to a formation time $\tau \sim 1$ fm/c

Total energy-momentum conservation:

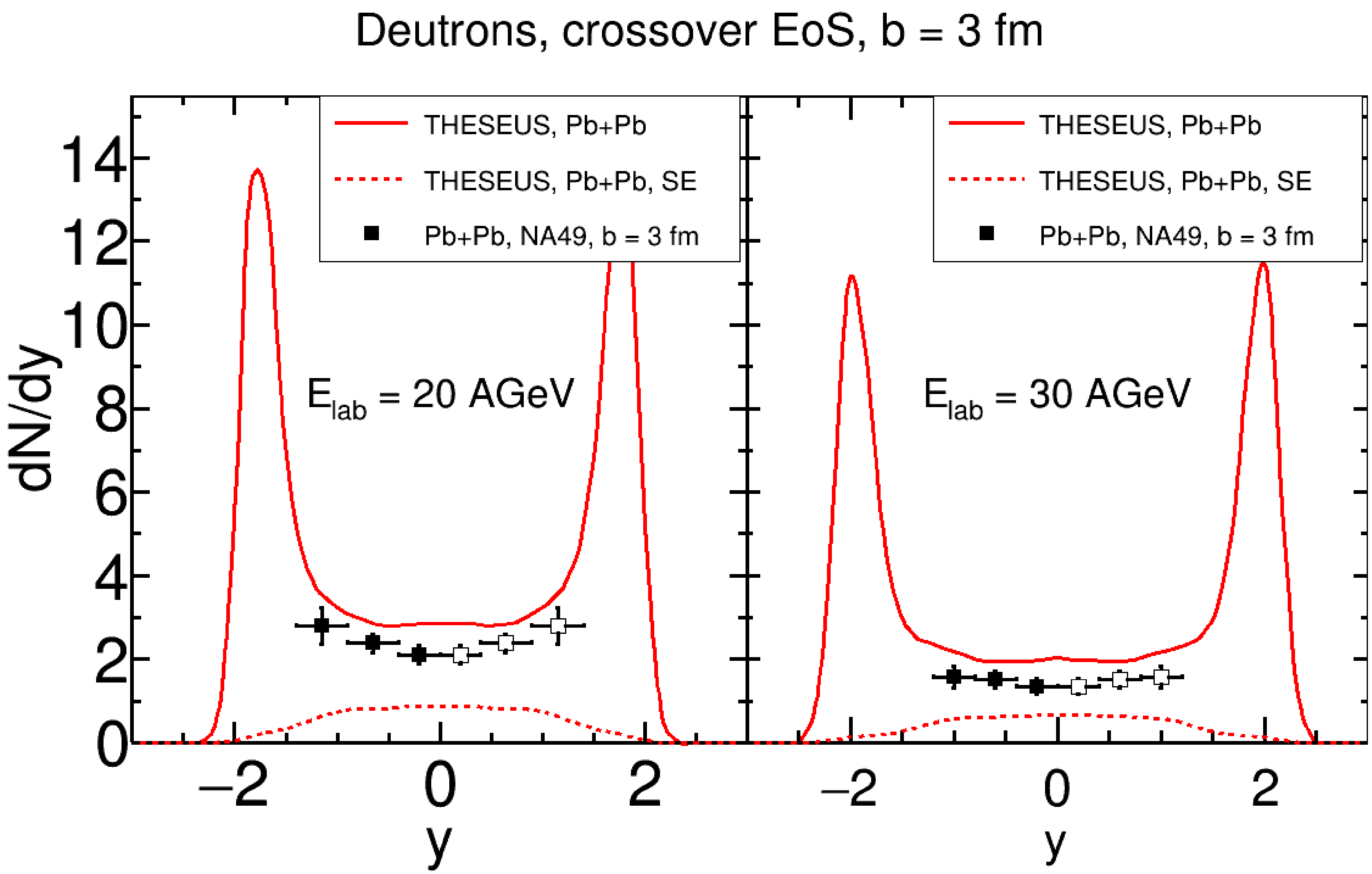
$$\partial_\mu (T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu}) = 0$$

http://mfd.jinr.ru

Yu.B. Ivanov, V.N. Russkikh and V.D. Toneev, Phys. Rev. C73, 044904 (2006)

Light fragment production at high baryon densities

First preliminary results:
Sudden freeze-out, with/without selfenergy (SE) shifts, no Pauli blocking yet



Courtesy: Yu. Ivanov, Iu. Karpenko, M. Kozhevnikova, G. Roepke

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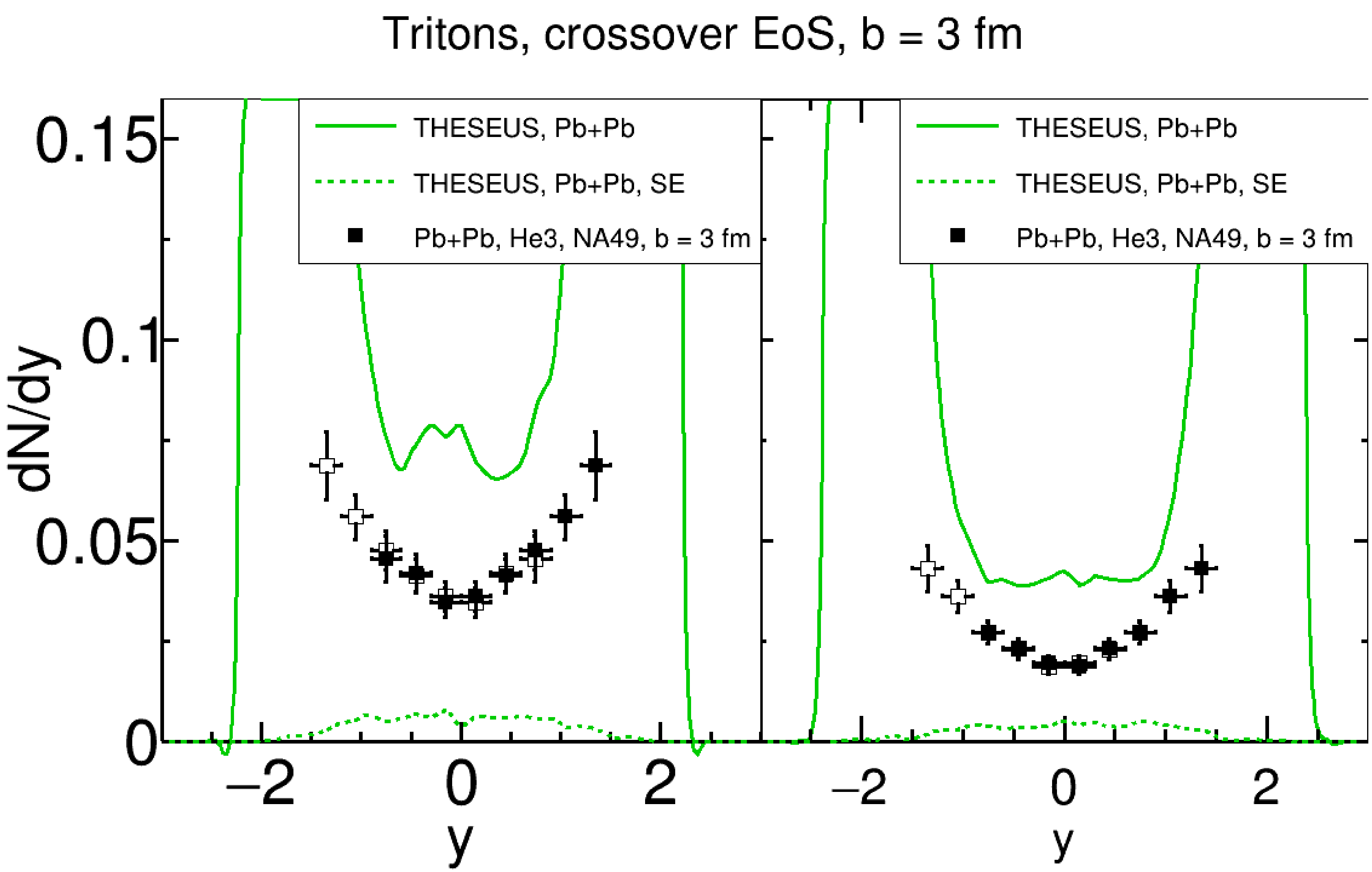

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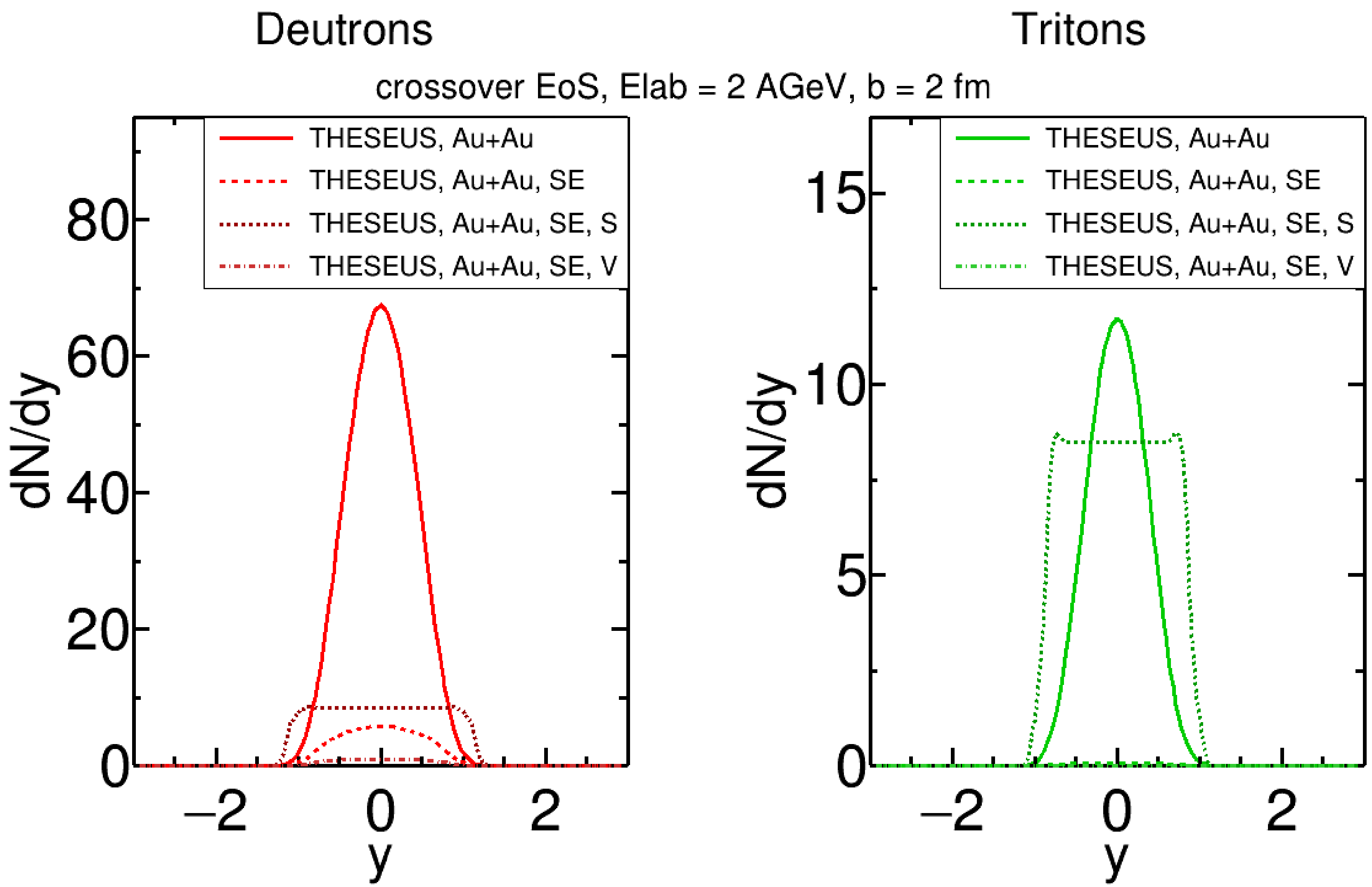

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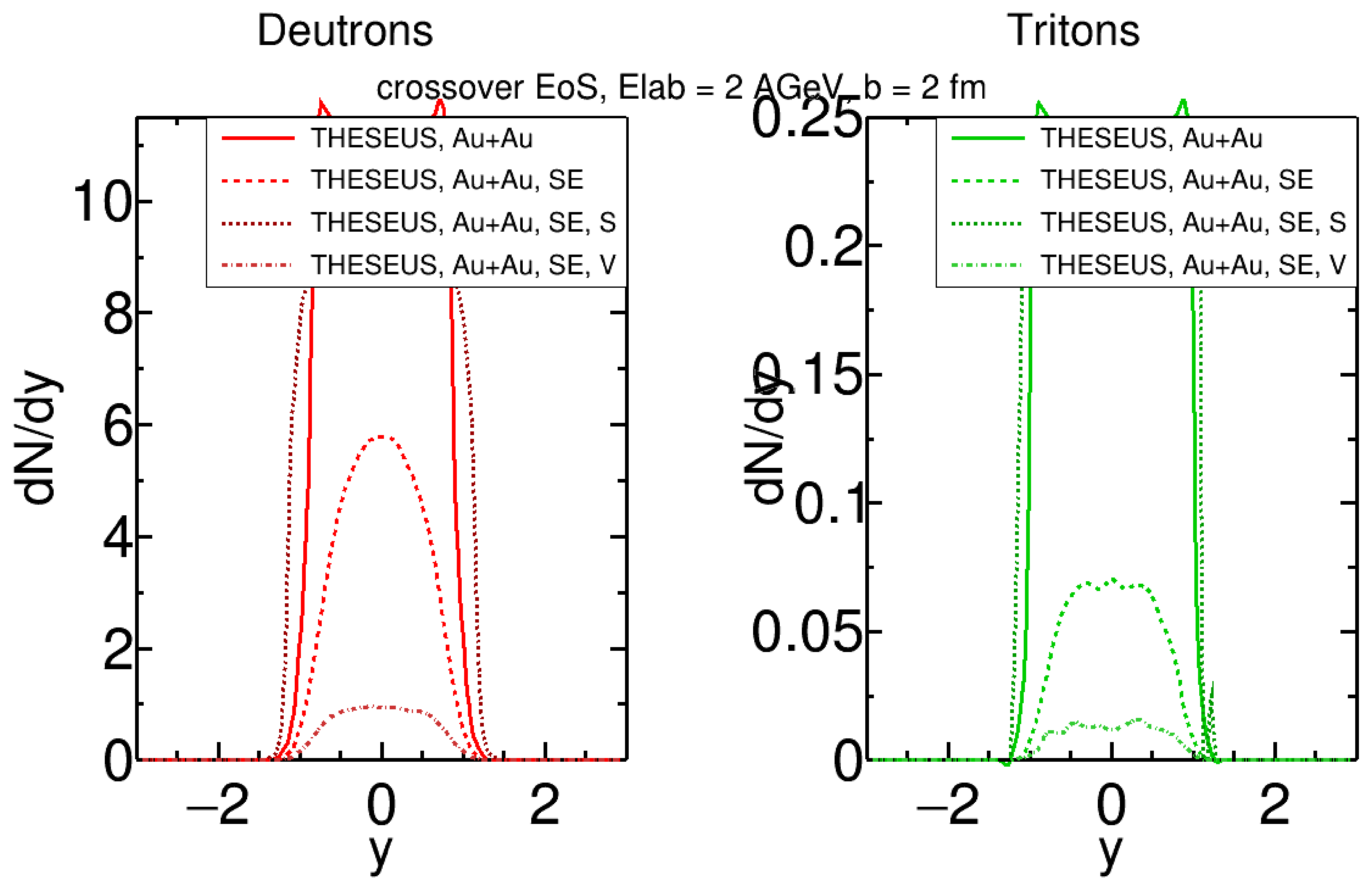


Courtesy: Yu. Ivanov, Iu. Karpenko, M. Kozhevnikova, G. Roepke

Mott-Anderson localization model for sudden freezeout

DB, J. Berdermann, J. Cleymans, K. Redlich, Phys. Part. Nucl. Lett. 8 (2011) 811

The basic idea: Localization of (certain) multiquark states ("cluster") = hadronization;
Reverse process = delocalization by quark exchange between hadrons

Freeze-out criterion:

$$H_{\rm exp}(\tau) = \frac{\dot{R}(\tau)}{R(\tau)} = \tau^{-1}_{{\rm coll},i}(T,\mu)\ ,$$

$$\tau^{-1}_{{\rm coll},i}(T,\mu) = \sum_j \sigma_{ij} v n_j(T,\mu)$$

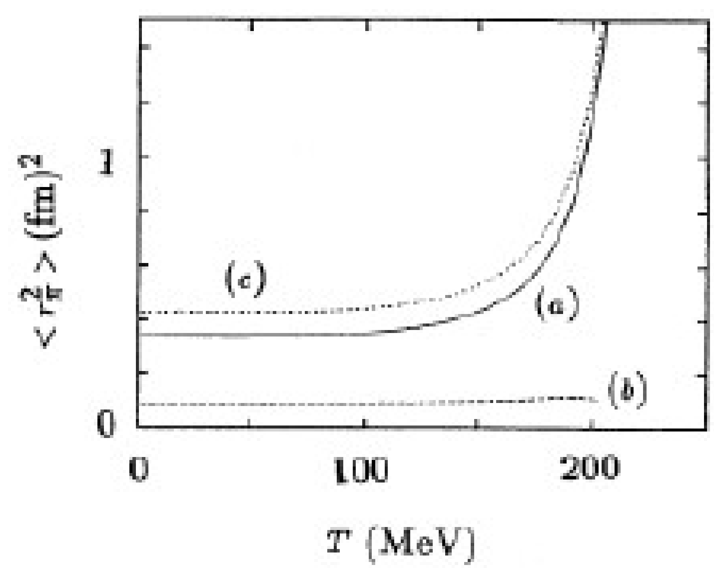
Povh-Huefner law,
PRC 46 (1992) 990
→ total x-section

$$\sigma_{ij} = \lambda \langle r_i^2\rangle \langle r_j^2\rangle$$

Hippe & Klevansky, PRC 52 (1995) 2172

$$r_\pi^2(T,\mu) = \frac{3}{4\pi^2} f_\pi^{-2}(T,\mu)$$

$$f_\pi^2(T,\mu) = -m_0 \langle \bar{q}q\rangle_{T,\mu}/M_\pi^2$$



$$r_\pi^2(T,\mu) = \frac{3M_\pi^2}{4\pi^2 m_q} |\langle \bar{q}q\rangle_{T,\mu}|^{-1}$$

$$\langle \bar{q}q\rangle = \langle \bar{q}q\rangle_{\rm MF}\left[1 - \frac{T^2}{8 f_\pi^2(T,\mu)} - \frac{\sigma_N n_{s,N}(T,\mu)}{M_\pi^2 f_\pi^2(T,\mu)}\right]$$

Mott-Anderson localization model for chemical freeze-out

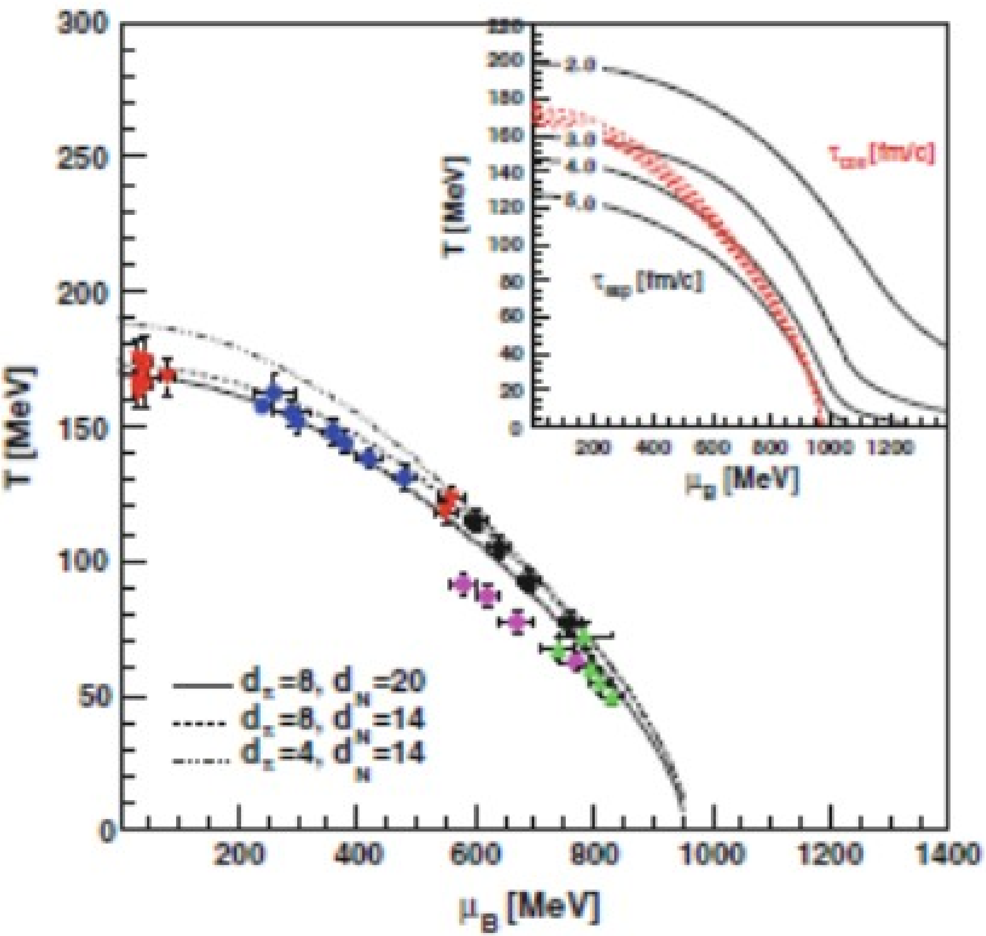
DB, J. Berdermann, J. Cleymans, K. Redlich, Phys. Part. Nucl. Lett. 8 (2011) 811

Model results:

$$\tau_{\rm exp}(T,\mu) = \tau_{\rm coll}(T,\mu)$$

Collision time strongly T, mu dependent !

Schematic resonance gas: dπ pions, dN nucleons

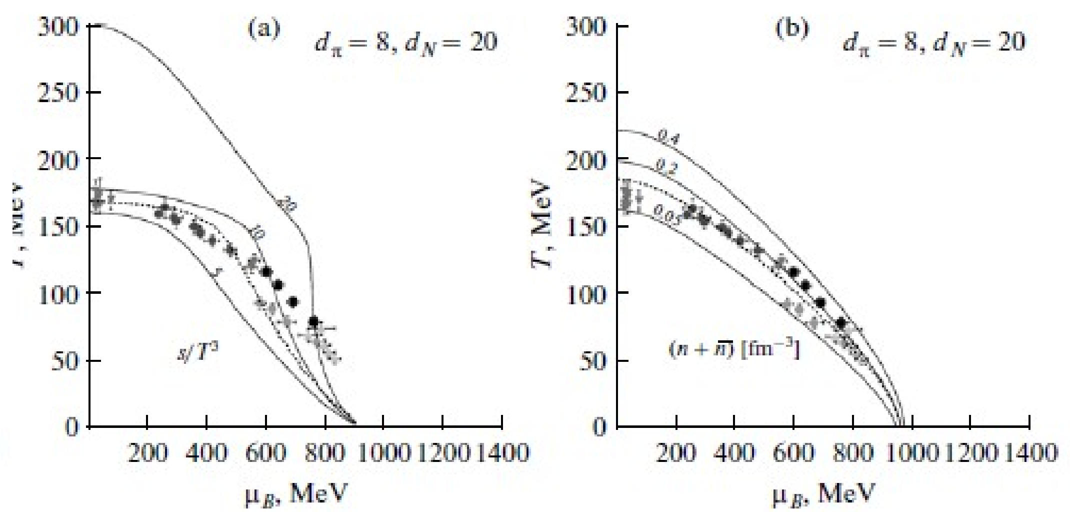


Expansion time scale from entropy conservation:

$$s(T,\mu)\, V(\tau_{\rm exp}) = {\rm const}$$

$$\tau_{\rm exp}(T,\mu) = a s^{-1/3}(T,\mu),$$

Thermodynamics consistent with phenomenological Freeze-out rules:

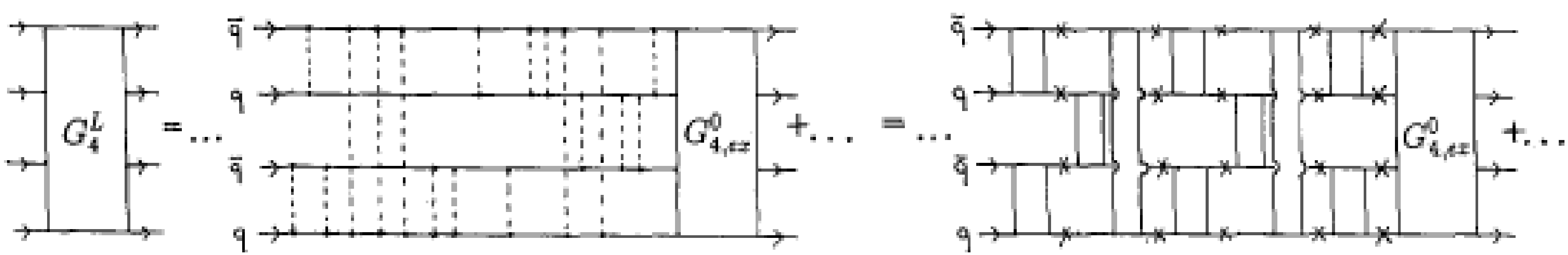


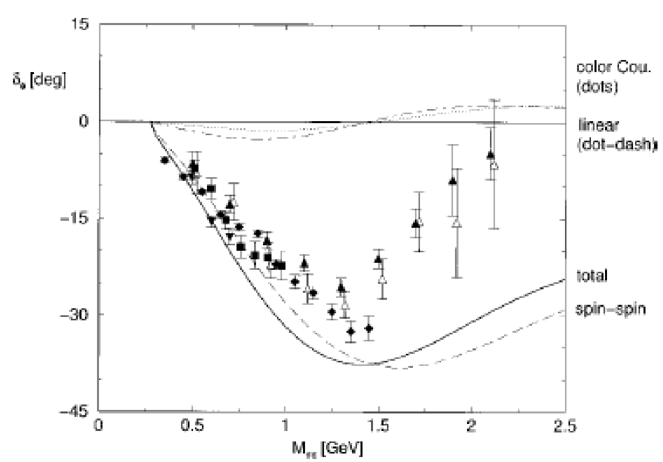
Povh-Huefner law: quark exchange in meson-meson scattering?

DB, G. Roepke, Phys. Lett. B 299 (1993) 332; T. Barnes et al., PRC 63 (2001) 025204

$$\sigma_{ij} = \lambda \langle r_i^2 \rangle \langle r_j^2 \rangle \qquad r_\pi^2(T,\mu) = \frac{3M_\pi^2}{4\pi^2 m_q} \left| \langle \bar{q} q \rangle_{T,\mu} \right|^{-1}$$

$$\mathcal{V}^{ss}(12,1'2') = \frac{16}{3\sqrt{3}} C_{SFC}(12,1'2') \frac{(2\pi)^3}{\Omega_0} \frac{\alpha_s}{3\pi^2 m_q^2} \exp\left(-\frac{1}{4b^2} (k'^2 + \tfrac{1}{3} k^2) \right) \delta_{K,K'}$$

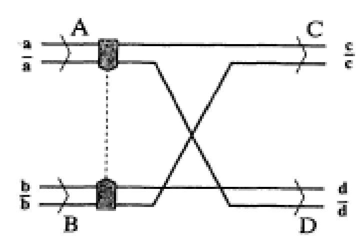


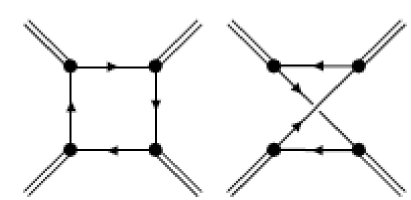


Quark exchange process in M-M scattering

Nonrelativistic → rel. quark loop integrals

$M_{fi} =$





Barnes & Swanson, PRD (1992)

Povh-Huefner law: quark exchange in meson-meson scattering?

PHYSICAL REVIEW C VOLUME 51, NUMBER 5 MAY 1995

Quark exchange model for charmonium dissociation in hot hadronic matter

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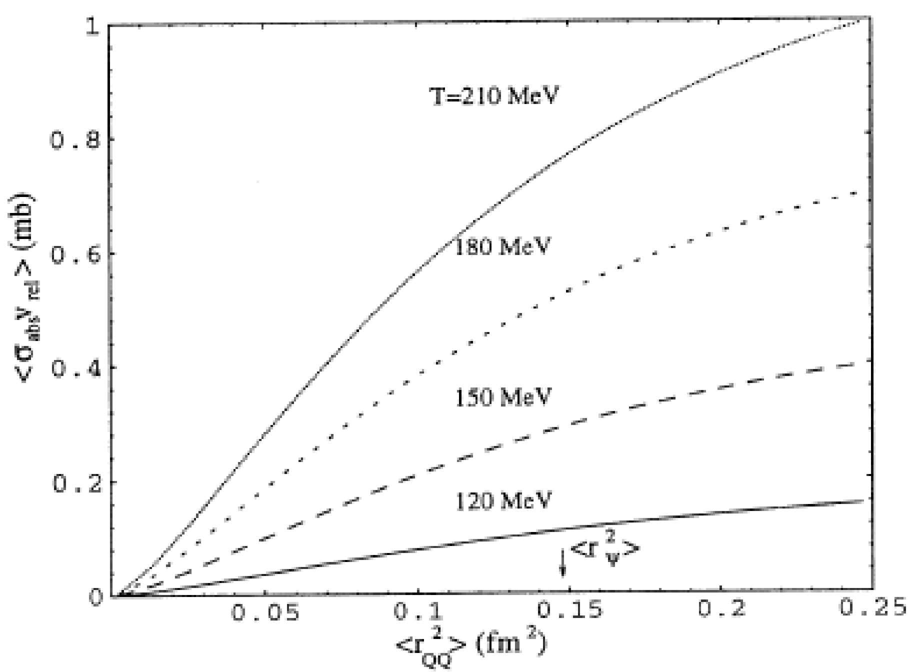
(Received 15 November 1994)

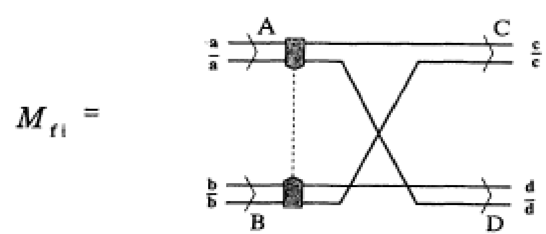


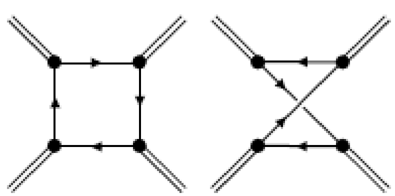
$$\langle \sigma_{\rm abs} v_{\rm rel} \rangle \propto \langle r^2 \rangle_{Q\bar{Q}} \langle r^2 \rangle_{q\bar{q}}$$

Flavor exchange processes

$$\phi + \pi \to K + \bar{K}, \qquad K^- + p \to \Lambda + X, \quad K^+ + p \to \Lambda + X,$$

Nonrelativistic → rel. quark loop integrals





Mott-Anderson localization model – refinement ...

DB, J. Jankowski, M. Naskret, arxiv:1705.00169

A) Chiral condensate for the full hadron resonance gas model → radii of hadrons

- nonstrange hadrons:

$$\langle r_\pi^2\rangle_{T,\mu} = \frac{3}{4\pi^2 f_\pi^2} \qquad f_\pi^2(T,\mu) = \frac{-m_q\langle\bar{q}q\rangle_{T,\mu}}{m_\pi^2}\ ,$$

$$\langle r_\pi^2\rangle_{T,\mu} = \frac{3m_\pi^2}{4\pi^2 m_q}|\langle\bar{q}q\rangle_{T,\mu}|^{-1} \qquad \langle r_{\rm N}^2\rangle_{T,\mu} = r_0^2 + \langle r_\pi^2\rangle_{T,\mu}$$

- strange hadrons:

$$f_K^2 m_K^2 = -\frac{\langle\bar{q}q\rangle_{T,\mu} + \langle\bar{s}s\rangle_{T,\mu}}{2}(m_q+m_s)$$

$$\langle r_{\rm K}^2\rangle_{T,\mu} = \frac{3}{4\pi^2 f_{\rm K}^2} = \frac{3}{2\pi^2}\frac{m_{\rm K}^2}{|\langle\bar{q}q\rangle_{T,\mu} + \langle\bar{s}s\rangle_{T,\mu}|(m_q+m_s)} \qquad \langle r_\Lambda^2\rangle_{T,\mu} = r_0^2 + \langle r_{\rm K}^2\rangle_{T,\mu}$$

B) Chemical freeze-out: only “reactive” cross section, flavor equilibration

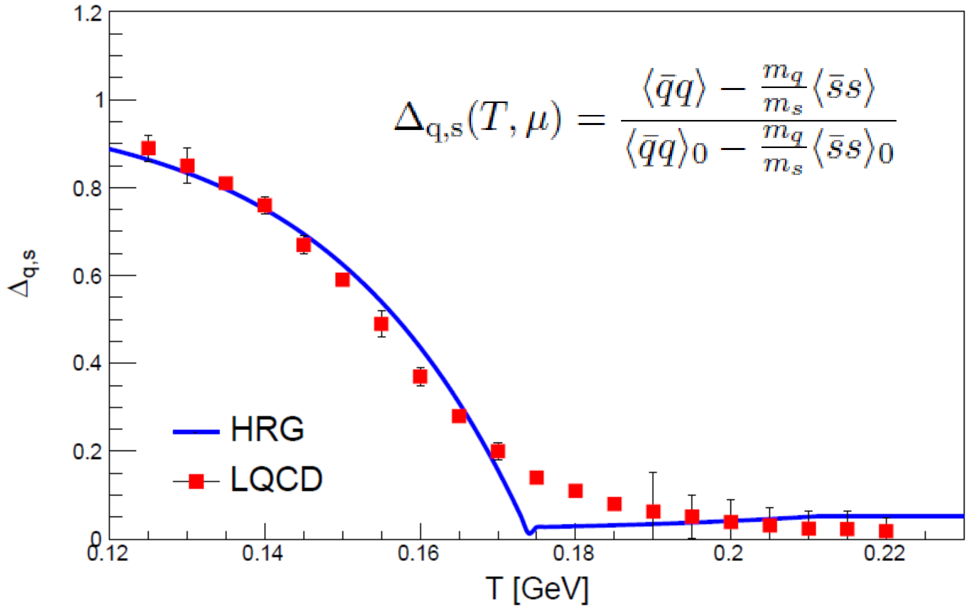
Some flavor changing processes involve reaction thresholds and need activation energy, like in the Eyring theory of chemical processes with activation:

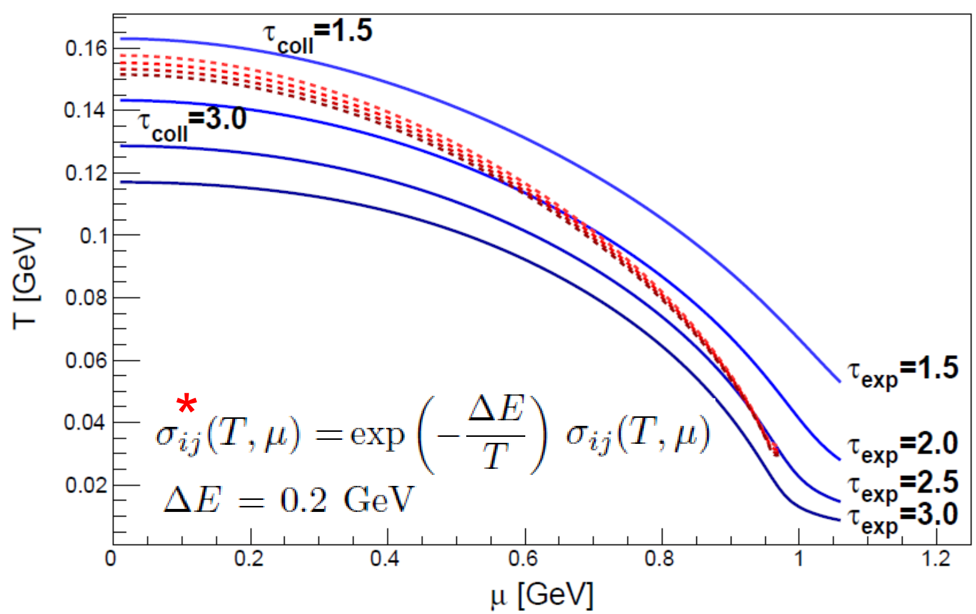
$$\sigma_{ij}^{*}(T,\mu) = \exp\left(-\frac{\Delta E}{T}\right)\sigma_{ij}(T,\mu) \qquad \sigma_{ij}(T,\mu) = \lambda\langle r_i^2\rangle_{T,\mu}\langle r_j^2\rangle_{T,\mu}$$

Assumption: average activation threshold for reactive processes: $\Delta E = 0.2\ {\rm GeV}$
(to be refined, account for all individual processes, e.g., SMASH)

Mott-Anderson localization model – refined, full HRG

DB, J. Jankowski, M. Naskret, arxiv:1705.00169





Full HRG model condensate;
J. Jankowski et al., Phys. Rev. D (2013)

$$\langle\bar{q}q\rangle_{T,\mu} = \langle\bar{q}q\rangle^{MF}_{T,\mu} + \sum_{h=M,B} \frac{\sigma_q^h}{m_q} n_h(T,\mu) \,,$$

$$n_h(T,\mu) = \frac{d_h}{2\pi^2}\int_0^\infty dk k^2 \frac{m_h}{E_h}\frac{1}{e^{(E_h-\mu_h)/T} \mp 1} \,.$$

$$\tau^{-1}_{\mathrm{coll},i}(T,\mu) = \sum_j \overset{*}{\sigma}_{ij} v n_j(T,\mu) \; ; \quad \sigma_{ij} = \lambda \langle r_i^2\rangle\langle r_j^2\rangle$$

$$\langle r_\pi^2\rangle_{T,\mu} \simeq \frac{3}{4\pi^2} f_\pi^{-2}(T,\mu) = \frac{3M_\pi^2}{4\pi^2 m_q}\left|\langle\bar{q}q\rangle_{T,\mu}\right|^{-1}$$

$$\langle r_K^2\rangle_{T,\mu} \simeq \frac{3M_K^2}{\pi^2(m_q+m_s)}\left|\langle\bar{q}q\rangle_{T,\mu} + \langle\bar{s}s\rangle_{T,\mu}\right|^{-1}$$

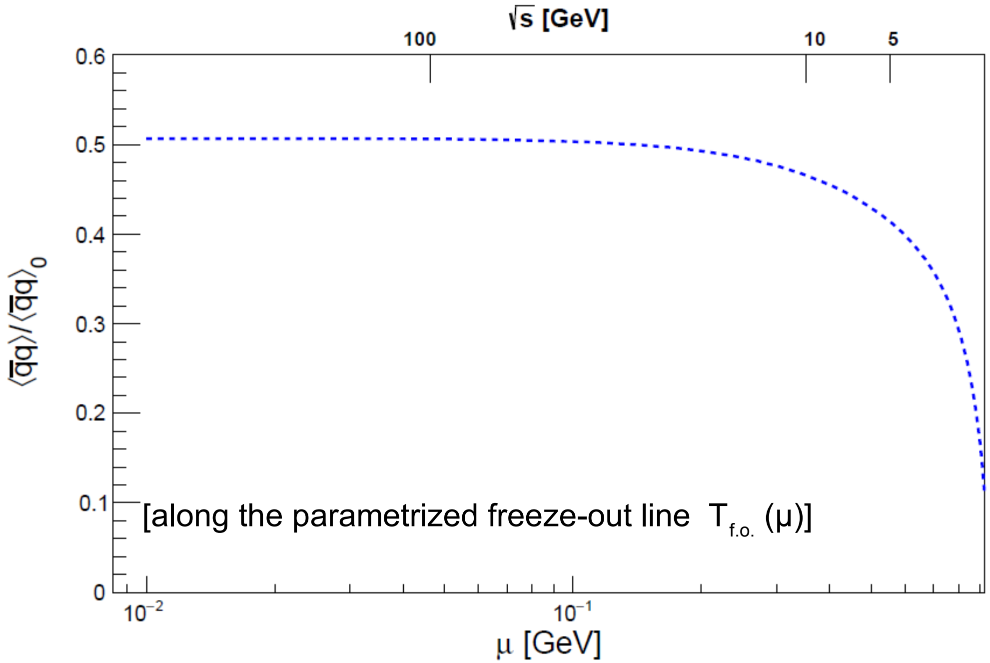
The factor a stands for the inverse system size in the formula

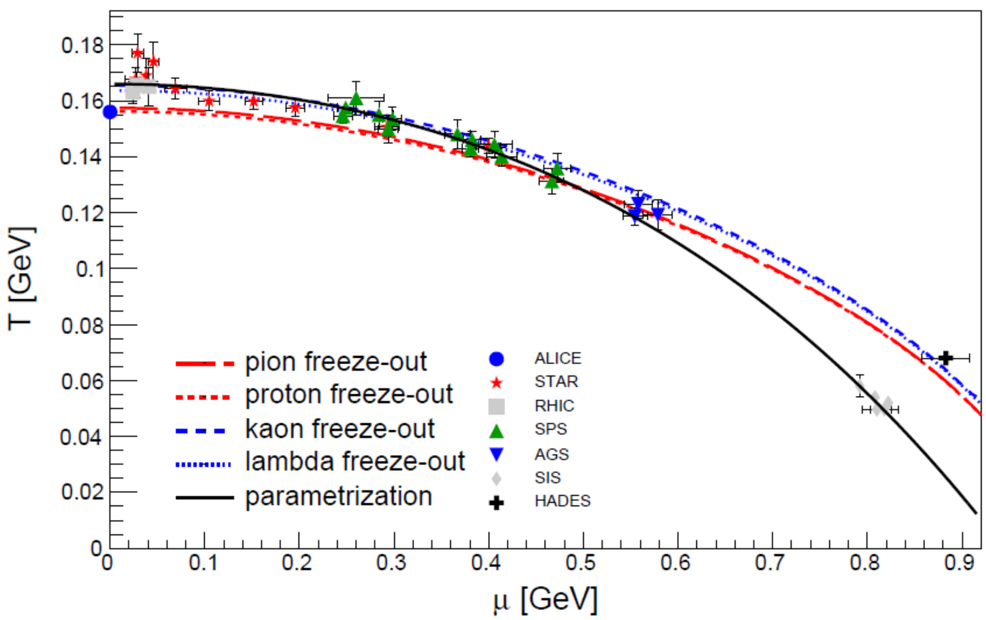
$$\tau_{\mathrm{exp}}(T,\mu) = \tau_{\mathrm{coll}}(T,\mu)$$

for the 3D expansion time scale assuming entropy conservation

Mott-Anderson localization model – refined, full HRG

DB, J. Jankowski, M. Naskret, arxiv:1705.00169





Full HRG model condensate;
J. Jankowski et al., Phys. Rev. D (2013)

$$\langle \bar{q}q\rangle_{T,\mu} = \langle \bar{q}q\rangle^{MF}_{T,\mu} + \sum_{h=M,B} \frac{\sigma^h_q}{m_q} n_h(T,\mu) \ ,$$

$$n_h(T,\mu) = \frac{d_h}{2\pi^2}\int_0^\infty dk k^2 \frac{m_h}{E_h}\frac{1}{e^{(E_h-\mu_h)/T} \mp 1} \ .$$

$$\tau^{-1}_{\mathrm{coll},i}(T,\mu) = \sum_j \sigma^{*}_{ij} v n_j(T,\mu) \ ; \ \sigma_{ij} = \lambda \langle r_i^2\rangle \langle r_j^2\rangle$$

$$\langle r_\pi^2\rangle_{T,\mu} \simeq \frac{3}{4\pi^2} f_\pi^{-2}(T,\mu) = \frac{3M_\pi^2}{4\pi^2 m_q}\left|\langle \bar{q}q\rangle_{T,\mu}\right|^{-1}$$

$$\langle r_K^2\rangle_{T,\mu} \simeq \frac{3M_K^2}{\pi^2(m_q+m_s)}\left|\langle \bar{q}q\rangle_{T,\mu} + \langle \bar{s}s\rangle_{T,\mu}\right|^{-1}$$

The factor a stands for the inverse system size in the formula

$$\tau_{\exp}(T,\mu) = \tau_{\mathrm{coll}}(T,\mu)$$

for the 3D expansion time scale assuming entropy conservation

Mott-Anderson localization model – refined, full HRG

DB, J. Jankowski, M. Naskret, arxiv:1705.00169

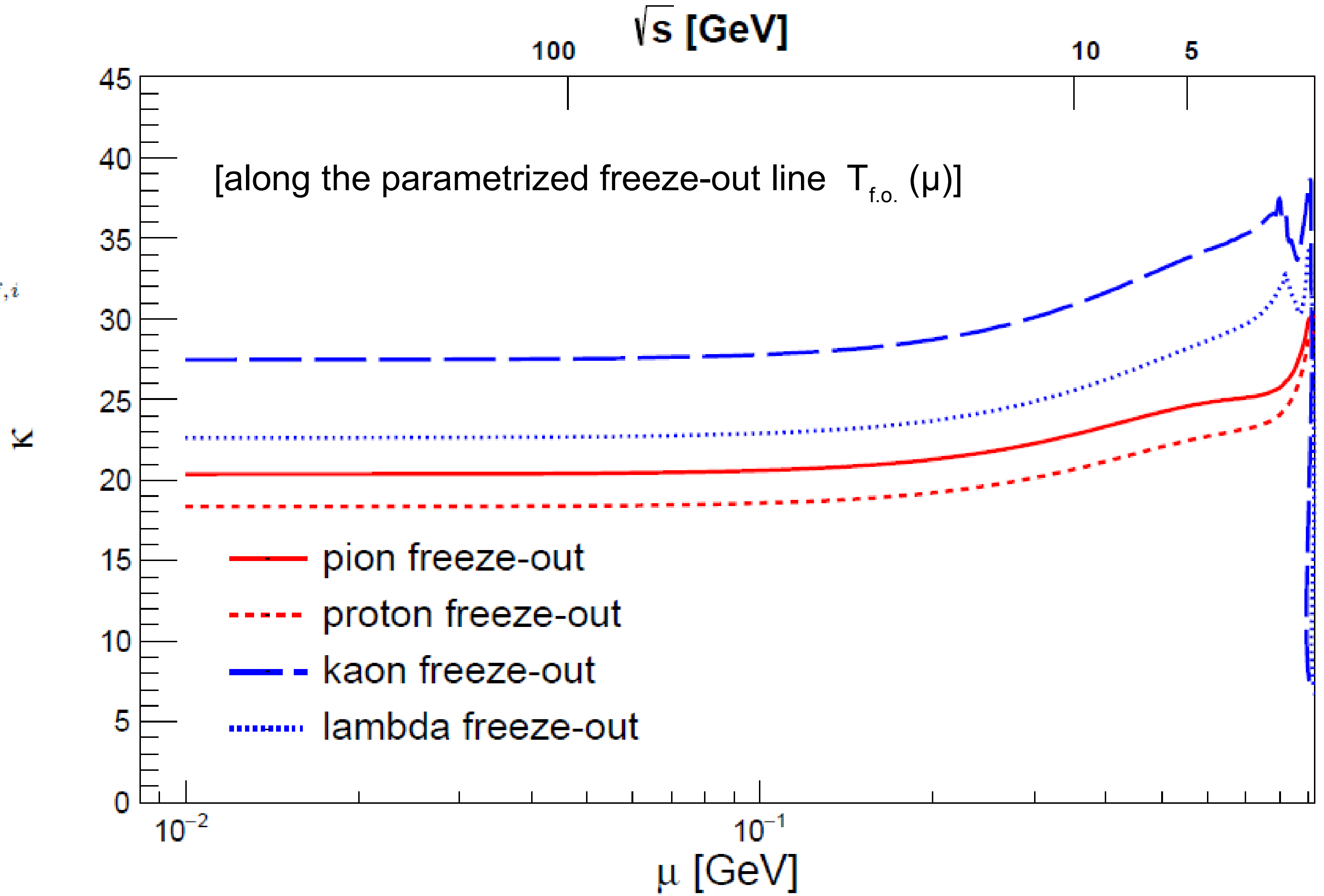
Inelastic collision rate $\tau_{\rm coll} \propto T^\kappa, \quad \kappa \gtrsim 20$ from fit to STAR data

U. Heinz and G. Kestin, PoS CPOD **2006**, 038 (2006) [nucl-th/0612105]

Species-dependent exponent of the power law,

$$\kappa_i = -\frac{d\ln\tau_{{\rm coll},i}(T,\mu)}{d\ln T}\Bigg|_{T_{f,i};\mu_{f,i}}$$

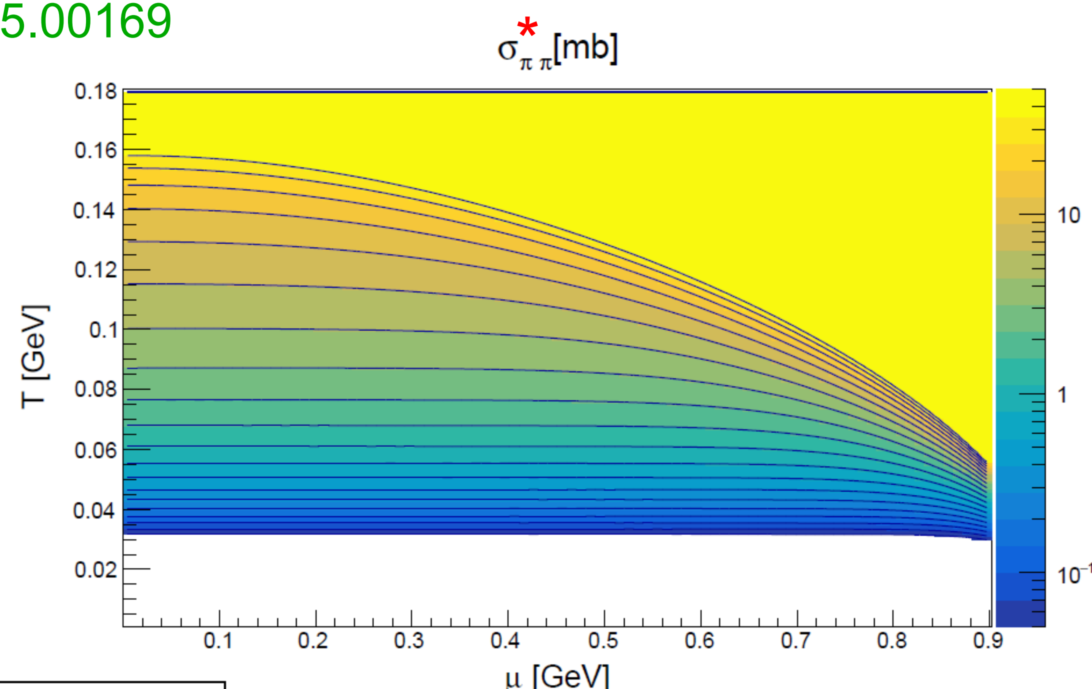
extracted from the model for the collision rate.

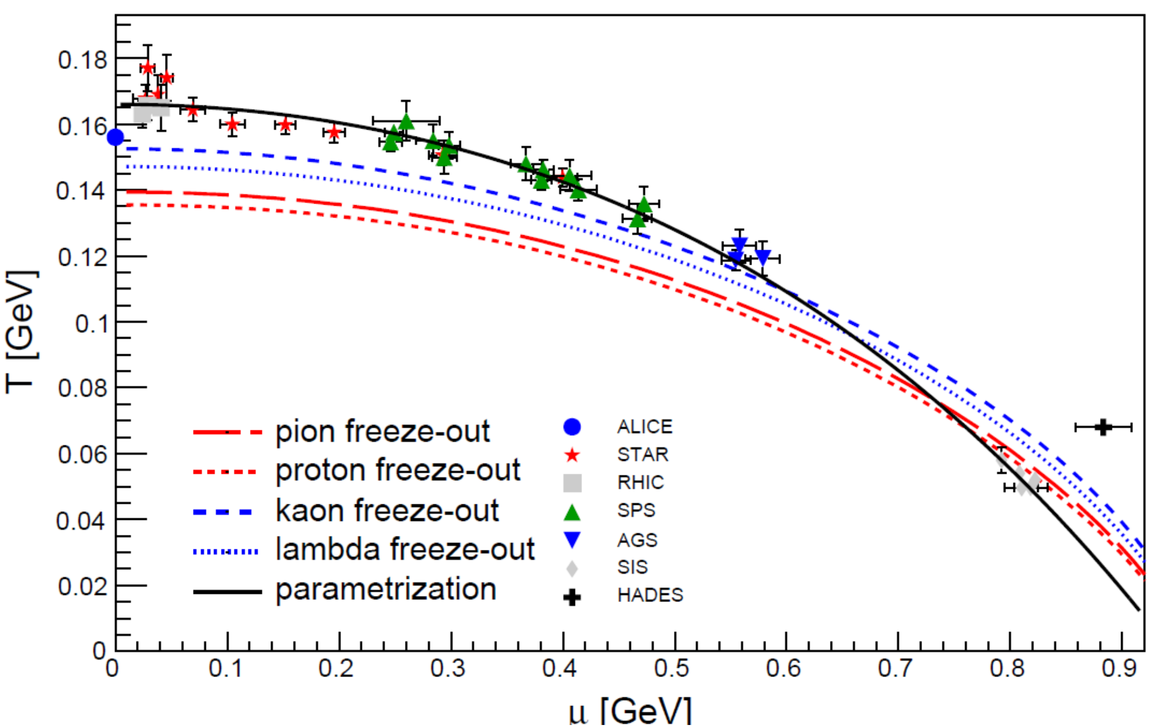


Mott-Anderson localization model – refined, full HRG

DB, J. Jankowski, M. Naskret, arxiv:1705.00169

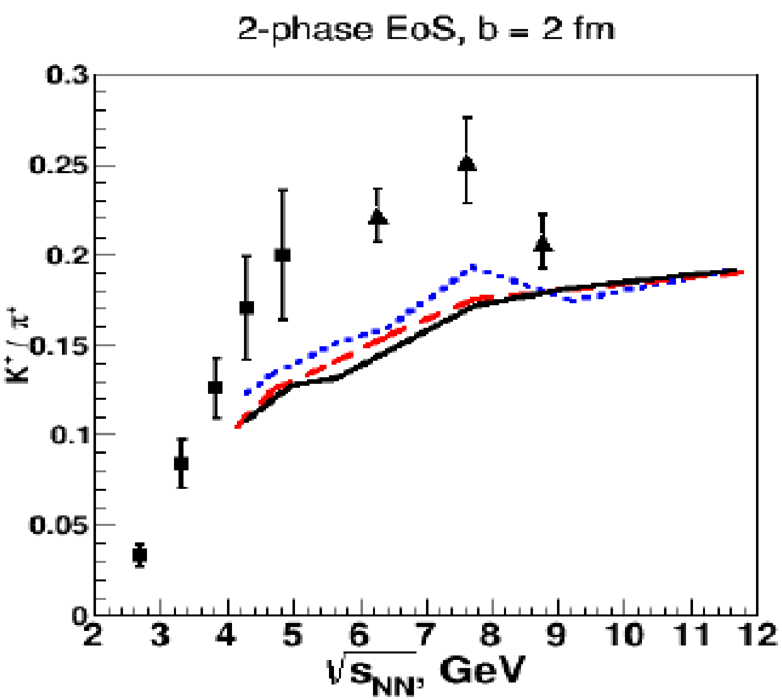
Behaviour of the reactive cross section in the T-mu plane, example of pi-pi parameters →

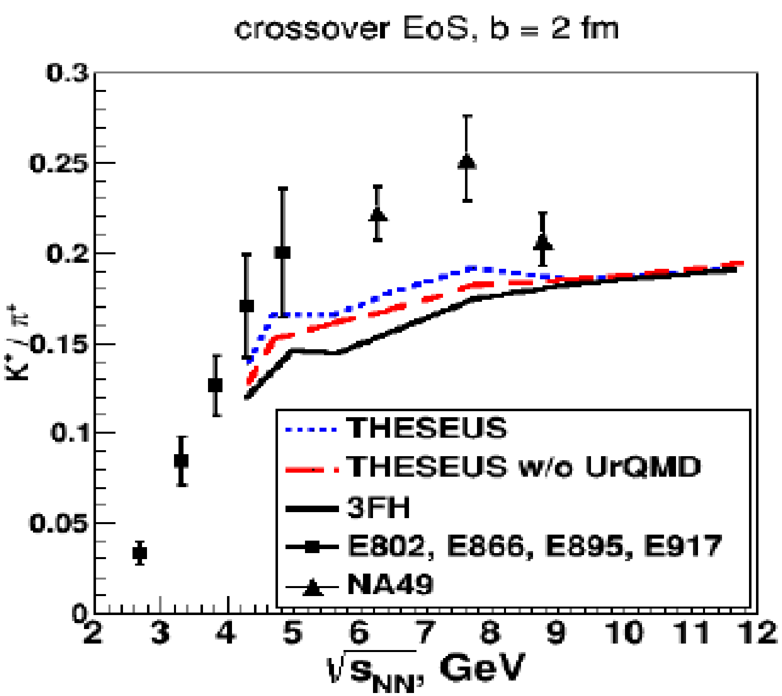




← Effect of the activation threshold

What about K+/π+ (Marek's horn) in THESEUS ?





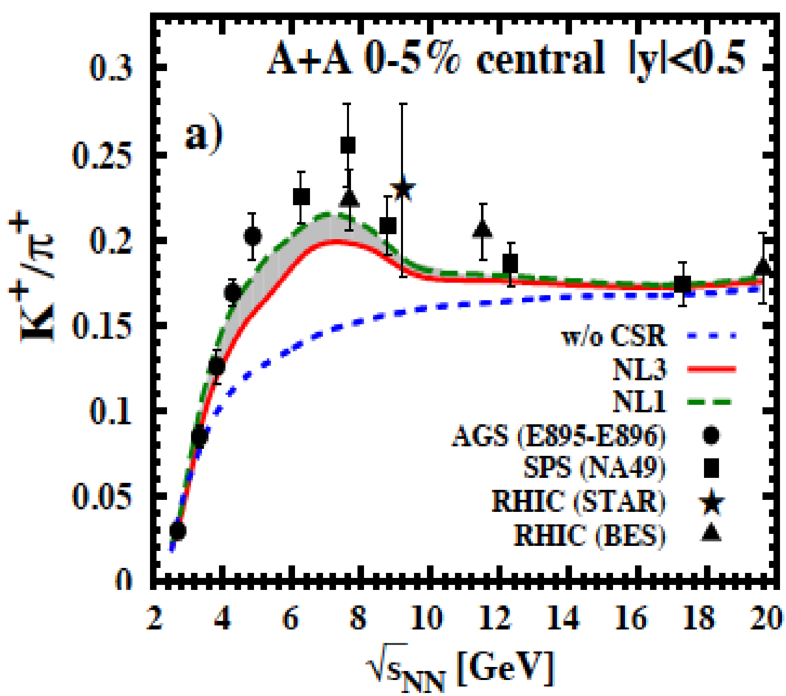
THESEUS simulation reproduces 3FH result,
Thus it has the same discrepancy with experiment

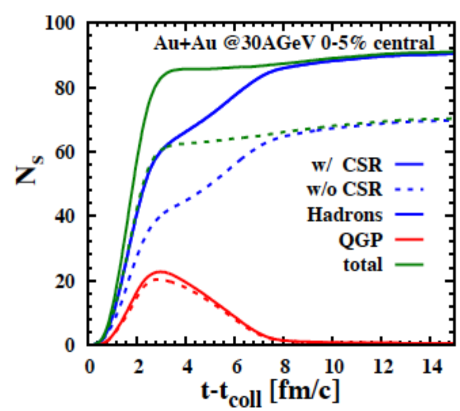
--> some key element still missing in the program

Batyuk, D.B., Bleicher, et al., PRC 94 (2016) 044917

Recent new development in PHSD

Chiral symmetry restoration in HIC at intermediate ...”
A. Palmese et al., PRC 94 (2016) 044912





Strange particle number increase by CSR

Mott dissociation of π and K in hot, dense quark matter

D. Blaschke, A. Dubinin, A. Radzhabov, A. Wergieluk, PRD 96 (2017) 094008; arxiv:1608.05383

Andrey Radzhabov in front of the University of Wroclaw

PNJL model for N_f=2+1 quark matter with π and K

$$\mathcal{L} = \bar{q}\left(i\gamma^\mu D_\mu + \hat{m}_0\right)q + G_S \sum_{a=0}^{8}\left[(\bar{q}\lambda^a q)^2 + (\bar{q}i\gamma_5\lambda^a q)^2\right] - \mathcal{U}\left(\Phi[A],\bar{\Phi}[A];T\right)$$

$$\Pi^{M^a}_{ff'}(q_0,\mathbf{q}) = 2N_c T\sum_n \int \frac{d^3p}{(2\pi)^3}\mathrm{tr}_D\left[S_f(p_n,\mathbf{p})\Gamma^{M^a}_{ff'}S_{f'}(p_n+q_0,\mathbf{p}+\mathbf{q})\Gamma^{M^a}_{ff'}\right]$$

$$\Gamma^{P^a}_{ff'} = i\gamma_5\, T^a_{ff'}\ ,\quad \Gamma^{S^a}_{ff'} = T^a_{ff'}\ ,\quad T^a_{ff'} = \begin{cases}(\lambda_3)_{ff'},\\ (\lambda_1 \pm i\lambda_2)_{ff'}/\sqrt{2},\\ (\lambda_4 \pm i\lambda_5)_{ff'}/\sqrt{2},\\ (\lambda_6 \pm i\lambda_7)_{ff'}/\sqrt{2},\end{cases}$$

$$P^a = \pi^0, \pi^\pm, K^\pm, K^0, \bar{K}^0$$

$$\Pi^{P^a,S^a}_{ff'}(q_0+i\eta,\mathbf{0}) = 4\left\{I_1^f(T,\mu_f) + I_1^{f'}(T,\mu_{f'}) \mp \left[(q_0+\mu_{ff'})^2 - (m_f \mp m_{f'})^2\right] I_2^{ff'}(z,T,\mu_{ff'})\right\}$$

$$I_1^f(T,\mu_f) = \frac{N_c}{4\pi^2}\int_0^\Lambda \frac{dp\,p^2}{E_f}\left(n_f^- - n_f^+\right),$$

$$I_2^{ff'}(z,T,\mu_{ff'}) = \frac{N_c}{4\pi^2}\int_0^\Lambda \frac{dp\,p^2}{E_f E_{f'}}\left[\frac{E_{f'}}{(z-E_f-\mu_{ff'})^2 - E_{f'}^2}\,n_f^- - \frac{E_{f'}}{(z+E_f-\mu_{ff'})^2 - E_{f'}^2}\,n_f^+ + \frac{E_f}{(z+E_{f'}-\mu_{ff'})^2 - E_f^2}\,n_{f'}^- - \frac{E_f}{(z-E_{f'}-\mu_{ff'})^2 - E_f^2}\,n_{f'}^+\right]$$

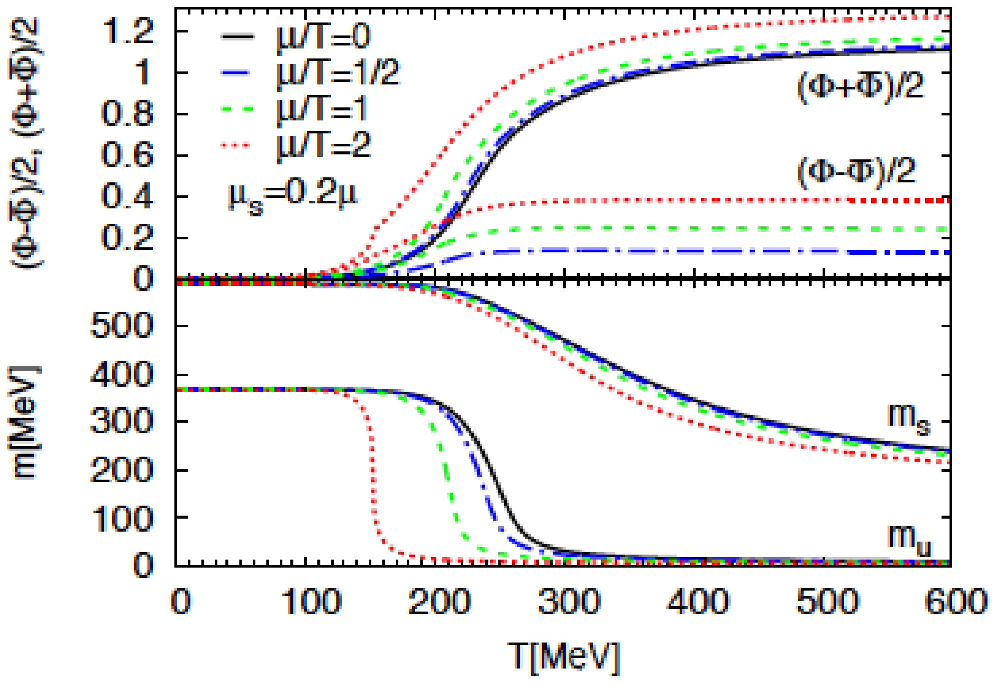
PNJL model for N_f=2+1 quark matter with π and K

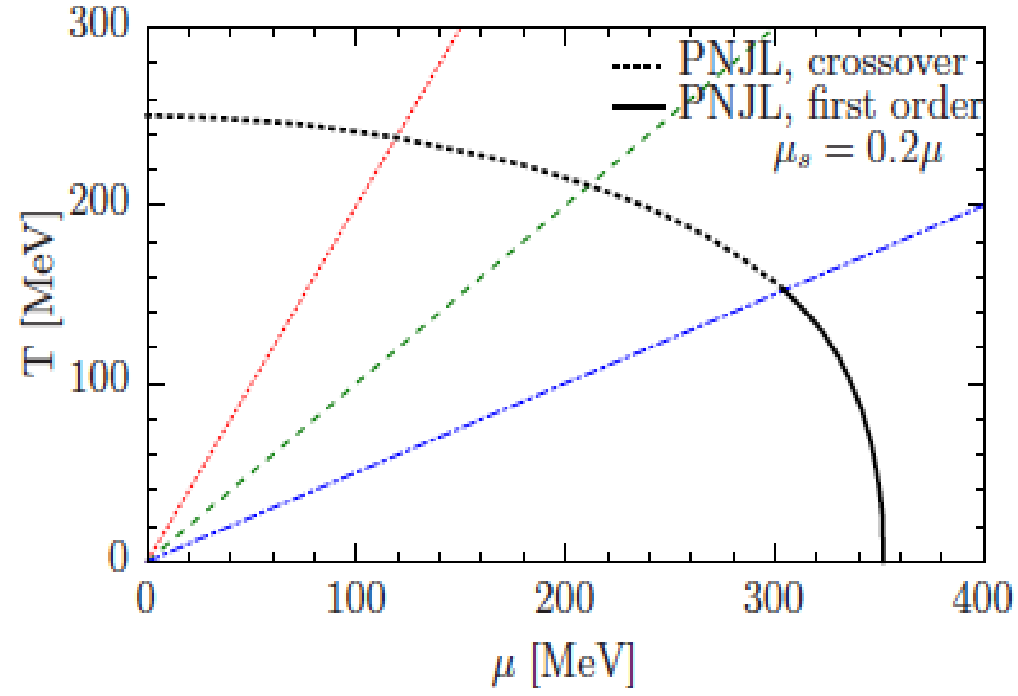
$$m_f = m_{0,f} + 16\, m_f G_S I_1^f(T,\mu), \quad \mathcal{P}_{ff'}^{M^a}(M_{M^a} + i\eta, \mathbf{0}) = 1 - 2G_S \Pi_{ff'}^{M^a}(M_{M^a} + i\eta, \mathbf{0}) = 0.$$

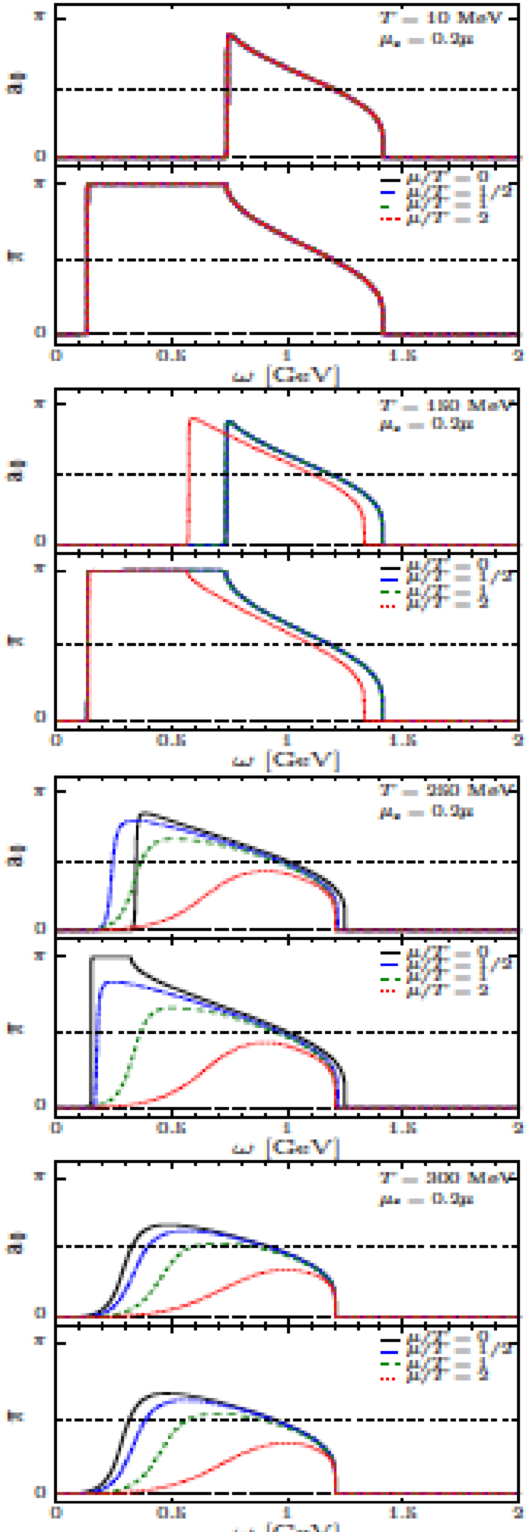
$$P_f = -\frac{(m_f - m_{0,f})^2}{8G} + \frac{N_c}{\pi^2}\int_0^\Lambda dp\, p^2 E_f + \frac{N_c}{3\pi^2}\int_0^\infty \frac{dp\, p^4}{E_f}\left[f_\Phi^+(E_f) + f_\Phi^-(E_f)\right]$$

$$P_M = d_M \int \frac{d^3q}{(2\pi)^3} \int_0^\infty \frac{d\omega}{2\pi} \left\{ g(\omega - \mu_M) + g(\omega + \mu_M) \right\} \delta_M(\omega, \mathbf{q})$$

$$\delta_M(\omega, \mathbf{q}) = -\arctan\left\{ \frac{\mathrm{Im}\left(\mathcal{P}_{ff'}^M(\omega - i\eta, \mathbf{q})\right)}{\mathrm{Re}\left(\mathcal{P}_{ff'}^M(\omega + i\eta, \mathbf{q})\right)} \right\}$$







Mott dissociation of pions and kaons in the Beth-Uhlenbeck approach ...

D.B., A. Dubinin, A. Radzhabov, A. Wergieluk, PRD 96 (2017) 094008
D.B., M. Buballa, A. Dubinin, G. Ropke, D. Zablocki, Ann. Phys. (2014)

Thermodynamics of resonances (M) via phase shifts

$$P_M = d_M \int \frac{d^3q}{(2\pi)^3} \int_0^\infty \frac{ds}{4\pi} \frac{1}{\sqrt{s+q^2}} \left\{ g(\sqrt{s+q^2} - \mu_M) \right\} \delta_M(\sqrt{s}; T, \mu)$$

Polyakov-loop Nambu – Jona-Lasinio modell

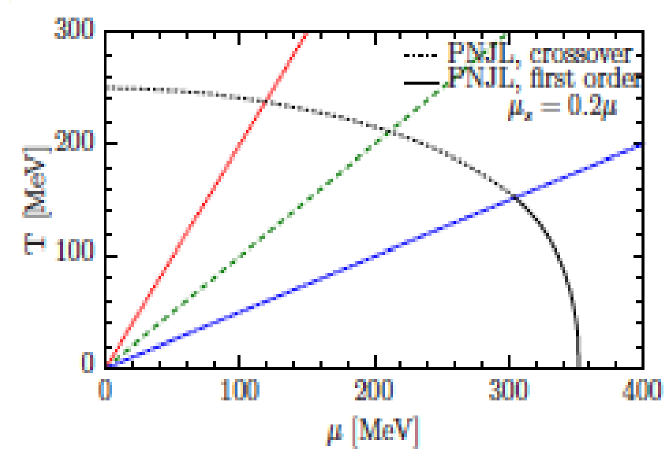
$$\Pi^{M^*}_{ff'}(q_0, \mathbf{q}) = 2N_c T \sum_n \int \frac{d^3p}{(2\pi)^3} \mathrm{tr}_D \left[S_f(p_n, \mathbf{p}) \Gamma^{M^*}_{ff'} S_{f'}(p_n + q_0, \mathbf{p} + \mathbf{q}) \Gamma^{M^*}_{ff'} \right],$$

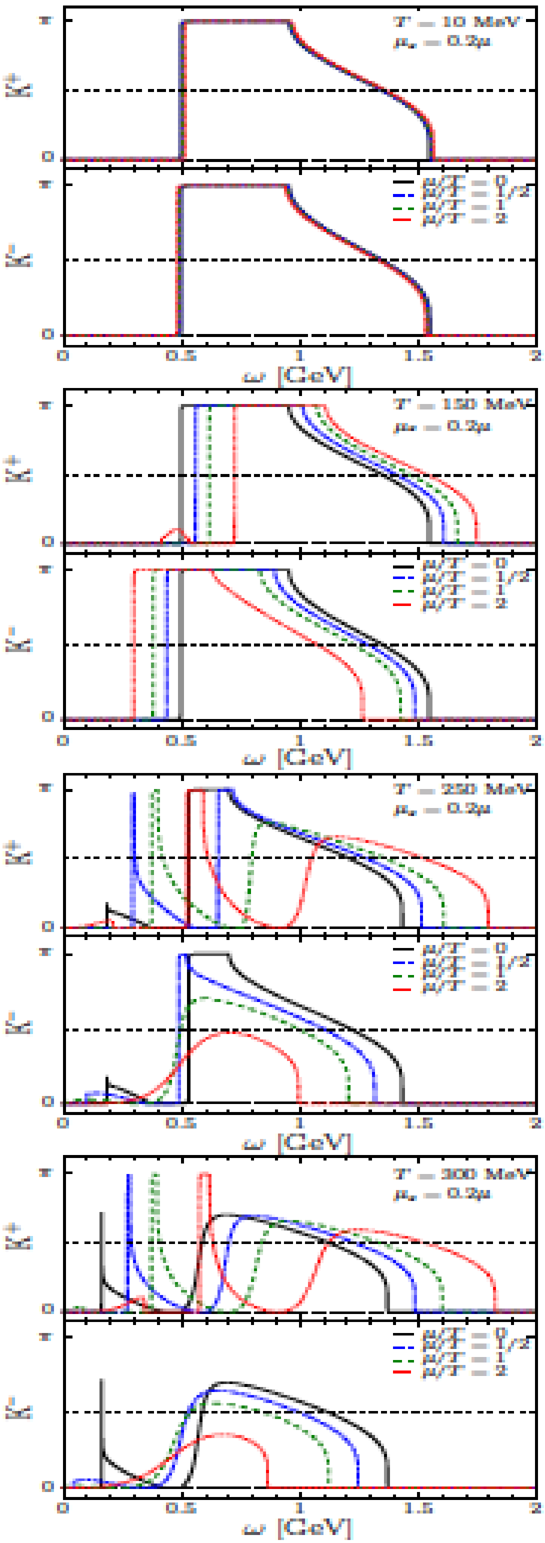
$$\mathcal{P}^{M^*}_{ff'}(M_{M^*} + i\eta, 0) = 1 - 2G_S \Pi^{M^*}_{ff'}(M_{M^*} + i\eta, 0)$$

$$\delta_M(\omega, \mathbf{q}) = -\arctan\left\{ \frac{\mathrm{Im}\left(\mathcal{P}^M_{ff'}(\omega - i\eta, \mathbf{q})\right)}{\mathrm{Re}\left(\mathcal{P}^M_{ff'}(\omega + i\eta, \mathbf{q})\right)} \right\}$$

Evaluation along trajectories μ/T=const in the phase diagram:

- Pion and a0 as partner states,
- Chiral symmetry restoration,
- Mott dissociation of bound states,
- Levinson theorem





Mott dissociation of pions and kaons in the Beth-Uhlenbeck approach ...

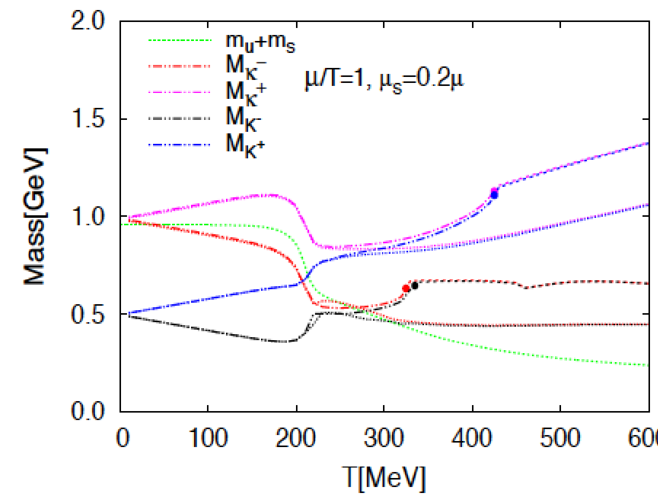
D.B., A. Dubinin, A. Radzhabov, A. Wergieluk, PRD 96 (2017) 094008

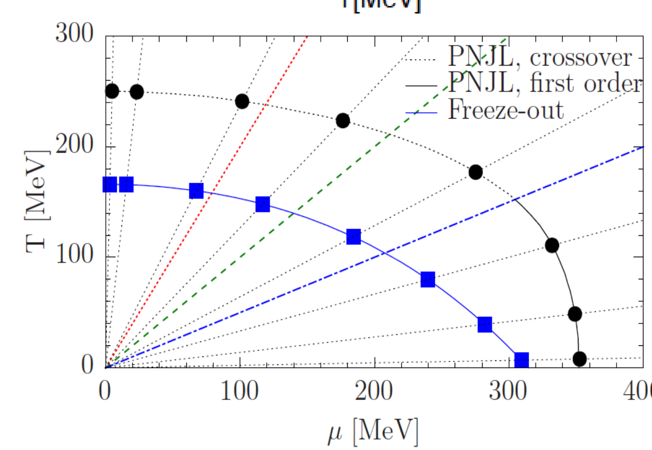
Polarization loop in Polyakov-loop Nambu – Jona-Lasinio model

$$\Pi^{P^a,S^a}_{ff'}(q_0+i\eta,\mathbf{0}) = 4\{I^f_1(T,\mu_f)+I^{f'}_1(T,\mu_{f'}) \mp \left[(q_0+\mu_{ff'})^2-(m_f\mp m_{f'})^2\right] I^{ff'}_2(z,T,\mu_{ff'})\}$$

$$I^f_1(T,\mu_f) = \frac{N_c}{4\pi^2}\int_0^\Lambda \frac{dp\,p^2}{E_f}\left(n_f^- - n_f^+\right),$$

$$I^{ff'}_2(z,T,\mu_{ff'}) = \frac{N_c}{4\pi^2}\int_0^\Lambda \frac{dp\,p^2}{E_f E_{f'}} \left[\frac{E_{f'}}{(z-E_f-\mu_{ff'})^2-E^2_{f'}}\,n_f^- - \frac{E_{f'}}{(z+E_f-\mu_{ff'})^2-E^2_{f'}}\,n_f^+ + \frac{E_f}{(z+E_{f'}-\mu_{ff'})^2-E^2_f}\,n_{f'}^- - \frac{E_f}{(z-E_{f'}-\mu_{ff'})^2-E^2_f}\,n_{f'}^+\right]$$



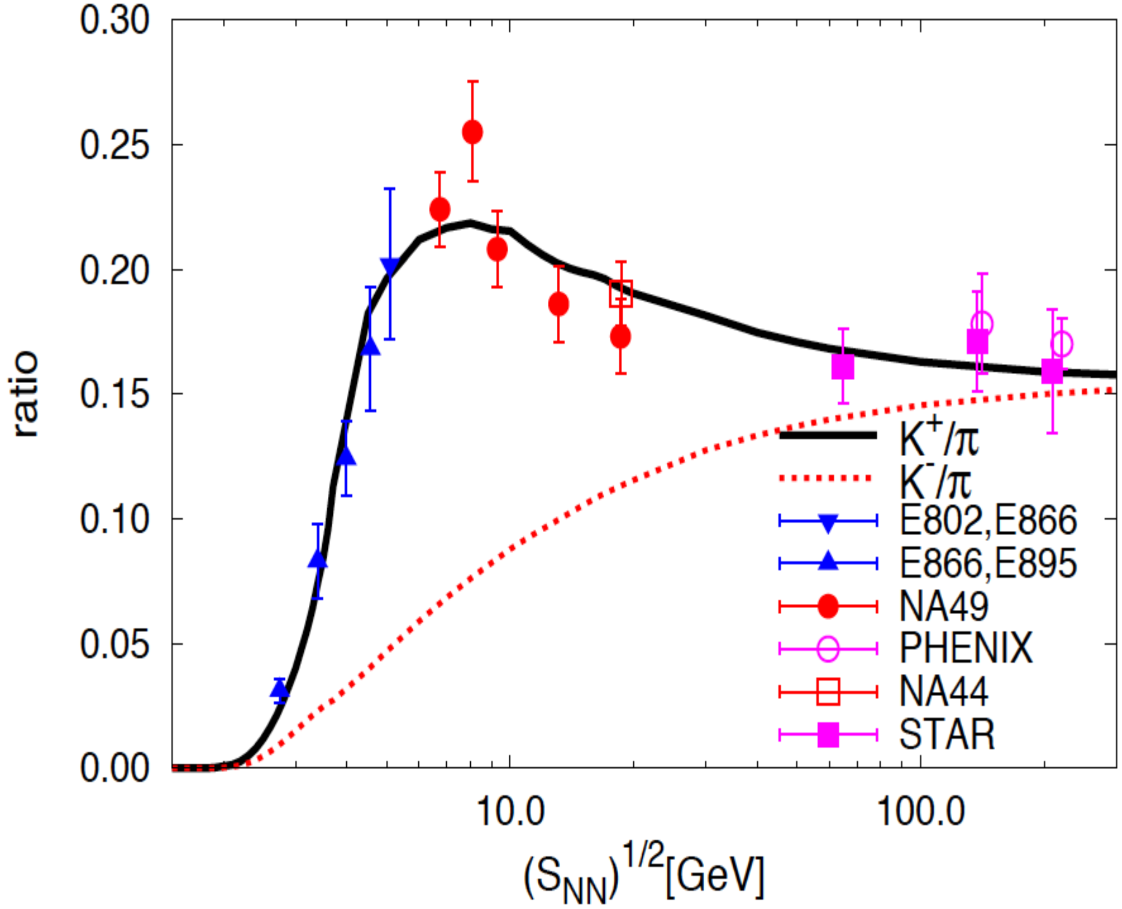


Anomalous low-mass mode for K+ in the dense medium !!

Mott dissociation of pions and kaons in Beth-Uhlenbeck: Explanation of the "horn" effect for K+/π+ in HIC?

Ratio of yields in BU approach
defined via phase shifts:

$$\frac{n_{K^\pm}}{n_{\pi^\pm}} = \frac{\int dM \int d^3p\ (M/E) g_{K^\pm}(E)[1 + g_{K^\pm}(E)]\delta_{K^\pm}(M)}{\int dM \int d^3p\ (M/E) g_{\pi^\pm}(E)[1 + g_{\pi^\pm}(E)]\delta_{\pi^\pm}(M)}$$



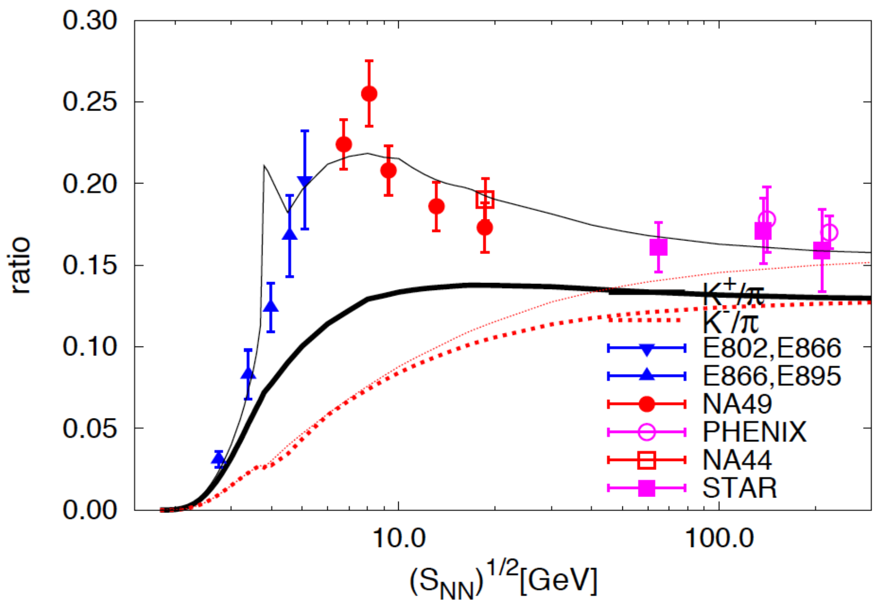
Evaluation along the freeze-out
Curve parametrized by Cleymans et al.

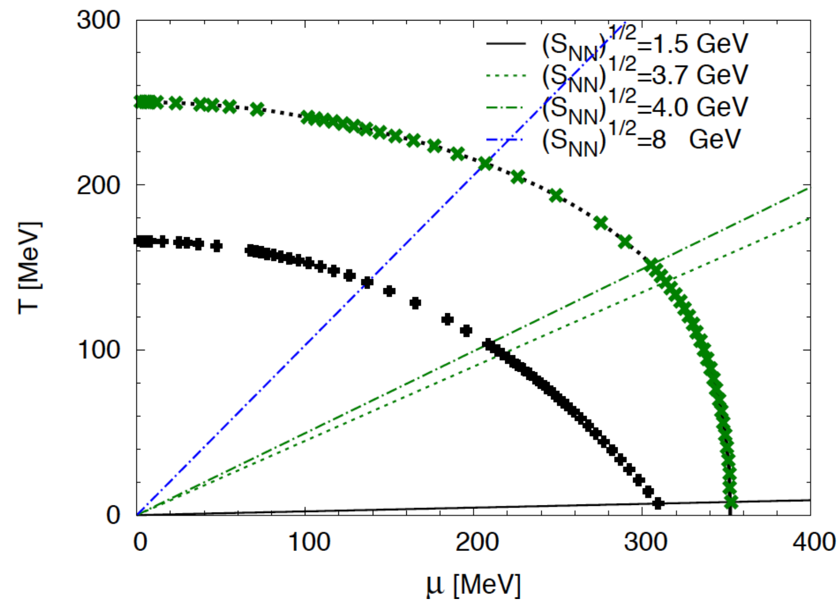
- enhancement for K+ due to anomalous in-medium bound state mode
- no such enhancement for K- or pions

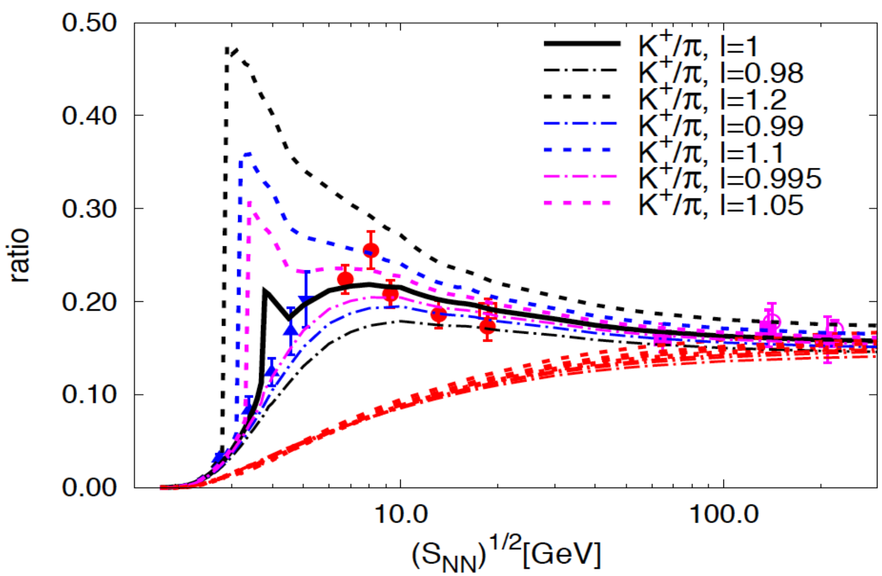
- explore the effect in thermal statistical models and in THESEUS ...

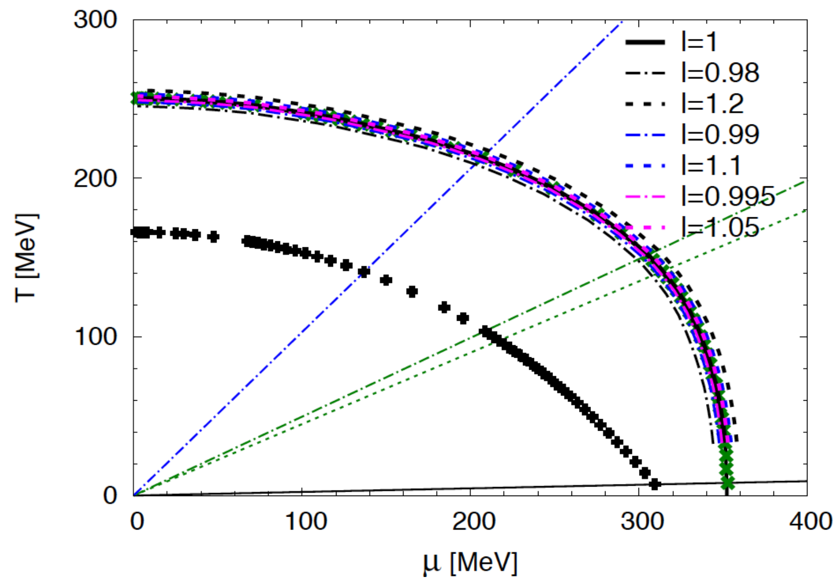
D.B., A. Dubinin, A. Radzhabov, A. Wergieluk,
PRD 96 (2017) 094008; arxiv:1608.05383

“Tooth” on the “horn” due to anomalous K+; sign of CEP?





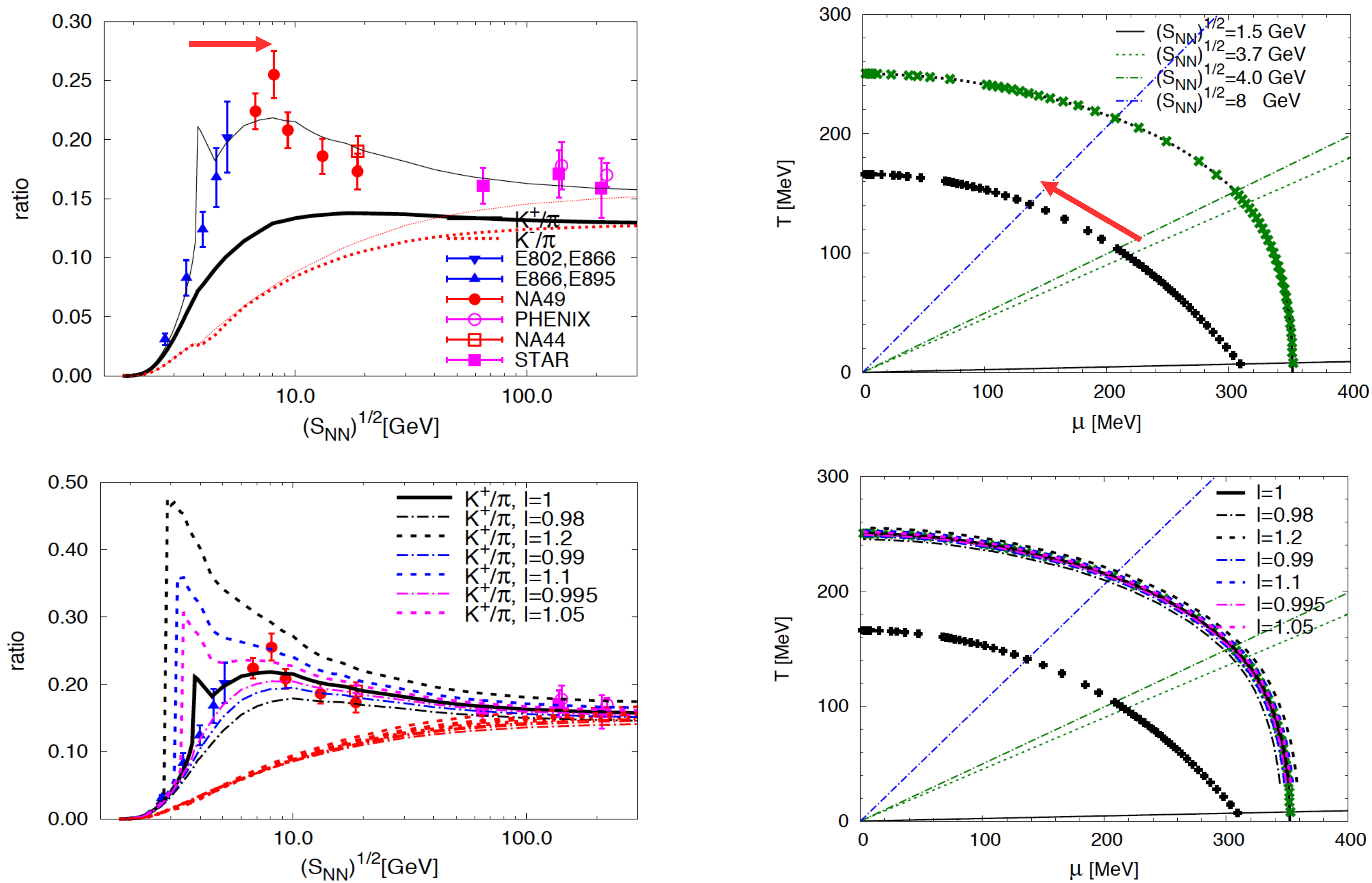




- enhancement for K+ due to anomalous in-medium bound state mode

D.B., A. Friesen, A. Radzhabov, in prep. (2019)

“Tooth” on the “horn” due to anomalous K+; sign of CEP?



- “tooth” correlated to the CEP → indicator for CEP !!

D.B., A. Friesen, A. Radzhabov, in prep. (2019)

Conclusions

- nuclear/hadronic medium effects determine the Mott-lines for light clusters in the QCD phase diagram: selfenergy and Pauli blocking (constituent exchange)

- at high energies sudden freeze-out from unmodified statistical model (left of Mott-line)

- at low energies (high baryon densities) freeze-out interferes with Mott effect !

- justification for sudden freeze-out picture may come from Mott-Anderson localization of hadron (multiquark) wave functions, enforced by confining interactions

- K+/pi+ horn effect: additional K+ mode in-medium from generalized (in-medium) Beth-Uhlenbeck approach with chiral quark model

- implementation to THESEUS code under way … in-medium modifications on the (sudden) freeze-out hypersurface

ECT*

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Light clusters in nuclei and nuclear matter: Nuclear structure and decay, heavy ion collisions, and astrophysics

From Monday, 2 September, 2019 - 08:00 to Friday, 6 September, 2019 - 14:00

Location: ECT* meeting room

Abstract:
Nuclear systems are important examples for strongly interacting quantum liquids. New experiments in nuclear physics and observations of compact astrophysical objects require an adequate description of correlations, in particular the formation of clusters and the occurrence of quantum condensates in low-density nuclear systems. Alpha clustering is an important phenomenon in light 4-n self-conjugated nuclei (Hoyle state). New results have been obtained for such nuclei with additional nucleons (e.g. the 9B and (9-11)Be nuclei). Collective excitations show also effects of α-like clustering. In addition, clustering is of relevance for radioactive decay, alpha preformation and the life-time of heavy nuclei. Cluster formation is essential to investigate nuclear systems in heavy ion collisions. Transport codes have to be worked out to describe the time evolution of correlations and bound states for expanding hot and dense matter. An interesting issue is the BEC-BCS transition in nuclear systems.

Registration period: 16 May 2019 to 12 Aug 2019

Website: https://indico.ectstar.eu/event/52/

http://www.ectstar.eu/node/4447

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