PHSD/PHQMD for FAIR

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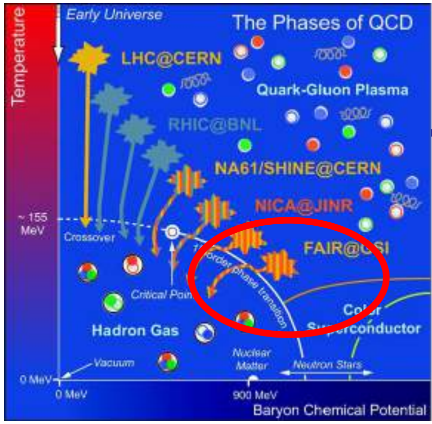
for the PHSD/PHQMD team

45th CBM Collaboration Meeting,

GSI, 19 February 2025



Study of QCD matter with heavy-ions

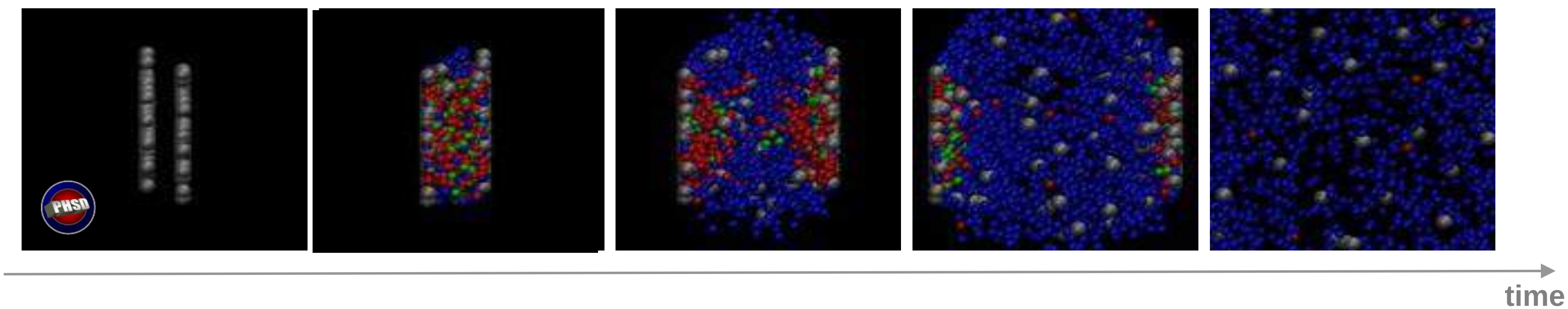
Goal: Microscopic modeling of heavy-ion collisions

PHSD & PHQMD

Parton-Hadron-String Dynamics & Parton-Hadron-Quantum-Molecular Dynamics

is a unified non-equilibrium microscopic transport approach for the description of the dynamics of strongly-interacting hadronic and partonic matter created in heavy-ion collisions and p+A, p+p, π+A reactions from SIS to LHC energies

Initial state: Au+Au | **Quark-Gluon Plasma: lQCD EoS non-perturbative QCD - quasiaprticles** | **Dynamical Hadronization** | **Hadronic interactions → final hadrons + leptons**



→ provides a continuous description of the HIC dynamics:
– no artificial transition from micro- to macro-description as in hydro-type models, no jump in entropy and energy density

PHSD,PHQMD are the open source codes, available for all experimental collaborations (used by GSI/FAIR collaborations, linked to the exp. software) and upon registration for other users

PHSD/PHQMD code

PHSD mode

Initialization A+A
+ propagation of baryons:
Mean Field dynamics
(BUU)

PHQMD mode

Initialization A+A
+ propagation of baryons:
Quantum Molecular dynamics
(QMD) – n-body model

Propagation of partons (quarks, gluons) and mesons:
Mean Field dynamics (Kadanoff-Baym, BUU)

Collision integral = interactions of hadrons and partons (QGP)

Optionally

Cluster recognition: MST (Minimum Spanning Tree)
or SACA (Simulated Annealing Clusterization Algorithm)
or coalescence mechanism + kinetic deuterons

Final output – "events" : OSCAR, ROOT, Rivet formats

Realization: parallel ensemble method

Computer language: Fortran

Special features of PHSD/PHQMD

- ✓ Kadanoff-Baym dynamics
- ✓ in-medium effects within G-matrix
- ✓ EoS in MF and QMD: momentum dependent potential
- ✓ Mechanisms for cluster production in PHQMD:
  dynamical, kinetic and coalescence
- ✓ QGP within DQPM → PHSD;
  phase transition from hadronic matter to QGP
- ✓ Dark matter – dark photons
- ○ Realization of n↔m reactions
- ○ chiral symmetry restoration via Schwinger mechanism
- ○ Charm/bottom dynamics

✓ **More information on these topics are in Backup slides**

Equations-of-Motion

Dynamics of heavy-ion collisions is a many-body problem!

Schrödinger eq. for system of N particles

$$i\hbar \frac{\partial}{\partial t} \Psi(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_N, t) = H(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_N, t) \quad \Psi(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_N, t)$$

N-body Hamiltonian:

$$H \approx \sum_{i=1}^{N} T(\vec{r}_i) + \sum_{i<j}^{N} V_{ij}(\vec{r}_1 - \vec{r}_2, t)$$

local two-body potential

N-body wave function:

$$\Psi(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_N, t) \approx \prod_{i=1}^{N} \psi_i(\vec{r}_i, t)$$

Mean field dynamics

Hartree-Fock eq. for a single particle *i*:

$$i\hbar \frac{\partial}{\partial t} \psi_i(\vec{r}, t) = \hat{h} \psi_i(\vec{r}, t)$$

h = T+U **- single particle Hamiltonian**
ψ_i **– single particle wave function**

Self-generated mean-field potential:

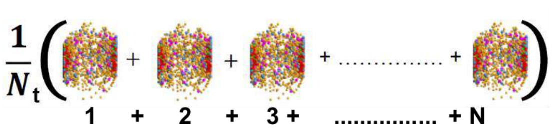
$$U(\vec{r}, t) = \frac{1}{(2\pi\hbar)^3} \int d^3r' \, d^3p \, V(\vec{r} - \vec{r}', t) f(\vec{r}', \vec{p}, t)$$

local two-body potential

Testparticle or parallel ensembles method:

$$f(\vec{r}, \vec{p}, t) = \frac{1}{N_t} \sum_{i=1}^{N \cdot N_t} \delta(\vec{r} - \vec{r}_i(t)) \delta(\vec{p} - \vec{p}_i(t))$$

MF- covariant



QMD dynamics

Ritz variational principle:

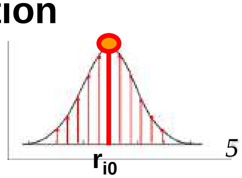
$$\delta \int_{t_1}^{t_2} dt < \psi(t) | i \frac{d}{dt} - H | \psi(t) >= 0$$

H - N-body Hamiltonian
Ψ - N-body wave function

Single-particle Wigner density of the nucleon wave function ψ_i :

$$f(\mathbf{r}_i, \mathbf{p}_i, \mathbf{r}_{i0}, \mathbf{p}_{i0}, t) = \frac{1}{\pi^3 \hbar^3} e^{-\frac{2}{L}[\mathbf{r}_i - \mathbf{r}_{i0}(t)]^2} e^{-\frac{L}{2\hbar^2}[\mathbf{p}_i - \mathbf{p}_{i0}(t)]^2}$$

Ansatz: Gaussian trial wave function with width *L* centered at r_{i0}, p_{i0}
➔ QMD - non-covariant !

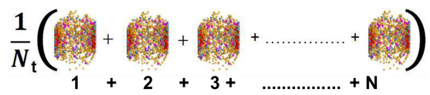


Equations-of-Motion

Mean field dynamics

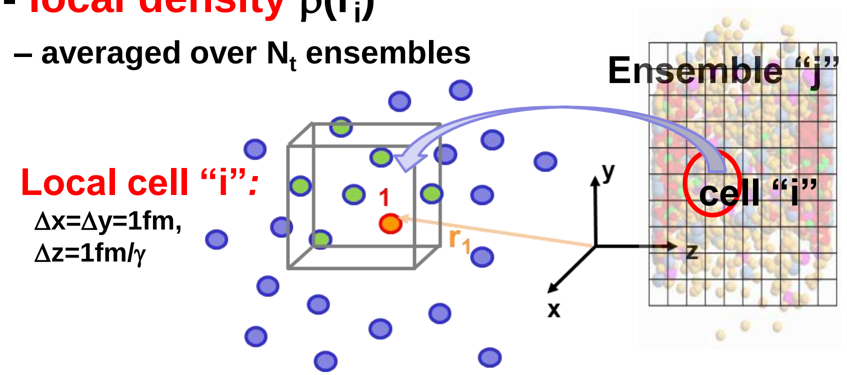
1 event: A+A nucleons

→ N_t ensembles with (A+A)*N_t test particles



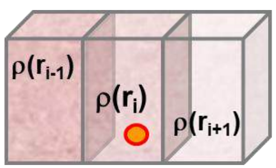
Step 1: grid cells

- local density $\rho(r_i)$
  – averaged over N_t ensembles



Step 2: forces

$$\vec{F} = -\vec{\nabla} U \sim \vec{\nabla}\rho \frac{\partial U}{\partial \rho}$$



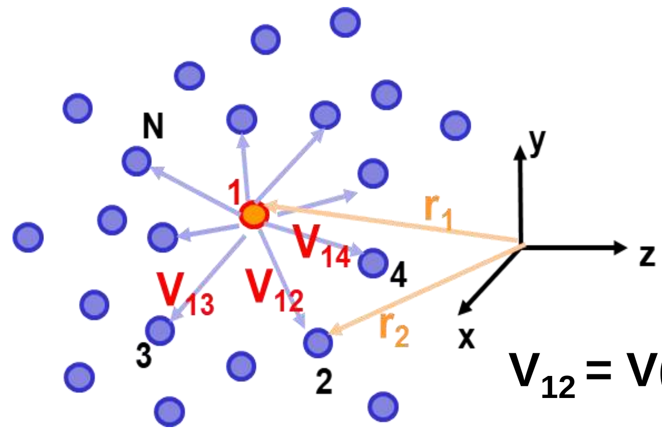
$$\dot{\vec{r}}_i = \frac{d\vec{r}_i}{dt} = \frac{\vec{p}_i}{m_i}$$

$$\dot{\vec{p}}_i = \frac{d\vec{p}_i}{dt} = -\vec{\nabla}_{\vec{r}_i} U(\vec{r}_i, t)$$

$U(\vec{r}, t)$ - mean-field potential

QMD dynamics

1 event: A+A nucleons



$V_{12} = V(r_1 - r_2)$

Expectation value of N-body Hamiltonian:

$$\langle H \rangle = \sum_i \langle H_i \rangle = \sum_i \left(\langle T_i \rangle + \sum_{j \neq i} \langle V_{i,j} \rangle \right)$$

$$\dot{r}_{i0} = \frac{\partial \langle H \rangle}{\partial p_{i0}} \qquad \dot{p}_{i0} = -\frac{\partial \langle H \rangle}{\partial r_{i0}}$$

$V_{ij} = V(r_i - r_j)$ - local two-body potential

→ QMD: N-body dynamics
via 2-body interaction potential

Where do we see differences in QMD vs MF dynamics?

- "Bulk" observables for hadrons are rather similar in QMD and MF!
  → tested with PHSD/PHQMD framework

- Cluster formation is sensitive to nucleon dynamics:
  - QMD – allows to keep over time NN correlations by potential interaction
  - MF – correlations are smeared out
  - Cascade – no correlations by potential interactions

Example: Cluster stability over time:

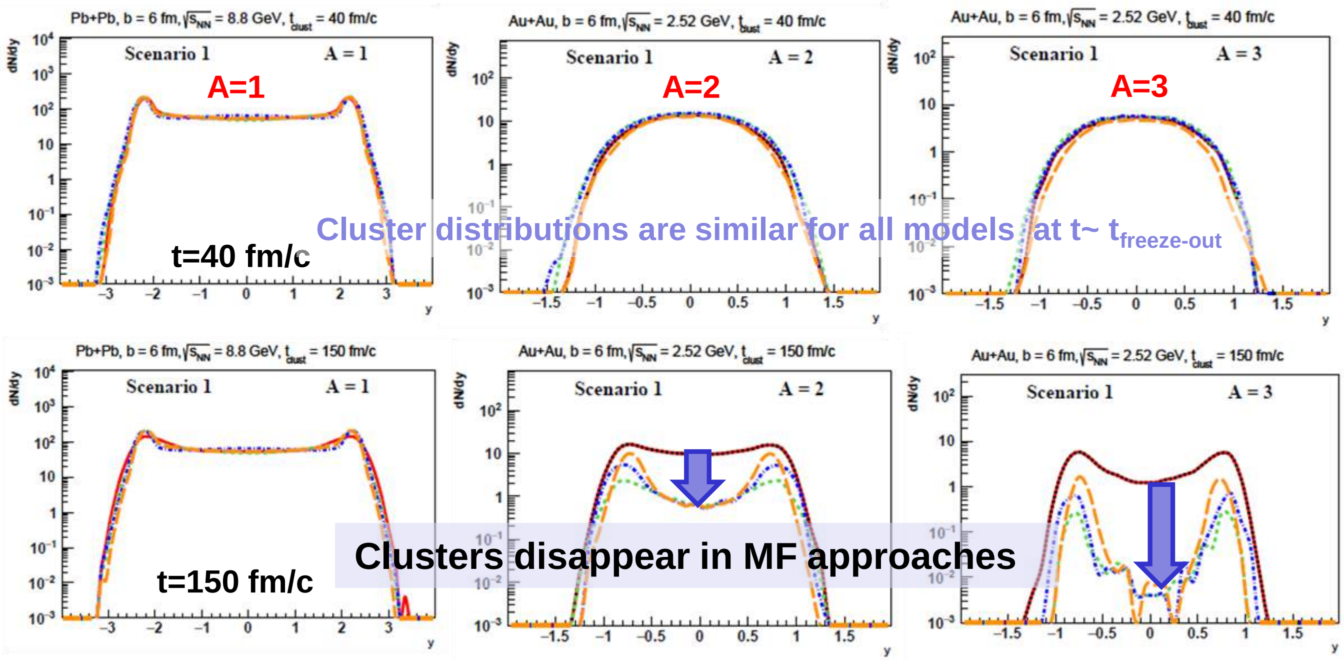
Viktar Kireyeu, Phys.Rev.C 103 (2021) 5

- Clusters identified by psMST for all models:

QMD:
PHQMD + psMST

MF:
PHSD + psMST

Cascade:
SMASH + psMST
UrQMD + psMST

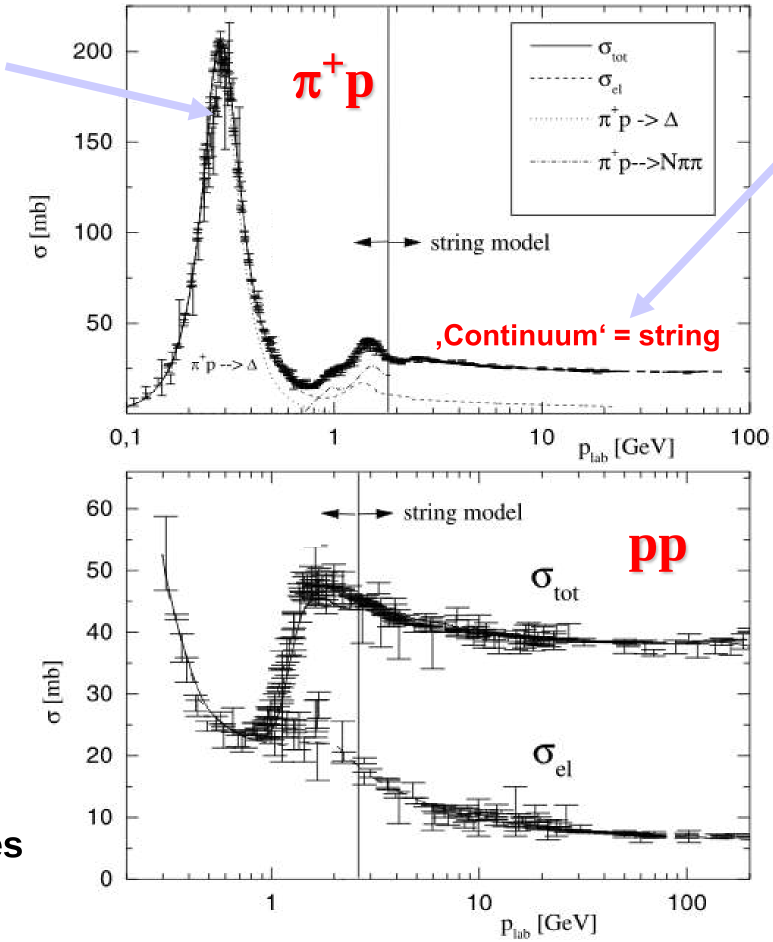


Elementary hadronic interactions in PHSD/PHQMD

Hadronic degrees-of-freedom:
- baryons (21 states): $B = p, n, \Delta(1232), N(1440), N(1535), ...$
- mesons (37 states): $M = \pi, \eta, \rho, \omega, \phi, ...$

Low energy reactions
- elastic and inelastic:
  $2 \leftrightarrow 2$, $2 \leftrightarrow 3(4)$
- resonance formation and decay $1 \leftrightarrow 2$

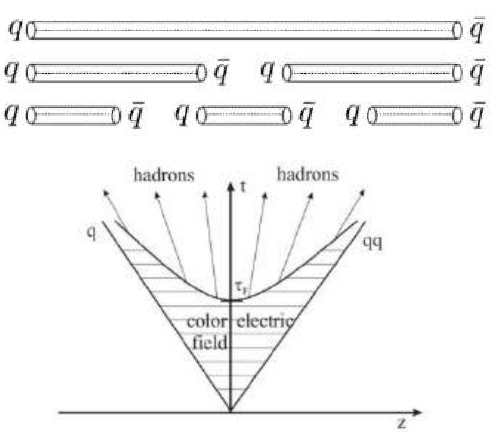
$$B + B \leftrightarrow B' + B'$$
$$B + B \leftrightarrow B' + B' + m$$
$$m + B \leftrightarrow m + B'$$
$$m + B \leftrightarrow B'$$
$$m + m \leftrightarrow m' + m'$$
$$m + m \leftrightarrow m', \ldots$$



* Modeling of in-medium hadronic interactions for strongly interacting particles (off-shell dynamics)

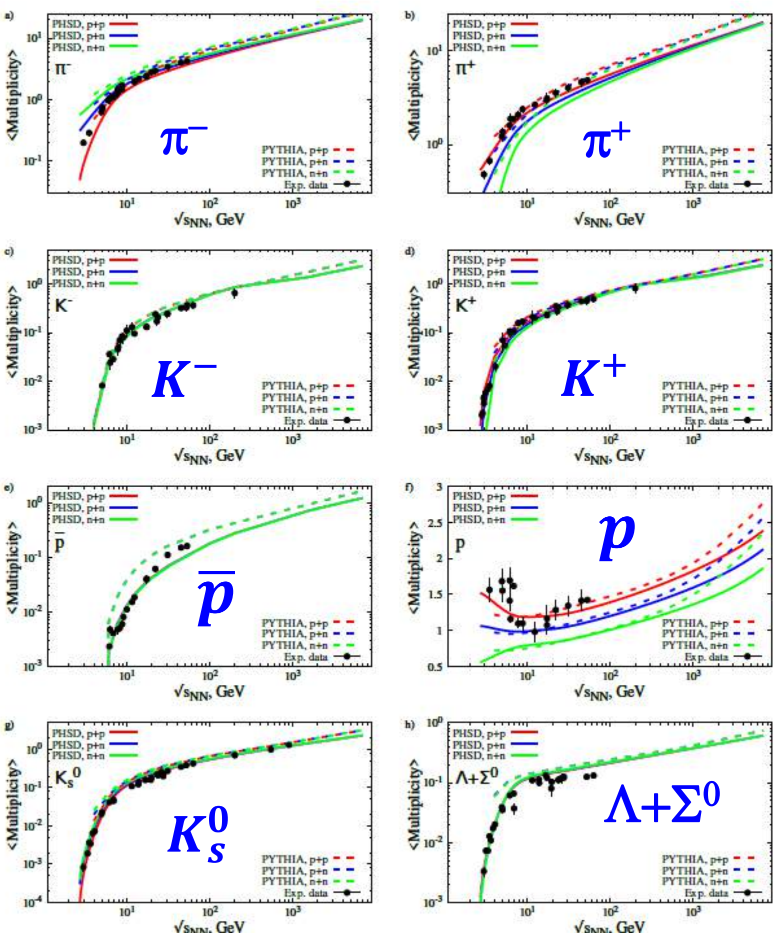
High energy collisions:
(above $s^{1/2}$~2.4 GeV)

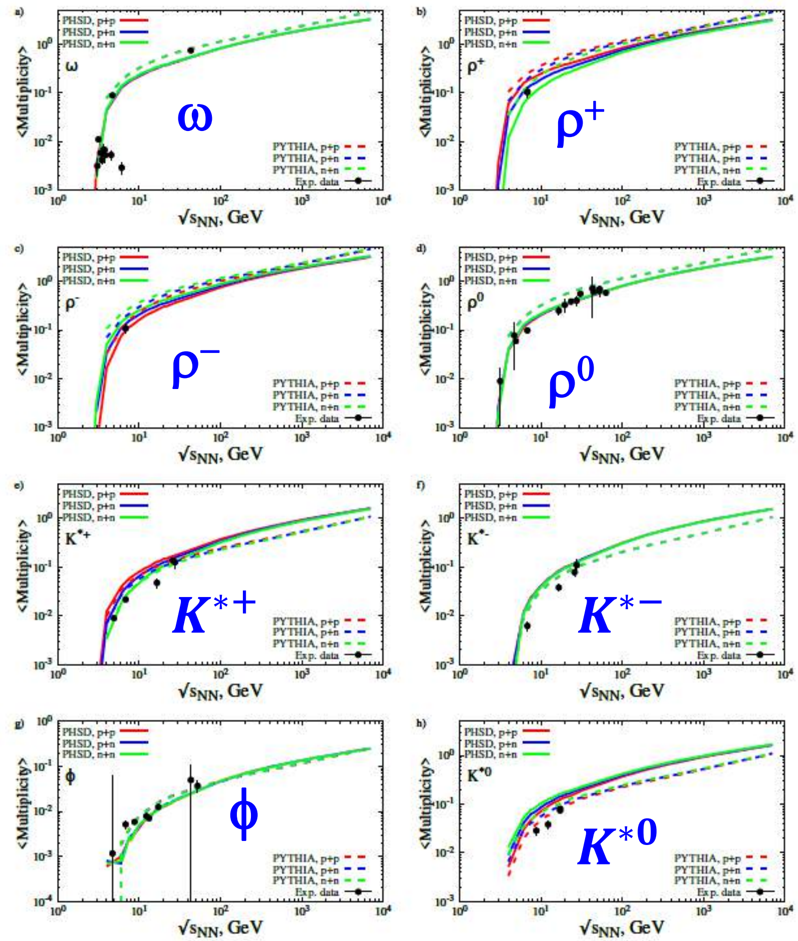
Inclusive particle production:
BB→X , mB→X, mm→X
X =many particles
described by
string formation and decay
using **LUND string model:**
strings = excited color singlet states *q-qq*, *q-qbar*
➔ color flux tube



Elementary reactions p+p, p+n, n+n

- LUND string model (FRITIOF, PYTHIA 6.4) with PHSD tune vs PYTHIA 8.2





- Existing experimental data on p+p are poor
  Practically NO data on p+n reactions

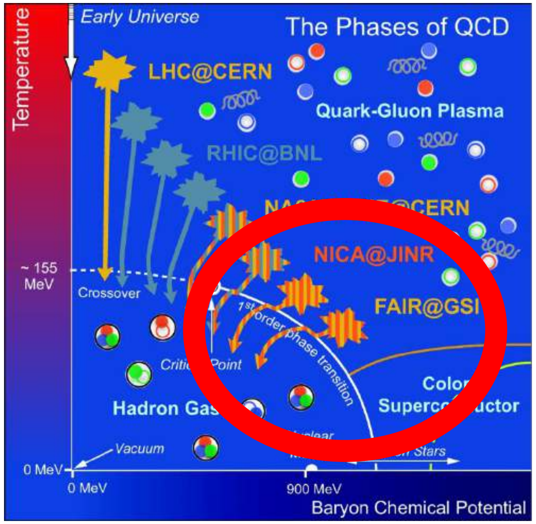
➔ FAIR data on elementary reactions are needed!

- Poor data on resonance production

V. Kireyeu et al., Eur.Phys.J.A 56 (2020) 223

Modeling of sQGP in microscopic transport theory:

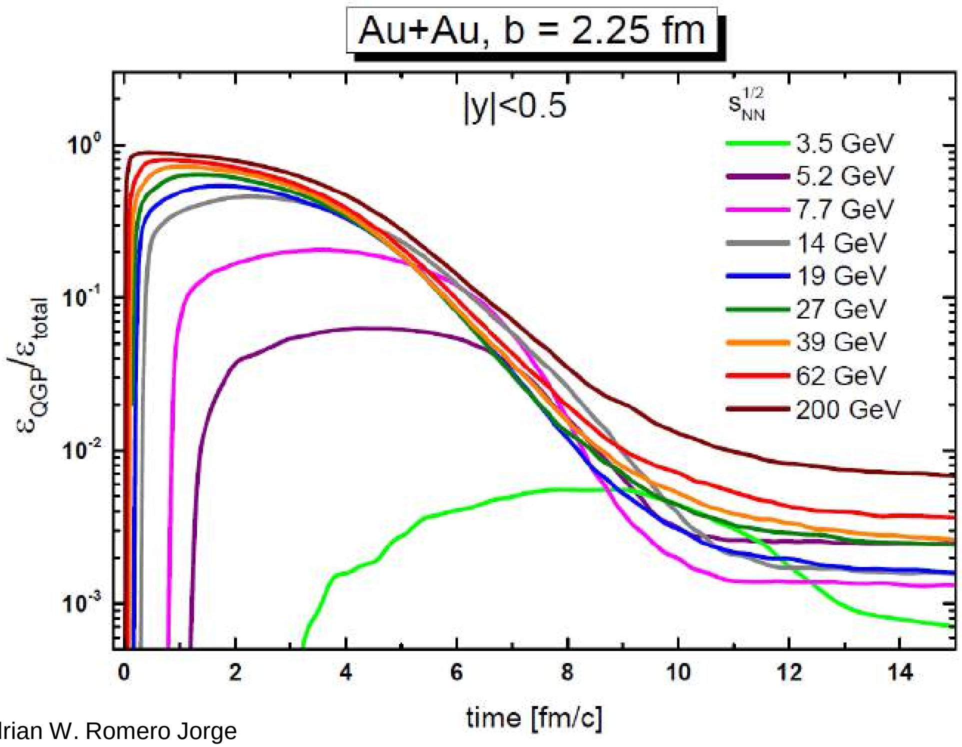
DQPM (T, μ_q) in PHSD/PHQMD



finite μ_q

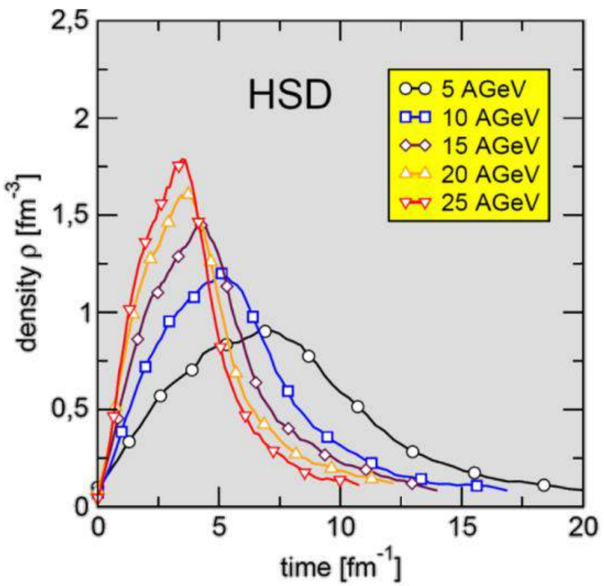
Dense and hot matter created in HICs

Time evolution of the partonic energy fraction



Plot by Adrian W. Romero Jorge

Time evolution of the baryon density ρ



Large energy and baryon densities (above critical $\varepsilon > \varepsilon_{crit} \sim 0.4$ GeV/fm^3) are reacheble in central reaction region at CBM energies*

➔ phase transition form hadronic matter to QGP

*** small volume of QGP (‚droplets‘) at low energies**

QGP: Dynamical QuasiParticle Model (DQPM)

DQPM – effective model for the description of non-perturbative (strongly interacting) QCD based on lQCD EoS

Degrees-of-freedom: strongly interacting dynamical quasiparticles - quarks and gluons

Theoretical basis :

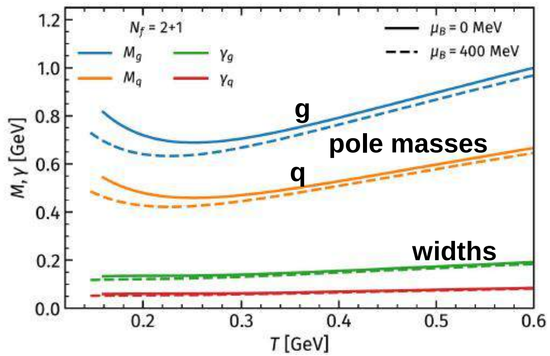
- ‚resummed' single-particle Green's functions ➔ quark (gluon) propagator (2PI) : $G_q^{-1} = P^2 - \Sigma_q$

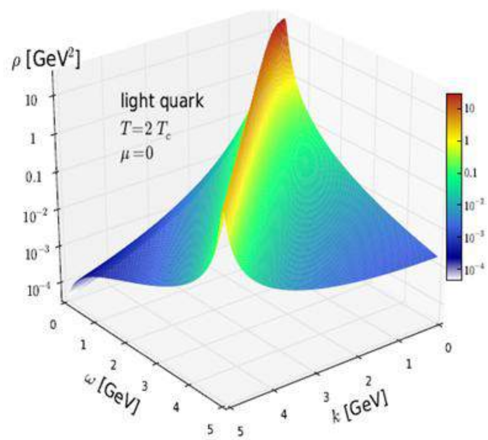
Properties of the quasiparticles are specified by scalar complex self-energies: $\Sigma_q = M_q^2 - i2\gamma_q\omega$

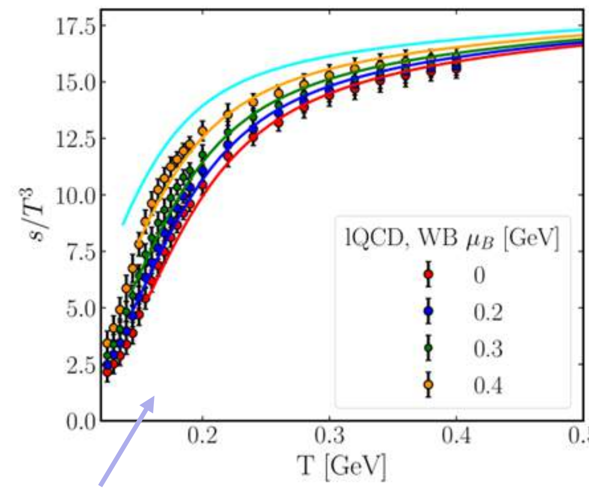
$Re\Sigma_q$: **thermal masses** (M_g, M_q); $Im\Sigma_q$: **interaction widths** (γ_g, γ_q) ➔ **spectral functions** $\rho_q = -2ImG_q$

- introduce an ansatz (HTL; with few parameters) for the (T, μ_B) dependence of masses/widths
- evaluate the QGP thermodynamics in equilibrium using the Kadanoff-Baym theory
- fix DQPM parameters by comparison of the DQPM entropy density to lQCD at μ_B=0

➔ **Quasi-particle properties at (T, μ_B) :**







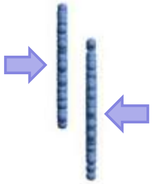
➔ **very good agreement with lQCD data for QGP thermodynamics at finite (T, μ_B)**

- **DQPM provides mean-fields (1PI) for q,g and effective 2-body partonic interactions (2PI); gives transition rates for the hadronization** → **sQGP in PHSD**

A. Peshier, W. Cassing, PRL 94 (2005) 172301; W. Cassing, NPA 791 (2007) 365: NPA 793 (2007), H. Berrehrah et al, Int.J.Mod.Phys. E25 (2016) 1642003; P. Moreau et al., PRC100 (2019) 014911; O. Soloveva et al., PRC101 (2020) 045203

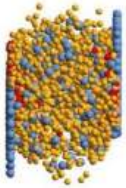
Time evolution in PHSD / PHQMD

Initial A+A collision

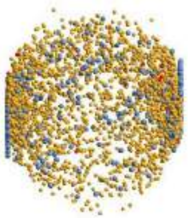


Partonic phase

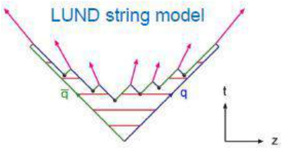
Hadronization



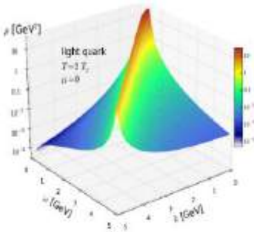
Hadronic phase



- ❑ **Initial A+A collisions :**
  N+N → string formation → decay to pre-hadrons + leading hadrons

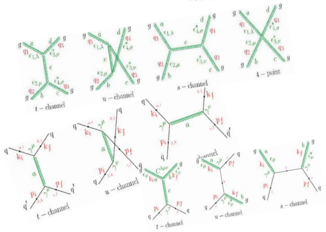


- ❑ **Formation of QGP stage** if local $\varepsilon > \varepsilon_{critical}$:
  dissolution of pre-hadrons → partons

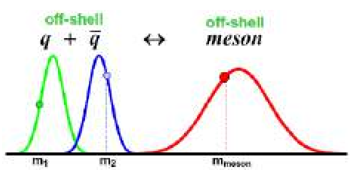


- ❑ **Partonic phase - QGP:**
  QGP is described by the Dynamical QuasiParticle Model (DQPM) matched to reproduce lattice QCD EoS for finite T and μ_B (crossover)

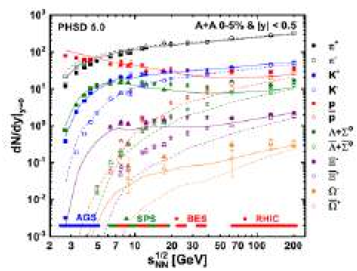
  - Degrees-of-freedom: strongly interacting quasiparticles: massive quarks and gluons (g,q,q_{bar}) with sizeable collisional widths in a self-generated mean-field potential
  - Interactions: (quasi-)elastic and inelastic collisions of partons
  - parton propagation within Kadanoff-Baym equations



- ❑ **Hadronization** to colorless off-shell mesons and baryons:
  Strict 4-momentum and quantum number conservation



- ❑ **Hadronic phase: hadron-hadron interactions – off-shell HSD**
  including $n \leftrightarrow m$ selected reactions
  (for strangeness, anti-baryons, deuteron production)

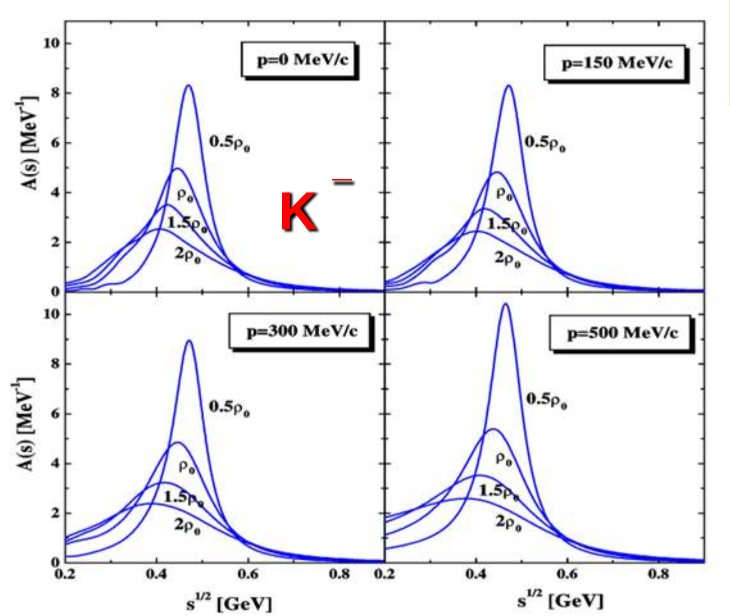


➔ PHSD/PHQMD provides a good description of 'bulk' hadronic and electromagnetic observables from SIS to LHC energies

PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; PHQMD: J. Aichelin et al., PRC 101 (2020) 044905

Strongly interacting hadrons (vector mesons, strange mesons) in hot and dense medium:

from BUU to Kadanoff-Baym



Tolos et al., NPA 690 (2001) 547

From weakly to strongly interacting systems

In-medium effects (on hadronic or partonic levels) = changes of particle properties in hot and dense medium

Examples: hadronic medium - vector mesons, strange mesons, baryons
QGP – dressing of partons

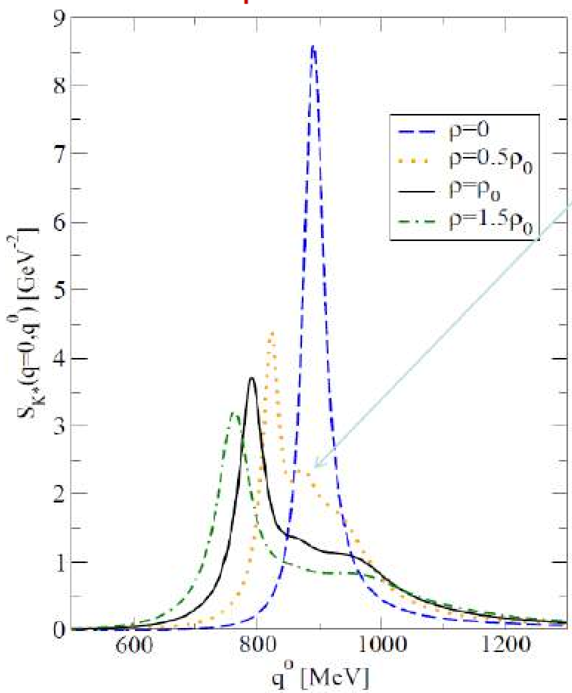
Many-body theory:
Strong interaction ➔ large widths ➔ broad spectral functions ➔ quantum objects

Semi-classical on-shell BUU: applies for a weakly interacting systems of particles

- **How to describe the dynamics of broad strongly interacting quantum states in transport theory?**

It is doable with quantum Kadanoff-Baym equations

Kbar* spectral function



Λ(1783)N[-1] and Σ(1830)N[-1] exitations

G-matrix:

Barcelona / Valencia group

Off-shell propagation: Kadanoff-Baym

After the first order gradient expansion of the Wigner transformed Kadanoff-Baym equations and separation into the real and imaginary parts one gets:

Generalized transport equations (GTE):

drift term — Vlasov term — backflow term — collision term = ‚gain' - ‚loss' term

$$\diamond \{ P^2 - M_0^2 - Re\Sigma^{ret}_{XP} \} \{ S^<_{XP} \} - \diamond \{ \Sigma^<_{XP} \} \{ Re S^{ret}_{XP} \} = \frac{i}{2} [\Sigma^>_{XP} S^<_{XP} - \Sigma^<_{XP} S^>_{XP}]$$

off-shell behavior

W. Botermans, R. Malfliet, Phys. Rep. 198 (1990) 115

- KB propagates 1-body 2-points Green functions $S^<(x,p) \rightarrow A(x,p)*N(x,p)$ in 8 dimensions
- $S^<$ carries information not only on the occupation number N_{XP} (as BUU), but also on the particle properties, interactions and correlations via spectral function A_{XP}

Spectral function:

$$A_{XP} = \frac{\Gamma_{XP}}{(P^2 - M_0^2 - Re\Sigma^{ret}_{XP})^2 + \Gamma^2_{XP}/4}$$

Reaction rate of particle:

$$\Gamma_{XP} = - Im\, \Sigma^{ret}_{XP} = 2\, p_0 \Gamma$$

On-shell limit of KB:

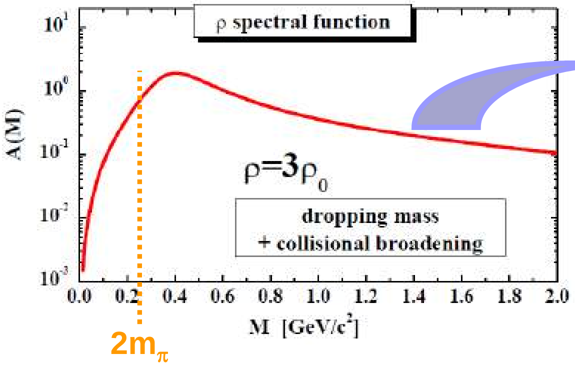
- $A_{XP} \rightarrow \delta(p^2 - M^2)$ or A_{XP} has a constant shape in a medium, i.e. $\nabla_X \Gamma = 0, \quad \nabla_P \Gamma = 0$
- backflow term vanishes: KB → BUU

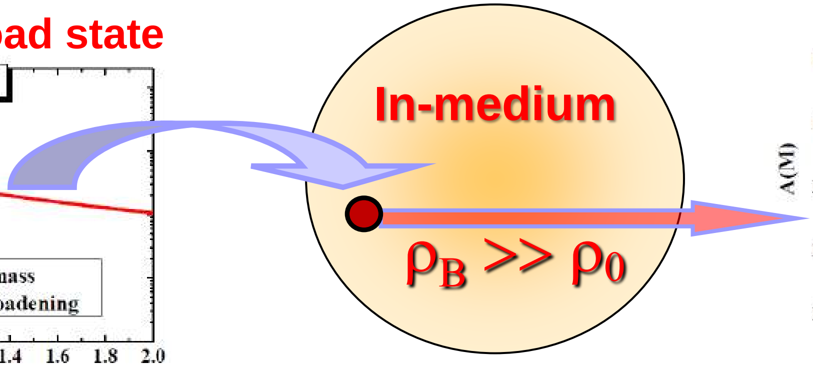
→ Generalized Cassing-Juchem off-shell equations of motion for testparticles → PHSD

W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

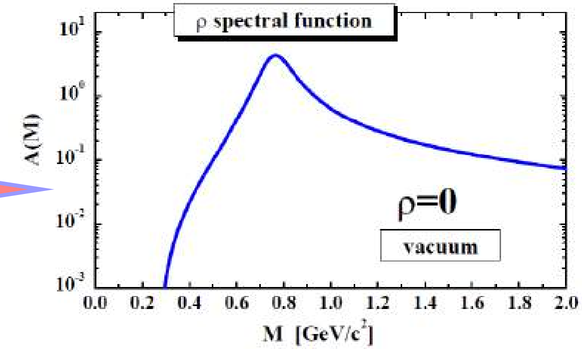
Off-shell vs. on-shell transport dynamics

In-medium: production of broad state

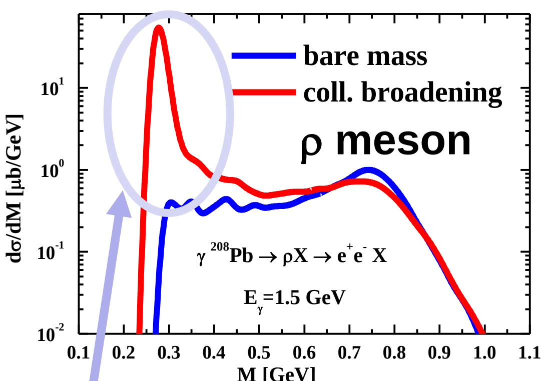




Vacuum (ρ =0) state



1999: dilepton spectra - if one propagates in-medium ρ with on-shell BUU:

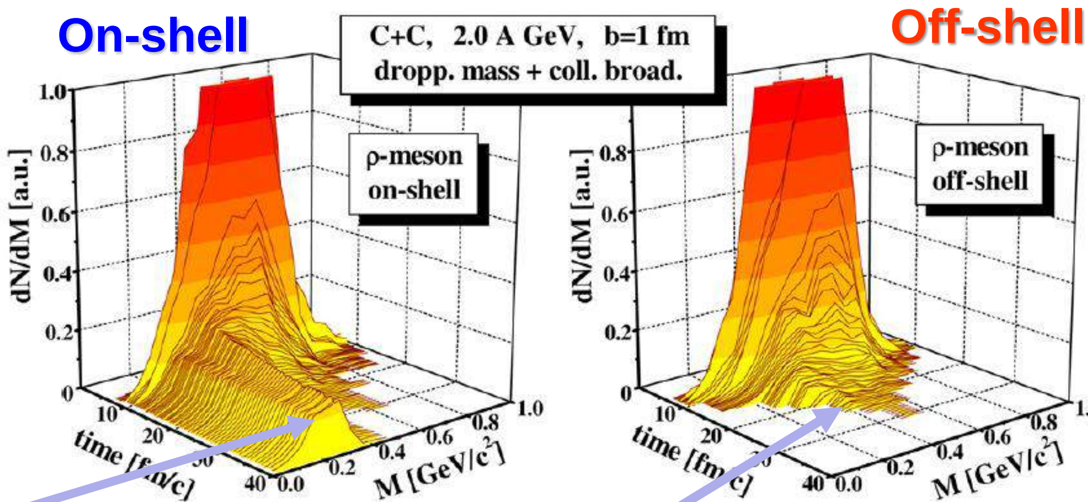


On-shell BUU:

low mass ρ and ω mesons live forever (and shine ‚fake' dileptons)!

(e)GiBUU: M. Effenberger et al, PRC60 (1999) 027601

Mass distribution of ρ mesons vs time



EB & Cassing, NPA 807 (2008) 214

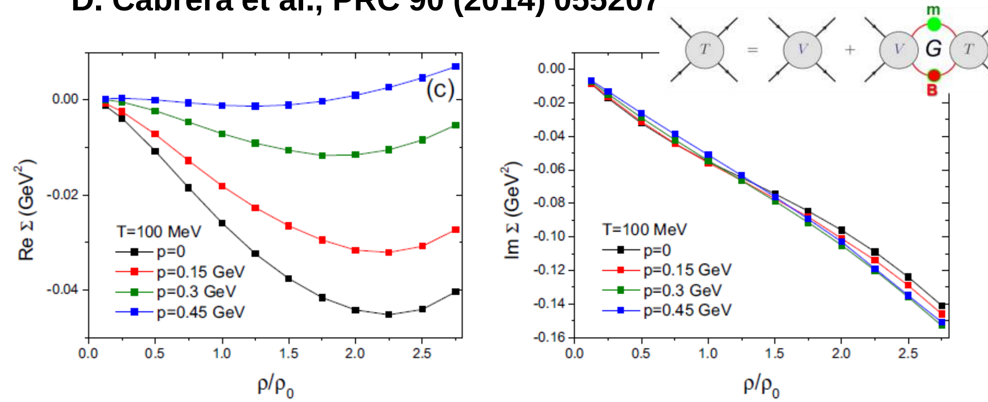
The off-shell spectral function comes to the vacuum shape dynamically by propagation through the medium!

Off-shell dynamics for antikaons at SIS energies

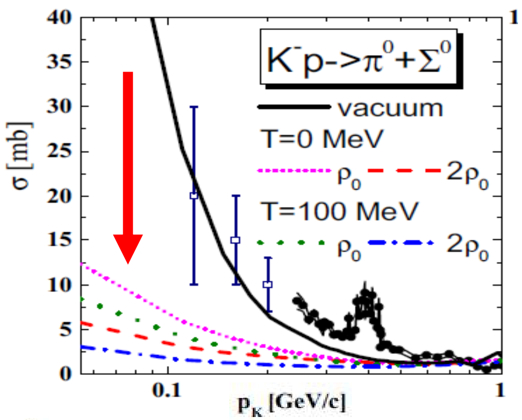
Spectral function of K^- within the G-matrix approach:

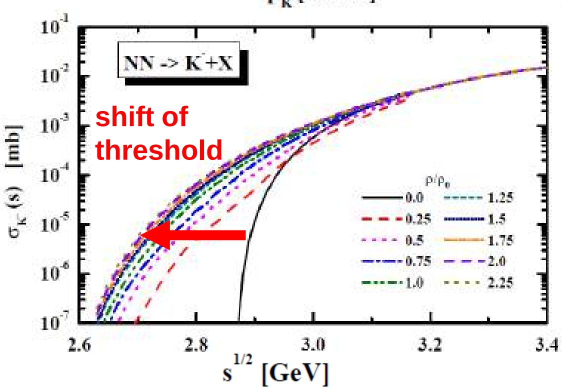
$$S_{\bar{K}}(k_0, \vec{k}; T) = -\frac{1}{\pi} \frac{\mathrm{Im}\, \Sigma_{\bar{K}}(k_0, \vec{k}; T)}{\left| k_0^2 - \vec{k}^{\,2} - m_{\bar{K}}^2 - \Sigma_{\bar{K}}(k_0, \vec{k}; T) \right|^2}.$$

D. Cabrera et al., PRC 90 (2014) 055207

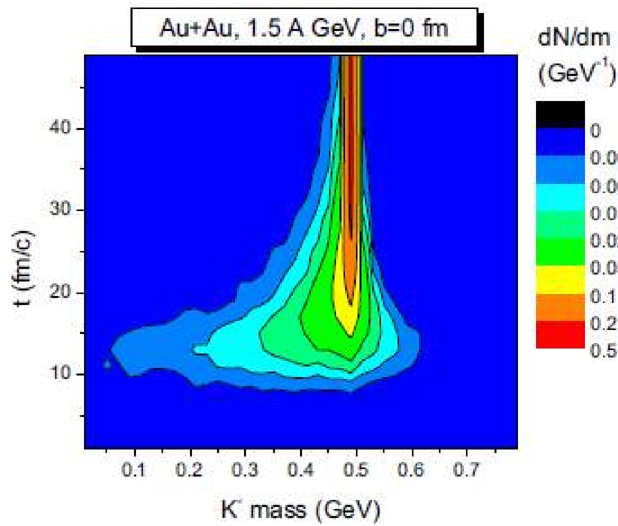


In-medium cross sections for K^- production and absorption are strongly modified in the medium:

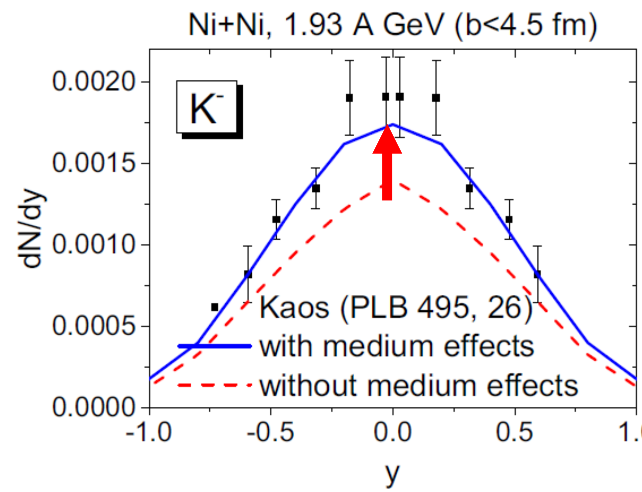




Time evolution of the K^- masses



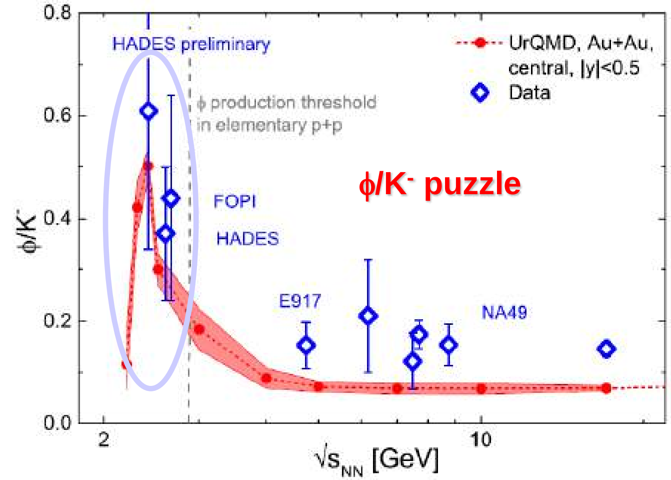
In-medium effects are mandatory for the description of experimental K^- spectra



Taesoo Song et al., PRC 103, 044901 (2021)

In-medium properties of ϕ mesons

Experiment:
strong enhancement of ϕ/K^- ratio at low $\sqrt{s}$



UrQMD, SMASH: ϕ/K^- ratio is qualitatively reproduced due to the multi-step processes for heavy baryonic resonance production and their hypothetic decay N* to ϕ mesons

Modelling of in-medium effects in off-shell PHSD:

- **ϕ mesons:**
  - **collisional broadening of the ϕ spectral function** [D. Cabrera et al., PRC 95 (2017) 015201]
  - **+ multi-step mB and mY reactions from SU(6) chiral Lagrangian**

For S=0, I_3=1/2, i, j=

$$\eta N,\ K\Lambda,\ K\Sigma,\ \rho N,\ K\Sigma^*,\ \rho\Delta,\ K^*\Lambda,\ K^*\Sigma,\ K^*\Sigma^* \to \phi N,$$

For S=0, I_3=3/2, i, j=

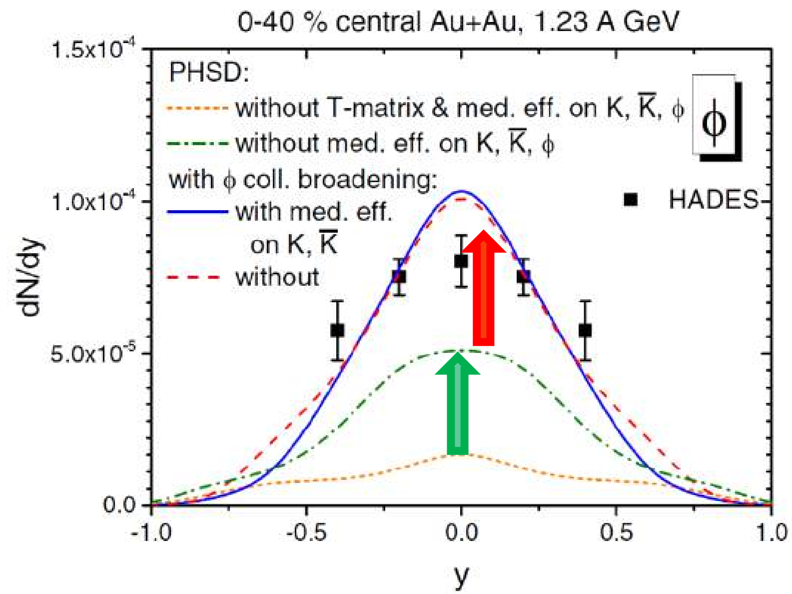
$$K\Sigma,\ \rho N,\ \eta\Delta,\ K\Sigma^*,\ \rho\Delta,\ K^*\Sigma,\ K^*\Sigma^* \to \phi\Delta$$

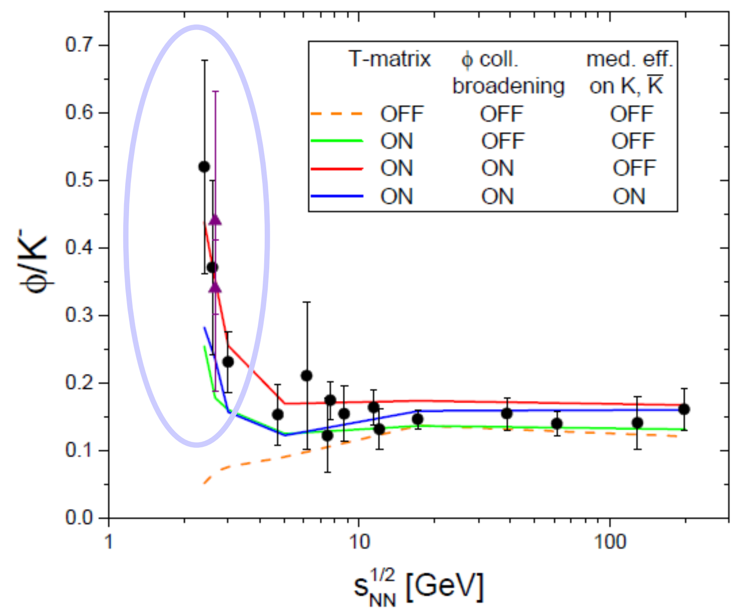
including in-medium effects for
- antikaon – improved G-matrix from SU(3) mB chiral Lagrangian [D. Cabrera et al., PRC 90 (2014) 055207]
- kaons - repulsive nuclear potential

PHSD: T. Song et al., PRC 106, 024903 (2022); PRC 103, 044901 (2021)
UrQMD: H.W. Barz et al., NPA 705 (2002) 223
SMASH: V. Steinberg et al., Phys. Rev. C 99 (2019) 064908 (2019)

ϕ/K^- ratio

T. Song et al., PRC 106, 24903 (2022)





Orange: without T-matrix, without coll. broadening ➔ underestimate the ratio at low energies

Green: with T-matrix, but without coll. broadening ➔ enhance the ratio

Red: with T-matrix + coll. broadening but without med. eff. on K, Kbar ➔ enhance the ratio

Blue: all included, i.e. with T-matrix + coll. broadening + med. eff. on K, Kbar ➔ suppress the ratio due to the too strong enhanced K^- production at low energy (compared to the HADES data)

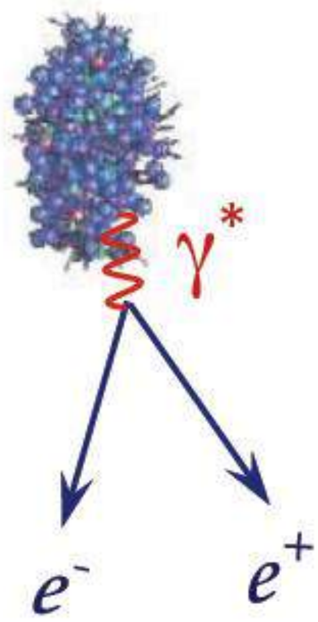
Can be clarified by CBM:

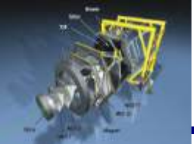
The "enhanced" ϕ multiplicity and ϕ/K^- ratio close to threshold can be understood:

PHSD: by incorporation of in-medium effects + novel mB production channels

UrQMD, SMASH: by assuming the hypothetic decay N* to ϕ mesons

Electromagnetic probes of the strongly interaction matter: dileptons

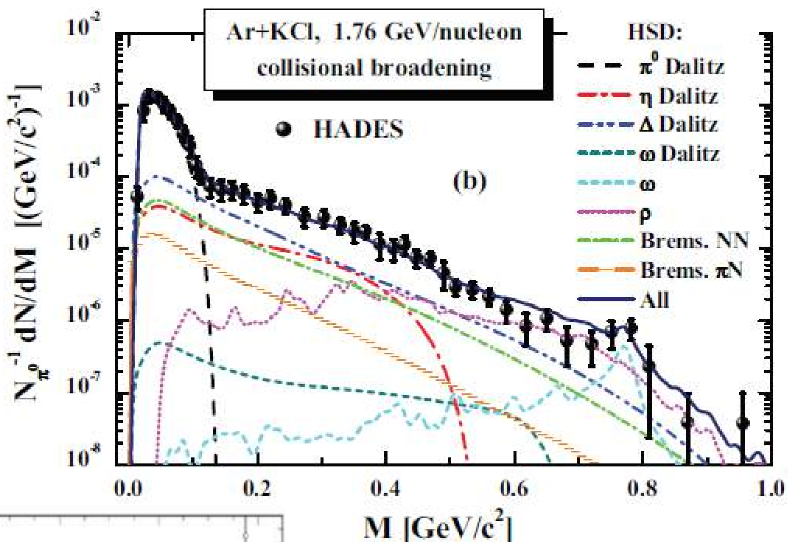


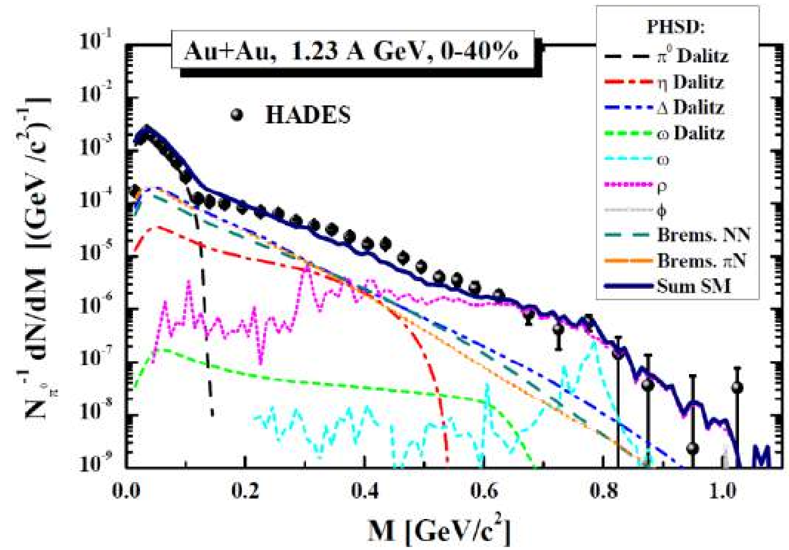


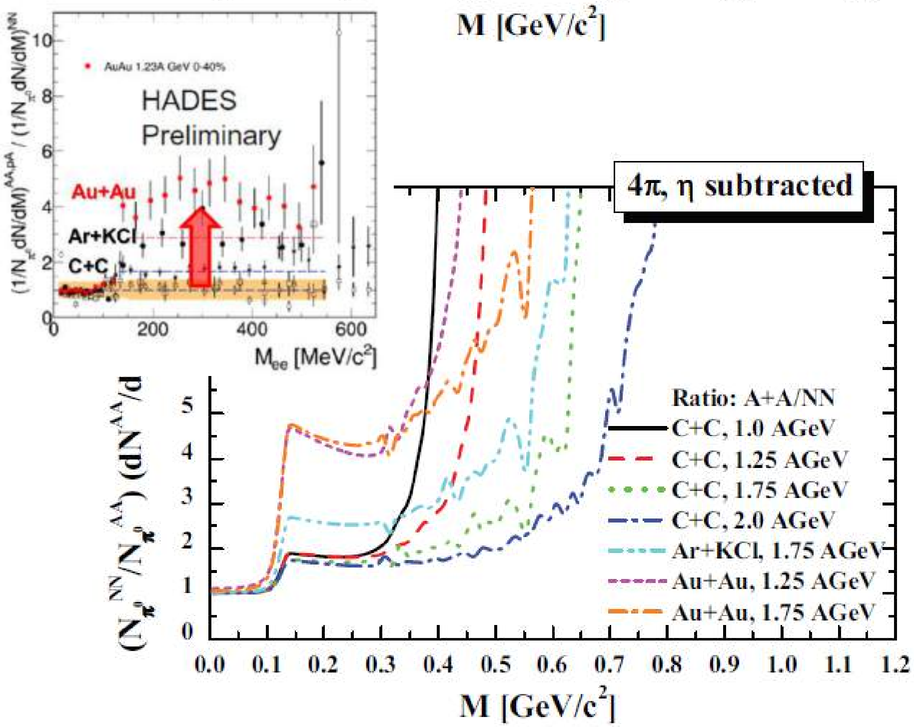
Dileptons at SIS energies - HADES

E. B., J. Aichelin, M. Thomere, S. Vogel, M. Bleicher, PRC 87 (2013) 064907

I. Schmidt, E.B., M. Gumberidze,R. Holzmann, PRD 104 (2021), 015008







❑ **Strong in-medium enhancement** of dilepton yield in Au+Au vs. NN

❑ **Increases with the system size:**

1) **multiple Δ regeneration** – dilepton emission from intermediate Δ's which are part of the reaction cycles Δ→πN; πN →Δ and NN→NΔ; NΔ→NN

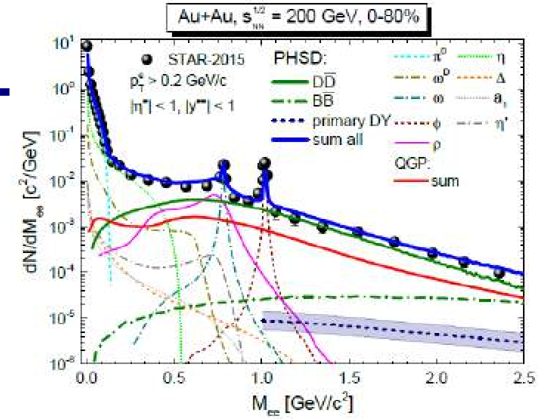
2) **pN bremsstrahlung** which scales with N_{bin} and not with N_{part} , i.e. pions

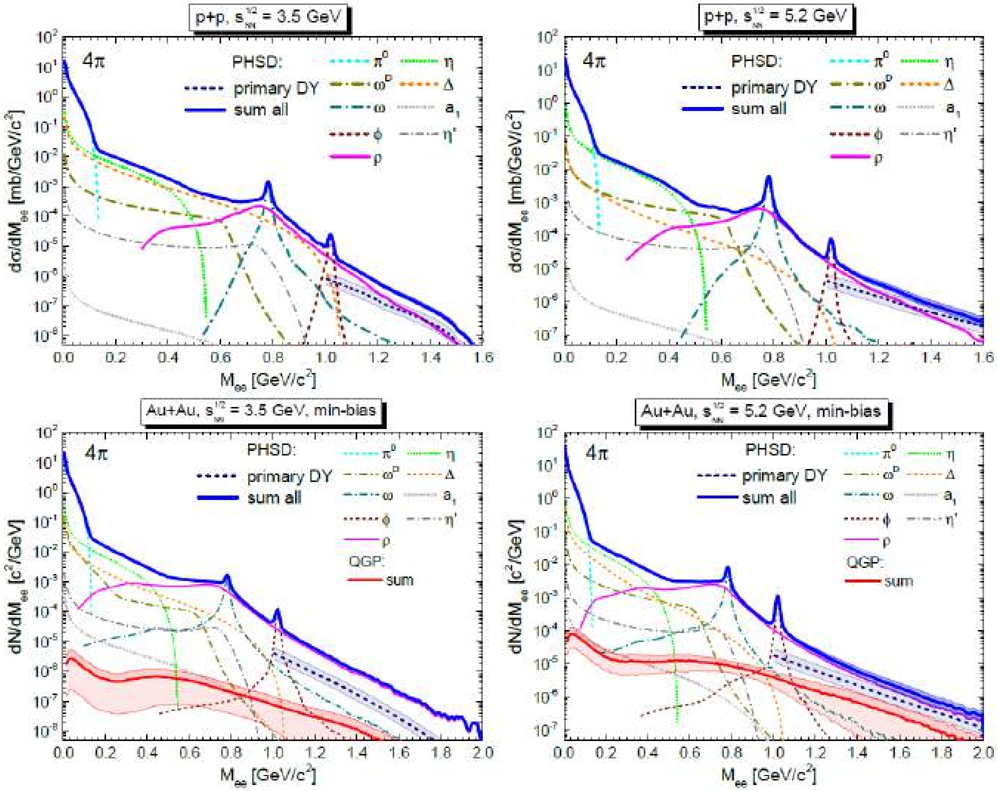
3) **Collisional broadening** of ρ,ω,ϕ mesons

Dileptons: predictions for CBM

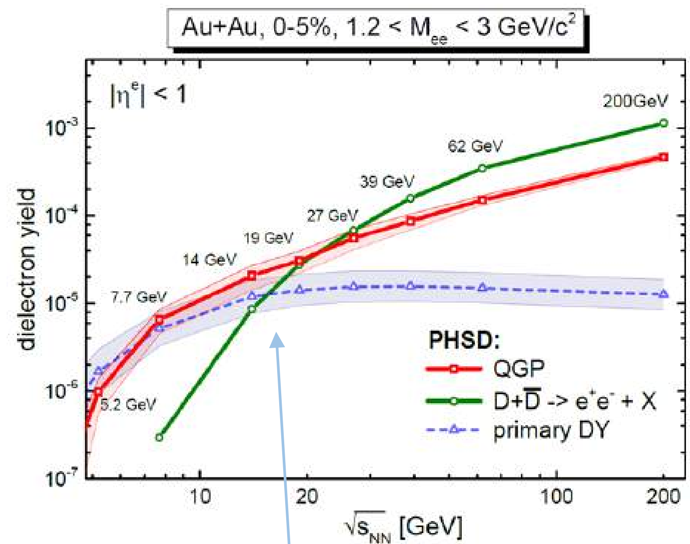
PHSD dilepton spectra including a collisional broadening of the vector meson spectral functions + primary DY + QGP + correlated charm

$q\bar{q} \to e^+e^-$
$q\bar{q} \to g e^+e^-$
$gq(\bar{q}) \to q(\bar{q}) e^+e^-$





Excitation function of dilepton yield integrated for 1.2<M<3GeV



- ❑ **Dileptons from QGP overshine charm dileptons with decreasing beam energy**
- ❑ **Primary DY could be “subtracted” from AA dilepton spectra using pp data**

➔ **Good perspectives for CBM!**

Adrian W. R. Jorge & Taesoo Song, in progress

Cf. T. Song et al., Phys. Rev. C97 (2018), 064907

QMD dynamics, cluster production

PHQMD:
J. Aichelin et al., PRC 101 (2020) 044905;
S. Gläßel et al., PRC 105 (2022) 1;
V. Kireyeu et al., PRC 105 (2022) 044909;
G. Coci et al., PRC 108 (2023) 1, 014902;
V. Kireyeu et al., arXiv:2411.04969

Cluster recognition: Minimum Spanning Tree (MST)

R. K. Puri, J. Aichelin, J.Comp. Phys. 162 (2000) 245-266

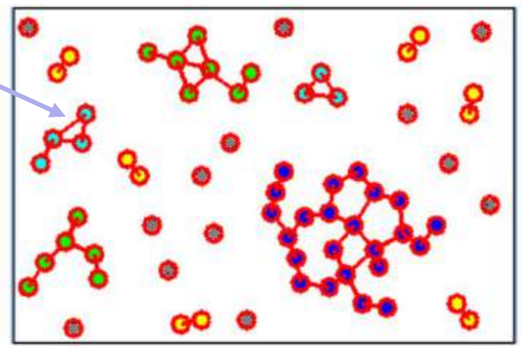
The **Minimum Spanning Tree** (MST) is a **cluster recognition** method applicable for the (asymptotic) **final states** where coordinate space correlations may only survive for bound states.

The MST algorithm searches for **accumulations of particles in coordinate space:**

1. Two particles are **'bound'** if their **distance in the cluster rest frame** fulfills

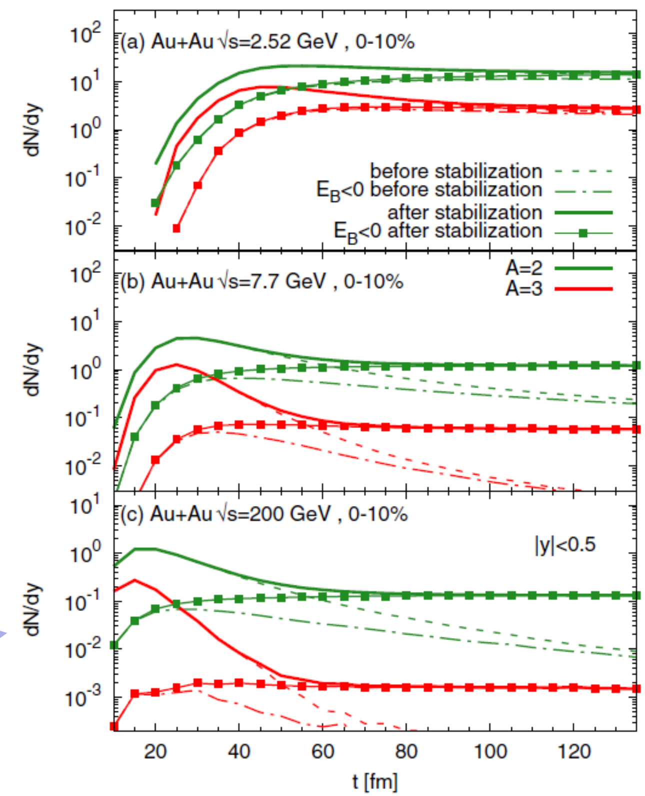
$$|\vec{r_i} - \vec{r_j}| \leq 4 \text{ fm} \quad \text{(range of NN potential)}$$

2. Particle is **bound to a cluster** if it **binds with at least one particle** of the cluster



Advanced MST (aMST)

- MST + extra condition: $E_B<0$ negative binding energy for identified clusters
- Stabilization procedure – to correct artifacts of the semi-classical QMD: recombine the final "lost" nucleons back into clusters if they left the cluster without rescattering



G. Coci et al., Phys.Rev.*C* 108 (2023) 014902

Kinetic mechanism for deutron production in HICs

G. Coci et al., PRC 108 (2023) 014902

"Kinetic mechanism"

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

Transition rate for 3→2 reactions:

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

$$P_{3,2}(\sqrt{s}) = F_{spin} F_{iso} P_{2,3}(\sqrt{s}) \frac{E_1^f E_2^f}{2E_3 E_4 E_5} \frac{R_2(\sqrt{s}, m_1, m_2)}{R_3(\sqrt{s}, m_3, m_4, m_5)} \frac{1}{\Delta V_{cell}}$$

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

Energy and momentum of final particles

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

W. Cassing, NPA 700 (2002) 618

➔ solved by **stochastic method**

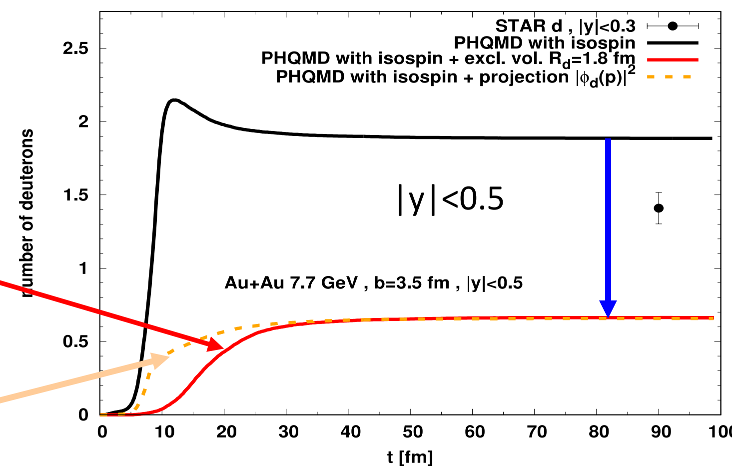
\+ inclusion of **all possible isospin channels** which enhance d production

\+ accounting of **quantum properties of d**, modelled by:

1) the **finite-size excluded volume effect** in coordinate space

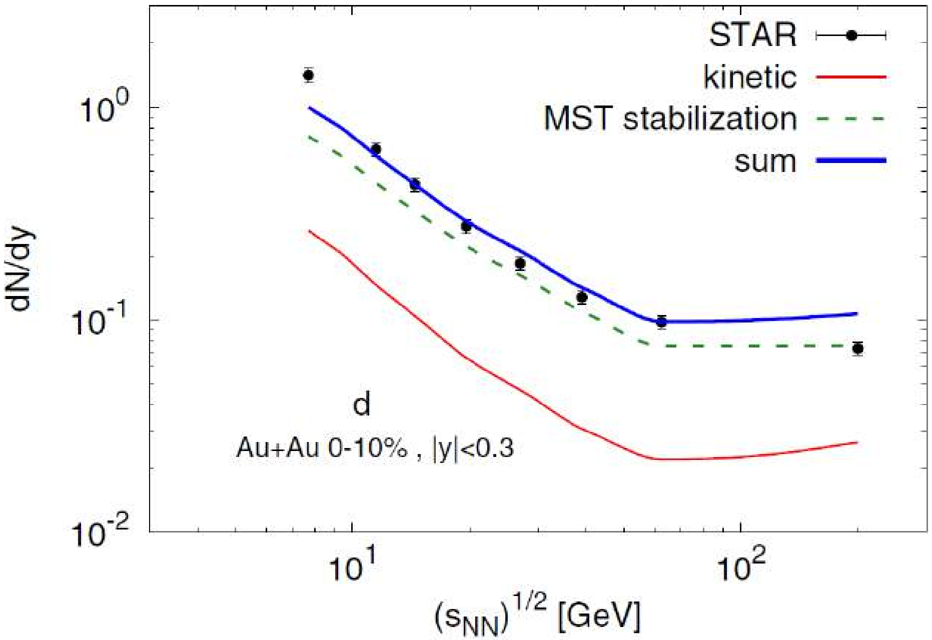
$$|\vec{r}(i)^* - \vec{r}(d)^*| < R_d$$

2) the **momentum correlations of p and n inside d** by and projection of relative momentum of p+n pair on d wave-function in momentum space $|\phi_d(p)|^2$ which lead to a **strong reduction** of d production

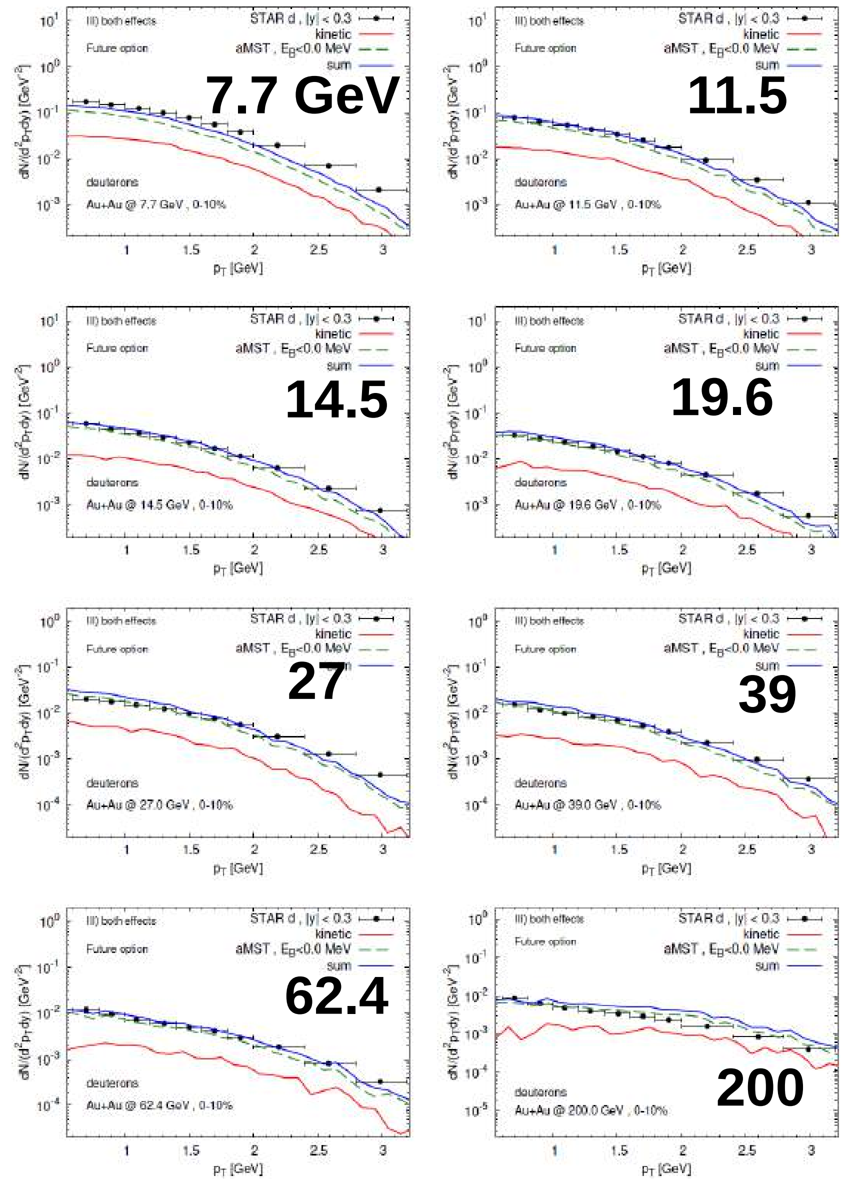


Kinetic vs. potential deuteron production

Excitation function dN/dy of deuterons at midrapidity



p_T – spectra (BES RHIC)



- PHQMD provides a good description of STAR data
- Functional forms of y- and p_T-spectra are slightly different for kinetic and potential deuterons
- **The potential mechanism is dominant for d production at all energies!**

G. Coci et al., Phys.Rev.*C* 108 (2023) 014902

How to learn about EoS from clusters:

➔ spectra and v_1, v_2 of light clusters
with different EoS in PHQMD:
hard, soft, momentum dependent potential

PHQMD

V. Kireyeu et al., arXiv:2411.04969
Yingjie Zhou et al., in progress

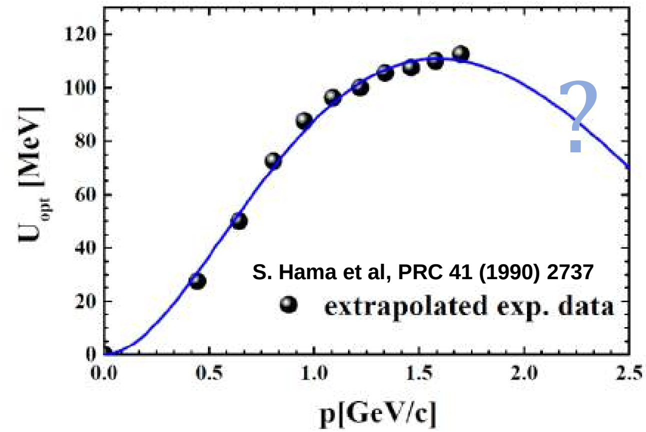
Momentum dependent potential → EoS in PHQMD

2) Momentum dependent potential :

$$V(\mathbf{r}_1, \mathbf{r}_2, \mathbf{p}_{01}, \mathbf{p}_{02}) = (a\Delta p + b\Delta p^2)\ exp[-c\sqrt{\Delta p}]\ \delta(\mathbf{r}_1 - \mathbf{r}_2)$$

$$\Delta p = \sqrt{(\mathbf{p}_{01} - \mathbf{p}_{02})^2}$$

Parameters a, b, c are fitted to the "optical" potential (Schrödinger equivalent potential U_{SEP}) extracted from elastic scattering data in pA: $U_{SEQ}(p) = \frac{\int^{p_F} V(\mathbf{p} - \mathbf{p}_1) dp_1^3}{\frac{4}{3}\pi p_F^3}$



- **In infinite matter a potential corresponds to an EoS:**

$$E/A(\rho) = \frac{3}{5}E_F + V_{Skyrme\ stat}(\rho) + V_{mom}(\rho)$$

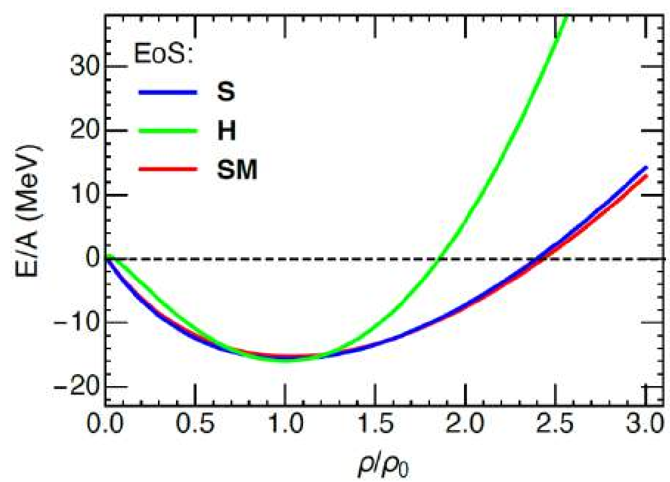
$$V_{Skyrme} = \alpha\frac{\rho}{\rho_0} + \beta\frac{\rho}{\rho_0}^{\gamma}$$

compression modulus K of nuclear matter:

$$K = -V\frac{dP}{dV} = 9\rho^2\frac{\partial^2(E/A(\rho))}{(\partial\rho)^2}|_{\rho=\rho_0}.$$

E.o.S.	$\alpha[MeV]$	$\beta[MeV]$	γ	K [MeV]
S	-383.5	329.5	1.15	200
H	-125.3	71.0	2.0	380
SM	-478.87	413.76	1.10	200
	a $[MeV^{-1}]$	b $[MeV^{-2}]$	c $[MeV^{-1}]$	
	236.326	-20.73	0.901	

EoS for infinite cold nuclear matter at rest

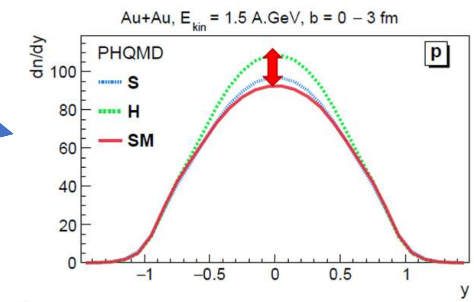


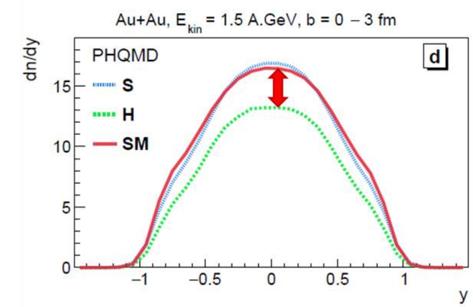
EoS dependence of flow at SIS : HADES

V. Kireyeu et al., arXiv:2411.04969

➔ **H,S,SM potentials** (forces) act differently on different **observables:**

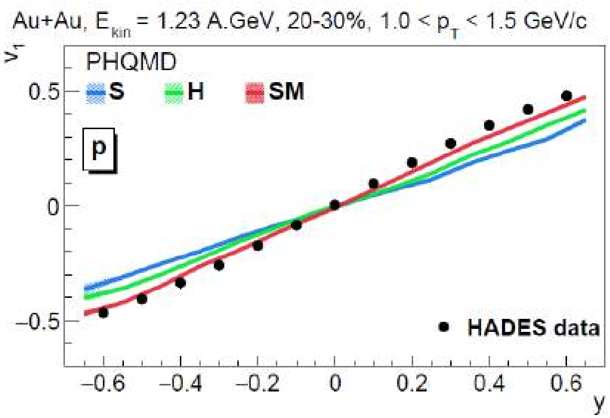
1) **yield dN/dy at midrapidity:**
   protons: SM = S < H
   deuterons: SM = S > H

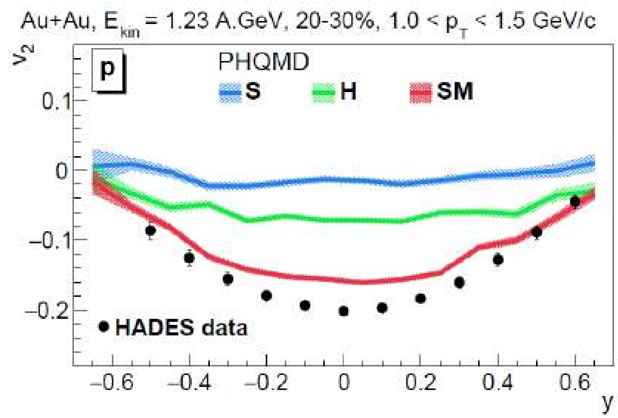


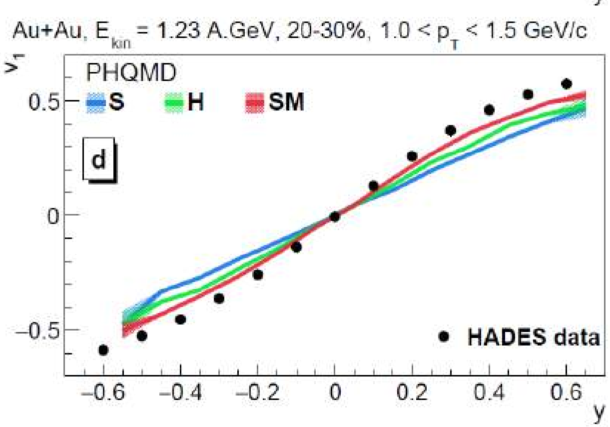


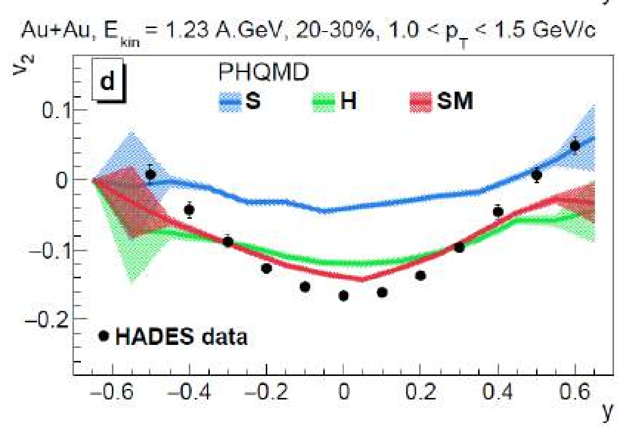
2) **directed flow v_1:**
   protons: SM $\geq$ H > S
   deuterons: SM $\geq$ H > S

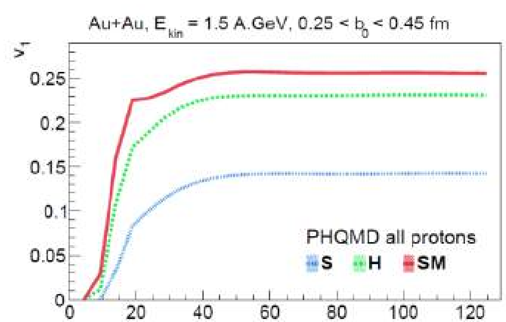
3) **eliptic flow $|v_2|$:**
   protons: SM > H > S
   deuterons: SM $\geq$ H > S







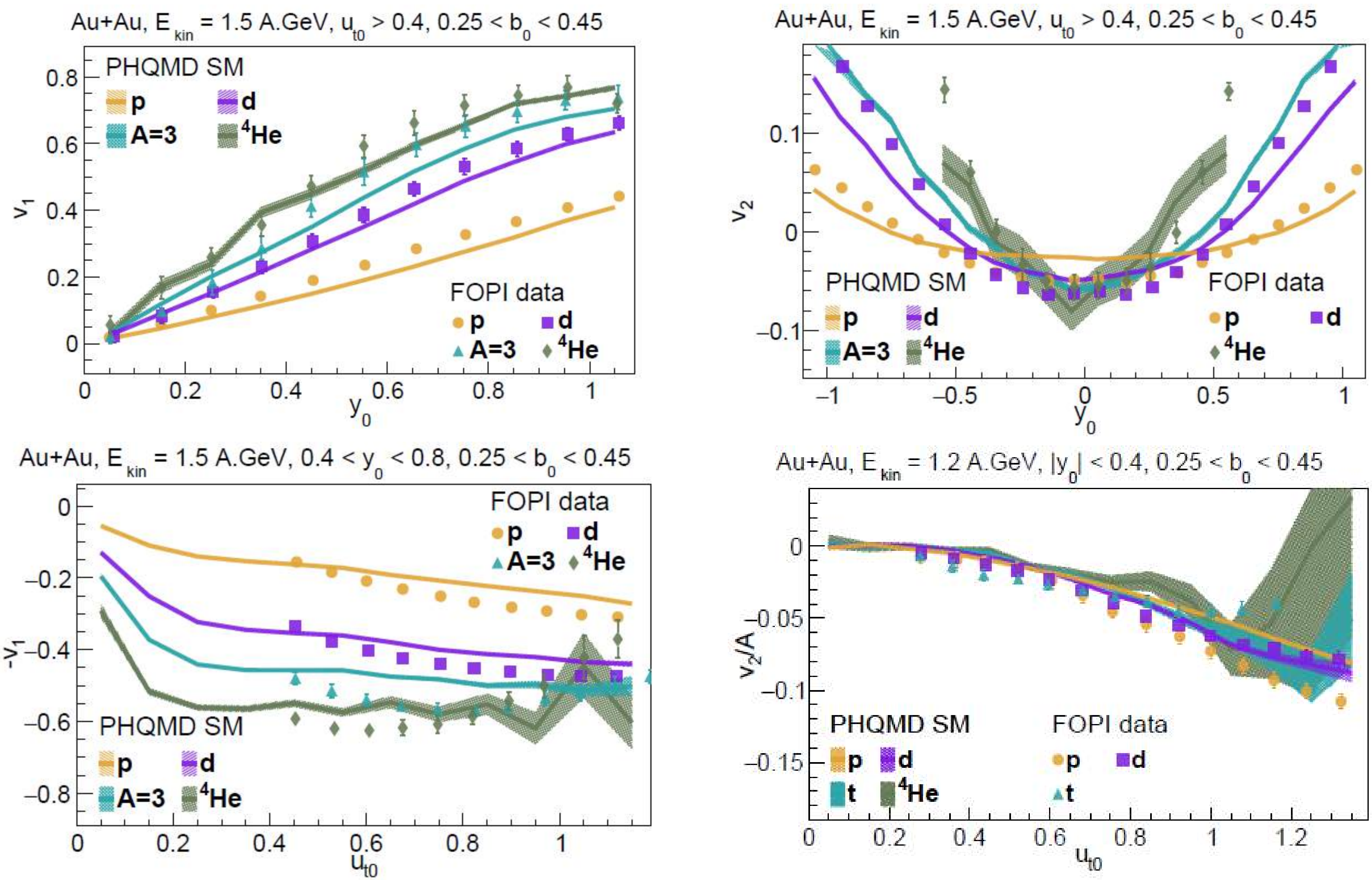




Flow v_1 with SM develops earlier than for H EoS and earlier than for S EoS

*Cf. earlier studies (80[th], 90[th], …) on p flow by J. Aichelin, W. Cassing, P. Danielewicz, C. Fuchs, C.-M. Ko, U. Mosel, H. Stoeker, ….

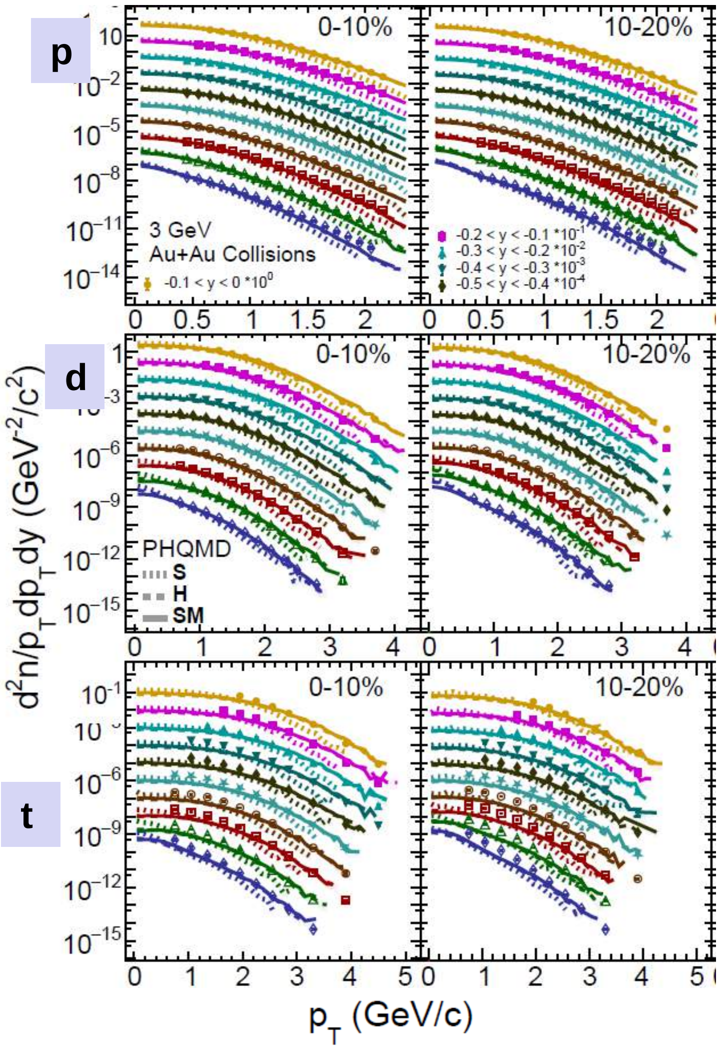
EoS dependence of flow at SIS: FOPI

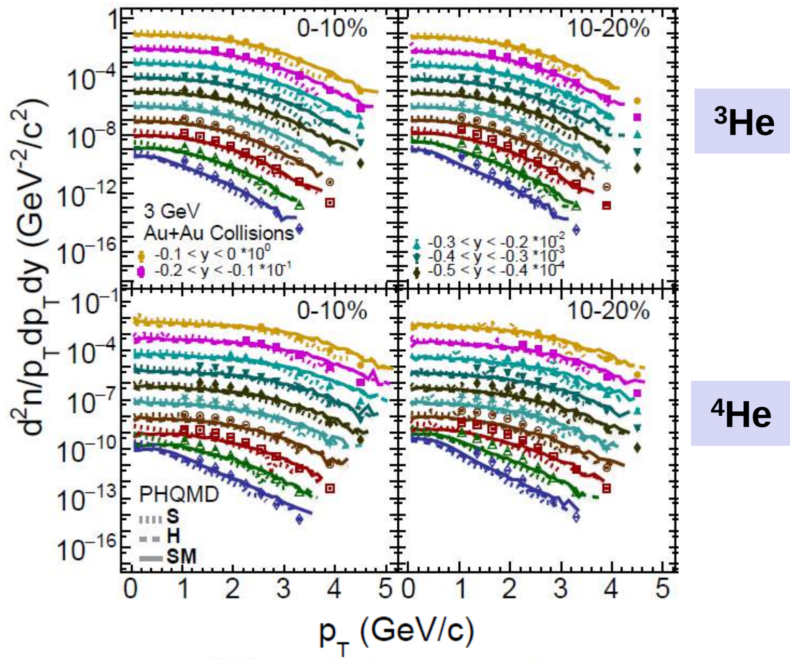


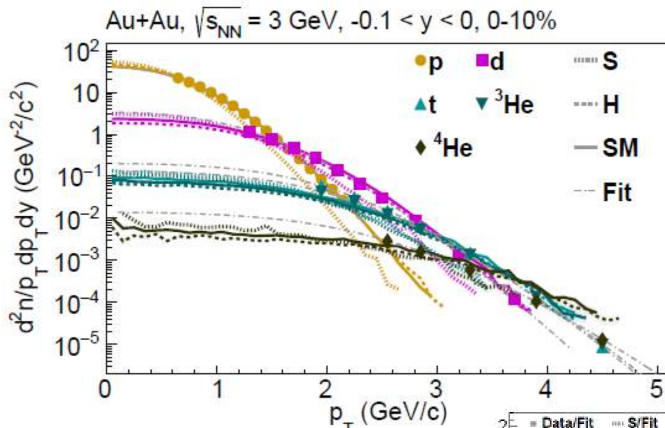
- **Strong EoS dependence** of $v_1(y)$, $v_2(y)$ and $v_2(p_T)$ of clusters
- **FOPI and HADES data favor a soft momentum dependent potential**

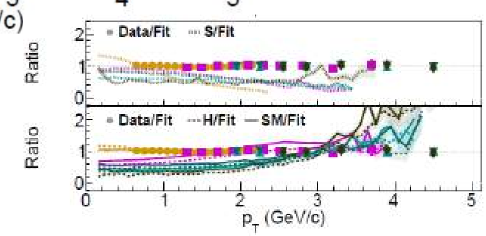
V. Kireyeu et al., arXiv:2411.04969

EoS dependence of p_T-spectra at STAR : $s^{1/2}$=3 GeV







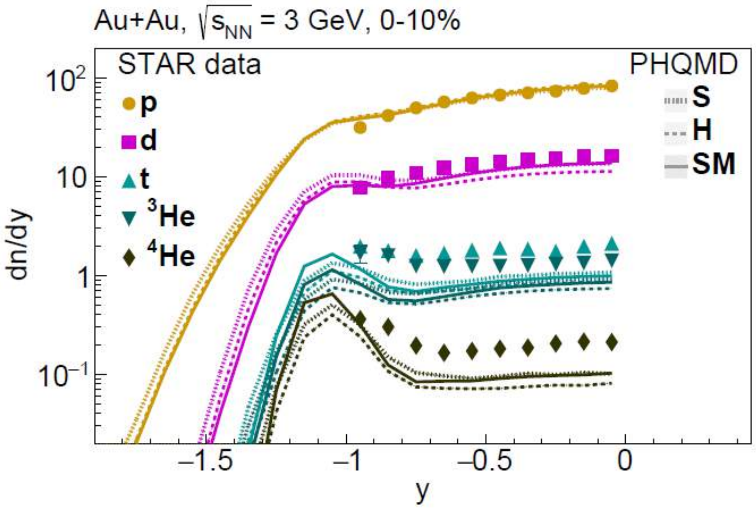


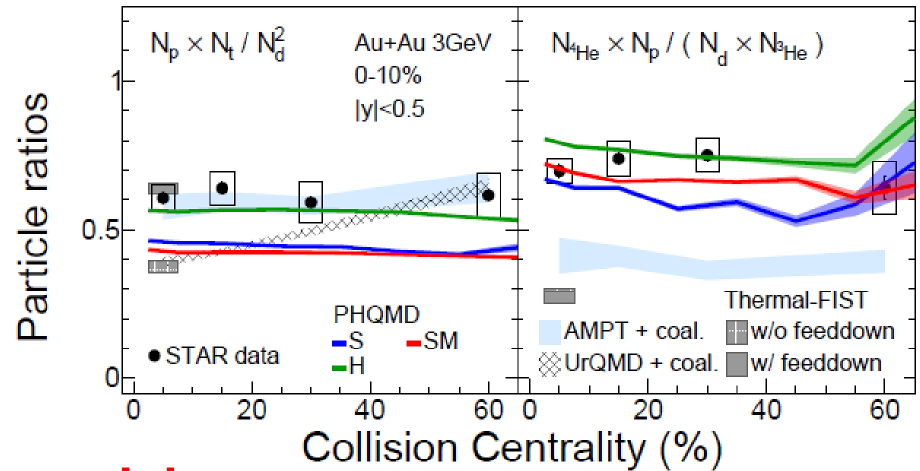
- **STAR p_T data favor a hard or soft-momentum dependent potential (H/SM)**

STAR: M. Abdulhamid et al., PRC 110 (2024) 5, 054911

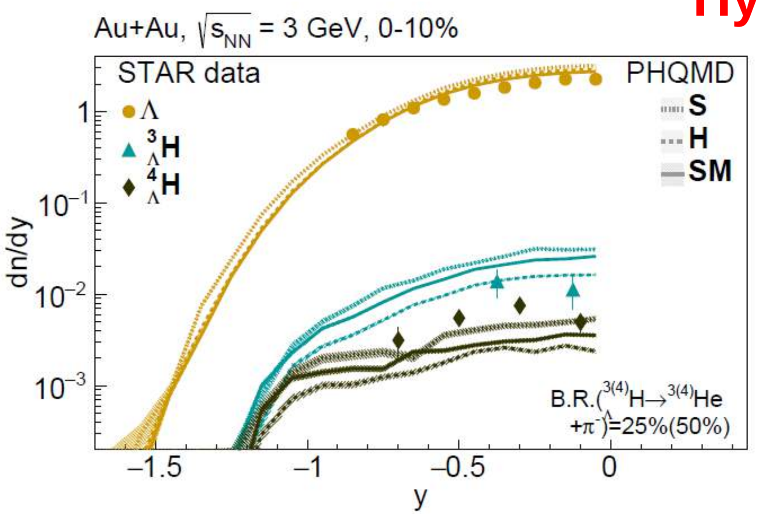
Yingjie Zhou et al., in progress

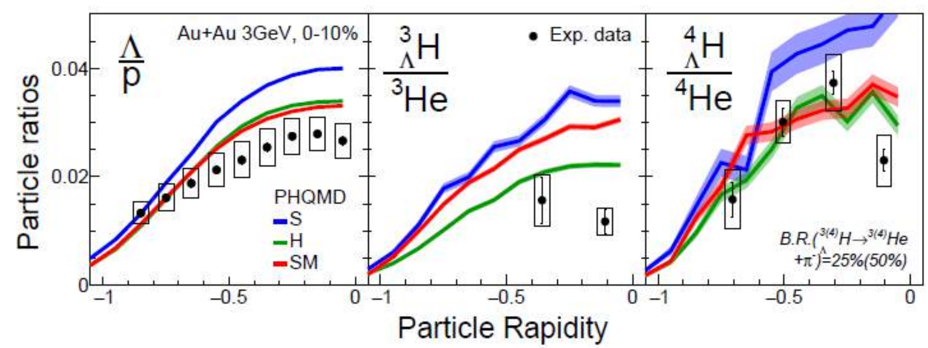
Cluster and hypernuclei at STAR : $s^{1/2}$=3 GeV





Hypernuclei:



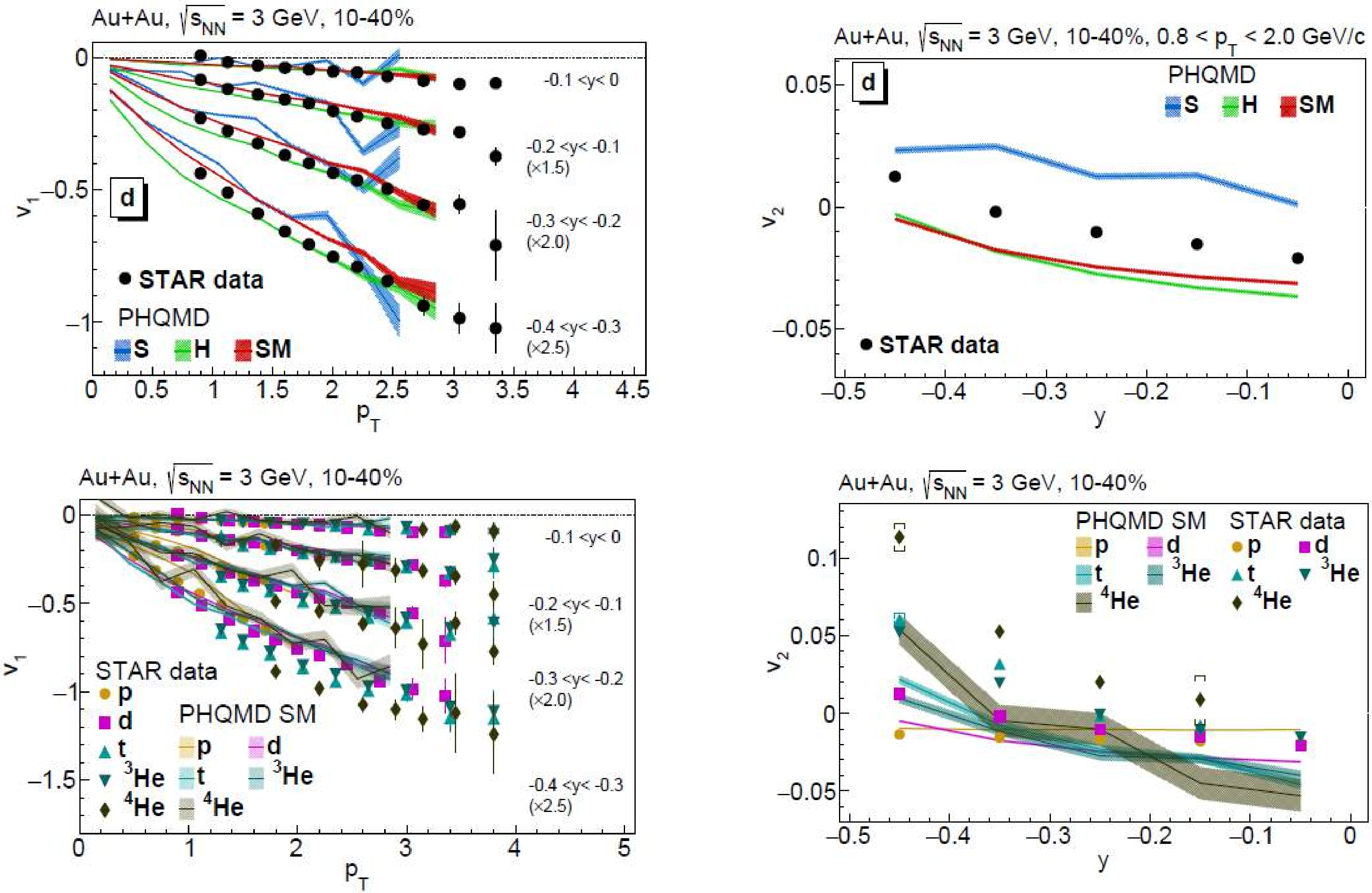


- **STAR** data on dn/dy favor a hard or soft-momentum dependent potential (H/SM)

Yingjie Zhou et al., in progress

STAR: M. Abdulhamid et al., Phys.Rev.C 110 (2024) 5, 054911

EoS dependence of flow at STAR : $s^{1/2}$=3 GeV



- **STAR** data on v_1, v_2 favor a hard or soft-momentum dependent potential (H/SM)

Yingjie Zhou et al., in progress

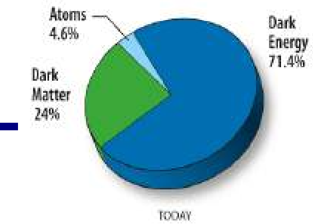
STAR: M. S. Abdallah et al., Phys. Lett. B 827, 136941 (2022), 2112.04066


Kazimir Malevich, “Black Square” (1915)

Physics beyond the standard model (SM): search for dark matter with dileptons

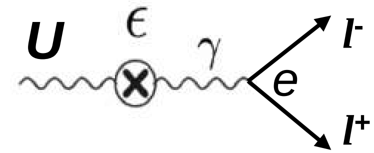
DM ‚candidate‘

Light dark photons searches with p+p, p+A



The 'vector' portal : existence of a U(1)-U(1)′ gauge symmetry group mixing

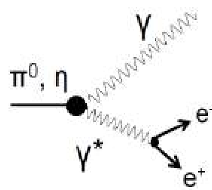
$$\mathcal{L}_{A'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}B^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu}$$



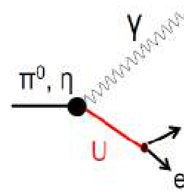
Notation for 'dark photon': A' or U- boson

B. Holdom, PL B 166, 196 (1986)
B. Batell et al., PRD 80, 095024 (2009)

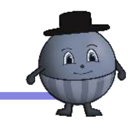
Unknown: kinetic mixing parameter ϵ and mass M_U



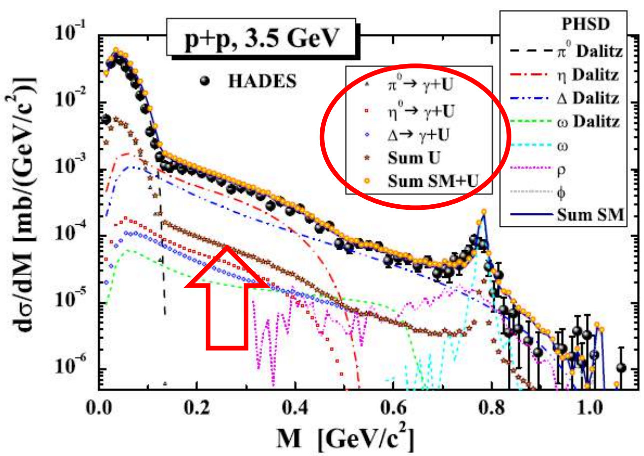
⇒ U(1)-U(1)′ kinetic mixing ⇒

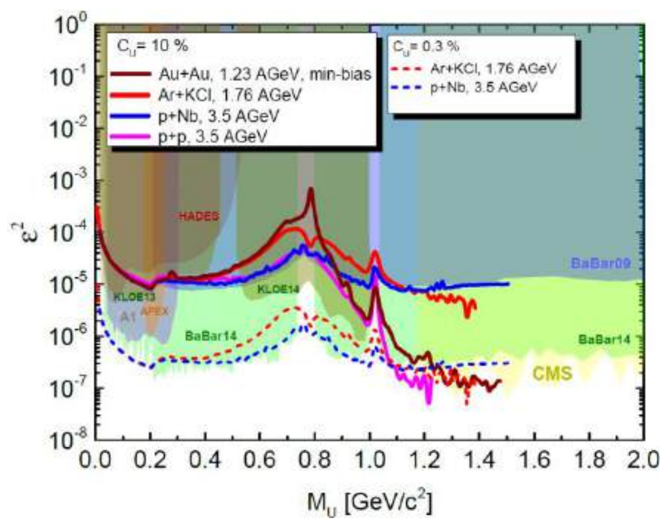


$\pi^0 \to \gamma$+U,
$\eta \to \gamma$+U, U→e^+e^-
$\Delta \to$ N+U
$K^+ \to \pi^+$ + U
V →U, …



The upper limit for the kinetic mixing parameter $\varepsilon^2(M_U)$ of light dark photons extracted from the PHSD dilepton spectra - with 10 and 3% allowed surplus of the total SM yield by an additional DM yield at given M:





HADES: G. Agakishiev et al., Phys. Lett. B 731, 265 (2014)
PHSD: I. Schmidt, E.B., M. Gumberidze, R. Holzmann, Phys.Rev.D 104 (2021) 015008

PHSD: Adrian W. Romero Jorge, 2409.20141, 2412.02536

Summary

- **FAIR is an excellent facility to study the properties of the strongly interacting matter at high density and finite temperature**

- **Transport theory is the general basis for an understanding of nuclear dynamics on a microscopic level**

Perspectives with CBM:

- **study of EoS by clusters,**
- **properties of QGP at high μ_B (in small volume – "droplets") by dileptons,**
- **possible 1st order phase transition,**
- **chiral symmetry restorations by dileptons and strangeness,**
- **subthreshold charm production,**
- **elementary reactions p+p, π+p and p+A**

- **search for dark matter (dark photons, axions) via dileptons (and missing tracks – using AI ?)**

PHSD/PHQMD is prepared for that!

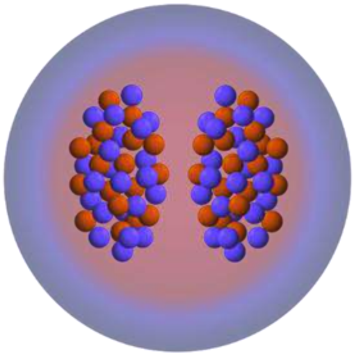
Outlook (challenges for theory):

- More precise EoS at large μ_B
- Possible 1st order phase transition at large μ_B?!

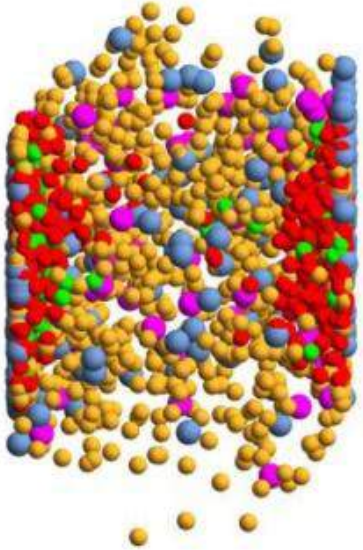
Thank you for your attention!

Thanks to the PHSD/PHQMD team!

Backup slides:



Development of the microscopic transport theory:
from BUU to Kadanoff-Baym dynamics



History: semi-classical BUU equation

Ludwig Boltzmann

Boltzmann-Uehling-Uhlenbeck equation (non-relativistic formulation)
- propagation of particles in the self-generated Hartree-Fock mean-field potential *U(r,t)* with an on-shell collision term:

$$\frac{\partial}{\partial t} f(\vec{r},\vec{p},t) + \frac{\vec{p}}{m}\vec{\nabla}_{\vec{r}}\; f(\vec{r},\vec{p},t) - \vec{\nabla}_{\vec{r}} U(\vec{r},t)\,\vec{\nabla}_{\vec{p}} f(\vec{r},\vec{p},t) = \left(\frac{\partial f}{\partial t}\right)_{coll}$$

collision term: elastic and inelastic reactions

$f(\vec{r},\vec{p},t)$ **is the single particle phase-space distribution function**
- probability to find the particle at position *r* with momentum *p* at time *t*

- **self-generated Hartree-Fock mean-field potential:**

$$U(\vec{r},t) = \frac{1}{(2\pi\hbar)^3}\sum_{\beta_{occ}}\int d^3r'\, d^3p\;\; V(\vec{r}-\vec{r}\,',t)\;\, f(\vec{r}\,',\vec{p},t) \;+\; (Fock\;\; term)$$

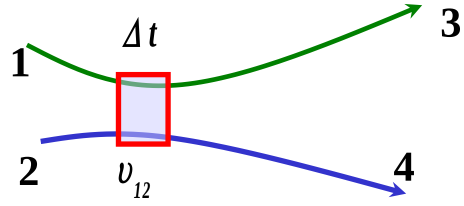
- **Collision term for 1+2→3+4 (let's consider fermions) :**

$$I_{coll} = \frac{4}{(2\pi)^3}\int d^3p_2\, d^3p_3 \int d\Omega\;\; |\upsilon_{12}|\,\delta^3(\vec{p}_1+\vec{p}_2-\vec{p}_3-\vec{p}_4)\cdot\frac{d\sigma}{d\Omega}(1+2\rightarrow 3+4)\cdot P$$

Probability including Pauli blocking of fermions:

$$P = f_3 f_4 (1-f_1)(1-f_2) \;-\; f_1 f_2 (1-f_3)(1-f_4)$$

Gain term: 3+4→1+2 **Loss term: 1+2→3+4**



History: developments of relativistic transport models

Low energy HIC → **High energy HIC**

Non-relativistic semi-classical BUU

→ **Relativistic transport models**

'Numerical simulation of medium energy heavy ion reactions',
J. Aichelin and G. Bertsch, Phys.Rev.C 31 (1985) 1730-1738

'Relativistic Vlasov-Uehling-Uhlenbeck model for heavy-ion collisions'
Che-Ming Ko, Qi Li, Phys.Rev. C37 (1988) 2270

'Covariant Boltzmann-Uehling-Uhlenbeck approach for heavy-ion collisions'
Bernhard Blaettel, Volker Koch, Wolfgang Cassing, Ulrich Mosel, Phys.Rev. C38 (1988) 1767;

'Relativistic BUU approach with momentum dependent mean fields'
T. Maruyama, B. Blaettel, W. Cassing, A. Lang, U. Mosel, K. Weber, Phys.Lett. B297 (1992) 228

'The Relativistic Landau-Vlasov method in heavy ion collisions'
C. Fuchs, H.H. Wolter, Nucl.Phys. A589 (1995) 732

. . .

*** Alternative to BUU: QMD – non-covariant EoM (contrary to BUU), but not a mean-field!**

Covariant transport equation

- **Covariant relativistic on-shell BUU equation :**

  from many-body theory by connected Green functions in phase-space + mean-field limit for the propagation part (VUU)

$$\left\{ \left(\Pi_\mu - \Pi_\nu (\partial_\mu^p U_V^\nu) - m^* (\partial_\mu^p U_S^\nu)\right) \partial_x^\mu + \left(\Pi_\nu (\partial_\mu^x U_V^\nu) + m^* (\partial_\mu^x U_S^\nu)\right) \partial_p^\mu \right\} f(x,p) = I_{coll}$$

$$I_{coll} \equiv \sum_{2,3,4} \int d2\, d3\, d4\;\; [G^+G]_{1+2\rightarrow 3+4}\; \delta^4(\Pi + \Pi_2 - \Pi_3 - \Pi_4)$$

$$d2 \equiv \frac{d^3 p_2}{E_2}$$

$$\times \{ f(x,p_3)\; f(x,p_4)\,(1 - f(x,p))\,(1 - f(x,p_2))$$

$$- f(x,p)\; f(x,p_2)\,(1 - f(x,p_3))\,(1 - f(x,p_4)) \}$$

Gain term $3+4 \rightarrow 1+2$

Loss term $1+2 \rightarrow 3+4$

where $\partial_\mu^x \equiv (\partial_t, \vec{\nabla}_r)$

$m^*(x,p) = m + U_s(x,p)$ - effective mass

$\Pi_\mu(x,p) = p_\mu - U_\mu(x,p)$ - effective momentum

$U_s(x,p)$, $U_\mu(x,p)$ are scalar and vector part of particle self-energies

$\delta(\Pi_\mu \Pi^\mu - m^{*2})$ – mass-shell constraint

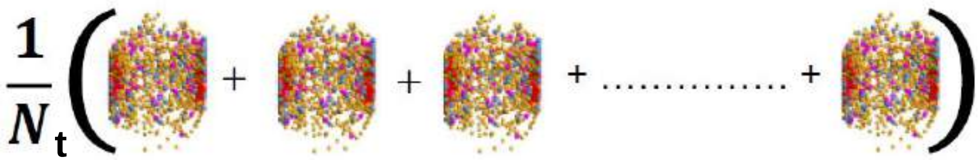
W. Ehehalt, W. Cassing, Nucl. Phys. A 602 (1996) 449

Numerical solution of BUU EoM

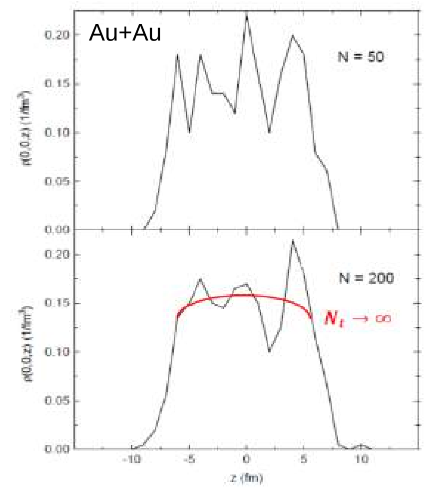
Testparticle method or method of parallel ensembles :

the 1-body phase space distribution function is described as a sum of N point-like particles (δ –functions).
In the limit of large number of parallel ensembles $N_t \to \infty$

$$f(\vec{r},\vec{p},t)=\frac{1}{N_t}\sum_{i=1}^{N\cdot N_t}\delta(\vec{r}-\vec{r}_i(t))\delta(\vec{p}-\vec{p}_i(t))$$ **is a solution of Vlasov EoM**



1 + 2 + 3 + ... + N



- **Testparticle method provides a smooth density distribution for calculation of mean-field potential for particle propagation.**
  - No exchange of particles between the parallel ensembles, particles collide only inside one ensemble

➔ **Propagation of test-particles in time following 'classical' EoM:**

$$\dot{\vec{r}}_i = \frac{d\vec{r}_i}{dt} = \frac{\vec{p}_i}{m_i}$$

$$\dot{\vec{p}}_i = \frac{d\vec{p}_i}{dt} = -\vec{\nabla}_{\vec{r}_i} U(\vec{r}_i, t)$$

Dynamical transport model: collision terms

- BUU eq. for different particles of type $i=1,\ldots n$

$$Df_i \equiv \frac{d}{dt} f_i = I_{coll}\left[f_1, f_2, ..., f_n\right]$$

Drift term=Vlasov eq. collision term

$$i: \quad Baryons: \; p, n, \Delta(1232), N(1440), N(1535), ..., \Lambda, \Sigma, \Sigma^*, \Xi, \Omega; \; \Lambda_C$$

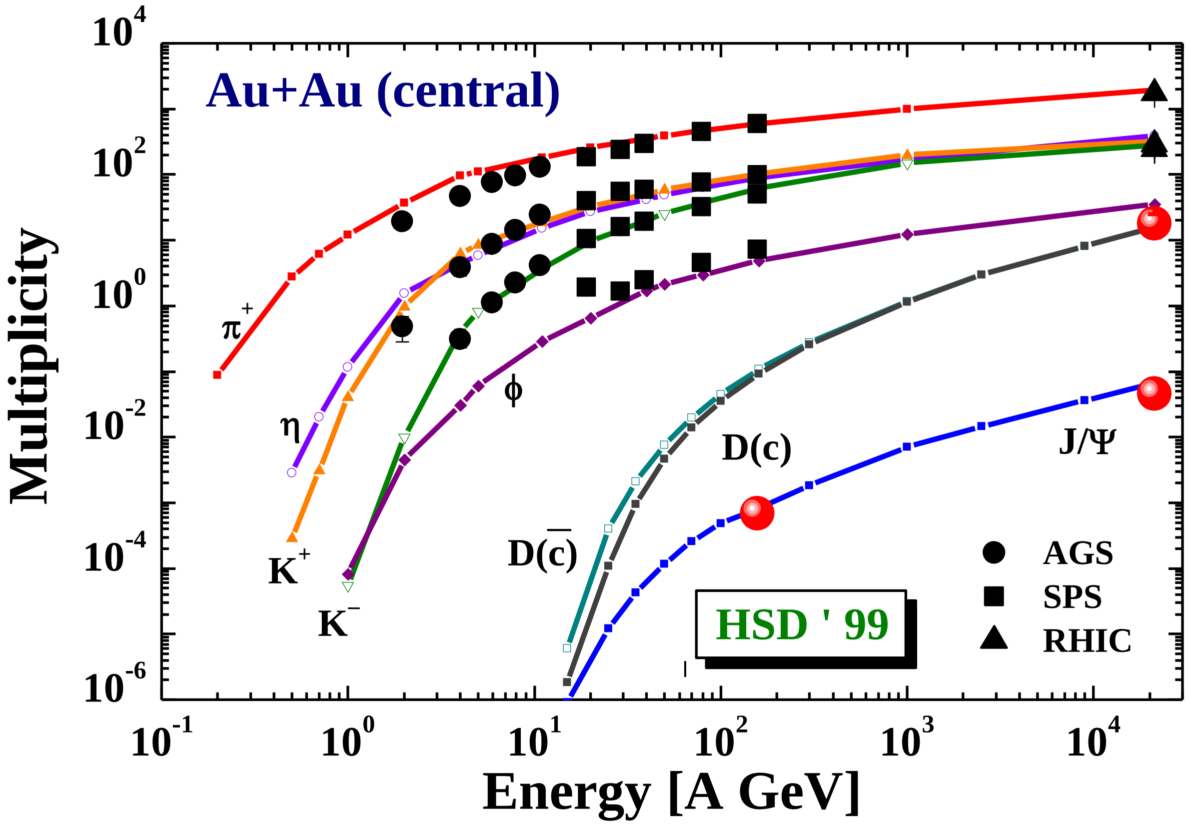
$$Mesons: \; \pi, \eta, K, \bar{K}, \rho, \omega, K^*, \eta', \phi, a_1, ..., D, \bar{D}, J/\Psi, \Psi', ...$$

➔ coupled set of BUU equations for different particles of type $i=1,\ldots n$

$$\begin{cases} Df_N = I_{coll}\left[f_N, f_\Delta, f_{N(1440)}, ..., f_\pi, f_\rho, ...\right] \\ Df_\Delta = I_{coll}\left[f_N, f_\Delta, f_{N(1440)}, ..., f_\pi, f_\rho, ...\right] \\ ... \\ Df_\pi = I_{coll}\left[f_N, f_\Delta, f_{N(1440)}, ..., f_\pi, f_\rho, ...\right] \\ ... \end{cases}$$

Microscopic transport model for heavy-ion collisions

- very good description of particle production in pp, pA, pA, AA reactions
- unique description of nuclear dynamics from low (~100 MeV) to ultrarelativistic (>20 TeV) energies



HSD predictions from 1999; data - from the new millenium

W. Cassing, E.B., Phys.Rept. 308 (1999) 65

From weakly to strongly interacting systems

Properties of matter (on hadronic and partonic levels) in heavy-ion collisions:
QGP – strongly interacting system! Degrees of freedom – dressed partons
Hadronic matter – in-medium effects – modification of hadron properties at finite T, μ_B (vector mesons, strange mesons)

Many-body theory:
Strong interaction ➔ large width = short life-time
➔ broad spectral function ➔ quantum object

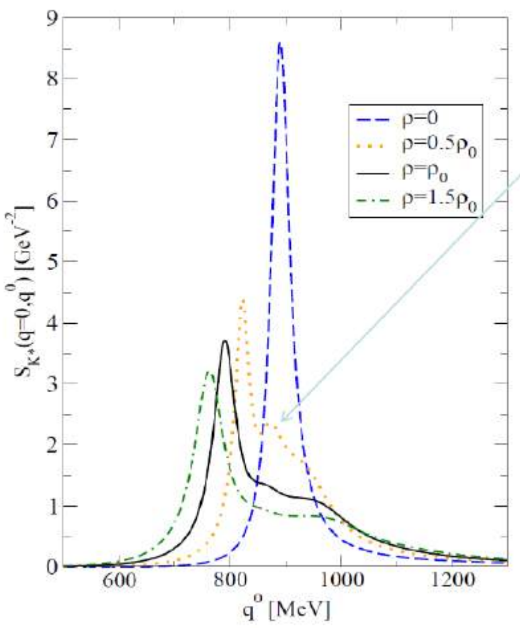
- **How to describe the dynamics of broad strongly interacting quantum states in transport theory?**

- **go beyond a semi-classical BUU**

It is doable with quantum Kadanoff-Baym equations

- **generalized transport equations based on Kadanoff-Baym dynamics**

Kbar* spectral function



$\Lambda(1783)N^{-1}$ and $\Sigma(1830)N^{-1}$ exitations

Barcelona / Valencia group

Dynamical description of strongly interacting systems

- **Quantum field theory ➔**

Kadanoff-Baym dynamics for resummed single-particle Green functions $S^<$

(1962)

$$\hat{S}^{-1}_{0x}\, S^<_{xy} = \Sigma^{ret}_{xz} \odot S^<_{zy} + \Sigma^<_{xz} \odot S^{adv}_{zy}$$

Integration over the intermediate spacetime

Green functions $S^<$ / self-energies Σ :

$$iS^<_{xy} = \eta \langle \{ \Phi^+(y)\Phi(x) \} \rangle$$

$$iS^>_{xy} = \langle \{ \Phi(y)\Phi^+(x) \} \rangle$$

$$iS^c_{xy} = \langle T^c \{ \Phi(x)\Phi^+(y) \} \rangle \quad - causal$$

$$iS^a_{xy} = \langle T^a \{ \Phi(x)\Phi^+(y) \} \rangle \quad - anticausal$$

$$S^{ret}_{xy} = S^c_{xy} - S^<_{xy} = S^>_{xy} - S^a_{xy} \quad - retarded$$

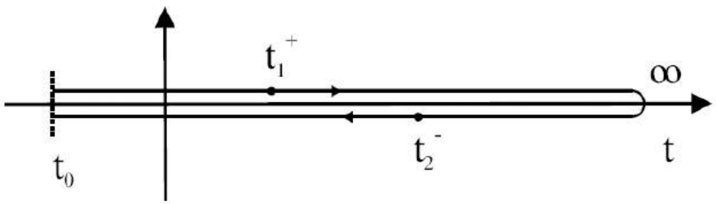
$$S^{adv}_{xy} = S^c_{xy} - S^>_{xy} = S^<_{xy} - S^a_{xy} \quad - advanced$$

$$\hat{S}^{-1}_{0x} \equiv -(\partial^\mu_x \partial^x_\mu + M^2_0)$$

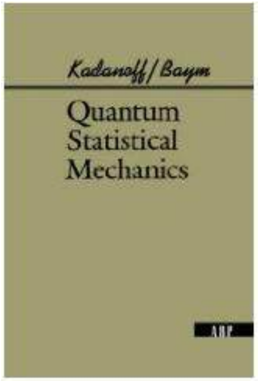
$$\eta = \pm 1 (bosons\ /\ fermions)$$

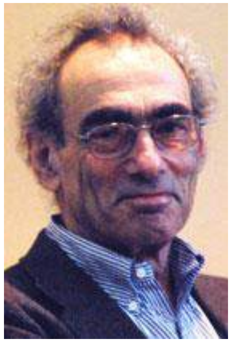
$$T^a(T^c) - (anti-)time-ordering\ operator$$

Real-time (Keldysh-) Contour



Leo Kadanoff





Gordon Baym

1st application for spacially homodeneous system with deformed Fermi sphere:
P. Danielewicz, Ann. Phys. 152, 305 (1984); … H.S. Köhler, Phys. Rev. 51, 3232 (1995); …

From Kadanoff-Baym equations to generalized transport equations

After the first-order gradient expansion of the Wigner transformed Kadanoff-Baym equations and separation into the real and imaginary parts one gets:

Generalized transport equations (GTE):

drift term | Vlasov term | backflow term | collision term = ‚gain' - ‚loss' term

$$\diamond\{P^2 - M_0^2 - Re\Sigma^{ret}_{XP}\}\{S^<_{XP}\} - \diamond\{\Sigma^<_{XP}\}\{ReS^{ret}_{XP}\} = \frac{i}{2}[\Sigma^>_{XP}S^<_{XP} - \Sigma^<_{XP}S^>_{XP}]$$

Backflow term incorporates the off-shell behavior in the particle propagation

! vanishes in the quasiparticle limit $A_{XP} \rightarrow \delta(p^2-M^2)$

- Propagation of the Green's function $iS^<_{XP}=A_{XP}N_{XP}$, which carries information not only on the number of particles (N_{XP}), but also on their properties, interactions and correlations (via A_{XP})

W. Botermans, R. Malfliet, Phys. Rep. 198 (1990) 115

- Spectral function:

$$A_{XP} = \frac{\Gamma_{XP}}{(P^2 - M_0^2 - Re\Sigma^{ret}_{XP})^2 + \Gamma^2_{XP}/4}$$

Reaction rate of particle (at space-time position X):

$$\Gamma_{XP} = -Im\,\Sigma^{ret}_{XP} = 2\,p_0\Gamma$$ where Γ is a ‚width' of spectral function

4-dimentional generalizaton of the Poisson-bracket:

$$\diamond\{F_1\}\{F_2\} := \frac{1}{2}\left(\frac{\partial F_1}{\partial X_\mu}\frac{\partial F_2}{\partial P^\mu} - \frac{\partial F_1}{\partial P_\mu}\frac{\partial F_2}{\partial X^\mu}\right)$$

- Life time $\tau = \frac{\hbar c}{\Gamma}$

W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

Generalalized testparticle off-shell equations of motion

W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

- **Employ testparticle Ansatz for the real valued quantity** $i\,S^{<}_{XP}$

$$F_{XP} = A_{XP} N_{XP} = i\,S^{<}_{XP} \sim \sum_{i=1}^{N} \delta^{(3)}(\vec{X} - \vec{X}_i(t))\ \delta^{(3)}(\vec{P} - \vec{P}_i(t))\ \delta(P_0 - \epsilon_i(t))$$

insert in generalized transport equations and determine equations of motion !

➔ **Generalized testparticle Cassing-Juchem off-shell equations of motion for the time-like particles:**

$$\frac{d\vec{X}_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[2\,\vec{P}_i + \vec{\nabla}_{P_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{P_i} \Gamma_{(i)} \right],$$

$$\frac{d\vec{P}_i}{dt} = -\frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[\vec{\nabla}_{X_i} Re\Sigma^{ret}_i + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{X_i} \Gamma_{(i)} \right],$$

$$\frac{d\epsilon_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[\frac{\partial Re\Sigma^{ret}_{(i)}}{\partial t} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial \Gamma_{(i)}}{\partial t} \right],$$

with $F_{(i)} \equiv F(t, \vec{X}_i(t), \vec{P}_i(t), \epsilon_i(t))$

$$C_{(i)} = \frac{1}{2\epsilon_i} \left[\frac{\partial}{\partial \epsilon_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial}{\partial \epsilon_i} \Gamma_{(i)} \right]$$

Realized in PHSD

Note: the common factor $1/(1-C_{(i)})$ **can be absorbed in an ‚eigentime' of particle (i) !**

On-shell limits: from KB to BUU

- **$\Gamma(X,P) \rightarrow 0$**

$$A_{XP} = \frac{\Gamma_{XP}}{(P^2 - M_0^2 - Re\Sigma^{ret}_{XP})^2 + \Gamma^2_{XP}/4}$$

⇒ **quasiparticle approximation :**

$$A_{XP} = 2\ p\ \delta(P^2 - M_0^2)$$

- **$\Gamma(X,P)$ such that**

$$\nabla_X \Gamma = 0 \quad \text{and} \quad \nabla_P \Gamma = 0$$

E.g.: Γ = const

$\Gamma = \Gamma_{vacuum}$ (M)

⇔ **‚Vacuum' spectral function with constant or mass dependent width Γ:**
i.e. spectral function A_{XP} does NOT change the shape (and pole position) during propagation through the medium (no density-, T-dependence)

⇓

In on-shell limits the ‚backflow term' - which incorporates the off-shell behavior in the particle propagation - vanishes:

$$\frac{d\vec{X}_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[2\,\vec{P}_i + \vec{\nabla}_{P_i} Re\Sigma^{ret}_{(i)} + \cancel{\frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{P_i} \Gamma_{(i)}} \right],$$

$$\frac{d\vec{P}_i}{dt} = -\frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[\vec{\nabla}_{X_i} Re\Sigma^{ret}_i + \cancel{\frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{X_i} \Gamma_{(i)}} \right],$$

$$\frac{d\epsilon_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[\frac{\partial Re\Sigma^{ret}_{(i)}}{\partial t} + \cancel{\frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial \Gamma_{(i)}}{\partial t}} \right],$$

⇒ **Hamilton equations of motion (independent on Γ) → BUU limit**

W. Cassing, Eur. Phys. J. ST 168 (2009) 3

Mean-field potential in off-shell transport models

- **Many-body theory:** Interacting relativistic particles have a **complex self-energy:**

$$\Sigma^{ret}_{XP} = Re\,\Sigma^{ret}_{XP} + i\,Im\,\Sigma^{ret}_{XP}$$

The neg. imaginary part $\Gamma_{XP} = -Im\,\Sigma^{ret}_{XP} = 2p_0\Gamma$ is related via the width $\Gamma = \Gamma_{coll} + \Gamma_{dec}$ to the inverse livetime of the particle $\tau \sim 1/\Gamma$

- The **collision width** Γ_{coll} is determined from the **loss term** of the collision integral I_{coll}

$$-I_{coll}(loss) = \Gamma_{coll}(X,\vec{P},M^2)N_{X\vec{P}M^2}$$

- By **dispersion relation** we get a contribution to the **real part of self-energy**:

$$Re\,\Sigma^{ret}_{XP}(p_0) = P\int_0^\infty dq\,\frac{Im\,\Sigma^{ret}_{XP}(q)}{(q-p_0)}$$

which gives **a mean-field potential U_{XP}** via: $Re\,\Sigma^{ret}_{XP}(p_0) = 2p_0U_{XP}$

➔ The **complex self-energy** relates in a self-consistent way to the **self-generated mean-field potential and collision width**

Collision term in off-shell transport approach

Collision term for reaction 1+2→3+4:

spectral functions:

$$I_{coll}(X,\vec{P},M^2) = Tr_2 Tr_3 Tr_4 A(X,\vec{P},M^2) A(X,\vec{P}_2,M_2^2) A(X,\vec{P}_3,M_3^2) A(X,\vec{P}_4,M_4^2)$$

$$|G((\vec{P},M^2)+(\vec{P}_2,M_2^2) \to (\vec{P}_3,M_3^2)+(\vec{P}_4,M_4^2))|^2_{\mathcal{A},\mathcal{S}} \; \delta^{(4)}(P+P_2-P_3-P_4)$$

$$[\, N_{X\vec{P}_3M_3^2}\, N_{X\vec{P}_4M_4^2}\, \bar{f}_{X\vec{P}M^2}\, \bar{f}_{X\vec{P}_2M_2^2} \; - \; N_{X\vec{P}M^2}\, N_{X\vec{P}_2M_2^2}\, \bar{f}_{X\vec{P}_3M_3^2}\, \bar{f}_{X\vec{P}_4M_4^2} \,]$$

‚gain' term ‚loss' term

with $\bar{f}_{X\vec{P}M^2} = 1 + \eta\, N_{X\vec{P}M^2}$ and $\eta = \pm 1$ for bosons/fermions, respectively.

The trace over particles 2,3,4 reads explicitly

for fermions

$$Tr_2 = \sum_{\sigma_2,\tau_2} \frac{1}{(2\pi)^4} \int d^3P_2 \frac{dM_2^2}{2\sqrt{\vec{P}_2^2 + M_2^2}}$$

for bosons

$$Tr_2 = \sum_{\sigma_2,\tau_2} \frac{1}{(2\pi)^4} \int d^3P_2 \frac{dP_{0,2}^2}{2}$$

additional integration

The off-shell transport approach and the particle spectral functions are fully determined once the in-medium transition amplitudes G are known in their off-shell dependence!

Advantages of Kadanoff-Baym dynamics vs Boltzmann

Kadanoff-Baym equations:

- propagate two-point Green functions
  $G^<(x,p) \rightarrow A(x,p)*N(x,p)$
  in 8 dimensions $x=(t,\vec{r})$ $p=(p_0,\vec{p})$
- $G^<$ carries information not only on the occupation number N_{XP}, but also on the particle properties, interactions and correlations via spectral function A_{XP}

Boltzmann equations

- propagate phase space distribution function $f(\vec{r},\vec{p},t)$ in 6+1 dimensions
- works well for small coupling
  = weakly interacting system,
  ➔ on-shell approach

- Applicable for strong coupling = strongly interacting system
- Dynamically generates a broad spectral function for strong coupling
- Includes memory effects (time integration) and off-shell transitions in collision term
- KB can be solved exactly for model cases such as Φ^4 – theory
- KB can be solved in 1st order gradient expansion in terms of generalized transport equations (in test particle ansatz) for realistic systems of HICs ➔ PHSD

➔ W. Cassing, *`Transport Theories for Strongly-Interacting Systems'*, Springer Nature: Lecture Notes in Physics 989, 2021
DOI: 10.1007/978-3-030-80295-0

Collision integral:
n↔m reactions

Detailed balance on the level of 2←→n: treatment of multi-particle collisions in transport approaches

W. Cassing, NPA 700 (2002) 618

Generalized off-shell collision integral for *n* ←→ *m* reactions:

$$I_{coll} = \sum_n \sum_m I_{coll}[n \leftrightarrow m]$$

$$I^i_{coll}[n \leftrightarrow m] =$$
$$\frac{1}{2} N_n^m \sum_\nu \sum_\lambda \left(\frac{1}{(2\pi)^4}\right)^{n+m-1} \int \left(\prod_{j=2}^n d^4p_j \; A_j(x,p_j)\right) \left(\prod_{k=1}^m d^4p_k \, A_k(x,p_k)\right)$$
$$\times A_i(x,p) \; W_{n,m}(p,p_j;i,\nu \mid p_k;\lambda) \; (2\pi)^4 \; \delta^4(p^\mu + \sum_{j=2}^n p_j^\mu - \sum_{k=1}^m p_k^\mu)$$
$$\times [\tilde{f}_i(x,p) \prod_{k=1}^m f_k(x,p_k) \prod_{j=2}^n \tilde{f}_j(x,p_j) - f_i(x,p) \prod_{j=2}^n f_j(x,p_j) \prod_{k=1}^m \tilde{f}_k(x,p_k)].$$

$\tilde{f} = 1 + \eta f$ **is Pauli-blocking or Bose-enhancement factors;**
η=1 for bosons and η=-1 for fermions

$W_{n,m}(p,p_j;i,\nu \mid p_k;\lambda)$ **is a transition matrix element squared**

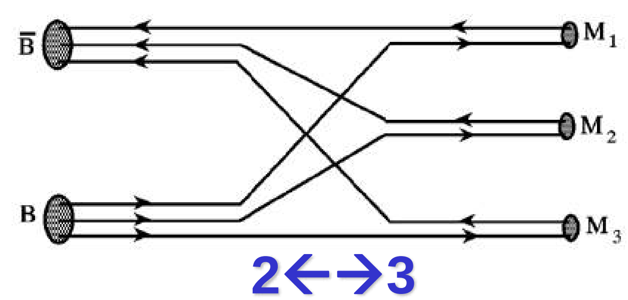
Multi-meson fusion in heavy-ion reactions

Multi-meson fusion reactions

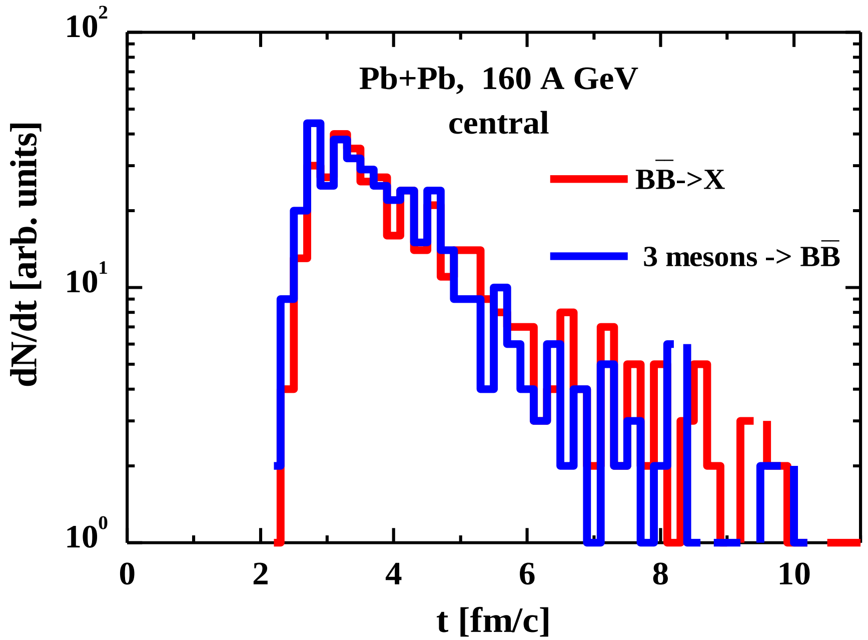
$m_1+m_2+\ldots+m_n \leftrightarrow B+\bar{B}$bar

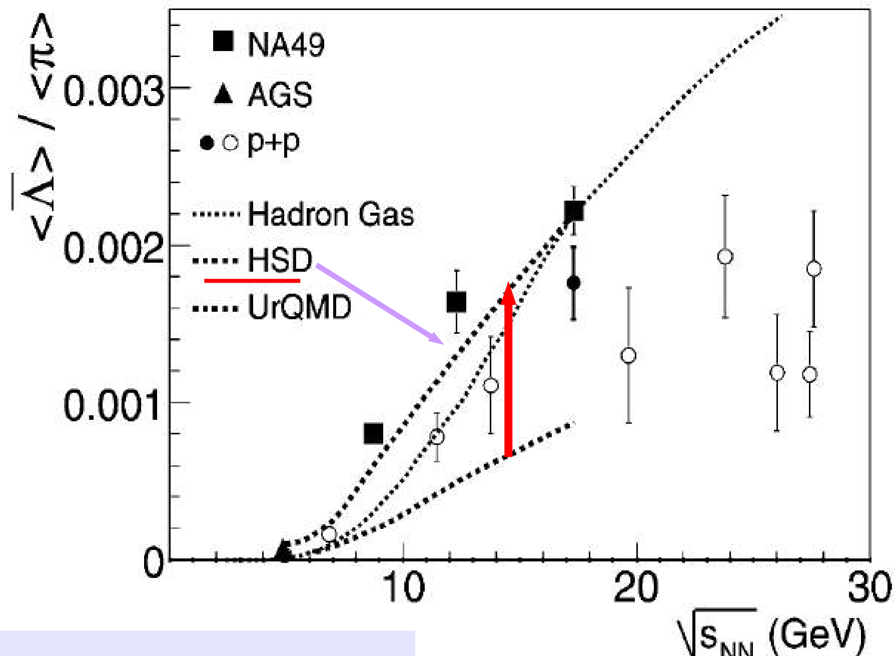
m=π,ρ,ω,.. B=p,Λ,Σ,Ξ,Ω, (>2000 channels)

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



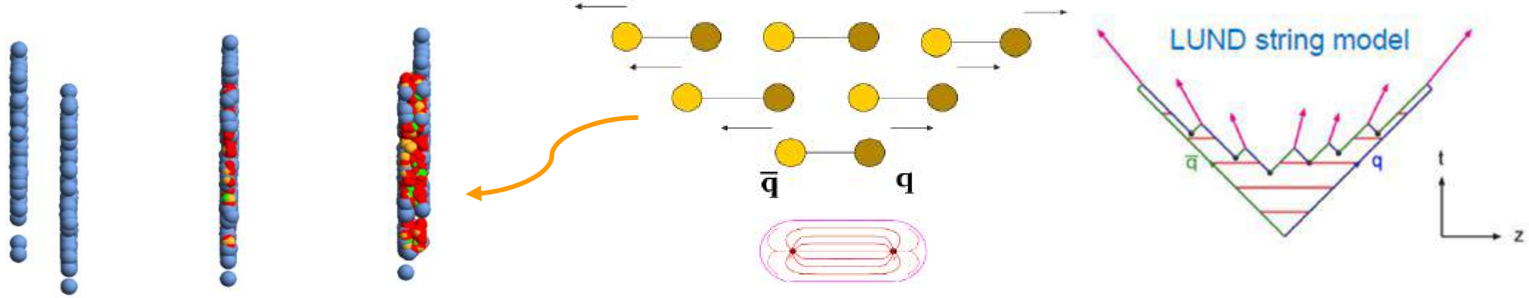
- important for anti-proton, anti-Λ, anti-Ξ, anti- Ω dynamics !





→ approximate equilibrium of annihilation and recreation

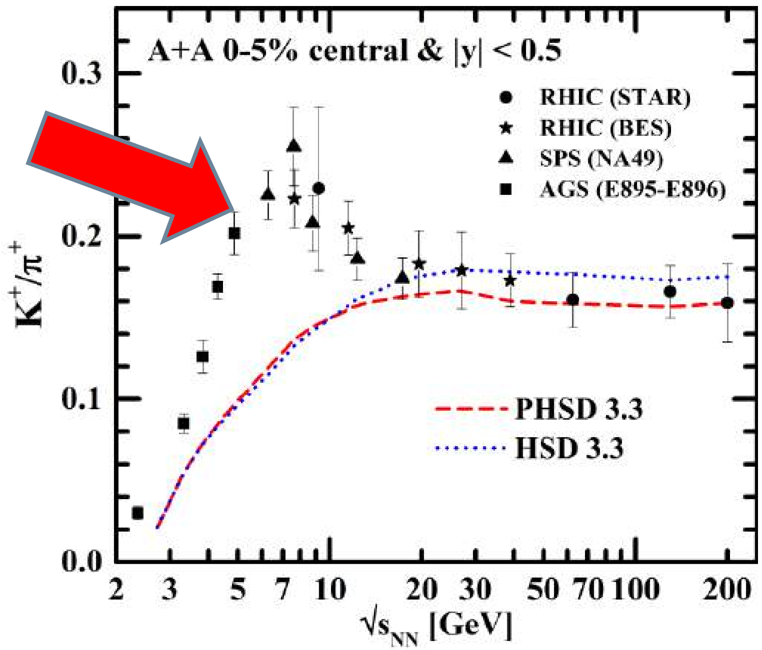
Modeling of the chiral symmetry restoration via Schwinger mechanism for string fragmentation in the initial phase of HIC



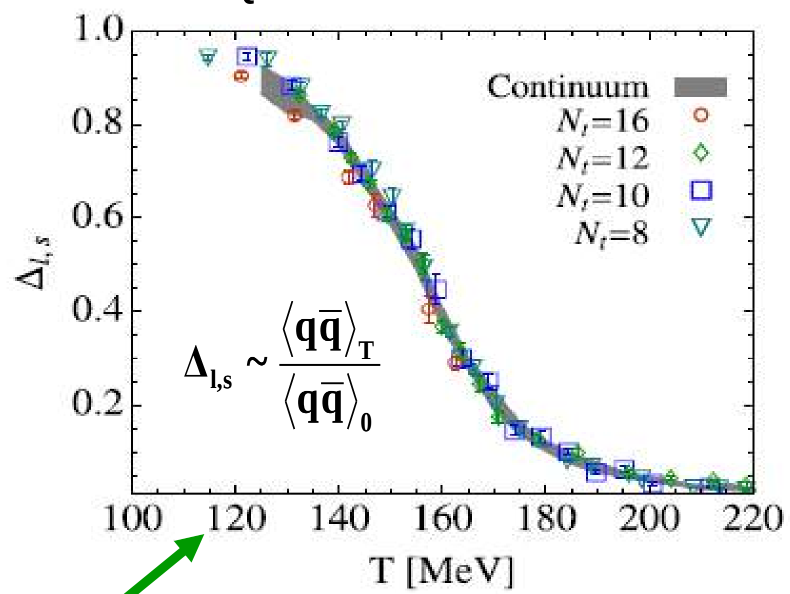
‚Flavour chemistry‘ of HIC: K^+/π^+ ‚horn‘ – 2015

PHSD: even when considering the creation of a QGP phase, the K^+/π^+ ‚horn‘ seen experimentally by NA49 and STAR at a bombarding energy ~30 A GeV (FAIR/NICA energies) remained unexplained (2015)!

➔ The origin of the ‘horn’ is not traced back to deconfinement ?!



lQCD BMW collaboration:



?

Can it be related to chiral symmetry restoration in the initial hadronic phase?!

W. Cassing, A. Palmese, P. Moreau, E.L. Bratkovskaya, PRC 93, 014902 (2016)

Scalar quark condensate in HIC

Non-linear $\sigma - \omega$ model:

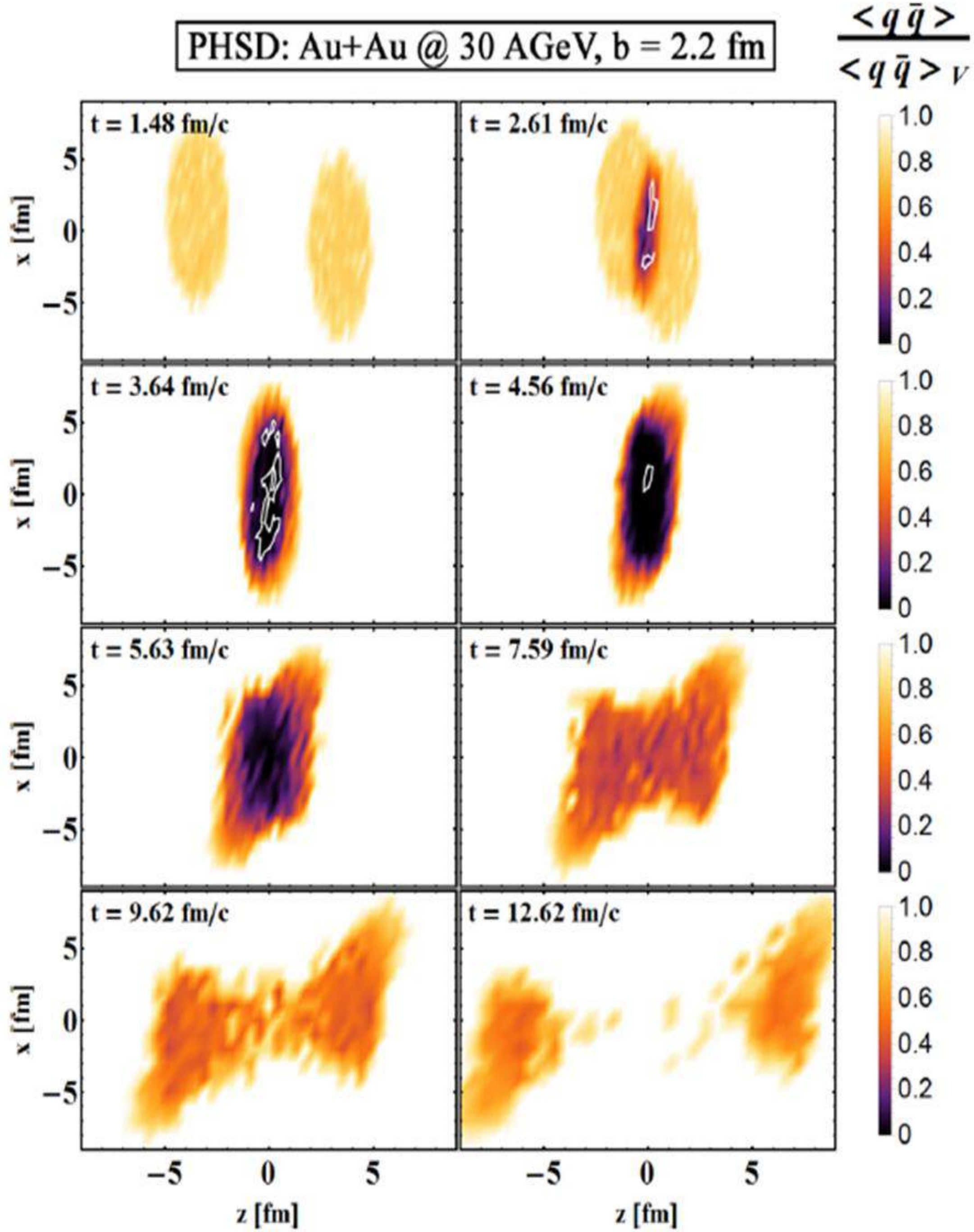
$$\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V} = 1 - \frac{\Sigma_\pi}{f_\pi^2 m_\pi^2}\rho_S - \sum_h \frac{\sigma_h \rho_S^h}{f_\pi^2 m_\pi^2}$$

baryonic medium — mesonic medium

PHSD:
Ratio of the scalar quark condensate:

$$\frac{<q\,\bar{q}>}{<q\,\bar{q}>_V}$$

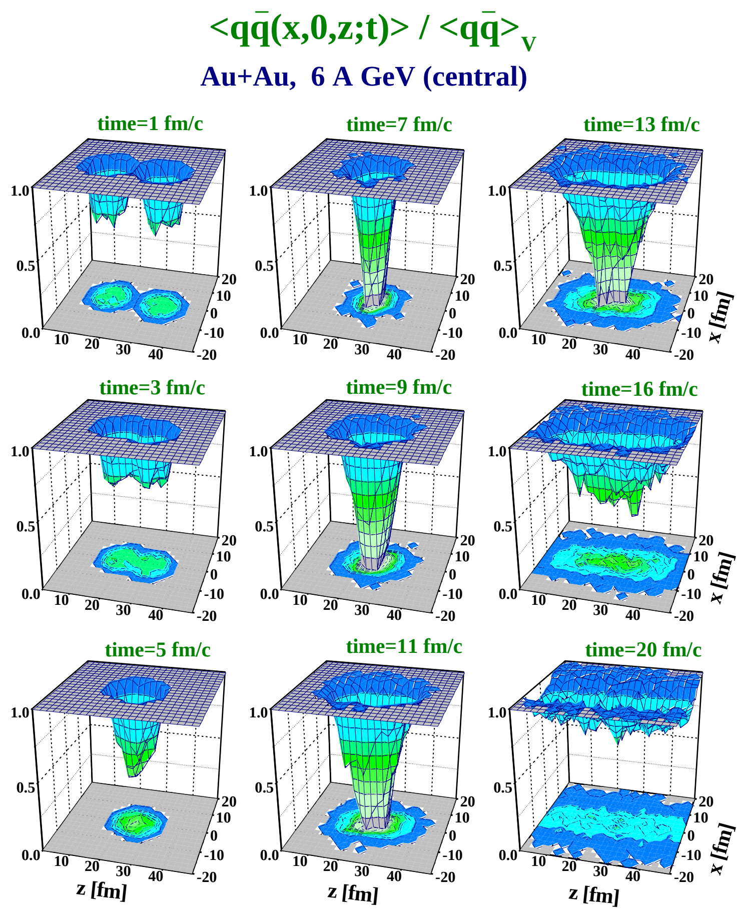
compared to the vacuum value as a function of *x,z (y=0)* at different time *t* for central Au+Au collisions at 30 AGeV

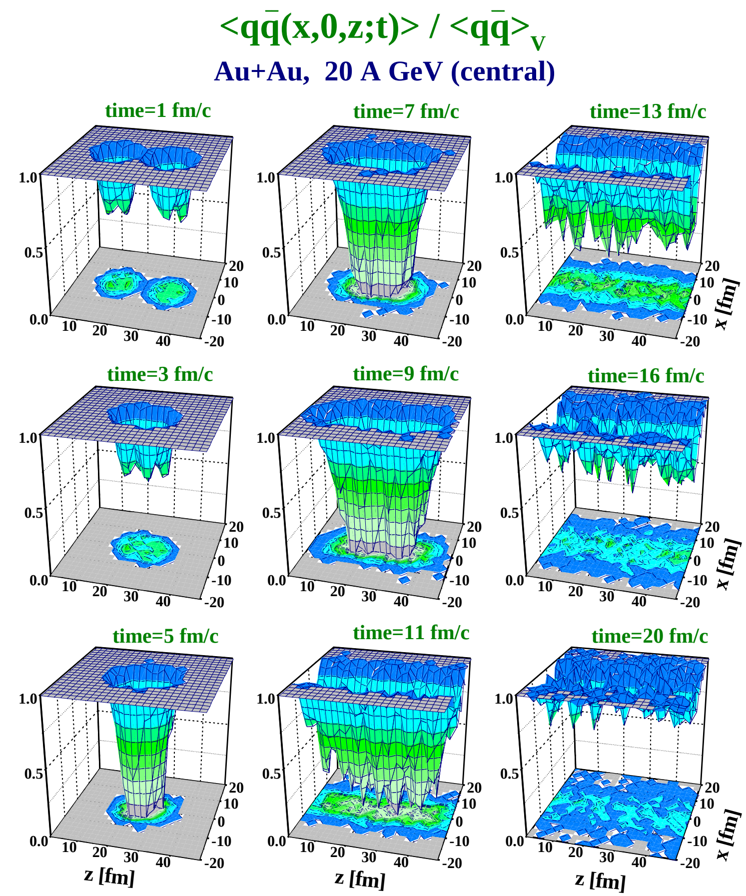


- restoration of chiral symmetry: $\langle q\bar{q}\rangle / \langle q\bar{q}\rangle_V \rightarrow 0$

W. Cassing, A. Palmese, P. Moreau, E.L. Bratkovskaya, PRC 93, 014902 (2016), arXiv:1510.04120

Quark condensate in central Au+Au



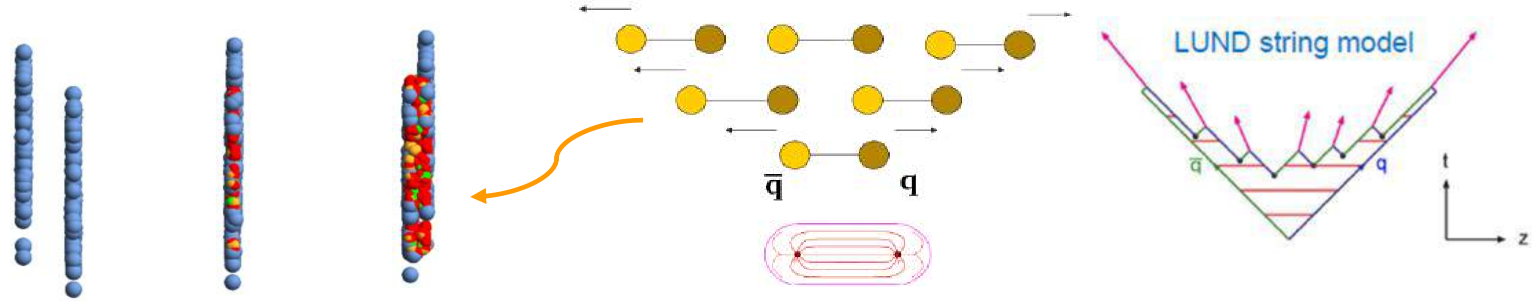


- **Quark condensate drops to zero already at lower AGS energies!**
- **➔ we are probing a new phase of matter already at ~5AGeV**

HSD calculations: NPA 674 (2000) 249

Chiral symmetry restoration via Schwinger mechanism

- **Initial stage of HIC: string formation**



- **the ‚flavor chemistry‘ of the final hadrons in the PHSD is mainly defined by the LUND string model**

- **‘quark flavor chemistry’ in the LUND model is determined by the Schwinger-formula**

- **According to the Schwinger-formula, the probability to form a massive $s\bar{s}$ pair in a string-decay is suppressed in comparison to a light flavor pair $(u\bar{u}, d\bar{d})$:**

$$\frac{P(s\bar{s})}{P(u\bar{u})} = \frac{P(s\bar{s})}{P(d\bar{d})} = \gamma_s = \exp\left(-\pi \frac{m_s^2 - m_q^2}{2\kappa}\right)$$

with κ- string tension;
in vacuum: κ~0.9 GeV/fm=0.176GeV²

- **m_s, m_q (q=u,d) – constituent (‘dressed’) quark masses**

Dressing of the quark masses

- m_s, m_q (q=u,d) – **constituent ('dressed') quark masses:** 'dressing' of bare quark masses is due to the coupling to the **scalar quark condensate** $< q\bar{q} >$:

I. In vacuum (e.g. p+p collisions) :

$$m_q^V = m_q^0 - g_s < q\bar{q} >_V$$

$$(V \equiv vacuum)$$

bare quark masses:

$$m_u^0 = m_d^0 \approx 7\,MeV, \; m_s^0 \approx 100\,MeV$$

vacuum scalar quark condensate fixed from Gell-Mann-Oakes-Renner relation

$$f_\pi^2 m_\pi^2 = -\frac{1}{2}(m_u^0 + m_d^0) < \bar{q}q >_V$$

$$\Rightarrow < q\bar{q} >_V \approx -3.2 fm^{-3}$$

➔ **Constituent quark masses in vacuum :**

$$(m_q \equiv m_q^V) \quad m_u^V = m_d^V \approx 0.35 GeV, \quad m_s^V \approx 0.5 GeV$$

II. In medium (e.g. A+A collisions) :

In the presence of **a hot and dense hadronic medium,** the degrees of freedom modify their properties, e.g. **the in-medium constituent quark masses**:

$$m_q^* = m_q^0 - g_s < q\bar{q} > \quad (q = u,d,s)$$

$$\Downarrow$$

$$m_q^* = m_q^0 + (m_q^V - m_q^0)\frac{< q\bar{q} >}{< q\bar{q} >_V}$$

* mean-field results (1PI)

Scalar quark condensate in the hadronic medium

- The behavior of the scalar quark condensate $\langle q\bar{q}\rangle$ in the hadronic medium (baryons + mesons) can be obtained e.g. from

B. Friman et al., Eur. Phys. J. A 3, 165, 1998

non-linear $\sigma - \omega$ model:

$$\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V} = 1 - \frac{\Sigma_\pi}{f_\pi^2 m_\pi^2}\rho_S - \sum_h \frac{\sigma_h \rho_S^h}{f_\pi^2 m_\pi^2}$$

baryonic medium — mesonic medium

where $\Sigma_\pi \approx 45$ MeV is the pion-nucleon Σ-term,
$\sigma_h = m_\pi/2$ for light mesons;
$= m_\pi/4$ - strange mesons

1) ρ_s is the scalar density of baryonic matter :

Scalar field $\sigma(x)$ mediates the scalar interaction of baryons with the surrounding medium with a g_s coupling

from non-linear $\sigma - \omega$ model: — from PHSD

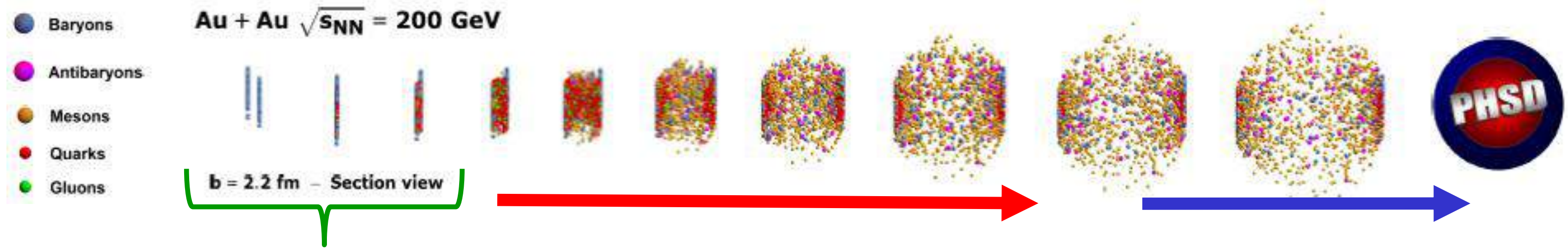
$$m_\sigma^2 \sigma(x) + B\sigma^2(x) + C\sigma^3(x) = g_s \rho_S = g_s d \int \frac{d^3p}{(2\pi)^3} \frac{m_N^*(x)}{\sqrt{p^2 + m_N^{*2}}} f_N(x, \mathbf{p})$$

$$m_N^*(x) = m_N^V - g_s \sigma(x)$$

- $\sigma(x)$ is determined locally by solution of the nonlinear gap equation ;
- parameters g_s, m_σ , B, C are fixed to reproduce the main nuclear matter quantities,
i.e. saturation density, binding energy per nucleon, compression modulus and the effective nucleon mass.

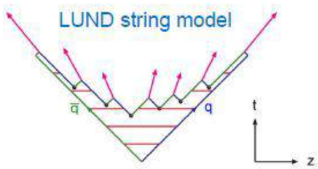
2) ρ_s^h is the scalar density of mesons of type *h* ➔ from PHSD

Chiral symmetry restoration vs. deconfinement



I. Initial stage of HICs:

Hadronic matter ➔ string formation



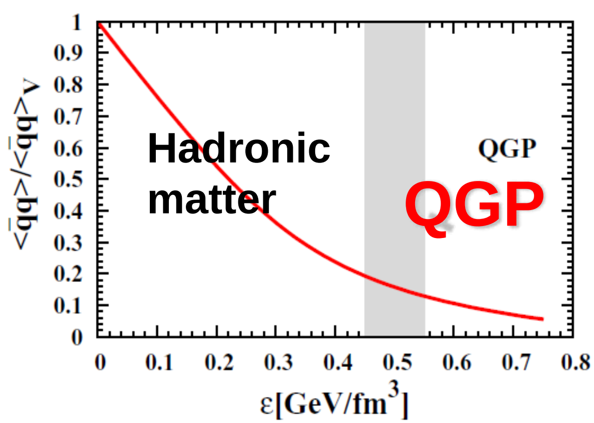
$$\frac{P(s\bar{s})}{P(u\bar{u})} = \frac{P(s\bar{s})}{P(d\bar{d})} = \gamma_S = \exp\left(-\pi\frac{m_S^{*2}-m_q^{*2}}{2\kappa}\right)$$

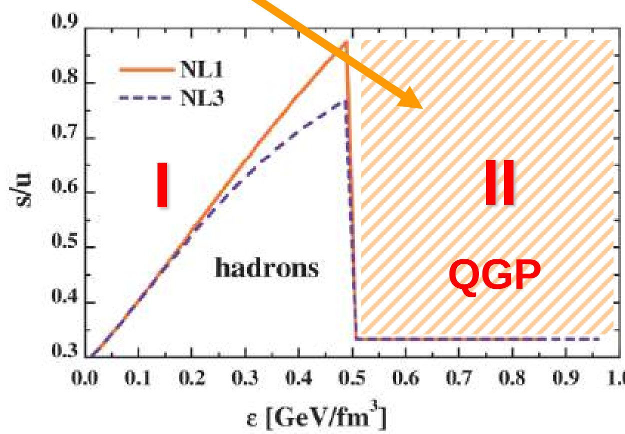
$$m_q^* = m_q^0 + (m_q^V - m_q^0)\frac{<q\bar{q}>}{<q\bar{q}>_V}$$

II. QGP

(time-like partons, explicit partonic interactions)

III. Hadronic phase



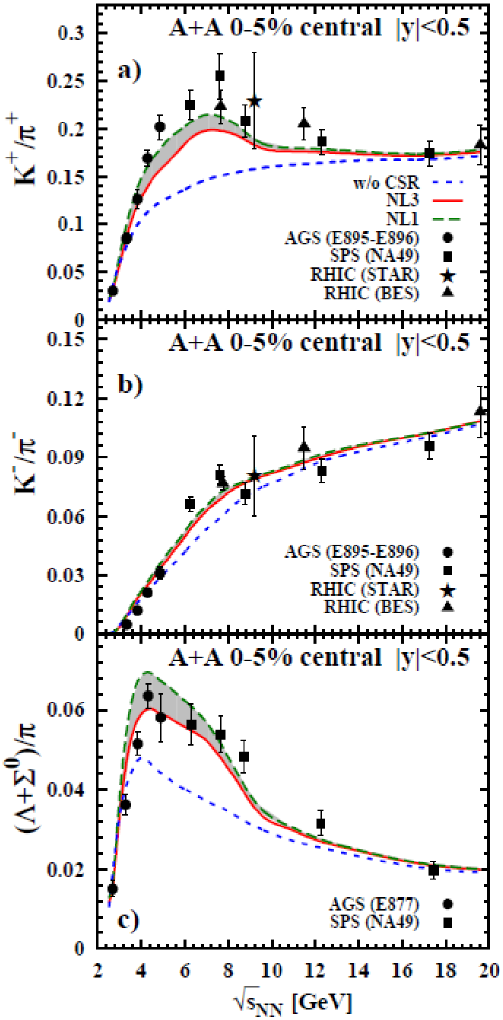


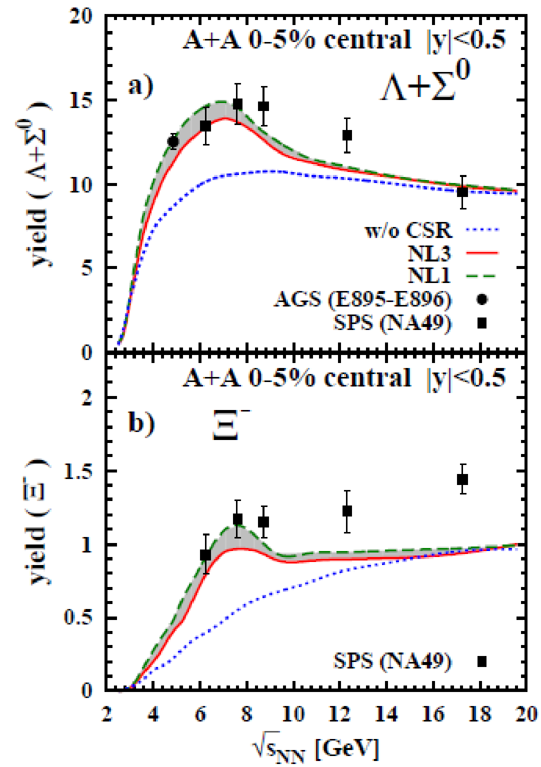
- Chiral symmetry restoration via Schwinger mechanism (and non-linear $\sigma-\omega$ model) changes the „flavour chemistry“ in string fragmentation (1PI):
  $\langle q\bar{q}\rangle/\langle q\bar{q}\rangle_V$ ➔ 0 ➔ m_s^* ➔ m_s^0 ➔ s/u grows

➔ the strangeness production probability increases with the local energy density ε (up to ε_C) due to the partial chiral symmetry restoration!

Excitation function of hadron ratios and yields

A. Palmese et al., PRC94 (2016) 044912 , arXiv:1607.04073

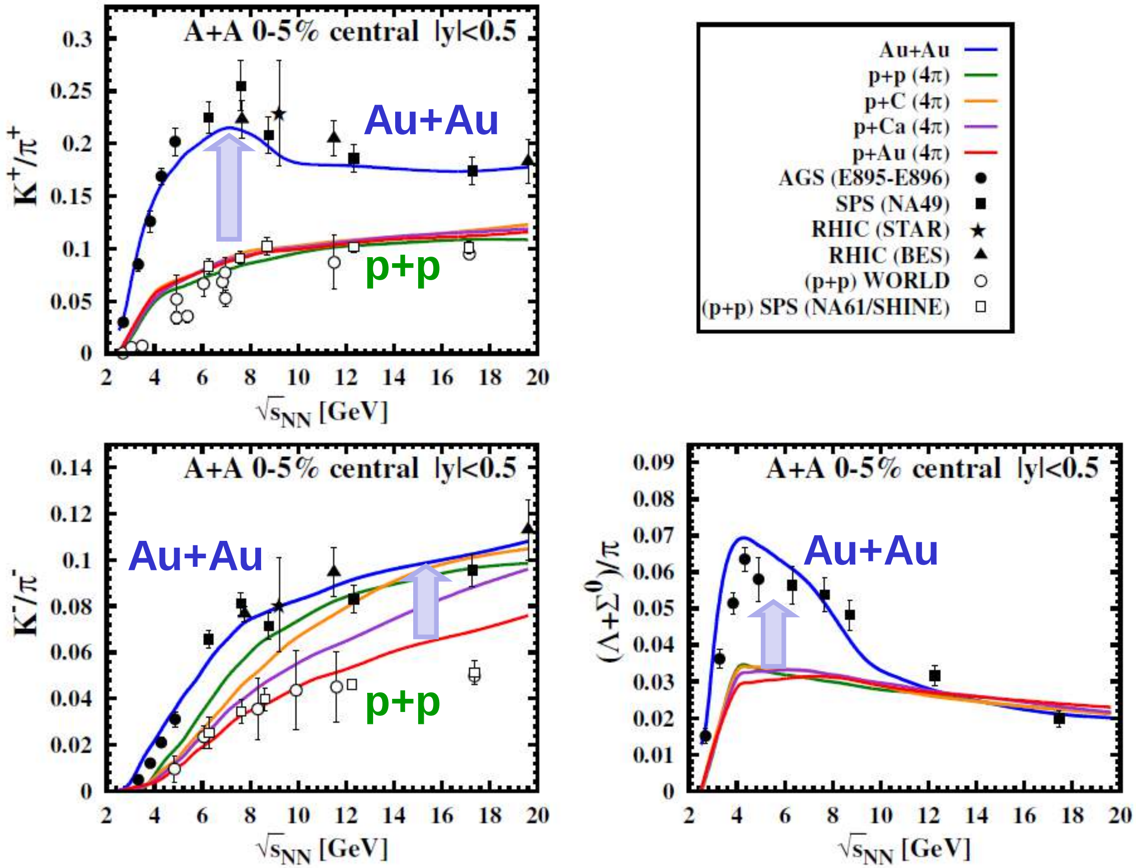




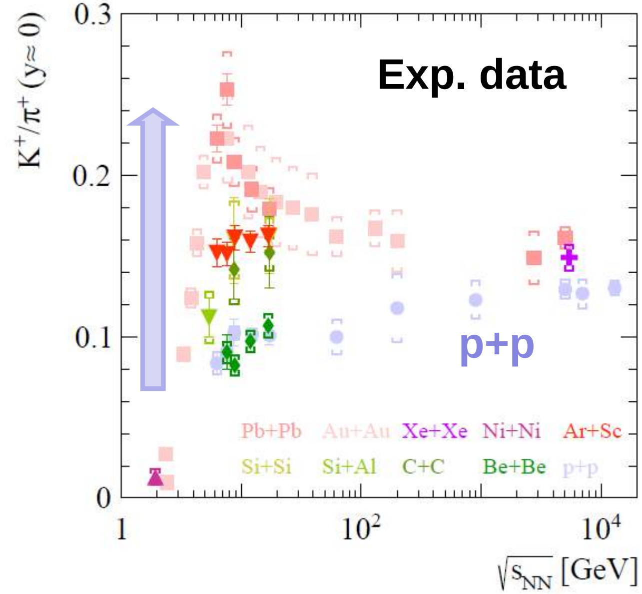
- **Influence of EoS: NL1 vs NL3 ➔ low sensitivity to the nuclear EoS**
- **Excitation function of the hyperons $\Lambda+\Sigma^0$ and Ξ^- show analogous peaks as K^+/π^+, $(\Lambda+\Sigma^0)/\pi$ ratios due to CSR**

Chiral symmetry restoration leads to the enhancement of strangeness production in string fragmentation in the beginning of HICs in the hadronic phase.
➔The „horn“ structure is due to the interplay between CSR and deconfinement (QGP)

Sensitivity to the system size: p+p, p+A, A+A



- Excitation function of hadron yields is very different in p+p and A+A

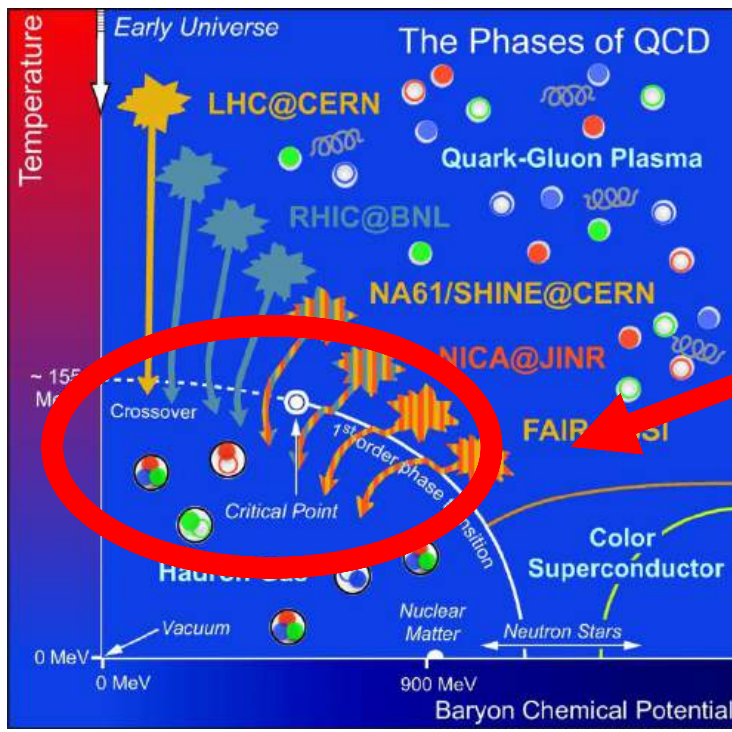


- p+p, p+A: monotonic increase with energy
- A+A: „horn“ structure is due to the interplay between chiral symmetry restoration and deconfinement (QGP) - within the PHSD

A. Palmese et al., PRC94 (2016) 044912 , arXiv:1607.04073

Modeling of sQGP →

DQPM (T, μ_q)



finite T,μ_q

pQCD: shear viscosity η

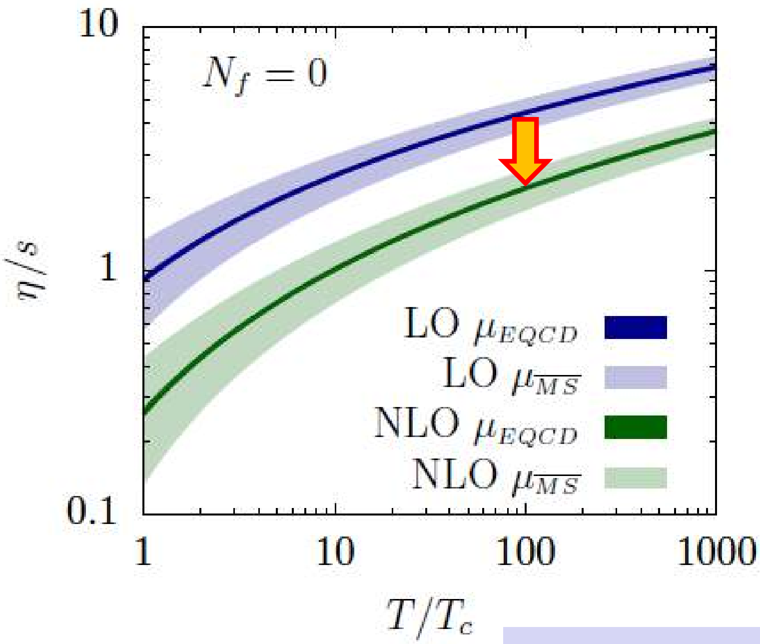
QCD: Pure Yang-Mills (only gluons)

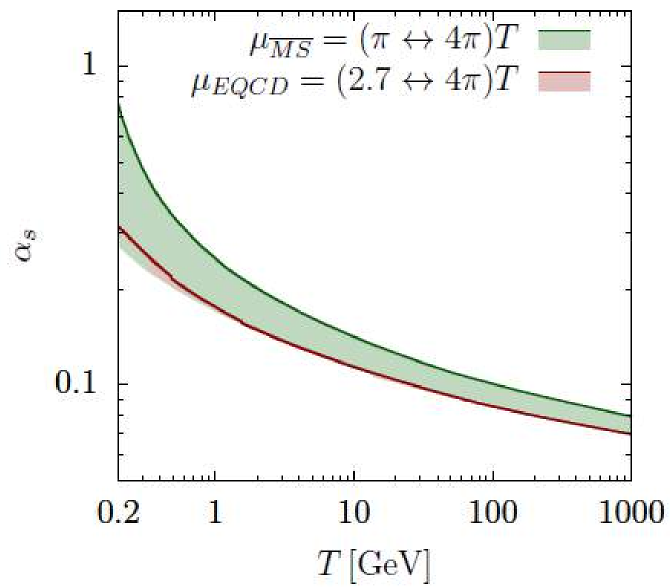
LO (Leading order) perturbative QCD calculations:

$\eta/s > 0.5$ at T near T_C **'AMY': P.B. Arnold, G.D. Moore and L.G. Yaffe,, JHEP 11 (2000) 001)**

NLO (Next-to-leading order): **J. Ghiglieri, G.D. Moore, D. Teaney, JHEP 1803 (2018) 179 :**

"The next-to-leading order corrections are large and bring η/s down by more than a factor of 3 at physically relevant couplings.
The perturbative expansion is problematic even at T ~100 GeV"





➔ from pQCD to effective models of QCD!

Dynamical QuasiParticle Model (DQPM)

DQPM – effective model for the description of non-perturbative (strongly interacting) QCD based on lQCD EoS

Degrees-of-freedom: strongly interacting dynamical quasiparticles - quarks and gluons

Theoretical basis :

- ❑ ‚resummed' single-particle Green's functions → quark (gluon) propagator (2PI) :

gluon propagator: $\Delta^{-1} = P^2 - \Pi$	&	quark propagator $S_q^{-1} = P^2 - \Sigma_q$
gluon self-energy: $\Pi = M_g^2 - i2\gamma_g\omega$	&	quark self-energy: $\Sigma_q = M_q^2 - i2\gamma_q\omega$

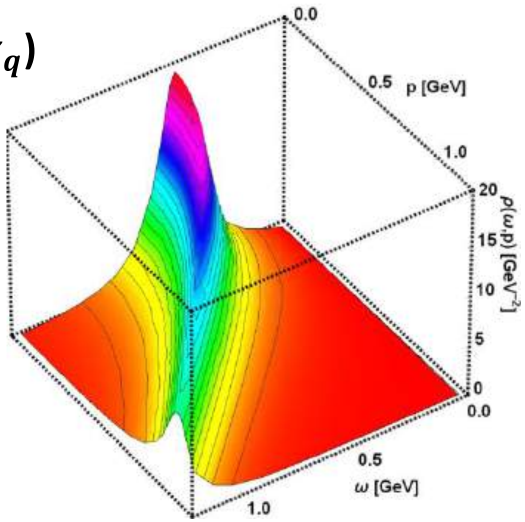
Properties of the quasiparticles are specified by scalar complex self-energies:

$Re\Sigma_q$: thermal masses (M_g, M_q); $Im\Sigma_q$: interaction widths (γ_g, γ_q)

→ spectral functions $\rho_q = -2ImS_q$ → Lorentzian form:

$$\rho_j(\omega,\mathbf{p}) = \frac{\gamma_j}{\tilde{E}_j}\left(\frac{1}{(\omega-\tilde{E}_j)^2+\gamma_j^2} - \frac{1}{(\omega+\tilde{E}_j)^2+\gamma_j^2}\right)$$

$$\equiv \frac{4\omega\gamma_j}{\left(\omega^2-\mathbf{p}^2-M_j^2\right)^2+4\gamma_j^2\omega^2} \qquad \tilde{E}_j^2(\mathbf{p}) = \mathbf{p}^2 + M_j^2 - \gamma_j^2$$



A. Peshier, W. Cassing, PRL 94 (2005) 172301; W. Cassing, NPA 791 (2007) 365: NPA 793 (2007), H. Berrehrah et al, Int.J.Mod.Phys. E25 (2016) 1642003; P. Moreau et al., PRC100 (2019) 014911; O. Soloveva et al., PRC101 (2020) 045203

Parton properties

- Modeling of the quark/gluon masses and widths (ansatz inspired by HTL calculations)

Masses:

$$M^2_{q(\bar{q})}(T,\mu_B) = \frac{N_c^2-1}{8N_c} g^2(T,\mu_B) \left(T^2 + \frac{\mu_q^2}{\pi^2} \right)$$

$$M^2_g(T,\mu_B) = \frac{g^2(T,\mu_B)}{6} \left(\left(N_c + \frac{1}{2} N_f \right) T^2 + \frac{N_c}{2} \sum_q \frac{\mu_q^2}{\pi^2} \right)$$

Widths:

$$\gamma_{q(\bar{q})}(T,\mu_B) = \frac{1}{3} \frac{N_c^2-1}{2N_c} \frac{g^2(T,\mu_B) T}{8\pi} \ln \left(\frac{2c}{g^2(T,\mu_B)} + 1 \right)$$

$$\gamma_g(T,\mu_B) = \frac{1}{3} N_c \frac{g^2(T,\mu_B) T}{8\pi} \ln \left(\frac{2c}{g^2(T,\mu_B)} + 1 \right)$$

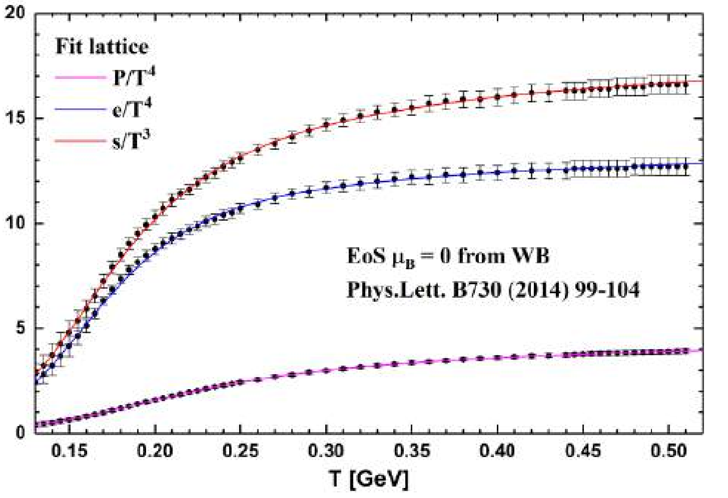
➔ **DQPM :**
only one parameter (c = 14.4) + (T, μ_B)- dependent coupling constant has to be determined from lattice results

- **Coupling g:** $\frac{\partial}{\partial T} \left(\frac{s_{DQPM}}{T^3} \right) = 0$

lQCD entropy density s function of T at μ_B=0

$$g^2(s/s_{SB}) = d\left((s/s_{SB})^e - 1 \right)^f$$

$$s_{SB}^{QCD} = 19/9 \pi^2 T^3$$



H. Berrehrah et al, PRC 93 (2016) 044914, Int.J.Mod.Phys. E25 (2016) 1642003,

DQPM thermodynamics at finite (T, μ_q)

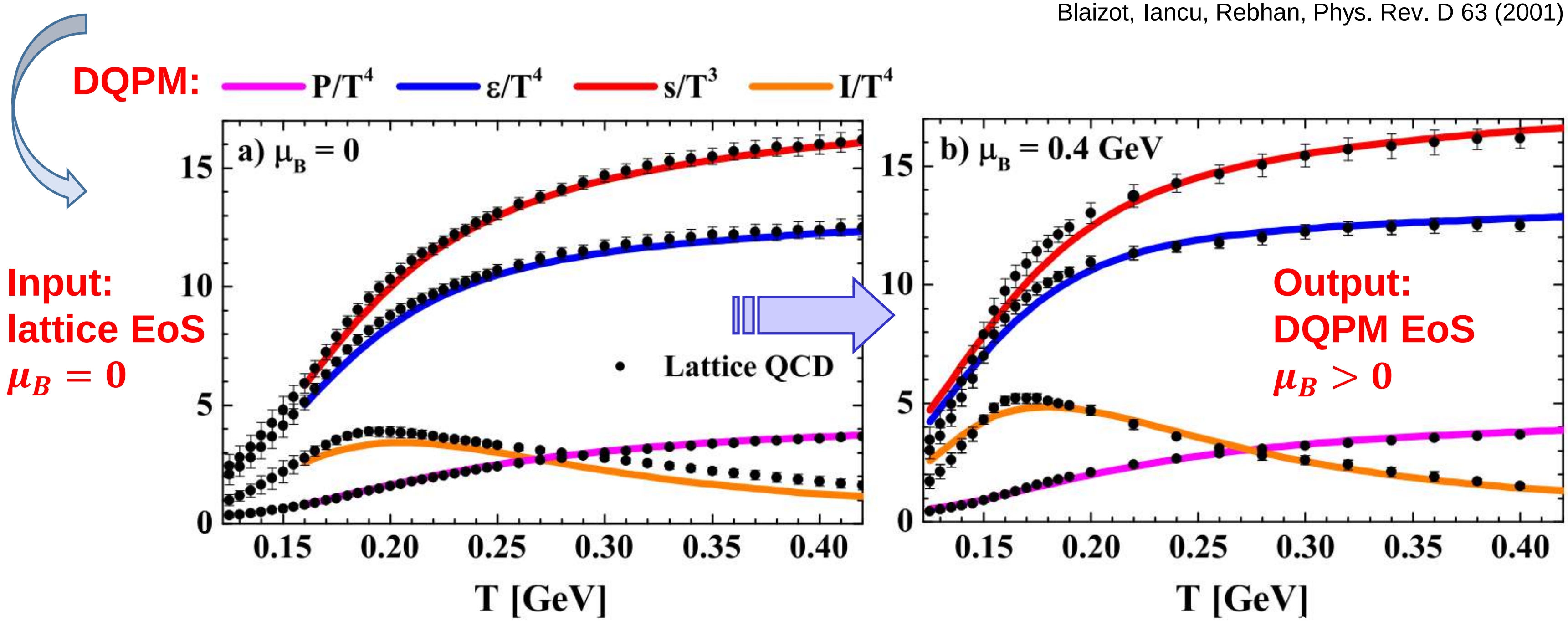
- **Entropy and baryon density** in the quasiparticle limit (G. Baym 1998):

$$s^{dqp} = -\int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\left[d_g \frac{\partial n_B}{\partial T}\left(\mathrm{Im}(\ln -\Delta^{-1}) + \mathrm{Im}\,\Pi\,\mathrm{Re}\,\Delta\right) + \sum_{q=u,d,s} d_q \frac{\partial n_F(\omega-\mu_q)}{\partial T}\left(\mathrm{Im}(\ln -S_q^{-1}) + \mathrm{Im}\,\Sigma_q\,\mathrm{Re}\,S_q\right) + \sum_{\bar q=\bar u,\bar d,\bar s} d_{\bar q} \frac{\partial n_F(\omega+\mu_q)}{\partial T}\left(\mathrm{Im}(\ln -S_{\bar q}^{-1}) + \mathrm{Im}\,\Sigma_{\bar q}\,\mathrm{Re}\,S_{\bar q}\right)\right]$$

$$n^{dqp} = -\int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\left[\sum_{q=u,d,s} d_q \frac{\partial n_F(\omega-\mu_q)}{\partial \mu_q}\left(\mathrm{Im}(\ln -S_q^{-1}) + \mathrm{Im}\,\Sigma_q\,\mathrm{Re}\,S_q\right) + \sum_{\bar q=\bar u,\bar d,\bar s} d_{\bar q} \frac{\partial n_F(\omega+\mu_q)}{\partial \mu_q}\left(\mathrm{Im}(\ln -S_{\bar q}^{-1}) + \mathrm{Im}\,\Sigma_{\bar q}\,\mathrm{Re}\,S_{\bar q}\right)\right]$$

B. Vanderheyden, G. Baym, J. Stat. Phys. 93 (1998) 843

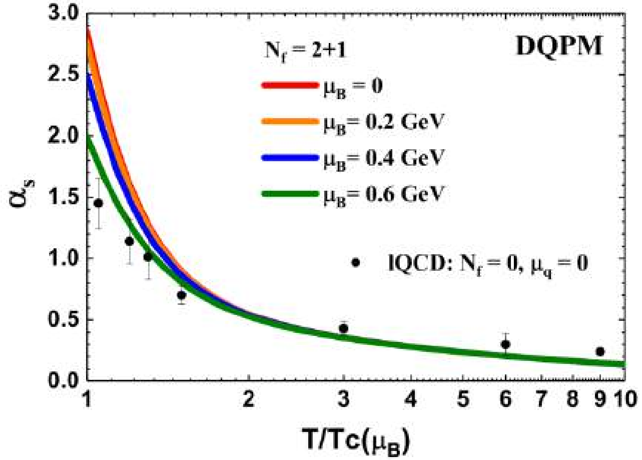
Blaizot, Iancu, Rebhan, Phys. Rev. D 63 (2001) 065003



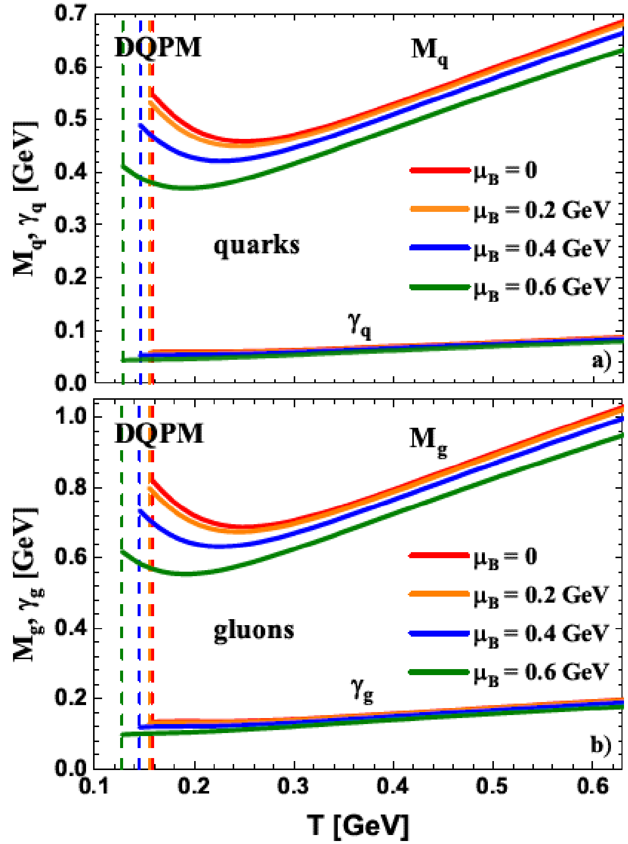
lQCD: Sz. Borsanyi et al., JHEP 1208 (2012) 053

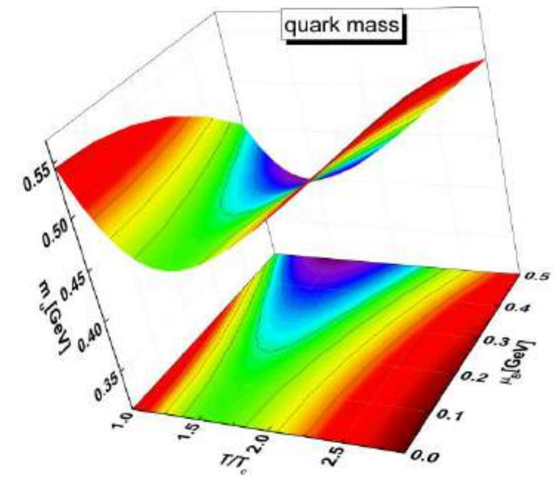
DQPM: parton properties

Coupling as a function of (T, μ_B)

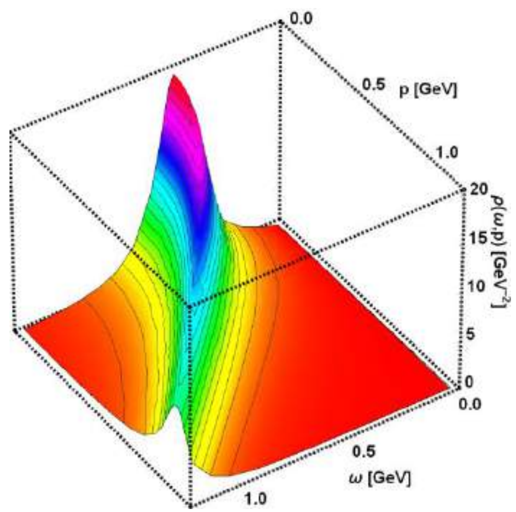


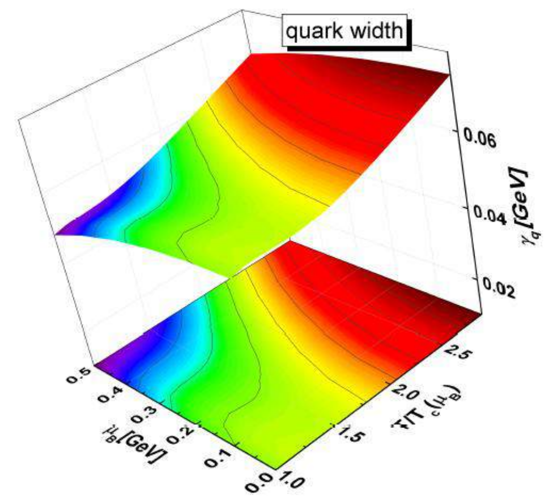
Pole masses and widths vs (T, μ_B)





➔ Lorentzian spectral function:



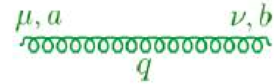


P. Moreau et al., PRC100 (2019) 014911;
O. Soloveva et al., PRC110 (2020) 045203

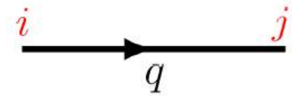
Partonic interactions: matrix elements

DQPM partonic cross sections → leading order diagrams

- **Propagators for massive bosons and fermions:**



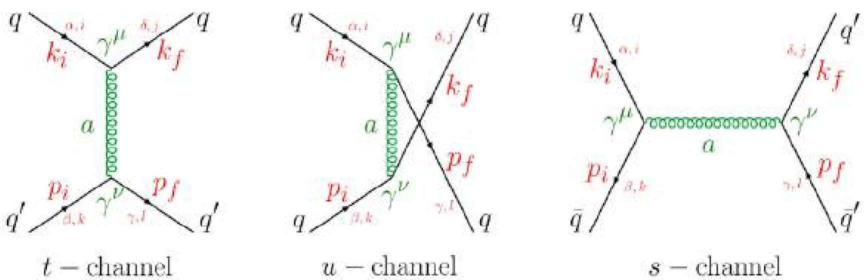
$$= -i\delta_{ab}\frac{g^{\mu\nu} - q^{\mu}q^{\nu}/M_g^2}{q^2 - M_g^2 + 2i\gamma_g q_0}$$



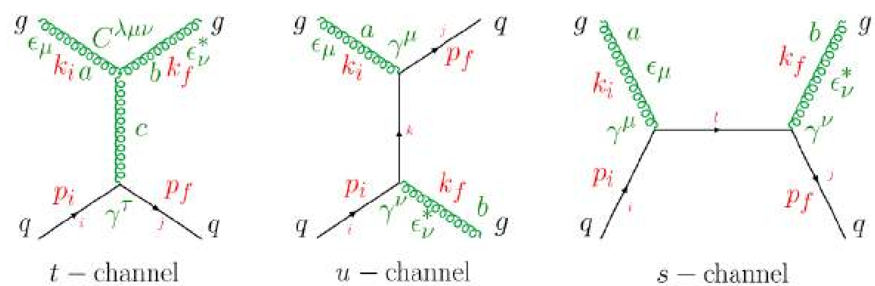
$$= i\delta_{ij}\frac{\not{q} + M_q}{q^2 - M_q^2 + 2i\gamma_q q_0}$$

- **(Quasi-) elastic channels:**

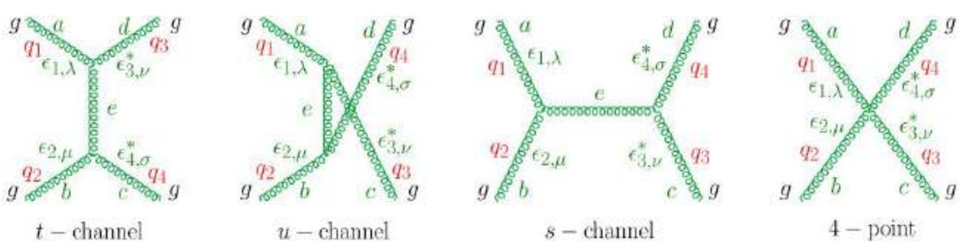
qq' → qq' scattering



gq → gq scattering



gg→ gg scattering



- **Inelastic channels:**

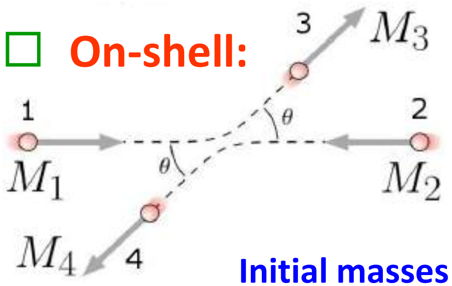
$$\mathrm{q} + \bar{\mathrm{q}} \rightarrow \mathrm{g}$$

$$\mathrm{g} \rightarrow \mathrm{q} + \bar{\mathrm{q}}$$

H. Berrehrah et al, PRC 93 (2016) 044914, Int.J.Mod.Phys. E25 (2016) 1642003, → **P. Moreau et al., PRC100 (2019) 014911**

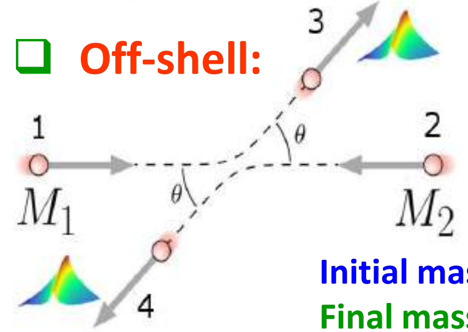
Differential cross sections

- **On-shell:**

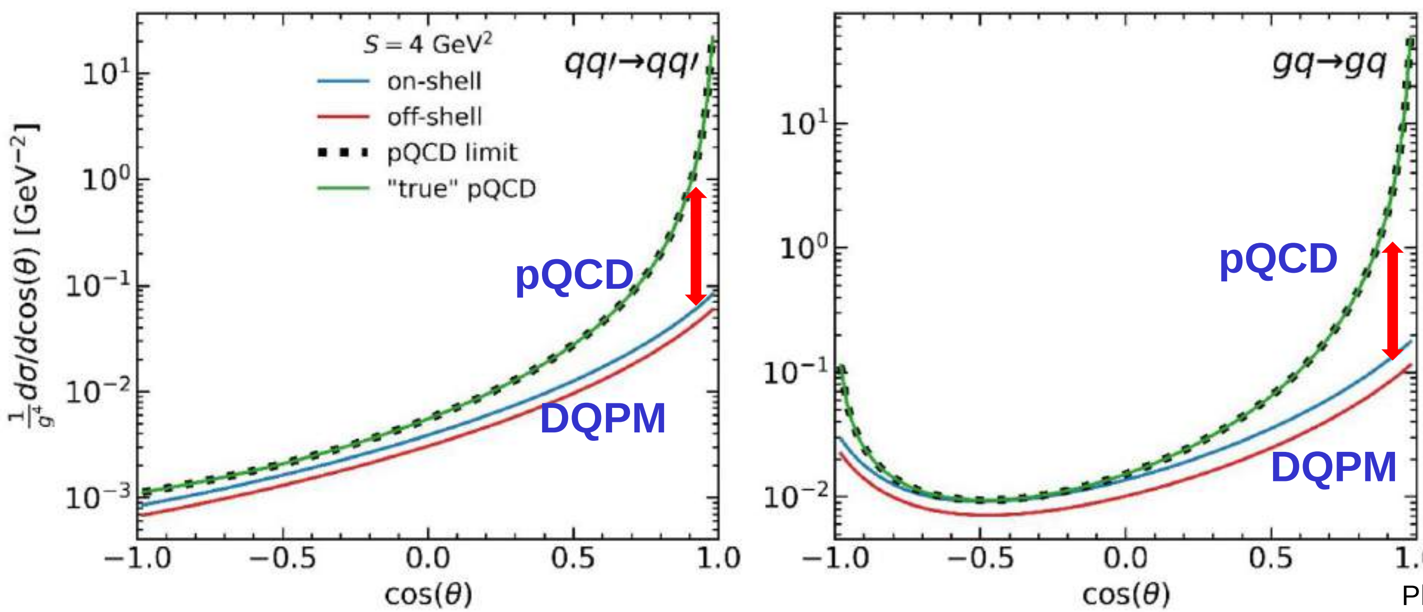


Initial masses: pole masses
Final masses: pole masses

- **Off-shell:**



Initial masses: pole masses
Final masses: integration over spectral functions



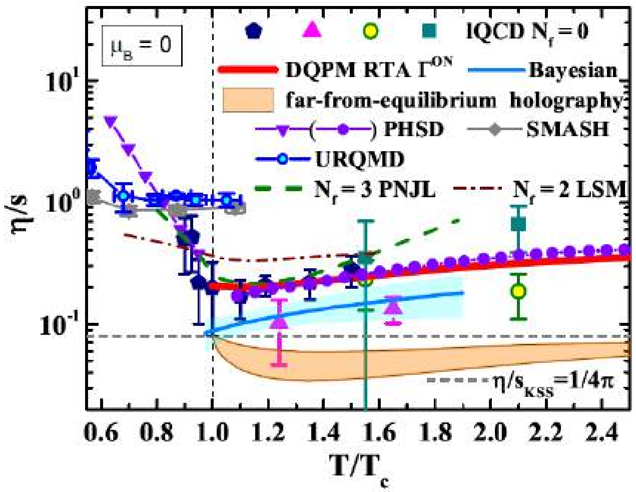
Plot: Ilia Grishmanovskii

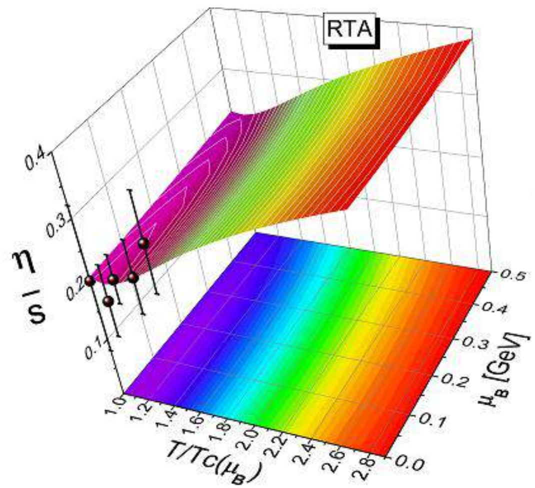
- **DQPM: M→0, γ→0 → reproduces pQCD limits**
- **Differences between DQPM and pQCD : less forward peaked angular distribution leads to more efficient momentum transfer**

P. Moreau et al., PRC100 (2019) 014911

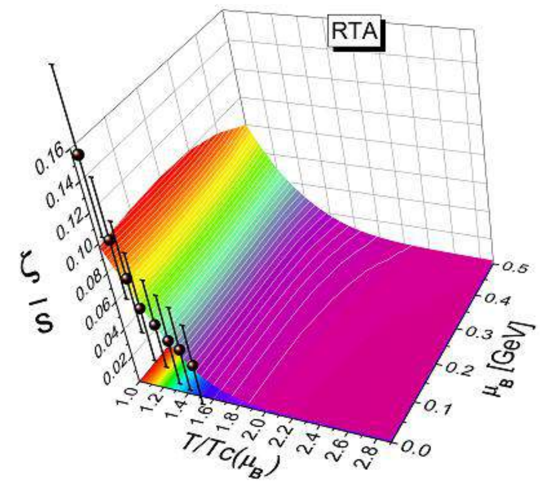
Transport coefficients

η/s versus (T,μ_B)

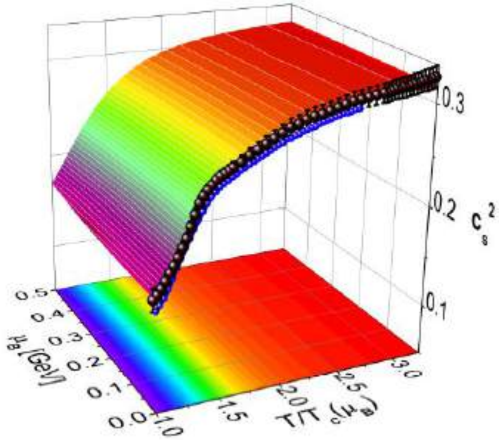




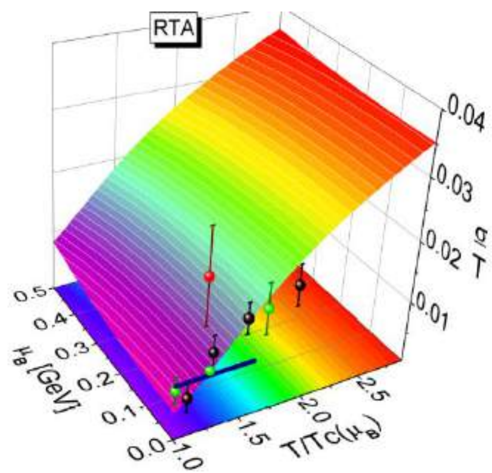
Bulk viscosity ζ/s



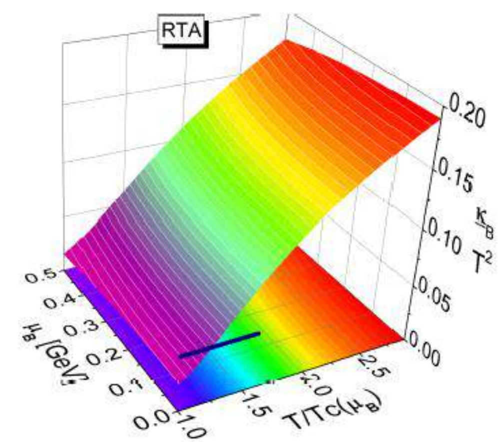
Speed of sound c_s^2



Electric conductivity σ_e/T



Baryon diffusion coefficient κ_B/T^2

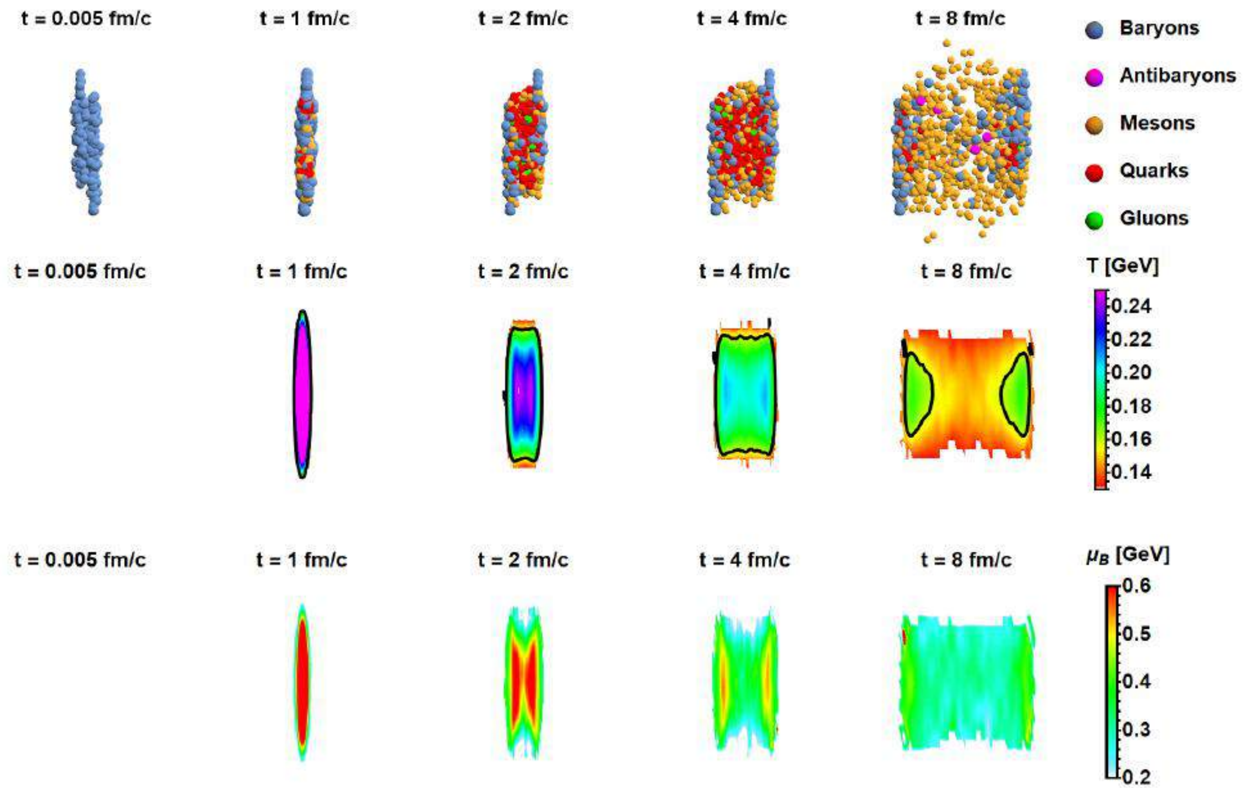


P. Moreau et al., PRC100 (2019) 014911;
O. Soloveva et al., PRC110 (2020) 045203

J. A. Fotakis, O. S., C. Greiner, O. Kaczmarek and E. Bratkovskaya PRD 104 (2021) , 034014

Traces of the QGP at finite μ_q in observables in high energy heavy-ion collisions

Au + Au $\sqrt{s_{NN}}$ = 19.6 GeV – b = 2 fm – Section view



PHSD: QGP evolution in HICs

Input:

ε^{PHSD} and n_B^{PHSD}

lQCD →

$$\frac{n_B}{T^3} \approx \chi_2^B(T)\left(\frac{\mu_B}{T}\right) + \ldots$$

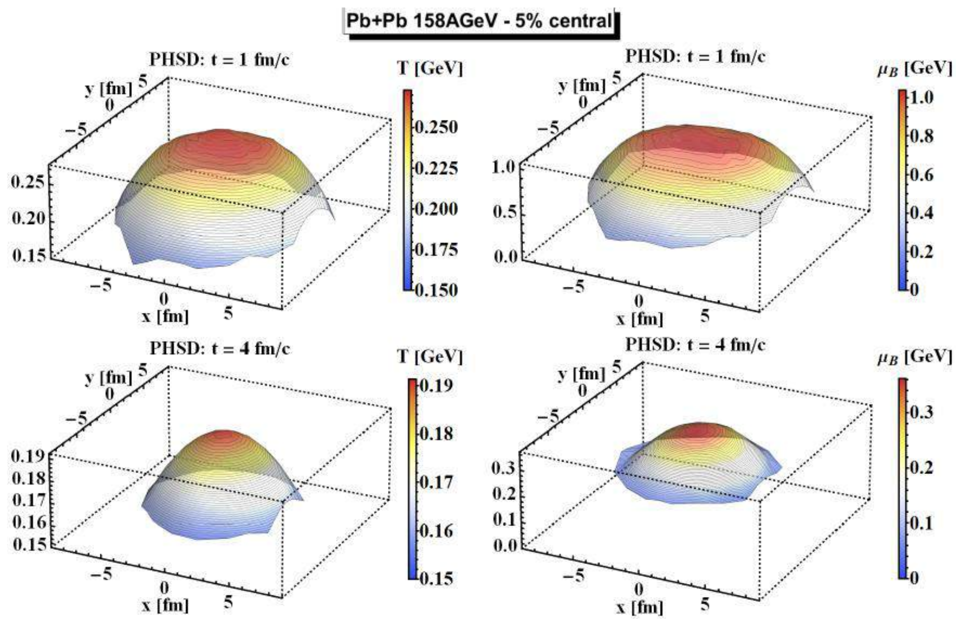
$$\Delta\epsilon/T^4 \approx \frac{1}{2}\left(T\frac{\partial\chi_2^B(T)}{\partial T} + 3\chi_2^B(T)\right)\left(\frac{\mu_B}{T}\right)^2 + \ldots$$

Output:

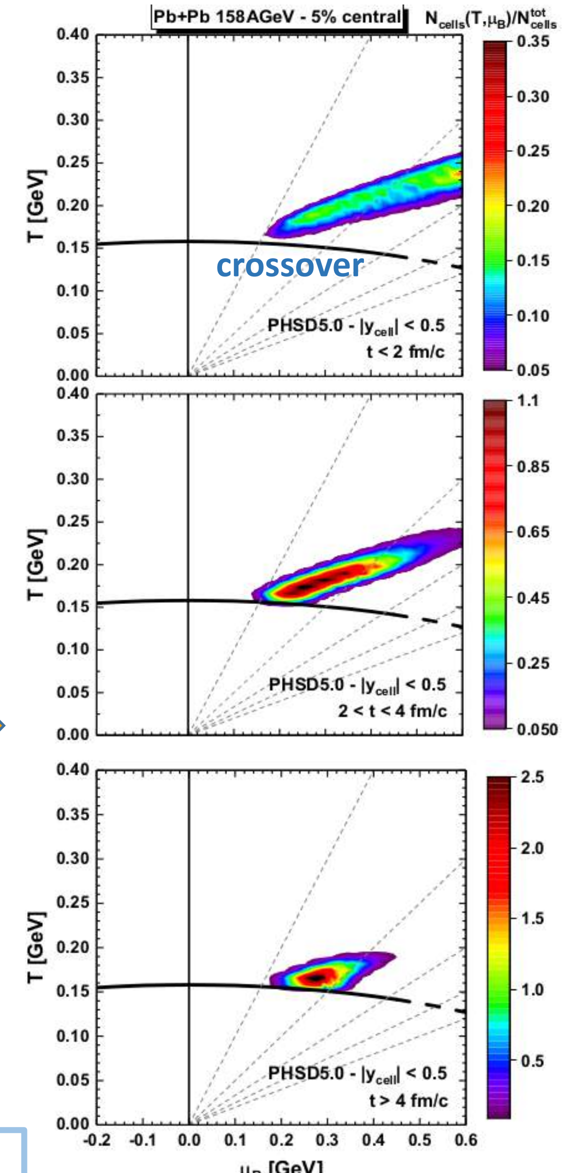
T, μ_B

T-profile in (x;y) & μ_B profile in (x;y)

at midrapidity ($|y_{cell}|$< 1) at fixed times(1 and 4 fm/c)



time evolution



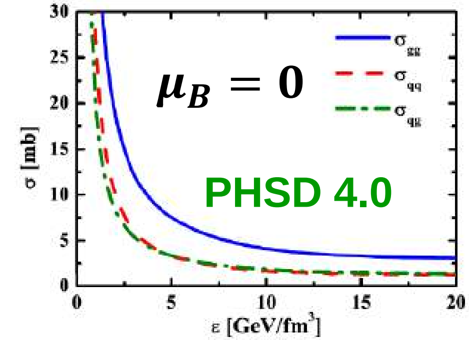
Path through the phase diagram is not trivial and not localized

Results for HICs from PHSD 4.0 and 5.0

Comparison between three different results:

- **PHSD 4.0 : only $\sigma(T)$ and $\rho(T)$**

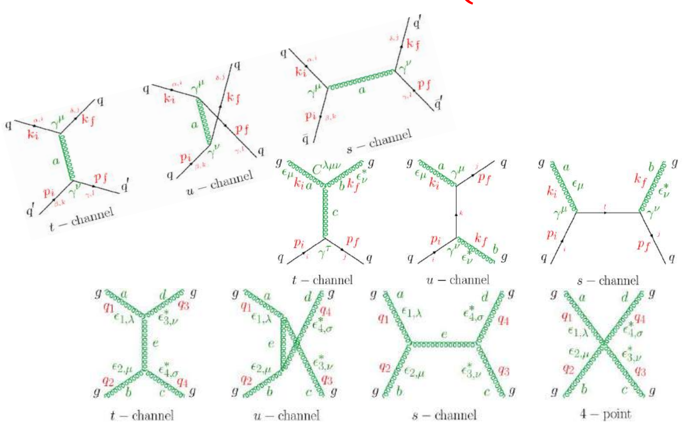
  $\sigma(T)$ – parton interaction cross sections
  $\rho(T)$ – spectral function of partons (masses and widths)

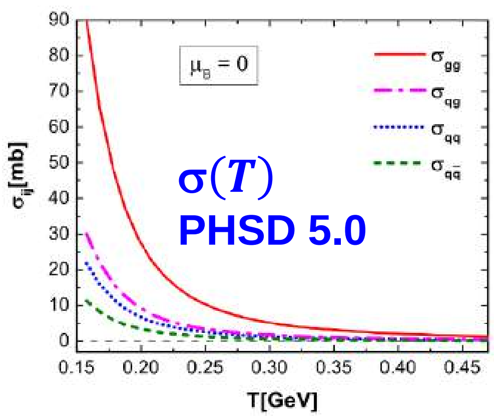


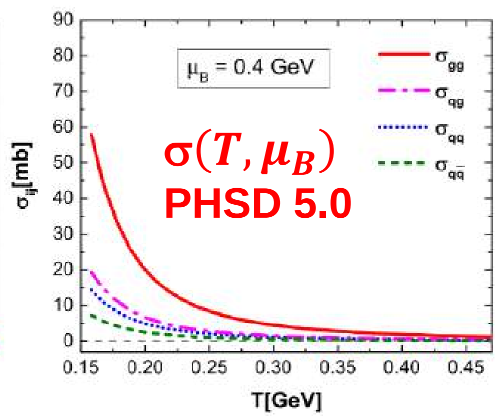
new PHSD 5.0 : $\sqrt{s} + \mu_B$ + angular dependence of $d\sigma/d\cos\theta$

- **PHSD 5.0 : with $\sigma(\sqrt{s}, m_1, m_2, T, \mu_B = 0)$ and $\rho(T, \mu_B = 0)$ with $d\sigma/d\cos\theta$**

- **PHSD 5.0 : with $\sigma(\sqrt{s}, m_1, m_2, T, \mu_B)$ and $\rho(T, \mu_B)$ with $d\sigma/d\cos\theta$**







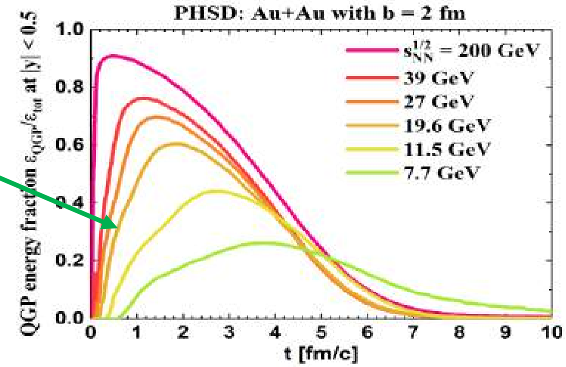
P. Moreau, O. Soloveva , L. Oliva, T. Song, W. Cassing, E. Bratkovskaya, PRC 100 (2019) , 014911;
O. Soloveva, P. Moreau, L. Oliva, V. Voronyuk, V. Kireyeu, T. Song, E. Bratkovskaya, Particles 3 (2020), 178-192

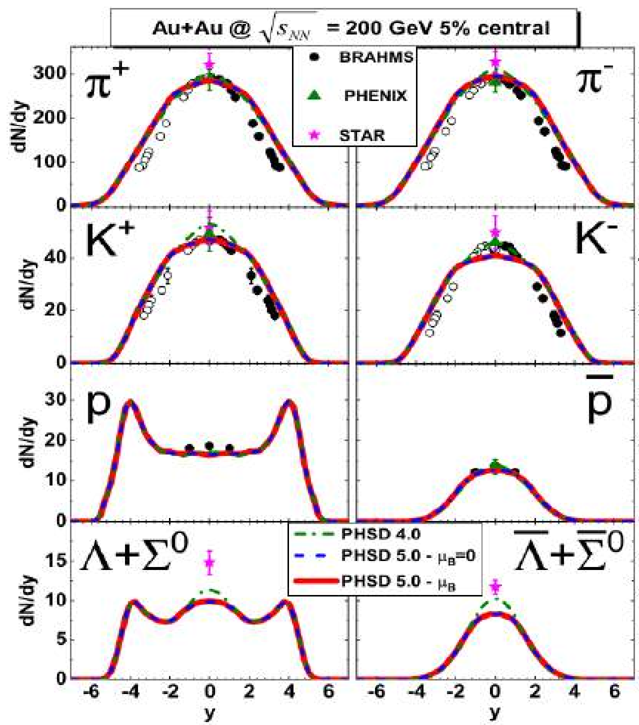
Results for ($\sqrt{s_{NN}} = 200$ GeV - 7 GeV)

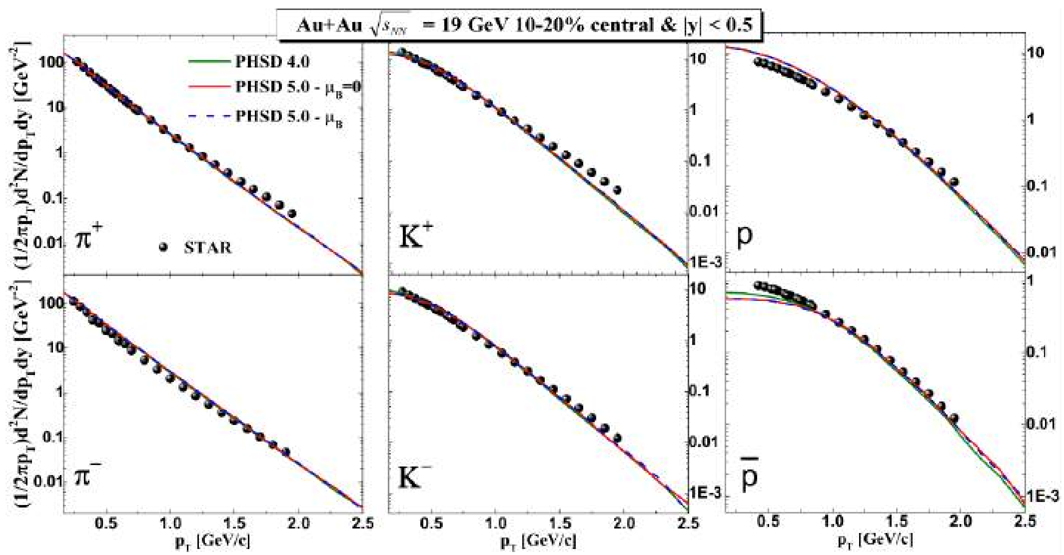
- **No visible effects on p_T-spectra, dN/dy of μ_B -dependence**
- **Small effect of the angular dependence of $d\sigma/d\cos\theta$**

at high $\sqrt{s_{NN}}$ - low μ_B

! QGP fraction is small at low $\sqrt{s_{NN}}$



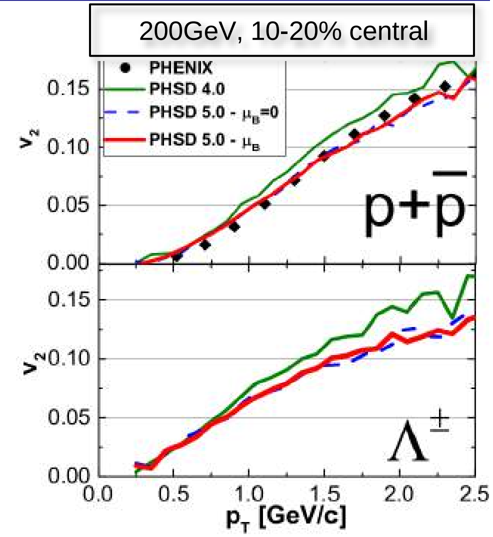




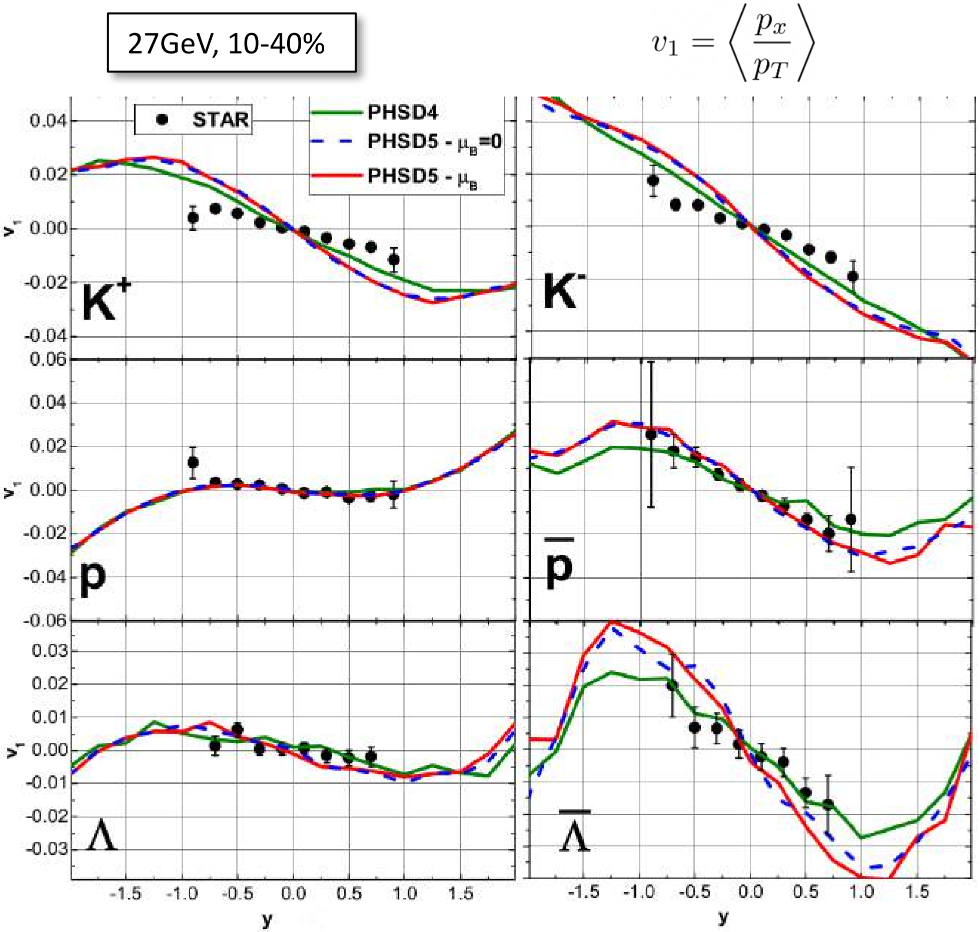
P. Moreau, O. Soloveva , L. Oliva, T. Song, W. Cassing, E. Bratkovskaya, PRC 100 (2019) , 014911;
O. Soloveva, P. Moreau, L. Oliva, V. Voronyuk, V. Kireyeu, T. Song, E. Bratkovskaya, Particles 3 (2020), 178-192

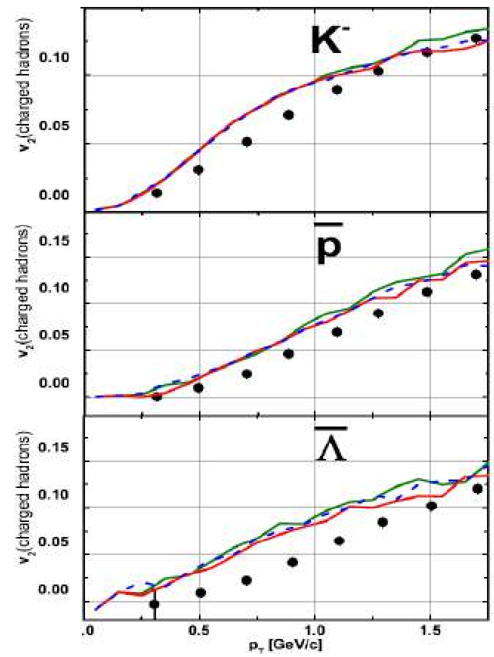
Elliptic flow ($\sqrt{s_{NN}} = 200$ GeV $- 27$GeV)

- **Weak μ_B –dependence – small fraction of QGP or low μ_B**
- **Small effect of the angular dependence of $d\sigma/d\cos\theta$**
- **Strong flavor dependence**



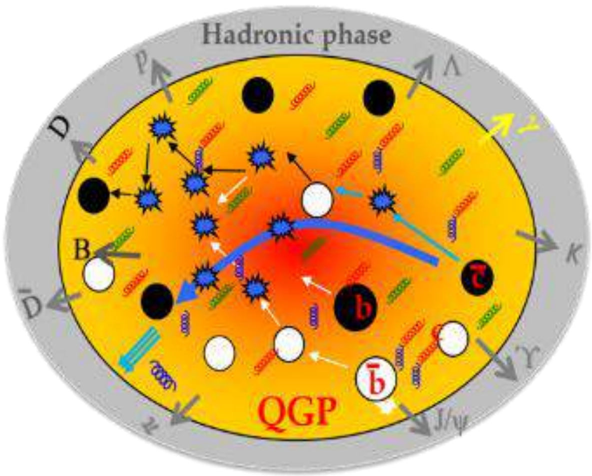
$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle \qquad v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$$



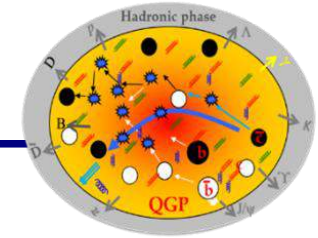


O. Soloveva, P. Moreau, L. Oliva, V. Voronyuk, V. Kireyeu, T. Song, E. Bratkovskaya, Particles 3 (2020), 178-192

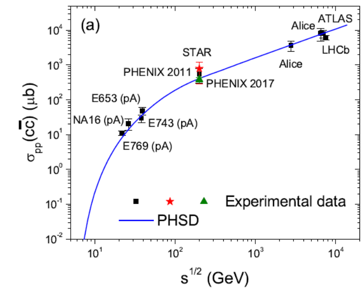
Dynamics of heavy quarks – open charm and beauty (D/Dbar, B/Bbar) – in heavy-ion collisions



Charm dynamics in PHSD

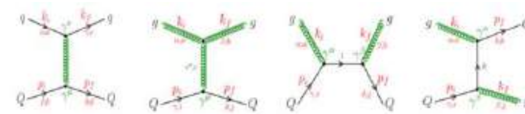


Dynamics of heavy quarks in A+A :



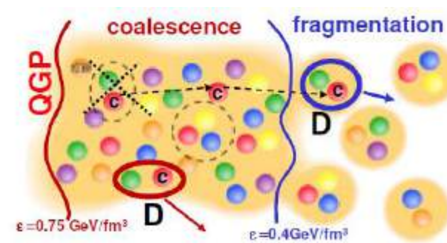
1. **Production of heavy (charm and bottom) quarks in initial binary collisions + shadowing and Cronin effects**

2. **Interactions in the non-perturbative QGP – according to the DQPM: elastic scattering with off-shell massive partons Q+q→Q+q**
   ➔ collisional energy loss

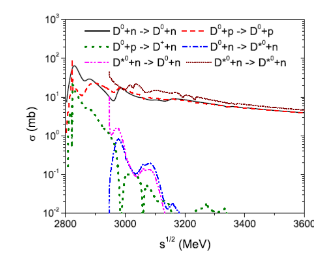


3. **Hadronization: c/cbar quarks →D(D*)-mesons:**

   Dynamical hadronization scenario for heavy quarks :
   coalescence with <r>=0.9 fm & fragmentation
   0.4< ε < 0.75 GeV/fm³ ε < 0.4 GeV/fm³



4. **Hadronic interactions:**
   D+baryons; D+mesons based on G-matrix and effective chiral Lagrangian approach with heavy-quark spin symmetry (>200 channels)
   (Juan Torres-Rincon, Laura Tolos)



* PHSD references on charm dynamics:

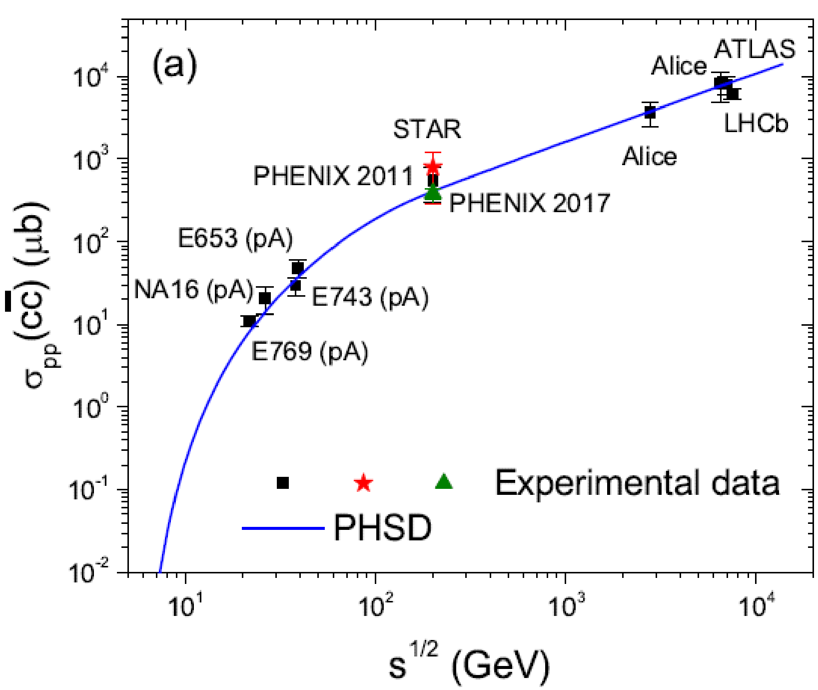
Taesoo Song et al., PRC 92 (2015) 014910, PRC 93 (2016) 034906, PRC 96 (2017) 014905

PRC 97 (2018) 064907; PRC 101 (2020) 044901; PRC 101 (2020) 044903

Charm production in NN collisions

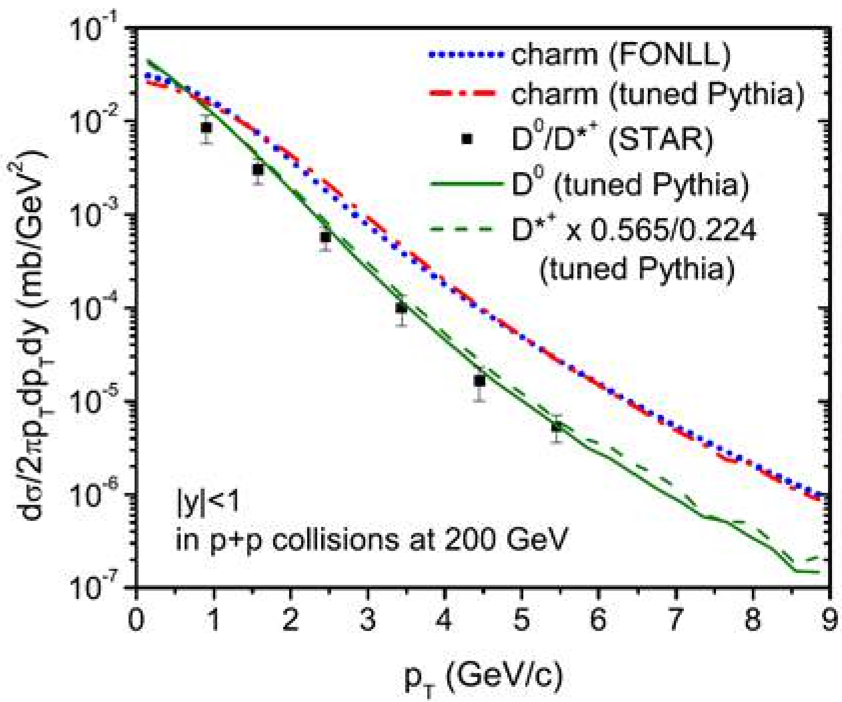
- A+A: charm production in initial NN binary collisions: probability $P = \frac{\sigma(c\bar{c})}{\sigma_{NN}^{inel}}$

The total cross section for charm production in p+p collisions σ(cc)



T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, PRC 97 (2018) 064907

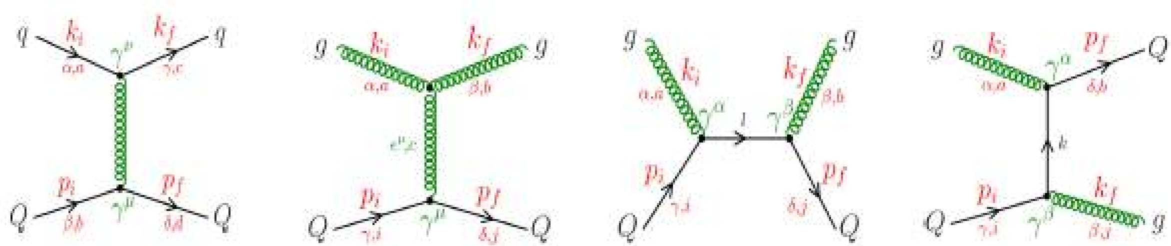
Momentum distribution of heavy quarks:
use ‚tuned' PYTHIA event generator to reproduce FONLL (fixed-order next-to-leading log) results



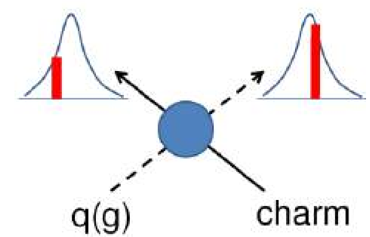
T. Song et al., PRC 92 (2015) 014910, PRC 93 (2016) 034906, PRC 96 (2017) 014905

Heavy quark scattering in the QGP (DQPM)

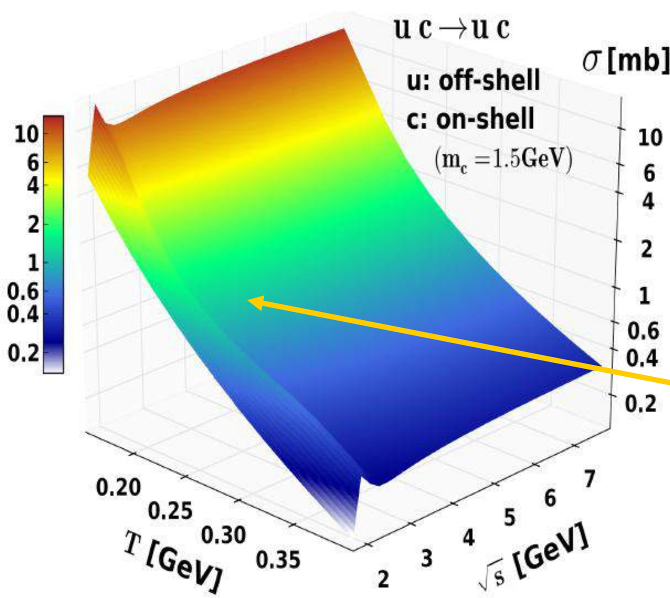
- Elastic scattering with off-shell massive partons Q+q(g)→Q+q(g)



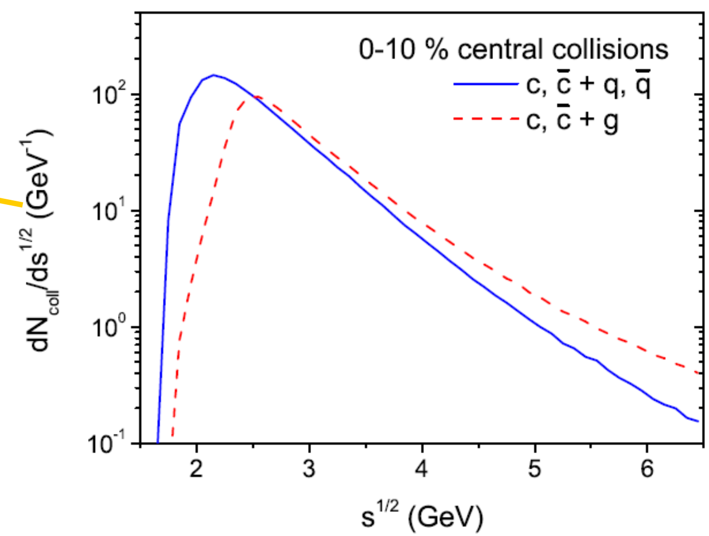
Non-perturbative QGP!



- Elastic cross section uc→uc



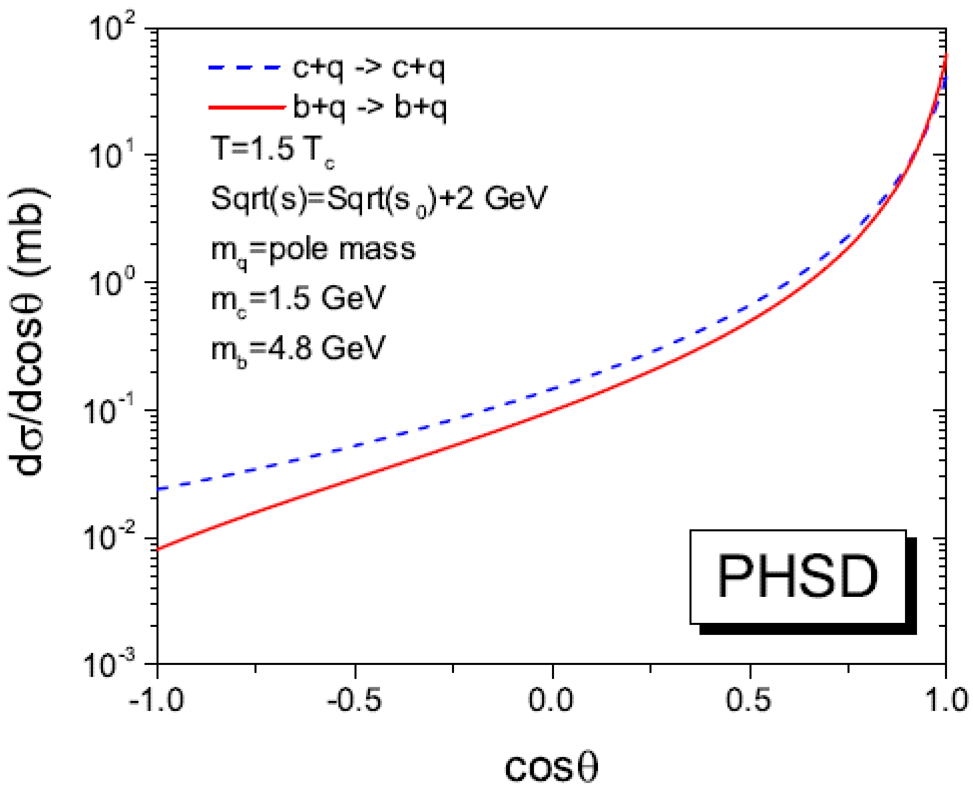
- Distributions of Q+q, Q+g collisions vs $s^{1/2}$ in Au+Au, 200 GeV, 10% central



H. Berrehrah et al, PRC 89 (2014) 054901;
PRC 90 (2014) 051901; PRC90 (2014) 064906

Heavy quark scattering in the QGP

- **Differential elastic cross section for cq→cq, bq→bq for $s^{½}=s_0^{½}$ +2GeV at 1.5T$_C$**



- **DQPM - anisotropic angular distribution**

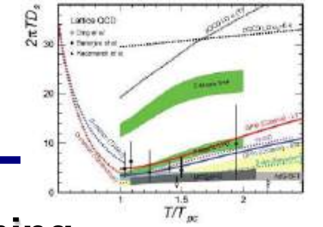
Note: pQCD - strongly forward peaked
→ Differences between DQPM and pQCD : less forward peaked angular distribution leads to more efficient momentum transfer

→ Smaller number (compared to pQCD) of elastic scatterings with massive partons leads to a larger energy loss

! Note: radiative energy loss is NOT included yet in PHSD,
it is expected to be small (at low p_T) due to the large gluon mass in the DQPM

H. Berrehrah et al, PRC 89 (2014) 054901; PRC 90 (2014) 051901; PRC90 (2014) 064906

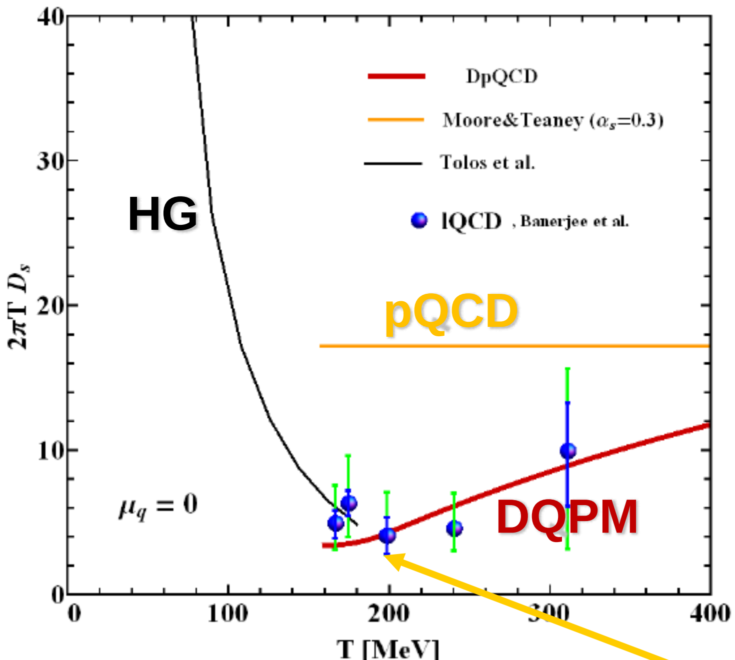
Charm spatial diffusion coefficient D_s



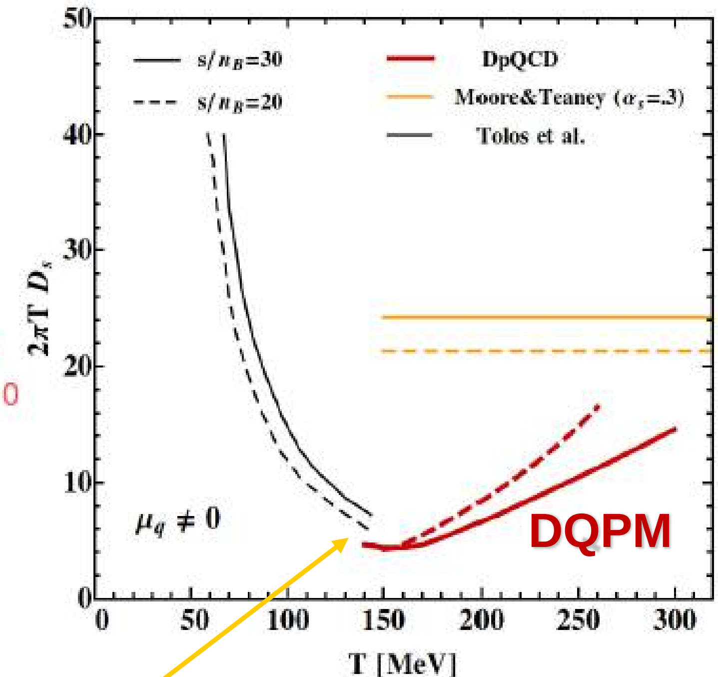
- **D_s for heavy quarks as a function of T for μ_q=0 and finite μ_q assuming adiabatic trajectories (constant entropy per net baryon s/n_B) for the expansion**

$$D_s = lim(\vec{p} \to 0) \frac{T}{M \eta_D}$$

where η_D = A/p ; A(p,T) = drag coefficient



$\Rightarrow$ $\mu_q \neq 0$



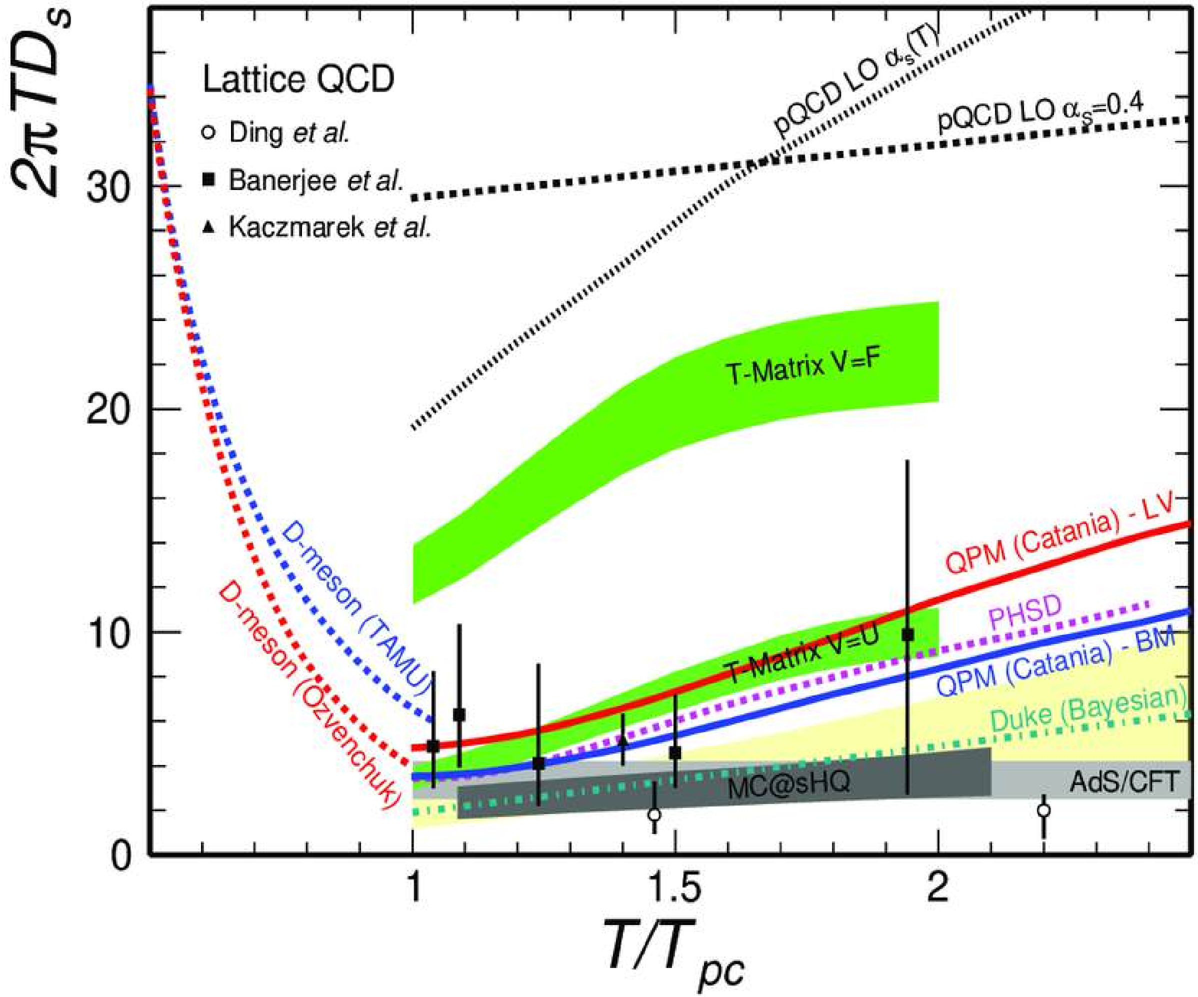
- **T < T_c : hadronic D_s**

L. Tolos , J. M. Torres-Rincon, PRD 88 (2013) 074019
V. Ozvenchuk et al., PRC90 (2014) 054909

➔ Continuous transition at T_C!

H. Berrehrah et al, PRC 90 (2014) 051901, arXiv:1406.5322

Charm spatial diffusion coefficient D_s



Hadronization of heavy quarks in A+A

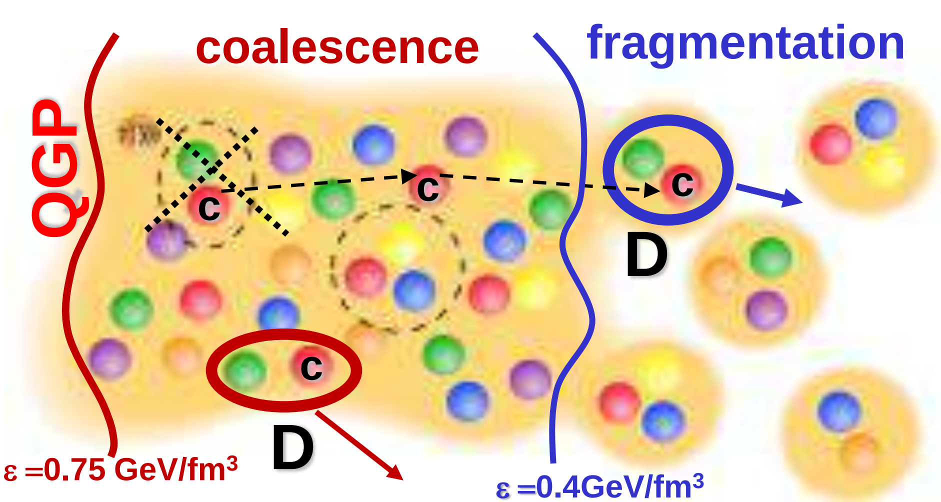
- PHSD: if the local energy density $\varepsilon \rightarrow \varepsilon_C$ ➔ hadronization of heavy quarks to hadrons

T. Song et al., PRC 93 (2016) 034906

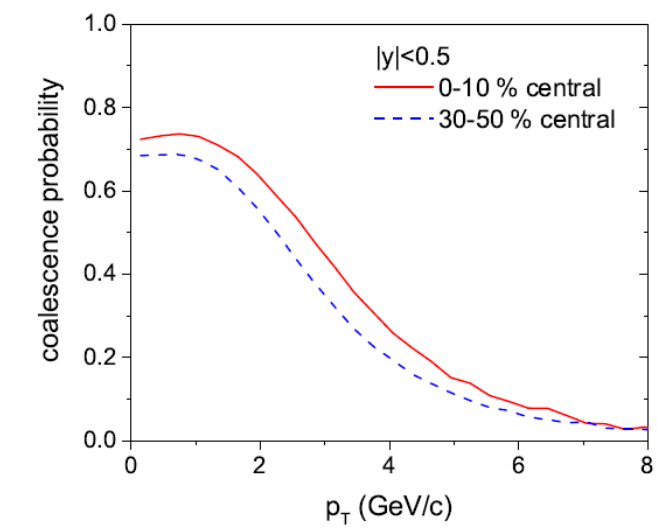
Dynamical hadronization scenario for heavy quarks :

coalescence with <r>=0.9 fm & fragmentation

$0.4 < \varepsilon < 0.75$ GeV/fm^3 $\varepsilon < 0.4$ GeV/fm^3



Coalescence probability in Au+Au at LHC



Coalescence probability for $c+\bar{q} \rightarrow D$

$$f(\boldsymbol{\rho}, \mathbf{k}_\rho) = \frac{8 g_M}{6^2} \exp\left[-\frac{\boldsymbol{\rho}^2}{\delta^2} - \mathbf{k}_\rho^2 \delta^2\right]$$

Width δ ← from root-mean-square radius of meson <r>:

where $\boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\mathbf{r}_1 - \mathbf{r}_2), \quad \mathbf{k}_\rho = \sqrt{2}\,\frac{m_2 \mathbf{k}_1 - m_1 \mathbf{k}_2}{m_1 + m_2}$

$$\langle r^2 \rangle = \frac{3}{2}\frac{m_1^2 + m_2^2}{(m_1+m_2)^2}\delta^2$$

Degeneracy factor : $g_M = 1$ for D, $= 3$ for $D^* = D^*_0(2400)^0$, $D^*_1(2420)^0$, $D^*_2(2460)^{0\pm}$

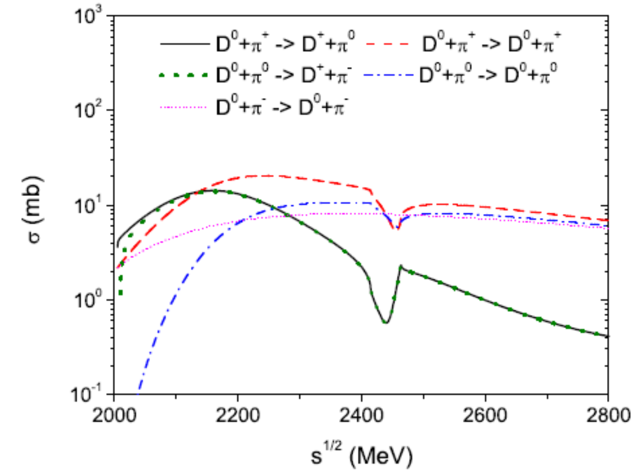
D-meson scattering in the hadronic phase

1. D-meson scattering with mesons

L. M. Abreu, D. Cabrera, F. J. Llanes-Estrada, J. M. Torres-Rincon, Annals Phys. 326, 2737 (2011)

Model: effective chiral Lagrangian approach with heavy-quark spin symmetry

Interaction of $D=(D^0,D^+,D^+_s)$ and $D^*=(D^{*0},D^{*+},D^{*+}_s)$ with octet $(\pi,K,\bar{K},\eta)$



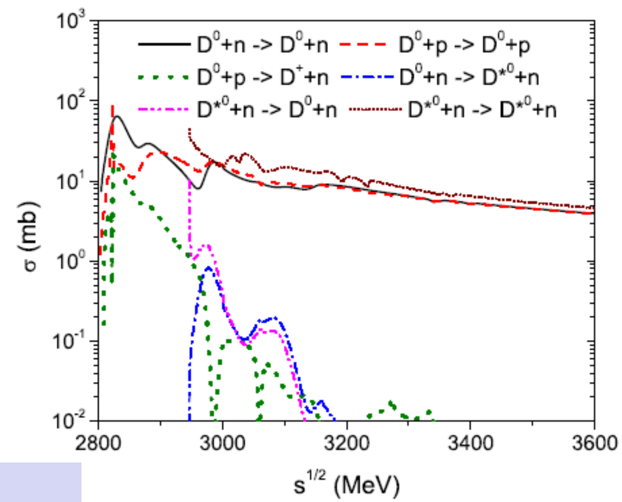
2. D-meson scattering with baryons

C. Garcia-Recio, J. Nieves, O. Romanets, L. L. Salcedo, L. Tolos, Phys. Rev. D 87, 074034 (2013)

Model: G-matrix approach: **interactions of $D=(D^0,D^+,D^+_s)$ and $D^*=(D^{*0},D^{*+},D^{*+}_s)$ with nucleon octet $J^P=1/2^+$ and Delta decuplet $J^P=3/2^+$**

Unitarized scattering amplitude ➔ solution of coupled-channel Bethe-Salpeter equations:

$$T = T + VGT$$

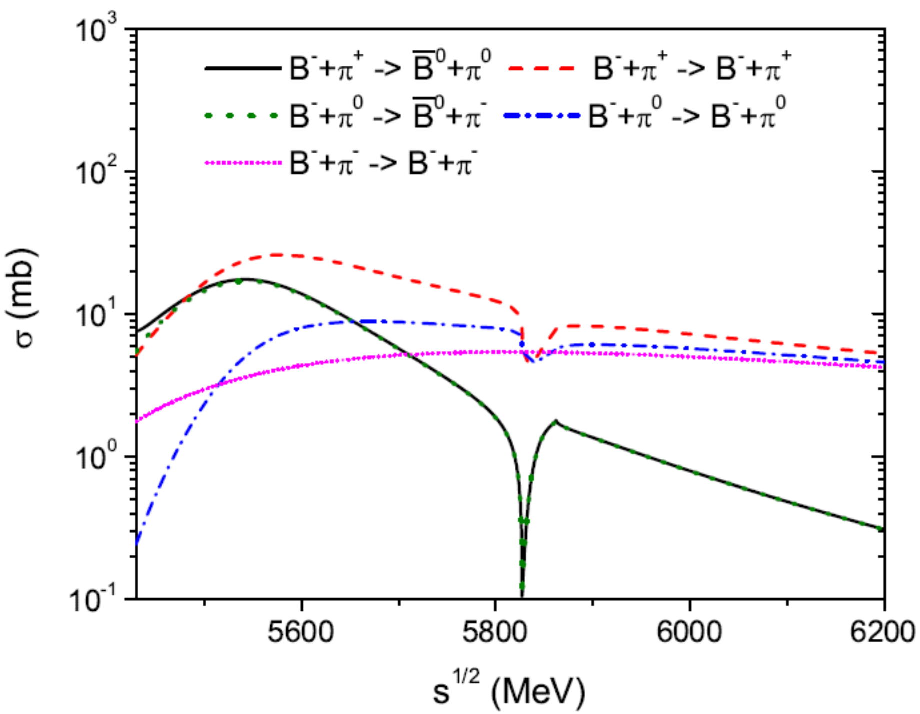


➔ **Strong isospin dependence and complicated structure (due to the resonance coupling) of D+m, D+B cross sections!**

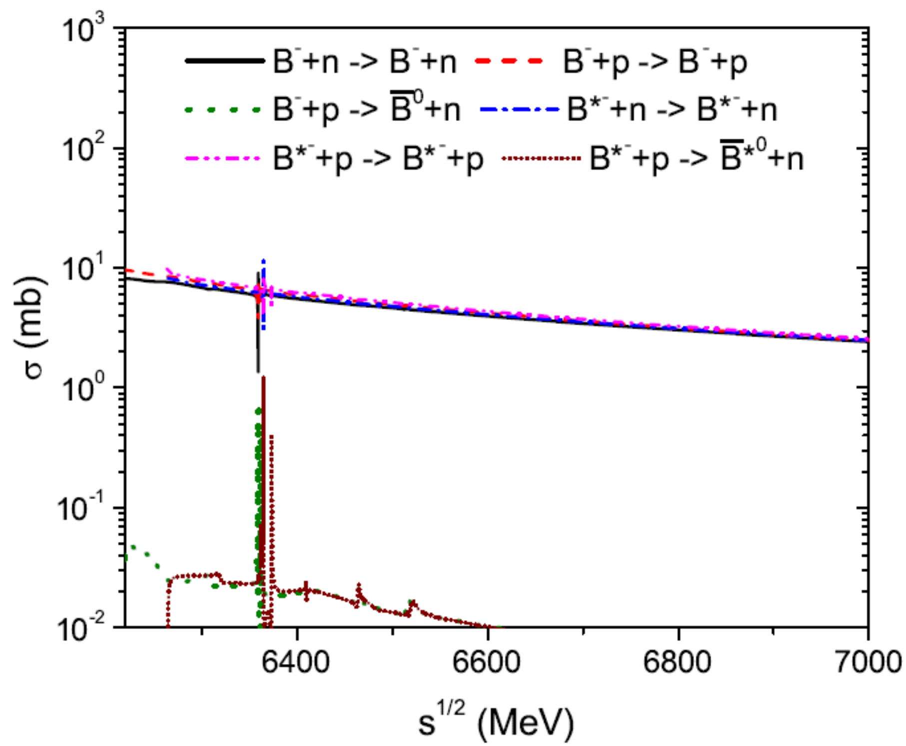
B-meson scattering in the hadron gas

L. Tolos and J. M. Torres-Rincon, Phys. Rev. D 88, 074019 (2013)
J. M. Torres-Rincon, L. Tolos and O. Romanets, Phys. Rev. D 89, 074042 (2014)

1. B-meson scattering with mesons



2. B-meson scattering with baryons

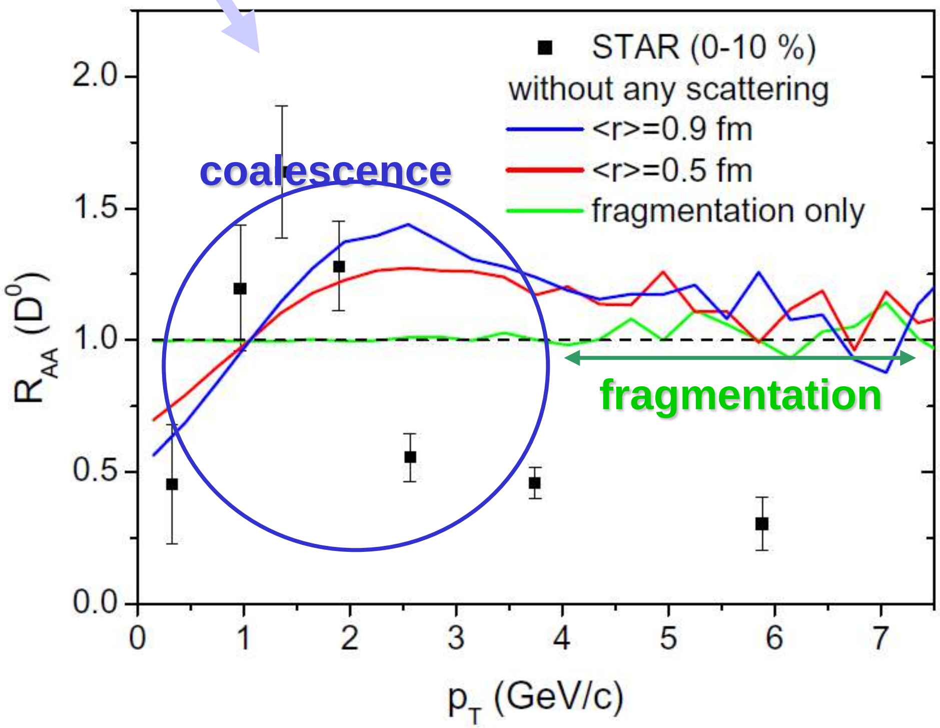


- **>200 hadronic channels ➔ implemented in the PHSD (by Taesoo Song)**

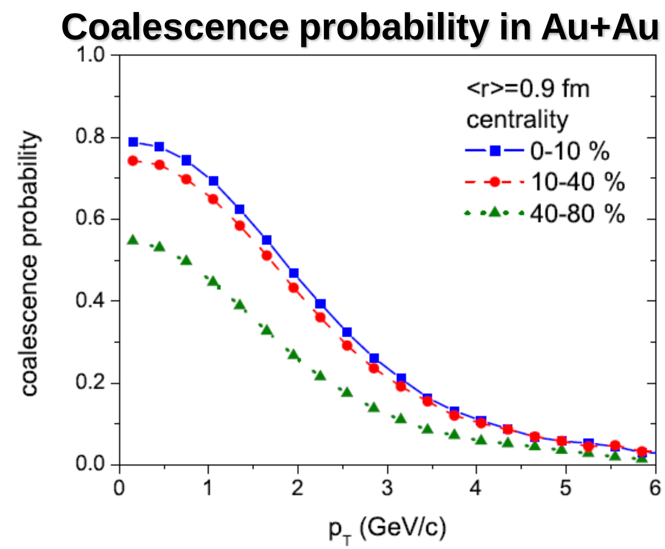
R_{AA} at RHIC - coalescence vs fragmentation

Influence of hadronization scenarios: coalescence vs fragmentation

! Model study: without any rescattering (partonic and hadronic)



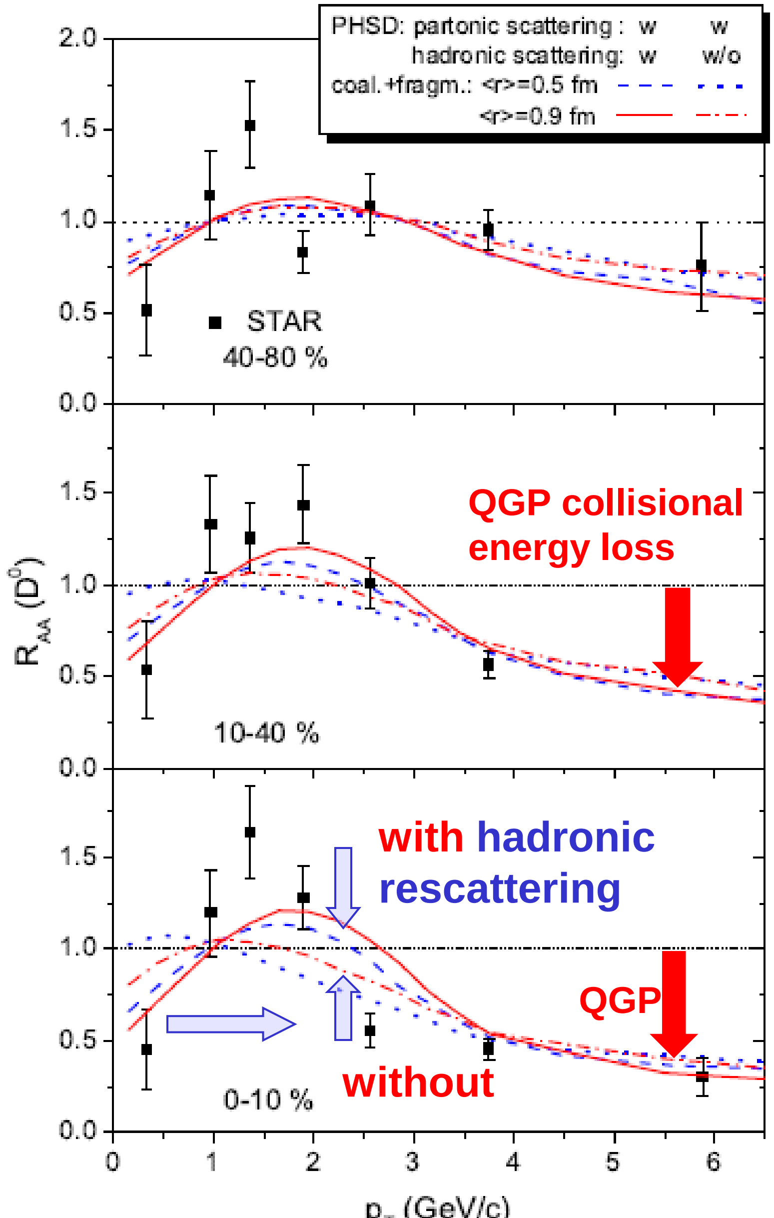
$$R_{AA}(p_T) \equiv \frac{dN_D^{\mathrm{Au+Au}}/dp_T}{N_{\mathrm{binary}}^{\mathrm{Au+Au}} \times dN_D^{\mathrm{p+p}}/dp_T}$$



- Expect: no scattering: R_{AA}=1
- Hadronization by fragmentation only (as in pp) → R_{AA}=1
- Coalescence (not in pp!) shifts R_{AA} to larger p_T → ‚nuclear matter' effect
- The hight of the R_{AA} peak depends on the balance: coalescence vs. fragmentation

T. Song et al., PRC 92 (2015) 014910

R_{AA} at RHIC: hadronic rescattering



Influence of hadronic rescattering:

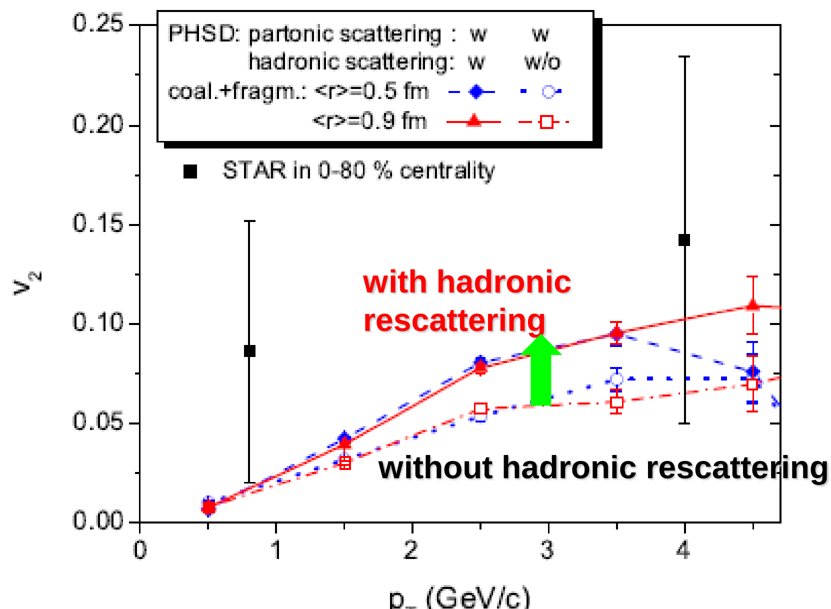
Central Au+Au at $s^{1/2}$ =200 GeV :

N(D,D*) ~30

N(D,D*+m) ~56 collisions

N(D,D*+B,Bbar) ~10 collisions

➔ **each D,D* makes ~ 2 scatterings with hadrons**



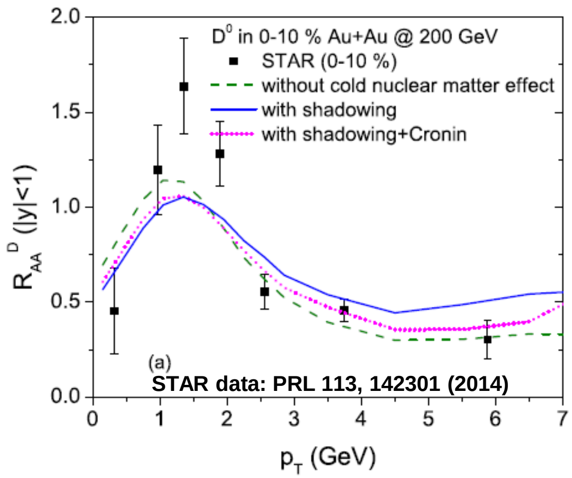
- ❑ **Hadronic rescattering moves R_{AA} peak to higher p_T !**
- ❑ **substantially increases v_2 at larger p_T**

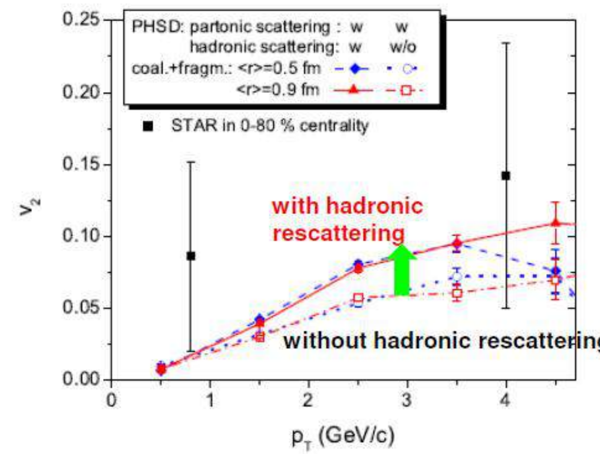
T. Song et al., PRC 92 (2015) 014910

PHSD vs charm observables at RHIC

STAR

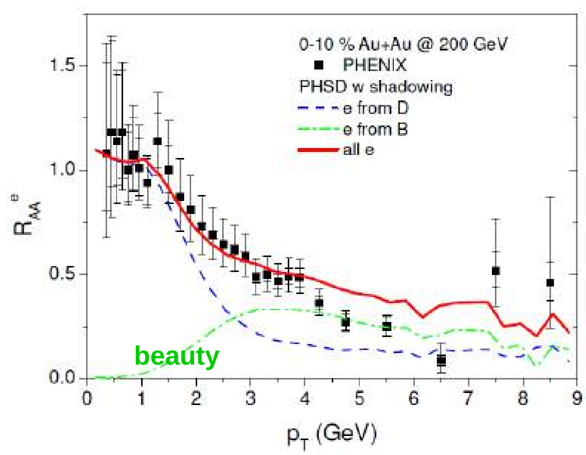
R_{AA} and v_2 vs p_T
from D^0 -mesons
in Au+Au @ 200 GeV ➔

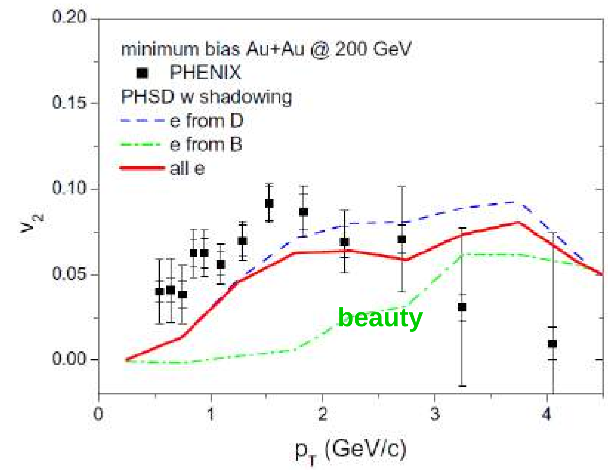




PHENIX

R_{AA} and v_2 vs p_T
from single electrons
in Au+Au @ 200 GeV ➔

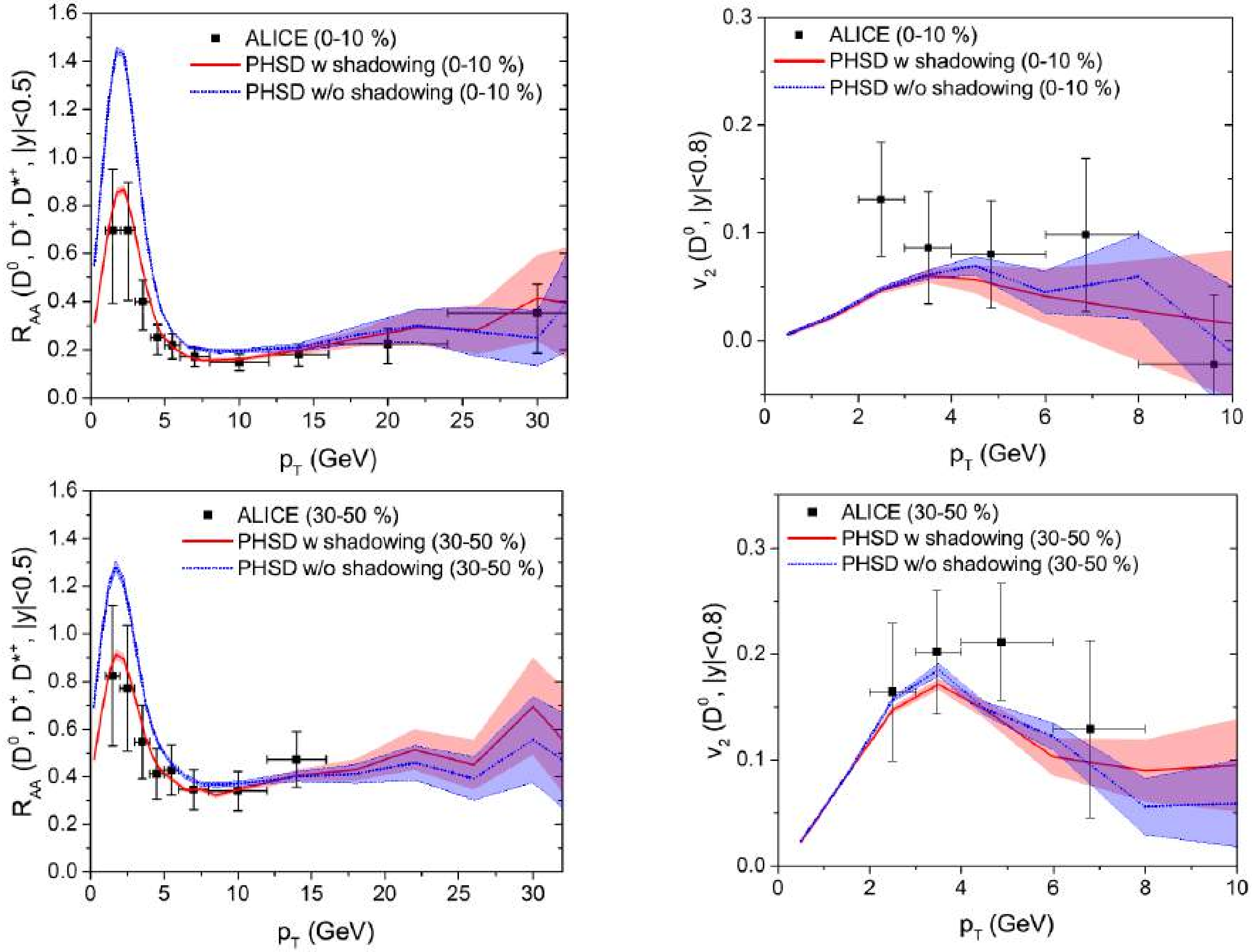




- ❑ The exp. data for the R_{AA} and v_2 are described in the PHSD by QGP collisional energy loss due to elastic scattering of charm quarks with massive quarks and gluons in the QGP
+ by the dynamical hadronization scenario „coalescence & fragmentation“
+ by strong hadronic interactions due to resonant elastic scattering of D,D* with mesons and baryons
- ❑ Feed back from beauty contribution becomes dominant for single electrons R_{AA} and v_2 at p_T >3 GeV

T. Song et al., PRC 92 (2015) 014910, PRC 93 (2016) 034906, PRC 96 (2017) 014905

Charm R_{AA} at LHC: PHSD vs ALICE

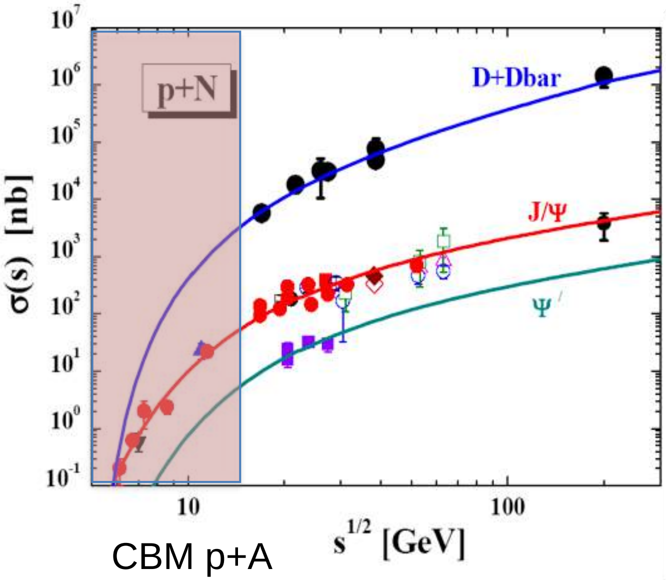


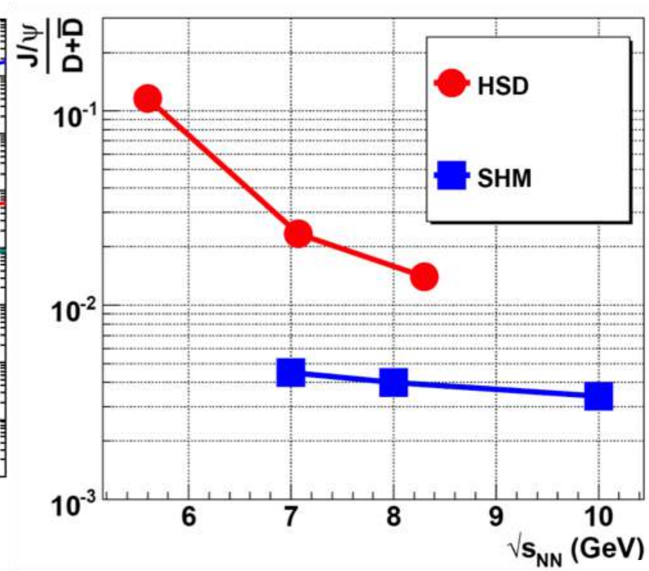
- **in PHSD the energy loss of D-mesons at high p_T can be dominantly attributed to partonic scattering**
- **Shadowing effect suppresses the low p_T and slightly enhances the high p_T part of R_{AA}**
- **Hadronic rescattering moves R_{AA} peak to higher p_T; increases v_2**

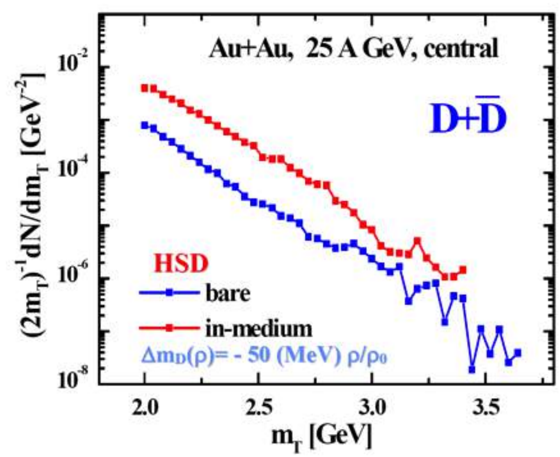
T. Song et al., PRC 93 (2016) 034906

Why Open Charm with CBM?

O. Lynnek et al., Nucl. Phys. A 786 (2007) 183







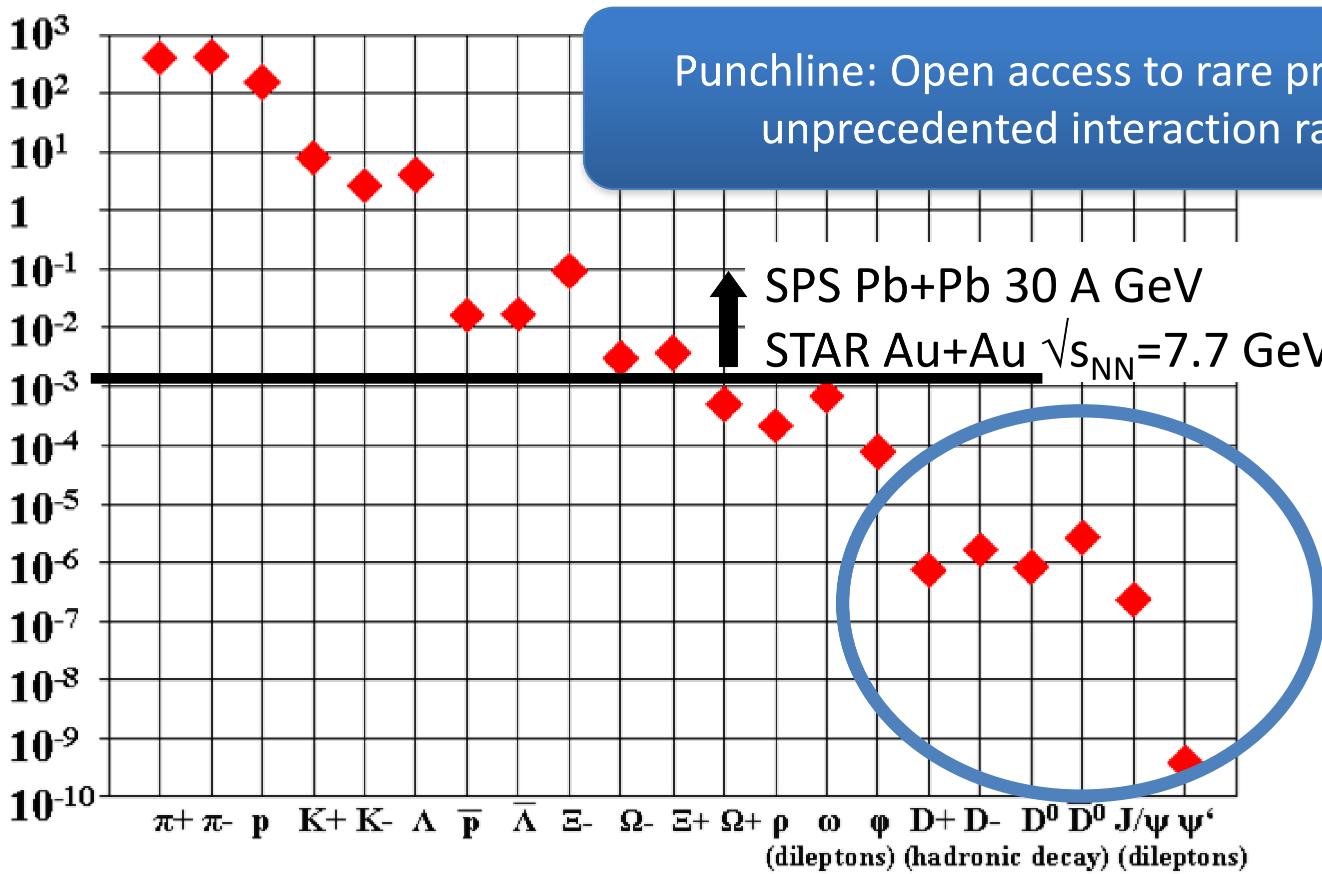
- elementary cross section experimentally unknown
- no data in A+A below RHIC energies
- open / hidden charm seems promising observable to distinguish phases
- in-medium modification of D masses?

Slide from

Experimental challenges: Rare probes

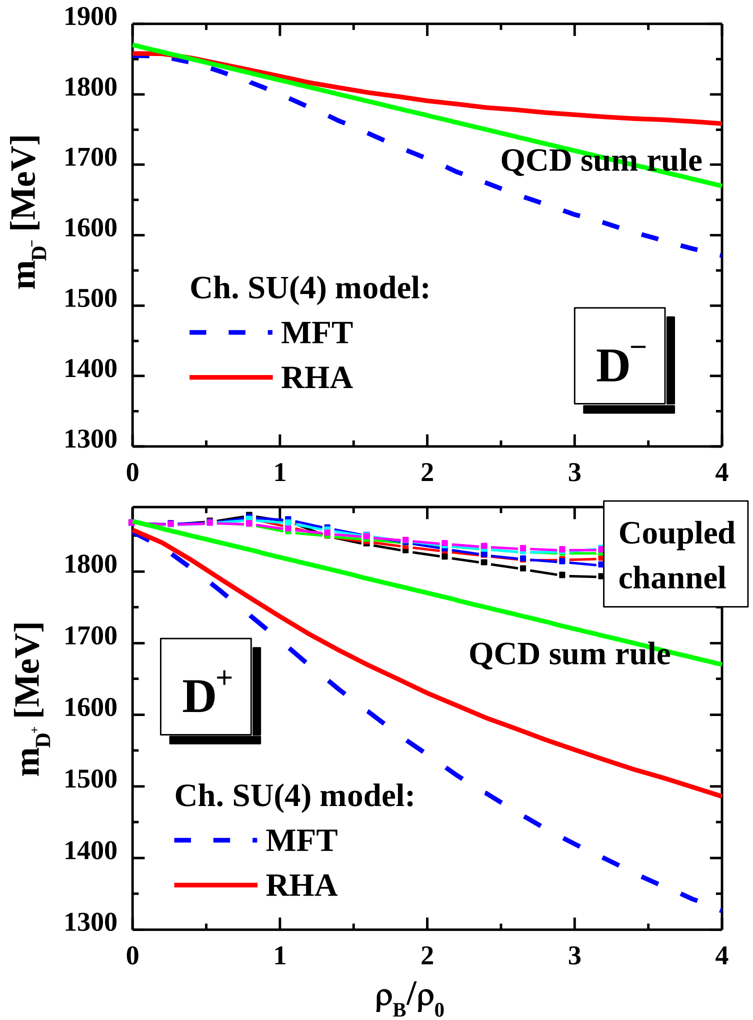
particle multiplicity
× branching ratio

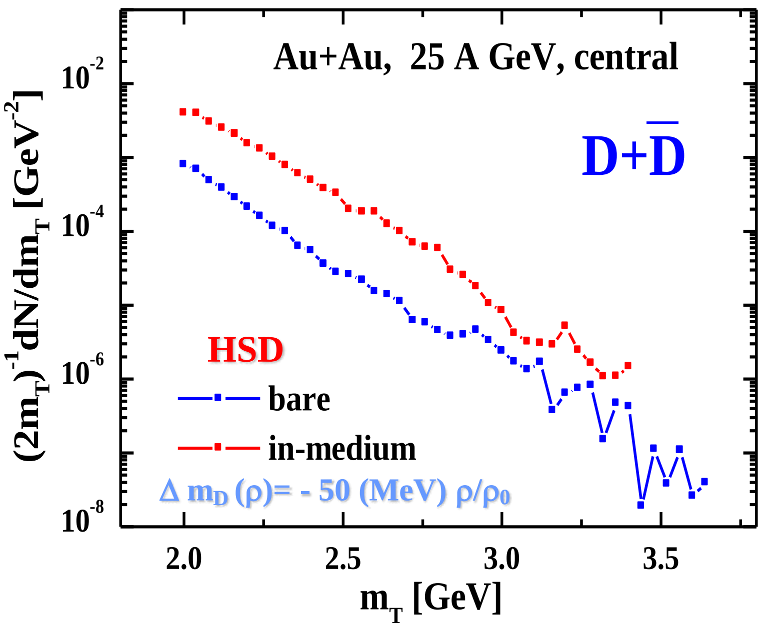
min. bias Au+Au collisions at 25 AGeV
(from HSD and thermal model)



Slide from

D/Dbar-mesons: in-medium effects





- Dropping D-meson masses with increasing light quark density might give a large enhancement of the open charm yield at 25 A GeV !

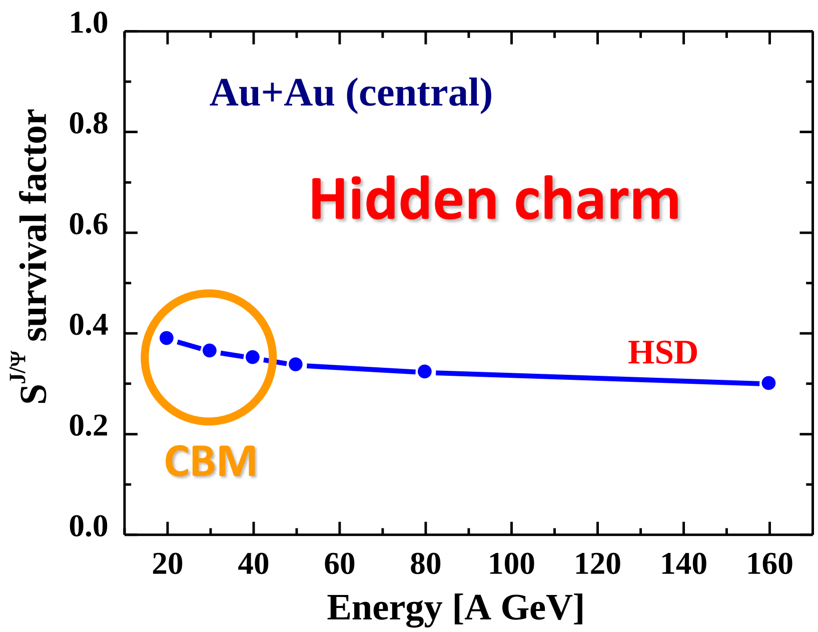
FAIR (CBM)

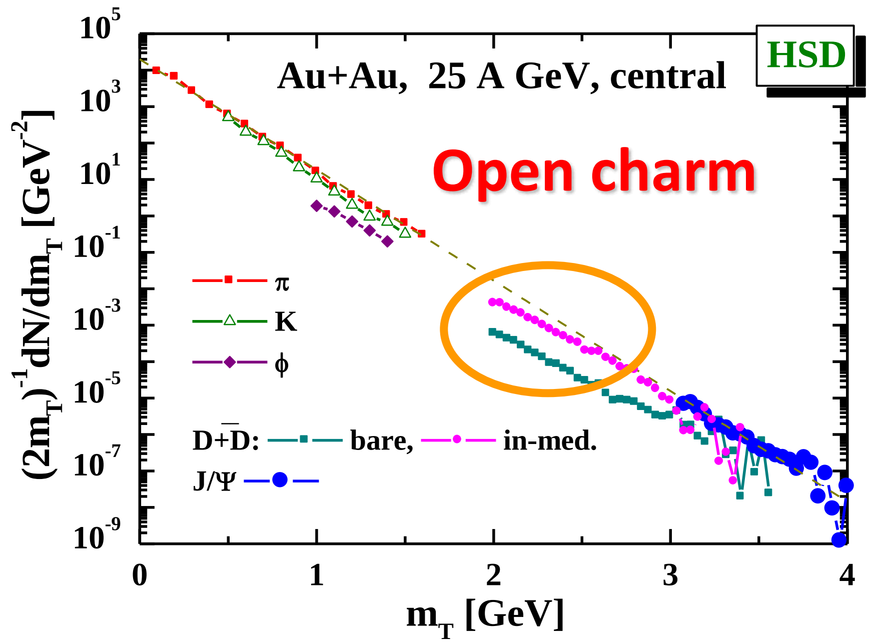
- Charmonium suppression increases for dropping D-meson masses!

Ch. SU(4): A. Mishra et al., PRC69 (2004) 015202
QCD sum rule: Hayashigaki, PLB487 (2000) 96
Coupled channel: Tolos et al., EPJ C43 (2005) 761

HSD: NPA691 (2001) 761

Open and hidden charm – HSD predictions for CBM





Open charm:

- **without medium effects:** suppression of D-meson spectra by factor ~ 10 relative to the global m_T-scaling
- **with medium effects:** restoration of the global m_T-scaling for the mesons

Hidden charm:

J/Ψ suppression due to comover absorption at FAIR is lower than at SPS

HSD: NPA691 (2001) 761