Dynamical description of heavy-ion collisions

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for the PHSD group

COST Workshop on Interplay of hard and soft QCD probes for collectivity in heavy-ion collisions

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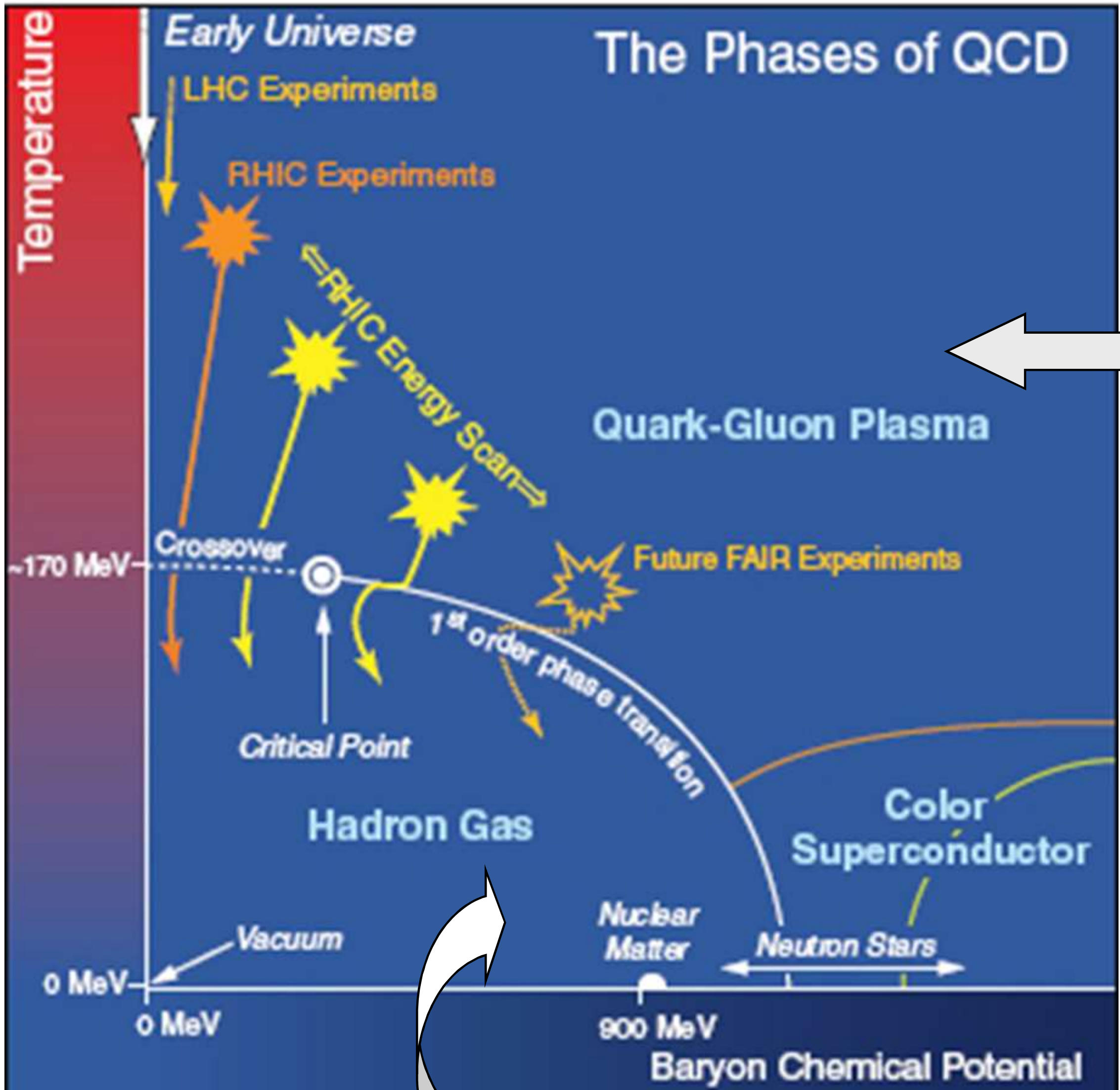
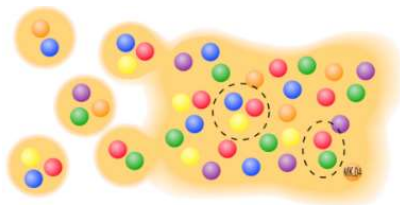
The ‚holy grail‘ of heavy-ion physics:



The phase diagram of QCD

- **Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma**

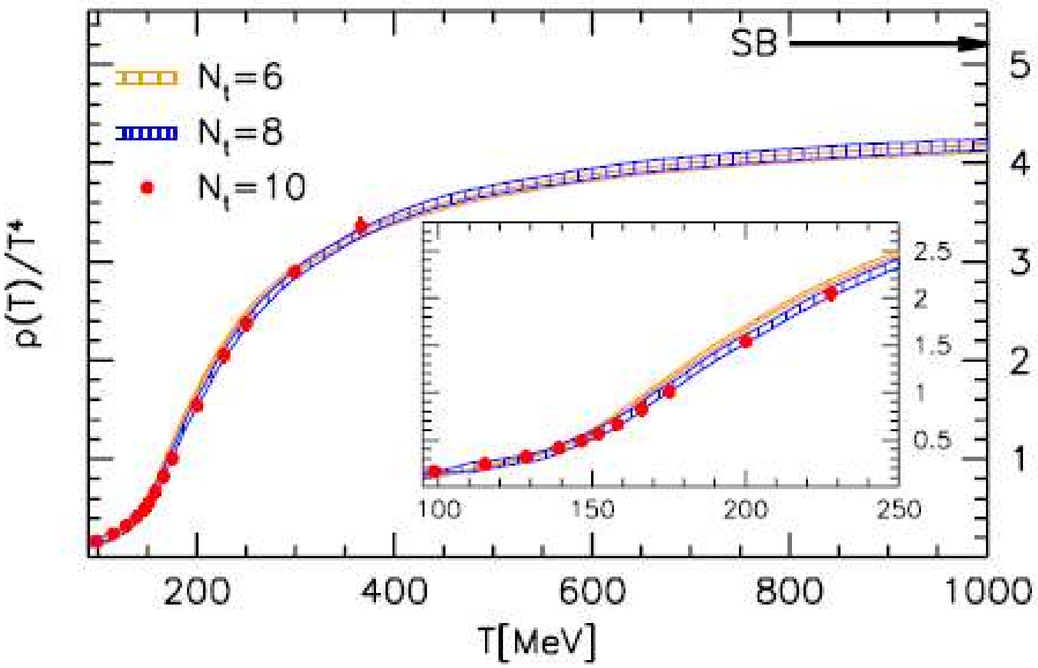


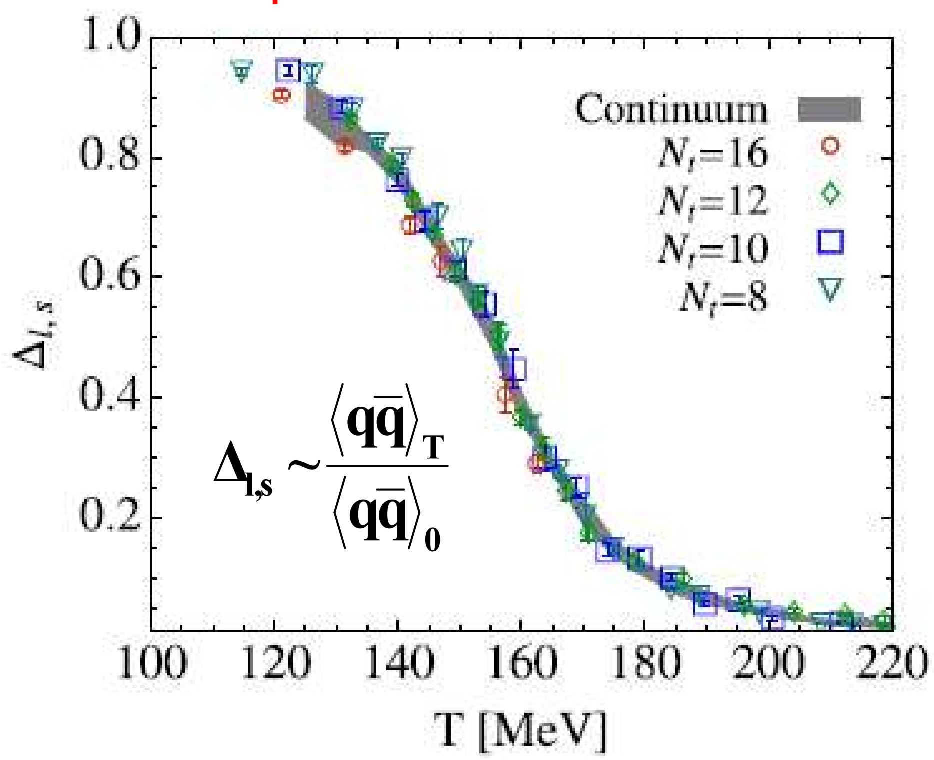
- **Search for the critical point**
- **Search for signatures of chiral symmetry restoration**
- **Study of the in-medium properties of hadrons at high baryon density and temperature**

Theory: Information from lattice QCD

I. deconfinement phase transition with increasing temperature **+** **II. chiral symmetry restoration** with increasing temperature

lQCD BMW collaboration: $\mu_q=0$





- **Crossover: hadron gas → QGP**
- **Scalar quark condensate $\langle q\bar{q}\rangle$ is viewed as an order parameter for the restoration of chiral symmetry:**

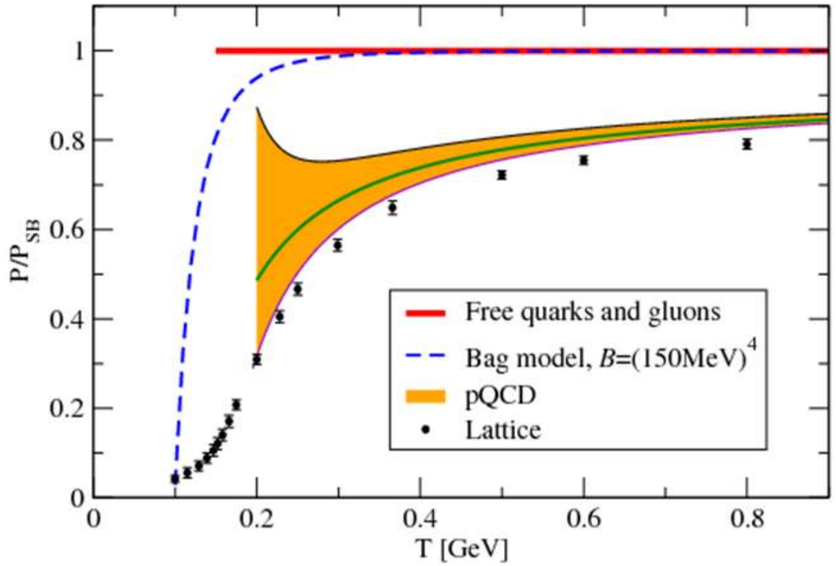
$$<\bar{q}q>=\begin{cases}\neq 0 & \text{chiral non-symmetric phase;}\\ =0 & \text{chiral symmetric phase.}\end{cases}$$

→ **both transitions occur at about the same temperature T_C for low chemical potentials**

Degrees-of-freedom of QGP

❖ lQCD gives QGP EoS at finite μ_B

! need to be interpreted in terms of degrees-of-freedom



Non-perturbative QCD ← pQCD

pQCD:

- ❑ weakly interacting system
- ❑ massless quarks and gluons

Thermal QCD
= QCD at high parton densities:

- ❑ strongly interacting system
- ❑ massive quarks and gluons

➔ quasiparticles
= effective degrees-of-freedom

❖ How to learn about degrees-of-freedom of QGP?

Theory ←→ HIC experiments

Basic models for heavy-ion collisions

- **Statistical models:**

basic assumption: system is described by a (grand) canonical ensemble of non-interacting fermions and bosons in thermal and chemical equilibrium
= thermal hadron gas at freeze-out with common T and μ_B

[- : no dynamical information]

- **Hydrodynamical models:**

basic assumption: conservation laws + equation of state (EoS);
assumption of local thermal and chemical equilibrium
- Interactions are ‚hidden' in properties of the fluid described by transport coefficients (shear and bulk viscosity η, ζ, ..), which is 'input' for the hydro models

[- : simplified dynamics]

- **Microscopic transport models:**

based on transport theory of relativistic quantum many-body systems
- Explicitly account for the interactions of all degrees of freedom (hadrons and partons) in terms of cross sections and potentials
- Provide a unique dynamical description of strongly interaction matter in- and out-off equilibrium:
- In-equilibrium: transport coefficients are calculated in a box – controled by lQCD
- Nonequilibrium dynamics – controled by HIC

Actual solutions: Monte Carlo simulations

[+ : full dynamics | - : very complicated]

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:**

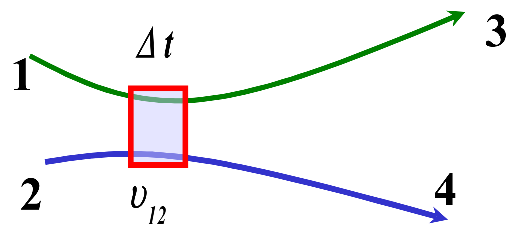
$$U(\vec{r},t) = \frac{1}{(2\pi\hbar)^3}\sum_{\beta_{occ}}\int d^3r' \, d^3p \;\; V(\vec{r}-\vec{r}',t)\; f(\vec{r}',\vec{p},t) \; + \; (Fock \;\; term)$$

- **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:**

$$P = \underbrace{f_3 f_4 (1-f_1)(1-f_2)}_{\text{Gain term: } 3+4\rightarrow 1+2} \; - \; \underbrace{f_1 f_2 (1-f_3)(1-f_4)}_{\text{Loss term: } 1+2\rightarrow 3+4}$$



Elementary hadronic interactions

Consider all possible interactions – eleastic and inelastic collisions - for the sytem of *(N,R,m)*, where *N*-nucleons, *R*- resonances, *m*-mesons, and resonance decays

Low energy collisions:

- **binary 2←→2 and 2←→3(4) reactions**
- **1←→2 : formation and decay of baryonic and mesonic resonances**

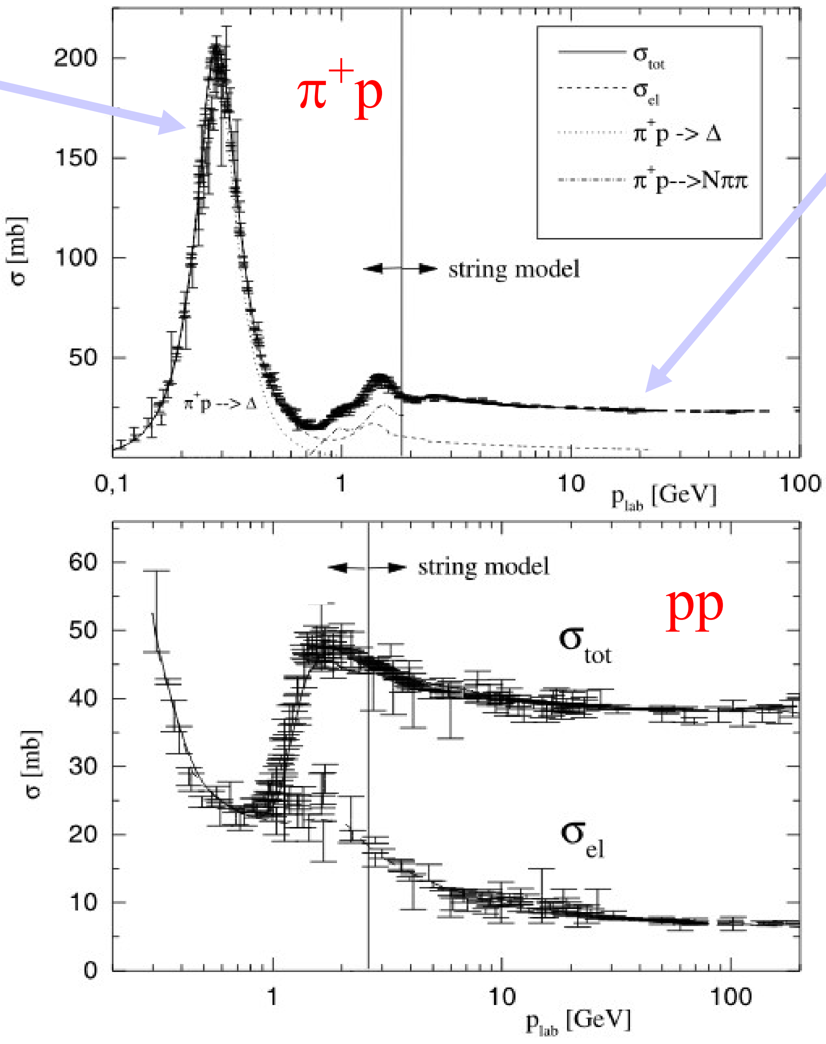
BB ←→ B´B´
BB ←→ B´B´m
mB ←→ m´B´
mB ←→ B´
mm ←→ m´m´
mm ←→ m´ . . .

Baryons:

B = p, n, Δ(1232), N(1440), N(1535), ...

Mesons:

M = π, η, ρ, ω, φ, ...



High energy collisions:

(above $s^{1/2}$~2.5 GeV)

Inclusive particle production:

BB→X , mB→X, mm→X

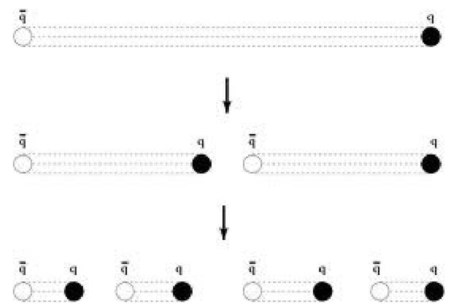
X =many particles

described by

string formation and decay

(string = excited color singlet states *q-qq*, *q-qbar*)

using LUND string model



From weakly to strongly interacting systems

In-medium effects (on hadronic or partonic levels!) = changes of particle properties in the hot and dense medium
Example: hadronic medium - vector mesons, strange mesons
QGP – dressing of partons

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

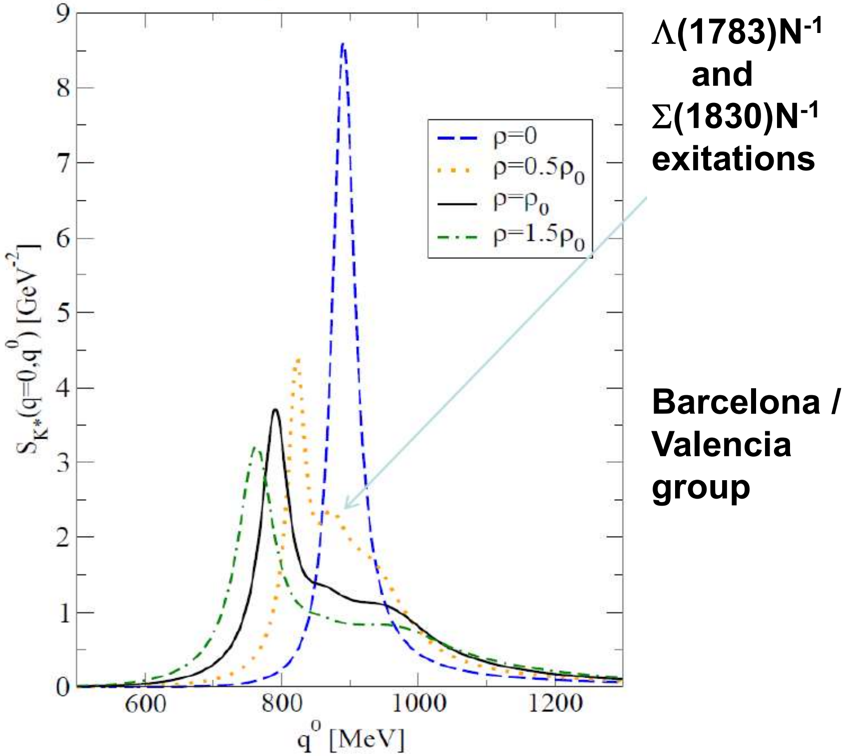
▪ **How to describe the dynamics of broad strongly interacting quantum states in transport theory?**

- ❑ **semi-classical BUU**

first order gradient expansion of quantum Kadanoff-Baym equations

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

Kbar* spectral function



Dynamical description of strongly interacting systems

- **Semi-classical on-shell BUU:** applies for small collisional width, i.e. for a weakly interacting systems of particles

How to describe strongly interacting systems?!

- **Quantum field theory →**

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

(1962)

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

Integration over the intermediate spacetime

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

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

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

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

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

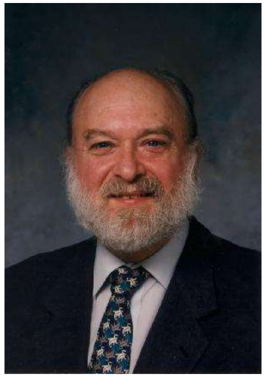
$$S_{xy}^{ret} = S_{xy}^{c} - S_{xy}^{<} = S_{xy}^{>} - S_{xy}^{a} \quad - retarded$$

$$S_{xy}^{adv} = S_{xy}^{c} - S_{xy}^{>} = S_{xy}^{<} - S_{xy}^{a} \quad - advanced$$

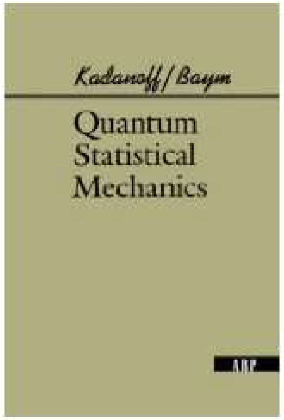
$$\hat{S}_{0x}^{-1} \equiv -(\partial_x^{\mu} \partial_{\mu}^{x} + M_0^2)$$

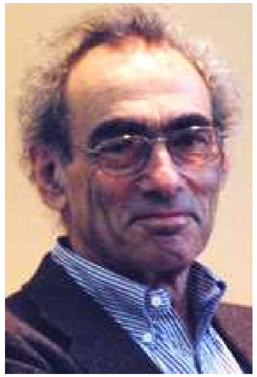
$$\eta = \pm 1 (bosons \, / \, fermions)$$

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



Leo Kadanoff





Gordon Baym

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

$$\diamondsuit\{P^2 - M_0^2 - Re\Sigma^{ret}_{XP}\}\{S^<_{XP}\} - \boxed{\diamondsuit\{\Sigma^<_{XP}\}\{ReS^{ret}_{XP}\}} = \frac{i}{2}\left[\Sigma^>_{XP}\,S^<_{XP} - \Sigma^<_{XP}\,S^>_{XP}\right]$$

Backflow term incorporates the off-shell behavior in the particle propagation
! vanishes in the quasiparticle limit $A_{XP} \to \delta(p^2-M^2)$

- **GTE: 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})**

- **Spectral function:**

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

$\Gamma_{XP} = -Im\,\Sigma^{ret}_{XP} = 2p_0\Gamma$ – **'width' of spectral function**
= reaction rate of particle (at space-time position X)

4-dimentional generalizaton of the Poisson-bracket:

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

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

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

General 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 !

➔ **General testparticle Cassing's 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 $F_{(i)} \equiv F(t, \vec{X}_i(t), \vec{P}_i(t), \epsilon_i(t))$

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

Collision term in off-shell transport models

Collision term for reaction 1+2->3+4:

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

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

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

‚gain' term ‚loss' term

with $\bar{f}_{X\vec{P}M^2} = 1+\eta\,N_{X\vec{P}M^2}$ and $\eta=\pm1$ for bosons/fermions, respectively.

The trace over particles 2,3,4 reads explicitly

for fermions

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

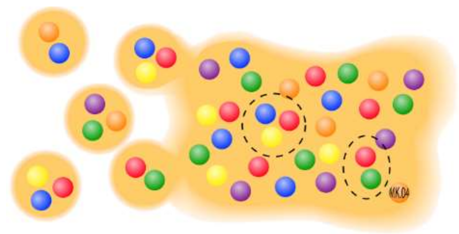
for bosons

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

additional integration

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

Goal: microscopic transport description of the partonic and hadronic phase



Problems:

- How to model a QGP phase in line with lQCD data?
- How to solve the hadronization problem?

Ways to go:

pQCD based models:

- QGP phase: pQCD cascade
- hadronization: quark coalescence

➔ AMPT, HIJING, BAMPS

‚Hybrid' models:

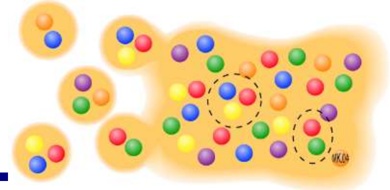
- QGP phase: hydro with QGP EoS
- hadronic freeze-out: after burner - hadron-string transport model

➔ Hybrid-UrQMD

- microscopic transport description of the partonic and hadronic phase in terms of strongly interacting dynamical quasi-particles and off-shell hadrons

➔ PHSD

From SIS to LHC: from hadrons to partons



The goal: to **study of the phase transition** from hadronic to partonic matter and properties of the Quark-Gluon-Plasma from a **microscopic origin**

➔ need a **consistent non-equilibrium transport model**

- ❑ with explicit **parton-parton interactions** (i.e. between quarks and gluons)
- ❑ explicit **phase transition** from hadronic to partonic degrees of freedom
- ❑ **lQCD EoS** for partonic phase (‚crossover' at small μ_q)

❑ **Transport theory:** **off-shell Kadanoff-Baym equations** for the Green-functions $S^<_h(x,p)$ in phase-space representation for the **partonic** and **hadronic phase**

⇒ **Parton-Hadron-String-Dynamics (PHSD)**

QGP phase described by

Dynamical QuasiParticle Model (DQPM)

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215;
W. Cassing, EPJ ST 168 (2009) 3

A. Peshier, W. Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Dynamical QuasiParticle Model (DQPM) - Basic ideas:

DQPM describes QCD properties in terms of ‚resummed' single-particle Green's functions (propagators) – in the sense of a two-particle irreducible (2PI) approach:

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: $\Sigma_q = M_q^2 - i2\gamma_q\omega$

(scalar approximation)

- the resummed properties are specified by complex (retarded) self-energies:
- the real part of self-energies (Σ_q, Π) describes a dynamically generated mass (M_q,M_g);
- the imaginary part describes the interaction width of partons (γ_q, γ_g)
- Spectral functions : $A_q \sim Im S_q^{ret}, \quad A_g \sim Im \Delta^{ret}$

- Entropy density of interacting bosons and fermions in the quasiparticle limit (2PI) (G. Baym 1998):

QGP

$$s^{dqp} = -d_g \int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\frac{\partial n_B}{\partial T}\left(\mathrm{Im}\ln(-\Delta^{-1}) + \mathrm{Im}\,\Pi\,\mathrm{Re}\,\Delta\right) \quad \text{gluons}$$

$$- d_q \int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\frac{\partial n_F((\omega-\mu_q)/T)}{\partial T}\left(\mathrm{Im}\ln(-S_q^{-1}) + \mathrm{Im}\,\Sigma_q\,\mathrm{Re}\,S_q\right) \quad \text{quarks}$$

$$- d_{\bar q} \int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\frac{\partial n_F((\omega+\mu_q)/T)}{\partial T}\left(\mathrm{Im}\ln(-S_{\bar q}^{-1}) + \mathrm{Im}\,\Sigma_{\bar q}\,\mathrm{Re}\,S_{\bar q}\right) \quad \text{antiquarks}$$

A. Peshier, W. Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

DQPM(T,μ_q): properties of quasiparticles

Properties of interacting quasi-particles: massive quarks and gluons (g, q, q_{bar}) with Lorentzian spectral functions :

$$A(\omega,\boldsymbol{p}) = \frac{\gamma}{E}\left(\frac{1}{(\omega-E)^2+\gamma^2} - \frac{1}{(\omega+E)^2+\gamma^2}\right)$$

$$E^2 = p^2 + M^2 - \gamma^2$$

- Modeling of the quark/gluon masses and widths → HTL limit at high T

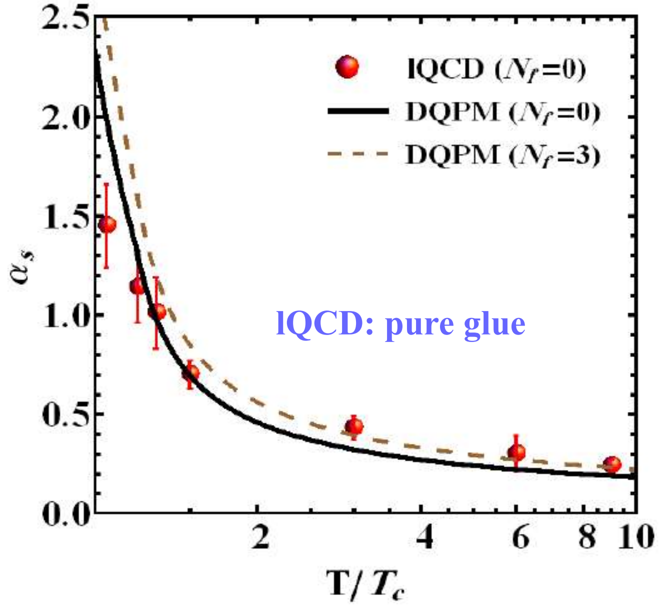
m~gT

masses: $m_g^2 = \frac{g^2}{6}\left(N_c + \frac{1}{2}N_f\right)T^2\,, \qquad m_q^2 = g^2\frac{N_c^2-1}{8N_c}T^2$

widths: $\gamma_g = \frac{1}{3}N_c\frac{g^2T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)\,, \quad \gamma_q = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$ for μ_q=0

- running coupling (pure glue):

$$\alpha_s(T) = \frac{g^2(T)}{4\pi} = \frac{12\pi}{(11N_c - 2N_f)\ln[\lambda^2(T/T_c - T_s/T_c)^2]}$$



❑ fit to lattice (lQCD) results (e.g. entropy density)

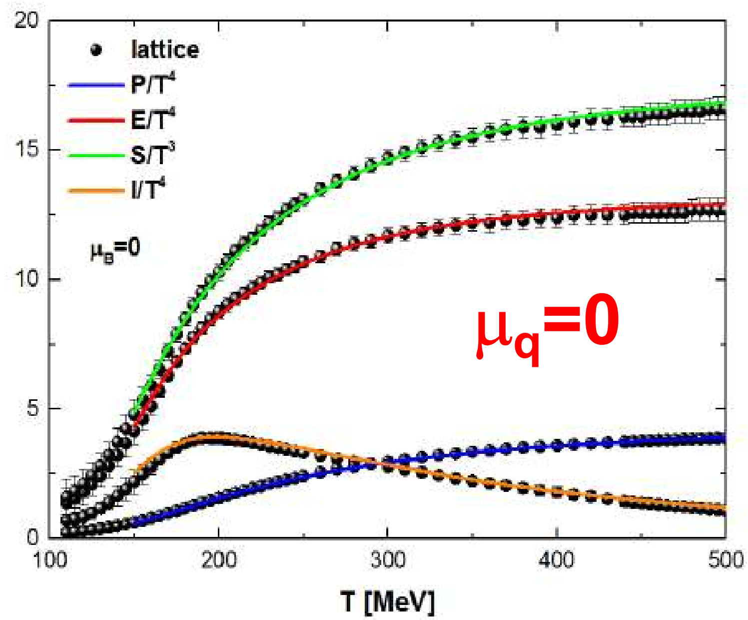
with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42 (for pure glue N_f=0)

Peshier, Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

DQPM at finite T and μ_q

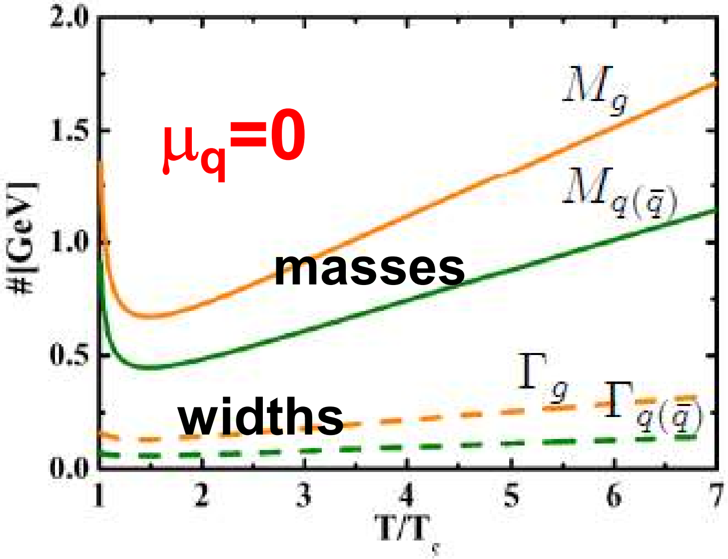
➢ **fit to lattice (lQCD) results**

* **BMW lQCD data S. Borsanyi et al., JHEP 1009 (2010) 073**



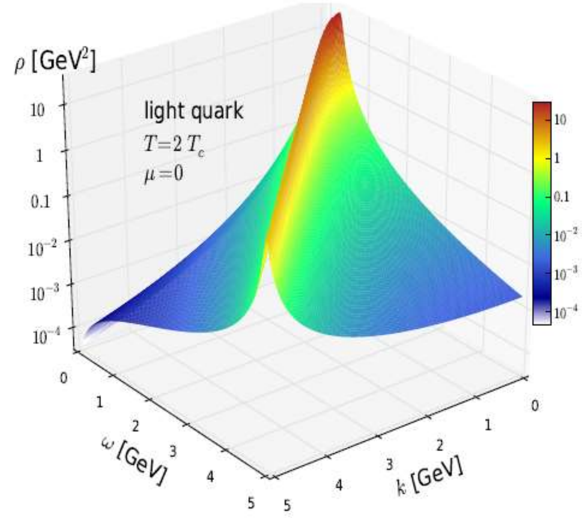
➔ **Quasiparticle properties:**

■ **large width and mass for gluons and quarks**



M~gT

T_C=158 MeV
ε_C=0.5 GeV/fm^3



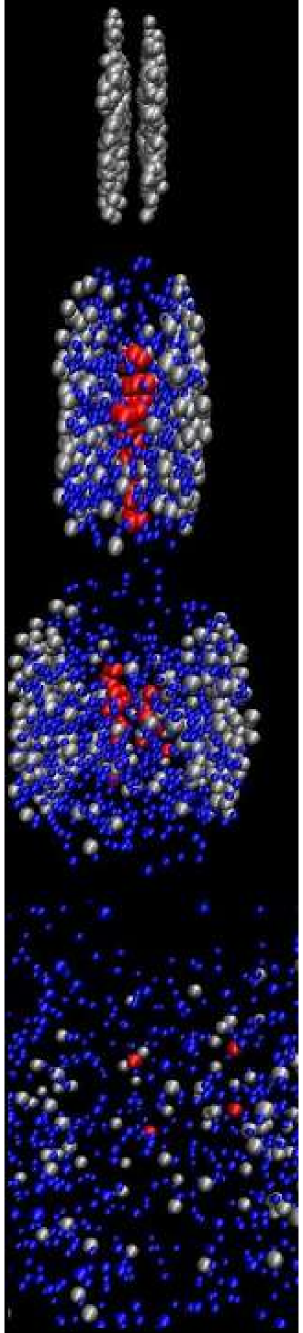
DQPM

- **matches well lattice QCD**
- **provides mean-fields (1PI) for gluons and quarks – from space-like part of $T_{\mu\nu}$ as well as effective 2-body interactions (2PI)**
- **gives transition rates for the formation of hadrons**

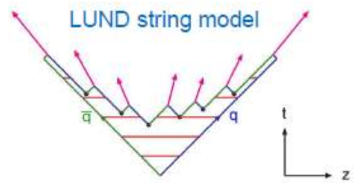
➔ **microscopic dynamical transport approach PHSD**

Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

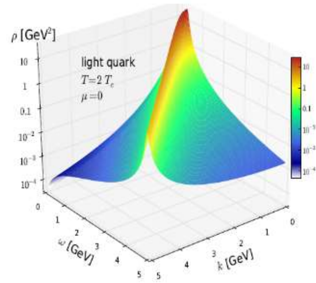
Parton-Hadron-String-Dynamics (PHSD)



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



- **Formation of QGP stage if $\varepsilon > \varepsilon_{critical}$:**
  dissolution of pre-hadrons → (DQPM) →
  → massive quarks/gluons + mean-field potential U_q



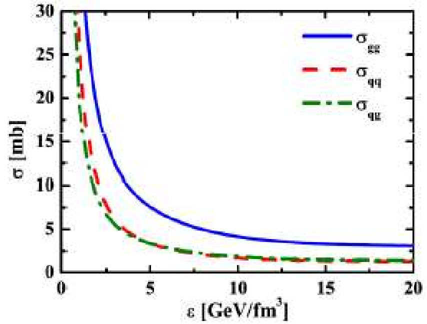
- **Partonic stage – QGP :**
  based on the Dynamical Quasi-Particle Model (DQPM)

  - (quasi-) elastic collisions:

$$q+q \to q+q \qquad g+q \to g+q$$
$$q+\bar{q} \to q+\bar{q} \qquad g+\bar{q} \to g+\bar{q}$$
$$\bar{q}+\bar{q} \to \bar{q}+\bar{q} \qquad g+g \to g+g$$

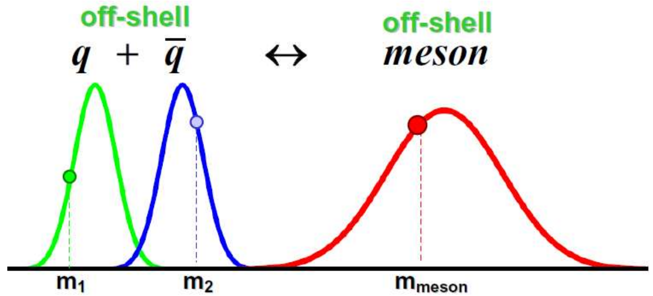
  - inelastic collisions:

$$q+\bar{q} \to g \qquad q+\bar{q} \to g+g$$
$$g \to q+\bar{q} \qquad g \to g+g$$



- **Hadronization (based on DQPM):**

$$g \to q+\bar{q}, \qquad q+\bar{q} \leftrightarrow meson \ \ (or \ 'string')$$
$$q+q+q \leftrightarrow baryon \ \ (or \ 'string')$$

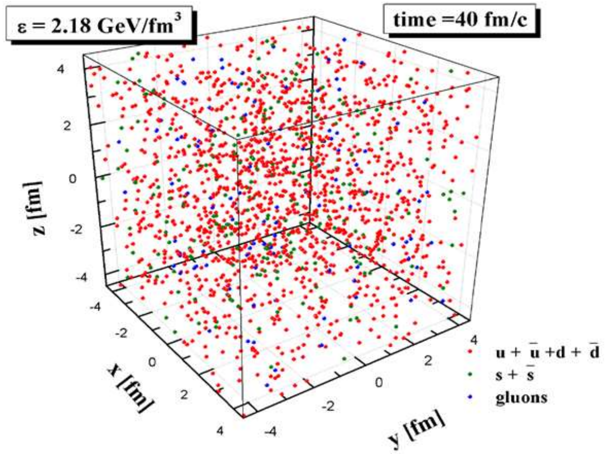


- **Hadronic phase: hadron-hadron interactions – off-shell HSD**

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

QGP in equilibrium: Transport properties at finite (T, μ_q): η/s

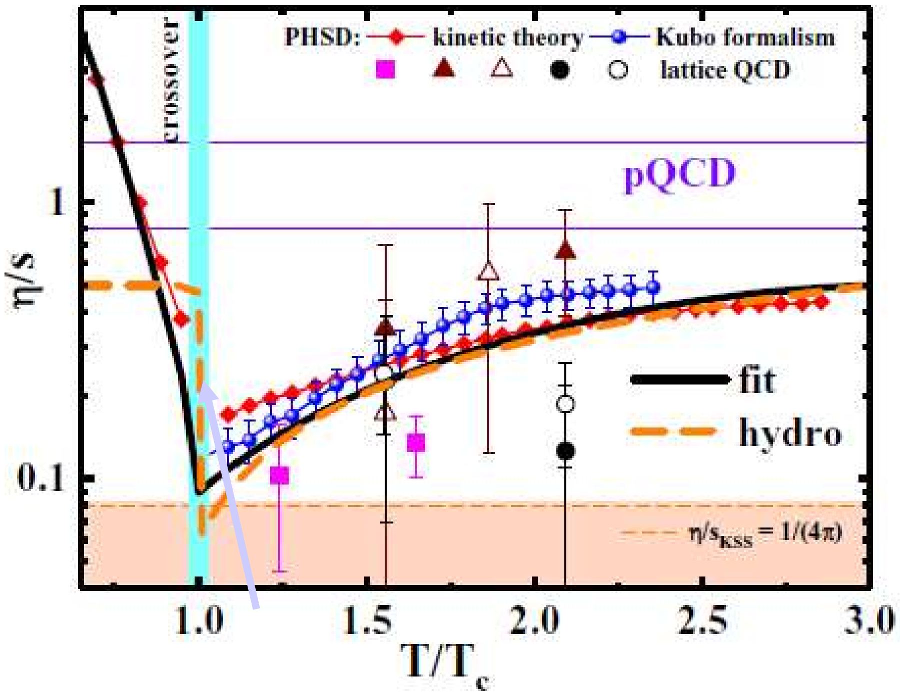
Infinite hot/dense matter = PHSD in a box:



Shear viscosity η/s at finite T

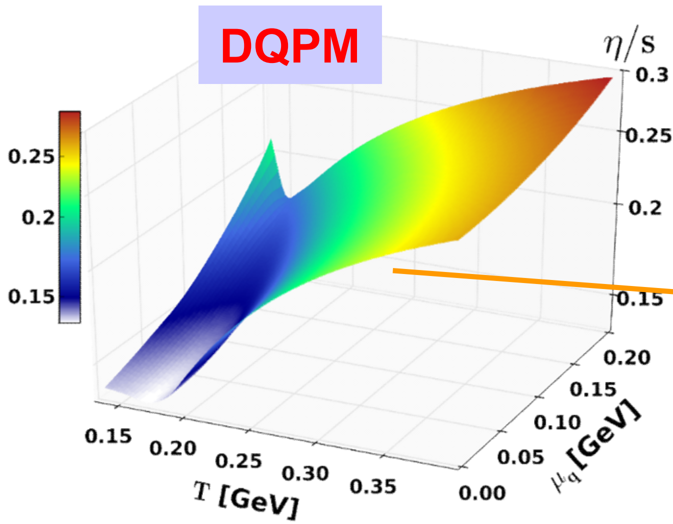
PHSD: V. Ozvenchuk et al., PRC 87 (2013) 064903

Hydro: Bayesian analysis, S. Bass et al. ,1704.07671



Shear viscosity η/s at finite (T, μ_q)

lQCD: $$\frac{T_c(\mu_q)}{T_c(\mu_q=0)} = \sqrt{1-\alpha\,\mu_q^2} \approx 1-\alpha/2\,\mu_q^2+\cdots$$

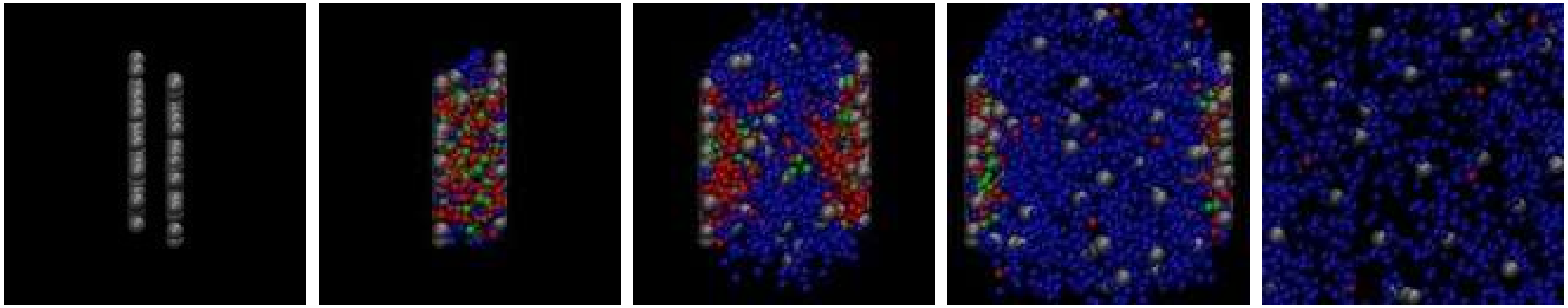


QGP in PHSD = strongly-interacting liquid-like system

η/s: μ_q=0 ➔ finite μ_q: smooth increase as a function of (T, μ_q)

Review: H. Berrehrah et al. Int.J.Mod.Phys. E25 (2016) 1642003

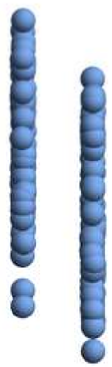
Traces of the QGP in observables in high energy heavy-ion collisions



http://theory.gsi.de/~ebratkov/phsd-project/PHSD/index1.html

Stages of a collision in PHSD

t = 0.05 fm/c



Au + Au $\sqrt{s_{NN}} = 200$ GeV

b = 2.2 fm – Section view

Baryons (394)

Antibaryons (0)

Mesons (0)

Quarks (0)

Gluons (0)

P.Moreau

Stages of a collision in PHSD

t = 1.6512 fm/c

Au + Au $\sqrt{s_{NN}} = 200$ GeV

b = 2.2 fm – Section view

Baryons (394)

Antibaryons (0)

Mesons (1523)

Quarks (4553)

Gluons (368)

P.Moreau

Stages of a collision in PHSD

t = 3.91921 fm/c

Au + Au $\sqrt{s_{NN}} = 200$ GeV

b = 2.2 fm – Section view

Baryons (426)

Antibaryons (29)

Mesons (1189)

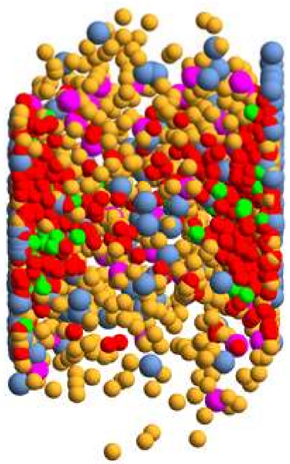
Quarks (4459)

Gluons (783)

P.Moreau

Stages of a collision in PHSD

t = 7.31921 fm/c



Au + Au $\sqrt{s_{NN}} = 200$ GeV

b = 2.2 fm – Section view

Baryons (540)

Antibaryons (120)

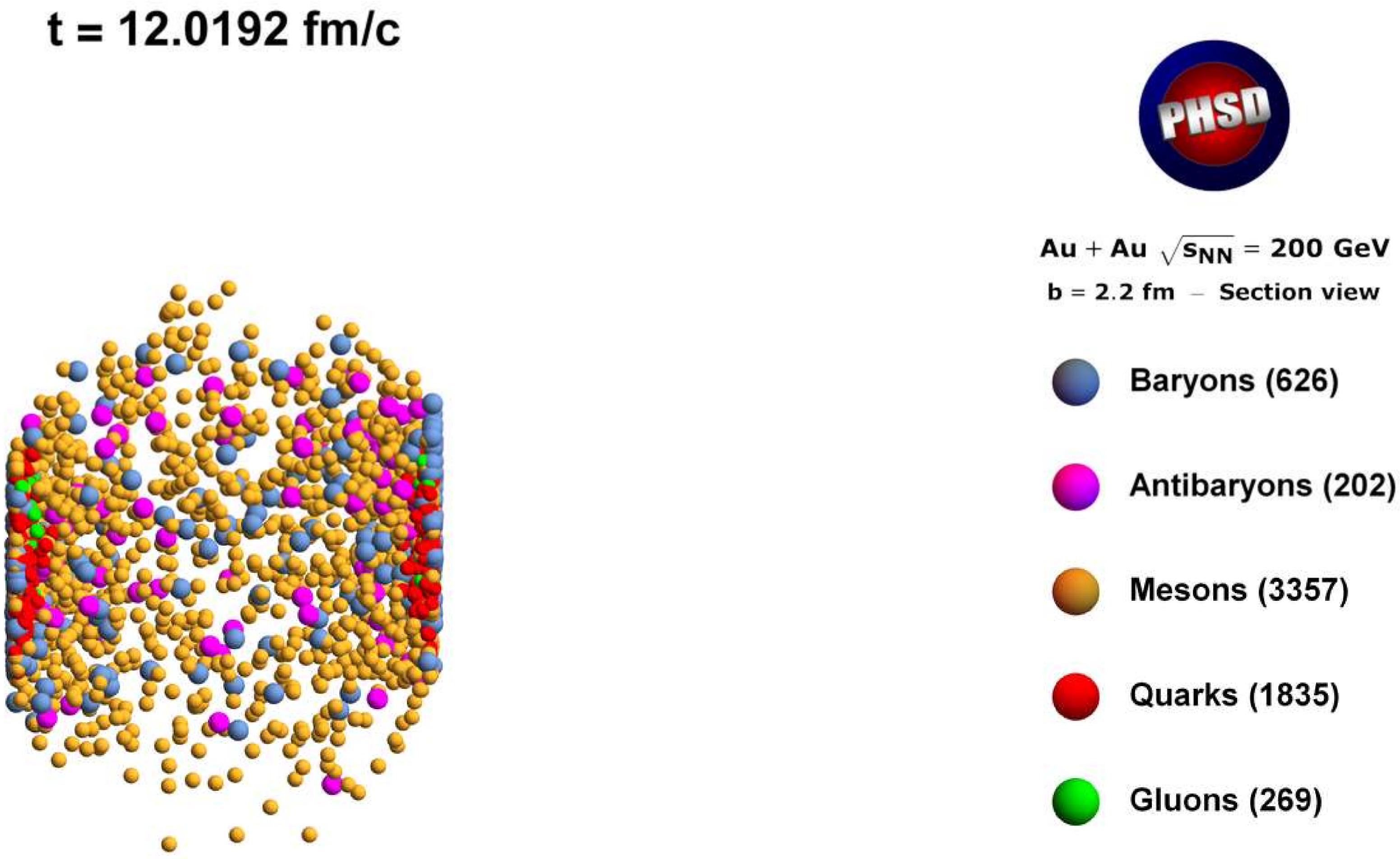
Mesons (2481)

Quarks (2901)

Gluons (492)

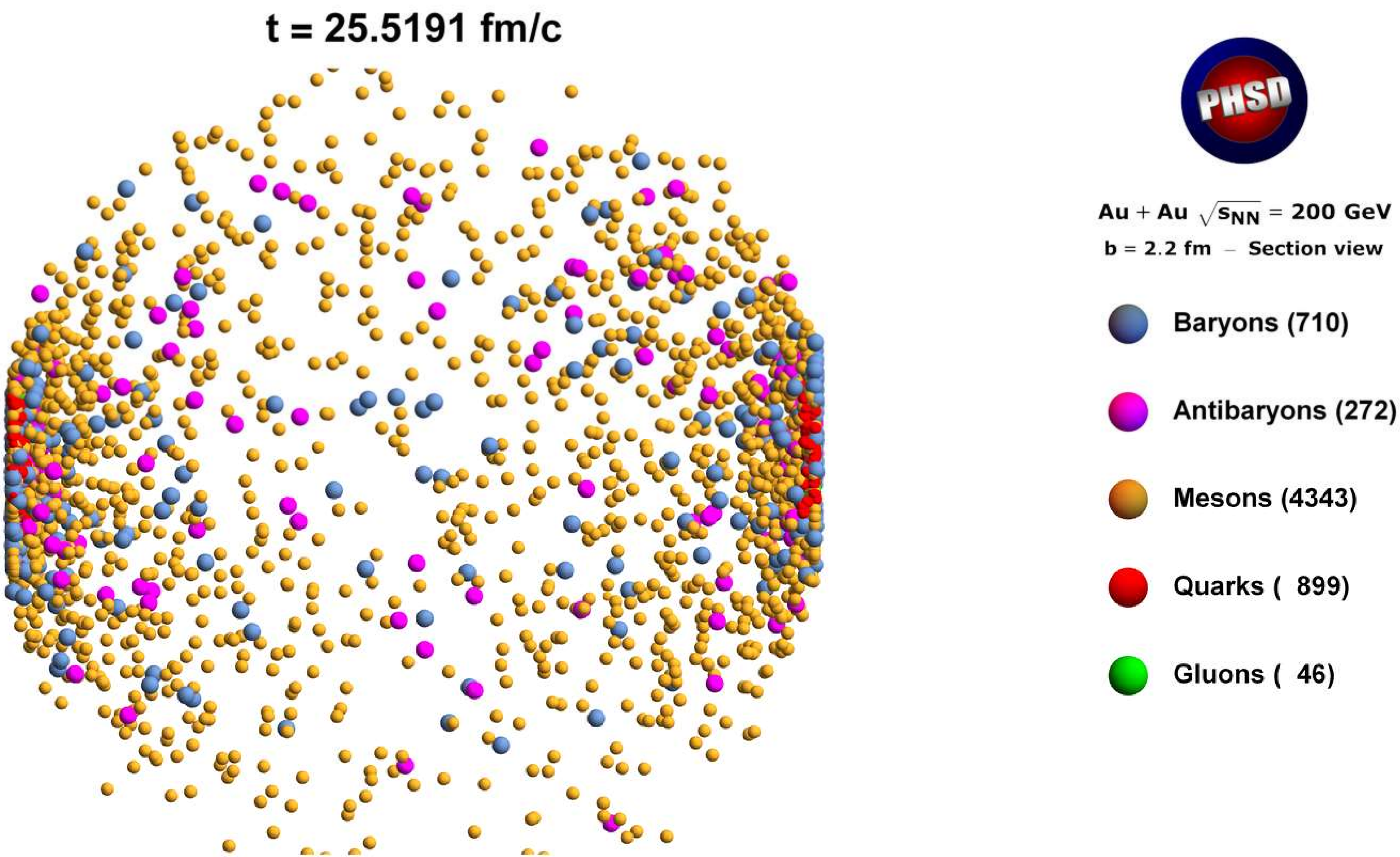
P.Moreau

Stages of a collision in PHSD



P.Moreau

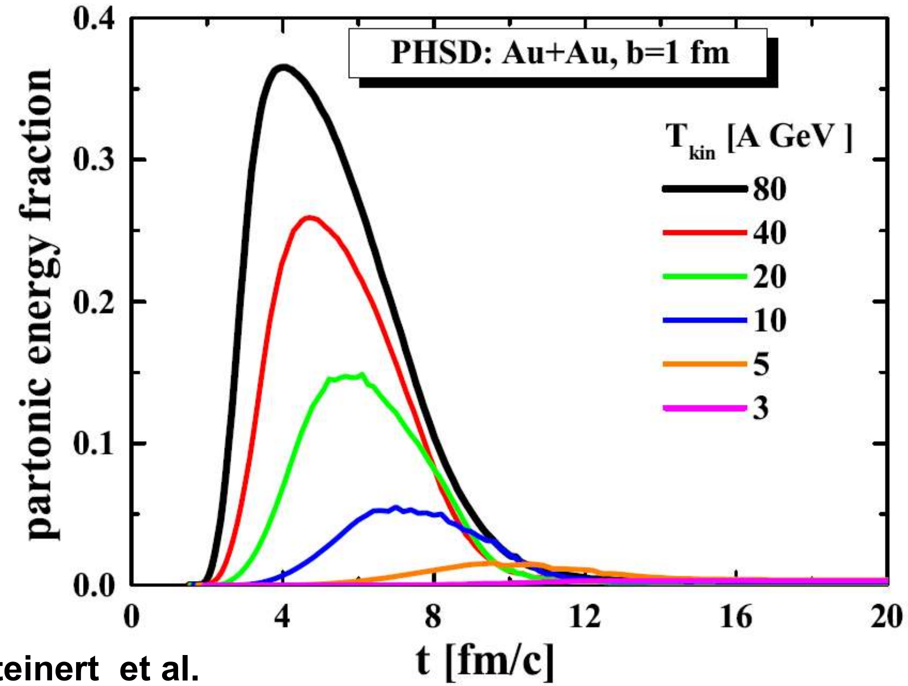
Stages of a collision in PHSD



P.Moreau

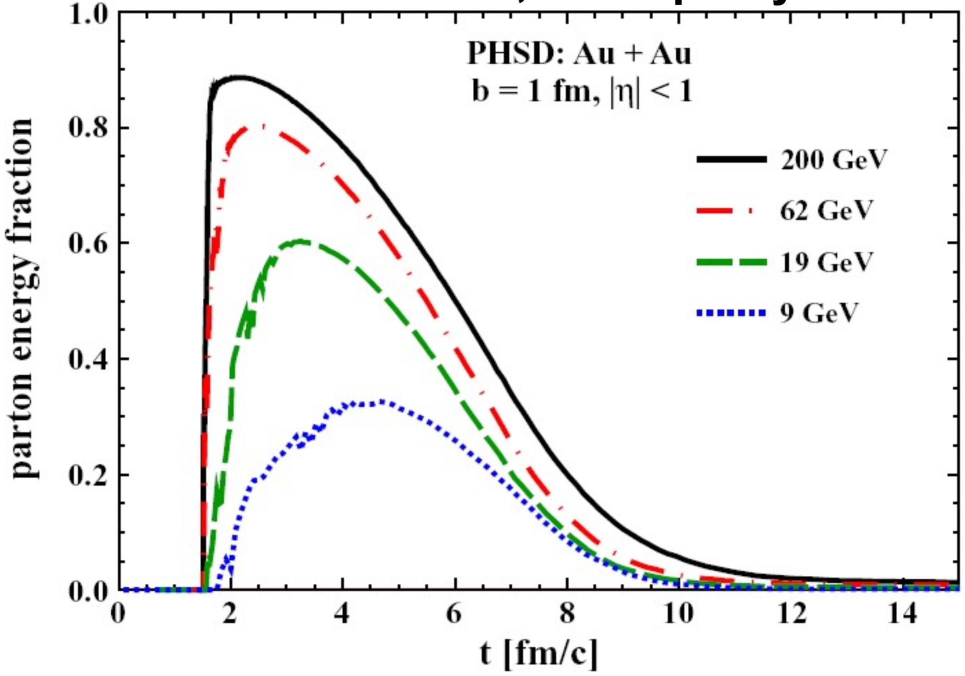
Partonic energy fraction in central A+A

Time evolution of the partonic energy fraction vs energy



T. Steinert et al.

Au+Au, midrapidity



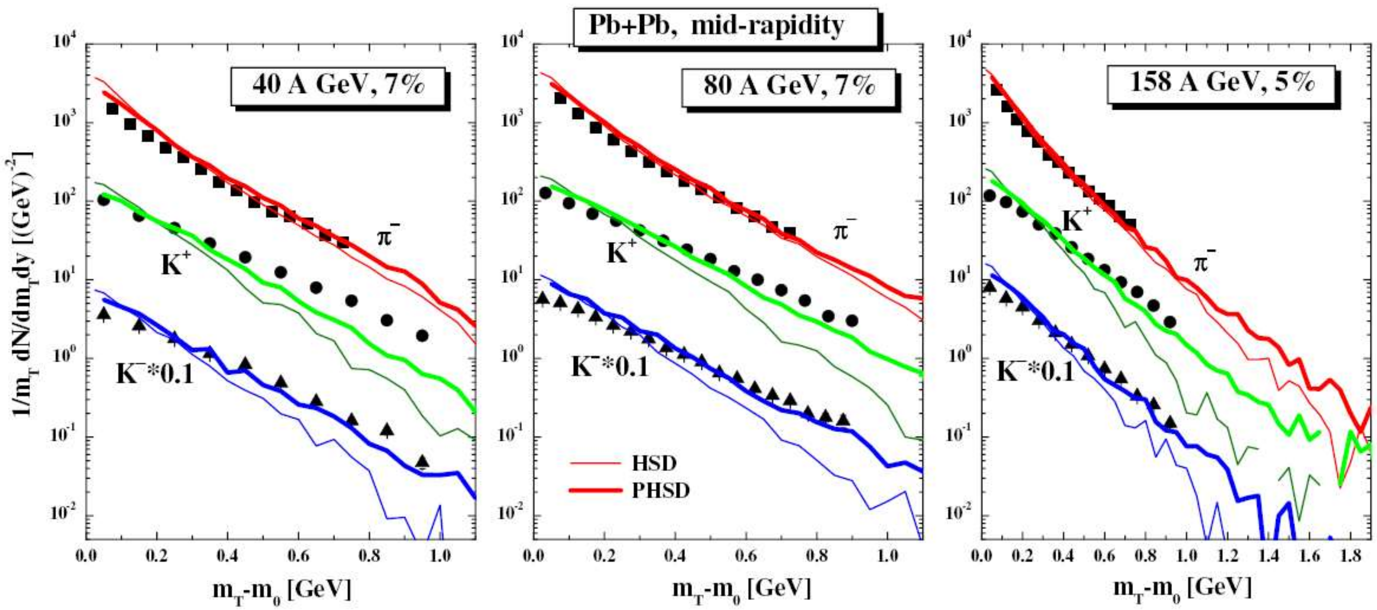
- Strong increase of partonic phase with energy from AGS to RHIC

- SPS: Pb+Pb, 160 A GeV: only about 40% of the converted energy goes to partons; the rest is contained in the large hadronic corona and leading partons
- RHIC: Au+Au, 21.3 A TeV: up to 90% - QGP

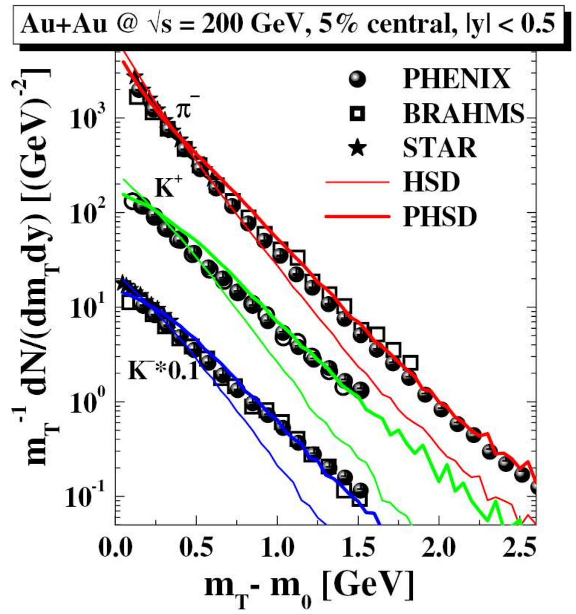
W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
V. Konchakovski et al., Phys. Rev. C 85 (2012) 011902

Transverse mass spectra from SPS to RHIC

Central Pb + Pb at SPS energies



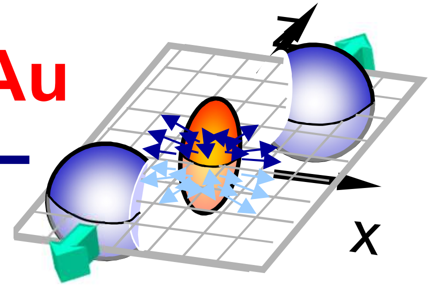
Central Au+Au at RHIC



- ❑ **PHSD gives harder m_T spectra and works better than HSD (wo QGP) at high energies – RHIC, SPS (and top FAIR, NICA)**
- ❑ **however, at low SPS (and low FAIR, NICA) energies the effect of the partonic phase decreases due to the decrease of the partonic fraction**

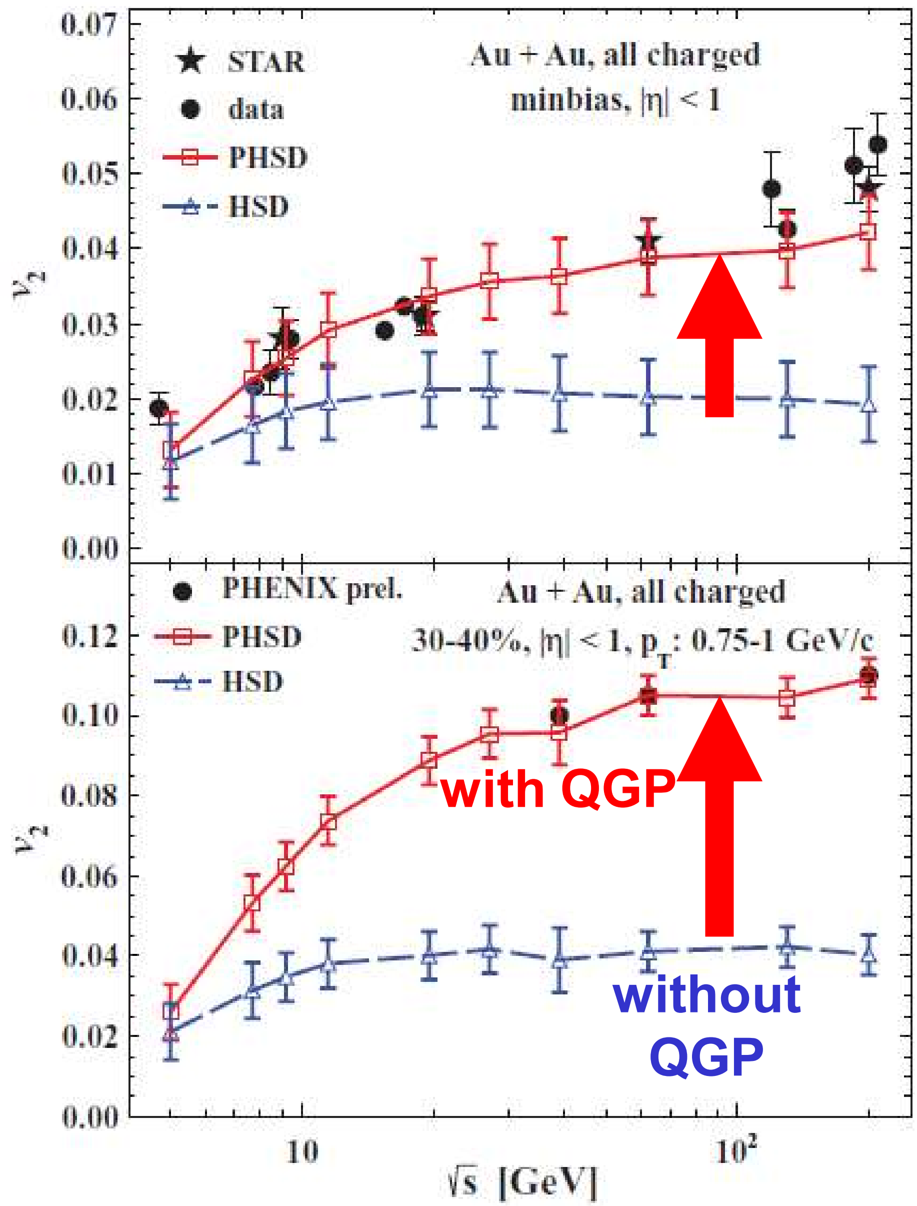
W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

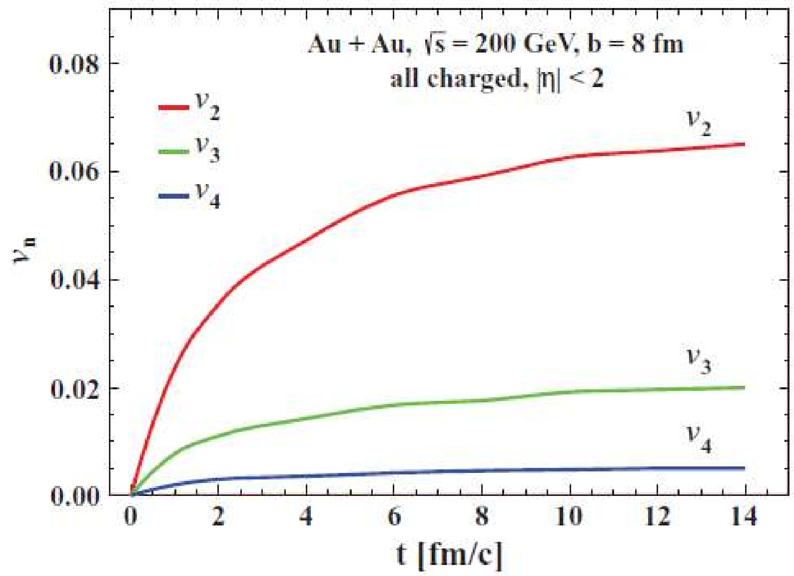
Elliptic flow v_2 vs. collision energy for Au+Au



$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right)$$

$$v_n = \left\langle \cos n\left(\varphi - \psi_n\right)\right\rangle, \quad n = 1,2,3..,$$

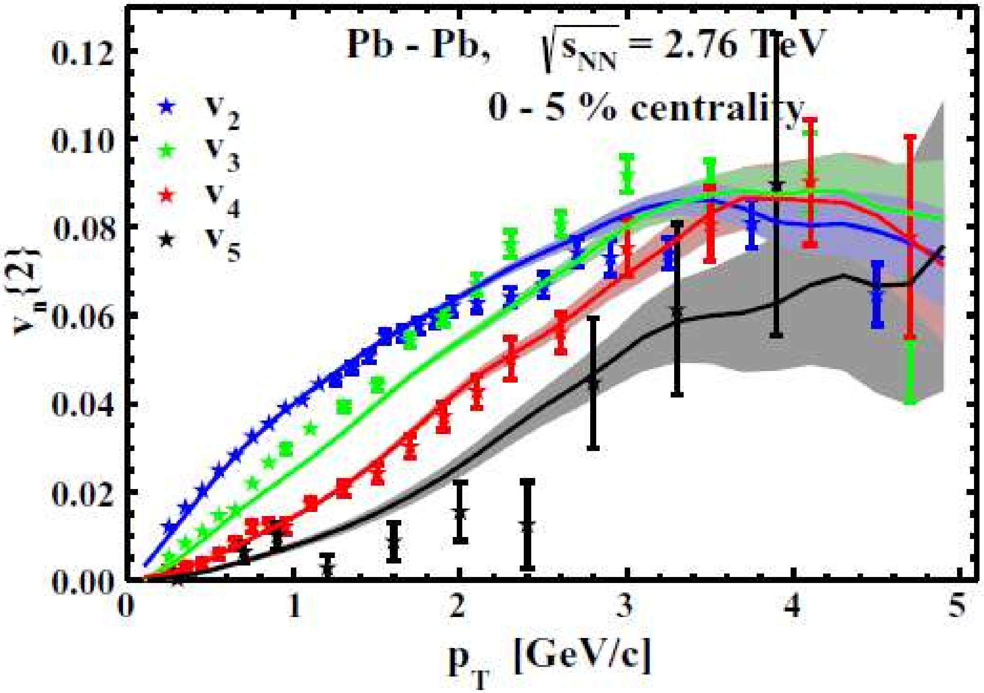


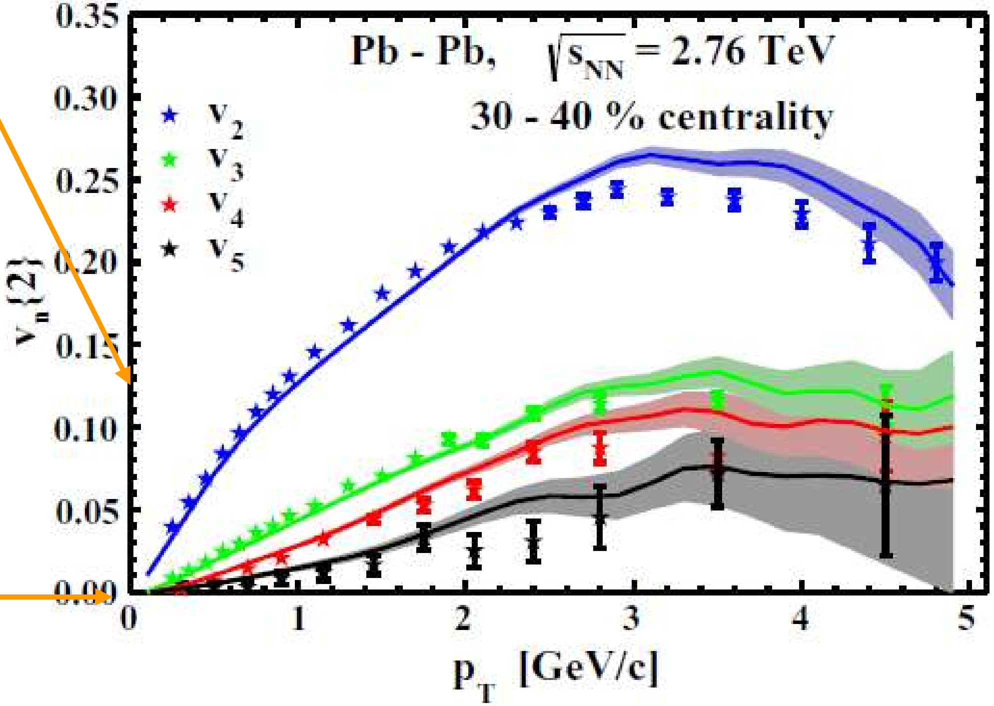


- v_2 in PHSD is larger than in HSD due to the repulsive scalar mean-field potential $U_s(\rho)$ for partons
- v_2 grows with bombarding energy due to the increase of the parton fraction

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 011902

V_n (n=2,3,4,5) of charged particles from PHSD at LHC





- PHSD: increase of v_n (n=2,3,4,5) with p_T
- v_2 increases with decreasing centrality
- v_n (n=3,4,5) show weak centrality dependence

symbols – ALICE

PRL 107 (2011) 032301

lines – PHSD (e-by-e)

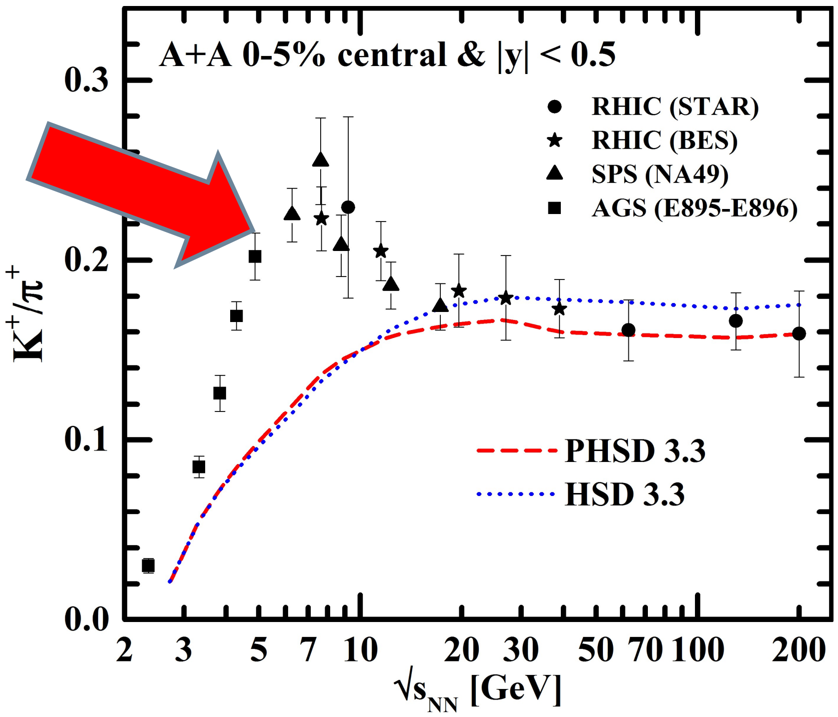
v_n (n=3,4,5) develops by interaction in the QGP and in the final hadronic phase

V. Konchakovski, W. Cassing, V. Toneev, J. Phys. G: Nucl. Part. Phys 42 (2015) 055106

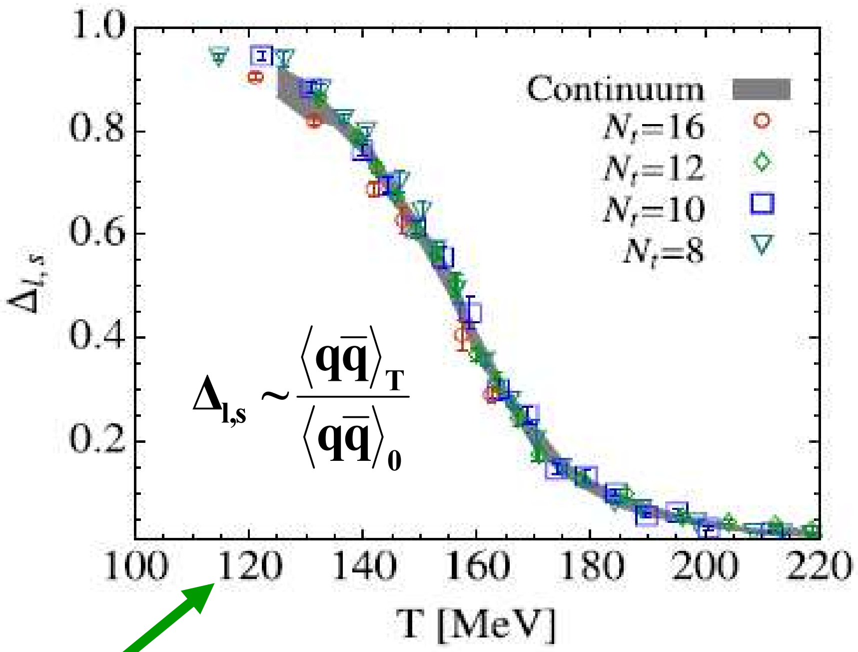
Problem: K^+/π^+ ‚horn' – 2015

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!) remains unexplained !

➔ **The origin of 'horn' is not traced back to deconfinement ?!**



lQCD BMW collaboration:



?

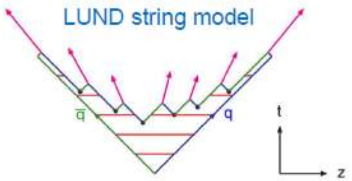
Can it be related to chiral symmetry restoration in the hadronic phase?!

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

Chiral symmetry restoration vs. deconfinement

I. Initial stage of HIC collisions:

Hadronic matter ➔ string formation



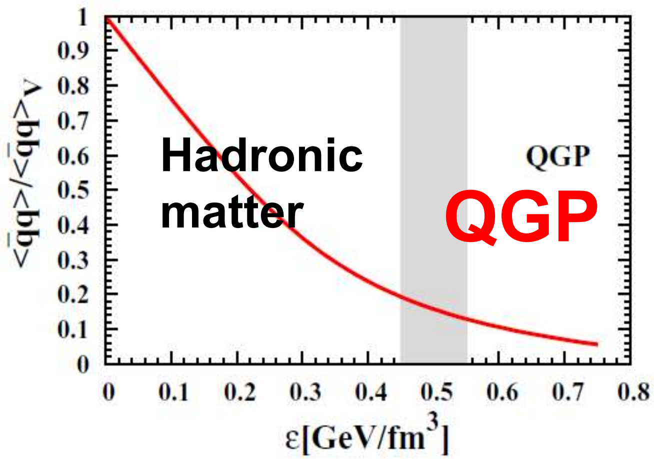
$$\frac{P(s\bar{s})}{P(u\bar{u})} = \frac{P(s\bar{s})}{P(d\bar{d})} = \gamma_S = \exp\left(-\pi \frac{m_S^{*2} - m_q^{*2}}{2\kappa}\right)$$

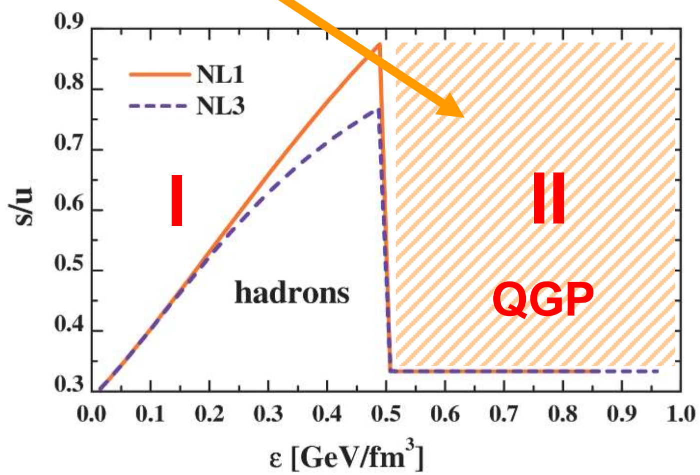
$$\mathbf{m}_q^* = \mathbf{m}_q^0 + (m_q^V - m_q^0)\frac{<\mathbf{q\bar{q}}>}{<\mathbf{q\bar{q}}>_V}$$

II. QGP

(time-like partons,
explicit partonic interactions)

III. Hadronic phase





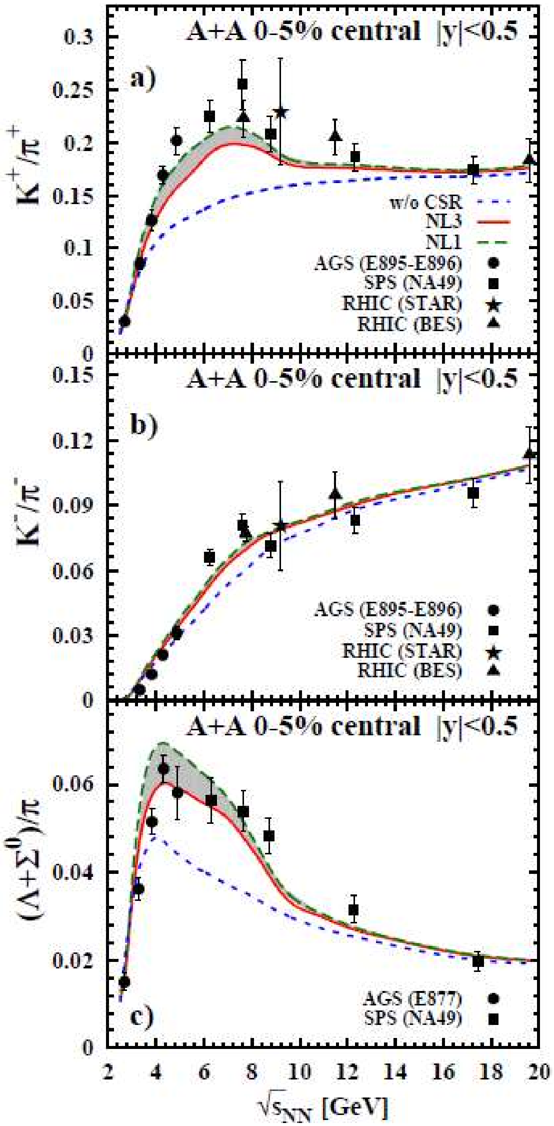
- ❑ Chiral symmetry restoration via Schwinger mechanism (and non-linear $\sigma - \omega$ model) changes the „flavour chemistry" in string fragmentation (1PI):

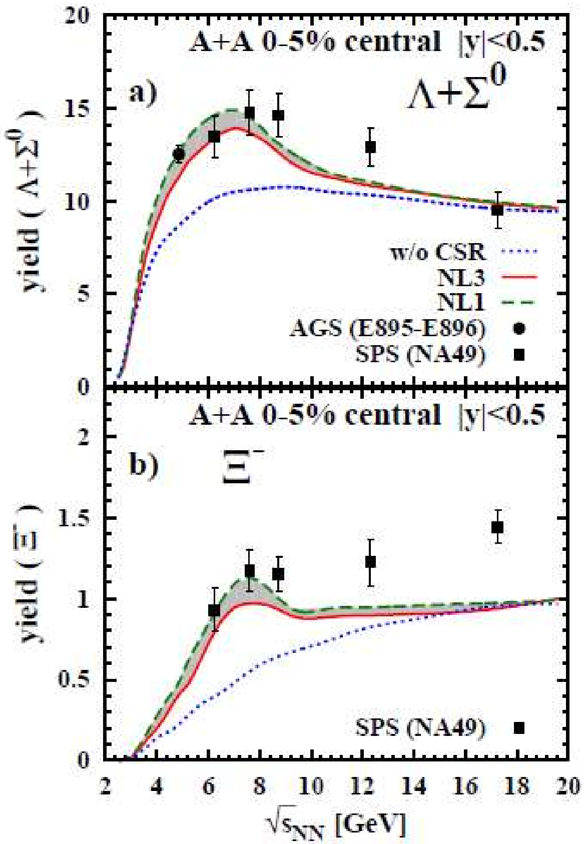
  $\langle q\bar{q}\rangle / \langle q\bar{q}\rangle_V \rightarrow 0$ ➔ $m_s^* \rightarrow m_s^0$ ➔ s/u grows

➔ 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 HIC in the hadronic phase

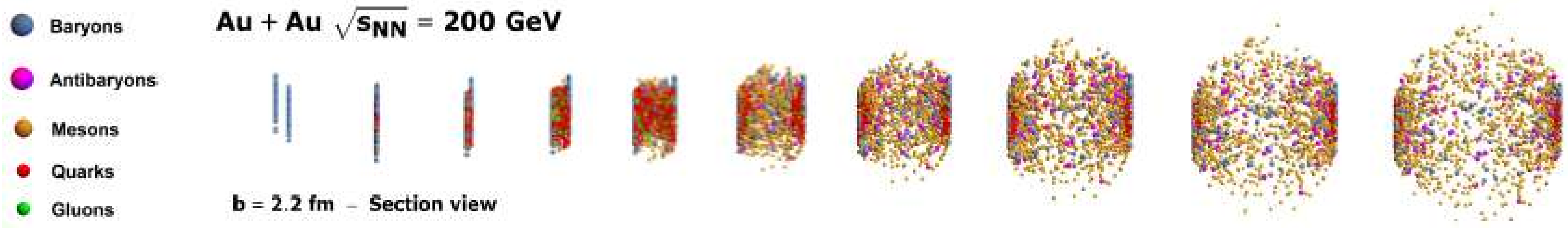
Summary

Microscopic transport approach PHSD versus experimental observables:

- ❑ **evidence for strong partonic interactions in the early phase of relativistic heavy-ion reactions**

- ❑ **indication for a partial chiral symmetry restoration**

⇒ **formation of the sQGP in HIC!**



http://theory.gsi.de/~ebratkov/phsd-project/PHSD/index1.html

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HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research
cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
Bundesministerium für Bildung und Forschung
DAAD
CRC-TR 211
DFG Deutsche Forschungsgemeinschaft
PHSD
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
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TEXAS A&M UNIVERSITY
JINR
UAB Universitat Autònoma de Barcelona
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Thank you for your attention !

Thanks to the Organizers !

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