Institut für Theoretische Physik

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Chiral symmetry restoration in heavy-ion collisions within the PHSD transport approach

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for the PHSD group

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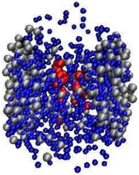
Meeting of the working group on theory of hadronic matter under extreme conditions, Dubna, 31 October 2016

HIC for FAIR Helmholtz International Center



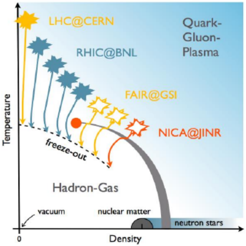
PHSD

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

H-QM Helmholtz Research School Quark Matter Studies

Motivation

Beam Energy scan is pointing at lower energies to explore systems with higher baryon density.



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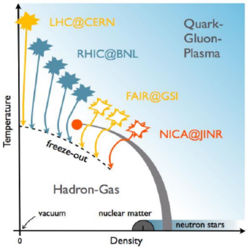
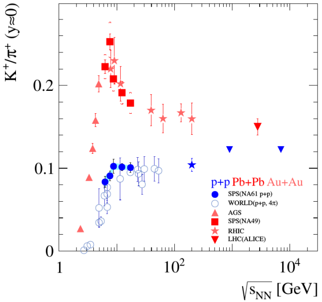


There are many open questions related to the **strangeness production** in Heavy-Ion Collisions (HIC)!



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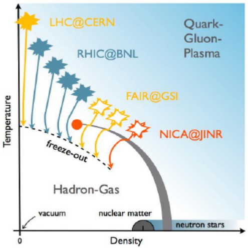

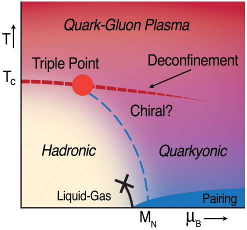

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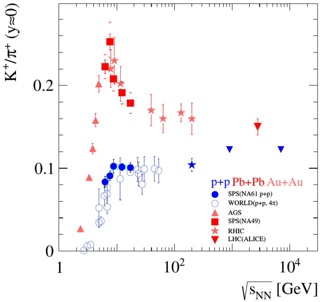


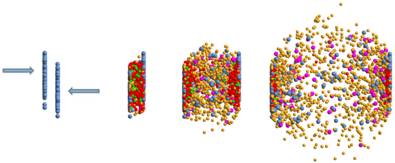
Can we find a manifestation of the Chiral Symmetry restoration in HIC observables?

Outline

1. Parton Hadron String Dynamics (PHSD)
   - Dynamical Quasi-Particle Model (DQPM)
   - Stages of a heavy-ion collision
2. Chiral Symmetry Restoration (CSR) in PHSD
3. Observables of CSR in heavy-ion collisions
   - Rapidity and transverse mass spectra
   - Particle ratios and abundances
   - Sensitivity to the system size
   - Centrality dependence
4. Summary

Parton Hadron String Dynamics (PHSD)

- Dynamical many-body transport approach.
- Consistently describes the full time evolution of a heavy-ion collision.
- Explicit parton-parton interactions, explicit phase transition from hadronic to partonic degrees of freedom.



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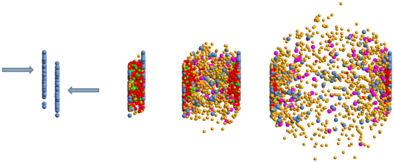
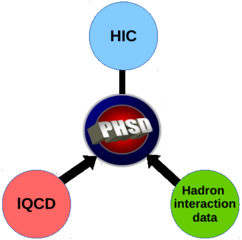


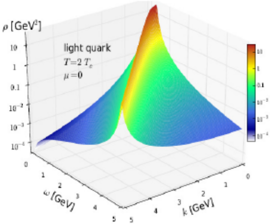


- Model applicable out-of equilibrium and in agreement with the lattice results in equilibrium as well as with the nuclear physics input.
- Transport theory: off-shell transport equations in phase-space representation based on Kadanoff-Baym equations for the partonic and hadronic phase.

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

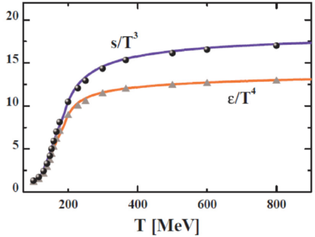
Dynamical Quasi-Particle Model (DQPM)

The QGP phase is described in terms of interacting quasi-particles with Lorentzian spectral functions:

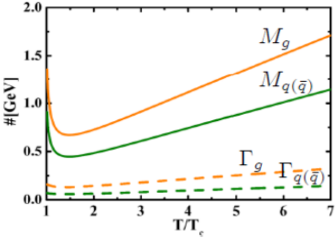


$$\rho_i(\omega, T) = \frac{4\omega\Gamma_i(T)}{(\omega^2 - \mathbf{p}^2 - M_i^2(T))^2 + 4\omega^2\Gamma_i^2(T)}, \quad (i = q, \bar{q}, g)$$

Properties of quasi-particles are fitted to the lattice QCD results:

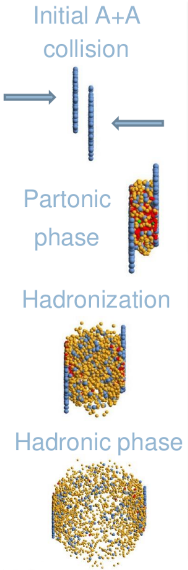


Masses and widths of partons depend on the temperature T and chemical potential μ_q of the medium:



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

Stages of a heavy-ion collision in PHSD



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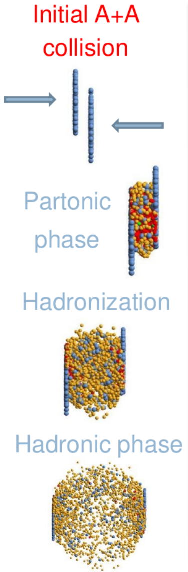
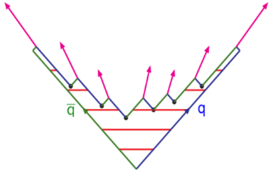


- **String formation** in primary NN Collisions.
- **String decays** to pre-hadrons (baryons and mesons).



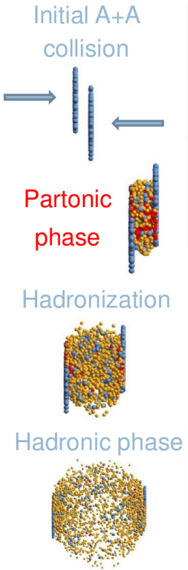
- Formation of a **QGP state** if the energy density $\epsilon > \epsilon_C \approx 0.5\ GeV\ fm^{-3}$.
- Dissolution of newly produced secondary hadrons into **massive colored quarks/antiquarks** and **mean-field energy** U_q:

$$B \rightarrow qqq\,(\bar{q}\bar{q}\bar{q}) \qquad M \rightarrow q\bar{q} \qquad + \quad U_q.$$

- **DQPM** defines the properties (masses and widths) of partons and mean-field potential at a given local energy density ϵ:

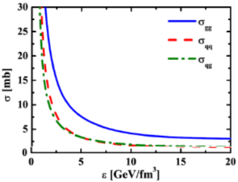
$$m_q(\epsilon) \qquad \Gamma_q(\epsilon) \qquad U_q(\epsilon).$$

Stages of a heavy-ion collision in PHSD



- **Propagation of partons**, considered as dynamical quasi-particles, in a self-generated mean-field potential from the DQPM.
- **EoS**: crossover at $\mu_q = 0$ from Lattice QCD fitted by DQPM.
- (Quasi-)elastic collisions:

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



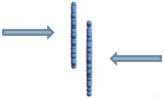
- Inelastic collisions:

$$q + \bar{q} \Rightarrow g \qquad ~~q + \bar{q} \Rightarrow g + g~~$$
$$g \Rightarrow q + \bar{q} \qquad ~~g \Rightarrow g + g~~$$

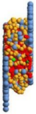
Suppressed due to the large gluon mass.

Stages of a heavy-ion collision in PHSD

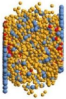
Initial A+A collision



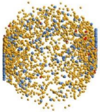
Partonic phase



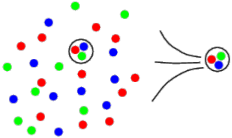
Hadronization



Hadronic phase



- **Massive and off-shell (anti-)quarks hadronize to colorless off-shell mesons and baryons**:

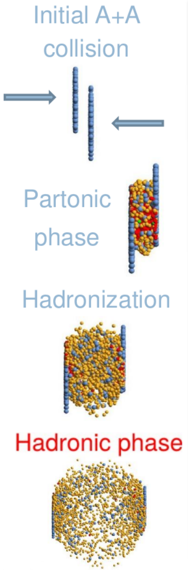


$$g \Rightarrow q + \bar{q}$$

$$q + \bar{q} \Rightarrow \text{meson ('string')}$$

$$q + q + q \Rightarrow \text{baryon ('string')}$$

- Local covariant off-shell transition rate.
- Strict 4-momentum and quantum number conservation.



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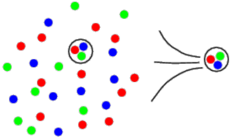

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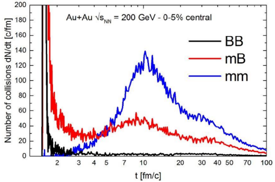
$$q + q + q \Rightarrow \text{baryon ('string')}$$

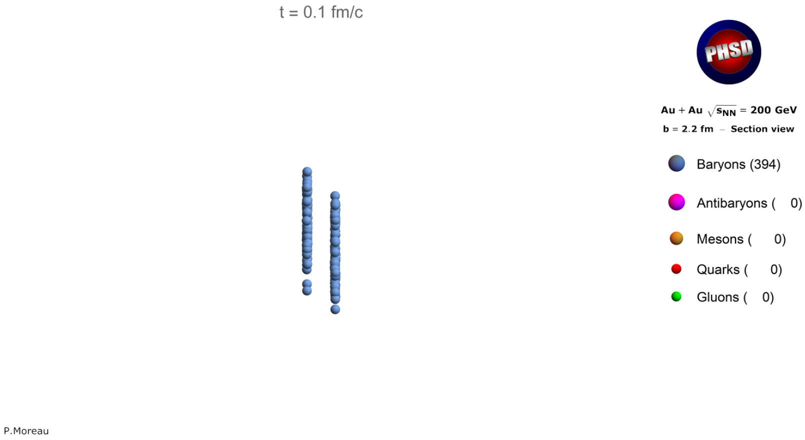
- Local covariant off-shell transition rate.
- Strict 4-momentum and quantum number conservation.

- Hadron-string interactions – **off-shell HSD**.
- Elastic and inelastic collisions between baryons (B), mesons (m) and resonances (R).

Distribution of hadron collisions as a function of time:



Stages of a heavy-ion collision in PHSD



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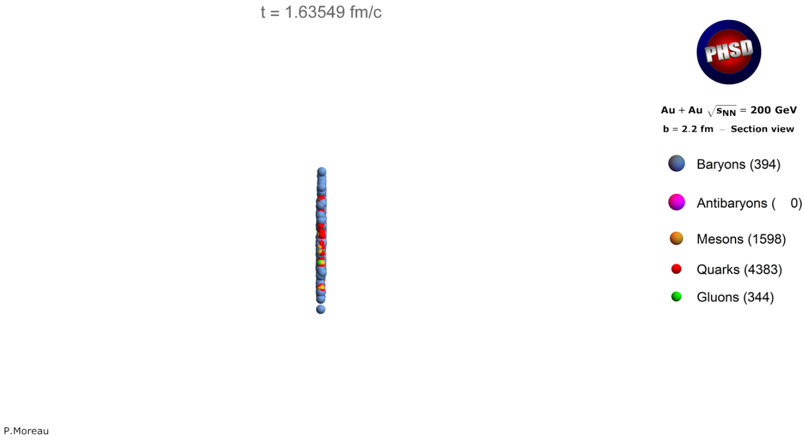

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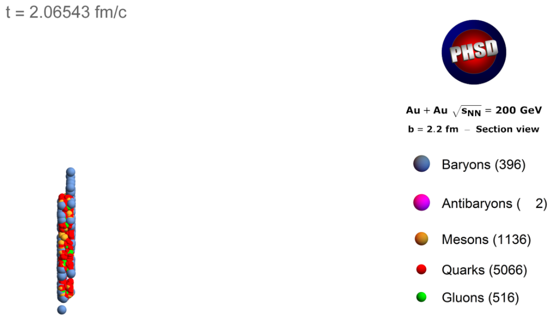

P.Moreau

Stages of a heavy-ion collision in PHSD

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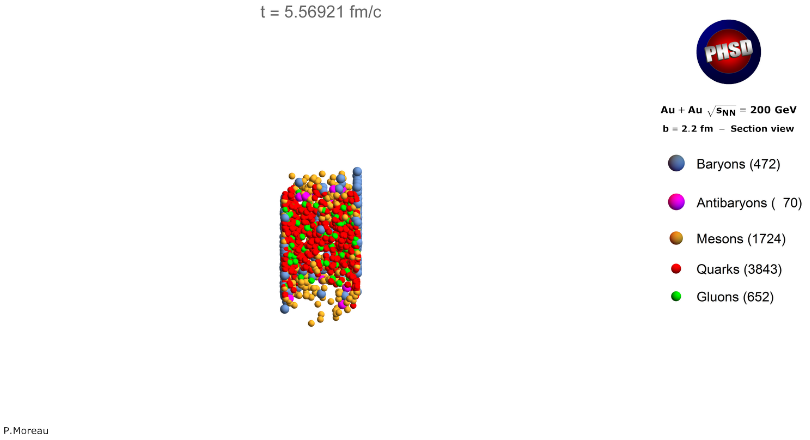

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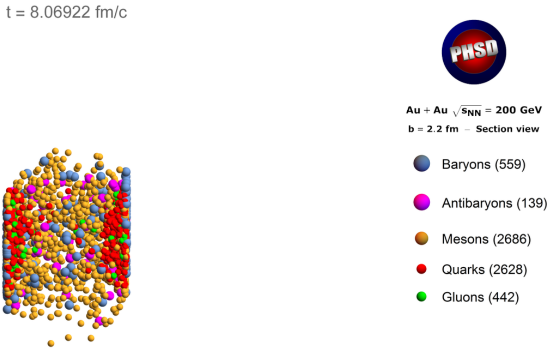

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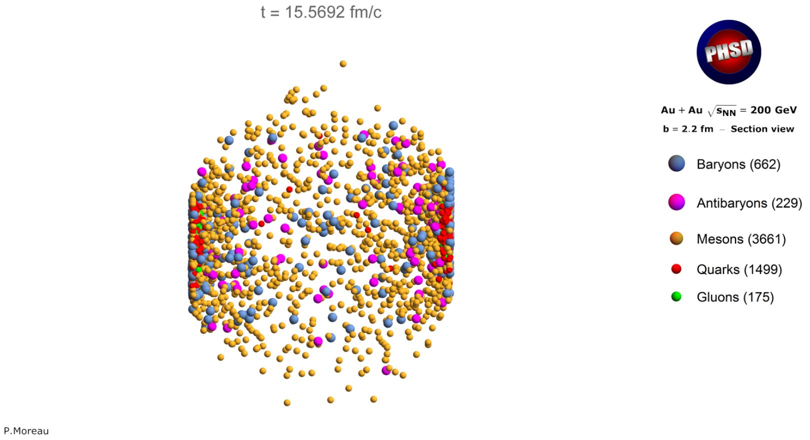

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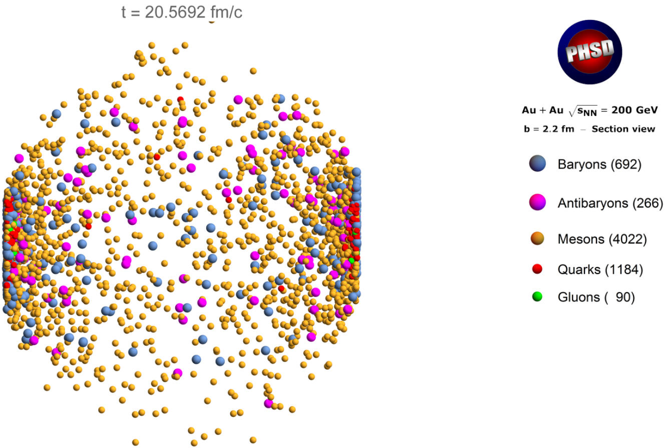
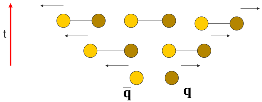


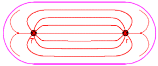
P.Moreau

String dynamics in PHSD

In PHSD the flavor chemistry of the final hadrons is defined by the **LUND string model**.

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





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

with $\kappa \approx 0.176\,\text{GeV}^2$ and $m_{u,d,s}$ as constituent ('dressed') masses due to the coupling to the vacuum.

In **vacuum** (e.g. p+p collisions) the dressing of the bare quark masses follows:

$$m_q^V = m_q^0 - g_s \langle \bar{q}q \rangle_V,$$

with $m_{u,d}^0 \approx 7\,\text{MeV}$, $m_s^0 \approx 100\,\text{MeV}$ and $\langle \bar{q}q \rangle_V \approx -3.2\,\text{fm}^{-3}$.

In **medium** (e.g. A+A collisions) the dressing of the bare quark masses follows:

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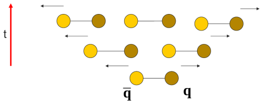

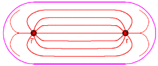

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➜ **We need to evaluate the scalar quark condensate in the medium!**

Chiral Symmetry restoration in PHSD

The scalar quark condensate $\langle \bar{q}q \rangle$ is viewed as an order parameter for the restoration of chiral symmetry.

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

An estimate for $\langle \bar{q}q \rangle$ is given by Friman et al., Eur. Phys. J. A **3**, 165, 1998:

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

with Σ_π as the pion-nucleon Σ-term, σ_h as the $\sigma-$commutator of the meson h, ρ_s as scalar density which can be obtained within the non-linear $\sigma - \omega$ model and f_π and m_π are the pion decay constant and pion mass, given by the Gell-Mann-Oakes-Renner relation.

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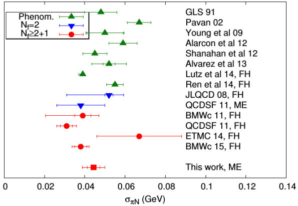
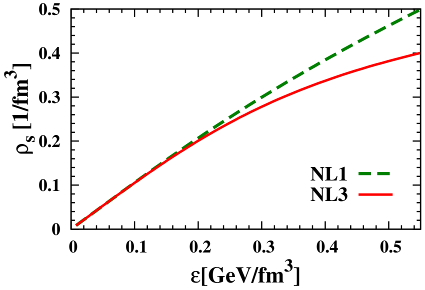
We adopt $\Sigma_\pi = 45\,\text{MeV}$.
Modifications on the value of Σ_π have no essential effect on our results.



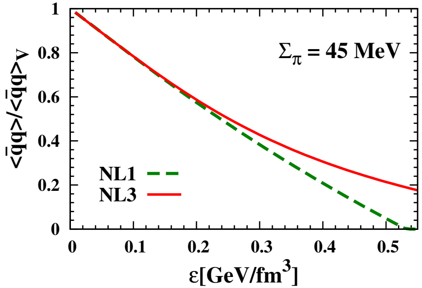
Yi-Bo Yang et al., Phys. Rev. D 94, 054503 (2016).

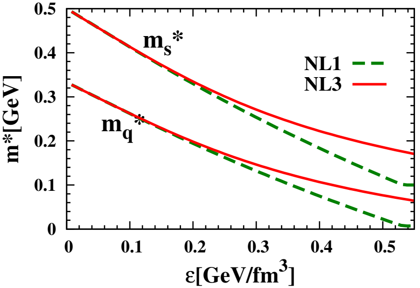
The scalar density ρ_s is obtained within the **non-linear $\sigma - \omega$ model** solving locally the gap equation for the σ-field.

We investigate different parametrizations for the hadronic EoS to estimate the uncertainty on our results.



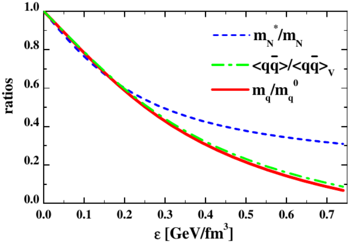
- There is a **moderate sensitivity related to the hadronic EoS**.
- NL1 parameter set for the EoS is associated to lower values for $\langle \bar{q}q \rangle / \langle \bar{q}q \rangle_V$.



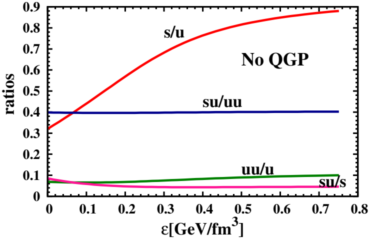


Chiral Symmetry restoration in PHSD

Considering effective quark masses $m^*_{q,s}$ in the **Schwinger formula**.



The **ratio s/u** increases with decreasing $\langle \bar{q}q \rangle$ and increasing ϵ.



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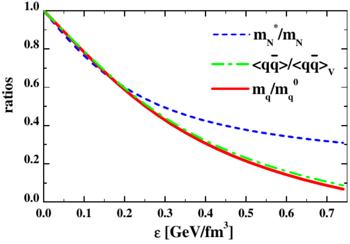
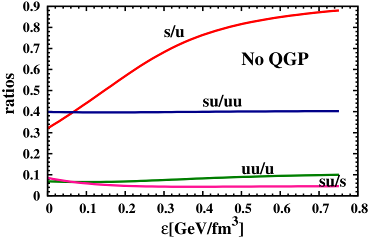
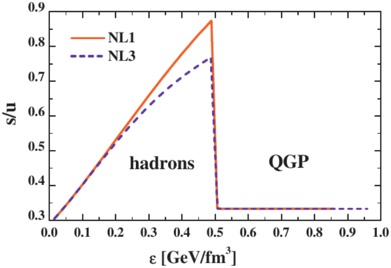


The **ratio s/u** increases with decreasing $\langle \bar{q}q \rangle$ and increasing ϵ.

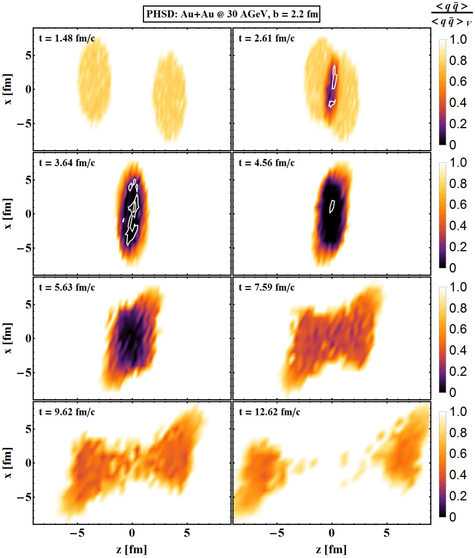


In the **QGP phase**, the string decay doesn't occur anymore and this effect is therefore suppressed.

A "Horn" feature emerges in the energy dependence of the s/u ratio!



Scalar quark condensate in HIC



W. Cassing et al., Phys. Rev. C93 (2016) 014902.

Time evolution of the ratio $\dfrac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_V}$ for Au+Au @ 30 AGeV.

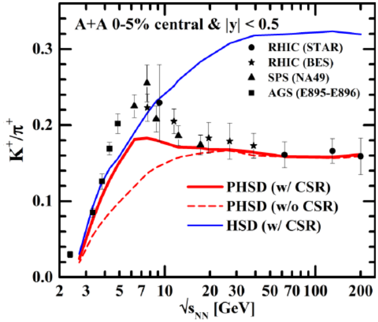
$$\langle \bar{q}q \rangle = \begin{cases} \neq 0 & \text{chiral non-symmetric phase;} \\ = 0 & \text{chiral symmetric phase.} \end{cases}$$

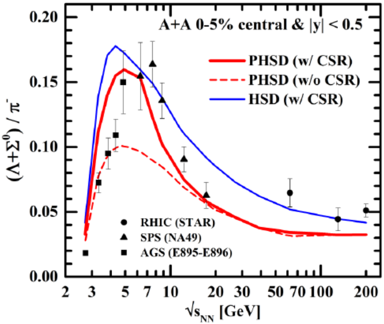
The scalar quark condensate $\langle \bar{q}q \rangle$ is not a direct observable.

Can we find manifestations of the chiral symmetry restoration indirectly in hadronic observables?

Chiral Symmetry restoration: Horn

We observe a rise in the ratio K^+/π^+ at low $\sqrt{s_{NN}}$ related to **Chiral Symmetry Restoration (CSR)** and then a drop due to the appearance of a **deconfined partonic medium**. ➜ A "**horn**"-structure emerges.



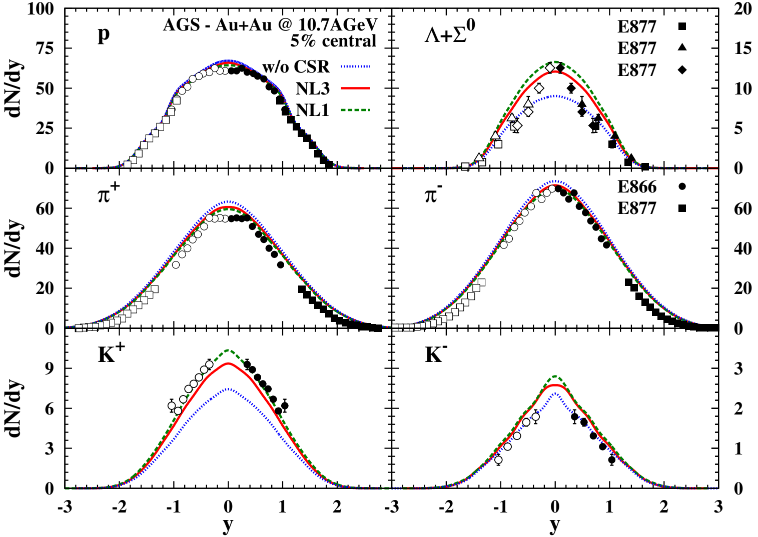


W. Cassing, A. P., P. Moreau, E.L. Bratkovskaya, Phys. Rev. C93 (2016) 014902.

What is the sensitivity to the equation of state?

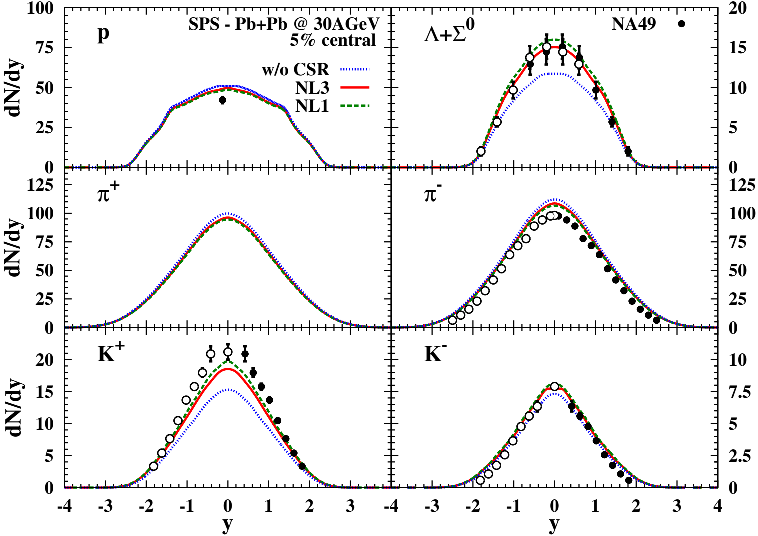
Rapidity spectra I

Au+Au @ 10.7 AGeV in comparison to data at AGS



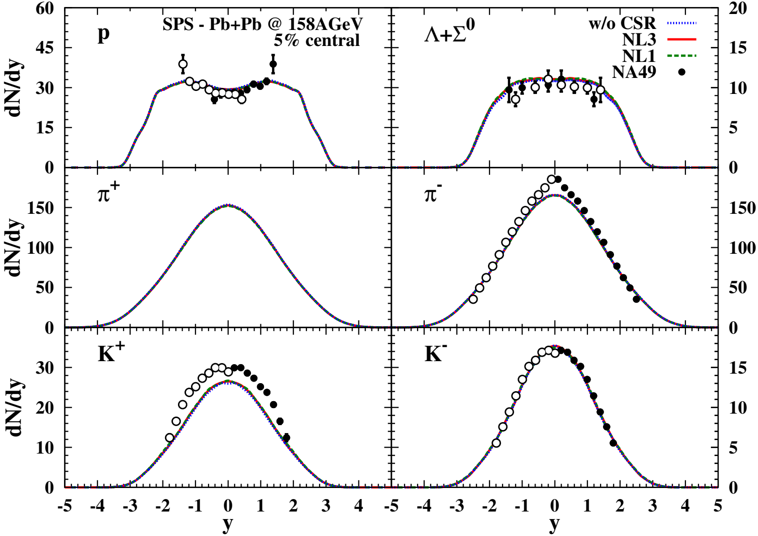
A. P. et al., Phys. Rev. C94 (2016) 044912.

Pb+Pb @ 30 AGeV in comparison to data at SPS



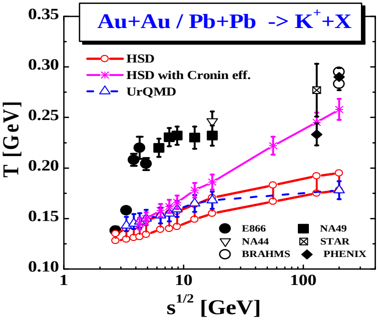
A. P. et al., Phys. Rev. C94 (2016) 044912.

Pb+Pb @ 158 AGeV in comparison to data at SPS

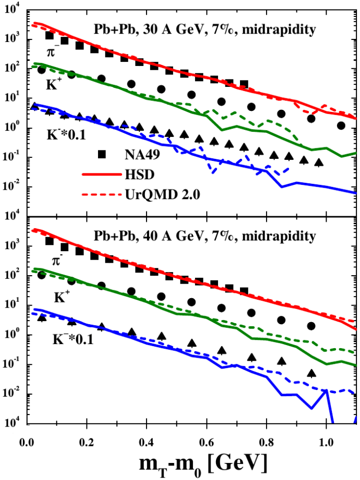


A. P. et al., Phys. Rev. C94 (2016) 044912.

Open issue: there was an underestimation of the transverse mass spectra of kaons in the whole energy range.

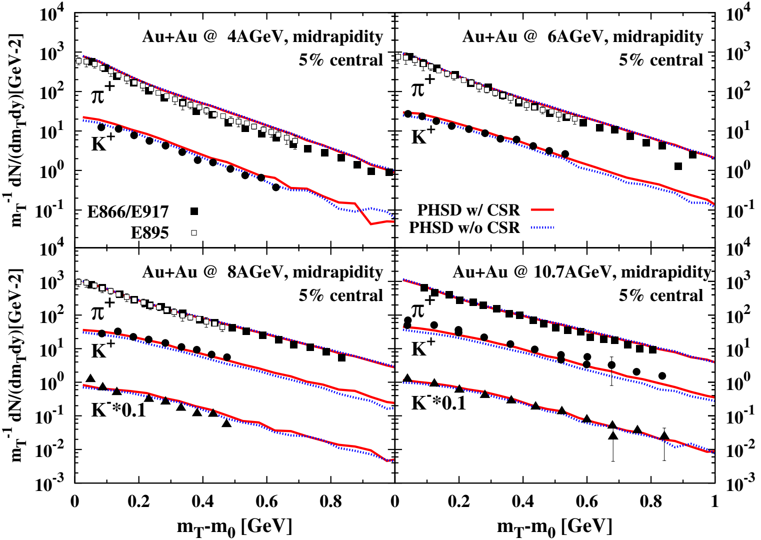


E.L. Bratkovskaya, Phys. Rev. C 69 (2004) 032302.



Transverse mass spectra I

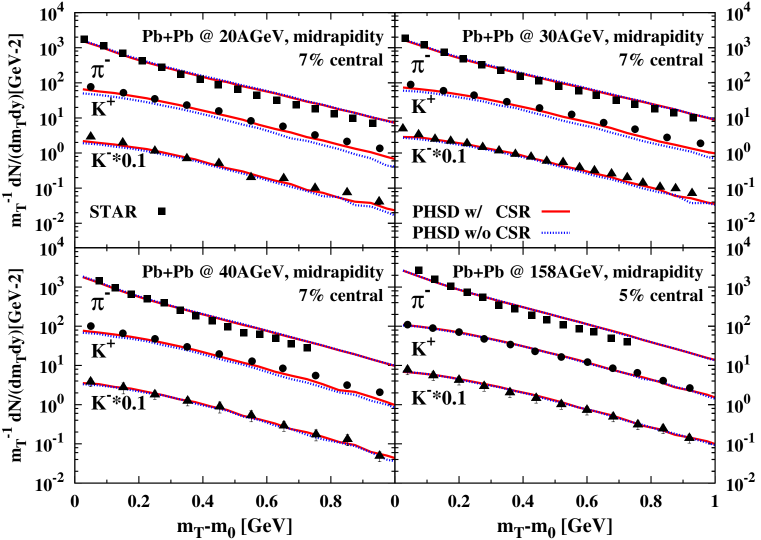
Au+Au collisions in comparison to data at AGS



A. P. et al., Phys. Rev. C94 (2016) 044912.

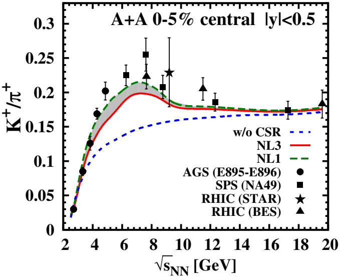
Transverse mass spectra II

Pb+Pb collisions in comparison to data at SPS



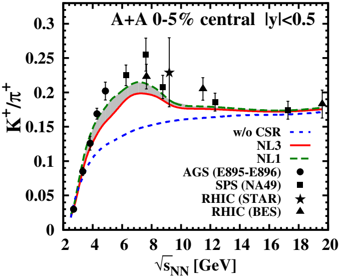
A. P. et al., Phys. Rev. C94 (2016) 044912.

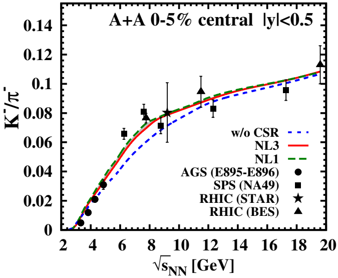
Strange to non-strange particle ratios



- There is a **moderate sensitivity related to the hadronic EoS** in our results.
- NL1 parameter set for the EoS shows a sharper peak in the K^+/π^+ ratio in good agreement with the data.

Strange to non-strange particle ratios





- There is a **moderate sensitivity related to the hadronic EoS** in our results.
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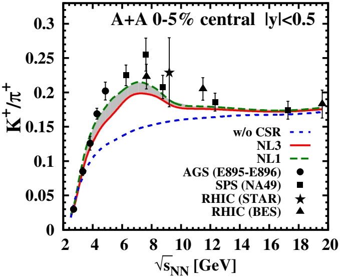
Strange to non-strange particle ratios



- There is a **moderate sensitivity related to the hadronic EoS** in our results.
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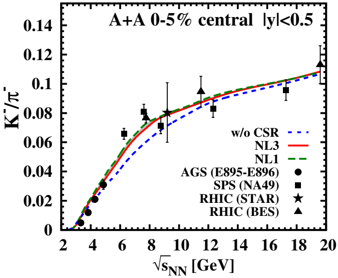
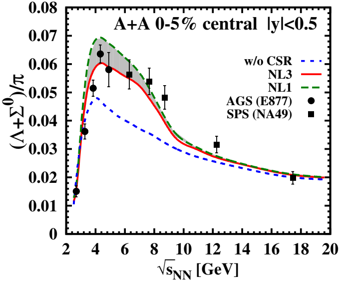
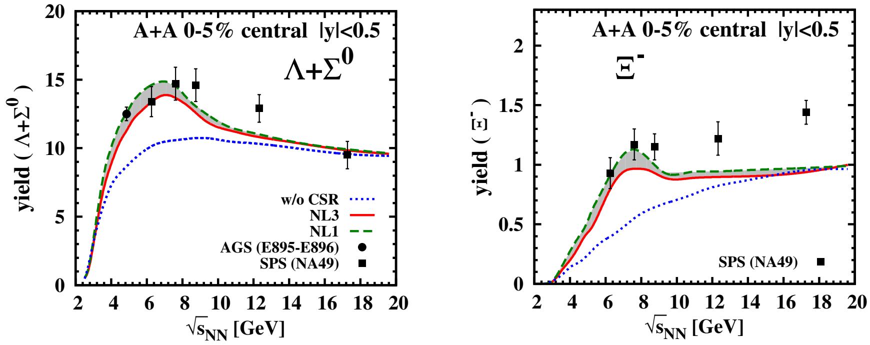




A. P. et al., Phys. Rev. C94 (2016) 044912.

Hyperon abundances

Excitation function of the **hyperons Λ and Ξ^-**.

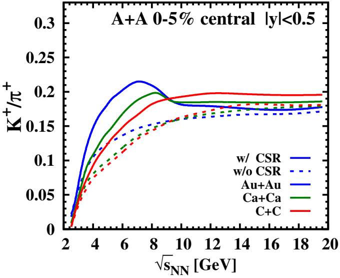


A. P. et al., Phys. Rev. C94 (2016) 044912.

They show **analogous peaks** as the K^+/π^+ and $(\Lambda + \Sigma_0)/\pi$ ratios due to CSR.

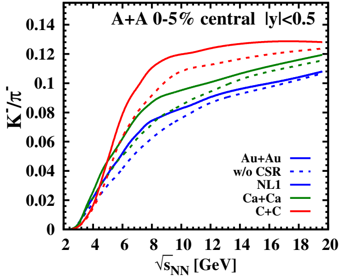
There is a small sensitivity on the parametrizations for the hadronic EoS.

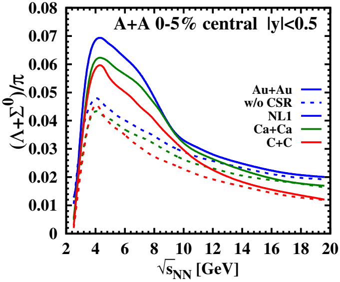
Sensitivity to the system size: A+A collisions



If the system size is smaller:

- **the peak of K^+/π^+ disappears**;
- **the peak of $(\Lambda + \Sigma^0)/\pi$ remains** in the same position in energy.

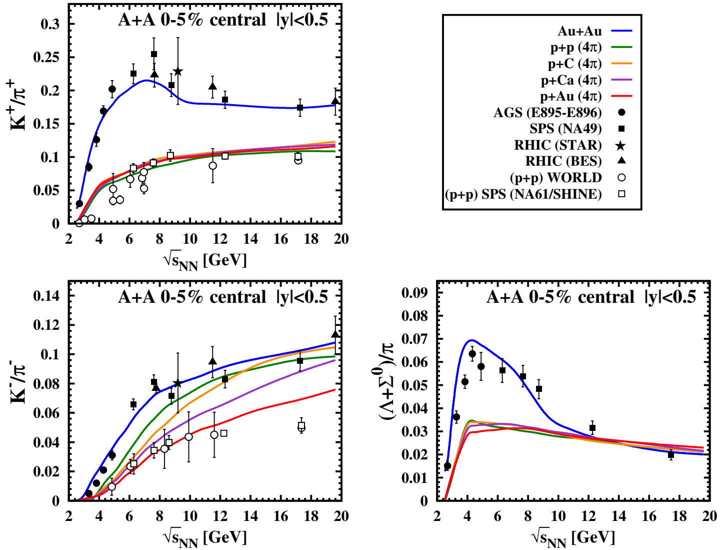




A. P. et al., Phys. Rev. C94 (2016) 044912.

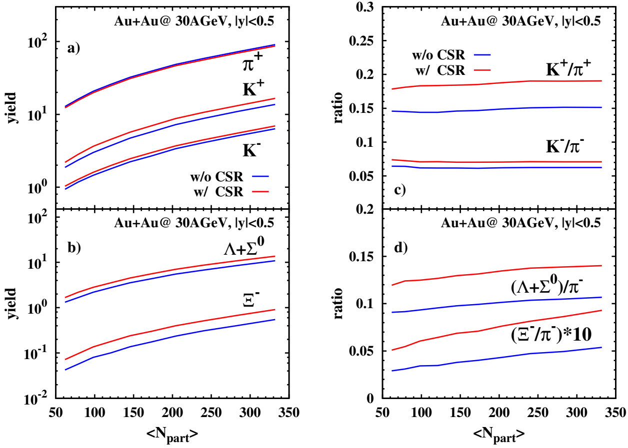
Sensitivity to the system size: p+A collisions

In **p+A collisions** strange to non-strange particle ratios show **no peaks**.



Centrality dependence

Particles abundances and ratios as a function of the number of participants in Au+Au @ 30 AGeV



A. P. et al., Phys. Rev. C94 (2016) 044912.

There is a **sizeable difference between** the results **with and without CSR**.

➜ Interesting to study experimentally!

Summary

Can we find a manifestation of CSR in HIC observables? **Yes!**

- Particle abundances and rapidity spectra are suitable probes to extract information about CSR.
- Transverse mass spectra are not so much sensitive to the CSR mechanism. The PHSD m_T-spectra are in good agreement with the data.
- There is a moderate sensitivity on the hadronic EoS in our results, especially in the excitation functions of the strange to non-strange particle ratios.
- The 'horn'-structure disappears in the K^+/π^+ ratio as the system size decreases, while it remains in the $(\Lambda + \Sigma^0)/\pi$ ratio.
- The difference between our results with and without CSR remains sizable in a large range of centralities.

Looking forward for NICA results!

Thank you for your attention!

PHSD group 2016

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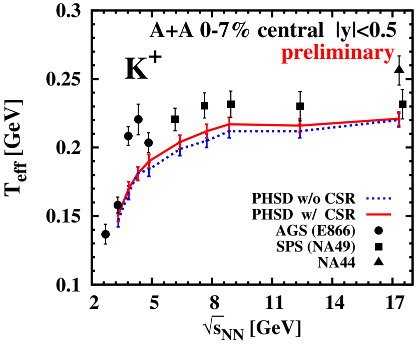
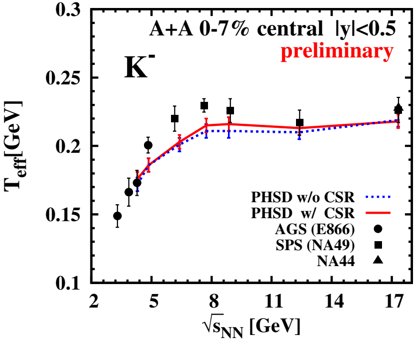
Barcelona University:
Laura Tolos
Angel Ramos

BACK-UP SLIDES

Kaon transverse mass spectra

Excitation function of T_{eff}





- Increase of slope T_{eff} due to the QGP.
- Small effect of chiral symmetry restoration on slope T_{eff}.

Chiral Symmetry restoration: Basic Principles

- The QCD Lagrangian for massless quarks is chirally symmetric, i.e. invariant under a transformation of the symmetry group $SU(2)_L \, x \, SU(2)_R$. The associated transformation for the quark field is:

$$\varphi \to \varphi' = e^{-i\frac{\tau_a}{2}\Theta_a P_L} e^{-i\frac{\tau_b}{2}\Theta_b P_R}\varphi, \qquad \text{with} \quad P_{L,R}{=}\tfrac{1}{2}(1{\mp}\gamma_5).$$

- This transformation can be rewritten in terms of transformation $\Lambda_V \, x \, \Lambda_A$ of the group $SU(2)_V \, x \, SU(2)_A$:

$$e^{-i\frac{\tau_a}{2}\Theta_a P_L} e^{-i\frac{\tau_b}{2}\Theta_b P_R}\varphi \to e^{-i\frac{\vec{\tau}}{2}\vec{\Theta}_V} e^{-i\gamma_5\frac{\vec{\tau}}{2}\vec{\Theta}_A}\varphi.$$

If the Chiral Symmetry holds, the vector and axial currents are equal.

- In case of massive quarks, the Chiral Symmetry is explicitly broken:

$$\Lambda_A : m(\bar{\varphi}\varphi) \to m(\bar{\varphi}\varphi) - 2im\vec{\Theta}\cdot\left(\bar{\varphi}\frac{\vec{\tau}}{2}\gamma_5\varphi\right).$$

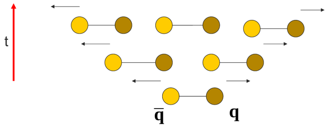
For energies larger than the particle masses, Λ_A may be treated as an approximate symmetry.

- The chiral condensate is adopted as an order parameter of the transition between the chiral non-symmetric and the chiral symmetric phase:

$$\langle\bar{\varphi}\varphi\rangle = -\frac{T}{V}\frac{\partial}{\partial m_q} logZ = \begin{cases} \neq 0 & \text{for } T < T_{ch} \text{ (chiral non-symmetric phase)} \\ = 0 & \text{for } T \geq T_{ch} \text{ (chiral symmetric phase).} \end{cases}$$

Low energy dynamics in QCD is dominated by **Strings**.

A color flux connects the rapidly receding string-ends.



Production of virtual $q\bar{q}$ or $qq\bar{q}\bar{q}$ pairs which break the color field tube.

Creation of mesons or baryon-antibaryon pairs with $\tau_f \approx 0.8\, fm/c$.

- **Chemistry** determined by the Schwinger formula:

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

with $\kappa \approx 0.176 GeV^2$ and $m_{u,d,s}$ as constituent masses.

The relative production factors in PHSD/HSD are:

$$u : d : s : uu = \begin{cases} 1 : 1 : 0.3 : 0.07 & \text{at SPS to RHIC;} \\ 1 : 1 : 0.4 : 0.07 & \text{at AGS energies.} \end{cases}$$

- **Kinematics** determined by the Fragmentation Function $f(x, m_T)$

$$f(x, m_T) \approx \frac{1}{x}(1 - x^a) exp(-b m_T^2 / x).$$

Chiral Symmetry Restoration (CSR) in PHSD

- In a hot and dense medium, the hadrons undergo modifications of their properties, e.g. the mass!

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

  where the scalar field $\sigma(x)$ mediates the scalar interaction with the surrounding medium through the coupling g_s.

- The value of $\sigma(x)$ for nucleons is determined locally by the non-linear gap equation:

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

- Within the non-linear $\sigma - \pi$ model for nuclear matter, the parameters g_s, m_σ, B, C can be fixed in order to reproduce the values of the main nuclear matter quantities at saturation,
  i.e. saturation density, binding energy per nucleon, compression modulus and the effective nucleon mass.
  (Actually there are different sets for the values of the parameters, due to the large experimental uncertainties on their values.)

Chiral Symmetry restoration in PHSD

An estimate for the quark scalar condensate is given by Friman et al., Eur. Phys. J. A **3**, 165, 1998:

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

with $\Sigma_\pi \approx 45 MeV$ (reduced in case of hyperons according to the light quark content), σ_h as the $\sigma-$commutator of the meson h ($= m_\pi/2$ for mesons made of light quarks, $= m_\pi/4$ for mesons composed of (anti-)strange quarks).

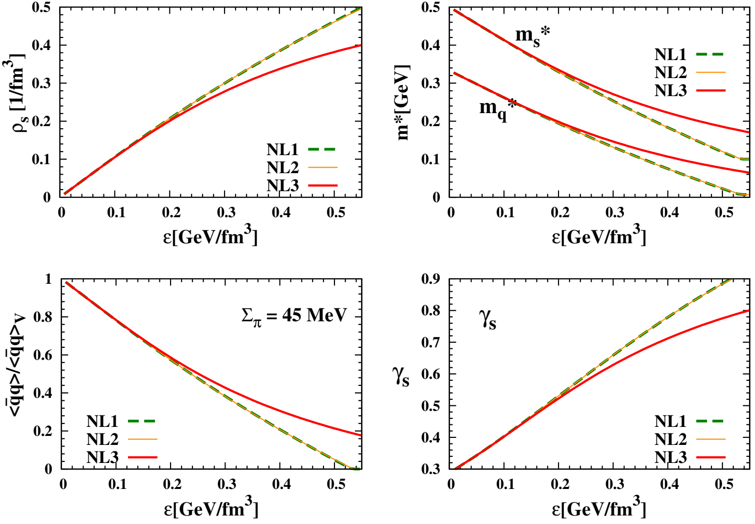
- The vacuum scalar condensate $\langle q\bar{q} \rangle_V$ is fixed by the Gell-Mann-Oakes-Renner relation:

$$f_\pi^2 m_\pi^2 = -\frac{1}{2}(m_u^0 + m_d^0)\langle \bar{q}q \rangle_V \quad \rightarrow \quad \langle \bar{q}q \rangle_V \approx -3.2\, fm^{-3}$$

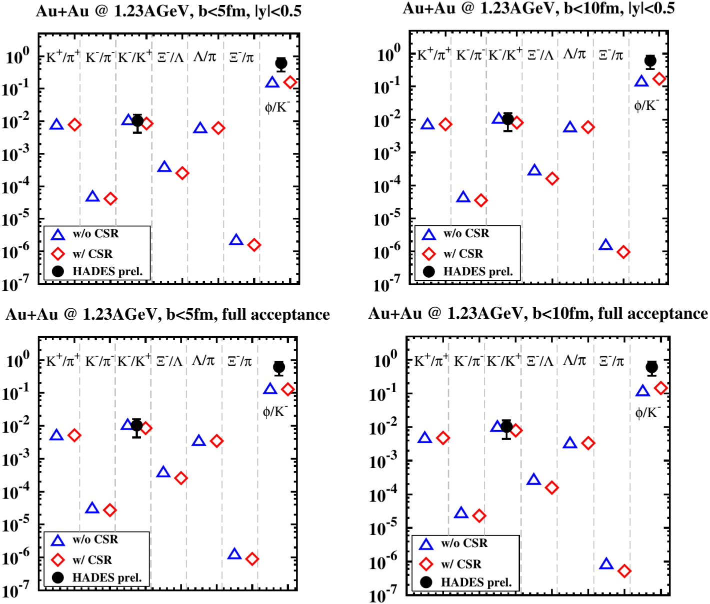
for the bare quark masses $m_u^0 = m_d^0 \approx 7 MeV$.

- The nucleon scalar density ρ_s is obtained after solving the gap equation for the field $\sigma(x)$.

The sensitivity to the nuclear EoS is dominantly driven by the effective mass of the nucleons.



Particle ratios at low energy



Many body theory

Kadanoff Baym Gleichungen (exact)

$$[\ss\partial_t - h(t)]\, G(t,t') = \delta(t-t') + \int_C d\bar{t}\, \Sigma[G](t,\bar{t})G(\bar{t},t')$$

$$[-\ss\partial_{t'} - h(t')]\, G(t,t') = \delta(t-t') + \int_C d\bar{t}\, G(t,\bar{t})\Sigma[G](\bar{t},t')$$

Limiting to two-particle correlations

$$\left\{ i\hbar\frac{\partial}{\partial\tau} - [\epsilon(\mathbf{p}) + \Delta(\mathbf{p}) + i\Gamma(\mathbf{p})] \right\} g^<(\mathbf{p},t,\tau) = I(\mathbf{p},t)$$

W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 4451

Off-shell (generalized) transport theory

Only one-particle distributions=diagonal Green's Functions, no correlations, weakly interacting or dilute systems

$$\frac{\partial}{\partial t} f(\mathbf{p},t) = I(\mathbf{p},t)$$

Boltzmann (BUU oder Vlasov-Boltzmann)