Chiral symmetry restoration in heavy-ion collisions

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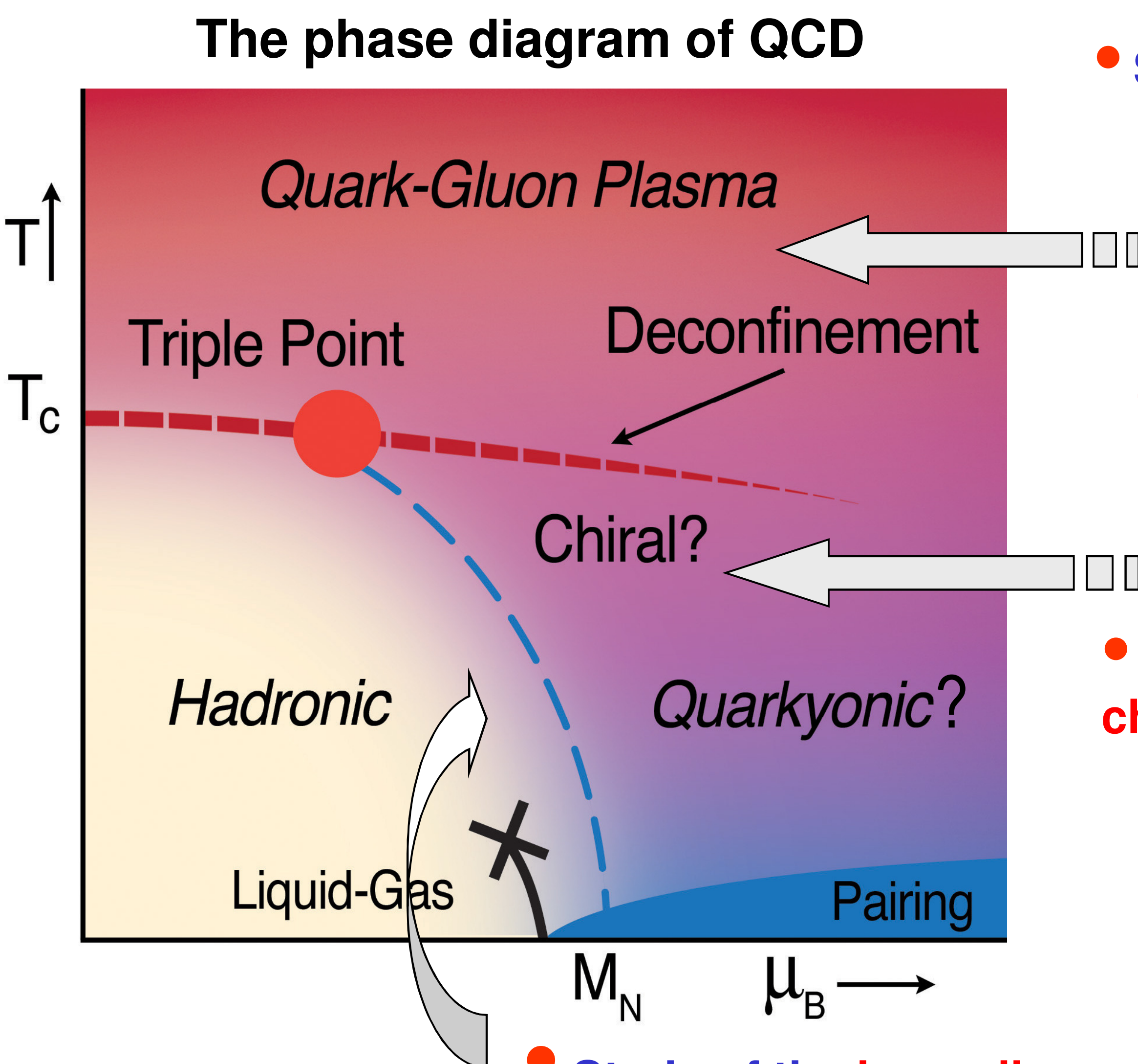
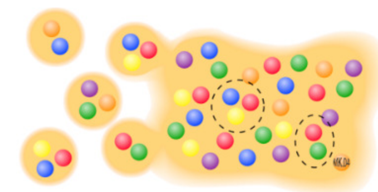
The ‚holy grail‘ of heavy-ion physics:



- Search for the critical point



- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma
- Search for the signatures of chiral symmetry restoration
- Study of the in-medium properties of hadrons at high baryon density and temperature

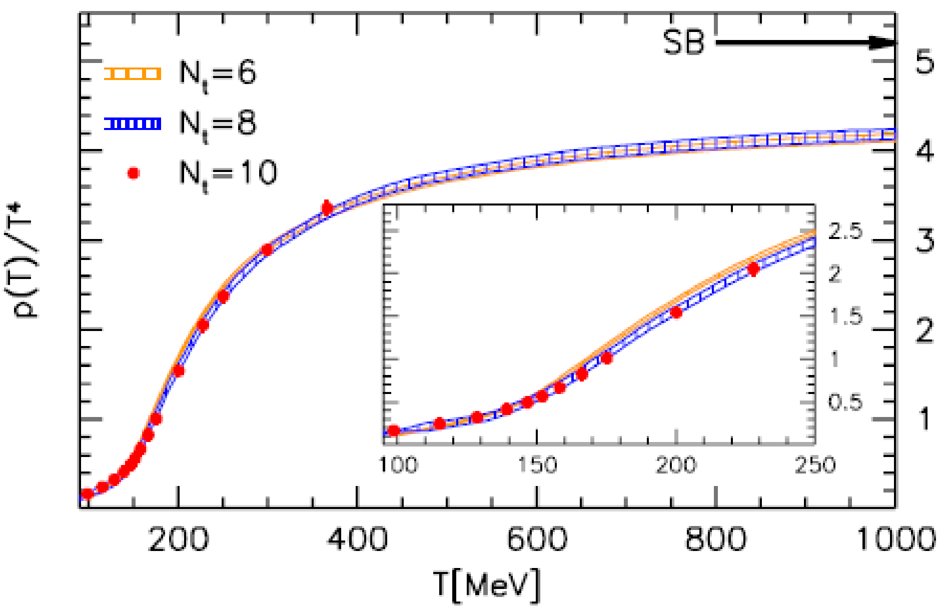
Information from lattice QCD

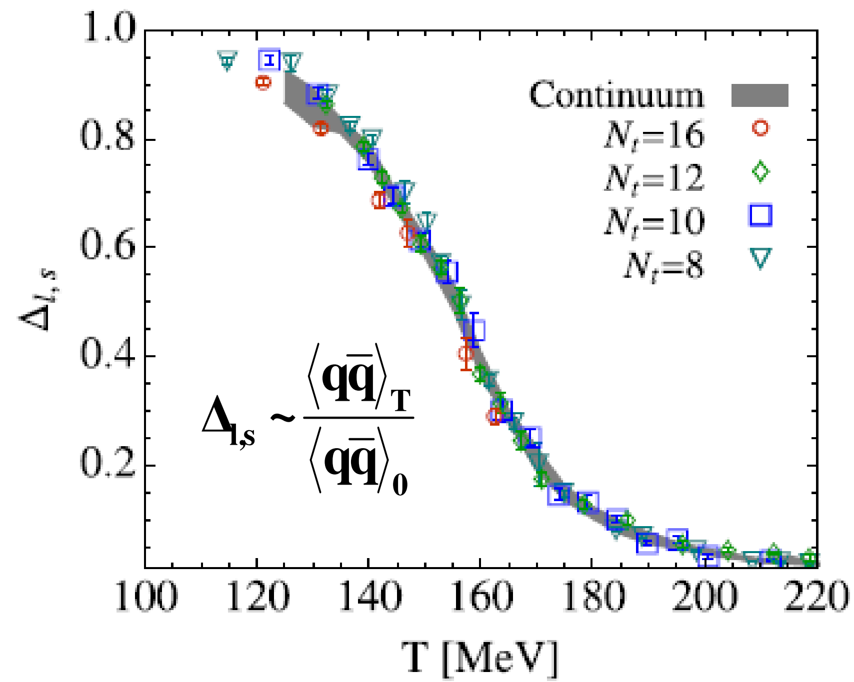
I. deconfinement phase transition
with increasing temperature

+

II. chiral symmetry restoration
with increasing temperature

lQCD BMW collaboration:





- **Scalar quark condensate $\langle q\overline{q}\rangle$ is viewed as an order parameter for the restoration of chiral symmetry:**

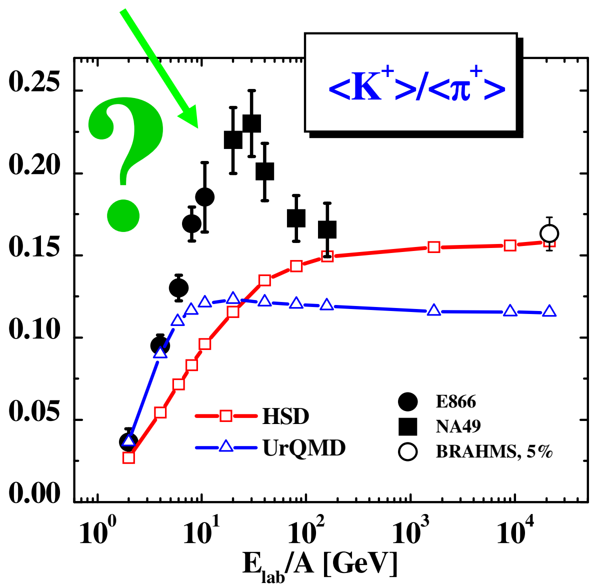
$$<\bar{q}q>=\begin{cases}\neq 0 & \text{chiral non-symmetric phase;}\\ =0 & \text{chiral symmetric phase.}\end{cases}$$

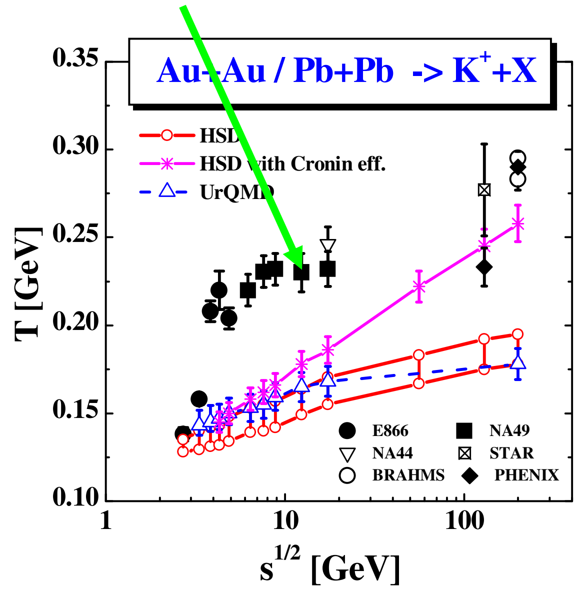
- **Crossover:**
  both transitions occur at about the same temperature T_C for low chemical potentials

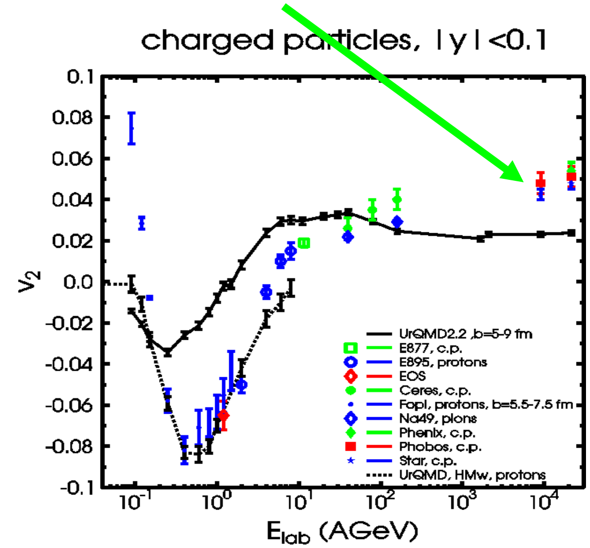
Signals for the phase transition

Hadron-string transport models (HSD, UrQMD) versus observables at ~ 2000

- ,horn‘ in K^+/π^+
- ,step‘ in slope T
- elliptic flow v_2







Exp. data are not reproduced in terms of the hadron-string picture
➔ evidence for partonic degrees of freedom + ... ?!

NA49: PRC66 (2002) 054902

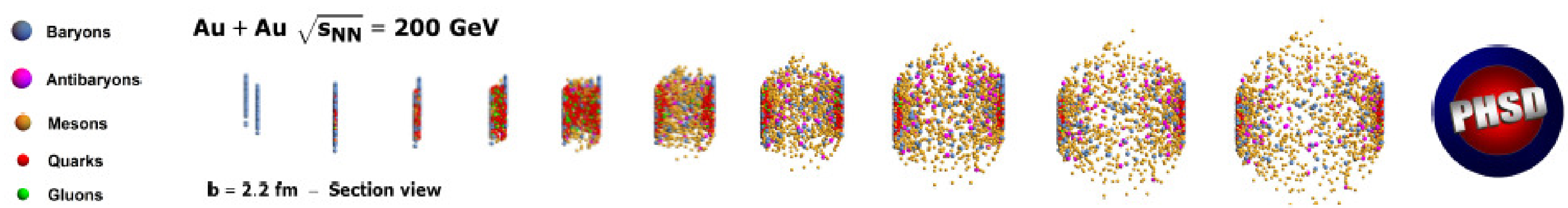
HSD, UrQMD: PRC 69 (2004) 032302

Dynamical description of heavy-ion collisions

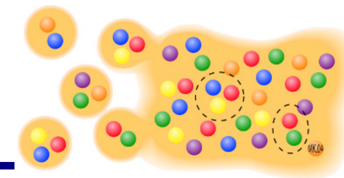
The goal:
to study the properties of strongly interacting matter under extreme conditions from a microscopic point of view

Realization:
to develop a dynamical many-body transport approach
1) applicable for strongly interacting systems,
which includes:
2) phase transition from hadronic matter to QGP
3) chiral symmetry restoration

2004-2016



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 on a microscopic level

➔ need a consistent <u>non-equilibrium</u> transport approach

- ❑ **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 (‚cross over' at μ_q=0)**

❑ **Transport theory for strongly interacting systems: 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 is 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)

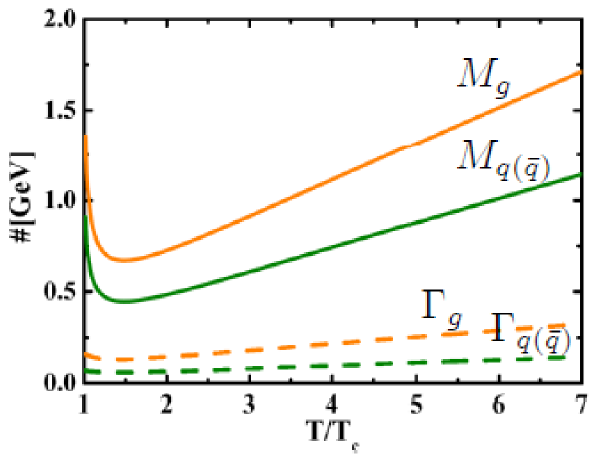
The Dynamical QuasiParticle Model (DQPM)

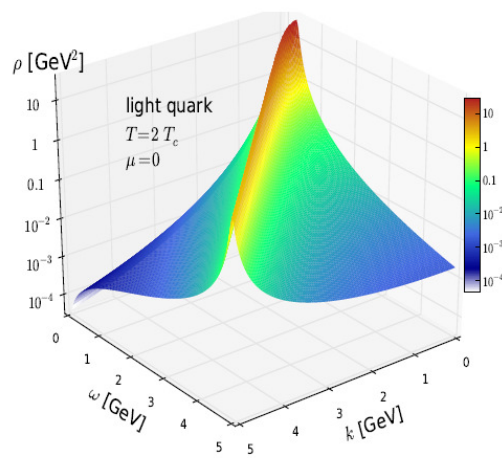
- **Basic idea: interacting quasi-particles: massive quarks and gluons (g, q, q_{bar}) with Lorentzian spectral functions :**

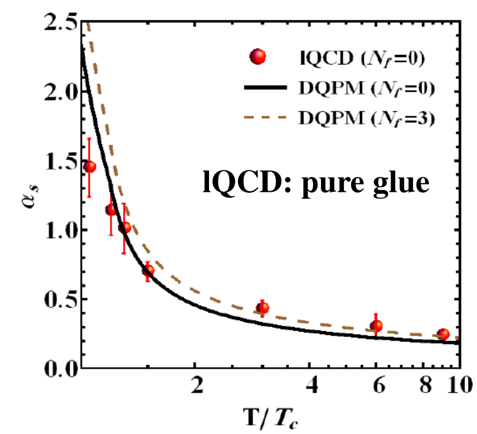
$$\rho_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)} \qquad (i = q, \bar{q}, g)$$

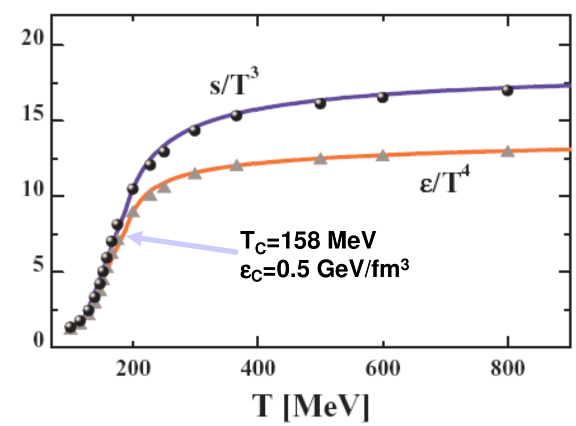
- **Modeling of the quark/gluon masses and widths → HTL limit at high T with 3 model parameters – fited to lattice QCD data**

→ Quasi-particle properties:
large width and mass for gluons and quarks



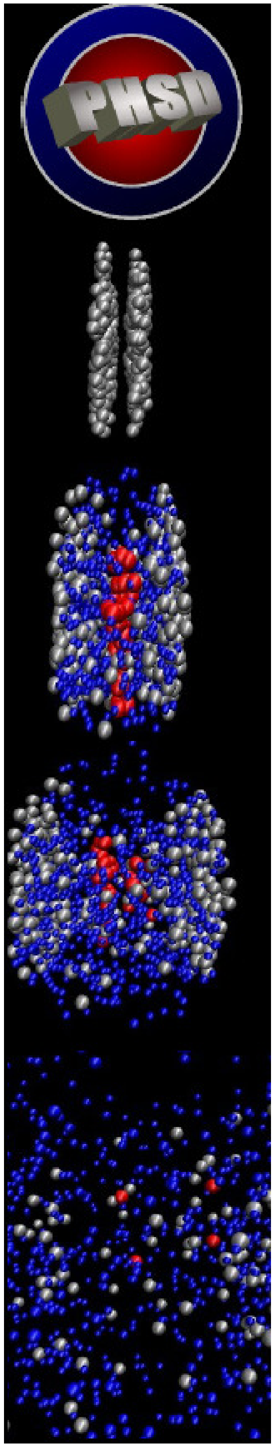






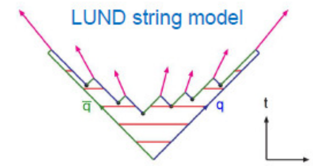
- **DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)**
- **DQPM gives transition rates for the formation of hadrons → PHSD**

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

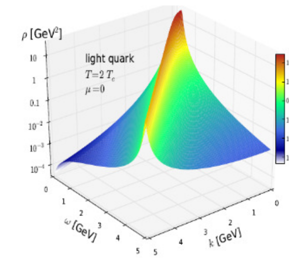


Parton-Hadron-String-Dynamics (PHSD)

- **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



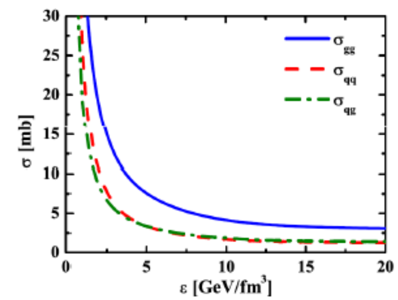
- **Partonic stage – QGP** :
  based on the Dynamical Quasi-Particle Model (DQPM)

  - (quasi-) elastic collisions:

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

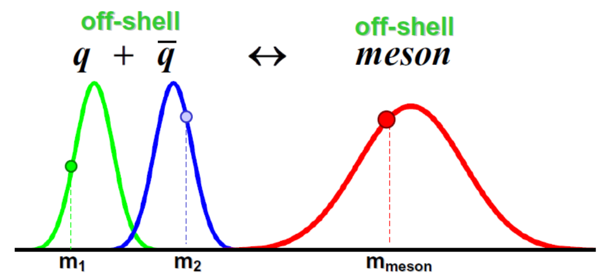
  - inelastic collisions:

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



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

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

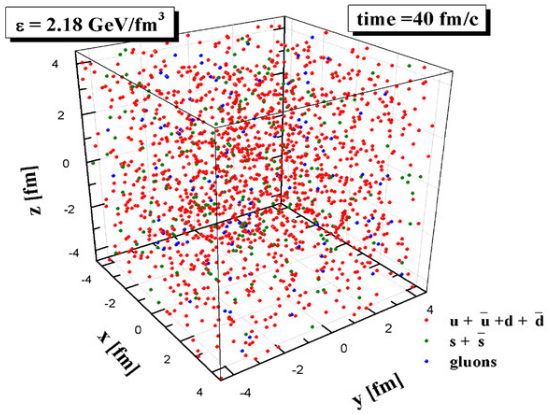


- **Hadronic phase: hadron-hadron interactions – off-shell HSD**

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

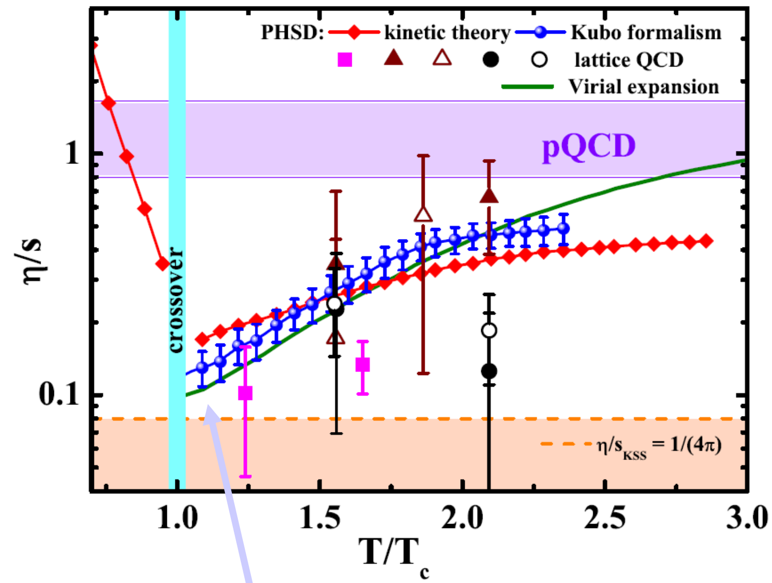
QGP in equilibrium: Transport properties at finite (T, μ_q): η/s

Infinite hot/dense matter =
PHSD in a box:



Shear viscosity η/s at finite T

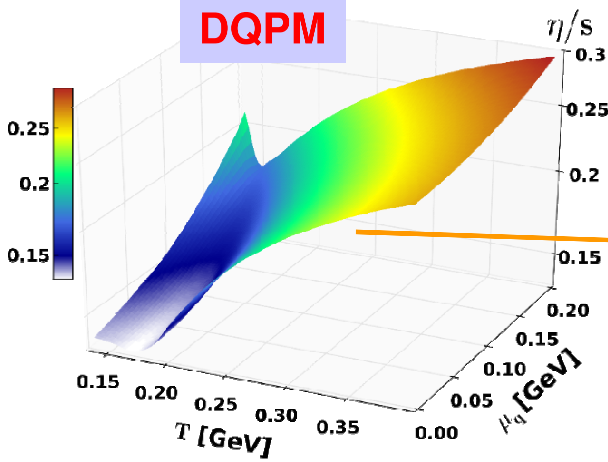
V. Ozvenchuk et al., PRC 87 (2013) 064903



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

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

DQPM

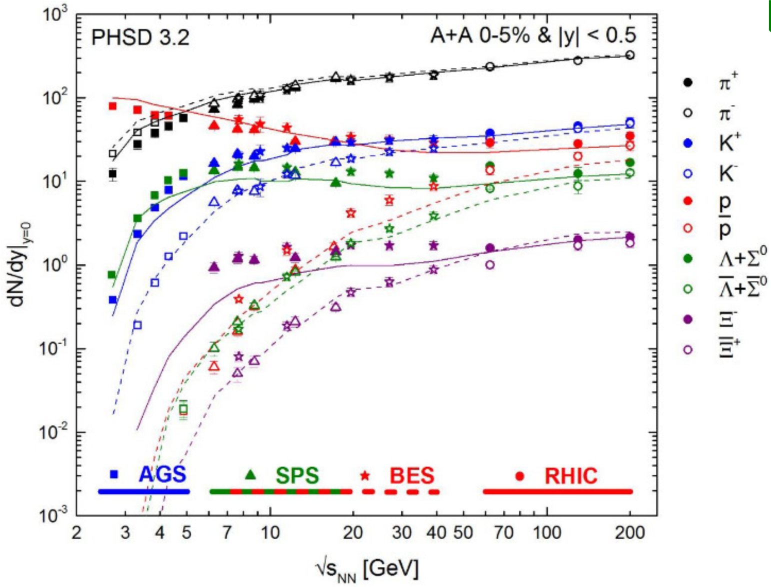


QGP in PHSD = strongly-interacting liquid-like system

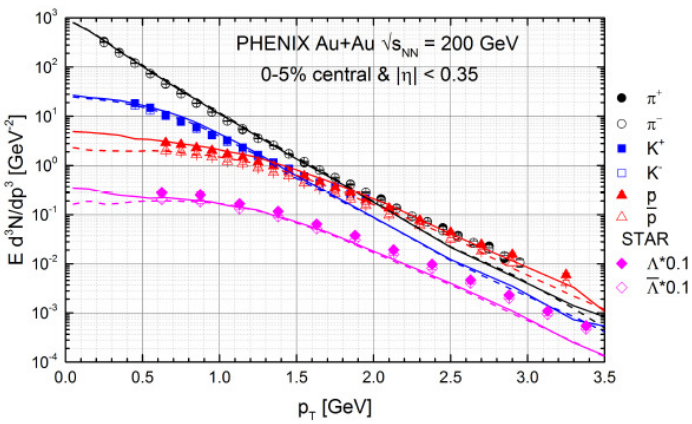
η/s: μ_q=0 ➔ finite μ_q: smooth increase as a function of (T, μ_q)

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

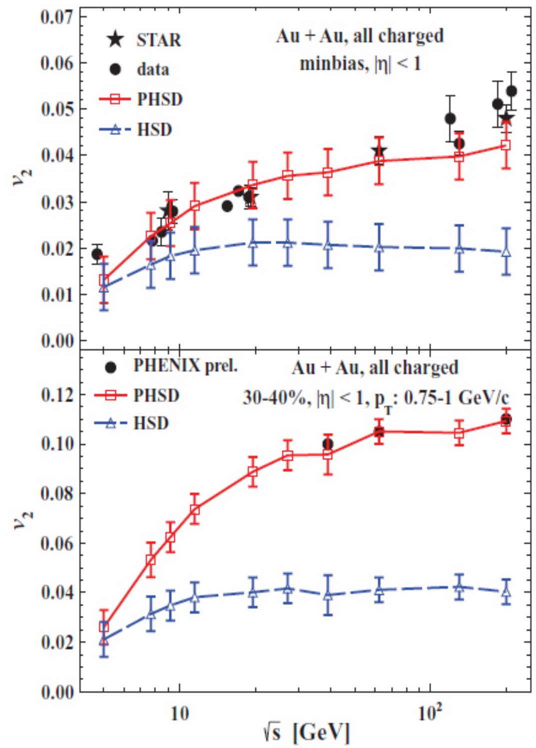
Non-equilibrium dynamics: description of A+A with PHSD

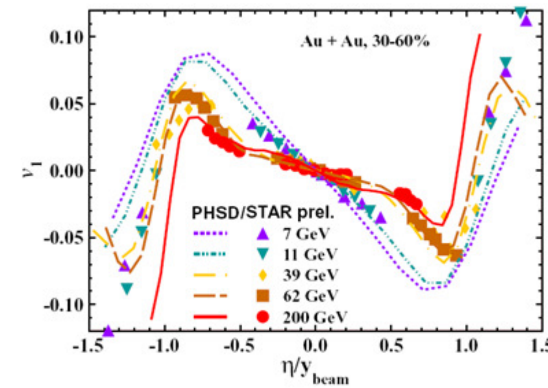


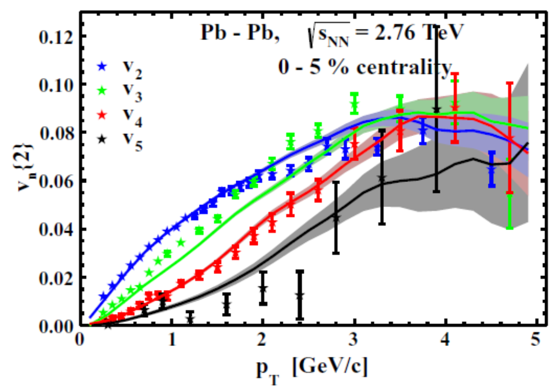
PHSD: P. Moreau



❑ PHSD: highlights







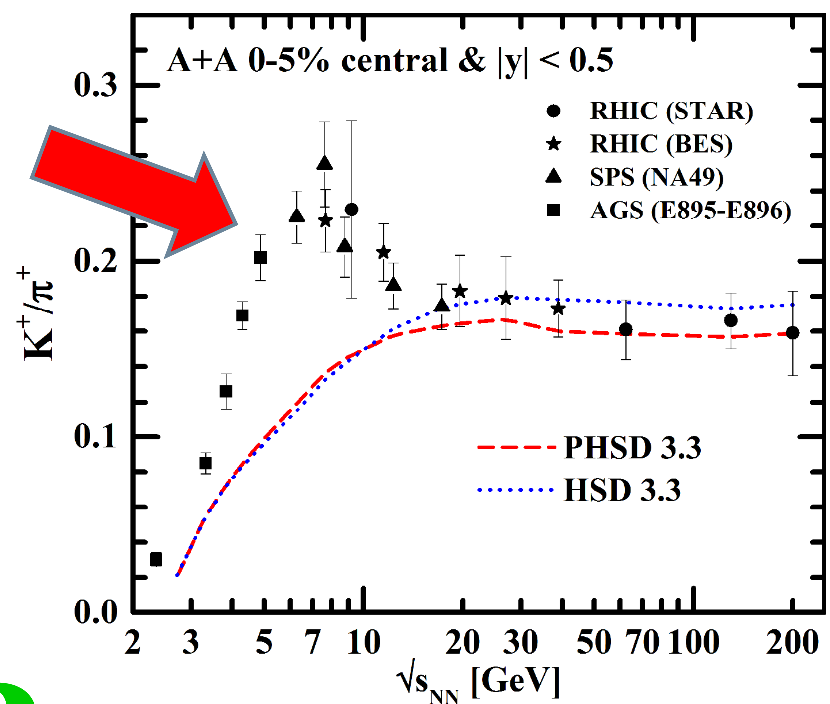
V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106

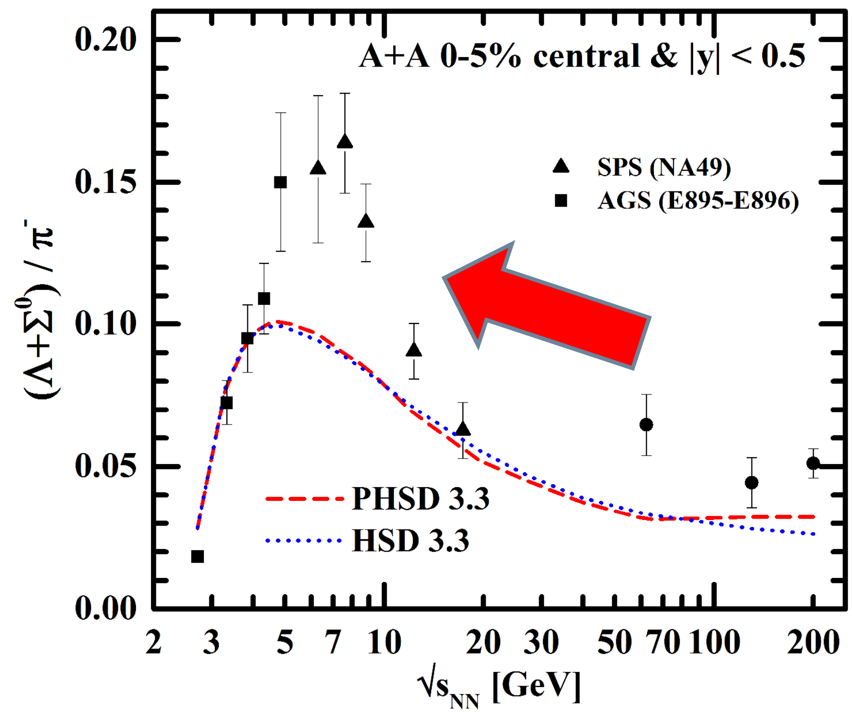
❑ **PHSD provides a good description of ‚bulk' observables (y-, p_T-distributions, flow coefficients v_n, …) from SIS to LHC**

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 ?!



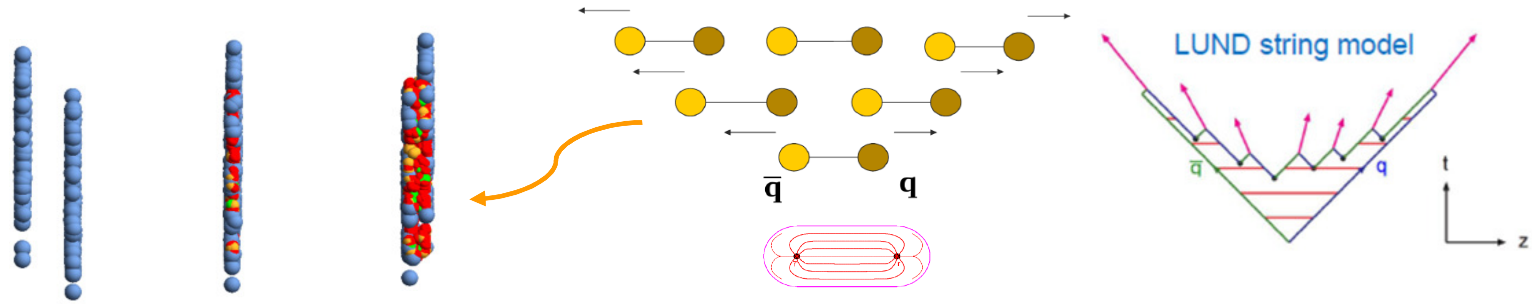


? Can it be related to chiral symmetry restoration in the hadronic phase?!

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

Chiral symmetry restoration 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:

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

vacuum scalar quark condensate fixed from Gell-Mann-Oakes-Renner relation $f_\pi^2 m_\pi^2 = -\frac{1}{2}(m_u^0 + m_d^0) < \bar{q}q >_V$

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

➔ Constituent quark masses in vacuum :

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

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

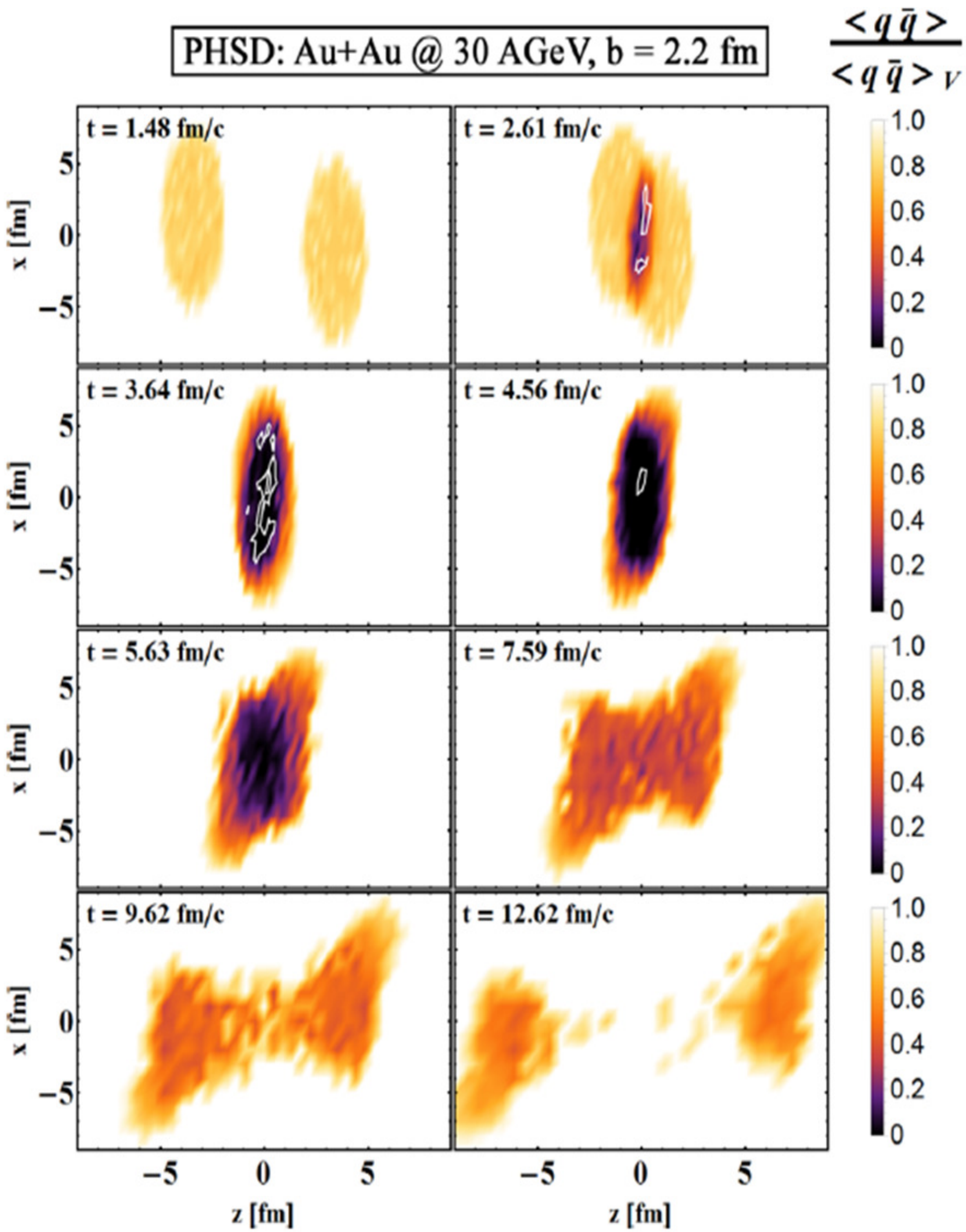
Scalar quark condensate in HIC

PHSD:
Ratio of the scalar quark condensate

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

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

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

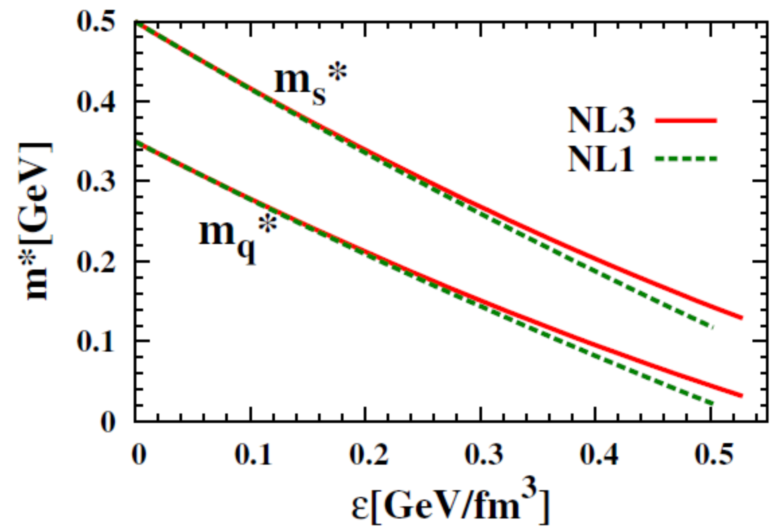


W. Cassing, A. Palmese, P. Moreau, E.L. Bratkovskaya, PRC 93, 014902 (2016), arXiv:1510.04120

Modeling of the chiral symmetry restoration in PHSD

- HIC: in the Schwinger formula the in-medium constituent masses $m^*_{q;s}$ (instead of vacuum $m_{q;s}$) have to be considered:

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



➔ Strangeness ratio *s/u*

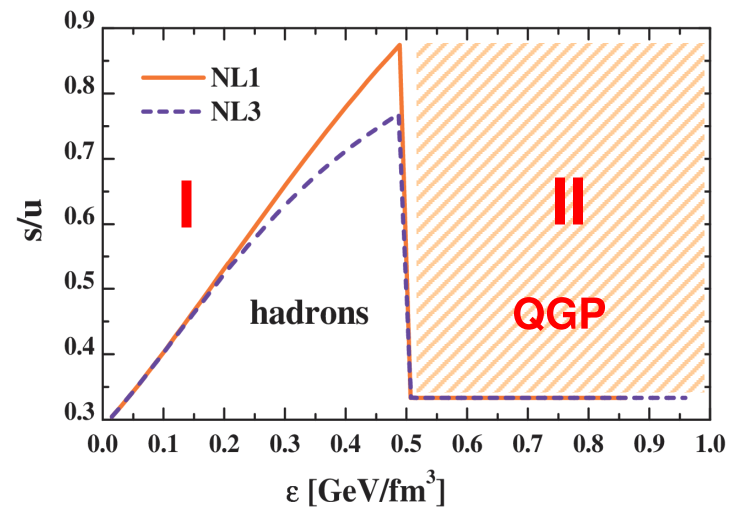
I. hadronic phase : $\varepsilon < \varepsilon_C$

As a consequence of the chiral symmetry restoration (CSR), the strangeness production probability increases with the local energy density ε.

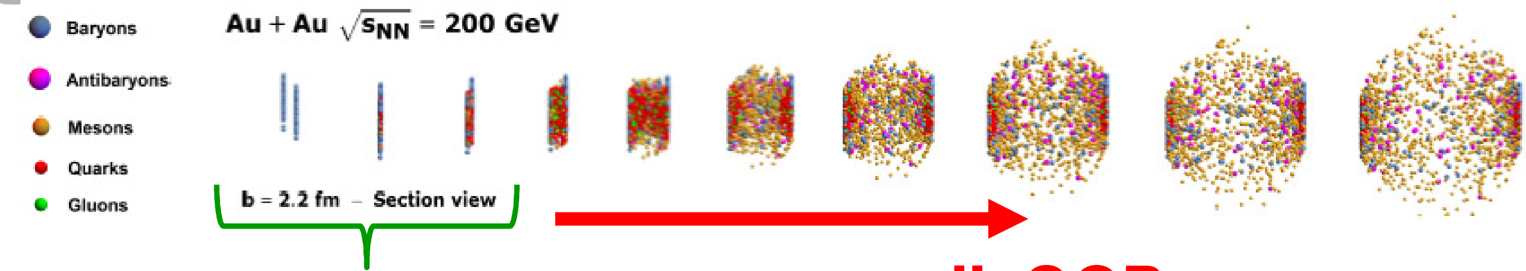
II. QGP: $\varepsilon > \varepsilon_C$

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

The strangeness ratio *s/u* in the string decay



Chiral symmetry restoration vs. deconfinement

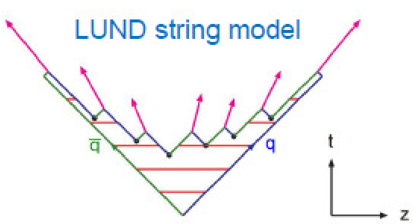


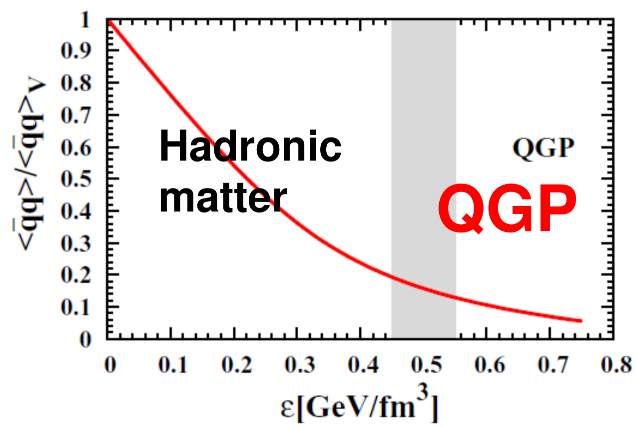
I. Initial stage of HIC collisions:

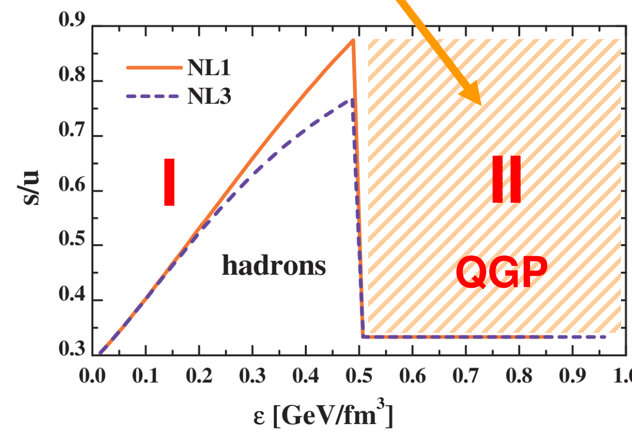
Hadronic matter ➔ string formation

II. QGP

(time-like partons, explicit partonic interactions, 2PI)







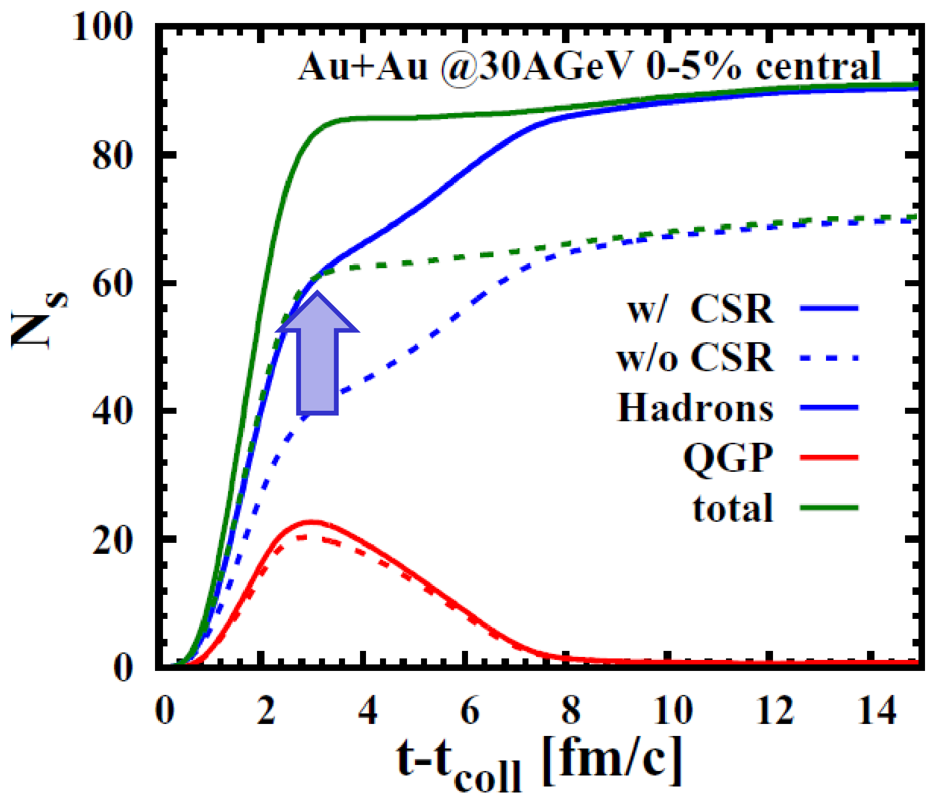
- **Chiral symmetry restoration via Schwinger mechanism (and non-linear $\sigma-\omega$ model) changes the „flavour chemistry" in string fragmentation (1PI):**

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

➔ **the strangeness production probability increases with the local energy density ε.**

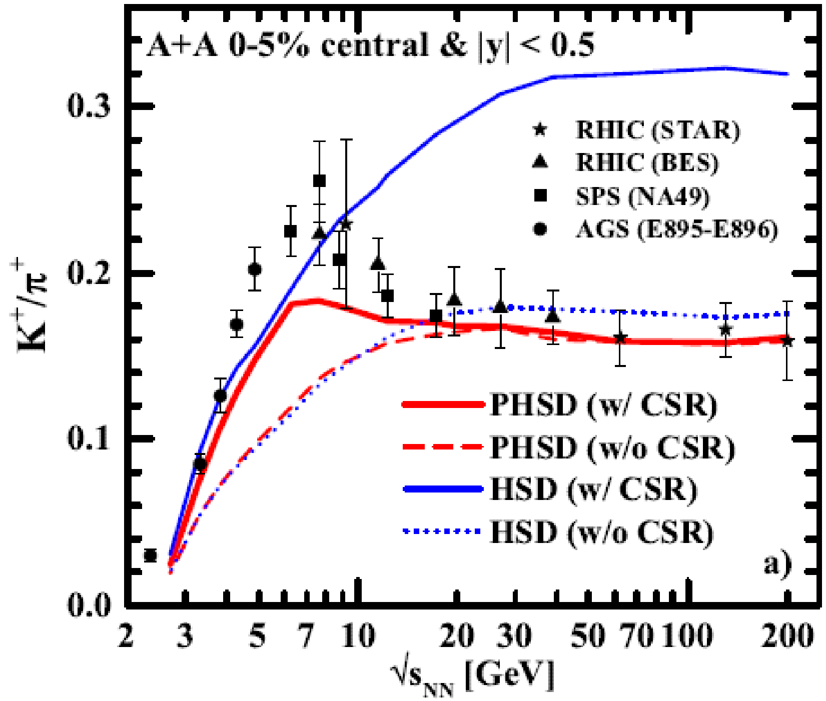
Time evolution of strangeness

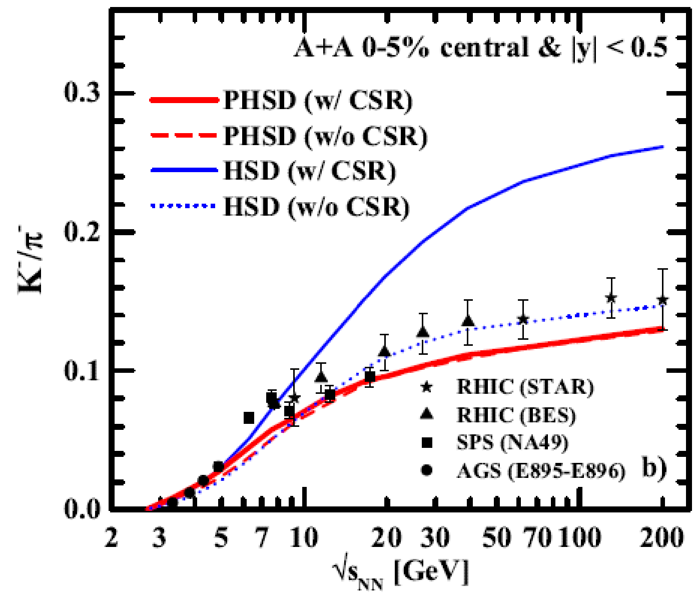
The strange particle number N_s as a function of time in 5% central Au+Au collision at 30 AGeV

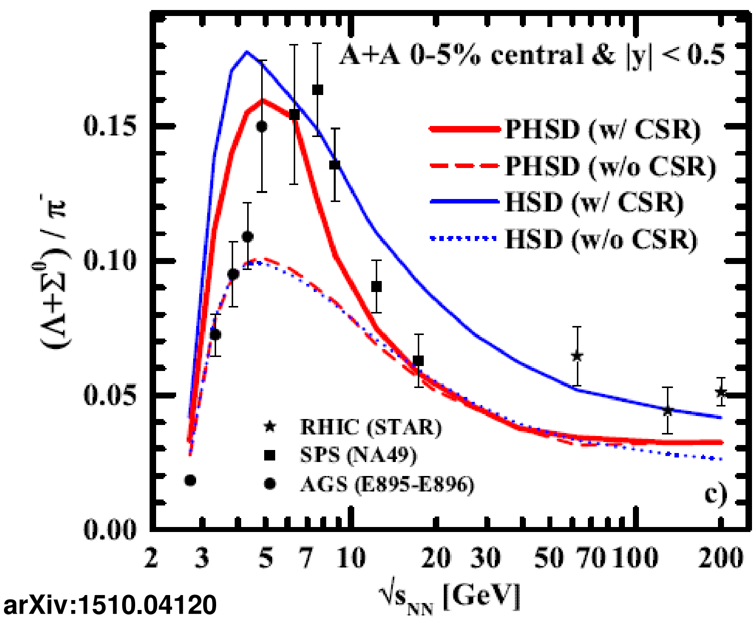


Chiral symmetry restoration leads to the enhancement of strangeness production during the string fragmentation in the beginning of HIC

PHSD results with chiral symmetry restoration



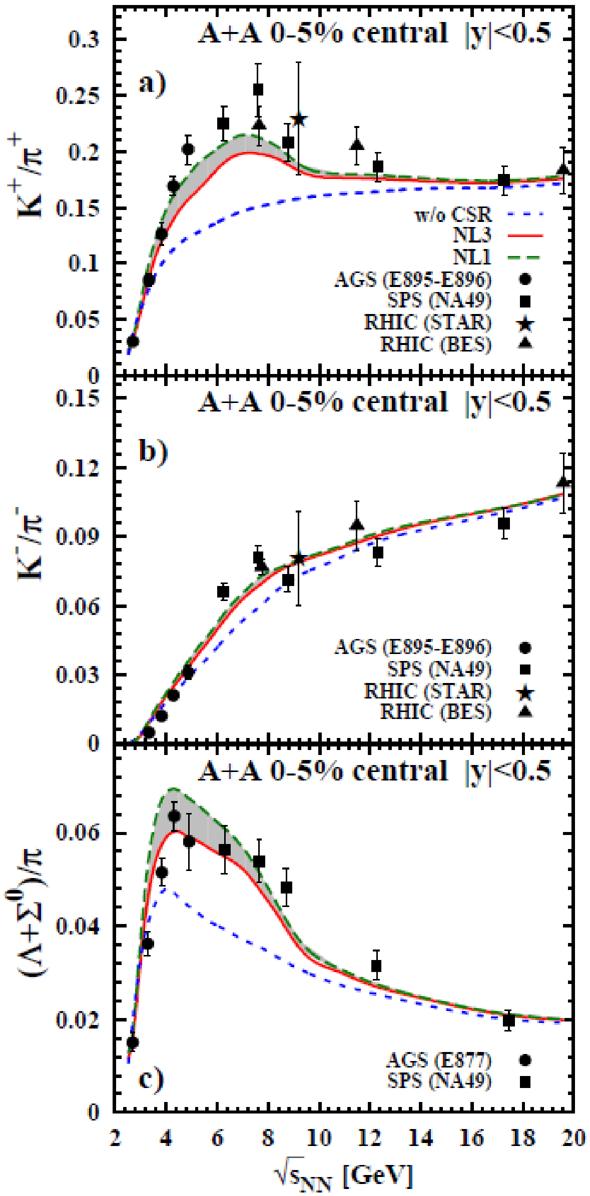


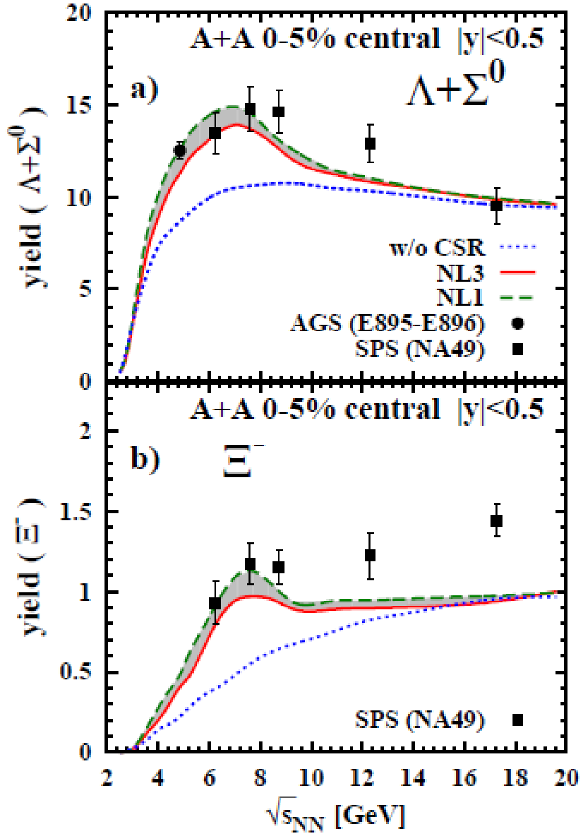


➔ **The strangeness enhancement seen experimentally at FAIR/NICA energies probably involves the approximate restoration of chiral symmetry in the hadronic phase**

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

Excitation function of hadron ratios and yields

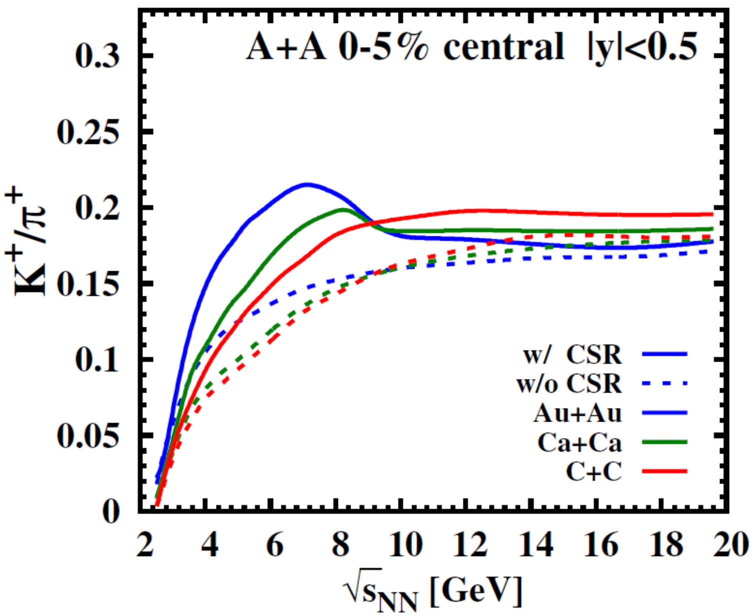


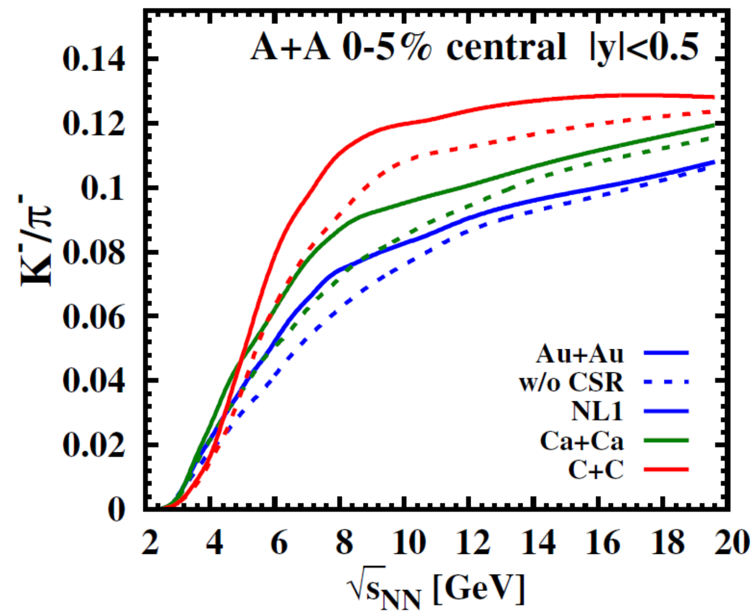


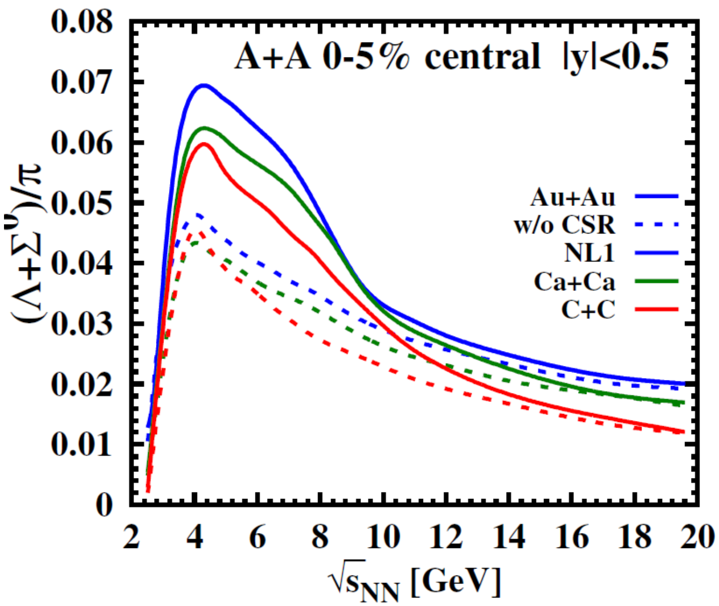
- Influence of EoS: NL1 vs NL3 ➔ low sensitivity to the nuclear EoS
- Excitation function of the hyperons $\Lambda+\Sigma^0$ and Ξ^- show analogous peak as K^+/π^+, $(\Lambda+\Sigma^0)/\pi$ ratios due to CSR

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

Sensitivity to the system size: A+A collisions







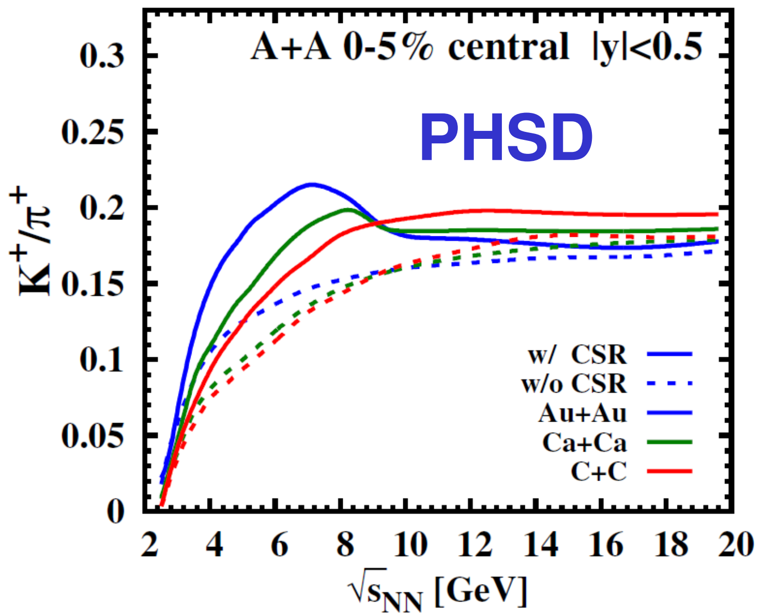
If the system size is smaller:

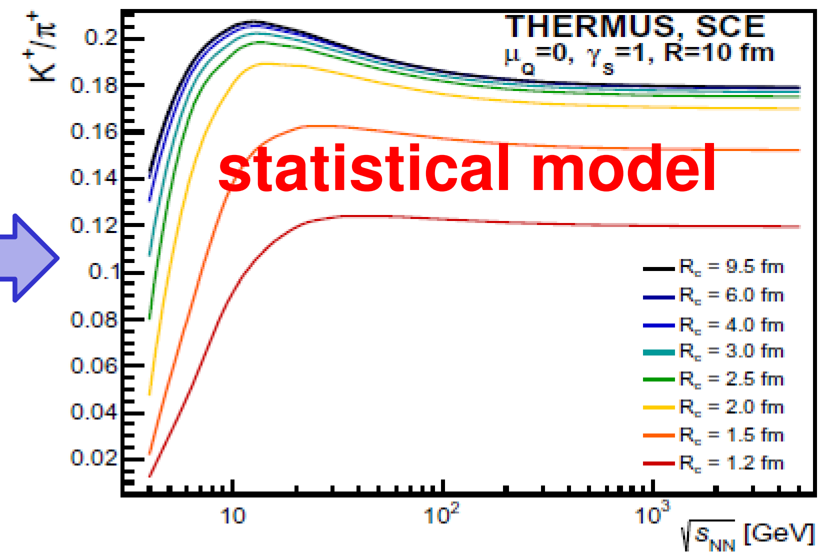
- **the peak of K^+/π^+ disappears**
- **the peak of $(\Lambda+\Sigma^0)/\pi$ remains in the same position in energy, but getting smaller**

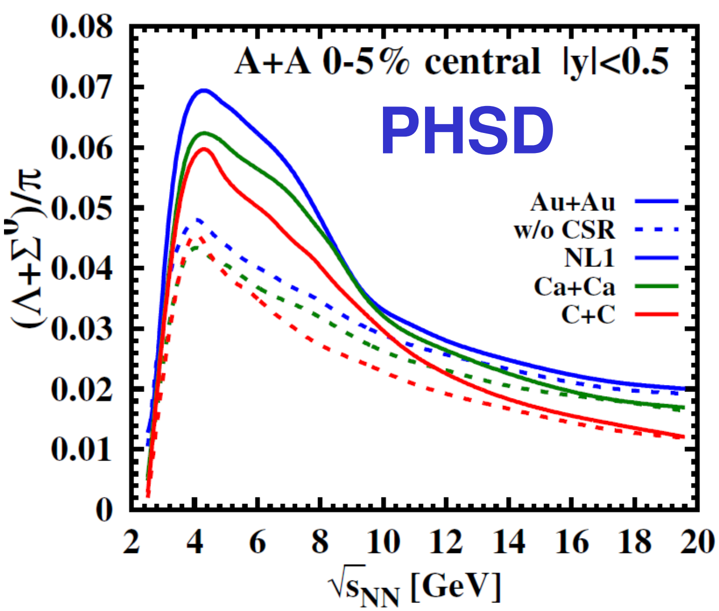
A. Palmese et al., PRC94 (2016) 044912 , arXiv:1607.04073

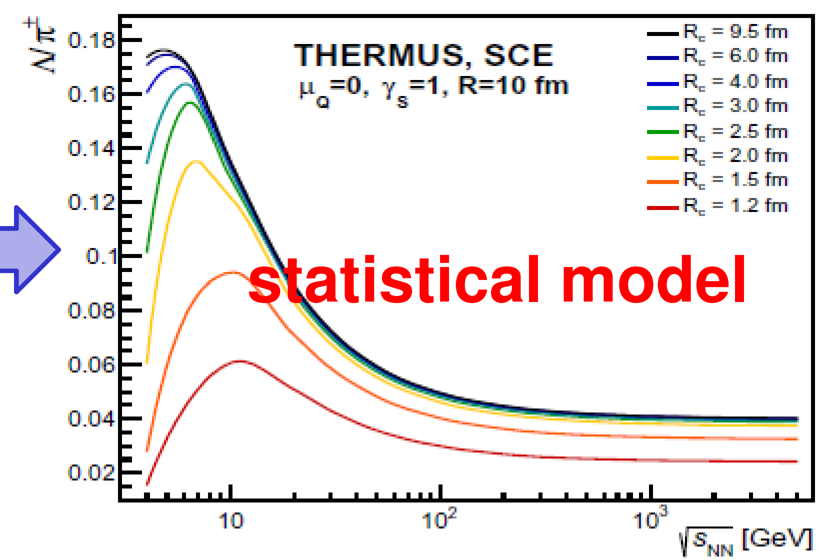
PHSD vs. statistical model

THERMUS: J. Cleymans et al., arXiv:1603.09553



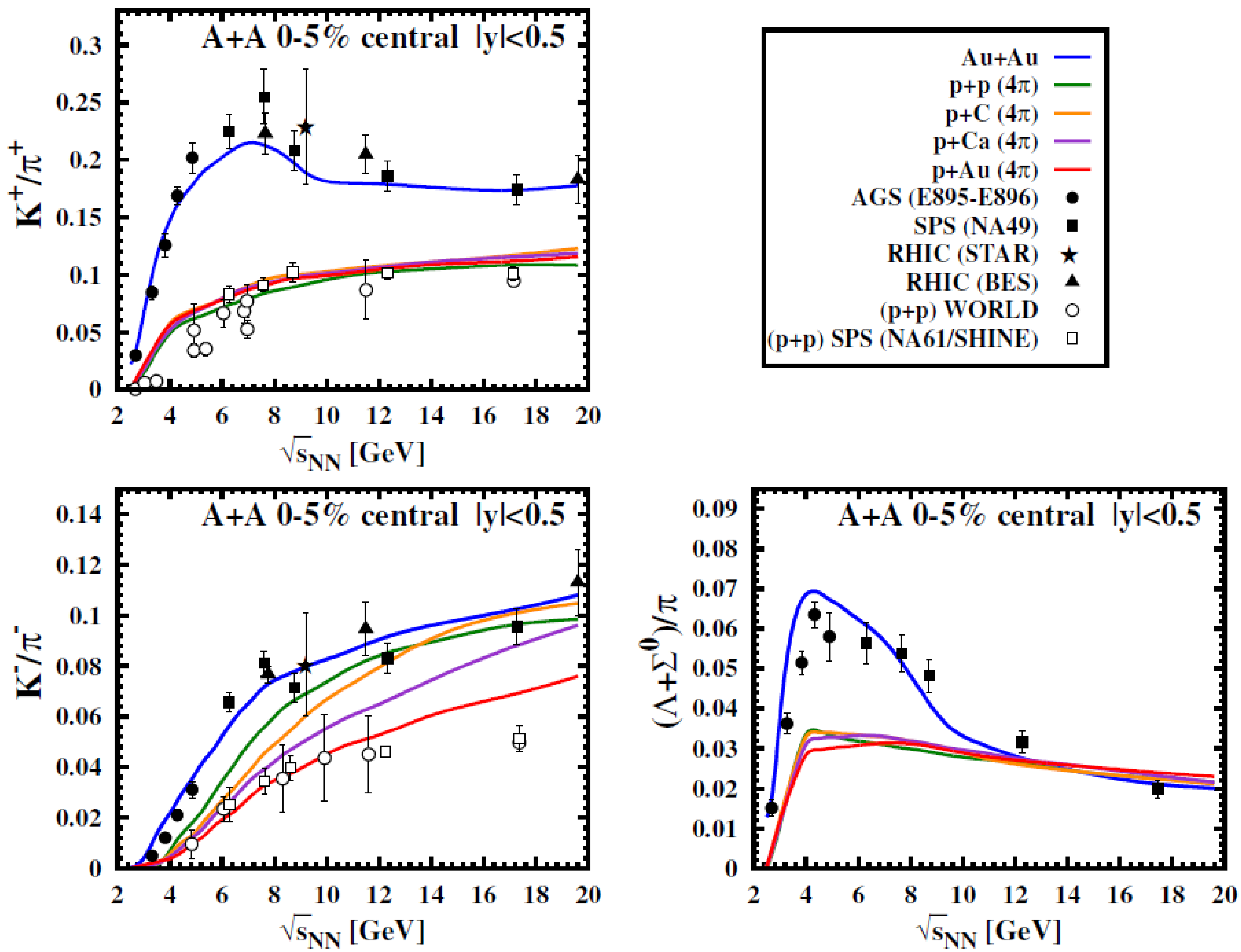






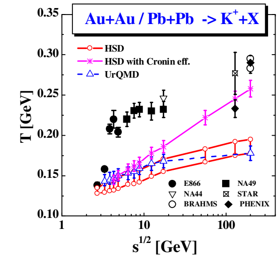
Sensitivity to the system size: p+A collisions

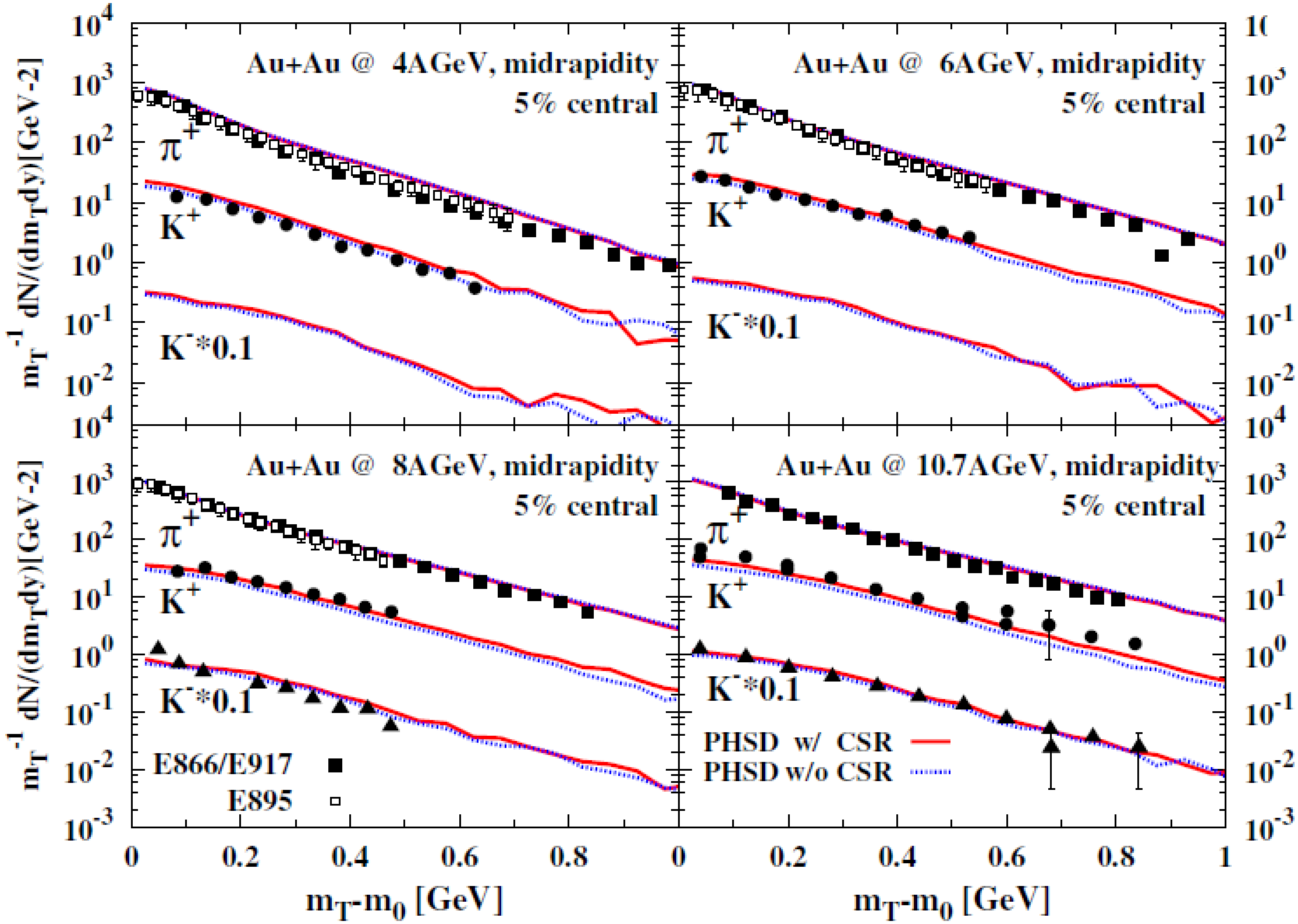
- In p+A collisions strange to non-strange particle ratios show no peaks



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

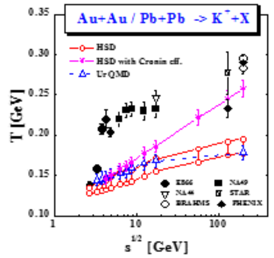
m_T spectra of pions and $K^{+/-}$ at AGS energies

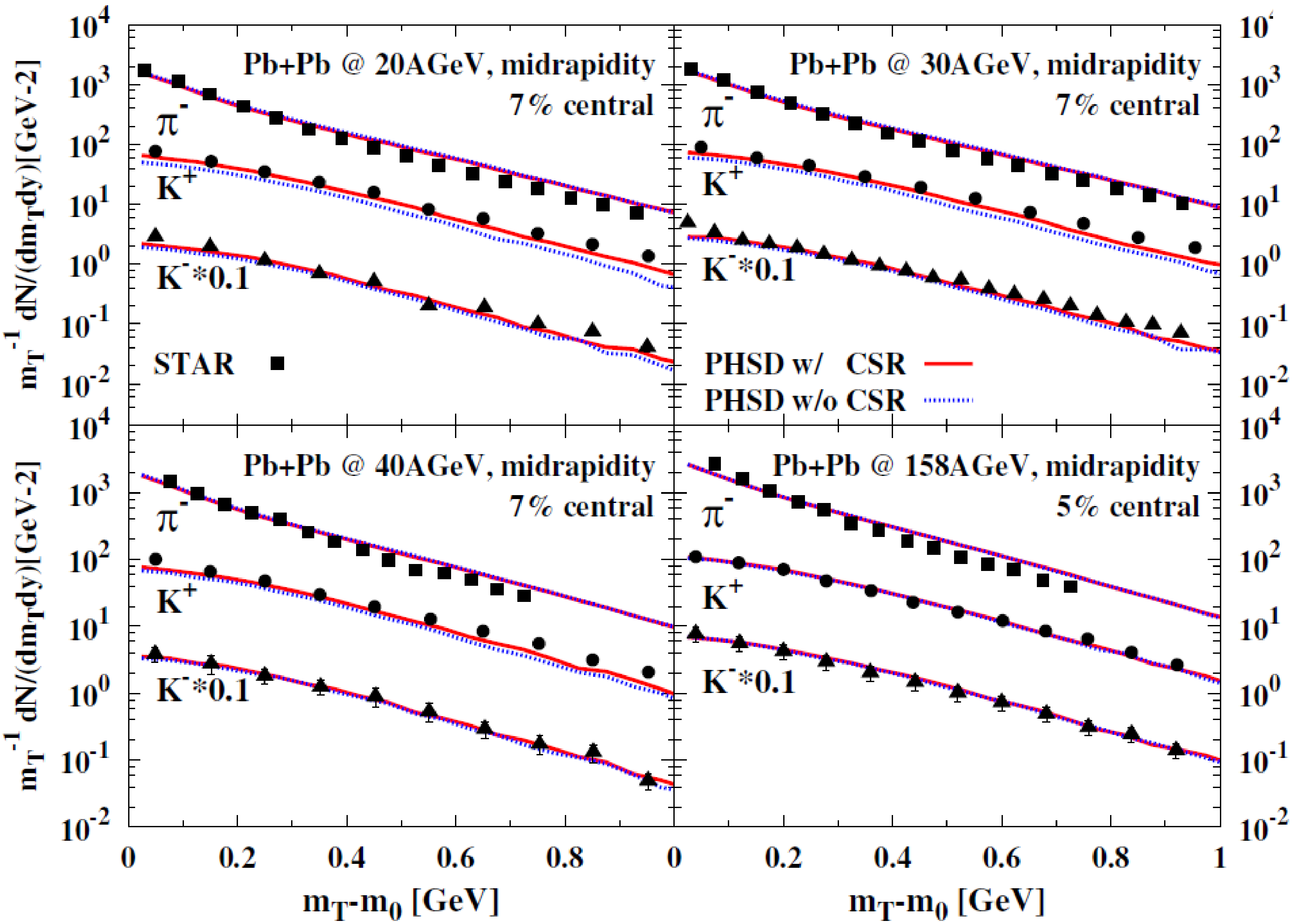




A. Palmese et al., PRC94 (2016) 044912 , arXiv:1607.04073

m_T spectra of pions and $K^{+/-}$ at SPS energies

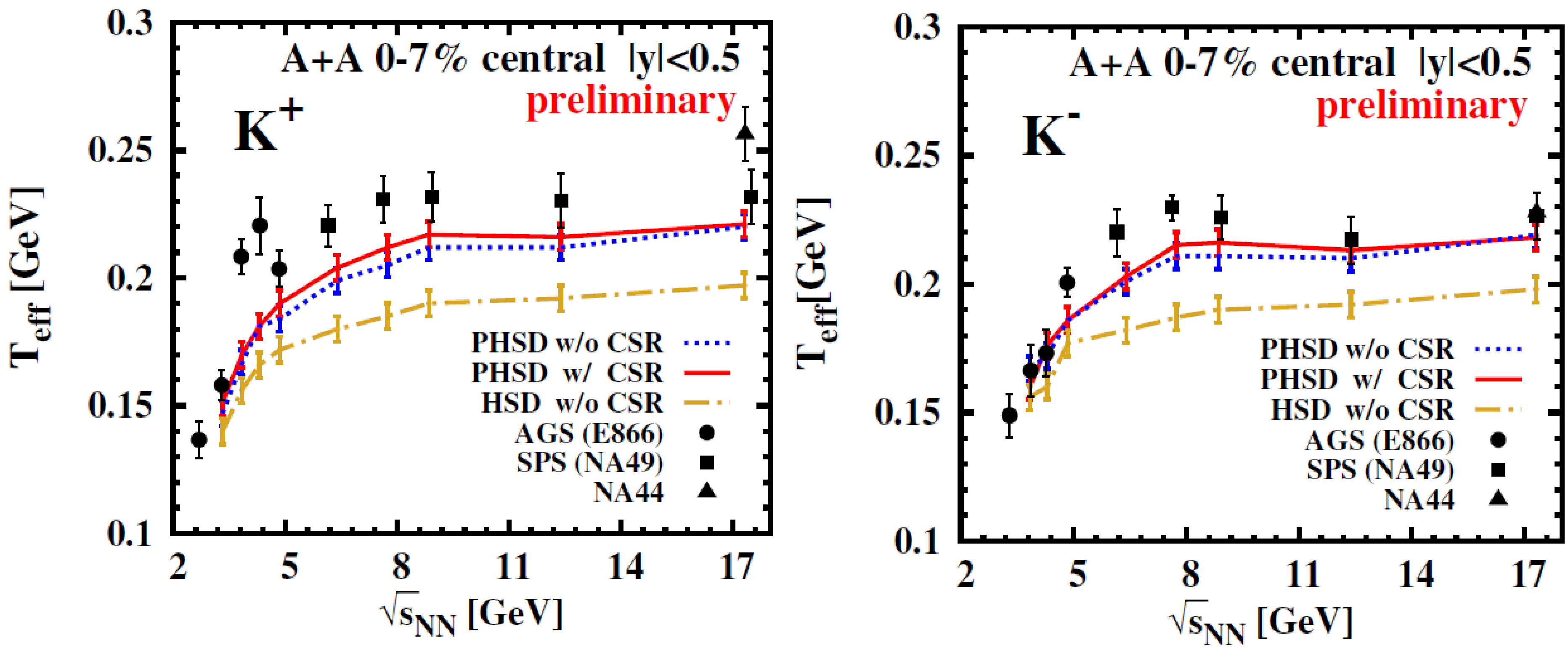




A. Palmese et al., PRC94 (2016) 044912 , arXiv:1607.04073

Excitation function of T_{eff}

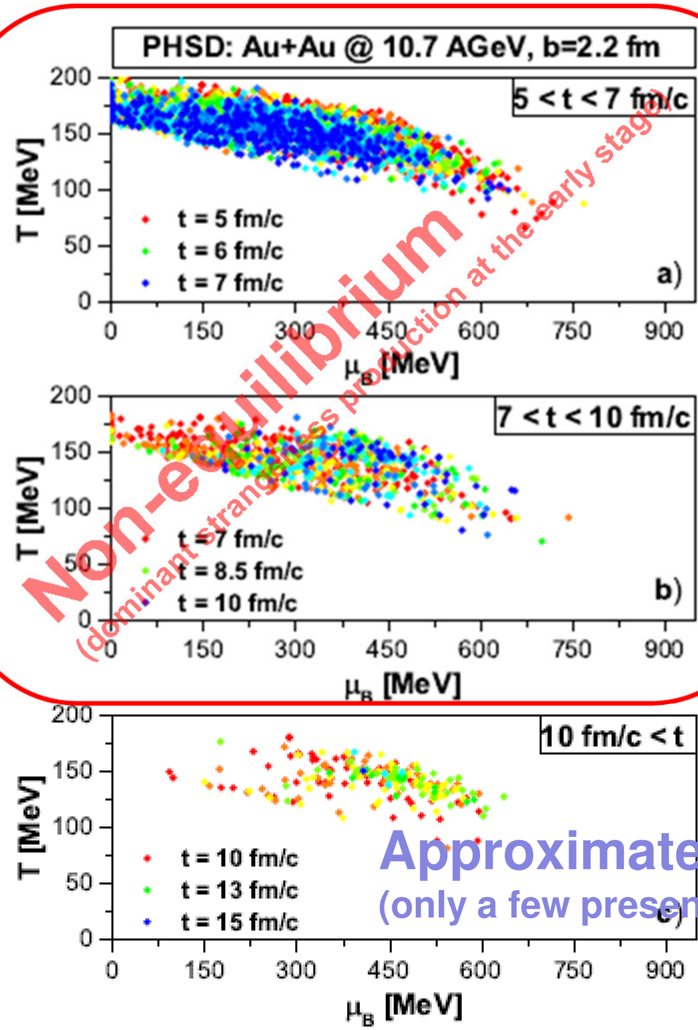
Alessia Palmese



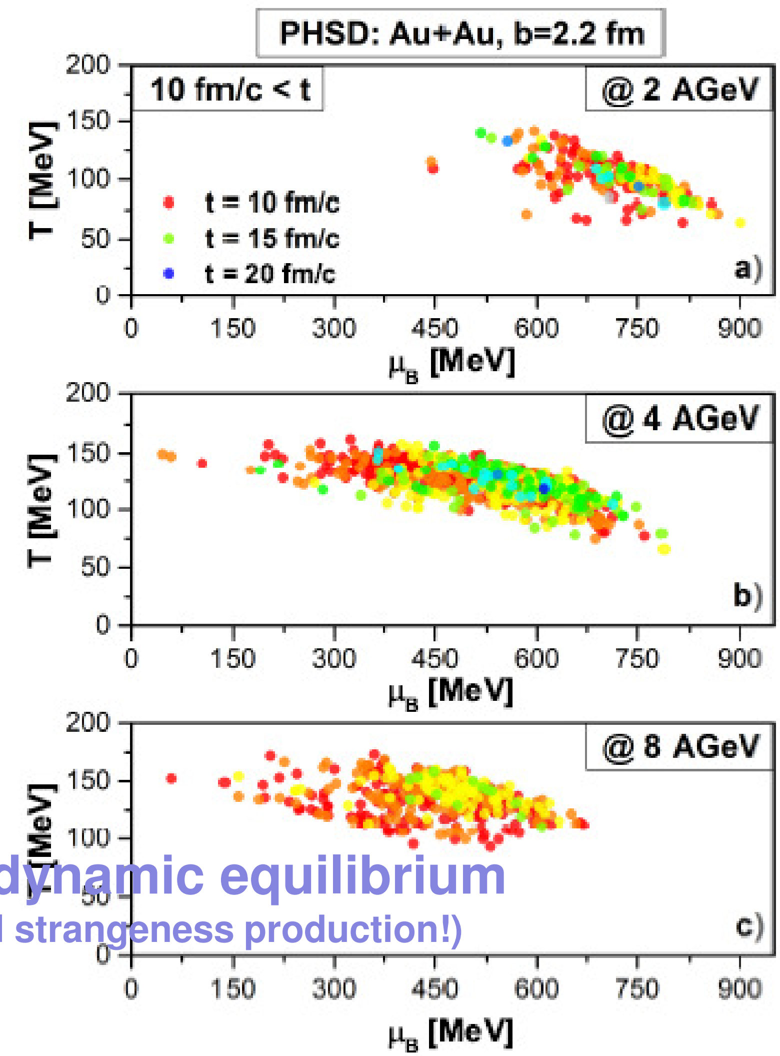
→ Increase of slope T_{eff} due to the QGP
→ Small effect of chiral symmetry restoration on slope Teff

Thermodynamics of strangeness in HIC

Which parts of the phase diagram in the (T, μ_B)-plane are probed by heavy-ion collisions via the strangeness production?



Non-equilibrium
(dominant strangeness production at the early stage)

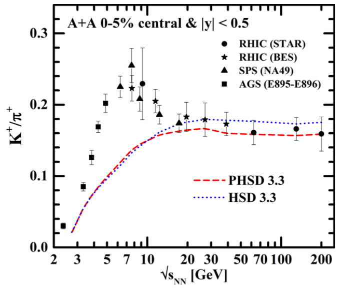


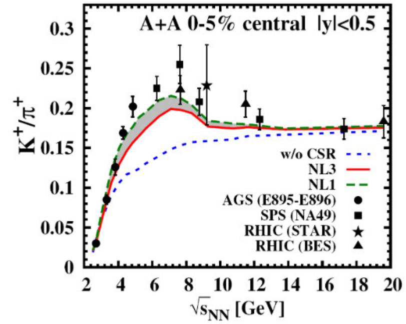
Approximate thermodynamic equilibrium
(only a few present of the total strangeness production!)

* T here corresponds to the pion, nucleon gas, i.e. a real T is smaller!

➔ **the spread in T and μ_B is very large !**

Summary

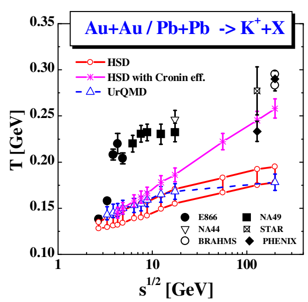


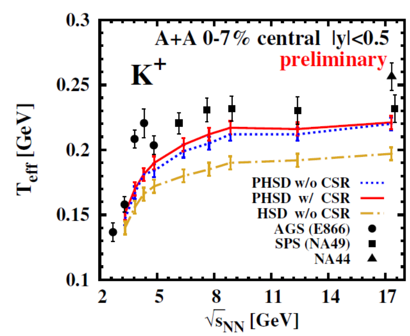


- The strangeness 'enhancement' ('horn') seen experimentally by NA49 and STAR at a bombarding energy ~20-30 A GeV (FAIR/NICA energies!) cannot be attributed to deconfinement

- Including essential aspects of chiral symmetry restoration in the hadronic phase, we observe a rise in the K^+/π^+ ratio at low $\sqrt{s_{NN}}$ and then a drop due to the appearance of a deconfined partonic medium → a 'horn' emerges

- Harderning of m_T spectra due to the QGP





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