Signatures of chiral symmetry restoration and its survival throughout the hadronic phase interactions

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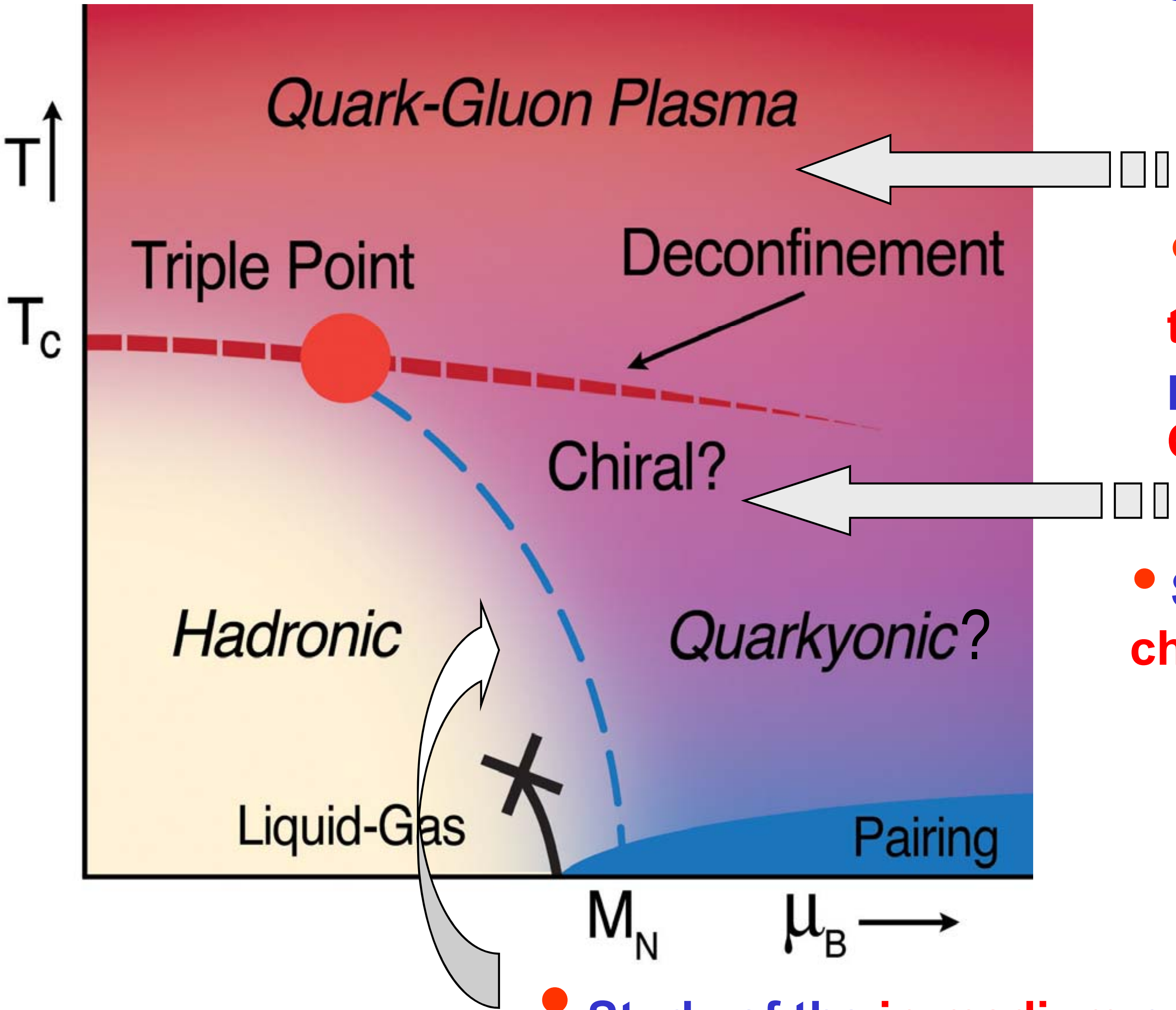
The ‚holy grail‘ of heavy-ion physics:

The phase diagram of QCD



- 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

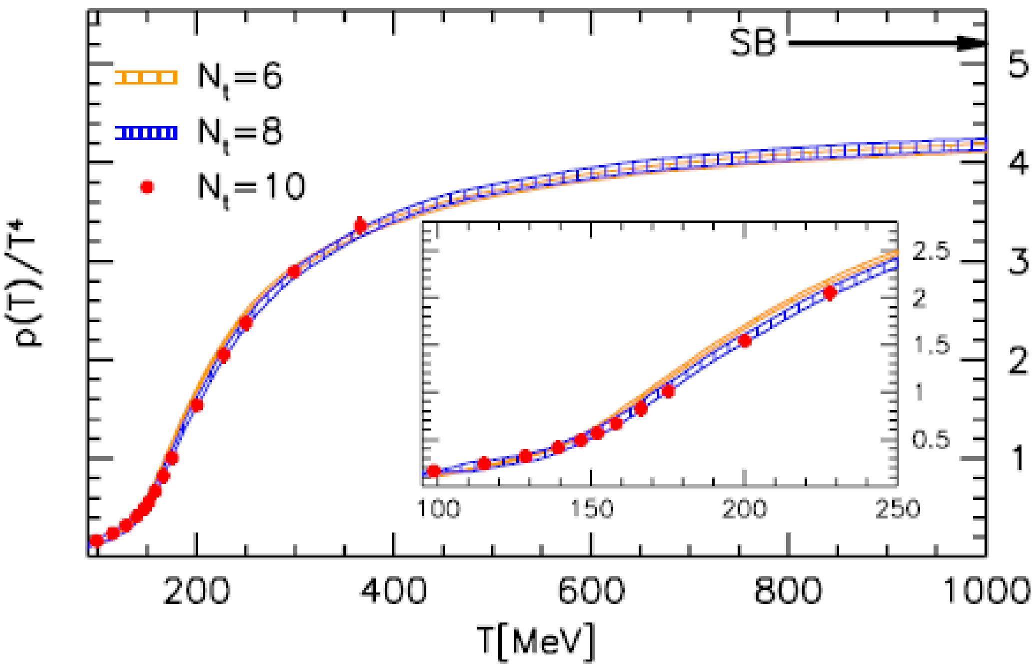
Information from lattice QCD

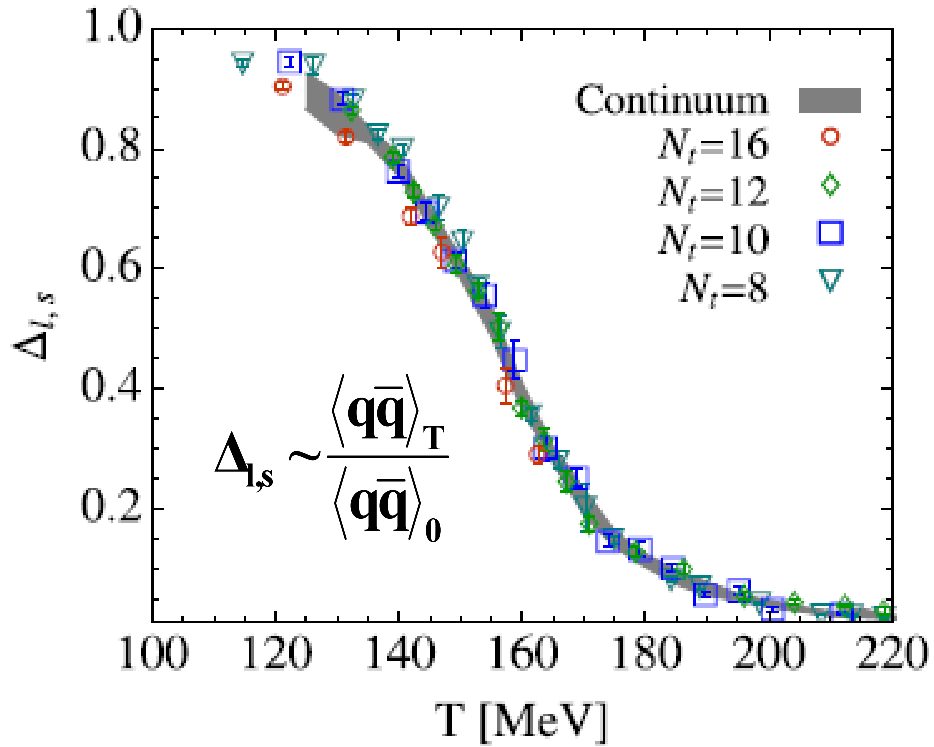
I. deconfinement phase transition
with increasing temperature

+

II. chiral symmetry restoration
with increasing temperature

lQCD BMW collaboration: $\mu_q=0$





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

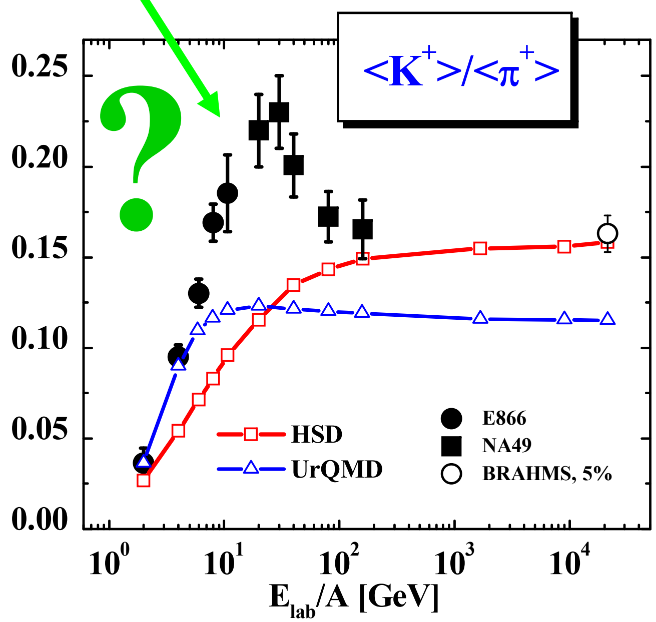
$$<\bar{q}q>= \begin{cases} \neq 0 & \text{chiral non-symmetric phase;} \\ = 0 & \text{chiral symmetric phase.} \end{cases}$$

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

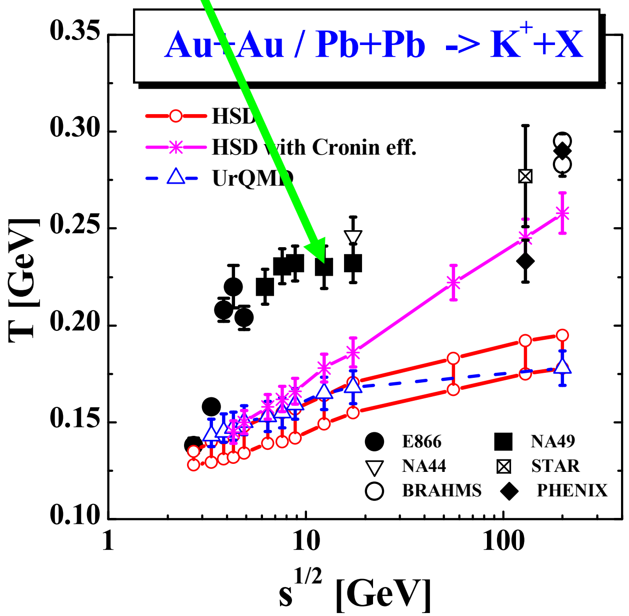
Signals for the phase transition

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

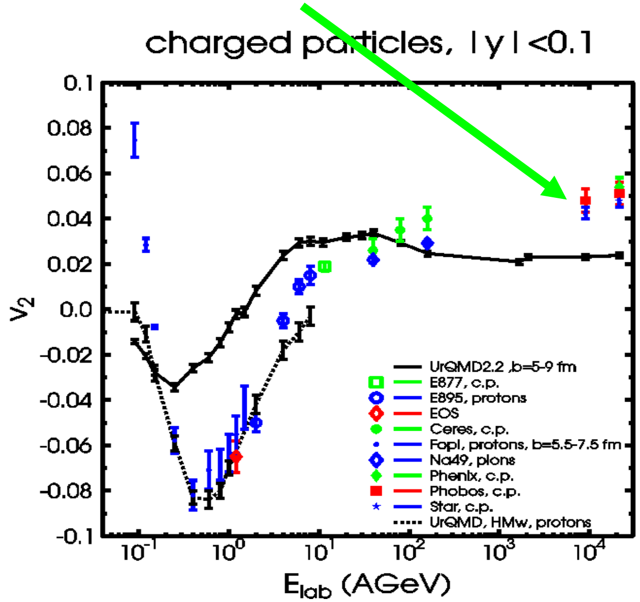
❑ ‚horn' in K^+/π^+



❑ ‚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:

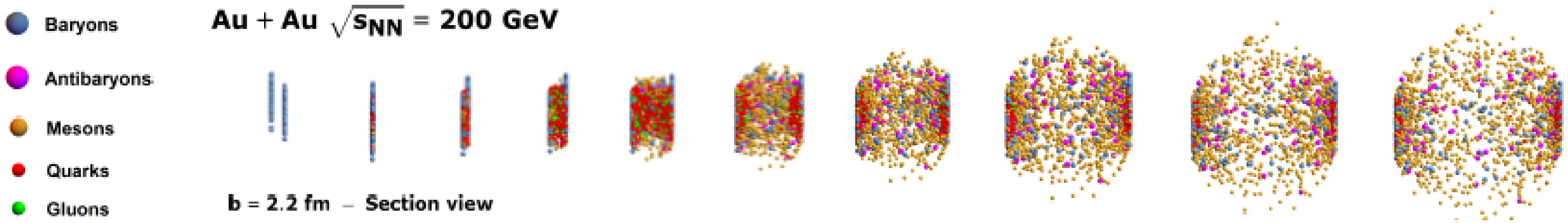
to develop a dynamical many-body transport approach

1) applicable for strongly interacting systems, which includes:

2) phase transition from hadronic matter to QGP

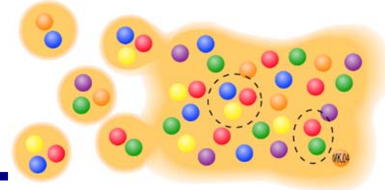
3) chiral symmetry restoration

2004-2017



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 on a microscopic level

➔ need a consistent non-equilibrium 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

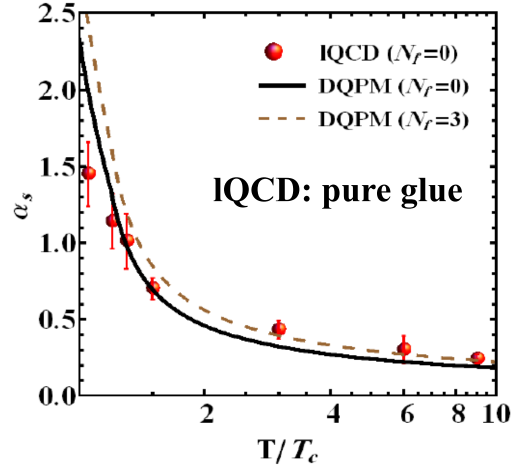
A. Peshier, W. Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

The Dynamical QuasiParticle Model (DQPM)

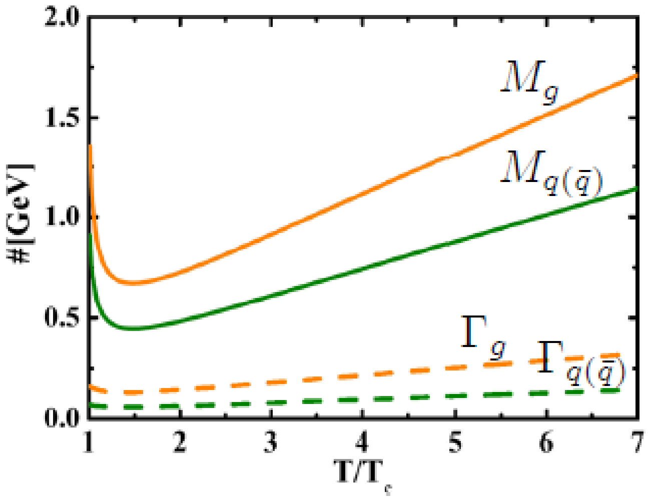
- **Basic idea: interacting quasi-particles: massive quarks and gluons (g, q, q_{bar}) with Lorentzian spectral functions :**

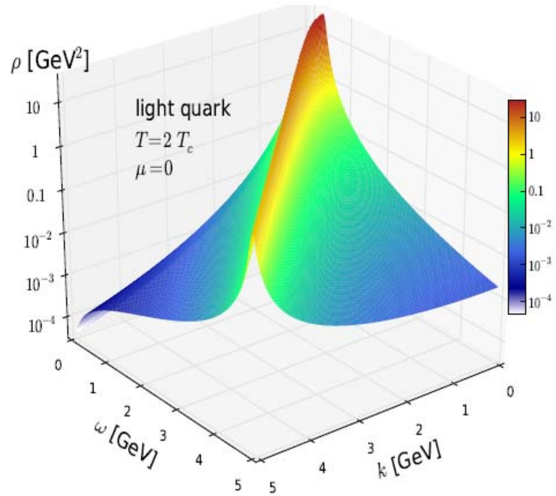
$$\rho_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)} \qquad (i = q, \bar{q}, g)$$

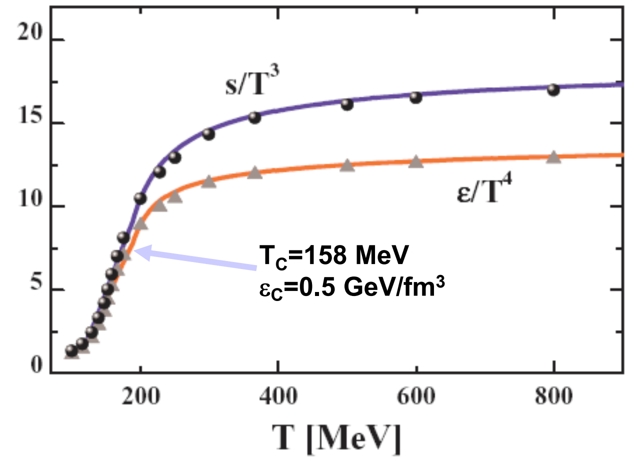
- **Modeling of the quark/gluon masses and widths → HTL limit at high T with 3 model parameters – fited to lattice QCD data**



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

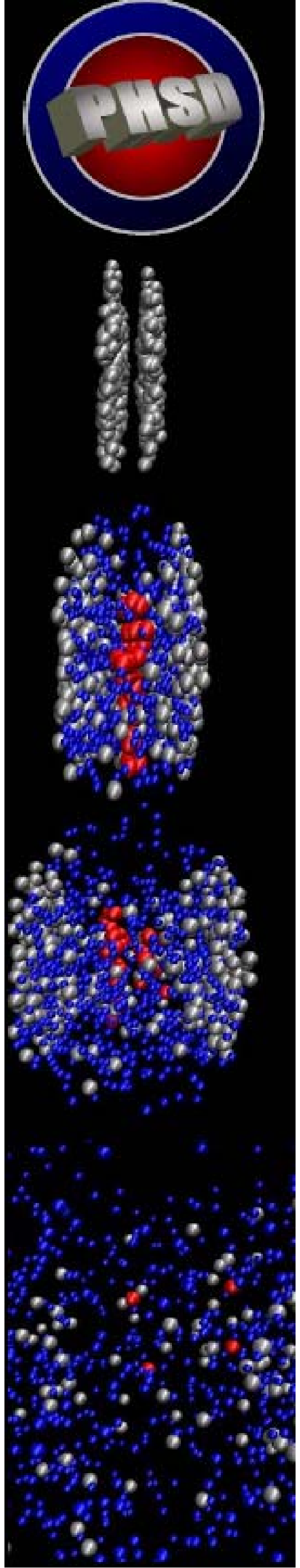






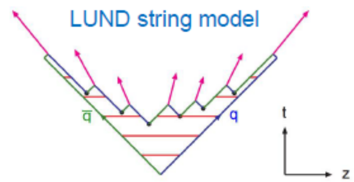
- **DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)**
- **DQPM gives transition rates for the formation of hadrons → PHSD**

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

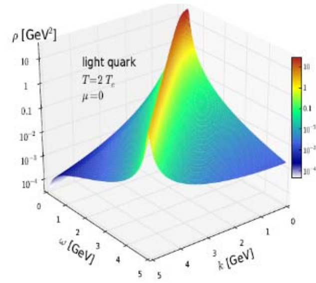


Parton-Hadron-String-Dynamics (PHSD)

- **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



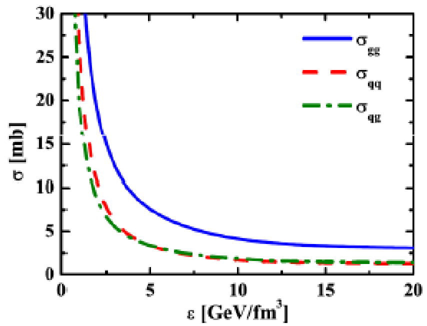
- **Partonic stage – QGP :**
  based on the Dynamical Quasi-Particle Model (DQPM)

  - (quasi-) elastic collisions:

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

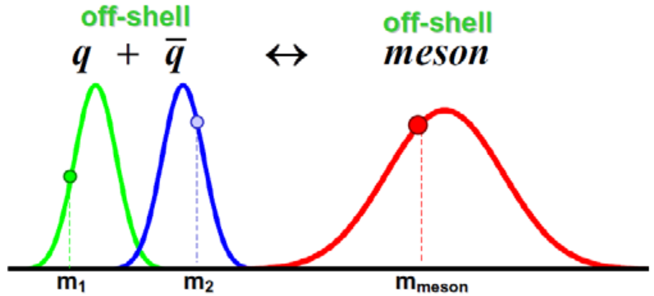
  - inelastic collisions:

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



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

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

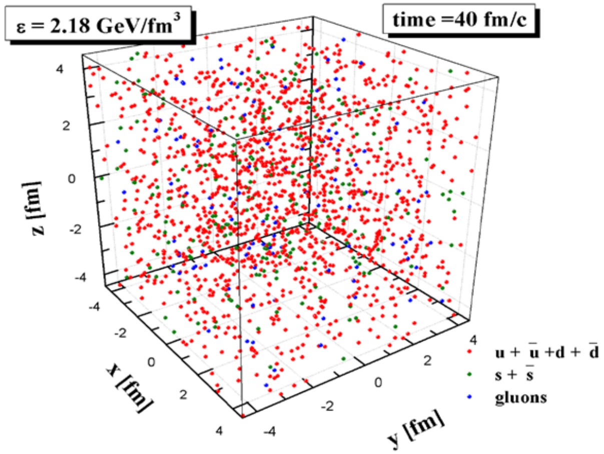


- **Hadronic phase: hadron-hadron interactions – off-shell HSD**

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

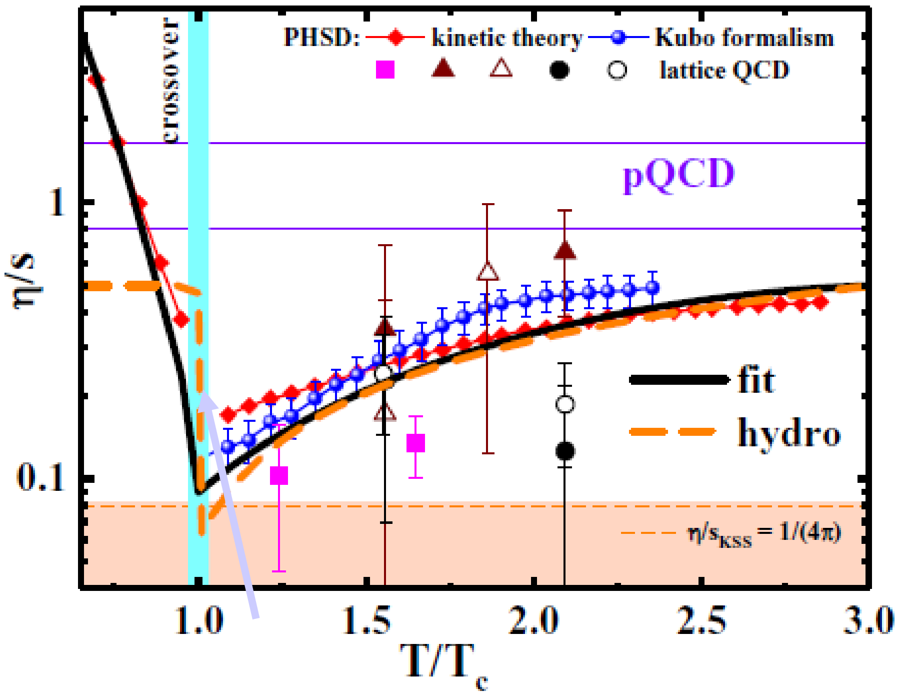
Infinite hot/dense matter = PHSD in a box:



Shear viscosity η/s at finite T

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

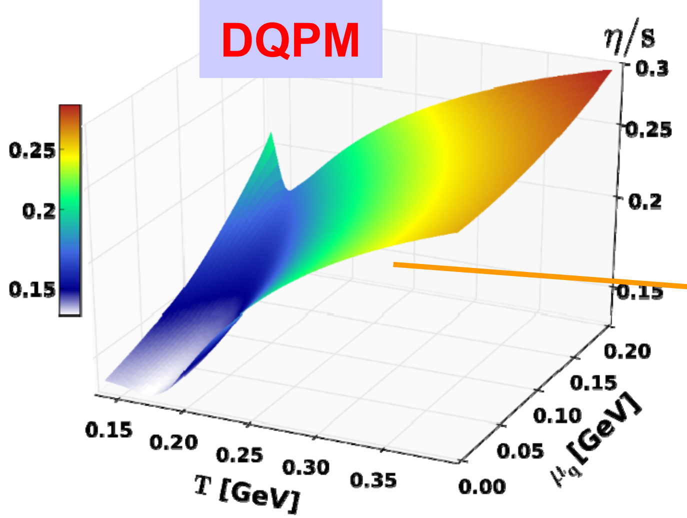
Hydro: Bayesian analysis, S. Bass et al.



QGP in PHSD = strongly-interacting liquid-like system

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

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

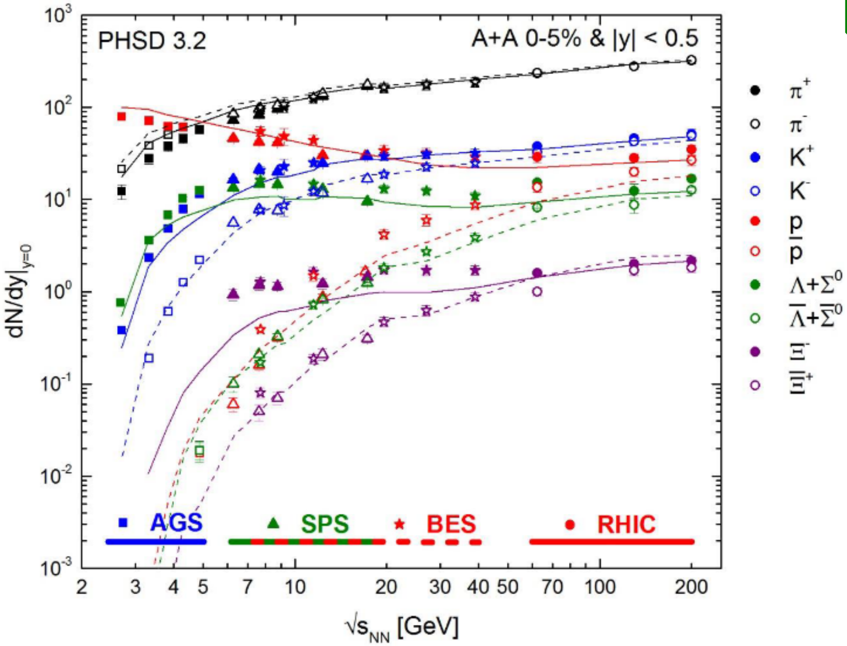


η/s: μ_q=0 ➔ finite μ_q: smooth increase as a function of (T, μ_q)

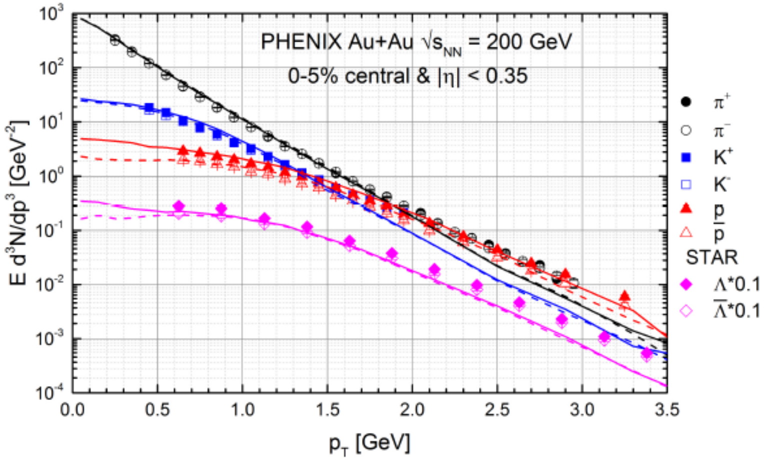
Review: H. Berrehrah et al. Int.J.Mod.Phys. E25 (2016) 1642003

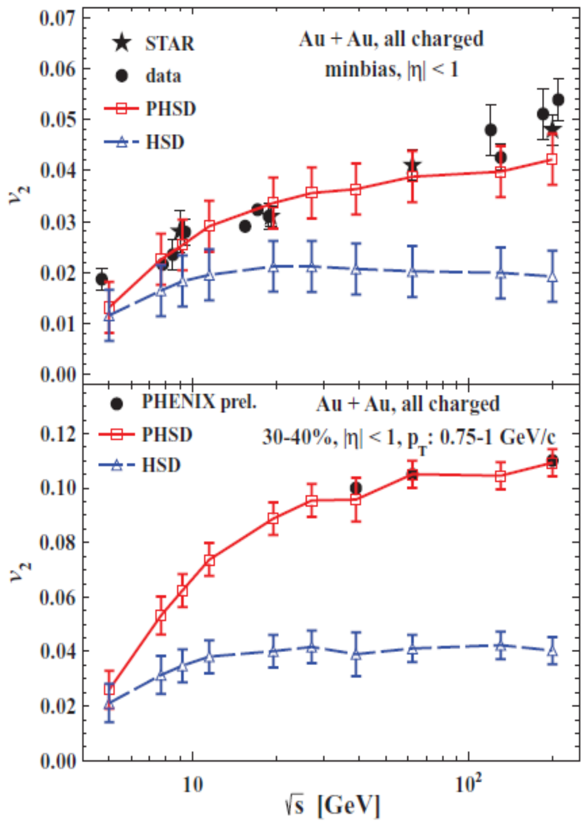
Non-equilibrium dynamics: description of A+A with PHSD

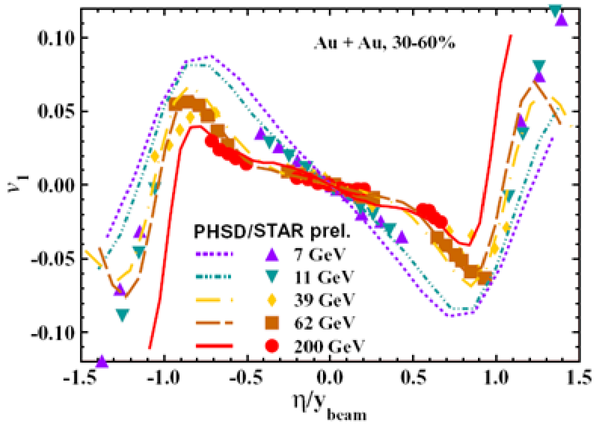
❑ PHSD: highlights

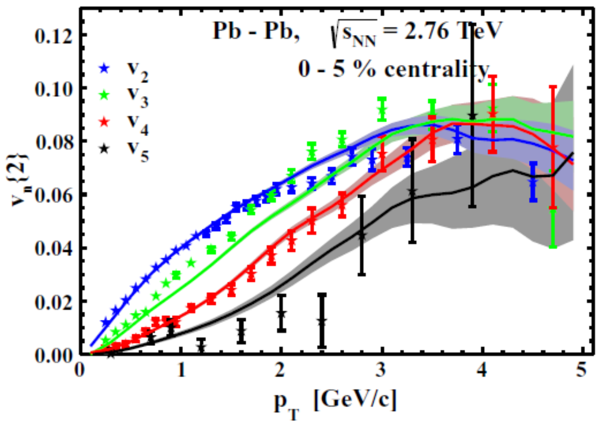


PHSD: P. Moreau









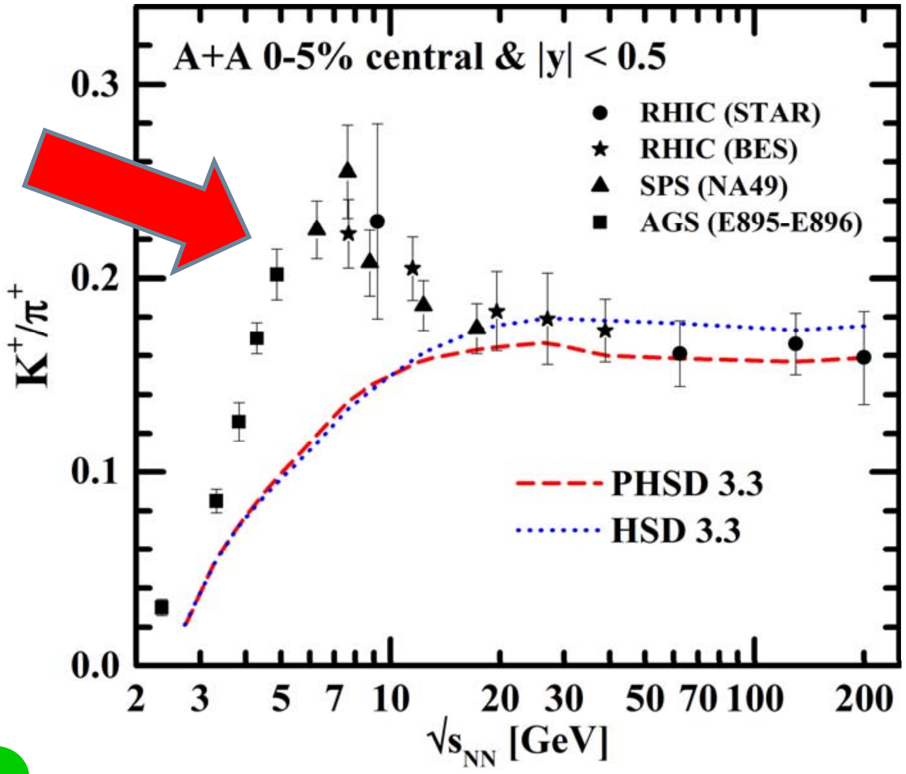
V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106

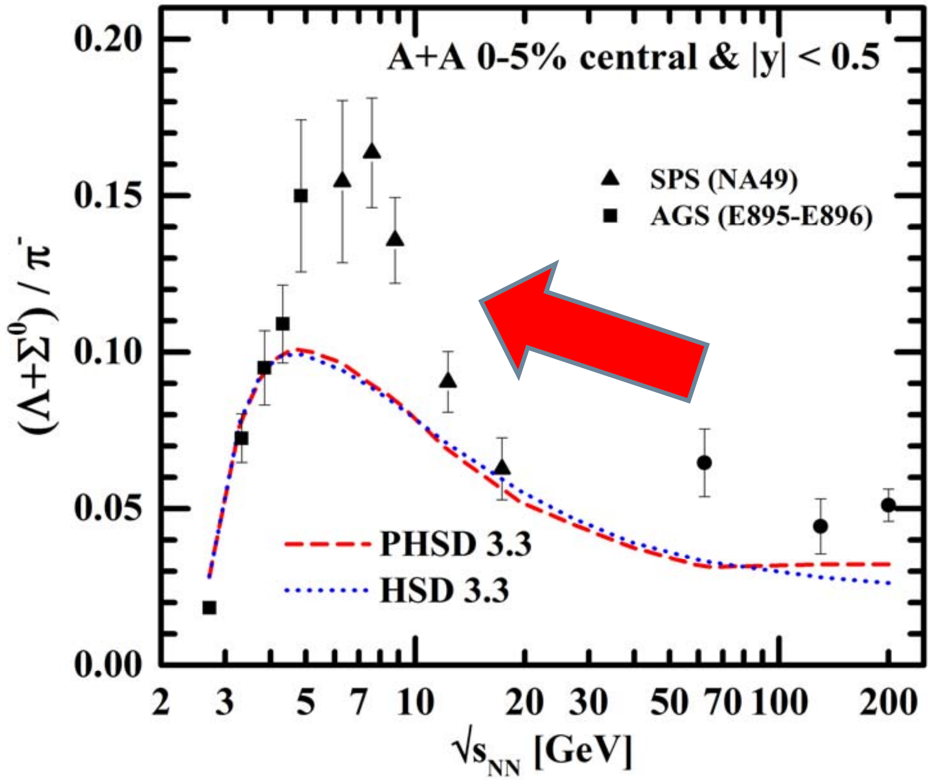
❑ **PHSD provides a good description of ‚bulk' observables (y-, p_T-distributions, flow coefficients v_n, …) from SIS to LHC**

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 ?!



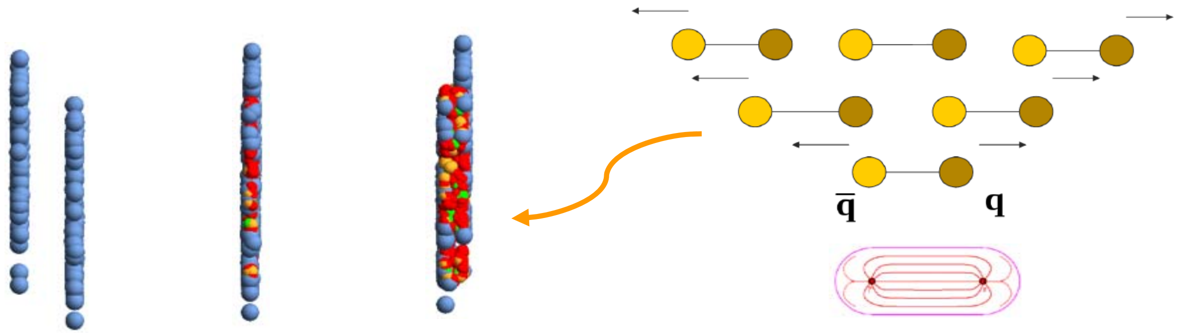


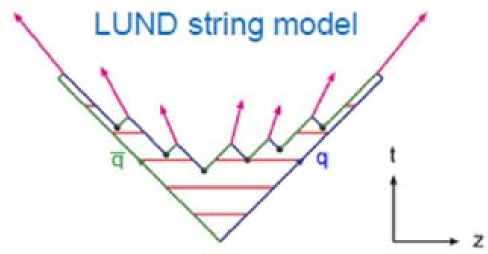
? Can it be related to chiral symmetry restoration in the hadronic phase?!

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) :

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

$$(V \equiv vacuum)$$

bare quark masses:

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

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

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

➔ Constituent quark masses in vacuum :

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

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:

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

$$\Downarrow$$

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

* 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:

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

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.

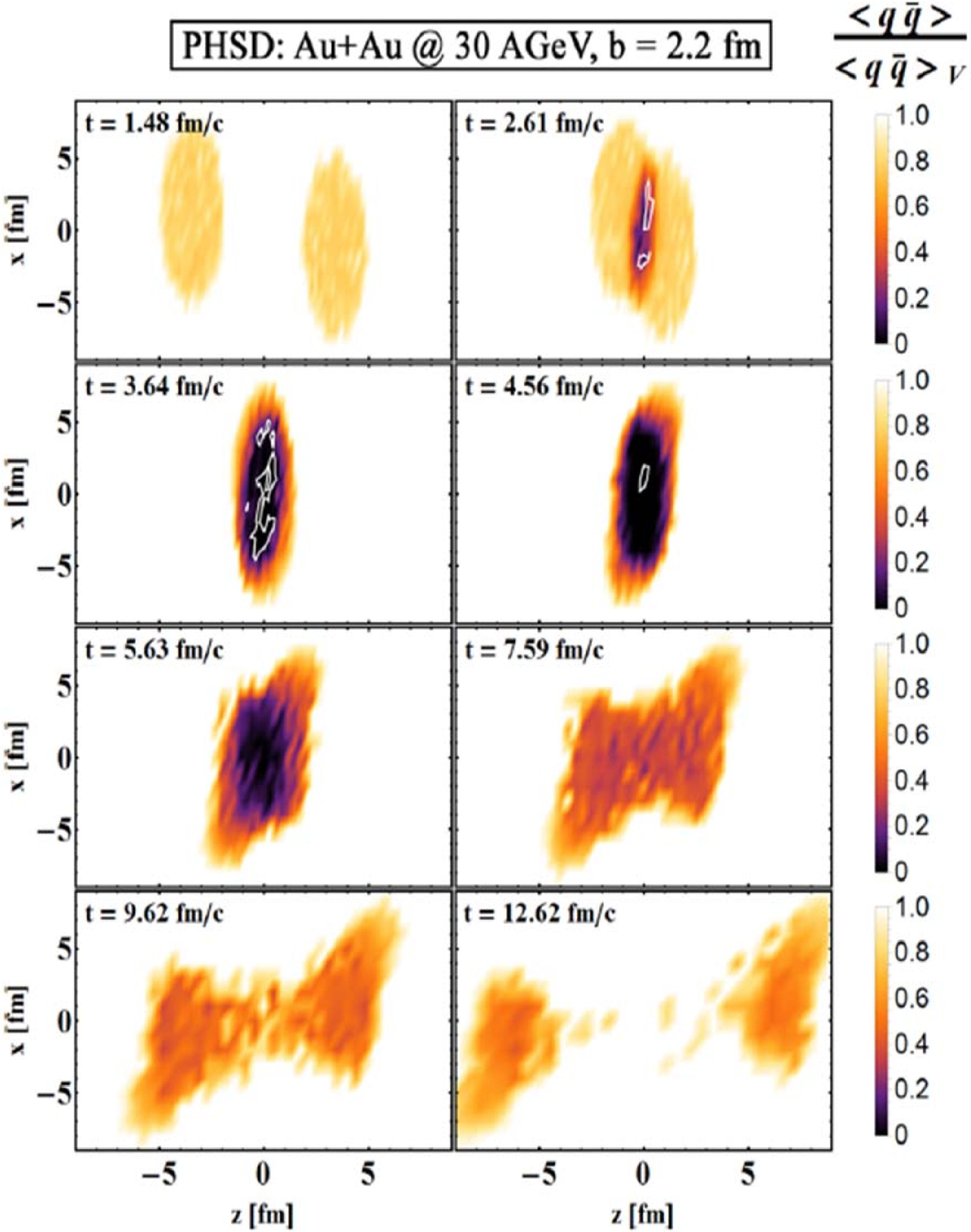
2) $\rho_s{}^h$ is the scalar density of mesons of type h → from PHSD

Scalar quark condensate in HIC

PHSD:
Ratio of the scalar quark condensate

$$\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V}$$

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



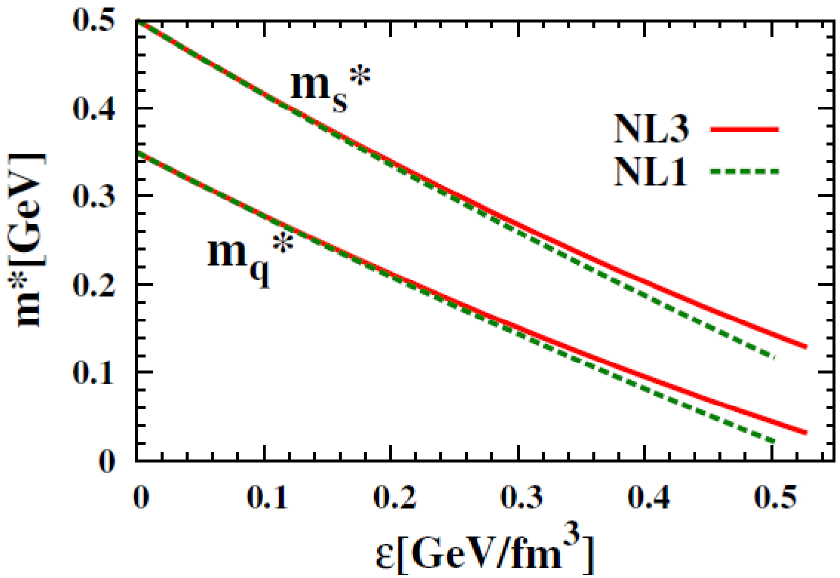
- **restoration of chiral symmetry:**
  $\langle q\bar{q}\rangle/\langle q\bar{q}\rangle_V \rightarrow 0$

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:

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



➔ Strangeness ratio *s/u*

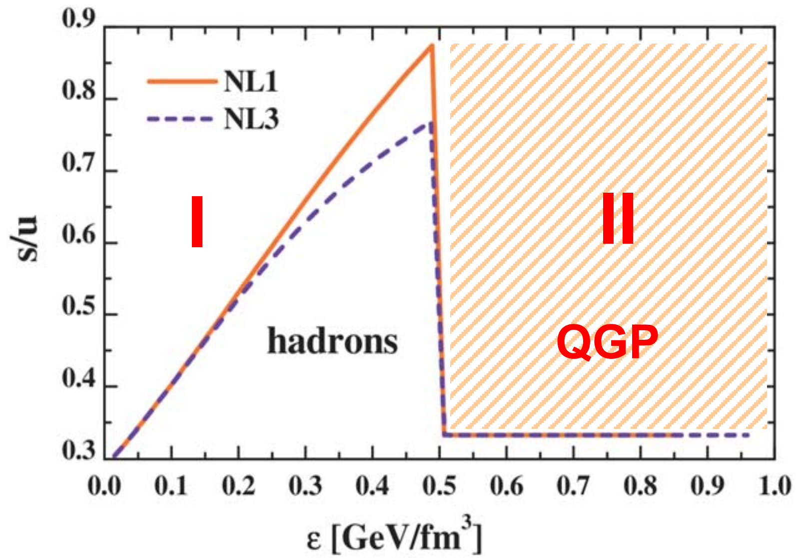
I. hadronic phase : $\varepsilon < \varepsilon_C$

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

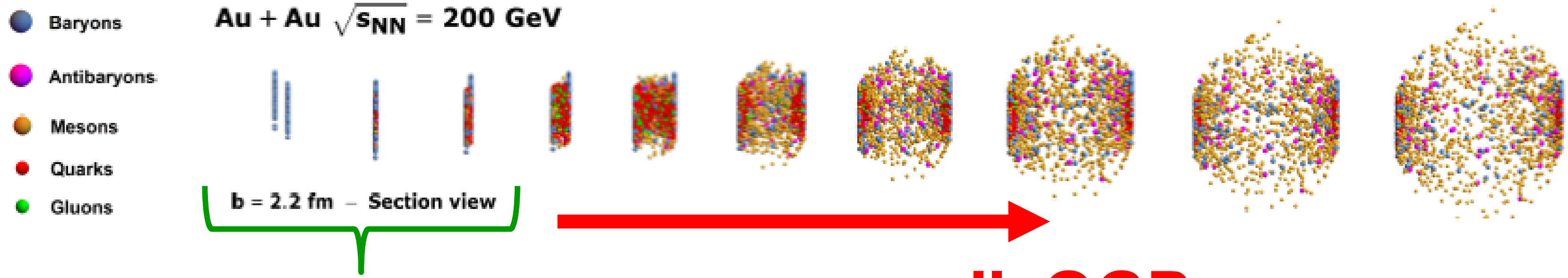
II. QGP: $\varepsilon > \varepsilon_C$

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

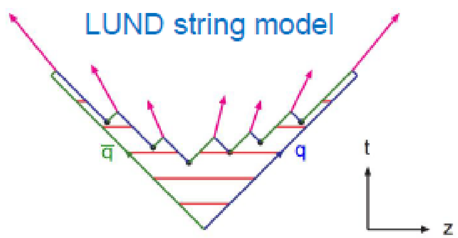


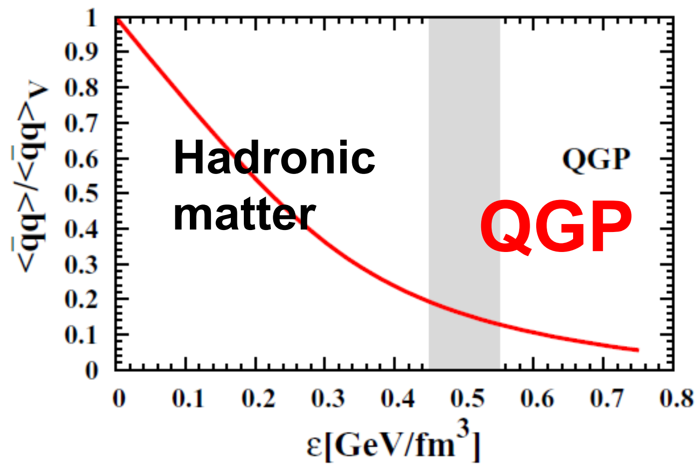
I. Initial stage of HIC collisions:

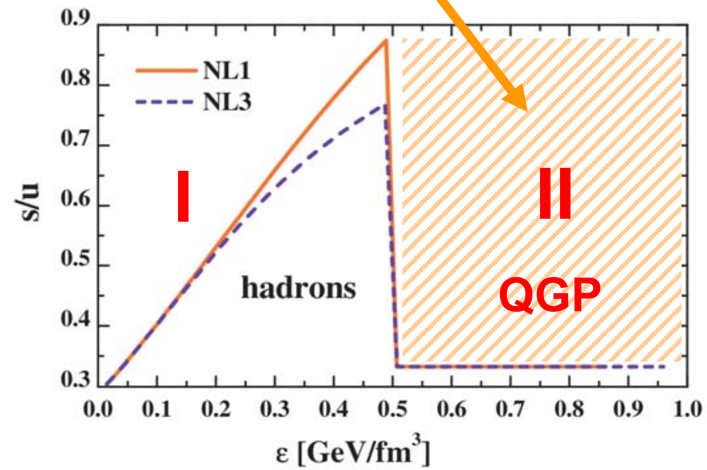
Hadronic matter ➔ string formation

II. QGP

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







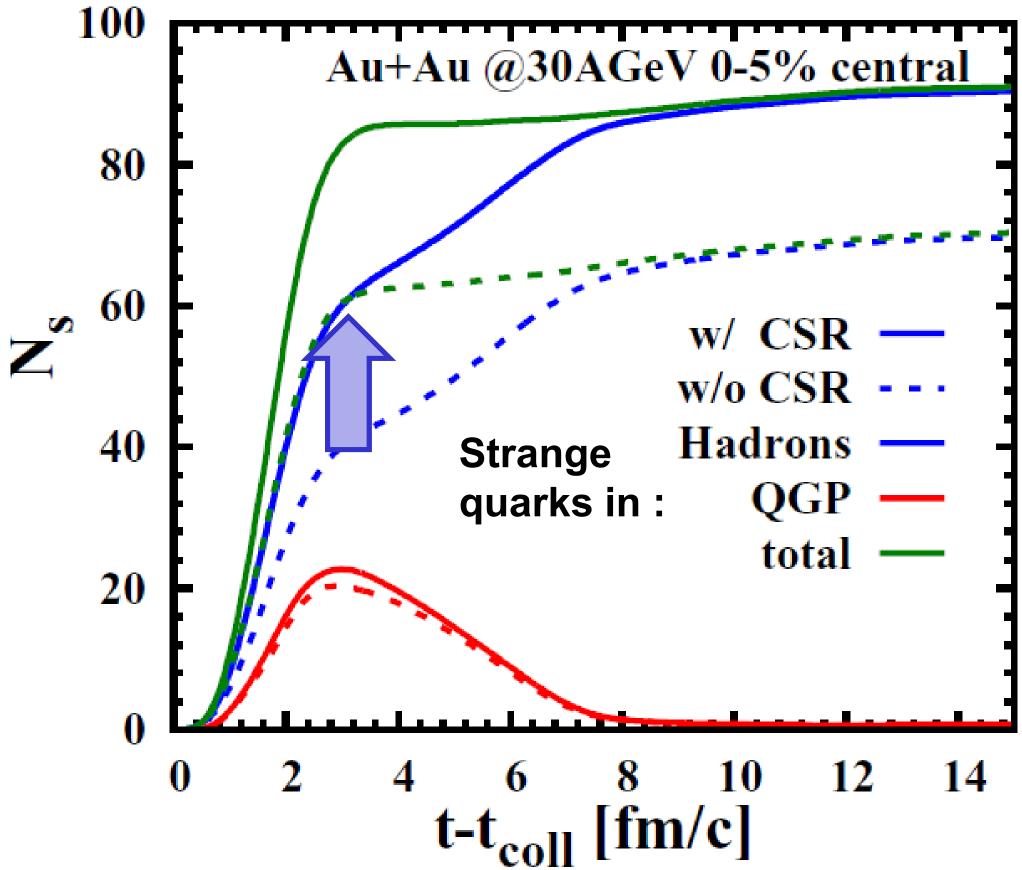
- ❑ Chiral symmetry restoration via Schwinger mechanism (and non-linear $\sigma-\omega$ model) changes the „flavour chemistry“ in string fragmentation (1PI):

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

➔ the strangeness production probability increases with the local energy density ε (up to ε_C).

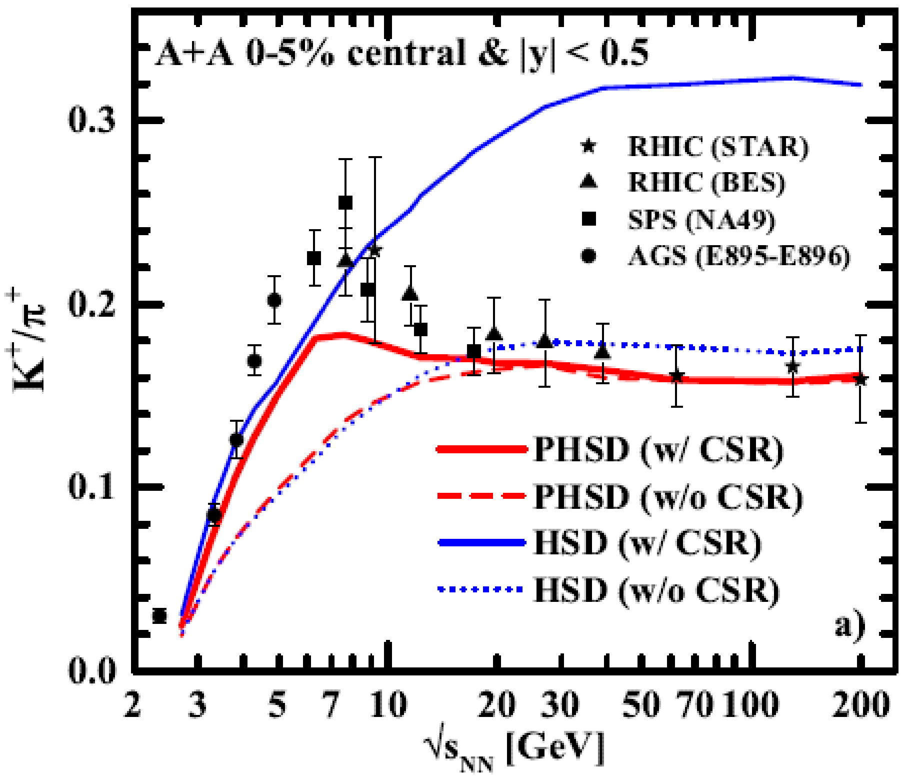
Time evolution of strangeness

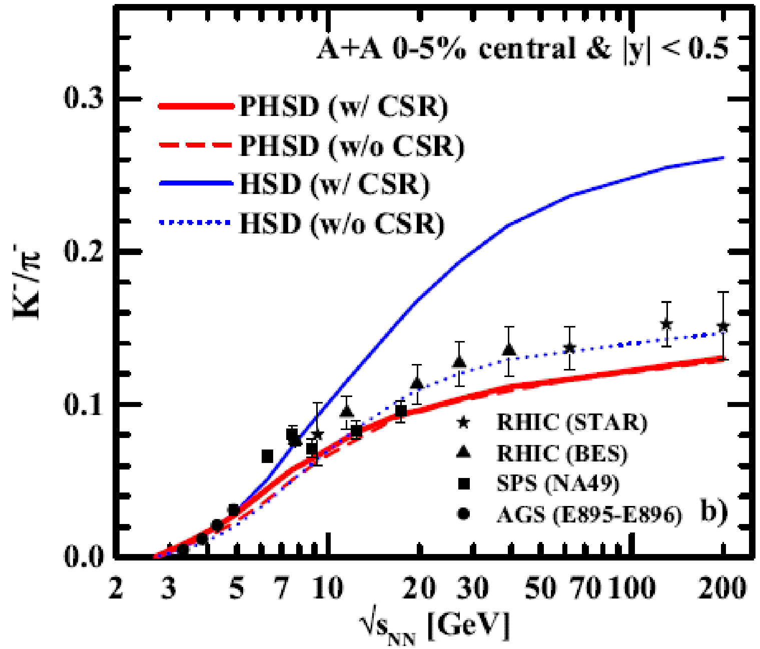
The strange quark number N_s as a function of time in 5% central Au+Au collision at 30 AGeV

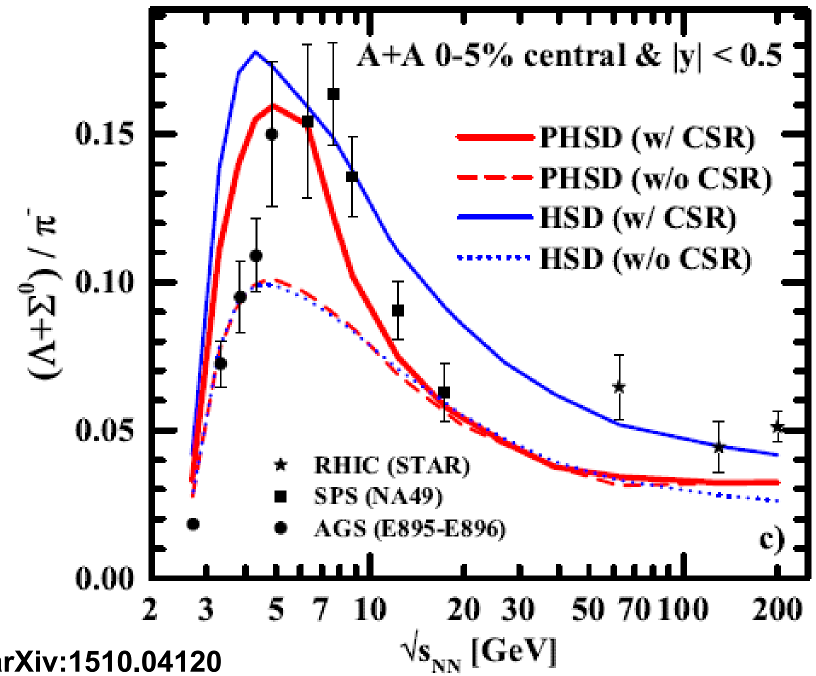


Chiral symmetry restoration leads to the enhancement of strangeness production during the string fragmentation in the beginning of HIC in the hadronic phase

PHSD results with chiral symmetry restoration



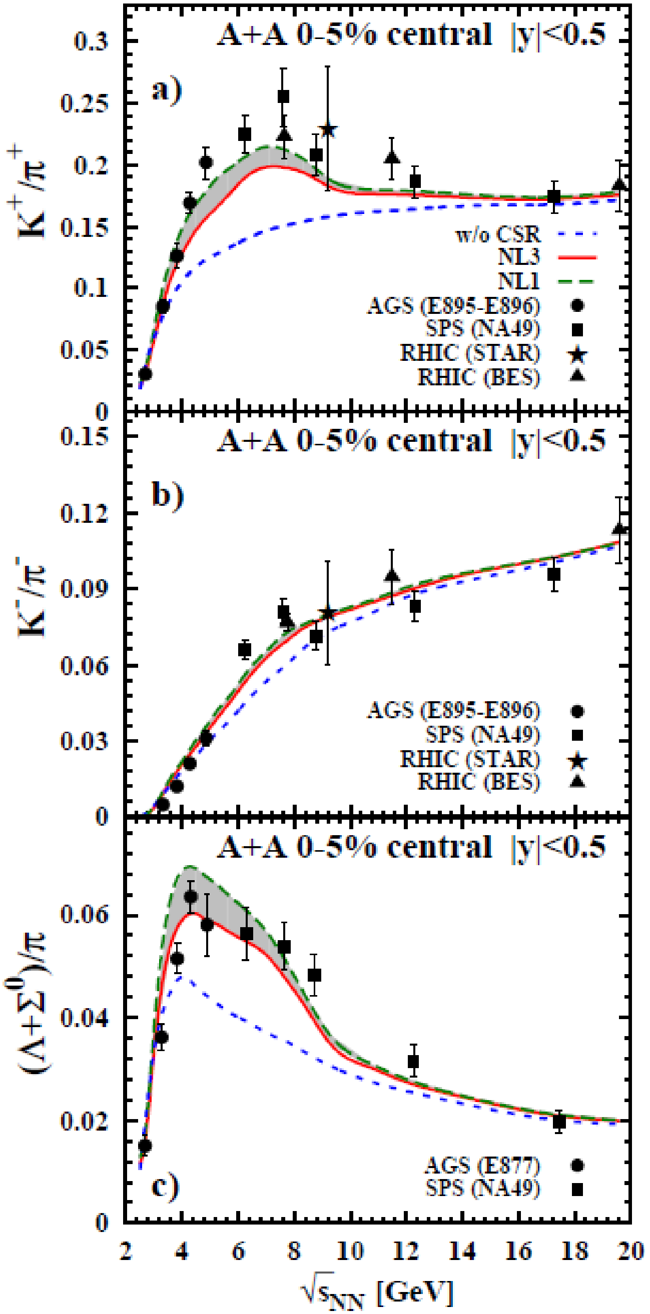


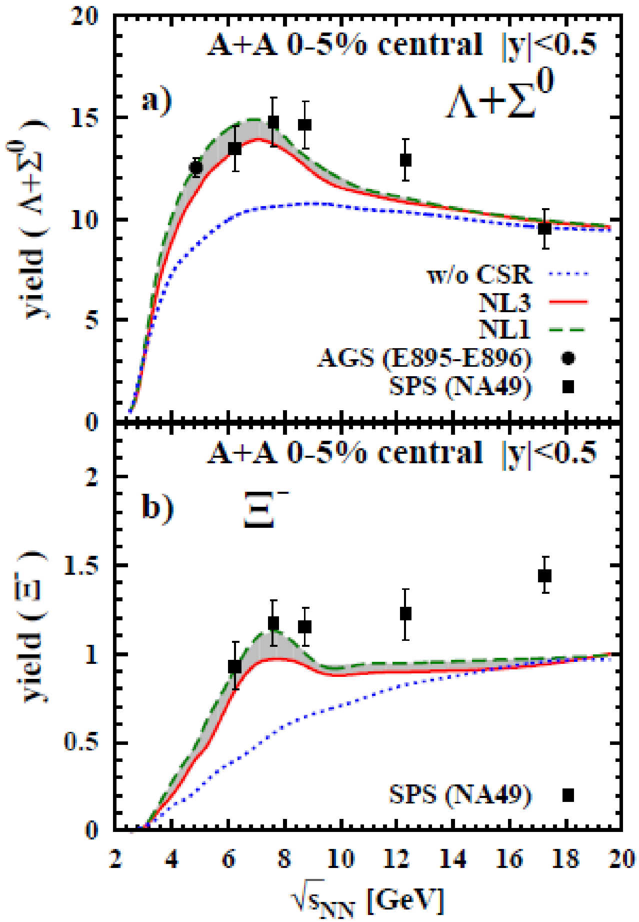


➔ The strangeness enhancement seen experimentally at FAIR/NICA energies probably involves the approximate restoration of chiral symmetry in the hadronic phase

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

Excitation function of hadron ratios and yields

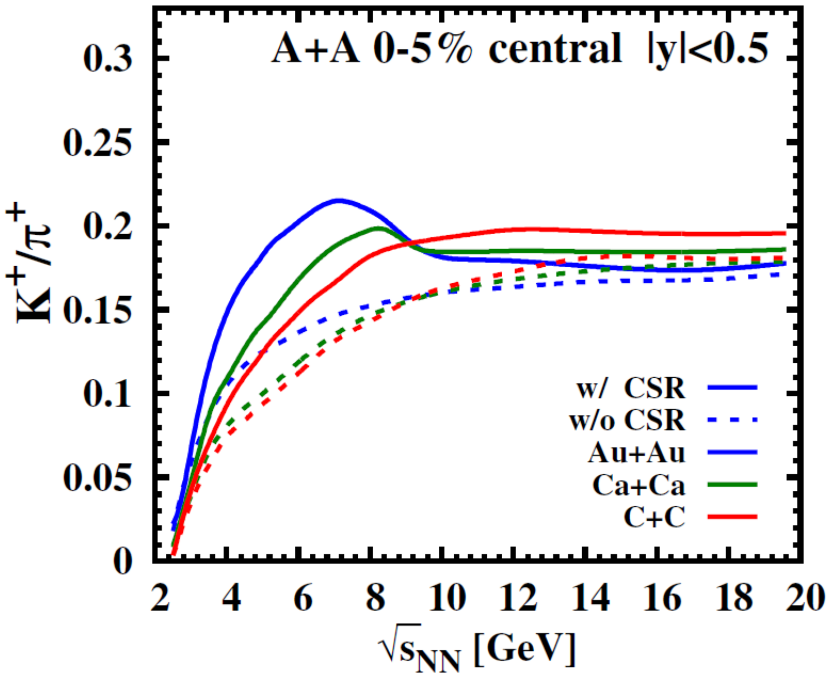


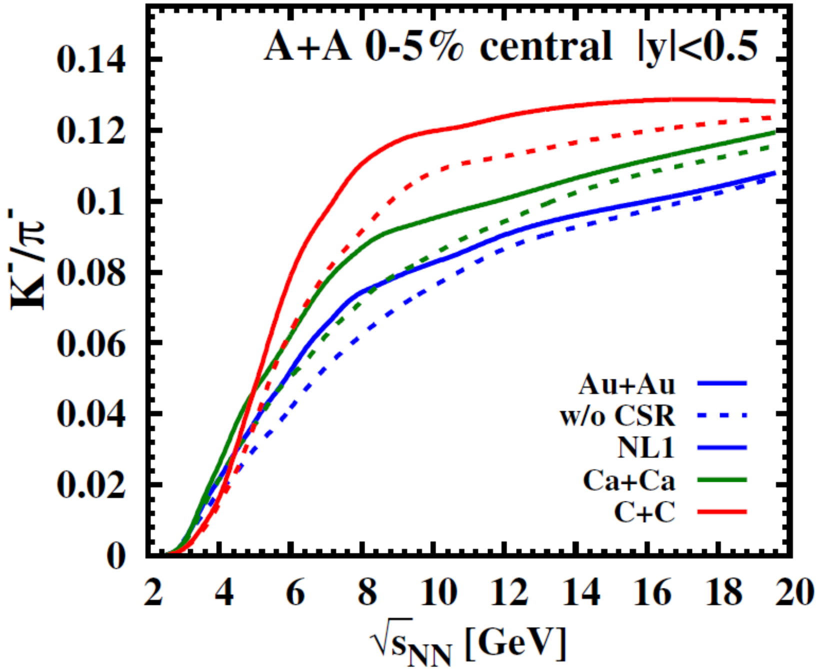


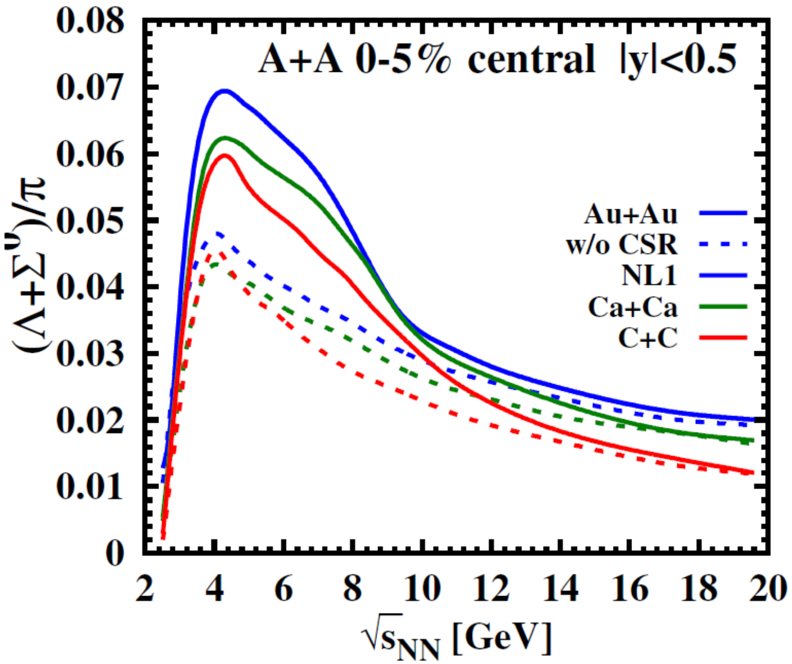
- Influence of EoS: NL1 vs NL3 ➔ low sensitivity to the nuclear EoS
- Excitation function of the hyperons $\Lambda+\Sigma^0$ and Ξ^- show analogous peak as K^+/π^+, $(\Lambda+\Sigma^0)/\pi$ ratios due to CSR

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

Sensitivity to the system size: A+A collisions







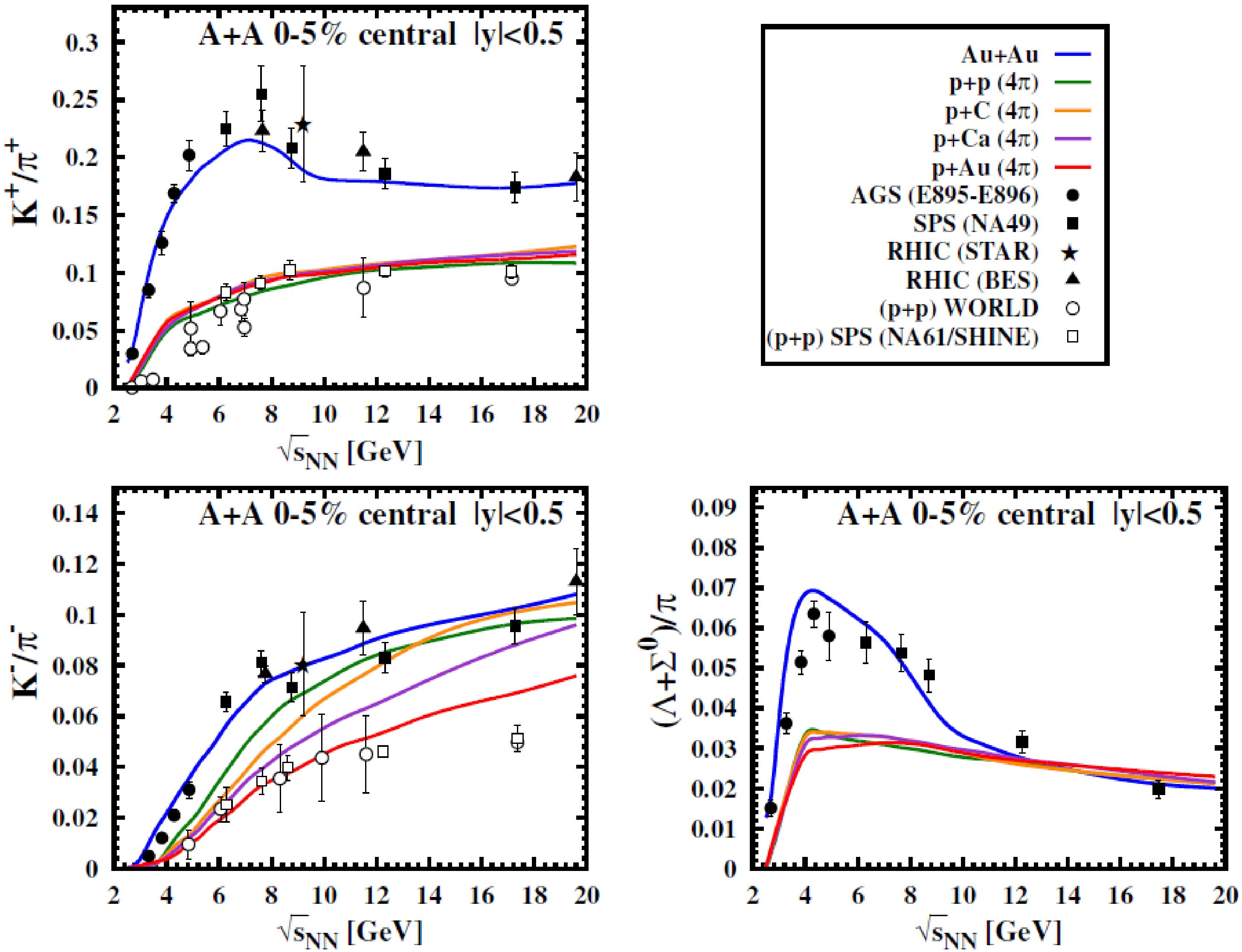
If the system size is smaller:

- 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

Sensitivity to the system size: p+A collisions

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

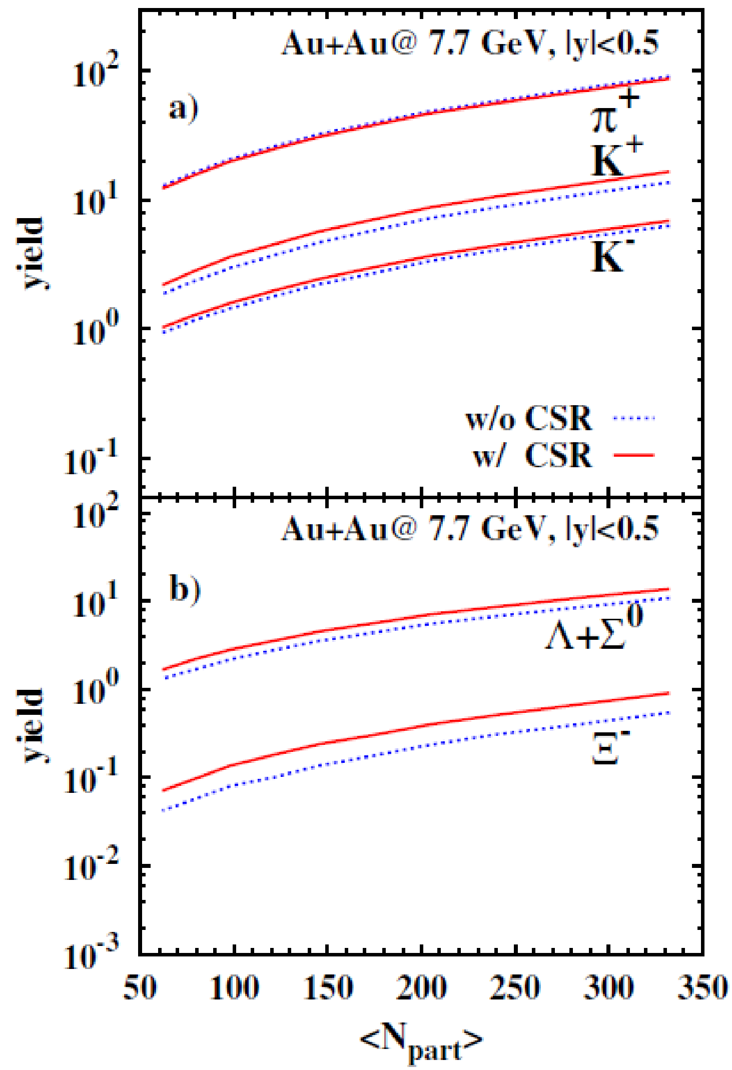


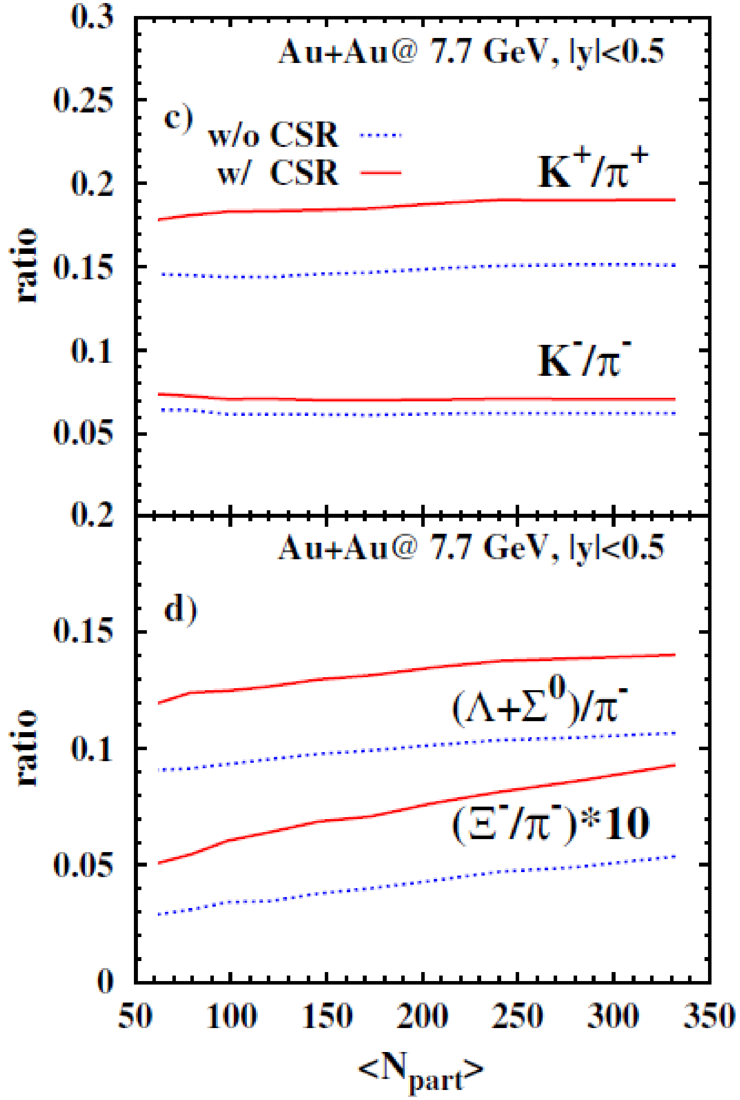
A. Palmese et al., PRC94 (2016) 044912 , arXiv:1607.04073

Centrality dependence of strangeness production

- Example: Au+Au at 7.7 GeV, midrapidity

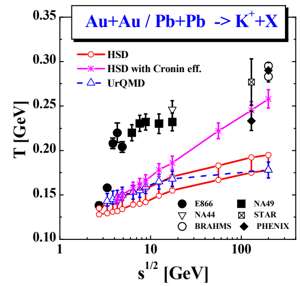
$$\left(\frac{\text{yield}}{\langle N_{\text{part}}\rangle}\right)_{A+A} \Big/ \left(\frac{\text{yield}}{\langle N_{\text{part}}\rangle}\right)_{p+p}$$

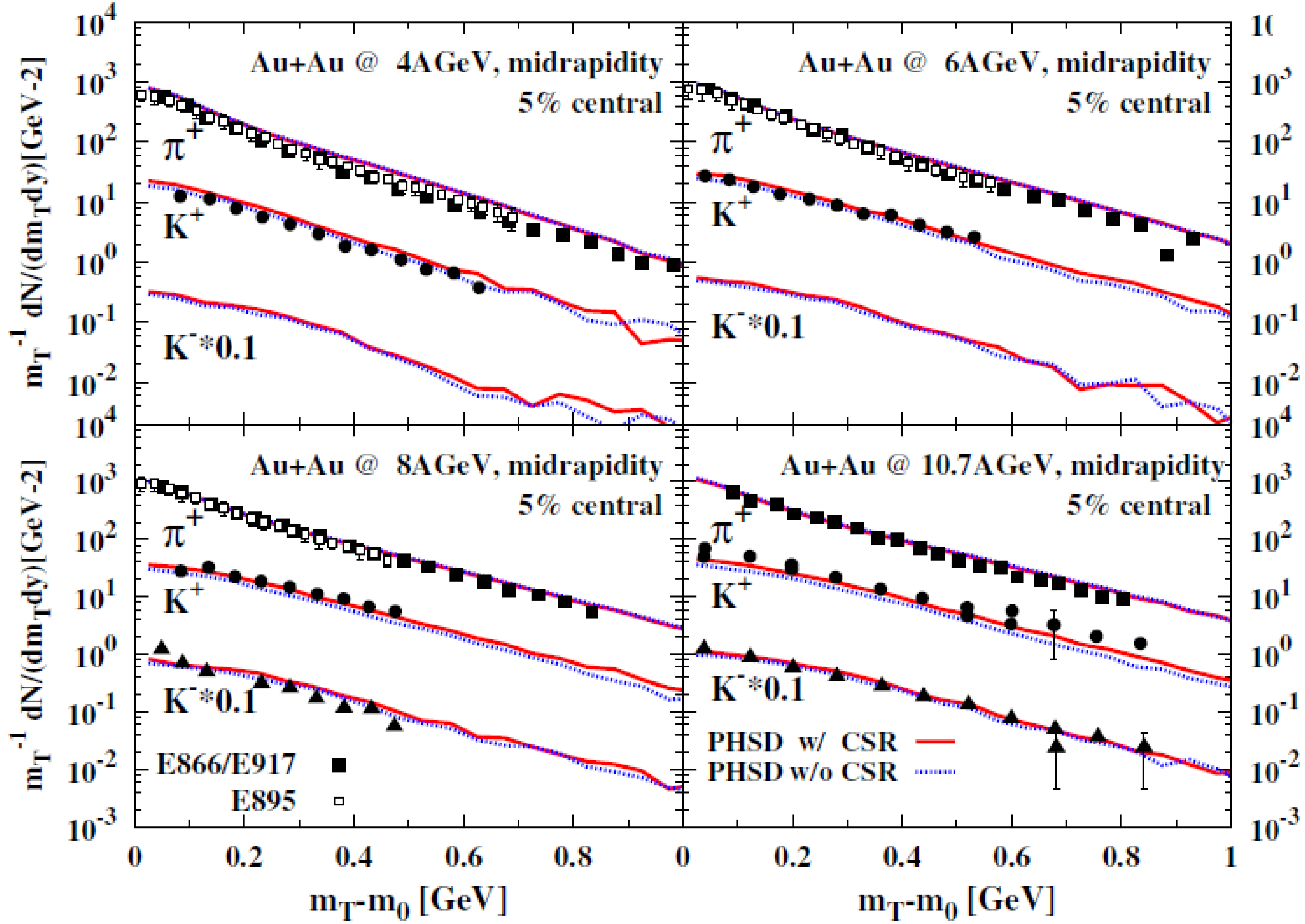




A. Palmese et al., PRC94 (2016) 044912 , arXiv:1607.04073

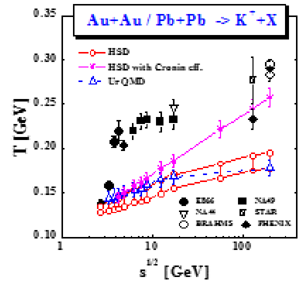
m_T spectra of pions and $K^{+/-}$ at AGS energies

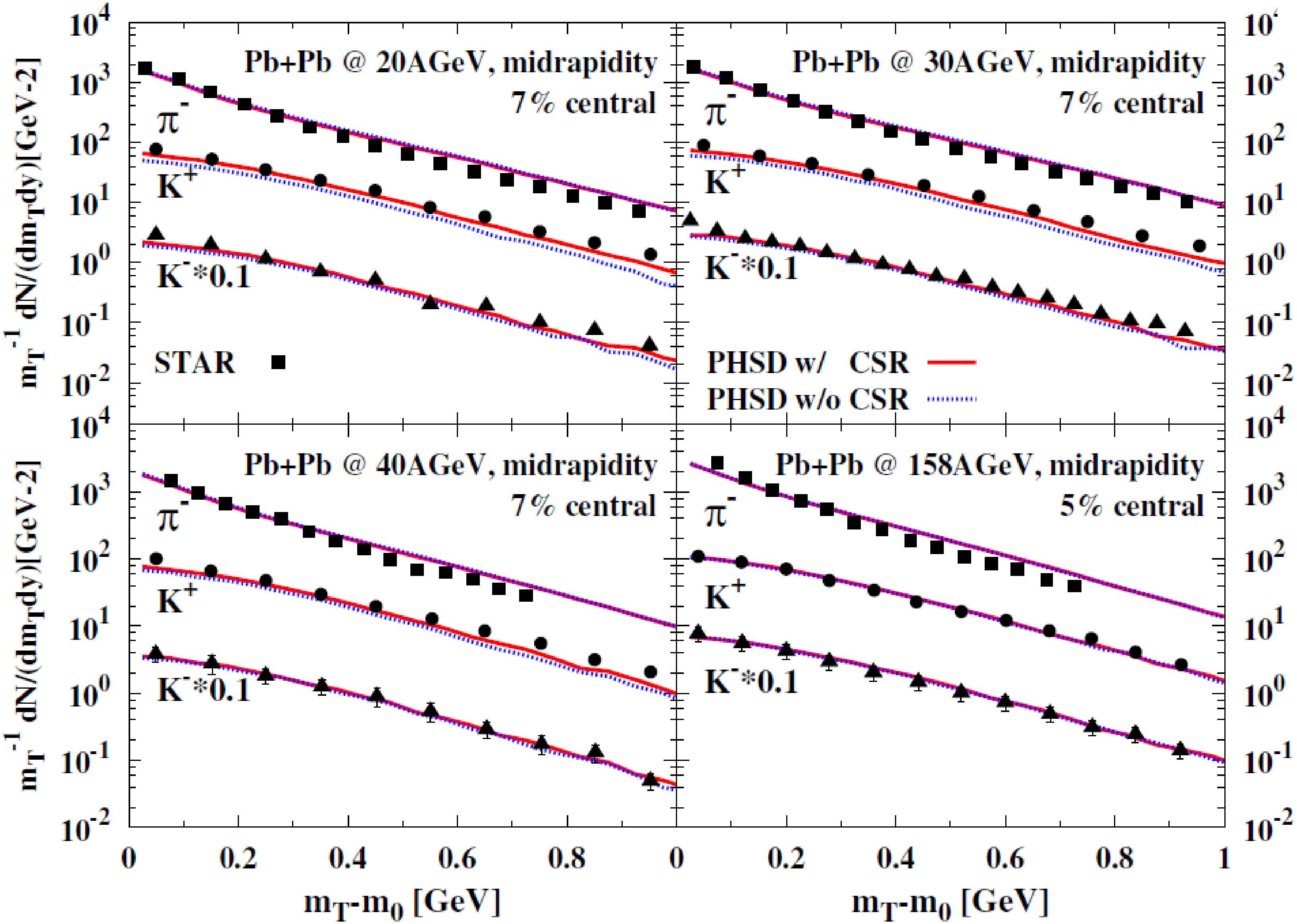




A. Palmese et al., PRC94 (2016) 044912 , arXiv:1607.04073

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

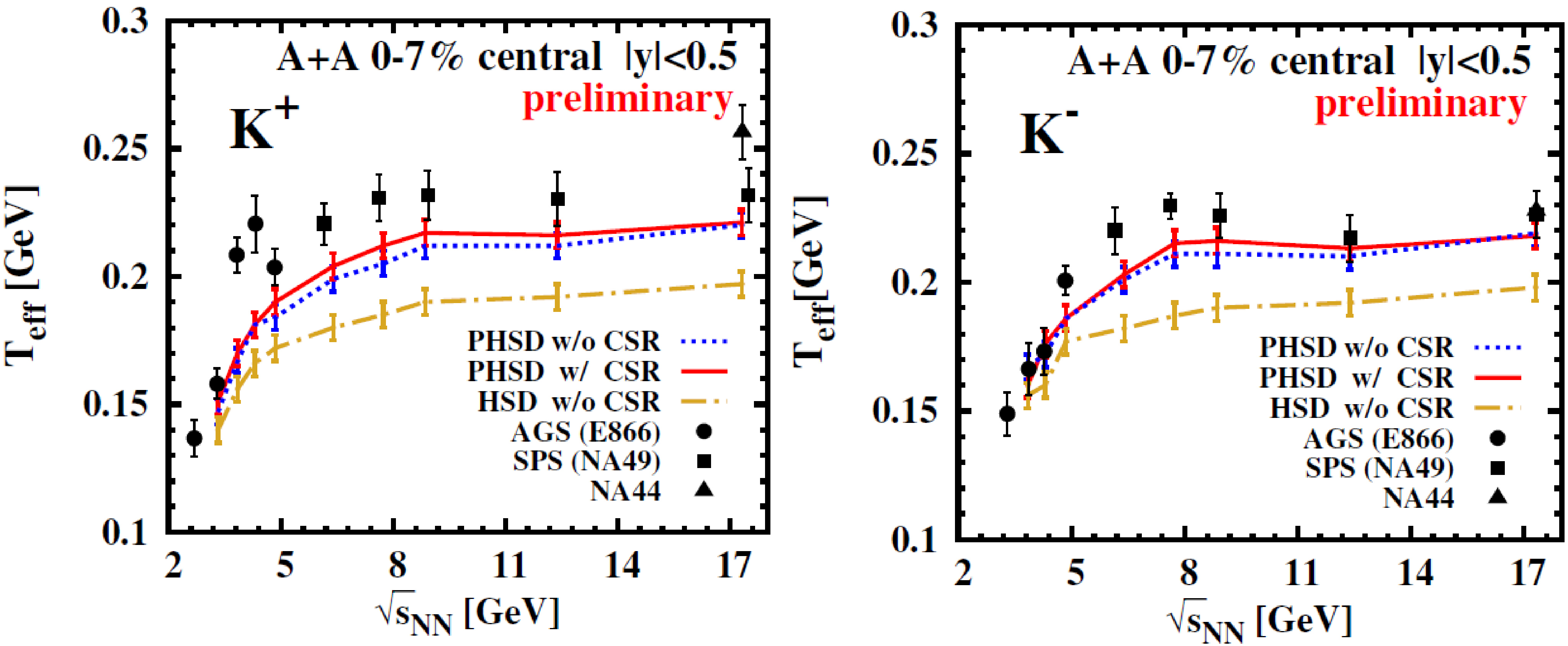




A. Palmese et al., PRC94 (2016) 044912 , arXiv:1607.04073

Excitation function of T_{eff}

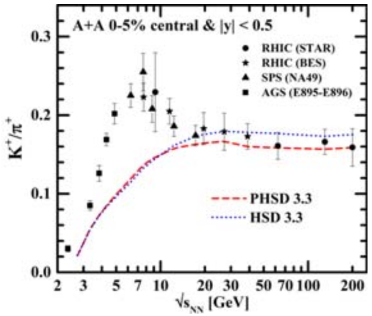
Alessia Palmese

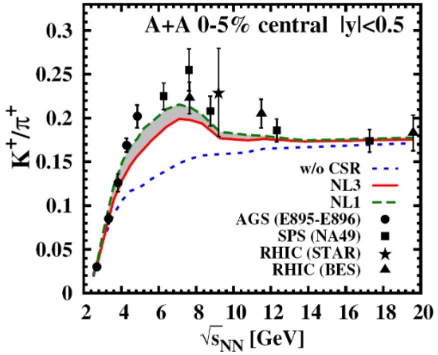


→ Increase of slope T_{eff} due to the QGP

→ Small effect of chiral symmetry restoration on slope Teff

Summary

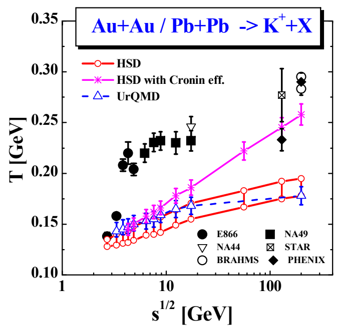


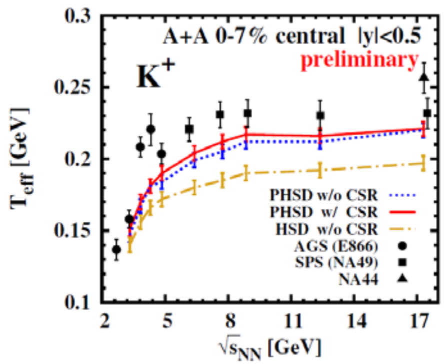


- The strangeness 'enhancement' ('horn') seen experimentally by NA49 and STAR at a bombarding energy ~20-30 A GeV (FAIR/NICA energies!) cannot be attributed to deconfinement

- 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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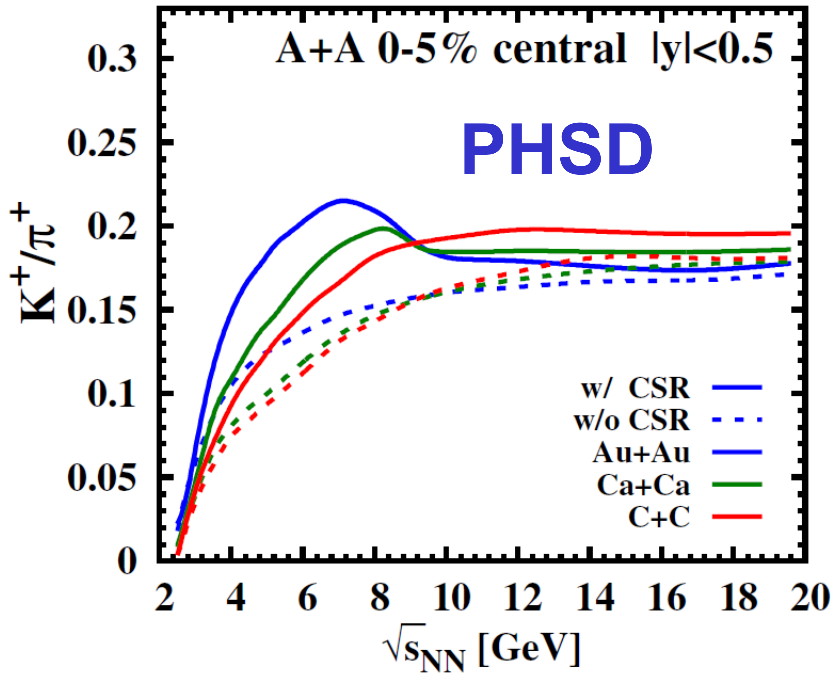
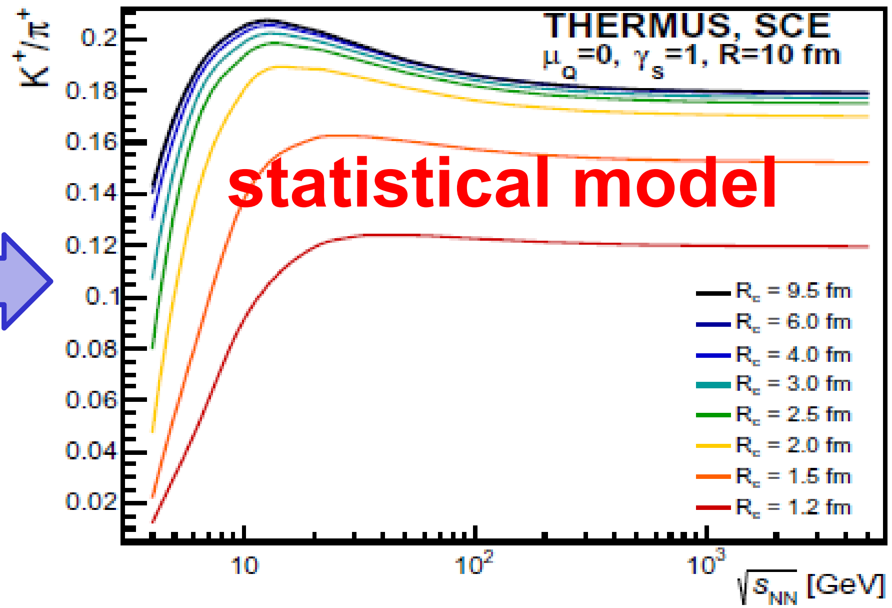
Thank you!

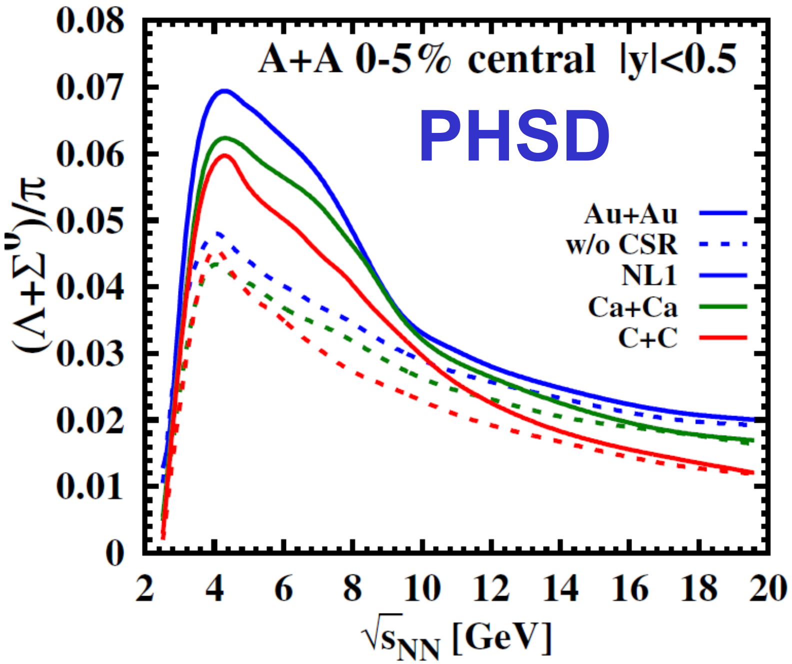
Utrecht 2017

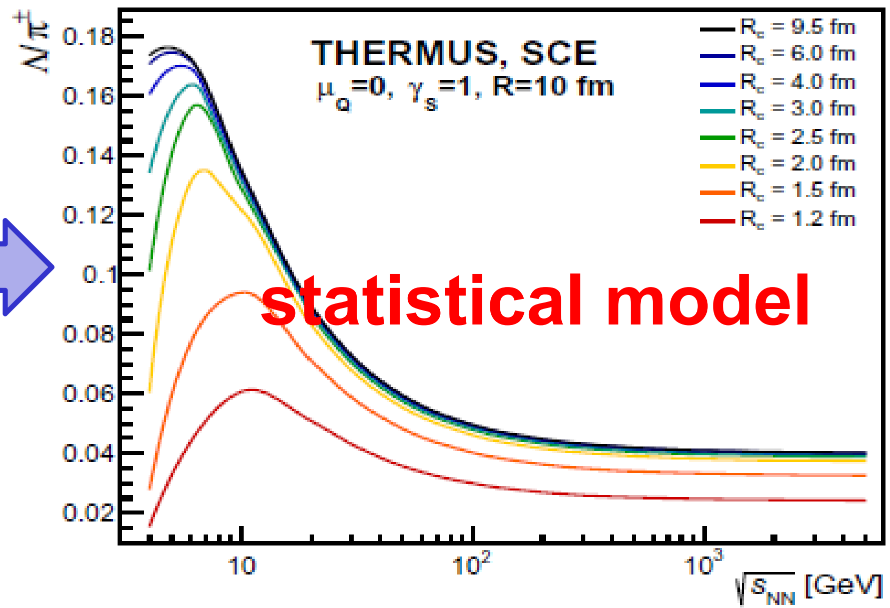
PHSD vs. statistical model

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



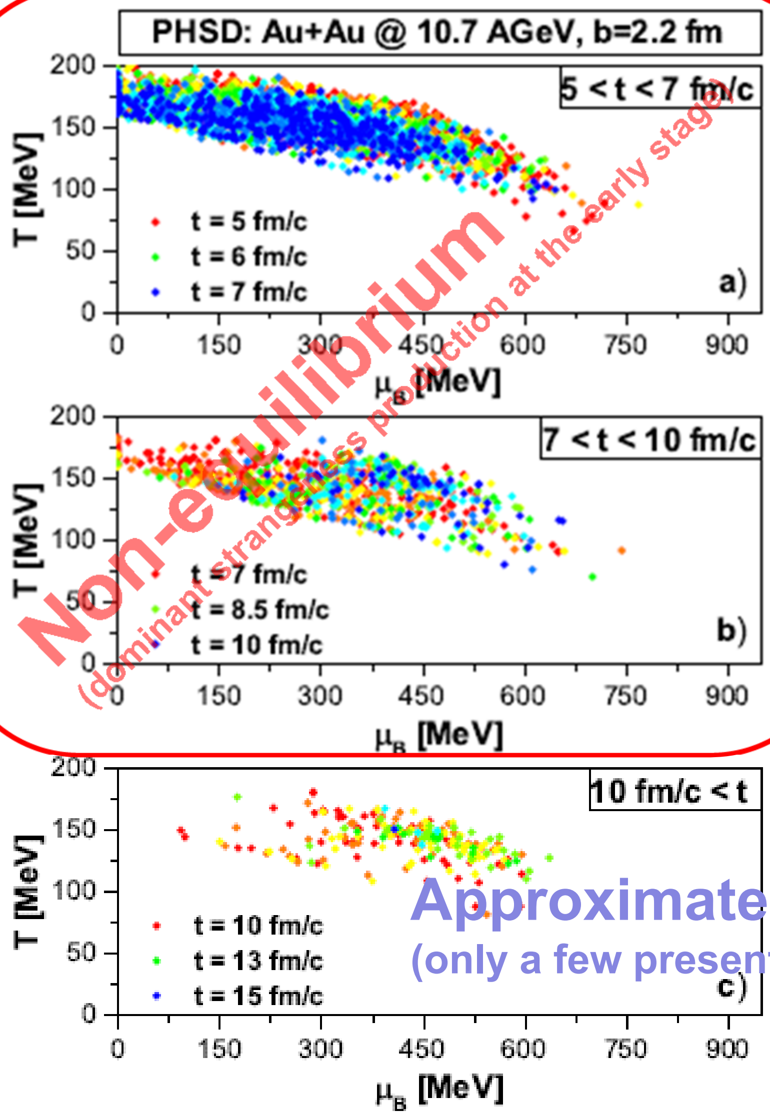




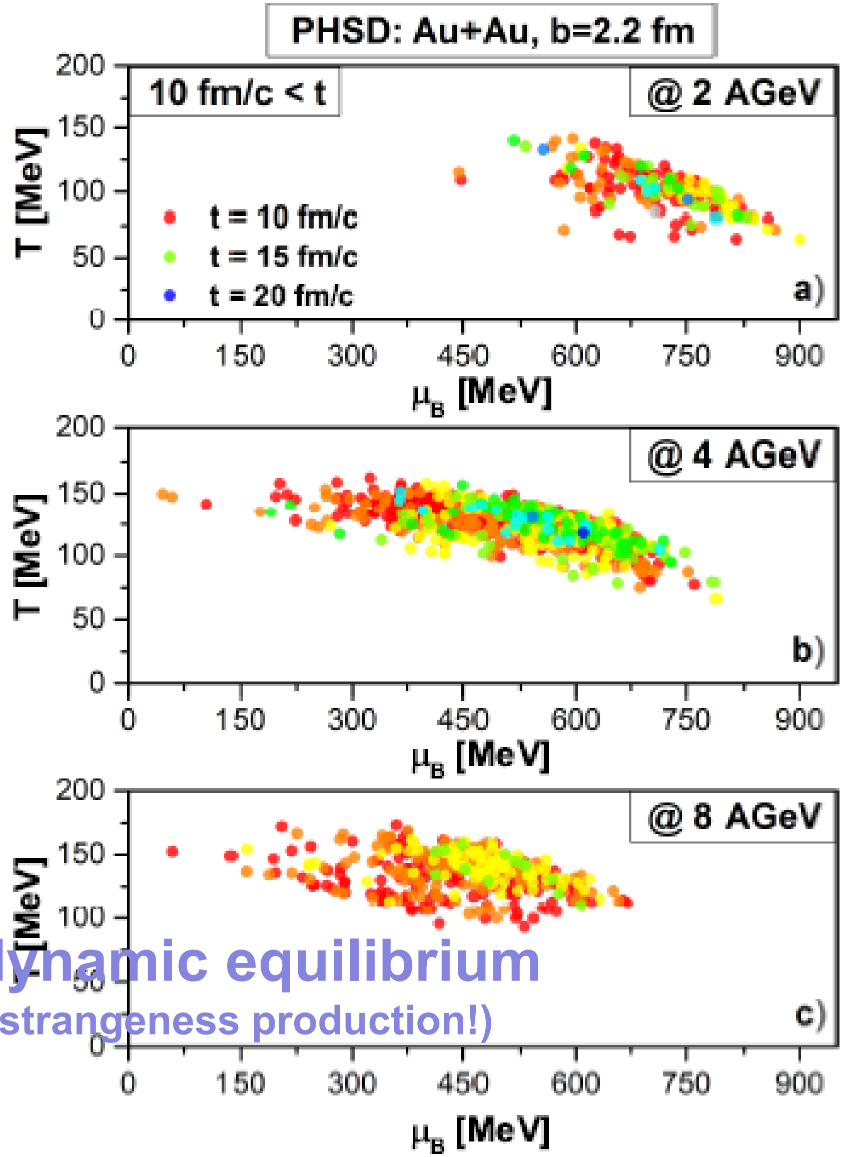


Thermodynamics of strangeness in HIC

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 !**

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