Chiral symmetry restoration versus deconfinement in heavy-ion collisions at high baryon density

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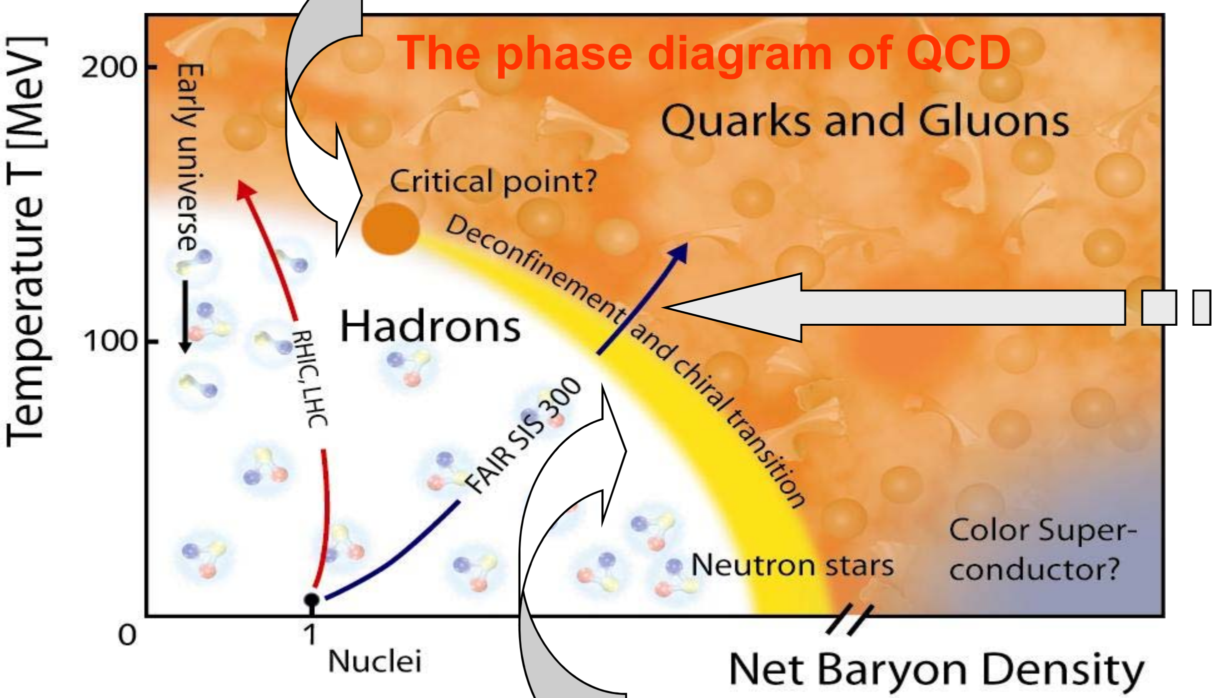
The ‚holy grail‘ of heavy-ion physics:

- **Search for the critical point**



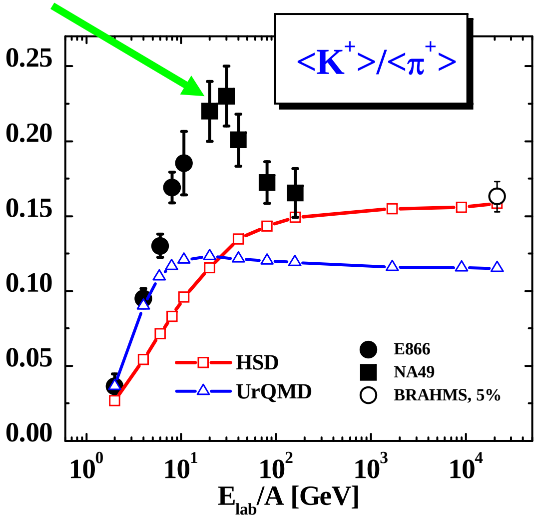
- **Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma**

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

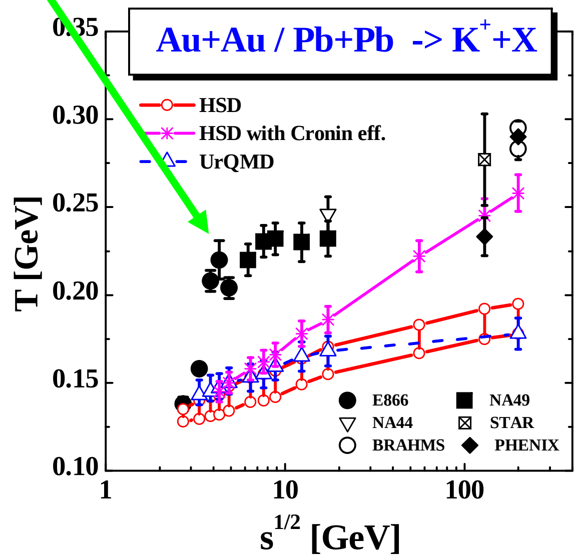
Hadron-string transport models (HSD, UrQMD) versus observables at ~ 2000

NA49: PRC66 (2002) 054902

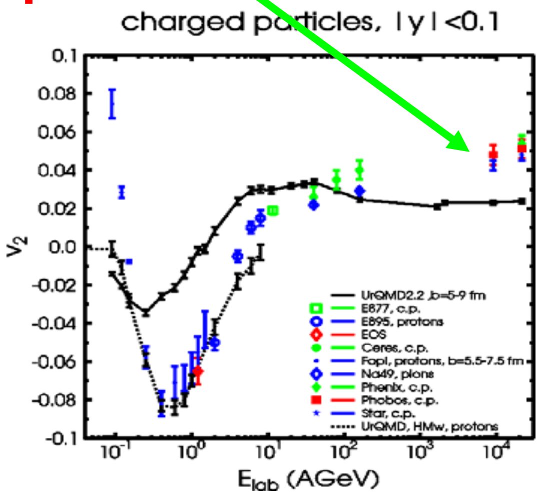
❑ ‚horn' in K^+/π^+



❑ ‚step' in slope T



❑ elliptic flow



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

HSD, UrQMD: PRC 69 (2004) 032302

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 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 (‚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

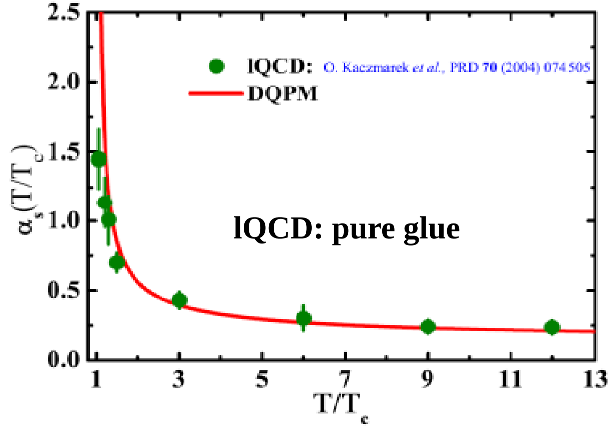
A. Peshier, W. Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

The Dynamical QuasiParticle Model (DQPM)

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

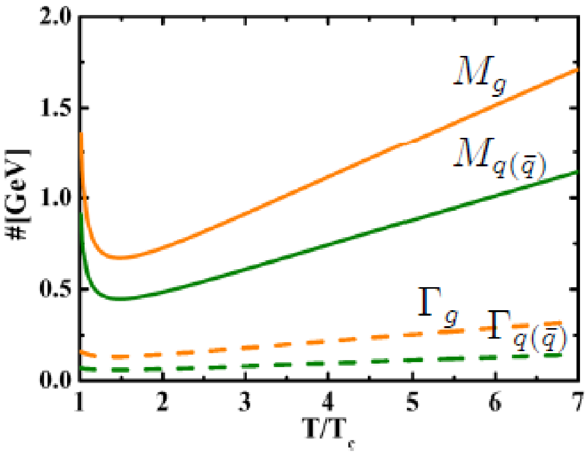
$$\boxed{\rho_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)}} \qquad (i = q, \bar{q}, g)$$

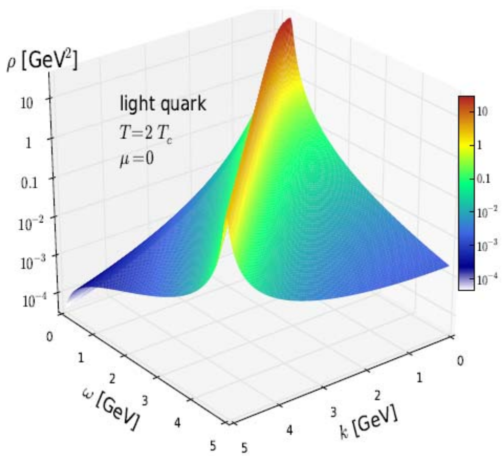
- Modeling of the quark/gluon masses and widths → HTL limit at high T with 3 model parameters – fited to lattice QCD data

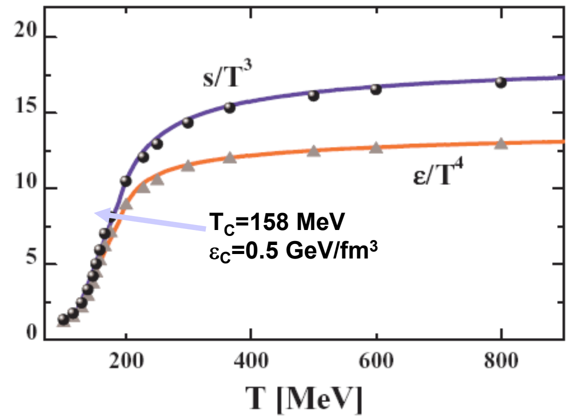


➔ Quasi-particle properties:

large width and mass for gluons and quarks



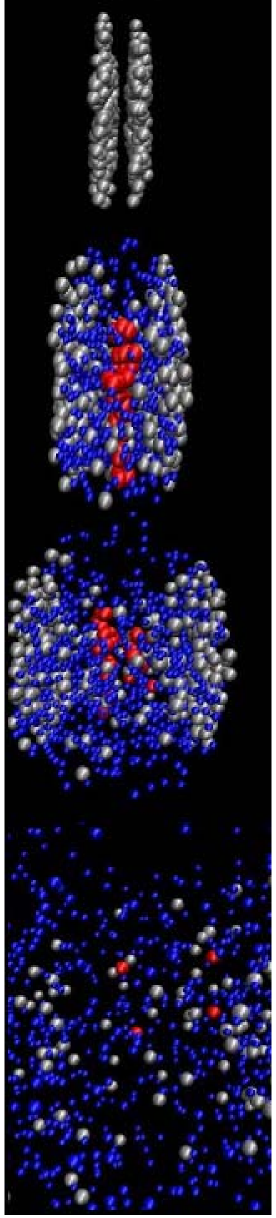




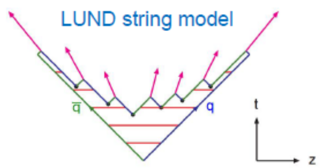
- DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)
- DQPM gives transition rates for the formation of hadrons → PHSD

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

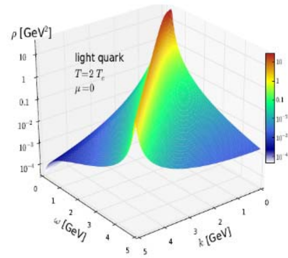
Parton-Hadron-String-Dynamics (PHSD)



- **Initial A+A collisions – HSD:**
  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



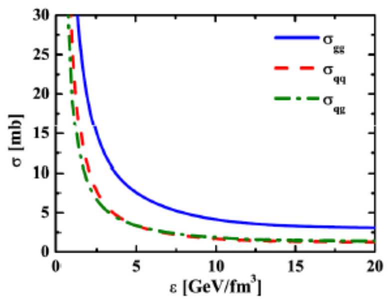
- **Partonic stage – QGP :**
  based on the Dynamical Quasi-Particle Model (DQPM)

  - (quasi-) elastic collisions:

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

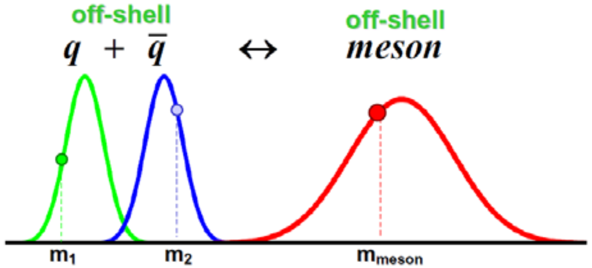
  - inelastic collisions:

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



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

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

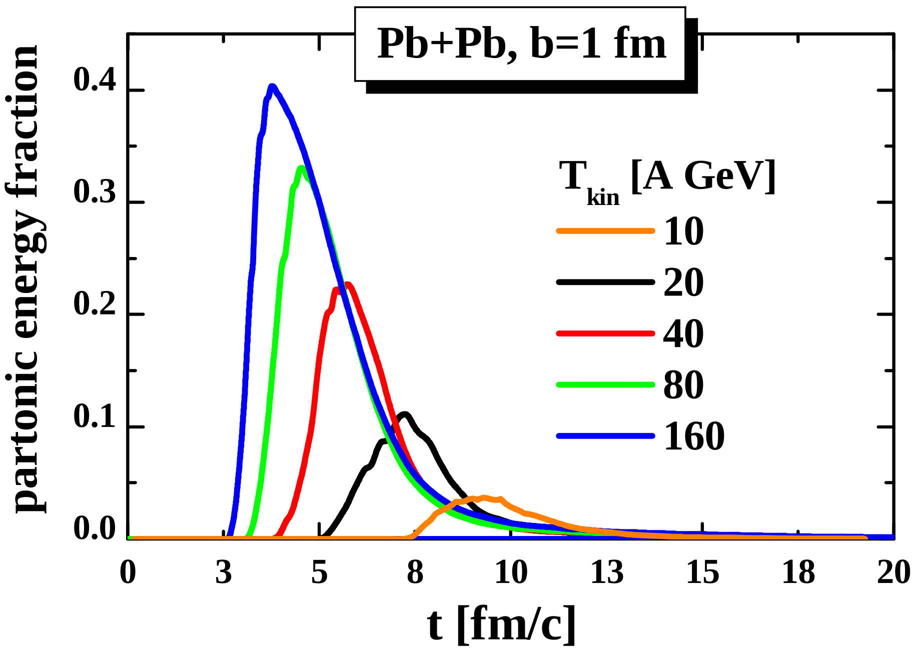


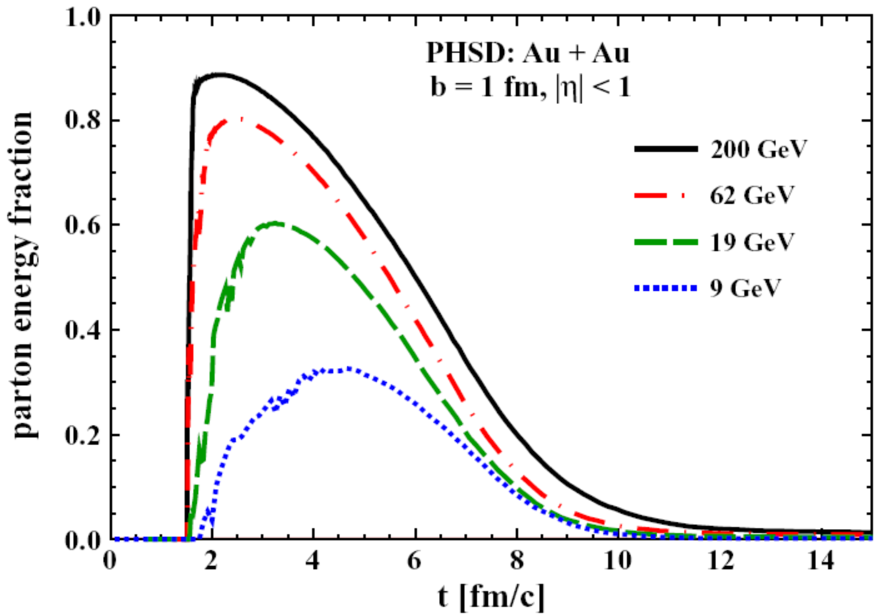
- **Hadronic phase: hadron-hadron interactions – off-shell HSD**

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

Partonic energy fraction in central A+A

Time evolution of the partonic energy fraction vs energy at midrapidity



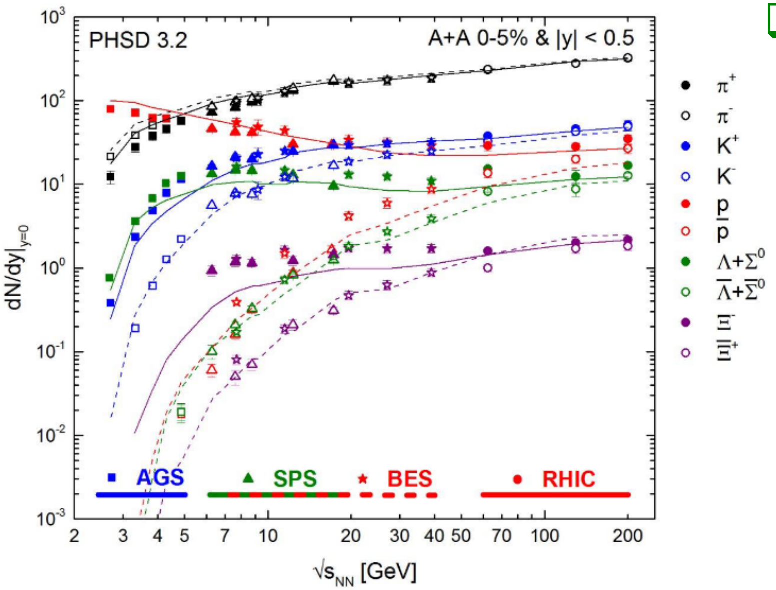


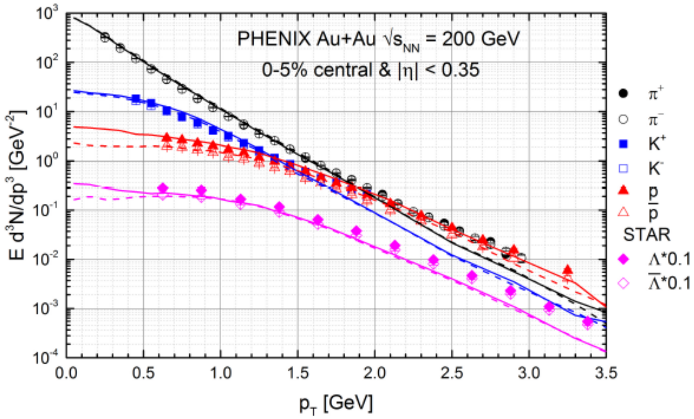
- Strong increase of partonic phase with energy from AGS to RHIC

- 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 particles
- 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

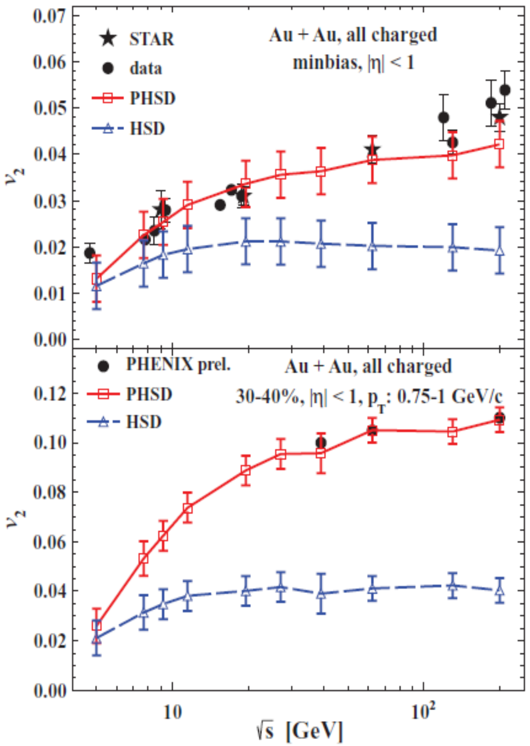
Non-equilibrium dynamics: description of A+A with PHSD

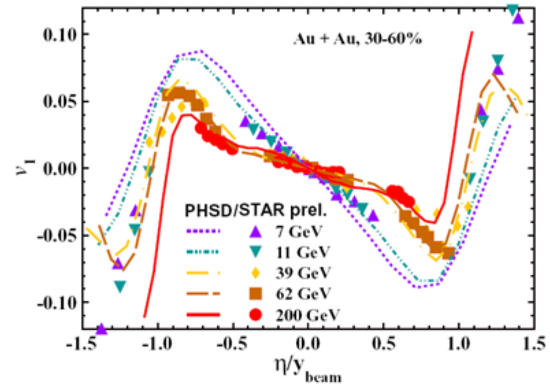


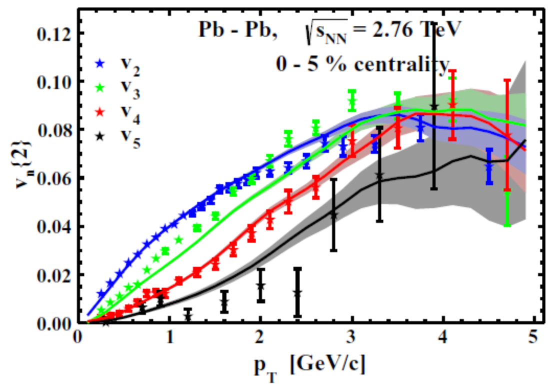


PHSD: P. Moreau

❑ PHSD: highlights







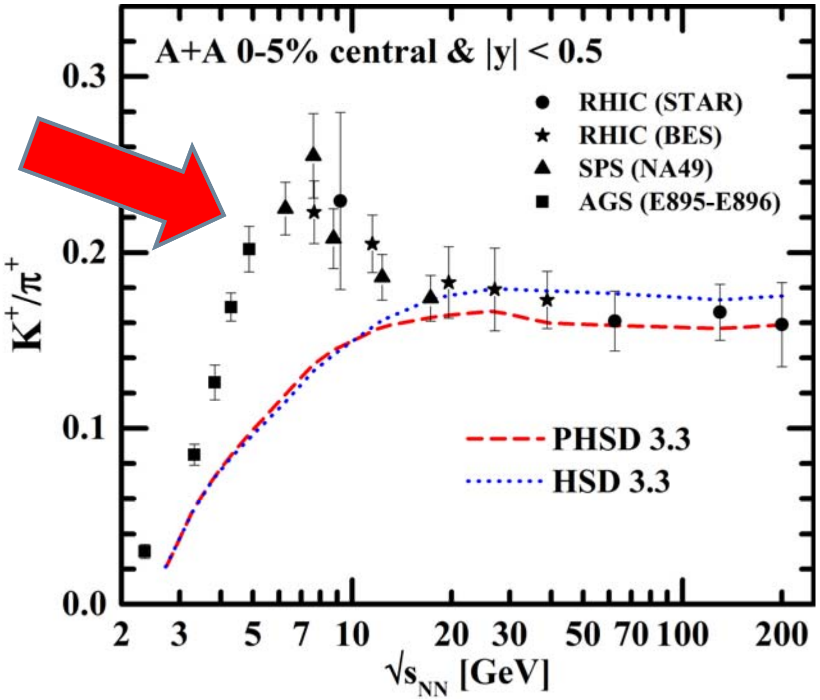
V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106

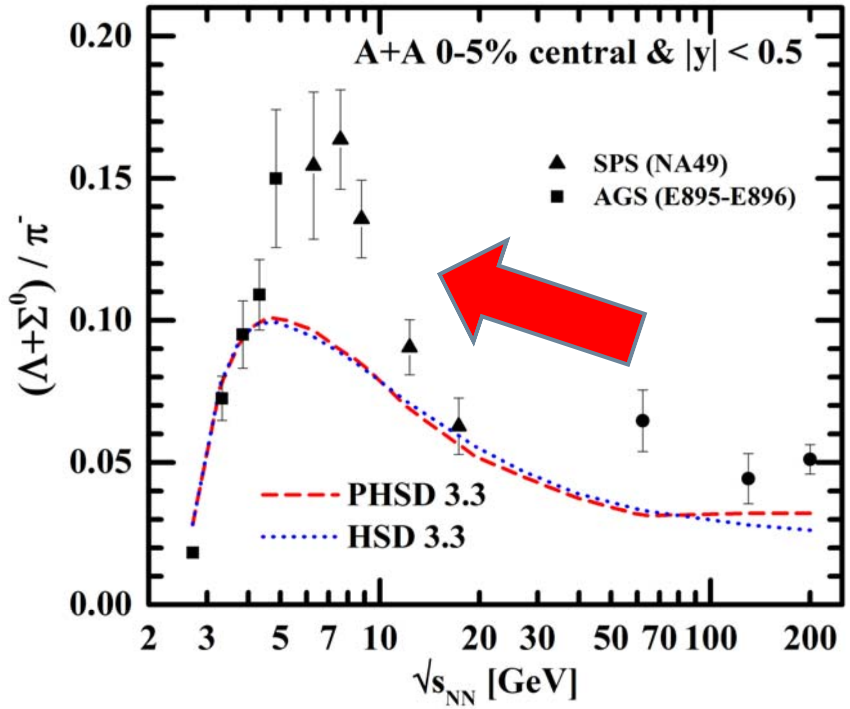
❑ **PHSD provides a good description of ‚bulk' observables (y-, p_T-distributions, flow coefficients v_n, …) from SPS to LHC**

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 !

➔ **'Horn' is not traced back to deconfinement ?!**

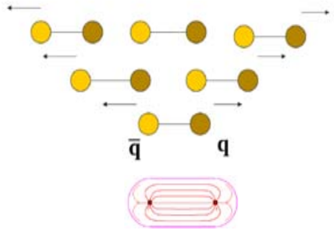


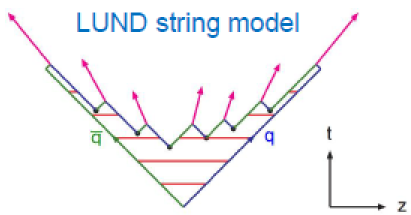


- **Can it be related to the chiral symmetry restoration in the hadronic phase?!**

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

‚Quark flavor chemistry‘ in the LUND string model





❑ **In PHSD:**
the ‚flavor chemistry‘ of the final hadrons is mainly defined by the LUND string model

❑ **LUND model:**
1) ‘quark flavor chemistry’ 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 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=0.176GeV^2

The relative production factors in PHSD/HSD are:

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

m_s, m_q (q=u,d) – constituent (‘dressed’) quark masses due to coupling to the vacuum

2) ‘Kinematics’ is determined by the fragmentation function f (x,m_T)

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

Schwinger mechanism in vacuum

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

- 'dressing' of bare quark masses is due to the coupling to the vacuum scalar quark condensate (cf. Dyson-Schwinger Bethe-Salpeter approaches)

$$\boxed{m_q^V = m_q^0 - g_s < q\bar{q} >_V} \qquad (V \equiv vacuum)$$

bare quark masses:
$m_u^0 = m_d^0 \approx 7 MeV,\ m_s^0 \approx 100 MeV$

- vacuum scalar quark condensate is fixed by Gell-Mann-Oakes-Renner relation:

$$f_\pi^2 m_\pi^2 = -\frac{1}{2}(m_u^0 + m_d^0) < \bar{q}q >_V \quad \Rightarrow \quad < \bar{q}q >_V \approx -3.2\, fm^{-3}$$

f_π and m_π are the pion decay constant and pion mass

➔ Constituent quark masses in vacuum : $m_q \equiv m_q^V$

$$\boxed{m_u^V = m_d^V \approx 0.35 GeV, \quad m_s^V \approx 0.5 GeV}$$

Schwinger mechanism in medium

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:

$$m_q^* = m_q^0 - g_s < q\bar{q} > \quad \Rightarrow \quad \boxed{m_q^* = m_q^0 + (m_q^V - m_q^0)\frac{< q\bar{q} >}{< q\bar{q} >_V}} \quad (q = u,d,s)$$

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

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

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

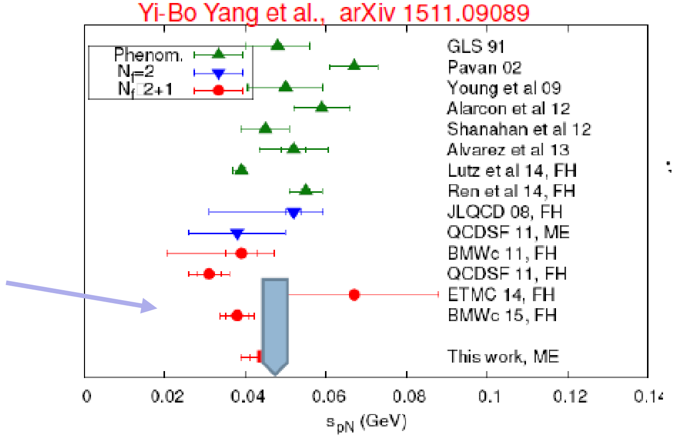
$$\boxed{\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V} = 1 - \underbrace{\frac{\Sigma_\pi}{f_\pi^2 m_\pi^2}\rho_S}_{\text{baryonic medium}} - \underbrace{\sum_h \frac{\sigma_h \rho_S^h}{f_\pi^2 m_\pi^2}}_{\text{mesonic medium}}}$$

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

where ρ_s is the scalar nuclear density,
ρ_s^h is the scalar meson density,
$\Sigma_\pi \approx 45$ MeV is the pion-nucleon Σ-term,
$\sigma_h = m_\pi/2$ for light mesons; $= m_\pi/4$ - strange mesons

- pion-nucleon Σ-term : 45 MeV

Yi-Bo Yang et al., arXiv 1511.09089



Scalar density in PHSD

1) ρ_s **is the scalar density of baryonic matter:**

d = 4 in case of isospin symmetric nuclear matter

$$\rho_s = d \int \frac{d^3p}{(2\pi)^3} \frac{m_N^*(x)}{\sqrt{p^2 + m_N^{*2}}} f_N(x, \mathbf{p})$$

Where the in-medium nucleon mass is

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

with m^V_N denoting the nucleon mass in vacuum
Scalar field *σ(x)* mediates the scalar interaction with the surrounding medium with a g_s coupling
***σ(x)* is defined/determined locally by the nonlinear 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 $\sigma - \omega$ model for nuclear matter, the parameters g_s , m_σ , B, C can be fixed in order to reproduce the main nuclear matter quantities at saturation, i.e. saturation density, binding energy per nucleon, compression modulus and the effective nucleon mass.

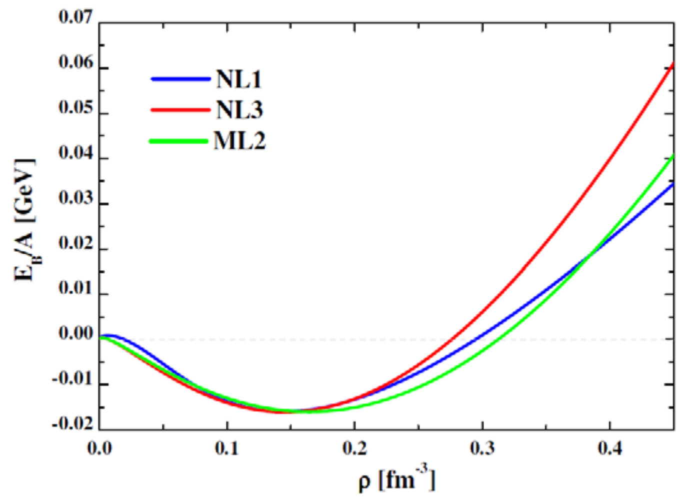
2) ρ_s^h **is the scalar density of mesons of type h (from PHSD):**

$$\rho_S^h(x) = \frac{(2s+1)(2t+1)}{(2\pi)^3} \int d^3\mathbf{p} \frac{m_h}{\sqrt{\mathbf{p}^2 + m_h^2}} f_h(x, \mathbf{p})$$

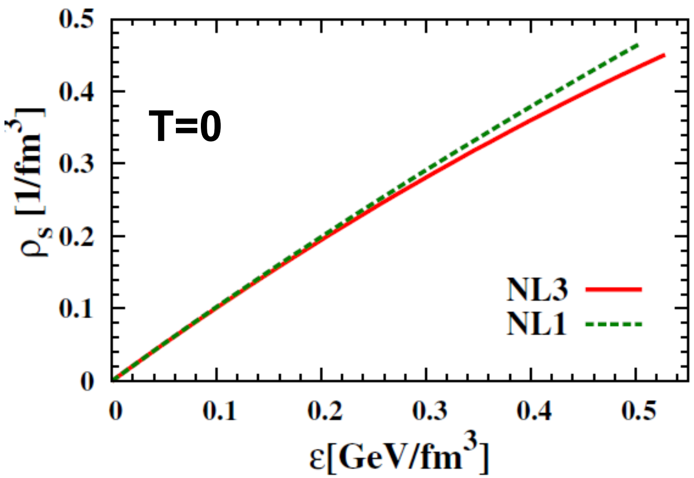
Sensitivity to the EoS of nuclear matter

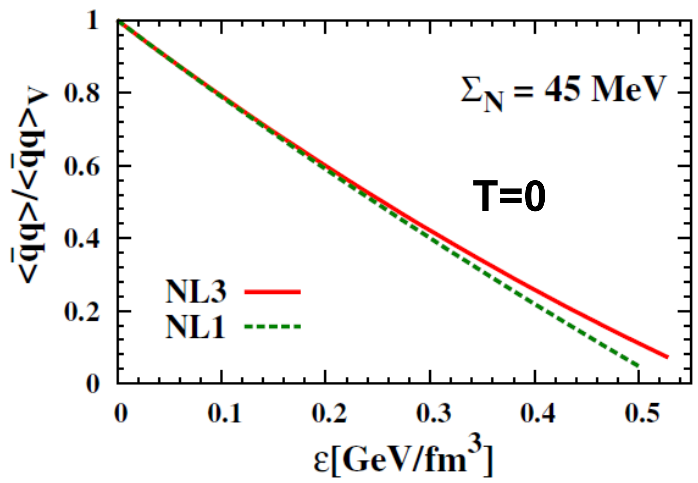
Parameter sets NL1, NL3 and ML2 for the nonlinear $\sigma - \omega$ model employed in the transport calculations

	NL1	ML2	NL3
g_s	6.91	9.28	9.50
g_v	7.54	10.59	10.95
B (1/fm)	−40.6	5.1	1.589
C	384.4	9.8	34.23
m_s (1/fm)	2.79	2.79	2.79
m_v (1/fm)	3.97	3.97	3.97
K (MeV)	380	354	380
m^*/m	0.83	0.68	0.70



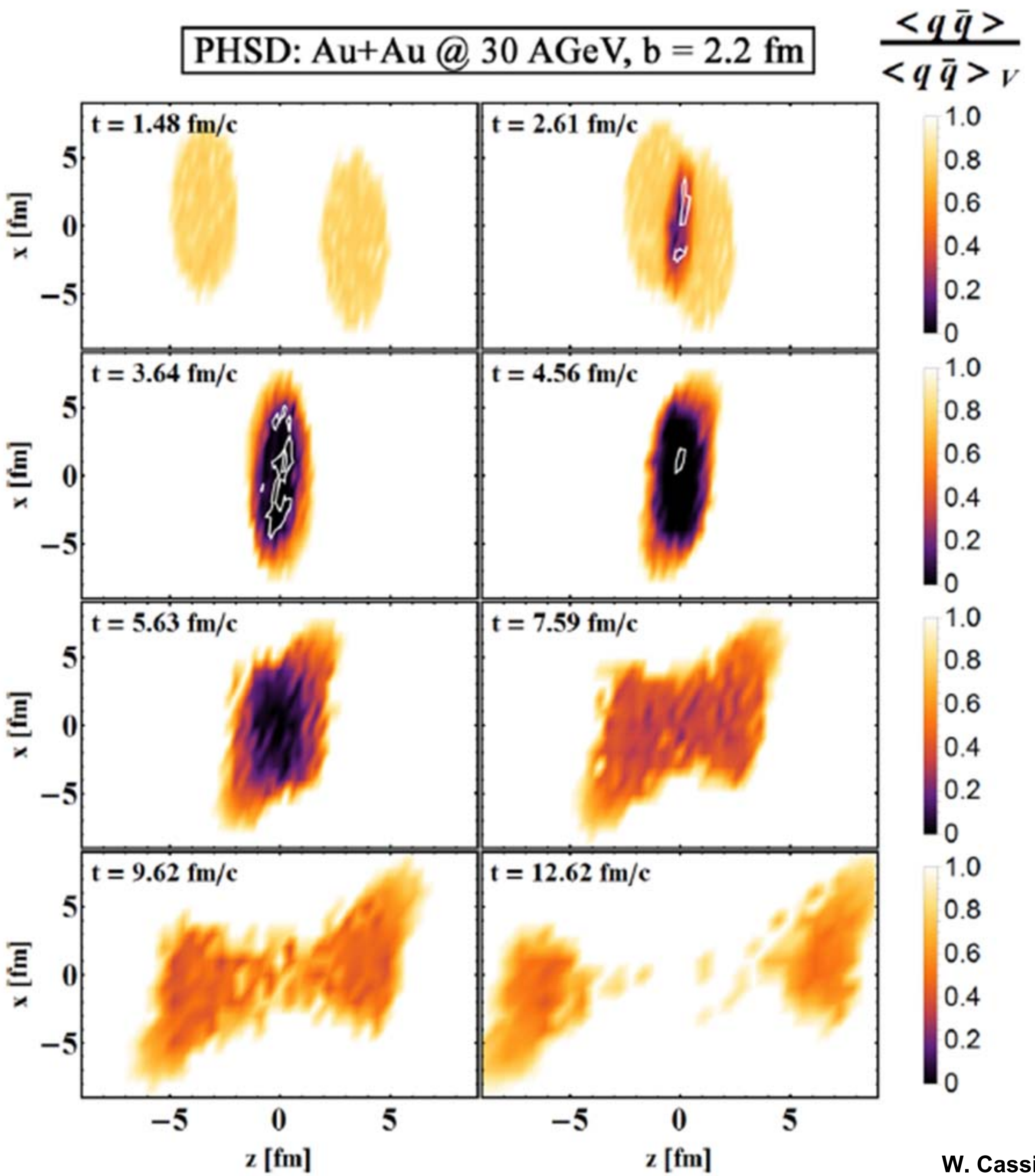
NL1,NL3: A. Lang *et al.*, Z. Phys. A 340, 287 (1991)
ML2: F. de Jong and R. Malfliet, Phys. Rev. C 44, 998 (1991).





ε is the energy density of nuclear matter

→ low sensitivity to the nuclear EoS



Ratio of the scalar quark condensate compared to the vacuum as a function of time:

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

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

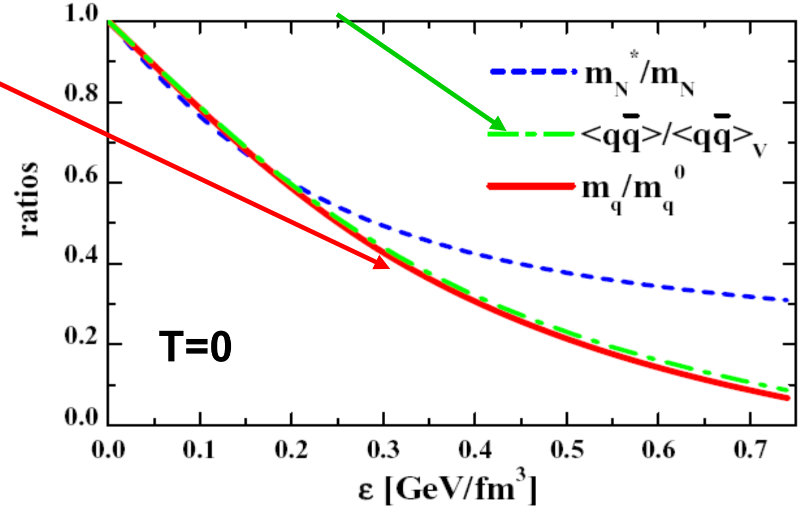
Modeling of the chiral symmetry restoration in PHSD

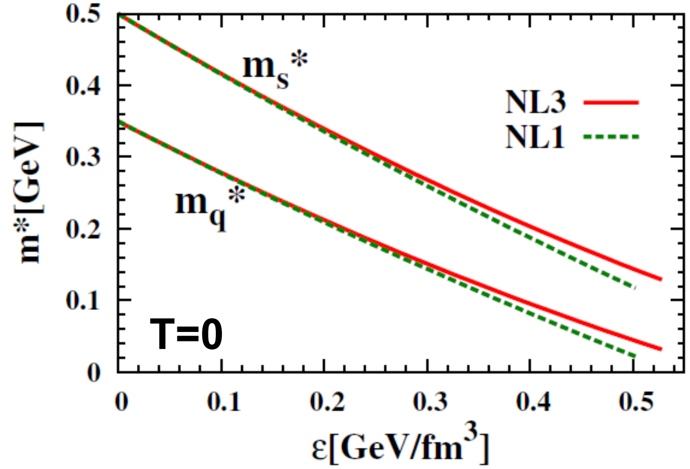
- In the Schwinger formula the in-medium constituent masses $m^*_{q;s} \rightarrow m_{q;s}$ have to be considered:

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

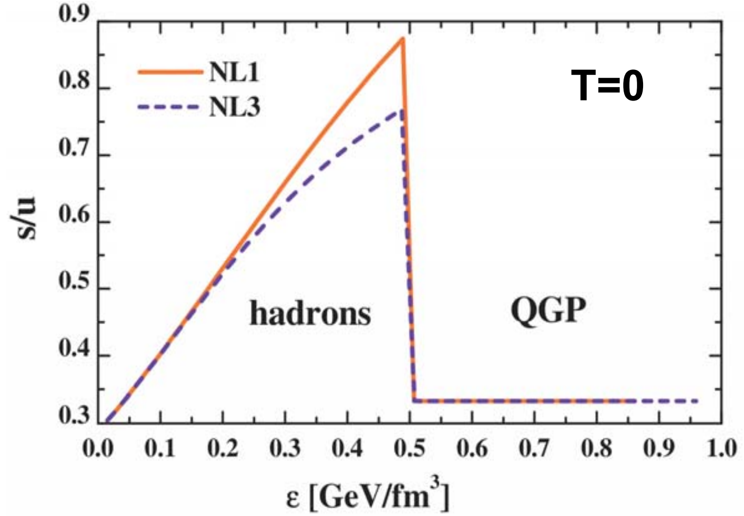
- As a consequence of the chiral symmetry restoration (CSR), the strangeness production probability increases with the local energy density ε.

scalar quark condensate $\langle q\bar{q}\rangle$ for NL3



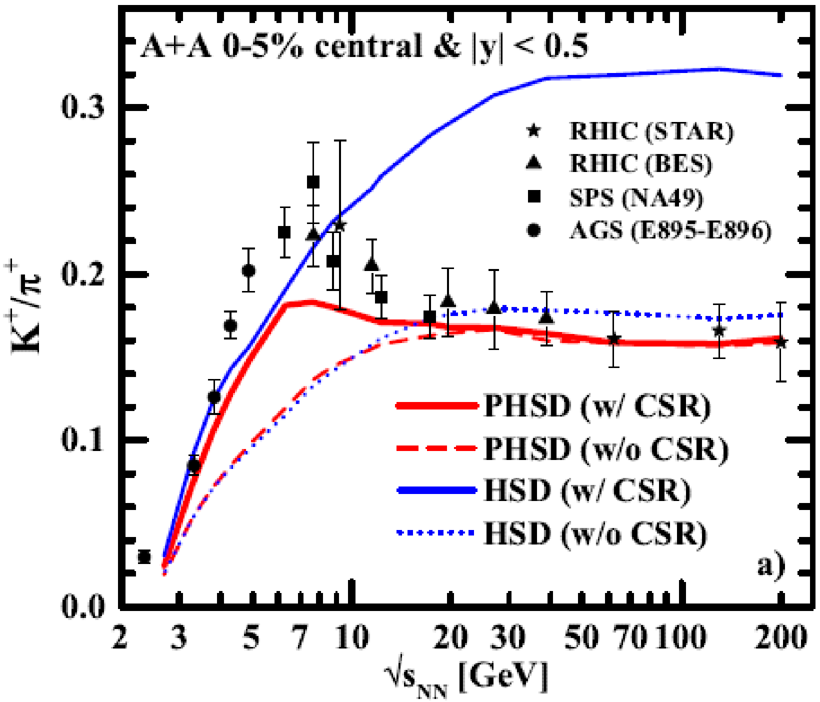


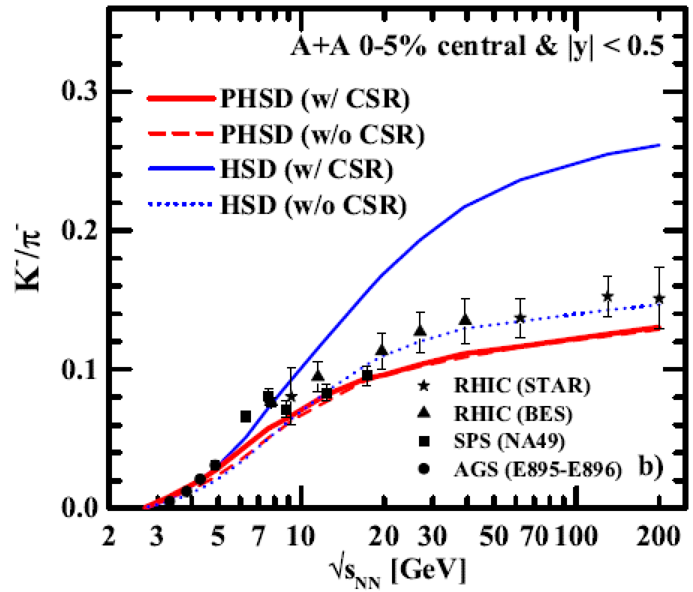
The strangeness ratio *s/u* in the string decay



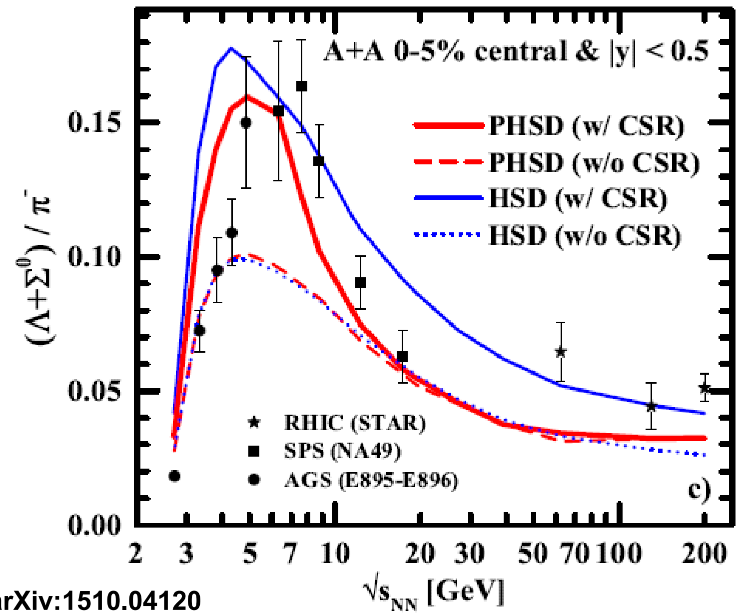
ε is the energy density of nuclear matter

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

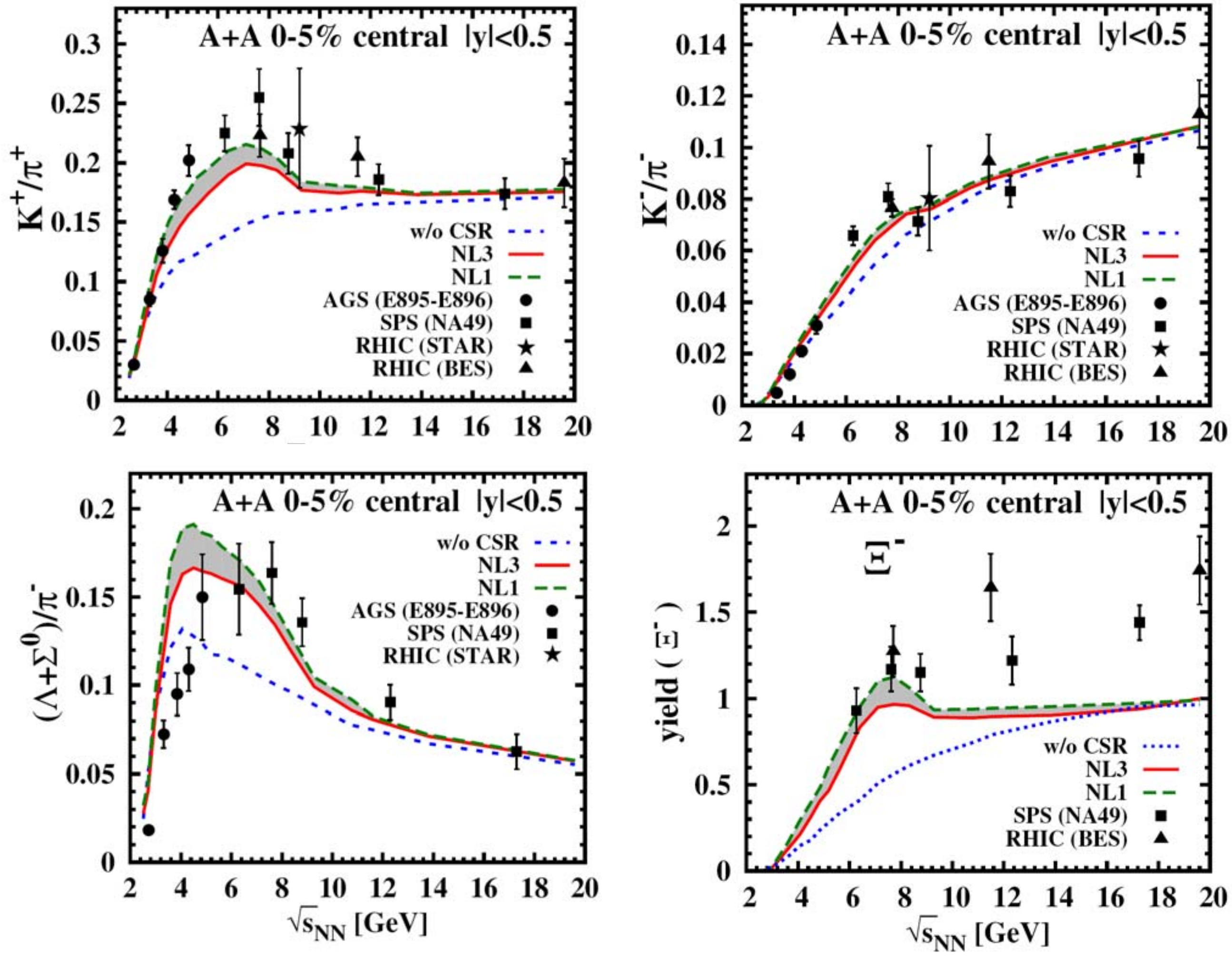


W. Cassing, A. Palmese, P. Moreau, E.L. Bratkovskaya, PRC 93, 014902 (2016), arXiv:1510.04120

Excitation function of hadron ratios

- Influence of EoS: NL1 vs NL3

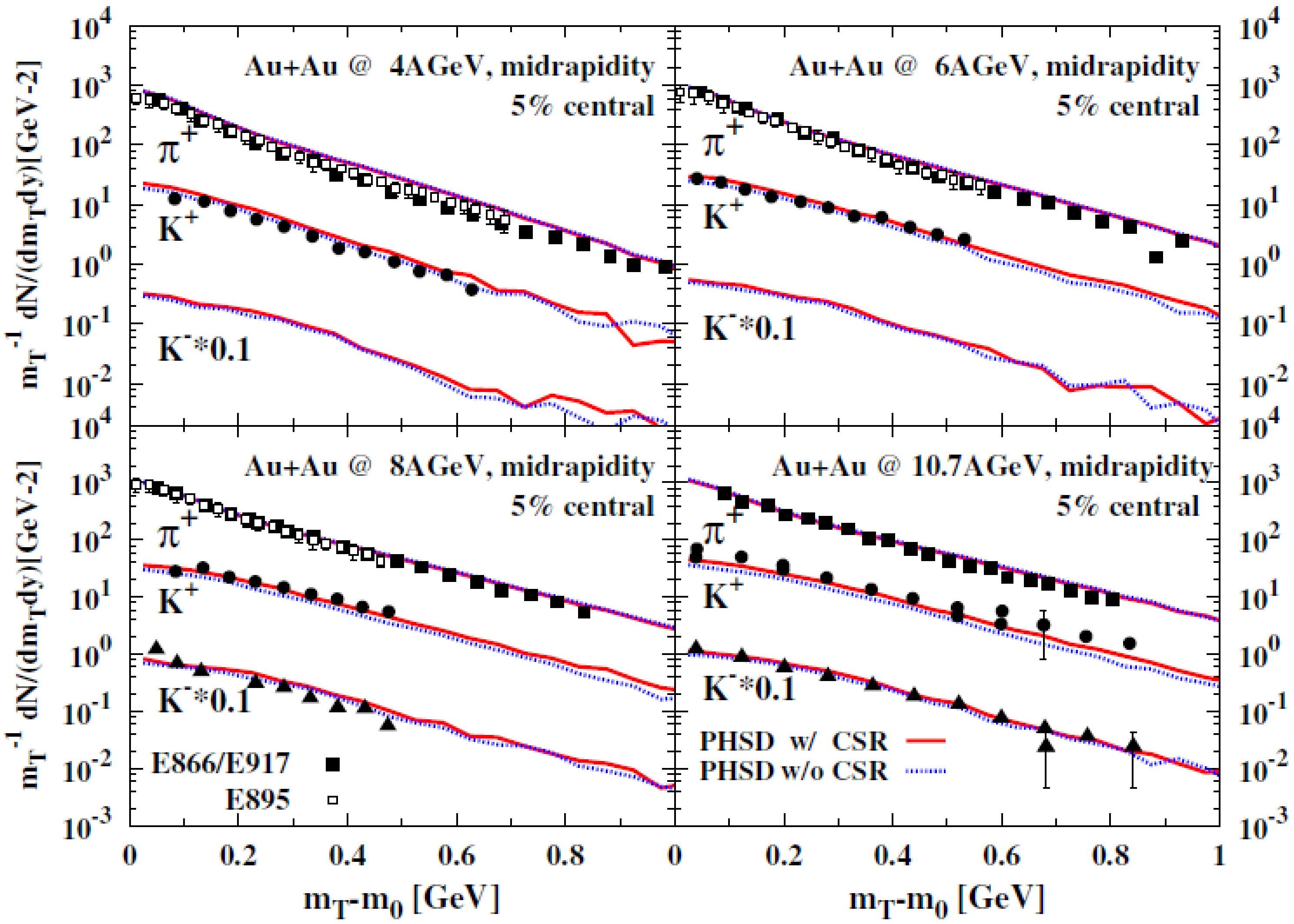
Alessia Palmese, Pierre Moreau:



→ **low sensitivity to the nuclear EoS**

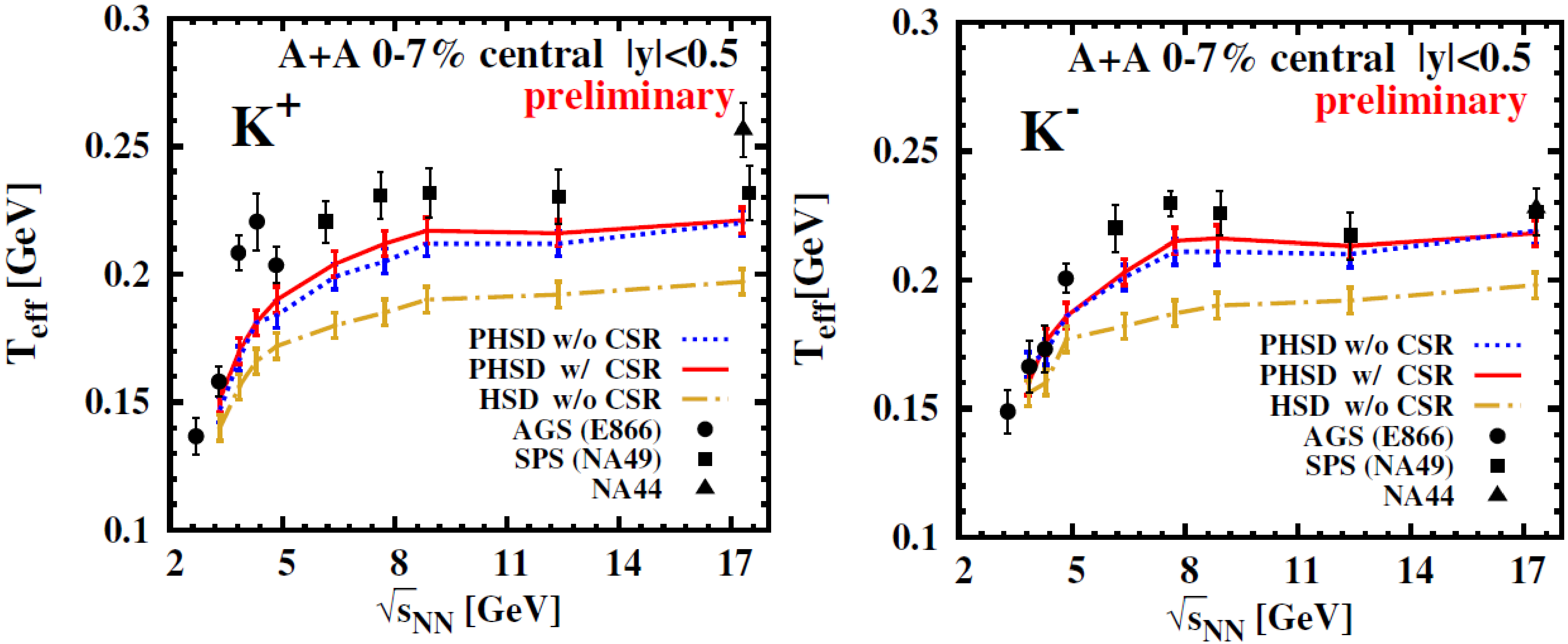
m_T spectra of pions and $K^{+/-}$

Alessia Palmese



Excitation function of T_{eff}

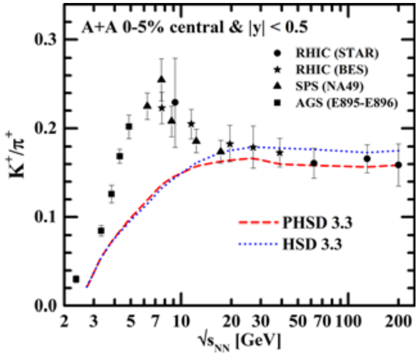
Alessia Palmese

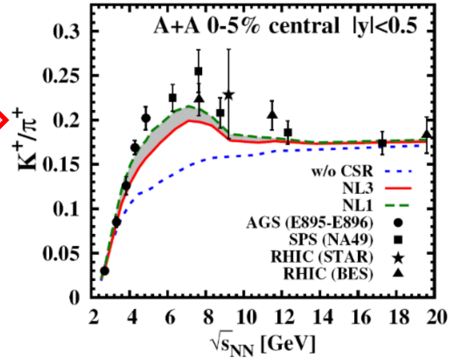


→ Increase of slope T_{eff} due to the QGP

→ Small effect of chiral symmetry restoration on slope Teff

Summary

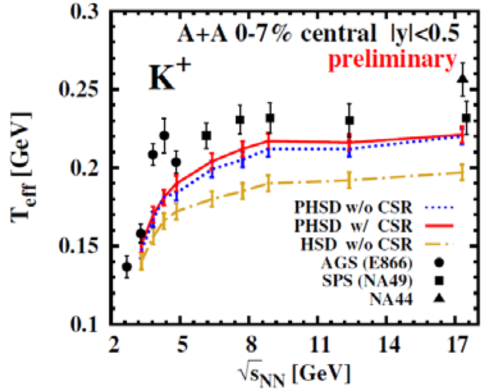




- The strangeness 'enhancement' ('horn') seen experimentally by NA49 and STAR at a bombarding energy ~20-30 A GeV (FAIR/NICA energies!) cannot be attributed to deconfinement

- 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

- Haderning of m_T spectra due to the QGP



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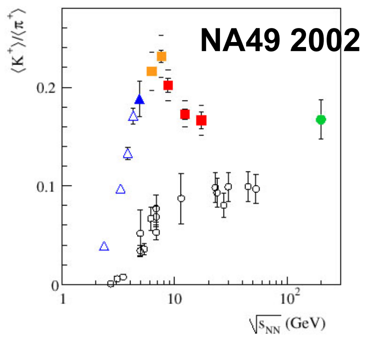
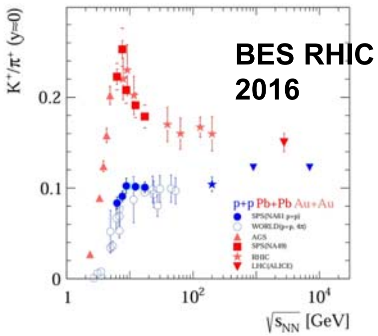
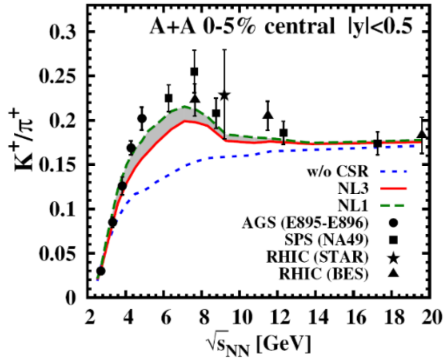
Happy birthday, dear Marek!







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