Phase transitions, chiral symmetries

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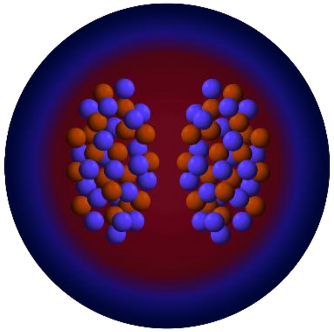
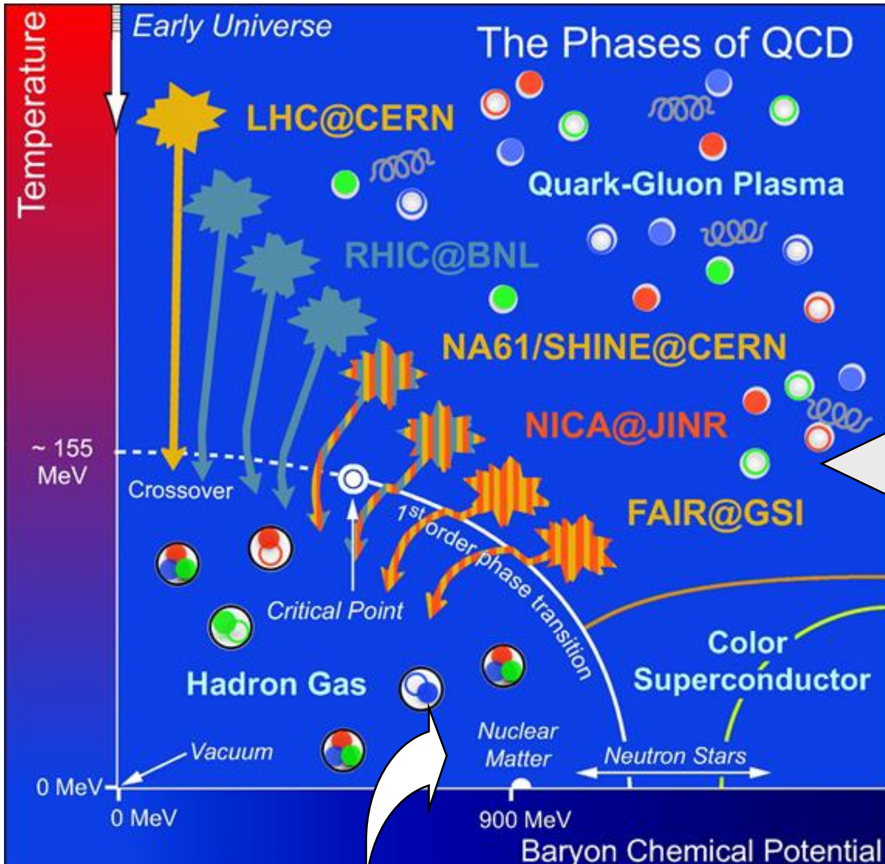
NA61++/SHINE: Physics opportunities from ions to pions

15-17 December, CERN

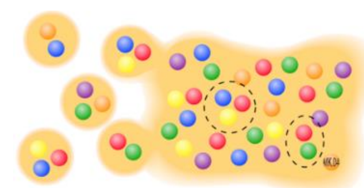


The ‚holy grail‘ of heavy-ion physics:

The phase diagram of QCD → thermal properties of QCD in the (T, μ_B) plain



- Equation-of-State of hot and dense matter?
- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma



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

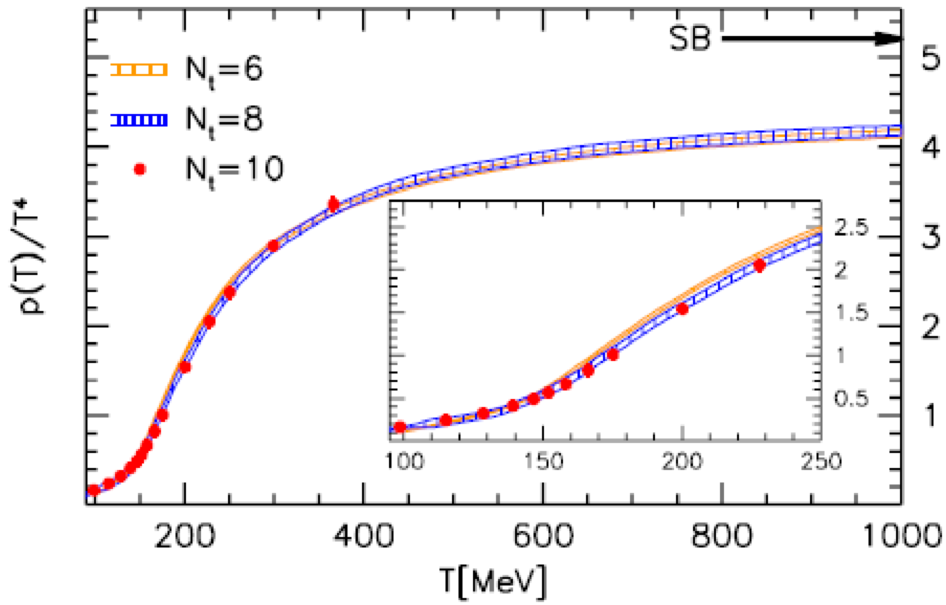
Information from lattice QCD

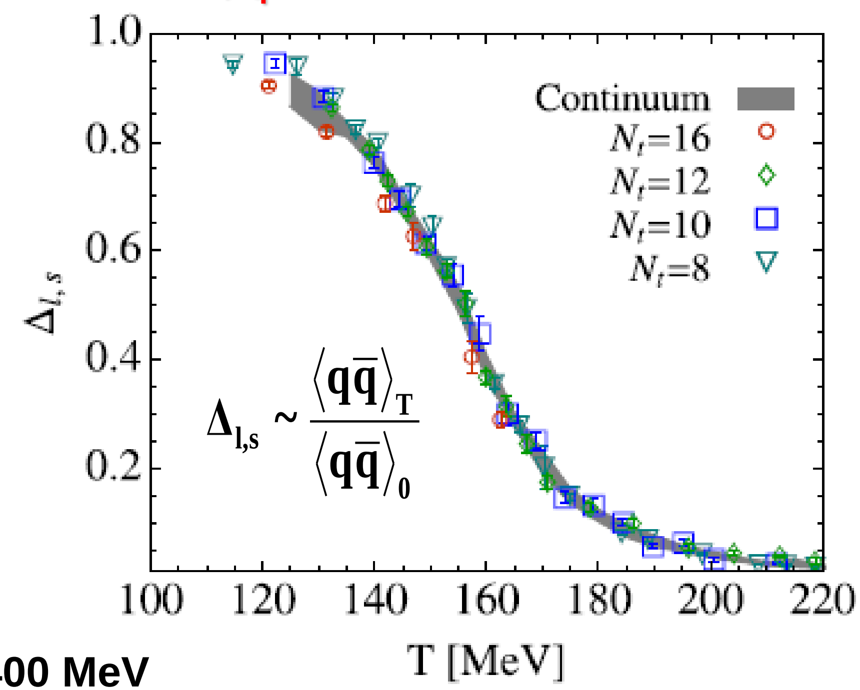
I. deconfinement phase transition
with increasing temperature

+

II. chiral symmetry restoration
with increasing temperature

lQCD BMW collaboration: μ_q=0





- **Crossover: hadron gas → QGP - up to μ_B < 400 MeV**
- **Scalar quark condensate $\langle q\bar{q}\rangle$ is viewed as an order parameter for the restoration of chiral symmetry:**

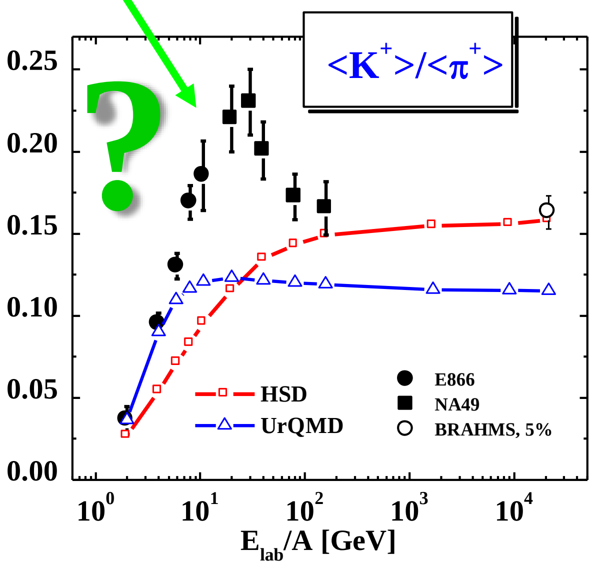
$$<\bar{q}q>= \begin{cases} \neq 0 & \text{chiral non-symmetric phase;} \\ = 0 & \text{chiral symmetric phase.} \end{cases}$$

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

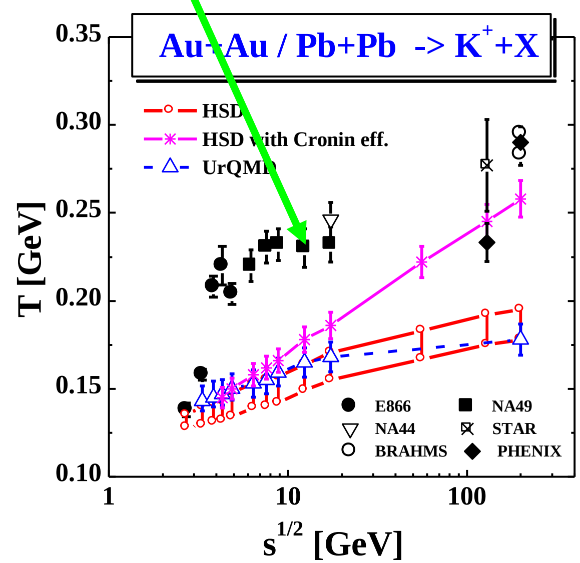
Signals for the phase transition

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

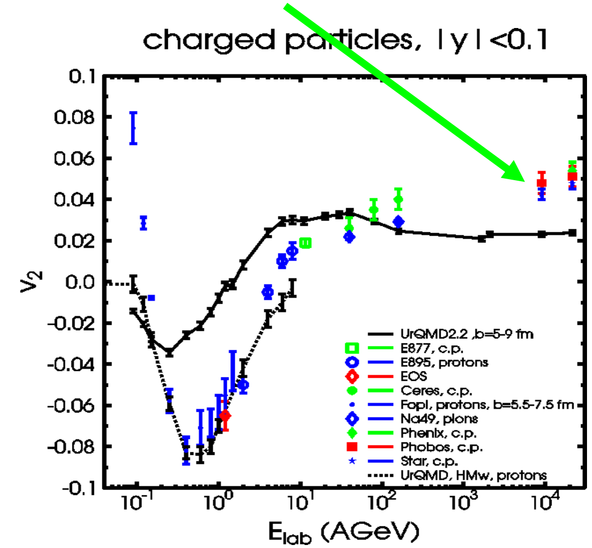
❑ ‚horn' in K^+/π^+



❑ ‚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

2004-2022

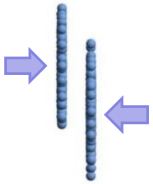
The tool: PHSD approach

Parton-Hadron-String-Dynamics (PHSD)

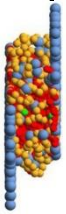
PHSD is a **non-equilibrium microscopic transport approach** for the description of **strongly-interacting hadronic and partonic matter** created in heavy-ion collisions

Dynamics: based on the solution of **generalized off-shell transport equations** derived from Kadanoff-Baym many-body theory

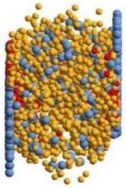
Initial A+A collision



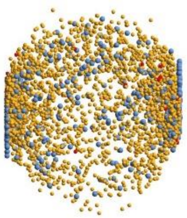
Partonic phase



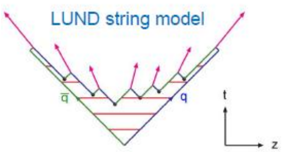
Hadronization



Hadronic phase

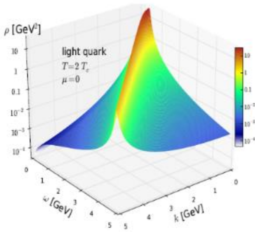


- ❑ **Initial A+A collisions** :
  N+N → string formation → decay to pre-hadrons + leading hadrons

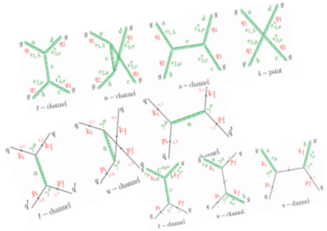


- ❑ **Formation of QGP stage** if local $\varepsilon > \varepsilon_{critical}$:
  dissolution of pre-hadrons → partons

- ❑ **Partonic phase - QGP:**
  QGP is described by the Dynamical QuasiParticle Model (DQPM)
  matched to reproduce lattice QCD EoS for finite T and μ_B (crossover)

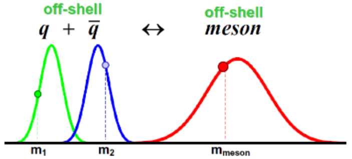


- Degrees-of-freedom: strongly interacting quasiparticles: massive quarks and gluons (g,q,q_{bar}) with sizeable collisional widths in a self-generated mean-field potential



- Interactions: (quasi-)elastic and inelastic collisions of partons

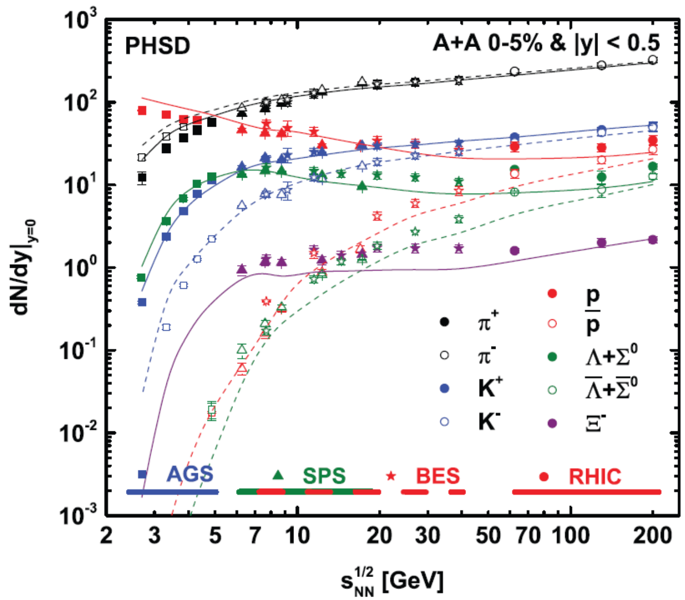
- ❑ **Hadronization** to colorless off-shell mesons and baryons:
  Strict 4-momentum and quantum number conservation



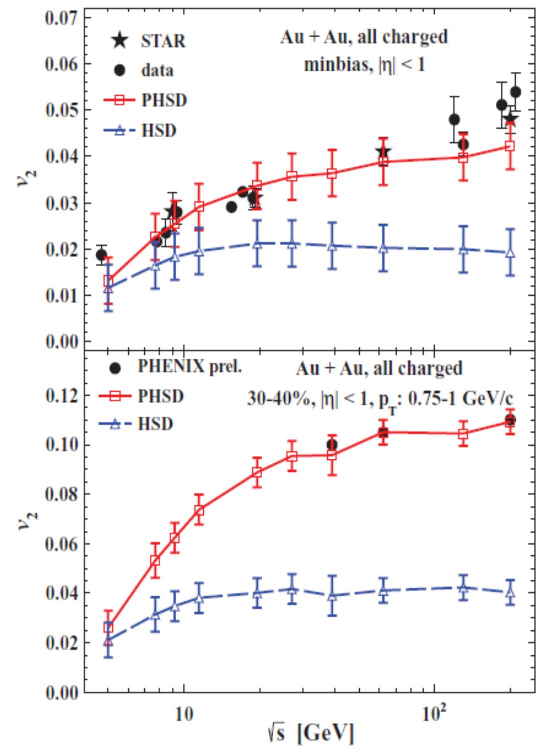
- ❑ **Hadronic phase: hadron-hadron interactions – off-shell HSD**

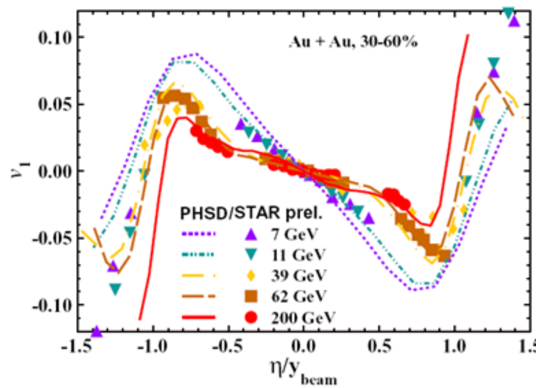
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

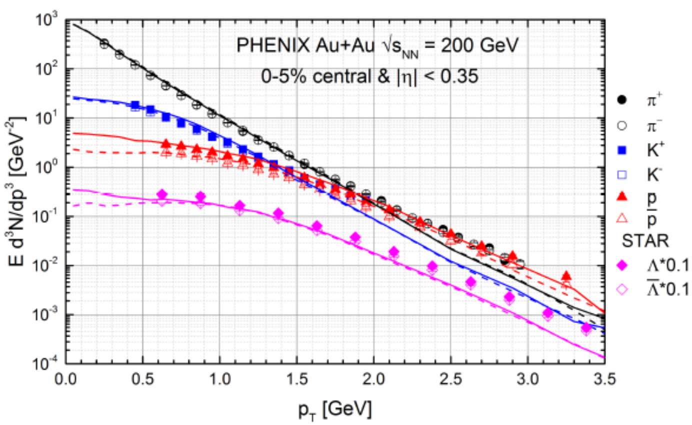
Non-equilibrium dynamics: description of A+A with PHSD

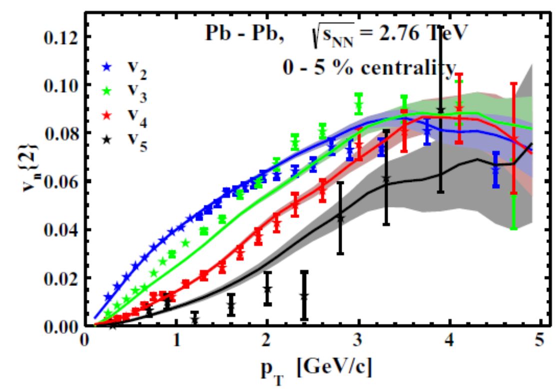


PHSD: highlights









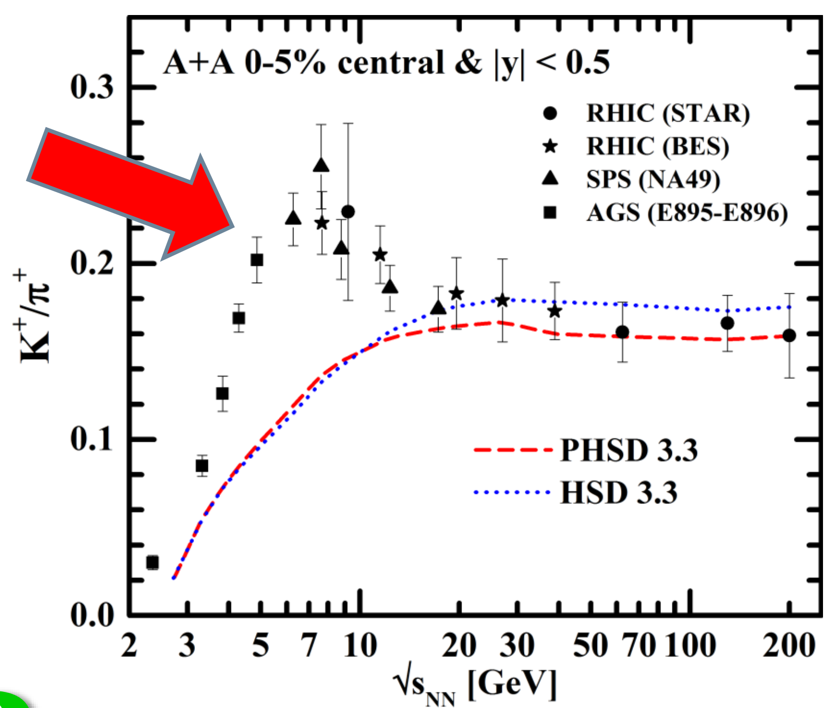
V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106; Astr. Nachr. 342 (2021) 715

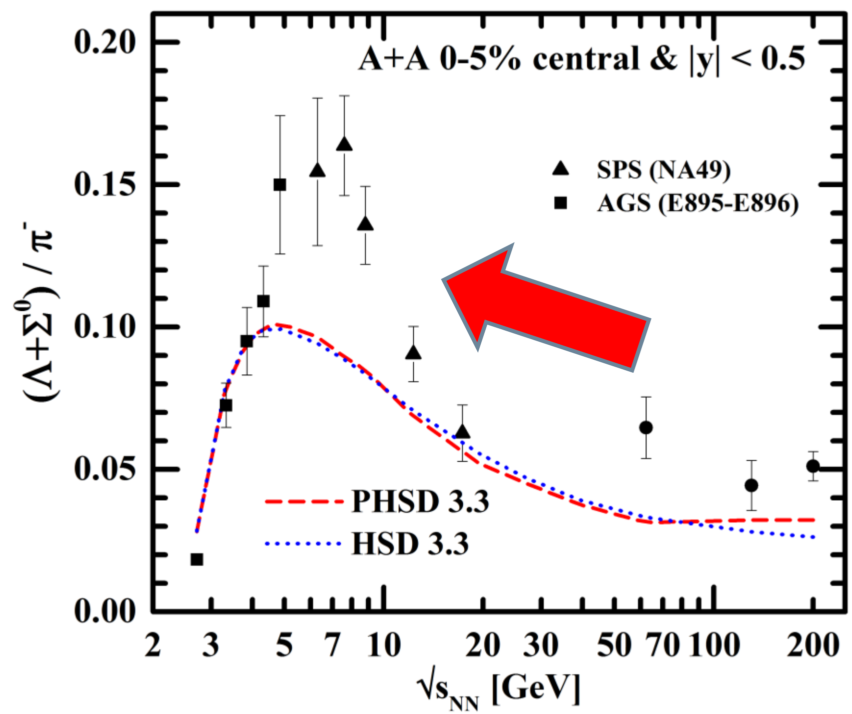
❑ PHSD provides a good description of ‚bulk' observables (y-, p_T-distributions, flow coefficients v_n, …) from SIS to LHC

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 ?!**



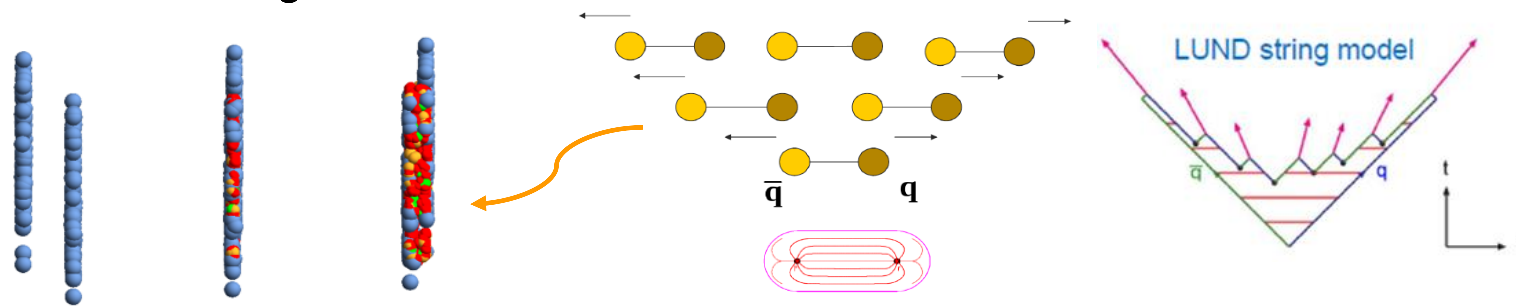


? Can it be related to chiral symmetry restoration in the hadronic phase?!

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:

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

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

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

➔ **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**:

$$m_q^* = m_q^0 - g_s < q\bar{q} >$$

$$(q = u, d, s)$$

⇓

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

* 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.

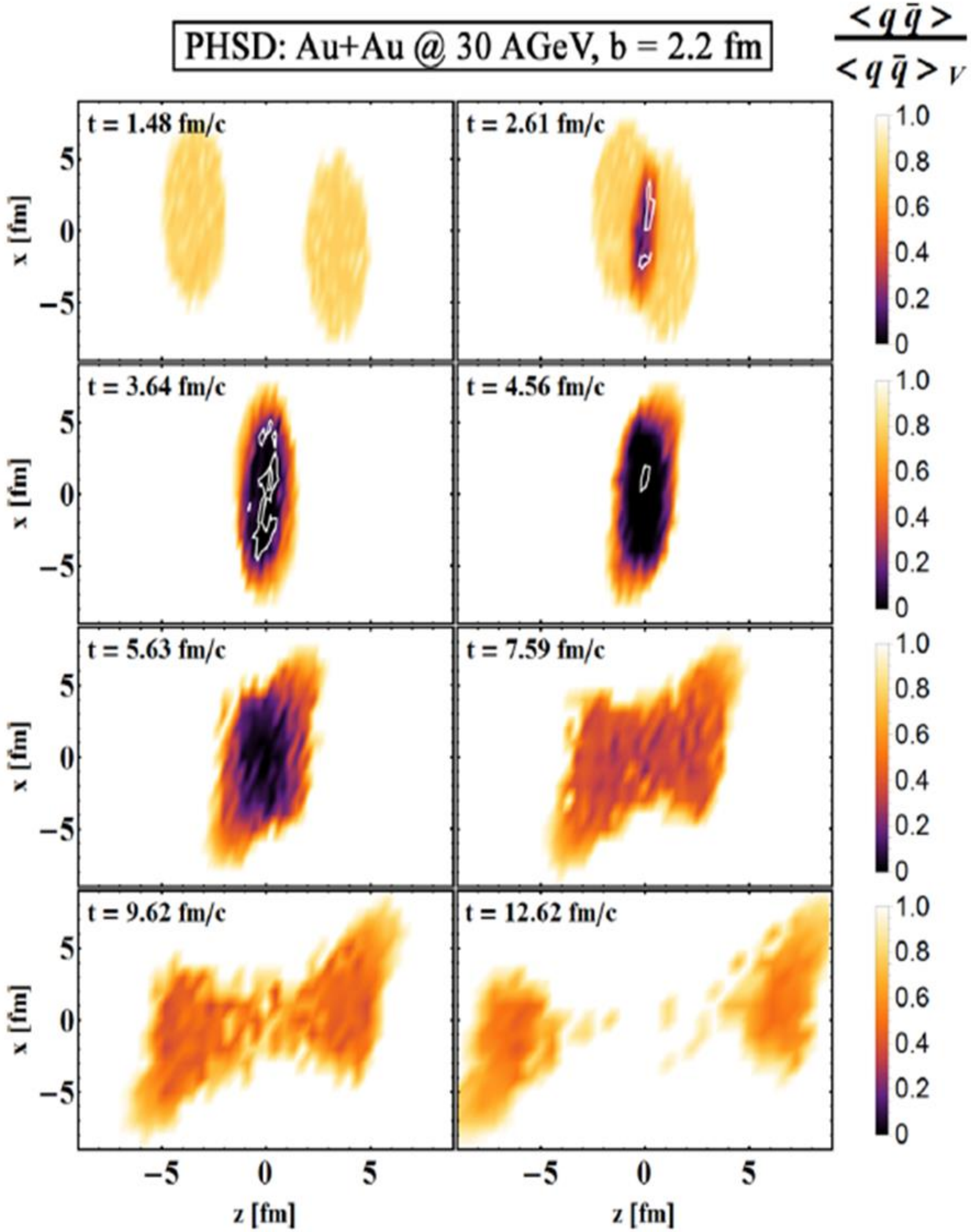
2) ρ_s^h is the scalar density of mesons of type *h* ➔ from PHSD

Scalar quark condensate in HIC

PHSD:
Ratio of the scalar quark condensate

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

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

Chiral symmetry restoration vs. deconfinement

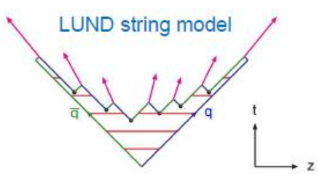
I. Initial stage of HIC collisions:

Hadronic matter ➔ string formation

II. QGP

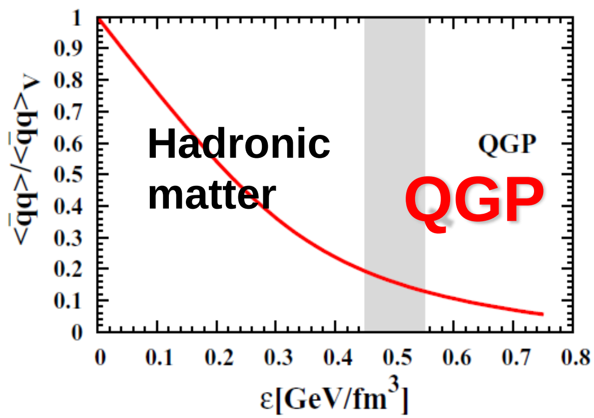
(time-like partons, explicit partonic interactions)

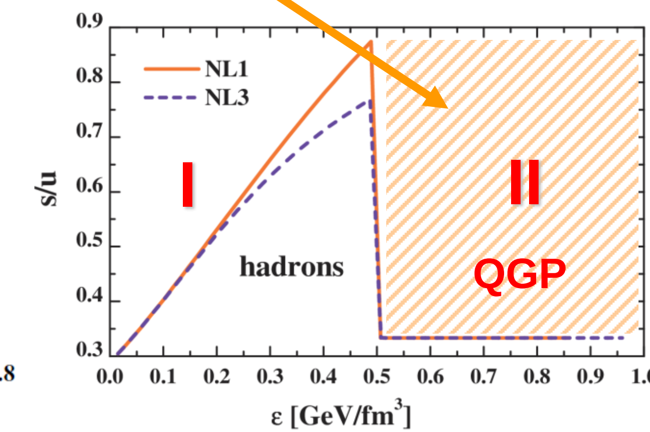
III. Hadronic phase



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

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





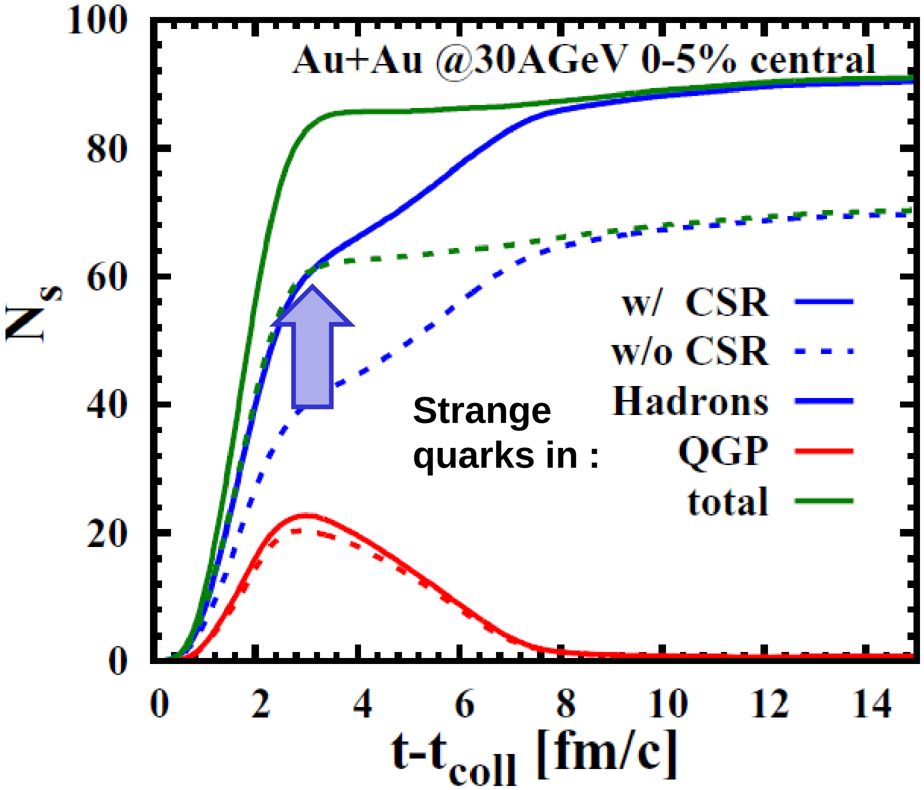
- **Chiral symmetry restoration via Schwinger mechanism (and non-linear $\sigma - \omega$ model) changes the „flavour chemistry" in string fragmentation (1PI):**

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

➔ the strangeness production probability increases with the local energy density ε (up to ε_C) due to the partial chiral symmetry restoration!

Time evolution of strangeness

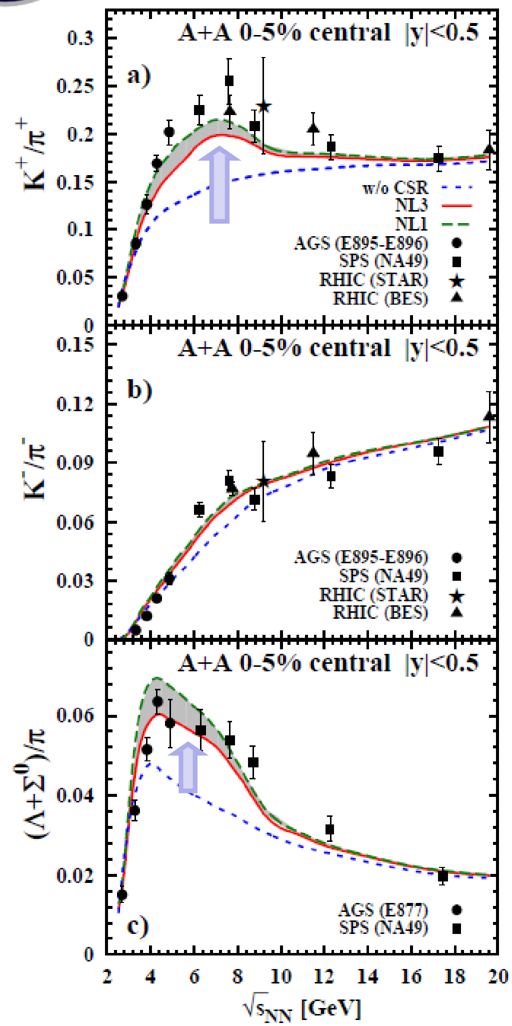
The strange quark number N_s as a function of time in 5% central Au+Au collision at 30 AGeV

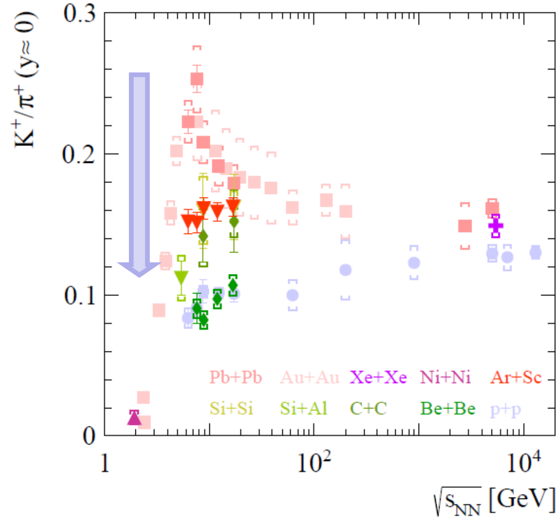


Chiral symmetry restoration leads to the enhancement of strangeness production during the string fragmentation in the beginning of HIC in the hadronic phase

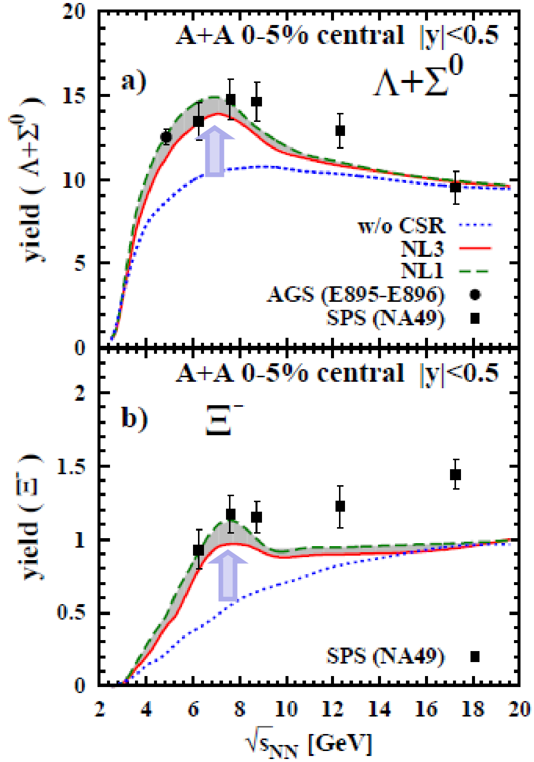
Excitation function of hadron ratios and yields

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





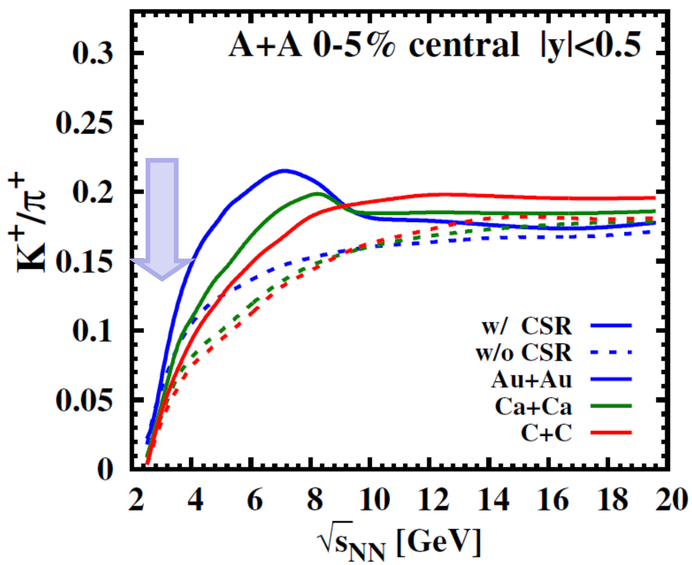
$K^+(u\bar{s})$
$K^-(s\bar{u})$
$\Lambda\,(uds)$

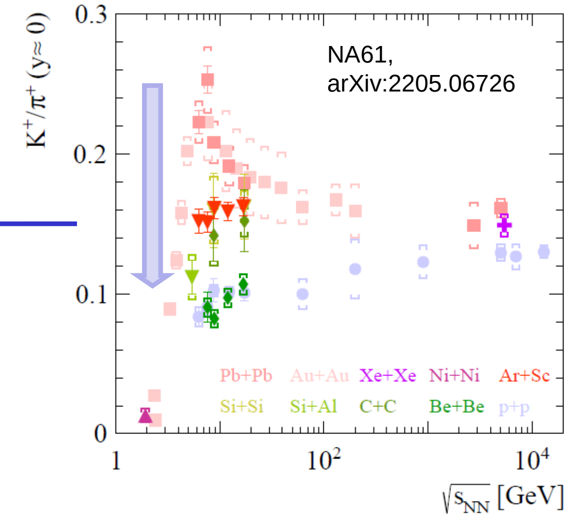


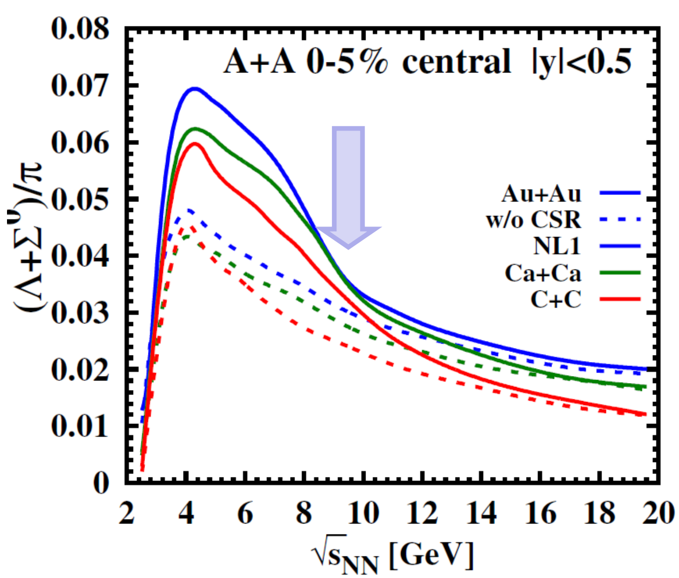
- Influence of EoS: NL1 vs NL3 ➔ low sensitivity to the nuclear EoS
- Excitation function of the hyperons $\Lambda+\Sigma^0$ and Ξ^- show analogous peaks as K^+/π^+, $(\Lambda+\Sigma^0)/\pi$ ratios due to CSR

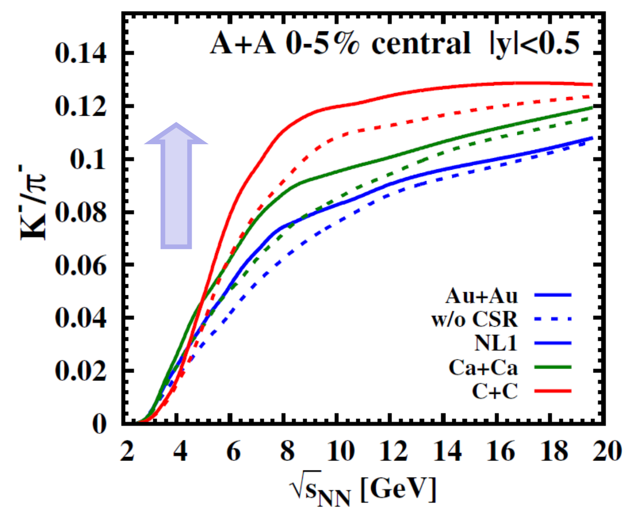
Chiral symmetry restoration leads to the enhancement of strangeness production in string fragmentation in the beginning of HICs in the hadronic phase.
➔The „horn“ structure is due to the interplay between CSR and deconfinement (QGP)

Sensitivity to the system size: A+A collisions









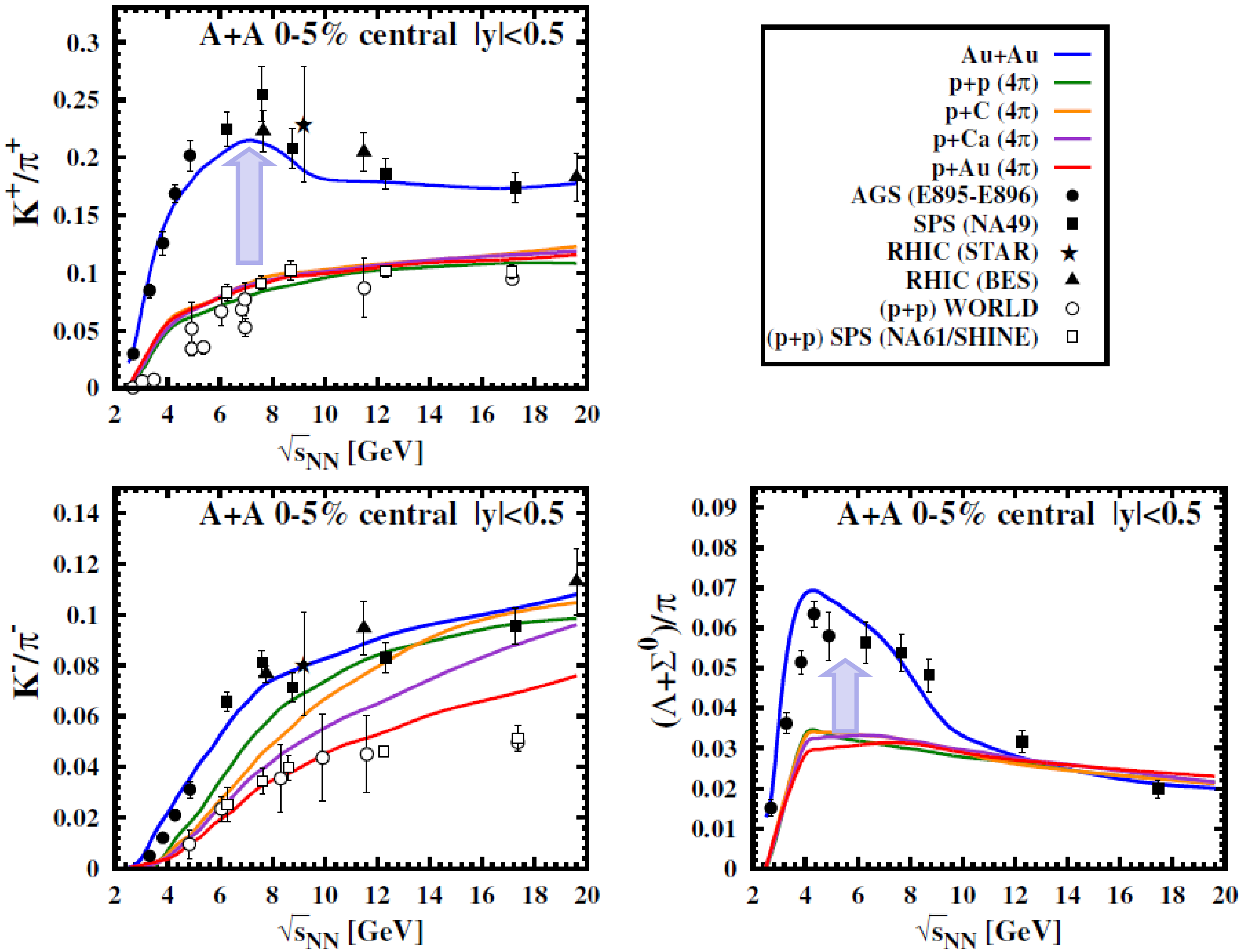
If the system size is smalle

- 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

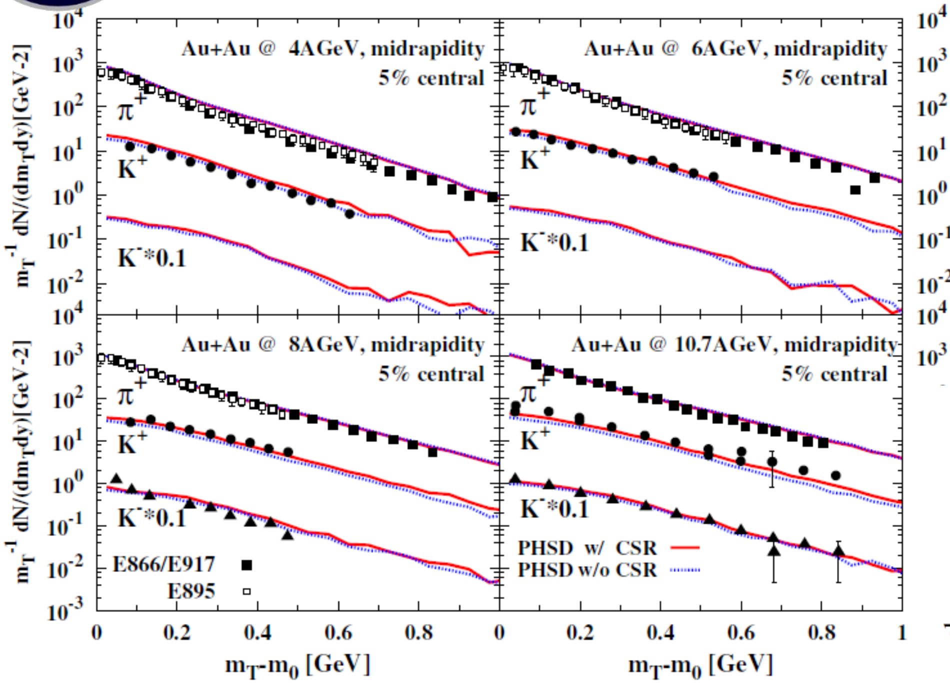
Sensitivity to the system size: p+A collisions

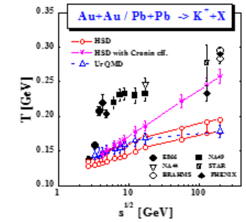
- In p+A collisions strange to non-strange particle ratios show no peaks



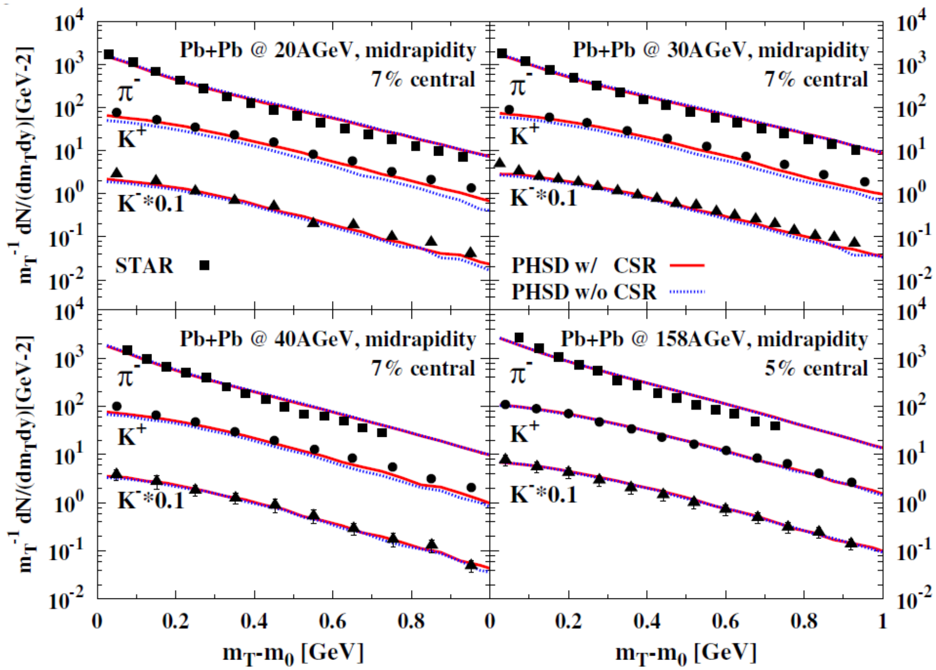
A. Palmese et al., PRC94 (2016) 044912 , arXiv:1607.04073

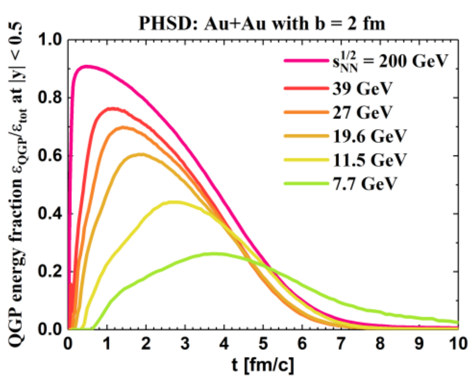
m_T spectra of pions and $K^{+/-}$ at AGS-SPS energies





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

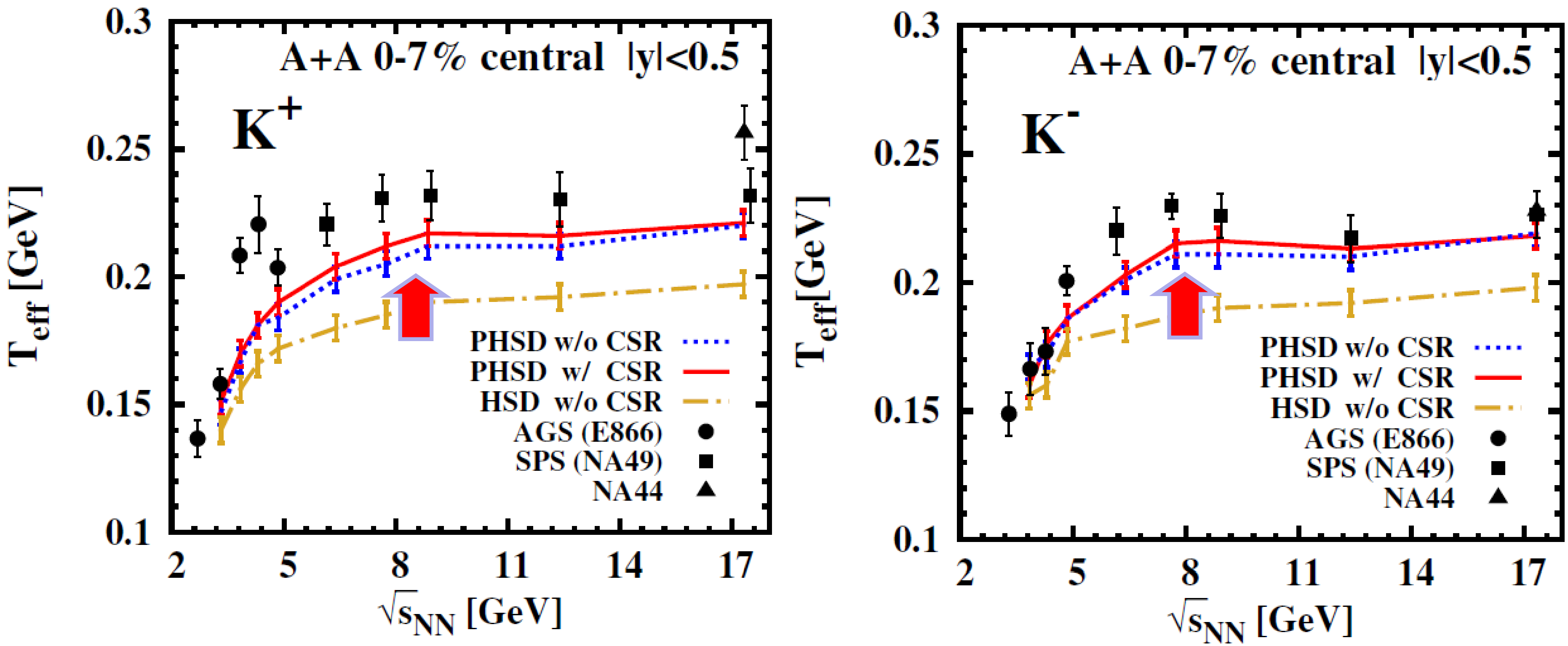




→ **Hardening of m_T spectra** of pions and kaons with increasing beam energy due to the growing fraction of the **QGP**

Excitation function of T_{eff}

Alessia Palmese

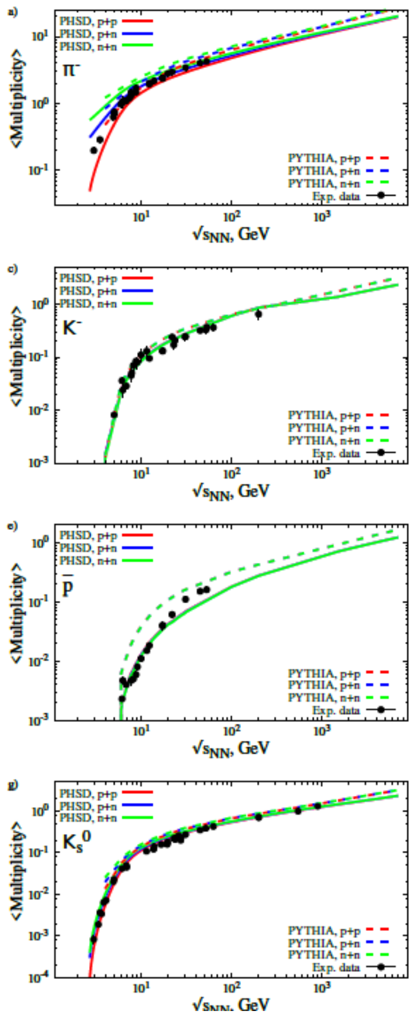


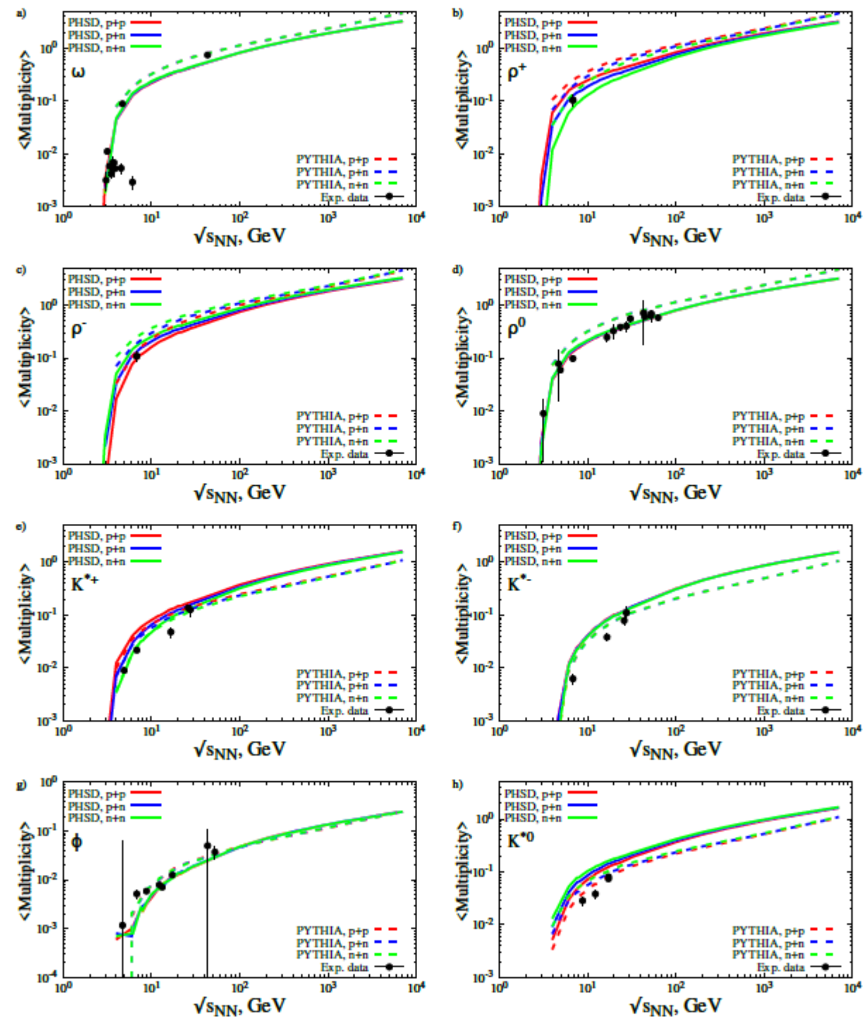
→ Increase of slope T_{eff} due to the QGP
→ Small effect of chiral symmetry restoration on slope Teff

Elementary p+p, p+n reactions: PHSD “tune” of LUND model (PYTHIA, FRITIOF)

V. Kireyeu, I. Grishmanovskii, V. Kolesnikov, V. Voronyuk, and E. B.,
Eur.Phys.J.A 56 (2020) 223; e-Print:2006.14739 [hep-ph]

Elementary reactions p+p, p+n, n+n



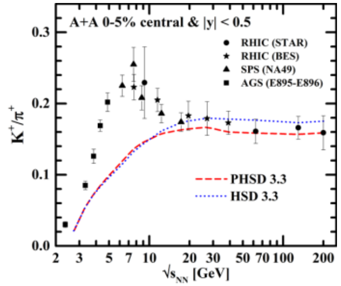


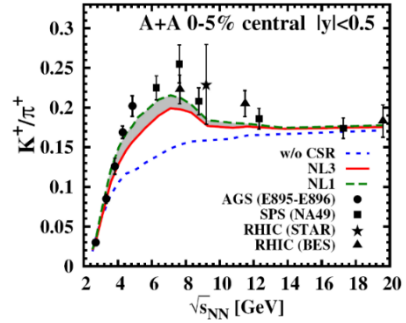
- Existing experimental data on p+p are pure
  Practically NO data on p+n reactions

V. Kireyeu et al., Eur.Phys.J.A 56 (2020) 223

➔ NA61++ can improve the situation with p+p data

Summary



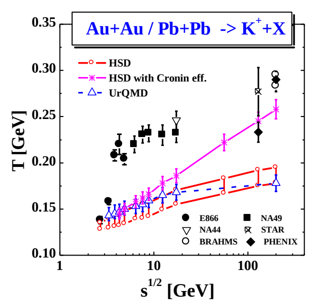


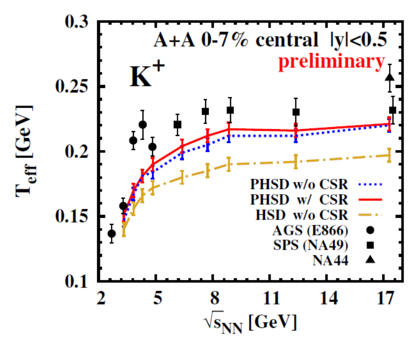
- The strangeness 'enhancement' ('horn') seen experimentally by NA49 and STAR at a bombarding energy ~20-30 A GeV (FAIR/NICA energies!) cannot be attributed only to the deconfinement

- 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 QGP medium

➔ the ‚horn' structure is due to the interplay between CSR and deconfinement (QGP)

- Hardening of m_T spectra due to the QGP



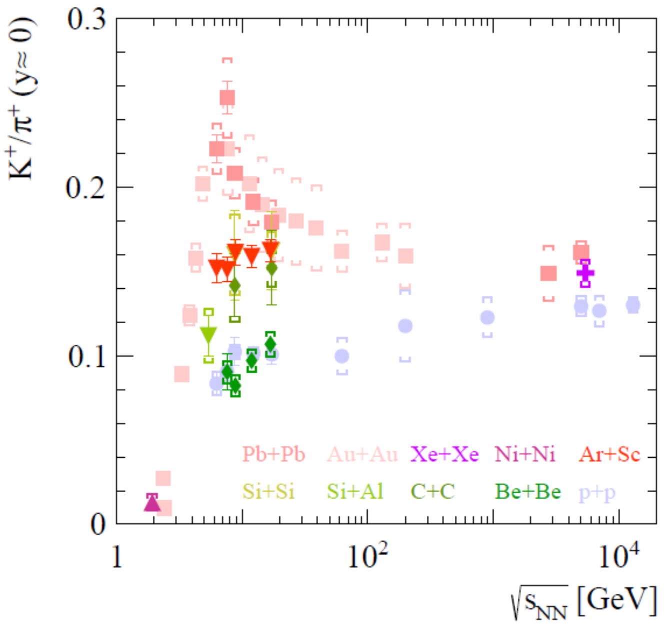


Outlook

HIC's:

- **Explore experimentally different strangeness observables: yields, ratios K^+/π^+, K^-/π^- and $(\Lambda+\Sigma^0)/\pi$ as well as y- and p_T – distributions and flow harmonics v_n**
  - **from heavy A+A to light A+A**
  - **for p+A**

➔ system size scan



- **The experimental data on p+p and p+n are needed!**

- **Cosmic rays:**
  can help to understand meson+baryon reactions (which are secondary elementary reactions in HIC's)
  ➔ study K^- + A, π^- +A reactions

NA61++/SHINE data are needed!