

EVIDENCE FOR CHIRAL SYMMETRY RESTORATION IN HEAVY-ION COLLISIONS

Pierre Moreau

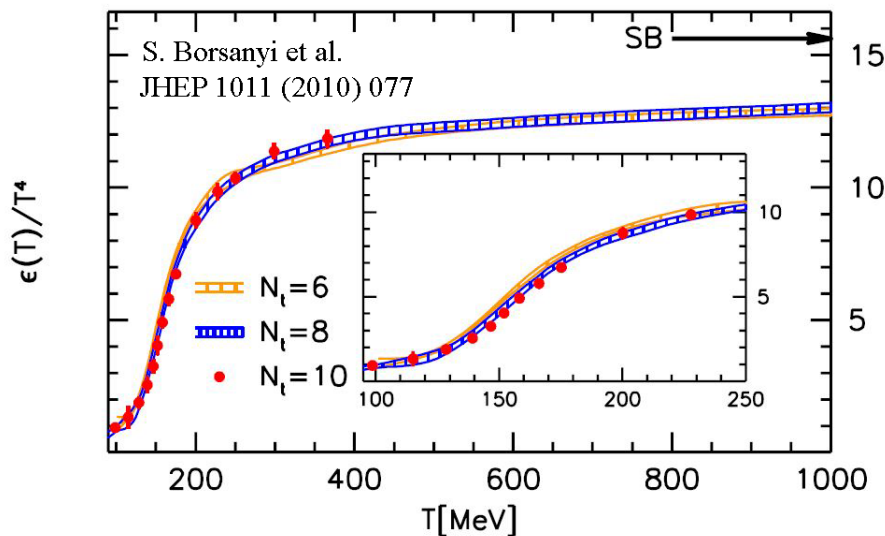
for the PHSD group



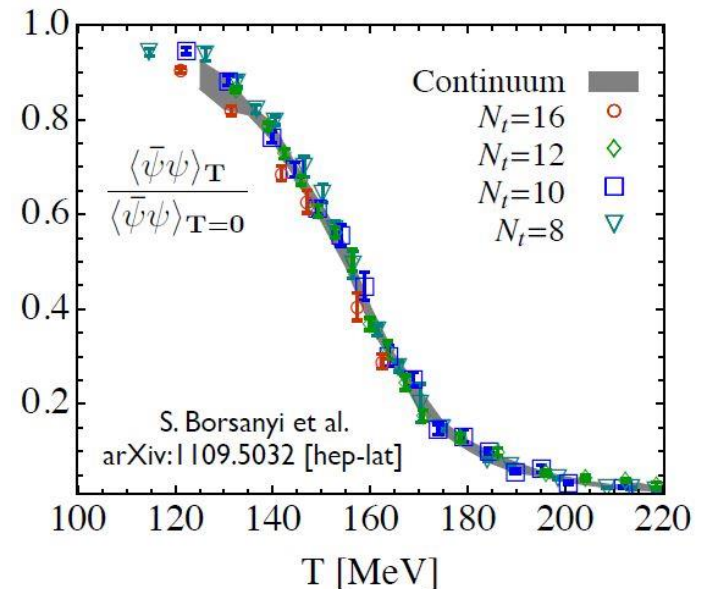
Quark Matter 2017, Chicago IL, USA

Information from lattice QCD

- **Deconfinement phase transition with increasing temperature**



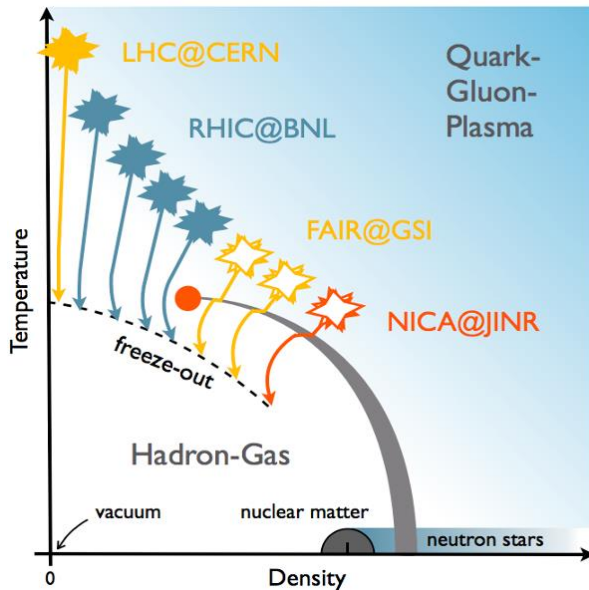
- **Chiral symmetry restoration with increasing temperature**



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

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

Dynamical description of heavy-ion collisions



- **Goal:** Study the properties of **strongly interacting matter** under extreme conditions from a **microscopic point of view**
- **Realization:** dynamical many-body transport approach

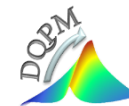
Parton-Hadron-String-Dynamics (PHSD)

- **Transport theory:** off-shell transport equations in phase-space representation based on **Kadanoff-Baym equations** for the **partonic** and **hadronic phase**



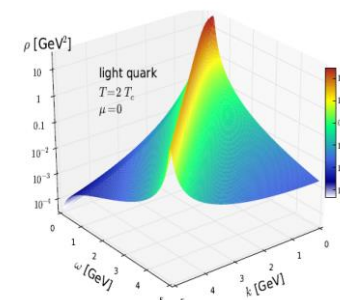
W.Cassing, E.Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W.Cassing, EPJ ST 168 (2009) 3

Dynamical Quasi-Particle Model (DQPM)

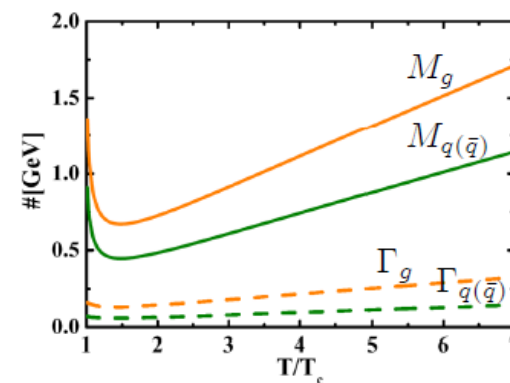
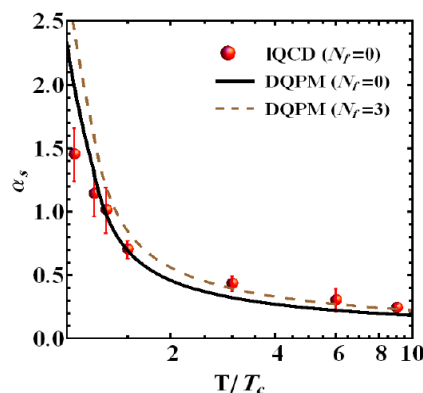
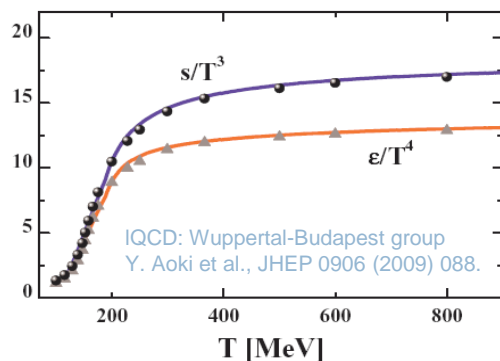


- The QGP phase is described in terms of **interacting quasiparticles: quarks and gluons** with Lorentzian spectral functions:

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



- Properties of quasiparticles (**large widths and masses**) are fitted to the lattice QCD results

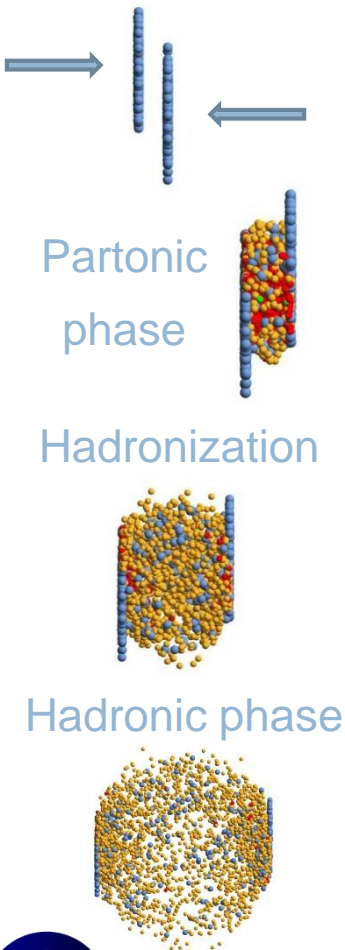


- DQPM provides **mean-fields (1P1)** for quarks and gluons as well as **effective 2-body interactions (2P1)**

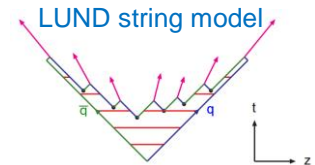
Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365; NPA 793 (2007)

Stages of a collision in PHSD

Initial A+A collision

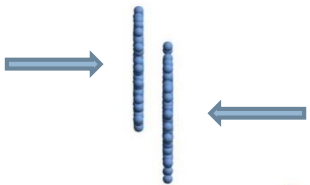


- String formation in primary NN collisions
→ decays to pre-hadrons (baryons and mesons)

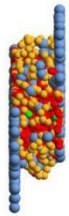


Stages of a collision in PHSD

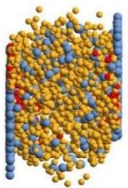
Initial A+A
collision



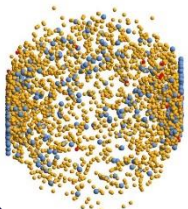
Partonic
phase



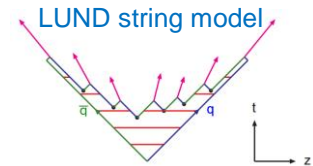
Hadronization



Hadronic phase

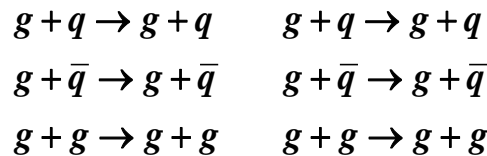


- String formation in primary NN collisions
→ decays to pre-hadrons (baryons and mesons)

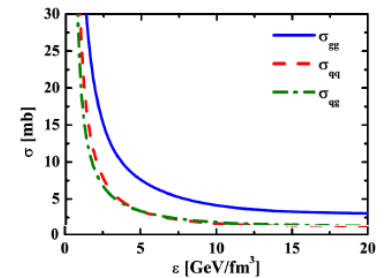
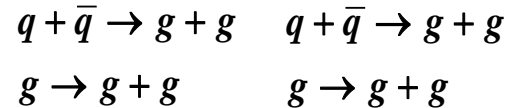


- Formation of a QGP state if $\epsilon > \epsilon_{critical}$:
Dissolution of pre-hadrons → DQPM
→ massive quarks/gluons and mean-field energy

(quasi-)elastic collisions :

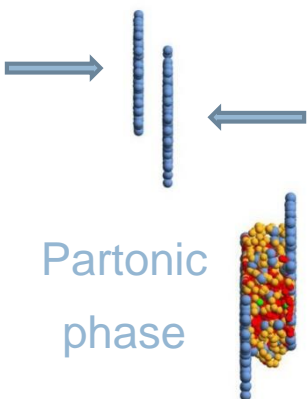


inelastic collisions :



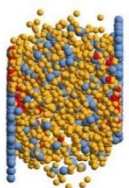
Stages of a collision in PHSD

Initial A+A
collision

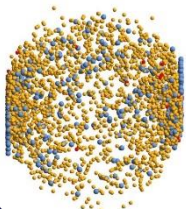


Partonic
phase

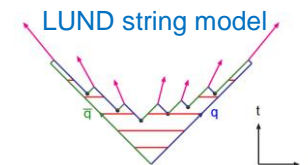
Hadronization



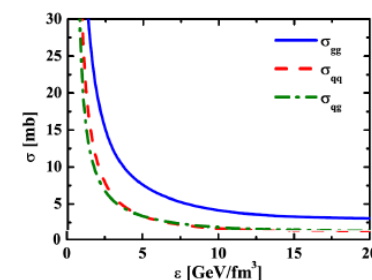
Hadronic phase



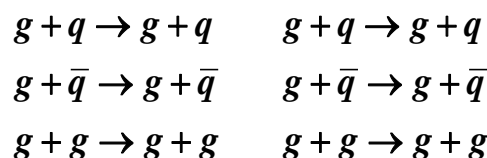
- **String formation** in primary NN collisions
→ **decays** to pre-hadrons (baryons and mesons)



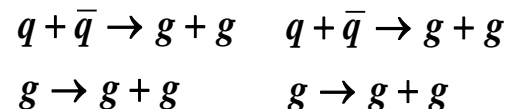
- **Formation of a QGP state** if $\epsilon > \epsilon_{critical}$:
Dissolution of pre-hadrons → DQPM
→ **massive quarks/gluons** and **mean-field energy**



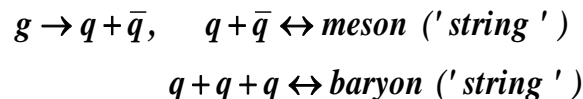
(quasi-)elastic collisions :



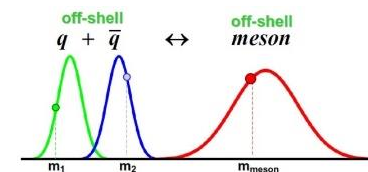
inelastic collisions :



- **Hadronization to colorless off-shell mesons and baryons**

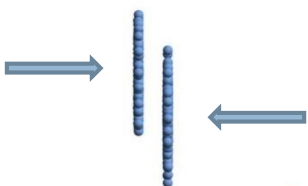


Strict 4-momentum and
quantum number conservation

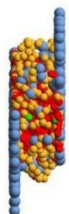


Stages of a collision in PHSD

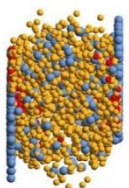
Initial A+A
collision



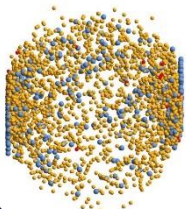
Partonic
phase



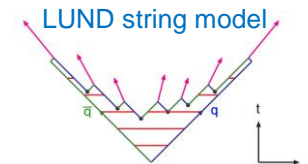
Hadronization



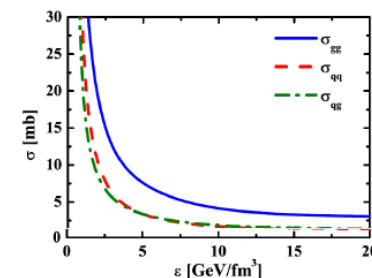
Hadronic phase



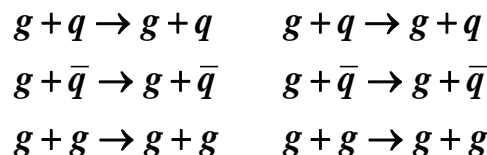
- String formation in primary NN collisions
→ decays to pre-hadrons (baryons and mesons)



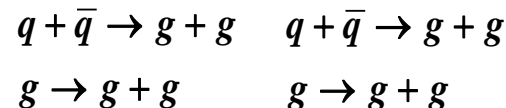
- Formation of a QGP state if $\epsilon > \epsilon_{critical}$:
Dissolution of pre-hadrons → DQPM
→ massive quarks/gluons and mean-field energy



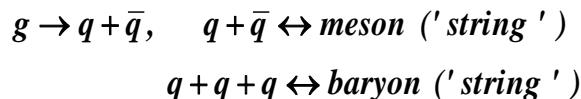
(quasi-)elastic collisions :



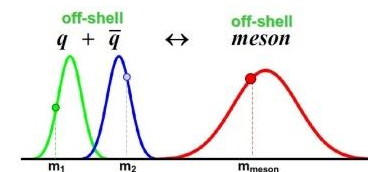
inelastic collisions :



- Hadronization to colorless off-shell mesons and baryons



Strict 4-momentum and
quantum number conservation



- Hadron-string interactions – off-shell HSD

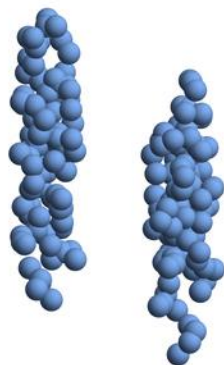
Stages of a collision in PHSD






$t = 0.15 \text{ fm}/c$



Au+Au @ 35 AGeV

b = 2.2 fm – Section view



-  Baryons (394)
-  Antibaryons (0)
-  Mesons (0)
-  Quarks (0)
-  Gluons (0)

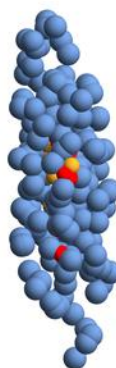
Stages of a collision in PHSD




$t = 2.55 \text{ fm}/c$



Au+Au @ 35 AGeV

b = 2.2 fm – Section view



-  Baryons (394)
-  Antibaryons (0)
-  Mesons (93)
-  Quarks (54)
-  Gluons (0)

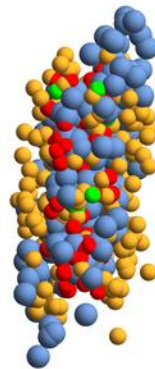
Stages of a collision in PHSD

$t = 5.25 \text{ fm}/c$



Au+Au @ 35 AGeV

b = 2.2 fm – Section view



-  Baryons (394)
-  Antibaryons (0)
-  Mesons (477)
-  Quarks (282)
-  Gluons (33)

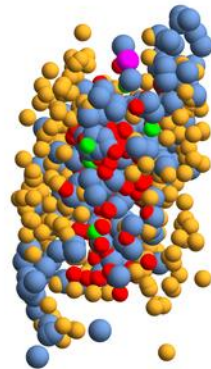
Stages of a collision in PHSD

$t = 6.55001 \text{ fm}/c$



Au+Au @ 35 AGeV

b = 2.2 fm – Section view



-  Baryons (397)
-  Antibaryons (3)
-  Mesons (554)
-  Quarks (199)
-  Gluons (20)

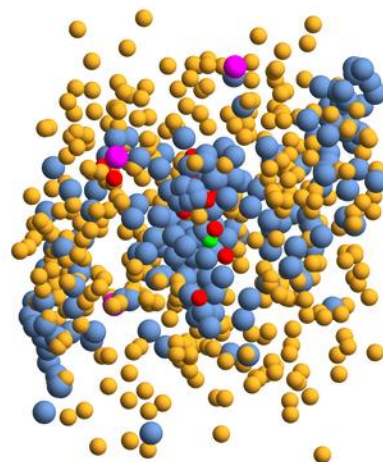
Stages of a collision in PHSD

$t = 10.45 \text{ fm}/c$



Au+Au @ 35 AGeV

b = 2.2 fm – Section view



-  Baryons (399)
-  Antibaryons (5)
-  Mesons (745)
-  Quarks (23)
-  Gluons (3)

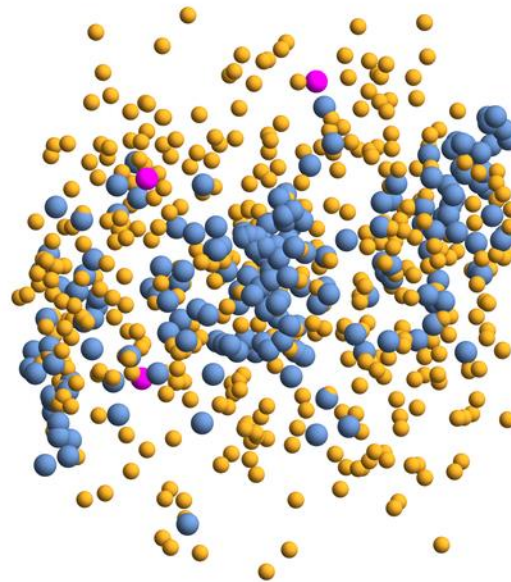
Stages of a collision in PHSD



$t = 13.55 \text{ fm}/c$



Au+Au @ 35 AGeV

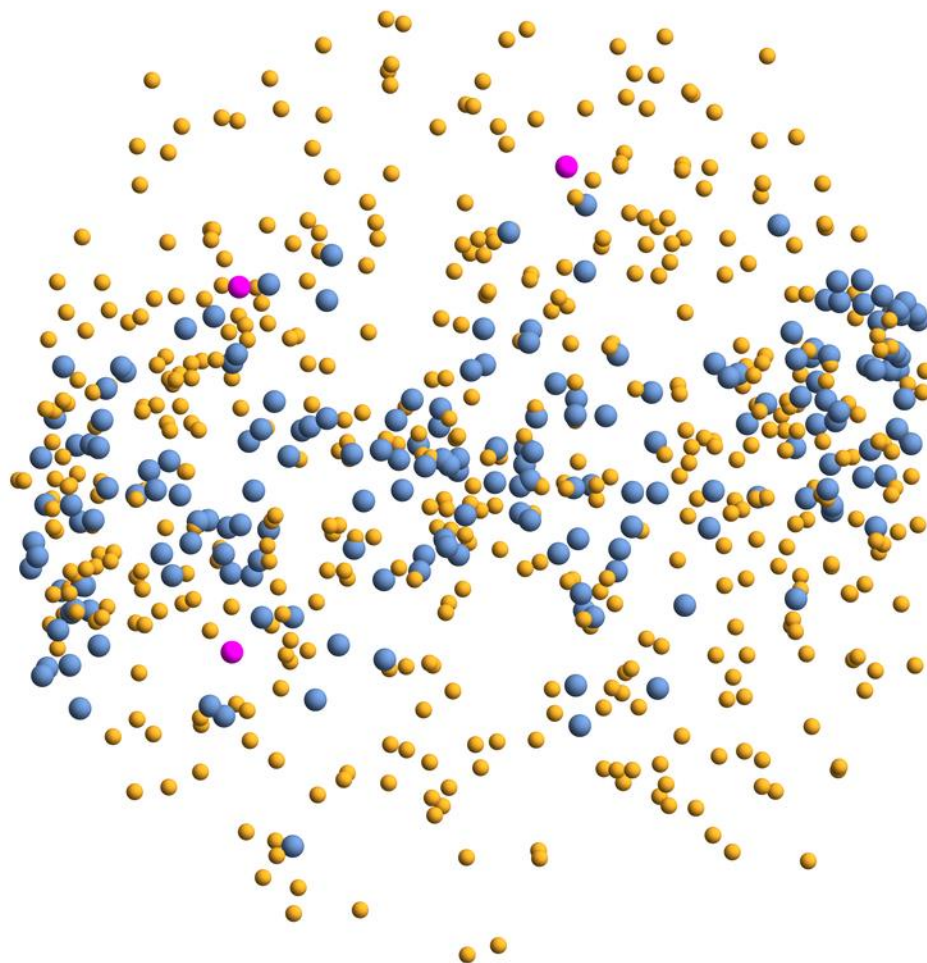
b = 2.2 fm – Section view



-  Baryons (399)
-  Antibaryons (5)
-  Mesons (817)
-  Quarks (0)
-  Gluons (0)






Stages of a collision in PHSD

$t = 23.0999 \text{ fm}/c$



Au+Au @ 35 AGeV

b = 2.2 fm – Section view

-  Baryons (399)
-  Antibaryons (5)
-  Mesons (947)
-  Quarks (0)
-  Gluons (0)


Stages of a collision in PHSD

$t = 37.6497 \text{ fm/c}$



Au+Au @ 35 AGeV

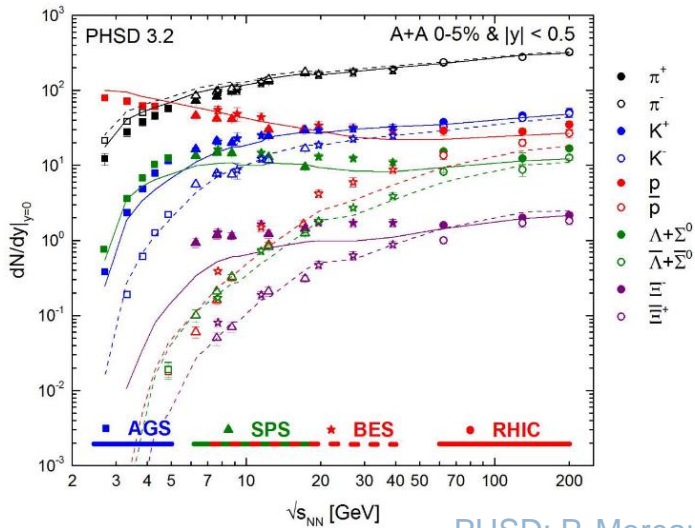
b = 2.2 fm – Section view

-  Baryons (399)
-  Antibaryons (5)
-  Mesons (1016)
-  Quarks (0)
-  Gluons (0)

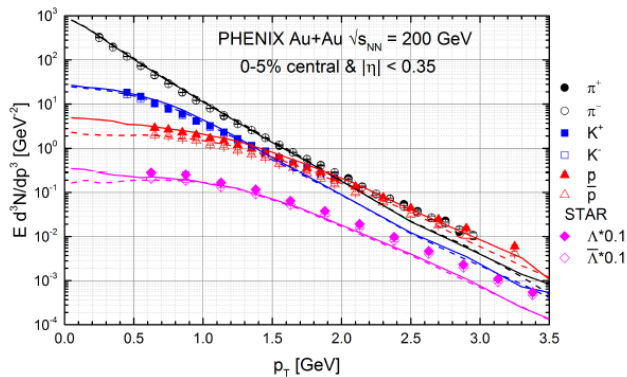
P. Moreau



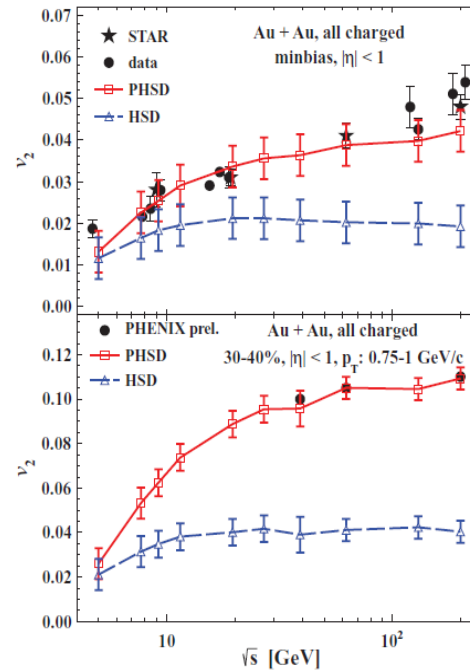
Description of A+A with PHSD



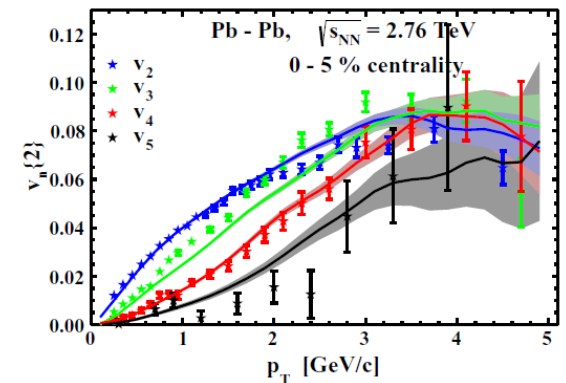
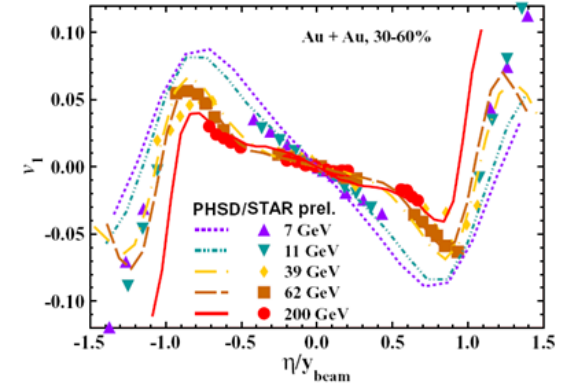
PHSD: P. Moreau



PHSD highlights



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

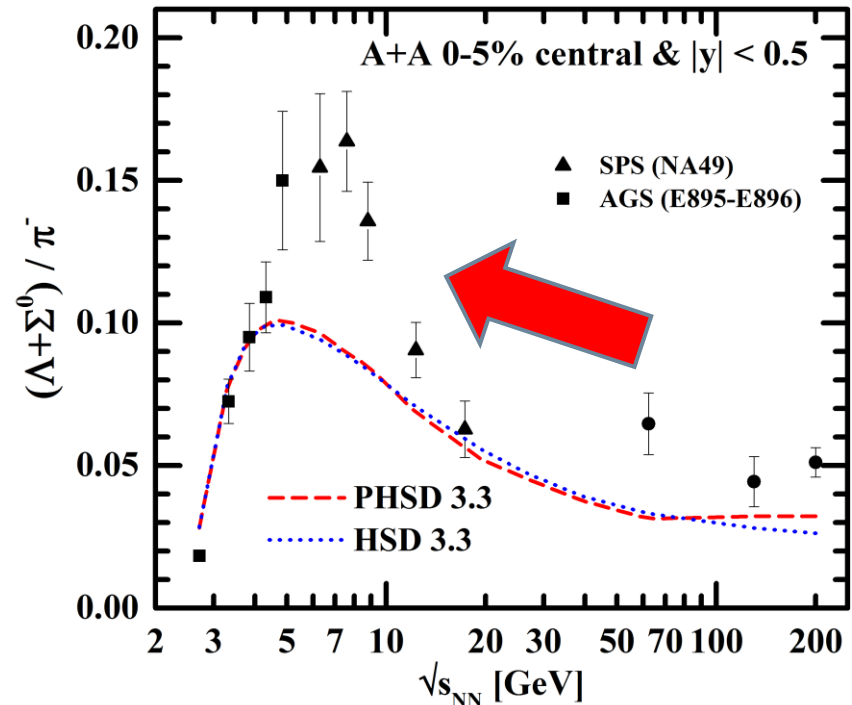
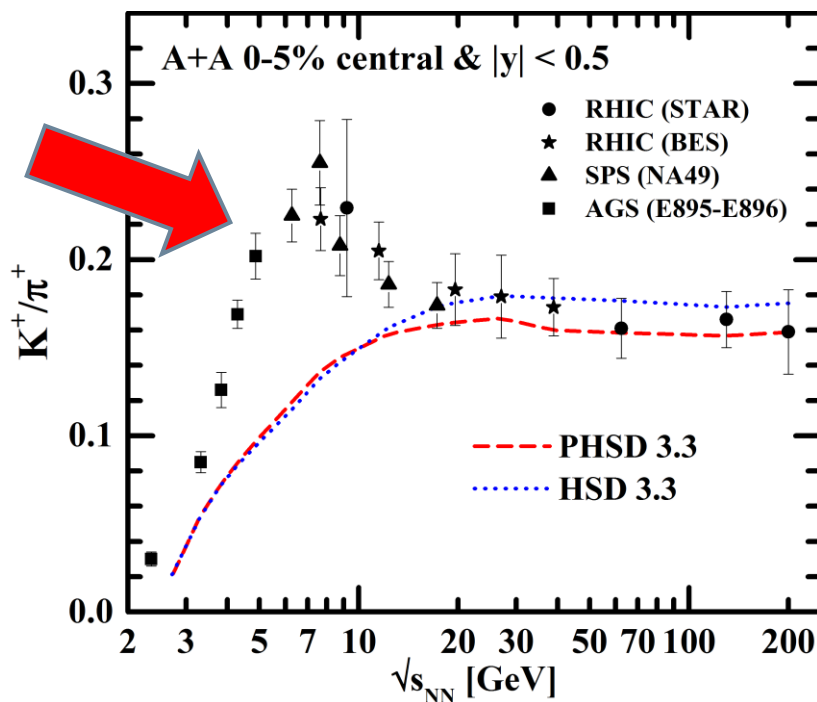


PHSD provides a good description of 'bulk' observables (y -, p_T -distributions, flow coefficients v_n) from SIS to LHC

Missing strangeness ?

- Even considering the **creation of a QGP phase**, the strangeness enhancement seen experimentally by NA49 and STAR at $\sim 20\text{-}30$ AGeV collisions remains puzzling

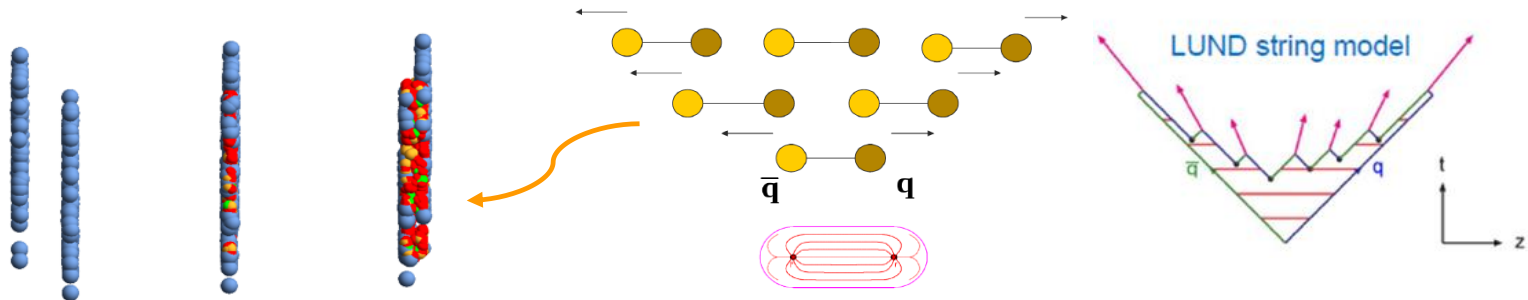
➤ 'Horn' not traced back to deconfinement



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

Production of quarks by string decays

- Initial state of heavy-ion collision:



- The 'flavor chemistry' of the final hadrons in the PHSD is mainly defined by the **LUND string model**
- According to the **Schwinger formula**, the probability to form a massive $s\bar{s}$ in a string-decay process is **suppressed** in comparison to light flavor ($u\bar{u}, d\bar{d}$)

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

m_s, m_q ($q = u, d$) : constituent quark masses

κ : string tension; in vacuum: $\kappa \sim 0.9 \text{ GeV/fm}$
 $= 0.176 \text{ GeV}^2$

Dressing of 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 $\langle \bar{q}q \rangle$

- **In vacuum (V)** (e.g. p+p collisions):

$\gamma_S \approx 0.3$ with constituent quark masses : m_q ($q = u, d$) ≈ 0.35 GeV and $m_s \approx 0.5$ GeV

- **In medium** (e.g. A+A collisions):

In the presence of a **hot and dense medium**, the **constituent quark masses are modified**

$$m_s^* = m_s^0 + (m_s^V - m_s^0) \frac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_V}$$

$$m_q^* = m_q^0 + (m_q^V - m_q^0) \frac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_V}$$

Gell-Mann-Oakes-Renner relation:

$$f_\pi^2 m_\pi^2 = -\frac{1}{2} (m_u^0 + m_d^0) \langle \bar{q}q \rangle_V$$

Bare quark masses:

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

Chiral symmetry restoration in the hadronic phase

- The behavior of the scalar quark condensate $\langle \bar{q}q \rangle$ in the hadronic medium (**baryons** + **mesons**) can be obtained from:

B.Friman et al.,
Eur. Phys. J, A 3, 165-170 (1998)

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

Baryonic medium
Mesonic medium

ρ_S : scalar density; $\Sigma_\pi \approx 45$ MeV : pion-nucleon Σ -term; f_π and m_π : pion decay constant and pion mass

- 1) ρ_S is the **scalar density of baryonic matter** from the $\sigma - \omega$ model:

Scalar field $\sigma(x)$ mediates the scalar interaction of baryons with a g_s coupling.
 $\sigma(x)$ is determined locally by the **nonlinear gap equation**:

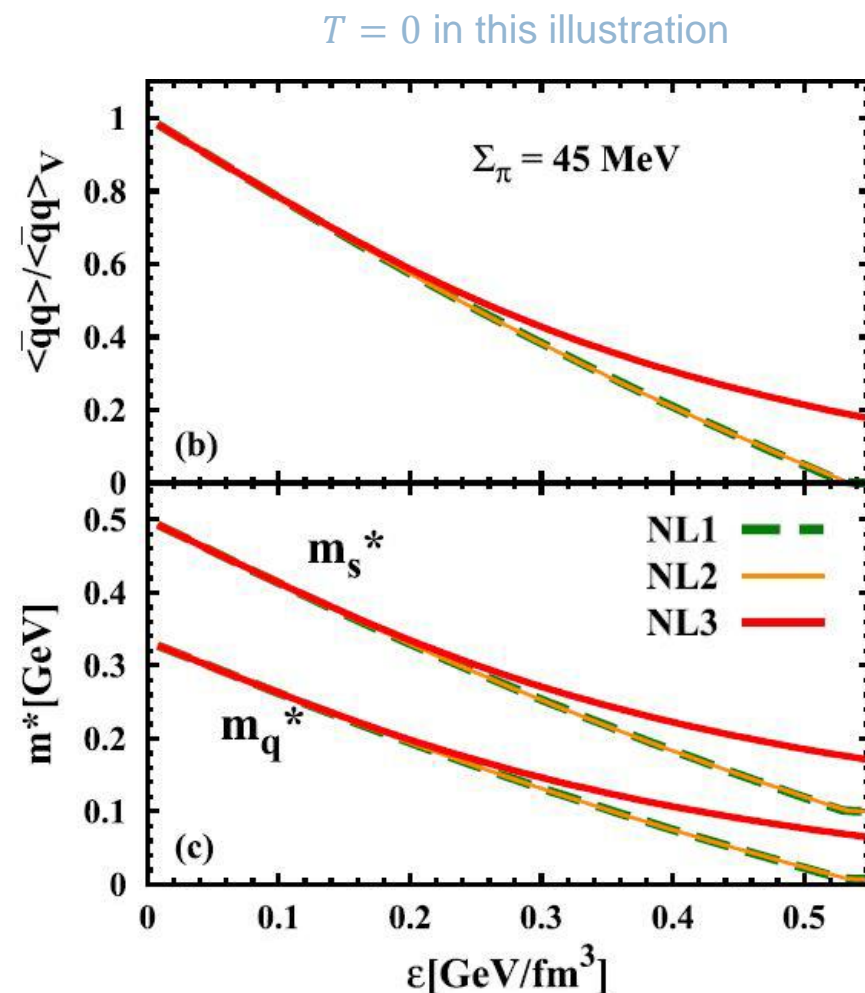
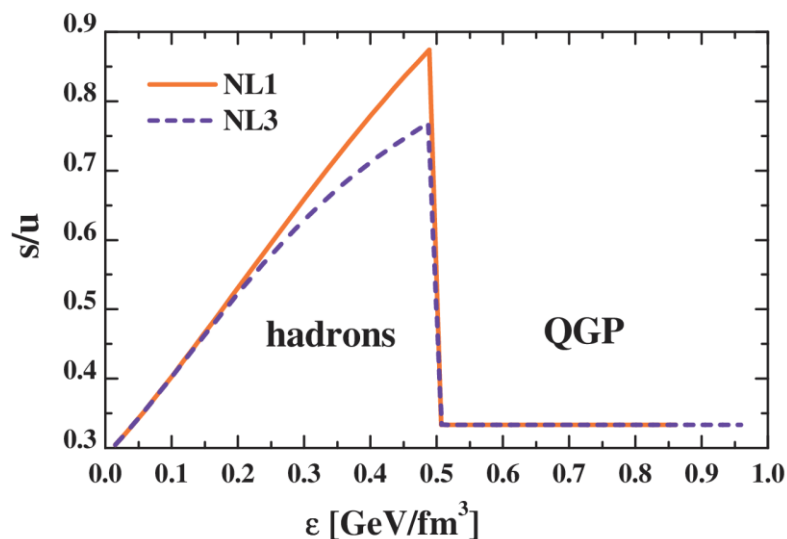
$$\begin{cases} m_\sigma^2 \sigma(x) + B\sigma^2(x) + C\sigma^3(x) = g_s \rho_S = g_s d \int \frac{d^3 p}{(2\pi)^3} \frac{m_N^*(x)}{\sqrt{p^2 + m_N^{*2}}} f_N(x, \mathbf{p}) \\ m_N^*(x) = m_N^V - g_s \sigma(x) \end{cases}$$

Parameters m_σ , g_s , B, C
are fixed to reproduce
properties of nuclear matter
at saturation

- 2) ρ_S^h is the **scalar density of meson of type h** (from PHSD)

Chiral symmetry restoration vs deconfinement

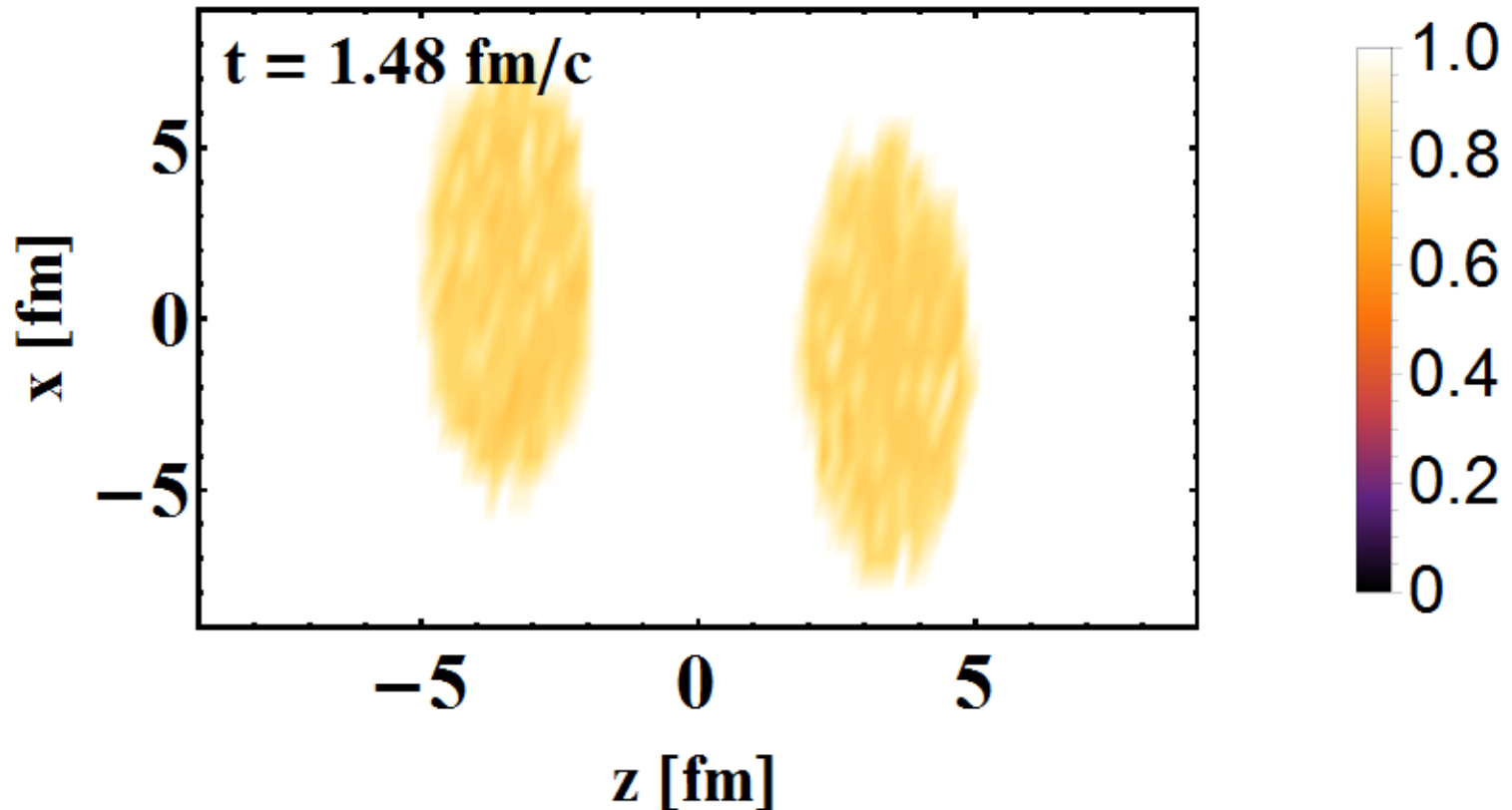
- **Hadronic phase** $\varepsilon < \varepsilon_c$: As a consequence of the **chiral symmetry restoration (CSR)**, the strangeness production probability increases with the local energy density ε
- **QGP phase** $\varepsilon > \varepsilon_c$: the string decay doesn't occur anymore and this effect is therefore suppressed.



Pb+Pb @ 30 AGeV – 0-5% central

Ratio of the quark scalar condensate compared to vacuum as a function of time ($y \approx 0$):

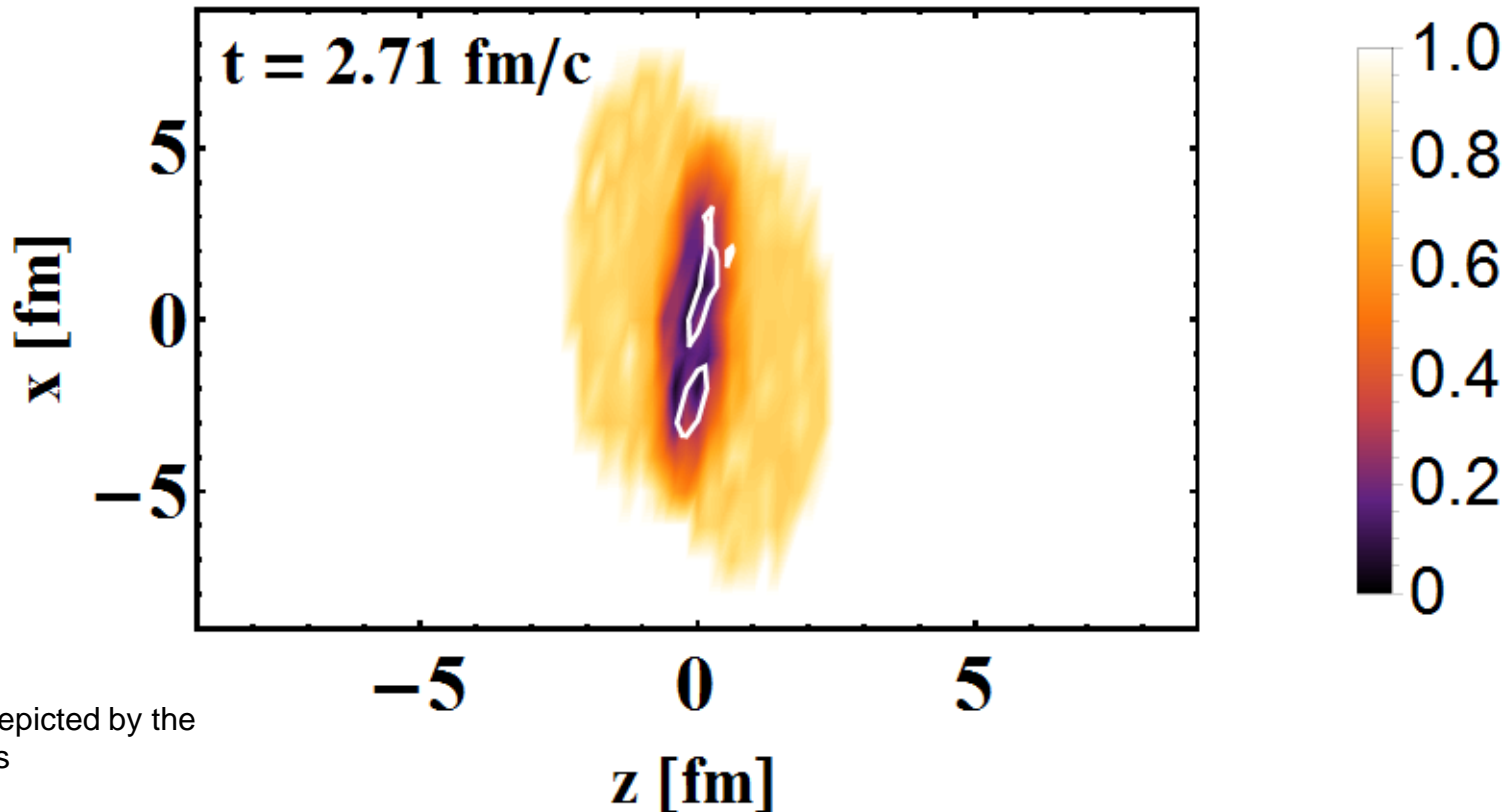
$$\frac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_V}$$



Pb+Pb @ 30 AGeV – 0-5% central

Ratio of the quark scalar condensate compared to vacuum as a function of time ($y \approx 0$):

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

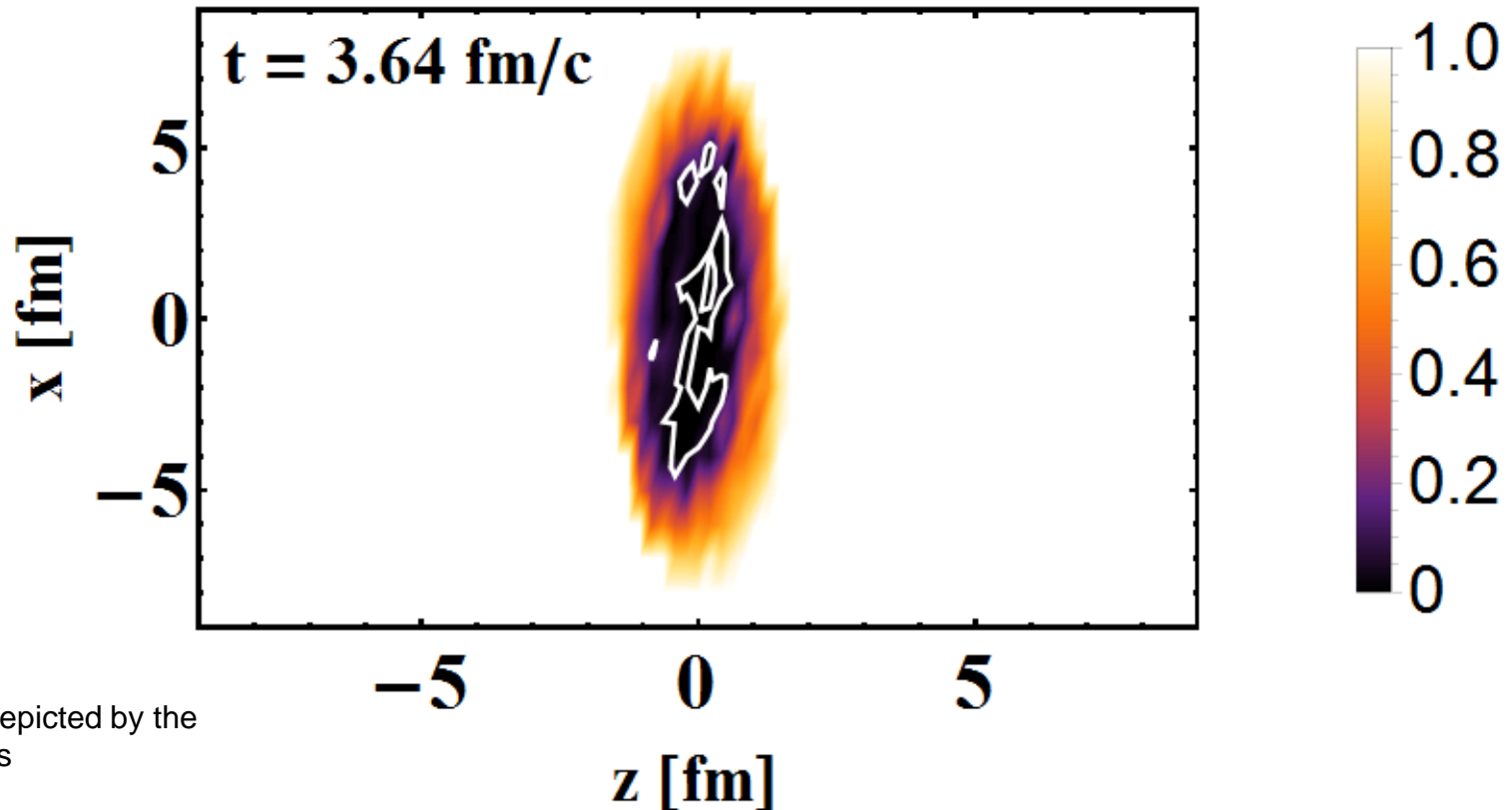


QGP phase depicted by the white contours

Pb+Pb @ 30 AGeV – 0-5% central

Ratio of the quark scalar condensate compared to vacuum
as a function of time ($y \approx 0$):

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

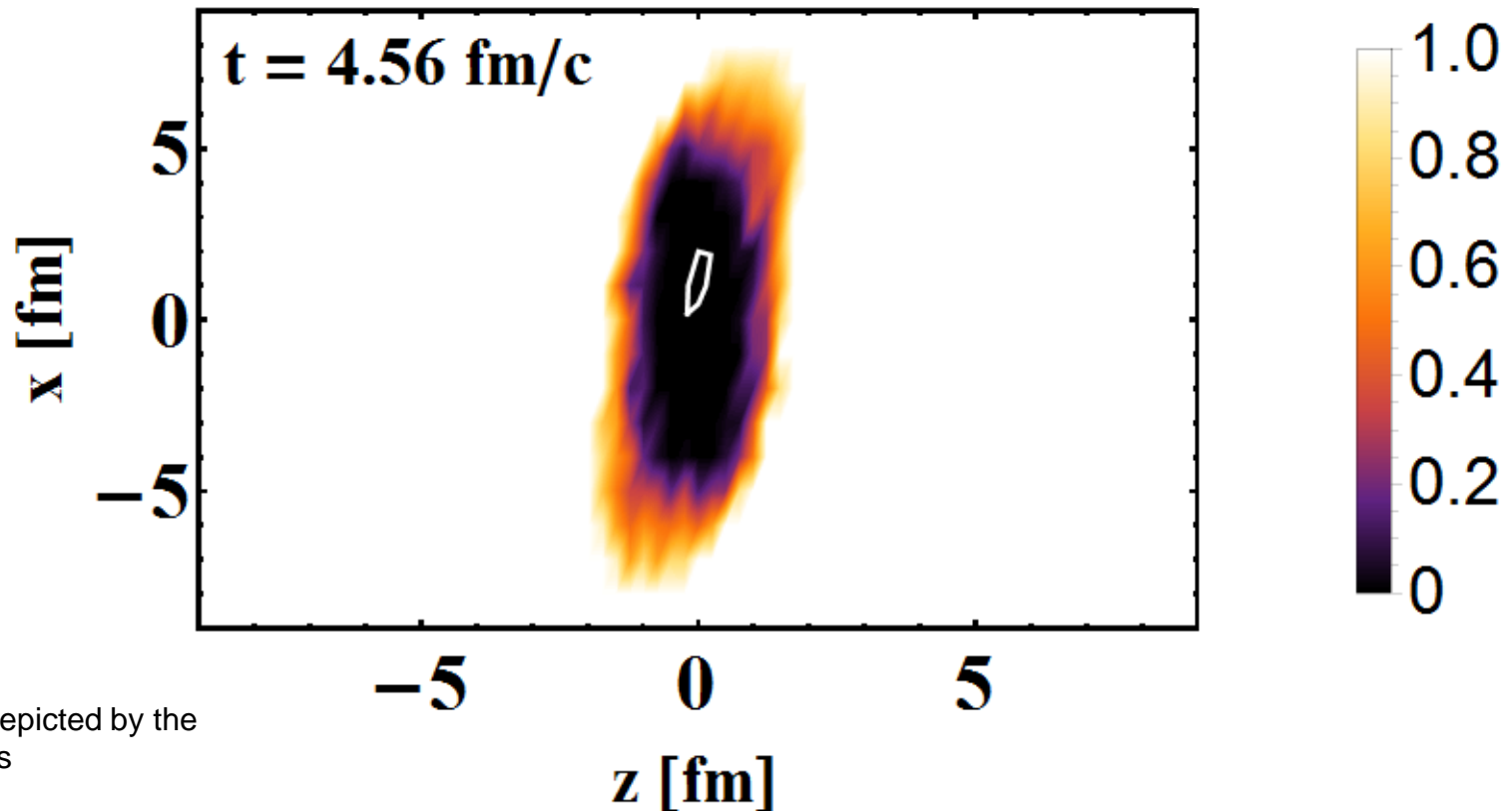


QGP phase depicted by the
white contours

Pb+Pb @ 30 AGeV – 0-5% central

Ratio of the quark scalar condensate compared to vacuum as a function of time ($y \approx 0$):

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

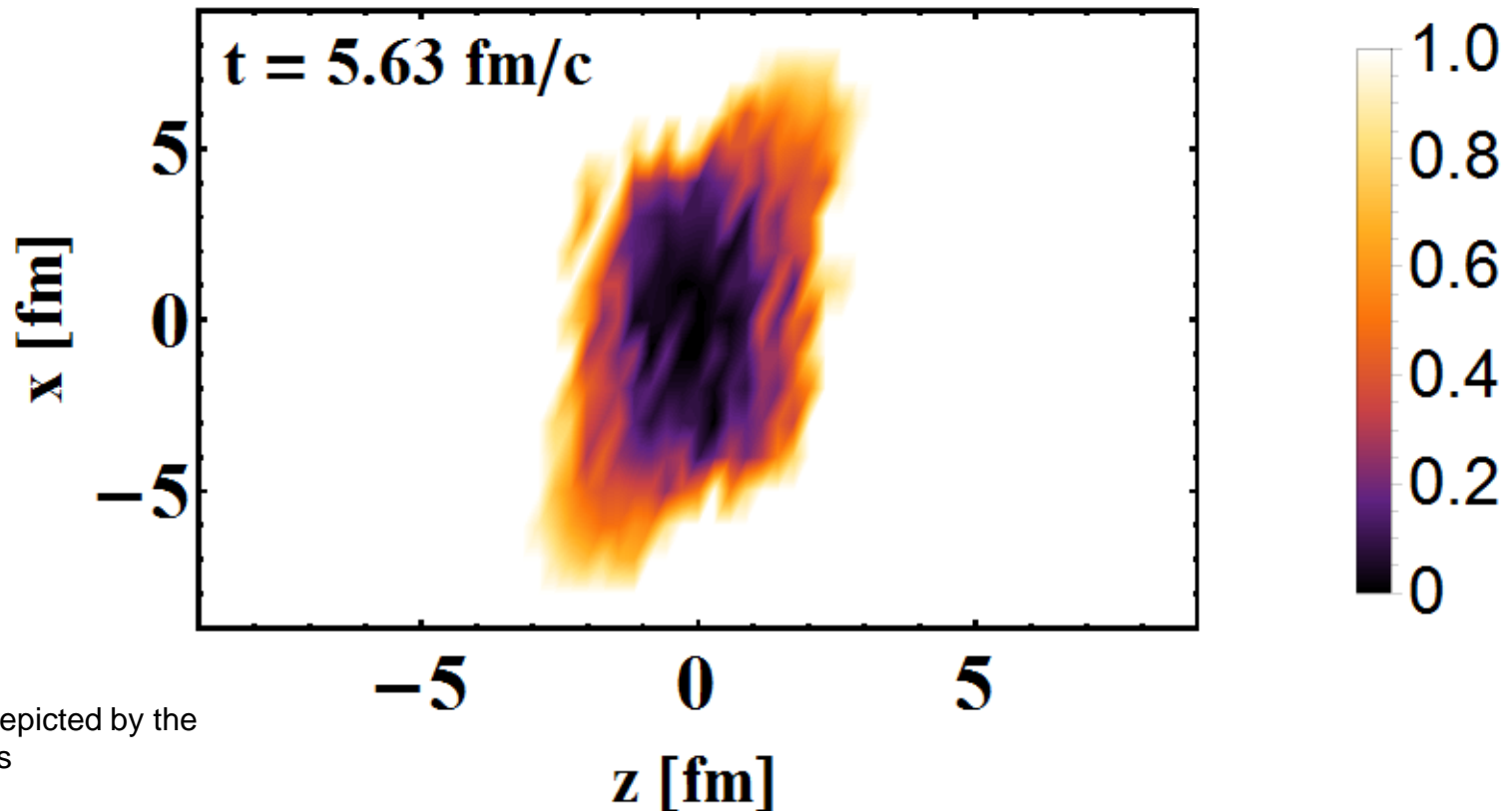


QGP phase depicted by the white contours

Pb+Pb @ 30 AGeV – 0-5% central

Ratio of the quark scalar condensate compared to vacuum as a function of time ($y \approx 0$):

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

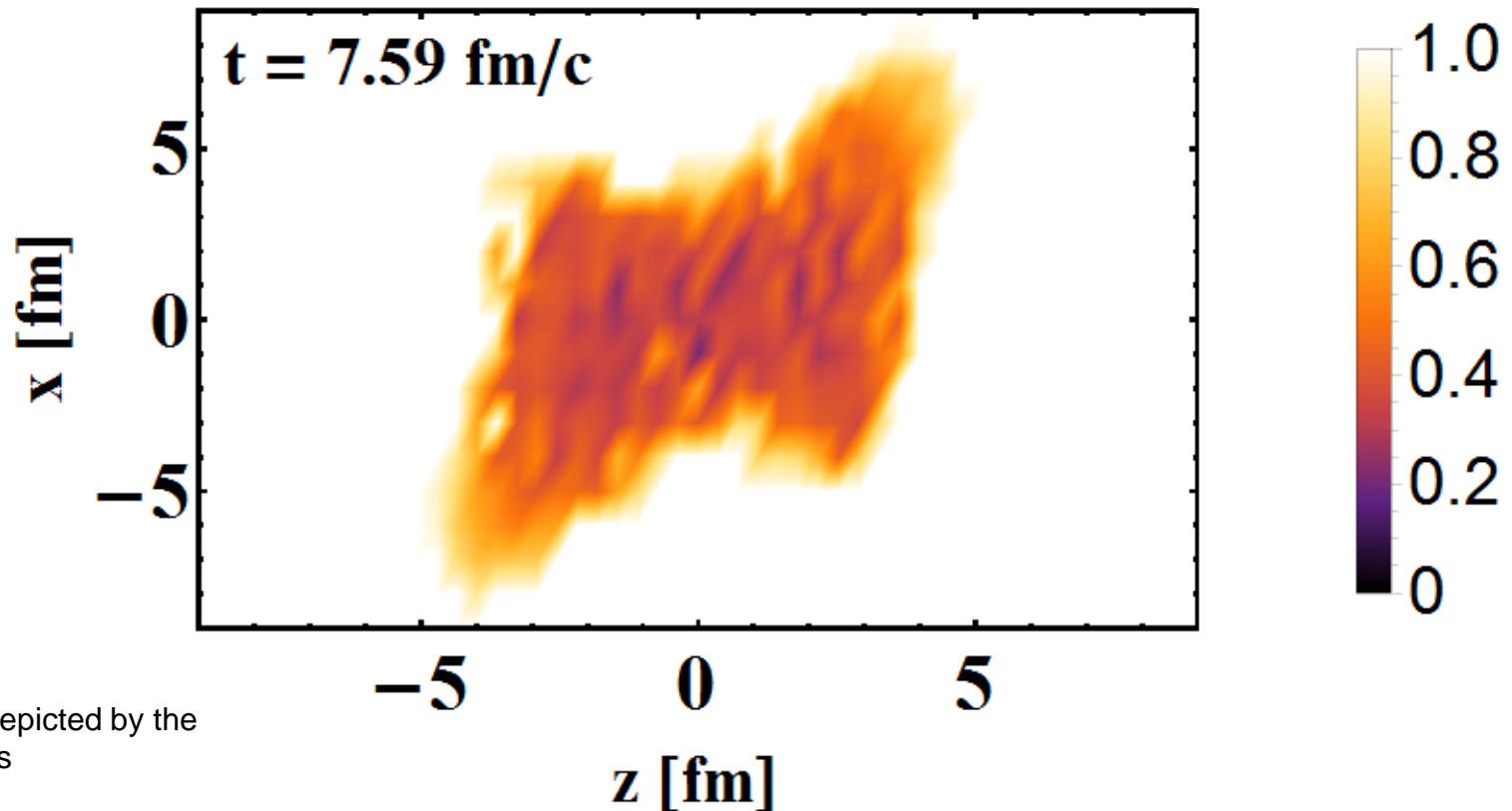


QGP phase depicted by the white contours

Pb+Pb @ 30 AGeV – 0-5% central

Ratio of the quark scalar condensate compared to vacuum
as a function of time ($y \approx 0$):

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

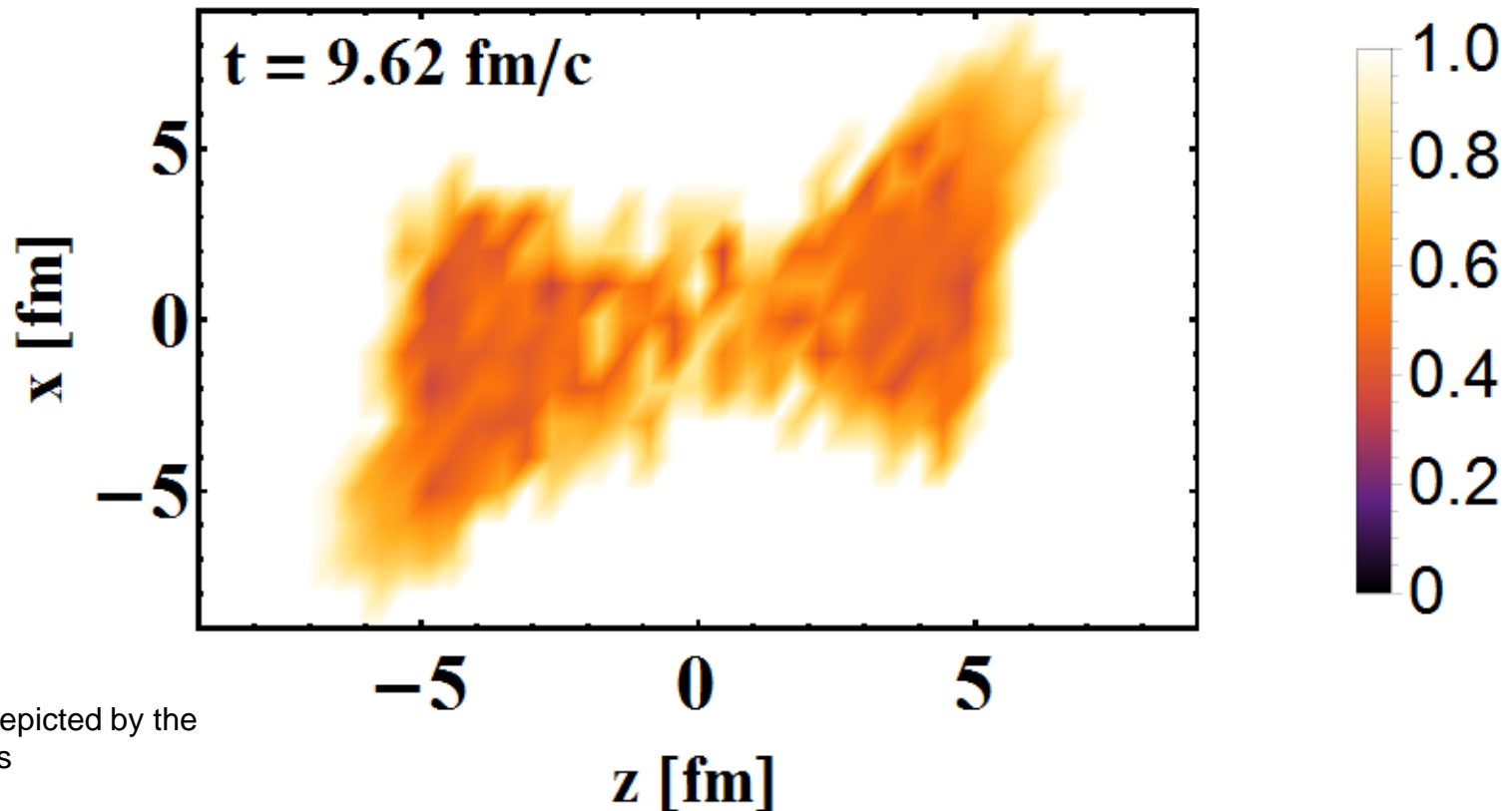


QGP phase depicted by the
white contours

Pb+Pb @ 30 AGeV – 0-5% central

Ratio of the quark scalar condensate compared to vacuum
as a function of time ($y \approx 0$):

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

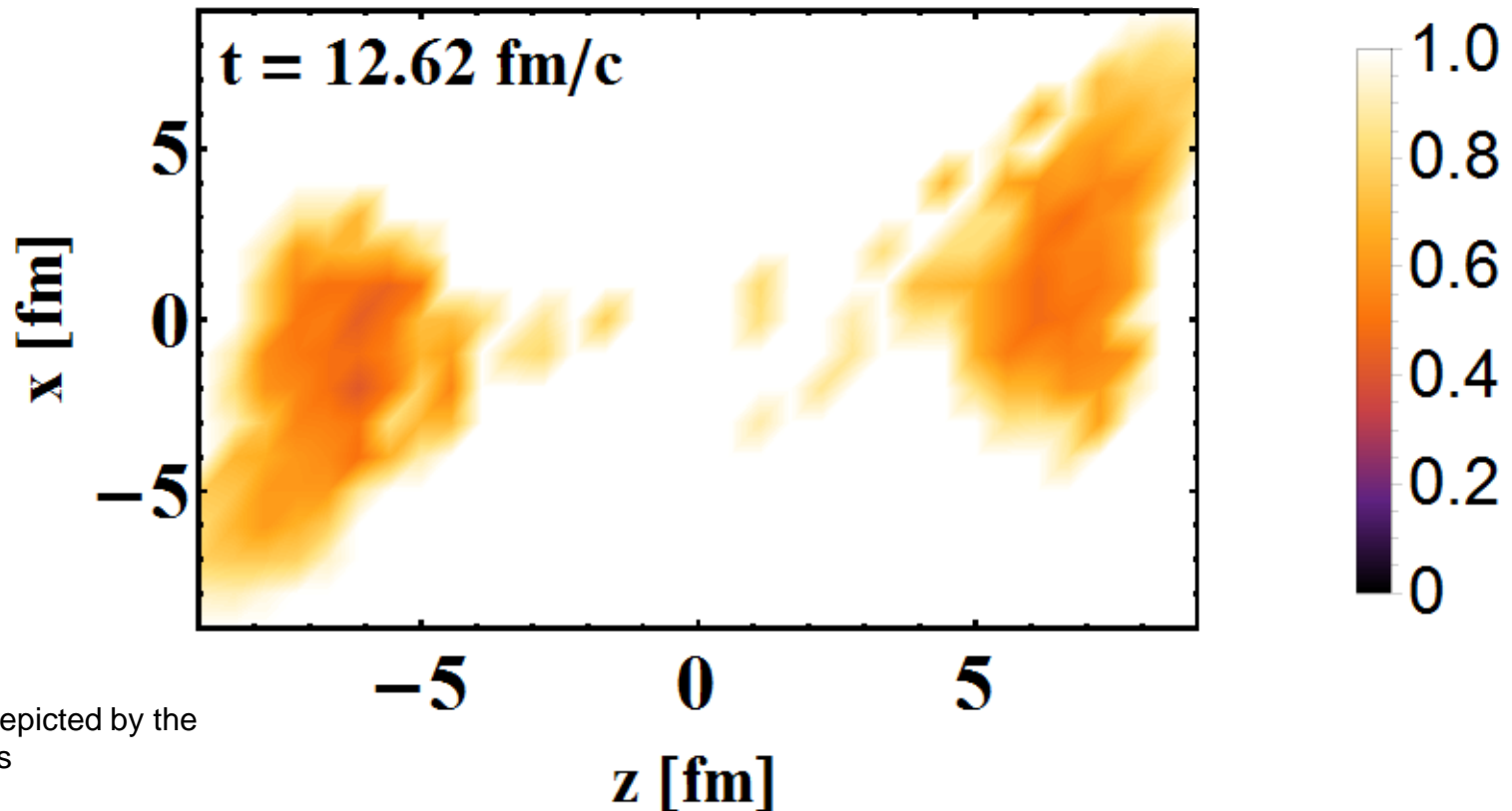


QGP phase depicted by the
white contours

Pb+Pb @ 30 AGeV – 0-5% central

Ratio of the quark scalar condensate compared to vacuum
as a function of time ($y \approx 0$):

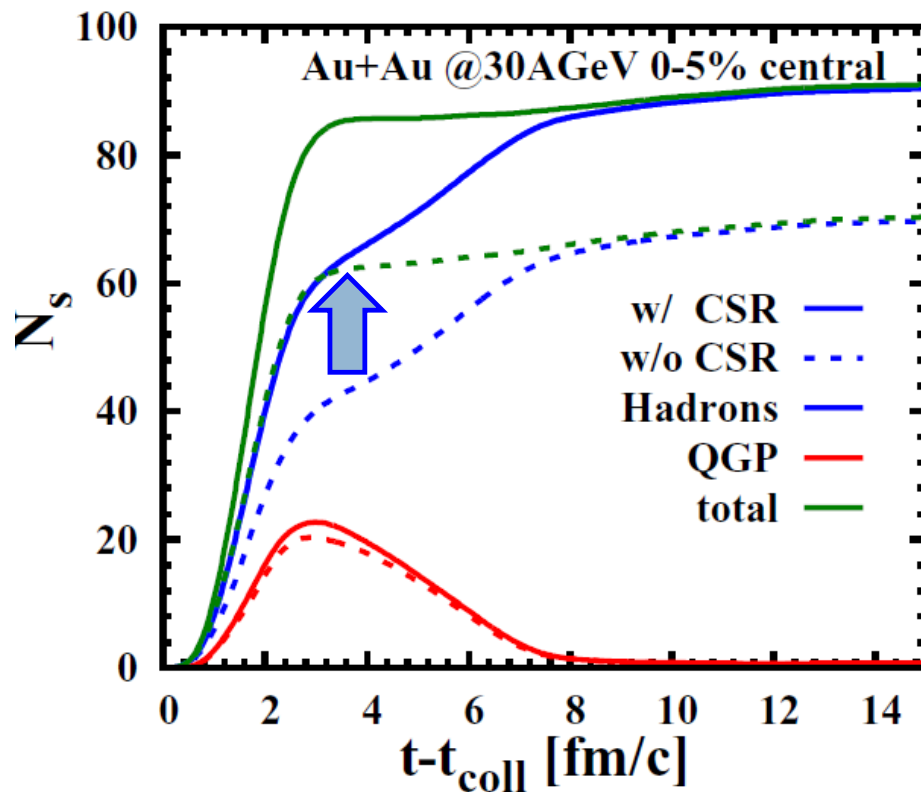
$$\frac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_V}$$



QGP phase depicted by the
white contours

Au+Au @ 30 AGeV – 0-5% central

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



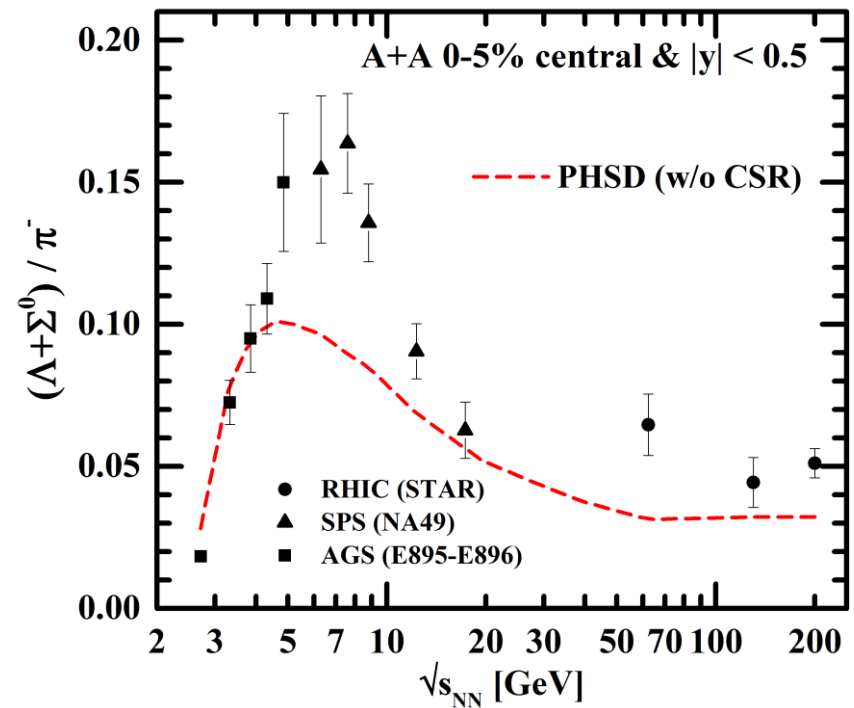
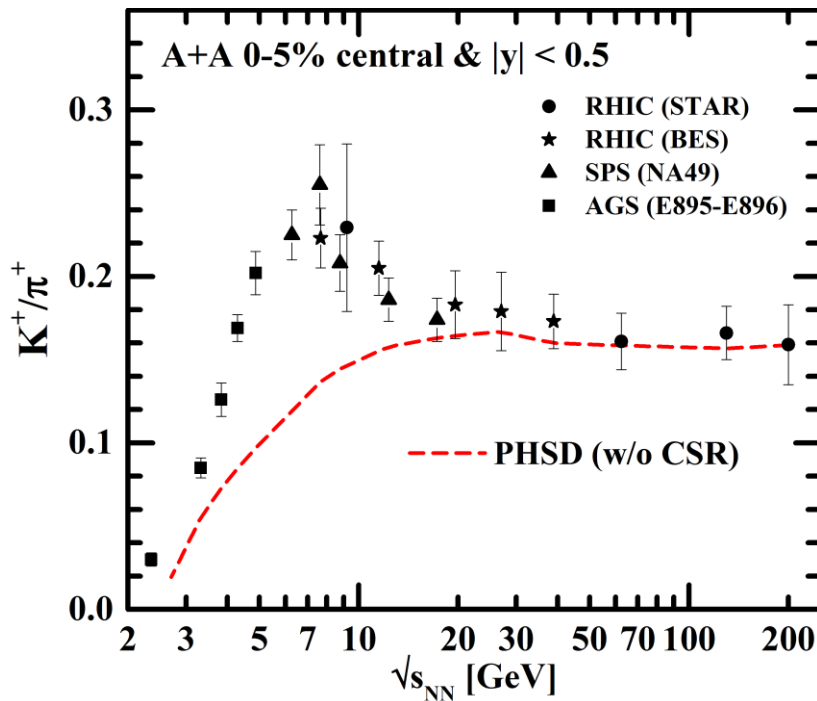
Palmese et al.,
 PRC94 (2016) 044912,
 arXiv:1607.04073

Strange particle number N_s as a function of time

Chiral symmetry restoration in the hadronic phase

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

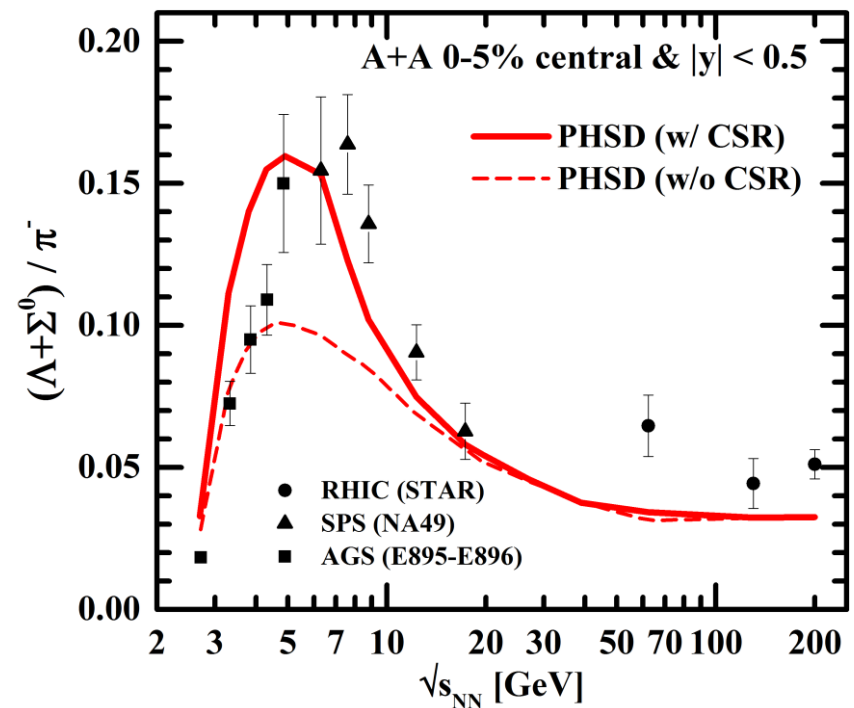
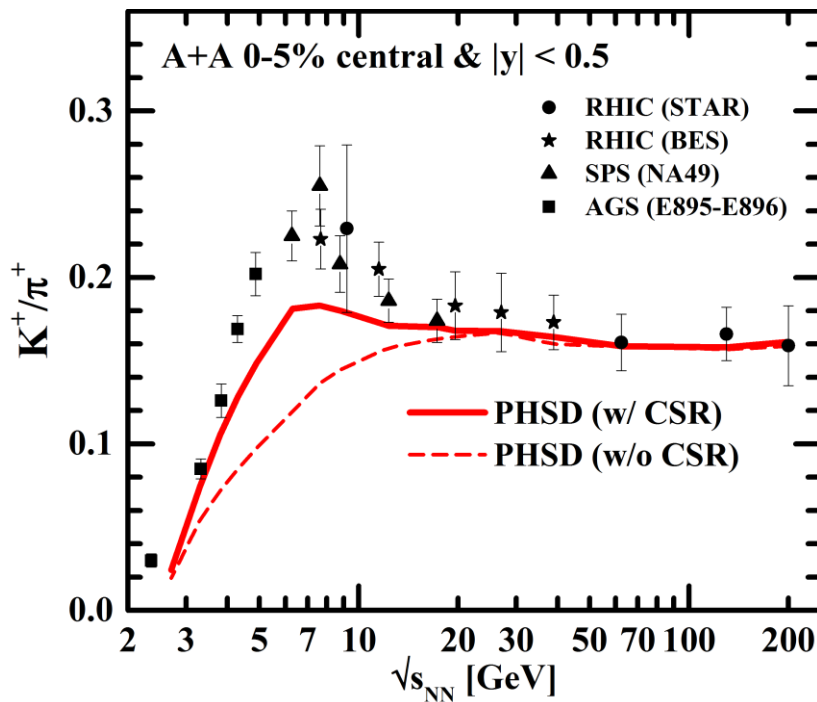
W. Cassing, A. Palmese, P. Moreau, E.L. Bratkovskaya - *Phys.Rev. C93 (2016), 014902*



Chiral symmetry restoration in the hadronic phase

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

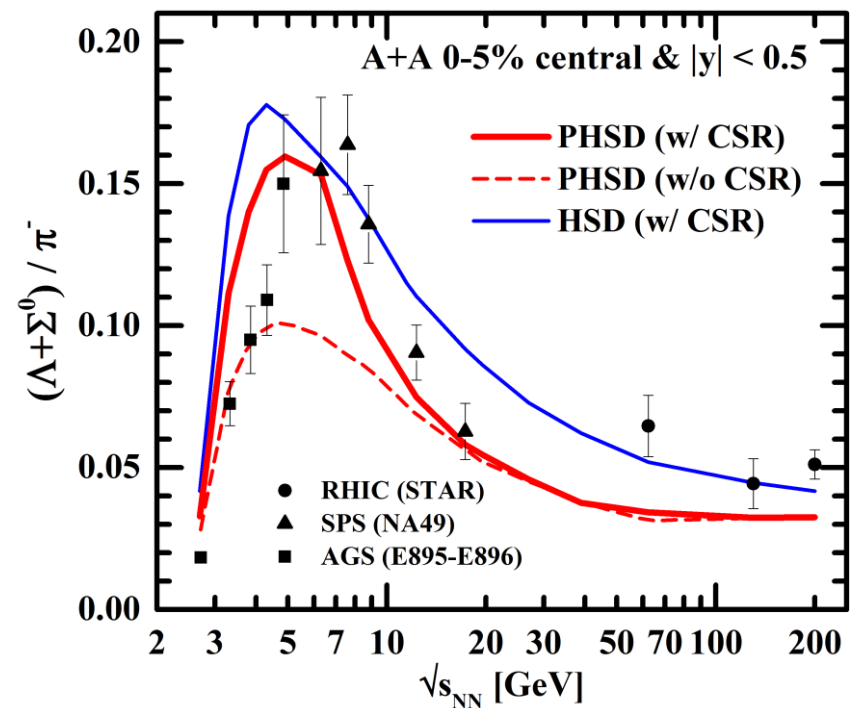
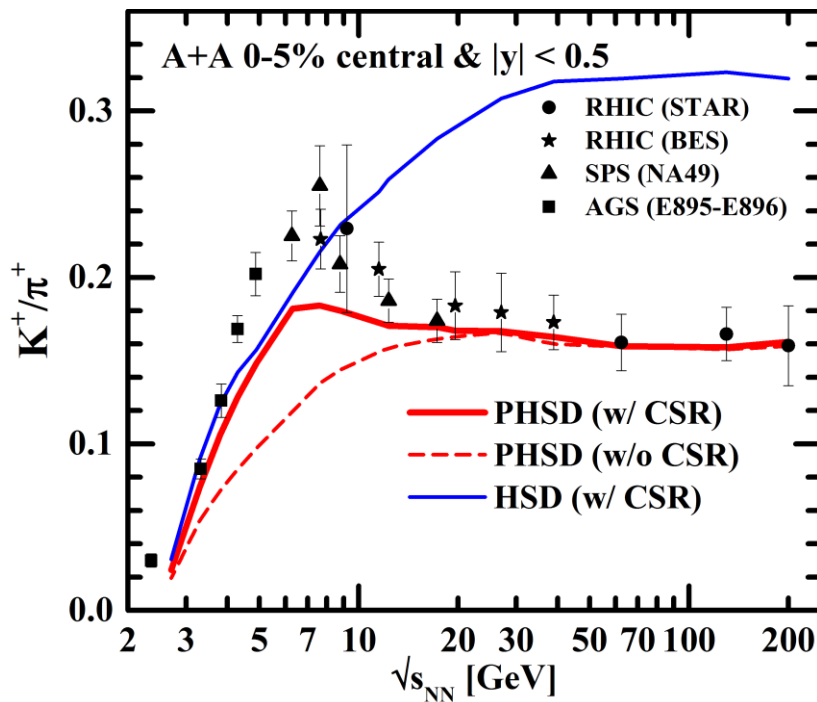
W. Cassing, A. Palmese, P. Moreau, E.L. Bratkovskaya - *Phys.Rev. C93 (2016), 014902*



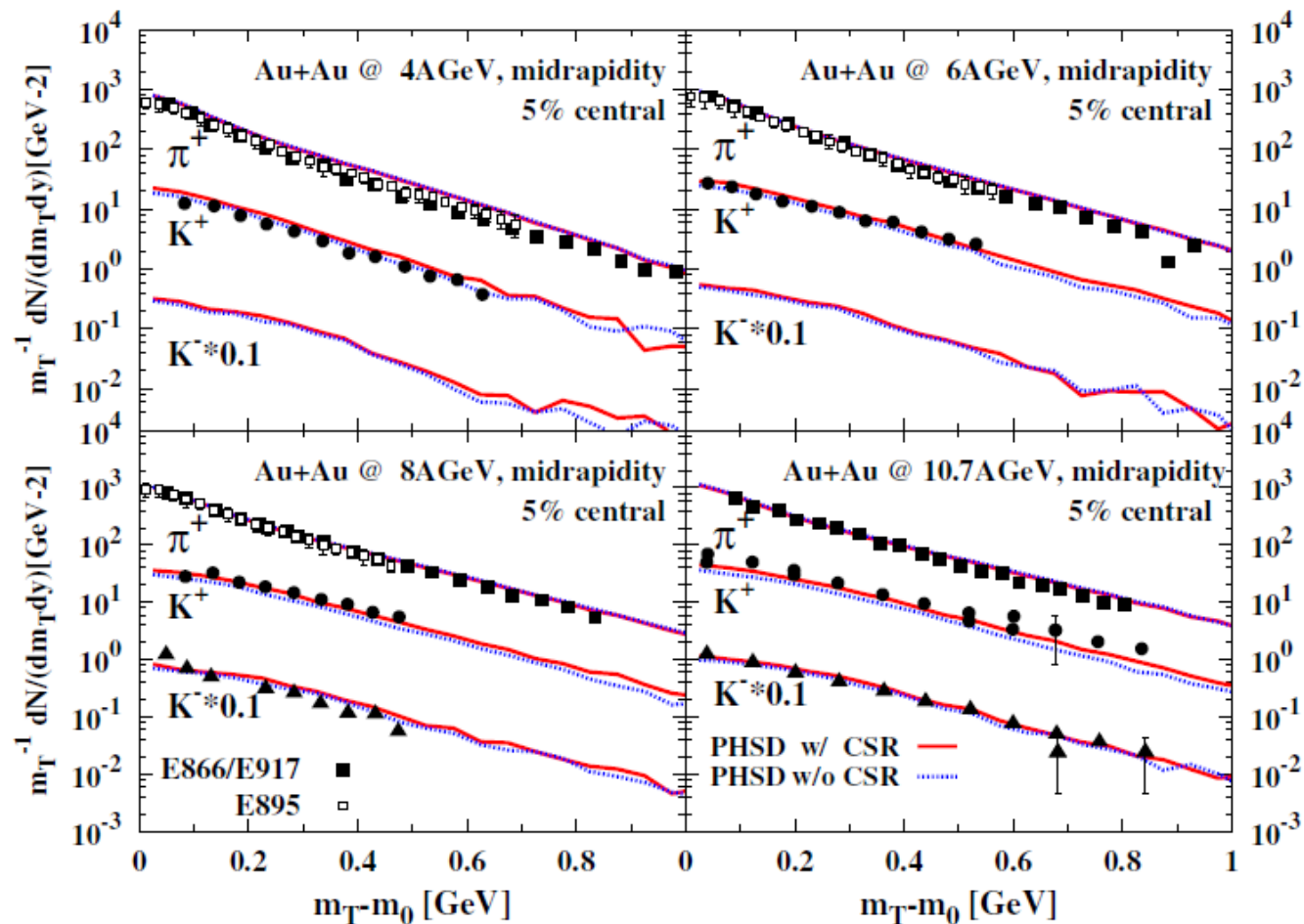
Chiral symmetry restoration in the hadronic phase

- 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 - Phys.Rev. C93 (2016), 014902

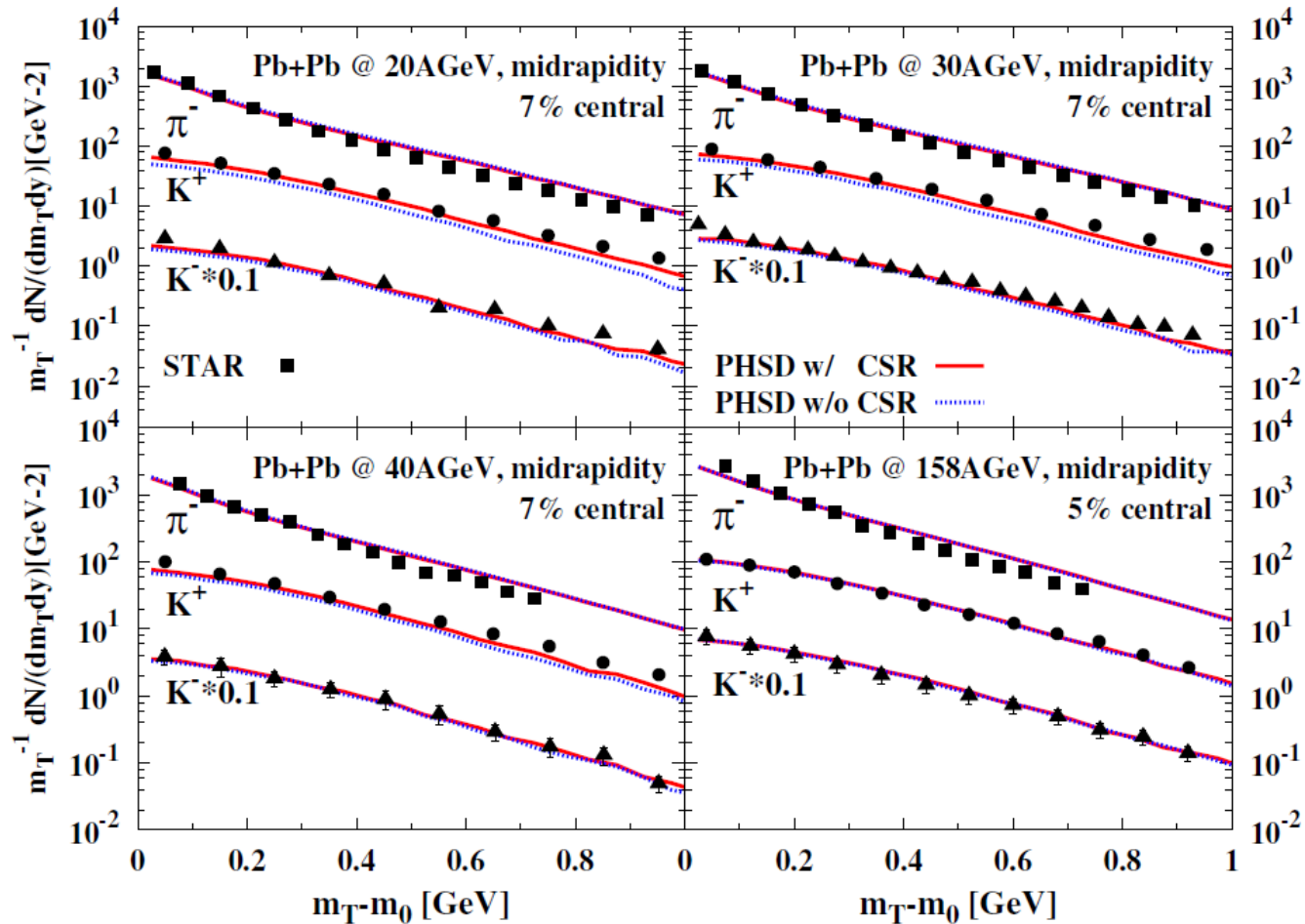


m_T spectra of pions and kaons at AGS energies



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

m_T spectra of pions and kaons at SPS energies

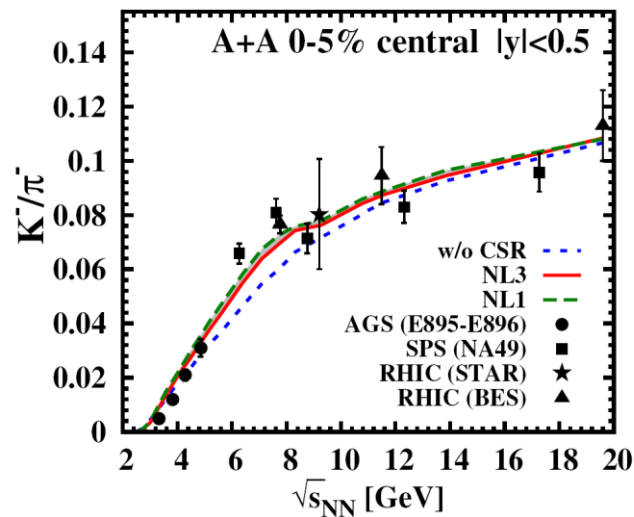
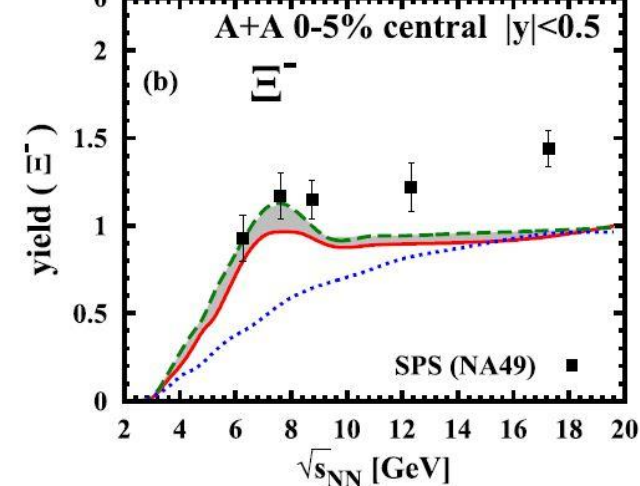
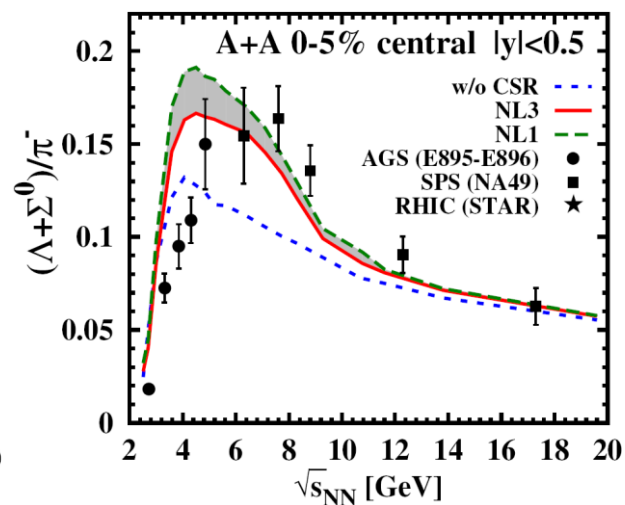
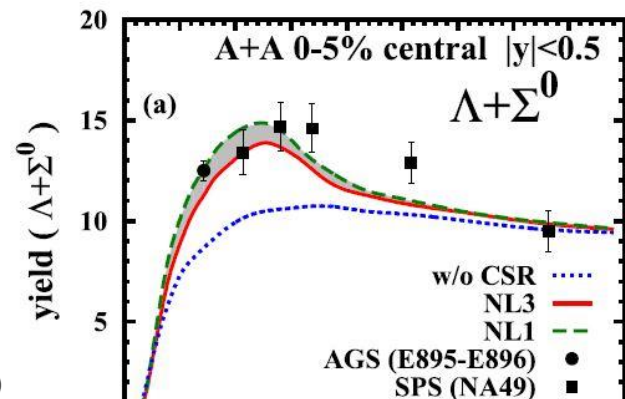
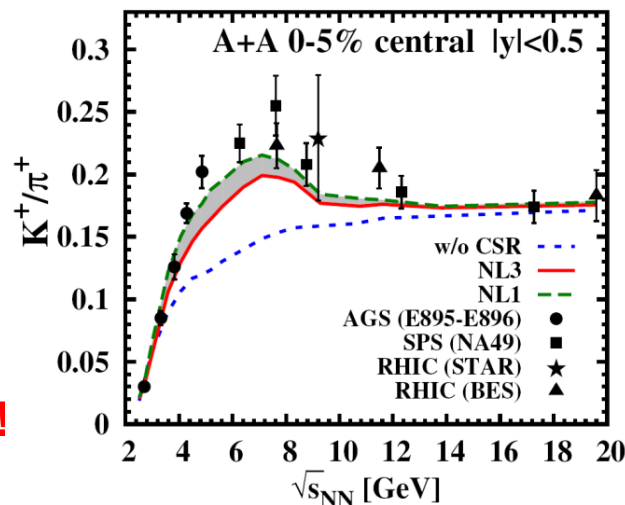


Palmese et al., [PRC94 \(2016\) 044912](#), [arXiv:1607.04073](#)

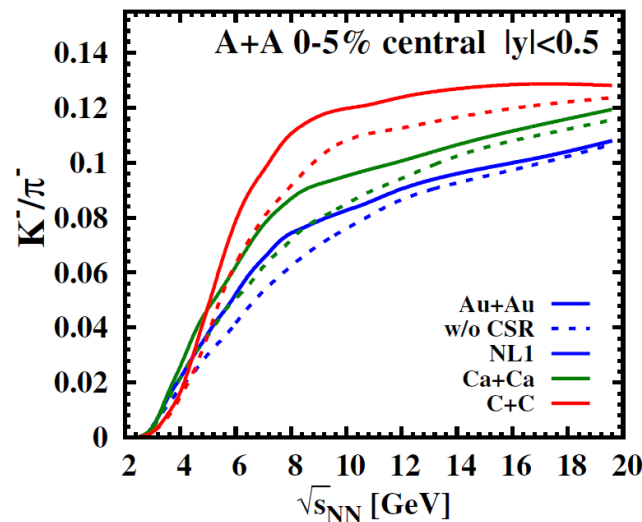
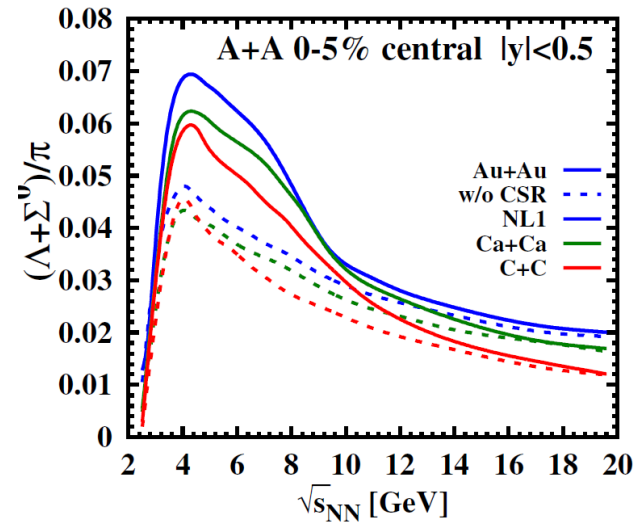
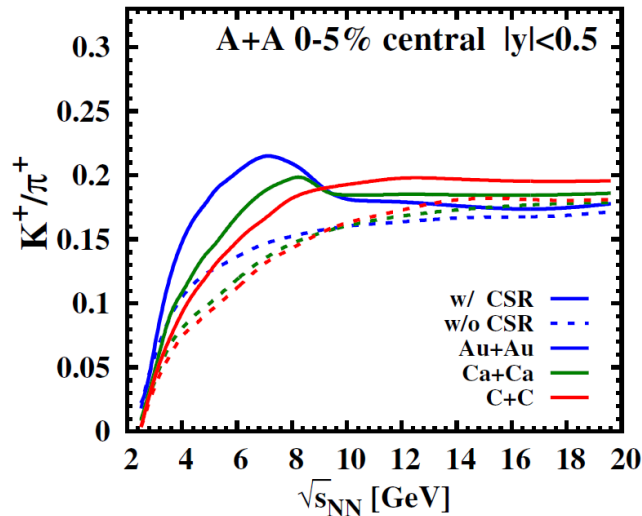
Sensitivity to the nuclear equation of state

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

**Low sensitivity to the
 nuclear equation of state!**



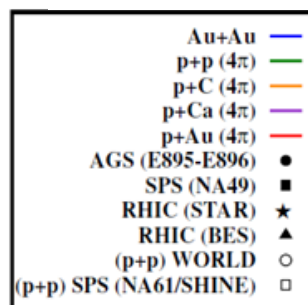
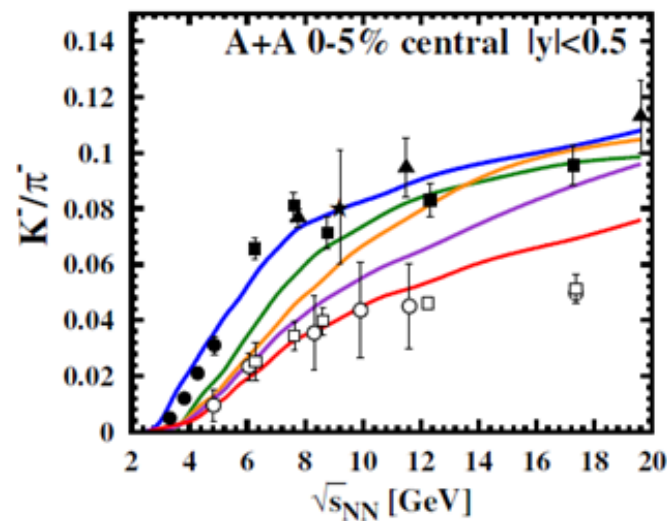
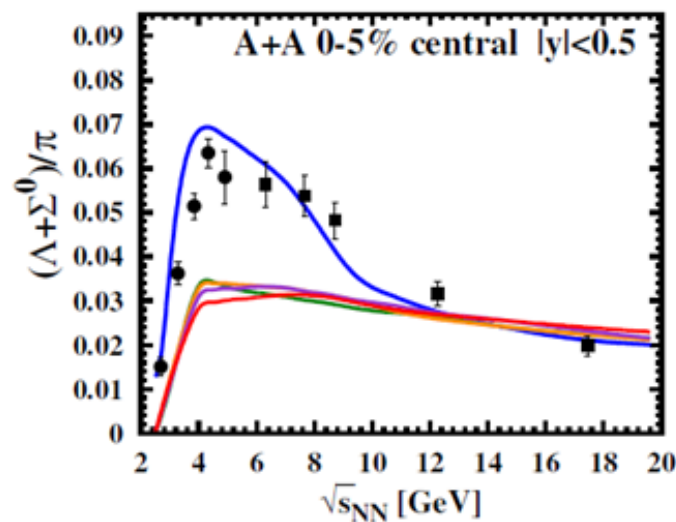
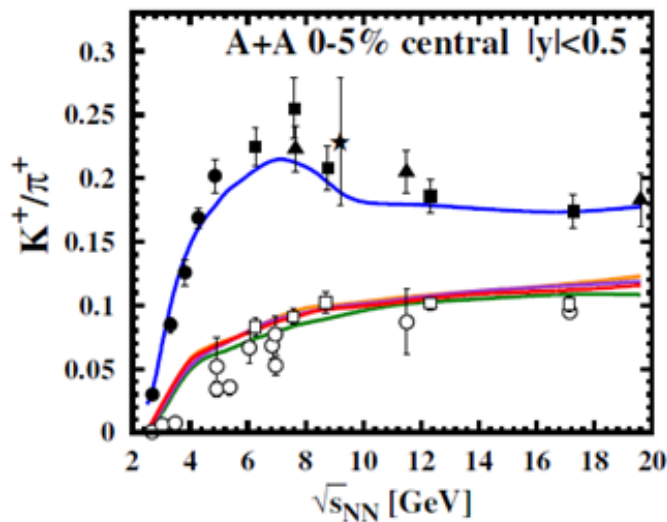
Sensitivity to the system size: A+A collisions



- 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

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

Sensitivity to the system size: p+A collisions

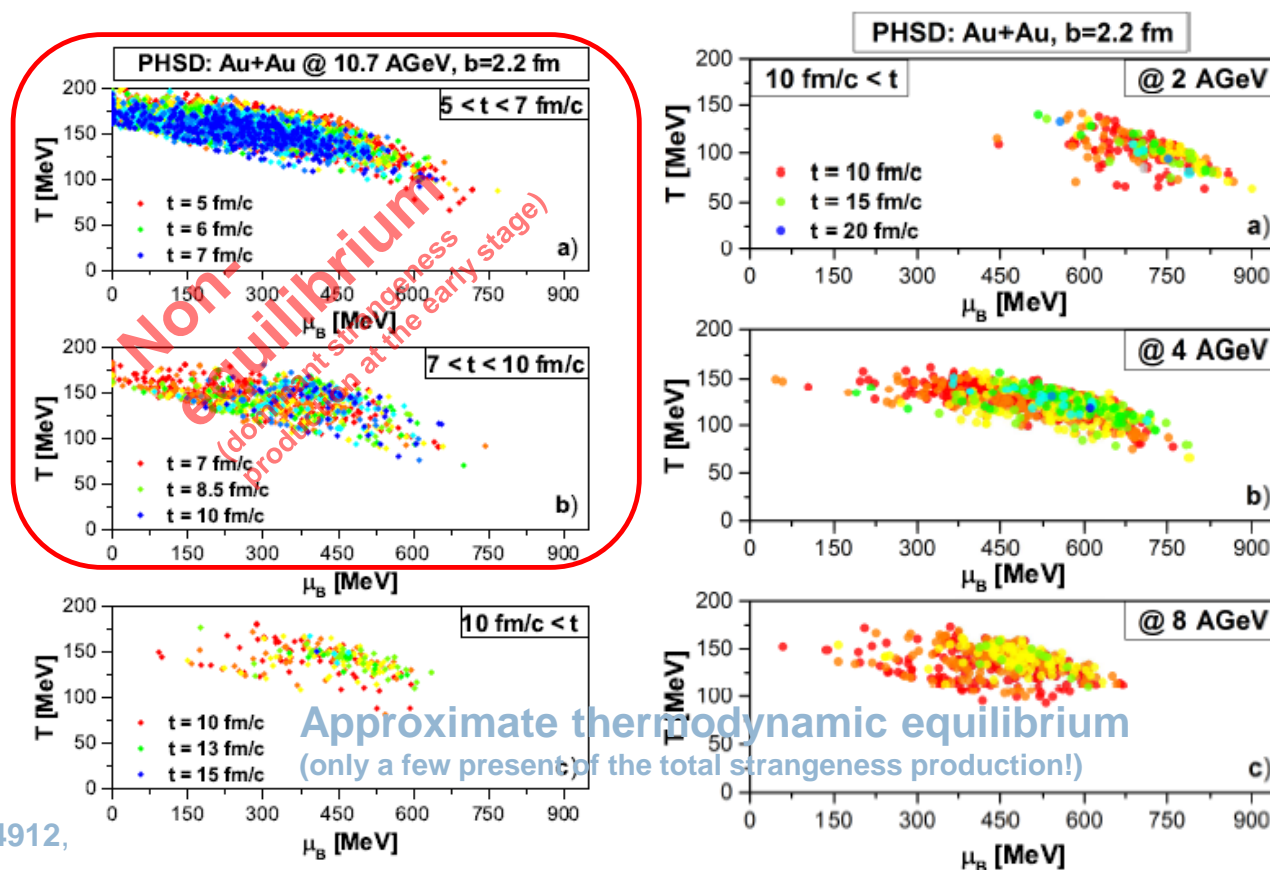


- In p+A collisions strange to non-strange particle ratios show no peaks

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

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?

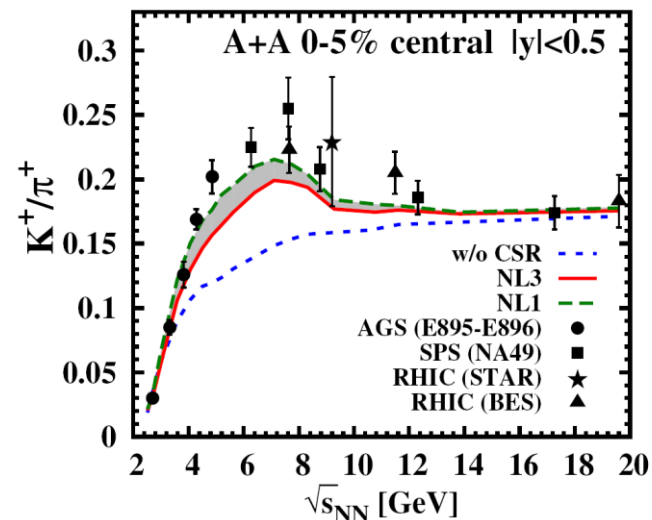
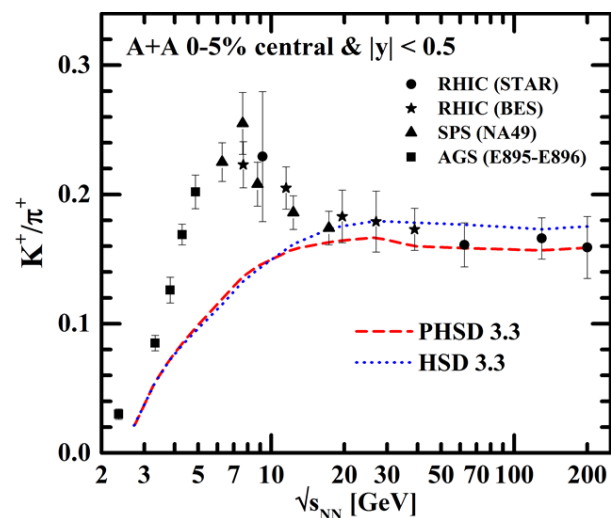


Palmese et al.,

PRC94 (2016) 044912,
arXiv:1607.04073

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 AGeV (FAIR/NICA energies) cannot be attributed to a 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 partonic medium \rightarrow a '**horn**' emerges

Thank you for your attention!



PHSD group

GSI - Frankfurt University - FIAS

Elena Bratkovskaya
Taesoo Song
Pierre Moreau
Andrej Ilners
Hamza Berrehrah

Giessen University

Wolfgang Cassing
Thorsten Steinert
Alessia Palmese
Eduard Seifert
Olena Linnyk



External PHSD Collaborations

SUBATECH, Nantes University:

Jörg Aichelin
Christoph Hartnack
Pol-Bernard Gossiaux
Marlene Nahrgang

Texas A&M University:

Che-Ming Ko

JINR, Dubna:

Viacheslav Toneev
Vadim Voronyuk



Valencia University:

Daniel Cabrera

Barcelona University:

Laura Tolos
Angel Ramos

Duke University:

Steffen Bass
Yingru Xu



Universitat Autònoma
de Barcelona

