CHIRAL SYMMETRY RESTORATION VERSUS DECONFINEMENT IN HEAVY-ION COLLISIONS

Pierre Moreau

for the PHSD group

STUDY OF HIGH-DENSITY NUCLEAR MATTER WITH HADRON BEAMS

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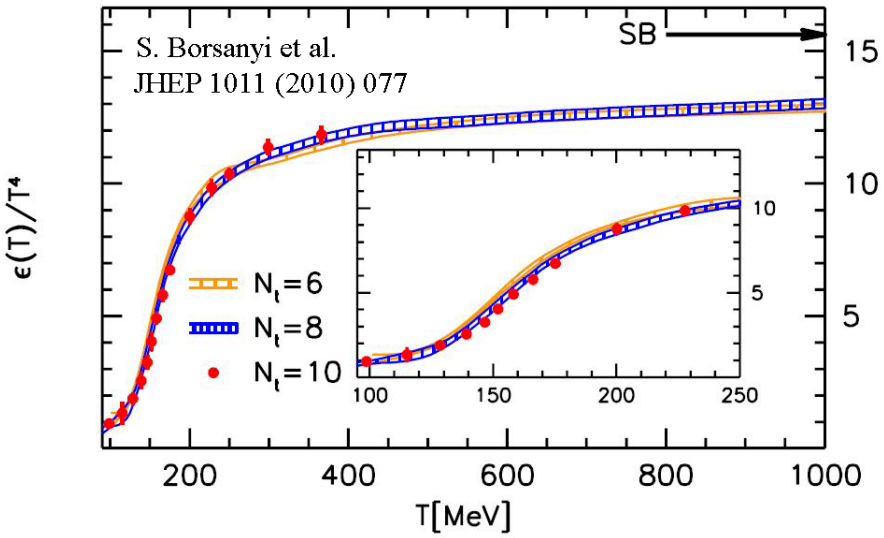
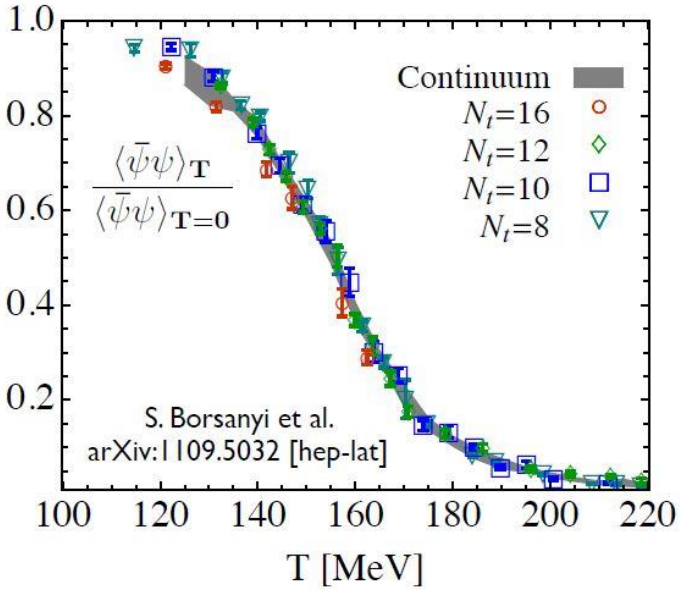
Information from lattice QCD

- **Deconfinement phase transition** with increasing temperature



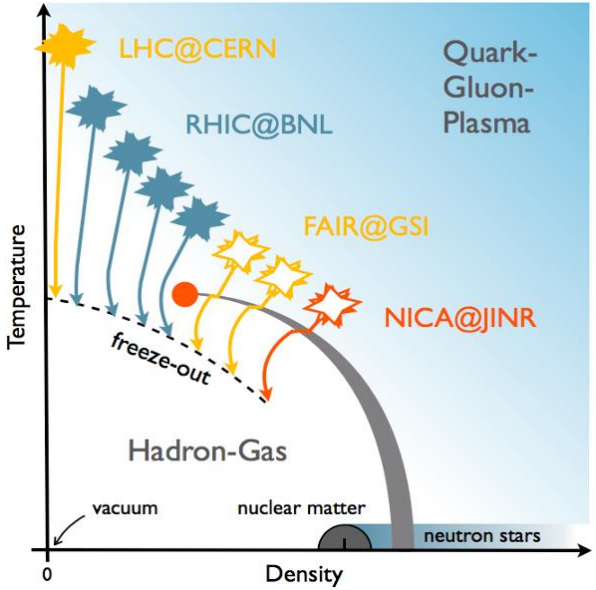
- **Chiral symmetry restoration** with increasing temperature



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

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

Dynamical description of heavy-ion collisions

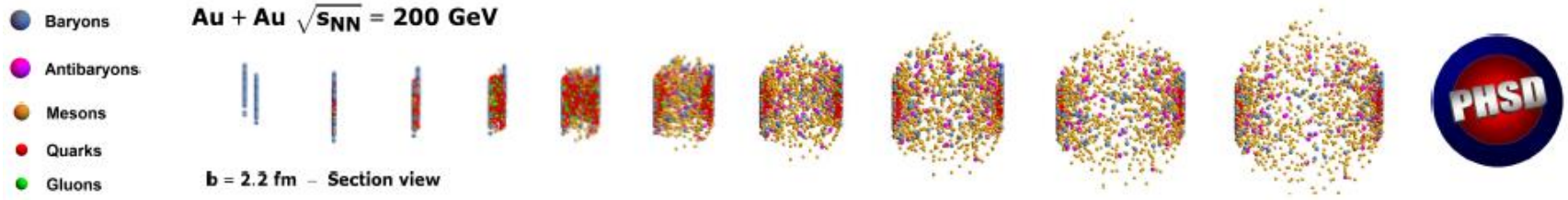


- **Goal:** Study the properties of strongly interacting matter under extreme conditions from a microscopic point of view
- **Realization:** dynamical many-body transport approach

Parton-Hadron-String-Dynamics (PHSD)

- Explicit parton-parton interactions, explicit phase transiton from hadronic to partonic degrees of freedom

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

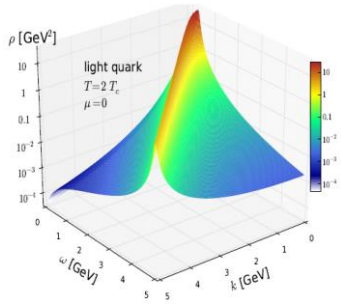


W.Cassing, E.Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W.Cassing, EPJ ST 168 (2009) 3

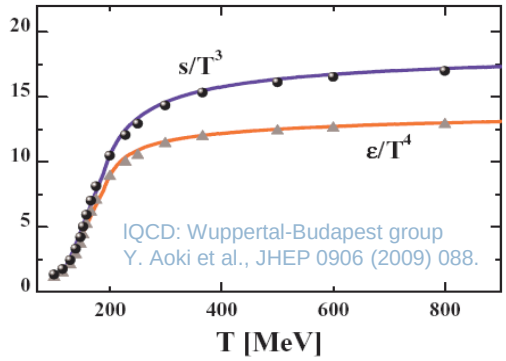
Dynamical Quasi-Particle Model (DQPM)

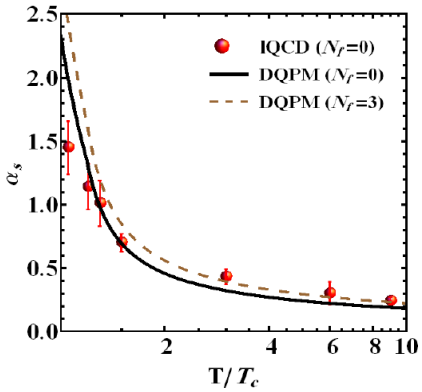
- **The QGP phase is described in terms of interacting quasiparticles: quarks and gluons with Lorentzian spectral functions:**

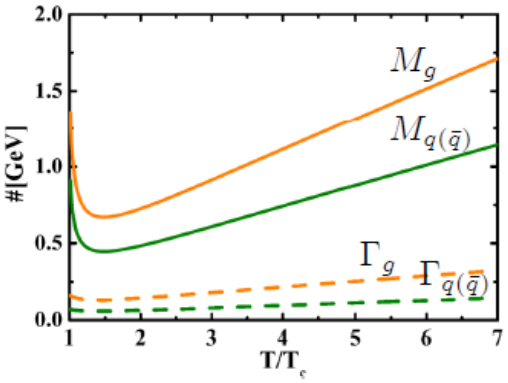
$$\rho_i(\omega, T) = \frac{4\omega\Gamma_i(T)}{(\omega^2 - \mathbf{p}^2 - M_i^2(T))^2 + 4\omega^2\Gamma_i^2(T)} \qquad (i = q, \bar{q}, g)$$



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





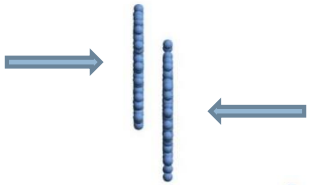


- **DQPM provides mean-fields (1P1) for quarks and gluons as well as effective 2-body interactions (2P1)**

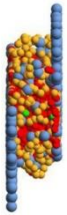
Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Stages of a collision in PHSD

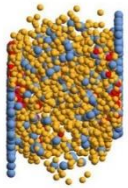
Initial A+A collision



Partonic phase



Hadronization



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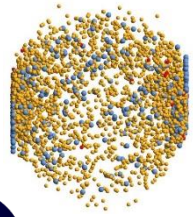
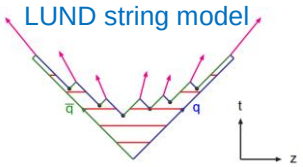


- **String formation in primary NN collisions**

→ **decays to pre-hadrons (baryons and mesons)**



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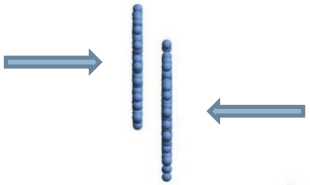

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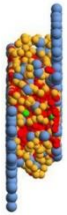

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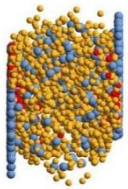

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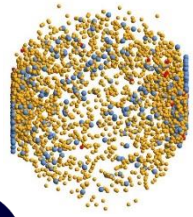

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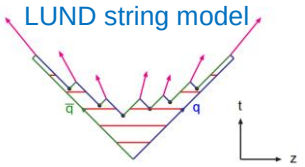

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Dissolution of pre-hadrons → DQPM

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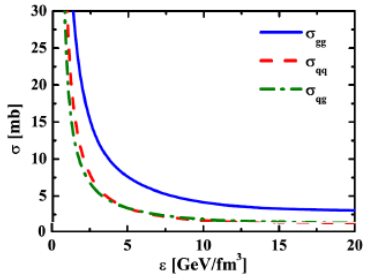

(quasi-)elastic collisions :

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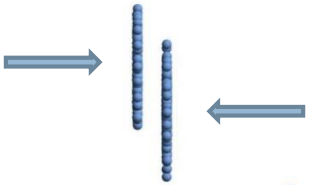

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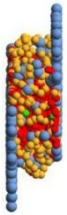

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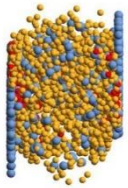

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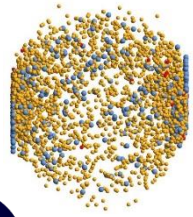

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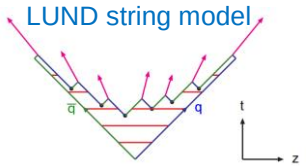

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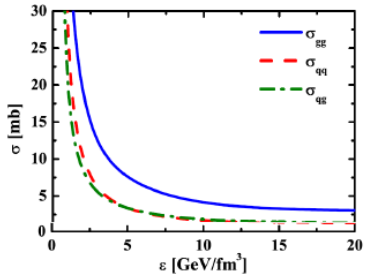

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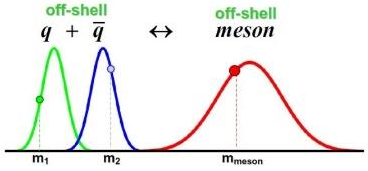
Strict 4-momentum and quantum number conservation



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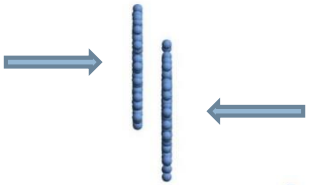

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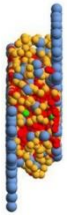

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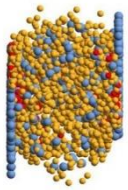

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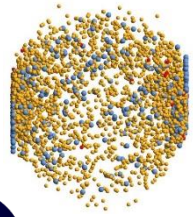

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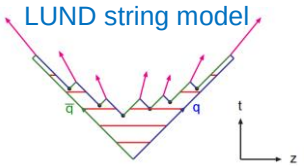

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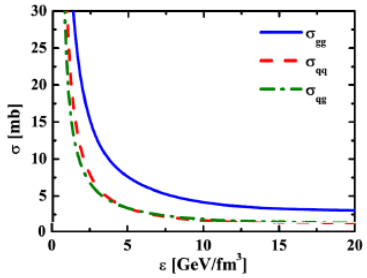

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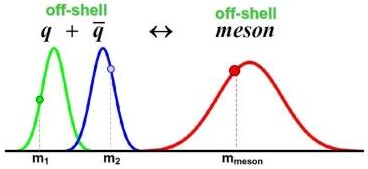
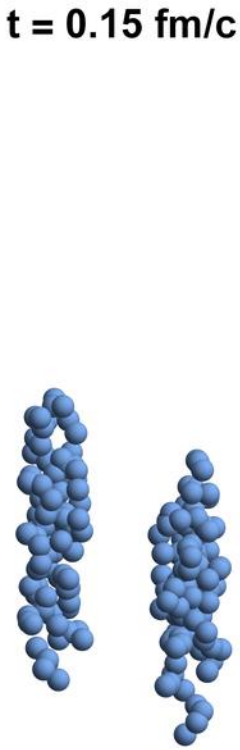


- **Hadron-string interactions – off-shell HSD**

Stages of a collision in PHSD



P.Moreau

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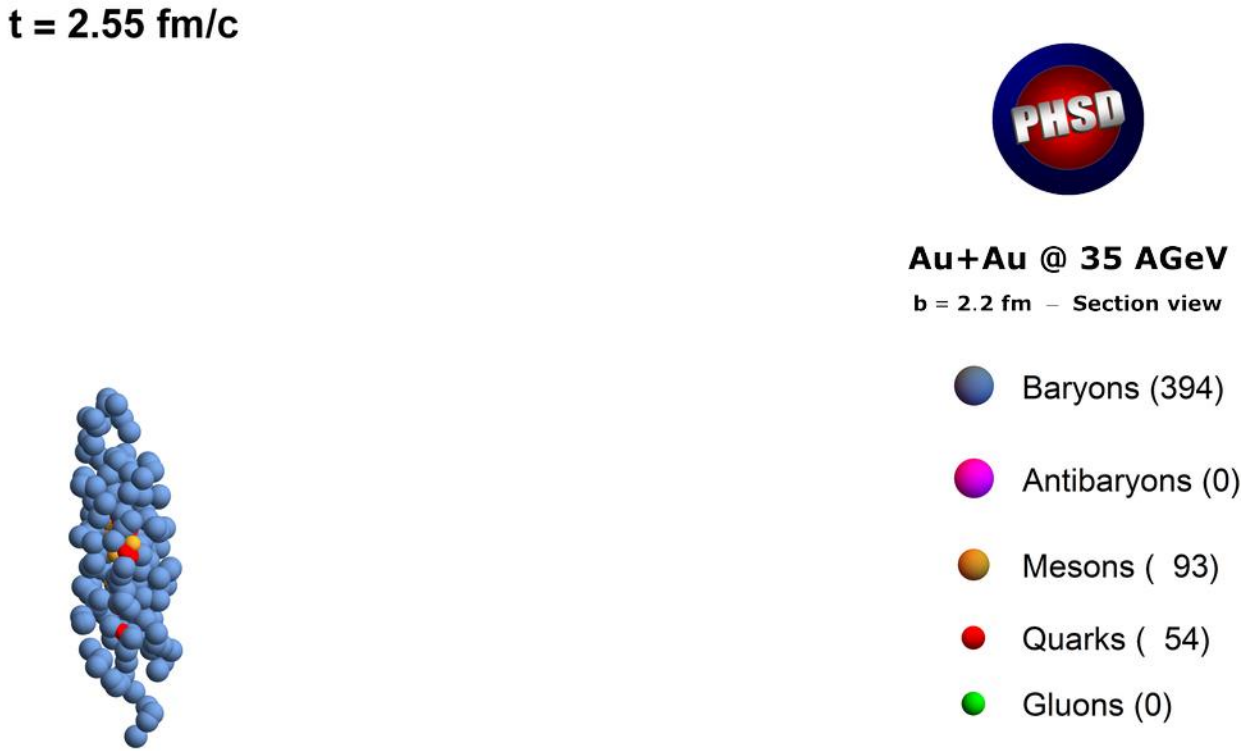

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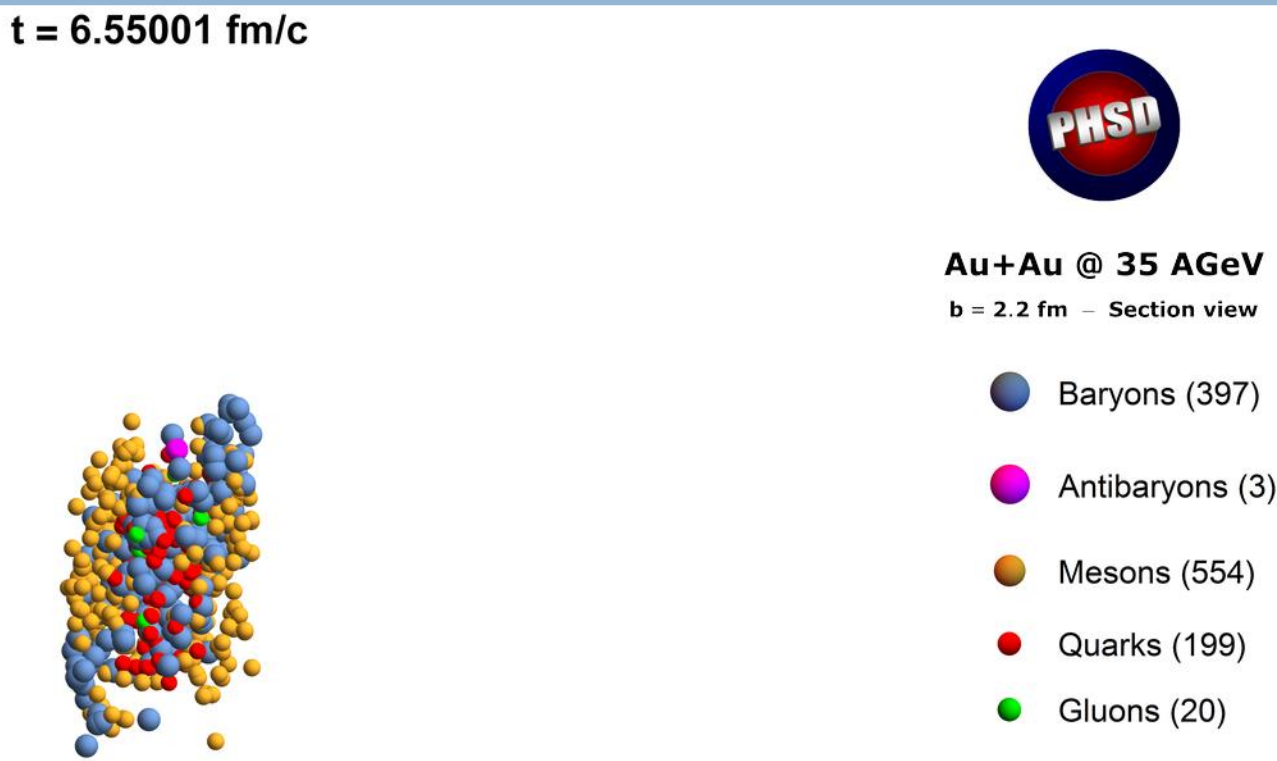

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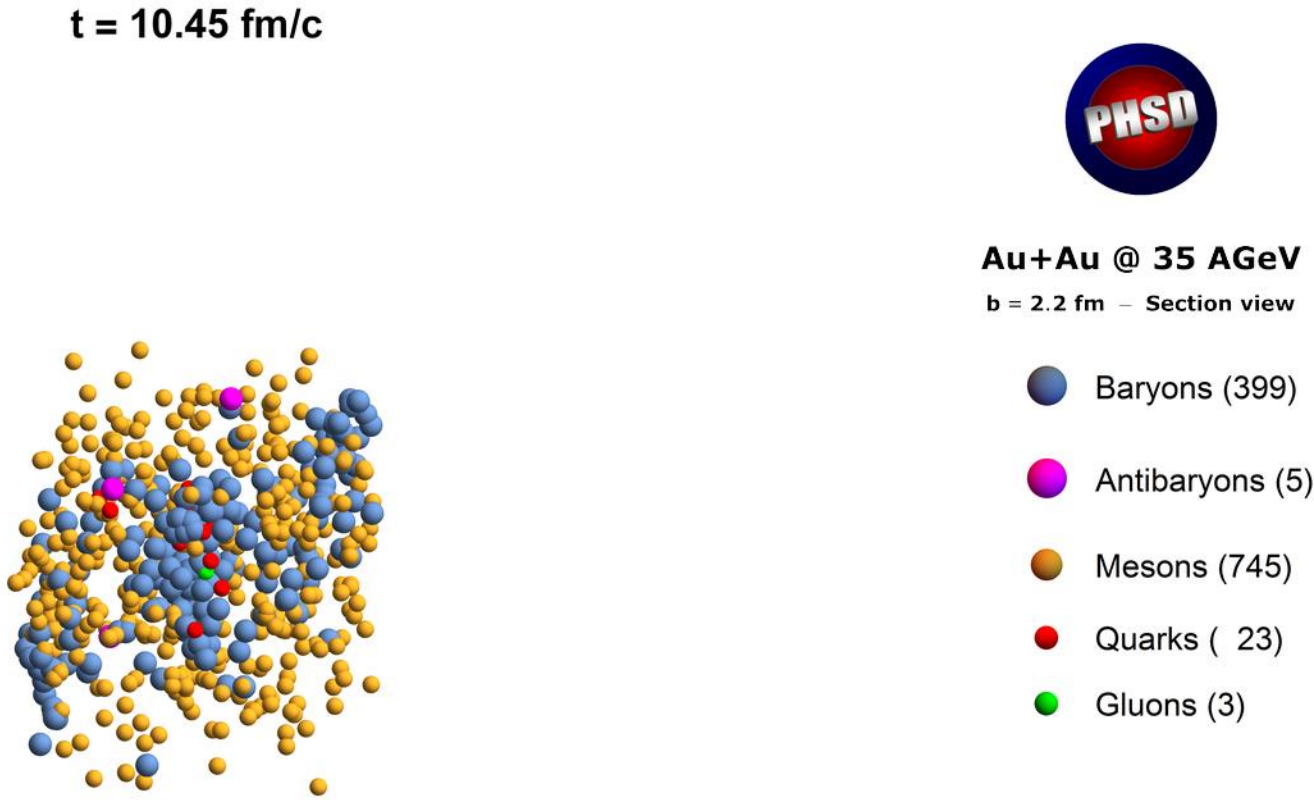

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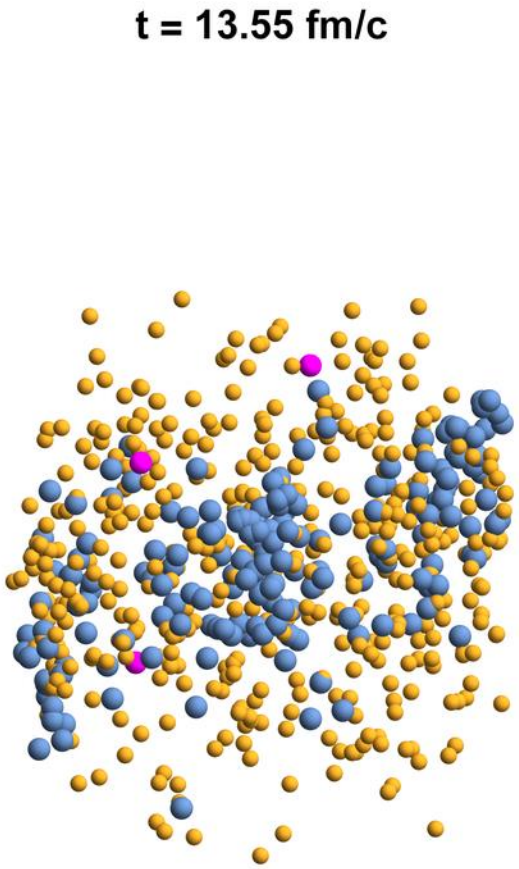

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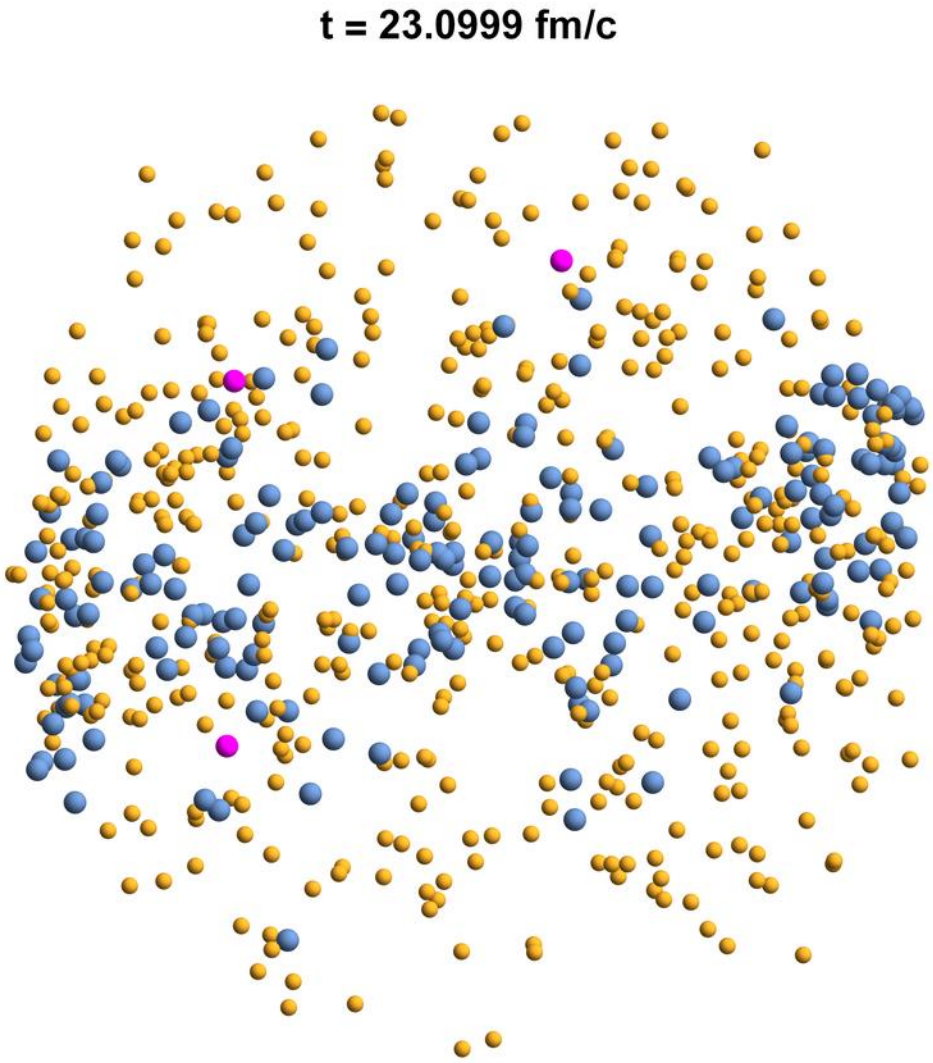

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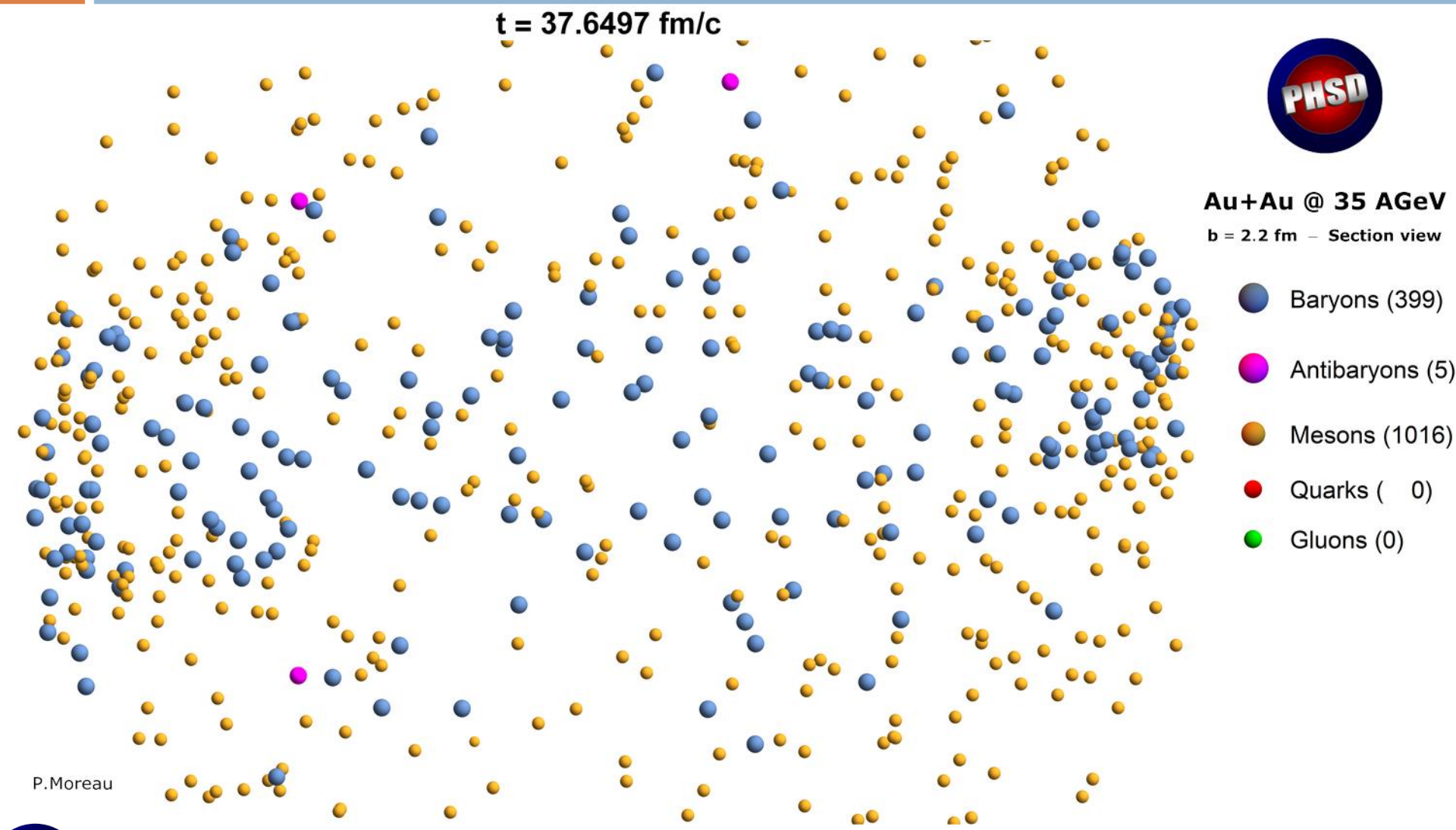
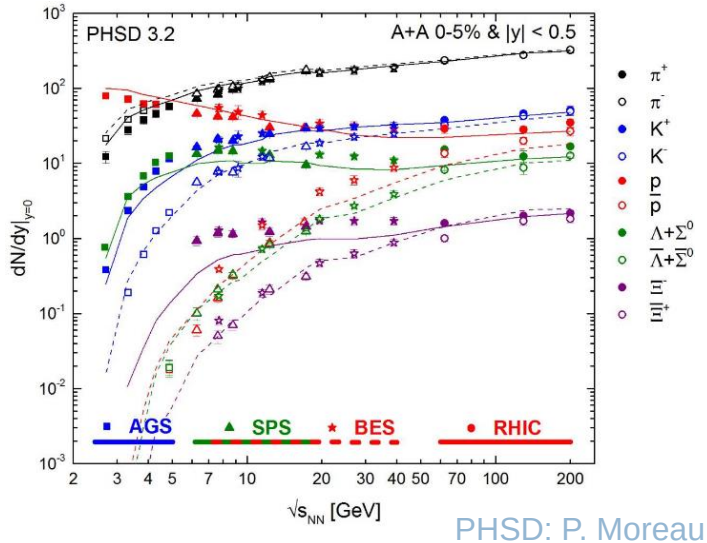
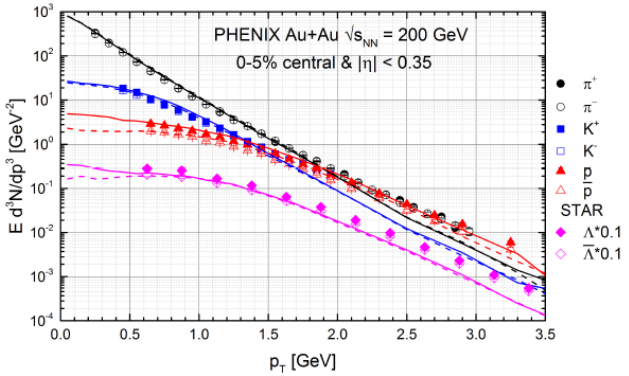


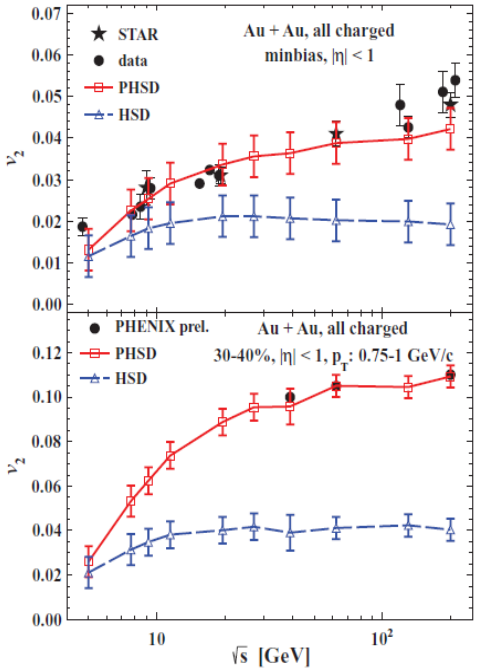
Description of A+A with PHSD



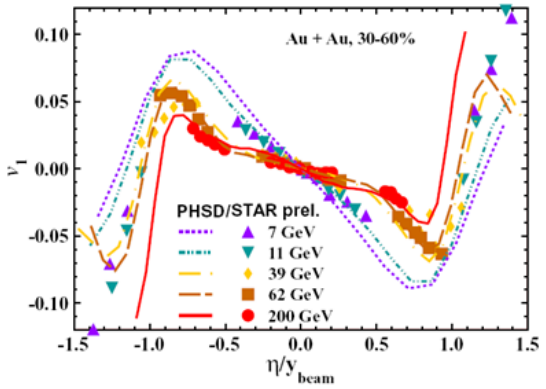
PHSD: P. Moreau

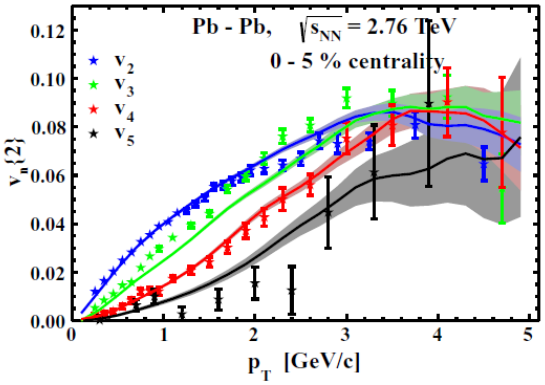


PHSD highlights



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

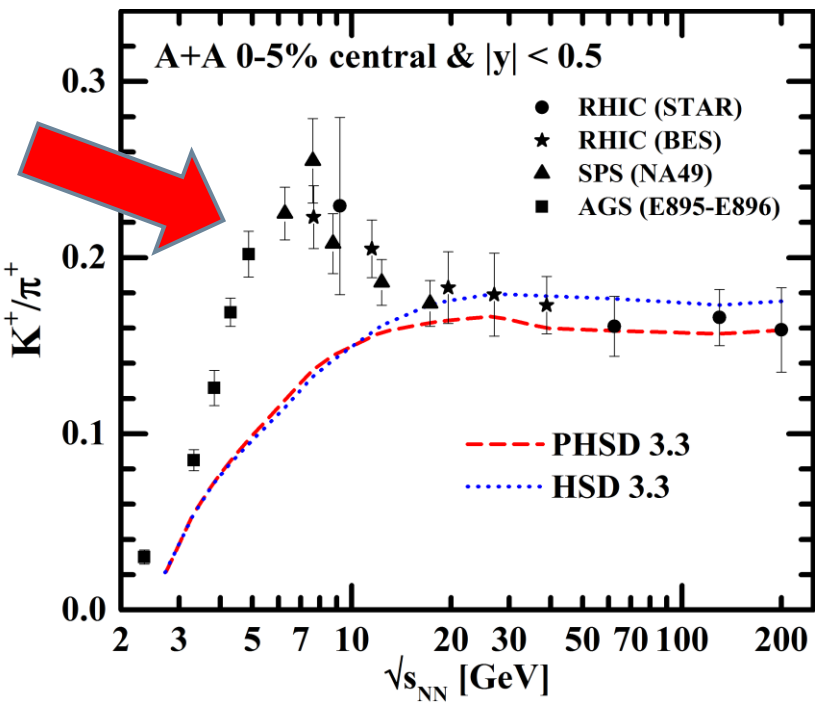


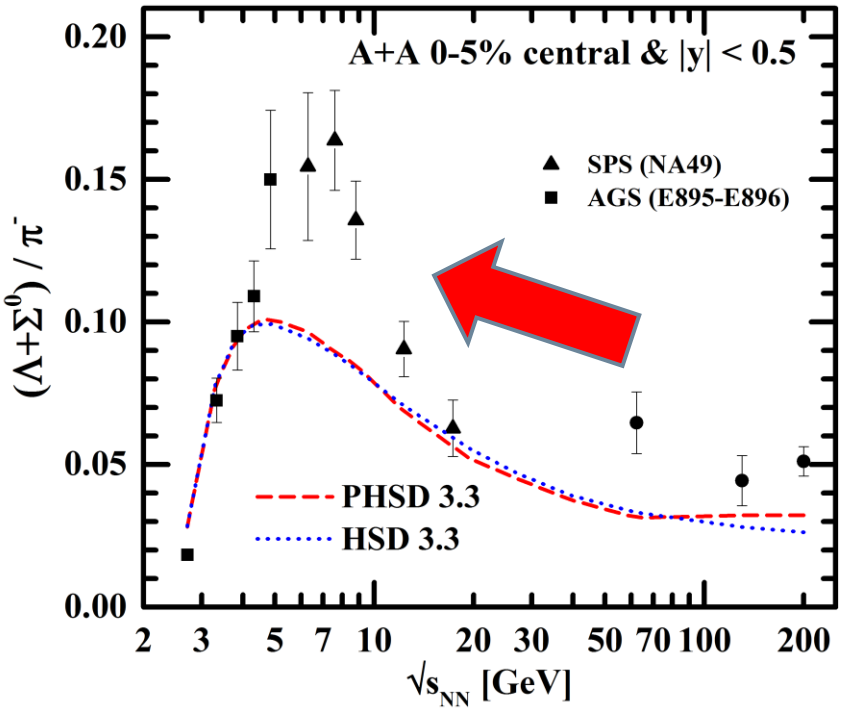


PHSD provides a good description of 'bulk' observables (y-, p_T-distributions, flow coefficients v_n) from SIS to LHC

Missing strangeness ?

- **Even considering the creation of a QGP phase, the strangeness enhancement seen experimentally by NA49 and STAR at ~ 20-30 AGeV collisions remains puzzling**
  - **'Horn' not traced back to deconfinement**

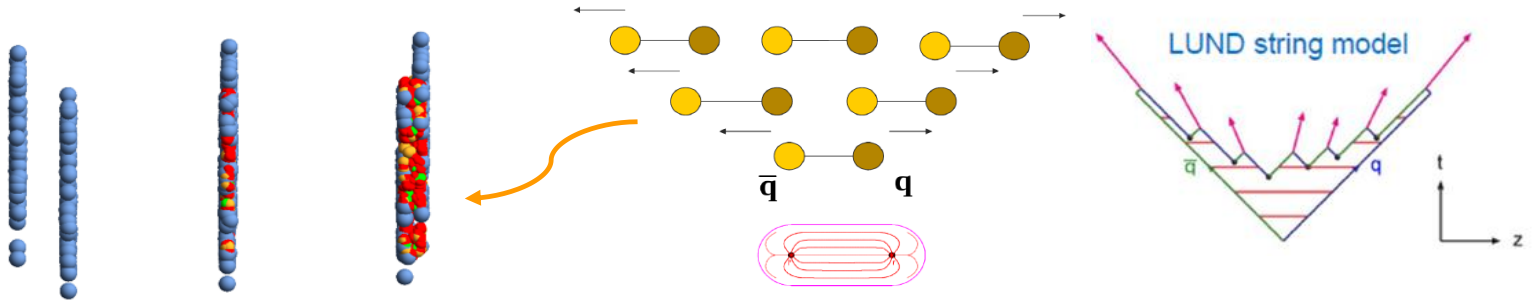




W. Cassing, A. Palmese, P. Moreau, E.L. Bratkovskaya - **Phys.Rev. C93 (2016), 014902**

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 vaccum: $\kappa \sim 0.9$ GeV/fm $= 0.176$ GeV²

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 :** $m_q\ (q = u, d) \approx 0.35$ **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

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

Gell-Mann-Oakes-Renner relation:

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

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 *σ(x)* mediates the scalar interaction of baryons with a g_s coupling. *σ(x)* is determined locally by the nonlinear gap equation:

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

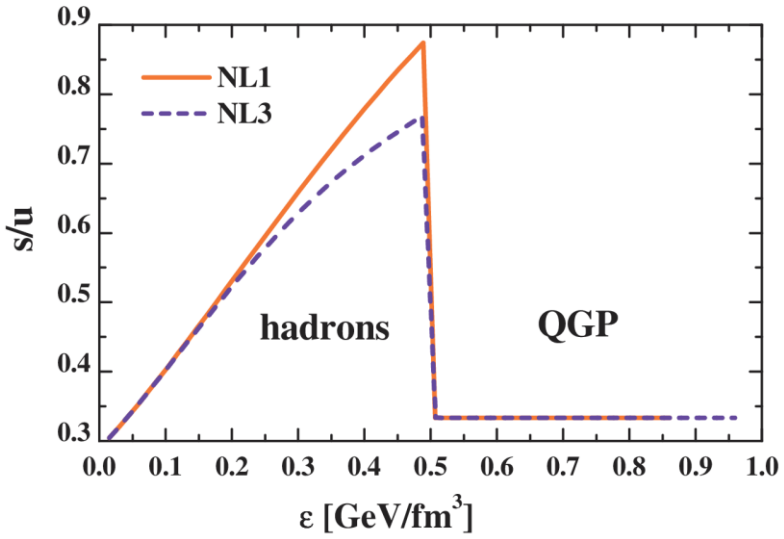
Parameters m_σ, g_s, B, C are fixed to reproduce properties of nuclear matter at saturation

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

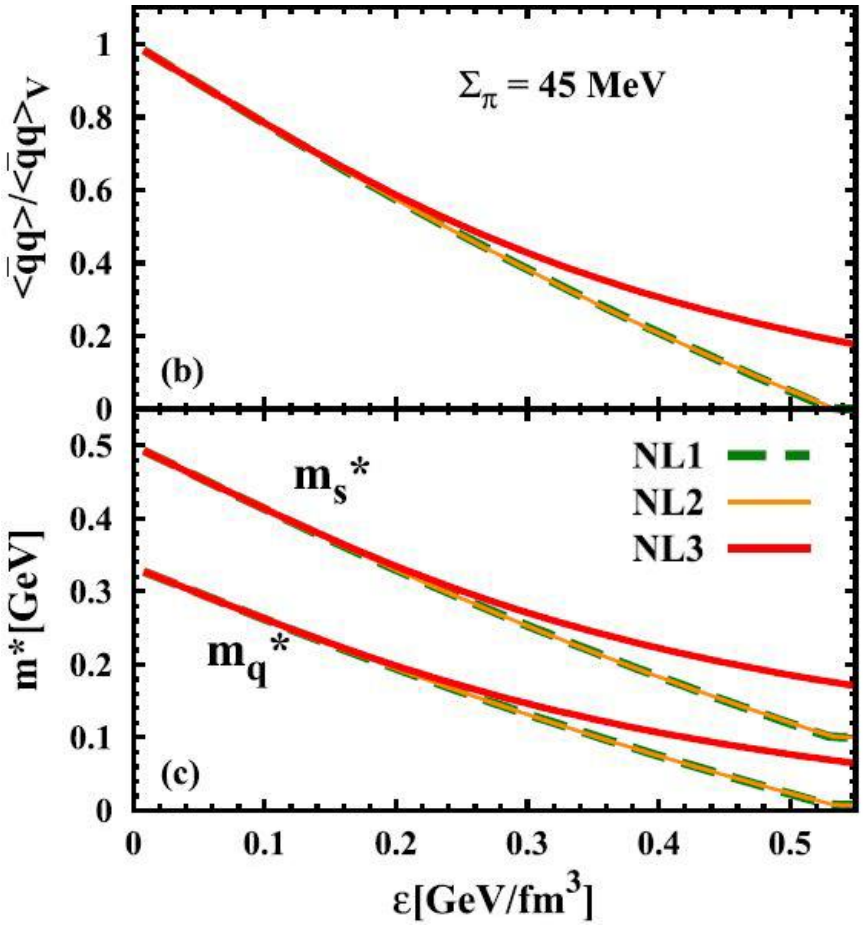
Chiral symmetry restoration vs deconfinement

- **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.**



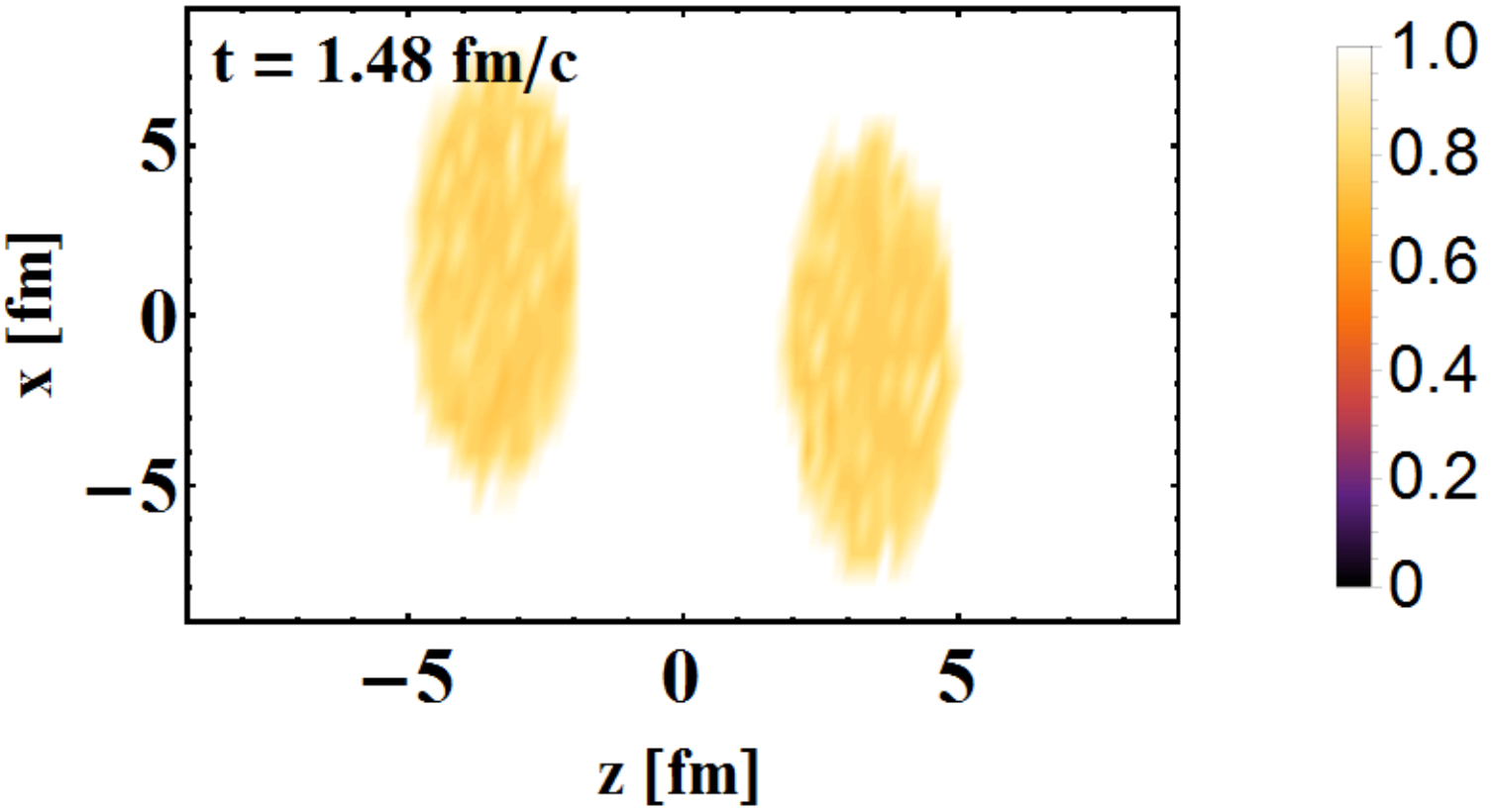
$T = 0$ in this illustration



Pb+Pb @ 30 AGeV – 0-5% central

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

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



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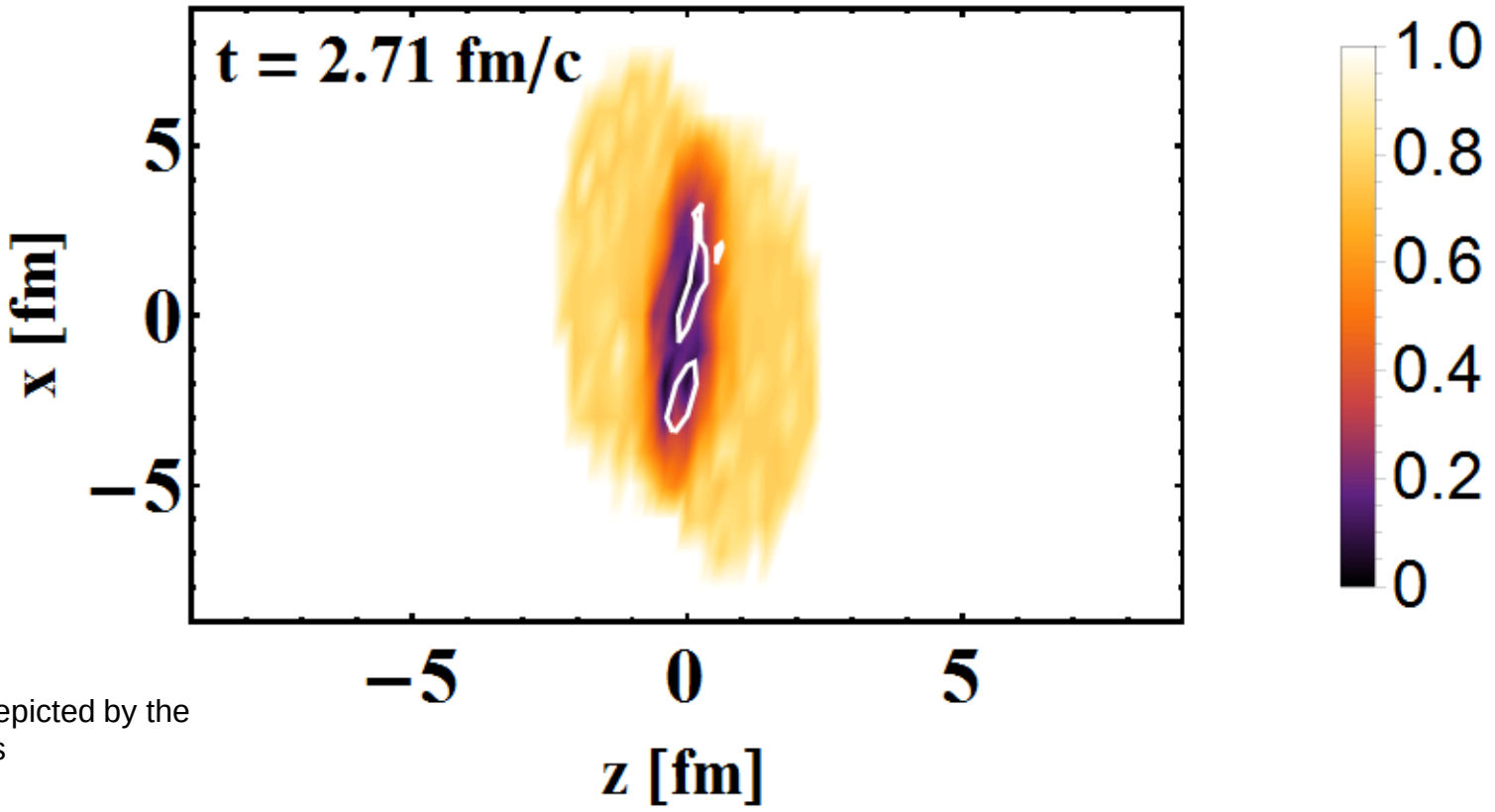

QGP phase depicted by the white contours

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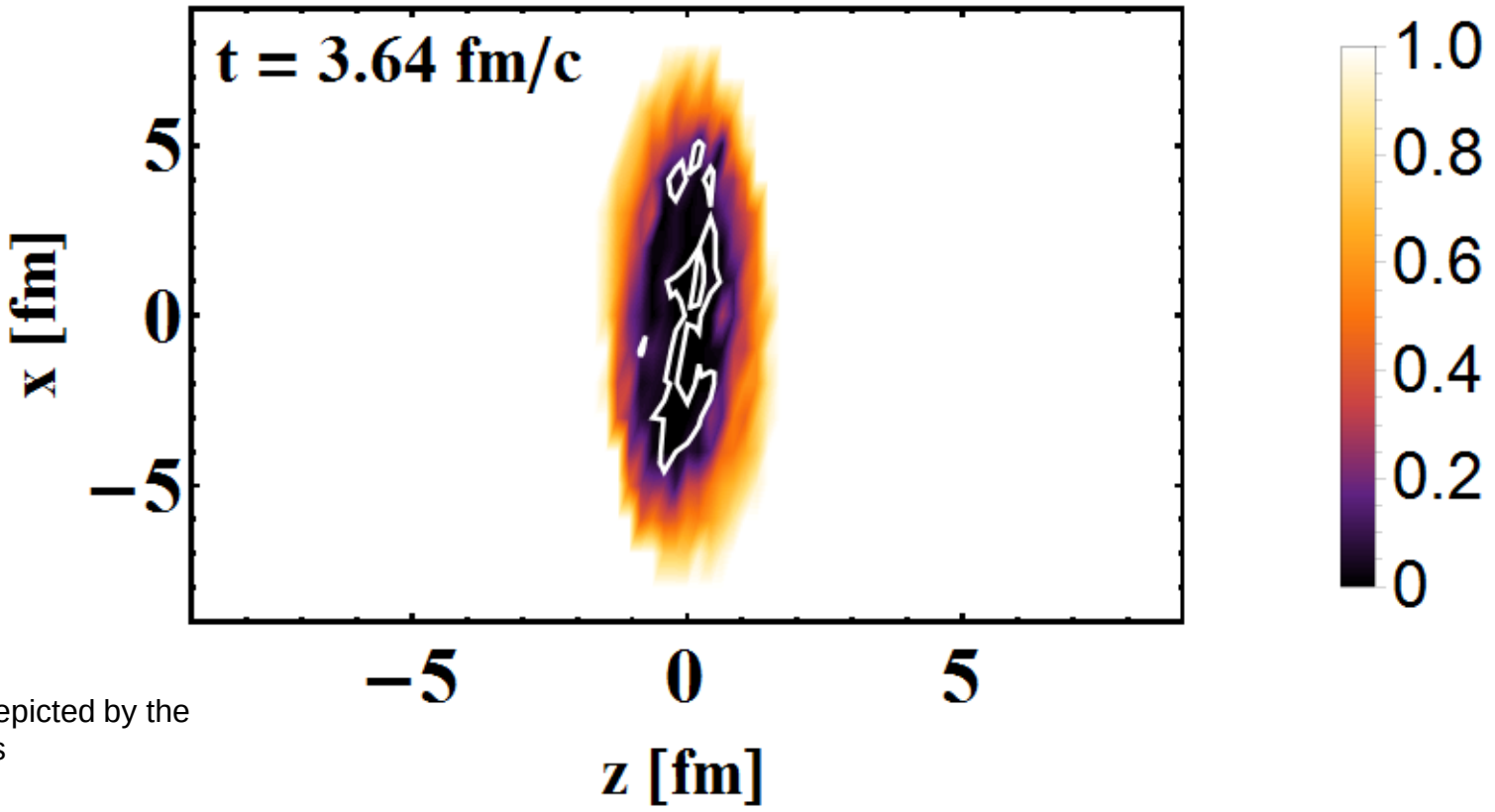

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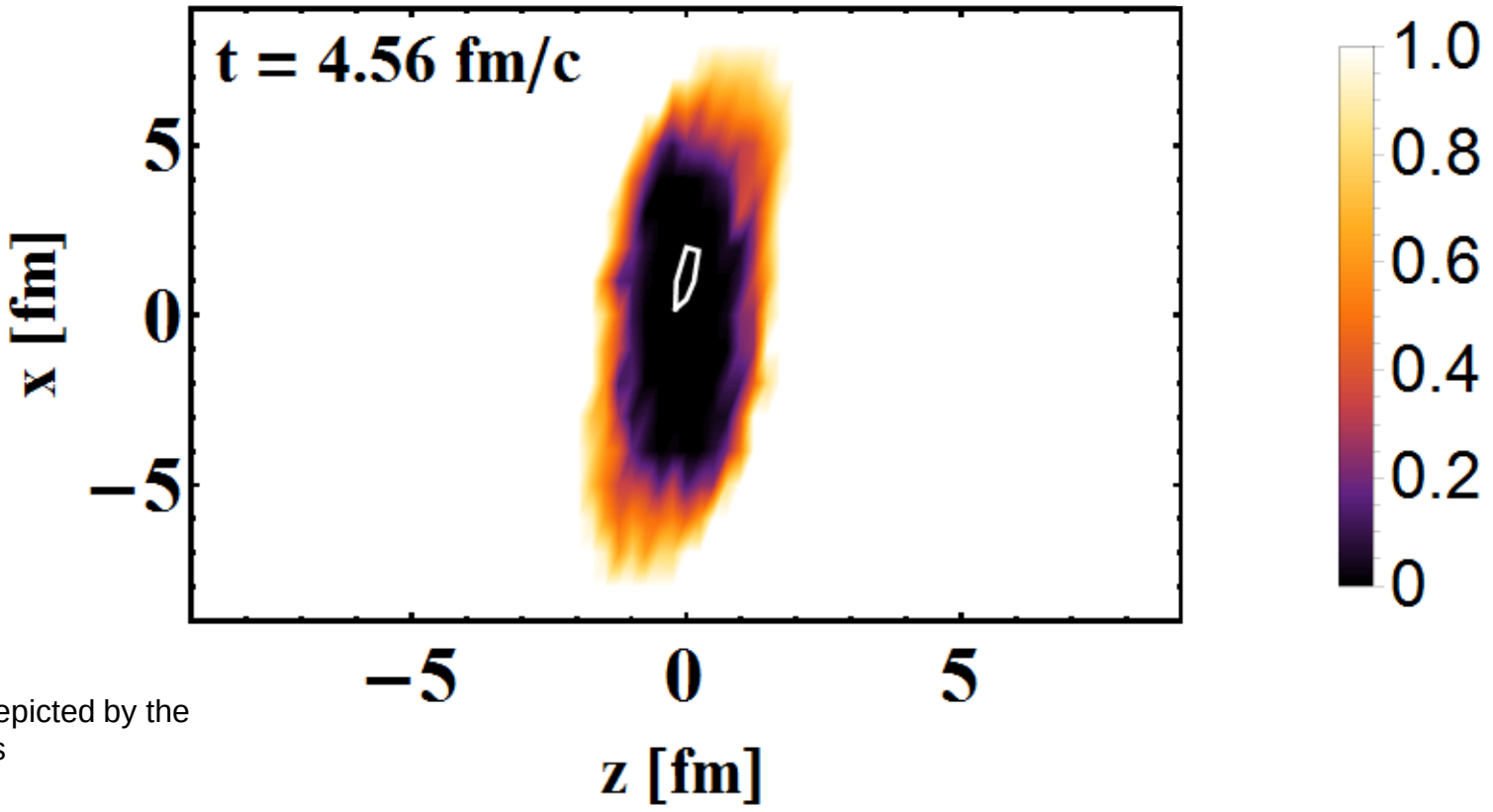

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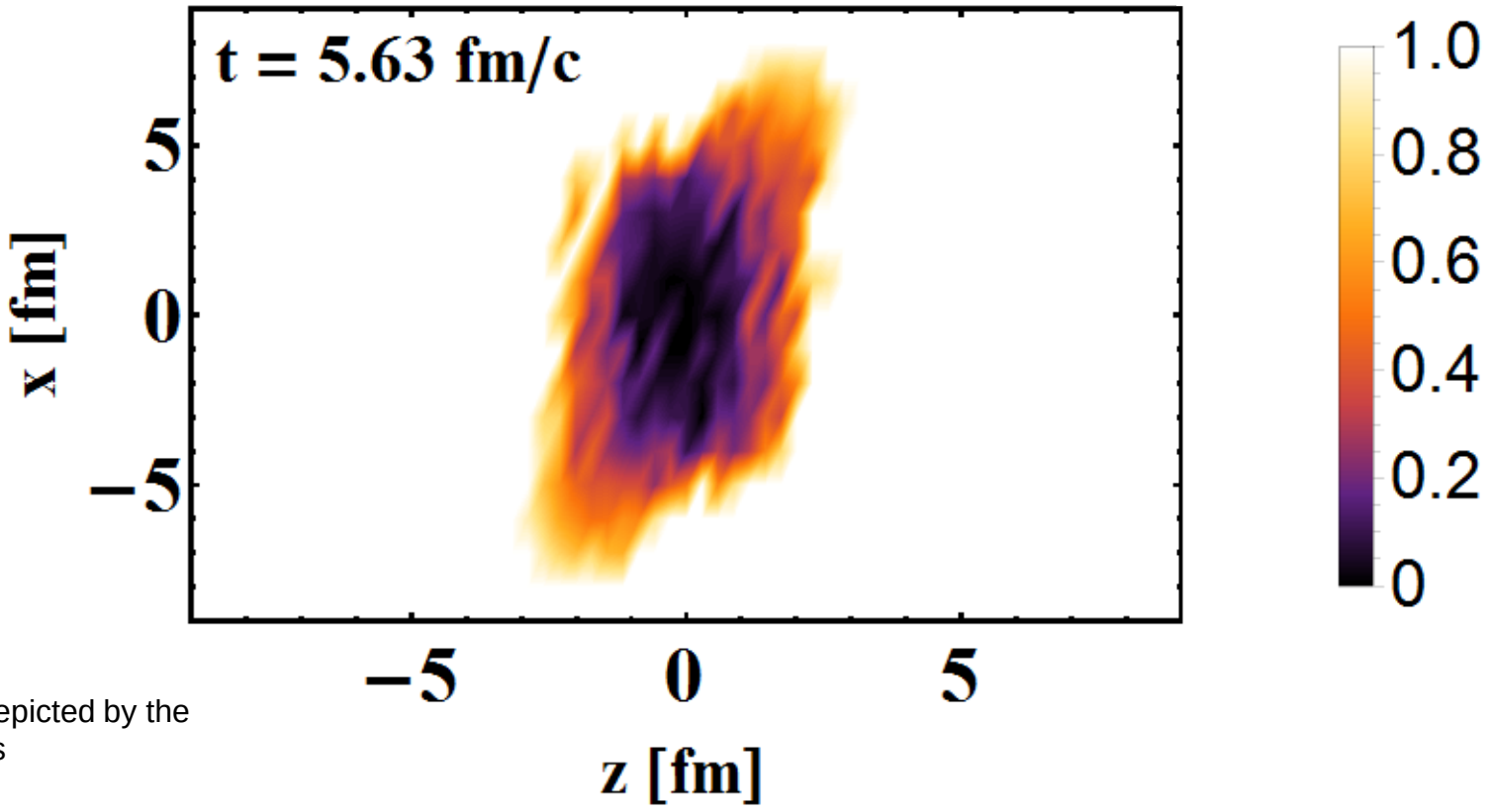

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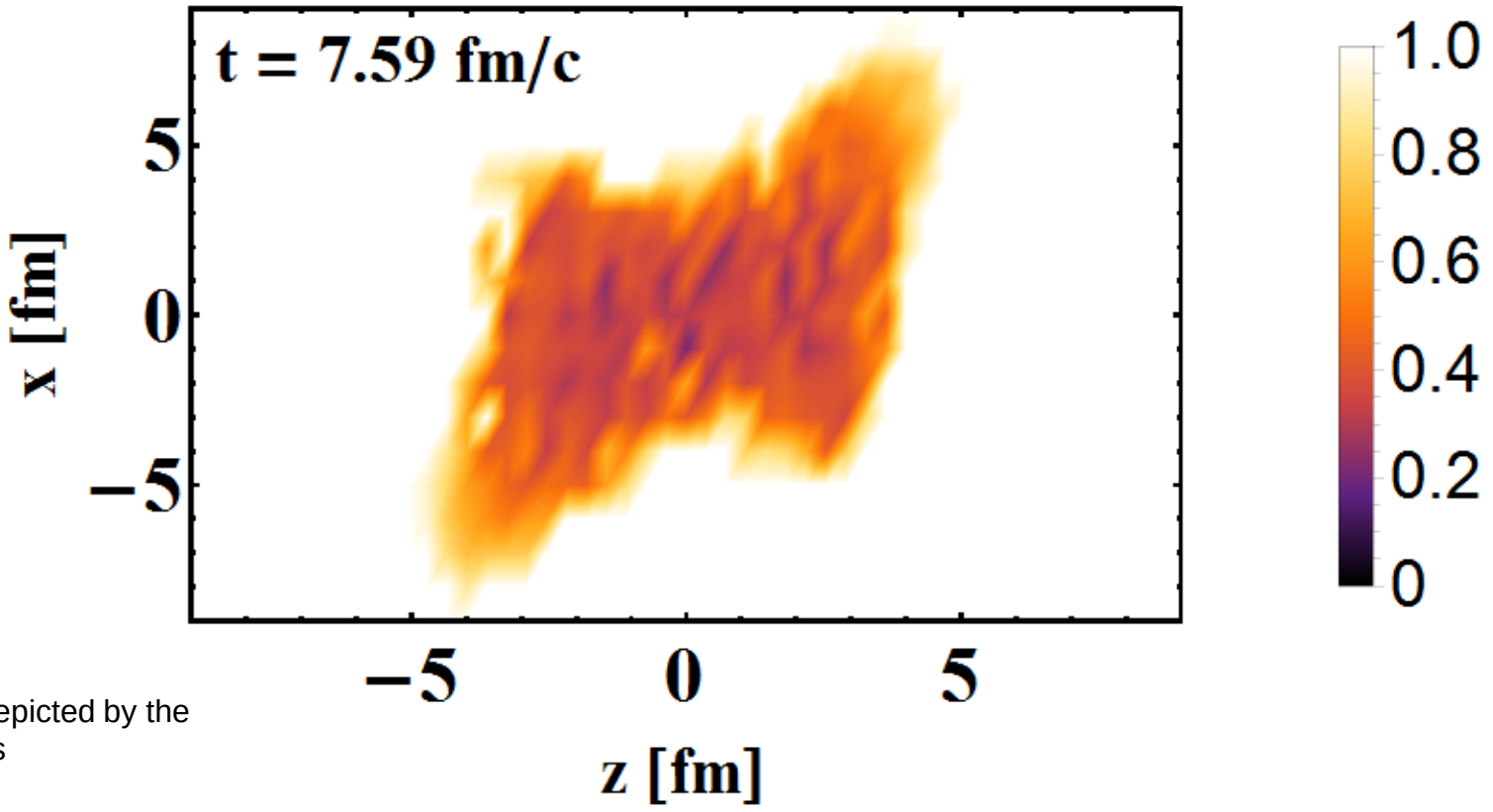

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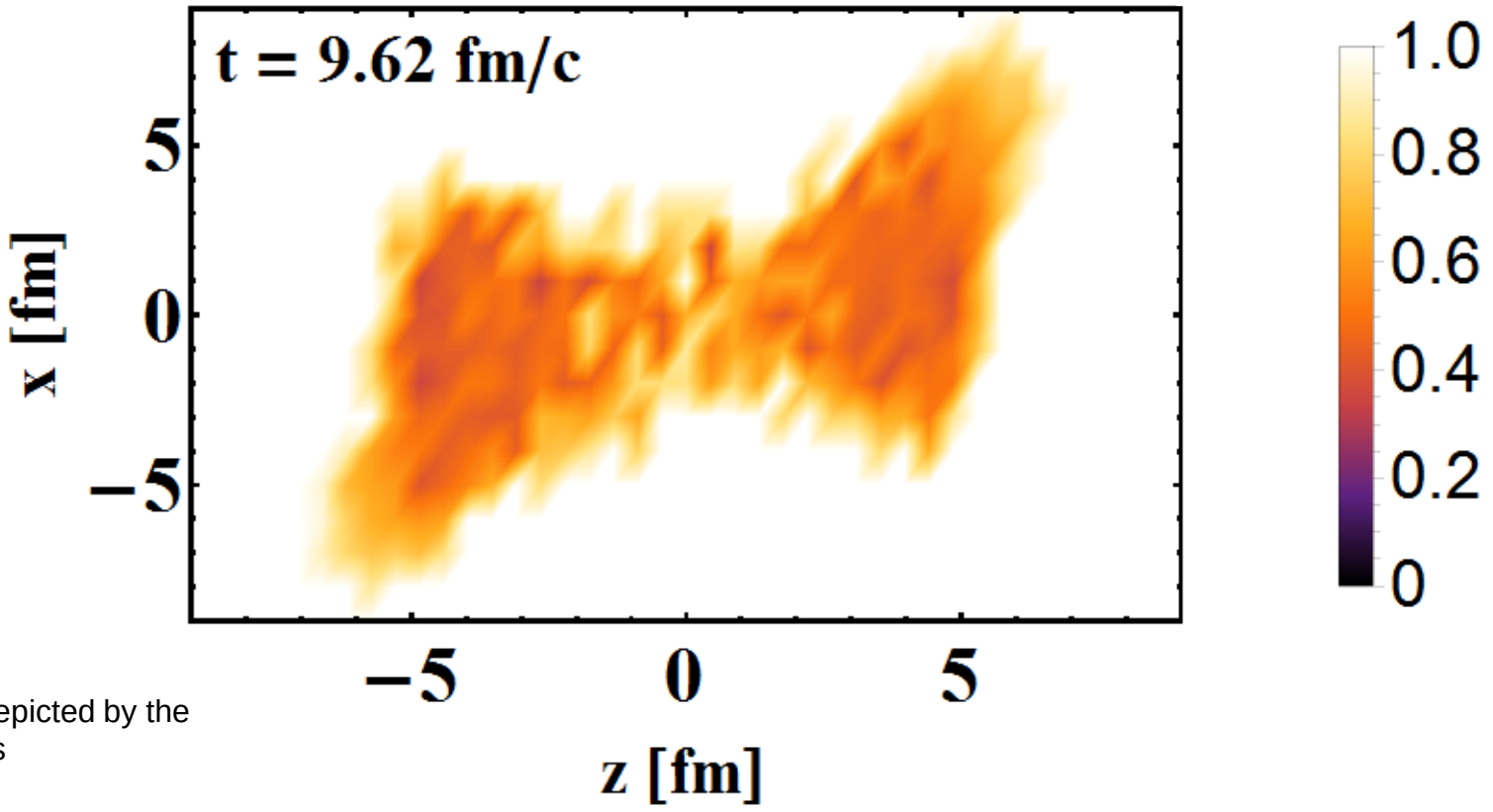

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Pb+Pb @ 30 AGeV – 0-5% central

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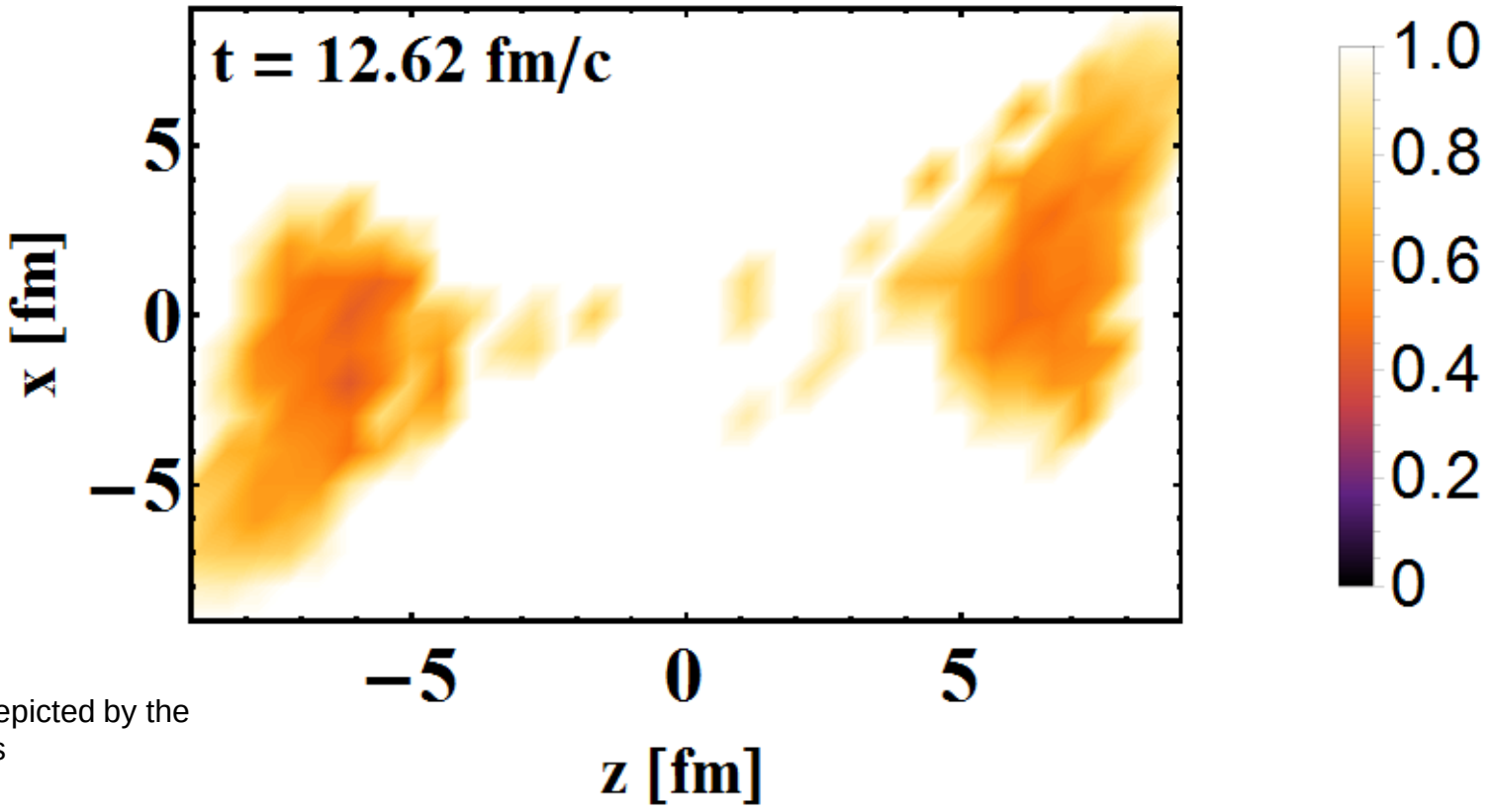
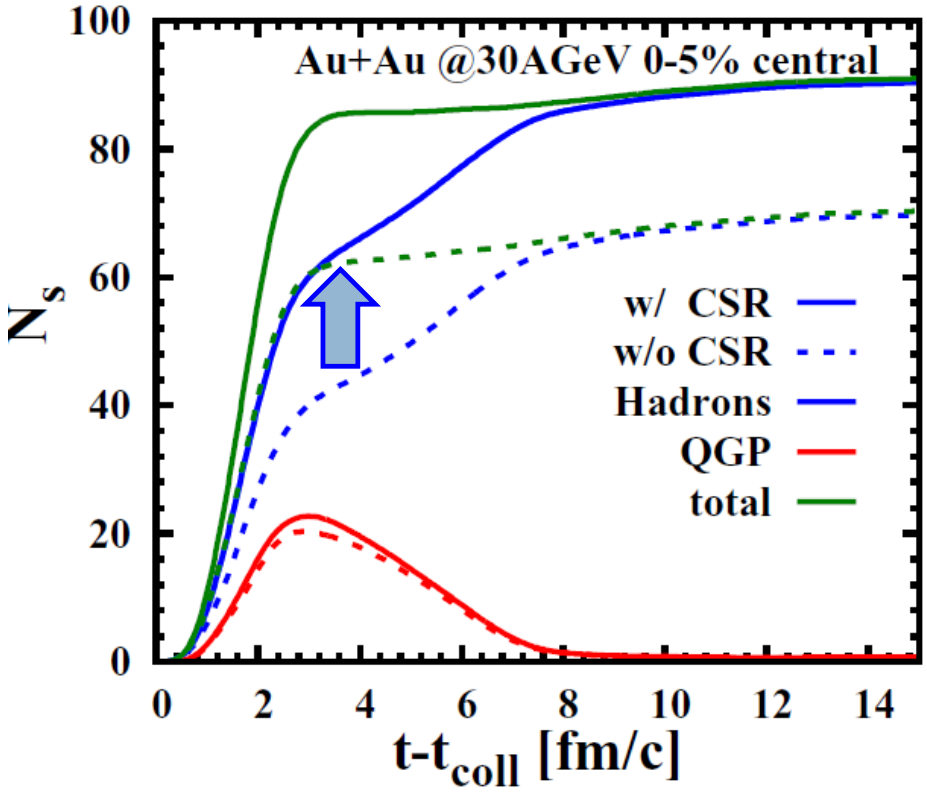


QGP phase depicted by the white contours

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

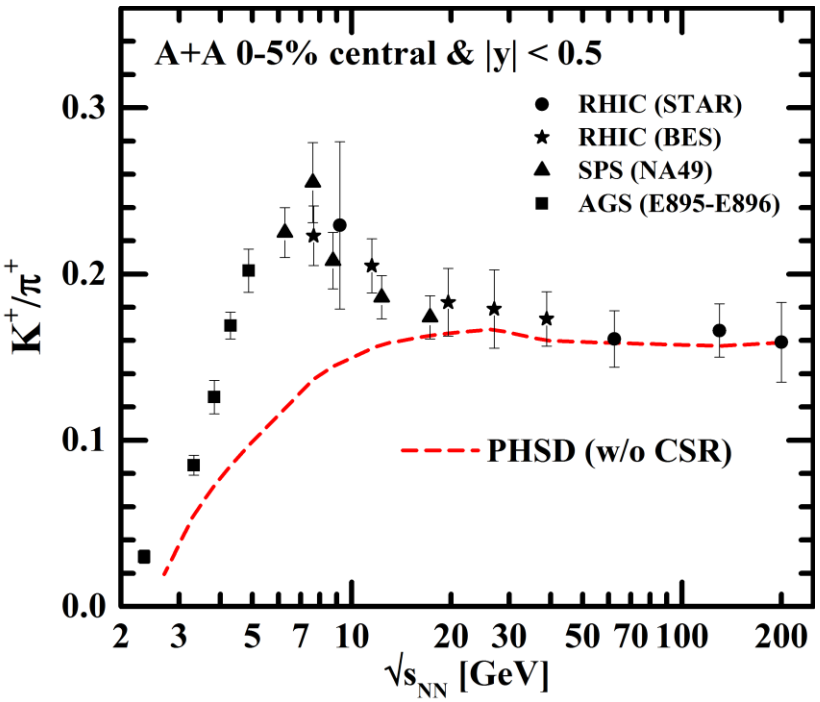
Strange particle number Ns as a function of time

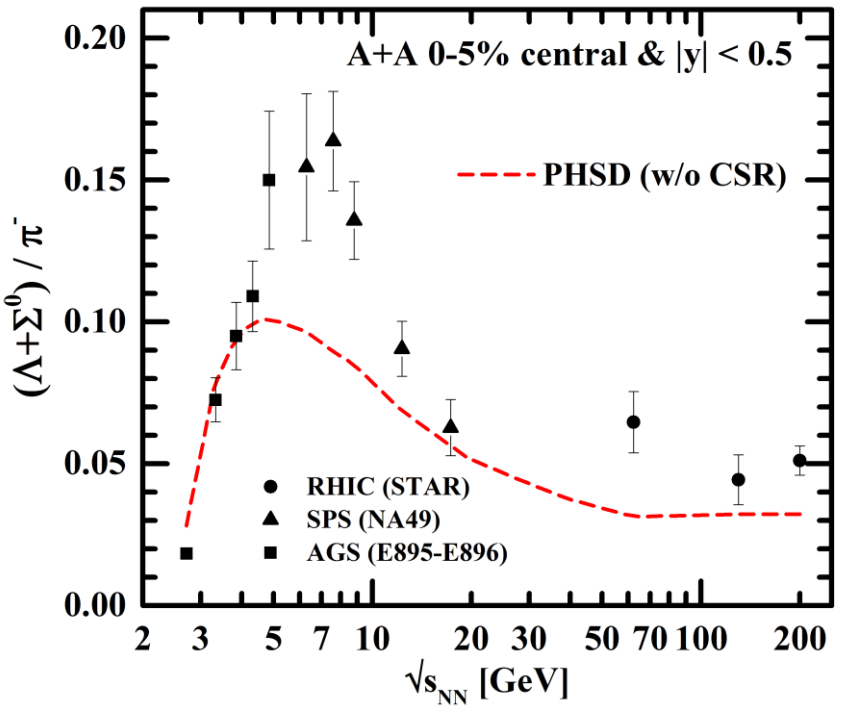
Chiral symmetry restoration in the hadronic phase

- **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**

$$\frac{K^+}{\pi^+} \sim \frac{u\bar{s}}{u\bar{d}} \qquad \frac{\Lambda+\Sigma^0}{\pi^-} \sim \frac{uds}{\bar{u}d}$$





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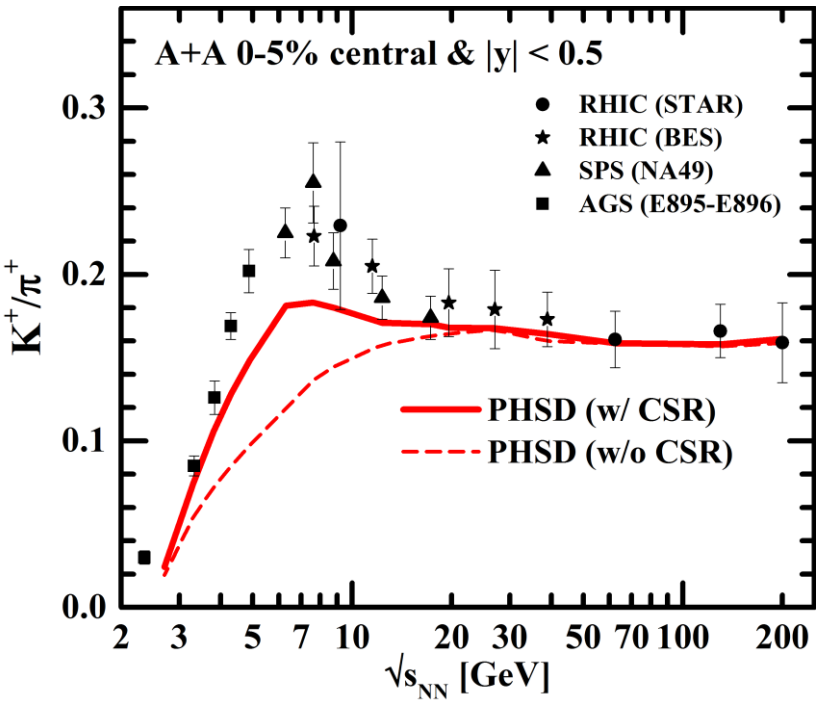

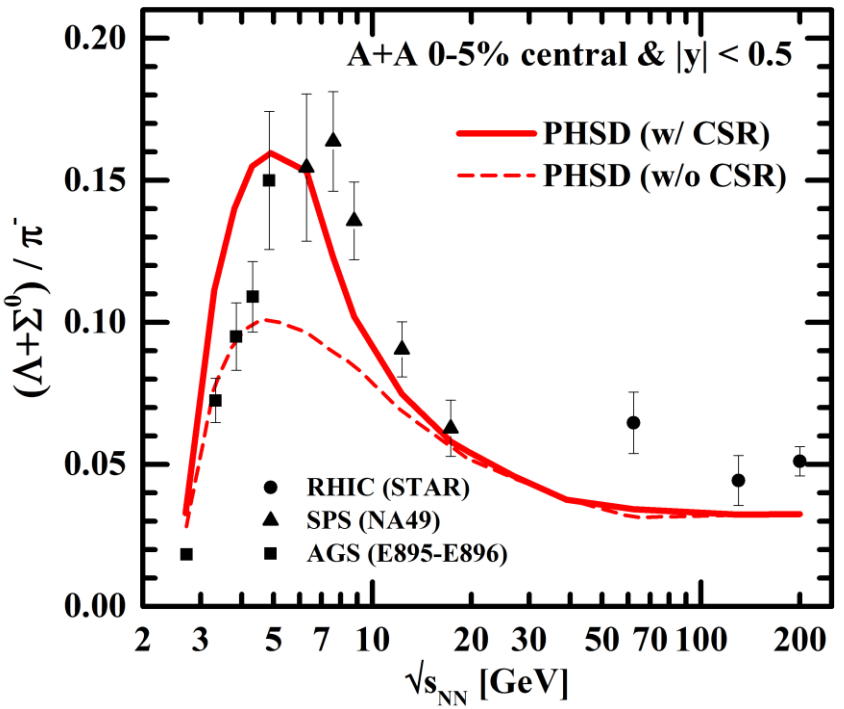

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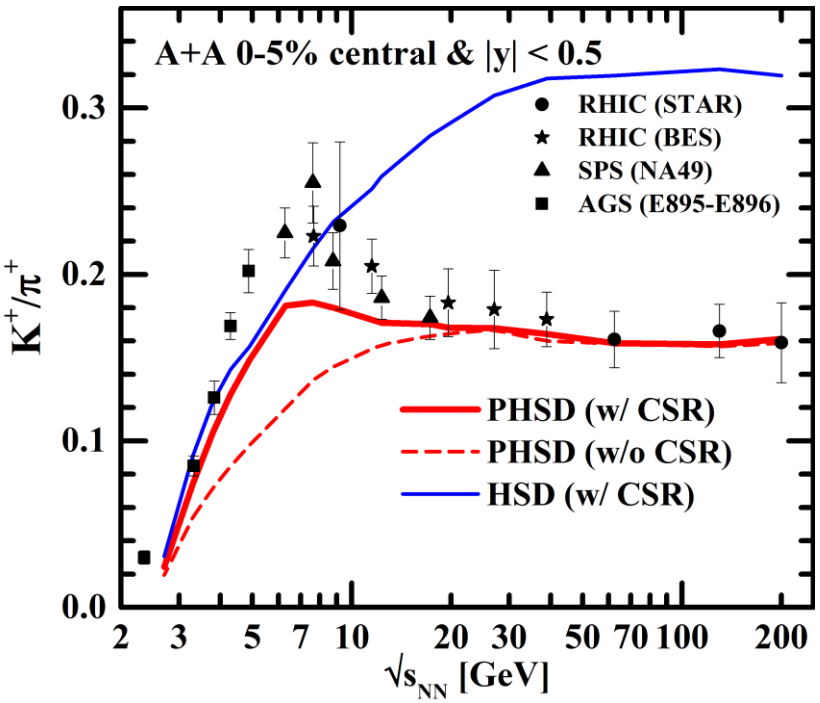
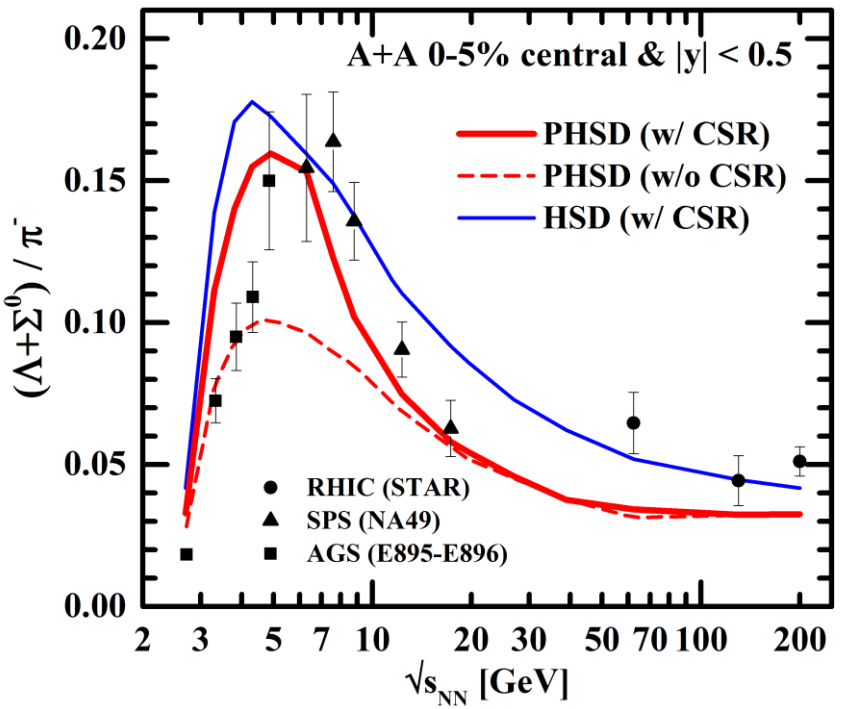
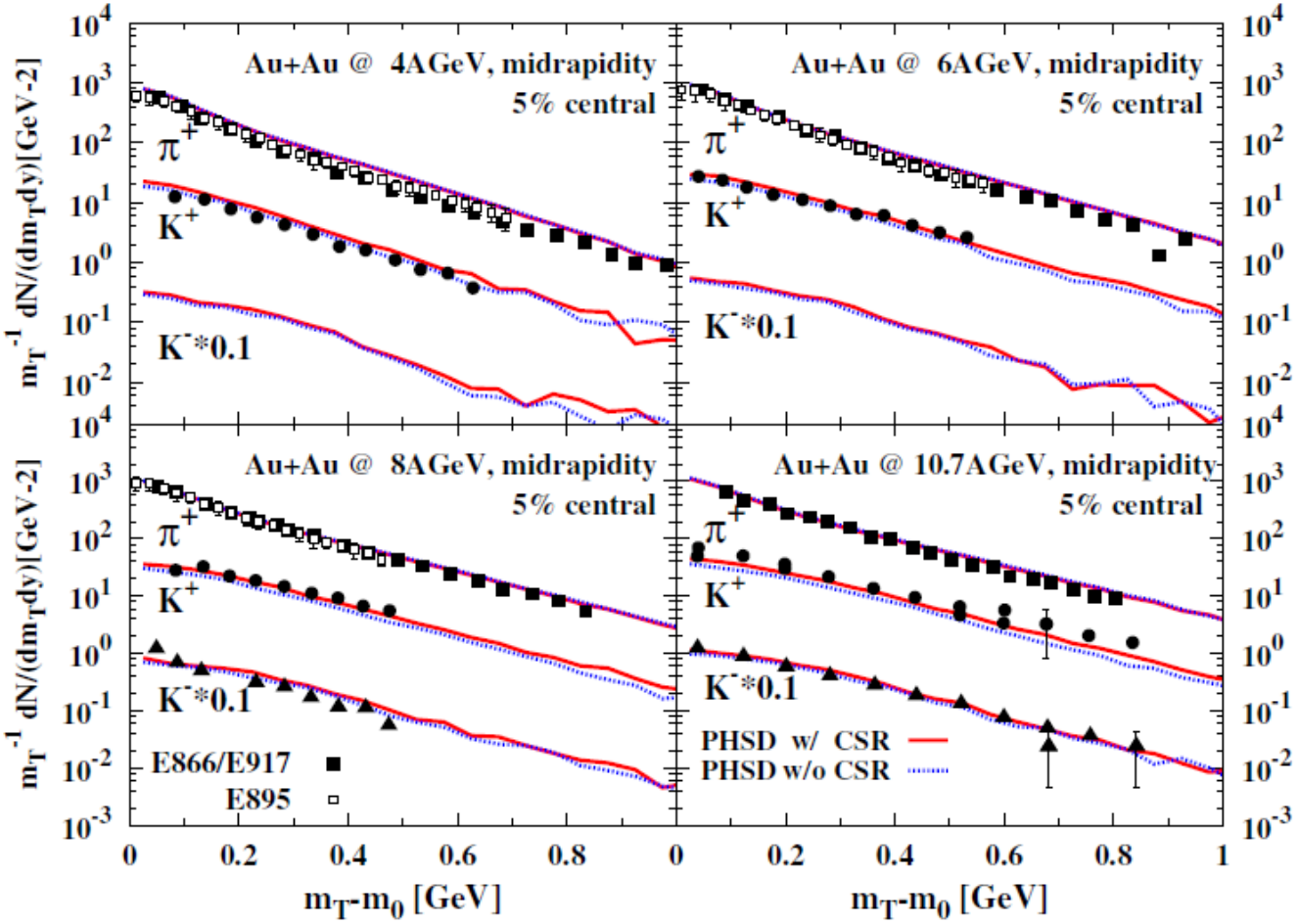


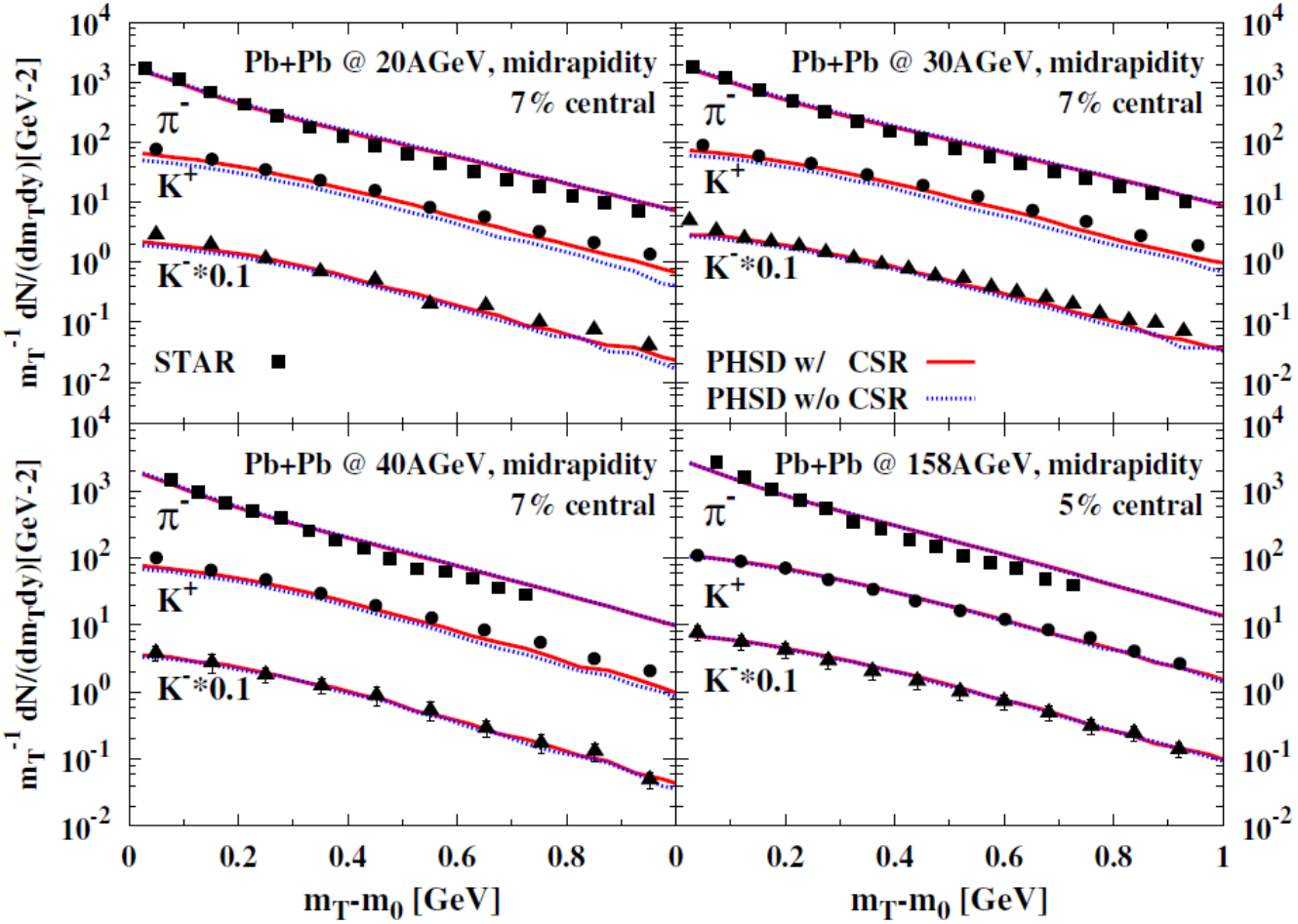


m_T spectra of pions and kaons at AGS energies



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

m_T spectra of pions and kaons at SPS energies

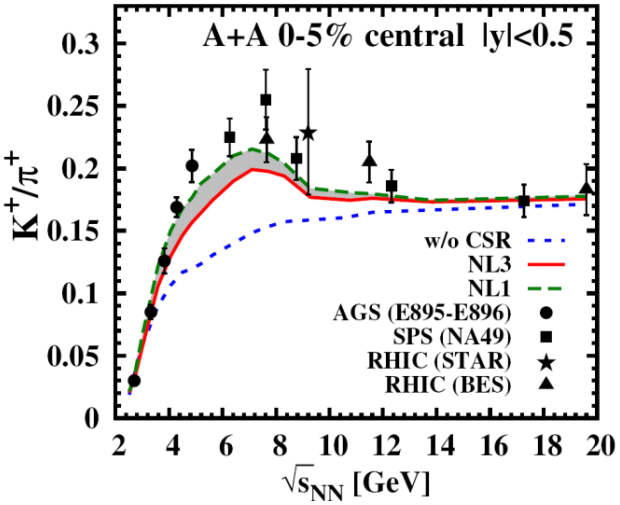


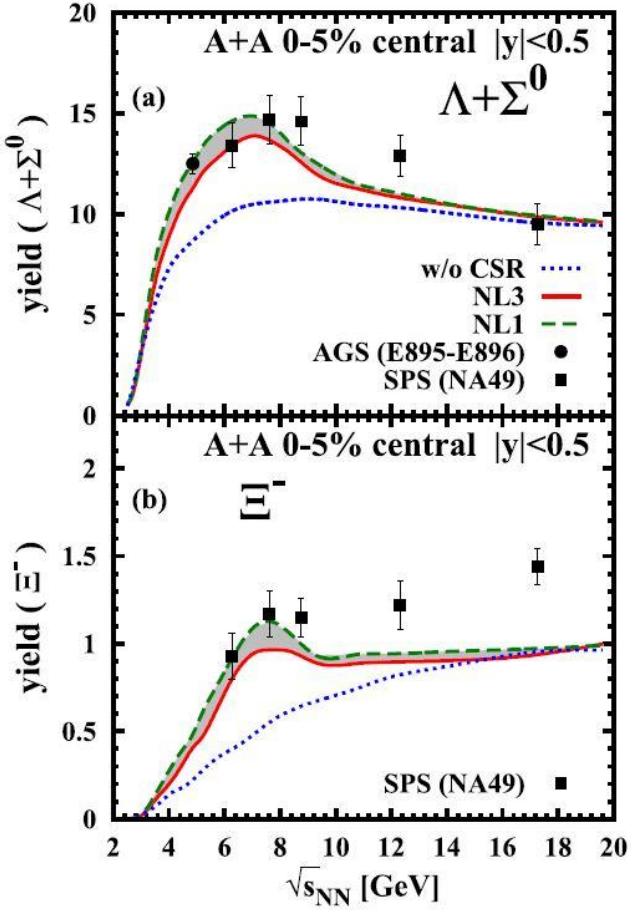
Palmese et al., **PRC94 (2016) 044912**, arXiv:1607.04073

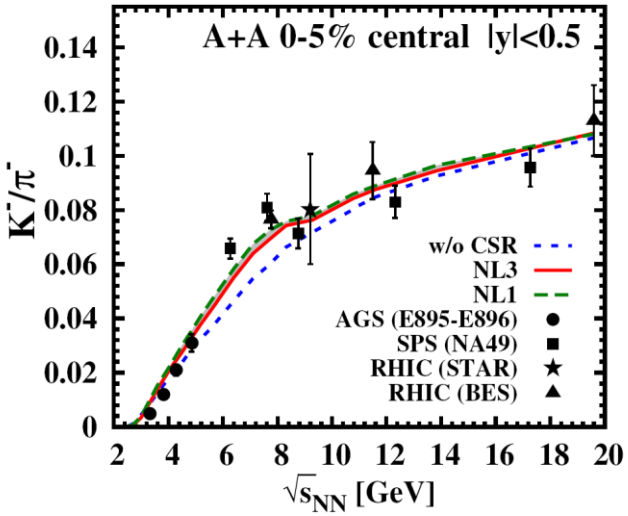
Sensitivity to the nuclear equation of state

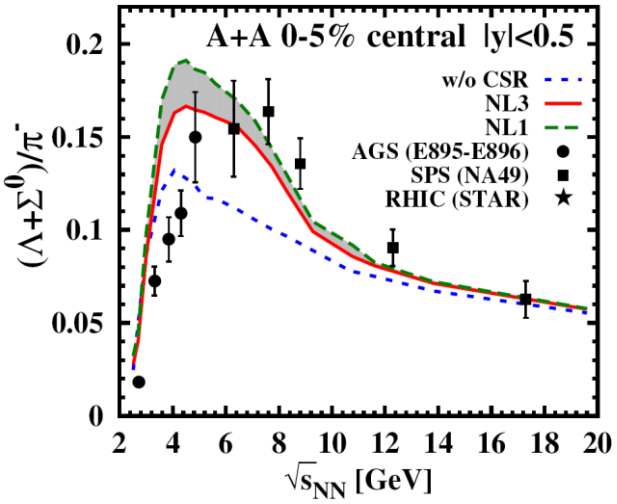
Palmese et al.,
PRC94 (2016) 044912,
arXiv:1607.04073

Low sensitivity to the nuclear equation of state!





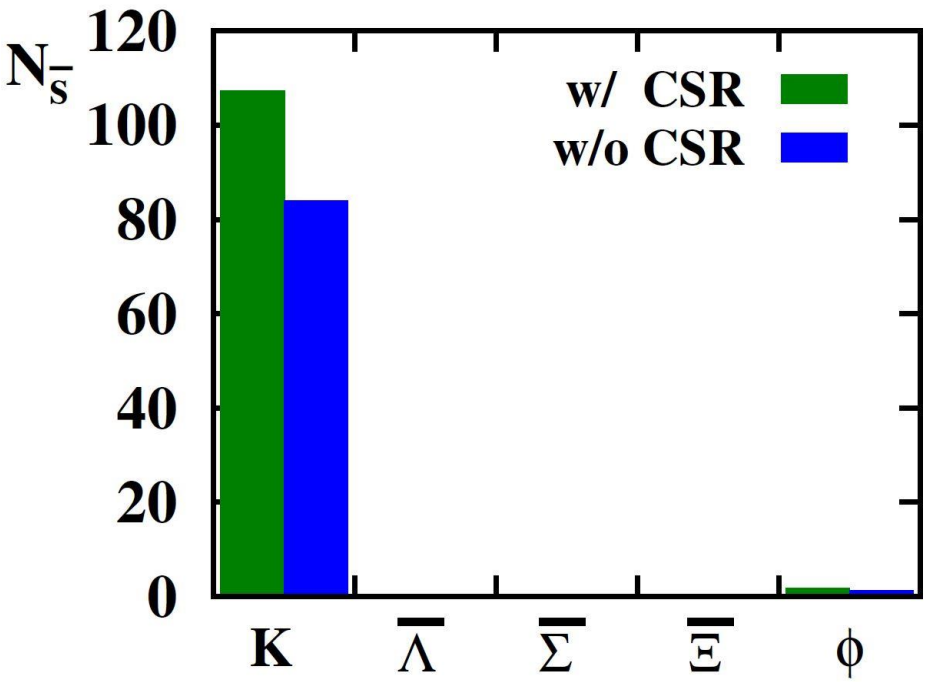


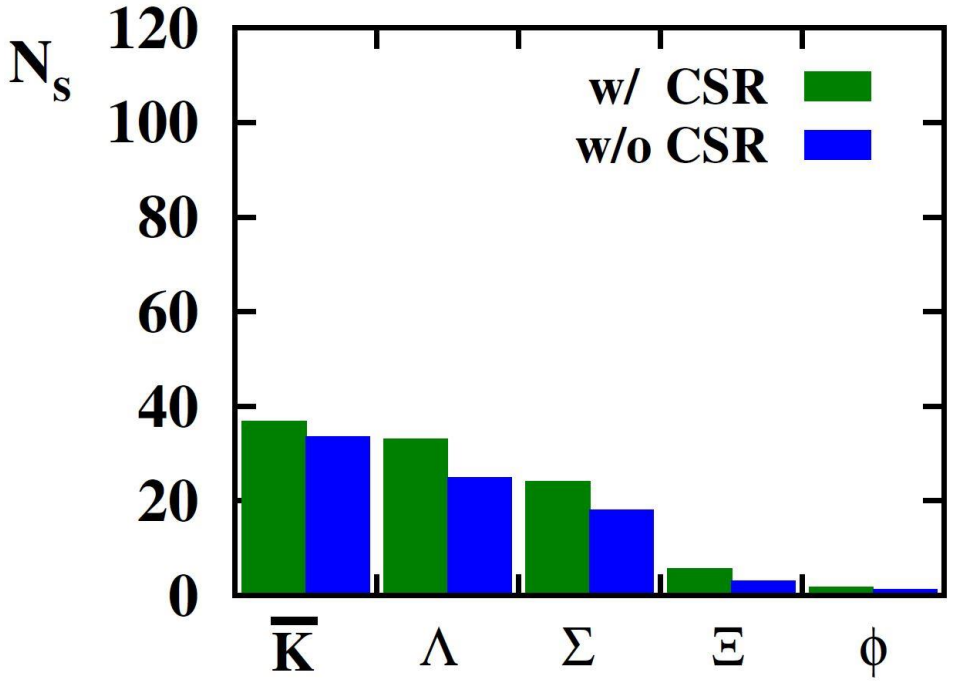


Strangeness content at low energies

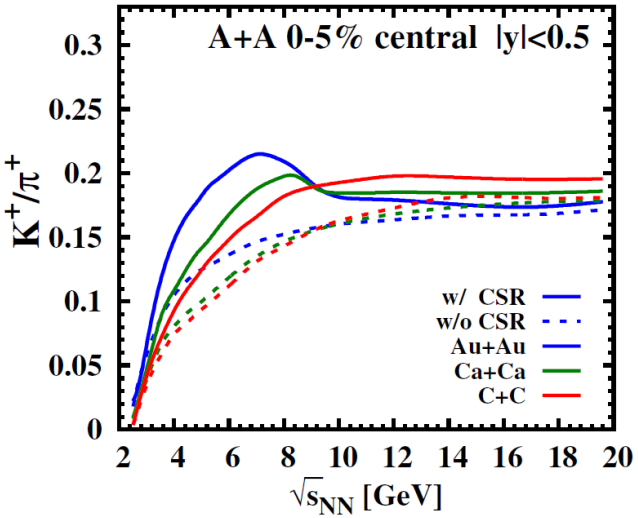
At low collisional energy, the composition of the final particles is conditioned by the composition of the initial state

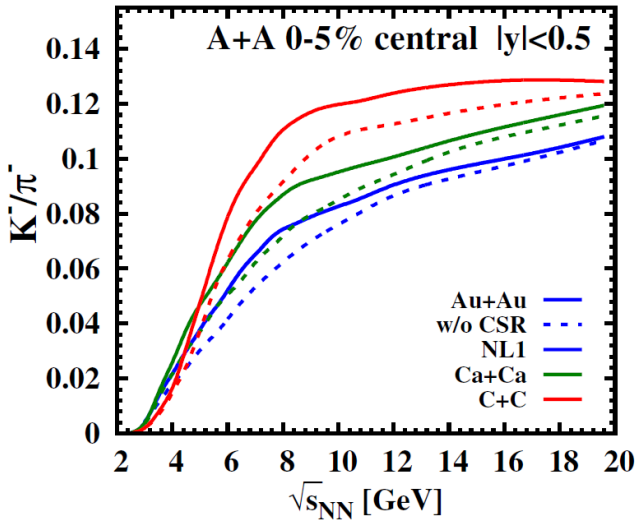
- **Production of particles containing u or d quarks is enhanced**

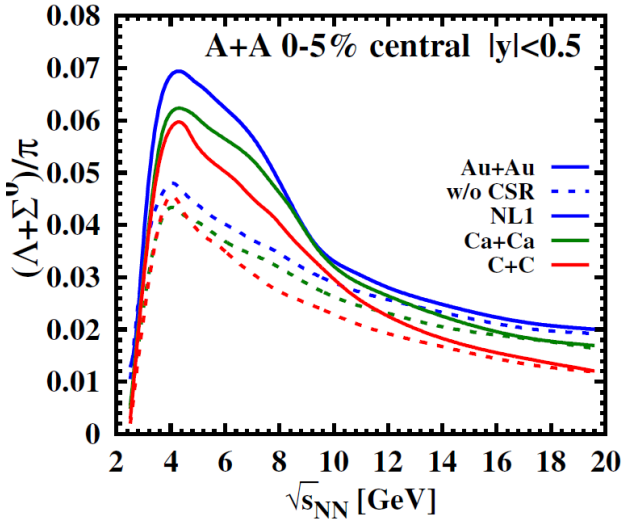




Sensitivity to the system size: A+A collisions



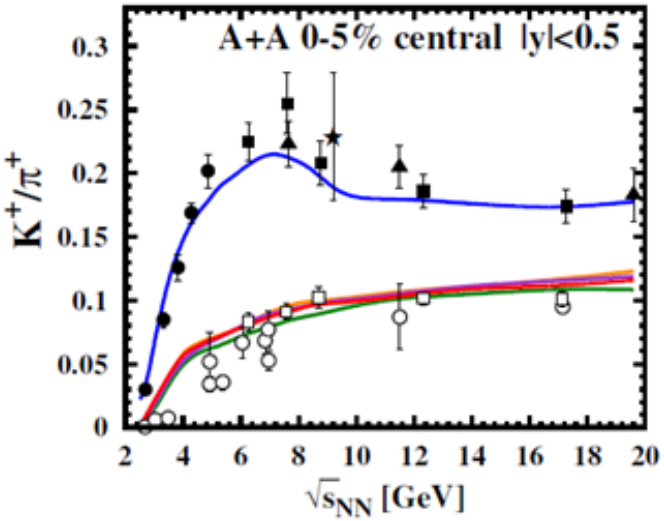


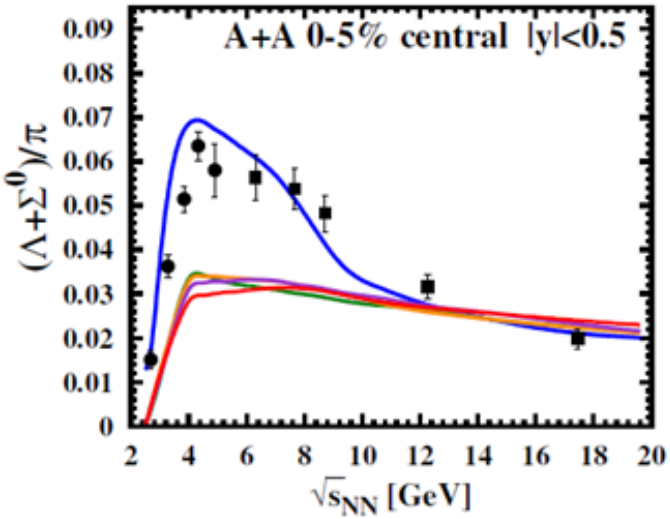


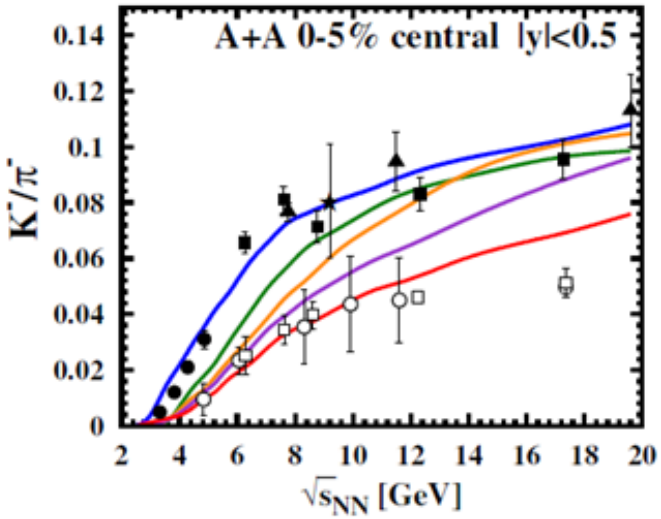
- **If the system size is smaller:**
  - **the peak of K^+/π^+ disappears**
  - **the peak of $(\Lambda+\Sigma^0)/\pi$ remains in the same position in energy, but getting smaller**

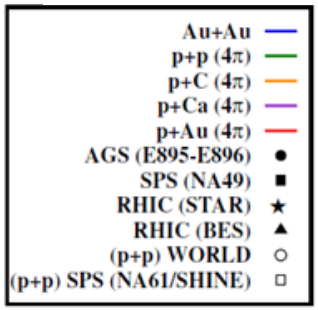
Palmese et al., **PRC94 (2016) 044912**, arXiv:1607.04073

Sensitivity to the system size: p+A collisions







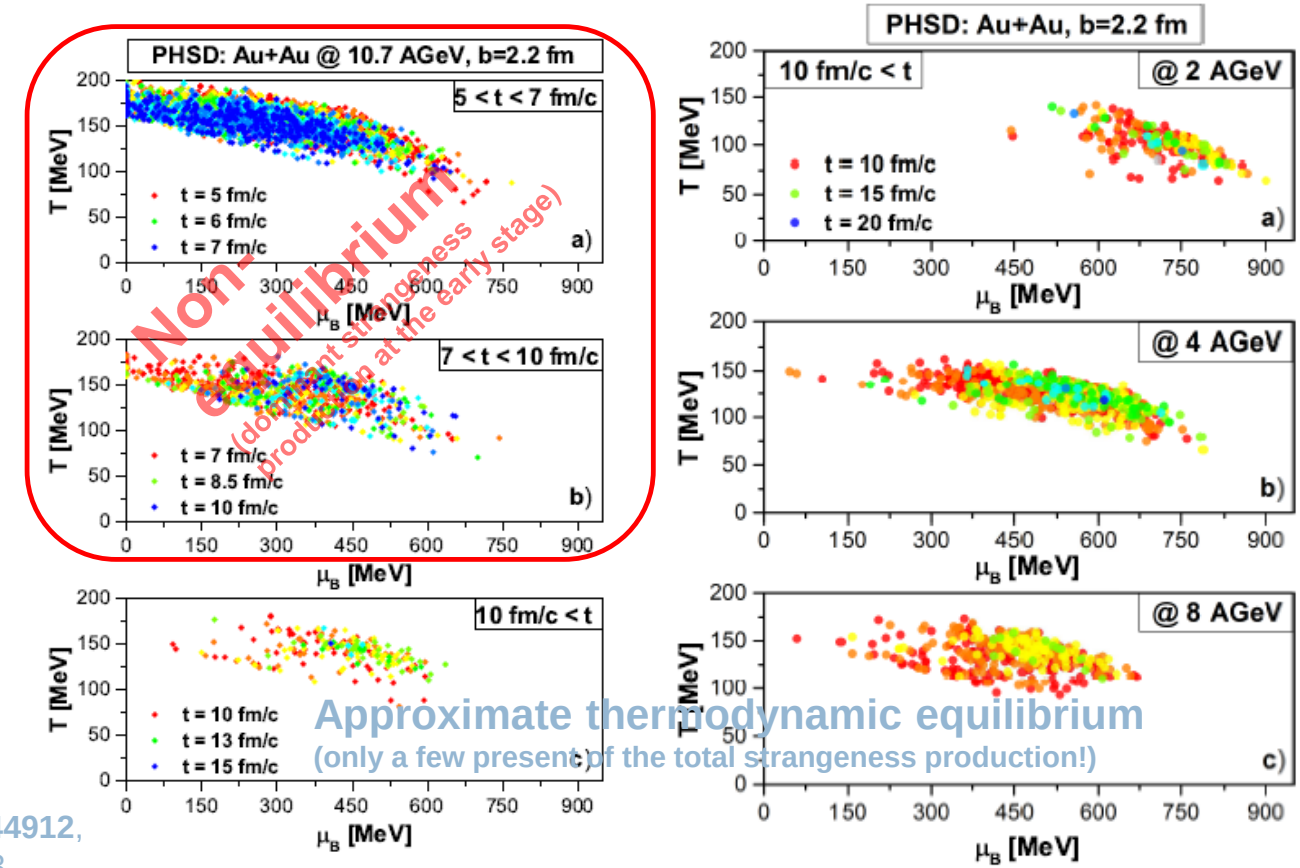


- **In p+A collisions strange to non-strange particle ratios show no peaks**

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?**

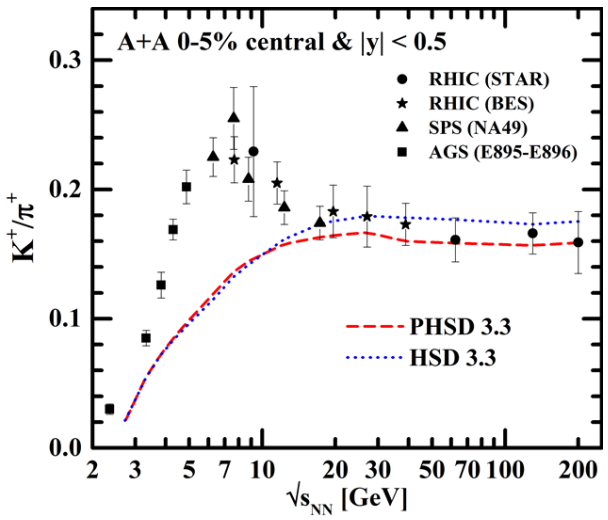


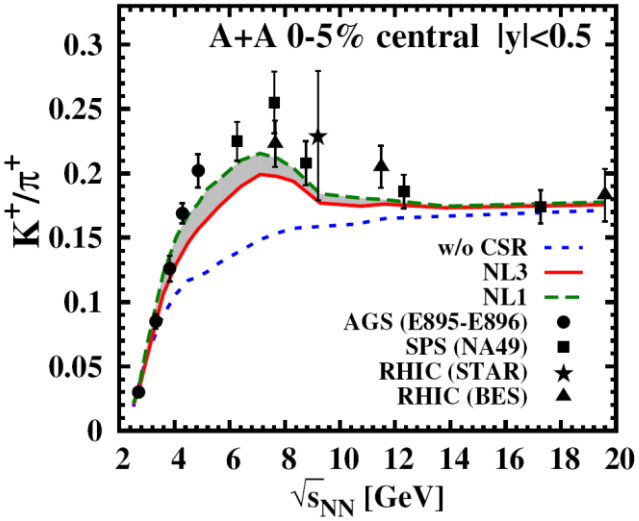
Palmese et al.,

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 → a 'horn' emerges**

Thank you for your attention!

PHSD group

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JINR, Dubna:
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Barcelona University:
Laura Tolos
Angel Ramos

Duke University:
Steffen Bass
Yingru Xu