(Anti-)strangeness in heavy ion collisions

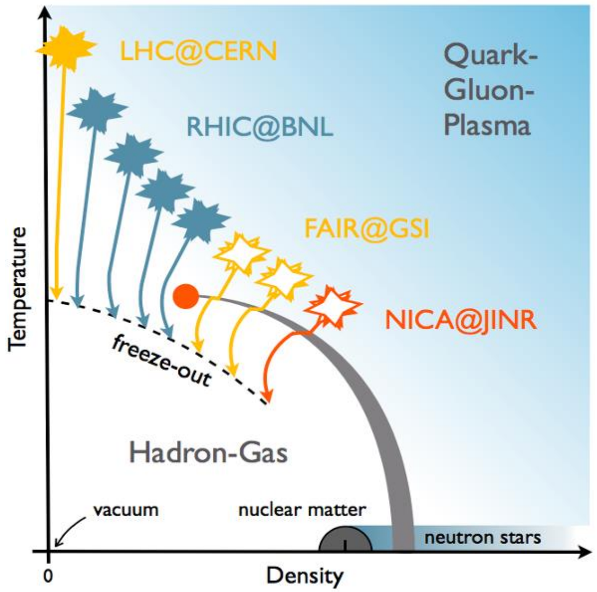
Pierre Moreau

for the PHSD group

FAIRNESS 2016, Garmisch-Partenkirchen, Germany

14 – 19 February 2016

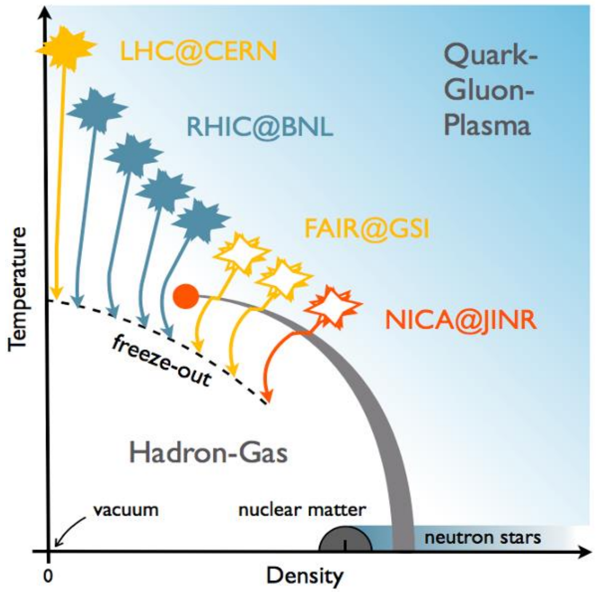
From NICA to LHC, passing by FAIR and RHIC…



- Explore the QCD phase diagram and properties of hadrons at high temperature or high baryon density
- Phase transition from hadronic to partonic matter

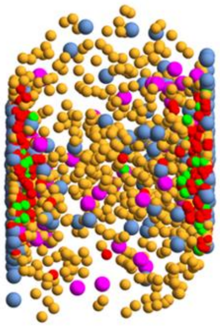
- Goal: Study the properties of strongly interacting matter under extreme conditions from a microscopic point of view

From NICA to LHC, passing by FAIR and RHIC…



- Explore the QCD phase diagram and properties of hadrons at high temperature or high baryon density
- Phase transition from hadronic to partonic matter
- Goal: Study the properties of strongly interacting matter under extreme conditions from a microscopic point of view
- Realization: dynamical many-body transport approach

- 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



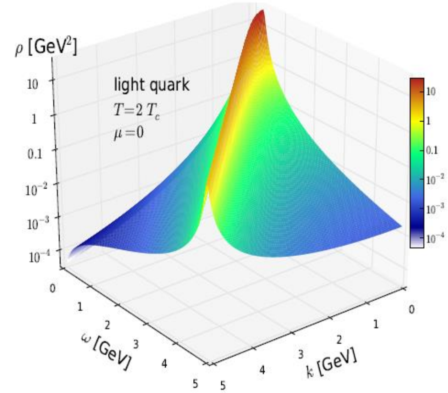
Parton-Hadron-String-Dynamics (PHSD)

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

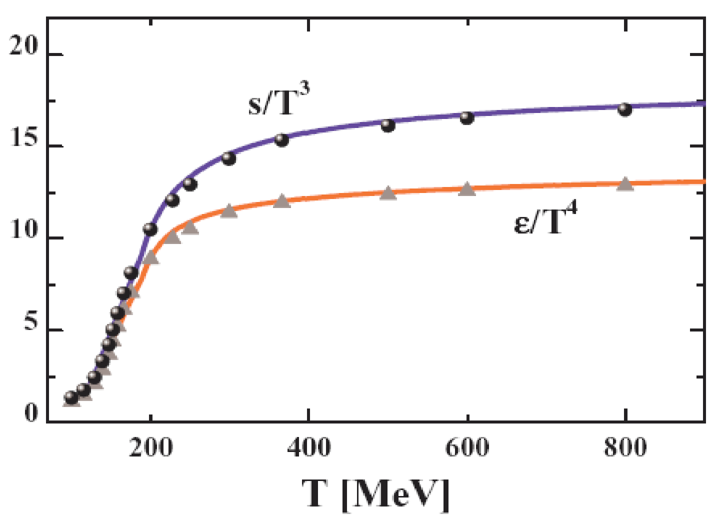
Dynamical Quasi-Particle Model (DQPM)

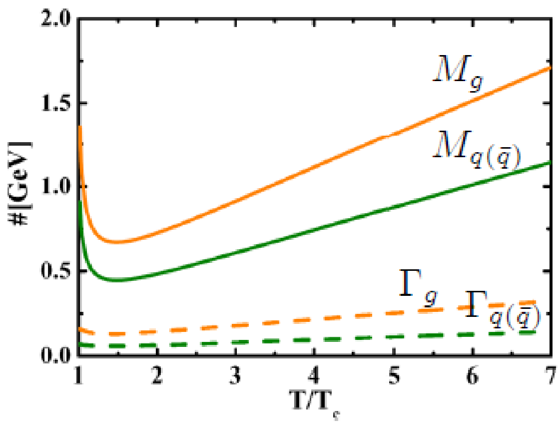
- The QGP phase is described in terms of interacting quasiparticles with Lorentzian spectral functions:

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



- Properties of quasiparticles are fitted to the lattice QCD results:



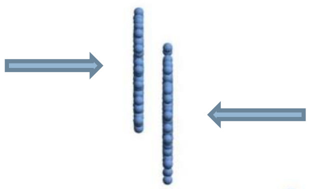


- Masses and widths of partons depend on the temperature of the medium

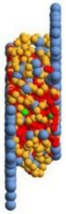
Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Stages of a collision in PHSD

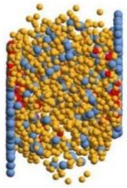
Initial A+A collision



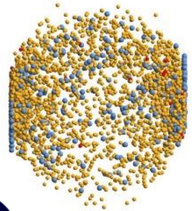
Partonic phase



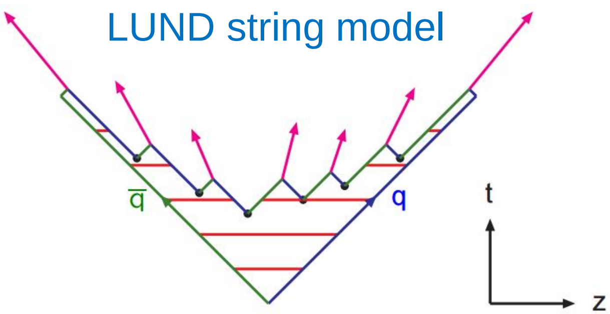
Hadronization



Hadronic phase



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



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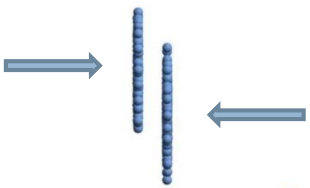

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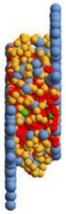

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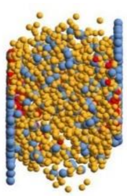

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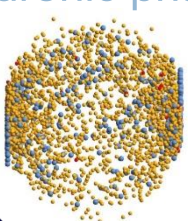

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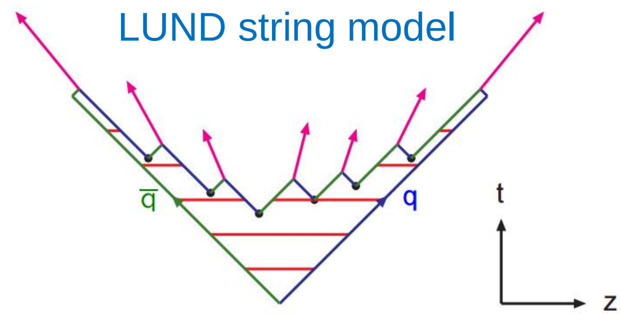

- Formation of a QGP state if $\epsilon > \epsilon_C = 0.5\ \mathrm{GeV.fm}^{-3}$
- Dissolution of new produced secondary hadrons into massive colored quarks and mean-field energy

$$B \rightarrow qqq\ (\bar{q}\bar{q}\bar{q}),\ m \rightarrow q\bar{q}\ +\ U_q$$

- DQPM define the properties (masses and widths) of partons

$$m_q(\epsilon) \quad \Gamma_q(\epsilon)$$

… and mean-field potential at a given local energy density ε

$$U_q(\epsilon)$$

Stages of a collision in PHSD

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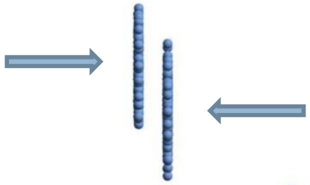

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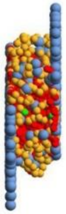

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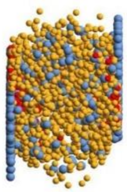

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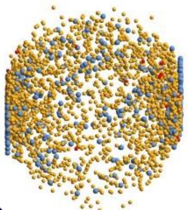
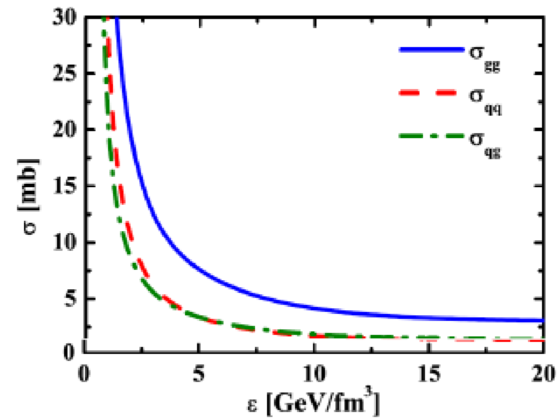


- Propagation of partons, considered as dynamical quasiparticles, in a self-generated mean-field potential from the DQPM
- EoS of partonic phase: ‚crossover' from Lattice QCD fitted by DQPM
- (quasi-)elastic collisions :

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



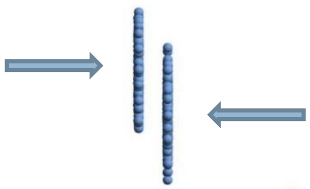
- inelastic collisions :

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

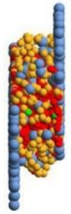
} Suppressed due to the large gluon mass

Stages of a collision in PHSD

Initial A+A collision



Partonic phase



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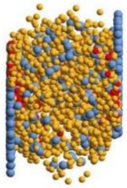

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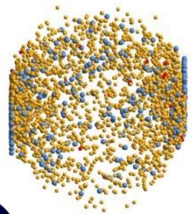
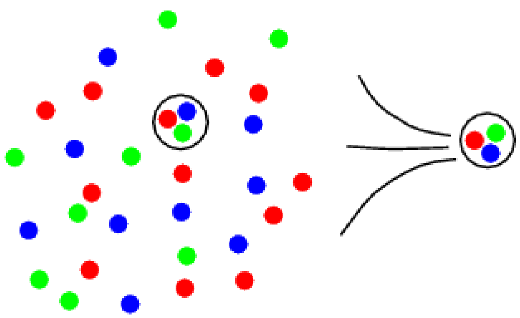


- Massive and off-shell (anti-)quarks hadronize to colorless off-shell mesons and baryons



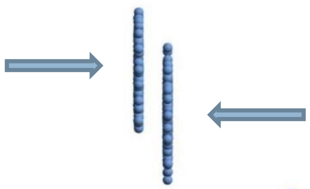
$$g \to q+\bar{q}, \qquad q+\bar{q} \leftrightarrow meson \ ('\,string\,')$$

$$q+q+q \leftrightarrow baryon \ ('\,string\,')$$

- Local covariant off-shell transition rate
- Strict 4-momentum and quantum number conservation

Stages of a collision in PHSD

Initial A+A collision



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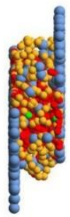

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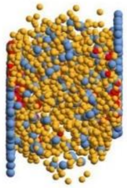

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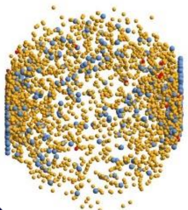

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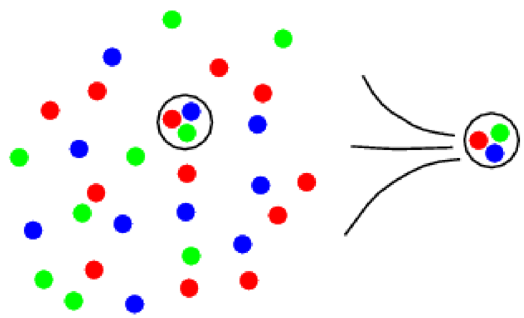

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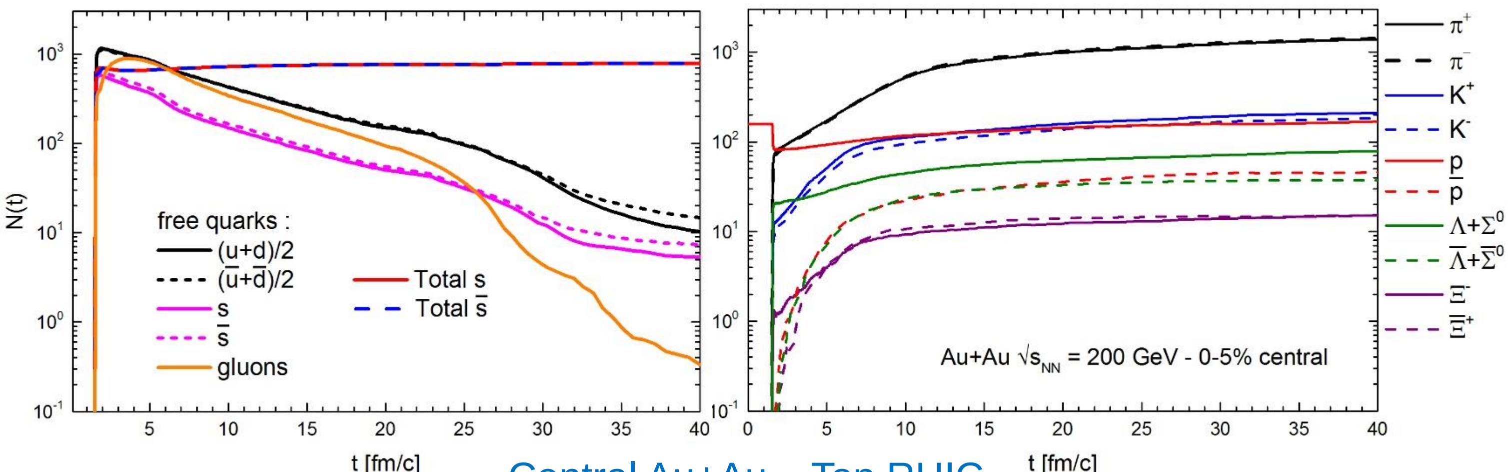
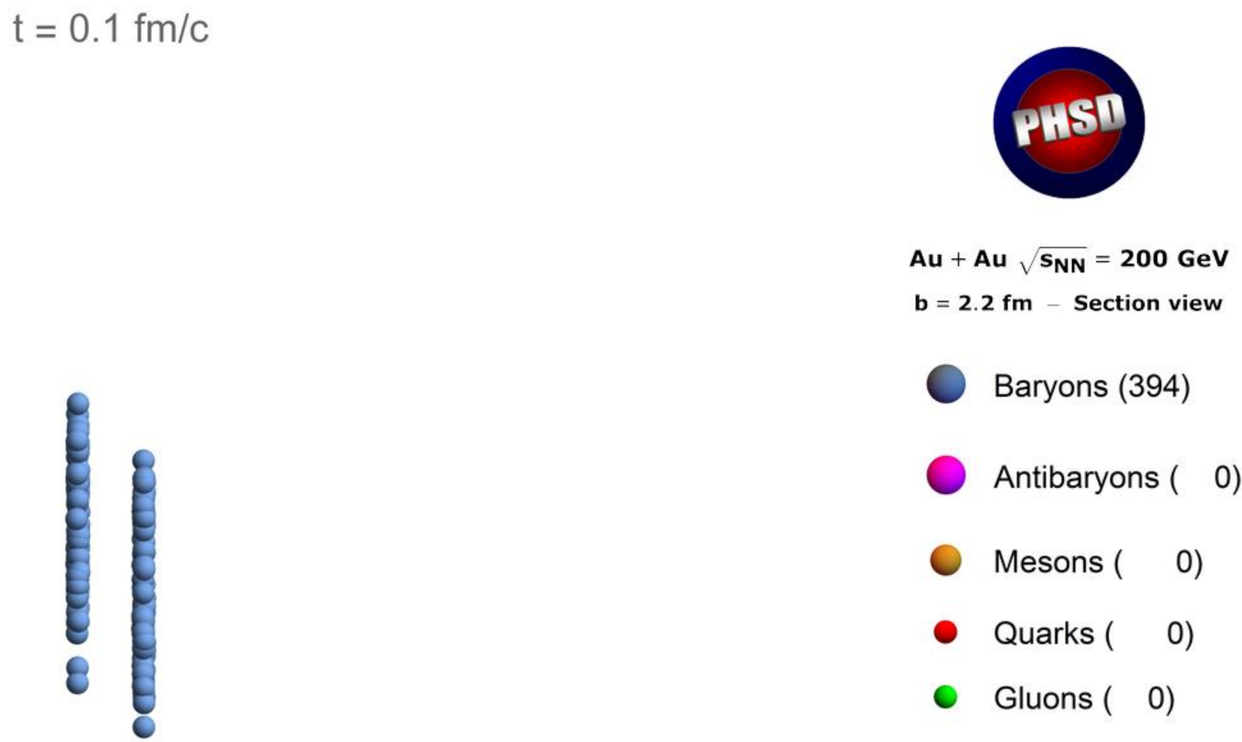
- Strict 4-momentum and quantum number conservation

Number of partons and hadrons as a function of time:



Central Au+Au – Top RHIC

Stages of a collision in PHSD



P.Moreau

Stages of a collision in PHSD

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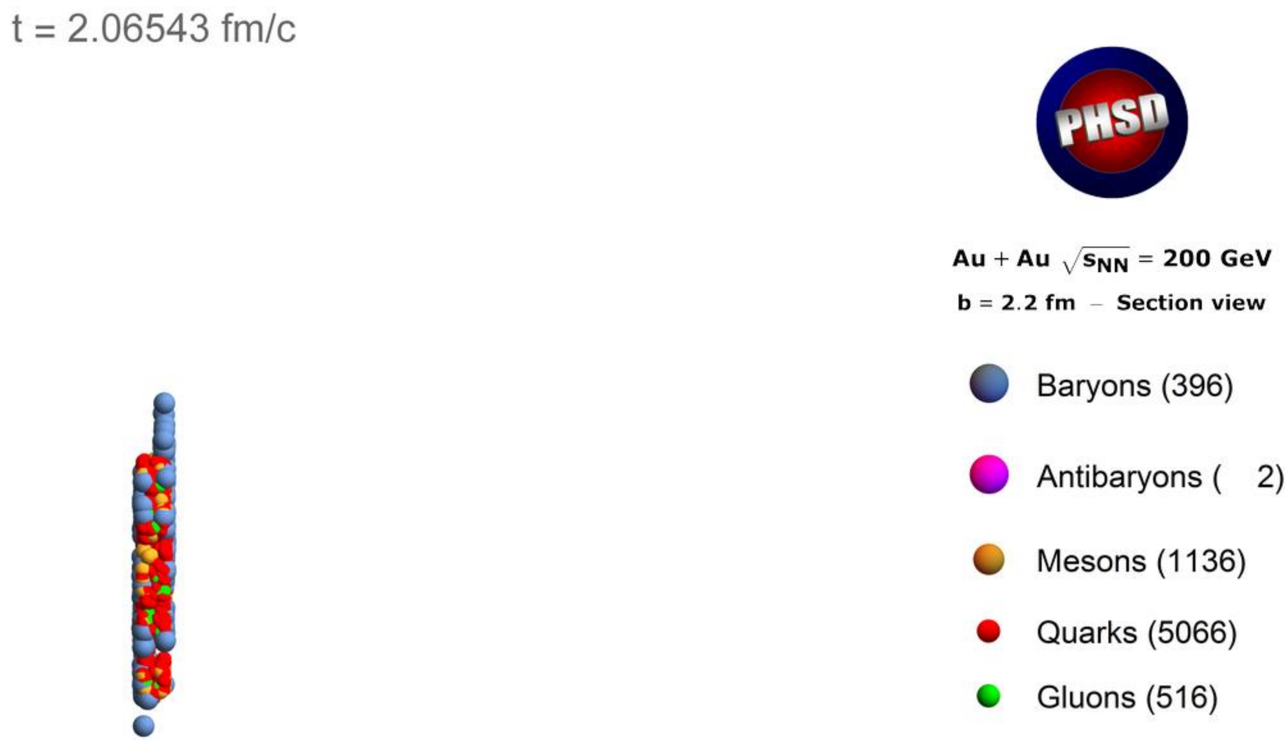

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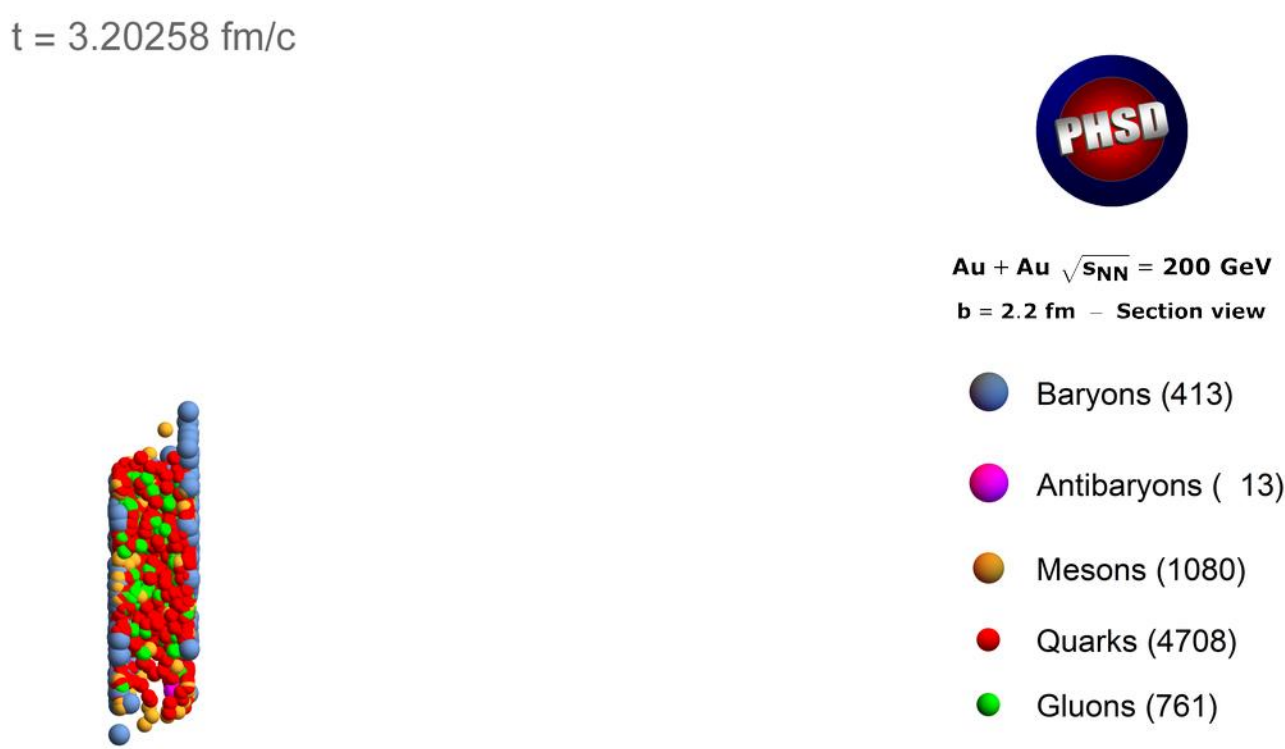

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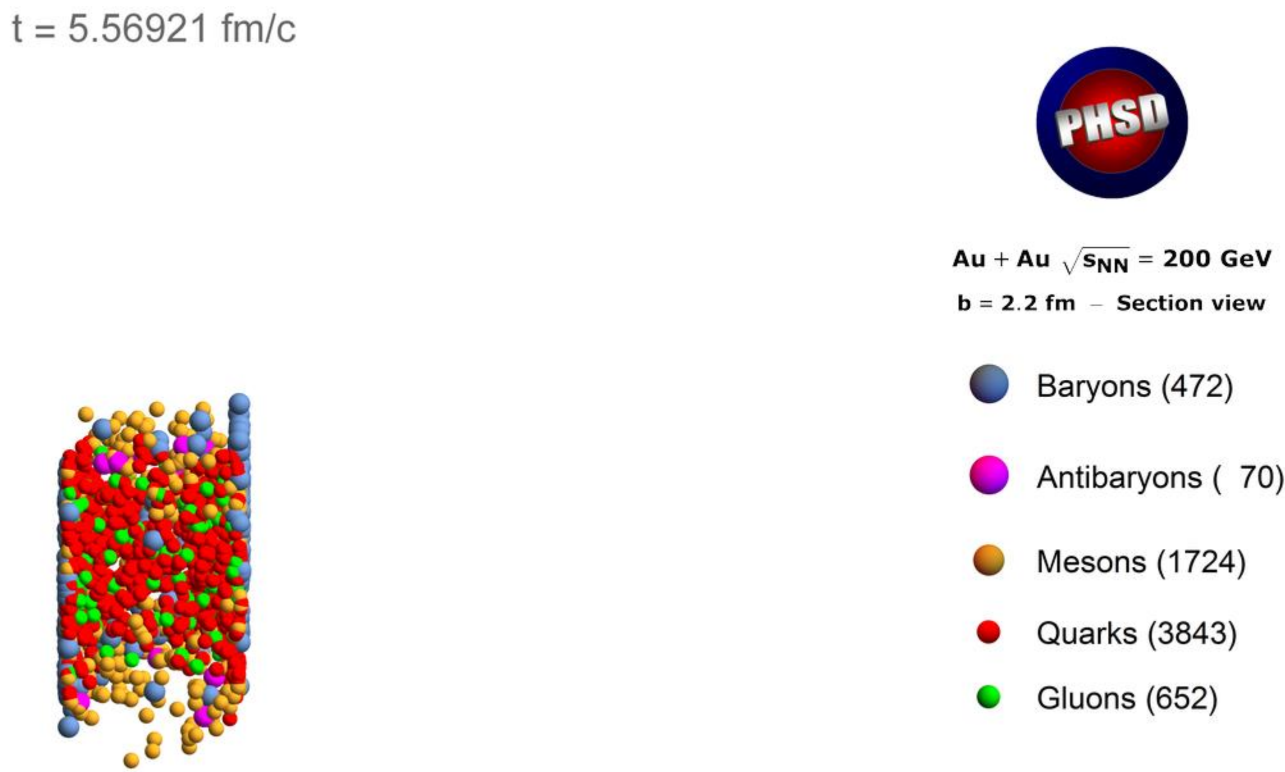

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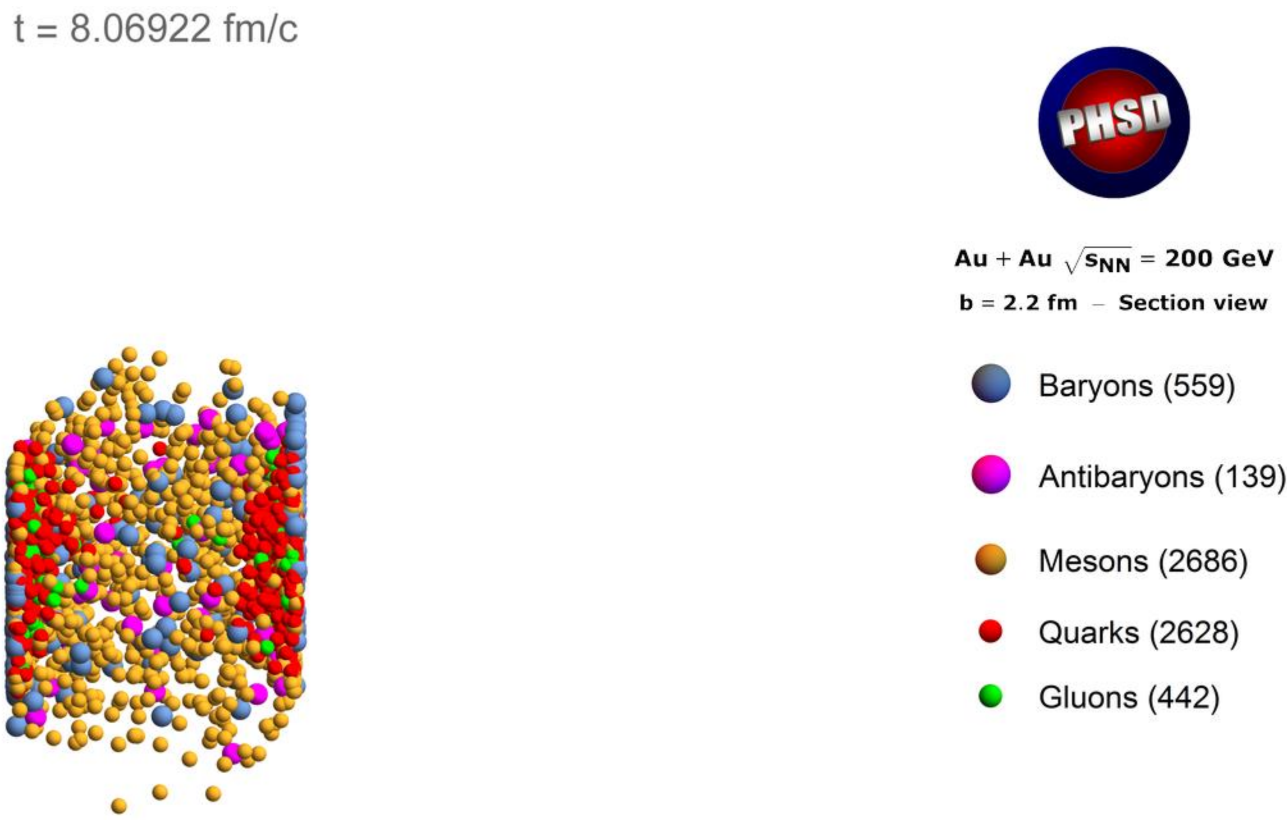
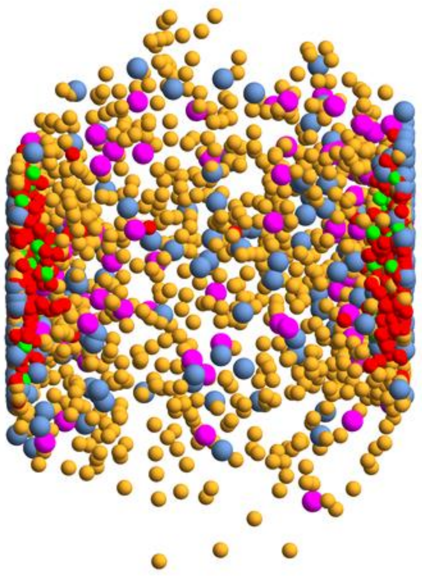


P.Moreau

Stages of a collision in PHSD

t = 10.5692 fm/c



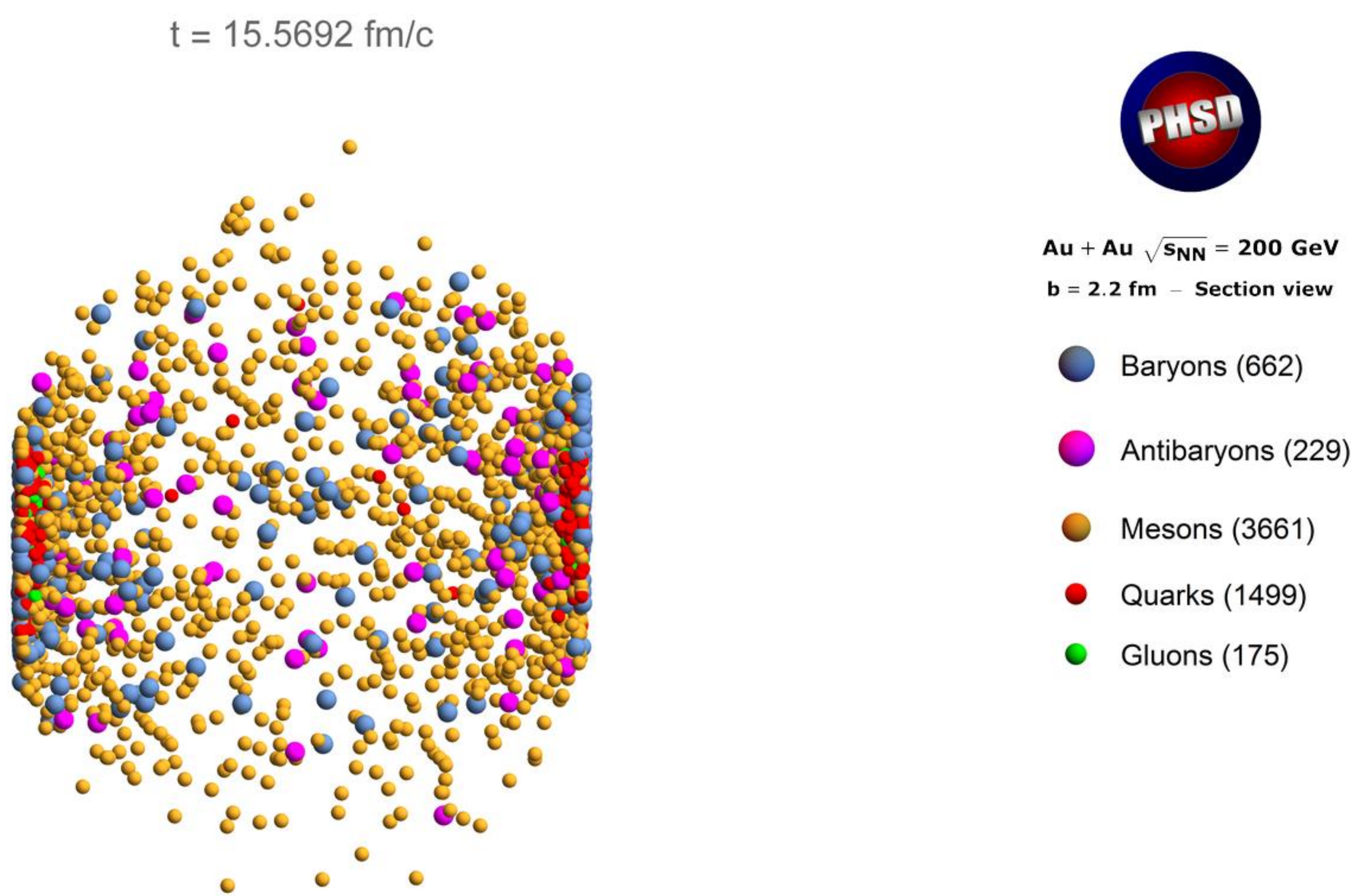
Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

- Baryons (604)
- Antibaryons (187)
- Mesons (3169)
- Quarks (2076)
- Gluons (319)

P.Moreau

Stages of a collision in PHSD



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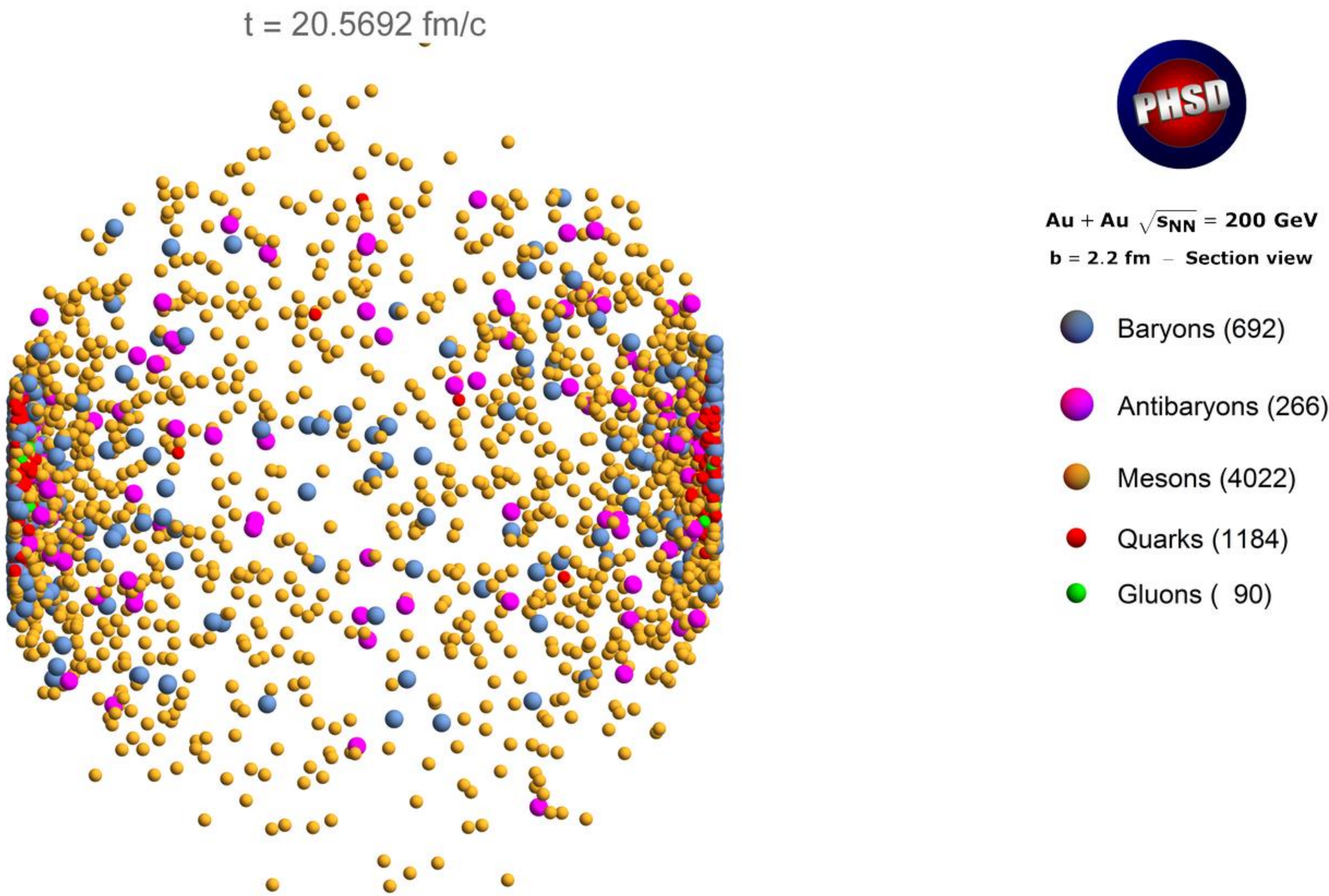
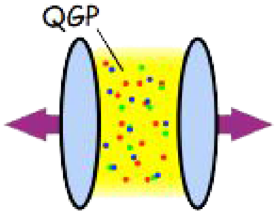
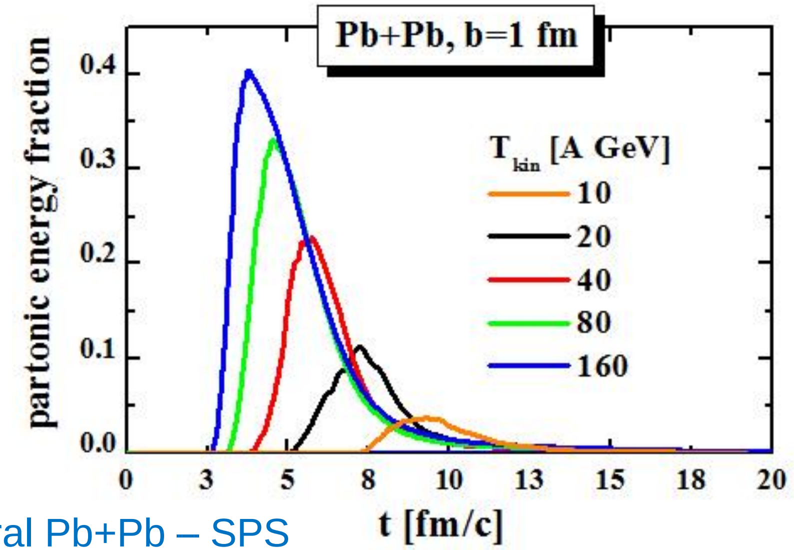


Partonic energy fraction in central A+A

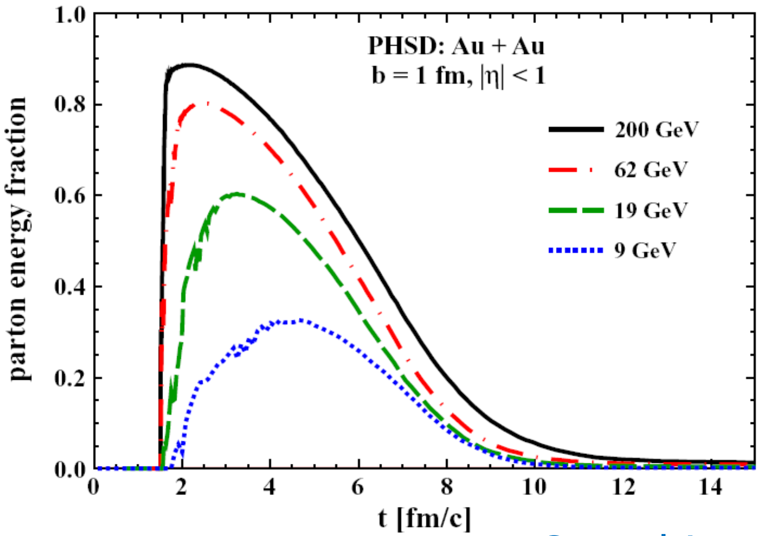


- At SPS, only a small part of the initial energy is converted into the QGP phase
- At top RHIC energies, the QGP phase at midrapidity contains roughly 90% of the energy

Time evolution of the partonic energy fraction for different energies:



Central Pb+Pb – SPS

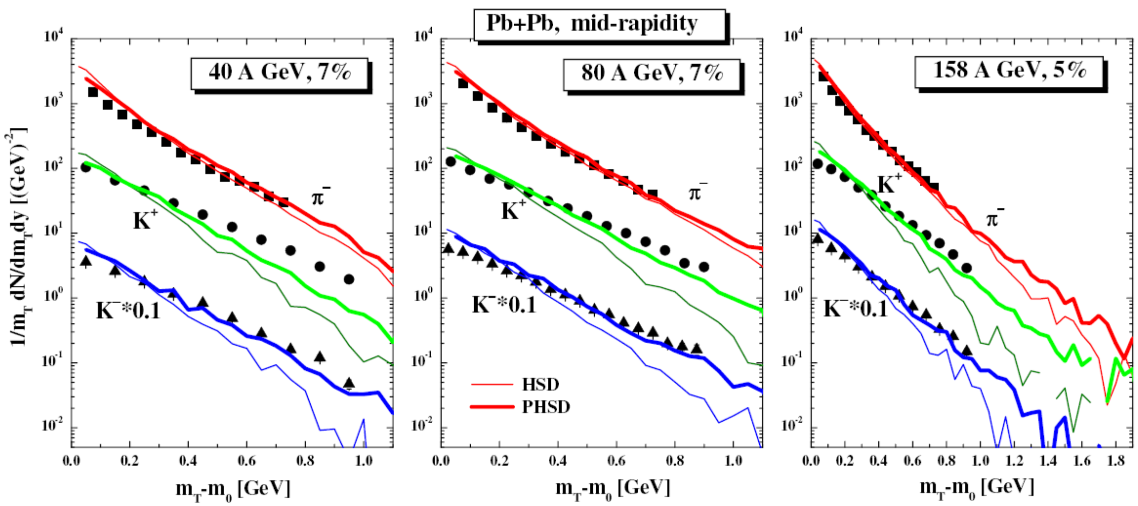


Central Au+Au

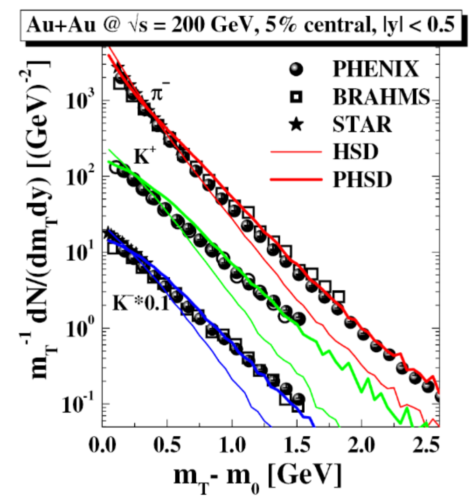
Transverse mass spectra (PHSD – HSD)

- With the HSD model, the high-pT spectra is not described properly especially at high energies where the parton energy fraction is major
- At low SPS energies, the difference is less visible since the partonic phase is not predominant

Transverse mass spectra for pions and kaons at different energies:



Central Pb+Pb – SPS energies



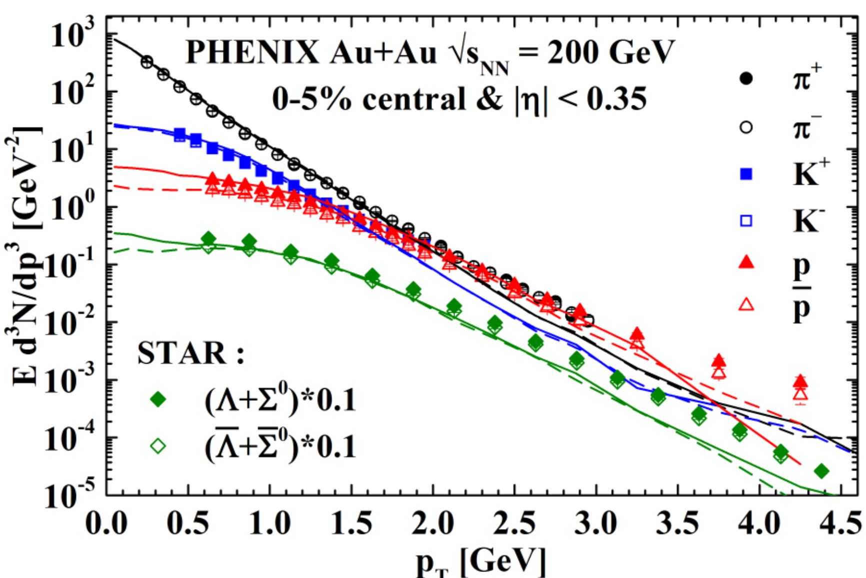
Central Au+Au – RHIC

W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215; E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

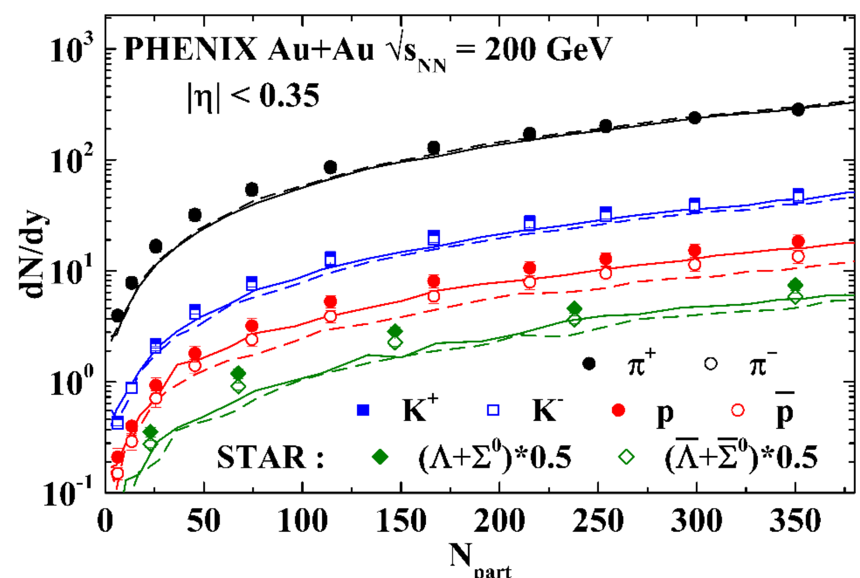
Au-Au at Top RHIC energies

- At high energies, particles and antiparticles are produced in quasi-equal quantities at midrapidity whatever the centrality of the collision
- Anti-baryon absorption at low pT is visible

pT spectra:



Production at midrapidity dN/dy:



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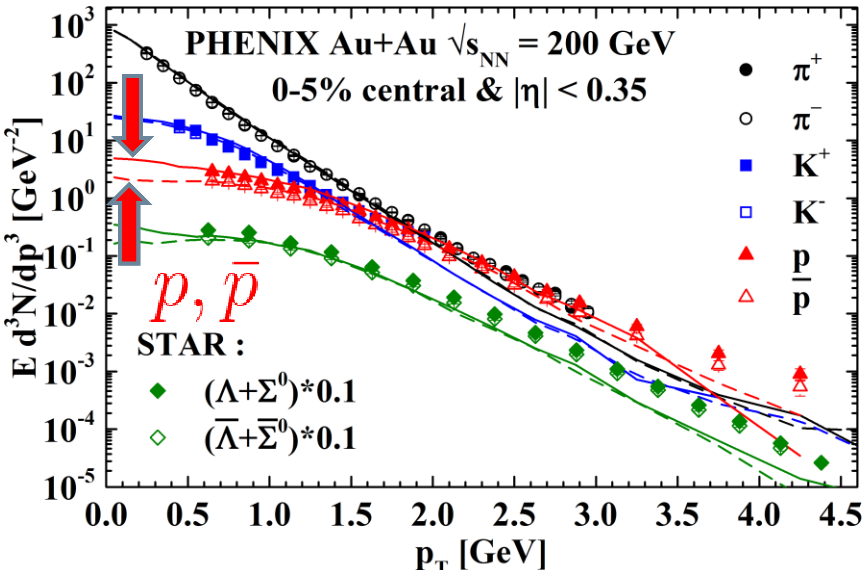

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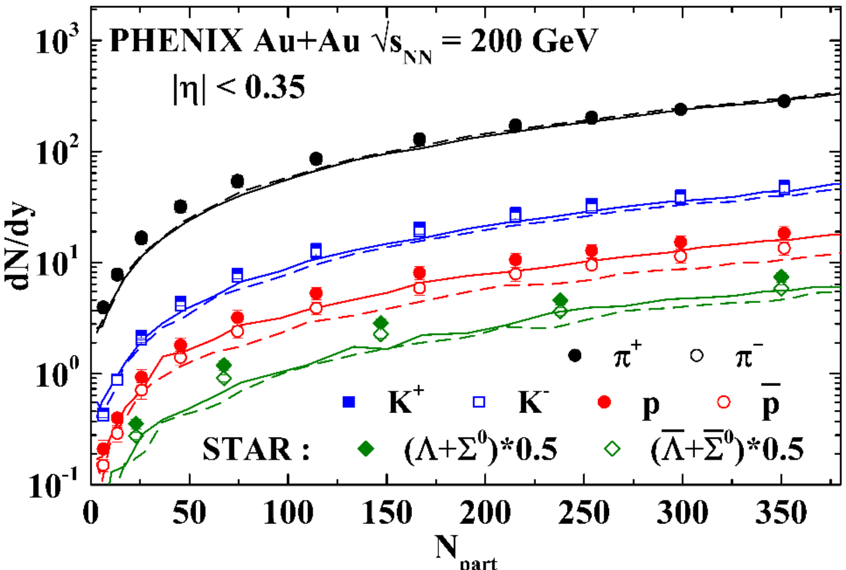
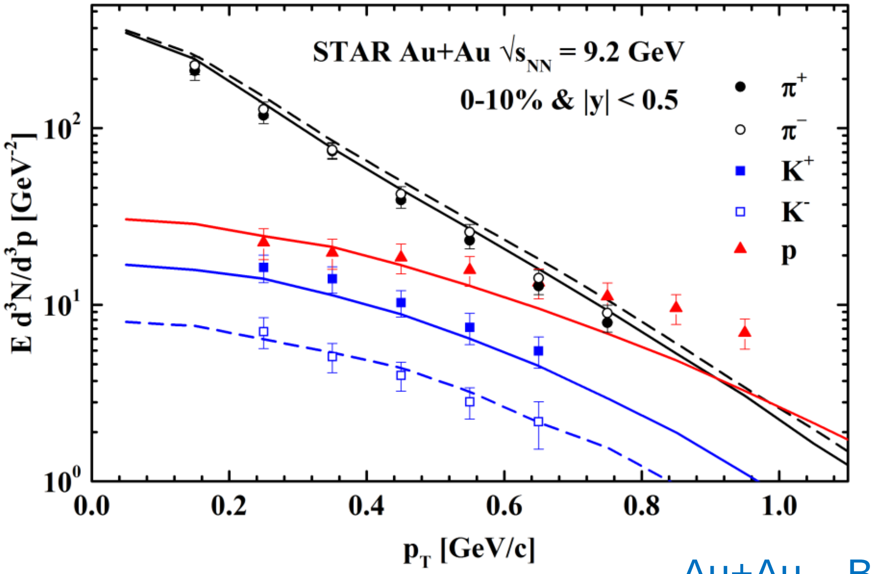


Au+Au – Top RHIC

Au-Au at BES @ RHIC energies

- At low energies, a clear difference appears between the production of particles and antiparticles, and also between positively and negatively charged mesons

pT spectra:



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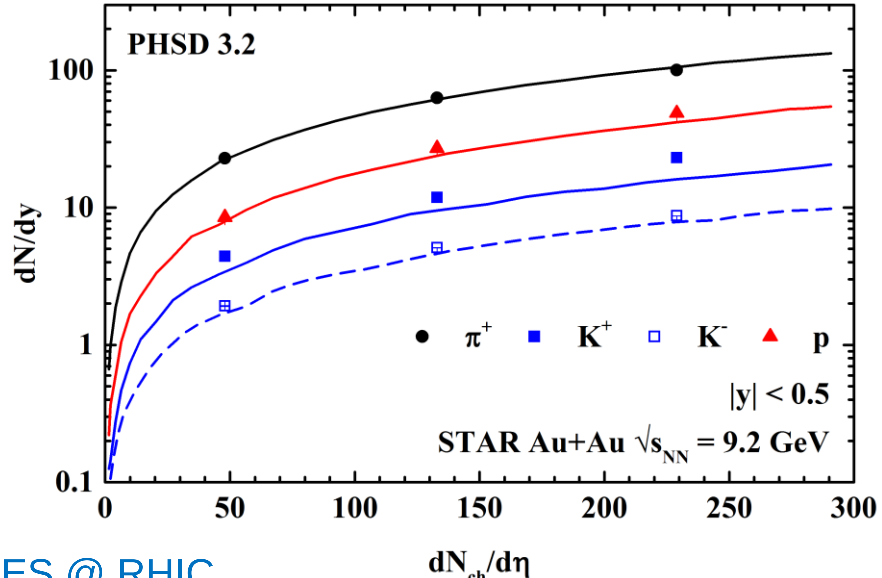
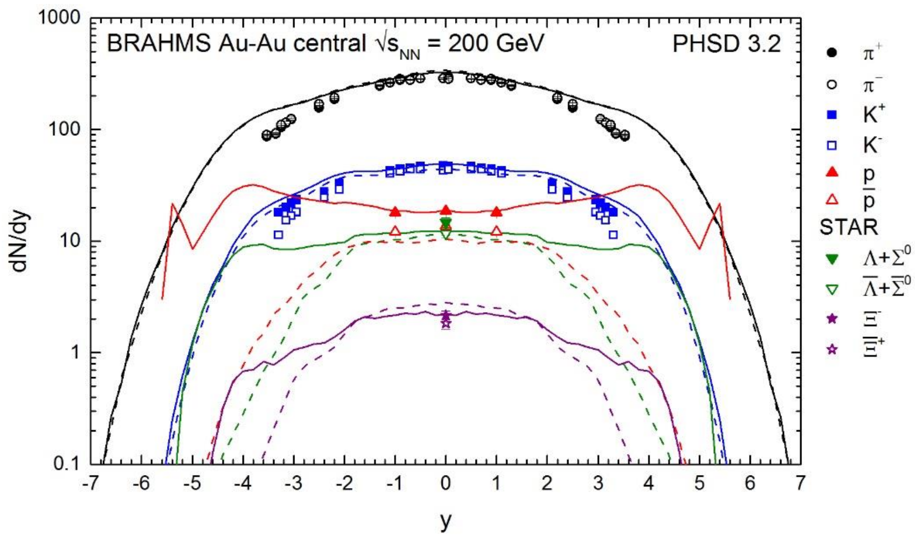


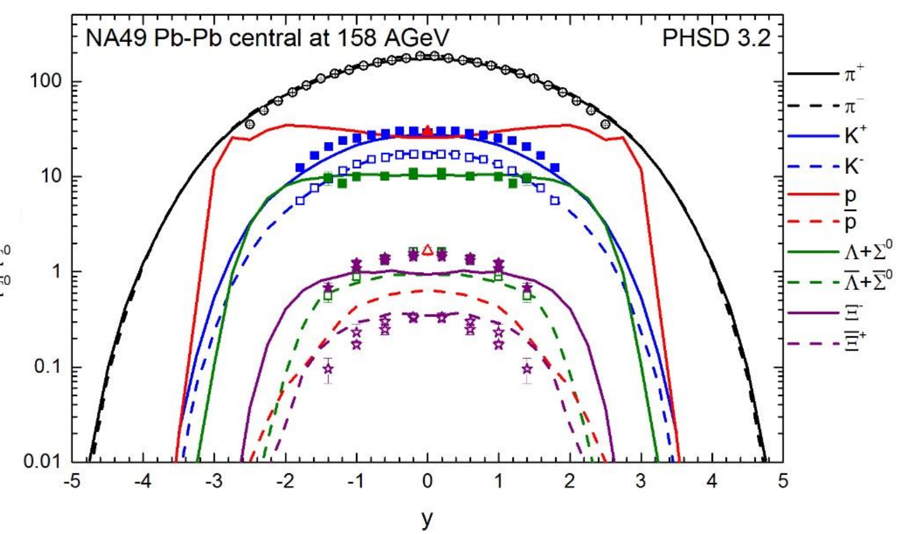
Au+Au – BES @ RHIC

Rapidity spectra

- At high energies, the hadrons produced at midrapidity come mostly from the QGP phase
- At high rapidity, particles are more produced than antiparticles due to the high baryon density
- At low energies, the stopping of initial nucleons induces a high baryon density even at midrapidty which favors the production of baryons compared to antibaryons

Rapidity spectras:





Central Au+Au – Top RHIC

Central Pb+Pb – Top SPS

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$p, \bar{p}$

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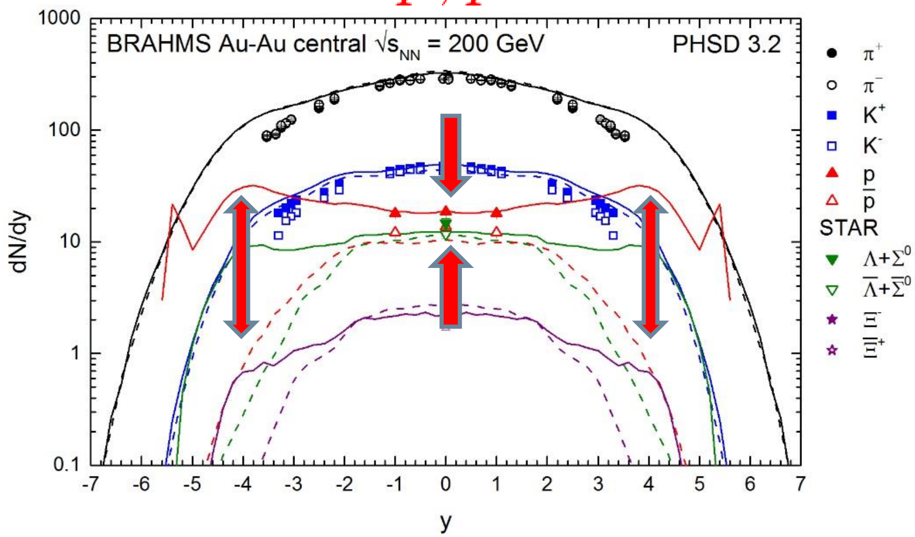

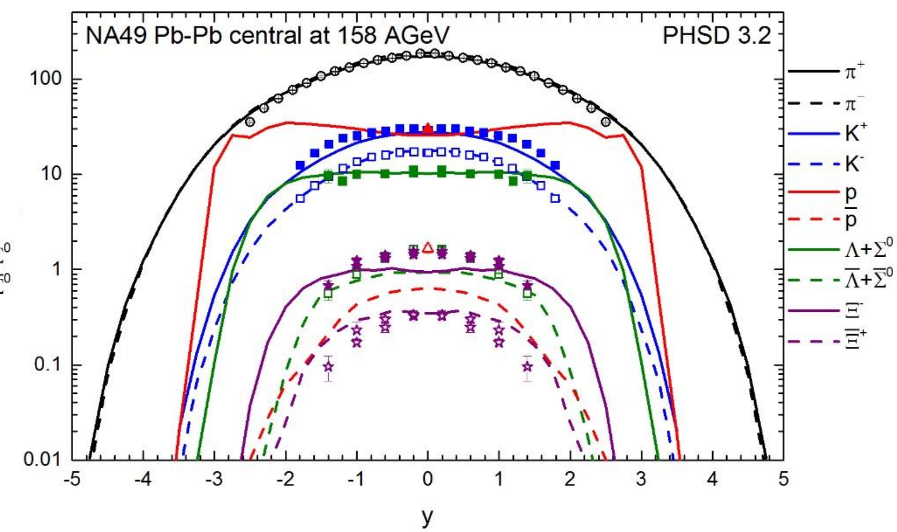

Central Au+Au – Top RHIC

Central Pb+Pb – Top SPS

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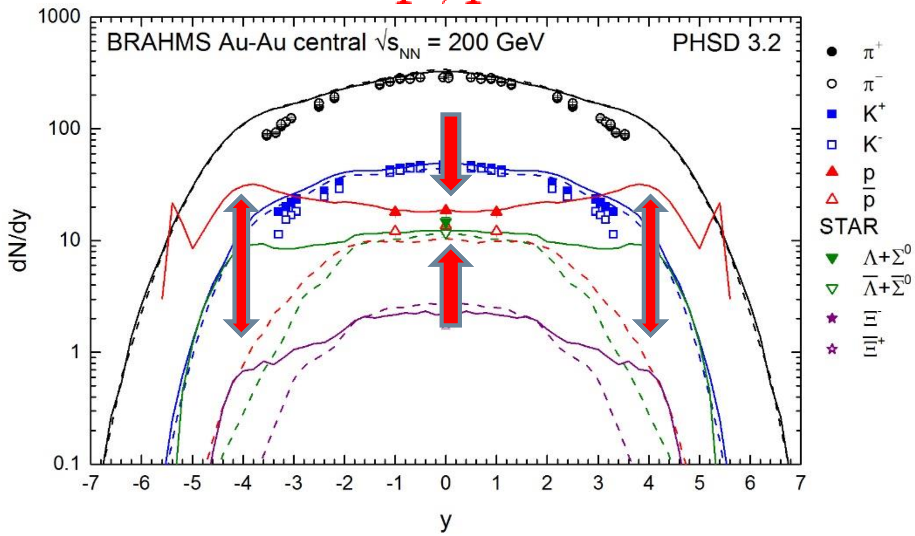
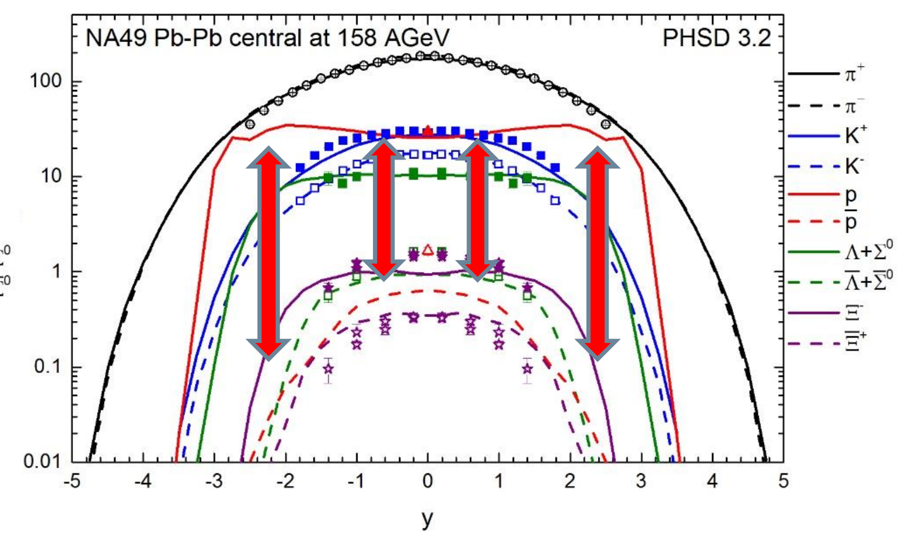


Central Au+Au – Top RHIC

$p, \bar{p}$



Central Pb+Pb – Top SPS

Rapidity spectra

- At high energies, the hadrons produced at midrapidity come mostly from the QGP phase
- At high rapidity, particles are more produced than antiparticles due to the high baryon density
- At low energies, the stopping of initial nucleons induces a high baryon density even at midrapidty which favors the production of baryons compared to antibaryons

Rapidity spectras: $\Lambda + \Sigma^0, \bar{\Lambda} + \bar{\Sigma}^0$

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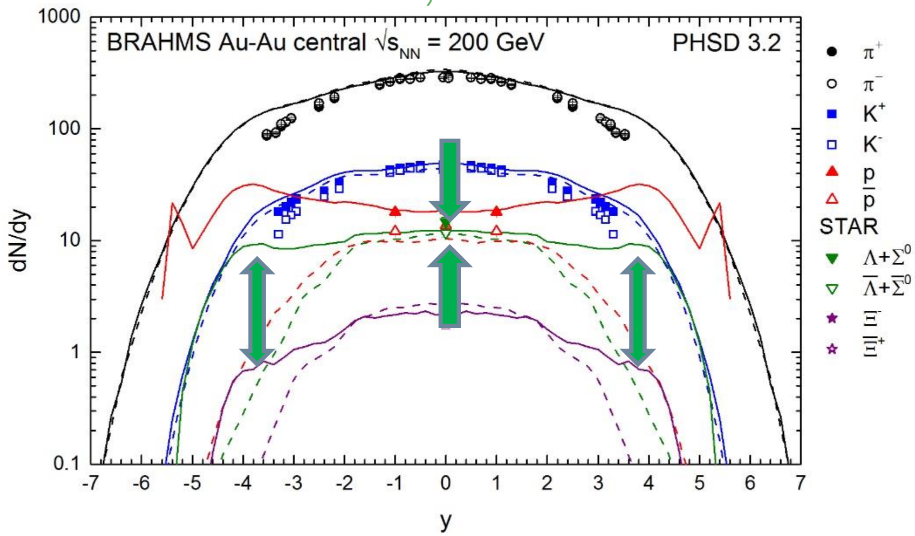

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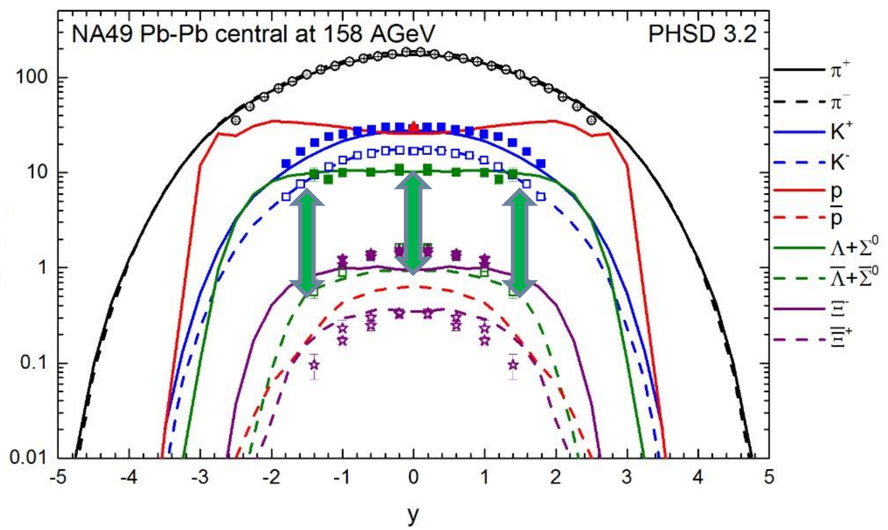


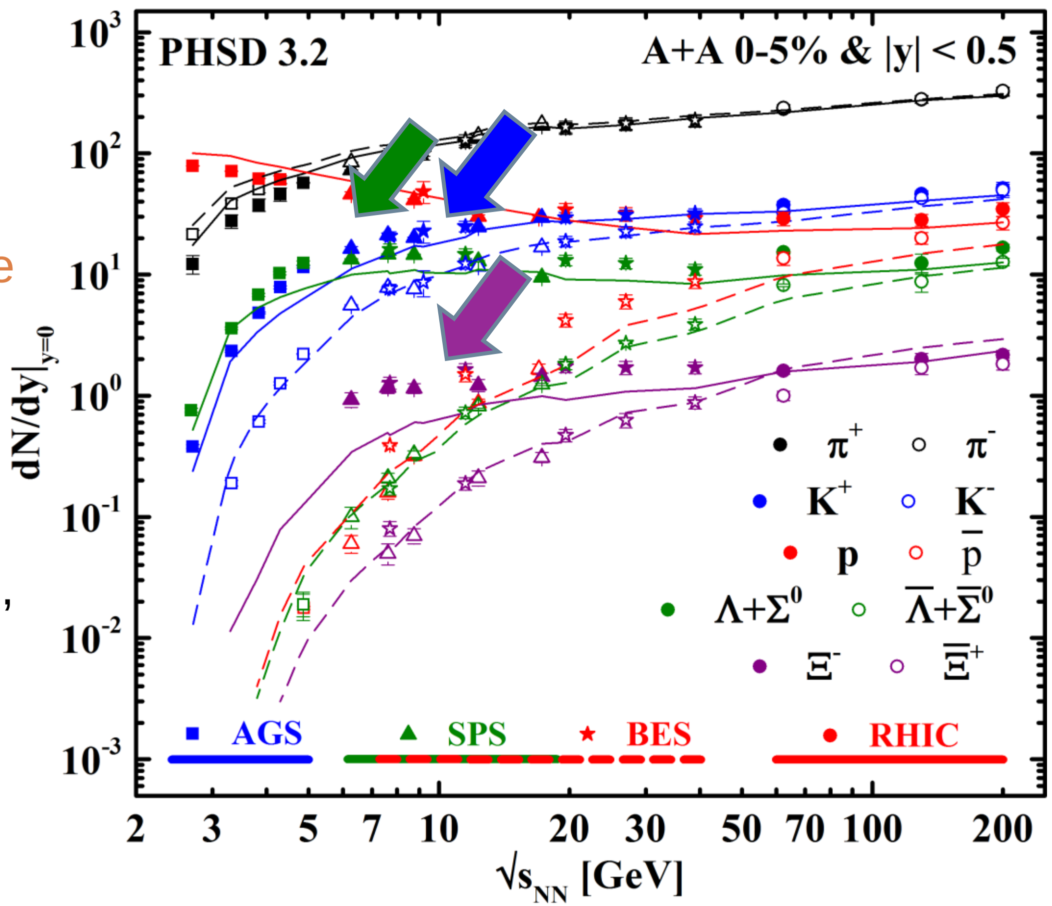
Central Pb+Pb – Top SPS

Beam energy scan study

Production at midrapidity as a function of the collisional energy:

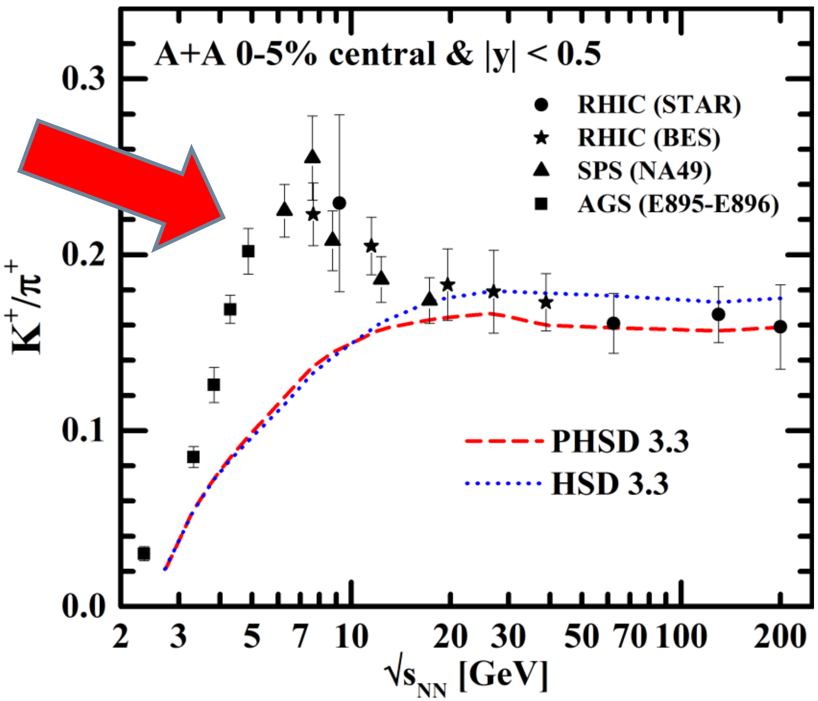
- Reasonable agreement for anti-strange baryons dominantly produced in the hadronization process from the QGP at midrapidity

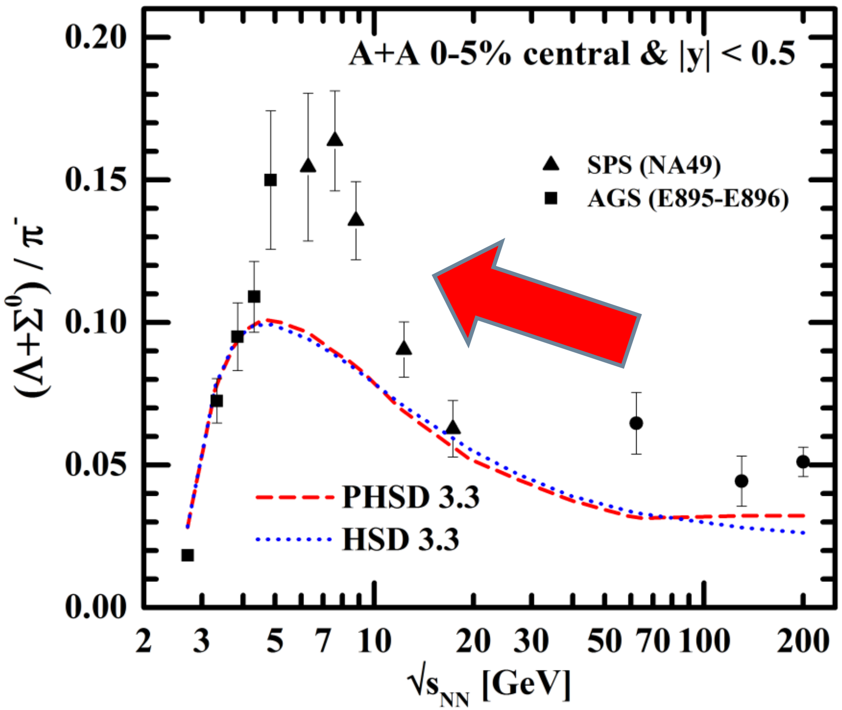
- Underestimation of strange baryons at AGS-SPS energies, mainly produced by hadronic processes



Missing strangeness ?

- Even considering the creation of a QGP phase, the strangeness enhancement seen experimentally at FAIR/NICA energies remains puzzling
  - **'Horn' not traced back to deconfinement**





Production of quarks by string decays

- According to a Schwinger-like formula, the probability to form a massive $s\bar{s}$ in a string-decay process is suppressed in comparison to light flavor $(u\bar{u}, d\bar{d})$

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

- Considering a hot and dense medium, the above formula remains the same but **effective quark masses** should be employed. This dressing is due to a scalar coupling with the **in-medium quark condensate $\langle q\bar{q}\rangle$** according to:

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

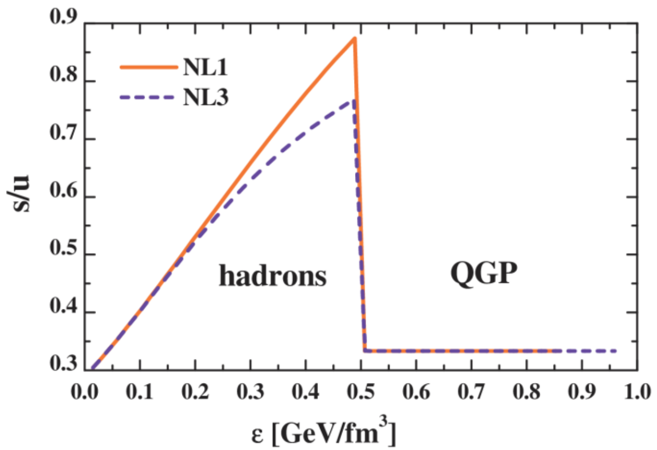
Chiral symmetry restoration in the hadronic phase

- The scalar quark condensate $\langle q\bar{q}\rangle$ is viewed as an **order parameter** for the **restoration of chiral symmetry** at high baryon density and temperature. It can be expressed by the following formula:

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

where ρ_s is the scalar density obtained according to the non-linear $\sigma - \omega$ model, $\Sigma_\pi \approx 45\ \mathrm{MeV}$ is the pion-nucleon Σ-term, and f_π and m_π are the pion decay constant and pion mass, given by the Gell-Mann-Oakes-Renner relation.

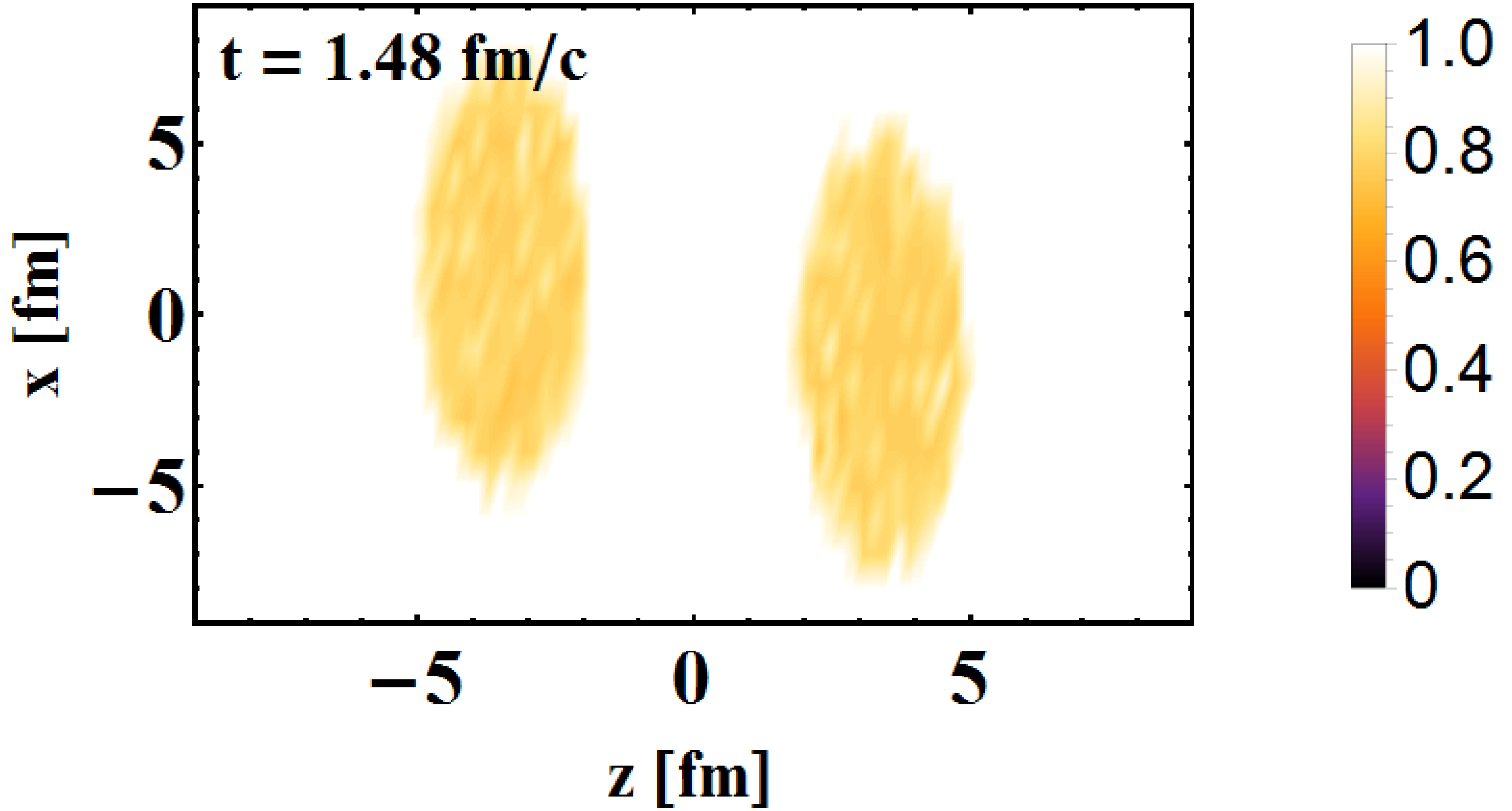
- As a consequence of the **chiral symmetry restoration (CSR)**, the strangeness production probability increases with the energy density ε. In the QGP phase, the string decay doesn't occur anymore and this effect is therefore suppressed.



Pb+Pb @ 30 AGeV – 0-5% central

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

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



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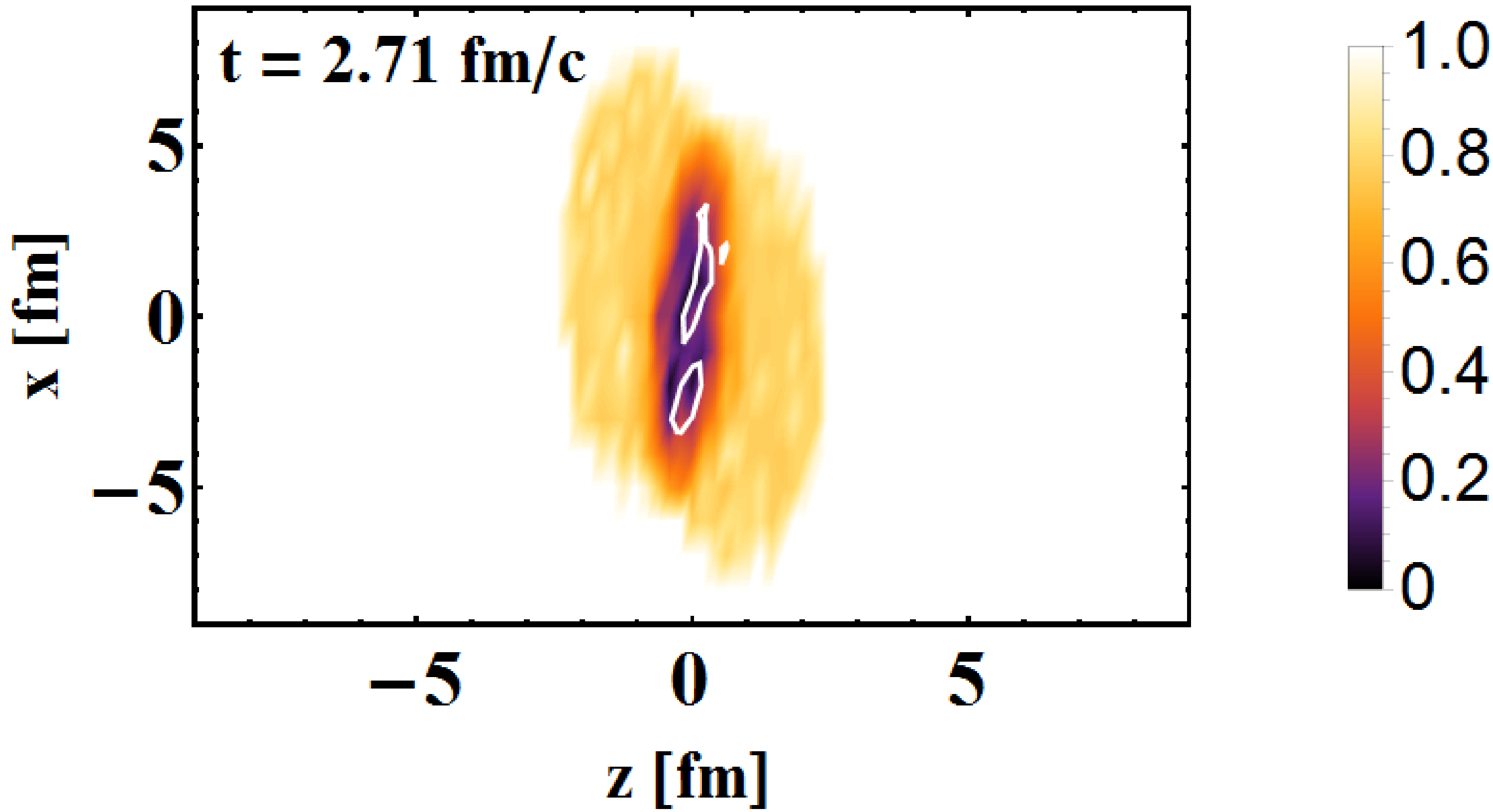

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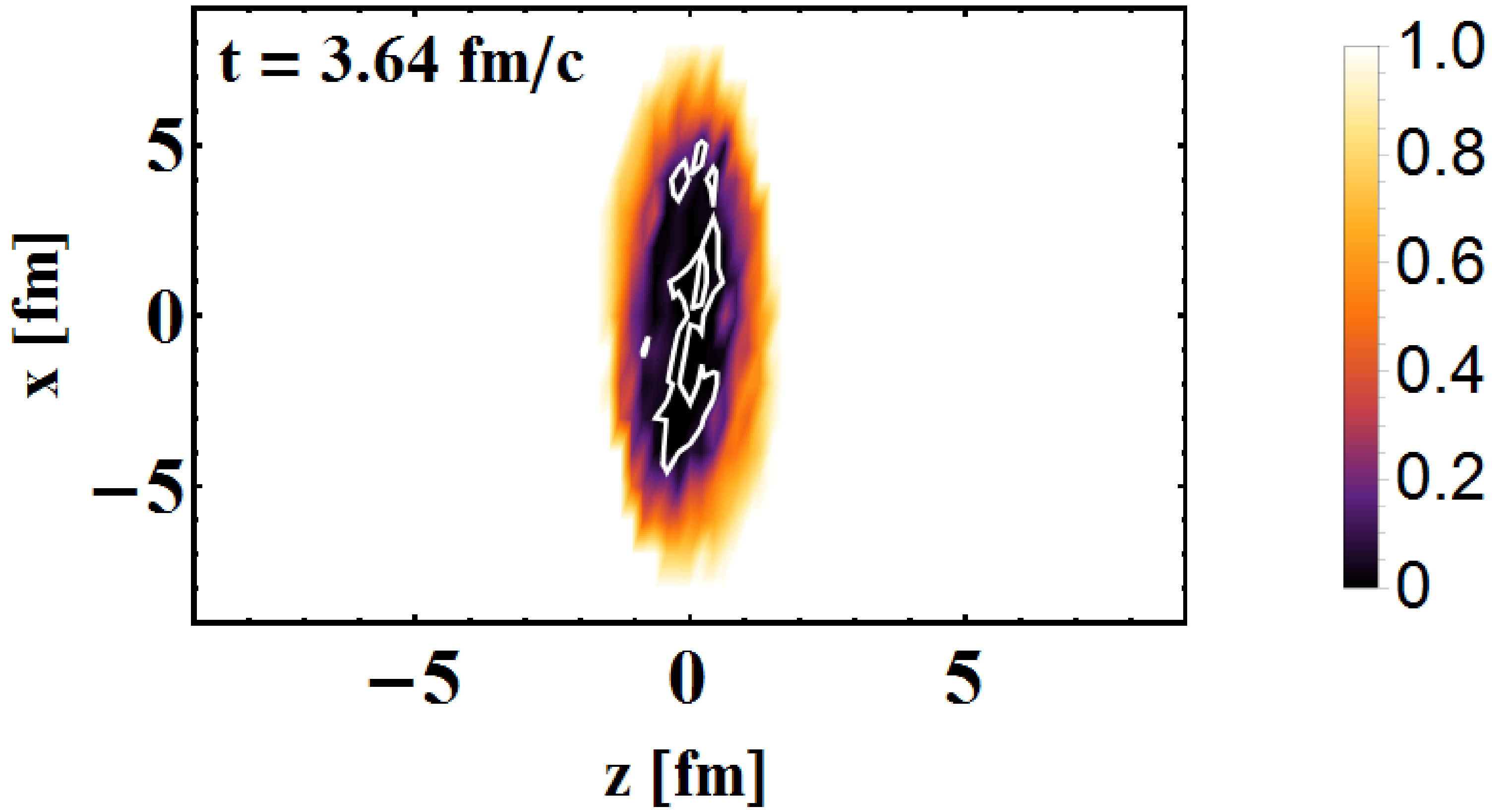

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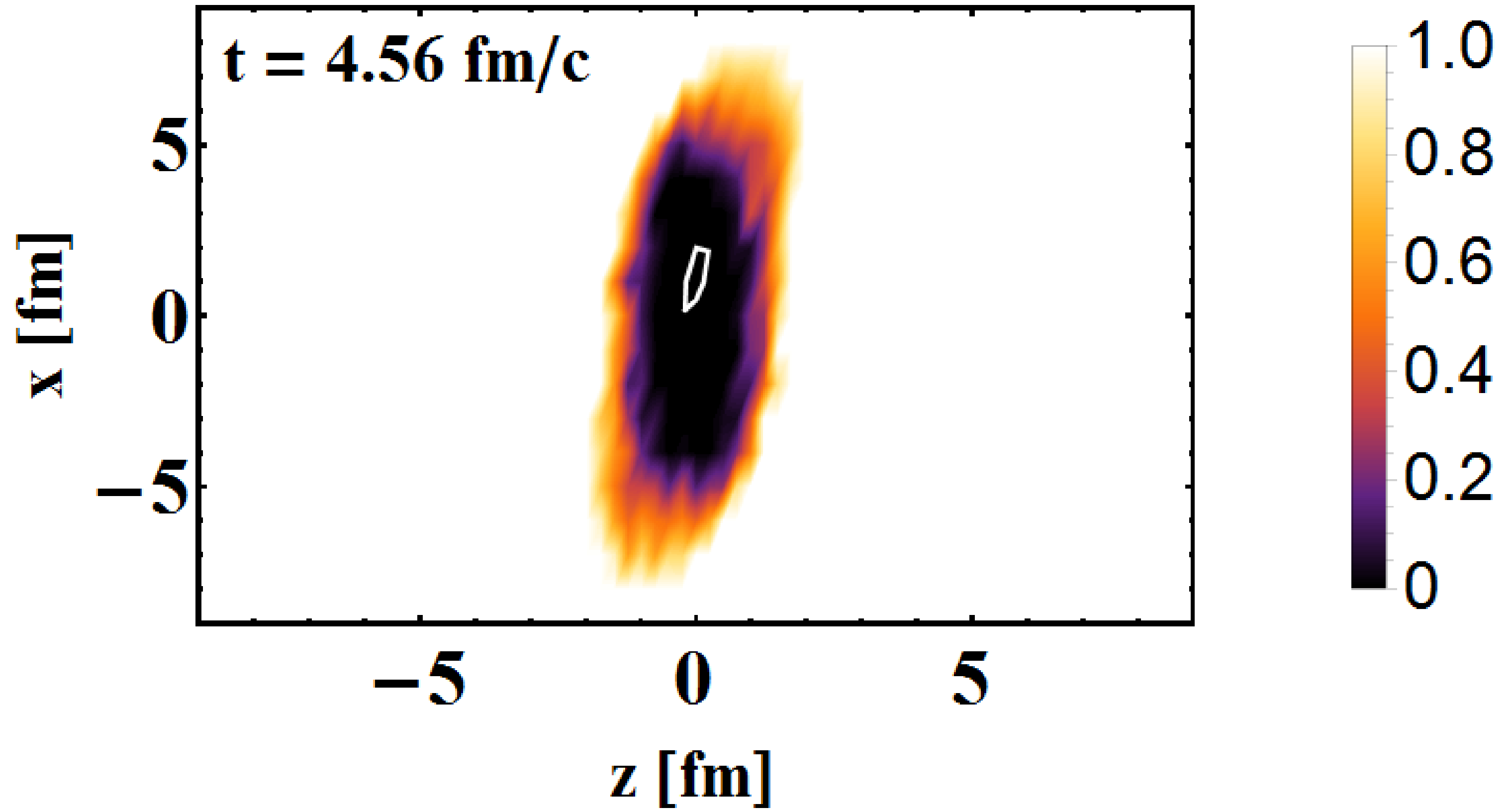

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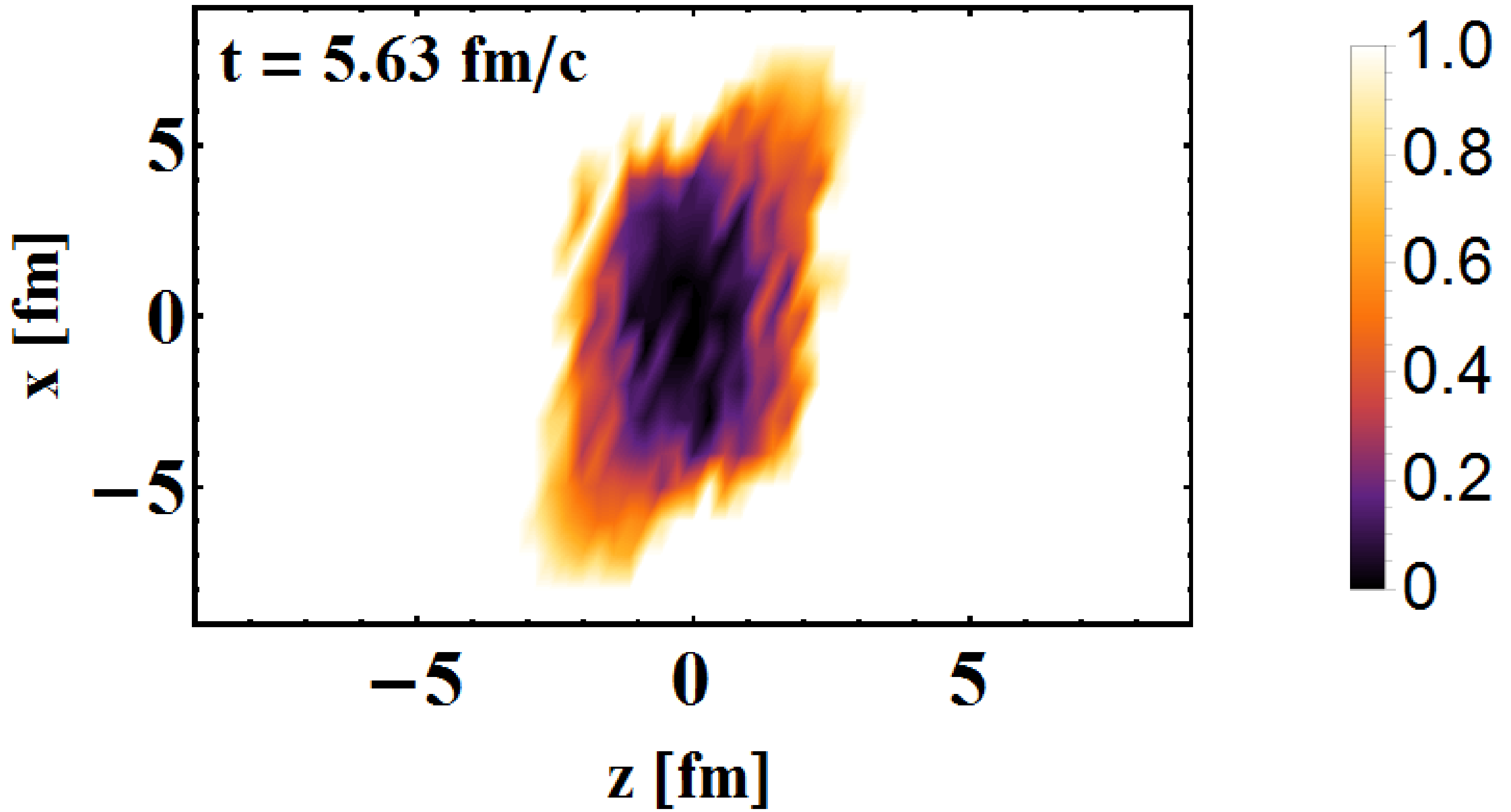

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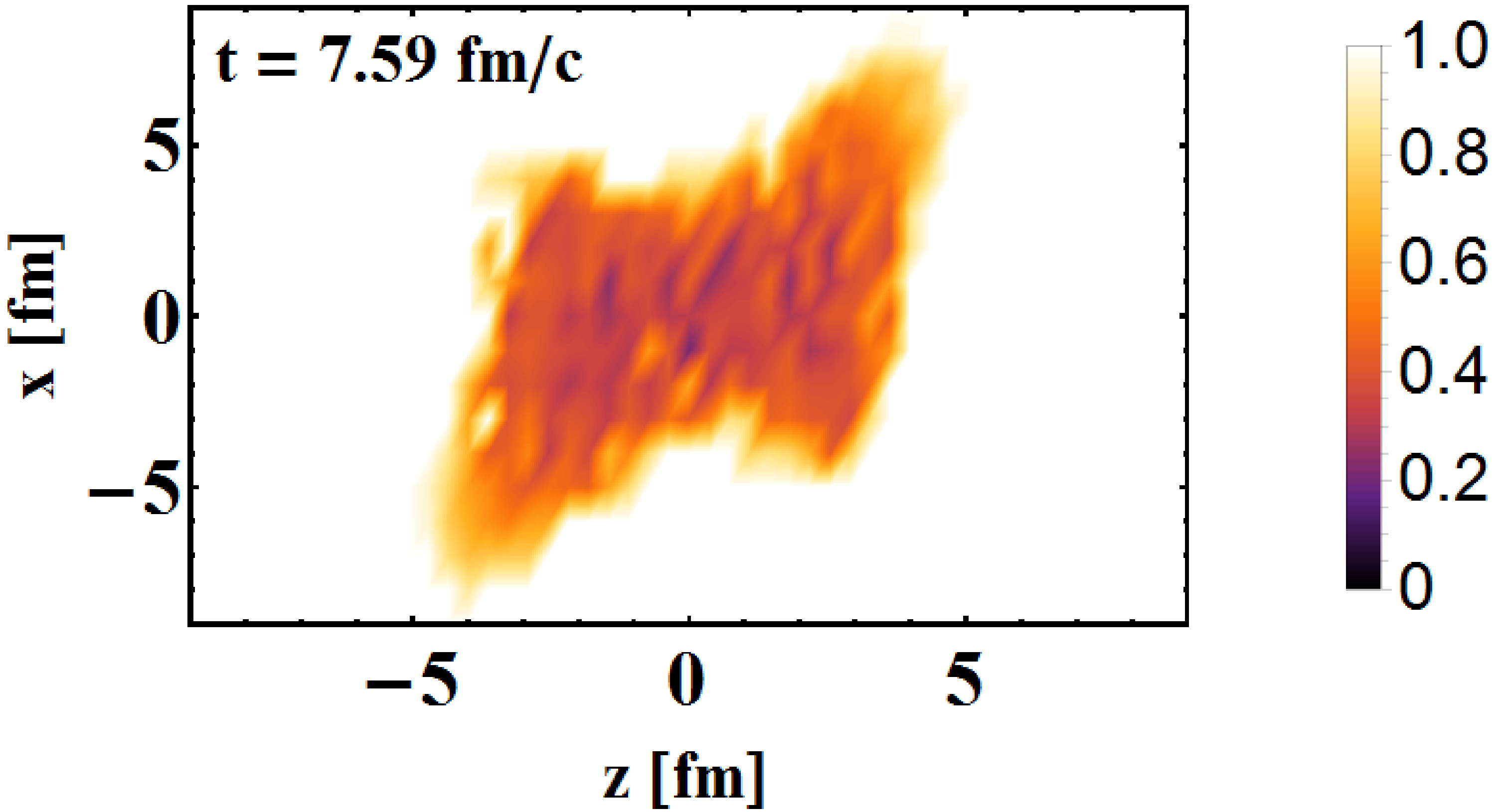

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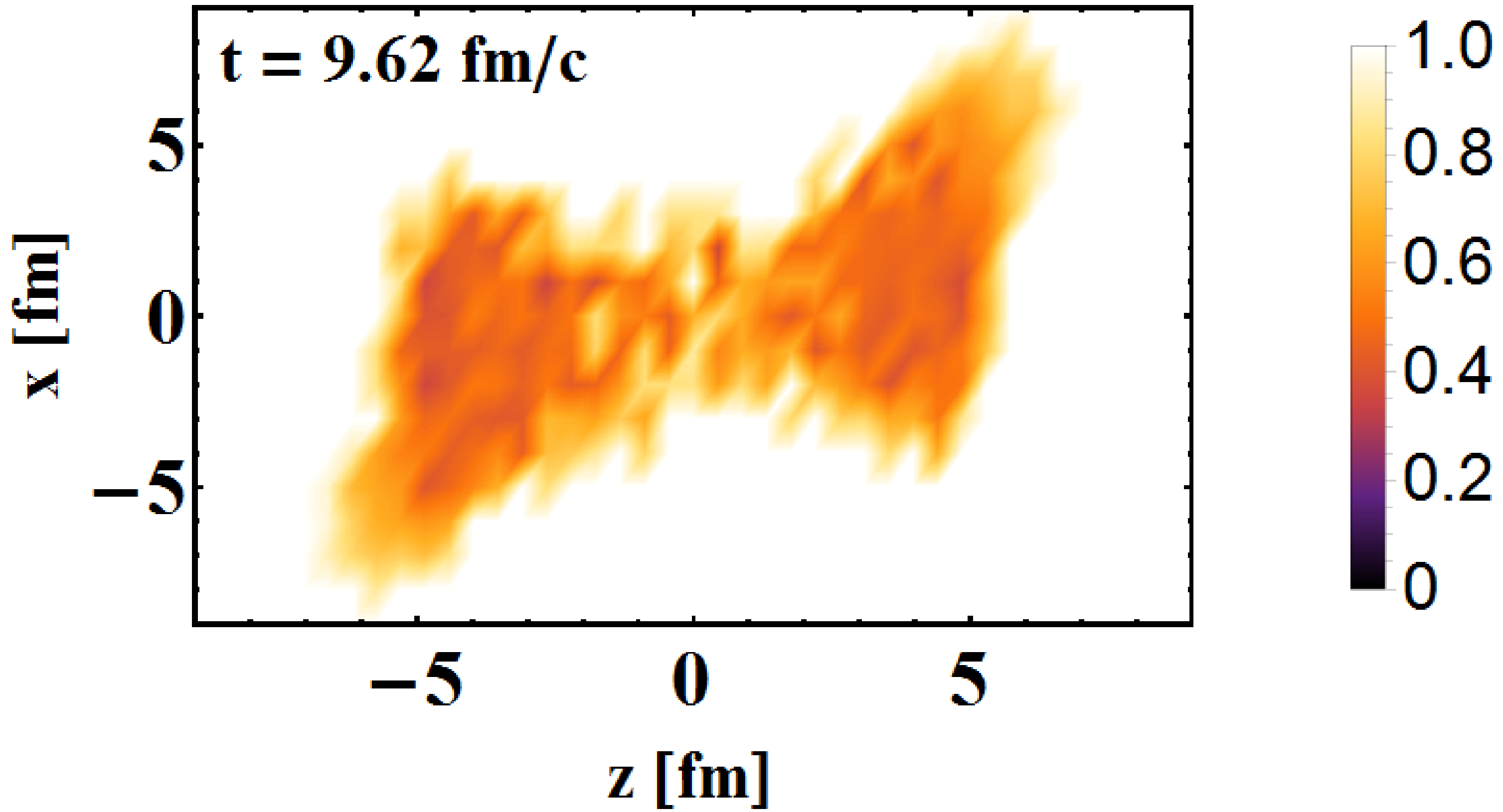

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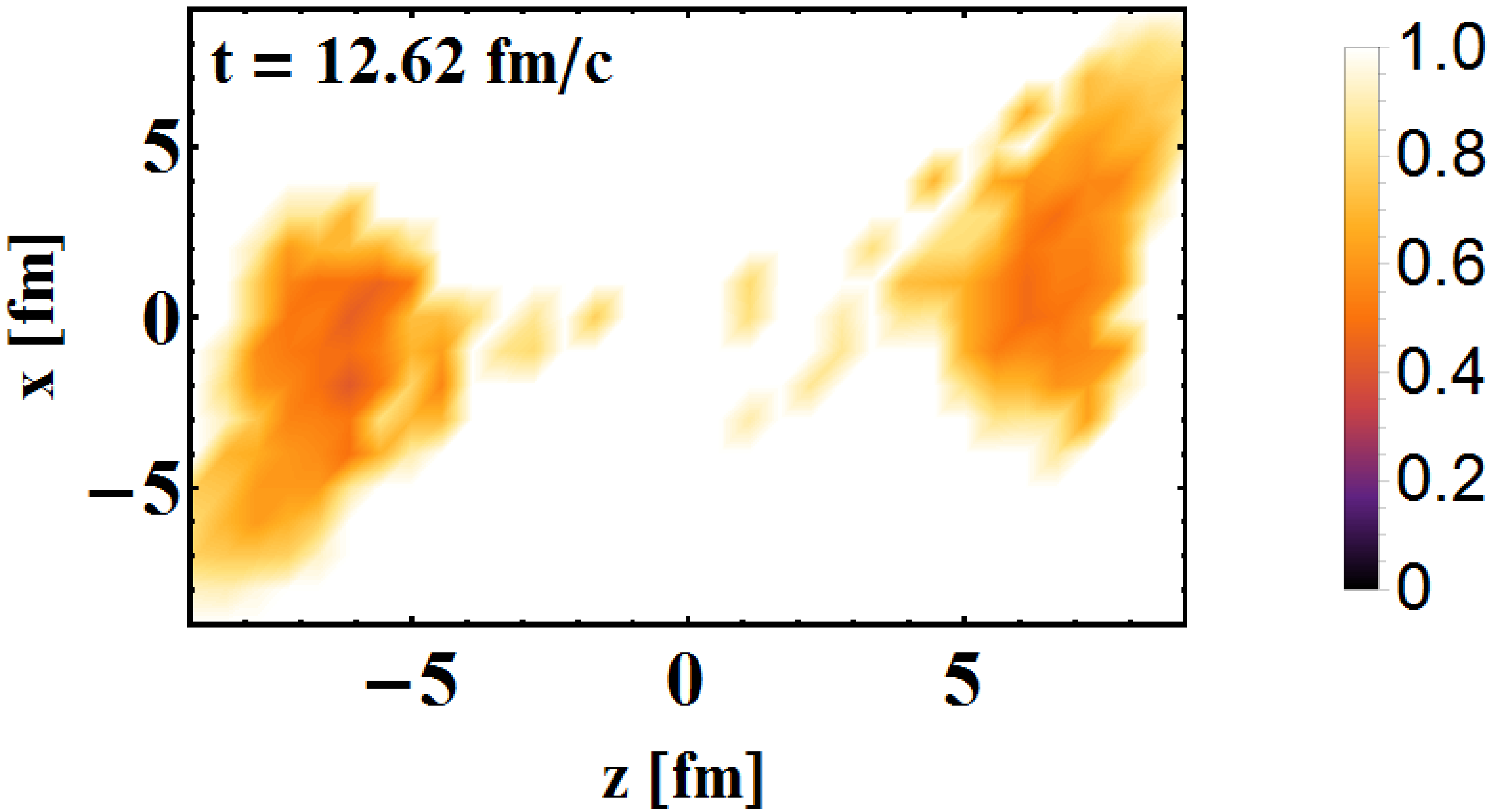
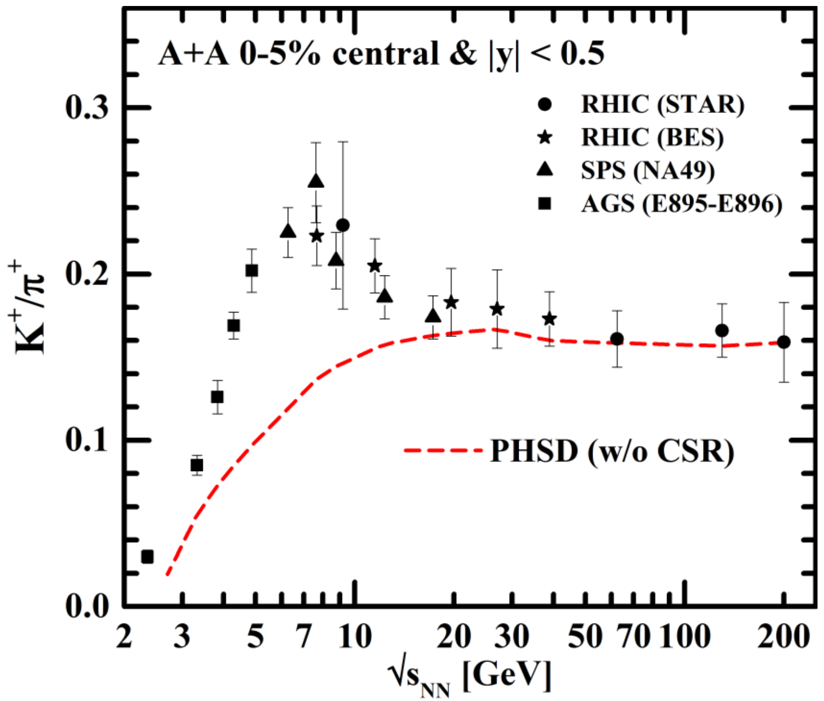
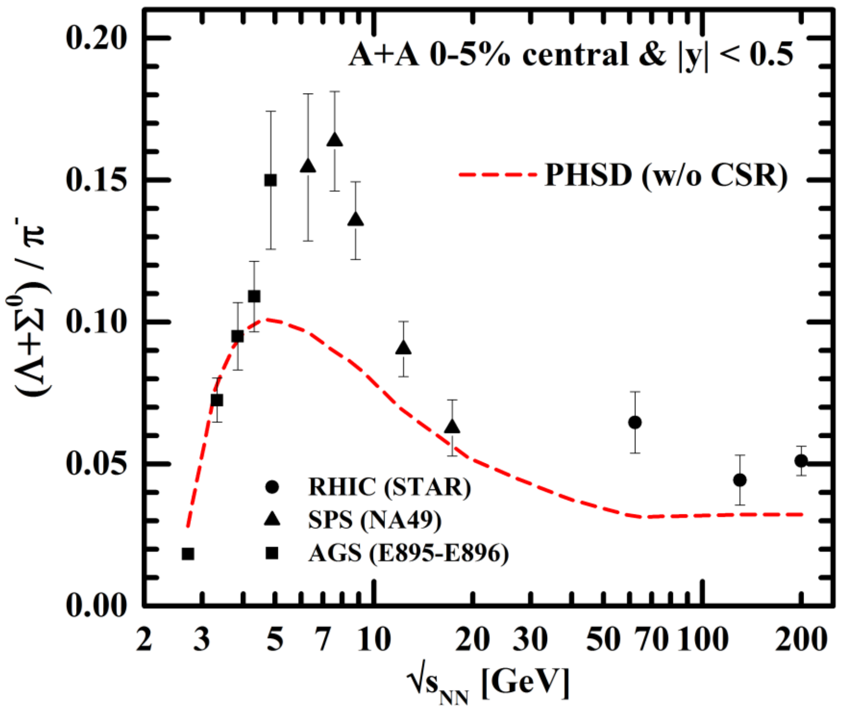


Chiral symmetry restoration in the hadronic phase

- 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**





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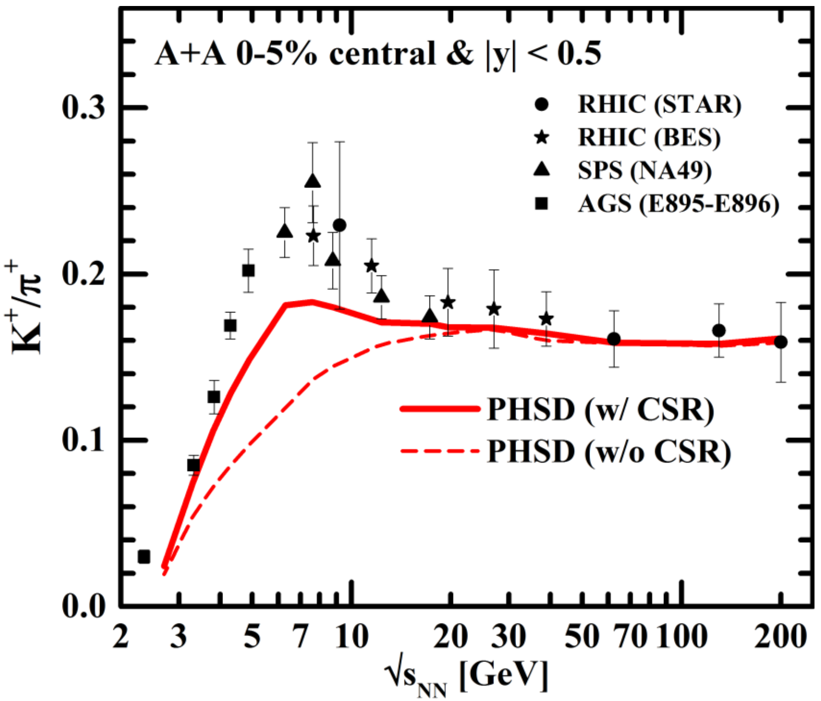

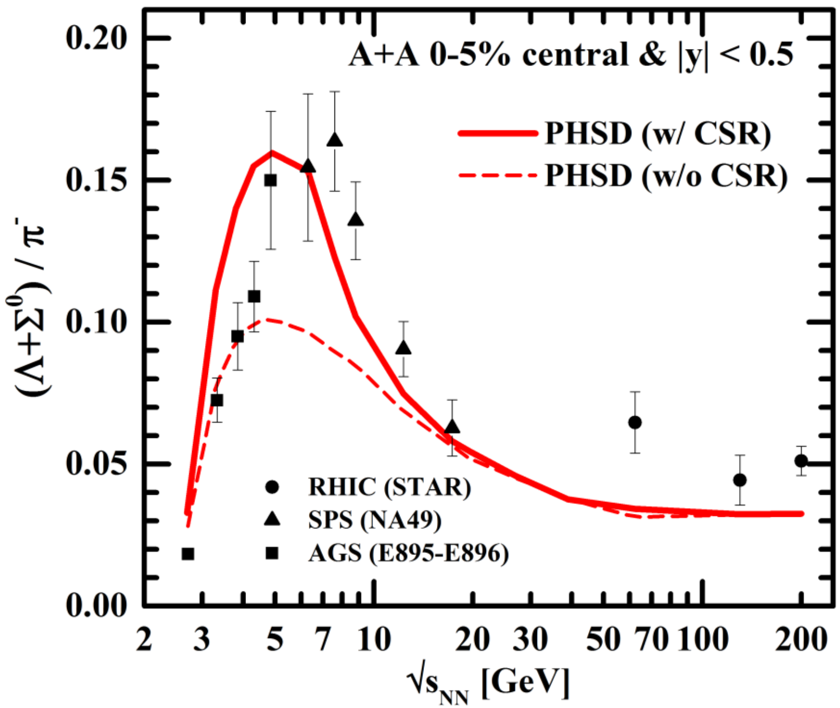

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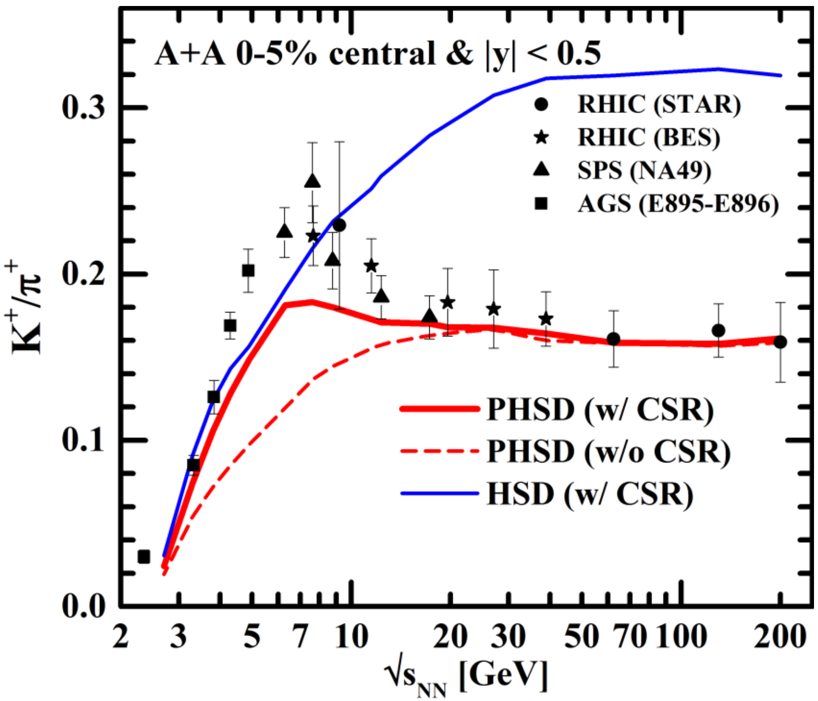
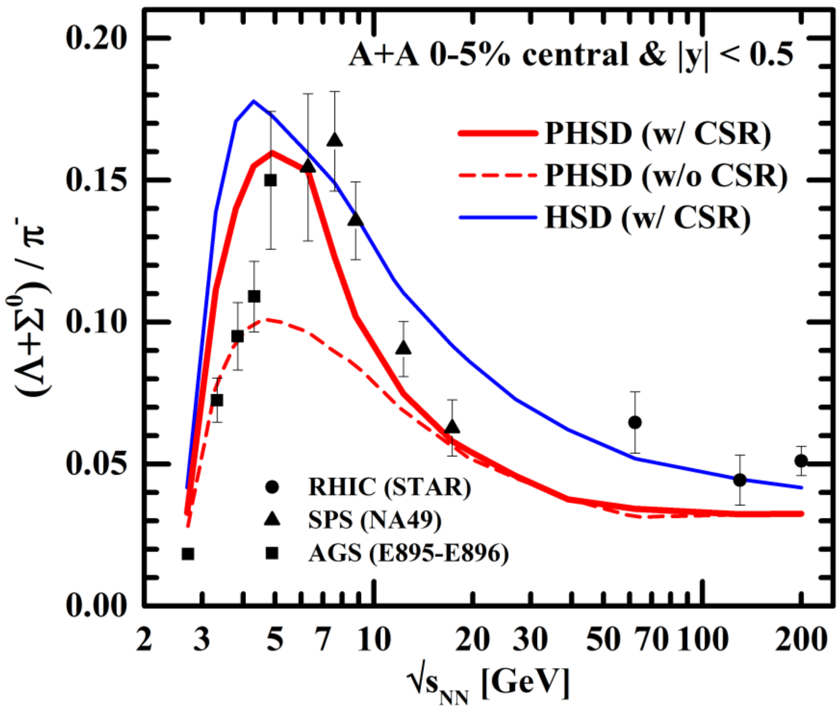
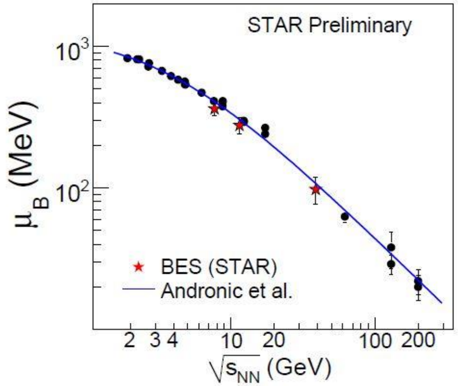




Conclusion

- At high energies, particles and antiparticles are produced in quasi-equal quantities at midrapidity in the hadronization process from the QGP phase
- By decreasing the collisional energy, more differences appear between the production of particle and antiparticle
- Cross sections from the DQPM at finite chemical potential may also play a significant role at low collisional energy



- Including 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

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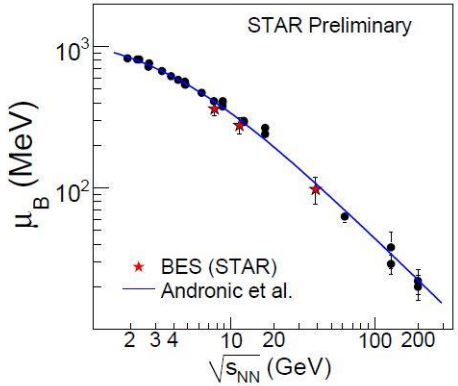

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THANK YOU FOR YOUR ATTENTION