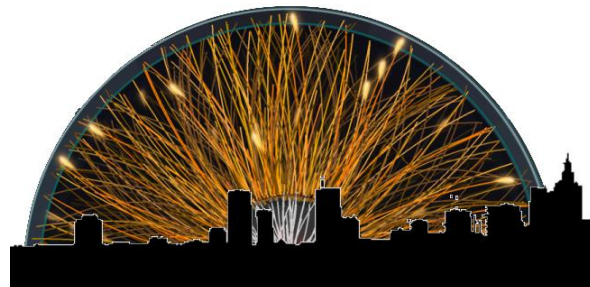# HADRON PRODUCTION WITHIN PHSD

Pierre Moreau
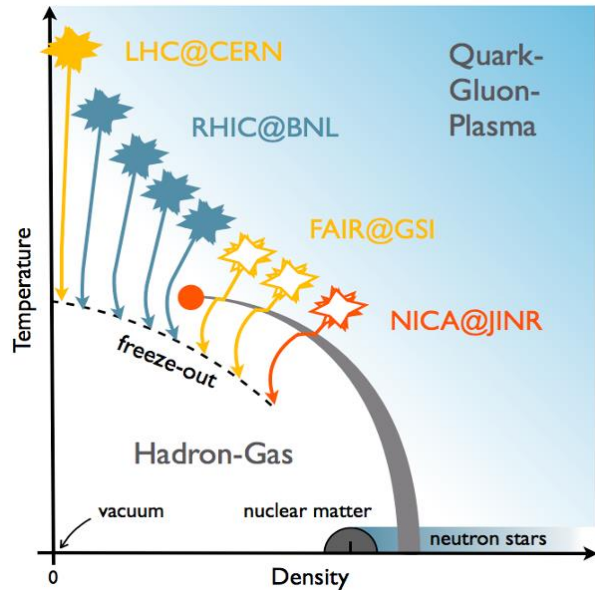
for the PHSD group

XI Workshop on Particle Correlations and Femtoscopy 2015, Warsaw, Poland
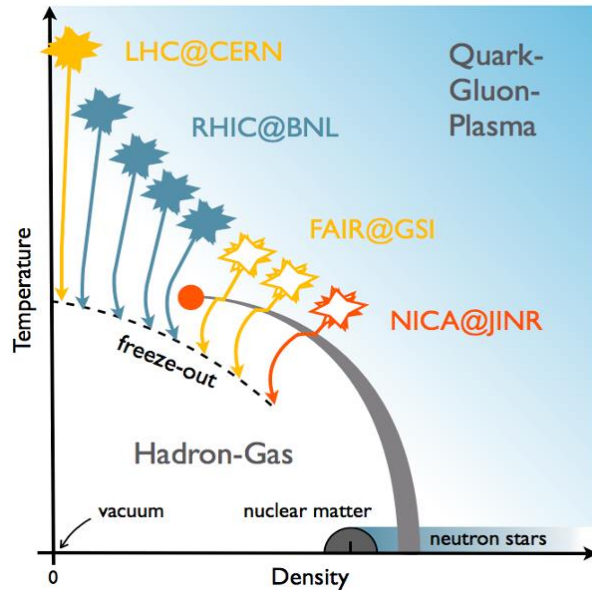


WPCF 2015

# 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
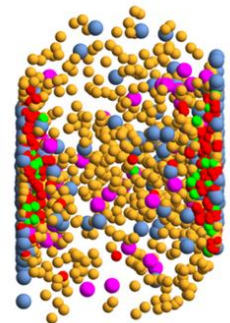
## Parton-Hadron-String-Dynamics (PHSD)

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

# Dynamical Quasi-Particle Model (DQPM)



$\rho$ [GeV$^2$]

light quark
$T = 2\,T_c$
$\mu = 0$

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

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

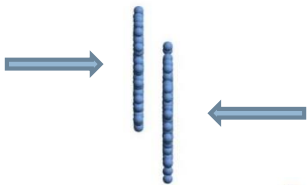□ Properties of quasiparticles are fitted to the lattice QCD results:
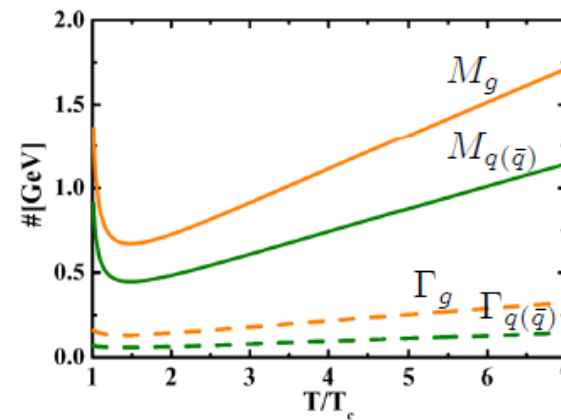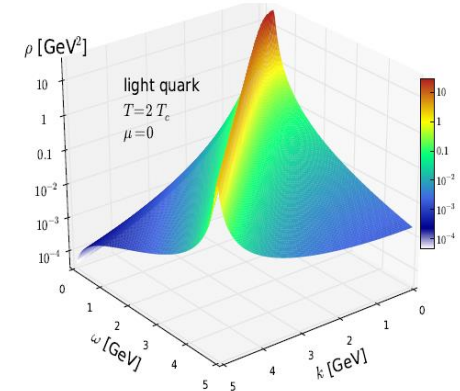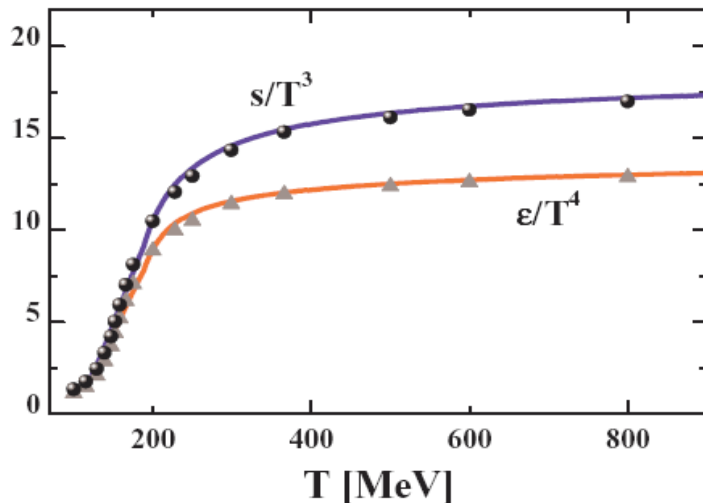




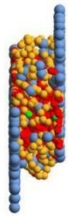□ Masses and widths of partons depend on the temperature of the medium

Peshier, Cassing, PRL 94 (2005) 172301;  Cassing,  NPA 791 (2007) 365: NPA 793 (2007)
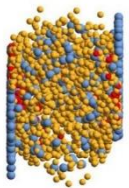
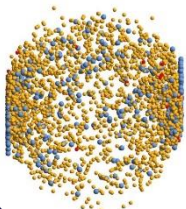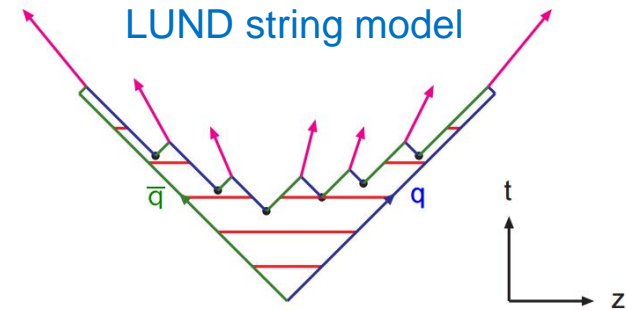# Stages of a collision in PHSD

**Initial A+A collision**

**Partonic phase**

**Hadronization**

**Hadronic phase**
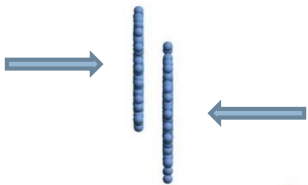
LUND string model

□ **String formation** in primary NN collisions
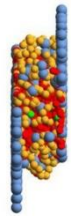
□ **String decays** to pre-hadrons (baryons and mesons)
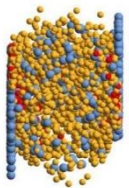
# Stages of a collision in PHSD
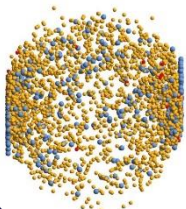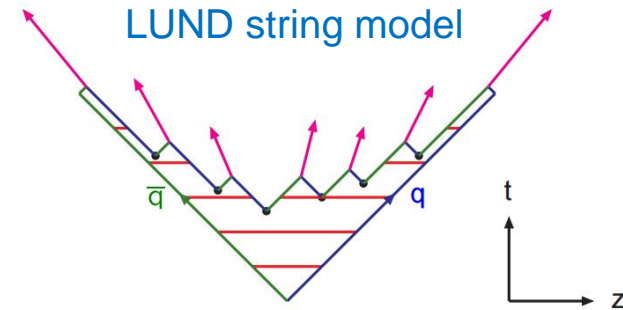
**Initial A+A collision**

**Partonic phase**

**Hadronization**

**Hadronic phase**

LUND string model



$\bar{q}$     q     t     z

- ☐ **String formation** in primary NN collisions

- ☐ **String decays** to pre-hadrons (baryons and mesons)

- ☐ Formation of a **QGP** state if $\epsilon > \epsilon_c = 0.5$ GeV.fm$^{-3}$

- ☐ Dissolution of new produced secondary hadrons into massive colored quarks and mean-field energy

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

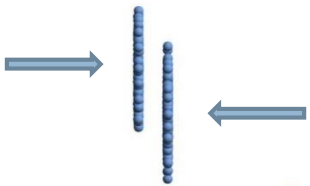- ☐ **DQPM** define the properties (masses and widths) of partons

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

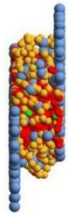$$m_q(\epsilon) \qquad \Gamma_q(\epsilon)$$
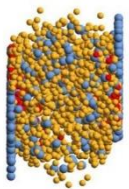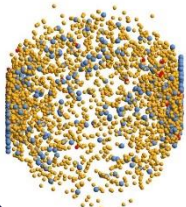
$$U_q(\epsilon)$$

# Stages of a collision in PHSD
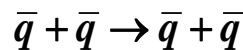
Initial A+A collision

Partonic phase

Hadronization

Hadronic phase
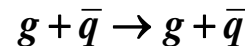
□ Propagation of partons, considered as dynamical quasiparticles, in a self-generated mean-field potential from the DQPM

□ EoS of partonic phase: ‚crossover' from Lattice QCD fitted by DQPM

□ (quasi-)elastic collisions :

$$q + q \rightarrow q + q \qquad g + q \rightarrow g + q$$
$$q + \bar{q} \rightarrow q + \bar{q} \qquad g + \bar{q} \rightarrow g + \bar{q}$$
$$\bar{q} + \bar{q} \rightarrow \bar{q} + \bar{q} \qquad g + g \rightarrow g + g$$
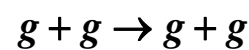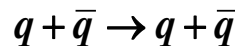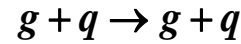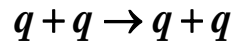
□ inelastic collisions :

$$q + \bar{q} \rightarrow g \qquad q + \bar{q} \rightarrow g + g$$
$$g \rightarrow q + \bar{q} \qquad g \rightarrow g + g$$
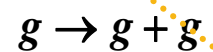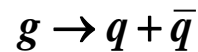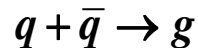
Suppressed due to the large gluon mass

# Stages of a collision in PHSD
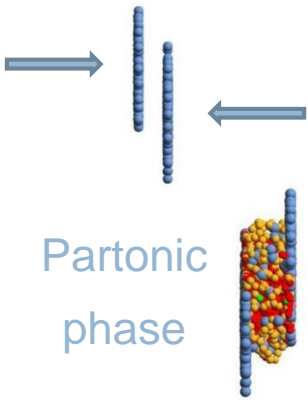
Initial A+A collision

Partonic phase

**Hadronization**

Hadronic phase

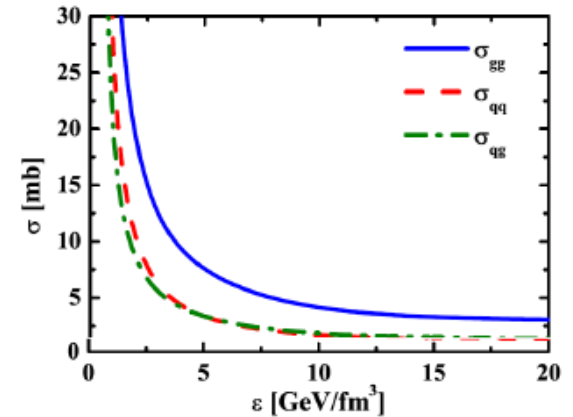□ Massive and off-shell (anti-)quarks hadronize to colorless off-shell mesons and baryons

$$g \rightarrow q + \bar{q}, \quad q + \bar{q} \leftrightarrow meson \ ('string')$$

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

□ Local covariant off-shell transition rate

□ Strict 4-momentum and quantum number conservation
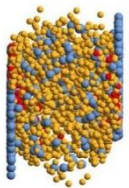
# Stages of a collision in PHSD
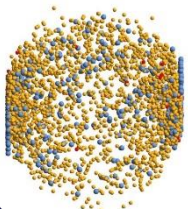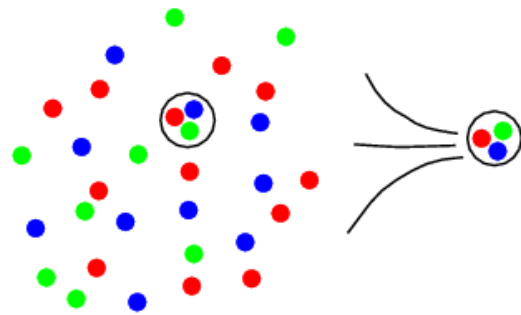
Initial A+A collision

Partonic phase

Hadronization

Hadronic phase

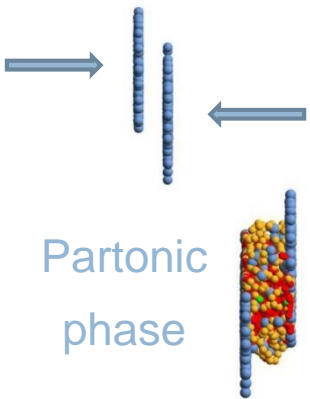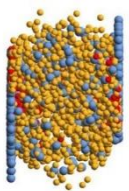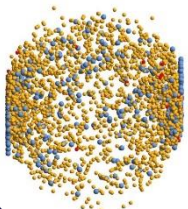☐ Massive and off-shell (anti-)quarks hadronize to colorless off-shell mesons and baryons
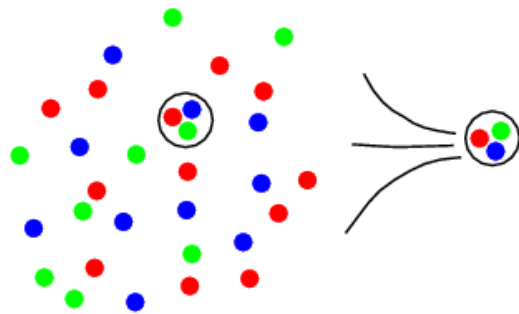
$$g \rightarrow q + \bar{q}, \quad q + \bar{q} \leftrightarrow meson \; (\,'string\,'\,)$$

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

☐ Local covariant off-shell transition rate

☐ Strict 4-momentum and quantum number conservation

Number of partons and hadrons as a function of time:



free quarks :
(u+d)/2
(ū+d̄)/2
s
s̄
gluons
Total s
Total s̄

$\pi^+$
$\pi^-$
$K^+$
$K^-$
$p$
$\bar{p}$
$\Lambda + \Sigma^0$
$\bar{\Lambda} + \bar{\Sigma}^0$
$\Xi^-$
$\bar{\Xi}^+$

Au+Au $\sqrt{s_{NN}}$ = 200 GeV - 0-5% central

Central Au+Au – Top RHIC
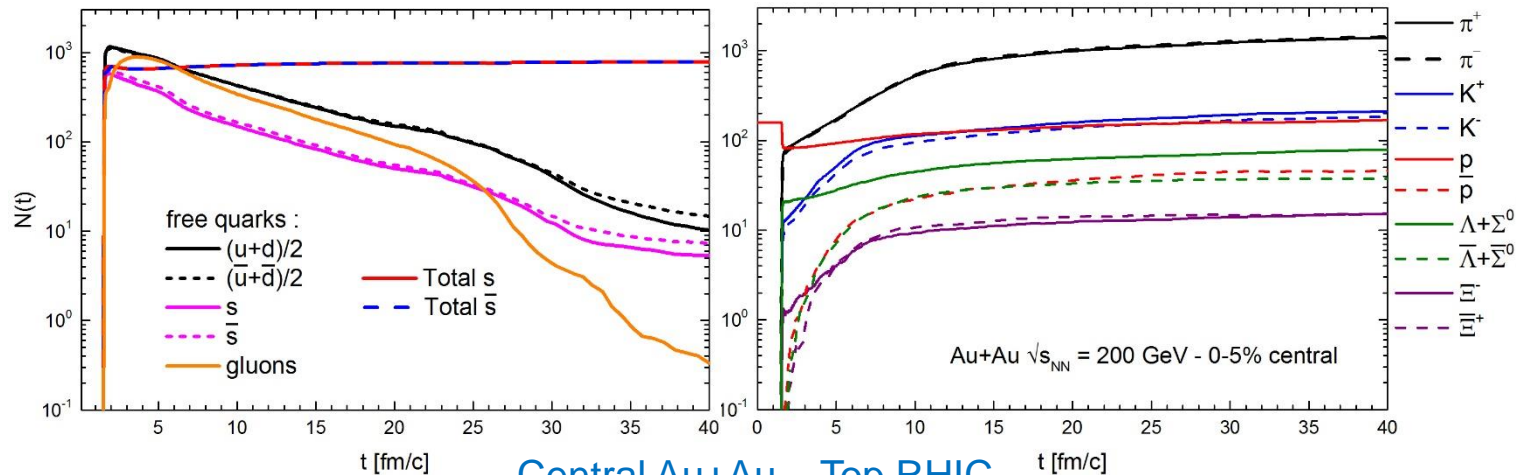
# Stages of a collision in PHSD



t = 0.1 fm/c

Au + Au $\sqrt{s_{NN}}$ = 200 GeV
b = 2.2 fm  —  Section view

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

P.Moreau

# Stages of a collision in PHSD



t = 1.63549 fm/c

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

b = 2.2 fm  –  Section view

Baryons (394)

Antibaryons ( 0)

Mesons (1598)

Quarks (4383)

Gluons (344)

P.Moreau

# Stages of a collision in PHSD



$t = 2.06543$ fm/c

Au + Au $\sqrt{s_{NN}} = 200$ GeV
b = 2.2 fm – Section view
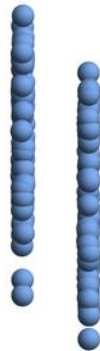
Baryons (396)
Antibaryons (   2)
Mesons (1136)
Quarks (5066)
Gluons (516)

P.Moreau

# Stages of a collision in PHSD

t = 3.20258 fm/c

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

b = 2.2 fm — Section view

Baryons (413)

Antibaryons ( 13)

Mesons (1080)

Quarks (4708)

Gluons (761)

P.Moreau

# Stages of a collision in PHSD

t = 5.56921 fm/c



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

b = 2.2 fm  —  Section view

- Baryons (472)
- Antibaryons ( 70)
- Mesons (1724)
- Quarks (3843)
- Gluons (652)

P.Moreau

# Stages of a collision in PHSD



t = 8.06922 fm/c

Au + Au $\sqrt{s_{NN}}$ = 200 GeV
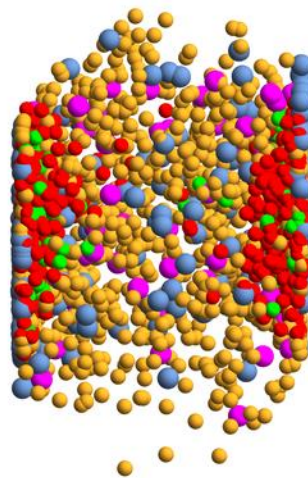
b = 2.2 fm — Section view

Baryons (559)

Antibaryons (139)

Mesons (2686)

Quarks (2628)

Gluons (442)

P.Moreau

# Stages of a collision in PHSD



$t = 10.5692$ fm/c

Au + Au $\sqrt{s_{NN}} = 200$ GeV
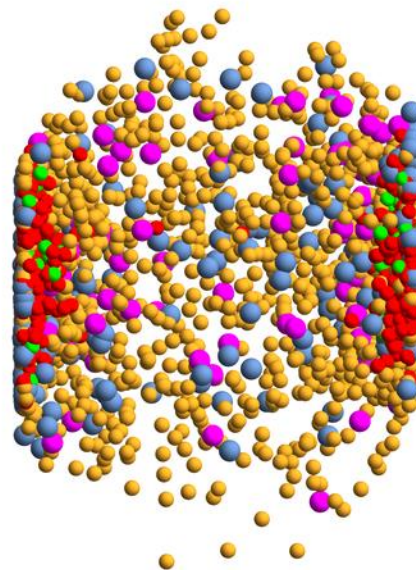
$b = 2.2$ fm — Section view

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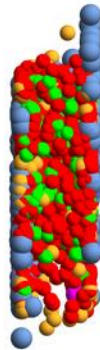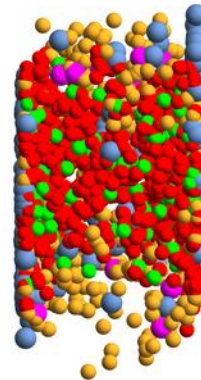- Antibaryons (187)
- Mesons (3169)
- Quarks (2076)
- Gluons (319)
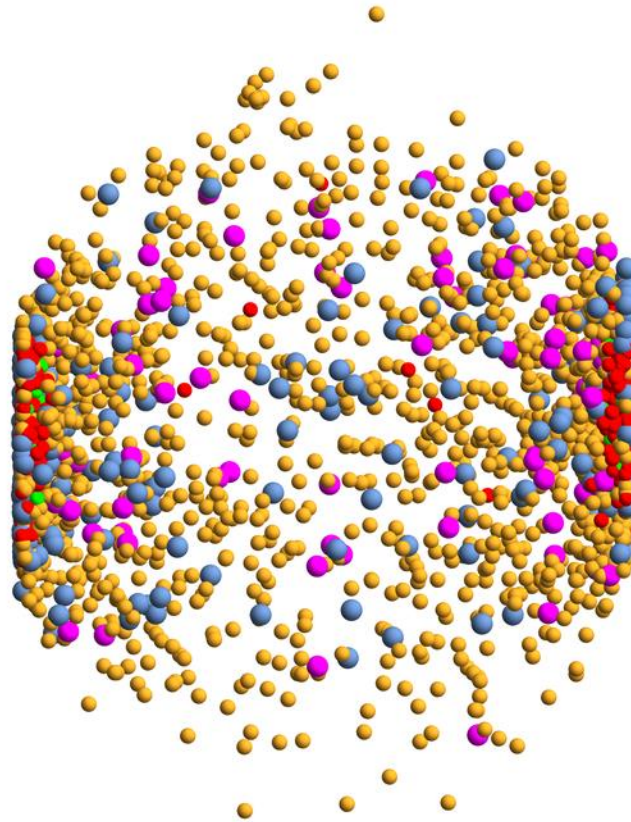
P.Moreau

# Stages of a collision in PHSD

# Stages of a collision in PHSD
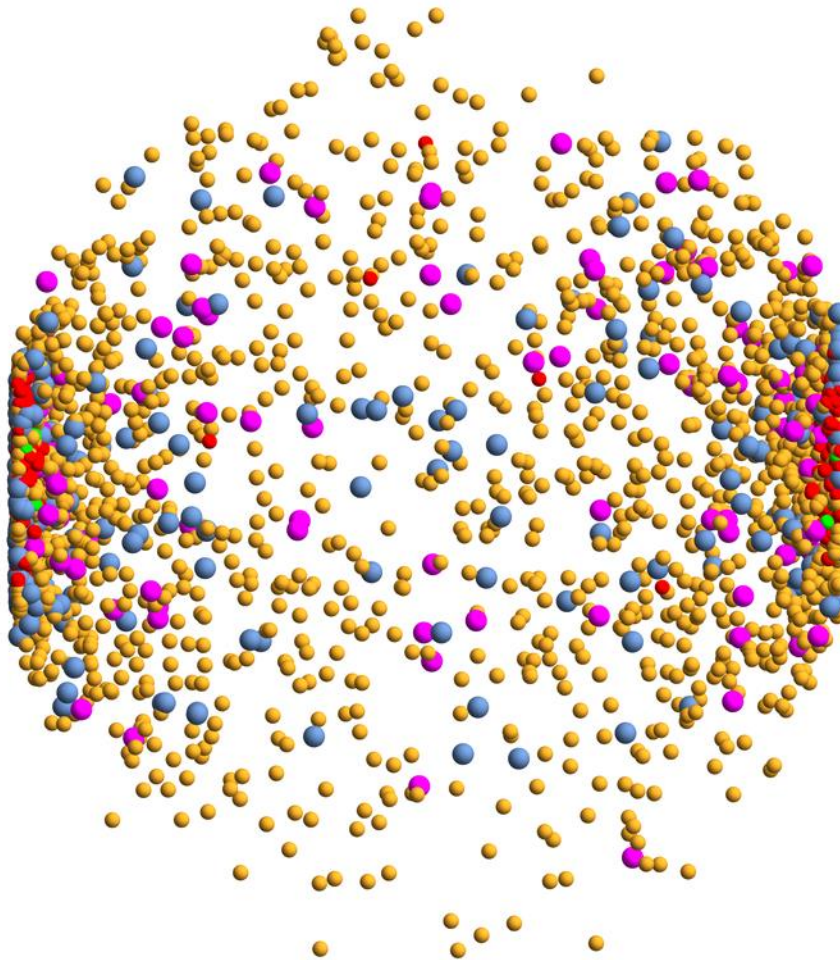
# Partonic energy fraction in central A+A

□ 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
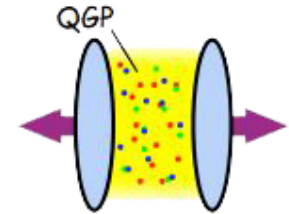
Time evolution of the partonic energy fraction for different energies:
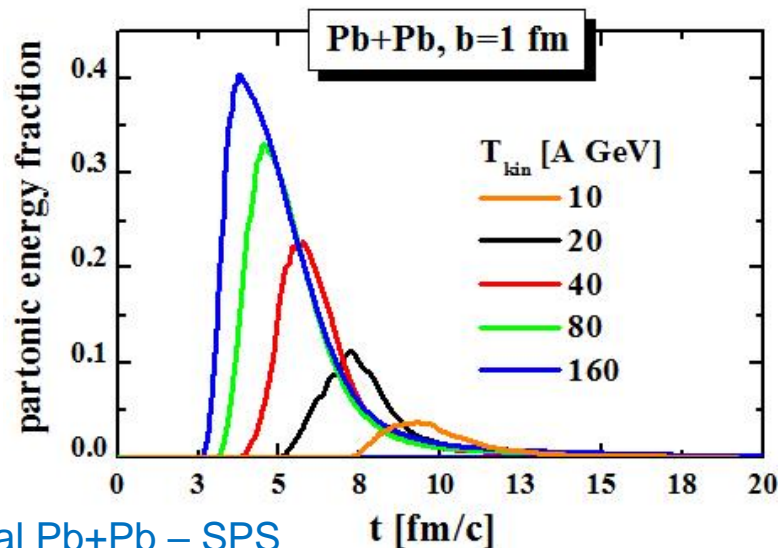


Central Pb+Pb – SPS
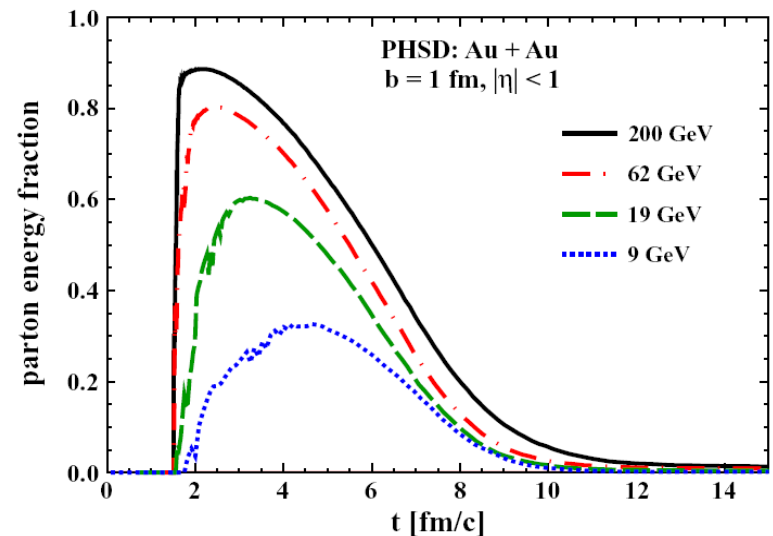
Central Au+Au

# 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:
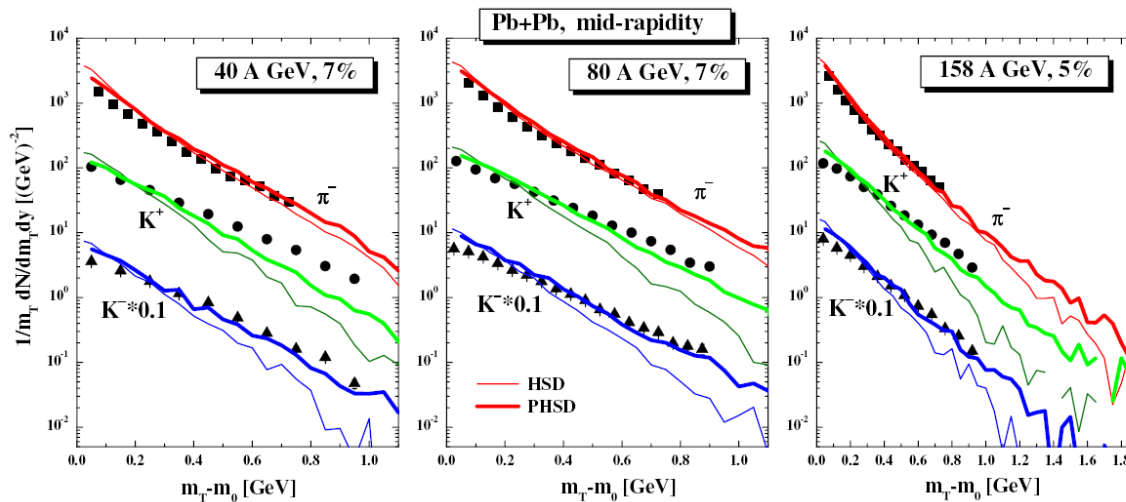


Central Pb+Pb – SPS energies                    Central Au+Au – RHIC
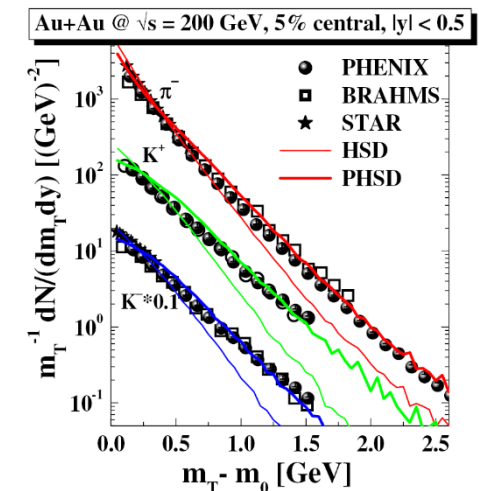
W. Cassing & E. Bratkovskaya,  NPA 831 (2009) 215; E. Bratkovskaya,  W. Cassing,  V. Konchakovski, O. Linnyk, NPA856 (2011) 162

# 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
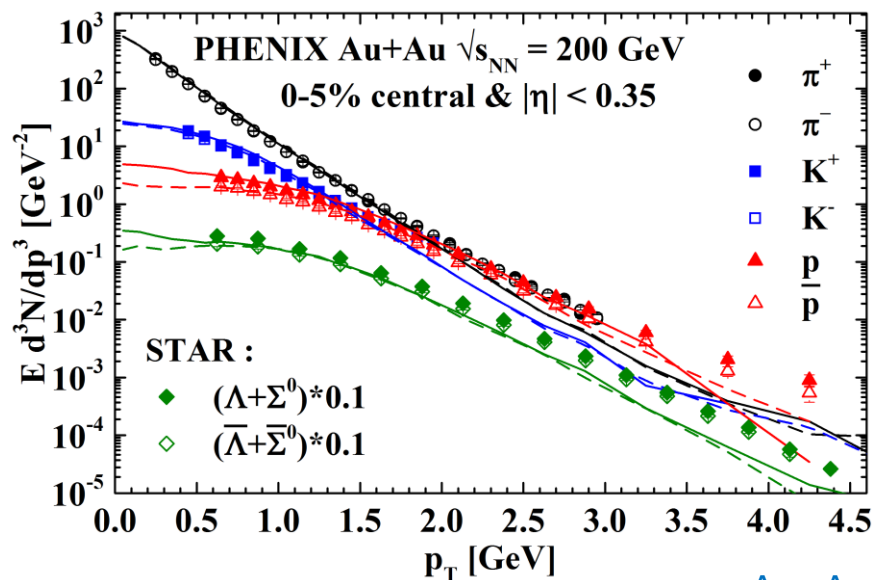
pT spectra:                                                Production at midrapidity dN/dy:
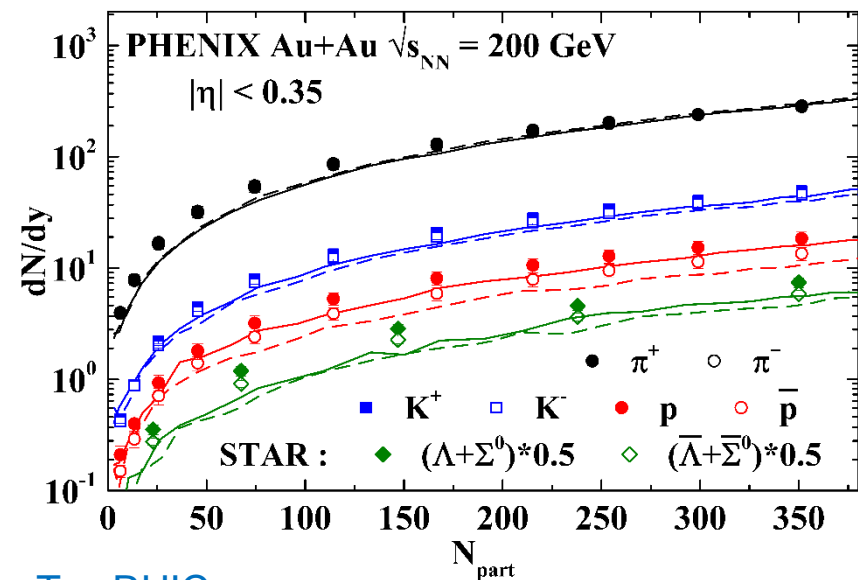


Au+Au – Top RHIC

# 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
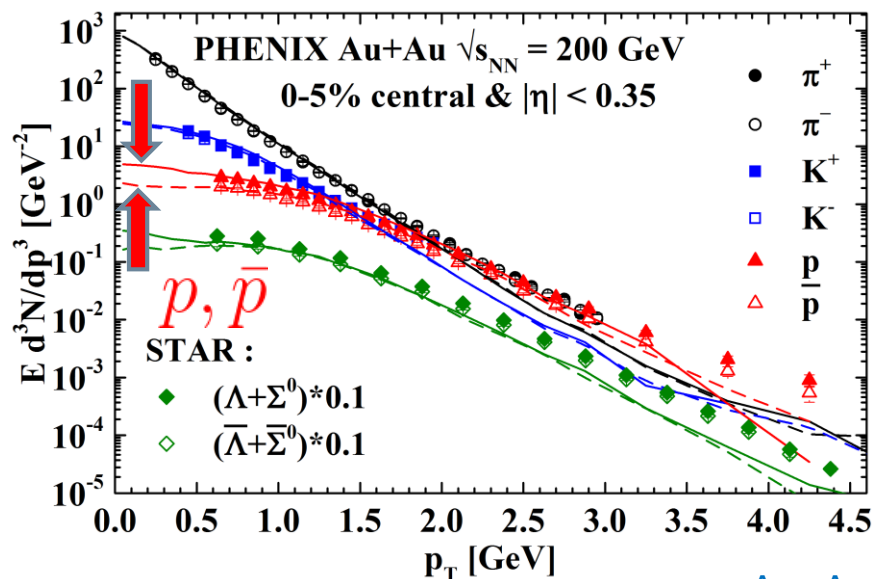
pT spectra:

Production at midrapidity dN/dy:
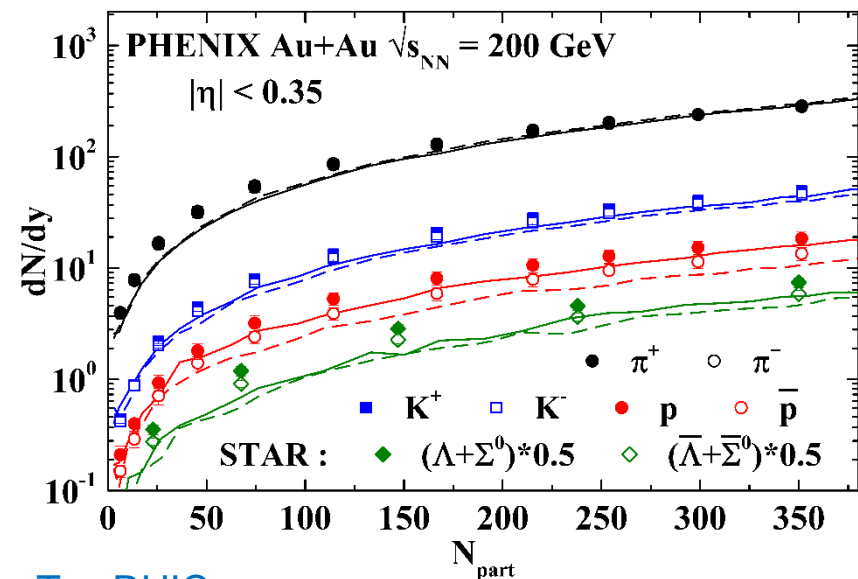


Au+Au – Top RHIC

# 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:
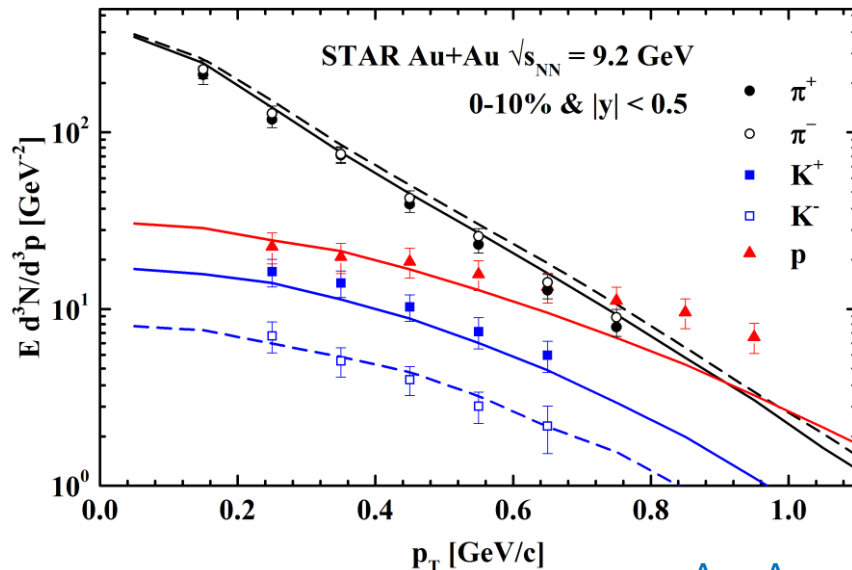
Production at midrapidity dN/dy:
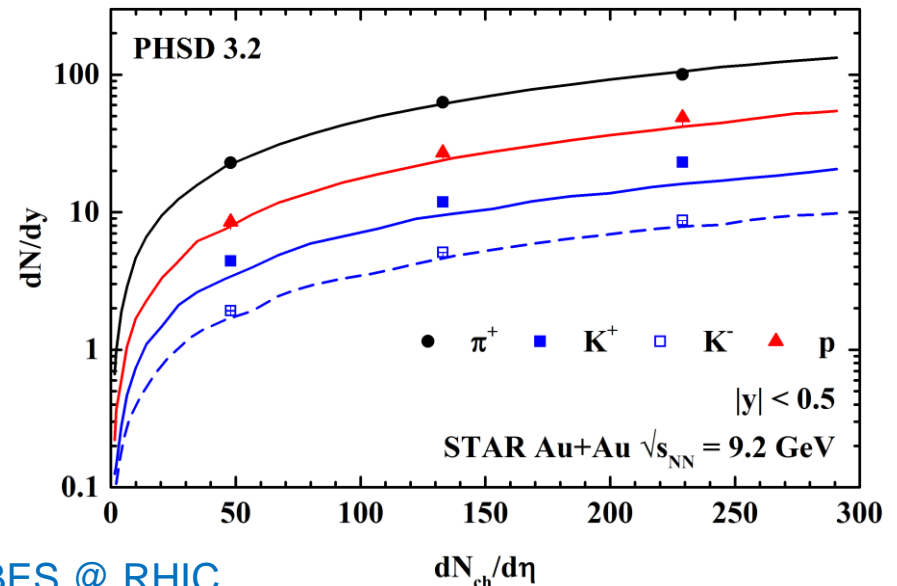


Au+Au – BES @ RHIC

# 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

# 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

$$p, \bar{p}$$

Rapidity spectras:



Central Au+Au – Top RHIC

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:

$p, \bar{p}$ $p, \bar{p}$



Central Au+Au – Top RHIC
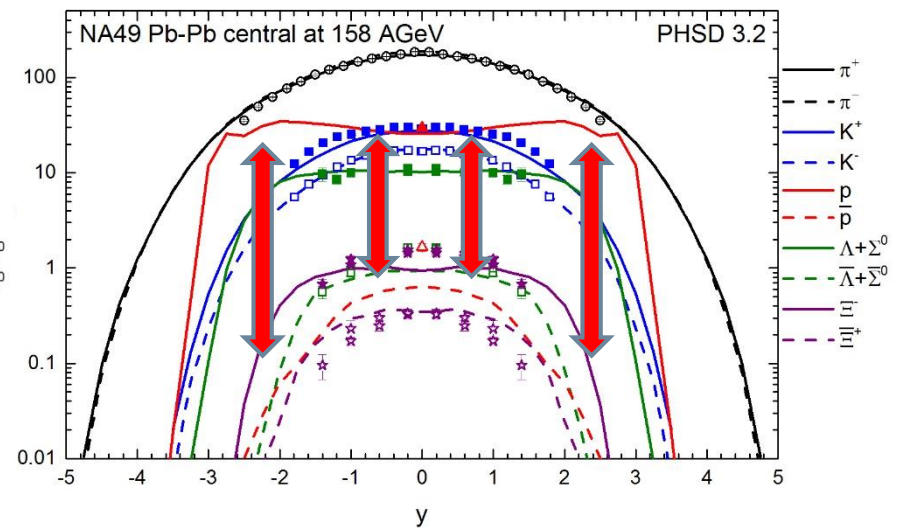
Central Pb+Pb – Top SPS
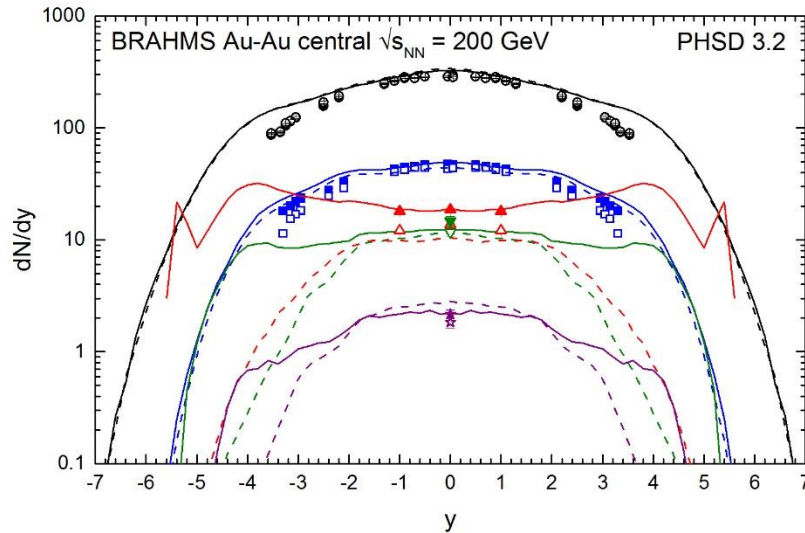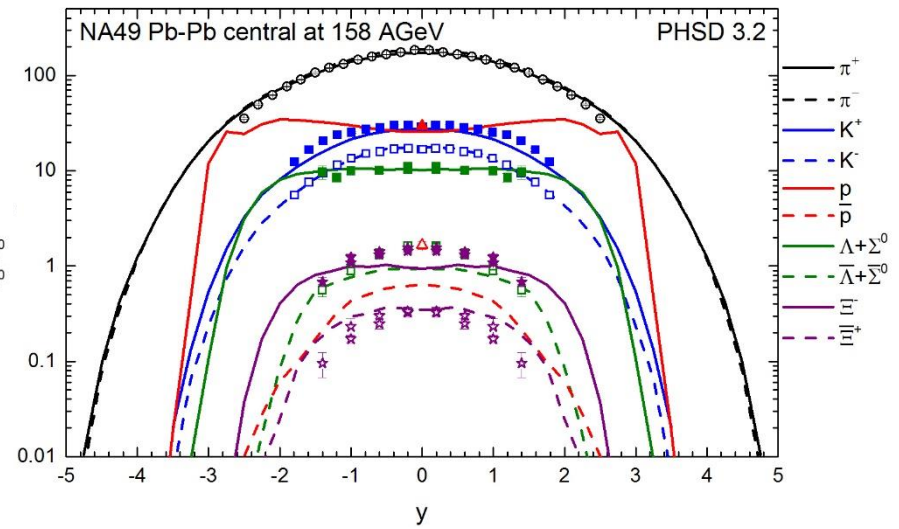
# Rapidity spectra

- 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
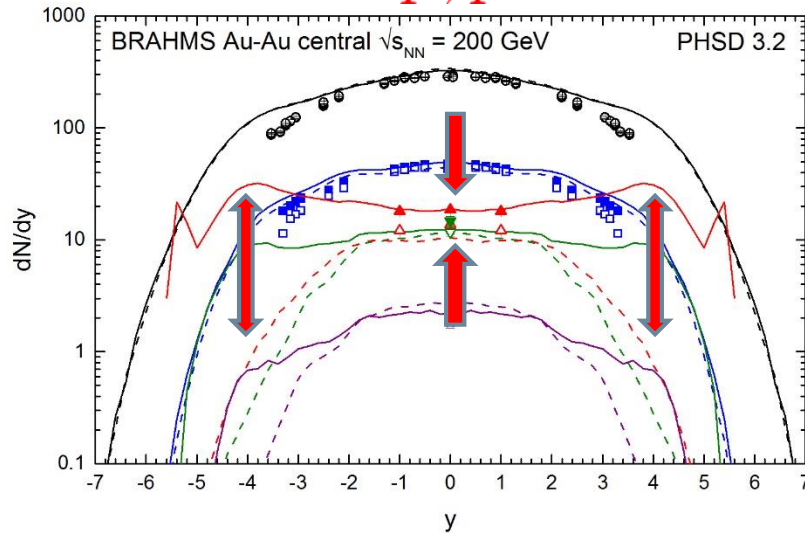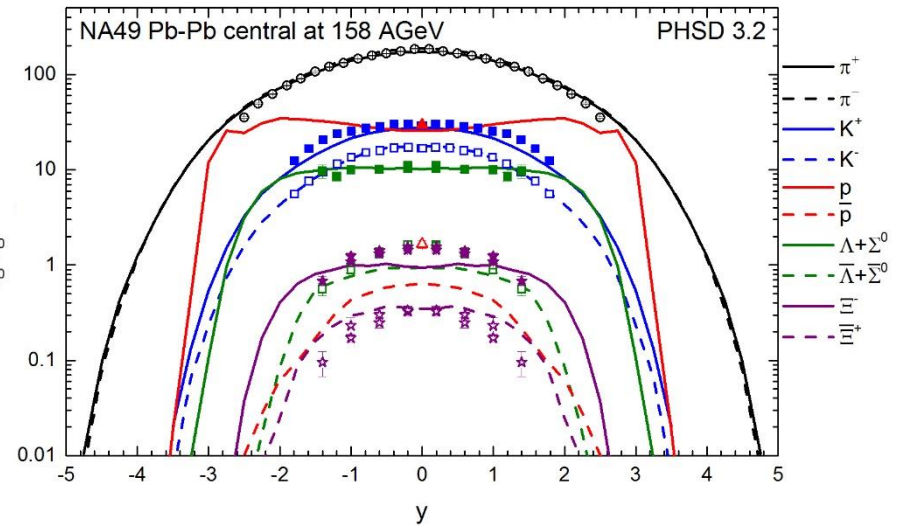
Rapidity spectras:
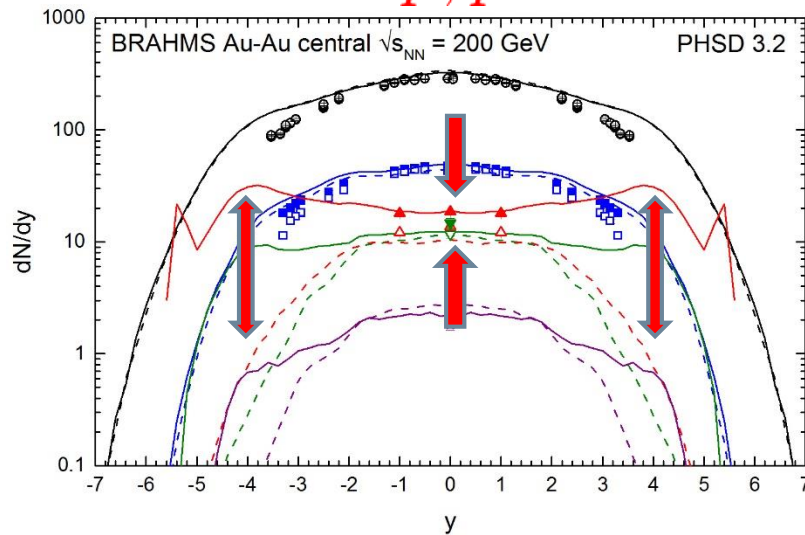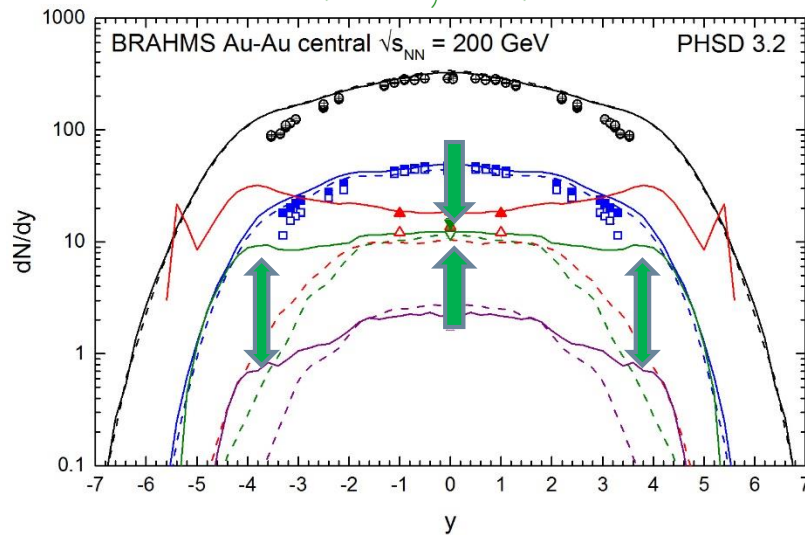


Central Au+Au – Top RHIC
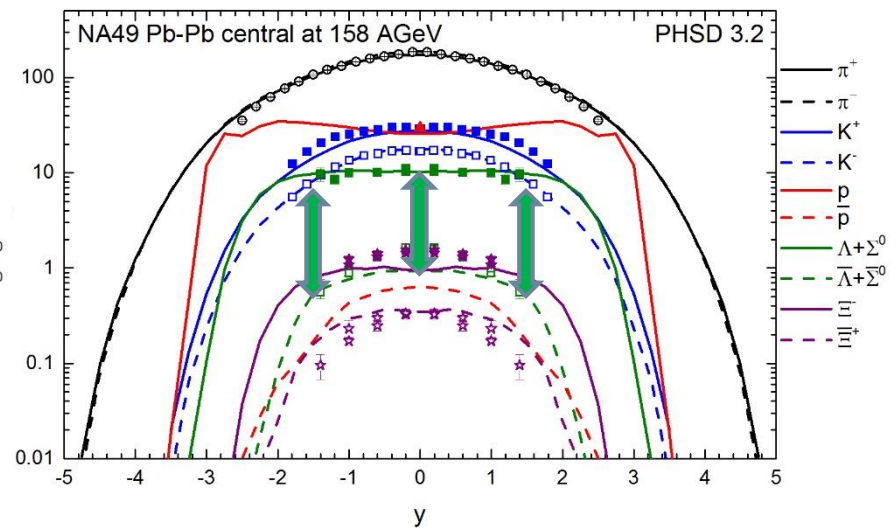
Central Pb+Pb – Top SPS

# 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
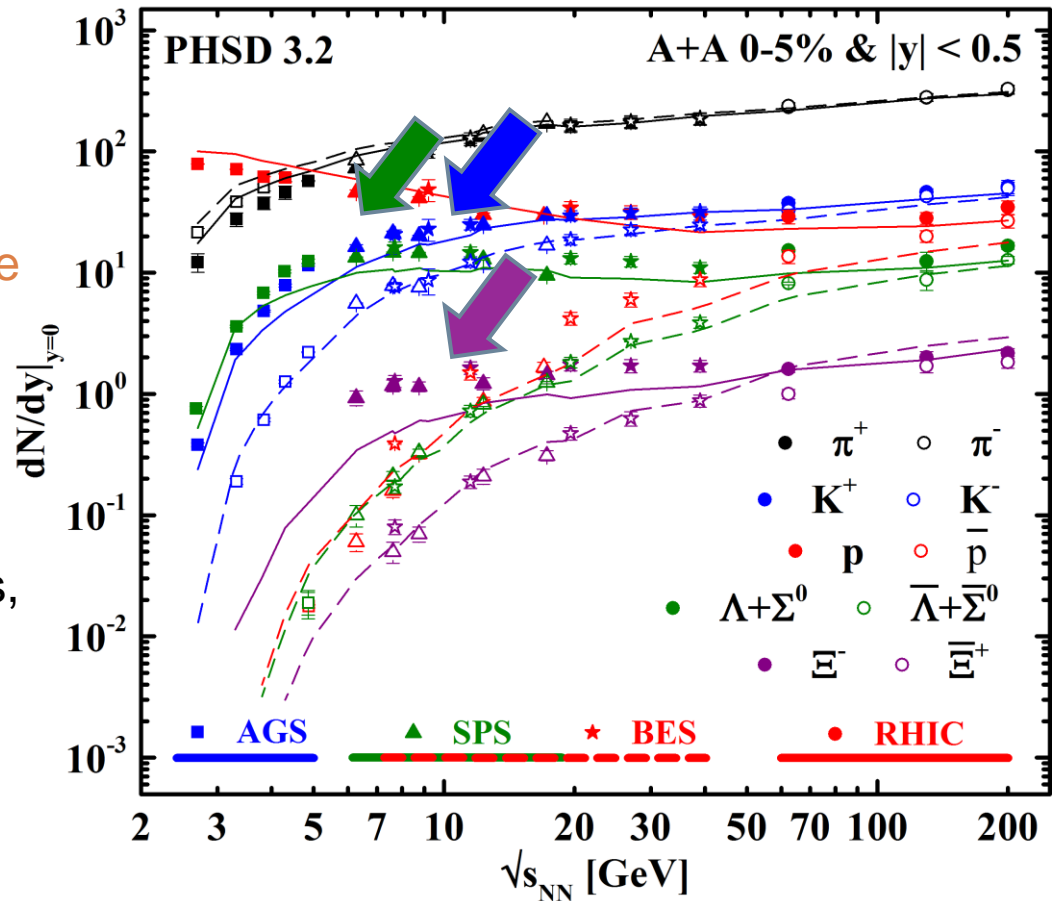
# Missing strangeness ?

☐ 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**
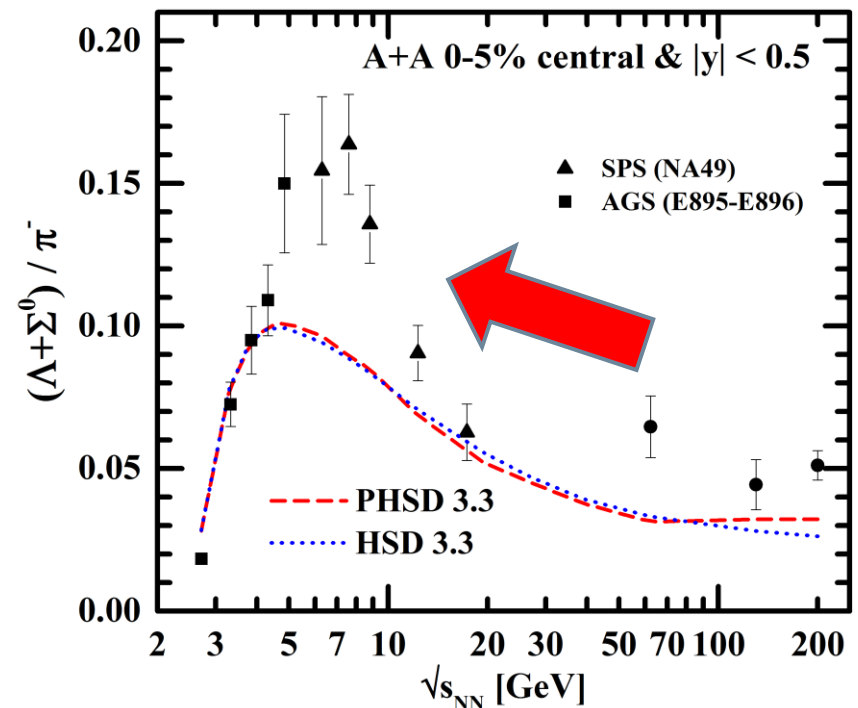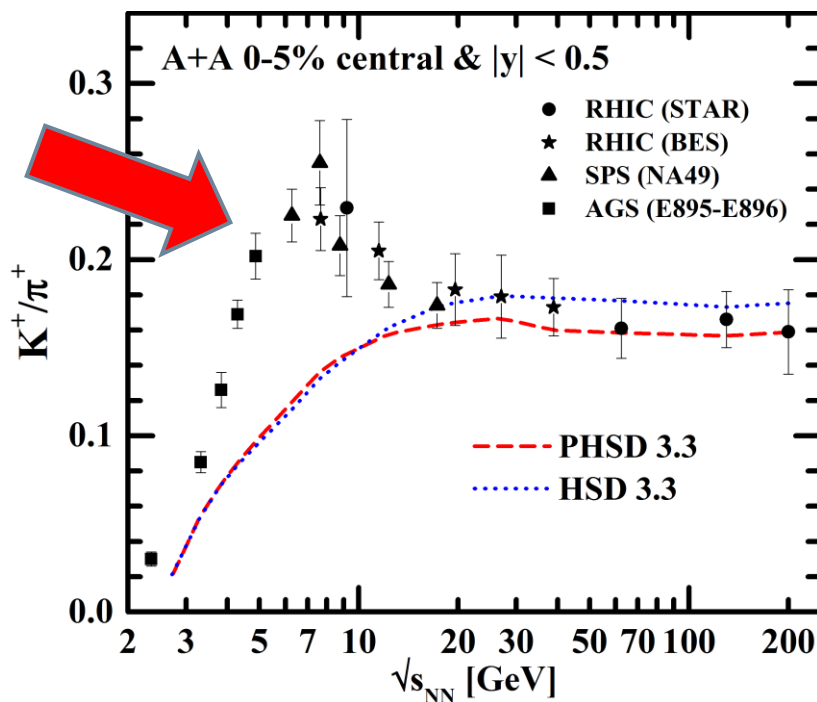
# Production of quarks by string decays

☐ 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:

$$m_s^* = m_s^0 + (m_s^v - m_s^0)\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V} \qquad m_q^* = m_q^0 + (m_q^v - m_q^0)\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V}$$
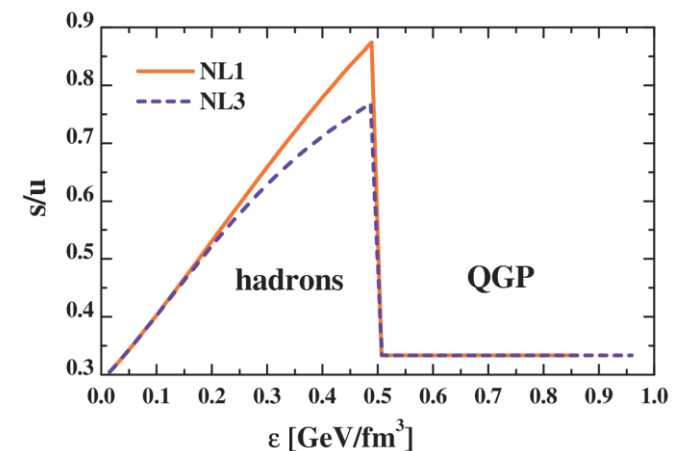
# Chiral symmetry restoration in the hadronic phase

☐ 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 $\rho_s$ is the scalar density obtained according to the non-linear $\sigma - \omega$ model, $\Sigma_\pi \approx 45$ MeV is the pion-nucleon $\Sigma$-term, and $f_\pi$ and $m_\pi$ are the pion decay constant and pion mass, given by the Gell-Mann-Oakes-Renner relation.
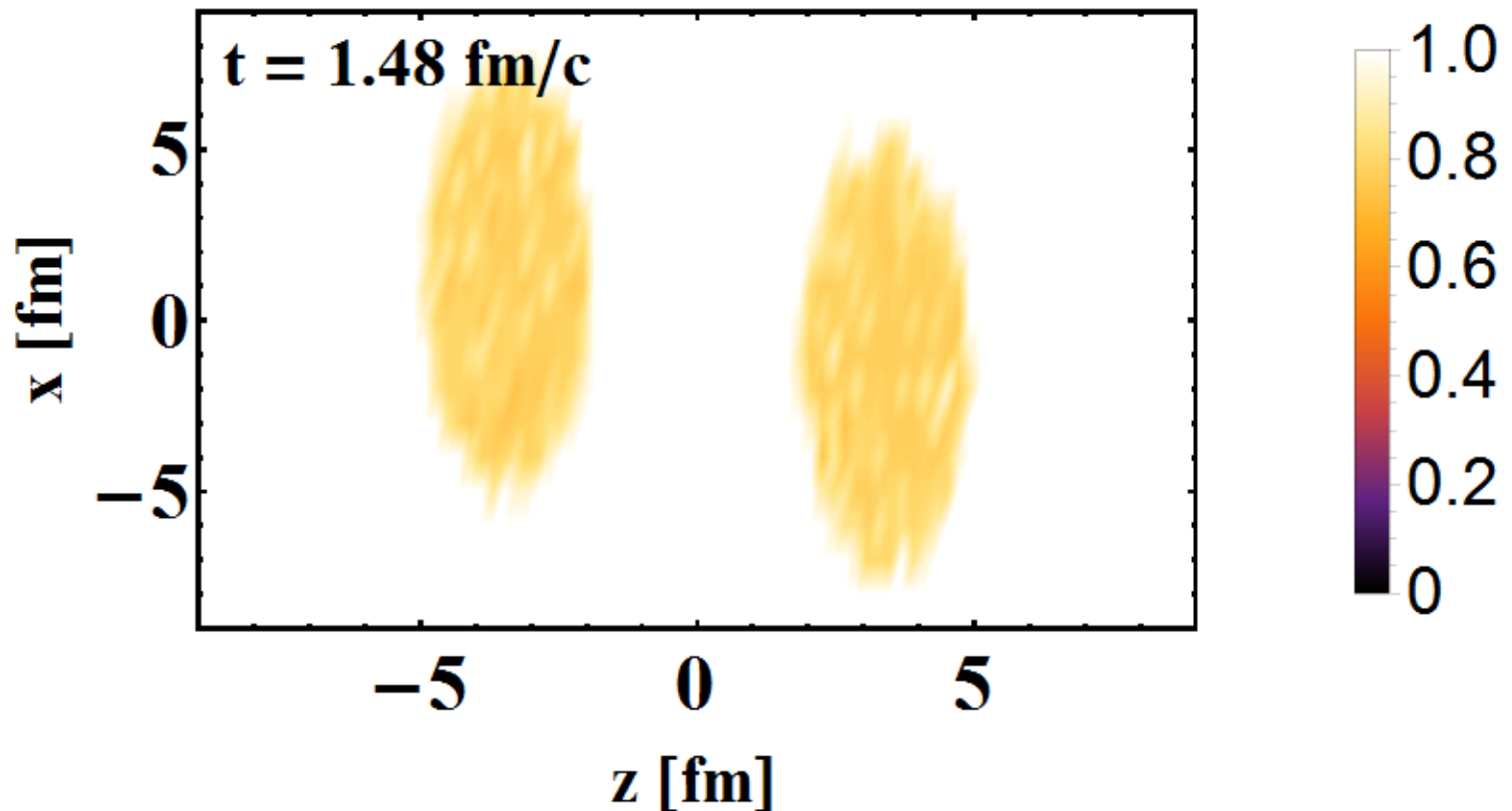
☐ As a consequence of the **chiral symmetry restoration (CSR)**, the strangeness production probability increases with the energy density $\varepsilon$. In the QGP phase, the string decay doesn't occur anymore and this effect is therefore suppressed.

# Pb+Pb @ 30 AGeV – 0-5% central

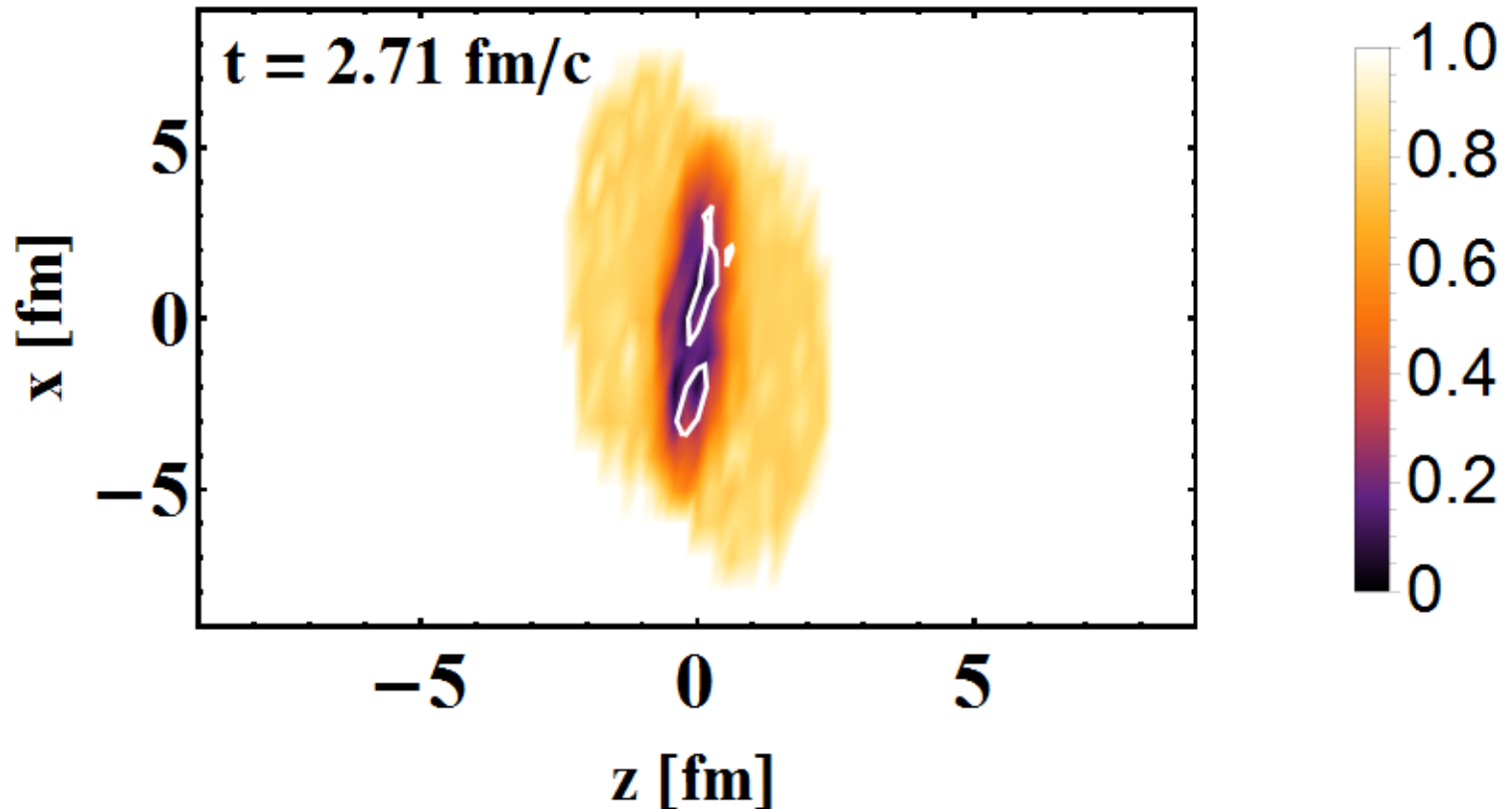Ratio of the quark scalar condensate compared to vacuum as a function of time:

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

# Pb+Pb @ 30 AGeV – 0-5% central

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

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

# Pb+Pb @ 30 AGeV – 0-5% central

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

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

# Pb+Pb @ 30 AGeV – 0-5% central

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

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

# Pb+Pb @ 30 AGeV – 0-5% central

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

$$\frac{<q\,\bar{q}>}{<q\,\bar{q}>_V}$$
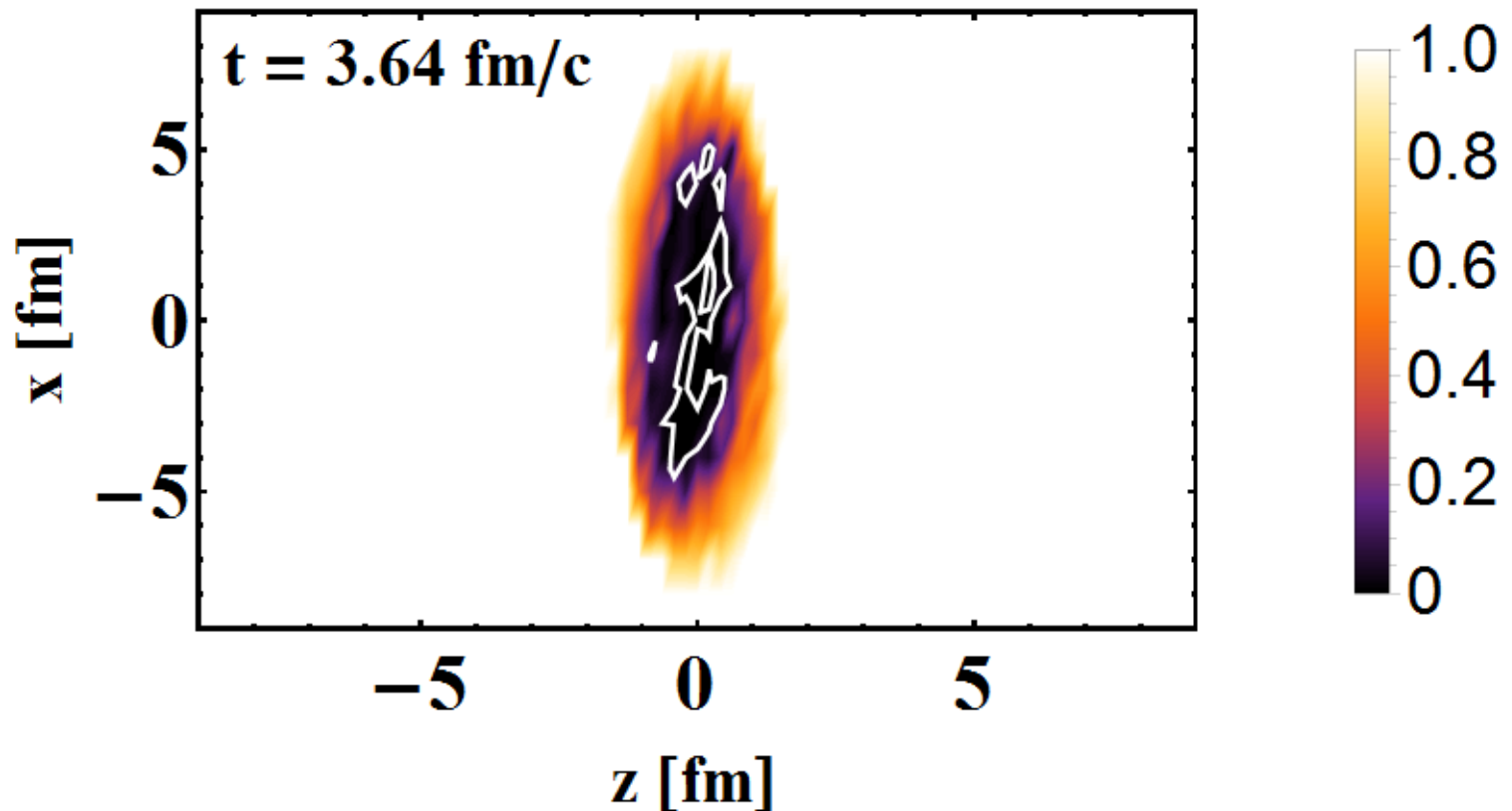
# Pb+Pb @ 30 AGeV – 0-5% central

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

$$\frac{<q\,\bar{q}>}{<q\,\bar{q}>_V}$$
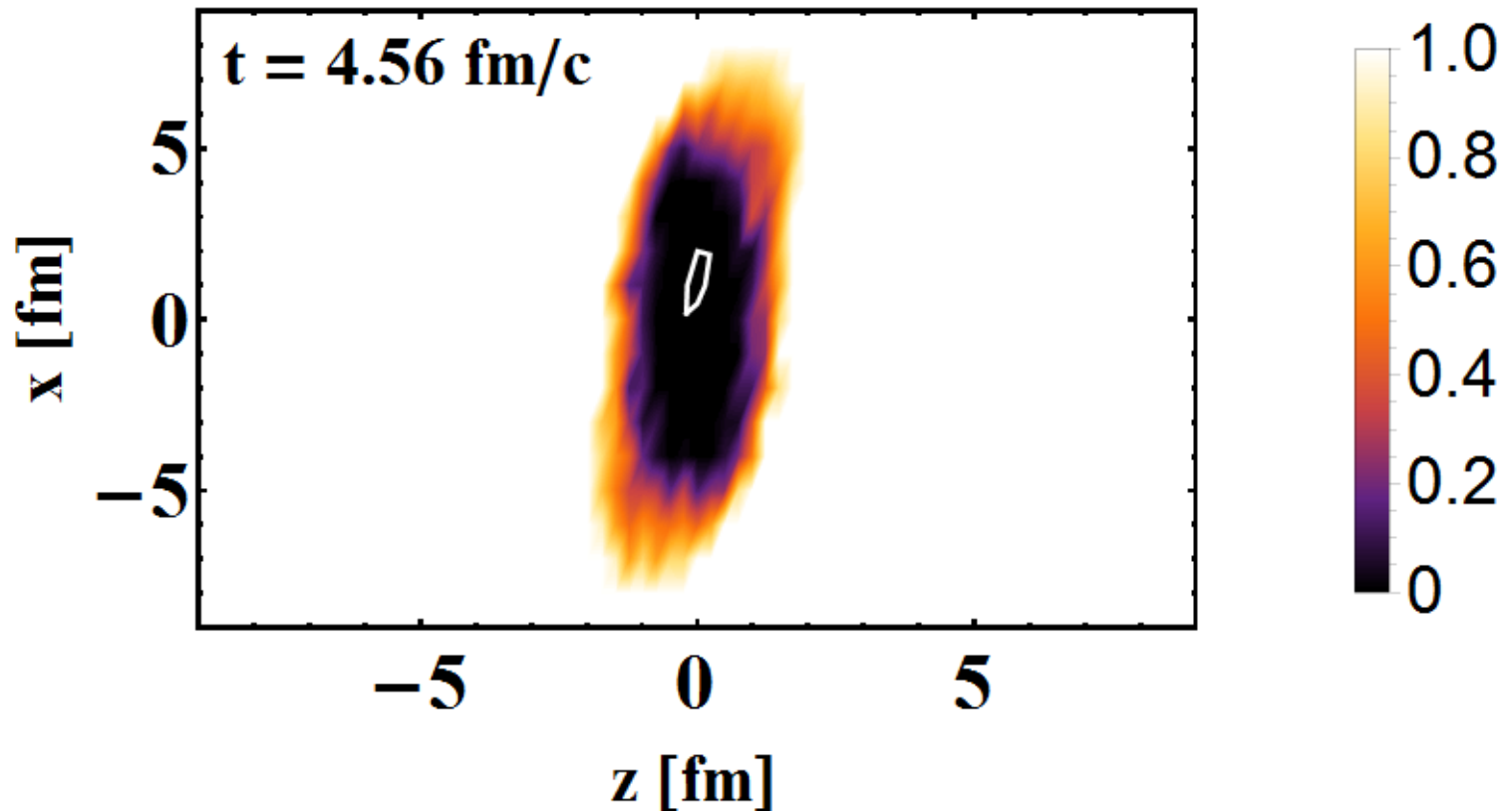
# Pb+Pb @ 30 AGeV – 0-5% central

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

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

# Pb+Pb @ 30 AGeV – 0-5% central

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

$$\frac{<q\bar{q}>}{<q\bar{q}>_V}$$
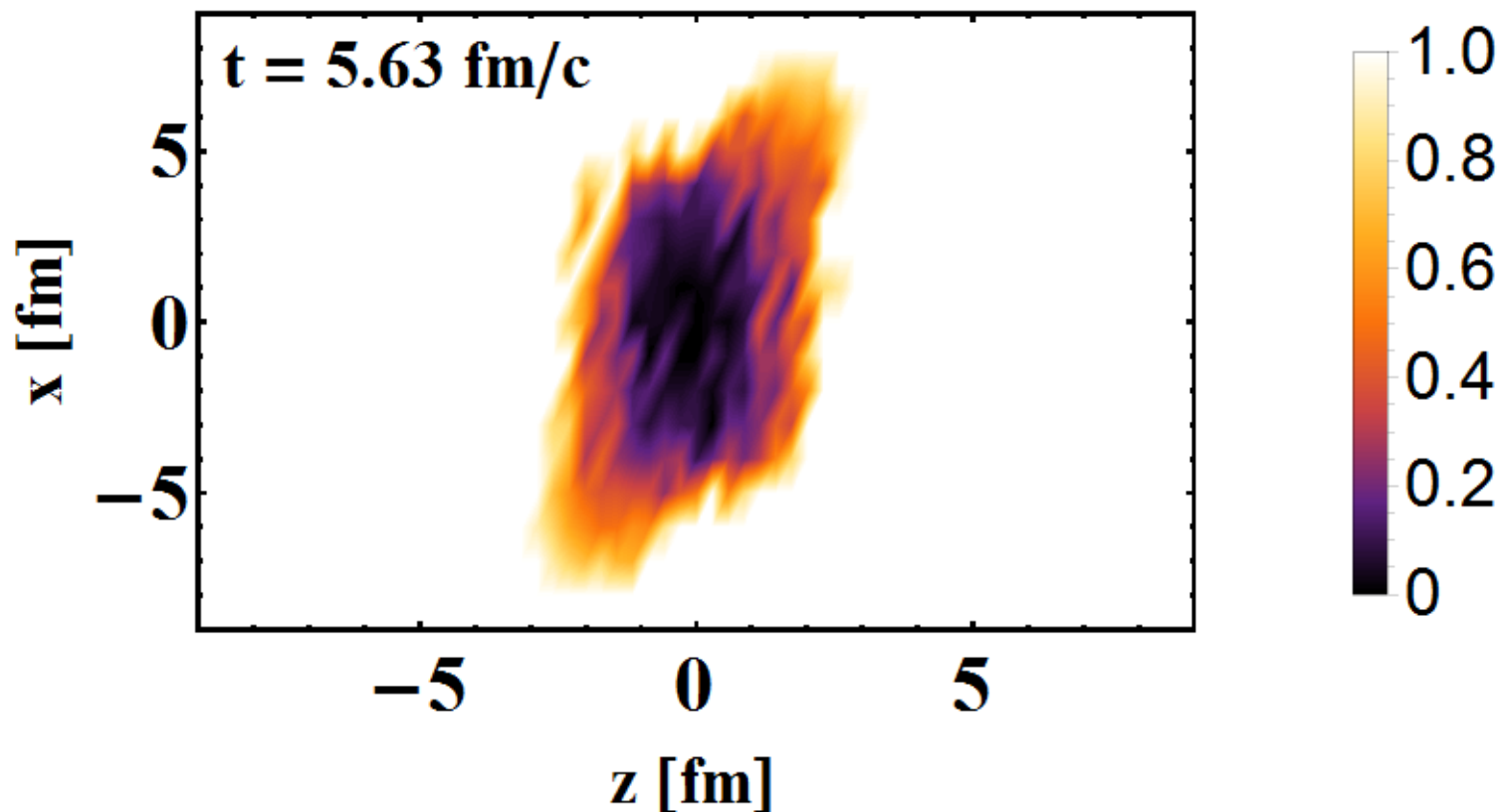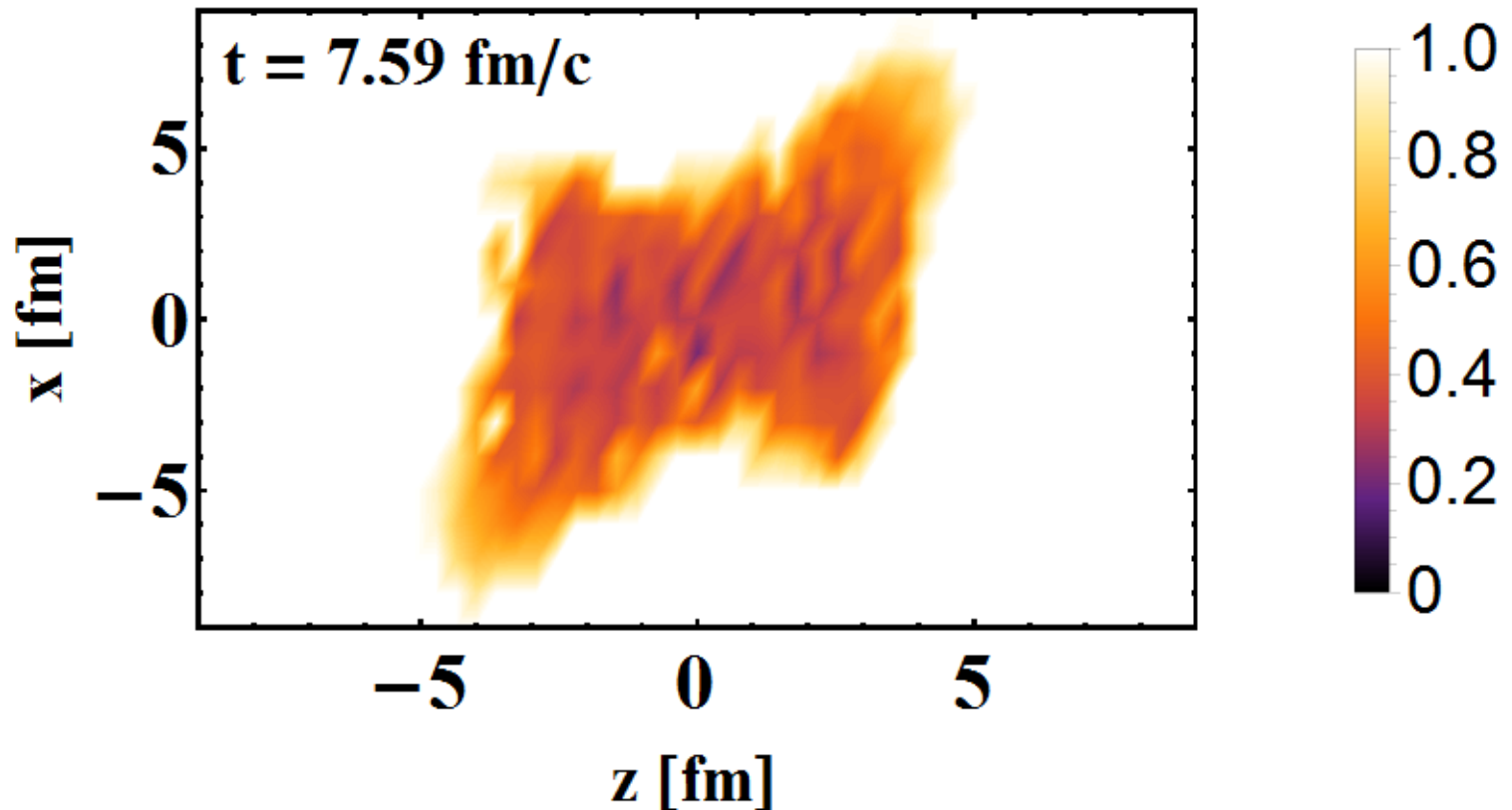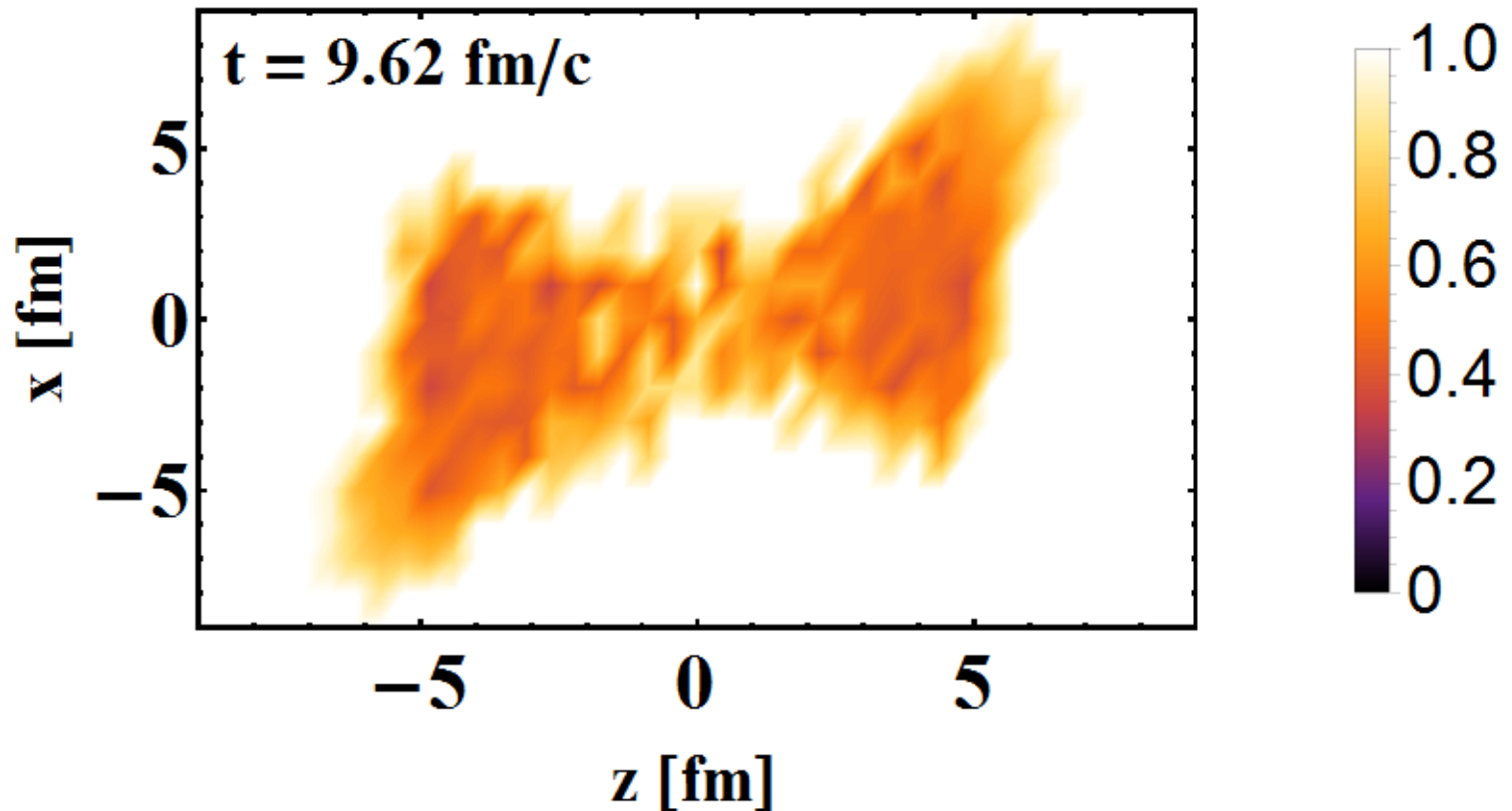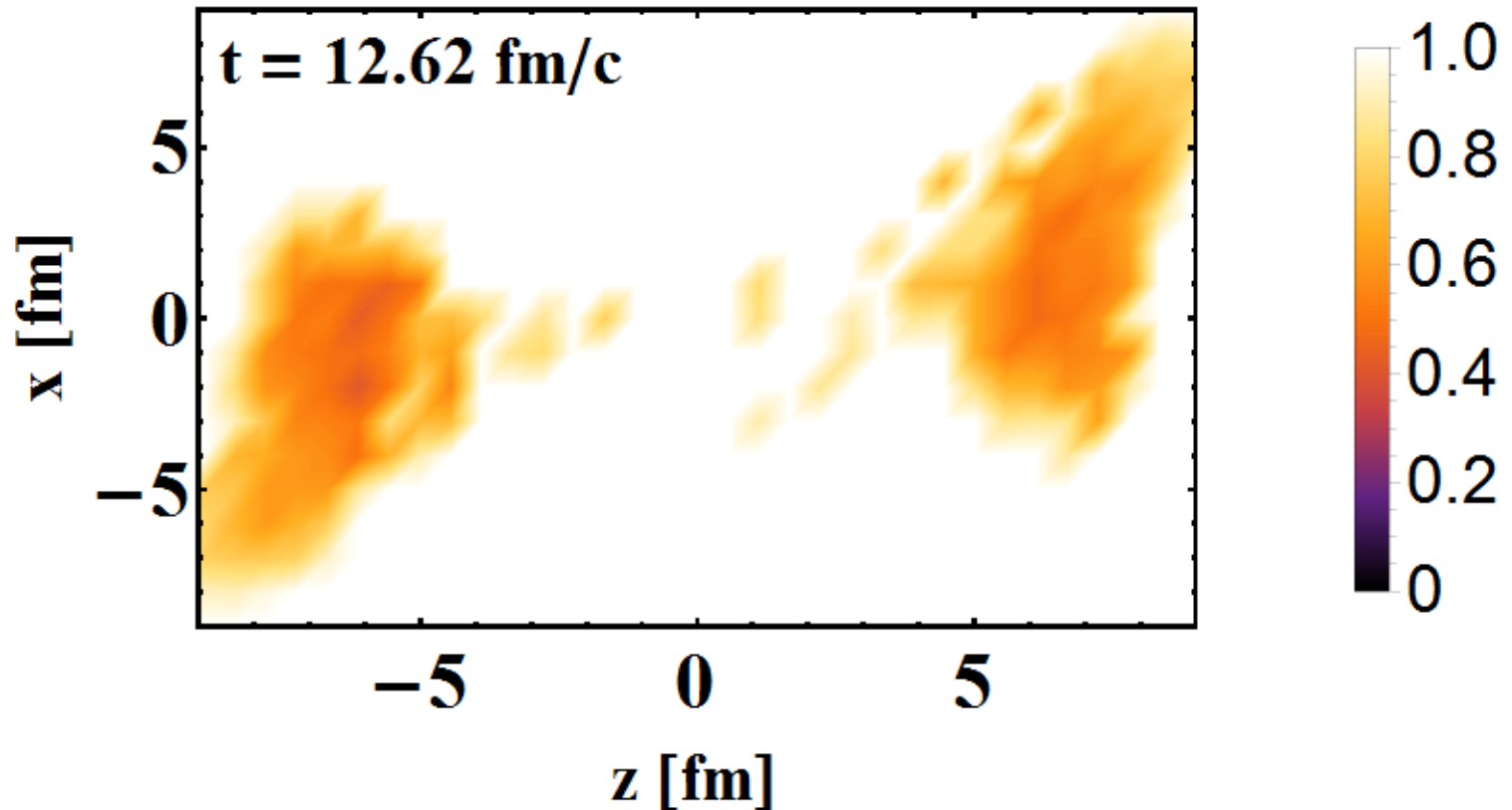
# Chiral symmetry restoration in the hadronic phase

□ 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 - **arXiv:1510.04120**

# 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 - **arXiv:1510.04120**

# 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**
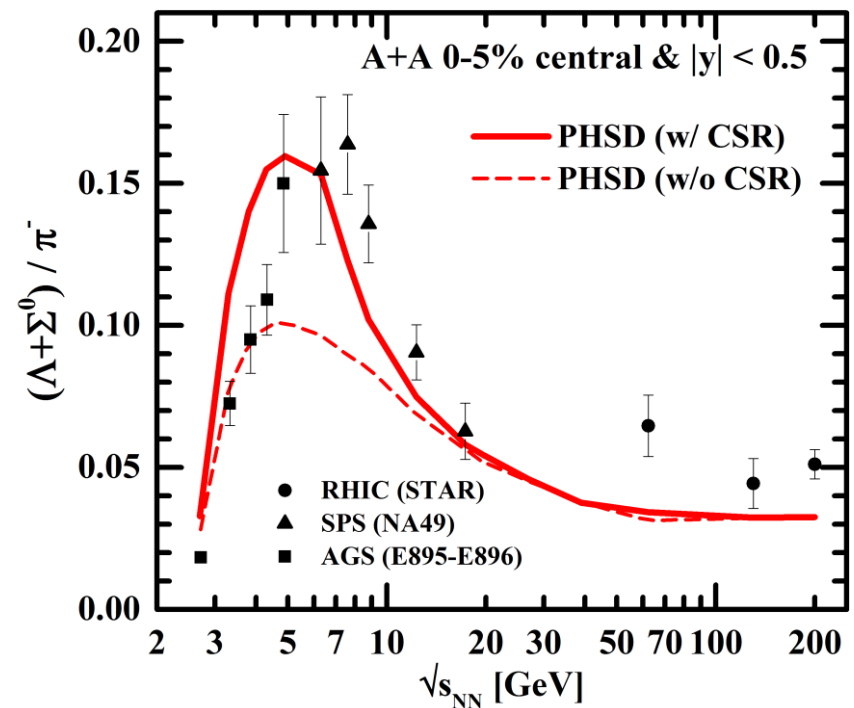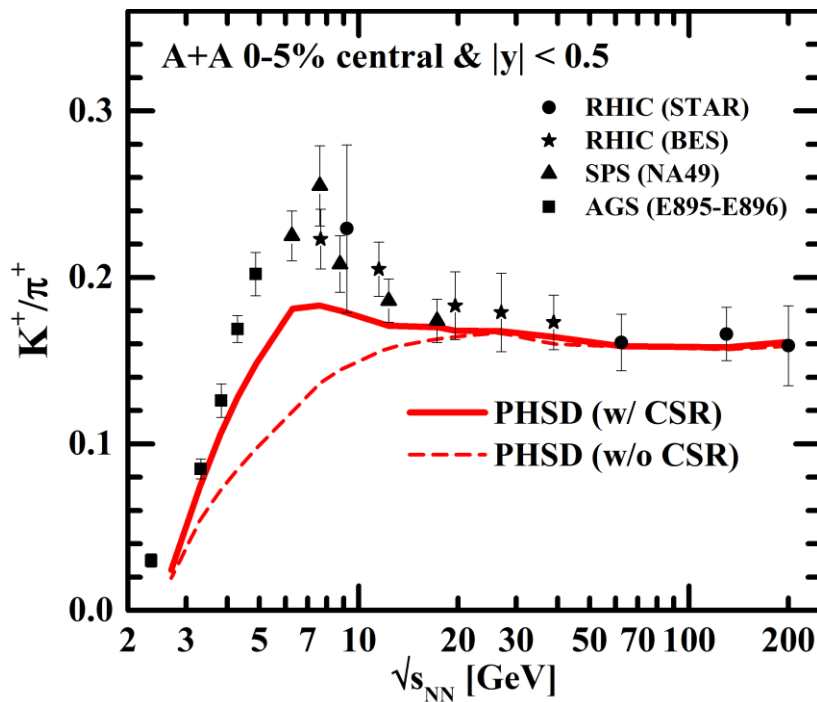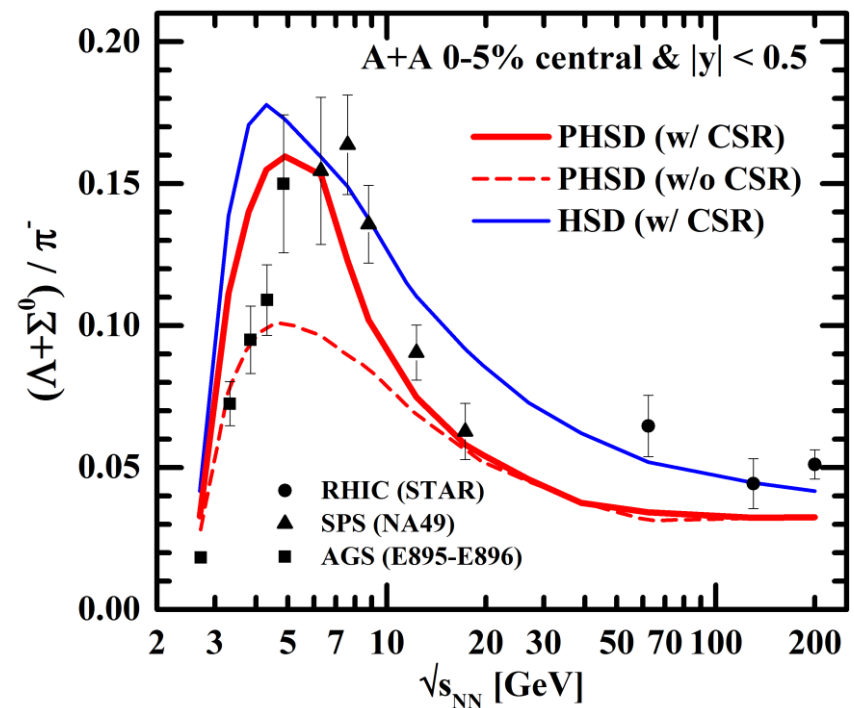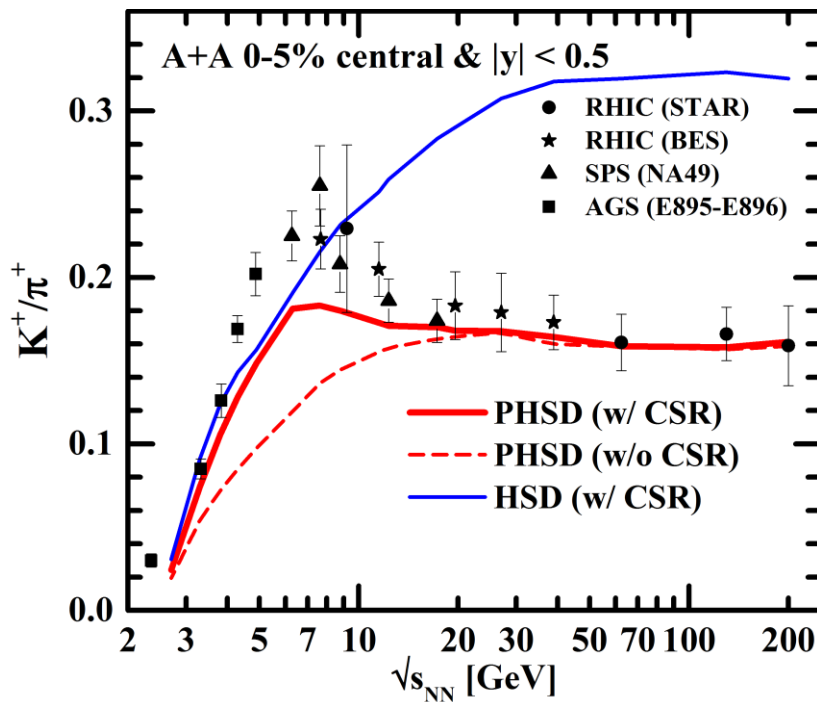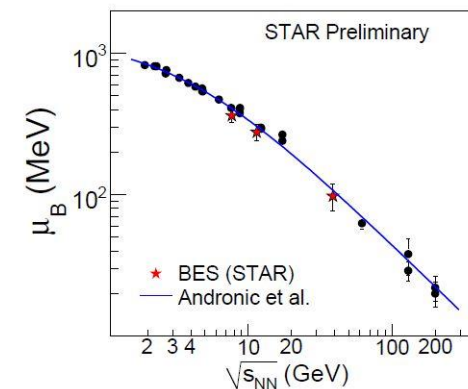
W. Cassing, A. Palmese, P. Moreau, E.L. Bratkovskaya - **arXiv:1510.04120**

# 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 $K^+/\pi^+$ ratio at low $\sqrt{s_{NN}}$ and then a drop due to the appearance of a partonic medium
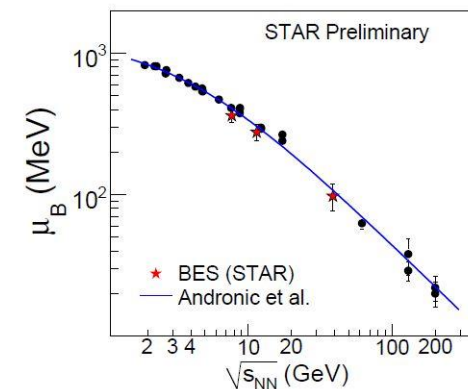
# Conclusion

- 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 $K^+/\pi^+$ ratio at low $\sqrt{s_{NN}}$ and then a drop due to the appearance of a partonic medium

## THANK YOU FOR YOUR ATTENTION