Institut für Theoretische Physik

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

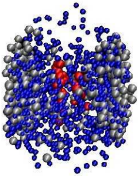
Hadron production from PHSD in heavy-ion reactions from 1 to 160 A GeV

Alessia Palmese

in collaboration with W. Cassing, P.Moreau, E.L. Bratkovskaya
Institut für Theoretische Physik, Gießen

The 3rd Strangeness Workshop, Warsaw, 22 April 2016

HIC for FAIR
Helmholtz International Center

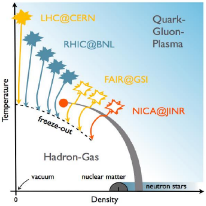


PHSD

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

Motivation

Beam Energy scan is pointing at lower energies to explore systems with higher baryon density.



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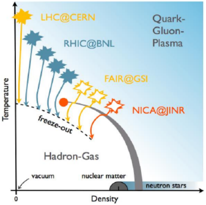
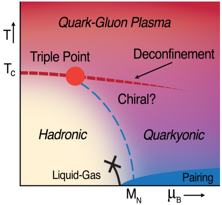


Can we find a manifestation of the **Chiral Symmetry restoration** in Heavy-Ion Collisions (HIC) observables?



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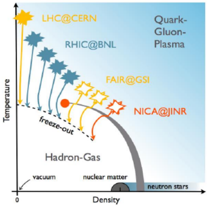

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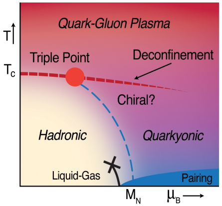

There are many open questions related to the **strangeness production** in HIC!

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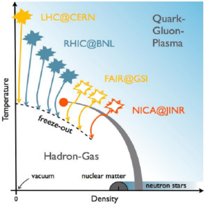
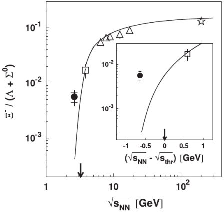


High multiplicities of Ξ^-.



(G. Agakishiev et al., HADES Collaboration, Phys. Rev. Lett. 103, 132301,2009.)

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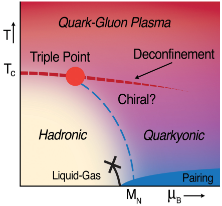

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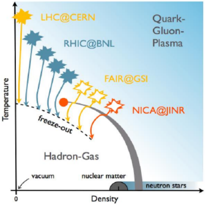

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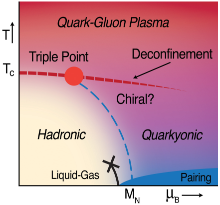

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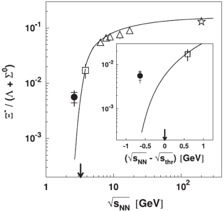

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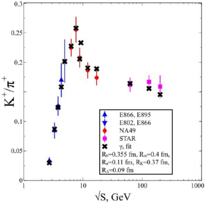
"Horn" feature of K^+/π^+.

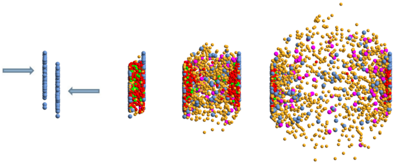


(K. A. Bugaev et al., arXiv:1511.06698v1, 2015.)

Outline

Parton Hadron String Dynamics (PHSD)

- Dynamical many-body transport approach.
- Consistently describes the full time evolution in HIC.
- Explicit parton-parton interactions, explicit phase transition from hadronic to partonic degrees of freedom.



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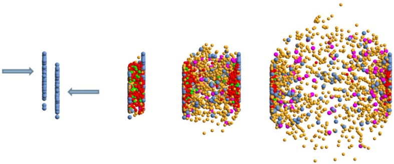
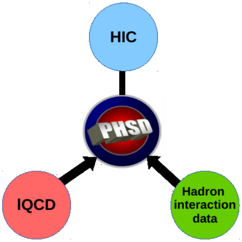




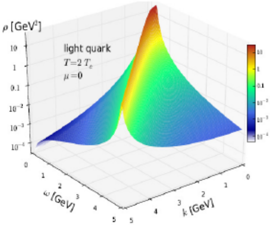
- Model applicable out of equilibrium and in agreement with the lattice results in equilibrium as well as with the nuclear physics input.
- Transport theory: off-shell transport equations in phase-space representation based on Kadanoff-Baym equations for the partonic and hadronic phase.

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

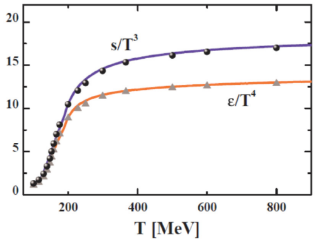
Dynamical Quasi-Particle Model (DQPM)

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

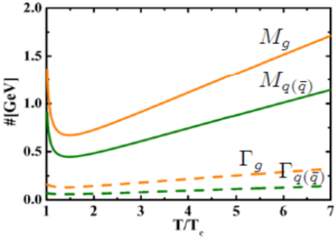
$$\rho_i(\omega, T) = \frac{4\omega\Gamma_i(T)}{(\omega^2 - \mathbf{p}^2 - M_i^2(T))^2 + 4\omega^2\Gamma_i^2(T)}\,, \quad (i = q, \bar{q}, g)$$



Properties of quasi-particles are fitted to the lattice QCD results:

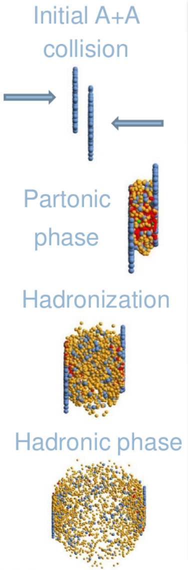


Masses and widths of partons depend on the temperature of the medium:



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

Stages of a heavy-ion collision in PHSD



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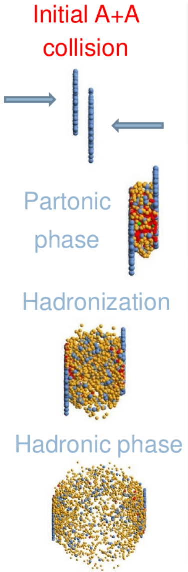
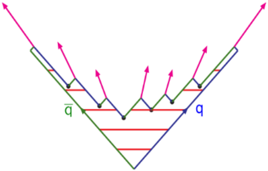


- **String formation** in primary NN Collisions.
- **String decays** to pre-hadrons(baryons and mesons).



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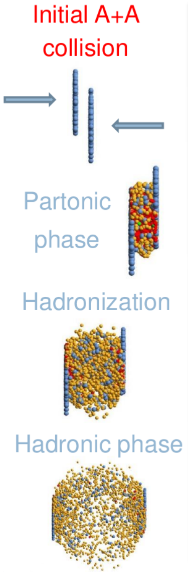

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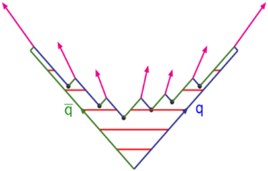


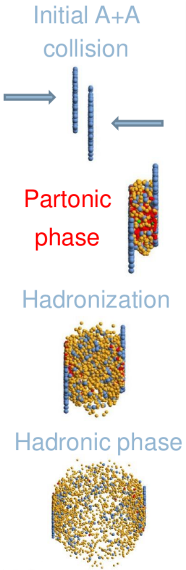
- Formation of a **QGP state** if $\epsilon > \epsilon_C \approx 0.5\ GeV\ fm^{-3}$.
- Dissolution of newly produced secondary hadrons into **massive colored quarks/antiquarks** and **mean-field energy** U_q:

$$B \rightarrow qqq\,(\bar{q}\bar{q}\bar{q}) \qquad M \rightarrow q\bar{q} \qquad + \quad U_q.$$

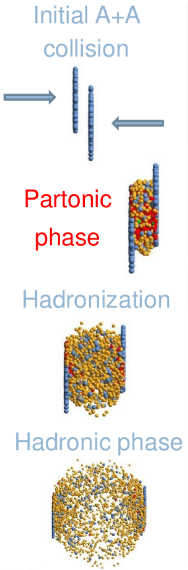
- **DQPM** defines the properties (masses and widths) of partons and mean-field potential at a given local energy density ϵ:

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

Stages of a heavy-ion collision in PHSD



- Propagation of partons, considered as dynamical quasi-particles, in a self-generated mean-field potential from the DQPM.
- EoS of partonic phase: crossover from Lattice QCD fitted by DQPM.



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

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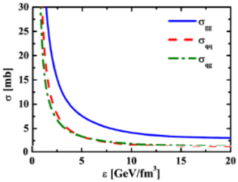
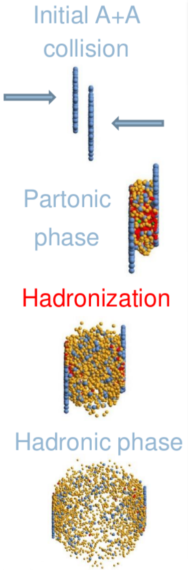


- Inelastic collisions:

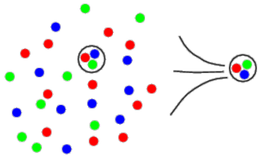
$$q + \bar{q} \Rightarrow g \qquad \text{~~}q + \bar{q} \Rightarrow g + g\text{~~}$$
$$g \Rightarrow q + \bar{q} \qquad \text{~~}g \Rightarrow g + g\text{~~}$$

~~$q + \bar{q} \Rightarrow g + g$~~, ~~$g \Rightarrow g + g$~~ } Suppressed due to the large gluon mass.

Stages of a heavy-ion collision in PHSD



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

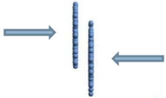


$$g \Rightarrow q + \bar{q}$$
$$q + \bar{q} \Rightarrow \text{meson ('string')}$$
$$q + q + q \Rightarrow \text{baryon ('string')}$$

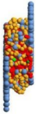
- Local covariant off-shell transition rate.
- Strict 4-momentum and quantum number conservation.

Stages of a heavy-ion collision in PHSD

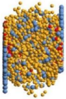
Initial A+A collision



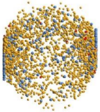
Partonic phase



Hadronization



Hadronic phase



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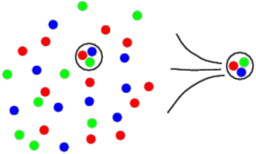

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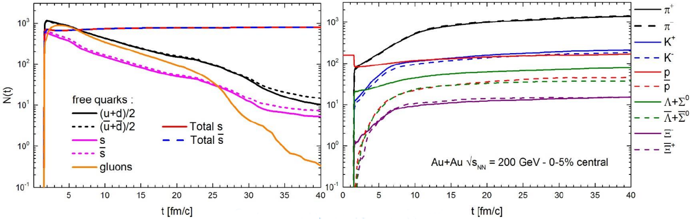
Central Au+Au — Top RHIC



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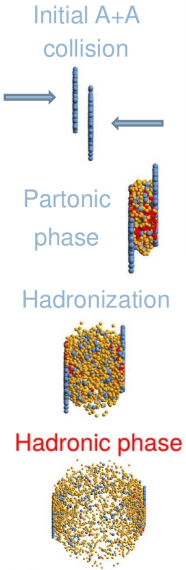
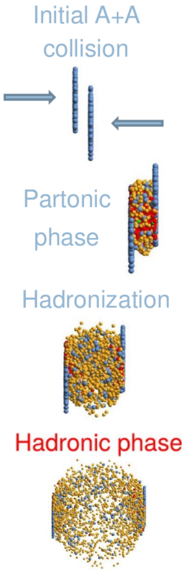


- Hadron-string interactions – **off-shell HSD**.
- Elastic and inelastic collisions between baryons (B), mesons (m) and resonances (R).

Stages of a heavy-ion collision in PHSD



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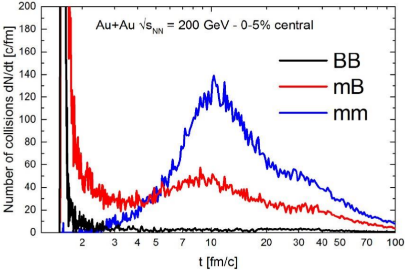
Distribution of hadron collisions as a function of time:



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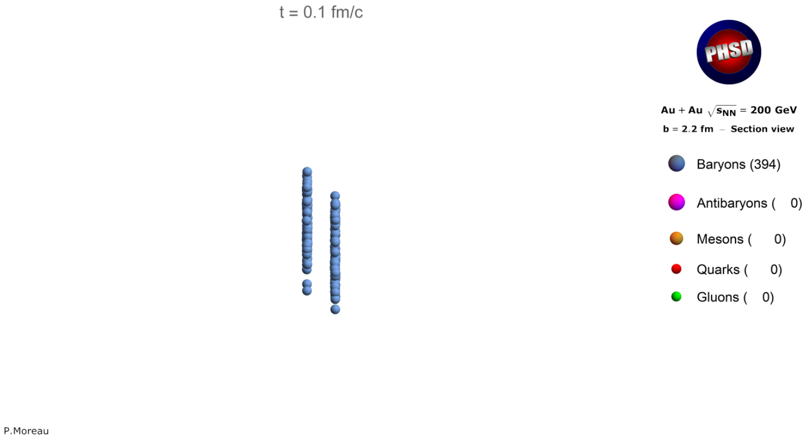

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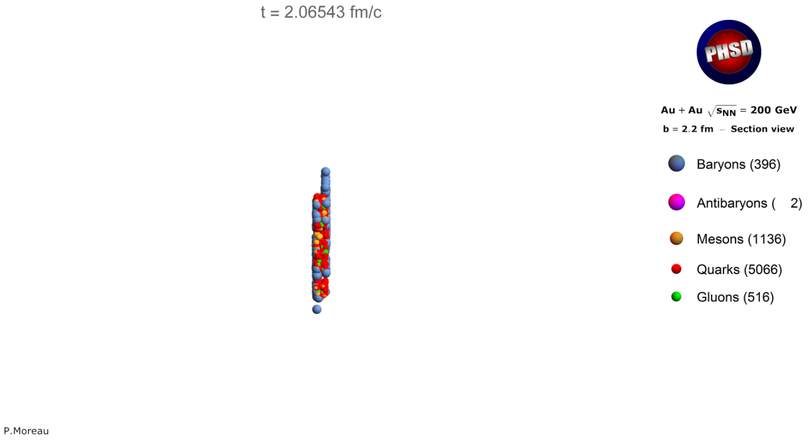

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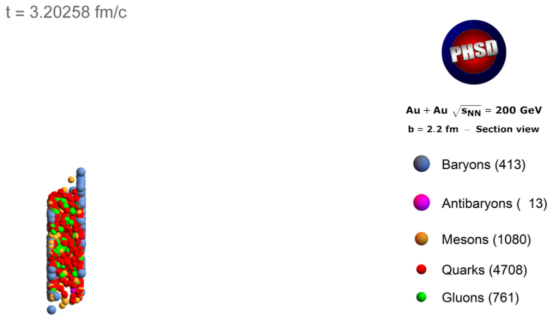

P.Moreau

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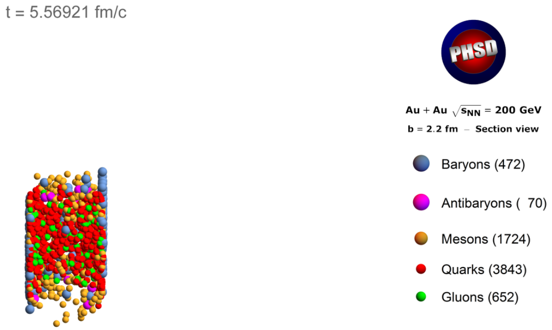

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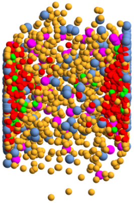
Stages of a heavy-ion collision in PHSD

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

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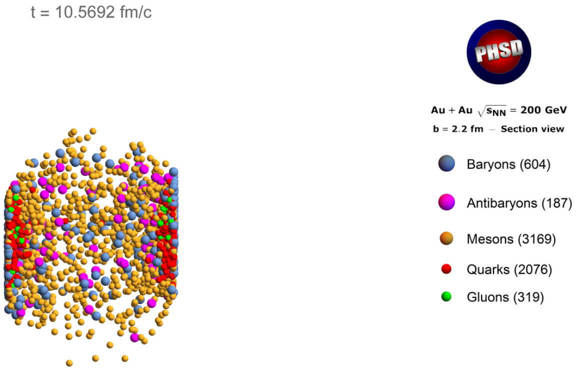

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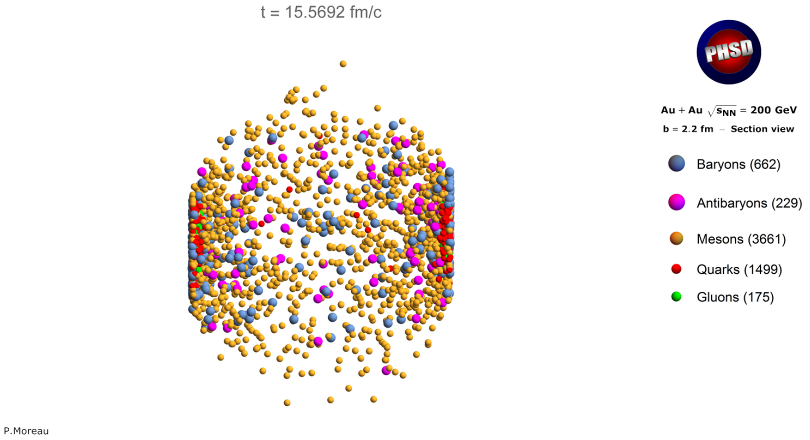

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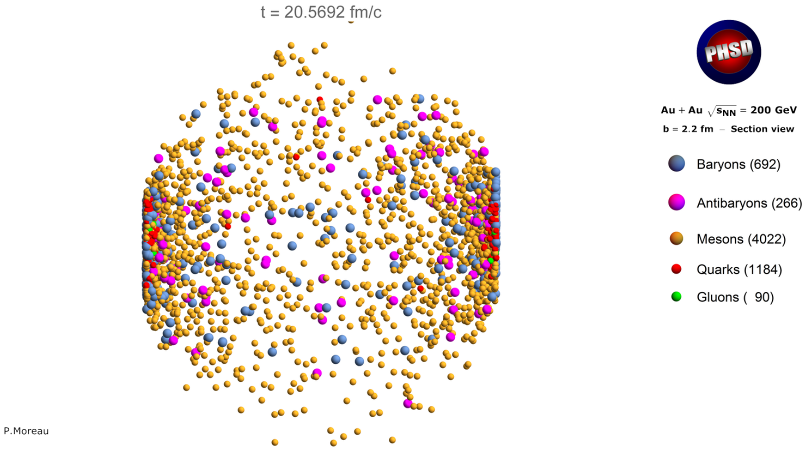

Low energy production channels in PHSD

List of **Baryon-Baryon channels** in PHSD

$NN \Leftrightarrow NN$ $\quad NN \Leftrightarrow NN^*$ $\quad N\Delta \Leftrightarrow NN^*$ $\quad NN \Leftrightarrow NN\pi$

$NN \Leftrightarrow N\Delta$ $\quad NN^* \Leftrightarrow NN'^*$ $\quad \Delta\Delta \Leftrightarrow NN^*$ $\quad (N^* = N(1440), N(1535))$

for $\sqrt{s} > \sqrt{s_{thre}} = 2.65 GeV \Rightarrow$ String Fragmentation
($NN \rightarrow NYK$, $NN \rightarrow \Delta YK$, $N\Delta \rightarrow NYK$, $\Delta\Delta \rightarrow NYK$).

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Strangeness is always produced in pairs $s\bar{s}$.
In $p + p$ collisions there is a strict energy threshold:

$\sqrt{s_{th1}} = m_p + m_K + m_{\Lambda(\Sigma)} = 2.55(2.62) GeV$ $\quad$ $\sqrt{s_{th2}} = m_p + 2 * m_K + m_{\Xi} = 3.24 GeV$

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Hyperon (Y= Λ, Σ) production

$\pi + N \Leftrightarrow K + Y$

$N + N \Leftrightarrow N + K + Y$

$N + \bar{K} \Leftrightarrow Y + \pi$

Cascade Ξ production

$Y + \bar{K} \Leftrightarrow \Xi + \pi$

$Y + Y \Leftrightarrow \Xi + N$

Cascade Ω production

$\Xi + \bar{K} \Leftrightarrow \Omega + \pi$

$\Xi + \Xi \Leftrightarrow \Omega + Y$

Low energy strange baryon production

Focus on the Ξ production from **strangeness exchange reactions**.

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Cross sections taken from the coupled-channel approach based on a SU(3)-invariant hadronic Lagrangian from:
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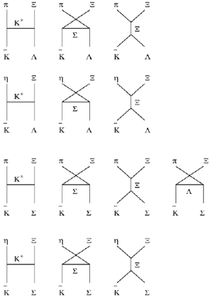

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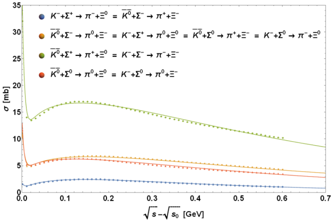

by Pierre Moreau

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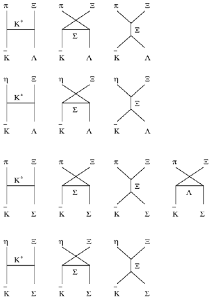

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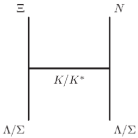

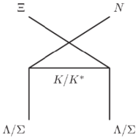

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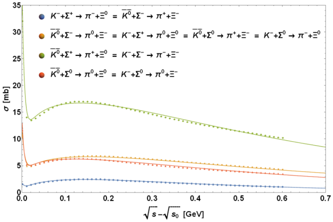
Born diagrams for Ξ production from strangeness B-B exchange reactions. →



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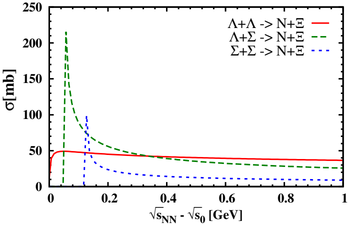
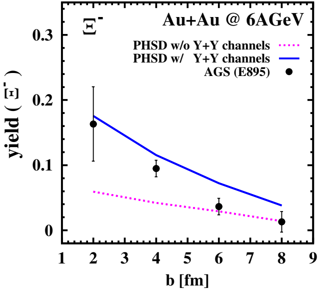
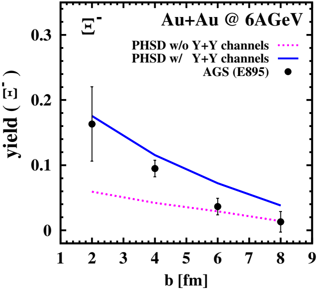


Results on the Ξ yield





- Strangeness exchange $B-B$ channels are extremely important at low energies.
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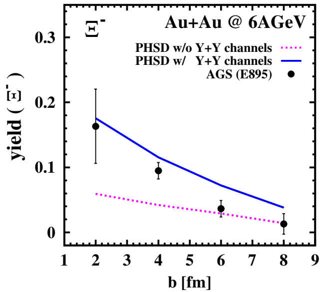

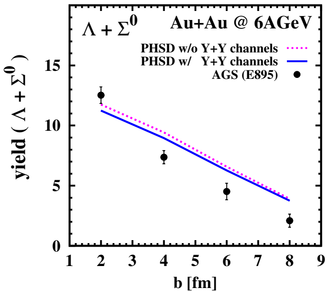

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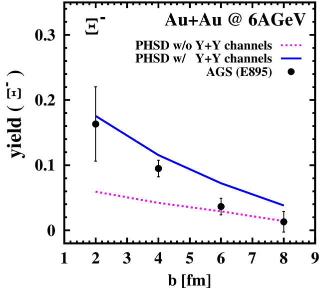

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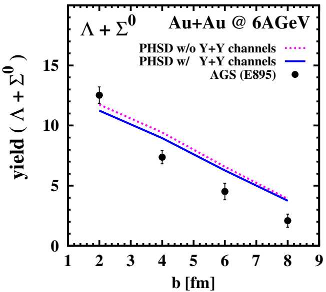

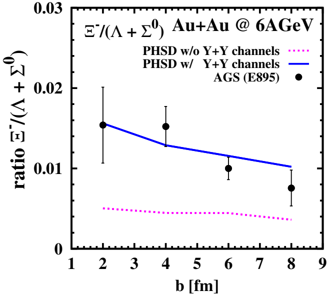

String dynamics

Low energy dynamics in QCD is dominated by **Strings**.

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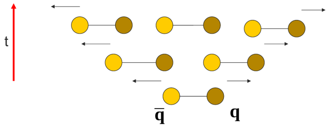
A color flux connects the rapidly receding string-ends.



Production of virtual $q\bar{q}$ or $qq\bar{q}\bar{q}$ pairs which break the color field tube.

Creation of mesons or baryon-antibaryon pairs with $\tau_f \approx 0.8\ fm/c$.

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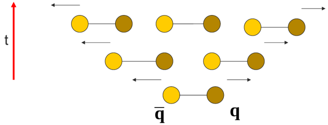

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with $\kappa \approx 0.176 GeV^2$ and $m_{u,d,s}$ as constituent masses.

The relative production factors in PHSD/HSD are:

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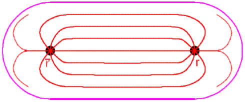

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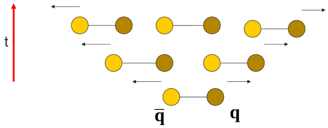

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$$f(x, m_T) \approx \frac{1}{x}(1 - x^a) exp(-b m_T^2 / x).$$

Chiral Symmetry restoration in PHSD

- In presence of a hot and dense hadronic medium, the degrees of freedom undergo modifications of their properties, e.g. the **mass**:

$$m^*_{q,s} = m^0_{q,s} + (m^v_{q,s} - m^0_{q,s}) \left| \frac{< \bar{q}q >}{< \bar{q}q >_V} \right|,$$

where $m^0_s \approx 100\ MeV$ and $m^0_q \approx 7\ MeV$ for the bare quark masses and $m^v_s \approx 500\ MeV$ and $m^v_q \approx 350\ MeV$ for the vacuum quark masses.

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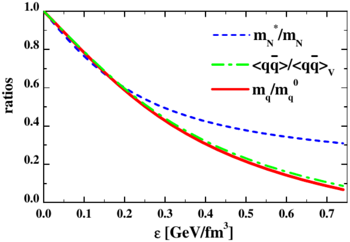
An estimate for $<\bar{q}q>$ is given by Friman et al., Eur. Phys. J. A **3**, 165, 1998:

$$\frac{<\bar{q}q>}{<\bar{q}q>_V} = 1 - \frac{\Sigma_\pi}{f_\pi^2 m_\pi^2}\rho_S - \sum_h \frac{\sigma_h \rho_S^h}{f_\pi^2 m_\pi^2},$$

with $\Sigma_\pi \approx 45 MeV$, σ_h as the $\sigma-$commutator of the meson h, $< q\bar{q} >_V \approx -3.2\ fm^{-3}$ (from the Gell-Mann-Oakes-Renner relation) and ρ_s as scalar density which can be obtained within the non-linear $\sigma - \omega$ model.

Chiral Symmetry restoration in PHSD

In the **Schwinger formula** effective quark masses $m^*_{q,s}$ have to be considered.



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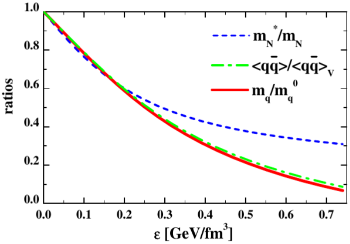
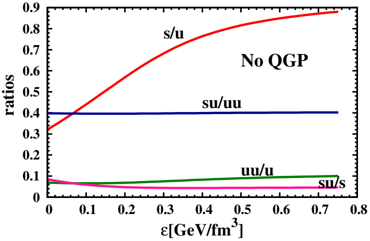


The **ratio s/u** increases with decreasing $< q\bar{q} >$ and increasing ϵ.



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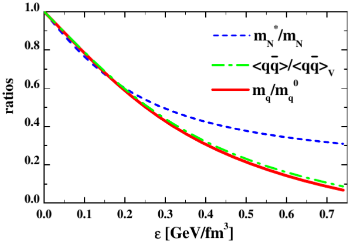

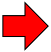

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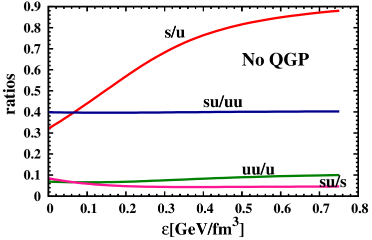
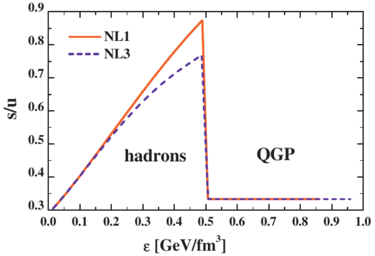


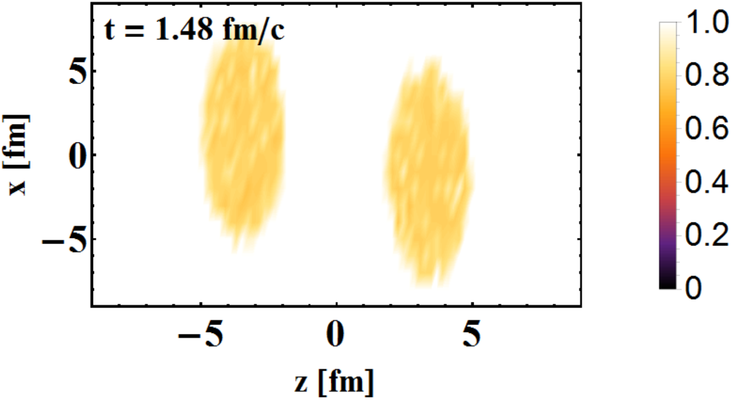
- **"Horn"** feature in the energy dependence of the s/u ratio!
- In the **QGP phase**, the string decay does not occur anymore and the s/u ratio drops.
- Some dependence on the nuclear EoS: **NL1 vs NL3**.



Chiral Symmetry restoration: Results

Time evolution of the ratio $\frac{<q\bar{q}>}{<q\bar{q}>_V}$

for $Pb + Pb$ @ $30\,AGeV$ (0-5% centrality class):



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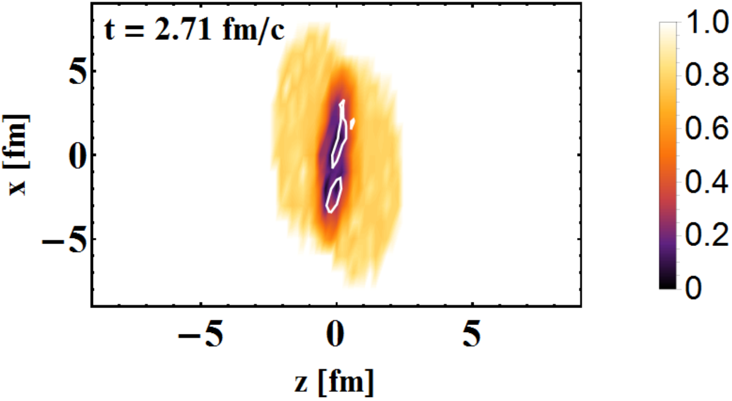

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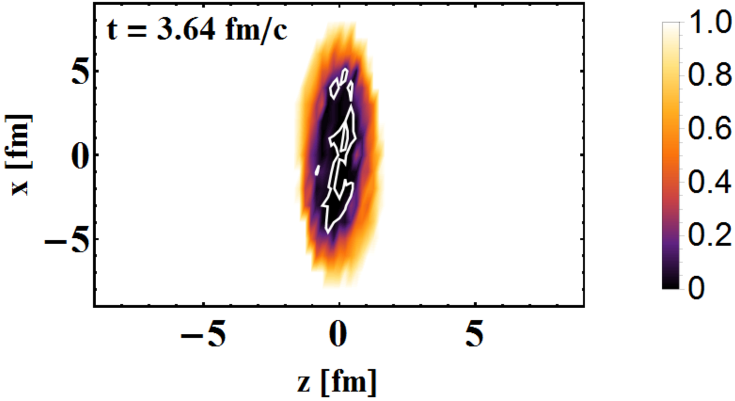

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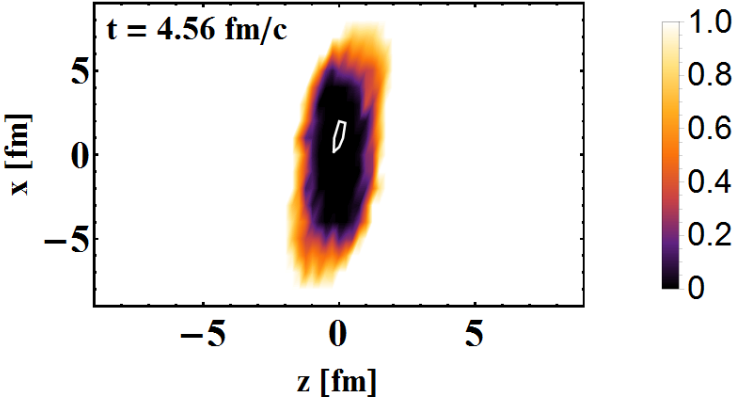

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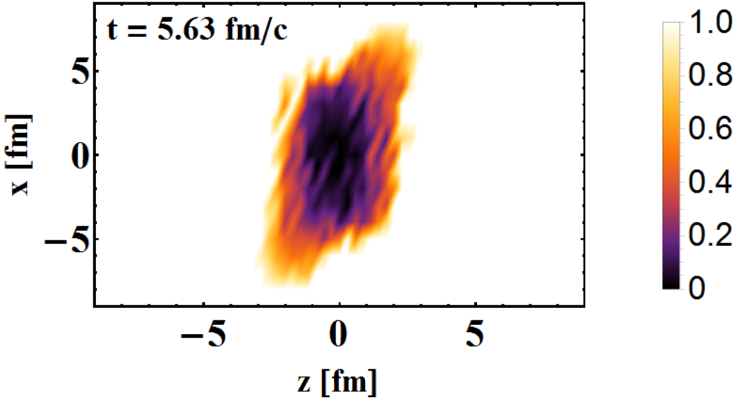

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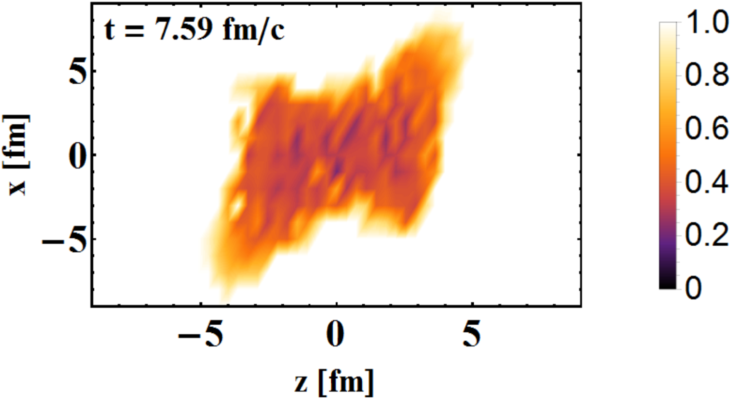

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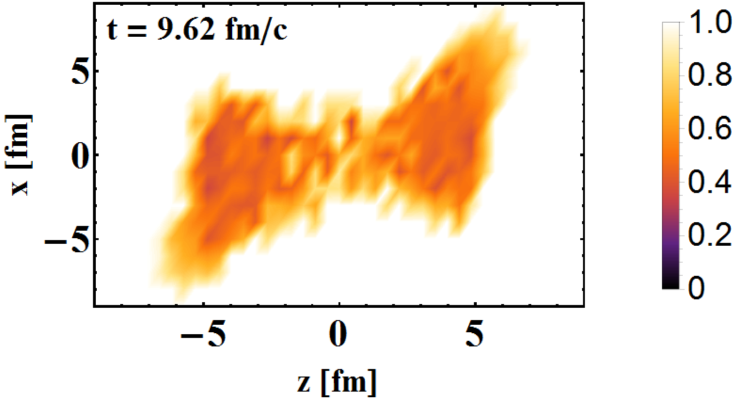

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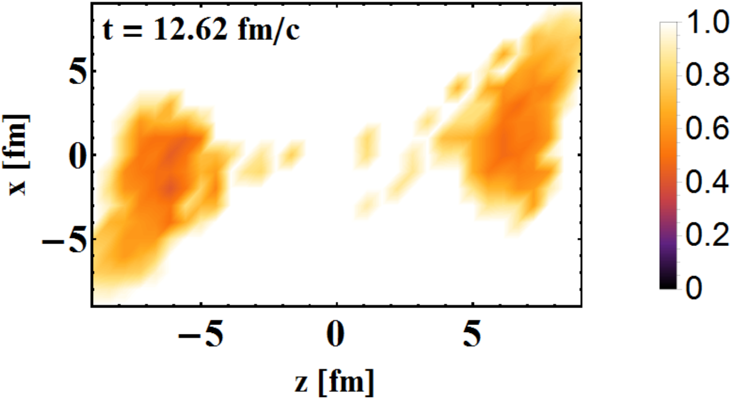
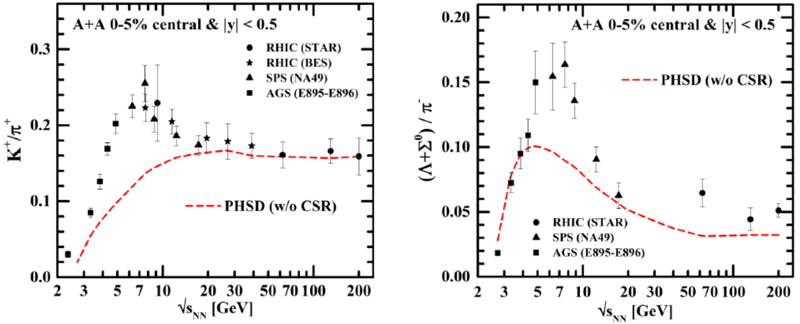


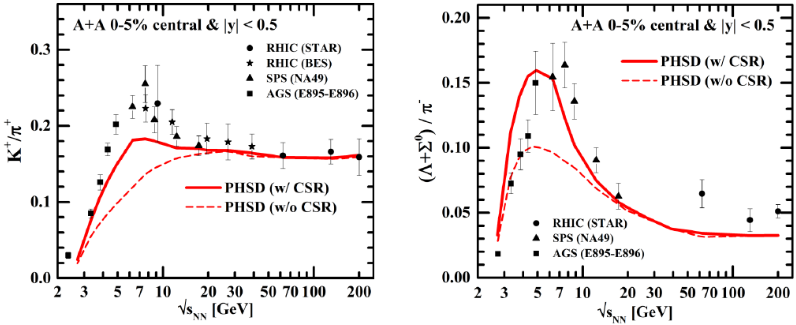
The scalar quark condensate $< q\bar{q} >$ is not a direct observable.
➜Can we find a manifestation of the Chiral Symmetry restoration indirectly in hadronic observables?



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

Chiral Symmetry restoration: Results

The strangeness enhancement at AGS/SPS energies (FAIR/NICA energies) is observed to be related to the partial restoration of Chiral Symmetry in the hadronic phase.



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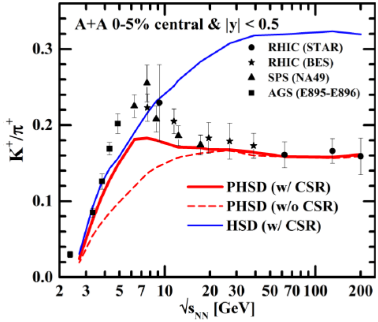
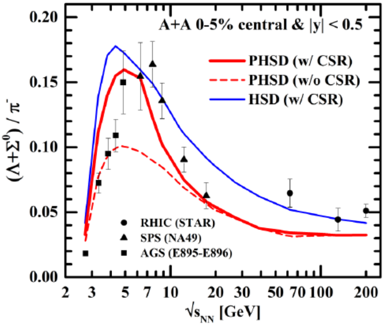
Chiral Symmetry restoration: Results

We observe a rise in the ratio K^+/π^+ at low $\sqrt{s_{NN}}$ related to Chiral Symmetry Restoration (CSR) and then a drop due to the appearance of a deconfined partonic medium. ➜ A "horn"-structure emerges.





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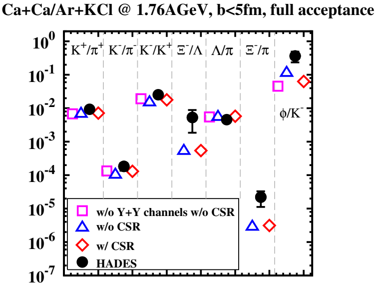
Low energy multiplicities



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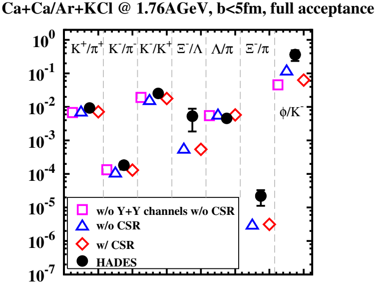

At low energies:

- CSR has not a sizeable effect.
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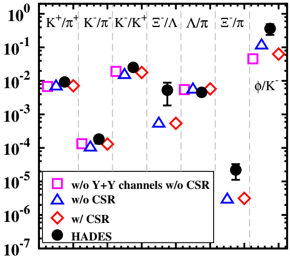
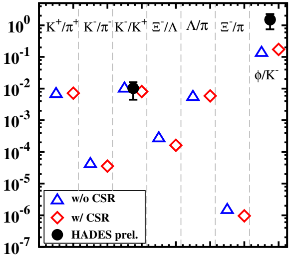
Still open question about the ϕ-yield.

Ca+Ca/Ar+KCl @ 1.76AGeV, b<5fm, full acceptance



Au+Au @ 1.23AGeV, b<10fm, |y|<0.5



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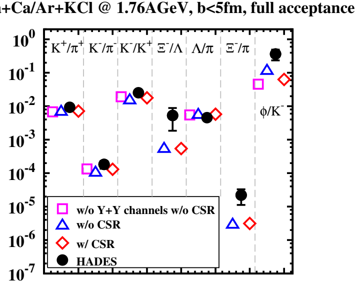

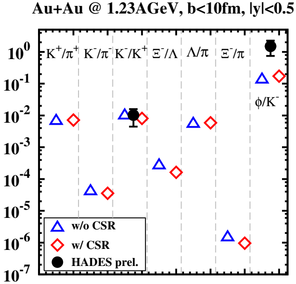

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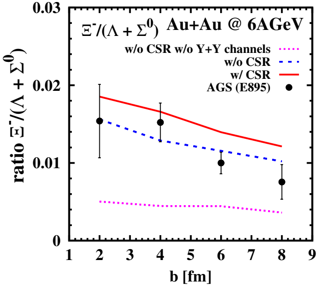
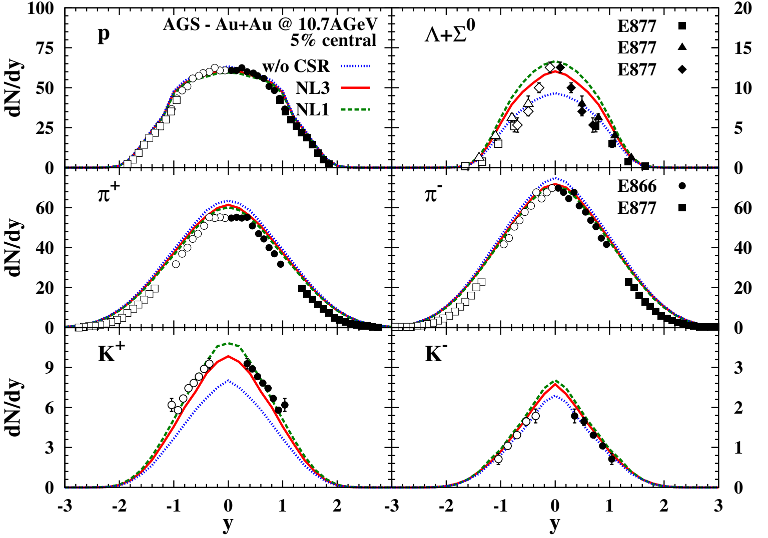
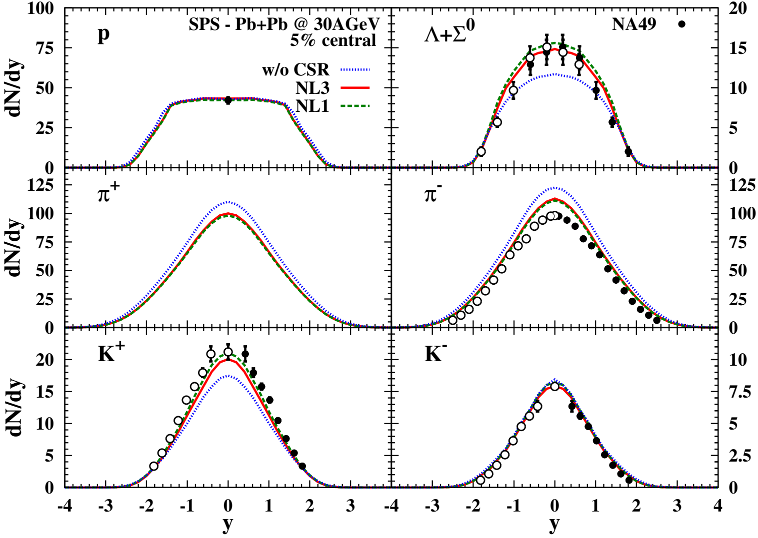


Rapidity spectra I

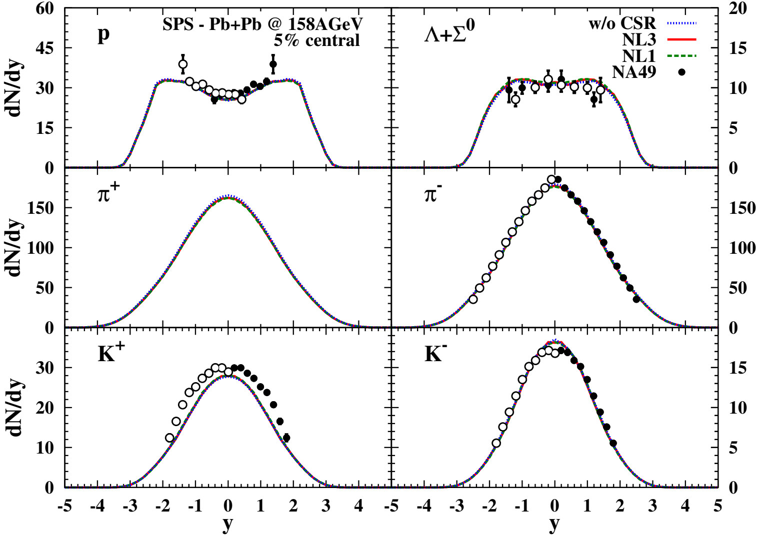
Au+Au @ 10.7AGeV in comparison to data at AGS



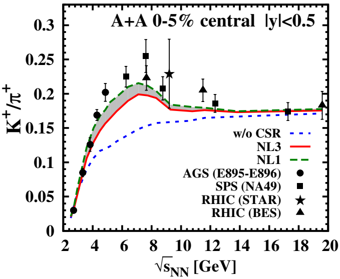
Pb+Pb @ 30AGeV in comparison to data at SPS



Pb+Pb @ 158AGeV in comparison to data at SPS



EoS: NL1 vs NL3



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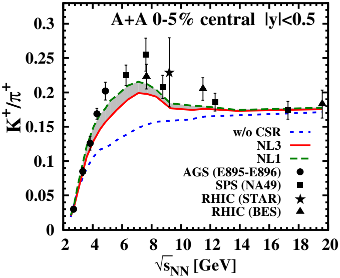

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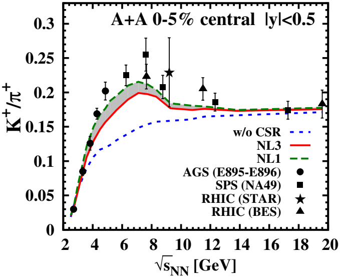

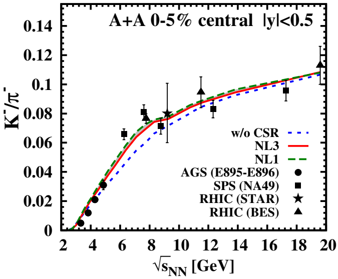

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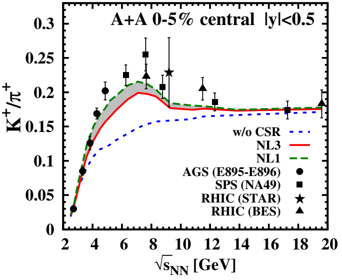

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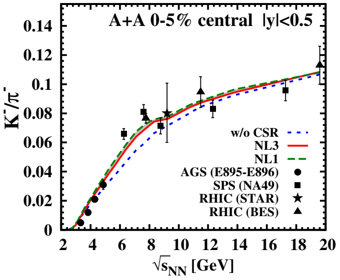

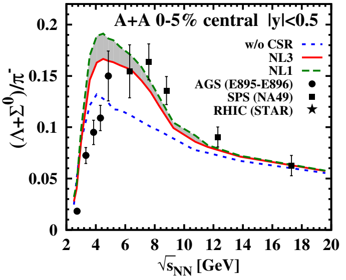

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  - First microscopic explanation of the "Horn": a rise in the ratio K^+/π^+ associated to the chiral symmetry restoration and then a drop due to the appearance of the deconfined partonic medium.
  - The small sensitivity related to the hadronic EoS in our PHSD calculations gives an uncertainty range of our results (apart from Σ_π).
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Conclusions

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Thank you for your attention!

BACK-UP SLIDES

Chiral Symmetry restoration: Basic Principles

- The QCD Lagrangian for massless quarks is chirally symmetric, namely invariant under a transformation of the symmetry group $SU(2)_L \, x \, SU(2)_R$. The associated transformation for the quark field is:

$$\varphi \rightarrow \varphi' = e^{-i\frac{\tau_a}{2}\Theta_a P_L} e^{-i\frac{\tau_b}{2}\Theta_b P_R}\varphi, \qquad \text{with} \quad P_{L,R}=\tfrac{1}{2}(1\mp\gamma_5).$$

- This transformation can be rewritten in terms of transformation $\Lambda_V \, x \, \Lambda_A$ of the group $SU(2)_V \, x \, SU(2)_A$:

$$e^{-i\frac{\tau_a}{2}\Theta_a P_L} e^{-i\frac{\tau_b}{2}\Theta_b P_R}\varphi \rightarrow e^{-i\frac{\vec{\tau}}{2}\vec{\Theta}_V} e^{-i\gamma_5\frac{\vec{\tau}}{2}\vec{\Theta}_A}\varphi.$$

If the Chiral Symmetry holds, the vector and axial currents are equal.

- In case of massive quarks, the Chiral Symmetry is explicitly broken:

$$\Lambda_A : m(\bar{\varphi}\varphi) \rightarrow m(\bar{\varphi}\varphi) - 2im\vec{\Theta}\cdot\left(\bar{\varphi}\frac{\vec{\tau}}{2}\gamma_5\varphi\right).$$

For energies larger than the particle masses, Λ_A may be treated as approximate symmetry.

- The chiral condensate is adopted as order parameter of the transition between the chiral non-symmetric and the chiral symmetric phase:

$$<\bar{\varphi}\varphi> = -\frac{T}{V}\frac{\partial}{\partial m_q} logZ = \begin{cases} \neq 0 & \text{for } T < T_{ch} \text{ (chiral non-symmetric phase)} \\ = 0 & \text{for } T \geq T_{ch} \text{ (chiral symmetric phase).} \end{cases}$$

Chiral Symmetry restoration in PHSD

- In presence of hot and dense medium, the hadrons undergo modifications of their properties, e.g. the mass!

$$m_N^*(x) = m_N^V - g_s\sigma(x),$$

where the scalar field $\sigma(x)$ mediates the scalar interaction with the surrounding medium through the coupling g_s.

- The value of $\sigma(x)$ is determined locally by the non-linear gap equation:

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

- Within the non-linear $\sigma - \pi$ model for nuclear matter, the parameters g_s, m_σ, B, C can be fixed in order to reproduce the values of the main nuclear matter quantities at saturation,
  i.e. saturation density, binding energy per nucleon, compression modulus and the effective nucleon mass.
  (Actually there are different sets for the values of the parameters, due to the large experimental uncertainties on their values.)

Chiral Symmetry restoration in PHSD

An estimate for the quark scalar condensate is given by Friman et al., Eur. Phys. J. A **3**, 165, 1998:

$$\frac{< \bar{q}q >}{< \bar{q}q >_V} = 1 - \frac{\Sigma_\pi}{f_\pi^2 m_\pi^2}\rho_S - \sum_h \frac{\sigma_h \rho_S^h}{f_\pi^2 m_\pi^2},$$

with $\Sigma_\pi \approx 45 MeV$ (reduced in case of hyperons according to the light quark content), σ_h as the $\sigma-$commutator of the meson h ($= m_\pi/2$ for mesons made of light quarks, $= m_\pi/4$ for mesons composed of (anti-)strange quarks).

- The vacuum scalar condensate $< q\bar{q} >_V$ is fixed by the Gell-Mann-Oakes-Renner relation:

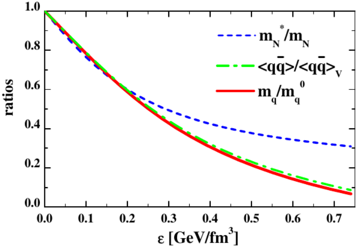
$$f_\pi^2 m_\pi^2 = -\frac{1}{2}(m_u^0 + m_d^0) < \bar{q}q >_V \quad \rightarrow \quad < \bar{q}q >_V \approx -3.2\, fm^{-3}$$

for the bare quark masses $m_u^0 = m_d^0 \approx 7 MeV$.

- The nucleon scalar density ρ_s is obtained after solving the gap equation for the field $\sigma(x)$.

Chiral Symmetry restoration in PHSD

In Schwinger-like formula effective masses have to be considered:



$$m^*_{q,s} = m^0_{q,s} + (m^v_{q,s} - m^0_{q,s}) \left| \frac{< \bar{q}q >}{< \bar{q}q >_V} \right|,$$

using $m^0_s \approx 100\ MeV$ and $m^0_q \approx 7\ MeV$ for the bare quark masses.

Chiral Symmetry restoration in PHSD

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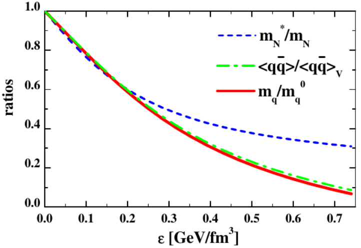
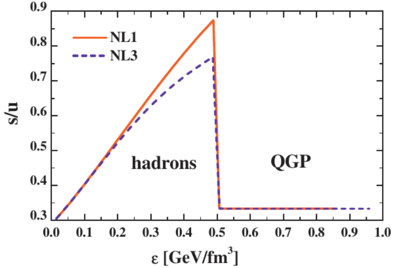


$$m^*_{q,s} = m^0_{q,s} + (m^v_{q,s} - m^0_{q,s}) \left| \frac{< \bar{q}q >}{< \bar{q}q >_V} \right|,$$

using $m_s^0 \approx 100\ MeV$ and $m_q^0 \approx 7\ MeV$ for the bare quark masses.

As long as the string tension remains approximately constant, the ratio s/u increases with decreasing $< q\bar{q} >$.

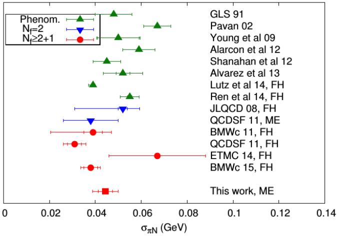


Within the deconfined phase the ratio s/u is fixed to $\sim 1/3$ by comparison to the strangeness production at RHIC and LHC energies observed experimentally.

Chiral Symmetry restoration: EOS

Dependence on the Hadronic EOS.

$\Sigma_{\pi N} = 45\, MeV$



Yi-Bo Yang et al., arXiv 1511.09089

Modifications on the value of $\Sigma_{\pi N}$ have no effect on the ratio K^+/π^+.

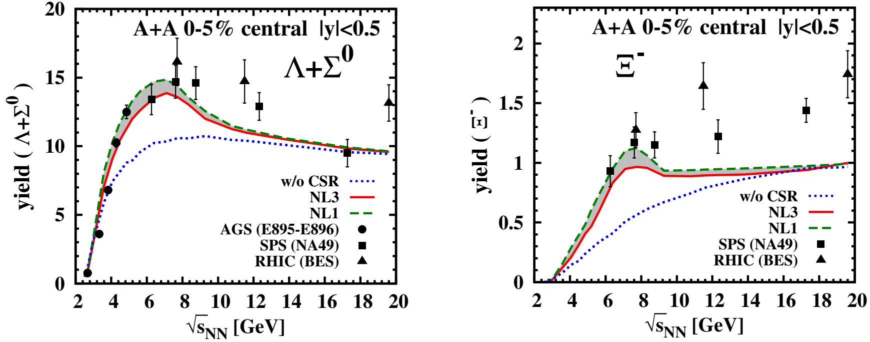
NL1 vs NL3

	NL1	NL3
g_s	6.91	9.50
g_v	7.54	10.95
B (1/fm)	-40.6	1.589
C	384.4	34.23
m_s (1/fm)	2.79	2.79
m_v (1/fm)	3.97	3.97
K (MeV)	380	380
m^*/m	0.83	0.70

A. Lang et al., Z. Phys. A 340, 287 (1991).

There is some sensitivity related to the hadronic EoS in our results.

Excitation function of the hyperons Λ and Ξ^-.



Many body theory

Kadanoff Baym Gleichungen (exact)

$$[\text{ß}\partial_t - h(t)]\, G(t,t') = \delta(t-t') + \int_C d\bar{t}\, \Sigma[G](t,\bar{t}) G(\bar{t},t')$$

$$[-\text{ß}\partial_{t'} - h(t')]\, G(t,t') = \delta(t-t') + \int_C d\bar{t}\, G(t,\bar{t}) \Sigma[G](\bar{t},t')$$

Limiting to two-particle correlations

$$\left\{ i\hbar \frac{\partial}{\partial \tau} - [\epsilon(\mathbf{p}) + \Delta(\mathbf{p}) + i\Gamma(\mathbf{p})] \right\} g^<(\mathbf{p},t,\tau) = I(\mathbf{p},t)$$

W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 4451

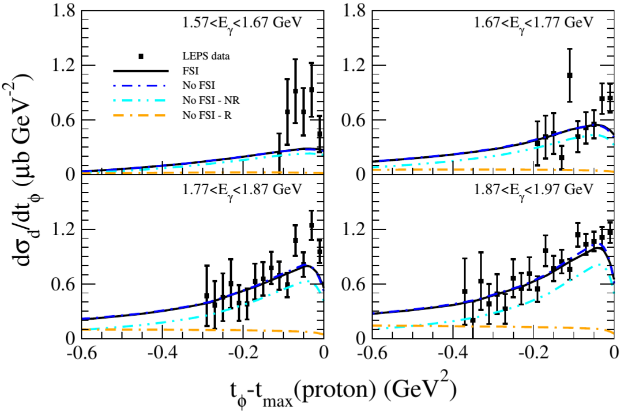
Off-shell (generalized) transport theory

Only one-particle distributions=diagonal Green's Functions, no correlations, weakly interacting or dilute systems

$$\frac{\partial}{\partial t} f(\mathbf{p},t) = I(\mathbf{p},t)$$

Boltzmann (BUU oder Vlasov-Boltzmann)

Phi production



A. Kiswandhi et al., arXiv:1604.01555, 2016.