Institut für Theoretische Physik

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Observables from heavy-ion collisions in the NICA energy regime

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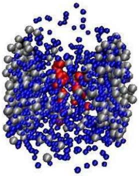
International Mini-Workshop on Simulations of HIC for NICA energies
Dubna, 10 April 2017

HIC for FAIR
Helmholtz International Center

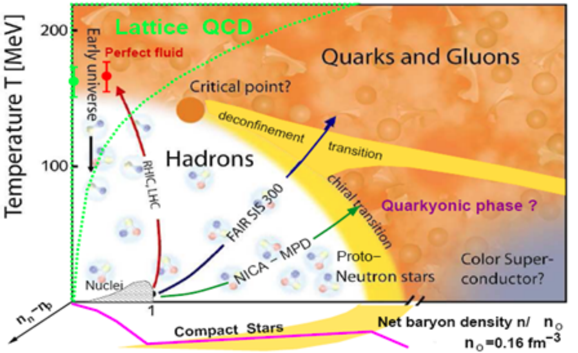


PHSD

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

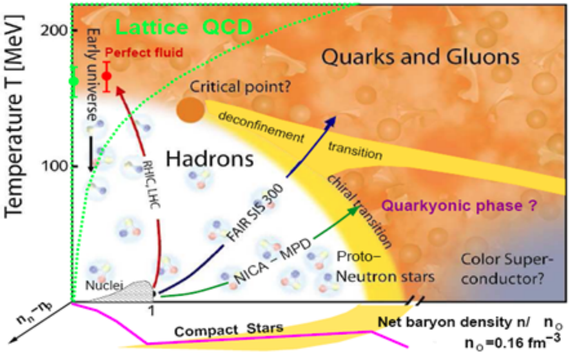
H-QM Helmholtz Research School Quark Matter Studies

Motivation



Temperature T [MeV]
200
100
Lattice QCD
Perfect fluid
Early universe
Quarks and Gluons
Critical point?
deconfinement
transition
Hadrons
RHIC, LHC
FAIR SIS 300
chiral transition
Quarkyonic phase ?
NICA – MPD
Proto–
Neutron stars
Color Super-
conductor?
Nuclei
1
$n_n - n_p$
Compact Stars
Net baryon density n/ n_0
n_0=0.16 fm^{-3}

Motivation

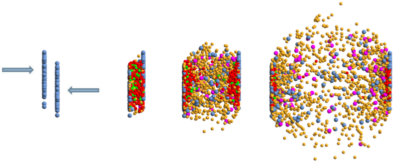


Which observables are suitable for the study of the chiral symmetry restoration and of the quark gluon plasma in the NICA energy regime?

Outline

Parton-Hadron-String Dynamics (PHSD)

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



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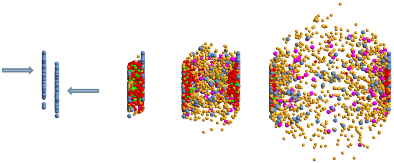
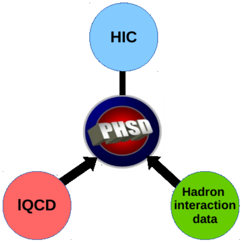




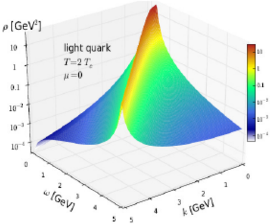
- Model applicable out-of equilibrium and in agreement with the lattice results in equilibrium as well as with the nuclear physics input.
- Transport theory: off-shell transport equations in phase-space representation based on Kadanoff-Baym equations for the partonic and hadronic phase.

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

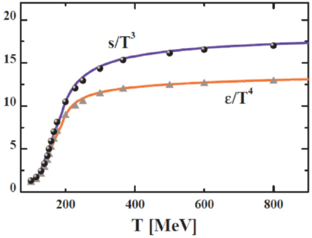
Dynamical Quasi-Particle Model (DQPM)

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

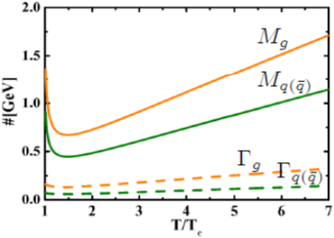
$$\rho_i(\omega, T) = \frac{4\omega\Gamma_i(T)}{(\omega^2 - \mathbf{p}^2 - M_i^2(T))^2 + 4\omega^2\Gamma_i^2(T)}, \quad (i = q, \bar{q}, g)$$



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

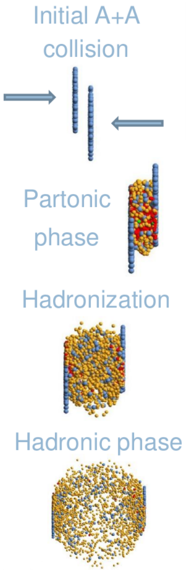


Masses and widths of partons depend on the temperature T and chemical potential μ_q of the medium:

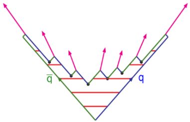


Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007) .

Stages of Parton Hadron String Dynamics (PHSD)



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



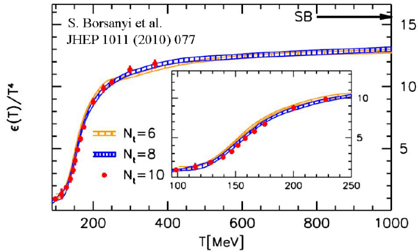
- Formation of a **QGP state** if $\epsilon > \epsilon_C \approx 0.5\,\mathrm{GeVfm}^{-3}$.
- Dissolution of newly produced secondary hadrons into **massive colored quarks/antiquarks** and **mean-field energy** U_q:

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

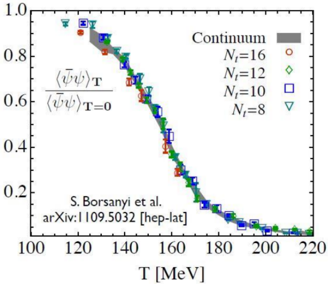
- **DQPM** defines the properties (masses and widths) of partons and mean-field potential at a given local energy density ϵ.
- **Hadronization** through a local covariant off-shell transition rate which conserves 4-momentum and quantum numbers.
- Hadron-string interactions – **off-shell HSD**.

Lattice QCD predicts two transitions of the strong matter at high temperature:

- Deconfinement phase transition



- Chiral Symmetry Restoration

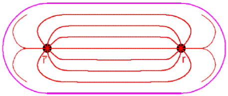


The scalar quark condensate $\langle \bar{q}q \rangle$ is viewed as an order parameter for the restoration of chiral symmetry.

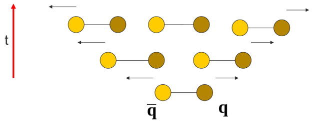
$$\langle \bar{q}q \rangle = \begin{cases} \neq 0 & \text{chiral non-symmetric phase;} \\ = 0 & \text{chiral symmetric phase.} \end{cases}$$

String dynamics in PHSD

In PHSD the flavor chemistry of the final hadrons is defined by the **LUND string model**.



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 $\tau_f \approx 0.8\, fm/c$.

- **Chemistry** determined by the Schwinger formula:

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

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

The relative production factors in PHSD/HSD are:

$$u : d : s : uu = \begin{cases} 1 : 1 : 0.3 : 0.07 & \text{at SPS to RHIC;} \\ 1 : 1 : 0.4 : 0.07 & \text{at AGS energies.} \end{cases}$$

- **Kinematics** determined by the Fragmentation Function $f(x, m_T)$

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

String dynamics in PHSD

In the **Schwinger-formula**, $m_{u,d,s}$ are the constituent ('dressed') masses due to the coupling to the scalar quark condensate.

$$\gamma_s = exp\left(-\pi \frac{\mathbf{m}_s^2 - \mathbf{m}_{u,d}{}^2}{2\kappa}\right)$$

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In **vacuum** (e.g. p+p collisions) the dressing of the bare quark masses follows:

$$m_q^V = m_q^0 - g_s\langle\bar{q}q\rangle_V,$$

with $m_{u,d}^0 \approx 7\,\mathrm{MeV}$, $m_s^0 \approx 100\,\mathrm{MeV}$ and $\langle\bar{q}q\rangle_V \approx -3.2\,\mathrm{fm}^{-3}$.

⇓

For $m_{u,d} = 0.33\,GeV$ and $m_s = 0.5\,GeV$:

$$\gamma_s = \exp\left(-\pi \frac{m_s^2 - m_{u,d}^2}{2\kappa}\right) = 0.3.$$

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In **medium** (e.g. A+A collisions) the dressing of the bare quark masses follows:

$$m_q^* = m_q^0 - g_s \langle \bar{\mathbf{q}} \mathbf{q} \rangle,$$
$$= m_q^0 + (m_q^V - m_q^0) \frac{\langle \bar{\mathbf{q}} \mathbf{q} \rangle}{\langle \bar{\mathbf{q}} \mathbf{q} \rangle_\mathbf{V}}.$$

⬇

We need to evaluate the scalar quark condensate in the medium!

Chiral Symmetry restoration in PHSD

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

$$\frac{\langle \bar{\mathbf{q}}\mathbf{q} \rangle}{\langle \bar{\mathbf{q}}\mathbf{q} \rangle_{\mathbf{V}}} = 1 - \frac{\boldsymbol{\Sigma_\pi}}{f_\pi^2 m_\pi^2} \boldsymbol{\rho_S} - \sum_h \frac{\sigma_h \rho_S^h}{f_\pi^2 m_\pi^2},$$

with Σ_π as the pion-nucleon Σ-term, σ_h as the $\sigma-$commutator of the meson h, ρ_s as scalar density which can be obtained within the non-linear $\sigma - \omega$ model and f_π and m_π are the pion decay constant and pion mass, given by the Gell-Mann-Oakes-Renner relation.

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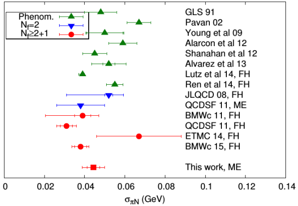
We adopt $\boldsymbol{\Sigma}_{\boldsymbol{\pi}} = 45\,\mathrm{MeV}$.
Modifications on the value of Σ_π have no essential effect on our results.



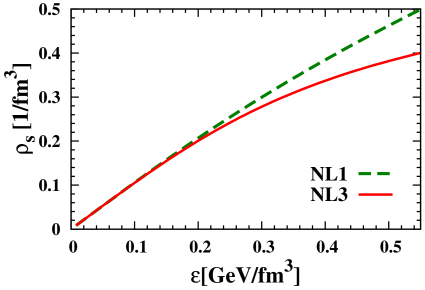
Yi-Bo Yang et al., Phys. Rev. D 94, 054503 (2016).

The scalar density $\boldsymbol{\rho}_{\mathbf{s}}$ is obtained within the **non-linear $\boldsymbol{\sigma} - \boldsymbol{\omega}$ model** solving locally the gap equation for the σ-field.

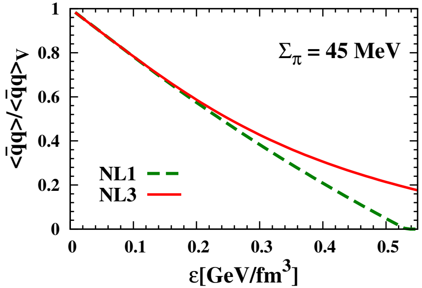
We investigate different parametrizations for the hadronic EoS to estimate the uncertainty on our results.

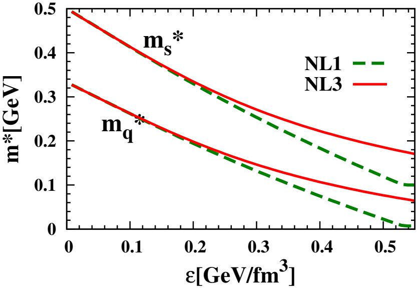
	NL1	NL3
g_s	6.91	9.50
K (MeV)	380	380
m^*/m	0.83	0.70

CSR: Dependence on the Hadronic EoS (at $T = 0$)

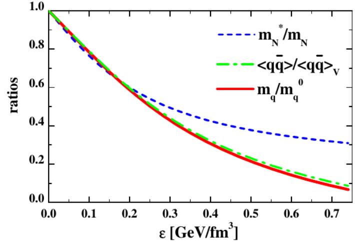


- There is a **moderate sensitivity related to the hadronic EoS**.
- NL1 parameter set for the EoS is associated to lower values for $\langle \bar{q}q \rangle / \langle \bar{q}q \rangle_V$.

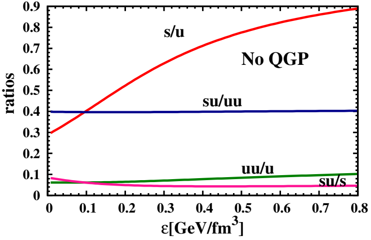




Considering effective quark masses $m^*_{q,s}$ in the **Schwinger formula**.



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



Chiral Symmetry restoration in PHSD

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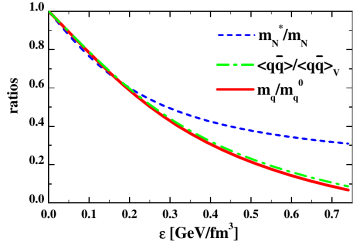

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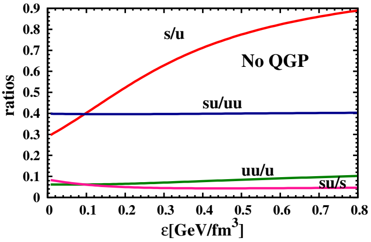
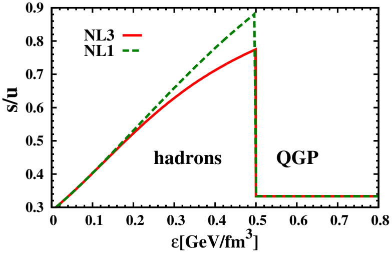
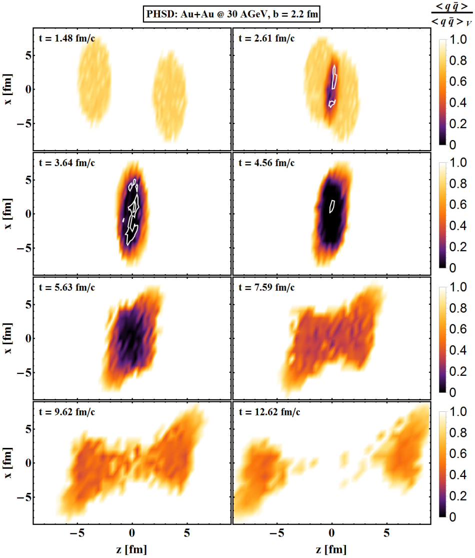


In the **QGP phase**, the string decay doesn't occur anymore and this effect is therefore suppressed.



A "Horn" feature emerges in the energy dependence of the s/u ratio!

Scalar quark condensate in HIC



W. Cassing et al., Phys. Rev. C93 (2016) 014902.

Time evolution of the ratio $\frac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_V}$ for Au+Au @ 30 AGeV.

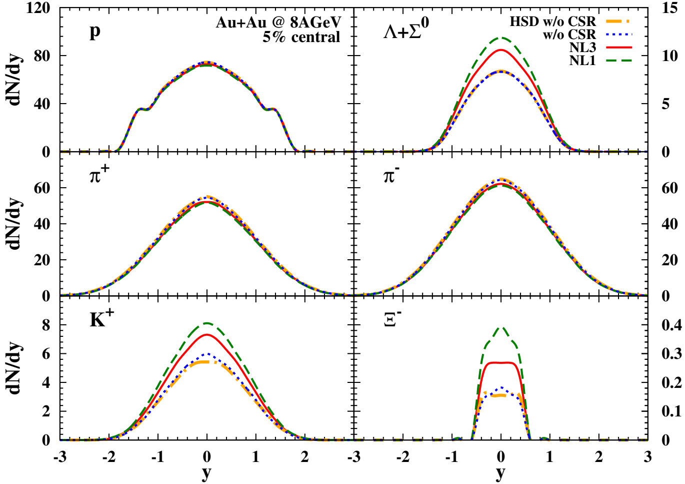
$$\langle \bar{q}q \rangle = \begin{cases} \neq 0 & \text{chiral non-symmetric phase;} \\ = 0 & \text{chiral symmetric phase.} \end{cases}$$

The scalar quark condensate $\langle \bar{q}q \rangle$ is not a direct observable.

Can we find manifestations of the chiral symmetry restoration indirectly in hadronic observables?

Rapidity spectra I

Au+Au @ 8 AGeV

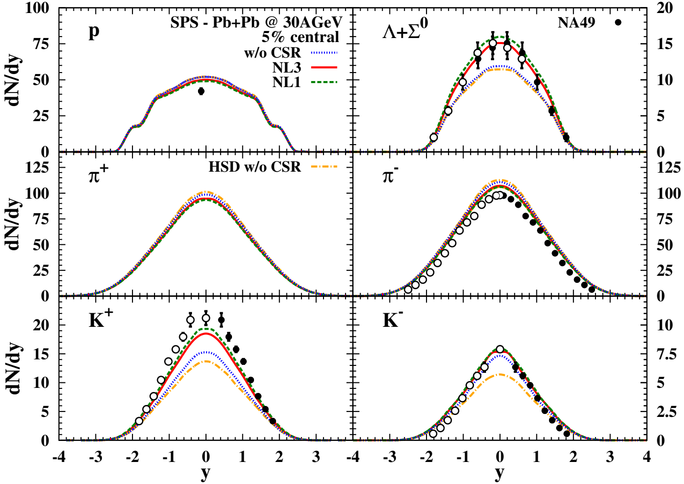


Vanishing contribution from QGP.

➜ HIC at low NICA energies are suited to isolate the role of CSR in the hadronic medium.

Rapidity spectra II

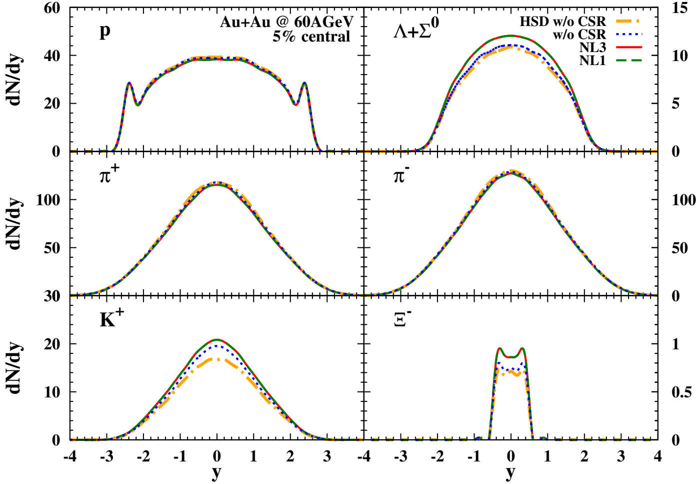
Pb+Pb @ 30 AGeV in comparison to data at SPS



A. P. et al., Phys. Rev. C94 (2016) 044912.

Rapidity spectra III

Au+Au @ 60 AGeV

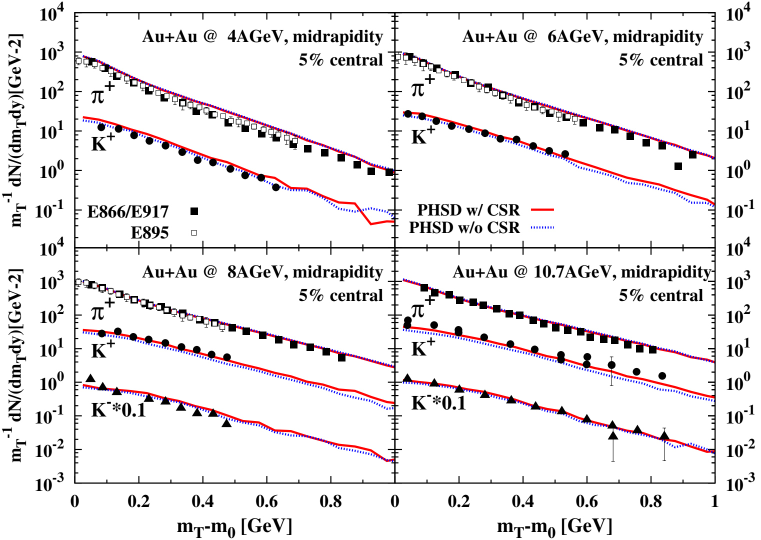


Finite contributions from both CSR and QGP.

➜ NICA energy scan is optimal to study the "interplay" between CSR and QGP.

Transverse mass spectra I

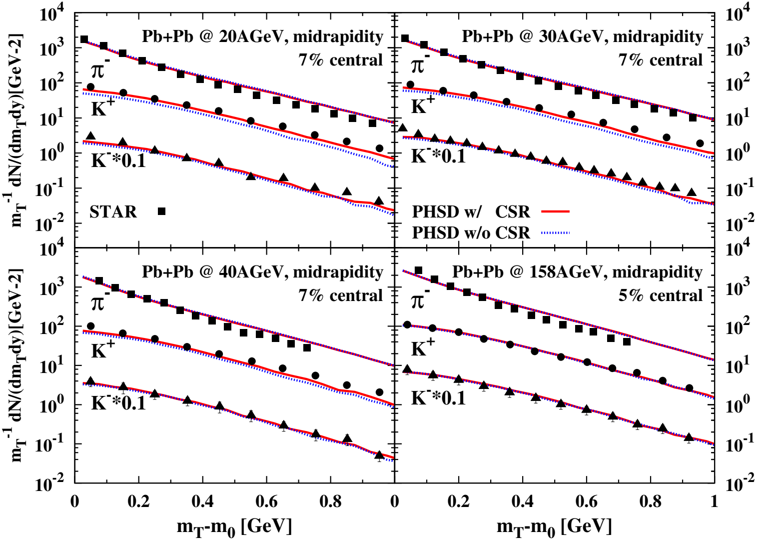
Au+Au collisions in comparison to data at AGS



A. P. et al., Phys. Rev. C94 (2016) 044912.

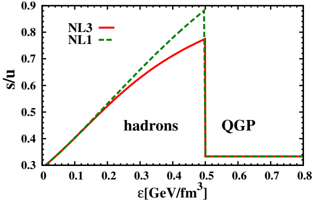
Transverse mass spectra II

Pb+Pb collisions in comparison to data at SPS



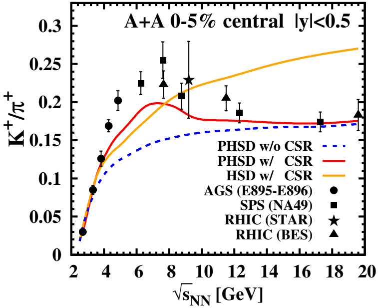
A. P. et al., Phys. Rev. C94 (2016) 044912.

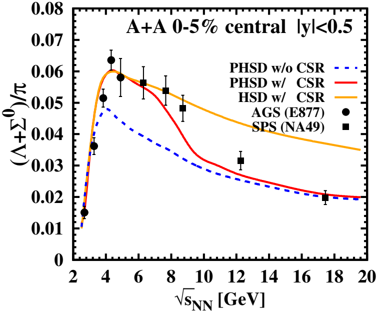
"Horn" in the K^+/π^+ ratio



- Strangeness enhancement at low $\sqrt{s_{NN}}$ related to **CSR**.
- Drop of the s/u ratio due to the appearance of a **QGP**.

➜ A **"horn"**-structure emerges.





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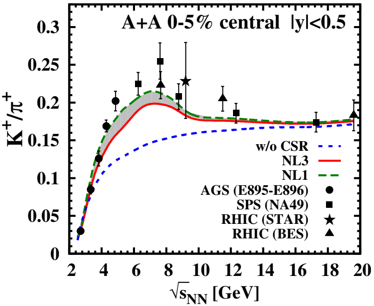
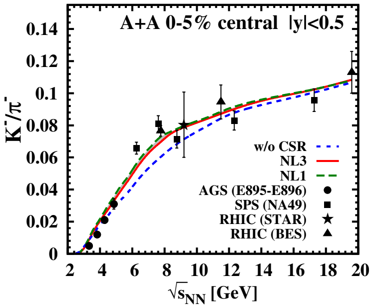
What is the sensitivity to the equation of state?

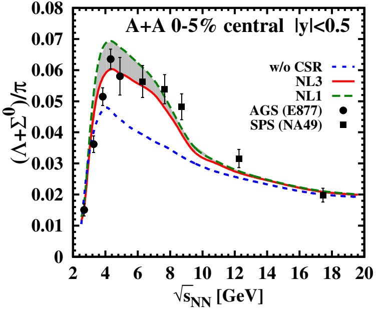
Strange to non-strange particle ratios



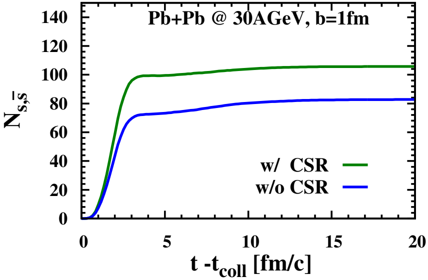
- There is a **moderate sensitivity related to the hadronic EoS** in our results.
- NL1 parameter set for the EoS shows a sharper peak in the K^+/π^+ ratio in good agreement with the data.

A. P. et al., Phys. Rev. C94 (2016) 044912.

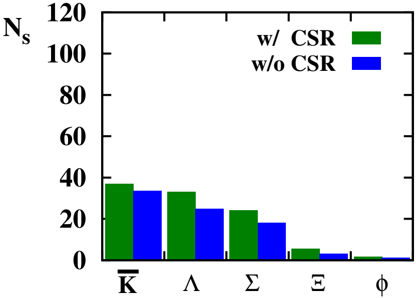


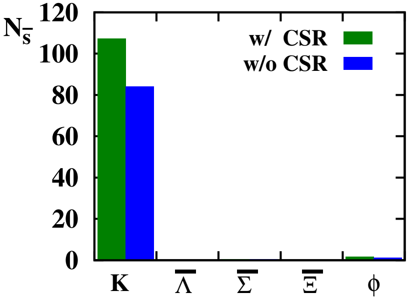


Strangeness production



- **s−quarks** mostly form hyperons, e.g. Λ and Σ.
- $\bar{s}$**−quarks** mostly form $K = (K^+, K^0)$.





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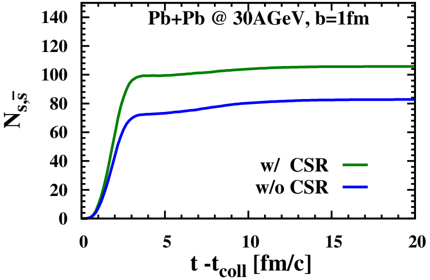
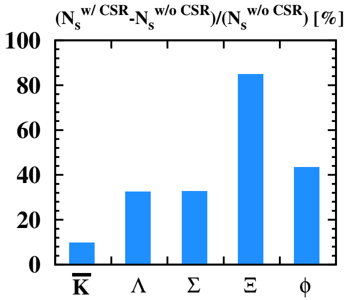
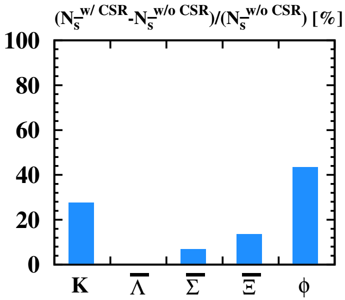


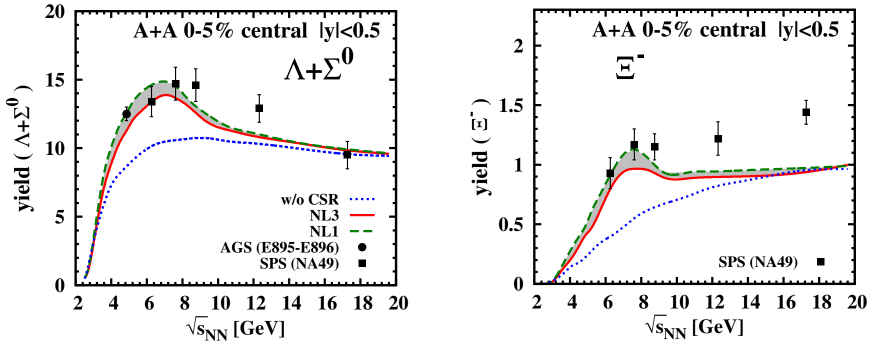
- The increase of $\overline{\mathbf{K}}$ due to CSR is $\approx 10\%$.
- The increase of $\mathbf{\Lambda}$ and $\mathbf{\Sigma}$ due to CSR is $\approx 32\%$.
- The increase of $\mathbf{K}$ due to CSR is $\approx 28\%$.





Hyperon abundances

Excitation function of the **hyperons Λ and Ξ^-**.

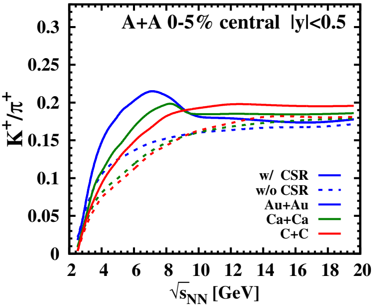


A. P. et al., Phys. Rev. C94 (2016) 044912.

They show **analogous peaks** as the K^+/π^+ and $(\Lambda + \Sigma_0)/\pi$ ratios due to CSR.

There is a small sensitivity on the parametrizations for the hadronic EoS.

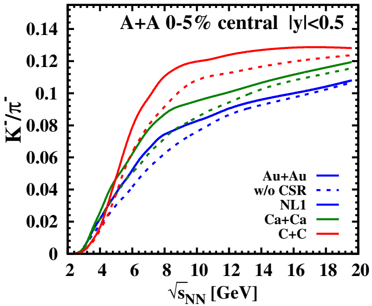
Sensitivity to the system size: A+A collisions

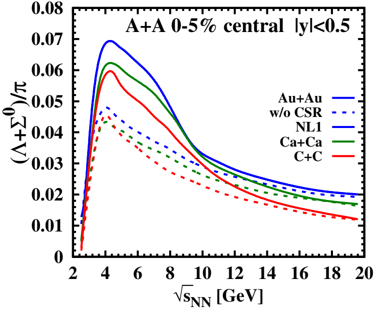


If the system size is smaller:

- **the peak of K^+/π^+ disappears**;
- **the peak of $(\Lambda + \Sigma^0)/\pi$ remains** in the same position in energy.

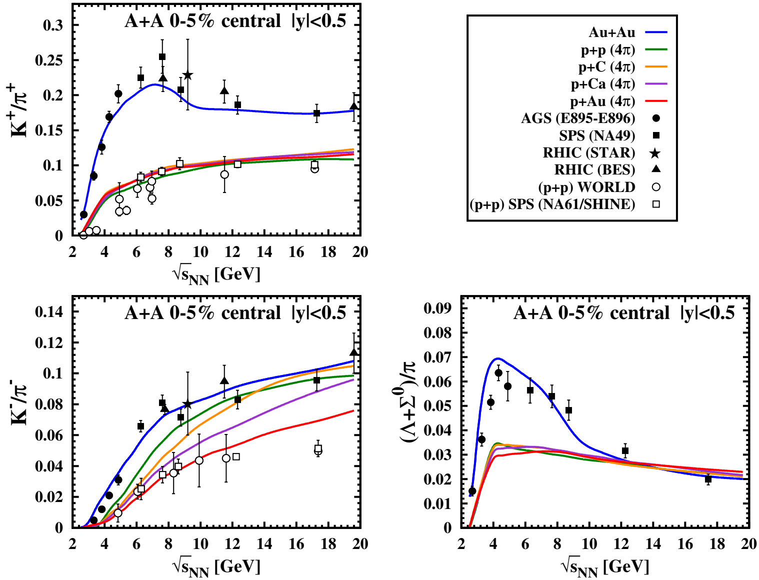
A. P. et al., Phys. Rev. C94 (2016) 044912.





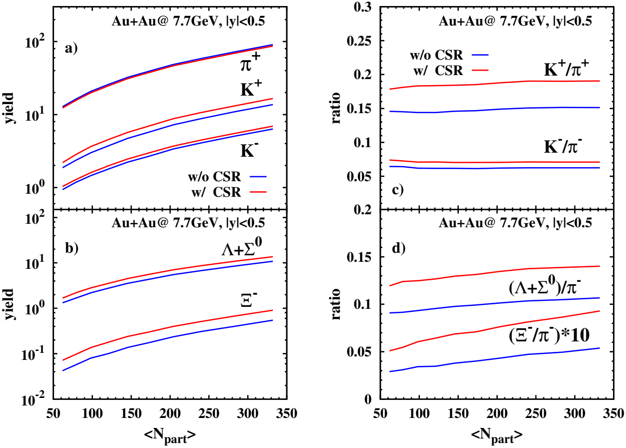
Sensitivity to the system size: p+A collisions

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



Centrality dependence

Particles abundances and ratios as a function of the number of participants in Au+Au @ 7.7 GeV



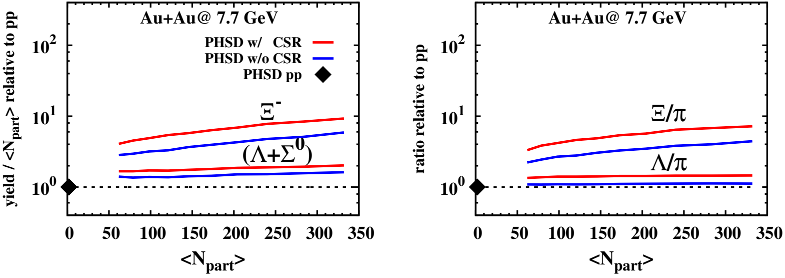
A. P. et al., Phys. Rev. C94 (2016) 044912.

CSR occurs in **central collisions** as well as in moderately **peripheral collisions**.

Centrality dependence

Strangeness enhancement in relation to the strange particle production in **p+p collisions**:

$$\left(\frac{\text{yield}}{\langle N_{\text{part}}\rangle}\right)_{A+A} \Big/ \left(\frac{\text{yield}}{\langle N_{\text{part}}\rangle}\right)_{p+p} . \qquad (1)$$



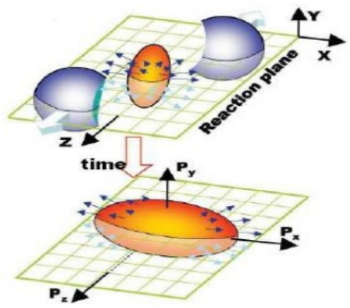
The enhancement in A+A collisions with respect to the p+p collisions is larger for the Ξ^- than for $(\Lambda + \Sigma^0)$.

Directed flow v_1

First type of collective motion to be identified among fragments of HIC.
It represents the deflection of the produced particles in the reaction plane.

$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} \nu_n cos[n(\varphi - \psi_n)]\right)$$

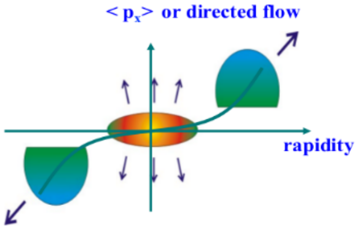
with $\nu_n = \langle cos[n(\varphi - \psi_n)] \rangle$ for $n = 1, 2, 3\ldots$



$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$

Interaction between constituents
↓
Pressure gradient
↓
Spatial asymmetry
↓
Asymmetry in momentum space
↓
Collective transverse motion

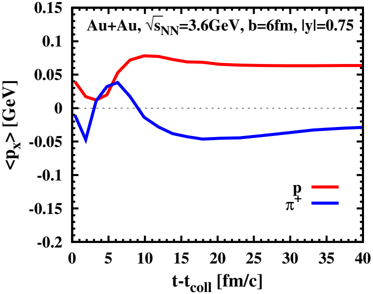
Directed flow v_1: slope F and time evolution



The directed flow is approximately linear at midrapidity:

$$\mathbf{v_1 \approx F \cdot y}$$

- **F > 0 normal flow**
- **F < 0 antiflow**



- **Protons**:
  v_1 is established in the early stage of the collision and marginally distorted during the evolution.
- **Pions**:
  mesons are sensitive to rescattering of hadrons; v_1 is positive at small values of time and becomes negative later on.

Directed flow v_1: baryon potentials

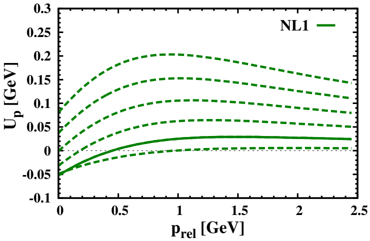
The particles propagating in a medium are sensitive to mean-field potentials. The nucleon potential is defined in terms of the Schrödinger-equivalent potential:

$$U_{sep}(E_{kin}) = U_S + U_0 + \frac{1}{2M}(U_S^2 - U_0^2) + \frac{U_0}{M}E_{kin}.$$

An explicit-momentum dependence is included for the potential components U_S and U_0:

$$f_S = \frac{1}{1 + p_{rel}}, \qquad f_V = \frac{1}{1 + p_{rel}^2/1.7},$$

in agreement with previous transport calculations (e.g. P. K. Sahu et al., NPA 712 (2002) 357.) and with Dirac-Brueckner calculations (e.g. T. Gross-Boelting et al, NPA 648 (1999) 105.).



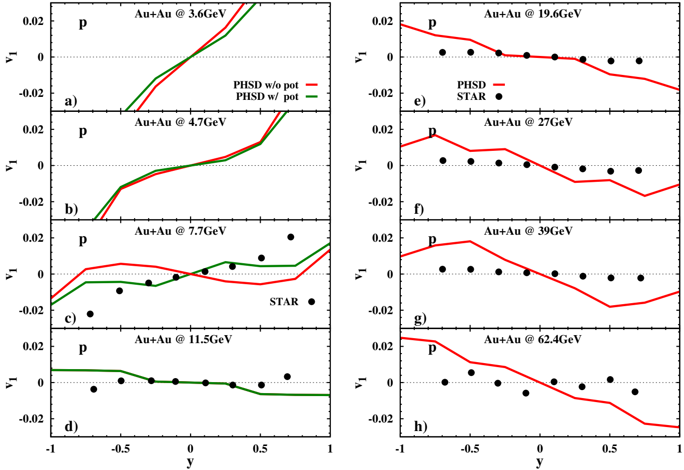
Each line refers to a fixed baryon density, from $\rho_0/2$ (lowest line) to $3\rho_0$ (highest line) with steps of $\rho_0/2$.

In PHSD the potentials are incorporated in the baryonic sector (weighted according to the light quark content of the baryon).

What is the sensitivity of v_1 to the baryon potentials?

The proton v_1 has a **normal flow behavior at small energies** and an **antiflow behavior at high energies**. The PHSD (CSR included) results show the same trend as the data, though there is not a perfect agreement.

p

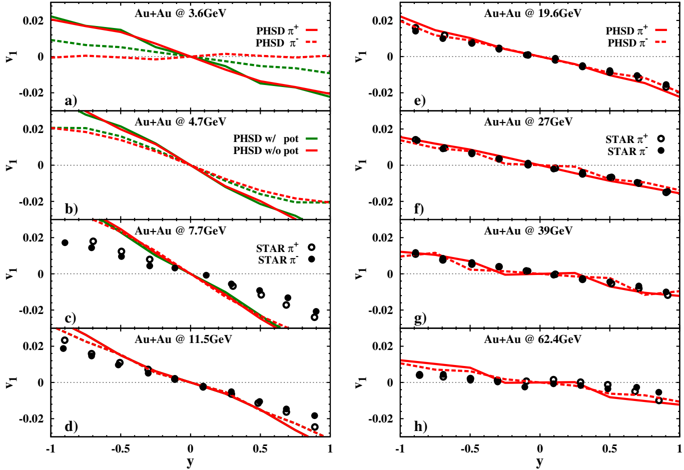


Data from: L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 112 (2014) 162301.

Pion flow in Au+Au collisions at RHIC energies in comparison to STAR data

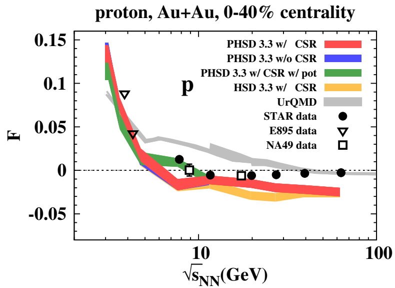
The pions are characterized by an **antiflow** behavior in the **whole investigated energy range**. The PHSD (CSR included) results are in good agreement with the data at high energies, while at small energies the PHSD antiflow is too large.

π

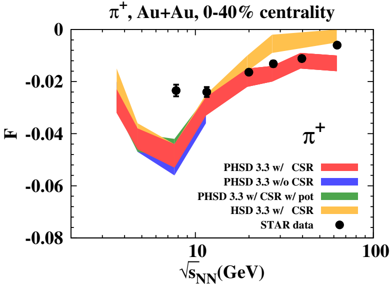


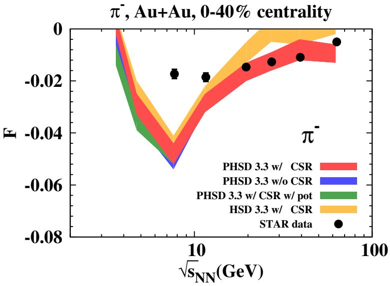
Data from: L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 112 (2014) 162301.

Excitation functions of the directed flow slopes



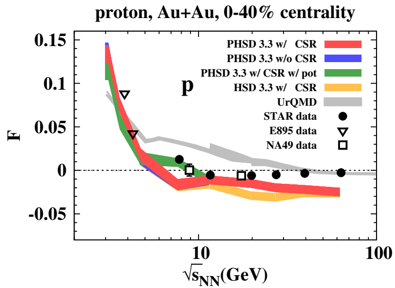
- The proton F is positive at small energies and negative at higher energies.
- The pion slopes are negative in the whole energy range.
- CSR does not modify F.
- v_1 is sensitive to potentials at low energies.





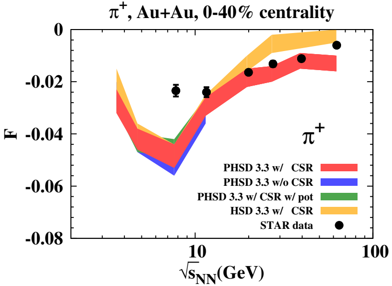
UrQMD and data from: L. Adamczyk et al. (STAR Coll.), Phys. Rev. Lett. 112 (2004) 162301; Y. Pandit (STAR Coll.), J. Phys. Conf. Ser. 636 (2015) 012001; V. P. Konchakovski et al., Phys. Rev. C 90 (2014) 014903.

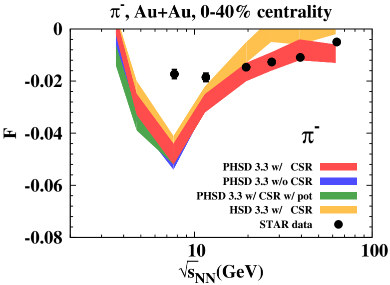
Excitation functions of the directed flow slopes



PHSD reproduces the trend of the data with some discrepancy for p at high energies and for π at small energies.

More experimental information are needed at low energies.





UrQMD and data from: L. Adamczyk et al. (STAR Coll.), Phys. Rev. Lett. 112 (2004) 162301; Y. Pandit (STAR Coll.), J. Phys. Conf. Ser. 636 (2015) 012001; V. P. Konchakovski et al., Phys. Rev. C 90 (2014) 014903.

Summary

The NICA energy scan is optimal to study CSR in the hadronic medium and its "interplay" with the QGP phase.

- Particle abundances and rapidity spectra are suitable probes to extract information about CSR.
- The 'horn'-structure in the strange to non-strange particle ratios is due to CSR and QGP.
- The 'horn'-structure disappears in the K^+/π^+ ratio as the system size decreases, while it remains in the $(\Lambda + \Sigma^0)/\pi$ ratio.
- CSR occurs in central collisions and in moderately peripheral collisions.
- The directed flow of protons is sensitive to baryon potentials at low energies.
- PHSD reproduces the experimental trend of the proton and pion flows with some discrepancy for p at high energies and for π at small energies.

Thank you for your attention!

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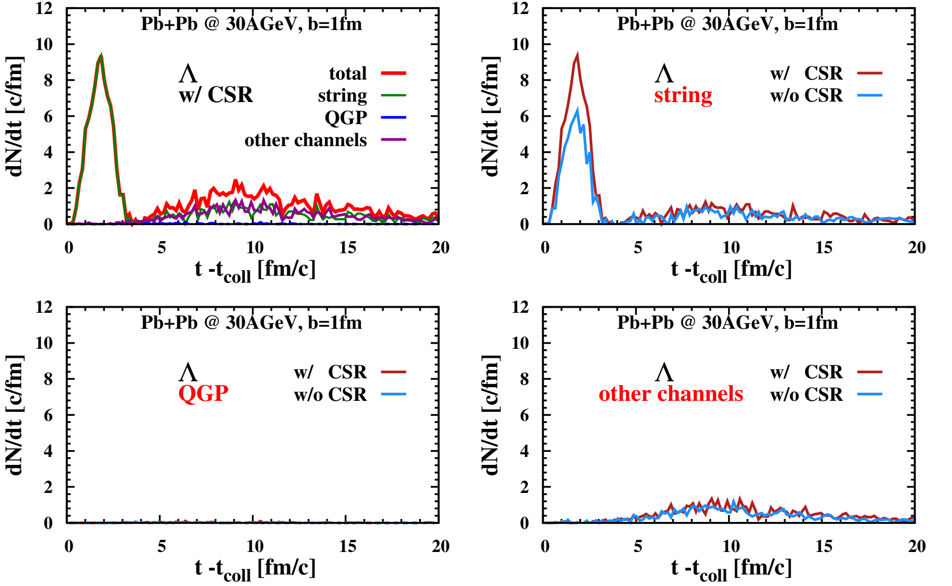
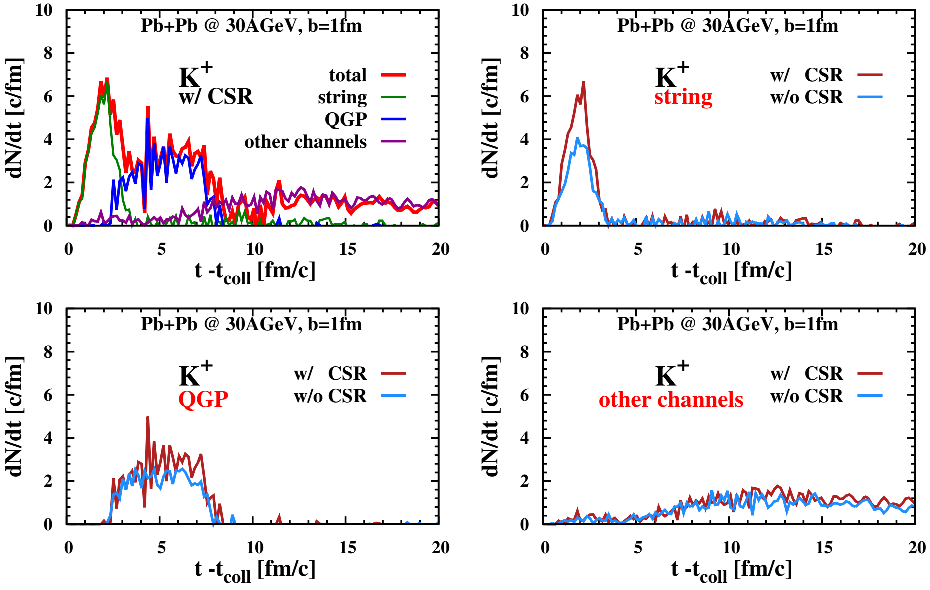
BACK-UP SLIDES

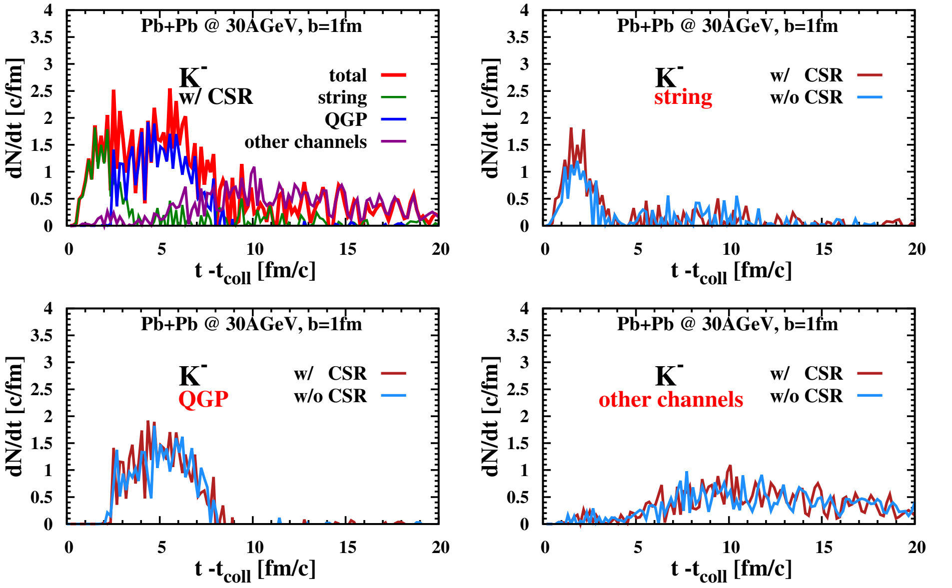
Λ production rate in Pb+Pb collision at 30AGeV



K^+ production rate in Pb+Pb collision at 30AGeV



K^- production rate in Pb+Pb collision at 30AGeV



Chiral Symmetry Restoration (CSR) in PHSD

- In a 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 $\sigma(x)$ for nucleons 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:

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

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 $\langle q\bar{q} \rangle_V$ is fixed by the Gell-Mann-Oakes-Renner relation:

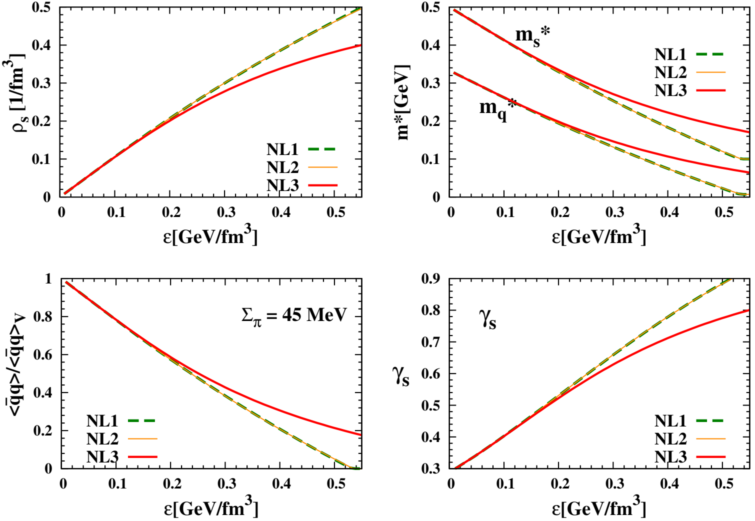
$$f_\pi^2 m_\pi^2 = -\frac{1}{2}(m_u^0 + m_d^0)\langle \bar{q}q \rangle_V \quad \rightarrow \quad \langle \bar{q}q \rangle_V \approx -3.2\, fm^{-3}$$

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 $\sigma(x)$.

CSR: Dependence on the Hadronic EoS

The sensitivity to the nuclear EoS is dominantly driven by the effective mass of the nucleons.



Chiral Symmetry restoration: Basic Principles

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

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

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

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

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

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

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

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

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

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