Observables of chiral symmetry restoration in heavy-ion collisions

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for the PHSD group

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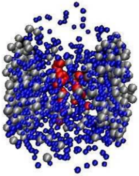
International School of Nuclear Physics, Erice, 21 September 2016

HIC for FAIR
Helmholtz International Center



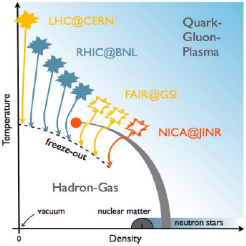
PHSD

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

H-QM Helmholtz Research School
Quark Matter Studies

Motivation

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



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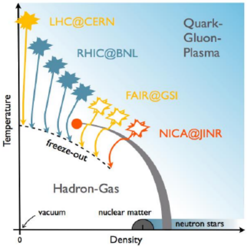
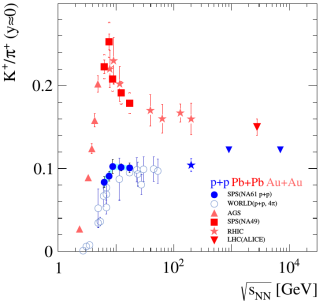


There are many open questions related to the **strangeness production** in Heavy-Ion Collisions (HIC)!



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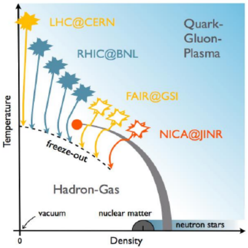

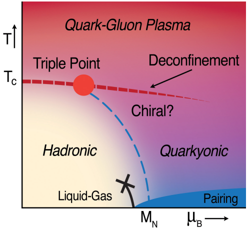

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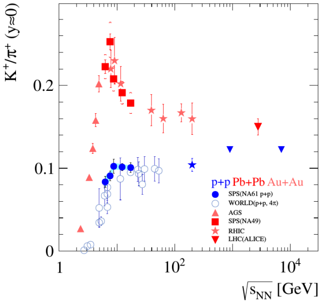
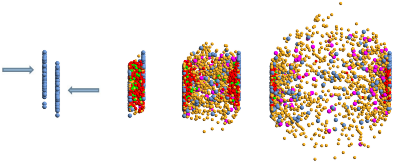


Can we find a manifestation of the Chiral Symmetry restoration in HIC observables?

Outline

Reminder of 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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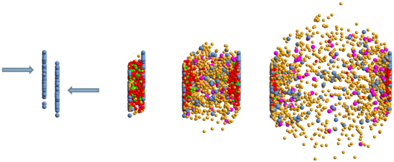
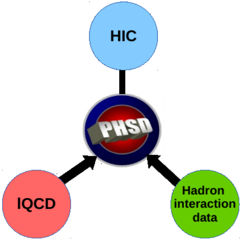


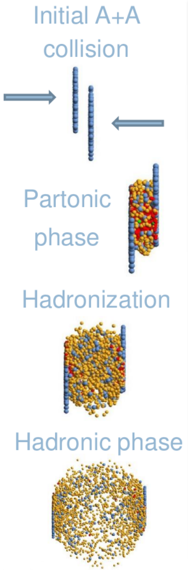


- Model applicable out of equilibrium and in agreement with the lattice results in equilibrium as well as with the nuclear physics input.
- Transport theory: off-shell transport equations in phase-space representation based on Kadanoff-Baym equations for the partonic and hadronic phase.

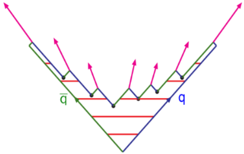
W.Cassing, E.Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W.Cassing, EPJ ST 168 (2009) 3.

More details were given by T. Steinert, E. Seifert and W. Cassing.

Reminder 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.
- **EoS**: crossover at $\mu_q = 0$ from Lattice QCD fitted by DQPM.

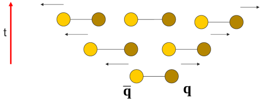
More details were given by T. Steinert, E. Seifert and W. Cassing.

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

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

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

with $\kappa \approx 0.176\,\mathrm{GeV}^2$ and $m_{u,d,s}$ as constituent ('dressed') masses due to the coupling to the vacuum.



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

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

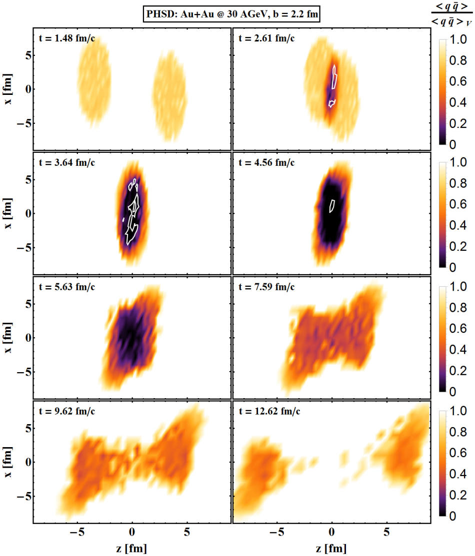
with $m_{u,d}^0 \approx 7\,\mathrm{MeV}$, $m_s^0 \approx 100\,\mathrm{MeV}$ and $\langle\bar{q}q\rangle_V \approx -3.2\,\mathrm{fm}^{-3}$.

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

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

More details were given by T. Steinert and W. Cassing.

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.

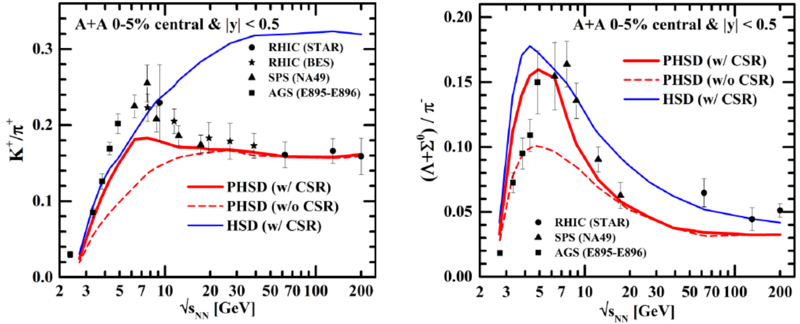
$$\langle \bar{q}q \rangle = \begin{cases} \neq 0 & \text{chiral non-symmetric phase;} \\ = 0 & \text{chiral symmetric phase.} \end{cases}$$

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?

Chiral Symmetry restoration: Horn

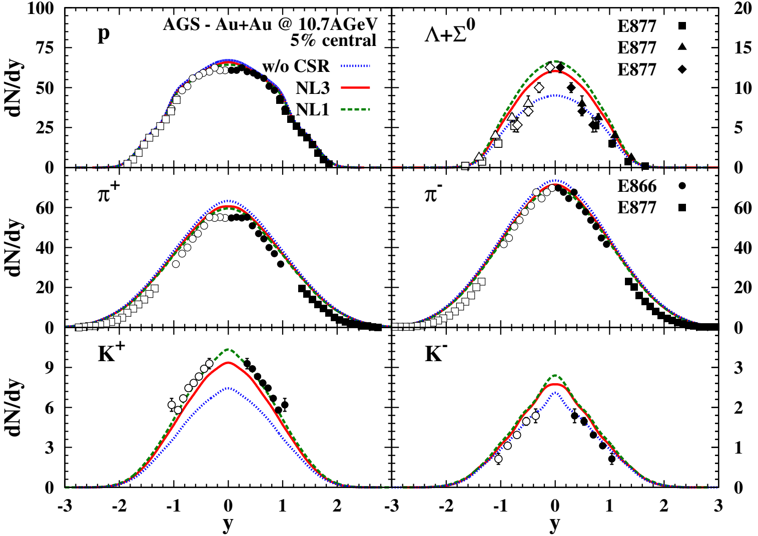
We observe a rise in the ratio K^+/π^+ at low $\sqrt{s_{NN}}$ related to **Chiral Symmetry Restoration (CSR)** and then a drop due to the appearance of a **deconfined partonic medium**. ➜ A **"horn"**-structure emerges.



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

What is the sensitivity to the equation of state?

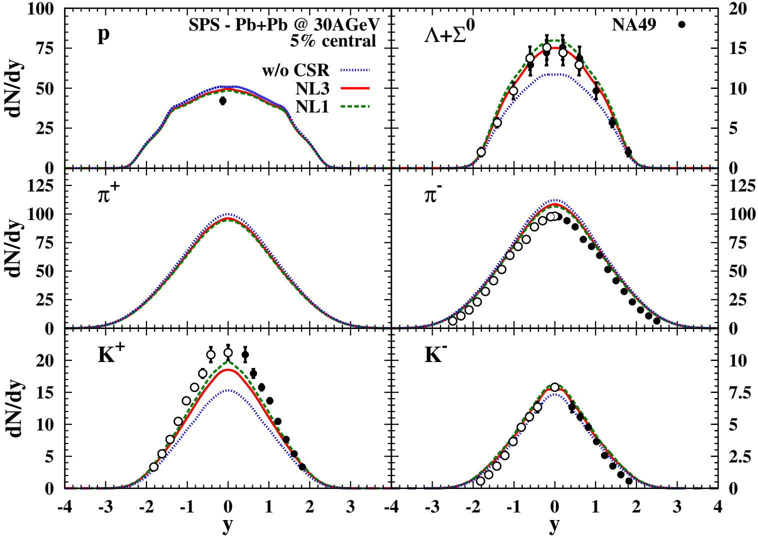
Au+Au @ 10.7 AGeV in comparison to data at AGS



A. P. et al., nucl-th:1607.04073 (2016).

Rapidity spectra II

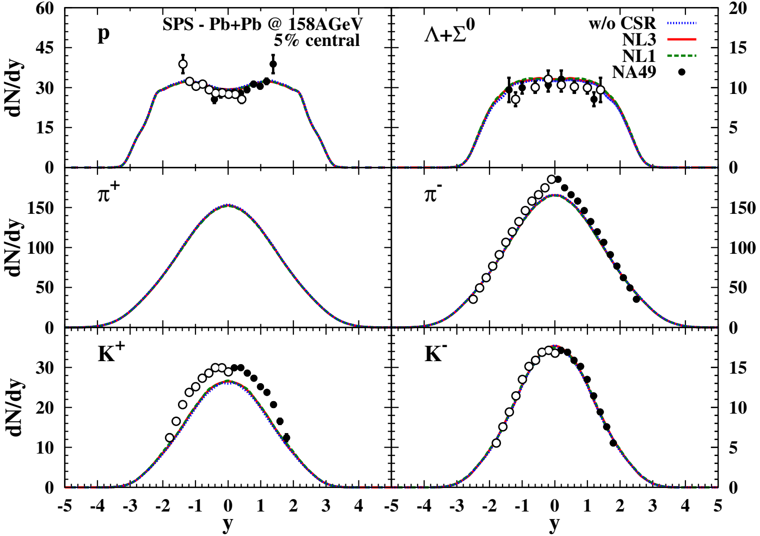
Pb+Pb @ 30 AGeV in comparison to data at SPS



A. P. et al., nucl-th:1607.04073 (2016).

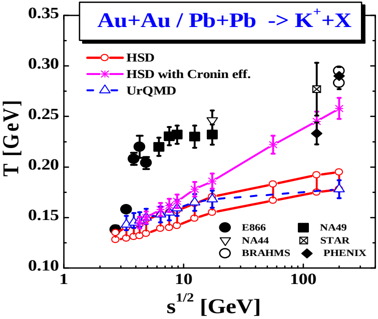
Rapidity spectra III

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

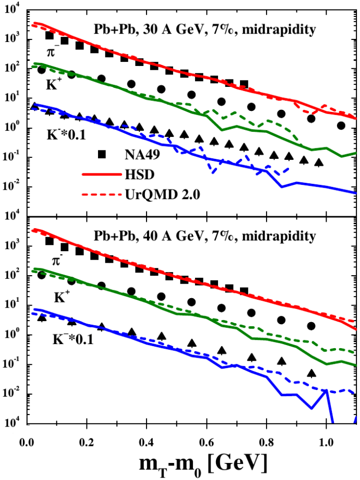


A. P. et al., nucl-th:1607.04073 (2016).

Open issue: there was an underestimation of the transverse mass spectra of kaons in the whole energy range.

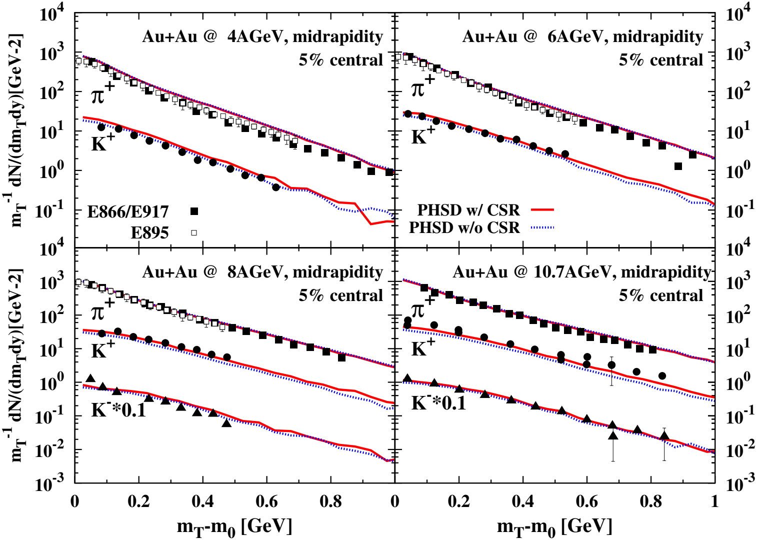


E.L. Bratkovskaya, Phys. Rev. C 69 (2004) 032302.



Transverse mass spectra I

Au+Au collisions in comparison to data at AGS



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Transverse mass spectra II

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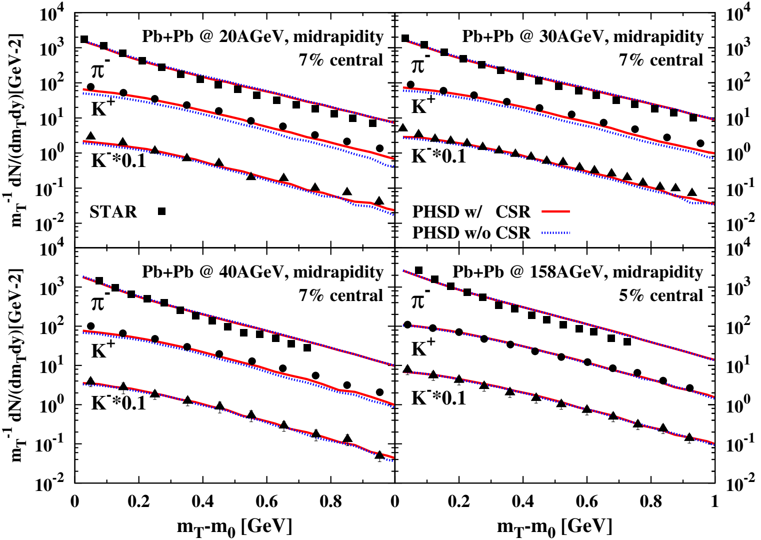

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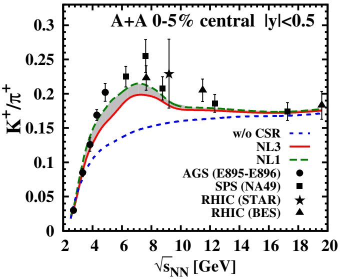
Strange to non-strange particle ratios



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- NL1 parameter set for the EoS shows a sharper peak in the K^+/π^+ ratio in good agreement with the data.

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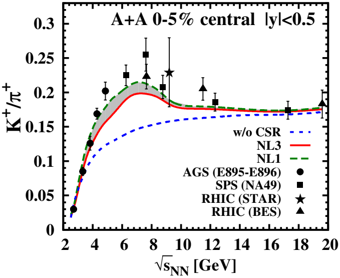

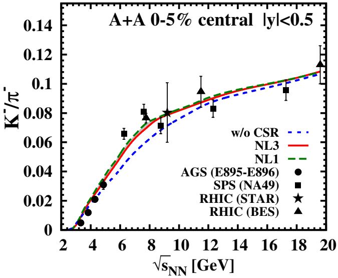

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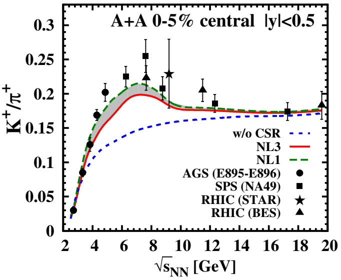

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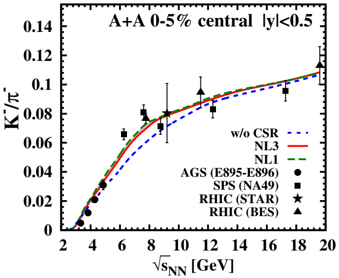
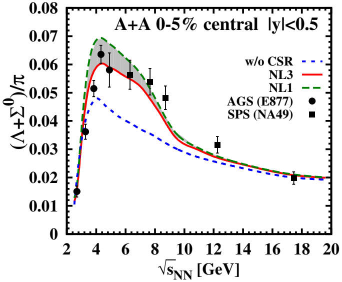
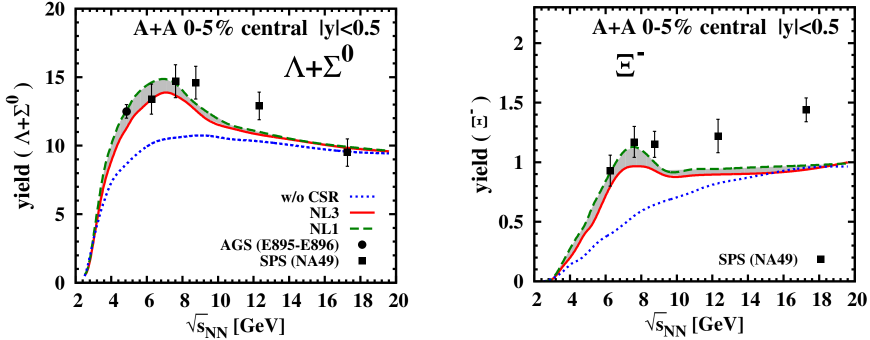




A. P. et al., nucl-th:1607.04073 (2016).

Hyperon abundances

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

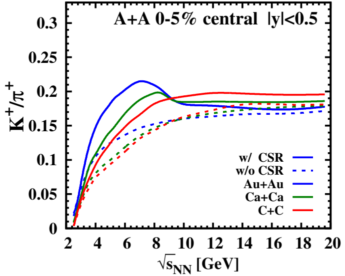


A. P. et al., nucl-th:1607.04073 (2016).

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

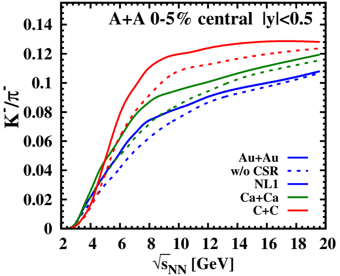
There is a small sensitivity on the parametrizations for the hadronic EoS.

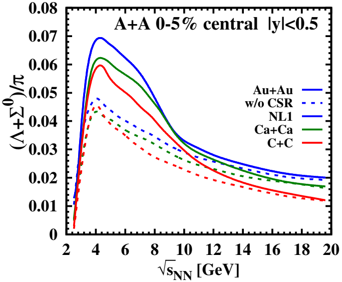
Sensitivity to the system size: A+A collisions



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.

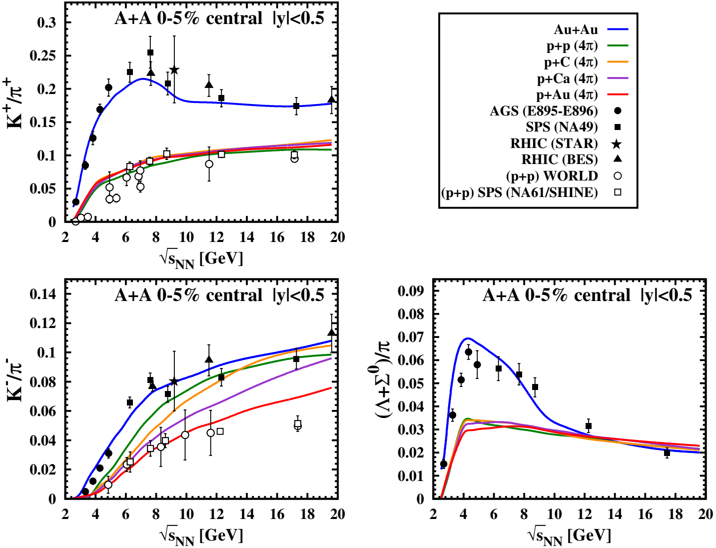




A. P. et al., nucl-th:1607.04073 (2016).

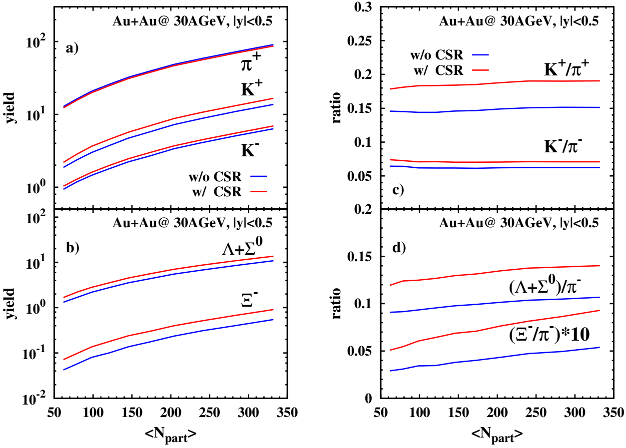
Sensitivity to the system size: p+A collisions

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 @ 30 AGeV



A. P. et al., nucl-th:1607.04073 (2016).

There is a **sizeable difference between** the results **with and without CSR**.

➜ Interesting to study experimentally!

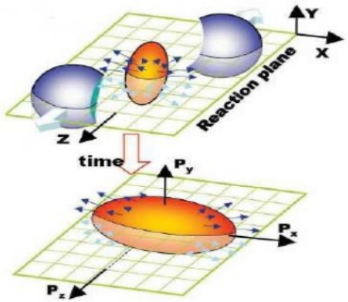
Directed flow v_1

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

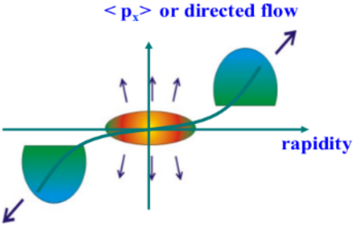
Pressure gradient

Spatial asymmetry

Asymmetry in momentum space

Collective transverse motion

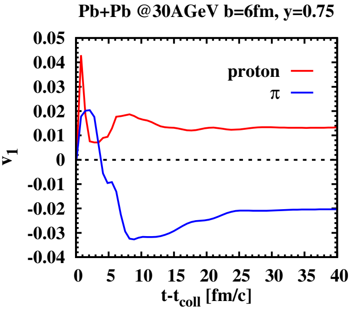
Directed flow v_1: slope F and time evolution



The directed flow is approximately linear at midrapidity:

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

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

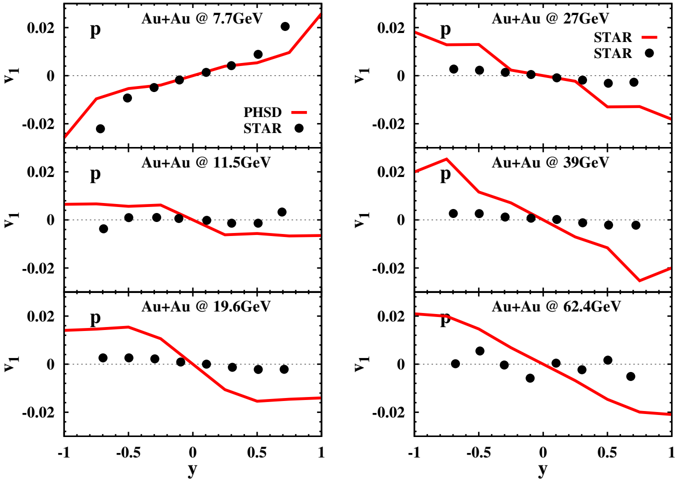


- **Protons**:
  v_1 is established in the early stage of the collision and marginally distorted during the evolution.
- **Pions**:
  mesons are sensitive to rescattering of hadrons; v_1 is positive at small values of time and becomes negative later on.

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

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

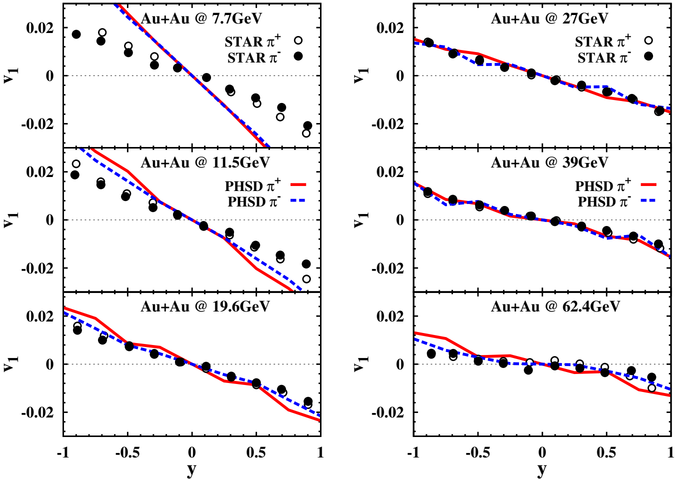


Data from: L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 112 (2014) 162301.

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

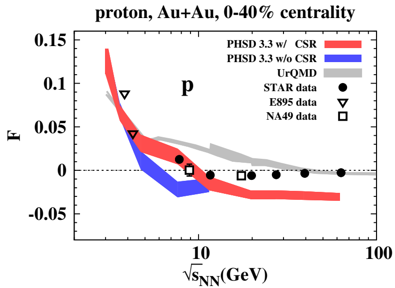
The pions are characterized by an **antiflow** behavior in the **whole investigated energy range**. The PHSD (CSR included) results are in good agreement with the data at high energies, while at small energies the PHSD antiflow is too large.

π

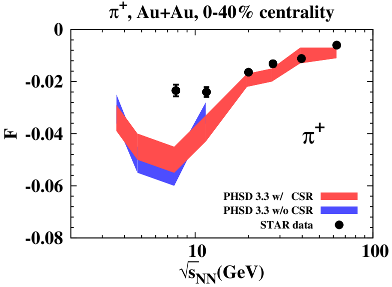


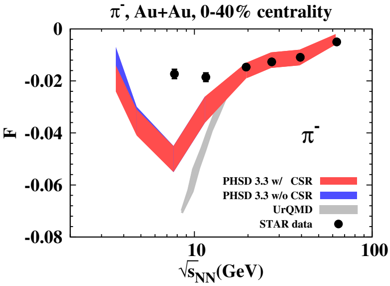
Data from: L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 112 (2014) 162301.

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 has an appreciable effect only on the F of the protons**: without CSR the slope becomes negative at smaller 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.

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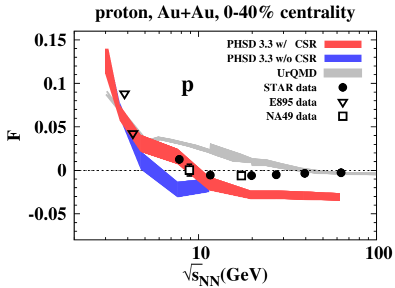
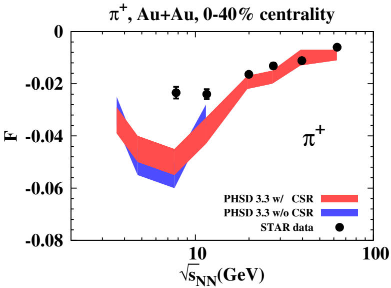
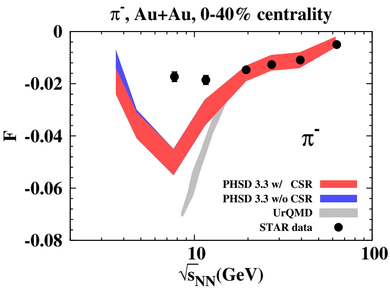


PHSD reproduces the trend of the data with some discrepancy for p at high energies and for π at small energies.





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Summary

- **Observables of CSR in HIC**
  - Particle abundances and rapidity spectra are suitable probes to extract information about CSR.
  - Transverse mass spectra are not so much sensitive to the CSR mechanism. The PHSD m_T-spectra are in good agreement with the data.
  - There is a moderate sensitivity on the hadronic EoS in our results, especially in the excitation functions of the strange to non-strange particle ratios.
  - The 'horn'-structure disappears in the K^+/π^+ ratio as the system size decreases, while it remains in the $(\Lambda + \Sigma^0)/\pi$ ratio.
  - The difference between our results with and without CSR remains sizable in a large range of centralities.
- **Directed flow**
  - CSR has a small effect only on the F of protons, the pion flow remains basically unchanged.
  - 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.

Looking forward for FAIR and NICA results!

Thank you for your attention!

PHSD group 2016

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Andrej Ilner

Giessen University
Wolfgang Cassing
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Alessia Palmese

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