(Anti-)strangeness production in heavy-ion collisions

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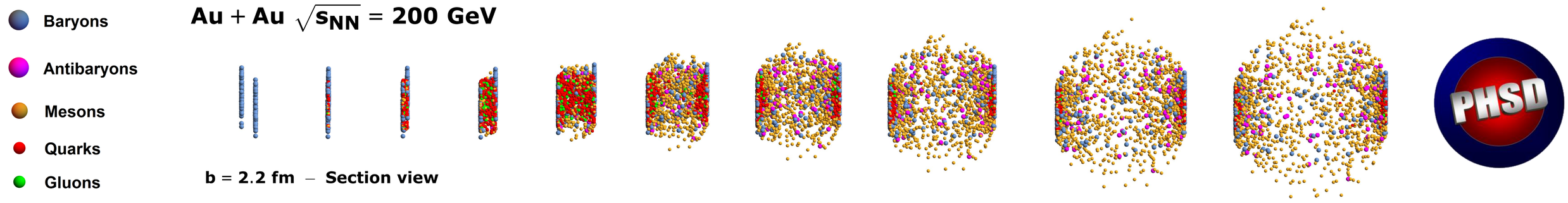
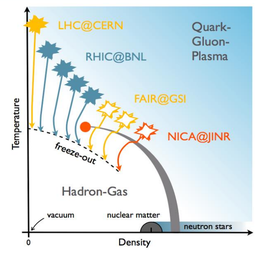


I - Motivations

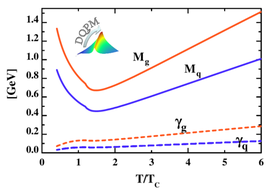
- The production of strangeness has been an important observable to probe the degrees-of-freedom in heavy-ion collisions.
  - The creation of a QGP would enhance the production of multi-(anti-)strange baryons which has been underestimated within hadron/string models (such as HSD or UrQMD).
  - Even considering the creation of a QGP phase, the strangeness enhancement seen experimentally at FAIR/NICA energies remains puzzling.

⇒ To this aim, an off-shell covariant transport approach – denoted as the **Parton-Hadron-String Dynamics (PHSD)** – has been developed to incorporate all necessary ingredients.



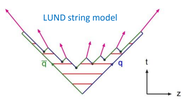
II - Description of the PHSD model

- PHSD is a covariant dynamical approach for strongly interacting systems:
  - The **off-shell transport equations** (on the basis of Kadanoff-Baym equations) in phase-space representation govern the time evolution of the system,

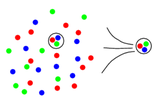


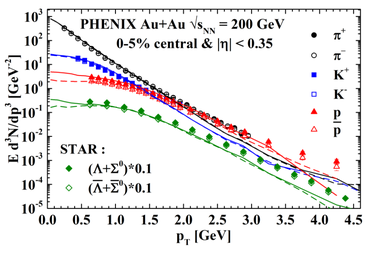
  - The **Dynamical-QuasiParticle Model (DQPM)** describes the QGP phase, interpreting the lQCD results from strongly interacting partonic quasiparticles with broad spectral functions.

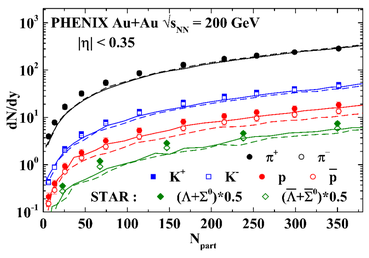
- Collision stages:



1) String formation in primary collisions – String decays to pre-hadrons,
2) If $\varepsilon > \varepsilon_c = 0.5\ \mathrm{GeV.fm}^{-3}$, the dissolution of new produced secondary hadrons into massive colored partons occurs,
3) Interactions between partons with properties defined by the DQPM,
4) Massive and off-shell (anti-)quarks hadronize to colorless off-shell mesons and baryons,
5) Hadron-string interactions.







III - Missing strangeness ?

Strangeness creation/exchange channels for strange baryons in PHSD:

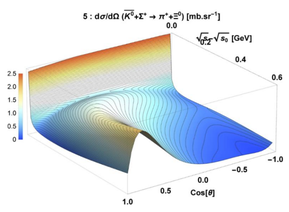
$\pi + N \leftrightarrow K + Y$
$N + N \leftrightarrow N + Y + K$
$N + \bar{K} \leftrightarrow Y + \pi$

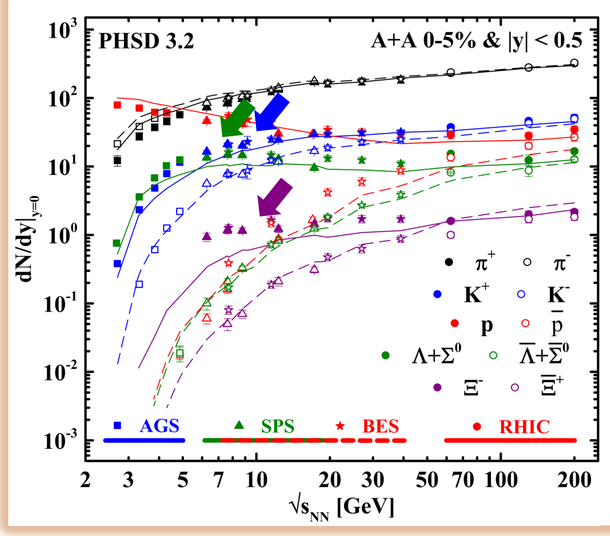
→

$Y + \bar{K} \leftrightarrow \Xi + \pi$
$Y + Y \leftrightarrow \Xi + N$

→

$\Xi + \bar{K} \leftrightarrow \Omega + \pi$
$\Xi + \Xi \leftrightarrow \Omega + Y$





- Underestimation of strange baryons at AGS-SPS energies, mainly produced by **hadronic processes**
- Reasonable agreement for anti-strange baryons dominantly produced in the **hadronization process from the QGP at y ≈ 0**
- Enhancement of strangeness at low energies **not traced back to deconfinement!**

IV - Aspects of chiral symmetry restoration in hadronic phase

- 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:

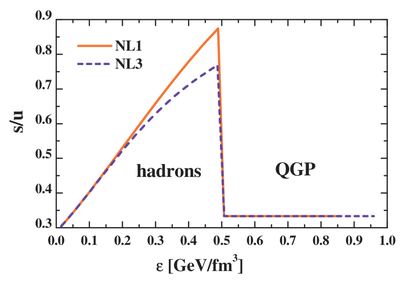
$$m_s^* = m_s^0 + (m_s^v - m_s^0)\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V} \qquad m_q^* = m_q^0 + (m_q^v - m_q^0)\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V}$$

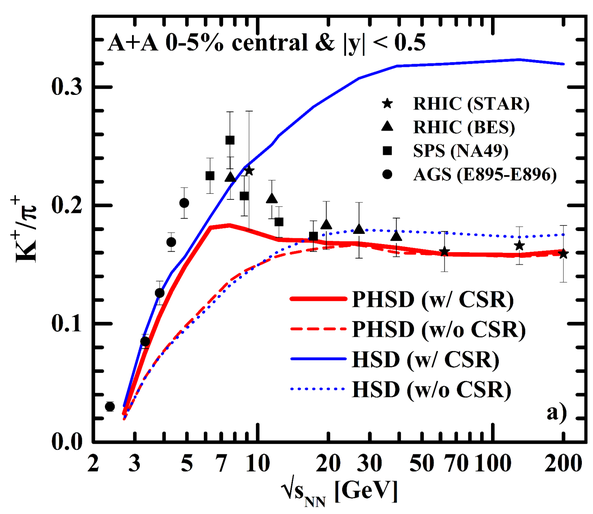
- The scalar quark condensate $\langle q\bar{q}\rangle$ is viewed as an **order parameter** for the **restoration of chiral symmetry** at high baryon density and temperature. It can be expressed by the following formula:

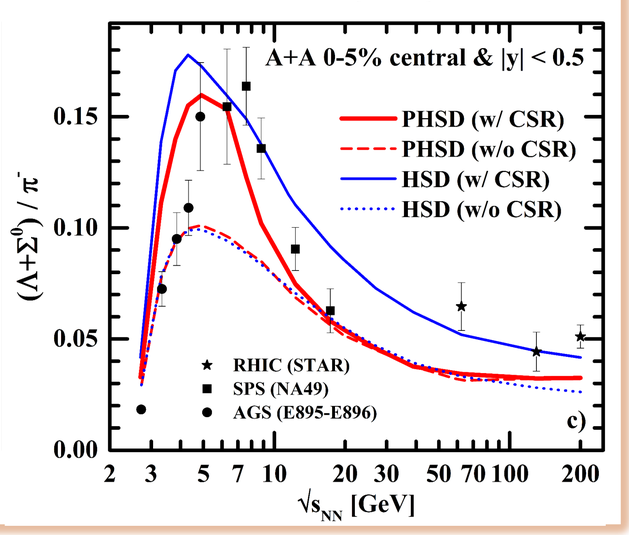
$$\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V} = 1 - \frac{\Sigma_\pi}{f_\pi^2 m_\pi^2}\rho_S - \sum_h \frac{\sigma_h \rho_S^h}{f_\pi^2 m_\pi^2}$$

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

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







V - Conclusion / outlook

- An **underestimation of strangeness** production at low $\sqrt{s_{NN}}$ is seen in the meson/baryon sector, whereas the multistrange baryon/antibaryon dynamics at the top SPS and RHIC energy are rather well described by hadronization from the QGP at $y \approx 0$.
- This finding implies that the strangeness enhancement seen experimentally at FAIR/NICA energies cannot be attributed to a deconfinement phase transition but probably involves the approximate **restoration of chiral symmetry in the hadronic phase**.
- Including this feature, we observe a **rise in the K^+/π^+ ratio** at low bombarding energies and then a drop since there is no longer hadronic string decay in the partonic medium created at higher energies.

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HIC for FAIR Helmholtz International Center
HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research
GOETHE UNIVERSITÄT FRANKFURT AM MAIN
FIAS Frankfurt Institute for Advanced Studies
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN