PROCEEDINGS OF SCIENCE

The soup that is not too hot

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The exploration of the QCD phase diagram is the goal of many experiments in the world. The low net baryon density region is relatively well studied, while the one corresponding to higher net densities still contains multiple unrevealed puzzles getting significant attention. In multiple experimental complexes such as STAR or HADES, heavy ions collide at relatively lower energies than those obtained at LHC, creating "not the hottest soup" of nuclear matter. The examination of it provides unique insights into understanding the properties of matter production and its transitions. In this paper, several of the significant experimental discoveries are reviewed.

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1. Introduction

Studies of the properties of strongly interacting matter are the goals of many experiments worldwide. The investigation of the so-called "hottest soup" - Quark-Gluon Plasma (QGP) - attracted nearly the full attention of heavy-ion physicists. Recently, the relatively colder and "denser" regions of the QCD phase diagram (shown in Fig. 1a) gained the interest of the community, still having many unsolved puzzles such as transitions between partonic and hadronic states or the description of Neutron Stars (NS) and Neutron Star Mergers (NSM) Equation of State (EoS). This paper briefly summarizes the most vital experimental discoveries in that region of the diagram.

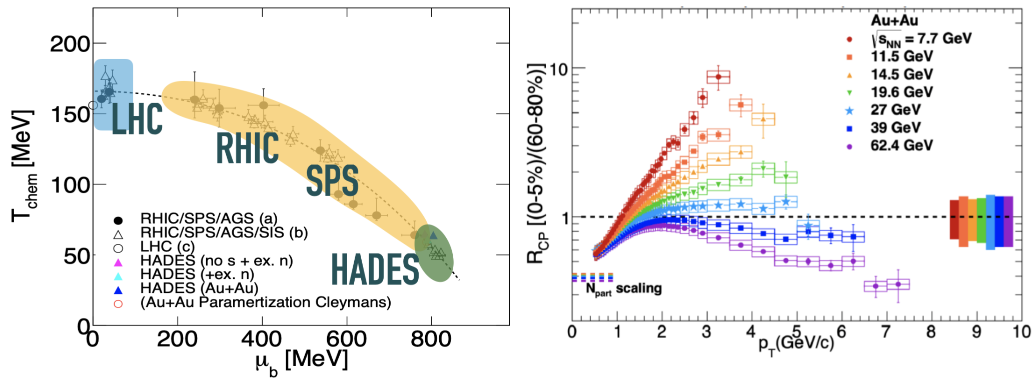

Figure 1: a) QCD phase diagram, with depicted regions of T and μ_B corresponding to these properties of the matter created at given experiments and facilities. b) Charged hadron R_{cp} for RHIC BES energies [1].

2. Onset of QGP

Nuclear modification factor: The non-monotonic collision energy dependence of the nuclear modification factor R_{cp} is one of the possible signatures of the disappearance of the partonic degrees of freedom. It is described with the following equation:

$$R_{CP} = \frac{\langle N_{bin}^{per} \rangle d^3 N_{AA}^{cen} / d\eta d^2 p_T}{\langle N_{bin}^{cen} \rangle d^3 N_{AA}^{per} / d\eta d^2 p_T} \tag{1}$$

The most peripheral AA collisions are expected to mimic the NN collisions and are used in the following studies due to the lack of data for proton-proton collisions at such a big range of collision energies. When the values of R_{CP} are lower than unity, the matter expansion is suppressed. The opacity of the partonic deconfined medium explains it. On the other hand, the enhanced R_{CP} is expected to be the effect of the domination of the hadronic interactions. The results obtained at the STAR experiment [1] are shown in the Fig. 1b. The clear collision energy dependence is visible. The suppression of R_{CP} is treated as a signature of the presence of the QGP phase for the higher energies.

Kink, horn, step: In [2] the authors suggested that measurements of entropy, strangeness, and temperature of the system as the function of Fermi energy are vital for the investigation of the onset of QGP. The changes in slopes of the three quantities are explained as the activation of the

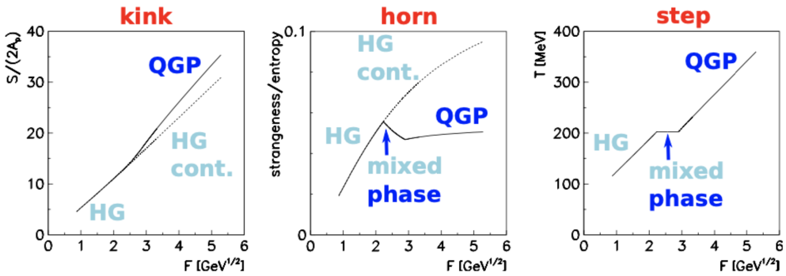

Figure 2: The kink, horn, and step structure proposed in [2] with depicted expected phases: HG - hadronic gas, QGP, and mixed phase.

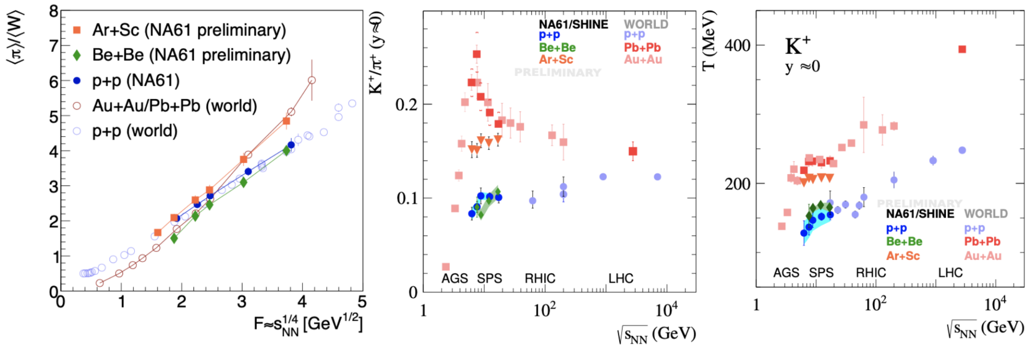

Figure 3: Energy dependence of: (from left) the total π multiplicity divided by the number of wounded nucleons W, K^+ to π^+ multiplicity ratio and temperature extracted form K p_T spectra [3].

partonic degrees of freedom, which is sketched in Fig. 2. The NA61/SHINE collaboration used pion production as a proxy for the entropy, charged kaons to pions ratio to stand for strangness to entropy, and finally, the temperature extracted from the inverse slope parameter of transverse mass spectra. Obtained results (see Fig. 3) are in remarkable agreement with the theoretical predictions. The slope changes are present for the AA collisions, while, in the case of p+p, where the QGP phase is not expected, are negligible.

3. First order phase transition

Directed flow of protons (v_1) is sensitive to the early stage of the collision and the compression of the medium. The v_1 slope as function of rapidity for all the hadrons does not change with the energy of the collision, except of protons [4]. A system undergoing a 1^{st} order phase transition characterized by the small pressure gradient due to mixed phase formation causes the change of sign in the slope of dv_1/dy for net baryons and/or due to softening of the EoS [5]. STAR performed the detailed measurements of v_1 for various collision energies and the non-monotonic trends are visible (Fig. 4a). It is treated as a signature of the first order phase transition and justified additionally by the lack of agreement with the UrQMD simulations [6], where the transition is not included.

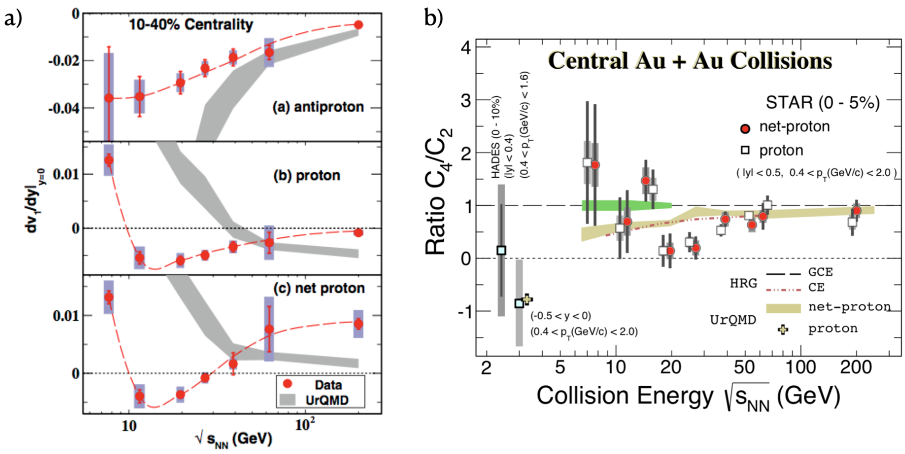

Figure 4: a)Directed flow slope dv_1/dy of net-protons near midrapidity versus beam energy for intermediate-centrality (10 – 40%) Au+Au collisions: STAR experiment data and UrQMD simulation. [4]b) Collision energy dependence of the ratios of cumulants, C_4/C_2, for proton (squares) and net-proton (red circles) from various experiments [7].

4. Critical Point

Fluctuations of net-baryon distributions: The non-monotonic behavior in the event-by-event fluctuations of globally conserved quantities is treated as one of the signatures of the presence of the Critical Point (CP) [8, 9]. The higher the cumulant order, the more sensitive it is to the correlation length. 4^{th} order is predicted to have a non-monotonic energy dependence due to the contribution from the CP. The observed C_4/C_2 suppression in [7] consistent with fluctuations driven by baryon number conservation indicates the domination of hadronic interaction - visible for lower $\sqrt{s_{NN}}$ in Fig. 4b.

5. Neutron stars and neutron star mergers

Virtual photons: Moving further on the phase diagram towards the higher baryon densities and lower temperatures, there is a region corresponding to NSs ($T < 10$ MeV, $\rho < 10\rho_0$[1],) and NSMs ($T < 50$ MeV, $\rho < 2 - 6\rho_0$). Systems with similar properties (T : 80 – 100 MeV, $\rho < 2 - 3\rho_0$) can be created in the HADES experiment, which can serve as a reference for the astrophysical research of NS and NSM. The production of virtual photons, which are expected to be created during the whole evolution of the system can provide information about the temperature of the system and consequently contribute to the process of EoS determination. In Fig. 5a, HADES used the reconstructed e^+e^- mass distribution as a manifestation of virtual photons [10]. The obtained excess radiation (Fig. 5b) shows nearly-exponential fall-off. The extracted temperature of the system's evolution is equal to $T = 71.8 \pm 2.1$ MeV/k_B, while theoretical models predict the $T = 50 - 80$ MeV for post-merger NS around the dense remnant core.

[1] $\rho_0 \approx 0.16 fm^{-3}$ - density of nuclear matter

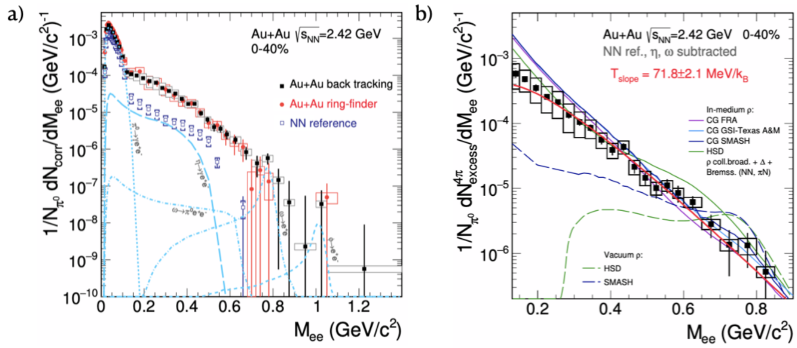

Figure 5: a) Reconstructed e^+e^- mass invariant distribution from Au+Au collisions and expected contributions from mesonic decays. b) Acceptance corrected dilepton excess yield [10].

6. Conclusions

Many observables were investigated, providing an excellent reference for the theoretical studies of properties of the strongly interacting matter and its transitions. The impressive spectrum of data collected by STAR, NA61/SHINE, and HADES experiments is still under investigation, possibly leading to ground-breaking discoveries and establishing the EoS valid for the wide range of QCD phase diagram.

7. Acknowledgments

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