International Journal of Modern Physics A

Recent highlights from the STAR experiment at RHIC

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These proceedings present findings from selected topics of the STAR experiment at RHIC, aimed to provide insights into the dynamics and characteristics of the medium produced in heavy-ion collisions. The proceedings consist of experimental measurements from the Beam Energy Scan (BES) program, including the Fixed-Target (FXT) program, focusing on particle production and thermal properties, as well as exploring the initial states of heavy-ion collisions (nuclear structure) and collective flow. Furthermore, the proceedings include experimental results from the BES related to the search for the QCD Critical Point (CP).

Keywords: STAR experiment at RHIC, Heavy-ion collisions, Quark-Gluon Plasma

PACS numbers: 25.75.Dw, 25.75.Ld, 25.75.Nq

1. STAR experiment at RHIC

Quantum Chromodynamics (QCD) predicts a transition from confined hadronic matter to a deconfined state known as Quark-Gluon Plasma (QGP), where quarks and gluons can move freely.[1] The Solenoidal Tracker at RHIC (STAR) experiment at the Relativistic Heavy Ion Collider (RHIC) plays a vital role in studying QGP properties through heavy-ion collisions. RHIC is a highly versatile collider, capable of colliding various nuclear species (U, Au, Ru, Zr, Cu, Al, O, ^{3}He and d) and protons, at energies between $\sqrt{s_{NN}} = 7.7$ GeV and 200 GeV in collider mode, and from 3.0 to 7.7 GeV in fixed-target mode.[2] The STAR experiment has collected significant data to probe QCD phase transitions, including particle momentum distributions, collective flow and thermal properties. These findings help characterize the phases of QCD and elucidate the properties of QGP.

Figure 1 shows the RHIC average luminosity at various collision species and beam energies from the year 2000 to 2021.

2. Collective phenomena and electromagnetic field effects

Collective flow refers to the azimuthal anisotropy of produced particles with respect to the collision symmetry plane. It is quantified by the Fourier decomposition of the azimuthal angle distribution of produced particles relative to the event plane angle (Ψ_n).[3] The flow coefficients, known as directed flow (v_1), elliptic flow (v_2), and triangular flow (v_3), are extensively used to study the QGP properties.

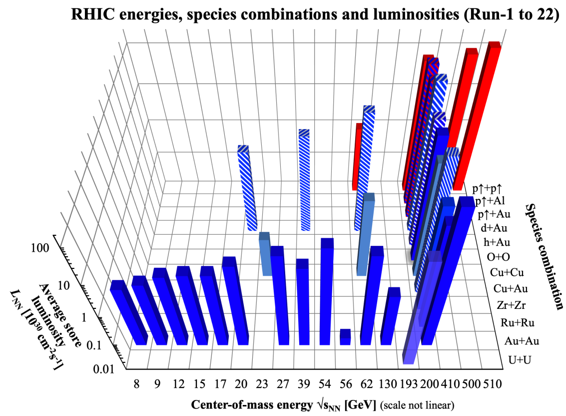

Fig. 1. RHIC average luminosity at various beam species as a function of center of mass energy from Run 1 to Run 22.

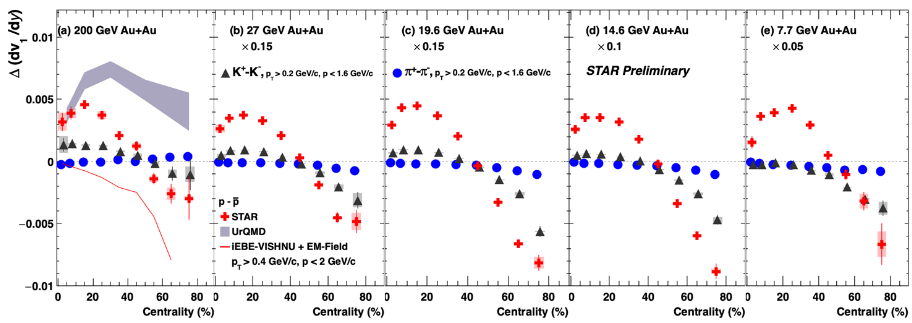

Fig. 2. The $\Delta(dv_1/dy)$ between particles and antiparticles as a function of centrality in Au+Au collisions at $\sqrt{s_{NN}} = 200$ to 7.7 GeV from the STAR experiment at RHIC.[5] Comparison with the UrQMD and iEBE-VISHNU model calculations for protons are also shown at $\sqrt{s_{NN}} = 200$ GeV.

The STAR experiment has studied the possible effects of the electromagnetic (EM) field in heavy-ion collisions by measuring directed flow. The slope difference in directed flow, denoted as $\Delta(dv_1/dy)$, between positively and negatively charged particles can indicate these EM-field effects.[4] Model predictions suggest that the Hall effect should produce a positive $\Delta(dv_1/dy)$, while the Faraday and Coulomb effects should lead to negative values. Additionally, the transported quark effect may cause a positive $\Delta(dv_1/dy)$ for protons and kaons, but a negative one for pions. Measurements from Au+Au collisions show a change in slope difference from central to peripheral events. Specifically, the negative $\Delta(dv_1/dy)$ in peripheral collisions aligns with expectations from the Faraday and Coulomb effects, while central collisions display a positive $\Delta(dv_1/dy)$ for protons, indicating contributions from transported quarks.[5]

The observation of large positive values and constituent quark (NCQ) scaling of v_2 indicates the formation of a hydrodynamically expanding medium composed of partonic degrees of freedom. Positive v_2 values for identified hadrons at mid-rapidity have been recorded from $\sqrt{s_{NN}} = 200$ down to 4.5 GeV at the RHIC.[6] Figure 3 illustrates v_2 as a function of transverse kinetic energy normalized by the number of constituent quarks for identified hadrons in 10-40% central Au+Au collisions. Notably, below $\sqrt{s_{NN}} \leq 3.2$ GeV, the negative v_2 values and the deviation from NCQ scaling is observed. This indicate a shift from a medium dominated by partonic to one dominated by hadronic degrees of freedom.

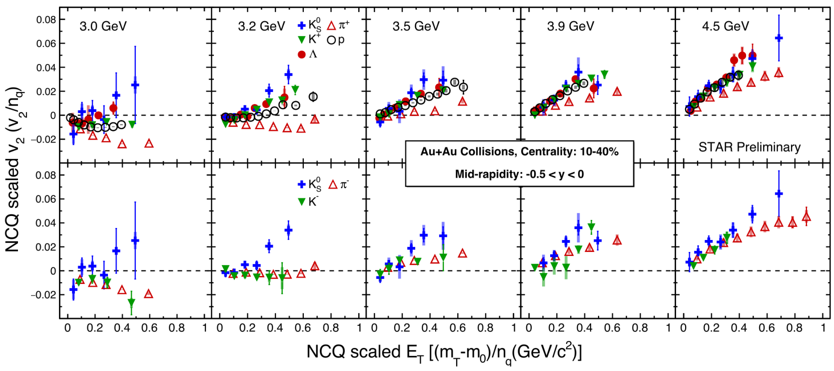

Fig. 3. NCQ scaled v_2 as function of NCQ scaled transverse kinetic energy for identified hadrons in 10-40% central Au+Au collisions at mid-rapidity from $\sqrt{s_{NN}} = 3.0$ to 4.5 GeV from the STAR experiment at RHIC.

3. QCD phase transition and freeze-out

To gain insights into the QCD phase transition, we measure particle spectra at various beam energies. By using thermal models, we can extract the freeze-out temperature, collective velocity, baryon chemical potential (μ_B), and strangeness chemical potential (μ_S) for each beam energy from the measured p_T-spectra. This information is crucial for exploring the QCD phase diagram across different μ_B, as it reflects the equation of state (EoS) of the fireball and helps characterize the phase transition. The STAR experiment at RHIC has measured p_T-spectra for identified particles during the BES and FXT program at beam energies from $\sqrt{s_{NN}} = 200$ to 3 GeV. Figure 4 shows the kinetic freeze-out temperature (T_{kin}) at similar collective velocities ($\langle\beta_T\rangle$) at $\sqrt{s_{NN}} = 3$ GeV are lower than those at higher energies ranging from $\sqrt{s_{NN}}$ =7.7 to 200 GeV. This suggests a different EoS, indicating that the medium at lower energies is more influenced by baryonic interactions than by quarks and gluons.[7]

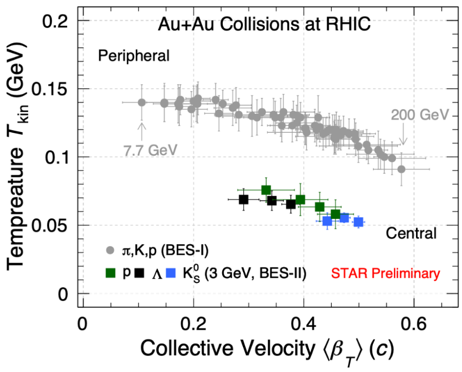

Fig. 4. Kinetic freeze-out temperature versus collective velocity for identified hadrons in Au+Au collisions at mid-rapidity from $\sqrt{s_{NN}} = 3.0$ to 200 GeV from the STAR experiment at RHIC.

3.1. *Insights on nuclear structure through collective effects*

The nuclear structure affects final state observables through collective effects. The STAR experiment collected data in 2018 on isobar nuclei ($^{96}_{44}$Ru and $^{96}_{40}$Zr), which have the same atomic mass but different atomic numbers and deformation parameters. Analyzing the ratios of quantities from isobar collisions can enhance our understanding of nuclear structure. Collective flow is sensitive to initial conditions such as overlap geometry, nuclear size, and deformation. Additionally, studying the flow of strange hadrons provides insights into initial state anisotropies due to their lower hadronic interaction cross-section compared to light hadrons.

Figure 5 shows v_2 of strange hadrons for $|y| < 1.0$ and $0.2 < p_T < 10$ GeV/c, as a function of centrality in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV. The bottom panels show the ratio of v_2 for Ru and Zr, fitted with a constant polynomial function for mid-central collisions (20-50%). A deviation of approximately 2% from unity, with a significance of 6.25σ for Λ and 1.83σ for K^0_s, indicates differences in the nuclear structures of the two isobar nuclei.[8]

4. Search for Critical phenomena

The QCD phase transition can be analyzed through the cumulants of net-particle distributions and their ratios, which are linked to susceptibilities. Higher-order cumulants, particularly net-proton kurtosis, are valuable for probing the QCD phase transition since protons serve as a reliable proxy for baryons. The BES program at RHIC focuses on searching for signals of a first-order phase transition and the critical point during the transition from hadronic matter to QGP. Measurements of net-proton cumulants in Au+Au collisions during the BES-I have shown a non-monotonic trend in kurtosis times variance with collision energy. As energy changes, the system can enter different states, which affects the distribution of net protons. The observed non-monotonic behavior may suggest a phase transition and critical fluctuations linked to a first-order phase transition, where small changes in energy

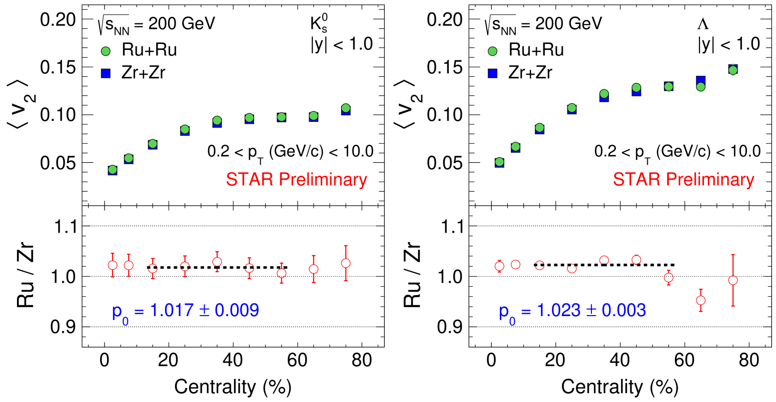

Fig. 5. Integrated elliptic flow ($\langle v_2 \rangle$) as a function centrality (%) for K_s^0 and Λ at mid-rapidity ($|y| < 1.0$) in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV from the STAR experiment at RHIC. The bottom panels show ratio of $\langle v_2 \rangle$ between Ru and Zr, fitted with a constant polynomial function.

can lead to significant changes in the system's properties. Recent measurements at $\sqrt{s_{NN}}$ = 3 GeV, indicate that baryon number conservation significantly impacts the net-proton kurtosis times variance at this energy.[10]

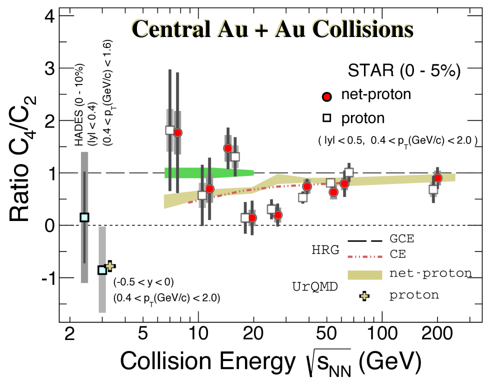

Fig. 6. The ratio of cumulants, C_4/C_2, for proton and net-proton, as a function of beam energy in 0–5% central Au+Au collisions at RHIC. Comparison with the results from HADES experiment and models (HRG and UrQMD) are also shown.[10]

5. Summary

In summary, results from the STAR experiment at RHIC on collective phenomena, QCD phase transition, and critical phenomena from the BES and FXT program are presented. These results include directed and elliptic flow of identified hadrons, freeze-out properties, and ratio of cumulants of proton and net-proton distributions.

Results for charge-dependent v_1 is consistent with expectations from the dominance of the Faraday and Coulomb effect in peripheral collisions. Absence of NCQ scaling of v_2 at $\sqrt{s_{NN}} \leq 3.2$ GeV indicates baryonic interactions dominate the nuclear EoS. Moreover, findings from the data collected on Isobars collisions, indicate that it is possible to explore nuclear structure in high-energy heavy-ion collisions. The BES program at RHIC aims to search for the first-order phase transition and the critical point between hadronic matter and quark-gluon plasma, through net-particle distribution cumulants and their ratios. The data from the STAR experiment in Au+Au collisions reveal a non-monotonic trend in kurtosis times variance with collision energy, with the measurements at $\sqrt{s_{NN}} = 3$ GeV being consistent with calculations from hadronic transport model UrQMD.

STAR is currently analyzing the extensive BES-II data set and high-energy collisions involving Au+Au, isobars, and O+O. The forward upgrade, introduced in run 22, enables STAR to conduct precision forward physics research. With the upgraded detector, STAR is prepared to collect high statistics data on Au+Au, p+p, and p+Au in the current RHIC run.

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