Highlights from the STAR experiment[*]

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Despite the challenges of pandemic the years 2020-21 were quite successful for STAR. We completed the Beam Energy Scan program phase 2 and installed the forward upgrade with which STAR finished data-taking for polarized p+p collisions at 510 GeV. In this contribution, we discuss STAR results on five different topics that were presented in twenty one parallel talks, forty-seven posters, and two flash talks at the Quark Matter 2022 conference.

1. Isobar collisions and strong field effects

An important program at STAR since the previous Quark Matter has been the blind analysis of isobar data at $\sqrt{s_{NN}} = 200$ GeV [1] to search for the chiral magnetic effect (CME). Isobars were collided to utilize the fact that Ru+Ru collisions produce larger magnetic fields than the Zr+Zr collisions. Therefore, the ratio of the CME-sensitive observables in Ru+Ru over Zr+Zr has to be greater than unity in the presence of CME. The run was specially designed to reduce the systematics in the ratio by alternating two species. This provides the best possible control of signal and background compared to all previous experiments for the search for CME. A precision in the measurements down to 0.4% was achieved in the blind analysis of the isobar data, and no predefined signatures of CME were observed. At this Quark Matter, we present important progress toward estimating the background expectations by incorporating the multiplicity difference between the two isobars and the non-flow effects [2].

In STAR we continue to search for the electromagnetic (EM) field driven effects. The consequence of the Faraday and Hall effects have been predicted to lead to differences in the slope of directed flow ($d\Delta v_1/dy$) with rapidity between positive and negative particles. Our measurements in Au+Au and isobar collisions for protons and anti-protons show a difference in slope that changes sign from central to peripheral events. In another measurement

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the v_1 slope difference is studied with respect to various values of electric charge difference between combinations of hadrons that are made up of only produced quarks. We see significant splitting with stronger strength in Au+Au collisions at $\sqrt{s_{NN}} = 27$ GeV compared to 200 GeV. These observations of splitting of v_1 slope cannot be explained by baryon transport. Model studies to interpret these results in the context of EM-field driven effects are highly anticipated [3].

Similar to strong EM fields, the presence of strong vortical fields is studied via measurements of the global polarization of Λ hyperons as a function of collision energy. Recently, we have extended our measurements to fixed target 3 GeV for Λ, fixed target 7.2 GeV for Λ, and to 19.6 GeV for $\Lambda + \bar{\Lambda}$. Our new measurements with high statistics data at 200 GeV for Au+Au and isobar collisions for Λ and $\bar{\Lambda}$ enable us to test three following predictions. We do not see a splitting between Λ and $\bar{\Lambda}$ polarization due the opposite sign of their magnetic moment. For either Λ or $\bar{\Lambda}$ we do not see a difference in the magnitude of global polarization due to the B-field difference between Ru+Ru and Zr+Zr collisions. Finally, we do not see any significant system size dependence while going from the larger size of the Au+Au to isobars at a given centrality [4].

A similar kind of effect is the spin alignment of vector mesons. The quantity of interest is the spin alignment coefficient (ρ_{00}) as a function of collision energy. For the ϕ-mesons we see almost 8.4σ deviation from the baseline of 1/3; the K^{*0} results are consistent with 1/3 in Au+Au collisions in the range of $\sqrt{s} = 7.7 - 200$ GeV. An outstanding question is what causes this vector meson spin alignment. For our measurement, we see a model that includes a very strong vector meson field of the order of m_π^2 can provide an explanation for ϕ-mesons. What about the K^{*0}? For that we perform new measurements of charged and neutral K^{*0} in isobar collisions to gain more insights [5].

As an another way to study the strong field effects, we try to test if the very early EM-field difference between the two isobars is reflected in the low p_T photon induced processes. The first process of interest is $\gamma + \gamma \rightarrow e^+ + e^-$, also known as the Breit-Wheeler process. The cross section of this process is expected to go as $\sigma \sim Z^4$, where Z is the atomic number of the nucleus emitting the soft photon. So, if we measure it in Ru+Ru over Zr+Zr collisions we expect to see a $(44/40)^4$ scaling. We perform measurements of the ratio of the $e^+ + e^-$ yields in Ru+Ru over Zr+Zr collisions as a function of p_T in $40 - 80\%$ centrality. At the lowest p_T we see above 3σ deviation of the yield ratio from unity and a value that is close to the expectation of $(44/40)^4$ scaling and QED predictions. A similar process is the photoproduction of J/ψ, which is expected to follow a Z^2 scaling. For that measurement we also see some hints of deviations for the yield ratio from unity in the direction of the Z^2 scaling. Therefore, isobar data suggest that low p_T photon induced processes follow "Z" scaling, consistent with the EM-field difference between the isobar collision systems [6].

The photon induced processes can also be used to constrain the nuclear charge and the mass radius in a novel way. The commonly used Woods-Saxon parameterization to characterize the spatial distribution of nucleons inside colliding nuclei includes parameters such as the charge radius and the skin depth. In modelling of heavy-ion collisions we normally use fixed values of such parameters extracted from low energy electron scattering data. Measuring the $\gamma + \gamma \rightarrow e^+ + e^-$ process, we have a novel way to constrain the combination of skin depth and the charge radius. On the other hand, using the diffractive vector meson production through the $\gamma + A \rightarrow \rho^0$ process, it is possible to constrain the strong interaction or the gluonic radius of the gold and uranium nuclei [6].

2. New insights on collective effects

The nuclear structure leaves imprints in the final observables through collective effects. Nuclear parameters, particularly the neutron skin and deformation, can be constrained through measurements of the ratio of various quantities in isobar collisions. Our measurements of the ratio of multiplicity distribution as well as the net-charge density at midrapidity in Ru+Ru over Zr+Zr collisions indicate that Zr nucleus has a thicker neutron skin than that of Ru nucleus. The measurements of the ratio of v_2, v_3, and transverse momentum fluctuations deviate from unity in central collisions in a significant way. These measurements indicate that Ru has a larger quadruple deformation (β_2) than Zr, while Zr has larger octuple deformation (β_3) than Ru. These studies in isobar collisions have pioneered new ways of constraining nuclear deformation parameters [7].

Nuclear deformation can also be constrained by another observable, which is known as the Pearson coefficient between flow harmonics v_n and mean transverse momentum $[p_T]$: $\rho(v_2^2, [p_T])$. This observable measures the correlation between shape and size of the fireball. The measurements of $\rho(v_2^2, [p_T])$ as a function of centrality in U+U collisions change sign from positive to negative values in central collisions indicating a highly deformed shape of uranium nucleus. In Au+Au collisions no sign change is observed indicating very little deformation. The measurements of $\rho(v_3^2, [p_T])$ also stay positive at all centralities and serve as a data-driven baseline. In order to investigate if the observable $\rho(v_2^2, [p_T])$ is sensitive to the lifetime and the nature of the hydrodynamic evolution of the system, we extend our measurements with Beam Energy Scan phase two (BES-II) data. Another measurement we perform with the BES-II data is the de-correlation of the event planes with pseudorapidity. The measurement indicates that the third order event plane decorrelates a lot more (40%) compared to the second order event plane (10%) over one unit of pseudorapidity around midrapidity. These measurements provide important insights on the longitudinal dynamics and three dimensional modeling of heavy-ion collisions [8].

At this Quark Matter, we present the observation of a new phenomenon which indicates that the triangular flow can drive local polarization of hyperons. Previously, the polarization of hyperons in the longitudinal direction due to the elliptic flow was observed. The origin of such a phenomenon led to puzzles in terms of explaining the periodic sign change of polarization with respect to the reaction plane. Our observation of a similar effect of local polarization driven by the triangular flow might shed some light on this puzzle and bring more insights into our understanding of the thermal vorticity [4].

3. Prerequisites for phase transitions and freeze-out

In STAR we perform measurements to gain insights on what happens before and after the QCD phase transitions in the medium formed in relativistic heavy-ion collisions. The mechanism of baryon stopping provides the necessary prerequisite for QCD phase transition and enables us to scan the phase diagram in varying baryon chemical potential. To understand baryon stopping we perform measurements of proton density with respect to the center of mass rapidity in Au+Au collisions in fixed target (FXT) mode at $\sqrt{s_{NN}} = 3$ GeV. An interesting observation is that the shape of the distribution changes while going from central to peripheral events. Since previous SPS measurements in this kinematics were performed only in central events, STAR's measurements provide an opportunity to study the mechanism of stopping with centrality in the largely unexplored regime of high baryon density [9].

We also study baryon stopping in photonuclear processes in which one of the colliding object is baryon-free. We use peripheral Au+Au collisions as a baseline. An interesting observation is that the double ratio of antiproton over proton yield in photonuclear over peripheral events is below unity and has a very strong rapidity dependence. The baryon stopping measured by the double ratio increases towards the rapidity direction of the target ion. These results can not be reproduced by PYTHIA simulations and help gain insights on the microscopic origin of baryon stopping. It has also the potential to shed light on fundamental questions such as what exactly carries the baryon number, is it quarks or non-perturbative objects like baryon junctions [10].

Another conserved quantity of importance in the context of QCD transition is strangeness. We perform measurements of the yields of ϕ meson and compare them to non-resonance particles such as K^- and Ξ in Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV. These results can constrain the strangeness correlation length in a canonical ensemble. In order to understand how strange hadrons survive freeze out we perform measurement of the yields of K^{*0} relative to K mesons using the BES-I data. We compare the results to the ratio of yields for ϕ meson over K as a baseline. When the yield ratios are plotted against $N_{\mathrm{ch}}^{1/3}$, a proxy for volume, K^{0*}/K decreases exponentially towards the central event. But for the ϕ/K no such trend is observed. This observation could be understood by the fact that K^{0*} may be lost in the medium due to the re-scattering because of its shorter lifetime, but longer lifetime of ϕ mesons can keep them unaffected. It turns out these results can be utilized to extract the lower limit of the hadronic phase lifetime [11].

To know more about the late time dynamics of freeze-out and interactions between nucleons and hyperons we perform measurements of the yields of hyper-nuclei and nuclei. High statistics BES-II data allow precision hyper-nuclei yield and lifetime measurements. For the first time we measure the lifetime of hyper-helium-4 in heavy-ion collisions. Our measurements of the relative yields of hyper-triton and hyper-hydrogen-4 indicate the possible formation of excited hyper-nuclei states in heavy-ion collisions. At this conference we report the first observation of anti-hyper-hydrogen-4. This particular hyper-nucleus is made of two anti-neutrons, one proton, and one anti-lambda; it decays to an anti-helium-4 and a π^+ [12].

We perform measurement of the yields of proton and light nuclei in Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV. We fit the measurement of p_T spectra using a cylindrical blast-wave model and extract the kinetic freeze-out parameters such as the effective kinetic freeze-out temperature T_{kin} and the collective velocity β_T. An important observation is that deuterons freeze out at a higher effective kinetic temperature than protons [13].

To understand more about deuteron production we perform femtoscopic measurements. We study deuteron-deuteron correlation functions for different centralities, which can be well explained by a coalescence model. To investigate whether a deuteron is really formed through coalescence of a proton and a neutron, we perform measurements of the Pearson coefficients between the number of protons and deuterons as a function of the collision energy. We see a negative Pearson coefficient. The measurement is explained by models that include baryon number conservation and coalescence. A general conclusion is that a coalescence between a proton and a neutron provides a consistent explanation of deuteron formation at RHIC [14, 15].

4. Critical phenomena and mapping of QCD phase diagram

We continue the search for the QCD critical point (CP) by studying the net-proton higher order cumulants as a function of collision energy. The measurements with the BES-I data have established a non-monotonic trend of kurtosis times variance with collision energy. The most recent addition to extend the CP search is the measurements in Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV. The results of net-proton kurtosis times variance at this energy indicate that the measurement is dominated by baryon number conservation. We also perform the measurements of the higher moments of deuteron number fluctuations as a function of collision energy. The kurtosis times variance for deuterons is found to be below unity over the energy range of $\sqrt{s_{NN}} = 7.7 - 200$ GeV, but no non-monotonicity is observed. The outstanding question is why there is a difference between the measurements of proton and deuteron fluctuations. In this context, the connection to the smaller yields of deuterons and different freeze-out parameters that were seen from the other measurements are being investigated [15, 16].

Another topic of prime interest is the search for chiral crossover that is predicted to happen at low baryon chemical potential (μ_B). For this we perform measurements of fifth (C_5) and sixth (C_6) order cumulants of net-protons and the ratios such as C_5/C_1 and C_6/C_2 at the top RHIC energy. Our measurements performed as a function of hadron multiplicity at mid-rapidity in $p + p$, isobar, and Au+Au collisions show that these ratios decrease with increasing multiplicity and eventually approach the predictions from lattice QCD, which also predicts a smooth crossover at $\mu_B = 0$ [17].

Another measurement from STAR that is compared to lattice QCD predictions uses the dilepton as a thermometer of the medium. Using the data from Au+Au collisions at $\sqrt{s_{NN}} = 27$ and 54.4 GeV we measure the excess yield of dileptons over the cocktail as a function of the invariant mass. We fit the data at the low-mass ($m_{ll} < 1$ GeV) and intermediate-mass ($1 < m_{ll} < 3$ GeV) regions to extract the medium temperature. When shown on a temperature (T) versus μ_B plot, the values of effective temperature extracted by the low-mass region T_{LMR} are very close to the chiral crossover band that is predicted by the lattice QCD. This is indicative of ρ mediated dilepton emissions dominating near the chiral crossover transition. The extracted T_{IMR} values (≈ 300 MeV) are much higher than T_{LMR}. This indicates the intermediate-mass dilepton spectrum probes the temperature of the QGP medium. This is the first blue-shift free measurement of QGP temperature at RHIC.

5. Hard probes

Another well known indicator of the QGP temperature, categorized as a hard probe, is quarkonium. In this context, we perform measurements of nuclear modification factor R_{AA} of J/ψ in isobar collisons at $\sqrt{s_{NN}} = 200$ GeV, and also in Au+Au collisions at $\sqrt{s_{NN}} = 54.4$ GeV. At a given number of participants (N_{part}), no significant difference is observed between different systems and energies. The values of R_{AA} at both energies, in central events, are significantly below unity, unlike what was observed at the LHC. This indicates that the RHIC measurements are consistent with the dominance of J/ψ dissociation. We perform the measurement of R_{AA} of charged hadrons at high $p_T > 5.1$ GeV/c in isobar collisions, which is also considered as a hard probe. We find a suppression in central events driven by mechanism that also leads to the phenomenon of jet quenching. In peripheral events, our measurements are affected by centrality bias which is investigated using PYTHIA combined with Monte-Carlo Glauber model simulations [18].

Using the Heavy Flavor Tracker of STAR, we have performed the first measurements of D^0 tagged jets at RHIC. We reconstruct jets that contain a D^0 with $p_{T,D^0} > 5$ GeV/c with resolution parameter of $R = 0.4$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Our measurements are unfolded using response matrix obtained from the PYTHIA-8 Detroit tune and the STAR GEANT simulation. We measure the nuclear modification factor (in reference to peripheral events) R_{CP} in central and mid-central events with the transverse momentum of the reconstructed jets $p_{T,\text{jet}}$. We see that R_{CP} increases against $p_{T,\text{jet}}$ to approach unity around $p_{T,\text{jet}} = 12$ GeV/c. To study the radial profile of D^0, we vary "r", the distance of the D^0 from the jet axis in the range of 0-0.2. For a given "r" we study the ratio of the yields between central or mid-central events to peripheral events. The ratio is found to be consistent with unity indicating no modification of D^0 radial profile with centrality, within measurement uncertainties. These measurements can constrain theoretical models on heavy quark diffusion and energy loss at RHIC [19].

To understand how the vacuum parton shower in p+p collisions gets modified in heavy-ion collisions due to in-medium gluon radiations, we perform measurements of the ratio of the recoil jet yield as a function of jet p_T with $R = 0.2$ over $R = 0.5$ in p+p, and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. We use π^0 and direct photon (γ^{dir}) triggered jets. We observe that the ratios in Au+Au collisions are significantly lower than that in p+p indicating medium-induced broadening of jet showers at RHIC. We also perform the first measurements of acoplanarity for both π^0 and γ-triggered jets. We observe medium-induced jet acoplanarity in heavy-ion collisions compared to the PYTHIA baseline for larger values of jet radius [20].

6. Upgrades and future program

In 2021, STAR has successfully installed the forward upgrades. Three different subsystems, the forward silicon tracker, the small strip thin gap chamber, and the forward calorimeter that includes electromagnetic and hadronic layers, have been fully installed and participated in data taking in p+p collisions at 510 GeV. These systems are installed in one of the forward directions at STAR, and will allow important measurements during the anticipated Au+Au runs in 2023 and 2025, and in polarized p+p and p+Au runs in 2024 [21]. An important plan is to perform measurements that can be repeated at the Electron-Ion Collider (EIC). In this direction we perform an exploratory measurement of di-hadron correlations in photo-nuclear events to search for signatures of collectivity. Although no such signature is observed now, this will be revisited in future measurements. STAR forward upgrade program will open paths to study the microstructure of the QGP and enable measurements informative towards EIC science.

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