Di-Hadron Correlations with Identified Leading Hadrons in 200 GeV Au+Au and d+Au Collisions at STAR

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(STAR Collaboration)
The STAR collaboration presents new two-dimensional di-hadron correlations with leading hadrons in 200 GeV central Au+Au and minimum bias d+Au collisions to explore hadronization mechanisms in the quark gluon plasma. The enhancement of the jet-like yield for leading pions in...
Au+Au data with respect to the d+Au reference and the absence of enhancement for leading non-pions (protons and kaons) are discussed within the context of quark recombination. The correlated yield at large angles, specifically in the ridge region, is significantly higher for leading non-pions than pions. The consistencies of the constituent quark scaling, azimuthal harmonic model and a mini-jet modification model description of the data are tested, providing further constraints on hadronization.

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Experimental data from heavy-ion collisions at ultra-relativistic energies achieved at the Relativistic Heavy Ion Collider (RHIC), and more recently at the Large Hadron Collider (LHC), are conventionally interpreted in terms of a unique form of matter, termed a strongly-interacting Quark Gluon Plasma (sQGP). It is estimated that temperatures reached in those collisions \[ T \] are well above the critical values predicted by lattice quantum chromodynamics calculations for the phase transition between hadronic and de-confined (partonic) matter \[ T_c \]. The RHIC experiments concluded that the RHIC experiments concluded that the RHIC experiments concluded that the RHIC experiments concluded that the RHIC experiments concluded that the RHIC experiments concluded that the RHIC experiments concluded that the hadronization. The latest observations of ridge-like correlations in central Au+Au data, comparing to reference measurements performed in d+Au collisions. Details of the short-range correlations can shed light on the interplay between parton fragmentation, energy loss, and recombination processes in the quark gluon plasma. The long-range correlations are studied with two approaches: (1) Fourier decomposition where we extract the azimuthal harmonic amplitudes which in some approaches are interpreted as hydrodynamic “flows” \[ \phi \], and (2) a mini-jet (defined in \[ \phi \]) modification model \[ \phi \].

The analysis was conducted using 152 × 10^6 central-triggered Au+Au events at \[ \sqrt{s_{NN}} = 200 \text{ GeV} \] from STAR’s 2010 data run, and 46 × 10^6 events from the 2008 minimum-bias 200 GeV d+Au data set. The STAR Time Projection Chamber (TPC) \[ \phi \] was used for tracking, momentum reconstruction and particle identification. Contamination by tracks from another collision (“pileup”), which can distort the shape of di-hadron correlations \[ \phi \], was removed by rejecting events with an abnormally large (over three standard deviations above the average) number of tracks not originating from the primary vertex.

Trigger particles are defined as the highest-\( p_T \) charged hadron in a given event with \( p_T \). The ratio of proton to pion yields in central Au+Au collisions exceeds by more than a factor of two that in d+Au and p+p. Similar baryon enhancements were reported in the strange-hadron sector \[ \phi \]. In the same kinematic region, baryons and mesons exhibit different trends in azimuthal anisotropy, which appear to scale with the number of constituent quarks \[ \phi \]. Recombination models, which incorporate the coalescence of two or three constituent quarks as a formation mechanism for mesons and baryons, are able to reproduce the observed enhancements in inclusive measurements \[ \phi \].
FIG. 1. (Color online) Two-dimensional $\Delta \phi$ vs. $\Delta \eta$ correlation functions for charged hadron (left), pion (middle), and non-pion (right) triggers from 0-10% most-central Au+Au data at 200 GeV. All trigger and associated charged hadrons are selected in the respective $p_T$ ranges $4 < p_T^{\text{trig}} < 5$ GeV/c and $1.5 < p_T^{\text{assoc}} < 4$ GeV/c.

five pseudorapidity and two trigger $p_T$ bins. Details of the particle identification (PID) technique are identical to those in refs. [16,25,26].

For each trigger hadron we construct the two-dimensional correlation with all other charged hadrons with $p_T$ between 1.5 and 4 GeV/c in an event, following the procedure outlined in ref. [8]. Pion identification is straightforward: selecting triggers with $dE/dx$ above the central (expected) pion value provides a sample with 98% pion purity and, by construction, 50% selection efficiency. The “pure-pion” correlation is constructed with those triggers. The remaining triggers are comprised of all protons, about 97% of all kaons, and the remaining 50% of pions.

We remove the pion contribution from the correlation with those remaining triggers by direct subtraction of the pure-pion-triggered correlation. The resulting “non-pion” correlation is then associated with a mixture of proton and kaon triggers (about three protons for every two kaons [27]). Separating kaons from protons is complicated by the small $dE/dx$ difference between the two and was not attempted in this Letter. All raw correlation functions are corrected for detector inefficiency derived from Monte Carlo tracks embedded into real data as in refs. [8,9,25]. Pair-acceptance effects are corrected using the mixed-event technique as in ref. [9]. The resulting correlations for Au+Au data are shown in Fig. 1, with visible differences between the two trigger types in both jet-like peak and large $\Delta \eta$ region. A significantly larger ridge amplitude is seen for non-pion triggers, while the jet-like peak is more pronounced for the pion triggers. In the following, we analyze these modifications individually.

Initially, we study the small-angle jet-like correlated signals. Assuming that all background contributions are $\Delta \eta$-independent, as shown in refs. [8,28], we subtract those contributions averaged over large $|\Delta \eta| = 0.9–1.5$ from the full correlations, resulting in “pure-cone” distributions. This procedure is supported by the two-dimensional fits to the data described below. We then calculate the fiducial jet-like yield in $|\Delta \eta| < 0.78$, $|\Delta \phi| < \pi/4$ as in ref. [2]. To isolate medium effects from initial-state nuclear effects, the Au+Au results are then compared to the correlation function constructed in an identical way for d+Au data (see Fig. 2). We report significant differences in the jet-like yield per trigger between the two systems for pion triggers. At the same time, correlations with non-pion triggers show, within uncertainties, similar yields for the two systems. For quantitative comparisons, the integrated yields are presented in Table I. The yield extrapolation outside the fiducial range is performed using cone-shape modeling described below. The systematic errors are dominated by the tracking efficiency uncertainty (5%); other sources include uncertainties from $p_T$ resolution (3%), PID uncertainty (2–3%), background level determination (2% for Au+Au; 2–5% for d+Au), track splitting/merging correction (1%), and pair acceptance (<1%).

TABLE I. Fiducial ($|\Delta \eta| < 0.78 \times |\Delta \phi| < \pi/4$) and extrapolated pure-cone yields for pion, non-pion and charged hadron (unidentified) triggers (see text), and the associated yield ratios.

| Trigger | $\text{Au+Au 0-10\%}$ | $\text{d+Au MinBias}$ |
|---------|----------------|----------------|
| $\pi$   | $0.211$ | $0.214$ | $3\%$ | $7\%$ | $0.171$ | $0.171$ | $4\%$ | $6\%$ |
| non-$\pi$ | $0.136$ | $0.142$ | $5\%$ | $6\%$ | $0.142$ | $0.148$ | $7\%$ | $8\%$ |
| All     | $0.176$ | $0.180$ | $2\%$ | $5\%$ | $0.161$ | $0.168$ | $2\%$ | $5\%$ |
| $Y_{\text{non-\pi}}/Y(\pi)$ | $0.643$ | $0.662$ | $6\%$ | $5\%$ | $0.835$ | $0.866$ | $8\%$ | $8\%$ |

The jet-like yield in the $p_T$ range 1.5–4 GeV/c associated with pion triggers in central Au+Au collisions is enhanced by $24 \pm 6\text{(stat.)} \pm 11\text{(sys.)}\%$ with respect to the reference measurement in d+Au. The yields for non-pion triggers are found to be similar between the two systems. A previous work found similar trends in
near-side associated yields [29]; however, in that one-dimensional analysis, no separation between jet-like peak and ridge contributions was possible. We find that the jet-like yield for unidentified charged hadron triggers is also enhanced, consistent with our identified trigger results. The enhancement of the jet-like yield for pion triggers could be caused by the jet-quenching effect and/or medium-induced modification of fragmentation functions, and is qualitatively consistent with other observations from non-identified correlations and direct jet measurements [30–32]. It is expected that a larger fraction of non-pion triggers are produced from gluon rather than quark jets compared to pion triggers [27, 33]. A suggested higher in-medium energy loss for gluons should then result in even larger jet-like yields for non-pion triggers [34]. The absence of an expected enhancement for non-pions could be reconciled if quark recombination contributes significantly to hadronization. Hadrons formed via recombination of soft partons would not have as many associated small-angle hadrons as is typical for fragmentation processes [35], leading to a dilution effect. This dilution, which effectively lowers associated per-trigger yields, would affect correlations for baryon and meson triggers differently, as more intermediate-$p_T$ baryons than mesons are expected to be formed through such a mechanism.

Currently, no quantitative predictions from recombination/coalescence models are available for direct comparison.

Outside of the jet-like cone region we find no $\Delta\eta$-dependence in the correlated yields within our fiducial range. To characterize the long-range contributions, we perform two-dimensional fits to the full correlation with two different models. One model attributes the ridge to modified fragmentation of produced mini-jets, and the other explains it in terms of higher-order hydrodynamic flows. In both models, the near-side jet-like peak is mathematically characterized by a two-dimensional generalized Gaussian $e^{-((\Delta\phi/\alpha_\phi)^2 + (\Delta\eta/\alpha_\eta)^2)}$. The resulting fit parameters for the jet cone are found to be identical between the two models and were used for extrapolation of the jet-like cone yields presented in Table I.

The $\Delta\phi$ projections of the pseudorapidity-independent parts of the two-dimensional correlations (after subtracting the jet-like peak), are shown in Fig. 3 panel (a), together with both fit functions discussed below. In the flow-based approach, based on a hydrodynamic expansion of an anisotropic medium, all $\Delta\eta$-independent parts of the correlations are described via Fourier expansion: $A(1 + \sum_{n=1}^{N} V_n \cos n\Delta\phi)$, where $A$ describes the magnitude of the uncorrelated background, $V_2$ is conventionally associated with “elliptic flow”, and $V_3$ with “triangular flow”. In this work, the first five terms ($N = 5$) exhaust all features of the correlation to the level of statistical uncertainty, and $V_n$ represents the combined trigger and associated hadron anisotropy parameters. We note that in this approach, the fragmentation contributions to the away-side correlations are expected to be strongly suppressed relative to flow effects, and they are therefore neglected [11, 12].

The fit results are shown in Fig. 3 (b). The second harmonic is dominant in all long-range correlations for...
the central data, followed by the triangular ($V_3$) term. Higher-order harmonic amplitudes rapidly decrease. All harmonic amplitudes for non-pion triggers are found to be larger than those for pion triggers, which is qualitatively consistent with recombination expectations. Elliptic flow parameters of identified hadrons have been shown to scale with the number of constituent quarks $n_q$, suggesting collective behavior at the partonic level [20]. The estimated baryon/meson ratio for $V_2$ in this analysis is also consistent with 3/2. We note that in our trigger $p_T$ range, azimuthal anisotropy is approximately independent of $p_T$, eliminating the need to address quark momentum dependence. To test whether this scaling extends to the triangular term, we examine the $V_3/V_2$ ratios. This test assumes that the measured Fourier coefficients factorize into $V_n = \langle v_n^{\text{trig}} \rangle / \langle v_n^{\text{assoc}} \rangle$, where $v_n^{\text{trig}}$ and $v_n^{\text{assoc}}$ measure azimuthal anisotropies of trigger and associated hadrons, respectively [12]. Since the selection of associated particles is identical for all correlations in this analysis, the anisotropy contributions from associated hadrons should cancel in the ratios of $V_n$ coefficients. Figure 3 (c) shows $V_3/V_2$ ratios extracted from long-range correlations versus average $n_q$ per particle for pion and non-pion triggers. The systematic uncertainty, determined by varying the fitting range and the $dE/dx$ cut position for pion/non-pion separation, was found to be similar to, or smaller than, the statistical uncertainty. We find that the ratio of triangular and elliptic flow is $0.546 \pm 0.025\text{(stat.)}\pm 0.018\text{(sys.)}$ for pion triggers and $0.681 \pm 0.025\text{(stat.)}\pm 0.015\text{(sys.)}$ for non-pions. If the measured final-state azimuthal anisotropies are indeed of collective partonic origin which transform into final-state hadronic observables through coalescence/recombination of constituent quarks, then we would expect the same dependence of all $v_n^{\text{trig}}$ on constituent quark number. Even with the significant meson contribution to non-pion triggers, the ratios give a strong indication of a breaking of the simple $n_q$ scaling behavior between the second and third Fourier harmonics. Assuming that kaons, as mesons, adhere to the pion scaling trend, and using the known $p/\pi$ ratio reported in refs. [27], we construct an estimate of the $V_3/V_2$ ratio for pure protons in Fig. 3 (c). The systematic uncertainty in the estimated “pure-proton” $V_3/V_2$ value of $0.736 \pm 0.038\text{(stat.)}\pm 0.032\text{(sys.)}$ includes an additional 1% uncertainty from PID. At the moment, only recombination/coalescence models are able to provide a physical description of the constituent quark scaling behavior observed in elliptic flow parameters of multiple identified hadron species.

The difference between the $V_3$ and $V_2$ scaling behavior demonstrated in Fig. 3 (c) therefore suggests the need for other contributions to long-range correlations to explain the data. We note that the $v_n$ scaling proposed in ref. [27] better describes our measured $V_3/V_2$ ratios, but still under-predicts the enhancement for non-pion triggers.

In the mini-jet model, in which the major component is in-medium modification of fragmentation, only the first two terms ($N = 2$) of the Fourier expansion are kept and the near-side ridge in this analysis is modeled by a one-dimensional Gaussian, resulting in $A(1 + 2V_1 \cos \Delta \phi + 2V_2 \cos 2\Delta \phi) + B e^{-\Delta \phi^2/2\sigma^2}$. Here $A$ is the uncorrelated yield, $B$ is the ridge amplitude, and $\sigma$ is the ridge width parameter. The dipole $V_1$ is designated to describe the away-side jet and/or momentum conservation effects, and $V_2$ describes a non-jet quadrupole (potentially of flow origin). The addition of the 1D near-side Gaussian, which differs from the original model elements in ref. [22], was necessary to reproduce the data, as noted in ref. [25]. The mini-jet model fit describes the measured correlations for all three trigger types equally well as the flow-based approach (Fig. 3 (a)), yielding identi-
cal uniformly distributed residuals and $\chi^2$ values. The extracted harmonic amplitudes are shown in Fig. 3 (b). As the away-side structure is for the most part described by the dipole term, the magnitude of the $V_1$ amplitude is found to be significantly larger for leading non-pions than for pions. For back-to-back jets, this $V_1$ increase is supposed to balance the near-side (leading) jet contributions, which would have to consist of both the jet-like peak and the ridge because the jet-like peak alone decreases for non-pion trigger particles. Understanding the behavior of the $V_2$ term in the mini-jet model fits is challenging: the $V_2$ amplitude, while consistent with zero for pion triggers, is significantly negative for non-pion triggers. This negative value for $V_2$, which is conventionally associated with elliptic flow, is not expected from any known source and calls into question the applicability of the assumed parameterization for the centrality and $p_T$ range studied here, the validity of the “mini-jets + quadrupole only” physics scenario, or both.

In summary, a statistical separation of pion and non-pion triggers was performed to study the systematic behavior of di-hadron correlations from central Au+Au and minimum-bias d+Au collisions at 200 GeV with the STAR experiment. The correlations, decomposed into short- and long-range parts in $\Delta\eta$, are analyzed for different identified trigger types to test the consistency of two models in order to improve our understanding of hadronization mechanisms in the quark gluon plasma. We find significant enhancement of intermediate-$p_T$ charged-hadron jet-like yields associated with pion triggers relative to a d+Au reference measurement, indicative of jet-medium interactions resulting in jet energy loss and/or fragmentation modification. No enhancement is observed for non-pion triggers in contrast to pQCD-based expectations for color charge dependence of energy loss. This lack of enhancement may indicate a competition between parton-medium interaction effects and trigger-pool dilution by quark recombination contributions.

We find a significantly larger ridge-like yield and away-side correlation strength for non-pion than for pion triggers. We use two fit models which are mathematically similar, but which are based on different physical assumptions. Both models, while describing the correlations well, attain parameter values which are problematic for the assumed physical scenarios. In the flow model, the observed differences of $V_3/V_2$ ratios imply that the explanation of the ridge and away-side modifications as resulting only from hydrodynamic flow of a partonic medium with constituent quark recombination at hadronization is incomplete. On the other hand, the negative $V_2$ result for the mini-jet based model for leading non-pions indicates that for the data reported here, either the assumed scenario or the mathematical parameterization for jets and dijets is inadequate, or both. These results have major implications for understanding the origin of the ridge and hadronization in the QGP.

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