Modifications of high- p_T di-hadron correlations for identified triggers

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Abstract.

Angular correlations with high transverse momentum hadrons have become an established tool for studying properties of the medium created in ultra-relativistic heavy ion collisions. When investigated in two dimensions, relative azimuth and relative pseudorapidity, the small-angle part of such correlations is commonly attributed to QCD jets, while long-range correlations, specifically ridge observed at low- and intermediate momentum, are often described as manifestations of hydrodynamic expansion of the system, e.g. flow. Comparative analysis of both features, presented in this work for correlations with identified leading hadrons, explores the particle type dependence of the jet structures, and challenges the flow-only hypotheses behind the ridge.

1. Introduction

The energy densities achieved in nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) and, more recently, at the Large Hadron Collider (LHC) provided an experimental environment to study new form of QCD matter. The increasing amount of evidence supports the QCD prediction of partonic deconfinement at the limits of high temperature and/or energy density. The creation of the strongly interacting Quark Gluon Plasma (sQGP) is evident, for example, in the collective behavior of the bulk particles in the soft sector (below transverse momentum $p_T < 1.5 \text{ GeV}/c$). The production rates of identified hadrons (including strange and multi-strange species), the mass-dependent modifications of the spectral distributions, and the strength of azimuthal correlations with respect to reaction plane (elliptic flow, v_2) are all consistently described by a thermalized, hydrodynamically expanding medium with properties resembling a "perfect fluid" [1]. More recently, new theoretical developments led to recognition of the importance of initial state non-uniformity due to density/geometry fluctuations. These fluctuations result in significant anisotropies of higher orders (v_3 and above), while originally it was expected that these terms would be negligible or canceled by symmetry. Investigation of particle-type dependence of v_n anisotropies is one of the goals of this work.

It has been now experimentally established that azimuthal anisotropies extend far above the soft momenta, although different physics mechanisms may be responsible for the effect in different kinematic regimes (see recent review in [2]). The hydrodynamic expansion under pressure gradients dominating the long-range correlations of soft hadrons, gives way to the pathdependent energy loss, or jet quenching, at high p_T . The jet quenching effect in the hard-sector $(p_T > 6 \text{ GeV}/c \text{ for hadrons}, E_T > 30 \text{ GeV for jets})$ is also established through the suppression of the hadron and jet production rates at both RHIC and LHC. While little modifications of the surviving jets in the high- p_T regime of heavy ion events compared to the reference measurements from pp collisions has been observed [3, 4], a number of novel phenomena has been discovered at the intermediate momentum range, $(1.5 < p_T < 6 \text{ GeV}/c)$, which is the focus of this study. Of particular interest are prominent excess of the near-side (small relative azimuth, $\Delta \phi$) yields that extends to large relative pseudorapidities ($\Delta \eta$), the ridge. This long-range ridge was discovered in 2-dimensional ($\Delta \eta, \Delta \phi$) correlations along with shape modifications of the away-side ($\Delta \phi \sim \pi$) in associated hadron distributions for high- p_T trigger hadrons [5]. A number of physics mechanisms has been initially proposed to describe the ridge, however, recently the most-widely accepted interpretation attributes the phenomenon to the higher order flow terms, the final state imprint of the inhomogeneous initial conditions [6].

Another important discovery of the intermediate momentum range is the observation of constituent quark scaling behavior in the measurements of elliptic flow for baryons and mesons, as well as in the different trends of nuclear modification factors for baryons and mesons [7]. The most natural explanation for the observed trends was put forward by recombination /coalescence models of hadron production [8, 9], in which constituent quark number scaling comes naturally. The recombination approach also provides effortlessly an explanation for the so-called baryon/meson puzzle: it has been observed that hadron composition in central Au+Au collisions at intermediate p_T is very different from pp events, with large relative baryon over meson enhancement across all measured hadron flavors reported.

For the di-hadron correlation measurements in the intermediate momentum range the dominance of hadronization through recombination mechanisms is expected to lead to a "trigger dilution" for the jet-like near-side per-trigger yields measured in Au+Au events compared to the pp reference. That is, the correlations measured in 200 GeV pp collisions for leading hadrons above 4 GeV/c are dominated by the QCD fragmentation contributions and capture the back-to-back di-jet structures left by fragmentation of the hard-scattered partons. In case of recombination of the thermal quarks from the medium created in the Au+Au collisions at the same energy, no near-side jet-like peak would accompany the resulting hadron, thus effectively reducing (diluting) the per-trigger associated yields. Moreover, this dilution effect would be stronger for baryon as compared to meson triggers. There is an earlier measurement of associated near-side yields for protons and pions [10] that shows an increasing difference of the correlation strength for more central events for proton, but not pion triggers, but in this work no separation of the short- and long-range contributions has been performed, complicating the interpretation. For the long-range correlations associated with baryons and mesons, if indeed dominated by the higher order flow terms from hydrodynamic expansion of the fluctuating initial state, one would expect the v_3 (and higher) harmonics to exhibit the same scaling behavior as elliptic flow (v^2) , e.g. stronger correlations for baryons than for mesons. Systematic studies of the two-dimensional di-hadron correlations with various identified leading hadrons are needed to provide further differential tests for establishing model interpretations.

The STAR detector has a great advantage for these types of studies, relying on its full azimuthal and extended pseudorapidity coverage at nearly uniform acceptance. One of the STAR main detectors, the Time Projection Chamber (TPC), provides multiple means to perform particle type identification for the charged hadrons recorded. The momentum information combined with measurements of ionization energy loss in the detector material allows identification of "common" charged hadrons, π^{\pm} , K^{\pm} , and (anti)protons in the soft sector, and, more recently, at higher momenta of the relativistic rise region [11]. Together with invariant mass calculations, this information also allows STAR to topologically identify neutral hadrons decaying weakly into charged particles, particularly, Λ and K_s^0 , as well as statistical identification of multiple resonances.

The high purity samples of Λ and K_s^0 from the intermediate momentum range have been



Figure 1. Multiplicity dependence of the ridge-like (left) and jet-like (right) yields associated with different types of identified triggers in 2-dimensional di-hadron correlations from 200 GeV Au+Au and Cu+Cu collisions of various centralities. All leading hadrons are selected to have transverse momenta p_T^{trig} between 3 and 6 GeV/*c*, while associated charged hadrons used to build angular correlations are required to have 1.5 GeV/*c* < p_T^{assoc} < p_T^{trig} . The band shows an estimate of systematic uncertainties errors due to subtraction of elliptic flow contributions. The figure is from [12].

used as leading hadrons to construct 2D di-hadron correlations in a first attempt in STAR to quantify the particle-type dependence of correlation strength [12]. In this early work measured correlations have been decomposed into a jet-like part (small $\Delta\phi$, small $\Delta\eta$) and a ridge (small $\Delta\phi$, large $\Delta\eta$) components. The v_2 -modulated background have been subtracted from both parts of the correlations for further analysis. The extracted yields have then been studied as a function of event centrality (expressed via number of participants, N_{part} , estimated by Glauber model) for Au+Au and Cu+Cu collisions at 200 GeV. It has been reported that while little or no dependence on N_{part} could be seen in the jet-like yields associated with different types of hadronic triggers (Fig. 1, right), the ridge yield increases approximately linearly for all correlations studied (Fig. 1, left). For our discussion the interest is in the comparative analysis of baryon vs. meson related yields. Unfortunately, the uncertainties of these preliminary measurements prevent decisive conclusions. However, we note that the jet-like yields associated with lambdas seem lower than these for kaons, while a reverse tendency is presented in the ridge measurements.

The goal of this work is to revisit the question of particle-type dependence in the correlation structures for leading baryons and mesons taking advantage of the new high luminosity data samples recorded by STAR in the years 2008 and 2010 for 200 GeV d+Au and Au+Au collisions, respectively. We focus on the Au+Au collisions from the top 10% centrality selection, where medium effects are expected to be maximal. The new d+Au dataset is used as a reference establishing a baseline in absence of the hot nuclear matter. Statistical separation of charged pions from (anti)proton and charged kaon triggers, performed in this work for correlation studies, provides new constraints for theoretical description of the data.

2. Analysis of Di-hadron Correlations with Identified Leading Hadrons

The highest p_T charged particle in an event is first selected as a trigger hadron. We require a trigger momentum threshold for all correlations to be between 4 and 5 GeV/c. Statistical hadron identification techniques employing measurements of ionization energy loss in the TPC material in the relativistic rise region are used, following established techniques [11]. The separation between the typical energy deposition (dE/dx) of pions and non-pions in the STAR TPC in the kinematic range of our trigger selection allows trivially obtaining a "pure pion" sample with a

single cut on the dE/dx-related variable. For the pion triggers presented in this work the purity of the sample is estimated to be 98% and contains approximately 50% of all charged pions recorded within the imposed p_T range. The remaining charged hadrons between 4 and 5 GeV/c that fell below our pion selection cut, are then kept as a "pion-depleted" trigger set, which contains majority of (anti)protons and charged kaons, and the remaining 50% of the charged pions. These two trigger samples are used to construct corresponding 2D di-hadron correlations following procedures and corrections established in previous di-hadron works [13]. The charged tracks used to construct the correlations with respect to trigger hadrons are required to have transverse momentum between 1.5 and 4 GeV/c, excluding potential overlap with the leading hadron pool. Figure 2 presents di-hadron correlations, resulting after the efficiency, acceptance, and track splitting/merging effects are taken into account. The left panel shows a baseline correlation made for all leading charged hadrons with $4 < p_T^{\text{trig}} < 5 \text{ GeV}/c$ and associated tracks with $1.5 < p_T^{\text{assoc}} < 1 \text{ GeV}/c$ without any identification. The middle panel shows correlation obtained with identical kinematic selection for the sample of pure-pion triggers. Even in these raw correlations (without subtraction of combinatorial background) the emerging differences are evident: the jet-like peak appears larger for the pion triggers than that for inclusive charged hadrons, while decrease in the strength of the long range ridge can also be spotted.

Once the 2D correlation for the pion triggers has been measured, this contribution can be directly subtracted from correlation with the pion-depleted sample, which after proper renormalization to account for the number of non-pion triggers left, provides the correlation measurement for proton and kaon mix of leading hadrons ("p+K" or "non-pions" in the following). The relative composition of the non-pion trigger sample is 60% (anti)protons vs. 40% charged kaons. Although further separation of the non-pion sample into pure-protons and pure-kaons is not performed in this work due to significant overlap of the ionization energy loss distributions for these species, comparative analysis of high-precision pure-pion and non-pion triggered correlations allows to infer the differences for baryon vs. mesons. assuming recombination as a dominant mechanism behind constituent quark scaling behavior. No additional treatments or data modeling is needed to note significant differences in both shortand long-range correlation components between the pion and non-pion trigger samples. As seen in the right panel of Fig.2 the non-pion triggered correlations has significantly smaller jet-like peak while the ridge amplitude is much higher than that for pion triggers (as expected from comparison of pion-triggered correlation to that with inclusive charged hadron triggers).



Figure 2. Two-dimensional $\Delta \phi - \Delta \eta$ correlation functions for leading particles with 4< $p_T^{\text{trig}} < 5 \text{ GeV}/c$ and associated charged hadrons of $1.5 < p_T^{\text{assoc}} < 4 \text{ GeV}/c$. Unidentified (inclusive) charged hadrons (left), charged pions (middle), and non-pions (right) from 0-10% most central Au+Au collisions at 200 GeV were used as trigger particles for the correlations shown.

3. Results and Discussion

Jet-like peak

We separate the short- and long-range components for each 2D correlation by direct subtraction of the ridge-dominated part $(0.9 < |\Delta\eta| < 1.5)$ from the small-angle $(|\Delta\eta| < 0.9)$ region (after proper normalization per unit $\Delta \eta$). The ridge/jet separation cut at 0.9 ensures that over 98% of jet-like peak is contained within the inner selection. Such subtraction assumes that contributions other than the jet-like peak are $\Delta\eta$ -independent; multiple fitting tests performed justify this assumption. The direct subtraction of the ridge region removes the contributions from combinatoric background modulated by hydrodynamic flow, minimizing the uncertainties on the extracted jet-like yields (modulo the assumption of rapidity independence of the flow harmonics in the kinematic region covered). We observe significantly larger jet-like yields associated with pion triggers compared to non-pion measurement. In theoretical calculations the leading pions and non-pions (specifically, protons) have different contributions from fragmentation of quarks and gluons. Thus, it is interesting to test if the color-charge effects in jet-medium interactions can be seen in the correlation data with identified triggers. To differentiate between the cold and hot nuclear matter effects we compare the jet-like yields for pion and non-pion triggers from central Au+Au collisions with the reference measurements obtained in identical way from the d+Au data. We notice no sizable changes in the peak shapes in either $\Delta \eta$ or $\Delta \phi$ dimensions between Au+Au and d+Au data for the same trigger types. The integrated jet-like yield for the pion triggers from central Au+Au data is significantly higher than for pion triggers from d+Au collisions, while non-pion triggers show little to no change. The relative enhancement of the pion-triggered yield is on the order of 30%, and could be attributed to the jet energy loss resulting in additional softer hadrons along the direction of the jet and/or modification of the jet fragmentation pattern due to the medium presence. Qualitatively, this result is consistent with the findings of the jet-track correlation analysis [14]. No change in the jet-like yield for non-pions is unlikely due to color-charge effects, as larger energy loss for leading gluon vs. quark jet would result in the opposite effect, increasing the associated yields even more. The alternative mechanism that would lead to a modification of relative non-pion to piontriggered yields can be readily provided by the recombination model. The larger contribution from recombination of thermal quarks to proton production compared to that of pions, which expected to be largely formed by through fragmentation by 4 or 5 GeV/c, would result in a trigger dilution effect mentioned earlier. Since the systematic uncertainty on the integrated jetlike yields is dominated by the overall uncertainty on tracking efficiency, which is uncorrelated between the d+Au and Au+Au data samples, but fully correlated for pions and non-pions in the same data, we construct a double ratio of the yields to eliminate this uncertainty source. We find that this double ratio of non-pion to pion triggered jet-like yields from Au+Au data over the same in d+Au is $0.7 \pm 0.1^{\text{stat}}$, pointing to an additional decrease of the associated yields for non-pion triggers in central Au+Au collisions with respect to a reference measurement from d+Au.

Ridge

The dependence of the ridge and away-side yield on trigger identity is another focus of this study. Recently, the ridge and away-side structures are commonly described in terms of higher order Fourier harmonics and rather successfully modeled hydrodynamically. Correlations with identified triggers allow to study scaling features (such as mass or quark number) to support or challenge this picture. To characterize the trigger-type dependence of the long-range components of the measured correlations, the corresponding jet-like near-side peak discussed in the previous section is first subtracted from full 2D measurement. We observe no rapidity-dependent residuals in the obtained correlations, and thus could continue the study with a 1D projection on relative azimuth. Left panel of Fig. 3 overlays the resulting projections for pion and non-pion triggers.

Significantly larger ridge and away-side yields are clearly seen for p+K triggers compared to pion triggers. Fourier fits including harmonics up to fifth order are performed on each of the projections, and are also shown in the Figure. The extracted Fourier coefficients, V_n , each containing the contributions from the corresponding n-th order term for trigger and associated hadrons, are plotted in the middle panel of Fig. 3. For comparison, Fourier coefficients for the correlation in the same kinematic range with unidentified charged triggers are also presented. We find a very small V_5 terms for all correlations, with higher harmonics vanishing completely. For the coefficients V_1 through V_4 , the values from non-pion-triggered correlation fit are consistently above those from pion-triggered correlation (with unidentified trigger results placed in between, as expected).



Figure 3. Left: the ridge – $\Delta\phi$ projection of $\Delta\eta$ -independent part of the 2D di-hadron correlation for pion and non-pion triggers from 10% most central Au+Au collisions at 200 GeV. The lines illustrate results of the Fourier fit described in the text. Middle: Coefficients of the Fourier fit for long-range correlations associated with pion, non-pion, and inclusive charged trigger particles from the same data. Right: The ratio of the V_3/V_2 coefficients of the Fourier expansion for correlations with pion and non-pion triggers (symbols), and the extrapolated estimate for this ratio for proton triggers (box). The extrapolation assumptions are detailed in the text. The straight line through the pion-related point is intended to guide the eye.

In the hydrodynamic picture the Fourier coefficients extracted from the data fits contain combined information about the flow of the trigger and of associated hadrons. For the separation of these contributions, the v_n factorization is widely accepted, e.g. $V_n = \langle v_n^{\text{trig}} \rangle \langle v_n^{assoc} \rangle$. For all correlations studied in this work, the kinematic selection for associated hadrons is identical, therefore one can assume that the associated hadron contributions will cancel in the ratios of the extracted coefficients. Moreover, under the factorization assumption, the constituent quark scaling behavior, if it hold for the third term as well, should lead to the identical ratio of the V_3/V_2 harmonics from each set of the identified triggers, as it would simply reflect per-quark v_3/v_2 . The ratios of the V_3/V_2 harmonics extracted from the Fourier decomposition of pionand non-pion triggered correlations is presented in the right panel of Fig. 3. A significantly larger ratio is observed for p+K triggers, despite consisting of a mix of baryons and mesons, indicating breaking of the scaling for the v_3 . For illustration, we extrapolate the measured ratio to baryons-only, assuming (under the constituent quark scaling hypothesis) that the kaon contribution is identical to that of pions, which naturally leads to an even bigger discrepancy. We conclude that triangular harmonic does not follow the same scaling pattern as the elliptic flow. In the context of di-hadron correlation studies, this indicates that the interpretation of the rapidity-independent terms through hydrodynamic flow only is incomplete.

4. Summary

In summary, new measurements of two-dimensional di-hadron correlations with identified leading hadrons from 200 GeV central Au+Au collisions recorded by STAR detector have been presented. For particle identification purposes the relativistic rise of the ionization energy loss in STAR/TPC for charged hadrons between 4 and 5 GeV/c was utilized to separate charged pion triggers. Statistical separation methods were used to extract the correlation measurements for a trigger sample without pions, consisting of about 60% (anti)proton and 40% charged kaon triggers. To study the medium-induced effects on the jet-like part of the correlation, a reference measurement from the minimum bias d+Au events at the same energy has been used. We find that for the pion-led correlation, the associated hadron yield in the jet-like peak is enhanced significantly in central Au+Au collisions compared to d+Au data for the charged hadrons with momenta between 1.5 and 4 GeV/c, studied in this work. At the same time, the non-pion triggers show no such trend for the jet-like peak associated yields. It is hard to expect such differences for the two trigger sets studied to come from color-charge dependence of energy loss, however, the relative decrease of non-pion to pion associated yields in the jet-cone from Au+Au events vs. d+Au events could have a natural explanation from recombination models. For the long-range component of the correlation functions, we observe significantly higher ridge and away-side amplitude associated with the non-pion triggers. Fourier expansion of the long range correlations yields non-zero terms up to the fifth order and allows comparing the constituent quark scaling behavior for the second and higher harmonics. We find that the ratios of V_3/V_2 Fourier coefficients from the fits to the pion-triggered data is significantly lower than from nonpion correlations, indicating the constituent quark scaling pattern is not preserved for the v_3 . This new observation strongly suggests that interpretation of the long-range component of the two-dimensional di-hadron correlation in terms of hydrodynamic flow terms only is incomplete.

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