Understanding the Role of Jet and Underlying Event in p+p and d+Au Collisions from PHENIX at RHIC

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Abstract

Dihadron azimuthal correlation measurements have revealed striking modifications of the jets by the dense medium created in heavy-ion collisions at RHIC. One important question is to what extent the modification can be attributed to cold nuclear matter effects. In this analysis, we carried out a detailed mapping of the correlation patterns using high-statistics RUN8 d+Au minimum bias data. A striking scaling behavior of the jet pair yields is observed at low and intermediate \( p_T \). The jet pair yields are found to be enhanced relative to \( N_{\text{coll}} \) scaled p+p jet pair yields. The nuclear modification factor for jet pair yields, \( J_{\text{dAu}} \), seems to scale with \( p_T^{\text{sum}} = p_T^a + p_T^b \) (scaler sum), and shows a characteristic Cronin-like enhancement at \( p_T^{\text{sum}} < 5-7\text{GeV/c} \). Interestingly, the level of yield modifications is similar between the near- and away-side pairs, and the jet shapes are not modified relative to p+p collisions. The pedestal yield under the jet peak is studied in p+p and d+Au collisions. The pedestal yield in p+p collisions is found to be larger than PYTHIA calculations. In d+Au collisions, it is found to exceed a simple sum of one p+p jet event and \( N_{\text{coll}} - 1 \) minimum bias p+p events. The possible interpretation of these results and their implications for Au+Au measurements are discussed.

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I. INTRODUCTION

It is generally believed that a strongly interacting Quark Gluon Plasma (sQGP) is created in central Au+Au collisions at the relativistic heavy ion collider (RHIC). The two most important evidences for sQGP are the observation of a large elliptic flow and a strong suppression of high $p_T$ jets (jet quenching) [1, 2]. These results were initially obtained from measurements of single particle production [3, 4, 5], and were subsequently confirmed by various correlation measurements [6, 7].

The information implied by correlation measurements, however, are much richer than by single particle measurements. The complicated correlation patterns can be better understood by studying them separately in a high $p_T$ region and a low $p_T$ region. The high $p_T$ region (> 5 GeV/c) is dominated by a suppressed but essentially p+p like jet fragmentation component, which can be interpreted as the combined result of jet quenching and surface bias [9]. The low $p_T$ region is characterized by a highly non-trivial modification that depends on the $p_T$, $\Delta \phi$ and $\Delta \eta$. This latter region seems to be driven by a detailed balance between the jet and the medium; the “jet” signal exhibits the famous “ridge” and ”cone” like structures in $\Delta \eta$ and $\Delta \phi$ [8, 9]; the bulk medium manifests a quark number scaling of elliptic flow [10] and an enhanced baryon/meson ratio [11]. Current efforts are focused on obtaining a quantitative understanding of the mutual influences between the jet and the medium [12, 13]. Both the modification of jets by the flowing medium and the response of the medium to quenched jets need to be taken in to account.

Study of single hadron production and dihadron correlation in p+A or p+A-like collision such as d+Au provides important baselines for understanding the results obtained in Au+Au collisions. Previous measurements established the dominance of the final state effects for the modifications of single particle production in Au+Au collisions [14]. However, various cold nuclear effects such as initial parton distribution functions, Cronin enhancements and cold nuclear energy loss etc, are also shown to be not negligible [15, 16]. Their influences depend on $p_T$ (see Figure 1), i.e. shadowing effects for low $p_T$ suppression, Cronin effects for intermediate $p_T$ enhancement, isospin and EMC effects for high $p_T$ suppression. There is also some room for a cold nuclear matter energy loss, which can reduce the overall yield [17].

Dihadron correlation techniques have certain advantages over single particle observables
in constraining cold nuclear effects. While single hadron spectra contain all contributions (including low $Q^2$, non-perturbative processes), dihadron correlations are more sensitive to hard-scattering processes. Previously published RUN3 d+Au results indicate little modification of jet properties [18]. However, those results are focused primarily on a high $p_T$ region that might not be very sensitive to cold nuclear effects. In this manuscript, we extend the measurements to low and intermediate $p_T$, where the cold nuclear effects are more pronounced. This study allows us to have a better understanding of the final state effects in Au+Au collisions.

Pairs in correlation analyses at RHIC energies are usually decomposed into a jet part and underlying event (UE) part (see Figure 2). The jet part contains correlated pairs from jet fragmentation and associated medium response, the UE part includes the combinatoric pairs that are uncorrelated with the trigger particle. Generally speaking, a rigorous decomposition is already impossible in p+p collisions, due to non-perturbative, long range correlations intrinsic to QCD. In A+A collisions, the situation is further complicated by strong coupling between jet and the flowing medium. The decomposition only makes sense if the disturbance caused by the jet is localized; but if the disturbance is dissipated to the whole medium, then all particles are correlated with each other and the decomposition becomes very difficult and
FIG. 2: Schematic illustration of dihadron azimuthal distribution in for p + p and d + Au collisions. It has two peaks corresponding to near- and away-side jet, and a component representing the underlying event pairs.

highly model dependent. This problem is not unique to dihadron correlations, it is also a serious issue for multi-particle correlations and analyses requiring full jet reconstruction.

Because of the intrinsic connection between jet and the UE, it is important to study both of them simultaneously in heavy-ion collisions, and to understand their mutual influences. Admittedly, this is a difficult task. As a first step in addressing this problem, we investigate the UE in simpler systems, i.e. p+p and d+Au, which do not require elliptic flow subtraction. Our studies not only provide the necessary handles on the cold nuclear effects, but also fulfil longstanding interests of high energy physics community [19, 20, 21]. In p+p collisions, the UE is one of the most important backgrounds for QCD processes and for the Higgs boson search [22]. The study of UE at RHIC energy can provide important inputs for tuning the dependence of phenomenological models, such as PYTHIA [23] and HERWIG [24].

II. ANALYSIS

This analysis uses the minimum bias p+p data from 2005 (2 billion events) and d+Au data from 2008 run (1.6 billion events) at $\sqrt{s_{NN}} = 200$ GeV. A standard event mixing technique
is applied to correct for finite pair acceptance in azimuth, and a ZYAM procedure is used to decompose the jet function into a jet part and a $\Delta \phi$ independent pedestal. Since the jet signal to background ratio is large in most kinematic region considered here and jet width is rather narrow (except at very low $p_T$), this should be a rather safe method for estimating the jet yield.

In most jet correlation analyses, it is customary to use the per-trigger yield, $\text{PTY} = \frac{\text{PairYield}}{\text{TriggerYield}}$, to measure the jet multiplicity. To quantify jet modification, we usually compare jet yield with p+p collisions using one of the three nuclear modification factors:

1. Modification of trigger yield

$$R_{dAu}(p_T) = \frac{\text{TriggerYield}_{dAu}}{N_{\text{coll}} \times \text{TriggerYield}_{pp}}$$

2. Modification of pair yield

$$J_{dAu}(p_T^a, p_T^b) = \frac{\text{PairYield}_{dAu}}{N_{\text{coll}} \times \text{PairYield}_{pp}}$$

3. Modification of per-trigger yield

$$I_{dAu}(p_T^a, p_T^b) = \frac{\text{Per-Trigger Yield}_{dAu}}{\text{Per-Trigger Yield}_{pp}}$$

where we use superscript “a” and “b” to indicate the two particles in the pair. In the absence of nuclear effects, both pair yield and trigger yield should scale with $N_{\text{coll}}$, hence deviations of $J_{dAu}$ and $R_{dAu}$ from unity can be attributed to nuclear effects.

It is straightforward to show that the three quantities are related to each other via the following relation:

$$J_{dAu}(p_T^a, p_T^b) = I_{dAu}(p_T^a, p_T^b) R_{dAu}(p_T^a)$$

This equation tell us that $I_{dAu} \neq 1$ may not necessary imply that jet is modified, it could be due to modification of trigger yield. This could happen if some trigger particles do come from jets and the yield of these triggers are modified. In this case, the jet multiplicity is simply re-scaled by a constant factor relative to p+p collisions, but the jet shape should remain unchanged. For this reason, $I_{dAu}$ may not be a good variable for low $p_T$ correlation. Instead, we should use $J_{dAu}$, which directly reflects the jet yield modification.
FIG. 3: Per-trigger yield distributions for fixed $p_T$ bins from low $p_T$ to high $p_T$. It demonstrates the disappearance of the modifications towards higher $p_T$.

III. JET MODIFICATIONS IN D+AU COLLISIONS

Modification of jet properties can be reflected by both the jet shape and jet yield. Figure 3 shows a sample of per-trigger yield distributions for p+p and d+Au collisions. A clear enhancement of the amplitude is observed at both the near-side and the away-side for d+Au collisions. The increase is limited to the low $p_T$ region and disappears when trigger and partner $p_T$ values rise above 2-3 GeV/c. This enhancement of per-trigger yield is about factor of two at low $p_T$ as measured by $I_{dAu}$ in Figure 4. It gradually disappears at large trigger and partner $p_T$.

As we argued before, a fraction of the enhancement seen in Fig. 4 is due to the suppression of trigger yield at low $p_T$ (see Fig. 1) which increases the per-trigger yield. To avoid that, we measure instead the absolute jet pair yield per event and construct the pair yield
nuclear modification factor, $J_{dAu}$, for each combination $p_T^a$ and $p_T^b$. A compilation of $J_{dAu}$ measurements are shown in Figure 5 for central d+Au collisions. It is plotted as a function of pair proxy energy $p_T^{sum} = p_T^a + p_T^b$, separately for the near- and the away-side. The high $p_T \pi^+ - h$ correlation data from RUN3 d+Au collisions [18] are included in this compilation. Figure 5 shows that the $J_{dAu}$ values approximately follow a common curve. It increases with $p_T^{sum}$ at low $p_T$, and peaks at a level significantly above one around $p_T^{sum} \approx 4$ GeV/c, then decreases towards larger $p_T^{sum}$. We do not see much yield modification for peripheral d+Au collisions (Figure 6). The shape of the enhancement of Figure 5 resembles the Cronin-like peak seen in single particle production. However, the level of enhancement is much bigger and it does not exhibit shadowing-like suppression at low $p_T$.

To study the modification of jet shape, we fit the jet yield distribution with a double Gaussian function and extract the near- and away-side width. Some examples of such fit are shown in Figure 3. The summary of the Gaussian widths from the fit are shown in Figure 7. The near-side widths are identical between p+p and d+Au. The away-side widths indicate a small broadening in central d+Au collisions, which is expected from multiple scattering.

FIG. 4: $I_{dAu}$ for the near-side and the away-side for 0-20% centrality selection.
FIG. 5: $J_{dAu}$ in 0-20% $d+Au$ centrality selection versus $p_T^{\text{sum}} = p_T^a + p_T^b$ for near-side (top panel) and away-side (bottom panel).

effects. But the level of broadening is well within the quoted 15% systematic errors. Work is underway to refine the systematic errors, such that we can better quantify this broadening in the future.
FIG. 6: $J_{dAu}$ in 60-88% d+Au centrality selection versus $p_T^{\text{sum}} = p_T^A + p_T^B$ for near-side (left panel) and away-side (right panel).

FIG. 7: Near-side width (left panel) and away-side width (right panel) obtained from double Gaussian fit in central d+Au (0-20%), peripheral d+Au (60-88%) and p+p collisions.

IV. THE UNDERLYING EVENT IN P+P AND D+AU COLLISIONS

Having examined the jet shape and yield modifications, we proceed to study the properties of the underlying event (UE). A natural question to ask is what is the relative contribution from the jet and the UE. The answer to this question gives us a first order estimation of the contribution from hard-scattering processes in p+p and d+Au collisions. And it is essential for us to properly understand the modification of these processes in Au+Au
FIG. 8: Fraction of pairs in p+p collisions contained in the jet peak, integrated over the full $2\pi$ range. The systematic errors shown reflect the ZYAM uncertainties.

collisions. Figure 8 shows the fraction of pairs in the jet peak (jet pair fraction) as a function of $p_T$ in p+p collisions. The jet pair fraction is already more than 15\% at lowest $p_T$ bin ($p_T^a \approx 2$ and $p_T^b \approx 0.5$ GeV/$c$) and quickly increases to close to 100\% at high $p_T$. This is much bigger than the typical level (few percent) seen in central Au+Au collisions. We want to point out that this estimation only gives the lower limit of jet contribution, since the UE contains contributions from uncorrelated jets as well as those from large angle radiations.

In heavy ion collisions, the jet signal is difficult to extract because of the large UE level. In p+p and d+Au collisions, we face the opposite problem: jet signal is so big that the UE can be strongly influenced by effects associated with the hard-scattering process such as the initial and final state radiation. Our definition of the UE is different from previous approaches used by the CDF Collaboration [19], where the azimuth correlation is made between reconstructed jets and charged hadrons. This method is cleaner in separating the jet from the UE. However, the dihadron correlation method is still useful for two reasons. First, full jet reconstruction is problematic and questionable at $p_T < 10$ GeV/$c$, where
dihadron correlation method can still be used. Second, it is currently the only method which allows a systematic study in p+p, d+Au and Au+Au at RHIC. In order to avoid potential confusion, we thereafter refer the UE obtained by dihadron correlation method as “pedestal”.

Due to the need for event mixing to account for finite azimuthal acceptance, PHENIX usually defines the correlation function as the ratio of pair distributions from same-events and mixed-events, where each is normalized separately by the number of events:

\[ C(\Delta \phi) = \frac{N_{f_{g}}(\Delta \phi)}{N_{mix}(\Delta \phi)} = \frac{\text{Jet pairs} + \text{UE pairs}}{\langle n_a \rangle \langle n_b \rangle} \]

In the second part of the equation, we decompose the foreground into the jet part and pedestal part via the ZYAM approach, and we use the fact that mixed event yield equal to the product of trigger yield, \( \langle n_a \rangle \), and partner yield, \( \langle n_b \rangle \). Because this way of constructing the correlation function, it is convenient for PHENIX to measure the pedestal yield relative to the p+p single particle yield. We define a ratio \( \zeta \):

\[
\zeta = \frac{\text{UE pairs/} \langle n_a \rangle}{\langle n_b \rangle} = \frac{\text{Assoc. Pedestal Yield Per-trig}}{\text{Min. Bias yield Per-event}}
\]

The advantage of this quantity is that the tracking efficiency cancels in the ratio. One can simply multiply \( \zeta \) with published single particle yield to obtain the pedestal yield.

Figure 9 summarizes \( \zeta \) values for various trigger \( p_T \) bins as a function of partner \( p_T \). The \( \zeta \) values are always above one and increase strongly with the \( p_T \) of the two hadrons. The change with \( p_T \) may be due to increase of the initial and final state radiation. The fact that \( \zeta > 1 \) can be attributed to a centrality bias in p+p events, caused by the requirement of a high \( p_T \) hadron pair. The impact parameter for these events are usually smaller than that for the minimum bias events used for the mixing, which may lead to more underlying event activity due to multiple parton-parton interactions (MPI).

Figure 10 compares the pedestal yield per-trigger integrated from \( 0.6 < p_T^b < 5 \) GeV/c as a function of trigger \( p_T \). The pedestal yield is expressed as transverse density per unit of azimuth and pseudo-rapidity, \( 1/N_a dN/d(\Delta \eta \Delta \phi) \), similar to [19]. The integrated UE yield increases rapidly at low trigger \( p_T \), then increases more slowly at high trigger \( p_T \). Again, the initial increase is related to the increase of MPI, while the slower rise for larger trigger \( p_T \) is mainly due to the initial and final state radiation effects.

Because of its non-perturbative nature, our current understanding of the UE is mainly obtained through tuning phenomenological monte carlo event generators, such as PYTHIA
FIG. 9: The summary of the $\zeta$ in various trigger $p_T$ bins as function of associated $p_T$ in p+p collisions.

and JIMMY [26], to match the data. In this analysis, we compare our results with calculations from PYTHIA. PYTHIA has a large set of parameters that can affect the jet yield and the UE yield. To facilitate the usage, PYTHIA pre-packages several collections of default parameter values, known as PYTHIA tunes (since version 6.410), each is identified with a unique integer number [27]. One of the popular tunes is the Rick Field tune that can reproduce the CDF RUN2 data, known as TUNE A (100). Another popular tune is TUNE S0A, which is based on the new PYTHIA UE framework introduced since version 6.3. The comparison also depends on the jet fragmentation scheme because we do the azimuthal correlation at the hadron level instead of reconstructing the full jet. In this analysis, we considered the following three different settings from PYTHIA 6.419.

- TUNE A (100), with parameter set tuned to CDF by Rick Field, string fragmentation.
- TUNE A (100), but with independent fragmentation.
FIG. 10: Pedestal yield per-trigger per unit of azimuth and pseudo-rapidity as a function of trigger $p_T$. The shaded band indicates the yield from minimum bias $p+p$ yield (corresponds to 21.9mb).

- TUNE S0A(303), with New UE/MI framework, string fragmentation.

For each setting, we generate enough simulated events, repeat the same ZYAM procedure as for the real data analysis, extract the jet yield and pedestal yield and compare with our measurements. A satisfying parameter setting should be able to reproduce all observables: single hadron spectra, jet yield and pedestal. Figure 11-13 show such comparison of the data to all three settings. None of the settings can describe all three observables simultaneously. In general, TUNE A with string fragmentation over-predicts the jet yield, but has the best match for the pedestal yield; TUNE A with independent fragmentation does a better job for the jet yield but it does an equally poor job for single spectra; TUNE S0A with string fragmentation can describe the single spectra and jet yield reasonably well, but greatly
FIG. 11: Comparison of PYTHIA tunes with the charged hadron spectra.

FIG. 12: Comparison of PYTHIA tunes with the per-trigger yield at the near-side (left panel) and away-side (right panel).

under-predicts the pedestal yield \(^1\). These comparisons show that our data can be used to optimize the parameter values at RHIC energy, and to tune their dependencies on collision

\(^1\) We would like to point out our UE study focuses at low \(p_T\) (< 5 GeV/c), it has been shown that the UE at high \(p_T\) in general has better agreement with the PYTHIA tunes \(^{28}\).
FIG. 13: Comparison of the $\zeta$ values with PYTHIA tunes in three trigger $p_T$ ranges.

If the enhancement of the pedestal is due to MPI (whose probability is proportional to overlap function), we should expect a strong centrality dependence of the pedestal yield in d+Au collisions. A systematic study of the pedestal yield from p+p to d+Au collisions thus can help us to understand the nature of the MPI in p+p. Figure 13 shows the $p_T$ dependence of $\zeta$ values for p+p and d+Au collisions. The $\zeta$ value at fixed $p_T$ decreases towards central d+Au collisions. The central d+Au collisions also show much weaker increase of $\zeta$ value with $p_T$. These results suggest that the centrality bias due to the triggering condition is much smaller in d+Au collisions than in p+p. In this case, the pedestal yield should be very close to the single particle yield for the corresponding centrality bin.

A simple model is used to understand the scaling behavior of the pedestal yield. In this model, we assume that hard-scattering giving rise to the jet signal occurs only in one nucleon-nucleon collision in each foreground d+Au event, all other nucleon-nucleon collisions in the same event are assumed to be the same as the normal minimum bias p+p collision. In this case, the ambient particle production should scale as $R_{dAu}$. The pedestal yields in p + p and d + Au, $UE_{dAu}$ and $UE_{pp}$, should be related to each other through the following relation.

$$UE_{dAu} = UE_{pp} + R_{dAu}(N_{coll} - 1)\min \text{BiasYield}_{pp}$$

(4)

From this equation, we can derive the following relation relating the $\zeta$ values in d+Au and p+p

$$\zeta_{dAu}N_{coll} = \zeta_{pp}/\epsilon_{mb} + R_{dAu}(N_{coll} - 1)$$

(5)
FIG. 14: The Centrality dependence of the $\zeta$ in d+Au collision and compared with $p+p$. The dashed lines are the estimated pedestal level based on Eq. 5. From top to bottom, the four lines corresponds to 60-88%, 40-60%, 20-40% and 0-20% d+Au collisions, respectively.

where $\epsilon_{mb}=0.694$ is the correction factor accounting for $p+p$ trigger efficiency in PHENIX. The calculated $\zeta$ values for d+Au collisions from this formula are indicated by the curves in Figure 14. Our model under-predicts the data at high $p_T$ and in central d+Au collisions, suggesting that more activities for ambient nucleon-nucleon collisions are preferred. It may also imply that initial state radiation associate with hard-scattering can further scatter with the Au nuclei, thus further increase the pedestal yield.

V. DISCUSSION

The results shown in Figure 5-7 are intriguing: while the jet shape in d+Au collisions is not modified much, the yield of correlated pairs is significantly enhanced relative to binary scaled $p+p$ collisions. This observation seems to imply that hard-scattering cross section is
enhanced but jet fragmentation and dijet acoplanarity are not modified much. Furthermore, the underlying event level in d+Au collisions exceeds their corresponding single particle yield (Figure14). This means that the cold nuclear matter effects already contribute a significant fraction of yield enhancement seen in Au+Au, but the shape modification in Au+Au collisions is mostly due to final state effects in dense medium. To make sense of these results, we examine in the following the list of known effects in d+Au collisions, and speculate the roles they may play in dihadron correlation results.

- **Shadowing/CGC effect**: This effect is responsible for the suppression of the single particle yield at low $p_T$. But our data seems to imply that it does not suppress the hard-scattering processes in the kinematic range considered in the analysis.

- **Power corrections**: The expectation of binary scaling relies on the factorization theorem, which should break down at small $Q^2$. The lowest pair momentum in our analysis is at around 1-1.5 GeV/$c$, which corresponds to a $Q^2$ value starting at around $Q^2 \approx 1 - 2(\text{GeV}/c)^2$. At such small $Q^2$ value, the modification jet signal due to power corrections might be significant.

- **Multi-parton collisions**: This refer to the situation where more than one hard-scattering happens in a given event, such processes in general break the factorization. The simplest case is double-parton collisions (two independent hard-scattering occurs in same event). The rate such scattering is greatly enhanced in nuclear environments. A simple estimation show that ratio of double-parton scattering to single hard-scattering is $\sigma_2^D/\sigma_1^D \approx 0.5(A/10)^{0.5}$.

- **Initial state multiple scattering effects**: The rate of multiple scattering, where a hard parton undergo one hard-scattering plus several soft scattering, is significantly enhanced in p+A collisions. Combined with steeply falling spectra can shift initial parton to higher $p_T$, it can increase the jet pair yield and pedestal yield. The fact that near-side jet shape is not modified suggests that the multiple scattering happens at the parton level before fragmentation.

- **Interaction of initial state radiation with the remaining nuclei**: In p+p collisions, such radiation simply fragments into final state hadrons. But in the d+Au environment,
they may undergo additional scattering with the nuclei, thus further increasing the observed jet pair yield and pedestal yield.

- **Cold nuclear jet energy loss:** This effect can increase the yield of the soft partons, which in turn leads to more pair yield at low $p_T$. However, this scenario also leads to a suppression of the high $p_T$ pair yield, which is not seen in our data. Thus this effect alone can not explain our data.

- **Isospin and EMC effects:** It can affect jet pair yield at very high $p_T^{\text{sum}}$ where the quark jet contribution are important. In the kinematic region of our analysis, most jet pairs should be dominated by gluon jets, hence these effects should not be important.

The exact contributions from each of these effects are not clear. It is possible that several effects conspire to give the observed modification on the jet correlation and the UE. Future theoretical efforts should use both single spectra and dihadron correlation results to better constraint these effects.

In summary, we performed a detailed study of the dihadron correlation in d+Au collisions over a broad $p_T$ range. A large Cronin-like enhancement is seen at low pair proxy energy while the jet shapes show little difference from p+p. This is the same region where a large modification of the jet properties are also observed in Au+Au collisions. This observation favors initial state multiple scattering effects at the partonic level. The jet properties in p+p are compared to several PYTHIA calculations. The most popular PYTHIA tunes that work well at Tevtron energy fail to simultaneously describe the single particle yield, jet pair yield, and especially the pedestal yield at RHIC energy. The scaling behavior of the pedestal yield from p+p to d+Au suggests that underlying event yield in d+Au exceeds a simple sum of one hard-scattering p+p collision and $N_{\text{coll}} - 1$ minimum bias p+p collisions. Theoretical investigation of the centrality dependence of the underlying event in d+Au can help us to understand the nature of the multiple parton interaction in p+p and d+Au.

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