Jet Structure from Dihadron Correlations in d+Au collisions at $\sqrt{s_{NN}}=200$ GeV

S.S. Adler, S. Afanasiev, C. Aidala, N.N. Ajitanand, Y. Akiba, A. Al-Jamel, K. Alexander, K. Aoki, L. Aphecetche, R. Armendariz, S.H. Arouson, R. Averbeck, T.C. Awes, V. Babintsev, A. Baldi, L. K.N. Barish, D.P. Barnes, B. Bassalleck, S. Bathe, S. Batsoulis, V. Baumbis, F. Bauer, A. Bazilevsky, S. Belikov, M.T. Bjornadal, J.G. Boissevain, H. Borel, M.L. Brooks, D.S. Brown, N. Brunner, D. Bucher, H. Buesching, V. Bunazhnov, G. Buve, J.M. Burward-Hoy, S. Butsyk, X. Camard, P. Chand, W.C. Chang, S. Chernichenko, C.Y. Chi, J. Chiba, M. Chiu, I.J. Choi, R.K. Choudhury, T. Chiu, V. Ciancio, Y. Cobigo, B.A. Cole, M.P. Comets, P. Constantin, M. Csanád, T. Csomó, J.P. Cussonneau, D. d’Enterria, K. Das, G. David, F. Desák, H. Delagrange, A. Denisov, A. Deshpande, E.J. Desmond, A. Devissems, O. Dietzsch, J.L. Drachenberg, O. Draper, A. Drees, A. Durum, D. Dutta, V. Dzhordzhadze, Y.V. Efremenko, H. En’yo, B. Espagnon, S. Esumi, D.E. Fields, C. Finck, F. Fleuret, S.L. Fokin, B.D. Fox, A. Fraenkel, E.J. Franz, A. Franz, A.D. Frawley, Y. Fukao, S.Y. Fung, S. Gadrat, M. Germain, A. Glemm, M. Gonin, J. Gossel, Y. Goto, R. Granier de Cassagnac, N. Grau, S.V. Greene, M. Grosse Perderkamp, H.-Á. Gustafsson, T. Hachiya, J.S. Haggerty, H. Hamagaki, A.G. Hansen, E.P. Hartouni, M. Harvey, K. Hasako, R. Hayano, X. He, M. Heffner, T.K. Hemmick, J.M. Heuser, P. Hidas, H. Hiejiama, J.C.H. Hill, R. Hobbs, W. Holzmann, K. Homma, B. Hong, A. Hoover, T. Horaguchi, T. Ichihara, H.I. Ikonomov, K. Imai, M. Inaba, M. Inuzuka, D. Isenhower, L. Isenhower, M. Ishihara, M. Issah, I. Isupov, B.V. Jakac, J. Jia, O. Jinnouchi, B.M. Johnson, S.C. Johnson, K.S. Jouo, D. Jouan, K. Jafar, S. Kametani, K. Kami, M. Kanada, J. Kang, S. Katou, T. Kawabata, A.V. Kazantsev, S. Kelly, K. Khachaturov, A. Khazadeev, J. Kikuchi, D.J. Kim, E. Kim, G.-B. Kim, H.J. Kim, E. Kinem, A. Kiss, E. Kistenev, A. Kiyomichi, M. Klein-Boesing, H. Kobayashi, L. Kochenda, V. Kochetkov, R. Kohara, B. Komok, M. Konno, D. Kotchetkov, A. Kozlov, P.J. Kroon, C.H. Kuberg, G.J. Kunde, K. Kurita, M.J. Kweon, Y.K. Kwon, G.S. Kyle, R. Lacey, L.J. Lajoie, Y. Le Borne, A. Lebedev, S. Leecy, D.M. Lee, M.J. Leitch, M.A.L. Leite, X.H. Li, A. Litvinenko, M.X. Li, C.F. Maguire, Y.I. Makdisi, A. Malakhov, V.I. Manko, Y. Mao, R. Martinez, H. Masui, M. Matthisas, T. Matsumoto, M.C. McCain, P.L. McGaughy, Y. Miao, T.E. Miller, A. Milov, S. Mioduszewski, G.C. Mishra, J.T. Mitchell, A.K. Mohanty, D.P. Morrison, J.M. Moses, D. Mukhopadhyay, M. Muniruzzaman, S. Nagamya, J.L. Nagle, T. Nakamura, J. Newby, A.S. Nyanin, J. Nystrand, E.O. O’Brien, C.A. Ogilvie, H. Ohnishi, J.D. Ojha, H. Okada, K. Okada, A. Oskarsson, J. Otterlund, K. Oyama, K. Ozawa, D. Pal, M.P. Palounek, V. Pantouv, V. Papavassiliou, J. Park, W.J. Park, S.F. Pate, H. Pei, V. Penev, J.-C. Peng, H. Pereira, V. Peresedov, A. Pierso, C. Pinkenburg, R.P. Pisani, M.L. Purschke, A.K. Purwar, J.M. Qualls, J. Rak, I. Ravonich, K.F. Read, M. Reuter, K. Reygers, V. Riabov, R. Riabov, G. Roche, A. Romana, M. Rosati, S.S.E. Rosendahl, P. Rosnet, V.L. Rykov, S.S. Ryu, N. Saito, T. Sakaguchi, S. Sakai, V. Samsonov, L. Sanfratello, R. Santo, H.D. Sato, S. Sato, S. Sawada, Y. Schultz, V. Semenov, R. Seto, I. Shein, T.-A. Shibata, K. Shigaki, M. Shimomura, A. Sickles, C.L. Silva, D. Silvermyr, K.S. Sim, A. Soldatov, R.A. Soltz, W.E. Sondhein, S.P. Sorensen, I.V. Sourkina, F. Staley, P.W. Stankus, E. Stenlund, M. Stepanov, A. Ster, S.P. Stoll, T. Sugitate, J.P. Sullivan, S. Takagi, E.M. Takagui, A. Taketani, K.H. Tanaka, K. Tanida, M.J. Tannenbaum, A. Taranenko, P. Tarján, T.L. Thomas, M. Togawa, T. Tojo, H. Torii, R.S. Towell, V.-N. Tram, I. Tseruyua, Y. Tsuchimoto, H. Tydesjö, T. Uyurin, H.W. van Hecke, J. Velkovský, M. Velkovský, V.V. Veszprémi, A.A. Vinogradov, M.A. Volkov, E. Vznuzdaev, X.R. Wang, W. Watanabe, S.N. White, N. Willis, F.K. Wohr, C.L. Woody, W. Xie, A. Yanovich, S. Yokoi, G.R. Young, I.E. Yushmanov, W.A. Zajc, C. Zhang, S. Zhou, Z. Jizhí, M. Zimányi, L. Zolim, X. Zong (PHENIX Collaboration)

1Abilene Christian University, Abilene, TX 79699, USA
2Institute of Physics, Academia Sinica, Taipei 11529, Taiwan
3Department of Physics, Banaras Hindu University, Varanasi 221005, India
4Bhabha Atomic Research Centre, Bombay 400 085, India
5Brookhaven National Laboratory, Upton, NY 11973-5000, USA
6University of California - Riverside, Riverside, CA 92521, USA

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Dihadron correlations at high transverse momentum in $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV at midrapidity are measured by the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC). From these correlations we extract several structural characteristics of jets: the root-mean-squared transverse momentum of fragmenting hadrons with respect to the jet $\sqrt{\langle p_T^2 \rangle}$, the mean sine-squared of the azimuthal angle between the jet axes $\langle \sin^2(\phi_{jj}) \rangle$, and the number of particles produced within the dijet that are associated with a high-$p_T$ particle ($dN/dx_E$ distributions). We observe that the fragmentation characteristics of jets in $d + Au$ collisions are very similar to those in $p + p$ collisions and that there is also little dependence on the centrality of the $d + Au$ collision. This is consistent with the nuclear medium having little influence on the fragmentation process. Furthermore, there is no statistically significant increase in the value of $\langle \sin^2(\phi_{jj}) \rangle$ from $p + p$ to $d + Au$ collisions. This constrains the effect of multiple scattering that partons undergo in the cold nuclear medium before and after a hard-collision.
I. INTRODUCTION

Jet production in high energy collisions is a useful tool to study the passage of scattered partons through a nuclear medium. A dominant hard-scattering process is two partons scattering to produce two high-\(p_T\) partons which then fragment to produce a dijet. In a nuclear environment the partons that participate in the collision can undergo multiple scattering within the nucleus, potentially changing the structure of the dijet. Such changes can provide information on the interaction of colored partons with the cold nuclear medium.

Some information on this interaction is already available at RHIC energies via the Cronin enhancement of the \(p_T\) spectra \[1\]. In \(d + A\) collisions at RHIC \[2\] \(k_T^2\), the cross-section for high-\(p_T\) particle production in \(d + A\) collisions is enhanced compared to \(p + p\) collisions, consistent with multiple scattering in the cold-nuclear medium increasing the transverse momentum of the partons. In this paper we report on a complimentary observable to the Cronin effect: the broadening of dijet distributions. Such broadening is directly related to the additional transverse momentum delivered to the partons during multiple scattering, and hence provides a complementary handle for comparison between experiment and theory.

Interpreting both \(d + A\) and \(A + A\) collisions requires solid knowledge of baseline \(p + p\) collisions, especially those dijet events at midrapidity that contain two, nearly back-to-back, jets produced from a hard (large \(Q^2\)) parton-parton interaction. Experimentally the jets are not exactly back-to-back and the acoplanarity momentum vector, \(k_T\), was measured in \(p + p\) collisions at ISR energies to have a magnitude, \(k_T\), on the order of 1 GeV/c \[3\]. This was much larger than the expectation that \(k_T\) was due to intrinsic parton transverse momentum governed by the hadron size, which would lead to \(k_T \sim 300\) MeV/c. It was realized early \[4\] that additional gluon radiation either before or after the hard scattering will increase the value of \(k_T\) and the dijet acoplanarity.

In collisions involving nuclei, multiple scattering within the nucleus increases the parton transverse momentum. E557 \[5\], E609 \[6\], and E683 \[7\] have all measured an increase in the dijet acoplanarity with atomic mass of the target. In the case of E683, they measured an \(A^2\) dependence of \(\langle k_T^2 \rangle\) for both \(\gamma + A\) and \(\pi + A\) collisions. This dependence is expected since the number of scatterings should be proportional to the length traversed in the nucleus (\(L \sim A^2\)). For large \(A\) the extracted \(\langle k_T^2 \rangle\) values are about 50% above that for collisions with the hydrogen target, implying that the multiple-scattering effects are as important to the broadening of the dijets as are the initial state effects at that energy. In the case of \(p + A\) reactions, the measured \(\langle k_T^2 \rangle\) values increase more slowly than \(A^2\). Since the \(\langle k_T^2 \rangle\) values show a strong energy dependence \[8\], we need to establish the initial and multiple-scattering contributions to \(\langle k_T^2 \rangle\) for \(p + A\) reactions at RHIC energies. The \(\langle k_T^2 \rangle\) values are also known to be dependent on the \(Q^2\) of the parton-parton interaction, increasing with rising \(Q^2\) \[9\] \[10\] \[11\].

No model is currently available that can reproduce all data on the Cronin effect and dijet broadening although most include multiple scattering as the underlying mechanism. A recent review \[12\] considered two large classes of models, 1) soft or Glauber scattering where the multiple scattering is either at the hadronic or partonic level and 2) semi-hard multiple scattering where the multiple scattering is at the partonic level. In both the soft and hard scattering models, the increase \(\Delta \langle k_T^2 \rangle = \langle k_T^2 \rangle_{p + A} - \langle k_T^2 \rangle_{p + p}\) is proportional to the product of the scattering cross section and the nuclear thickness function,

\[
\Delta \langle k_T^2 \rangle \propto \nu(b, \sqrt{s}) - 1 = \sigma_{MS}(\sqrt{s}) T_A(b) \tag{1}
\]

where \(\nu(b, \sqrt{s})\) is the number of interactions, \(b\) is the impact parameter of the collision, \(\sigma_{MS}\) is the multiple scattering cross-section, and \(T_A(b)\) is the nuclear thickness function. For the soft scattering models, \(\sigma_{MS}\) is defined to be \(\sigma_{NN}(\sqrt{s})\), the nucleon-nucleon scattering cross section, while for the semi-hard models \(\sigma_{MS}\) is \(\sigma_{iH}^N(\sqrt{s})\), the parton-nucleon semi-hard cross-section. In the specific case of hard sphere nucleon scattering \[13\]

\[
\nu(b, \sqrt{s}) = \sigma_{NN}(\sqrt{s}) \frac{4\pi}{\mu^2} \sqrt{1 - \frac{b^2}{R^2}}, \quad \text{where} \quad R \quad \text{is the nuclear radius, which gives an} \ A^2 \ \text{increase in} \ \Delta \langle k_T^2 \rangle.
\]

Both types of these models give the same trend in centrality and the same dependence on the target’s atomic mass. The difference between them is in the strength of the increase with respect to \(T_A(b)\) and how this changes with beam energy. We will compare the data in this paper to two specific implementations of the hard-scattering models from Qiu and Vitev \[14\], and Barnafoldi et al. \[15\].

An alternative view of the Cronin effect was recently proposed by Hwa and Yang \[16\]. These authors calculate the recombination of hard partons with soft partons released during the multiple collisions. Because this model reproduces the measured Cronin effect at RHIC without imparting successive transverse momentum kicks to the scattered partons, the authors suggest that there may be little to no increase in \(k_T\) from \(p + p\) to \(d + A\) collisions.

We also use jet-fragmentation observables to probe multiple scattering in cold nuclei, in particular \(\sqrt{\langle J_T^2 \rangle}\), the RMS of the mean transverse momentum of hadrons with respect to the fragmenting parton, and the frag-
mendment function of the parton, $D(z,Q^2)$, where $z$ is the fraction of the parton’s momentum that a hadron carries. If the parton suffers semi-hard inelastic collisions within the nuclear environment, the parton will lose energy and its subsequent hadronization will produce fewer high-$z$ fragments and more low-$z$ fragments. We cannot directly measure fragmentation functions via dihadron correlations, but we do measure the distribution of hadrons produced in association with a high-$p_T$ trigger particle. We plot these distributions as a function of $x_E$, where $x_E$ is defined as

$$x_E = \frac{p_{T,\text{trig}} - p_{T,\text{assoc}}}{|p_{T,\text{trig}}|^2} \quad (2)$$

The motivation for the variable $x_E$ can be most easily seen in the simple case where $z = 1$ for the trigger particle and the two hadrons are emitted back-to-back. In this case, $p_{T,\text{trig}}$ is the transverse momentum of the scattered parton ($q_{\text{parton}}$) and for the far-side $x_E = z_{\text{assoc}} = p_{T,\text{assoc}}/q_{T,\text{parton}}$. Relaxing the assumption on $z_{\text{trig}}$, there is still a simple relation between $x_E$ and $z$ for back-to-back jets at high-$p_T$, where $x_E \approx z_{\text{assoc}}/z_{\text{trig}}$. Hence the $dN/dx_E$ distribution for hadrons emitted back-to-back from the trigger hadron can be related to the fragmentation function: for more details see the end of Section II.

There is considerable information on $x_E$ distributions from $p+p$ collisions. The CCHK collaboration demonstrated that the $x_E$ distribution scaled, i.e. the distribution was approximately independent of $p_{T,\text{trig}}$. Scaling at higher $p_{T,\text{trig}}$ was also established by Fisk et al. and the CCOR collaboration, providing support for the idea that fragmentation of high-$p_T$ partons is independent of the momentum of the parton.

This scaling is however approximate and scaling violation was understood by Feynman et al. to be caused by the radiation of semi-hard gluons. Scaling violation of the fragmentation function $D(z,Q^2)$ is now well established experimentally (20) and references therein). For the $Q^2$ range considered in this paper ($10 < Q^2 < 1000$ GeV/$c^2$), the fragmentation functions used in NLO calculations drop by 25% for $z = 0.6$ over the range $10 < Q^2 < 100$ GeV/$c^2$. At higher $Q^2$ the fragmentation functions are less dependent on $Q^2$, e.g. the fragmentation drops by less than 20% at $z = 0.6$ over the much larger range of $100 < Q^2 < 1500$ GeV/$c^2$.

In this paper we quantify the extent to which our measured $x_E$ distributions in $d + $ Au collisions scale and compare the $x_E$ distributions to those from $p + p$ collisions at RHIC. The goal is to establish whether inelastic scattering in the cold medium or the recombination mechanism changes the effective fragmentation function. The $x_E$ distributions provide a stringent test the recombination model from Hwa and Wang. This model reproduces the Cronin effect in $d + $ Au collisions through shower thermal recombination mechanisms and predicts an increase in jet associated multiplicity, i.e. an increase in the near-angle $dN/dx_E$, in $d + $ Au relative to $p + p$ collisions.

The measured $x_E$ distributions in $d + $ Au also serve as a critical baseline for $Au + Au$ collisions, where the strong energy-loss in the dense, hot medium is expected to dramatically change the shape of these distributions.

Our three goals for this paper are 1) to report the characteristics of jet structures in $d + $ Au collisions at RHIC energies, 2) to establish the extent to which multiple scattering changes these structures as a function of centrality and by comparison with data from $p + p$ collisions, and 3) to establish the baseline for jet-structure measurements in heavy ion reactions. Any difference between jet properties in $Au + Au$ and $d + $ Au collisions should be attributable to the hot, dense nuclear matter created in the heavy ion collisions. The main results in this paper are presented in Section IV which details the measured values of $\langle j_2^2 \rangle$, $\langle \sin^2(\phi_{jj}) \rangle$, and the $p_T$, and $x_E$ distributions from $d + $ Au collisions at $\sqrt{s_{NN}}=200$ GeV. These results are derived from the fitted widths and yields of two-particle azimuthal correlations which are reported in Section IV. The experimental methods used to obtain these correlations are described in Section III and the jet quantities we use throughout the paper are fully defined in Section IV.

II. JET ANGULAR (AZIMUTHAL) CORRELATIONS

A. Two particle correlation

The defining characteristic of a jet is the production of a large number of particles clustered in a cone in the direction of the fragmenting parton. Traditionally, energetic jets are identified directly using standard jet reconstruction algorithms. In heavy-ion collisions, due to the large amount of soft background, direct jet reconstruction is difficult. Even in $p + A$ or $p + p$ collisions, the range of energy accessible to direct jet reconstruction is probably limited to $p_T > 5 - 10$ GeV/$c$, below which the jet cone becomes too broad and contamination from the ‘underlying event’ background is significant. Jet identification is even more complicated for detectors with limited acceptance, such as the PHENIX central arms, due to leakage of the jet cone outside the acceptance.

The two-particle azimuthal angle correlation technique provides an alternative way to access the properties of jets. It is based on the fact that the fragments are strongly correlated in azimuth ($\phi$) and pseudo-rapidity ($\eta$). Thus, the jet signal manifests itself as a narrow peak in $\Delta \phi$ and $\Delta \eta$ space. Jet properties can be extracted on a statistical basis by accumulating many events to build $dN/d\Delta \phi$ and $dN/d\Delta \eta$ distributions from $p + p$ collisions.

In heavy-ion collisions at CERN’s ISR facility, the two-particle azimuthal angle correlation technique was initially used in the 70’s to search for jet signals in $p + p$ collisions. More recently, $\Delta \phi$ distributions and correlation functions have been exploited for analysis of...
jet correlations at RHIC [27, 28, 29, 30, 31]. A detailed discussion of the two-particle correlation method can be found in [32]. These approaches overcome problems due to background and limited acceptance, and extend the study of jet observables to lower \( p_T \).

In the correlation method, two classes of particles are correlated with each other – trigger particles, and associated particles. Although the distinction between these two classes is artificial, trigger particles are typically selected from a higher \( p_T \) range. In this work, we distinguish between two primary categories of correlations:

- **Assorted-\( p_T \) correlation (AC)**, where the \( p_T \) ranges of trigger and associated particle do not overlap.
- **Fixed-\( p_T \) correlation (FC)**, where the \( p_T \) ranges for trigger and associated particles are identical.

In this paper, correlations are further categorized via a scheme which uses the identity of the trigger and associated particles. Four different types of such correlations are presented. Denoting the trigger particle \( p_T \) as \( p_{T,\text{trig}} \) and associated particle \( p_T \) as \( p_{T,\text{assoc}} \),

- **\( h^\pm - h^\pm \) FC**
  The \( p_T \) range of both the trigger and associated particle is \( 1 < p_T < 5 \) GeV/c.
- **\( h^\pm - h^\pm \) AC**
  There are three different selections,
  
  1. \( 2.5 < p_{T,\text{trig}} < 4 \) GeV/c with \( 0.5 < p_{T,\text{assoc}} < 2.5 \) GeV/c
  2. \( 4 < p_{T,\text{trig}} < 6 \) GeV/c with \( 0.5 < p_{T,\text{assoc}} < 4 \) GeV/c
  3. \( 3 < p_{T,\text{trig}} < 5 \) GeV/c with \( 0.5 < p_{T,\text{assoc}} < 3 \) GeV/c
- **\( p^0 - h^\pm \) AC**
  The trigger particle is a neutral pion and the associated particle is a charged hadron, where \( 5 < p_{T,\text{trig}} < 10 \) GeV/c with \( 1 < p_{T,\text{assoc}} < 5 \) GeV/c.

**B. Extraction of \( j_T \), \( \sin^2(\phi_{jj}) \) from the Correlation Function**

In this section, we discuss the framework for the two particle correlation method. Figures 1 and 2 illustrate the relation between the two particles and their parent jets, for the case when the parents are the same jet or the dijet, respectively. The figures also show the relationship between \( j_T \), \( \sin^2(\phi_{jj}) \) and the kinematic variables describing the trigger and associated particle. \( j_T \) is the component of the particle momentum perpendicular to the jet momentum. Its projection into the azimuthal plane is \( j_T \). The quantity \( p_{out} \) (denoted with \( N \) or \( F \) for near- or far-side, respectively) is the component of the associated particle’s \( p_T \) that is perpendicular to the trigger particle’s \( p_T \). The vector sum of \( k_{T,1} \) and \( k_{T,2} \) produces the dijet acoplanarity and the azimuthal angle between the jet axes is \( \phi_{jj} \).

The RMS value of \( j_T \) can be derived from the correlation functions. For the single jet fragmentation of Fig. 1 if we denote \( \Delta \phi \), \( \phi_{tj} \), and \( \phi_{aj} \), as the angles between trigger-associated, trigger-jet and associated-jet, respectively, then the following relations are true:

\[
\begin{align*}
\sin(\phi_{tj}) &= \frac{j_{T,\text{trig}}}{p_{T,\text{trig}}} \equiv x_{j,\text{trig}} \\
\sin(\phi_{aj}) &= \frac{j_{T,\text{assoc}}}{p_{T,\text{assoc}}} \equiv x_{j,\text{assoc}} \\
\sin(\Delta \phi) &= \frac{p_{out,N}}{p_{T,\text{assoc}}} \\
\Delta \phi &= \phi_{tj} + \phi_{aj}
\end{align*}
\]

Assuming \( \phi_{tj} \) and \( \phi_{aj} \) are statistically independent, we have (cross terms average to 0) for the near-side,

\[
\langle \sin^2 \Delta \phi_N \rangle = \langle \sin^2 \phi_{tj} \cos^2 \phi_{aj} \rangle + \langle \sin^2 \phi_{aj} \cos^2 \phi_{tj} \rangle
\]

Substituting the sin and cos terms from Eq. 3 into
Eq. 4, we obtain the equation for the RMS value of \( j_{\perp} \)
\[
\sqrt{\langle j_{\perp}^2 \rangle} = \sqrt{\left( \frac{\langle p_{\text{out},N}^2 \rangle}{1 + (x_h^2) - 2 \langle x_{\text{trig},j}^2 \rangle} \right)}.
\] (5)
where \( x_h = p_{T,\text{assoc}}/p_{T,\text{trig}} \).

In the gaussian approximation for the near-side azimuthal distributions, a simple Taylor expansion connects \( p_{\text{out}} \) with the jet width, \( \sigma \):
\[
\langle p_{\text{out}}^2 \rangle = 2 \langle p_{T,\text{assoc}} \rangle \sin^2 \Delta \phi
\approx \langle p_{T,\text{assoc}} \rangle \sin (\Delta \phi^2) - \frac{\Delta \phi^4}{3}
\approx \langle p_{T,\text{assoc}} \rangle \sin \sigma^2 - \sigma^4
\] (6)

Since Eq. 5 contains the variable \( x_{\text{trig},j} \) that depends on \( j_{\perp} \), we should calculate \( \sqrt{\langle j_{\perp}^2 \rangle} \) iteratively. In cases when trigger and associated particle \( p_T \) are much larger than the typical \( p_T \) value, the near-side jet width \( \sigma_N \) is small and \( x_{\text{trig},j} \approx 0 \). Hence Eq. 5 can be simplified as,
\[
\sqrt{\langle j_{\perp}^2 \rangle} \approx \frac{\sigma_N \langle p_{T,\text{assoc}} \rangle}{\sqrt{1 + (x_h^2)}}
\approx \sigma_N \frac{\langle p_{T,\text{trig}} \rangle \langle p_{T,\text{assoc}} \rangle}{\sqrt{\langle p_{T,\text{trig}} \rangle^2 + \langle p_{T,\text{assoc}} \rangle^2}}
\] (7)

Since \( j_{\perp} \) is the projection of hadron \( p_T \) perpendicular to \( p_T,j \), \( j_{\perp} \) is necessarily less than \( p_T \). So, for any given \( p_T \) range, there is always a upper kinematic cut off on the \( j_{\perp} \) distribution. This effect, known as the seagull effect, leads to a reduction on the observed \( \sqrt{\langle j_{\perp}^2 \rangle} \) from the expected value. It is important at low \( p_{T,\text{trig}} \) and becomes negligible once \( p_{T,\text{trig}} \gg \sqrt{\langle j_{\perp}^2 \rangle} \). The seagull effect can be parameterized and removed from the \( j_{\perp} \) values.

For the far-side correlation from Fig. 2 we have
\[
\pi - \Delta \phi_F = \phi_T + \phi_T + \phi_T
\sin(\Delta \phi_F) = \frac{\langle p_{\text{out},F} \rangle}{p_{T,\text{assoc}}}
\] (8)
where \( \phi_T \) is the azimuthal angle between the two jet axes. Expanding \( \sin^2 \Delta \phi_F \) and dropping all cross terms (which average to 0), we get
\[
\langle \sin^2 \Delta \phi_F \rangle = \langle \sin \phi_T \cos \phi_T \cos \phi_T \rangle^2 + \langle \sin \phi_T \cos \phi_T \cos \phi_T \rangle^2
\] (9)

We substitute Eq. 4 to get
\[
\langle \sin^2 \phi_T \rangle = \frac{\langle \sin^2 \phi_T \rangle^2}{\langle \sin^2 \phi_T \rangle^2 - \langle \sin^2 \phi_T \rangle^2}
\] (10)

Collecting terms in \( \phi_T \) produces
\[
\langle \sin^2 \phi_T \rangle = \frac{\langle \sin^2 \phi_T \rangle - \langle \sin^2 \phi_T \rangle^2}{1 - 2 \langle \sin^2 \phi_T \rangle^2}
\] (11)

Note that since \( \phi_T \) is the azimuthal angle between the jet axes, \( \sin^2(\phi_T) \) is one measure of the extent to which the jets are not back-to-back, and is hence a quantity that is sensitive to any additional scattering in \( d + Au \) collisions. We express the right side in terms of the observables \( \sigma_N \) and \( \sigma_F \), the RMS widths of distribution that we measure by expanding the sine term
\[
\langle \sin^2 \phi_T \rangle = \sigma^2 - \sigma^4 + 2/3 \sigma^6
\] (12)
which is good to 2% for rms widths at 0.5 rad and good to 0.6% for rms widths of 0.2 rad. Therefore
\[
\langle \sin^2 \phi_T \rangle = \frac{\left( \sigma_F^2 - \sigma_F^2 + 2/3 \sigma_F^6 \right) - \left( \sigma_N^2 - \sigma_N^2 + 2/3 \sigma_N^6 \right)}{1 - 2 \left( \sigma_N^2 - \sigma_N^2 + 2/3 \sigma_N^6 \right)}
\] (13)

The right hand side is now in terms of experimental observables which we will use to extract \( \sin(\phi_T) \).

We have attempted to extract \( k_T \) from \( \sin^2(\phi_{jj}) \). This requires assumptions on the scattered quark distribution, the magnitude of the momentum asymmetry between the partons due to the kt-kick, as well as the detailed shape of the fragmentation function. The current paper is focused on the comparison between \( p+p \) and \( d + Au \) collisions, which can be made with \( \sin^2(\phi_{jj}) \). Hence we leave the extraction of \( k_T \) to future work.

In this paper we report the RMS values of \( j_T \) and \( \sin^2(\phi_{jj}) \), where \( \sqrt{\langle j_T^2 \rangle} = \sqrt{2 \langle j_{\perp}^2 \rangle} \). In the literature, a \( j_T \) value is sometimes reported as the geometrical mean,
C. Conditional Yields

We also present in this paper the associated yield per trigger particle, referred to as the conditional yield (CY), as a function of $p_T$ and $x_E$. The CY is the number of particles produced in the same or opposite jet associated with a trigger particle

$$\text{CY}(p_T) = \frac{1}{N_{\text{trig}}} \frac{dN_h}{dp_T}$$  \hspace{1cm} (14)

and can be directly extracted from the measured Gaussian yields in the correlation functions.

To emphasize the importance of the CY, we note that it is related to the single- and two-particle cross sections:

$$\text{CY} = \frac{d^2\sigma}{dp_0 dp_b} \left/ \frac{d\sigma}{dp_T} \right.$$  \hspace{1cm} (16)

The interpretation for the two-particle cross section depends on whether one is studying the near- or far-side jet correlations. The conditional yield for particles from the near-side jet depends on the dihadron fragmentation function, while the conditional yield from the far-side jet depends on two independent fragmentation functions: one parton fragments to produce a hadron with $p_{T,\text{trig}}$, while the other scattered parton on the far-side fragments to produce a hadron with $p_{T,\text{assoc}}$. For the far-side conditional yield at high-$p_T$, $x_E \simeq z_{\text{assoc}}/z_{\text{trig}}$ (see Eq. 2). Hence, $d(x_E) \simeq d(z_{\text{assoc}})/z_{\text{trig}}$ and the slope of the far-side CY ($x_E$) is $z_{\text{trig}}$ times the slope of the fragmentation function $D(z)$.

III. EXPERIMENT AND DATA ANALYSIS

A. Data Collection

The data presented in this paper were collected by the PHENIX experiment at the Relativistic Heavy Ion Collider during the $d + Au$ and $p + p$ run of January – May 2003. During that time integrated luminosities were recorded of 2.7 nb$^{-1}$ for $d + Au$ collisions and 0.35 pb$^{-1}$ for $p + p$ collisions each at $\sqrt{s_{NN}}=200$ GeV.

The PHENIX detector consists of two central spectrometer arms, two forward muon arms and several global detectors used for triggering, vertex detection, and centrality selection. This analysis utilizes the two central spectrometer arms that each cover a region of $|\eta| < 0.35$ units of pseudorapidity and $90^\circ$ in azimuth. The spectrometer arms are not exactly back-to-back in azimuth, so while there is large acceptance for the detection of two particles separated by $180^\circ$ there is also finite acceptance for two particles separated by $90^\circ$. Figure 3 shows a beam cross-section view of the PHENIX central spectrometer arms. A complete overview of the whole PHENIX detector is found in reference [31]. In this section we will only focus on those subsystems relevant for the analysis of the dihadron data.

1. Global Event Characteristics

For event characterization the Beam-Beam Counters (BBCs) are utilized. The BBCs are sets of 64 Cherenkov counters placed symmetrically along the beam line, covering $3 < |\eta| < 3.9$ units of pseudorapidity and located 144 cm from the center of the interaction region. The BBCs determine the event vertex and the initial collision time, $t_0$, from the time difference between particles reaching each BBC. For this analysis we include only events with an offline cut of $|z_{\text{vertex}}| < 30$ cm.

The BBC facing the direction of the Au beam was used to determine the centrality. Fig. 4 shows the BBC charge distribution and the centrality classes used in this analysis. The centrality is defined as

$$\%\text{Centrality} = 88.5\%(1 - \text{frac}(Q_{\text{BBC}}))$$  \hspace{1cm} (17)

where frac($Q_{\text{BBC}}$) is the fraction of the total BBC charge distribution integrated from zero to $Q_{\text{BBC}}$ and $88.5\%$ is the efficiency of the minimum bias trigger. This centrality can be related to the mean number of Au participants, $\langle N_{\text{part}} \rangle$, and mean number of collisions, $\langle N_{\text{coll}} \rangle$. To determine the centrality we model the BBC charge distribution as a negative binomial distribution with a width...
TABLE I: Table of the mean number of collisions for \( d + Au \), \( N_{coll} \), versus the percentage of the total inelastic cross section and the nuclear overlap function \( T_A(b) \).

| Percent \( \sigma_{inel} \) | \( \langle N_{coll} \rangle \) | \( \langle T_A(b) \rangle (\text{mb}^{-1}) \) |
|---------------------------|-----------------|-------------------------------|
| 0–20%                     | 15.4 ± 1.0      | 0.367 ± 0.024                 |
| 20–40%                    | 10.6 ± 0.7      | 0.252 ± 0.017                 |
| 40–88%                    | 4.7 ± 0.3       | 0.112 ± 0.007                 |

and mean proportional to \( N_{part} \). So, for a given centrality, there are several negative binomial distributions (defined by \( N_{part} \)) that contribute to the overall distribution and as such \( N_{part} \) is not uniquely defined. We calculate a weighted average of \( N_{part} \), where the weight is given by the negative binomial distribution for a given \( N_{part} \) and the probability for having a collision with \( N_{part} \). The latter probabilities were computed using a Glauber model, with a Hulthen wave function for the deuteron and an inelastic cross section of 42 mb. Finally, the \( \langle N_{coll} \rangle \) was determined for a given \( \langle N_{part} \rangle \) from the same Glauber model. The resulting centrality bins and \( \langle N_{coll} \rangle \) used in this analysis are outlined in Table I.

The dihadron events were recorded using several different Level-1 triggers. The minimum bias trigger required at least one hit in each of the BBCs and that the collision vertex (computed online) satisfies \(|z_{\text{vertex}}| < 75 \text{ cm}\). It was sensitive to 88.5% of the inelastic \( d + Au \) cross section. PHENIX also employed a series of Level-1 triggers to select electrons, photons and, with lower efficiency, high-\( p_T \) hadrons. These triggers are called the ERT triggers and they utilized the Ring Imaging Cerenkov (RICH) for electron identification, together with the Electromagnetic Calorimeter (EMC) \(^{[36]}\), which consists of 8 sectors, 6 of which are Lead-Scintillator (PbSc) sampling calorimeters and 2 are Lead-Glass (PbGl) Cherenkov counters. The EMC has excellent timing and energy resolution for electromagnetic showers. The ERT triggers were produced by summing signals from tiles, where a tile was 4x5 photomultipliers (PMTs) in the RICH and either 2x2 or 4x4 PMTs in the EMC.

The electron trigger was defined by the coincidence between the minimum bias trigger and the RICH and EMC 2x2 trigger where the threshold for the RICH tile was 3 photo-electrons and the EMC threshold varied between 400–800 MeV. Three different thresholds were available for the 4x4 photon triggers. These thresholds differed between the PbGl and PbSc and varied within and between the \( p + p \) and \( d + Au \) runs. The lowest threshold setting (1.4 GeV–2.8 GeV) was most sensitive to hadron showers in the EMC. The threshold values and rejection factors (rejection = \( N_{\text{minBiasEvents}}/N_{\text{triggerEvents}} \)) for the ERT triggers, in coincidence with the minimum bias trigger, are given in Table I. The \( h^+ - h^\pm \) correlations use only the minimum bias triggered data, while the \( \pi^0 - h^\pm \) correlations use only the ERT photon triggers. The \( \pi^\pm - h^\pm \) correlations use the minimum bias, ERT photon and ERT electron triggers. A detailed knowledge of the ERT trigger efficiency is not necessary, since we present the conditional yield distributions per trigger, for which this efficiency cancels out.

2. Tracking and Particle Identification

In this section we discuss the tracking and identification of the particles used in the different correlation analyses. There are three types of particles included: Charged hadrons are used in all analyses, neutral pions are used as trigger particles for the \( \pi^0 - h^\pm \) correlations and charged pions are used as trigger particles for the \( \pi^\pm - h^\pm \) correlations.

Charged hadron tracks are measured outside the PHENIX central magnetic field by the Drift Chamber (DC), located 2.0 m from the vertex, and two layers of multi-wire proportional chamber (PC1 and PC3), located 2.5 and 5.0 m, respectively, from the vertex \(^{[37]}\). The DC determines the momentum and the azimuthal position of the track, while PC1 determines the polar angle \(^{[38]}\). The momentum resolution is determined to be 0.7% ± 1.1%\( p \) (GeV/c) \(^{[2]}\). Tracks are confirmed by requiring that an associated hit in PC3 lies within a 2.5\( \sigma \) (for \( h^\pm - h^\pm \)) or 3\( \sigma \) (for \( \pi - h^\pm \)) matching window in both the \( \phi \) and \( z \) directions. This cut reduces the background from particles not originating in the direction of the vertex. The remaining background tracks are mainly decays and conversion particles \(^{[39]}\). The background level for single-tracks is less than 5% below 3 GeV/c, increasing to about 30% at 5 GeV/c. However, the background is smaller for high-\( p_T \) triggered events (see Section II B). The charged particle tracking efficiency for the active region of the DC, PC1 and PC3 is better than 98%. Since we perform a pair analysis, the two track resolution is bet-

FIG. 4: (Color online) Total charge distribution on the Au-going side Beam-Beam Counter (BBC) for \( d + Au \) collisions and the centrality selection (see Table I).
The electron trigger requires the coincidence of the RICH trigger (threshold of 3 photo-electrons) for both $\gamma$ and the RICH and EMC detectors. Charged particles decreasing with increasing centrality.

There is a slight dependence on centrality with the $\pi$ for electrons, 3.5 GeV/c in the RICH [40]. This threshold corresponds to 18 MeV/c.

Electrons from photon conversions. The efficiency for detecting charged pions rises quickly past 4.9 GeV/c, reaching an efficiency of > 90% at $p_T > 6$ GeV/c.

To reject the conversion backgrounds in the pion candidates, the shower information at the EMC is used. Since most of the background electrons are genuine low $p_T$ particles that were mis-reconstructed as high $p_T$ particles, simply requiring a large deposit of shower energy in the EMC is very effective in suppressing the electron background. In this analysis a momentum dependent energy cut at EMC is applied

\[ E > 0.3 + 0.15 p_T \]  

Table II: EMC threshold and rejection factors for the electron and photon ERT triggers in coincidence with the minimum bias trigger for $p+p$ and $d+Au$. The photon triggers are defined by the energy sum of 4x4 PMTs in the EMC above threshold. The electron trigger requires the coincidence of the RICH trigger (threshold of 3 photo-electrons) for both $p+p$ and $d+Au$ runs) and the energy sum of 2x2 PMTs in the EMC above threshold.

|        | $p+p$            | $d+Au$            | $p+p$            | $d+Au$            | rejection | rejection |
|--------|------------------|-------------------|------------------|-------------------|-----------|-----------|
| PbSc threshold | 2.1 GeV          | 2.1 GeV           | 2.8 GeV          | 3.5 GeV           | 400–1200  | 125–300   |
| PbGl threshold | 2.1 GeV          | 2.8 GeV           | 2.8–3.5 GeV      | 3.5–4.2 GeV       | 1500–3100 | 450–900   |
| Gamma1 | 2.1 GeV          | 2.1 GeV           | 2.8 GeV          | 2.8 GeV           | 70–160   | 15–60     |
| Gamma2 | 2.8–3.5 GeV      | 3.5–4.2 GeV       | 6–0.8 GeV        | 5–1200            | 30–170   |           |
| Gamma3 | 1.4 GeV          | 1.4 GeV           | 0.6–0.8 GeV      | 5–1200            | 30–170   |           |
| Electron | 0.4–0.8 GeV      | 0.4–0.8 GeV       | 0.6–0.8 GeV      | 5–1200            | 30–170   |           |

Neutral pions are detected by the statistical reconstruction of their $\gamma\gamma$ decay channel. These decay photons are detected by the EMC and identified by their time-of-flight (TOF) and shower shape. The electromagnetic shower shape is typically characterized by the $\chi^2$ variable $\chi_i^2$,

\[ \chi^2 = \sum_i \left( \frac{E_i^{\text{meas}} - E_i^{\text{pred}}}{\sigma_i^{\text{pred}}} \right)^2 \]  

where $E_i^{\text{meas}}$ is the energy measured at tower $i$ and $E_i^{\text{pred}}$ is the predicted energy for an electromagnetic particle of total energy $\sum_i E_i^{\text{meas}}$. This $\chi^2$ value is useful for the discrimination of electromagnetic from hadron showers. The $\chi^2$ and TOF cuts used give a very clean sample of photons with contamination of other particles at $< 1\%$.

Using pairs of photons that pass these EMC cuts, we create the invariant mass spectra for each photon pair $p_T$. A sample invariant mass distribution with a $S/B$ of approximately twelve is given in Fig. 5. The background distribution can be reproduced by mixing clusters from different events and normalizing that distribution to the real event distribution outside the $\pi^0$ mass region. The peak position and width of the invariant mass distribution were parameterized as a function of pair $p_T$, in order to select $\pi^0$ candidates from a region of invariant mass within 2$\sigma$ of the peak position. The $S/B$ for a $\pi^0$ with $p_T > 5$ GeV is 10–20, increasing as a function of $p_T$. There is a slight dependence on centrality with the $\pi^0$ $S/B$ deceasing with increasing centrality.

PHENIX identifies high momentum charged pions with the RICH and EMC detectors. Charged particles with velocities above the Cherenkov threshold of $\gamma_{\text{th}} = 35$ (CO$_2$ radiator) emit Cherenkov photons, which are detected by photo-multiplier tubes (PMTs) in the RICH [40]. This threshold corresponds to 18 MeV/c for electrons, 3.5 GeV/c for muons and 4.9 GeV/c for charged pions. In a previous PHENIX publication [39], we have shown that charged particles with reconstructed $p_T$ above 4.9 GeV/c, which have an associated hit in the RICH, are dominantly charged pions and background electrons from photon conversions. The efficiency for detecting charged pions rises quickly past 4.9 GeV/c, reaching an efficiency of > 90% at $p_T > 6$ GeV/c.

To reject the conversion backgrounds in the pion candidates, the shower information at the EMC is used. Since most of the background electrons are genuine low $p_T$ particles that were mis-reconstructed as high $p_T$ particles, simply requiring a large deposit of shower energy in the EMC is very effective in suppressing the electron background. In this analysis a momentum dependent energy cut at EMC is applied

\[ E > 0.3 + 0.15 p_T \]  

In addition to this energy cut, the shower shape information $\chi_i^2$ is used to further separate the broad hadronic showers from the narrow electromagnetic showers and hence reduce the conversion backgrounds. In this analysis we use the probability (prob) calculated from the $\chi^2$ value (Eq. 15) for an EM shower. The probability values range from 0 to 1, with a flat distribution expected for an EM shower and a peak around 0 for a hadronic shower. Fig. 5 shows the probability distribution for the pion can-
didates and electrons, normalized by the integral, where the pions candidates were required to pass the energy cut and the electrons were selected using particle ID cuts similar to that used in Ref. [41]. Indeed, the electron distribution is relatively flat, while the charged pions peak at 0. A cut of prob < 0.2 selects pions above the energy cut with an efficiency of $\gtrsim 80\%$. Detailed knowledge of the pion efficiency is not necessary, since we present in this paper the per trigger pion conditional-yield distributions, for which this efficiency cancels out.

Since the energy and prob cuts are independent of each other, we can fix one cut and then vary the second to check the remaining background level from conversions. The energy cut in Eq. 19 is chosen such that the raw pion yield is found to be insensitive to the variation in prob. Fig. 7 shows the raw pion spectra for ERT triggered events as function of $p_T$, with the above cuts applied. The pion turn on from 4.9 – 7 GeV/c is clearly visible. Below $p_T$ of 5 GeV/c, the remaining background comes mainly from the random association of charged particles with hits in the RICH detector. The background level is less than 5% from 5 – 16 GeV/c, which is the $p_T$ range for the charged pion data presented in this paper.

B. Data Analysis

In this section we outline the method to obtain correlation functions and distributions. From these we extract the jet shapes and yields outlined in Section 11. For the extraction of the jet-yield from the azimuthal distributions we discuss how we obtain the absolute normalization of the distribution, while for the jet shape properties, $J_T$, and $\langle \sin^2\phi_{jj} \rangle$, the absolute normalization is not necessary.

Azimuthal correlations functions are generally defined as

$$ C (\Delta \phi) \propto \frac{N_{\text{cor}} (\Delta \phi)}{N_{\text{mix}} (\Delta \phi)} $$

Similarly, one can also define the correlation function in pseudo-rapidity,

$$ C (\Delta \eta) \propto \frac{N_{\text{cor}} (\Delta \eta)}{N_{\text{mix}} (\Delta \eta)} $$

The same-event pair distribution, $N_{\text{cor}} (\Delta \phi)$ or $N_{\text{cor}} (\Delta \eta)$, is constructed for trigger-associated particle pairs. The mixed-event pair distribution, $N_{\text{mix}} (\Delta \phi)$ or $N_{\text{mix}} (\Delta \eta)$, is determined by combining trigger particles with associated particles from randomly selected events.

This definition of the correlation function relies on the fact that detector acceptance and efficiency cancels. It is therefore important that the pair efficiencies of the average mixed event background and the average foreground distributions are the same. For this reason we generate mixed event distributions only for events with similar centrality and event vertex. More precisely, mixed events were required to match within $\pm 10\%$ centrality and the event vertices were also required to be within $\pm 3$ cm. For $h^\pm - h^\pm$ correlations the real and mixed events are minimum bias data. For $\pi^0 - h^\pm$ correlations the real and mixed events are ERT-triggered data. For $\pi^\pm - h^\pm$ correlations the real events are ERT-triggered and minimum bias data while the mixed events mix ERT-triggered events with minimum bias events.

For $h^\pm - h^\mp$ and $\pi^\pm - h^\pm$ correlations, due to finite two track resolution for charged particles at the DC and PC, the reconstruction efficiency for same-event charged
track pair drops at small $\Delta \phi$ and $\Delta \eta$. To minimize the difference of the pair efficiency between $N_{\text{mix}}(\Delta \phi)$ and $N_{\text{mix}}(\Delta \phi)$, the pairs are required to have a minimal separation of about two times the resolution at the various tracking detectors. This corresponds to about 0.28 cm, 8 cm and 15 cm at the DC, PC1 and PC3, respectively. However, these pair cuts are not required for $\pi^0 - h^\pm$ correlations, because different detector subsystems are used for reconstructing trigger-$\pi^0$ and the associated charged tracks as outlined earlier.

Given the similarity of the analysis techniques between $\Delta \phi$ and $\Delta \eta$ correlations, in this paper we focus on the $\Delta \phi$ correlation. The $\Delta \phi$ correlation functions are obtained with two different normalizations. For $h^\pm - h^\pm$ assorted correlations, the correlation function is area normalized

$$C_{\text{norm}}(\Delta \phi) = \frac{N_{\text{cor}}(\Delta \phi)}{N_{\text{mix}}(\Delta \phi)} \times \int d\Delta \phi(N_{\text{mix}}(\Delta \phi)) \int d\Delta \phi(N_{\text{cor}}(\Delta \phi))$$  \hspace{1cm} (22)

The details concerning this normalization are discussed in Section [I A]. The second normalization is used in both the $\pi^0 - h^\pm$ and $\pi^\pm - h^\pm$ correlations. It was shown in Ref. [32] that the CY can be derived from the measured correlation function with an appropriate normalization,

$$\frac{1}{N_{\text{trig}}} \frac{dN}{d\Delta \phi} = \frac{R_{\Delta \eta}}{N_{\text{trig}}} \frac{N_{\text{cor}}(\Delta \phi)}{2\pi N_{\text{mix}}(\Delta \phi)} \int d\Delta \phi N_{\text{mix}}(\Delta \phi)$$  \hspace{1cm} (23)

where $N_{0}^{\text{trig}}$ and $N_{\text{trig}}$ are the true and detected number of triggers respectively, and $\epsilon$ is the average single particle efficiency for the associated particles in $2\pi$ in azimuth and $\pm 0.35$ in pseudo-rapidity. $R_{\Delta \eta}$ corrects for the loss of jet pairs outside a given $\Delta \eta$ acceptance, determined by PHENIX’s finite acceptance in $\eta$. This second normalization is defined so that the integral of the resulting correlation function should be $N_{0}/N_{\text{trig}}$, the total number of pairs per trigger particle in a given azimuthal and eta range.

For the normalization in Eq. (23) there are two separate efficiencies that must be determined, the $\Delta \eta$ correction and the single particle efficiency. The near-side correlation has a well-behaved peak around $\Delta \eta = 0$. As we show in Section [I A], the near-side jet width in $\Delta \phi$ and $\Delta \eta$ are consistent with each other within errors. So we correct the near-side yield to the full-jet yield assuming the shape of the jet is Gaussian and the widths are equal in $\Delta \phi$ and $\Delta \eta$. This correction, according to Ref. [32], is

$$R_{\Delta \eta} = \frac{1}{\int_{-0.7}^{0.7} d\Delta \eta e^{-\frac{(\Delta \eta - 0.7)^2}{2\sigma^2}}}$$  \hspace{1cm} (24)

where $acc(\Delta \eta)$ represent the PHENIX pair acceptance function in $|\Delta \eta|$. It can be obtained by convoluting two flat distributions in $|\eta| < 0.35$, so $acc(\Delta \eta)$ has a simple triangular shape: $acc(\Delta \eta) = (0.7 - |\Delta \eta|)/0.7$. The PHENIX single particle acceptance is flat in $\eta$ to within 5%.

In the far-side the jet signal is much broader than the PHENIX acceptance due to the broad range of momentum-fraction $x$ of the partons that participate in the hard-scattering. In fact, we studied the far-side jet shape for $\pi^\pm - h^\pm$ correlation (Fig. 17) and found the true jet correlation strength is almost constant in the PHENIX pair acceptance $|\Delta \eta| < 0.7$. Based on that, we assume that the far-side jet strength is constant and correct the far-side yield to the corresponding accessible pair range of $|\Delta \eta| < 0.7$,

$$R_{\Delta \eta}^{\text{far}} = \frac{2 \times 0.7}{\int_{-0.7}^{0.7} d\Delta \eta e^{-\frac{(\Delta \eta - 0.7)^2}{2\sigma^2}}} = 2$$  \hspace{1cm} (25)

$R_{\Delta \eta}^{\text{far}}$ equals two, because the pair efficiency has a triangular shape in $|\Delta \eta| < 0.7$, which results in 50% average efficiency when the real jet pair distribution is flat in $|\Delta \eta| < 0.7$. Figure 8 shows the correction factor $R_{\Delta \eta}$ as a function of jet width. The typical range of the near-side jet width in all analysis (see Section [I A]) is below 0.5 radian. The maximum correction is about a factor of 2 for the near-side jet.

The single particle efficiency for associated particles, $\epsilon$, includes detector acceptance and reconstruction efficiency. It is evaluated in a way similar to previously published Au + Au [39] and $d + Au$ [2] analyses. However, the jet associated charged hadron spectrum in $d + Au$ is much flatter than the inclusive charged hadron spectra, so the corrections due to momentum scale and momentum resolution are much smaller than that for inclusive charged hadron. For the same reason, the background contamination at high $p_T$, mainly coming from decay and photon conversions which are falsely reconstructed as high $p_T$ tracks [2, 39], is also reduced. We studied

\footnote{For example in Fig. 21 the jet associated yields decreases by a factor of 100 from 0.5 to 5 GeV/c. However the typical single inclusive hadron spectra decrease by a factor of 100000 [2].}
both effects using a full GEANT simulation of PYTHIA events through PHENIX detectors. The jet associated yields were extracted in the same manner as for the real data analysis. By comparing it with the input jet associated yield spectra, we can quantitatively study the effect of momentum smearing and high $p_T$ background contamination. The corrections due to momentum scale and resolution are found to be less than 5% with 3% systematic errors. For high-$p_T$ triggered events, the background contamination to the associated charged hadrons is found to be 5% independent of $p_T$ from 1–5 GeV/c.

2. Extracting jet properties

The normalized correlation functions and conditional yield distributions are both fitted with a sum of two Gaussians to extract the jet widths and the conditional yield of hadrons in the near-side ($\Delta \phi \sim 0$) and far-side ($\Delta \phi \sim \pi$). The fit for the normalized correlation functions is described in Section IV A. For the conditional yield, we fit with the following function

$$\frac{1}{N_{trig}} \frac{dN_0}{d\Delta \phi} = B + \frac{\text{Yield}_N}{2\pi \sigma_N} e^{-\Delta \phi^2 / 2 \sigma_N^2} + \frac{\text{Yield}_F}{2\pi \sigma_F} e^{-\Delta \phi^2 / 2 \sigma_F^2},$$

where $B$ reflects the combinatoric background level in the real distribution relative to the mixed distribution and the other two terms represent the near-side jet and far-side jet signal, respectively. The resulting widths, $\sigma_N$ and $\sigma_F$, are then used to calculate the jet shapes via Eqs. 7 and 13. For each choice of trigger and associated particle $p_T$ range, Yield$_N$ and Yield$_F$ directly reflects the jet associated yield, $dN/dp_{T, assoc}$ at the near and far-side, respectively.

Two methods were used to calculate the $dN/dx_E$ distribution. The first method was used for $\pi^0 - h^\pm$ correlations. Since these correlations are binned in $p_T$ there is a distribution of $x_E$ for each trigger-associated $p_T$ bin. This distribution is approximately Gaussian. The fitted peak value is used as the bin center of the $dN/dx_E$ distributions and the fitted gaussian width is used as the horizontal error bar. To estimate the bin-width in $x_E$, we use the definition Eq. 2 which can be written as (ignoring the sign) $x_E = p_{T,assoc} \cos(\Delta \phi) / p_{T, trig}$. We estimate $\cos(\Delta \phi) \approx 1$ and write the bin-width as

$$\Delta x_E = \frac{p_{T, assoc}^{\text{max}} - p_{T, assoc}^{\text{min}}}{(p_{T, trig})},$$

where we have an associated $p_T$ bin from $[p_{T, trig}^{\text{min}}, p_{T, trig}^{\text{max}}]$ and a trigger $p_T$ bin with a mean $(p_{T, trig})$.

The second method is adopted by $\pi^\pm - h^\pm$ analysis. It is statistically based and can be used to calculate the distribution for any pair variable $p_{T, trig}, p_{T, assoc}, \Delta \phi, \Delta \eta, x_E, p_{out}$ etc. In the following we show two examples: the $dN/d\Delta \phi$ and $dN/dx_E$ distributions. For each pair we calculate the $\Delta \phi$ and $x_E$ value, then from Eq. 28 we calculate the same correction factor that was used for the $dN/d\Delta \phi$ distribution.

$$w(\Delta \phi) = \frac{R_{\Delta \eta} \frac{1}{2\pi N_{mix}(\Delta \phi)} \frac{1}{d\Delta \phi N_{mix}(\Delta \phi)}}$$

If this weight is used to fill the $\Delta \phi$ histogram for the real and mixed distribution, we obtain the $CY$ for the true real pairs,

$$\frac{1}{N_{trig}} \frac{dN_0}{d\Delta \phi} = \sum_i \Delta \phi_{\text{real}} w(\Delta \phi_{\text{real}})$$

and for the mixed pair the sum should be one by definition,

$$\text{background}(\Delta \phi) = \sum_i \Delta \phi_{\text{mix}} w(\Delta \phi_{\text{mix}}) \equiv 1.$$

Thus the jet signal can be extracted as

$$\frac{1}{N_{trig}} \frac{dN_{\text{jet}}}{d\Delta \phi} = \sum_i \Delta \phi_{\text{real}} w(\Delta \phi_{\text{real}}) - \frac{B}{\sum_i \Delta \phi_{\text{mix}} w(\Delta \phi_{\text{mix}})}$$

consistent with Eq 26.

When this weight is used to fill the $x_E$ histogram for both real and mixed distributions, we obtain the $dN/dx_E$ by subtracting the mixed $x_E$ distribution from the real $x_E$ distribution,

$$\frac{1}{N_{trig}} \frac{dN_{\text{jet}}}{dx_E} = \sum_i x_{\text{real}} w(\Delta \phi_{\text{real}}) - \frac{B \times \sum_i x_{\text{mix}} w(\Delta \phi_{\text{mix}})}.$$

Equation 31 is rather trivial, because the weighting procedure is equivalent to Eq. 28, for which we know the shape of the distribution (Eq. 20). But the advantage of the weighting procedure is that it allows for the determination of the absolute background pair distribution in any pair variables.

Similarly, the statistical method is used to extract the $p_{T,assoc}$ and $p_{out}$ spectra as

$$\frac{1}{N_{trig}} \frac{dN_{\text{jet}}}{dp_{T,assoc}} = \sum_i p_{T,assoc}^{\text{real}} w(\Delta \phi_{\text{real}}) - \frac{B \times \sum_i p_{T,assoc}^{\text{mix}} w(\Delta \phi_{\text{mix}})}$$

$$\frac{1}{N_{trig}} \frac{dN_{\text{jet}}}{dp_{out}} = \sum_i p_{out}^{\text{real}} w(\Delta \phi_{\text{real}}) - \frac{B \times \sum_i p_{out}^{\text{mix}} w(\Delta \phi_{\text{mix}})}$$

By construction, the integral of the jet yield should be conserved independent of the pair variable used, i.e.:
\[
\int d\Delta \phi \frac{dN_{0}}{d\Delta \phi} = \int dx_{E} \frac{dN_{\text{jet}}}{dx_{E}} = (35)
\]

\[
\int dp_{T, \text{assoc}} \frac{dN_{0}^{\text{jet}}}{dp_{T, \text{assoc}}} = \int dp_{\text{out}} \frac{dN_{0}^{\text{jet}}}{dp_{\text{out}}}
\]

C. Systematic Uncertainties

The correlation analyses presented here consist of several steps ranging from the generation of correlation functions to the extraction of the final physics variables (\(J_{T}, \sin(\phi_{jj})\), per trigger yields, etc.) from these correlation functions. Systematic error estimations for each of these steps have been evaluated and combined to determine the overall error quoted for each measurement. All errors quoted are maximum extent.

Systematic errors associated with the generation of correlation functions can result from shape distortions in either the foreground or the background distributions. These distortions can arise if the requisite quality cuts (see section IIIA) are not stable. In order to minimize such errors, the track-pair and quality cuts were assigned such that the correlation functions were essentially insensitive to reasonable cut variations. Systematic errors associated with such cut variations are estimated to be less than 4%. A further source of systematic errors is related to the efficiency of the background rejection when requiring a confirmation hit in the outer pad chamber. The yields have been corrected for remaining background. The systematic error on the background estimate is \(\approx 3\%\) for tracks with a transverse momentum \((p_{T}) < 4\) GeV/c and \(\approx 7\%\) for particles with \(4 < p_{T} < 6\) GeV/c. For the calculation of the conditional yields, the systematic error is dominated by the uncertainties associated with the determination of the efficiency corrected single particle yields. These systematic errors have been estimated to be \(\approx 10\%\) as obtained from Ref. [2]. This error has two parts: the normalization error includes the error on PC3 matching and active area. The momentum smearing error includes contributions from momentum resolution and momentum scale.

A separate error is estimated for \(\pi^{0} - h^{\pm}\) correlations due to the background contamination of the \(\pi^{0}\)'s within the mass bin. To estimate the width and yield contribution of the background \(\gamma\gamma\) pairs, we created correlations of \(\gamma\gamma\) outside the \(\pi^{0}\) mass with hadrons. From these we extrapolated the background contribution at the \(\pi^{0}\) mass. These systematic errors are \(p_{T}\)-dependent. For the near and far angle width the variation is \(1 - 3\%\), the near yield variation is \(1\%\), the far yield variation is \(1 - 5\%\) and increases with increasing \(p_{T}\).

The event mixing technique has been used to correct for the limited detector acceptance and inefficiency. In addition, the \(CY\) has been corrected for limited \(\Delta \eta\) coverage. To cross check these procedures we have run a detailed simulation using the PYTHIA event generator [42] coupled to a single particle acceptance filter that randomly accepts charged particles according to the detector efficiency. In the following, we shall use \(\pi^{\pm} - h^{\pm}\) as an example for this cross check. Figure 8 shows a typical PHENIX two dimensional single particle acceptance used in this analysis.

We generated 1 million PYTHIA events, each required to have at least one \(> 6\) GeV/c charged pion. To speed up the event generation, a \(Q^{2}\) cut of 100 GeV\(^{2}\) on the underlying parton-parton scattering is required. These events were filtered through the single particle acceptance filter. As an approximation, we ignore the \(p_{T}\) dependence of acceptance. The same event and mixed pair \(\Delta \phi\) distributions were then built by combining the accepted \(\pi^{\pm}\) and charged hadrons. The jet width and raw yield were extracted by fitting the \(\frac{dN_{\text{jet}}}{dp_{T}}\) with a constant plus double gaussian function. The raw yields were then corrected via Eq. (24) to full jet yield for the near-side and the yield in \(|\Delta \eta| < 0.7\) for the far-side. We also extracted the true \(CY\) and jet width without the acceptance requirement. The comparison of the \(CY\) and jet width with and without the acceptance requirement are shown in Fig. 10. The trigger particles are \(\pi^{\pm}\) with \(6 < p_{T, \text{trig}} < 10\) GeV/c, the associated particles are \(h^{\pm}\). In the near-side, the corrected yield (top left panel) and width (bottom left panel) are compared with those extracted without acceptance filter. In the far-side, the yield corrected back to \(|\Delta \eta| < 0.7\) (top right panel) and the width (bottom right panel) are compared with those extracted without the acceptance filter. The data requiring the acceptance filter are always indicated by the filled circles, while the expected yield or width are indicated with open circles.

The agreement between the two data sets can be better seen by plotting the ratios, which are shown in Fig. 11. The yields agree within 10% and the widths agree within 5%. Since \(\sqrt{\langle J^{2}_{T} \rangle}, \langle \sin^{2}(\phi_{jj}) \rangle\) are derived from the jet widths, the agreement in width naturally leads to the agreement in the \(\sqrt{\langle J^{2}_{T} \rangle}\) and \(\langle \sin^{2}(\phi_{jj}) \rangle\). One notices
that there are some systematic differences in the comparison of the yield at low $p_{T,\text{assoc}}$. This might indicate that the Gaussian assumption is not good enough when the jet width is wide and the extrapolation for $|\Delta \eta| > 0.7$ become sizeable. (At $p_{T,\text{assoc}} = 0.5$ GeV/c, the jet width $\sigma_N = 0.5$ (rad) and the extrapolation is about 20%).

The approximations in the formulas used to extract $j_{Ty}$ and $\sin^2(\phi_{jj})$ are used to estimate the systematic error on these quantities. We estimate the systematic uncertainty in the formulation at the level of 5% for the $\sqrt{j_{Ty}^2}$ and 3-4% for the $\sqrt{\sin^2(\phi_{jj})}$.

Table III summarizes the systematic errors for the extracted widths, $\sqrt{j_{Ty}^2}$ and $\sqrt{\sin^2(\phi_{jj})}$, while Tables IV and V summarize the list of systematic errors on the CY for the hadron-hadron, neutral pion-hadron, and charged pion-hadron correlations, respectively. Table VI outlines the systematic errors on the $p_{out}$ extraction from pion-hadron correlations.

IV. RESULTS

We present the minimum bias and centrality dependent results on extracted jet widths and yields in Section IV A which are used in Section IV B to calculate quantities describing the jet-structures: the values of $\sqrt{j_{Ty}^2}$, $\sin^2(\phi_{jj})$, and jet fragmentation conditional yields $dN/dp_T$ and $dN/dx_E$. The minimum-bias $d + Au$ results are compared with results from $p + p$ in Section IV C to establish the extent of effects due to medium modification in $d + Au$ with as much statistical precision as possible. The $d + Au$ centrality dependence of the derived quantities is presented in Section IV D. This provides a larger lever-arm in nuclear thickness function, at the cost of dividing the available minimum-bias data into different centrality bins.

A. Correlation Functions, Widths and Yields

The baseline data from which jet structures are extracted are the correlation functions and conditional pair distributions that were defined in Section III A. Figure 12 shows representative correlation functions between two charged hadrons, while Figs. 13 and 14 show representative conditional yield distributions triggered on neutral pions ($\pi^0$) and charged pions respectively. All three correlation sets (Fig. 12 to 14) show relatively narrow peaks centered at $\Delta \phi = 0$ and $\pi$ radians. The widths of these structures decrease with larger $p_T$, which is consistent with narrowing of the jet cone for increasing $p_T$.

The fractional area under the jet peak relative to the flat underlying background also increases significantly as function of associated particle $p_T$, indicating increasing (di)jet contributions to the correlation function. In particular, Fig. 14 shows that for events where there is a high $p_T$ trigger, a large fraction of the low $p_T$ (as low as 0.4 – 1 GeV/c) particles are coming from the dijet fragmentation, and the jet contribution dominates at $p_T > 2$ GeV/c. Events tagged with a high $p_T$ jet are much harder than a typical minimum bias event.

We characterize the jet correlations shown in Figs. 12 to 14 by assuming that there are only two contributions to the correlation function – (di)jet correlations and an isotropic underlying event. This scenario can then be expressed as:
TABLE III: Summary of the systematic errors on the widths and $j_T$, $\langle \sin^2(\phi_{jj}) \rangle$.

| Error source                                      | $< 4\%$ | $< 5\%$ | $1 \text{–} 3\%$ |
|--------------------------------------------------|---------|---------|------------------|
| tracking cuts, pair cuts                         |         |         |                  |
| assumptions used in formula                      |         |         |                  |
| S/B correction ($\pi^0$ only)                     |         |         |                  |

TABLE IV: Summary of the systematic errors on the Conditional Yields for $h^\pm - h^\pm$ analysis.

| Error source                                      | $< 4 \text{ GeV/c}$ | $4 \text{–} 6 \text{ GeV/c}$ |
|--------------------------------------------------|----------------------|--------------------------------|
| quality cuts                                     | $< 4\%$             | $< 4\%$                        |
| background correction                            | 3%                   | 30%                             |
| error on single particle yields                  | 10%                  | 10%                             |

TABLE V: Summary of the systematic errors on the Conditional Yields for $\pi^0 - h^\pm$ analysis.

| Single Particle | $p_T, \text{assoc}$ (GeV/c) | $< 2$ | 2–3 | $> 3$ |
|-----------------|----------------------------|-------|-----|-------|
| $\epsilon_{\text{single}}$ normalization | 6.5% |       |      |       |
| $p$ smearing (reso+scale)               | 3%   |       |      |       |
| near-side yield                              | 1%   |       |      |       |
| S/B                                         |      | 5%    | 2%  | 1%    |

TABLE VI: Summary of the systematic errors on the Conditional Yields for $\pi^\pm - h^\pm$ analysis.

| Single Particle | $p_T, \text{assoc}$ (GeV/c) | $< 1$ | 1–2 | 2–3 | 3–4 | 4–5 |
|-----------------|----------------------------|-------|-----|-----|-----|-----|
| $\epsilon_{\text{single}}$ normalization | 6.5% |       |     |     |     |     |
| $p$ smearing (reso+scale)               | 3%   |       |     |     |     |     |
| trigger pion background | 5%  |       |     |     |     |     |
| centrality dependent part                | 5%   |       |     |     |     |     |
| pair cuts                                   | 1%   | 1%   | 2%  | 3%  | 4%  |
| near-side yield                            | 20%  | 10%  | 6%  | 6%  | 6%  |
| far-side yield                             | 6%   |      |     |     |     |
| error on the fit                           | 10–20% | 6%  | 4%  | 4%  | 4%  |

TABLE VII: Summary of the systematic errors on the $p_{out}$ distribution for $\pi^\pm - h^\pm$ analysis.

| $p_{out}$ (GeV/c) | $< 0.5$ | 0.5–1  | 1–2   | 2–2.5 |
|-------------------|---------|--------|-------|-------|
| yield extraction (near) | 8%  | 15%   | 20%   | 20%   |
| yield extraction (far) | 8% | 15%   | 20%   | 30%   |
| other errors       | 10.6%  | 10.6%  | 10.6% | 10.6% |

\[
C(\Delta \phi) = A_o (1 + J(\Delta \phi)) \tag{36}
\]

where $A_o$ denotes the isotropic background and $J(\Delta \phi)$ is the jet-function. Approximating the jet-function as the sum of two Gaussians, we fit the correlations with:

\[
C(\Delta \phi) = A_o (1 + \frac{\lambda_N}{\sqrt{2\pi}\sigma_N} e^{-\frac{\Delta \phi^2}{2\sigma_N^2}} + \frac{\lambda_F}{\sqrt{2\pi}\sigma_F} e^{-\frac{(\Delta \phi - \pi)^2}{2\sigma_F^2}}) \tag{37}
\]

Here, $\lambda_{N,F}$ are the normalized Gaussian areas and $\sigma_{N,F}$ are the Gaussian widths for the near and far-side jets respectively. For the pair distribution functions we fit with the same shaped function, but with a different normalization (Eq. 26) as outlined in section III B.

Figure 15 shows the associated-\textit{p_T} dependence of the extracted widths for both the near- and far-side peaks. The results here are not sensitive to the slightly different range.
from the charged-hadron correlation functions with the trigger range for the charged hadron being 3 – 5 GeV/c. The data are tabulated in Table VII.

TABLE VII: Near and far-side widths as a function of $p_{T,\text{assoc}}$ for charged hadron triggers (3 – 5 GeV/c) and associated charged hadrons from $d + Au$ collisions.

| $\langle p_{T,\text{assoc}} \rangle$ (GeV/c) | $\sigma_{\text{near}}$ (rad) | $\sigma_{\text{far}}$ (rad) |
|-----------------------------------------|------------------|------------------|
| 0.59                                    | 0.411 ± 0.055    | 0.89 ± 0.28      |
| 0.83                                    | 0.395 ± 0.039    | 0.807 ± 0.128    |
| 1.2                                     | 0.364 ± 0.032    | 0.636 ± 0.079    |
| 1.7                                     | 0.291 ± 0.023    | 0.688 ± 0.103    |
| 2.2                                     | 0.246 ± 0.019    | 0.637 ± 0.146    |
| 2.7                                     | 0.236 ± 0.023    | 0.415 ± 0.114    |

In Fig. 12 we present the same quantities from the table for identified pions, where there is excellent agreement between the $\pi^0$ and charged-pion data sets. For both types of identified pions the trigger $p_T$ range is 5 – 10 GeV/c and these data are tabulated in Tables X and XI.

The far-side widths shown in Figs. 15 and 16 are larger than the near-side widths, as expected, since the far-side structure is a convolution of two jet fragmentations as well as any $k_T$ of the scattered partons. The widths of the correlation functions also steadily decrease as a function of $p_{T,\text{assoc}}$ as expected from (di)jet fragmentation. For completeness we also tabulate the near- and far-side widths extracted as a function of $p_{T,\text{trig}}$ for identified pions. These data are tabulated in Tables XIX and XXI.

Although PHENIX single particle acceptance is lim-
TABLE IX: Near and far-side widths as a function of $p_{T,\text{assoc}}$ for charged pion triggers ($5 - 10$ GeV/c) and associated charged hadrons from minimum-bias $d + Au$ collisions.

| $p_{T,\text{assoc}}$ (GeV/c) | $\sigma_{\text{near}}$ (rad) | $\sigma_{\text{far}}$ (rad) |
|-----------------------------|-----------------------------|-----------------------------|
| 0.50                        | 0.440 ± 0.044               | 0.651 ± 0.052               |
| 0.70                        | 0.391 ± 0.026               | 0.587 ± 0.039               |
| 0.90                        | 0.331 ± 0.023               | 0.613 ± 0.044               |
| 1.23                        | 0.271 ± 0.010               | 0.517 ± 0.024               |
| 1.75                        | 0.210 ± 0.008               | 0.433 ± 0.022               |
| 2.24                        | 0.193 ± 0.009               | 0.372 ± 0.023               |
| 2.73                        | 0.165 ± 0.007               | 0.317 ± 0.020               |
| 3.44                        | 0.135 ± 0.006               | 0.307 ± 0.020               |
| 4.42                        | 0.128 ± 0.008               | 0.287 ± 0.023               |

FIG. 15: Near (a) and far-side (b) widths as a function of $p_{T,\text{assoc}}$ for charged hadron correlations from minimum-bias $d + Au$ collisions (see text). Bars are statistical errors.

TABLE X: Near and far-side widths as a function of $p_{T,\text{assoc}}$ for neutral pion triggers ($5 - 10$ GeV/c) and associated charged hadrons from minimum-bias $d + Au$ collisions.

| $p_{T,\text{assoc}}$ (GeV/c) | $\sigma_{\text{near}}$ (rad) | $\sigma_{\text{far}}$ (rad) |
|-----------------------------|-----------------------------|-----------------------------|
| 1.21                        | 0.284 ± 0.011               | 0.494 ± 0.022               |
| 1.71                        | 0.227 ± 0.007               | 0.410 ± 0.019               |
| 2.37                        | 0.193 ± 0.005               | 0.380 ± 0.015               |
| 3.39                        | 0.177 ± 0.006               | 0.322 ± 0.020               |
| 4.41                        | 0.130 ± 0.007               | 0.315 ± 0.026               |

FIG. 16: (Color online) a) near-side width, b) far-side width as a function of $p_{T,\text{assoc}}$ for a charged pion (open symbols) and neutral pion (closed symbols) triggers from the $p_{T,\text{trig}}$ range of $5 - 10$ GeV/c in minimum-bias $d + Au$ collisions (see text). Bars are statistical errors.

| $p_{T,\text{assoc}}$ (GeV/c) | Near side, $\sigma$ (rad) | Far side, $\sigma$ (rad) |
|-----------------------------|---------------------------|--------------------------|
| 1.21                        | 0.284 ± 0.011             | 0.494 ± 0.022             |
| 1.71                        | 0.227 ± 0.007             | 0.410 ± 0.019             |
| 2.37                        | 0.193 ± 0.005             | 0.380 ± 0.015             |
| 3.39                        | 0.177 ± 0.006             | 0.322 ± 0.020             |
| 4.41                        | 0.130 ± 0.007             | 0.315 ± 0.026             |

are consistent in both directions. Figure 15 shows the far-side jet shape in $\Delta \eta$, the associated pair distribution is flat within ±10%.

Figure 16 shows the comparison of the near-side jet width in $\Delta \phi$ and $\Delta \eta$ from $d + Au$. There is overall very good agreement between the two data sets. However, the width in $\Delta \eta$ is systematically lower than that in $\Delta \phi$ at small $p_{T,\text{assoc}}$. This is due to the fact that the the underlying background is not completely flat in $\Delta \eta$, but varies by up to 10% in $|\Delta \eta| < 0.7$. Thus the procedure of dividing by the mixed-event distribution (Eq. 21) introduces some distortion of the jet shape at large $\Delta \eta$, and consequently leads to a slightly different value for the jet width. In fact for $p + p$ collisions, Figure 15 indicates a similar discrepancy between $\Delta \phi$ and $\Delta \eta$ at small $p_{T,\text{assoc}}$ for $p + p$ collisions. Thus this deviation is not likely due to the cold medium effect in $d + Au$.

We extract not only the widths of the jet-structures but also the conditional yields of how many hadrons are in the near-side and far-side structures for each high-$p_T$ trigger. The conditional yield defined in Eq. 14 can be obtained from either a correlation function or conditional pair distribution, both of which produce identical results. For the conditional pair distributions the conditional yield is directly extracted from the fit parameters

$^3$ $\eta$ dependence of the single particle yield is very weak in $0 < |\eta| < 1$ [43]. Thus the underlying pair distribution in $|\Delta \eta| < 0.7$ is almost flat.
(Eq. 20), while for correlation functions several normalization factors need to be applied to obtain the per trigger yield, as described below.

For correlation functions, it is convenient to define the fraction of jet-correlated particle pairs per event, $n_{jet \, pair} / n_{total \, pair}$. Following the basic ansatz outlined in Eq. 36, the fraction of jet-correlated particle pairs is obtained by summing the jet function over all bins in $\Delta \phi$ and dividing by the total summing the jet function over all bins in $\Delta \phi$ and dividing by the total sum of the correlation function

$$n_{jet \, pair} / n_{total \, pair} = \frac{\sum A_{trig}(\Delta \phi) \cdot C(\Delta \phi)}{\sum C(\Delta \phi)}. \quad (38)$$

Such pair fractions are shown as a function of $p_{T,assoc}$ for a trigger hadron of $3.0 < p_{T} < 5.0$ GeV/c and a centrality selection of 0 – 80% in Fig. [19]. The results, shown for both the near and far-side jets, indicate an increase in the average fraction of jet-correlated particle pairs with $p_{T}$ as might be expected if jet fragmentation becomes the dominant particle production mechanism as $p_{T}$ is increased.

The pair-fraction is multiplied by the ratio $n_{pairs} / n_{trig} n_{assoc}$, is obtained via multiplication by the efficiency corrected single particle yield ($n_{assoc}^{corr}$) for the selected associated $p_{T}$ bin of interest;

$$n_{jet \, pair} / n_{trig} = \frac{n_{jet \, pair}}{n_{trig} n_{assoc}} \cdot \frac{n_{assoc}^{corr}}{n_{assoc}}. \quad (40)$$

The per trigger yields for hadron triggers (found using Eq. 10) are corrected for the azimuthal acceptance and tracking efficiency but are reported within the PHENIX $\eta$ acceptance for the central arms, i.e. no $R(\Delta \eta)$ corrections are applied to the hadron-triggered conditional yields.

Figure 20 plots the near- and far-side invariant conditional yields extracted via Eq. 10 for different trigger $p_{T}$ selections as indicated. An approximate exponential decrease with $p_{T}$ is observed, i.e. there are more low-$p_{T}$ particles associated with each high-$p_{T}$ trigger hadron. The data are tabulated in Tables XI and XII.

In Fig. 21 the conditional yields for identified pion triggers are plotted as function of $p_{T,assoc}$ for both near-side correlation and far-side correlation. For this high-$p_{T}$ data, the conditional yields are extracted from the fits to
FIG. 18: The comparison of jet width as function of $p_{T,\text{assoc}}$ in $\Delta \phi$ (solid circles) and $\Delta \eta$ (open boxes) from $\pi^+ - h^+$ correlation with $5 < p_{T,\text{trig}} < 10$ GeV/c. a) results for $d + Au$. b) results for $p + p$. Bars are statistical errors.

FIG. 19: Average jet pair fraction per event as a function of $p_{T,\text{assoc}}$ in $\Delta \phi$ (solid circles) and $\Delta \eta$ (open boxes) from $\pi^+ - h^+$ correlation with $5 < p_{T,\text{trig}} < 10$ GeV/c. a) results for $d + Au$. b) results for $p + p$. Bars are statistical errors.

The conditional yields presented in FigOAs. b) results for $d + Au$ and associated charged hadrons from $d + Au$ collisions. The data for the widths are tabulated in Table XV and XVII Centrality dependence of various jet-structure observables. This work is extended in Section XVII where we present the centrality dependence of various jet-structure observables.

The agreement between the two pion-triggered data sets is good, which indicates that the jet fragmentation function is independent of whether a neutral pion or a charged pion trigger is used. The difference in the magnitudes of far-side and near-side yield reflect the fact that the far-side correlations measures a hadron triggered effective fragmentation while the near-side correlation measures dihadron fragmentation.

The conditional yields presented in FigOAs. b) results for $d + Au$ and associated charged hadrons from $d + Au$ collisions. The data for the widths are tabulated in Table XV and XVII Centrality dependence of various jet-structure observables. This work is extended in Section XVII where we present the centrality dependence of various jet-structure observables.

Since multiple scattering should increase with centrality, we examine whether these jet characteristics exhibit any centrality dependence. Figure XXIX shows the compilation of $\langle p_{T,\text{assoc}} \rangle$ and associated charged hadrons from $d + Au$ collisions.

| $\langle p_{T,\text{assoc}} \rangle$ (GeV/c) | $dN/dp_{T,\text{near}}$ | $dN/dp_{T,\text{far}}$ |
|------------------------------------------|----------------|----------------|
| 0.592 | 0.327 ± 0.092 | 0.383 ± 0.182 |
| 0.831 | 0.307 ± 0.045 | 0.339 ± 0.079 |
| 1.190 | 0.174 ± 0.018 | 0.158 ± 0.024 |
| 1.702 | 0.081 ± 0.009 | 0.066 ± 0.014 |
| 2.205 | 0.042 ± 0.006 | 0.028 ± 0.009 |

| $\langle p_{T,\text{assoc}} \rangle$ (GeV/c) | $dN/dp_{T,\text{near}}$ | $dN/dp_{T,\text{far}}$ |
|------------------------------------------|----------------|----------------|
| 0.831 | 4.437 ± 1.040 | 6.031 ± 2.010 |
| 1.200 | 2.725 ± 0.506 | 2.051 ± 0.562 |
| 1.700 | 1.907 ± 0.278 | 2.046 ± 0.447 |
| 2.210 | 0.819 ± 0.152 | 0.804 ± 0.244 |
| 2.931 | 0.497 ± 0.107 | 0.258 ± 0.061 |

TABLE XIII: Near and far-side conditional yields as a function of $p_{T,\text{assoc}}$ for charged hadron triggers (2.5 - 4 GeV/c) and associated charged hadrons from $d + Au$ collisions.

TABLE XIV: Near and far-side conditional yields as a function of $p_{T,\text{assoc}}$ for charged hadron triggers (4 - 6 GeV/c) and associated charged hadrons from $d + Au$ collisions.

B. Jet Properties in Minimum Bias $d + Au$ Collisions

From the angular widths and yields in the previous section, we calculate the following quantities that characterize the jet structures: transverse momentum of hadrons with respect to the jet ($p_T$), the dijet acoplanarity ($\sin^2(\phi_{jj})$), and the $dN/dx_E$ distributions. These quantities are first presented for minimum-bias $d + Au$ collisions, which have the highest statistical precision, and are then compared with results from $p + p$ in Section XVIII.

Figure XXVII shows the compilation of $\sqrt{\langle j_T^2 \rangle}$ values ex-
FIG. 20: (Color online) Per trigger yield (a) and invariant and solid stars, respectively. The efficiency and are reported in the PHENIX eta acceptance. the open points are the far-side yields. The centrality range respectively. The closed points are the near-side yields and ranges of 2.

The values for at approximately the same for all four analysis. The near dN/dp near collisions.

TABLE XV: Near and far-side conditional yields as a function of p_{T,assoc} for charged pion triggers (5 – 10 GeV/c) and associated charged hadrons from minimum-bias d + Au collisions.

| p_{T,assoc} (GeV/c) | dN/dp_{T,near} | dN/dp_{T,far} |
|---------------------|----------------|---------------|
| 0.5                 | 1.57 ± 0.083   | 2.54 ± 0.15   |
| 0.7                 | 0.91 ± 0.049   | 1.53 ± 0.13   |
| 0.9                 | 0.574 ± 0.031  | 1.00 ± 0.087  |
| 1.1                 | 0.542 ± 0.032  | 0.727 ± 0.068 |
| 1.3                 | 0.456 ± 0.026  | 0.801 ± 0.058 |
| 1.5                 | 0.351 ± 0.022  | 0.451 ± 0.044 |
| 1.7                 | 0.303 ± 0.018  | 0.365 ± 0.038 |
| 1.9                 | 0.235 ± 0.015  | 0.327 ± 0.031 |
| 2.1                 | 0.172 ± 0.012  | 0.222 ± 0.025 |
| 2.3                 | 0.135 ± 0.010  | 0.203 ± 0.022 |
| 2.5                 | 0.108 ± 0.008  | 0.162 ± 0.018 |
| 2.7                 | 0.0905 ± 0.0075| 0.145 ± 0.017 |
| 2.9                 | 0.0742 ± 0.0064| 0.107 ± 0.013 |
| 3.1                 | 0.0645 ± 0.0059| 0.070 ± 0.011 |
| 3.3                 | 0.0490 ± 0.0052| 0.0819 ± 0.0113|
| 3.5                 | 0.0473 ± 0.0047| 0.0647 ± 0.0097|
| 3.7                 | 0.0439 ± 0.0045| 0.0636 ± 0.0084|
| 3.9                 | 0.0367 ± 0.0040| 0.0495 ± 0.0075|
| 4.1                 | 0.0281 ± 0.0034| 0.0327 ± 0.0064|
| 4.3                 | 0.0297 ± 0.0034| 0.0446 ± 0.0068|
| 4.5                 | 0.0256 ± 0.0031| 0.0238 ± 0.0048|
| 4.7                 | 0.0192 ± 0.0027| 0.0397 ± 0.0061|
| 4.9                 | 0.0112 ± 0.0021| 0.0137 ± 0.0036|

TABLE XVI: Near and far-side conditional yields as a function of p_{T,assoc} for neutral pion triggers (5 – 10 GeV/c) and associated charged hadrons from minimum-bias d + Au collisions.

| p_{T,assoc} (GeV/c) | dN/dp_{T,near} | dN/dp_{T,far} |
|---------------------|----------------|---------------|
| 1.21                | 0.545 ± 0.035  | 0.718 ± 0.076 |
| 1.71                | 0.289 ± 0.014  | 0.389 ± 0.030 |
| 2.21                | 0.236 ± 0.009  | 0.203 ± 0.018 |
| 2.72                | 0.102 ± 0.006  | 0.155 ± 0.012 |
| 3.22                | 0.0724 ± 0.0049| 0.090 ± 0.012 |
| 3.73                | 0.0448 ± 0.0039| 0.0560 ± 0.0071|
| 4.23                | 0.0308 ± 0.0029| 0.0481 ± 0.0058|
| 4.72                | 0.0152 ± 0.0017| 0.0495 ± 0.0060|

A combined fit based on data points at p_T > 2 GeV/c gives a plateau value of $\sqrt{j_T}$ = 0.64 ± 0.02(stat) ± 0.04(sys) GeV/c for minimum bias d + Au collisions. A key quantity that provides information on multi-
ple scattering in the cold nuclear medium is \( \langle \sin^2(\phi_{jj}) \rangle \), where \( \phi_{jj} \) is the azimuthal angle between the jet axes. As described in Section II, we calculate \( \sin^2(\phi_{jj}) \) from the experimental values of the near- and far-side widths (Eq. 13). Figure 25 shows \( \langle \sin^2(\phi_{jj}) \rangle \) as function of \( p_{T,\text{assoc}} \) for high-\( p_T \) pion triggers. We observe that the RMS of the sine of the angle between the jet axes, \( \langle \sin^2(\phi_{jj}) \rangle \), decreases as higher-\( p_T \) associated particles are selected. There is good agreement between the two data sets. Figure 26 plots \( \langle \sin^2(\phi_{jj}) \rangle \) as a function of \( p_{T,\text{trig}} \), where a similar decrease with \( p_T \) is observed.

In the next section we will calculate the quadrature difference \( \langle \sin^2(\phi_{jj}) \rangle \) between \( d+Au \) and \( p+p \) collisions, and use that to quantify the affect of additional final-state scattering in \( d+Au \) collisions.

In Section IV A we defined the near-side and far-side \( p_{\text{out}} \). With this observable, it is possible to move beyond calculating means or RMS values and hence the \( p_{\text{out}} \) distribution potentially carries more information about the dijet acoplanarity. The measured \( p_{\text{out}} \) distributions for \( \pi^\pm - h^\pm \) are shown in Fig. 27 for the near-side and far-side. The far-side \( p_{\text{out}} \) has a broader distribution than the near-side \( p_{\text{out}} \), reflecting the fact that \( k_T \) is larger than \( j_T \). The \( p_{\text{out}} \) distributions have a power law tail, possibly due to strong radiative processes driving large values of \( p_{\text{out}} \).

In Section IV A we reported the yields of associated hadrons per trigger particle, or the conditional yield. A more comprehensive way of quantifying the fragmentation function is to plot the conditional yields as a function of \( x_E \). This is shown in Fig. 28 for \( \pi^\pm - h \) (solid circles) and \( \pi^0 - h \) (open crosses).

Previously, in ISR experiments, the slope of the \( x_E \) distribution has been determined to be around 5.3 (GeV/c)^{-1}. In Fig. 29 the conditional yields as a function of \( x_E \) are plotted for trigger \( p_T \) range of \( 5 - 6 \) GeV/c. In order to compare data with the previous ISR results, we have determined the exponential

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TABLE XVII: Near and far-side widths as a function of \( N_{\text{coll}} \) for charged hadron triggers (2.5 – 4 GeV/c) and associated charged hadrons (1-2.5 GeV/c) from \( d+Au \) collisions.

| Centrality | \( \sigma_{\text{near}} \) (rad) | \( \sigma_{\text{far}} \) (rad) |
|------------|-----------------|-----------------|
| 0-20 %     | 0.351 ± 0.021   | 0.669 ± 0.072   |
| 20-40 %    | 0.364 ± 0.024   | 0.670 ± 0.068   |
| 40-80 %    | 0.325 ± 0.018   | 0.628 ± 0.070   |

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TABLE XVIII: Near and far-side conditional yields as a function of \( N_{\text{coll}} \) for charged hadron triggers (2.5 – 4 GeV/c) and associated charged hadrons (1-2.5 GeV/c) from \( d+Au \) collisions.

| Centrality | \( dN/dp_T \) near | \( dN/dp_T \) far |
|------------|-----------------|-----------------|
| 0-20 %     | 0.150 ± 0.021   | 0.113 ± 0.030   |
| 20-40 %    | 0.182 ± 0.023   | 0.118 ± 0.033   |
| 40-80 %    | 0.151 ± 0.014   | 0.102 ± 0.023   |

---
The smaller inverse slope for the near-side. Note, however, that the difference between dihadron fragmentation and sinh-polarization ranges.

To check whether this is still true in d + Au collisions, we plot in Fig. 30 the conditional yields for two trigger $p_T$ ranges, $2.5 < p_T < 4$ GeV/c and $4 < p_T < 6$ GeV/c, respectively. The dashed lines represent exponential fits to the data. The slopes extracted are $6.3 \pm 1.2$ for the lower trigger $p_T$ range and $6.1 \pm 0.8$ for the higher trigger $p_T$ window, respectively. Within the statistics of the charged hadron dataset we do not observe a strong sensitivity of the slope of the $x_E$ distributions to the trigger $p_T$.

A direct way of quantifying the scale dependence of the $x_E$ distribution is to plot the far-side conditional yields versus $p_T$ for a fixed range of $x_E$. This is shown in Fig. 24, where the conditional yields are found to be independent of $p_T$, i.e. there is no significant deviation from scaling. We will quantify any scaling violation in this data when we compare these $x_E$ distributions from $d + Au$ to distributions from $p+p$ collisions in Section IV C.

In Fig. 23, near- and far-side widths for several centrality selections from $d + Au$ collisions. Results are shown for $\pi^0 - h$ correlations with the trigger $\pi^0 < p_T < 10$ GeV/c and the associated $p_T$ range of $2 < p_T < 3$ GeV/c. Bars are statistical errors.

Inverse slope $0.3 < x_E < 0.7$ and obtain the inverse slope parameter of $6.0 \pm 0.3$ (GeV/c)$^{-1}$ in the near-side and $7.1 \pm 0.5$ (GeV/c)$^{-1}$ in the far-side. The near-side $x_E$ inverse slope is smaller than that for the far-side, reflecting the difference between dihadron fragmentation and single hadron fragmentation. By requiring a trigger particle on the near-side, one reduces the jet energy available for fragmenting to the second hadrons and consequently a smaller inverse slope for the near-side. Note, however, that the $x_E$ distributions do not have pure exponential shape, and the fitted inverse slope is sensitive to the fitting ranges.

It is well known that fragmentation functions $D(z)$ approximately scale in $e^+e^-$ or $p + p$ collisions, i.e. are independent of jet energy. To check whether this is still true in d + Au collisions, we plot in Fig. 23 the conditional yields as a function of $x_E$ for different ranges of trigger $p_T$ from $\pi^\pm - h^\pm$ correlations. All curves fall on top of each other, indicating a universal behavior of the jet fragmentation function.

At lower $p_T$ we have $x_E$ distributions from the h- correlations. In Fig. 24, far-side conditional yields as obtained from charged hadron correlation functions are plotted versus $<p_T>$. Here, $<p_T>$ has been calculated from the $<p_{T,\text{trig}}>$ and $<p_{T,\text{assoc}}>$ extracted angular widths. Results are shown for two trigger $p_T$ ranges, $2.5 < p_{T,\text{trig}} < 4$ GeV/c and $4 < p_{T,\text{trig}} < 6$ GeV/c, respectively. The dashed lines represent exponential fits to the data.

While the slopes extracted are $6.3 \pm 1.2$ for the lower trigger $p_T$ range and $6.1 \pm 0.8$ for the higher trigger $p_T$ window, respectively. Within the statistics of the charged hadron dataset we do not observe a strong sensitivity of the slope of the $x_E$ distributions to the trigger $p_T$.

FIG. 23: Near- and far-side widths for several centrality selections from $d + Au$ collisions. Results are shown for $\pi^0 - h$ correlations with the trigger $\pi^0 < p_T < 10$ GeV/c and the associated $p_T$ range of $2 < p_T < 3$ GeV/c. Bars are statistical errors.

FIG. 24: (Color online) the extracted $\sqrt{<j^2>}$ for minimum bias $d + Au$ collisions from all four dihadron correlations. The trigger $p_T$ ranges are $3 - 5$ GeV/c, $5 - 10$ GeV/c and $5 - 10$ GeV/c for $h^\pm - h^\pm$ (filled boxes), $\pi^0 - h^\pm$ (open crosses) and $\pi^\pm - h^\pm$ (filled circles) distributions. The $h^\pm - h^\pm$ fixed-$p_T$ correlation is shown by filled stars. The statistical and systematic errors are combined for the $h^\pm - h^\pm$ correlations, while the fixed-$p_T$ correlation shows the systematic error separately as shaded boxes.

| Centrality | $\sigma_{\text{near}}$(rad) | $\sigma_{\text{far}}$(rad) |
|------------|-----------------------------|-----------------------------|
| 0-20 %     | $0.199 \pm 0.009$           | $0.387 \pm 0.024$           |
| 20-40 %    | $0.195 \pm 0.009$           | $0.401 \pm 0.031$           |
| 40-88 %    | $0.190 \pm 0.008$           | $0.376 \pm 0.024$           |

TABLE XIX: Near and far-side widths as a function of centrality for neutral pion triggers ($5 - 10$ GeV/c) and associated charged hadrons (2-3 GeV/c) from $d +Au$ collisions.

| Centrality | $dN/dp_{\text{near}}$ | $dN/dp_{\text{far}}$ |
|------------|-----------------------|-----------------------|
| 0-20 %     | $0.0816 \pm 0.0037$   | $0.116 \pm 0.008$     |
| 20-40 %    | $0.0947 \pm 0.0045$   | $0.141 \pm 0.011$     |
| 40-88 %    | $0.0967 \pm 0.0043$   | $0.144 \pm 0.009$     |

TABLE XX: Near and far-side conditional yields as a function of centrality from $d + Au$ collisions for neutral pion triggers ($5 - 10$ GeV/c) and associated charged hadrons (2-3 GeV/c).

| Centrality | $dN/dp_{\text{near}}$ | $dN/dp_{\text{far}}$ |
|------------|-----------------------|-----------------------|
| 0-20 %     | $0.0816 \pm 0.0037$   | $0.116 \pm 0.008$     |
| 20-40 %    | $0.0947 \pm 0.0045$   | $0.141 \pm 0.011$     |
| 40-88 %    | $0.0967 \pm 0.0043$   | $0.144 \pm 0.009$     |
C. Comparison between $d + Au$ and $p + p$

As discussed in Section II, multiple scattering in the cold nuclear-medium may broaden the far-side correlation and possibly modify the fragmentation properties. In the previous section we presented the measured jet structures from minimum-bias $d + Au$ collisions. In this section we compare that data to results from $p + p$ collisions. The goal is to establish the extent to which the nuclear-medium modifies the properties of jets.

Figure 27 shows the comparison of the extracted $\langle \sin^2 \phi_{jj} \rangle$ values as function of $p_{T,\text{assoc}}$ from $d + Au$ and $p + p$ collisions. The $\sqrt{\langle J_T^2 \rangle}$ values show no change from $p + p$ to $d + Au$ collisions.

Similarly, the $\langle \sin^2 (\phi_{jj}) \rangle$ values shown in Fig. 34 for $d + Au$ are comparable to those from $p + p$ within errors, although the values from $d + Au$ collisions are systematically higher for $\pi^\pm - h^\pm$. Since there is no strong difference between the $d + Au$ and $p + p$ results, there is little indication for increased multiple-scattering in the $d + Au$ final state.

Any additional radiation can be quantified by calculating the point-by-point quadrature difference in $\langle \sin^2 \phi_{jj} \rangle$ between $d + Au$ and $p + p$ collisions. This is shown in Fig. 35 and this difference is consistent with zero.
The average value for $\pi^0 - h$ is $\Delta \langle \sin^2 \phi_{jj} \rangle = -0.005 \pm 0.012$(stat)$\pm 0.003$(sys); for $\pi^\pm - h$ $\Delta \langle \sin^2 \phi_{jj} \rangle = 0.011 \pm 0.011$(stat)$\pm 0.010$(sys). Combining the two data sets, we find $\Delta \langle \sin^2 \phi_{jj} \rangle = +0.004 \pm 0.008$(stat)$\pm 0.009$(sys).

Figure 29 shows the comparison of the $p_{out}$ distribution between central $d +Au$ and $p + p$ from $\pi^\pm - h^\pm$ correlation, no apparent differences are observed in both the near and far-side. This is consistent with the observations that both $\sqrt{\langle j_T^2 \rangle}$ and $\langle \sin^2 \phi_{jj} \rangle$ are similar between $d + Au$ and $p + p$.

A second set of comparisons between $d + Au$ and $p + p$ collisions is the number of hadrons in the near- and far-angle jet structures associated with a high-$p_T$ trigger. Figure 30 shows the comparison of the conditional yield as a function of $x_E$ and no apparent difference between $d + Au$ and $p + p$ collisions is observed for either the near- or far-side.

In the previous section we examined the level of scaling violations in the far-side $dN/dx_E$ distribution for $d + Au$ collisions by plotting different $x_E$ ranges as a function of $p_{T,\text{trig}}$ (Fig. 22). The comparable plot for $p + p$ collisions is shown in Fig. 31. For both $d + Au$ and $p + p$ collisions the amount of scaling violations, i.e. the dependence of $dN/dx_E$ on $p_{T,\text{trig}}$, can be quantified by fitting the data in each $x_E$ range with a straight line as a function of $p_{T,\text{trig}}$.

$$\frac{dN}{dx_E} = \frac{dN}{dx_{E,0}} (1 + \beta p_T)$$

The fitted slopes ($\beta$) represent the fractional change in $dN/dx_E$ per GeV/c and are shown in Fig. 31. For the $d + Au$ data $\beta$ is consistent with zero, i.e. there is no significant scaling violation across the whole $x_E$ range.
while there may be a slight scaling violation at high $x_E$ for the $p + p$ data. On a point-by-point basis there is no systematic difference between the $d + Au$ and $p + p$ data.

Taken as a whole, all the results presented in this section indicate that there is no significant change in jet fragmentation between $d + Au$ and $p + p$ collisions due to the presence of the cold nuclear-medium. In addition there is no strong evidence for an increase in $\langle \sin^2(\phi_{jj}) \rangle$ due to multiple scattering in the Au nucleus. Using the minimum-bias $d + Au$ data has the advantage of the highest statistical precision. In the next section we examine whether there is any change in jet-structures as a function of collision centrality in $d + Au$, i.e. we split the statistics into a few centrality classes to increase the lever arm of the nuclear-thickness function.

D. Centrality Dependence

As discussed in Section II $\langle \sin^2(\phi_{jj}) \rangle$ is expected to increase as $d + Au$ collisions become more central due to increased multiple scattering. Models of multiple scattering \cite{12} predict that the increase in $\langle k_T^2 \rangle$ is proportional to $T_A(b)$, the nuclear thickness function. We are not aware of predictions of how $\langle \sin^2(\phi_{jj}) \rangle$ will change with centrality, but note that any increase in $\langle k_T^2 \rangle$ will also increase $\langle \sin^2(\phi_{jj}) \rangle$.

To probe this physics, we have measured angular correlations in three centrality bins for $d + Au$ collisions (0-20%, 20-40%, and 40-88%) to extract angular-widths of the jet-structures and hence $\sqrt{(jj)}$ and $\langle \sin^2(\phi_{jj}) \rangle$. Figure 34 shows the independent data sets of $\langle \sin^2(\phi_{jj}) \rangle$ including results from $p + p$ collisions as well as the three centrality classes from $d + Au$ collisions.

All the $\langle \sin^2(\phi_{jj}) \rangle$ data in Fig. 34 have been simultaneously fit with the following linear equation in $T_A(b)$

$$\langle \sin^2(\phi_{jj}) \rangle = \langle \sin^2(\phi_{jj}) \rangle_0 (1 + a_{frac} T_A(b)) \quad (42)$$

The slope parameter, $a_{frac}$, is assumed to be common to all data sets, while the pre-factors, $\langle \sin^2(\phi_{jj}) \rangle_0$, depend...
FIG. 35: (Color online) Quadrature difference between minimum-bias \(d + Au\) and \(p + p\) \(\langle \sin^2 \phi_{jj} \rangle\) values. Closed circles are \(\pi^\pm - h^\pm\) values and the open circles are \(\pi^0 - h^0\) values. Bars are statistical errors. The boxes represent the total systematic errors on each point.

FIG. 36: (Color online) The comparison of the \(p_{out}\) distribution at the near-side (left panel) and far-side (right panel) between central \(d + Au\) collisions and \(p + p\) collisions. Results are obtained for \(\pi^\pm - h^\pm\) correlations with the associated hadron range \(0.5 < p_{T,assoc} < 5 \text{ GeV/c}\) and trigger pion range of \(5 < p_{T,\text{trig}} < 10 \text{ GeV/c}\). Bars are statistical errors.

FIG. 37: (Color online) The comparison of the \(x_E\) distribution from \(\pi^\pm - h^\pm\) correlation at the near-side (left panel) and far-side (right panel) between minimum bias \(d + Au\) collisions (filled circles) and \(p + p\) collisions (open circles). The trigger \(\pi^\pm\) are from \(5 - 10 \text{ GeV/c}\). Bars are statistical errors. The boxes represent the total systematic errors on each point.

FIG. 38: Far-side conditional yield as function of \(p_{T,\text{trig}}\) for different ranges of \(x_E\) from \(p + p\) collisions, triggers are \(\pi^\pm\) from \(5 - 10 \text{ GeV/c}\). Bars are statistical errors.

Vitev’s predicted effect compared to our experimental results, we recast Eq. (43) into the same form as Eq. (44)

\[ \langle k_T^2 \rangle_{\text{dijet}} = 2 \langle k_T^2 \rangle_{\text{vac}} (1 + \frac{0.72}{2 \langle k_T^2 \rangle_{\text{vac}} T_{A(minbias)}} T_A(b)) \]  
(44)

Hence their prediction for the fractional increase in \(\langle k_T^2 \rangle\) with \(T_A(b)\) is from 0.51 to 0.72 depending on the range \(0.25 < \langle k_T^2 \rangle_{\text{vac}} < 0.35 \text{ (GeV/c)}^2\) suggested by Qiu and Vitev. Though the predicted fractional increase is of a different quantity, it should provide an estimate of the magnitude of the fractional increase in \(\sin^2 \phi_{jj}\). The prediction is slightly larger than one standard deviation (statistical) from our experimental result, \(a_{frac} = \)

\[ \text{For } 0 - 88\% \text{ d + Au collisions, } T_A_{\text{minbias}} = 0.20 \text{ mb}^{-1} \]

on the \(p_T\) of the trigger and associated particles. The extracted slope \(a_{frac} = -0.01 \pm 0.40 \text{ mb} \) with chi-squared per degree-of-freedom, \(\chi^2/\nu = 27/22\). This slope is consistent with zero, i.e. we do not observe any significant increase in \(\langle \sin^2 \phi_{jj} \rangle\) with centrality.

This can be compared to predictions from Hwa and Wang who assume no increase in \(k_T\) with centrality to reproduce the Cronin effect data at RHIC and Qiu and Vitev who calculate

\[ \langle k_T^2 \rangle_{\text{dijet}} = 2 \langle k_T^2 \rangle_{\text{vac}} + \frac{0.72}{T_{A(minbias)} T_A(b)} \]  
(43)

To gain some insight into the magnitude of Qiu and
recombination model of Ref. [22] predicted a factor of 3.8 between yields in $p+p$ and $d+Au$ data. In other momentum ranges there is no consistent difference. Taking the ratio (d$d$+Au) with a high-$p_T$ trigger, then it saturates. Their prediction is

\[
\langle k_T^2 \rangle = \langle k_T^2 \rangle_0 (1 + \frac{0.35}{\langle k_T^2 \rangle_0} \times (40 \times T_A)) \quad T_A < 0.1
\]

\[
\langle k_T^2 \rangle = (\langle k_T^2 \rangle_0 / 40 \times 0.1) \quad T_A > 0.1
\]

(45)

Barnafodli et al. have also predicted the increase in $k_T$ due to multiple scattering in $d+Au$ collisions. They calculate that $\langle k_T^2 \rangle$ increases by $C = 0.35 \text{GeV/c}^2$ per collision up to the first four collisions, then it saturates. Their prediction is

\[
\langle k_T^2 \rangle = \langle k_T^2 \rangle_0 (1 + \frac{0.35}{\langle k_T^2 \rangle_0} \times (40 \times T_A)) \quad T_A < 0.1
\]

\[
\langle k_T^2 \rangle = (\langle k_T^2 \rangle_0 / 40 \times 0.1) \quad T_A > 0.1
\]

(45)

Barnafodli et al. do not provide values for $\langle k_T^2 \rangle_0$, however if we use the range $0.25 < \langle k_T^2 \rangle_0 < 0.35 \text{GeV/c}^2$ suggested by Qiu and Vitev [14] then the fractional increase with $T_A$ is 40 to 56 for $T_A < 0.1$ followed by no further increase. This rapid increase is not observable in our data set because the model saturates already in the most peripheral $d+Au$ bin where $T_A = 0.11 \text{mb}^{-1}$.

As discussed in Section [10] inelastic scattering of the hard parton in the cold-medium may also increase the conditional yields (CY) of hadrons that are associated with a high-$p_T$ trigger. Figure [11] shows the centrality dependence of the extracted CY, together with CY from $p+p$ collisions. The difference can be better illustrated by taking the ratio ($d+Au/p+p$) of the per trigger yield as shown in Fig. [12]. There is a possible increase in near-side particle yield for $p_T < 1 \text{GeV/c}$ in the $d+Au$ collisions. In other momentum ranges there is no consistent difference between yields in $d+Au$ and $p+p$ collisions. The recombination model of Ref. [22] predicted a factor of 3.8 increase in CY peripheral to central $d+Au$ collisions which is much larger than observed in the data. A later recombination model by the same authors postdicted only a 30% increase in CY for associated particles at $p_T = 2 \text{GeV/c}$, which is comparable or perhaps slightly larger than is observed in the data.

V. CONCLUSIONS

We have measured several properties of jet fragmentation and dijet correlations using two-particle correlations with three different particle combinations: $h^\pm - h^\pm$, $\pi^0 - h^\pm$, and $\pi^\pm - h^\pm$. From the correlation functions we have extracted the widths of the near- and far-angle correlations as a function of the momentum of the two hadrons, $p_T,_{\text{trig}}$ and $p_T,_{\text{assoc}}$. These widths decrease as a
hadrons with respect to the hard parton. The value of the RMS of the transverse momentum of fragmented

correlations (upper) and \( \pi^0 - h^\pm \) correlations (lower). The filled circles are from 0-20% centrality, the open circles are from 20-40% centrality, the filled squares are from 40-88% centrality in \( d + Au \) collisions, while the open squares are from \( p + p \) collisions. Bars are statistical errors.

function of both the trigger and associated particle's momenta. From the near-angle widths we calculate \( \sqrt{\langle \Delta T^2 \rangle} \), the RMS of the transverse momentum of fragmented hadrons with respect to the hard parton. The value of \( \sqrt{\langle \Delta T^2 \rangle} \) saturates at 0.64 ± 0.02 (stat) ± 0.04 (sys) GeV/c for \( p_T,assoc > 2 \) GeV/c and is consistent with being independent of \( p_T,\text{trig} \) and trigger species. The \( \sqrt{\langle \Delta T^2 \rangle} \) is similar for \( d + Au \) and \( p + p \) collisions consistent with the fragmentation process not being affected by the presence of the cold nuclear medium.

We have also compared the measured \( x_E \) distributions in \( d + Au \) collisions to the baseline distributions from \( p + p \) collisions. The \( x_E \) distributions extracted from the far-angle correlations provide information on the fragmentation of a back-to-back parton triggered on a high-\( p_T \) hadron in the opposite hemisphere. The measured \( dN/dx_E \) distributions in \( d + Au \) are approximately independent of \( p_T,\text{trig} \), i.e. they scale. We have quantified the level of scaling violation by extracting the slope \( \beta = d(dN/dx_E)/dp_{T,\text{trig}} \) for different ranges of \( x_E \). The slopes are consistent with zero for \( d + Au \) collisions, i.e. there is no significant scaling violation. Point-by-point the scaling-violation slopes for \( p + p \) collisions are not significantly different than the \( d + Au \) data. This suggests that if there is any additional gluon radiation in \( d + Au \) reactions due to multiple scattering, then this has little observable influence on the fragmentation of the hard parton.

We observe no centrality dependence of the conditional yield in \( d + Au \) and these yields are very similar to those from \( p + p \) collisions. The recombination model of Ref. [23] postdicted a 30% increase in conditional yield between \( d + Au \) and \( p + p \), which is perhaps slightly larger than is observed in the data.

We have extracted the dijet acoplanarity (\( \sin^2(\phi_{jj}) \)) from the widths of the back-to-back correlations in \( d + Au \) and \( p + p \) collisions. In collisions involving nuclei, multiple interactions within the nucleus would tend to increase the parton transverse momentum which would be observable as a larger dijet acoplanarity, i.e., the back-to-back distribution of jets should broaden. However, in \( d + Au \) collisions the extracted values of \( \langle \sin^2(\phi_{jj}) \rangle \) are very similar to those observed in \( p + p \) collisions. Indeed, the quadrature difference (\( \Delta \)) between
\[ \sin^2(\phi_{jj}) \] in d + Au and p + p is consistent with zero, \[ \Delta(\sin^2(\phi_{jj})) = +0.004 \pm 0.008 \text{(stat)} \pm 0.000 \text{(sys)} \]. The extracted \( \sin^2(\phi_{jj}) \) is also measured to be independent of the nuclear thickness function \( T_A(b) \), which is in contrast to the strong A-dependence of \( k_T \) observed at lower beam energies. This model reproduces the measured Cronin effect of single-particle spectra at RHIC and predicts a finite increase of \( k_T \) data with nuclear thickness function. When converted to a fractional increase, the prediction is at a level that is within the experimental uncertainty of the current data. Hence our present data on \( \sin^2(\phi_{jj}) \) are not inconsistent with the level of multiple scattering deduced from the single-particle Cronin effect.

Taken together, we observe no change in fragmentation and no indication of the effects of multiple-scattering, i.e. the jet-structures are very similar in d+Au and p+p collisions at RHIC energies. Our measurements also provide a critical baseline for jet measurements in Au+Au collisions at RHIC.

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