Three-Particle Azimuthal Correlations

Jason Glyndwr Ulery∗†

Purdue University
E-mail: ulery@physics.purdue.edu

Two-particle azimuthal correlations in central Au+Au collisional at RHIC have revealed a broadened away-side structure, with respect to peripheral Au+Au, pp, and d+Au. This could be explained by different physics mechanisms such as: large angle gluon radiation, deflected jets, Čerenkov gluon radiation, and conical flow generated by hydrodynamic shock-waves. We can discriminate the scenarios with conical emission, Čerenkov radiation and conical flow, from the other mechanisms though three-particle correlations. In addition, the associated particle $p_T$ dependence can be used to distinguish conical flow from simple Čerenkov gluon radiation. We will discuss three-particle correlation analyses that have been performed at RHIC and what can be done at the LHC.
1. Introduction

Heavy-ion collisions create a medium that could be the quark gluon plasma (QGP). Jets and jet-correlations can be used to study this medium through the effects of the medium on the jet and the effects of the jet on the medium. Jets make a good probe because their properties can be calculated in the vacuum with perturbative quantum chromodynamic (pQCD). Two-particle jet-like azimuthal correlations have shown a broadened (with respect to what is seen in \( pp \) and \( d+Au \) and peripheral Au+Au collisions) or even double-humped\[1, 2\] away-side structure in Au+Au central collisions (see Fig. 3). The broadening of the away-side structure is consistent with different physics mechanisms including: large angle gluon radiation \[3, 4\], jets deflected by radial flow\[5\] or preferential selection of particles due to path-length dependent energy loss\[6\], hydrodynamic conical flow generated by Mach-cone shock waves \[7, 8\], and Čerenkov radiation \[9, 10\]. Three-particle correlations can be used to differentiate the mechanisms with conical emission, Mach-cone and Čerenkov gluon radiation, from other physics mechanisms. Three different 3-particle correlation analyses have been done at RHIC. Two of these analyses are azimuthal 3-particle correlations and will be discussed here. The third analysis makes use of the full 3D information available and is discussed in detail elsewhere in these proceedings\[11\] and elsewhere\[12\].

2. Three-Particle Cumulant

The 3-particle cumulant has previously shown preliminary results\[13\] and been rigorously described in\[14\]. This method has the advantage that it is independent of any model. This method is performed by computing 1-, 2-, and 3-particle densities and then computing the quantity:

\[
C_3(\Delta \phi_1, \Delta \phi_2) = \rho_3(\Delta \phi_1, \Delta \phi_2) - \rho_2(\Delta \phi_1)\rho_1(\phi_2) - \rho_2(\Delta \phi_2)\rho_1(\phi_1) - \rho_2(\phi_1 - \phi_2)\rho_1(\phi_T) - \rho_1(\phi_T)\rho_1(\phi_1)\rho_1(\phi_2)
\]

where \( \rho_1, \rho_2, \text{and } \rho_3 \) are the 1-, 2-, and 3-particle densities respectively, \( \phi_T, \phi_1, \) and \( \phi_2 \) are the azimuthal angles of the trigger and 2 associated particles respectively, and \( \Delta \phi_1 = \phi_T - \phi_1 \) and \( \Delta \phi_2 = \phi_2 - \phi_1 \). Figure 4 shows the terms \( \rho_3(\Delta \phi_1, \Delta \phi_2), \rho_2(\Delta \phi_1)\rho_1(\phi_2), \rho_2(\Delta \phi_2)\rho_1(\phi_1), \) and \( \rho_2(\phi_1 - \phi_2)\rho_1(\phi_T) \).

If the events are Posson the 2-particle correlations are fully removed from the 3-particle cumulant and only the correlations of 3 or more particles remain. Therefore the presence of a signal signifies the existence of correlations of 3 or more particles. Figure 5 shows the 3-particle cumulant for three different centrality bins in Au+Au collisions. The cumulants are for trigger particles of \( 3 < p_T < 4 \) GeV/c with two associated particles of \( 1 < p_T < 2 \) GeV/c. All particles are charged particles within the STAR TPC. A signal is seen for all centrality bins signifying the presence of correlations of three or more particles, under the assumption the events are Posson. A centrality dependence is seen for the 3-particle cumulant. The away-side structure are inconsistent with those predicted for global momentum conservation in the cumulant\[15\]. Any further interperation requires invoking a model and studying the effects of components of the model on the cumulant. To extract additional information we will proceed to discuss a model dependent analysis.
Three-Particle Azimuthal Correlations

Jason Glyndwr Ulery

Figure 1: Cumulant raw signal and backgrounds which contain structure. Top Left: Cumulant raw signal, \( \rho_3(\Delta \phi_1, \Delta \phi_2) \). Top right: \( \rho_2(\Delta \phi_1)\rho_1(\phi_2) \). Bottom Left: \( \rho_2(\Delta \phi_2)\rho_1(\phi_1) \). Bottom Right: \( \rho_2(\phi_1 - \phi_2)\rho_1(\phi_T) \). All results are preliminary.

Figure 2: Three-particle cumulants for Au+Au collisions in centrality bins 50-80\% (left), 10-30\% (middle), and 0-10\% (right) with \( 3 < p_T^{\text{Trig}} < 4 \) and \( 1 < p_T^{\text{Assoc}} < 2 \text{ GeV/c} \). All results are preliminary.

3. Model Dependent Analysis

This analysis strives to extract the 3-particle jet-like correlations. The method has been described in detail\[16\] and previously reported preliminary results\[17, 18, 13\]. This method makes a few assumptions. The first is the event can be composed into two components, particles that are jet-like correlated with the trigger particle and particles that are not. The other assumptions are that the background in the 2-particle correlation is ZYA1 (zero yield at 1) and that the number of associated pairs in the three-particle signal is the square of the number of associated particles in the 2-particle signal. Results are shown for charged trigger particles of \( 3 < p_T < 4 \text{ GeV/c} \) correlated with charged associated particles for \( 1 < p_T < 2 \text{ GeV/c} \) taken in the STAR TPC. Results are for \( pp \), \( d+Au \), and \( Au+Au \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \).

Figure 3b shows the raw 3-particle correlation signal in \( \Delta \phi_1 = \phi_1 - \phi_T \) and \( \Delta \phi_2 = \phi_2 - \phi_T \). Combinatorial backgrounds must be removed to obtain the genuine 3-particle jet-like correlation signal. One source of background, the hard-soft background, is obtained by folding the background
Au+Au collisions, there is an off-diagonal structure at about $k_T$ broadening. There is additional flow that is not accounted for by the soft-soft term. The associated particles are also correlated with the trigger via flow. The trigger flow is added in triplet-wise from mixed-inclusive events. We shall refer to the background from trigger flow as $B_3^{inc,TF}$. The total background is then, $\hat{J}_2 \otimes aB_2^{inc} + \beta \alpha^2 (B_3^{inc} + B_3^{inc,TF})$ where $\alpha^2$ accounts for the multiplicity bias from requiring a trigger particle and $b$ accounts for the effect of non-Poisson multiplicity distributions. The normalization factor $b$ is obtained such that the number of associated pairs in the background subtracted jet-like 3-particle correlation signal equals the square of the number of associated particles in the background subtracted jet-like 2-particle correlation signal.

Figure 4 shows the background subtracted results for jet-like 3-particle correlations. The $pp$ and $d+Au$ results are similar and show on-diagonal broadening qualitatively consistent with $k_T$ broadening. Au+Au collisions show additional on-diagonal broadening. In the more central Au+Au collisions, there is an off-diagonal structure at about $\pi \pm 1.45$ radians. This structure is consistent with conical emission and increases in magnitude with centrality.

Figure 5 shows the centrality dependence of the average signal strengths in different regions. The off-diagonal signals increase with centrality and significantly deviate from zero in central
Three-Particle Azimuthal Correlations

Figure 4: Background subtracted 3-particle correlations for pp (top left), d+Au (top center), and Au+Au 50-80% (top right), 30-50% (bottom left), 10-30% (bottom center), and ZDC triggered 0-12% (bottom right) collisions at $\sqrt{s_{NN}}=200$ GeV/c.

Figure 5: Average signals in $0.7 \times 0.7$ boxes at $(\pi, \pi)$, left, $(\pi \pm 1.45, \pi \mp 1.45)$, center, and $(\pi \pm 1.45, \pi \pm 1.45)$, right. Solid error bars are statistical and shaded are systematic. $N_{\text{part}}$ is the number of participants. The ZDC 0-12% points (open symbols) are shifted to the left for clarity.
Au+Au collisions. The systematic errors are semi-correlated between centralities and data sets. In figure 6, the off-diagonal projection is shown in the solid symbols and the on-diagonal projection is shown in open symbols. There is additional contribution along the diagonal relative to the off-diagonal. The locations of the off-diagonal signals were determined from a fit to a central Gaussian and symmetric side Gaussians to a strip projected to the off-diagonal (Fig. 6) and were found to be about 1.45 radians from $\pi$. This could be due to any combination of jets deflected by flow, path-length dependent energy loss, large angle gluon radiation, and conical emission from Mach-cones[20]. Differentiation of the contribution to the on-diagonal projection from these processes cannot be determined experimentally and would require information from theoretical models.

![STAR Preliminary](image)

**Figure 6:** Away-side projections of a strip of width 0.7 radians for (left) d+Au and (right) 0-12% ZDC Triggered Au+Au. Off-diagonal projection (solid) is $(\Delta \phi_{aT} - \Delta \phi_{bT})/2$ and on-diagonal projection (open) is $(\Delta \phi_{aT} + \Delta \phi_{bT})/2 - \pi$. Shaded bands are systematic errors on the on-diagonal projections. The systematic errors on the off-diagonal projections are not shown for clarity.

4. Summary

Three different 3-particle analyses are being pursued at RHIC, two of which are reported on in these proceedings. The RHIC results show the existence of 3 or more particle correlations in the cumulant analysis with only the assumption of Poisson statistics. Additionally model dependent results show a signal consistent with conical emission in central Au+Au collisions at about $\pi \pm 1.45$ radians. All three of these analyses can be performed at the LHC. Additionally 4 or more particle correlations may be possible and may give additional information. Also at the ALICE detector 3-particle correlations with identified particles should be possible.

References

[1] J. Adams et al. (STAR Collaboration), *Distributions of Charged Hadrons Associated with High Transverse Momentum Particles in pp and Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV*, *Phys. Rev. Lett.* **95** 152301 (2005) [nucl-ex/0501016].

[2] S.S. Adler et al. (PHENIX Collaboration), *Modifications to Di-jet Hadron Pair Correlations in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV*, *Phys. Rev. Lett.* **97** 052301 (2006) [nucl-ex/0507004].
Three-Particle Azimuthal Correlations

Jason Glyndwr Ulery

[3] I. Vitev, *Large angle Hadron Correlations from Medium-Induced Gluon Radiation*, Phys. Lett. B 630 78 (2005) [hep-ph/0501255].

[4] A.D. Polosa and C.A. Salgado, *Jet Shapes in Opaque Media*, Phys. Lett. C 75 041901 (2007) [hep-ph/0607295].

[5] N Armesto, C.A. Salgado, and U.A. Wiedemann, *Measuring the Collective Flow with Jets*, Phys. Rev. Lett. 93 242301 (2004). [hep-ph/0405301]

[6] C.B. Chiu, and R.C. Hwa, *Away-side Azimuthal Distribution in a Markovian Parton Scattering Model*, Phys. Rev. C 74 064909 (2006). [nucl-th/0609038]

[7] H. Stoecker, *Collective Flow Signals the Quark Gluon Plasma*, Nucl. Phys. A 750 121 (2005) [nucl-th/0406018].

[8] J. Casalderrey-Solana, E. Shuryak and D. Teaney, *Conical Flow Induced by Quenched QCD Jets*, J. Phys. Conf. Ser 27 22 (2006) [hep-ph/0411315].

[9] I.M. Dremin, *Ring-like events: Cerenkov Gluons or Mach Waves?*, Nucl. Phys. A 767 233 (2006) [hep-ph/0507167].

[10] V. Koch, A. Majumder, X.N. Wang, *Cerenkov Radiation from Jets in Heavy-ion Collisions*, Phys. Rev. Lett. 96 172302 (2006). [nucl-th/0507063].

[11] N. Ajitanand, *These proceedings*.

[12] N. Ajitanand et al. (PHENIX Collaboration), *Extraction of Jet Topology Using Three Particle Correlations*, Nucl. Phys. A 783 519 (2007) [nucl-ex/0609038].

[13] C. Pruneau et al. (STAR Collaboration), *Search for Conical Emission with Three-Particle Correlations*, [nucl-ex/0703010].

[14] C. Pruneau, *Methods for Jet Studies with Three-Particle Correlations*, Phys. Rev. C 74 064910 (2006) [nucl-ex/0608002].

[15] N. Borghini, *Momentum Conservation and Correlation Analyses in Heavy-ion Collisions at Ultrarelativistic Energies*, Phys. Rev. C 75 021904 (2007).

[16] J. Ulery and F. Wang, [nucl-ex/0609016].

[17] J. Ulery et al. (STAR Collaboration), *Two- and Three-Particle Jet correlations from STAR*, Nucl. Phys. A 774 581 (2006) [nucl-ex/0510055].

[18] J. Ulery et al. (STAR Collaboration), *Three-Particle Azimuthal Correlations*, Nucl. Phys. A 783 511 (2007) [nucl-ex/0609047].

[19] J. Adams et al. (STAR Collaboration), *Azimuthal Anisotropy in Au+Au Collisions at √sNN = 200 GeV*, Phys. Rev. C 72 014904 (2005) [nucl-ex/0409033].

[20] T. Renk and J. Ruppert *Three-Particle Azimuthal Correlations and Mach Shocks*, [hep-ph/0702102].