The broad away side of azimuthal correlations: 3 vs 2 final state particles in high energy nuclear collisions

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Abstract. In high energy heavy ion collisions at RHIC there are important aspects of the medium induced dynamics, that are still not well understood. In particular, there is a broadening and even a double hump structure of the away-side peak appearing in azimuthal correlation studies in Au+Au collisions which is absent in p+p collisions at the same energies. These features are already present but suppressed in p+p collisions: 2 to 3 parton processes produce such structures but are suppressed with respect to 2 to 2 processes. We argue that in A+A collisions the different geometry for the trajectories of 3 as opposed to 2 particles in the final state, together with the medium induced energy loss effects on the different cross sections, create a scenario that enhances processes with 3 particles in the final state, which gives on average this double hump structure.

Keywords: RHIC, azimuthal correlations, ridge
PACS: 25.75.-q, 25.75.Gz

1. INTRODUCTION

During the last few years there has been many interesting phenomena observed in experiments at RHIC. The vast majority of such phenomena has been studied and interpreted using well known models that incorporate energy loss dynamics. The broadening of the away-side peak appearing in azimuthal correlation studies in Au+Au collisions and absent in p+p collisions at the same energies, is one of these remarkable observations. This has yet to have a complete understanding that incorporates the medium characteristics and, at the same time, that is coherent with previous correlation studies. In fact, this particular double hump structure has been the subject of different theoretical analysis which are based on the assumption that unlike p+p collisions, A+A collisions are strongly influenced by collective phenomena. The purpose of this work is to put forward our particular approach to explore the origins of such structure in the away side. The details of this work have been provided in [1] and soon will be reported in greater extent elsewhere [2].

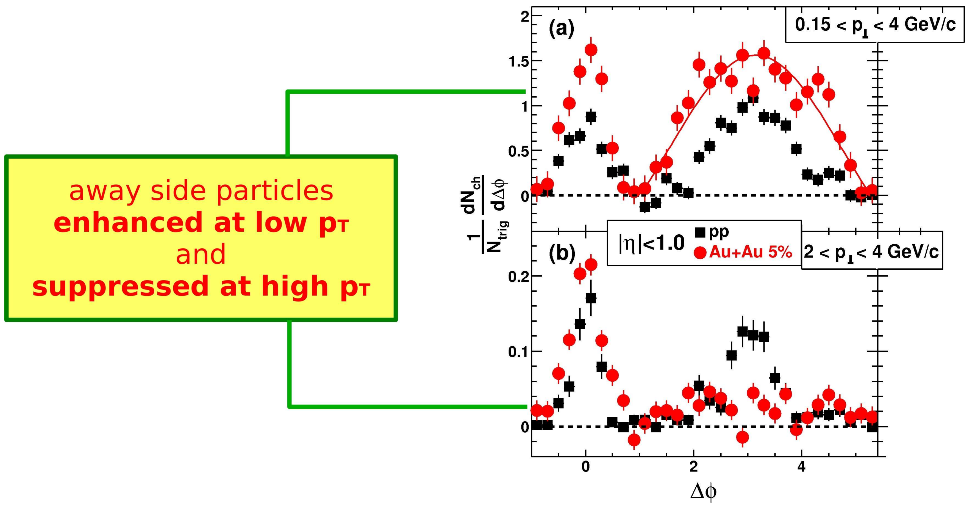

FIGURE 1. Azimuthal correlations between particle pairs for two p_T ranges in p+p and Au+Au collisions. Reprinted figure with permission from STAR Collaboration (J. Adams et al.), Phys.Rev.Lett. **95**, 152301, 2005. Copyright 2005 by the American Physical Society. [5]

1.1. High p_T partons as probes of the medium

In relativistic heavy ion collisions, high p_T partons are produced through hard processes in the initial binary nucleon collisions and they are the perfect tool to probe the dynamics of such ephimeral conditions. In fact, just by studying the way partons hadronize under such conditions, we can obtain information on the nature of the medium.

Just after the ion collision, many partons are produced due to the binary collisions between nucleons. These partons have to travel through the hot and dense medium, before they can hadronize. If these partons were to hadronize with little interaction, then the number of produced high p_T hadrons detected, should scale with the number of binary collisions.

It was quickly realised some time ago that the experimental evidence was telling a different story: the number of produced high p_T hadrons is reduced significantly in these sort of collisions: up to 5 times in most central Au + Au collisions [3]. This strengthens the idea that the medium produced in such collisions is opaque for high p_T partons.

To study these ideas further, more differential studies were devised by measuring azimuthal correlations between particle pairs at high p_T. And, as it is shown in FIG. 1, the near-side correlation is similar for the p + p and Au + Au collisions, while the away-side correlation is not there for central Au + Au events [4].

Many ideas were put forward to encompass a coherent explanation to what was being observed in these correlation studies. Among others, there were many *elliptic flow studies* implemented. These studies are based on the fact that an anisotropy in the momentum distribution of particles may arise after the initial binary collisions. They consider that the initial geometry of the collision region is anisotropic in the azimuthal direction so that after the interacting system reaches local thermal equilibrium, preassure gradients are steeper in the impact parameter direction and these generate the elliptic flow.

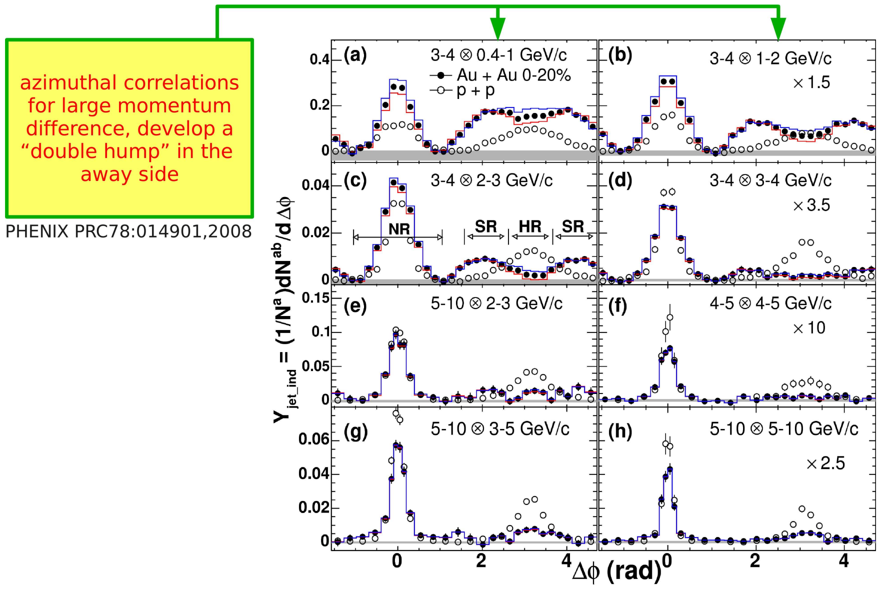

FIGURE 2. Two particle correlations for p+p and Au+Au in different p_T bins. Reprinted figure with permission from PHENIX Collaboration (A. Adare et al.), Phys. Rev. C **78**, 014901, 2008. Copyright 2008 by the American Physical Society. [7]

So up until then, the elliptic flow together with the two particle correlation studies applied on different analisis, gave an indication that an opaque, strongly interacting partonic matter had been created in the high energy Au + Au collisions at RHIC.

1.2. A puzzle in correlation studies

In 2005 there was a rich correlation structure in Au + Au vs p + p reported by the leading collaborations at RHIC. They observed a *ridge* and *broad away side* in the correlation studies performed at the time. More precisely, they reported an excess yield of correlated particles at $\Delta\phi = 0^\circ$ and $\Delta\phi \approx 180^\circ$ extending out to $\Delta\eta > 2$ [6]

In FIG. 2 we can see that, to analize the origins of such structure the PHENIX collaboration identified *head* and *shoulders* regions and defined a ratio R_{HS} (*head/shoulder*). Looking closely at the ratio R_{HS} in FIG. 3, we can see that for p+p collisions R_{HS} grows with p_T, which can be interpreted as a production of a narrower jet, whereas for Au + Au, jet fragmentation dominates at high p_T over medium effects.

Several theoretical models have been proposed to look for the origins of such structures, among others the literature focuses mainly on

- Mach or Cerenkov cone due to medium reaction [8]: the *double hump* can be explained by considering how the medium reacts to the passing of a fast parton. In principle this would produce such structures since the medium would eject two bunches of hadrons in the away side.
- Triangularity and triangular flow [9]: the *double hump* can be explained by considering event-by-event fluctuations in the initial collision geometry as a next order

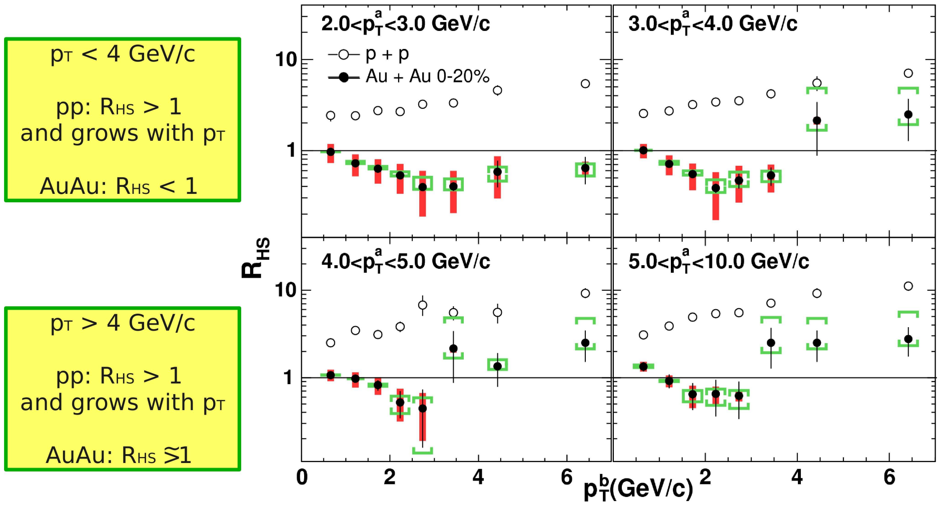

FIGURE 3. Ratio R_{HS} (*head/shoulder*) for different p_T bins. Reprinted figure with permission from PHENIX Collaboration (A. Adare et al.), Phys. Rev. C **78**, 014901, 2008. Copyright 2008 by the American Physical Society. [7]

collective flow effect, after considering the elliptic flow effects.

We can see that all of the theoretical models rely on the description of such away-side structures as the manifestation of emergent behaviour due to the collective (e.g. triangular flow: relies crucially on the existence of initial geometry fluctuations). In fact, there are a couple of recent reviews on the models posed to solve this puzzle: up until 2009, J. L. Nagle [10] argued that "...none of the theoretical models are succesful to describe all the special characteristics of these structures..." and this year, M. J. Tannenbaum [11] argued that "...no clear paradigm has emerged for the two-lobed wide away-jet structure..."

2. SOLVING THE PUZZLE: OUR PROPOSAL

In a nutshell, our proposal [1, 2] regarding the origins of the double-hump in the away side of two-particle correlation studies in A + A collisions, is as follows

- $\surd$ we account for the medium induced energy loss effects on the calculation of $2 \to \{2, 3\}$ cross sections
- $\surd$ we also take into account the different path lengths for the trajectories of 3 as opposed to 2 particles in the final state of an A + A collision
- $\surd$ finally, considering that one particle is absorbed by the medium and the other one punches through
- $\to$ this gives on average, a double hump structure

In other words, when we have a $2 \to 2$ scattering process, we have a correlation between the leading and the away side that looks, schematically as shown in FIG. 4. There, one expects the defined humps to be around 0 and π. But when one considers

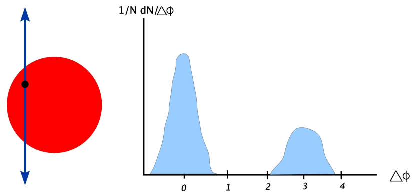

FIGURE 4. Schematic plot of a correlation study for a $2 \to 2$ process.

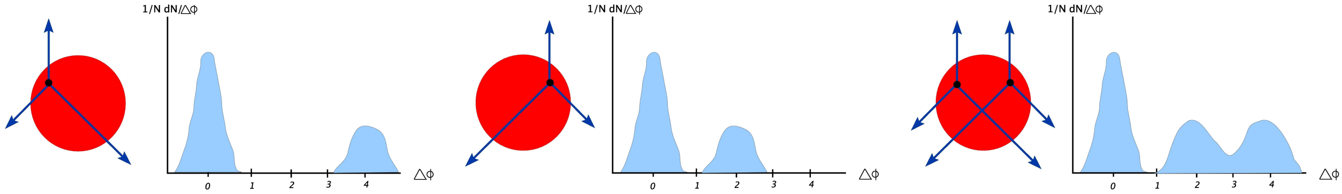

FIGURE 5. From left to right: schematic plots of a correlation studies for a $2 \to 3$ process, with particle at angle $2\pi/3$ absorbed, with particle at angle $4\pi/3$ absorbed and combined.

the possibility of a significant contribution to this correlation studies, coming from a promotion of the $2 \to 3$ scattering processes, on average one has a double hump structure (roughly at around $2\pi/3$ and $4\pi/3$), as shown in FIG. 5, again schematically.

As we summarized before, in order to build our proposal we need to account for energy loss efects in the calculation of the cross sections that are relevant to this study. In particular the $2 \to 2$ and $2 \to 3$ differential cross sections can be represented as follows:

$$\frac{d\sigma^{pp\to h1\,h2\,X}}{dy_1 dy_2 dh_{1t} dh_{2t} d\phi_2} \propto \int dz_2 |\mathcal{M}^{2\to 2}|^2 f_{i/p}(x_1,\mu^2) f_{j/p}(x_2,\mu^2) \times D^0_{h1/k}(z_1,\mu^2) D^0_{h2/m}(z_2,\mu^2) \tag{1}$$

$$\frac{d\sigma^{pp\to h1\,h2\,h3\,X}}{dy_1 dy_2 dy_3 dh_{1t} dh_{2t} dh_{3t} d\phi_2 d\phi_3} \propto \int dz_3 |\mathcal{M}^{2\to 3}|^2 f_{i/p}(x_1,\mu^2) f_{j/p}(x_2,\mu^2) \times D^0_{h1/k}(z_1,\mu^2) D^0_{h2/m}(z_2,\mu^2) D^0_{h3/n}(z_3,\mu^2). \tag{2}$$

We can see that for both p + p and Au + Au collisions we need to calculate the scattering amplitudes $\mathcal{M}^{2\to 2}$, $\mathcal{M}^{2\to 3}$ and use them together with their corresponding parton distribution functions $f_{i/p}$ and parton fragmentation functions $D_{h/k}$, when integrating over the appropiate phase space.

For the lowest order amplitudes $\mathcal{M}^{2\to 2}$ and $\mathcal{M}^{2\to 3}$ we need to consider 4 classes of diagrams and their crossings at the parton level (see for example [12]), as is schematically shown in FIG. 6.

In our calculation, we use the CTEQ6 parametrization for the parton distribution functions [13] and the KKP parametrization [14] for the (unmodified) parton fragmentation funtions together with LO-DIPHOX [15] to compare with the $2 \to 2$ result.

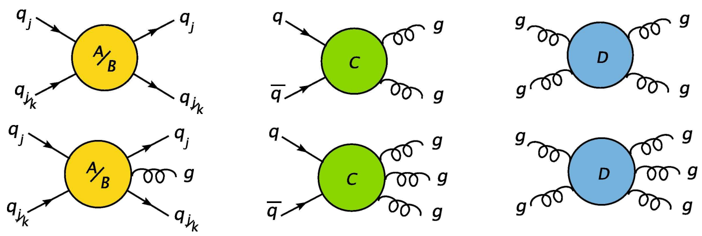

FIGURE 6. Scattering amplitudes for $2 \rightarrow 2$ and $2 \rightarrow 3$ processes considering all possible external states with crossings.

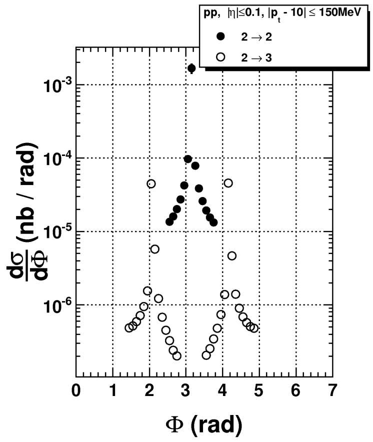

FIGURE 7. $2,3$ final state particle differential cross section at $\sqrt{S} = 200$ GeV for p + p collisions [1]

In the case of p + p collisions the $2,3$ final state particle differential cross section at $\sqrt{S} = 200$ GeV is shown in FIG. 7 for the away side hadrons as a function of the azimuthal angle. We focus on midrapidity region ($y_i = 0$) and as an example that simplifies the calculation, consider a situation in which all hadrons carry 10 GeV/c. We can see that we have two well defined peaks at $\Delta\phi = \pi$ ($\Delta\phi = 2\pi/3, 4\pi/3$), for a 2 (3) particle final state.

In order to describe the same observables but for a Au + Au collision, we now use modified parton fragmentation functions proposed by Zhang et al [16], to account for the effects of the medium on the propagation of the produced partons. These fragmentation functions are parametrized as follows:

$$D_{h/i}(z_i,\mu^2) \quad = \quad (1-e^{-\langle\frac{L}{\lambda}\rangle})\left[\frac{z_i'}{z_i}D^0_{h/i}(z_i',\mu^2)+\langle\frac{L}{\lambda}\rangle\frac{z_g'}{z_i}D^0_{h/g}(z_g',\mu^2)\right]+e^{-\langle\frac{L}{\lambda}\rangle}D^0_{h/i}(z_i,\mu^2) \tag{3}$$

where

$z_i' = \frac{h_t}{(b_{ti}-\Delta E_i)}$ is the rescaled momentum fraction of the leading parton with flavor i,

$z_g' = \langle\frac{L}{\lambda}\rangle\frac{b_t}{\Delta E_i}$ is the rescaled momentum fraction of the radiated gluon,

$\langle\frac{L}{\lambda}\rangle$ is the average number of scatterings

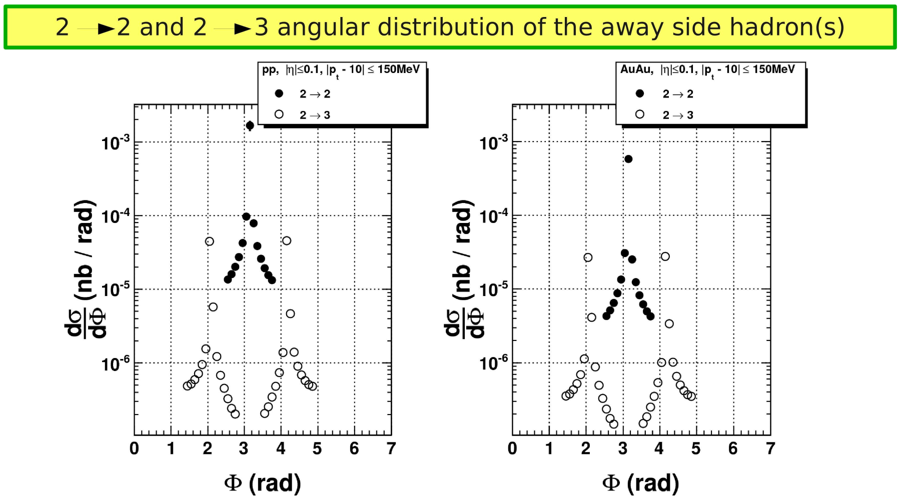

FIGURE 8. 2,3 final state particle differential cross section at $\sqrt{S} = 200$ GeV for Au + Au collisions [1]

and the average radiative parton energy loss is taken to be

$$\Delta E \propto \langle \frac{dE}{dL} \rangle_{1d} \int_{\tau_0}^{\infty} d\tau \Delta\tau \rho_g(\tau, \vec{r}_t + \vec{n}\tau).$$

Also $\vec{r}_t$ is the transverse plane location of the hard scattering where the partons are produced, $\vec{n}$ is the direction in which the produced hard parton travels in the medium and for most central collisions $\vec{b}_\perp = 0$. In our calculation, we use $\langle \frac{L}{\lambda} \rangle$, $\langle \frac{dE}{dL} \rangle_{1d}$ and ρ_g (motivated by the geometry) as suggested in [16].

Taking into account the modified parton fragmentation function, in FIG. 8 we show the appropiate differential cross section for a 2,3 particle final state in Au + Au collisions, as was done previously for p + p. Notice that in both cases the 3 hadron production cross section is suppressed with respect to the 2 hadron final state result. However, this suppression is smaller in A + A collisions than in p + p collisions. Dividing this ratio in A + A to that in p + p, we get as a function of ϕ approximately a constant:

$$\frac{\text{Au + Au}: \frac{2\to3}{2\to2}}{\text{p + p}: \frac{2\to3}{2\to2}} \sim 2.26. \tag{4}$$

Notice that the sole ingredient that induced this enhancement from the calculation of $2 \to 3$ vs $2 \to 2$ in Au + Au to that of p + p collisions is the energy loss of partons that hadronize collinearly. So this must be correlated to the different geometry for the trajectories of 3 as opposed to 2 particles in the final state. In order to test this idea we computed the distribution of path lengths with two and three hadrons in the final state by taking a nuclear overlap area with a distribution of scattering centers denser in the middle and decreasing toward the edge, as shown in FIG. 9.

In each case we disregard the path length that would correspond to the trigger particle and in FIG. 10 we compute the distribution of the path lengths corresponding to the away side particles.

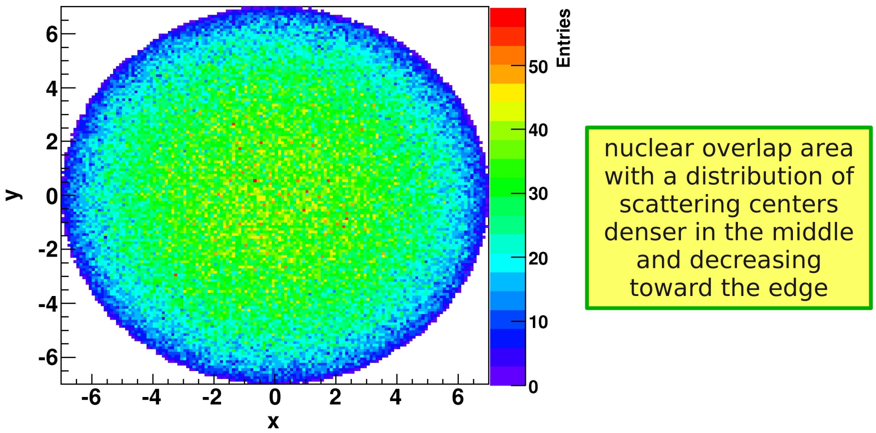

FIGURE 9. Distribution of scattering centers in the nuclear overlap area [1]

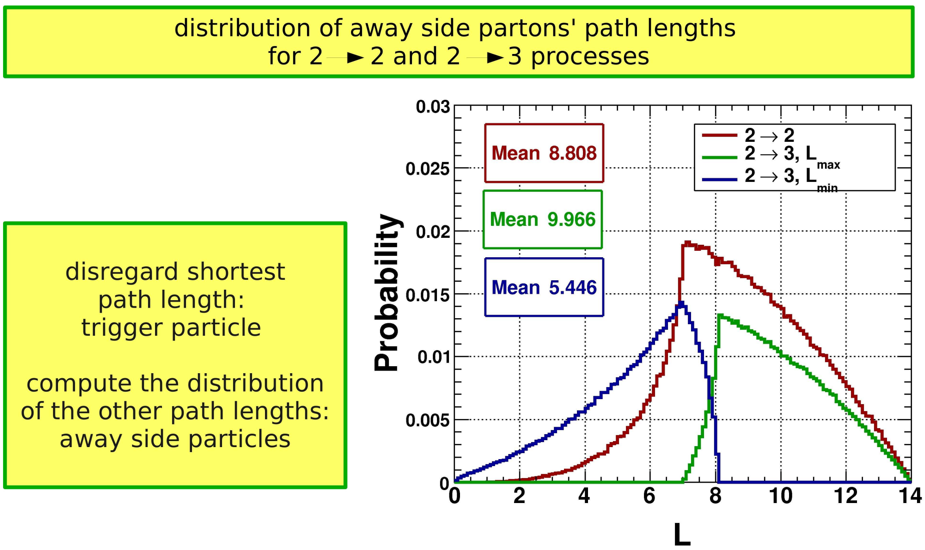

FIGURE 10. Distribution of path lenghts for the away side particles [1]

As you can see, when there are three hadrons in the final state, the large (short) path length in the away side is greater (smaller) than the case of the away side particle when there are two hadrons in the final state, i.e. $L^{2\to3}_{min} < L^{2\to2} < L^{2\to3}_{max}$.

This means that for the case of three particles in the final state, even if one of the non-leading particles with the largest path length gets absorbed by the medium, the remaining particle has a larger probability of punching through than in the case when one has two particles in the final state. So, in processes with 3 particles in the final state, there is a large probability to have one of the two away side particles being absorbed and the other randomly getting out, producing on the average, a double hump structure in the correlation studies.

3. FINAL REMARKS

We want to emphasize that $2 \to 3$ processes have to be accounted for in current heavy ion experiments, given that the medium levels out the $2 \to 2$ processes rates. In other words, their observation should be enhanced with respect to suppressed $2 \to 2$ processes. Moreover, we claim that this effect may have bearing on the away side shape for different kinematical cuts in Au + Au collisions.

We realize that we need three-particle-correlation measurements to distinguish between ours and other scenarios that might be responsible for this shape in 2 particle correlation studies and in fact we are working towards providing our predictions in this context.

ACKNOWLEDGMENTS

The authors would like to thank the organizers of the *5th International Workshop on High p_T physics at the LHC, 2010* at ICN-UNAM, Mexico, where this work was presented. M.E.T. appreciates the support provided by *Red CONACyT de Física de Altas Energías* and Departamento de Física, DCEN at Universidad de Sonora.

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