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How to Measure Squeeze Out.

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Abstract

Squeeze out happens when the expanding central fireball flows around a large surface flux tube in a central Au-Au collision at RHIC. We model such an effect in a flux tube model. Two particle correlations with respect to the v_2 axis formed by the soft fireball particles flowing around this large flux tube is a way of measuring the effect.

1 Introduction

The flux tube model does well in describing a central Au-Au collision at RHIC[1, 2]. However the tubes on the inside of colliding central Au-Au will undergo plasma instabilities[3, 4] and create a locally thermalized system. A hydro system with transverse flow builds causing a radially flowing blast wave[5]. The flux tubes that are near the surface of the fireball gets the largest radial flow and are emitting particles from the surface. The hydro flow of particles quarks and gluons around a larger flux tube on the fireball surface we will call squeeze out. This is an analogy to tooth paste squeezing out the sides of a tooth paste tube opening when the opening is blocked by a dried and harden tooth paste plug. This squeeze out has been simulated in Ref.[6] but was called flux tube shadowing. The major conclusion of flux tube shadowing from the above reference is the development of a strong v_3 azimuthal correlation. This v_3 will extend over the length of the flux tube which was created by the initial glasma conditions[1]. The flux tube model of Ref.[2] assumed that the locally thermalized system formed spherically symmetric blast wave. We need to add to this model a hydro squeeze out around the largest flux tube. By hand we will add this modification and explore possible two particle correlations with respect the flow axis(v_2) defined by the squeeze out particles. This flow axis will be at right angles the the largest flux tube.

The paper is organized in the following manner:

Sec. 1 is the introduction of the squeeze out. Sec. 2 presents the flux tube model and how squeeze out is added. Sec. 3 defines an angular correlation between v_3 and p_t dependent v_1 with respect to the v_2 reaction plane Sec. 4 defines an angular correlation between v_1 and p_t dependent v_1 with respect to the v_2 reaction plane. Sec. 5 explores two major components to the angular correlation between v_3 and p_t dependent v_1 with respect to the v_2 reaction plane. Sec. 6 explores the same two major components to the angular correlation between v_1 and p_t dependent v_1 with respect to the v_2 reaction plane. Sec. 7 presents the summary and discussion.

2 Flux Tube Model and the addition of Squeeze Out

The Glasma flux tube model for RHIC[1, 2] central Au-Au collision at $\sqrt{s_{NN}} = 200.0$ GeV has an arrangement of surface flux tubes which are formed in the initial collision and conserve momentum between them. The tubes expand longitudinally and are pushed out radially. The higher p_t particles come mainly from particle emission from the tubes. Some arrangements of the tubes favor a large v_2 among the higher p_t particles while other arrangements of the tubes favor a large v_3 (see the top two figures of Figure 1.).

The Flux Tube Model of Ref.[2] approximate the soft particle of the hydro system with particle production given by Ref.[7]. In each central event we rotate the largest flux tube into the X axis as shown in Figure 1. Each particle from the flux tube fragmentation is given a unique tag, where the largest flux tube has tag number 1.

Next we adjust the momentum vector direction of some of the soft particles such that we achieve the flow pattern of the lower figure of Figure 1. We use a particle by particle one up the Y axis and then one down the Y axis. One flowing towards $+45^0$ and one flowing towards -45^0 . A 180^0 particle of around twice the momentum is moved into place to conserve momentum. Each of the $\pm 45^0$ and 180^0 is given a tag. The flux tubes has a built in momentum conservation however we must make a final adjustment of the soft particles in order to conserve momentum in the X and Y direction. This is done by simply scaling up or down the positive components of the soft particles This is a very small change because of the care used in imposing the squeeze out flow. We sum over many generated central event to make sure that the overall v_2 lies along the Y axis, while the v_3 is pointed in the 180^0 direction or the minus X axis.

3 Angular Correlation between v_3 and p_t dependent v_1 with respect to the v_2 reaction plane

In the last section we created our simulation of squeeze out to have a global v_3 pointed in the minus X direction(see lower figure of Figure 1.). At low p_t v_1 will also point in this minus X direction. However as we move to higher p_t the largest flux tube will take over and v_1 will switch to the positive X axis. We can capture this behavior through a two particle correlation with respect to the reaction plane(Ψ_{RP}) given by global v_2 .

$$\langle \cos(3\phi_1 - \phi_2(p_t) - 2\Psi_{RP}) \rangle, \quad (1)$$

where Ψ_{RP} , ϕ_1 , ϕ_2 denote the azimuthal angles of the reaction plane, produced particle 1, and produced particle 2. This two particle azimuthal correlation measures the difference between the global v_3 and the p_t dependent v_1 . If we would rotate all events such that $\Psi_{RP} = 0.0$, then we have

$$\langle \cos(3\phi_1 - \phi_2(p_t)) \rangle. \quad (2)$$

We calculate this correlation over the simulated central events and obtain the values

Central Collisions

High P_t both v_2 v_3 positive 0°
In the center particle flow

Figure 1: Flux Tubes on the surface are arranged around the boundary with some events having a strong v_2 , while other events may have a stronger v_3 with respect to the largest Tube(see top two figures). This makes a v_2 and a v_3 aligned at 0° at high p_t . Soft particles flowing around the largest Flux Tube creates at low p_t a v_2 at 90° to the largest Tube and a v_3 at 180° (see bottom figure).

shown in Figure 2. where the p_t is that of the second particle. This sign change moving from lower p_t to higher p_t is the shift of v_1 from aligned with global v_3 at lower p_t to anti-aligned at higher p_t . more insight on this will be seen in later sections.

4 Angular Correlation between v_1 and p_t dependent v_1 with respect to the v_2 reaction plane

At low p_t v_1 will points in this minus X direction. However as we move to higher p_t the largest flux tube will take over and v_1 will switch to the positive X axis. However the global v_1 of the event is not so simple to understand. Let us form a two particle correlation with respect to the reaction plane(Ψ_{RP}) given by global v_2 , and take the sum of global v_1 vs p_t dependent v_1 ,

$$\langle \cos(\phi_1 + \phi_2(p_t) - 2\Psi_{RP}) \rangle, \quad (3)$$

where Ψ_{RP} , ϕ_1 , ϕ_2 denote the azimuthal angles of the reaction plane, produced particle 1, and produced particle 2. This two particle azimuthal correlation measures the sum between the global v_1 and the p_t dependent v_1 . If we would rotate all events such that $\Psi_{RP} = 0.0$, then we have

$$\langle \cos(\phi_1 + \phi_2(p_t)) \rangle. \quad (4)$$

We calculate this correlation over the simulated central events and obtain the values shown in Figure 3. where the p_t is that of the second particle. This sign does not change moving from lower p_t to higher p_t , however there is a shift toward the positive. More insight on this will be seen in later sections.

5 Two Major Components to the Angular Correlation between v_3 and p_t dependent v_1 with respect to the v_2 reaction plane

In our simulation the flux tubes and the squeeze out particles have unique tags thus making it possible to explore their contribution to the over all correlation function show in Figure 2. Each of the p_t bins of the correlation in Figure 2. has a normalization. If we retain this normalization and only use subsets of particle pairs, we achieve the same correlation function when we add up all the different pair correlations. For this section we will consider one particle coming from the flux tubes with another coming from the squeeze out particles. This sub correlation function is shown in Figure 4.

If we consider all the other pairs of particles leaving out the above pairs between the flux tubes and the squeeze out particles we arrive at the correlation of Figure 5. We see that all the other pairs seem to more or less cancel out giving us insight into the drivers of

Figure 2: An angular correlation between v_3 and p_t dependent v_1 with respect to the v_2 reaction plane. $\langle \cos(3\phi_1 - \phi_2(p_t) - 2\Psi_{RP}) \rangle$ is a sum over the simulated central events(see text) and is a two particle correlation using particle 1 and 2 since the reaction plane is a fixed axis constructed by the squeeze out particles.

Figure 3: An angular correlation between v_1 and p_t dependent v_1 with respect to the v_2 reaction plane. $\langle \cos(\phi_1 + \phi_2(p_t) - 2\Psi_{RP}) \rangle$ is a sum over the simulated central events(see text) and is a two particle correlation using particle 1 and 2 since the reaction plane is a fixed axis constructed by the squeeze out particles.

Figure 4: An angular correlation between v_3 and p_t dependent v_1 with respect to the v_2 reaction plane one particle coming from the flux tubes with another coming from the squeeze out particles. $\langle \cos(3\phi_1 - \phi_2(p_t) - 2\Psi_{RP}) \rangle$ is a sum over subset of particles in the simulated central events(see text) and is a two particle correlation using particle 1 and 2 since the reaction plane is a fixed axis constructed by the squeeze out particles. We retain the normalization of all pairs and only use subsets of particle pairs in the correlation.

Figure 5: An angular correlation between v_3 and p_t dependent v_1 with respect to the v_2 reaction plane using particle not coming from pairs between the flux tubes and the squeeze out particles. $\langle \cos(3\phi_1 - \phi_2(p_t) - 2\Psi_{RP}) \rangle$ is a sum over subset of particles in the simulated central events(see text) and is a two particle correlation using particle 1 and 2 since the reaction plane is a fixed axis constructed by the squeeze out particles. We retain the normalization of all pairs and only use subsets of particle pairs in the correlation. We see that all the other pairs pairs except those between the flux tubes and the squeeze out particles seem to more or less cancel out giving us insight into the drivers of the observed correlation.

the observed correlation. Let us look into the flux tube part of the pair correlation. The largest flux tube has a special tag(tag 1). In Figure 6. we plot the correlation of all tag 1 particles(largest flux tube) with the squeeze out particles. We see that in this correlation the v_3 of the squeeze out particles are pointing in the 180^0 direction the same as the global v_3 , while the largest flux tube v_1 points in the 0^0 direction(see Figure 1.). With increasing p_t this correlation becomes stronger and stronger, because there is an increase in higher p_t particles coming from the strongest flux tube.

The other flux tubes on the surface conserve the momentum of the strongest flux tube thus generate a v_1 along the 180^0 direction. This makes the squeeze out v_3 (same as the global v_3) point in the same direction generating a negative correlation between the particles of the other flux tubes and the squeeze out particles. This correlation is shown in Figure 7. and is very constant in p_t because the other flux tube particles are more spread out in p_t .

6 The same Two Major Components to the Angular Correlation between v_1 and p_t dependent v_1 with respect to the v_2 reaction plane

We will explore the same two major correlations of the last section since these correlation gave us insight into the overall correlations in the squeeze out system. We will use the same unique tags thus making it possible to follow the v_1 in p_t with respect to the global v_1 and explore their contribution to the over all correlation function show in Figure 3. As we did in the last section we will consider one particle coming from the flux tubes with another coming from the squeeze out particles. This sub correlation function is shown in Figure 8. This correlation shows a negative and quit flat correlation of momentum conservation between the flux tubes and the squeeze out particles.

If we consider all the other pairs of particles leaving out the above pairs between the flux tubes and the squeeze out particles we arrive at the correlation of Figure 9. We see that all the other pairs except those between the flux tubes and the squeeze out particles seem to be aligned with a positive correlation acting together to conserve momentum of the flux tube and squeeze out system. The largest flux tube has a special tag(tag 1). In Figure 10. we plot the correlation of all tag 1 particles(largest flux tube) with the squeeze out particles. We see that the large flux tube and the squeeze out particles have a negative correlation from momentum conservation.

The other flux tubes on the surface conserve the momentum of the strongest flux tube thus generate a v_1 along the 180^0 direction. This makes the squeeze out v_1 which is also pointing in the 180^0 direction be aligned at high p_t thus drives a positive correlation. However as a whole the flux tube system forms a momentum conserving system. The softer particles of the other flux tubes are a part of this system and have the momentum direction of the system which generates a negative correlation between the squeeze out particles and flux tubes(see Figure 11.).

Figure 6: An angular correlation between v_3 and p_t dependent v_1 with respect to the v_2 reaction plane one particle coming from the largest flux tube and the other coming from the squeeze out particles. $\langle \cos(3\phi_1 - \phi_2(p_t) - 2\Psi_{RP}) \rangle$ is a sum over subset of particles in the squeeze out particles. $\langle \cos(3\phi_1 - \phi_2(p_t) - 2\Psi_{RP}) \rangle$ is a sum over subset of particles in the simulated central events(see text) and is a two particle correlation using particle 1 and 2 since the reaction plane is a fixed axis constructed by the squeeze out particles. We retain the normalization of all pairs and only use subsets of particle pairs in the correlation. We see a large increase in a positive correlation with p_t since the largest flux tube particles(v_1) are back to back to the squeeze out particles(v_3). This gives us insight into the drivers of the observed correlation of Figure 2..

Figure 7: An angular correlation between v_3 and p_t dependent v_1 with respect to the v_2 reaction plane one particle coming from the other flux tubes with the second coming from the squeeze out particles. $\langle \cos(3\phi_1 - \phi_2(p_t) - 2\Psi_{RP}) \rangle$ is a sum over subset of particles in the simulated central events(see text) and is a two particle correlation using particle 1 and 2 since the reaction plane is a fixed axis constructed by the squeeze out particles. We retain the normalization of all pairs and only use subsets of particle pairs in the correlation. We see that the correlation is negative since the v_1 of the other flux tubes particles and the v_3 of the squeeze out particles point in the same direction. The correlation is very flat in p_t because of wider range of values of particle p_t in the other flux tubes.

Figure 8: An angular correlation between v_1 and p_t dependent v_1 with respect to the v_2 reaction plane one particle coming from the flux tubes and the other coming from the squeeze out particles. $\langle \cos(\phi_1 + \phi_2(p_t) - 2\Psi_{RP}) \rangle$ is a sum over subset of particles in the simulated central events(see text) and is a two particle correlation using particle 1 and 2 since the reaction plane is a fixed axis constructed by the squeeze out particles. We retain the normalization of all pairs and only use subsets of particle pairs in the correlation. We see that the correlation is negative and quit flat showing momentum conservation between the flux tubes and the squeeze out particles.

Figure 9: An angular correlation between v_1 and p_t dependent v_1 with respect to the v_2 reaction plane using particle not coming from pairs between the flux tubes and the squeeze out particles. $\langle \cos(\phi_1 + \phi_2(p_t) - 2\Psi_{RP}) \rangle$ is a sum over subset of particles in the simulated central events(see text) and is a two particle correlation using particle 1 and 2 since the reaction plane is a fixed axis constructed by the squeeze out particles. We retain the normalization of all pairs and only use subsets of particle pairs in the correlation. We see that all the other pairs except those between the flux tubes and the squeeze out particles seem to be aligned with a positive correlation acting together to conserve momentum of the flux tube and squeeze out system.

Figure 10: An angular correlation between v_1 and p_t dependent v_1 with respect to the v_2 reaction plane one particle coming from the largest flux tube and the other coming from the squeeze out particles. $\langle \cos(\phi_1 + \phi_2(p_t) - 2\Psi_{RP}) \rangle$ is a sum over subset of particles in the simulated central events(see text) and is a two particle correlation using particle 1 and 2 since the reaction plane is a fixed axis constructed by the squeeze out particles. We retain the normalization of all pairs and only use subsets of particle pairs in the correlation. We see that the large flux tube and the squeeze out particles have a negative correlation from momentum conservation.

Figure 11: An angular correlation between v_1 and p_t dependent v_1 with respect to the v_2 reaction plane one particle coming from the other flux tubes with the second coming from the squeeze out particles. $\langle \cos(\phi_1 + \phi_2(p_t) - 2\Psi_{RP}) \rangle$ is a sum over subset of particles in the simulated central events(see text) and is a two particle correlation using particle 1 and 2 since the reaction plane is a fixed axis constructed by the squeeze out particles. We retain the normalization of all pairs and only use subsets of particle pairs in the correlation. We see that at low p_t there is a negative correlation between the particles of the flux tubes and the particles of the squeeze out(conservation of momentum between flux tube system). At higher p_t the momentum conserving between the largest flux tube and the other flux tubes then align the other flux tube particles with the squeeze out particles and drives a positive correlation.

7 Summary and Discussion

The flux tube model does well in describing a central Au-Au collision at RHIC[1, 2]. However the hydro flow of particles quarks and gluons around the largest flux tube on the fireball surface which we will call squeeze out is predicted [6]. This is an analogy to tooth paste squeezing out the sides of a tooth paste tube opening when the opening is blocked by a dried and harden tooth paste plug. This squeeze out has been simulated in Ref.[6] but was called flux tube shadowing. The major conclusion of flux tube shadowing from the above reference is the development of a strong v_3 azimuthal correlation. This v_3 will extend over the length of the flux tube which was created by the initial glasma conditions[1]. We needed to add to the flux tube model of Ref.[2] a hydro squeeze out around the largest flux tube. By hand we will add this modification and explore possible two particle correlations with respect the flow axis(v_2) defined by the squeeze out particles. This flow axis will be at right angles the the largest flux tube.

We have created a simulation of squeeze out to have a global v_3 pointing in the minus X direction(see lower figure of Figure 1.). At low p_t v_1 will also point in this minus X direction. However as we move to higher p_t the largest flux tube will take over and v_1 will switch to the positive X axis. We can capture this behavior through a two particle correlation with respect to the reaction plane(Ψ_{RP}) given by global v_2 .

$$\langle \cos(3\phi_1 - \phi_2(p_t) - 2\Psi_{RP}) \rangle, \quad (5)$$

where Ψ_{RP} , ϕ_1 , ϕ_2 denote the azimuthal angles of the reaction plane, produced particle 1, and produced particle 2. This two particle azimuthal correlation measures the difference between the global v_3 and the p_t dependent v_1 . If we would rotate all events such that $\Psi_{RP} = 0.0$, then we have

$$\langle \cos(3\phi_1 - \phi_2(p_t)) \rangle. \quad (6)$$

We calculate this correlation over the simulated central events and obtain the values shown in Figure 2. where the p_t is that of the second particle. This sign change moving from lower p_t to higher p_t is the shift of v_1 from aligned with global v_3 at lower p_t to anti-aligned at higher p_t .

In our simulation the flux tubes and the squeeze out particles have unique tags thus making it possible to explore their contribution to the over all correlation function show in Figure 2. We can achieve about the same correlation as Figure 2 if we consider particle coming from the flux tubes with particles coming from the squeeze out particles(Figure 4.).

The largest flux tube has a special tag. In Figure 6. we plot the correlation of the largest flux tube particles(v_1) and particles of the squeeze(global v_3). The largest flux tube v_1 points in the 0^0 direction(see Figure 1.) while squeeze out particles(v_3) point in the 180^0 (see Figure 1.). With increasing p_t this correlation becomes stronger and stronger, because there is an increase in higher p_t particles coming from the strongest flux tube.

The other flux tubes on the surface conserve the momentum of the strongest flux tube thus generate a v_1 along the 180^0 direction. This makes the squeeze out v_3 (same as the

global v_3) point in the same direction generating a negative correlation between the particles of the other flux tubes and the squeeze out particles. This correlation is shown in Figure 7. and is very constant in p_t because the other flux tube particles are more spread out in p_t .

This squeeze out particle flow is a true hydro effect and can be detected using the correlation functions presented in this write up. In RHIC central Au-Au collision there is a very large v_2, v_3 and p_t dependent v_1 which is driven by this largest flux tube with squeeze out flowing particles around the tube.

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References

- [1] A.Dumitru, F. Gelis, L. McLerran, and R. Venugopalan, Nucl. Phys. A 810 (2008) 91.
- [2] Ron S. Longacre, arXiv:1105.5321[nucl-th].
- [3] T. Lappi and L. McLerran, Nucl. Phys. A 772 (2006) 200.
- [4] P. Romatschke and R. Venugopalan, Phys. Rev. D 74 (2006) 045011.
- [5] S. Gavin, L. McLerran and G. Moschelli, Phys. Rev. C 79 (2009) 051902.
- [6] Wei-Liang Qian *et al.*, arXiv:1305.4673[hep-ph].
- [7] X.N. Wang and M. Gyulassy, Phys. Rev. D 44 (1991) 3501.