Possible asymmetry of particle distribution around axes of hard jets in ultrarelativistic heavy ion collisions

M. Yu. Kopysov and Yu. E. Pokrovsky

Russian Research Centre "Kurchatov Institute",
123182, Moscow, Russia
Abstract

We discuss a possible new manifestation of the formation of an initial nonequilibrium flux tube stage in high energy heavy ion collisions. It is shown that a strong asymmetry in particle distributions around axes of hard-transverse jets takes place due to a large difference between longitudinal and transverse forces acting on the hardly scattered quarks or gluons crossing the flux tubes.

Jet formation and evolution in hot-dense hadron matter has been a subject of recent papers. This problem is considered in many studies: interaction of the leading partons of di-jets with the excited matter produced in ultrarelativistic nucleus-nucleus collisions leads to energy-momentum transfer to the hot and dense medium, which may manifest itself as jet quenching [1, 2], a broadening of the acoplanarity distribution [3, 4, 5] and possible appearance of dynamic instabilities in quark-gluon plasma (QGP) [6, 7, 8] which leads to characteristic pion and photon emission. Also the quantum–chromodynamics (QCD) flux tube dynamics at finite temperature can lead to broader $p_T$ distribution and increased strangeness yield [9].

In this paper we suggest a new signature of the formation of an initial flux tube like stage [10]. It is shown that presence of the flux tube stage in collisions leads to a modification of distributions of secondary particles in hard transverse jets. In contrast to a single jet case, in which the distributions are axially symmetrical relative to the jet axis, the modification appears as the symmetry violation (Fig. 1). This phenomenon should take place due to the large difference between the longitudinal and transverse forces acting on the hardly scattered and almost transversely moved quarks or gluons which crossed the flux tubes and formed the jets. So QCD hard jets can serve as probes of the hot and dense matter in the flux tube stage.

Let us assume that formation of the multi flux tube state in nucleus–nucleus collisions takes place at the initial stage: during the collision of two heavy nuclei a system of flux tubes begin to form in the volume of the overlap of the colliding nuclei. At a later stage, if the conditions reached in relativistic heavy ion collisions are adequate, colorless QGP may be formed via fusion of the tubes and the color would no longer be confined to hadronic or flux tube.
Figure 1: An illustration for the asymmetry of the secondary particle distribution in the hard jets and the initial nonequilibrium flux tube stage. The cone of dashed lines corresponds to the jet in the case of no flux tube stage and the cone of full lines corresponds to the asymmetric jet. Black circles denote quarks (triplet color representation) and white circles denote antiquarks or diquarks (antitriplet representation).
This flux tube initial state, if created, immediately begins its complicated evolution to ordinary hadronic matter — directly or passing through the QGP state. The question is, which probes can provide direct information about this flux tube crossover form of the matter? Considering the longitudinal flux–tube–like field fluctuations oriented along the reaction axis which cannot be realized in a pure hadronic case or in a case of equilibrium QGP, we suggest a new backgroundless signature of the formation of the initial stage in contrast to most known experimental phenomena which do not give clear information about the pre-equilibrium stage.

Let’s consider the flux tube stage for the central nucleus–nucleus collision (Fig. 1). The tube–like fluctuations of the color fields are oriented along the collision axis. This anisotropy of the field fluctuations affects the secondary particle distributions.

For a first estimation in a frame of the classic approach, consider a hardly scattered parton which is moving in a direction transverse to the reaction axis. This parton may create a flux tube which may decay to a hard jet. An interaction of this parton with QCD fields in the longitudinal flux tubes affects the parton’s momentum distribution which determines the distribution of secondary particles in the jet relative to the jet axis. In particular, bremsstrahlung gluon radiation takes place in a tangential direction by the quark crossing the strong gluon field in each tube. This is the main dynamical reason for an asymmetry: the mean square projection of momentum of secondary particles in the jet along the reaction axis (Fig. 1, axis $z$) becomes larger than in the transverse direction (axis $x$). Because the fluctuations of the fields are isotropic in a vacuum, hadron matter, or QGP states, the distribution of the jet particles in these cases is axially symmetrical relative to the jet axis.

Our estimations show that this asymmetry can be visible in nucleus–nucleus collisions if the flux tube stage takes place. The value of the asymmetry can be characterized by the ratio $R_a = \frac{\langle p_z^2 \rangle^{1/2}}{\langle p_x^2 \rangle^{1/2}}$. Let’s estimate the value of the asymmetry of the parton distribution relative to axis of its initial direction of movement (immediately after the hard scattering).

$R_a$ depends on energy of colliding nuclei because of energy de-
dependence of the mean number of flux tubes and mean square transverse momentum of particles in a jet relative to jet axis. Consider $e^+e^-$-annihilation to estimate the energy dependence of $<p_x^2>^{1/2} = <p_y^2>^{1/2}$. In this case charge particle multiplicity can be parametrized as

$$M_{ch}(W) = a + b \ln W^2 + c \ln^2 W^2,$$

(1)

where $a = 3.33$, $b = -0.40$, $c = 0.26$ and $W$ is invariant mass of $e^+e^-$ pair. The total particle multiplicity can be roughly estimated as $M(W) = \frac{3}{2}M_{ch}(W)$, and the value of $<p_x^2>^{1/2}$ can be expressed from sphericity $S$

$$S = \frac{3}{2} \sum_i (p_{ix}^2 + p_{iz}^2),$$

(2)

and the asymptotic dependence of $W$

$$S \propto 0.8W^{-1/2}.$$ 

(3)

If the jet is not too wide ($<p_x^2> + <p_y^2> \ll <p_y^2> \simeq <p^2>$), see Fig. [4], then $W \approx M<p^2>^{1/2}$ and

$$\sum_i p_i^2 = M \left(\frac{W}{M}\right)^2 = \frac{W^2}{M}.$$ 

(4)

From (4) we get

$$<p_x^2>^{1/2} = \sqrt{\frac{1}{2} \left( <p_x^2> + p_y^2 \right)} = \sqrt{\frac{1}{2M} \sum_i (p_{ix}^2 + p_{iz}^2)} \simeq 0.52 \frac{W^{3/4}}{M(W)}.$$ 

(5)

For SpS, RHIC and LHC energies we obtain $<p_x^2>^{1/2} = 0.26, 0.44$ and $1.8$ GeV/c respectively.

Now let’s estimate the additional momentum of the hard transverse quark crossed the longitudinal flux tubes. Consider the simplest case of static cylindrical flux tubes in ground states with a constant uniform chromoelectric field pointed along the axis of symmetry (the reaction axis).

Then consider a quark ($q_1$) passing through the flux tube transverse to the tube axis. Static tube approximation can be used for
the piece of the tube (crossed by the quark) which is almost at rest in the equal velocity frame. Because in static tubes chromomagnetic fields vanish, and soft interactions of the hard quark $q_1$ with its own (transverse) tube (Fig. 2) can be neglected for a study of the transverse dynamics, the force acting on the quark can be written as

$$ F = \frac{g}{2} \lambda^a E^a, $$

(6)

where $g$ is the QCD coupling constant, $\lambda^a$ are the Gell-Mann matrices, the lower index 1 means that the matrix acts on $q_1$ and $E^a$ is the chromoelectric field. For simplicity, the flux tube lengths are assumed to be much greater than their radii, and the flux tube radii to be small enough to neglect the overlap of the tubes. For the quark induced case the tube ends have triplet color representations. The quark $q_1$ moves with almost light velocity, therefore, in the thin tube case, the end quarks have no time to change their color states when $q_1$ crosses the flux tube. So the values of $E^a$ are distributed among the tubes in accordance with their color states and can be considered time independent.

Find the change of the mean transverse momentum of the hard quark after crossing one flux tube with an arbitrary distribution of

Figure 2: An illustration of the calculation of quark momentum and for discussion of the interaction between a hard scattered quark and flux tubes.
the gluonic field over the tube section
\[ E^a = E^a(x, y). \]  

Let axes \( x \) and \( y \) be the coordinate system in the section where \( q_1 \) crosses the tube, let axis \( y \) be pointed along \( q_1 \)'s direction of motion and let \( \xi \) be the distance between axis \( y \) and line of \( q_1 \) movement.
Then \( q_1 \) will cross the tube surface in points \((\xi, y_1(\xi))\) and \((\xi, y_2(\xi))\).
The quark momentum change may be written as
\[ \Delta p(\xi) = \int F(\xi, t) \, dt = \int_{y_1(\xi)}^{y_2(\xi)} F(\xi, y) \, dy = \int_{y_1(\xi)}^{y_2(\xi)} g_2 \lambda_1^a E^a(\xi, y) \, dy. \]  

Here and below the light velocity \((c)\) is assumed to be \(c = 1\). Average \( \Delta p \) over all \( \xi \) (\( \rho_{\text{tube}} \) is the flux tube radius):
\[ \Delta p = \frac{1}{\rho_{\text{tube}}} \int_{-\rho_{\text{tube}}}^{\rho_{\text{tube}}} \, d\xi \int_{y_1(\xi)}^{y_2(\xi)} \frac{1}{2} \lambda_1^a E^a(x, y) \, dy = \frac{1}{2\rho_{\text{tube}}} \int_S g_2 \lambda_1^a E^a(x, y) \, dS. \]  

Here \( S \) is a transverse flux tube section. Applying the Gauss theorem (see Fig. 2) we get:
\[ \Delta p = \frac{\hat{z}}{2\rho_{\text{tube}}} g_2 \frac{1}{2} \lambda_1^a \oint_S E^a \, dS = \frac{\hat{z}}{2\rho_{\text{tube}}} g_2 \frac{1}{2} \lambda_1^a \int_{\vec{V}} \text{div} E^a \, dV = \frac{\hat{z}}{2\rho_{\text{tube}}} g_2 \frac{1}{2} \lambda_1^a g_2 \frac{1}{2} \lambda_2^a = \frac{\hat{z}}{8\rho_{\text{tube}}} \lambda_1^a \lambda_2^a, \]  

where \( g_2 \lambda_1^a \lambda_2^a \) is the "color charge" of the quark \( q_2 \) and \( \hat{z} \) is the unit vector in the longitudinal tube direction. This result does not depend on the field distribution over the tube section.

For estimation of the asymmetry of distribution of particles in the jet mentioned above we need to know \( <\Delta p^2> \):
\[ <\Delta p^2> = \frac{g_4^4}{64\rho_{\text{tube}}^2} <(\lambda_1^a \lambda_2^a)^2> c. \]  

\( 7 \)
Here the index $c$ means averaging over the color states of $q_1$ and $q_2$. To calculate $\langle (\lambda_1^a \lambda_2^b)^2 \rangle_c$ let’s consider matrices $\lambda_1^a$ and $\lambda_2^a$ as vectors in eight-dimensional space. Choose the axis $x_8$ to be directed along the vector $\lambda_1^a$ (its distribution is assumed to be isotropic). Take into account that the mean square of the scalar product $(\lambda_1^a \lambda_2^b)^2$ averaged over all $\lambda_2^a$ directions and the mean value of the square of the projection of $\lambda_2^a$ onto the direction of $\lambda_1^a$ (i.e. $\langle (\lambda^8)^2 \rangle_c$) multiplied by the absolute value of $\lambda_1^a$ squared are equal to each other. This takes place because the color states of $q_1$ and $q_2$ are assumed to be independent. Taking into account that all mean square components of the vector $\lambda^a$ are equal to each other we get:

$$\langle \lambda^2 \rangle_c = \langle \lambda^a \lambda^a \rangle_c = \sum_{a=1}^{8} \langle (\lambda^a)^2 \rangle_c = 8 \langle (\lambda^8)^2 \rangle_c,$$

$$\langle (\lambda^8)^2 \rangle_c = \frac{1}{8} \langle \lambda^2 \rangle_c = \frac{1}{8} \lambda^2. \quad (12)$$

For $\lambda^2 = \frac{16}{3}$,

$$\langle (\lambda_1^a \lambda_2^a)^2 \rangle_c = \frac{1}{8} \left( \frac{16}{3} \right)^2. \quad (13)$$

Let $\Delta p = \sqrt{\langle \Delta p^2 \rangle_c}$. Then after crossing one flux tube

$$\Delta p = \frac{g^2}{8 \rho_{\text{tube}}} \sqrt{\langle (\lambda_1^a \lambda_2^a)^2 \rangle_c} = \frac{4\pi \alpha_s}{3 \sqrt{2} \rho_{\text{tube}}}, \quad (14)$$

where $\alpha_s = \frac{\pi}{4 \epsilon}$ is the QCD fine structure constant.

For a tube radius $\approx 0.3$ Fm [13] we get for QCD running coupling constant $\alpha_s(\frac{\pi}{\Lambda_{\text{QCD}} \rho_{\text{tube}}}) = 0.3$ (in 3-loop approximation) and $\Delta p \approx 0.6$ GeV. In the cases of SpS and RHIC (see Table 2 below) this value is greater than or close to $\langle p_x^2 \rangle^{1/2}$ and asymmetry $R_a \approx 1.7–2.5$ is larger than in the case of LHC ($R_a \approx 1.05$).

This asymmetry is expected to be visible for hadron–hadron collisions, and increases together with the atomic number $A$ of the colliding nuclei because the quark crosses more and more tubes. In this paper we consider the jet asymmetry in the large $A$ case for the reaction of $^{238}\text{U} + ^{238}\text{U}$.

Now let’s estimate the average number of flux tubes crossed by the quark in its traveling across the reaction zone in central
nucleus–nucleus collisions. For kinematical reasons in addition to the quark $q_1$ there is a quark $q'_1$ hardly collided with $q_1$ and moving in the opposite direction from $q_1$. The mean distance travelled by each quark in the nuclear reaction zone with uniform distribution of the flux tubes is then

$$<l> = \frac{8R}{3\pi}. \tag{15}$$

Here $R$ is the reaction zone radius (in the case of the central interactions of nuclei it is almost equal to the radius of the lightest nucleus).

We assume that the mean number of flux tubes is about $3/2$ for each nucleon because for each nucleon there are four possible numbers $0, 1, 2, 3$ of the tubes encountered with almost equal probability. This rough estimation is in good agreement with FRITIOF \cite{14} calculations.

Consider a central collision of two identical nuclei with atomic number $A$. In this case the number of flux tubes per unit area of the transverse section is

$$n = \frac{3A}{2\pi R^2} = \frac{3A^{1/3}}{2\pi r_0^2}. \tag{16}$$

Here $R = r_0 A^{1/3}$ is the nucleus radius. Then the average number of flux tubes crossed by $q_1$ will be

$$N = 2\rho_{\text{tube}} <l>n = \frac{8A^{2/3}}{\pi^2 r_0^2} \rho_{\text{tube}}. \tag{17}$$

For $^{238}\text{U}$ we get $N \approx 8$.

Let’s find the average transverse momentum of quark $q_1$ after it crosses $N$ flux tubes. After crossing $m$ flux tubes

$$<\Delta P_{zm}^2> = <(\Delta P_{zm-1} + \Delta p_z)^2> =$$

$$= <\Delta P_{zm-1}^2> + <\Delta p_z^2> + 2<\Delta P_{zm-1} \Delta p_z>. \tag{18}$$

Here $\Delta P_{zm-1}$ is the transverse momentum of $q_1$ after it crossed $m-1$ flux tubes. The last term vanishes because $\Delta P_{zm-1}$ and $\Delta p_z$ may be pointed in any direction along the tube axis independently. So, we get

$$<\Delta P_{zm}^2> = <\Delta P_{zm-1}^2> + <\Delta p_z^2>. \tag{19}$$
And

\[ <\Delta P> = \sqrt{<\Delta P_z^2> N_s} \approx \sqrt{N(\Delta p)^2} = \sqrt{N\Delta p} \]  (20)

\[ <\Delta P> = \sqrt{\frac{8A^{2/3}}{\pi^2 r_0} \rho_{\text{tube}} \frac{4\pi\alpha_s(\rho_{\text{tube}})}{3\sqrt{2}\rho_{\text{tube}}} = \frac{2\pi A^{1/3} \alpha_s(\rho_{\text{tube}})}{\sqrt{6}r_0} \sqrt{\rho_{\text{tube}}} \approx 1.7 \text{ GeV/c.} \]  (21)

This estimation is accurate for the case of non-overlapping flux tubes. If the flux tube radii are not too large then this assumption is quite reasonable.

Let’s estimate the asymmetry of particle distribution in a jet characterized by \( R_a = \frac{<p^2_z>^{1/2}/<p^2_x>^{1/2}}{<p^2_x>^{1/2}} \). The value of \( <p^2_z>^{1/2} \) is determined by average transverse momentum of the hard quark \( <\Delta P> \) and by typical transverse momentum of particles in the jet \( <p^2_x>^{1/2} \):

\[ R_a = \frac{<p^2_z>^{1/2}}{<p^2_x>^{1/2}} = \frac{\sqrt{<\Delta P>^2 + <p^2_z>}}{<p^2_x>^{1/2}} = \sqrt{1 + \frac{<\Delta P>^2}{<p^2_x>}} = \sqrt{\frac{1 + \frac{16}{3} \frac{A^{2/3}\alpha_s^2}{r_0\rho_{\text{tube}}<p^2_z>}}{<p^2_x>}}. \]  (22)

The values of asymmetry \( R_a \) at various energies of colliding nuclei are shown in Table 2 (see below). One can see that in the cases of SpS and RHIC \( R_a \gg 1 \) and so large asymmetry can be measured experimentally. In the case of LHC the asymmetry is not very large but may be observed in high statistics experiments.

It should be noted that our calculation of quark interaction with flux tubes is not complete yet. For the first step we concentrated on the subject of phenomenon and did not take into account the quark’s interaction with fields in its own flux tube or the interactions between tubes. We consider only quark jets here although we would expect the more noticeable effect for gluon-induced jets. The flux tubes are assumed to be non-overlapping. In Table 3 we present the results of our estimation (based on event generator FRITIOF) of the mean numbers of essentially overlapped tubes for different tube radii for the reaction of \( {}^{238}\text{U} + {}^{238}\text{U} \). We suppose here that the tubes are essentially overlapped when the distance between their
Table 1: Mean numbers of $n$-fold overlapped flux tubes for different tube radii ($n = 0$ corresponds to the not overlapped single flux tube).

| n  | Tube radius (Fm) | 0.1 | 0.2 | 0.3 | 0.4 |
|----|------------------|-----|-----|-----|-----|
| 0  |                  | 330.9 | 261.6 | 175.9 | 102.7 |
| 1  |                  | 25.4 | 82.0 | 123.9 | 120.9 |
| 2  |                  | 0.7  | 11.6 | 43.5  | 81.3 |
| 3  |                  | 0.0  | 1.6  | 10.5  | 35.3 |
| 4  |                  | 0.0  | 0.2  | 2.3   | 12.0 |

axes is less than the tube radius. The resulting value \( \rho_0 \) takes into account only the most important contributions and needs in more precise calculations which we plan to make in our following works. The small value of tube radius 0.2–0.3 Fm are of great interest (in connection with percolation \[15\] and lattice calculations \[16\]). One can see from the Table [1] that in this case the most of tubes are not overlapped.

It should be noted that a jet’s properties can be studied in the experiment if its angular size is sufficiently large to cover more than one detector module and if there is no dominance of essentially overlapped jets.

To estimate the angular size of the jets let’s consider a jet in the equal velocity frame where the partons have been elastically scattered off each other at the angle of 90 degrees. Each parton carries about $x = 1/3$ of the total nucleon momentum $p_0$ (sea quarks and gluons do not change strongly this value). The angular size of a jet is determined by (Fig. \[3\])

$$
\sin \frac{\theta}{2} = \frac{<p_x^2>^{1/2}}{<p_y^2>^{1/2}} \simeq M \frac{<p_x^2>^{1/2}}{2p_0/3} = \frac{M(W)}{W} <p_x^2>^{1/2},
$$

\(23\)

where $<p_x^2>^{1/2}$ is shown in \(\[3\]\) and the factor 2 in the denominator appears because $M$ is the multiplicity of the two jets propagating in opposite directions. In Table \[2\] we present values of $p_0$, $<p_x^2>^{1/2}$, $<p_y^2>^{1/2}$, $R_a$ and $\theta$ for SpS, RHIC and LHC energies. One can see that in all cases the angular size of the jets is large enough to be...
detected experimentally.

We have yet no estimations of the numbers of overlapping jets at different transverse momenta. But in any case there are transverse jets with high momentum which are rare enough to be single.

Other corrections may arise from the decay of the longitudinal tubes on fragments due to their rotation in evolution of the flux-tube stage. The largest asymmetry takes place in the case when the quark crosses the flux tubes transversely. Because the angular velocity of tube rotation is greater in case of short tube fragments (the mean square transverse momentum of fragment ends does not depend on the fragment lengths), events in which the long tube fragments dominate are more favorable for studying the asymmetry. In particular such events may be selected by using the fact that longer tubes accumulate more kinetic energy in their tension and their fragments after decay should be concentrated in the middle rapidity range. We plan to present more detailed calculations of this effect in our future works. In any case the large value of asymmetry (≈ 670%) means that this asymmetry can be observed in experiments even if the corrections would be taken into account.

Another reason for decreasing of the asymmetry is the percolation effect. As shown in \cite{15} even in central Pb–Pb collisions string
density is so high that practically all tubes are fused. It means that there is no jet asymmetry. But it is not yet known if this picture is real or not. Observing any asymmetry or its absence in experiments may give information about the way of evolution of heavy ion collisions.

In conclusion it should be noted that a new possible manifestation of the formation of the initial nonequilibrium flux tube stage for the QGP transition in high energy heavy ion collisions is suggested: the longitudinal anisotropy in the flux tube fluctuations of color electric fields formed in the pre-equilibrium (flux tube) stage leads to a strong azimuthal asymmetry in the particle distributions in the hard-transverse jets around their axes. It is concerned with the large difference between the transverse and longitudinal (with respect to the beam axis) momentum components of the hardly scattered partons. This increasing of the longitudinal momentum component takes place due to the interaction of the transverse jet quark with gluon fields in the longitudinally oriented flux tubes. The value of the additional longitudinal momentum of the jet quark after crossing the flux tubes ($\langle \Delta P \rangle \approx 1.7 \text{ GeV}$) is sufficiently large to be observable in experiments. Because this asymmetry is produced by the axially symmetrical field fluctuations, it should be

| Collider | SPS | RHIC | LHC |
|----------|-----|------|-----|
| $p_0$, GeV/c | 10 | 100 | 3150 |
| $W$, GeV | $20/3$ | $200/3$ | $6300/3$ |
| $M$ | 8.33 | 27.5 | 87.1 |
| $<p_z^2>^{1/2}$, GeV/c | 0.26 | 0.44 | 1.8 |
| $<p_x^2>^{1/2}$, GeV/c | 1.7 | 1.7 | 2.5 |
| $R_a$ | 6.7 | 4.0 | 1.4 |
| $\theta,^\circ$ | 38 | 21 | 8.7 |
absent in both the cases of hadronic matter and QGP and may serve as a backgroundless signature of the flux tube stage in heavy ion collisions.

References

[1] Dilella L., *Ann. Rev. Nucl. Part. Sci.*, 1985, vol. 35, p. 107.

[2] Gyulassy, M., and Plümer, M., *Phys. Lett. B*, 1990, vol. 243, p. 432.

[3] Appel, D.A., *Phys. Rev. D*, 1986, vol. 33, p. 717.

[4] Blaizot, J.P., and McLerran, L.D., *Phys. Rev. D*, 1986, vol. 34, p. 2739.

[5] Rammestorfer, M., and Heinz, U., *Phys. Rev. D*, 1990, vol. 41, p. 306.

[6] Silin, V.P., Ursov, V.N, Proc. Joint Varenna–Abastumani Int. School Workshop on Plasma Astrophysics, ESA SP-251, 1986, p. 513.

[7] Pokrovsky, Yu.E., Selikhov, A.V., *JETP Lett.*, 1988, vol. 47, No. 1, p. 11.

[8] Pavlenko, O.P., *Yad. Phys.*, 1991, vol. 54, p. 1448, *Yad. Phys.*, 1992, vol. 55, p. 2239.

[9] Jändel, M., *Phys. Rev. D*, 1986, vol. 34, p. 162.

[10] Casher, A., et. al., *Phys. Rev. D*, 1979, vol. 20, p. 179.

[11] Althoff, M., et al. *Zs. Phys. C*, 1984, vol. 22, p. 307.

[12] Wolf, G. *Preprint DESY 80/85*. — Hamburg, 1980; *Preprint DESY 81/86*. — Hamburg, 1981; *Preprint DESY/82/077*. — Hamburg, 1982.

[13] Pokrovsky, Yu.E., in *Proceedings of the XXIX International Winter Meeting On Nuclear Physics*, Bormio, Italy, 14-19 January 1991, Suppl. N., vol. 83, p. 338, edited by I. Iori (Dept of Physics, University of Milano),
[14] Ding Linkai, Evert Stenlund: A Monte Carlo for Nuclear Collision Geometry, LU TP 89-6 (1989).

[15] Armesto, N., Braun, M.A., Ferreiro, E.G. and Pajares, C. [hep-ph/9607239]. Submitted to Phys. Rev. Lett..

[16] Haymaker, R.W., Singh, V., Peng, Y-C., Wosiek, J. Phys. Rev. D, 1996, vol. 53, p. 389.