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Event shape engineering via Glauber MC model

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Abstract. In our exploration of event shape engineering, the Glauber model served as a foundational tool for under- standing the anisotropic geometry of the Quark-Gluon Plasma (QGP). Utilizing the TGlauberMC-3.2* model within ROOT, we systematically analyzed one million events. From the $\epsilon 2$ & Npart plot, our data revealed an average maximum dN value of 12.00 with associated parameters: $\epsilon 2$ = 0.91, $\psi 2$ =2.74, $\psi 3$ =0.91 and Npart = 14.00. These findings illuminate the distinct configurations that yield the most pronounced anisotropic geometries of the QGP, providing insights into optimizing event shape configurations.

Keywords: Event Shape Engineering, Glauber Model, Quark-Gluon Plasma (QGP), TGlauberMC-3.2, Anisotropic Geometries.

1. Introduction

1.1. QGP and event shape engineering

Quark gluon plasma is the state of matter, consisting of free gluons and quarks, produced in ultra relativistic heavy ion collisions with extremely high temperature and density. It's believed that QGP existed shortly after the big bang, thus by studying the QGP, valuable insights can be gained to better understand the fundamental properties of matter and early formation of the universe.

* (http://www.hepforge.org/downloads/tglaubermc) for the most recent TGlauberMC release (currently version 3.2).

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1.2. The Glauber Monte Carlo model and path length measurement

Event shape engineering is the technique to manipulate the shapes of QGP and extract the property of produced particles. In this letter we focus on the anisotropy flow that provide insight into the initial and subsequent evolution of the collision system. By disentangling various flow components, the dynamics of the created QGP can be shown.

In heavy ion collisions, QGP is formed in the overlap region of the colliding nucleus. We use the Glauber model to describe the collision. It is assumed that the nucleus-nucleus collision can be simplified to uncorrelated nucleon-nucleon collisions.[1]

The position of each nucleon is sampled from the Fermi distribution [2]. Collisions can be simulated with either a random or fixed impact parameter and then projected onto the x-y plane. In the Monte Carlo approach, a nucleon-nucleon collision occurs if the distance between the nucleons in the x-y plane satisfies the condition given by

$$r = \sqrt{\frac{\text{cross section}}{\pi}}.$$

The TGlauberMC code, integrated within Root, is employed to execute the Monte Carlo simulations and simulate collisions. The code produces data related to collision positions and other pertinent parameters, such as the impact parameter b, elliptical eccentricity ϵ_2, triangular eccentricity ϵ_3 [3], number of collisions N_{coll}, and number of participants N_{part}.

The study of the QGP often evolves the anisotropy of its shape. In this experiment we use the path length difference to manifest the anisotropy. Paths are possible route traversed by partons. [4] Due to the high density of the QGP, the path length is measured by counting the number of nucleons along the path. The path length difference is defined as the length difference between minor axis and major axis. The direction of the minor axis is determined by angle ψ_2 and the direction of major axis is perpendicular to the minor axis.

2. Methodology and approach

2.1. C++ based ROOT frame

ROOT frame is a framework used to process data first born at CERN. The frame work is dominant to the researches of high energy physics.[5] In this paper, C++ based ROOT frame is used to run the Monte Carlo Glauber (MCG) model of version 3.2 to simulate $Au + Au$ collisions and generate data of these collisions, the model is run directly on terminal of MacOS in this project.

2.2. Visualisation of data

2.2.1. Verification of generated data

Function runAndSaveNtuple() generates a series of different MCG events and saves related physical quantities.[1] In this paper, cross section is set to 40mb, which corresponds to collision energy of 200Gev and nucleon radius of 0.564fm. The graph relating *Ncoll* and impact parameter is plotted using ROOT shown in Figure 1. The shape and values of the graph match with the result in Reference [2], which verifies the process of generating data using the MCG model.

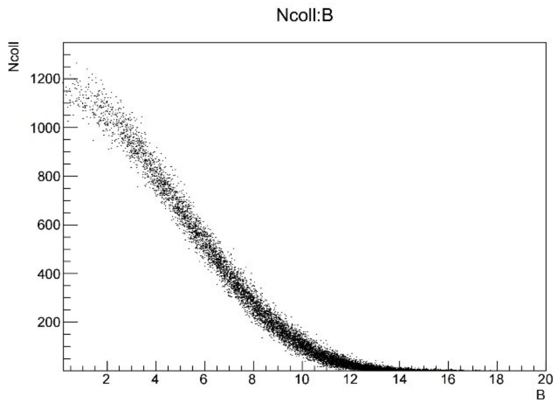

Figure 1. Illustration of the relationship between the number of collisions N_{part} and the impact parameter B over 10,000 elastic $Au + Au$ collisions.

2.2.2. *Visualisation of the Quark-Gluon Plasma (QGP)*

The coordinates and number of collisions on an individual nucleon during one $Au + Au$ event with cross section 40*mb* is calculated by the MCG model. The typical shapes of collisions can be seen By plotting the positions of nucleons in the collisions. In Figure 2, a collision of impact parameter 8 is shown, with red and blue dotted-line circles representing the spectators of nucleus A and nucleus *B*, and red and blue full-line circles representing the wounded nucleons (nucleons that participate in the collision) of nucleus A and nucleus B.

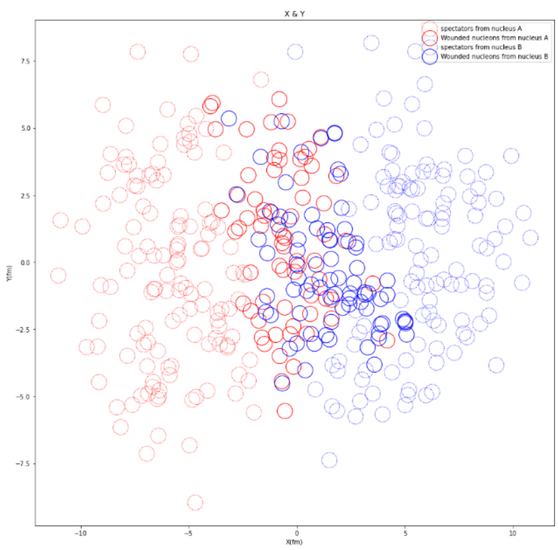

Figure 2. Representation of the Quark-Gluon Plasma in the XY plane.

2.2.3. *Correlation between N_1 and N_2*

In this step, an arbitrary wounded nucleon is chosen. A line with random direction in the XY plane passing through the random nucleon is divided by it into two segment: L_1 and L_2. Wounded nucleons whose distance to the line is smaller than the radius of Au nucleons (r=0.564*fm*) can be considered as passing through the line .The number of wounded nucleons passing through L_1 is defined as N_1, and the number of wounded nucleons passing through L_2 is defined as N_2.

In Figure 4, the plots of N_1 and N_2 of different impact parameters are illustrated. A strong anti-correlation between N_1 and N_2 can be seen clearly. The aver- age value of both N_1 and N_2 are decreasing as B increases, which is as predicted due to a decrease of average number of participants with the increase of B. Possible errors can contribute to this result such as when no nucleon is passing through the line with a random angle, and the possibility of fetch- ing wounded nucleons on the edge of the QGP. To avoid the latter error, the process of fetching a ran- dom point is weighted using the N_{coll} of nucleons.

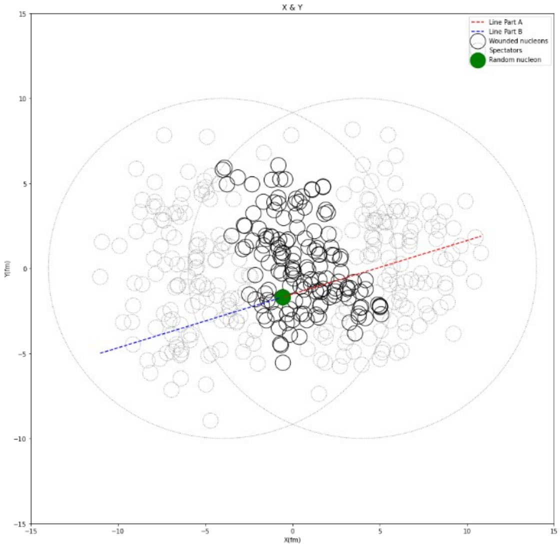

Figure 3. Computation of N_1 and N_2. The segment L_1, depicted in red, represents points possessing x-coordinates greater than the designated random point. Conversely, the segment L_2, illustrated in blue, encompasses points with x-coordinates less than this random point. In the provided illustration, for instance, the values are determined as $N_1 = 20$ and $N_2 = 5$.

2.2.4. Event shape engineering for ellipse

In our investigation, we introduce N_1 and N_2 as the quantities representing the number of nucleons along the major and minor axes, respectively. As illustrated in Figure 5, N_2 corresponds to the count of wounded nucleons intersecting with the ray L_2. This ray, depicted in red within Figure 5, is conceptualized as a vector in a unit circle for the purposes of this algorithm. It is angled at ψ_2, which signifies the inclination of the minor axis of an ellipse with respect to the horizontal axis. For the specific event displayed in Figure 5, N_2 is found to be 9.

On the other hand, N_1 is associated with the number of wounded nucleons traversing the ray L_1. This ray, visualized in blue in Figure 5, is perpendicular to L_2. Importantly, it encompasses a greater number of nucleons than the ray situated in the opposing direction. For the event under consideration, N_1 is ascertained to be 24. The Perpendicular Detector Algorithm was employed to determine the values of N_1 and N_2.

For event shape engineering, our endeavor was centered around identifying an ellipse exhibiting optimal symmetry, and pinpointing an ellipse characterized

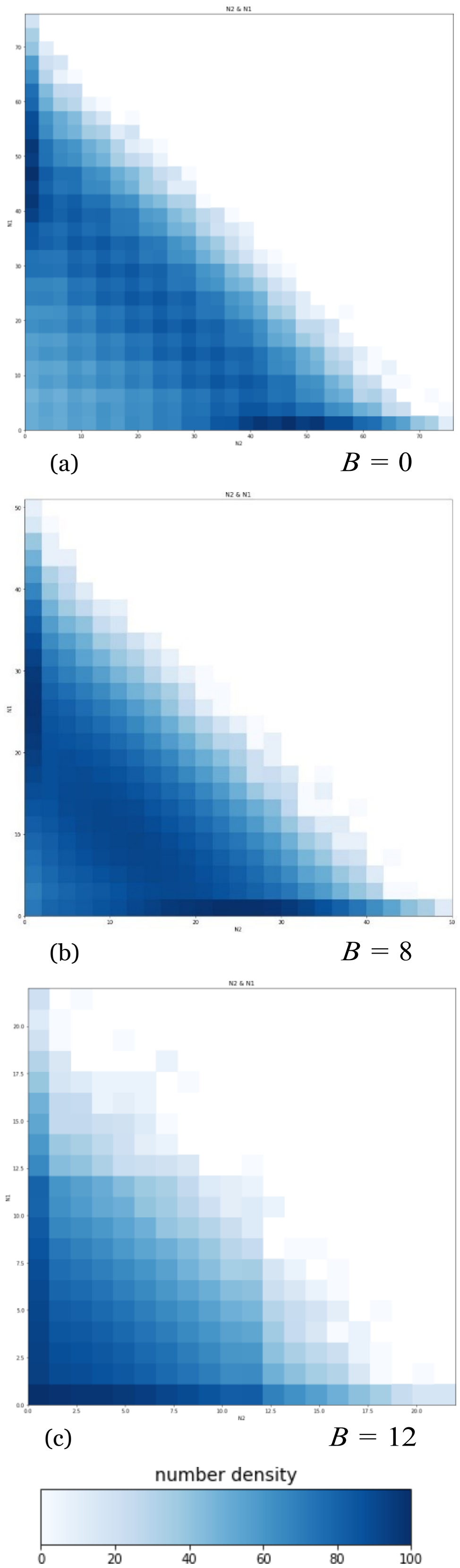

Figure 4. Depiction of the relationship between N_1 and N_2 for impact parameters of 0, 8, and 12.

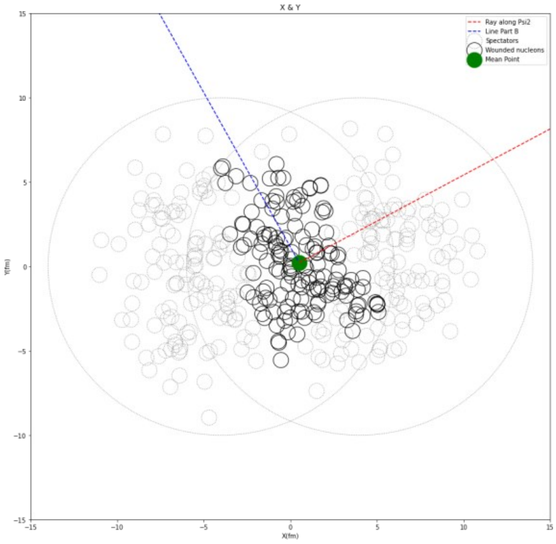

Figure 5. Depiction of the major and minor axes. The blue line signifies the major axis, while the red line denotes the minor axis oriented in the direction of ψ_2.

by the most marked difference in its dimensions, represented as $N1 - N2$ or dN. After analyzing 1,102,826 events, we secured equivalent sets of N_1 and N_2 values. The distribution of dN is charted in Figure 6. For an in-depth scrutiny, we selected regions manifesting a pronounced dN, specifically in cases where $dN > 15$.

For data with $dN > 15$, contour lines are plotted on histograms. Figure 7(a) is for ϵ_2(used to determine the level of symmetry of a shape to an ellipse) and N_{part}, Figure 7(b) is for ϵ_3(used to determine the level of symmetry of a shape to a triangle) and N_{part}.

3-dimensional graphs are also plotted to show the cor- relation between those physical quantities and aver- age values of dN by using surface 3d plotting tools from Matplotlib. For calculating the average values of dN, a histogram of a physical quantity chosen from ϵ_2, ϵ_3, ψ_2, ψ_3 as the y-axis and N_{part} as the x-axis is drawn with weight 1, and a histogram of the same quantities is drawn with weight dN. By dividing the two histograms, the average values of dN is represented as the colour depth of the histogram. Then the colour depth (average dN) is used as the third axis(z-axis) of the surface 3d graphs. In Figure 9(a) and 9(b), surface 3d graphs are plotted for ϵ_2 and ϵ_3 being the y-axis respectively, and N_{part} for x-axis, average dN for z-axis.

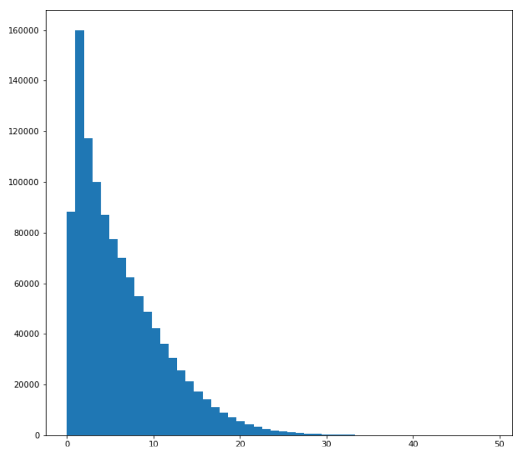

Figure 6. Presentation of the dN distribution, with values extending from 0 to 30. For the Quark-Gluon Plasma (QGP), a substantial path difference is inferred when dN surpasses 15.

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3. Result

In a detailed examination of the anisotropy of the Quark-Gluon Plasma (QGP), several intriguing observations can be made. Referring to Fig. 9(a), there is a notable increase in the path difference with ϵ_2. This increase reaches its maximum, approximately at 12.00, when the number of participating nucleons, N_{part}, is 14.00. Conversely, as depicted in Fig. 9(b), the path difference remains substantial even for small values of ϵ_3.

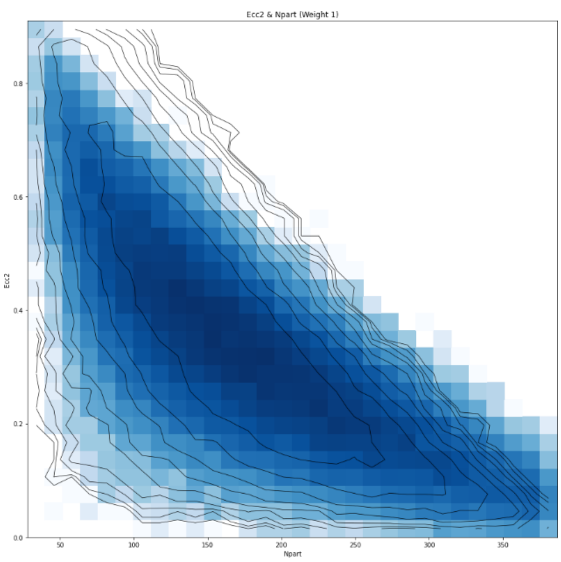
The optimal combination resulting in the largest path difference is achieved when $\psi_2 = 2.74$, $\psi_3 = 0.91$, and $\epsilon_2 = 0.91$. This suggests that the anisotropy is at its zenith when the collision is peripheral and the number of participants is minimal. For a central collision, N_{part} approaches 400, corresponding to $\epsilon_2 = 0.22$.

Interestingly, when N_{part} falls below 10, the QGP exhibits maximum asymmetry. However, due to the inherent limitation that dN cannot surpass N_{part}, this observation is bounded by the relatively small value of N_{part}.

4. Conclusion

In the present study, emphasis has been laid on modulating the path length difference of the Quark-Gluon Plasma (QGP) employing the Glauber model. The optimal set of parameters yielding the maximal path length difference comprises $\epsilon_2 = 0.91$, $\psi_2 = 2.74$, $\psi_3 = 0.91$, and $N_{\text{part}} = 14.00$. This particular combination is indicative of a highly peripheral collision. The magnitude of the path length difference is intrinsically contingent upon the size of the QGP, represented by the number of participating nucleons, as well as its anisotropic nature.

The pinnacle of path length difference can be realized only in the presence of an adequate number of participating nucleons in conjunction with a pronounced anisotropic geometry of the QGP. To bolster the veracity of the path length distribution, further simulation of data is recommended. Such an approach would not only augment the reliability but also ameliorate the effects of anomalies stemming from random fluctuations.



(a) $\epsilon 2$ and Npart

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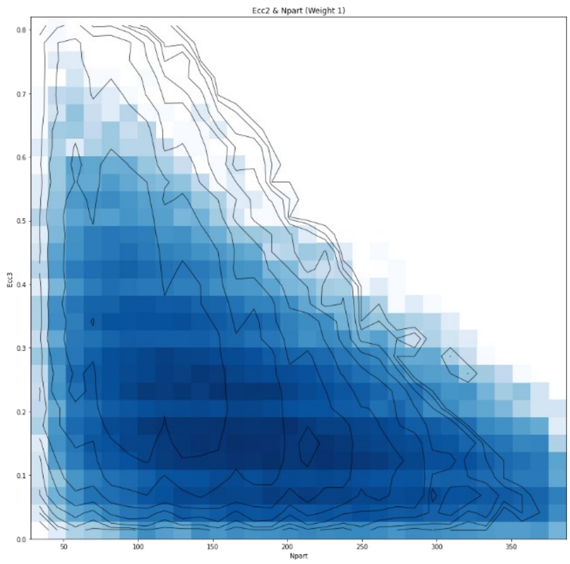
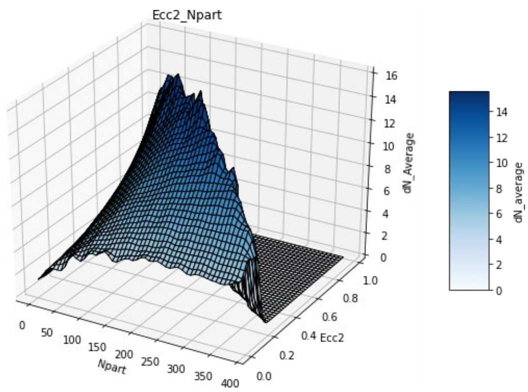
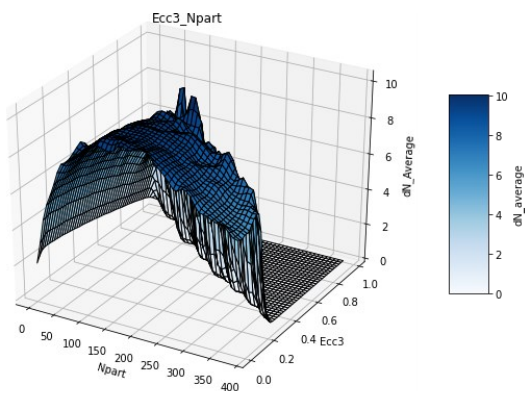


(b) $\epsilon 3$ and Npart

Figure 7. Contour plots and histograms illustrating the relationships of ϵ_2 with N_{part} and ϵ_3 with N_{part} for datasets where $dN > 15$.



(a) Three-dimensional depiction showcasing the relationship between $\epsilon 2$ and Npart, with the mean dN functioning as the vertical axis.



(b) Three-dimensional visualization depicting the association between $\epsilon 3$ and Npart, with the mean dN acting as the vertical axis.

Figure 8. Three-dimensional surface plots.

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