Analysis of the Charged-particle Multiplicity Density in Centrality from Track Lets

Xuanyu Shi[1], Hanwen Zhang[2, *], Chengchenyu Wang[3], Yuanyuan Mu[4]
[1] Nanjing Foreign Language School, Nanjing, 210008, China
[2] Qingdao Academy, Qingdao, 266213, China
[3] School of Physics, Shandong University, Jinan, Shandong 250100, China
[4] Hangzhou No14 High School, Hangzhou, 310006, China

*Corresponding author. Email: nanqiu2003@163.com

Abstract. This paper shows the relationship between charged hadron diversity and centrality in hadron Pb-Pb collisions at a certain collision energy(2.76 TeV) per nucleon pair. It is found that the centrality from $70-80\%$ to $0-5\%$, each normalized charged particle density of participating nucleon pair increases by about twice. The collision of particles in the experiment was simulated by ALICE, a detector dedicating heavy-ion physics at the Large Hadron Collider. This work compares the data sample with models based on different mechanisms for particle production in nuclear collisions. And the error analysis of data in the end of this passage ensures the correctness of the experiment.

Keywords: tracklets, charged hadron diversity, centrality.

1. Introduction

ALICE is a detector dedicating heavy-ion physics at the Large Hadron Collider. which is designed to study strongly interacting matter at extreme energy densities. The LHC simulates quark-gluon plasma under extreme conditions of protons and neutrons. This extreme condition is similar to those reproduced in laboratory conditions after the Big Bang. In the theory of quantum chromodynamics, our current primary issue is closely related to quark-gluon plasma and its properties.

Quantum Chromodynamics (QCD), the theory of the strong interaction, predicts a phase transition at high temperature between hadronic and deconfined matter (the Quark–Gluon Plasma). The ALICE Collaboration reported the measurement of hadron Pb Pb collisions at a collision energy of 2.76 TeV per nucleon pair. In this report, we do research on the non-central collisions. And the measurement of the centrality dependence of the multiplicity density of charged primary particles $\mathrm{d}N_{ch}/\mathrm{d}\eta$ with $|\eta| < 0.2$ is presented in our research. It provides the charged-particle density per participant-pair, $(\mathrm{d}N_{ch}/\mathrm{d}\eta)/(\langle N_{part}\rangle/2)$, which covers the most central 80% of the hadronic cross section. And it is divided into nine centrality classes. Glauber modeling is used to calculate the average number of nucleons involved in a

Journal of Physics: Conference Series **2386** (2022) 012051 doi:10.1088/1742-6596/2386/1/012051

collision in a certain centrality class [1].

2. Methods

All the calculations in this paper to estimate the charged particle multiplicity using data from the Silicon Pixel Detector (SPD), the innermost part of the Inner Tracking System (ITS), were performed in Spyder, a type of integrated development environment (IDE) of python. More specifically, the SPD is composed of two cylindrical layers of hybrid silicon pixel assemblies, both of which cover $|\eta| < 1$. (the definition of η will be given below). The tracklets are built using the reconstructed points of the SPD and the reconstructed main vertex position.

A beam line from the vertex to each cluster in the innermost part of the ITS is considered. For each cluster, or in this case, the tracklet in the inner layer, two differences are computed through Spyder using the reconstructed vertex as the origin. (1) The difference in the azimuthal angles ($\Delta\phi$) between the innermost layer and the outermost layer of SPD in the $x - y$ coordinate is computed, as is shown in the picture below. (2) The difference in the pseudorapidity ($\Delta\eta$) between the innermost layer and the outermost layer of SPD in the $y - z$ coordinate is computed, as is also shown in the picture below, where η could be calculated using the formula : $\eta \equiv -\ln\tan(\theta/2)$ [2]. (Figure 1 [3])

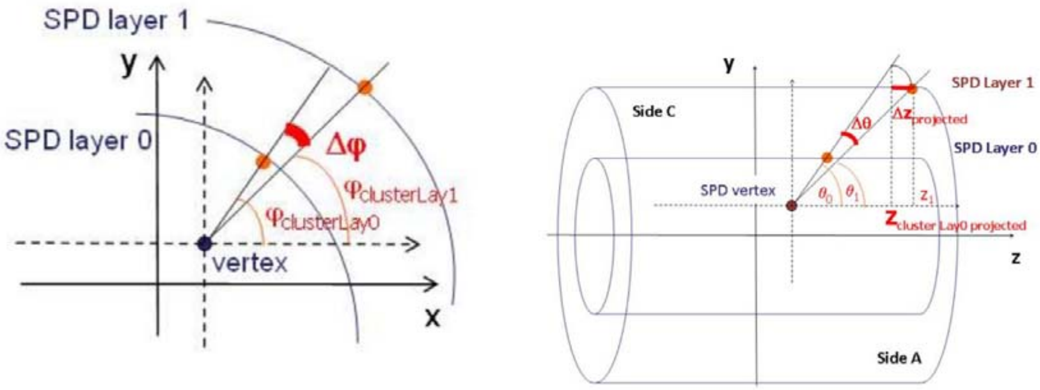

Figure 1. Graph of the two differences are shown in the picture. In the left picture of x-y plane, the difference in the azimuthal angles (Δϕ) is presented. In the right picture of y-z plane, the difference in the pseudorapidity (Δη) , or in this case, Δθ is presented.

3. Determination of parameters

The parameters for characterizing the charged particle multiplicity are $(\langle N_{part}\rangle, \mathrm{d}N_{ch}/\mathrm{d}\eta)$, where $\langle N_{part}\rangle$ stands for the total number of nucleons in the two Pb-Pb nuclei that experienced no less than 1 inelastic collision and $\mathrm{d}N_{ch}/\mathrm{d}\eta$ stands for the density of charged particles. The ways to obtain these data are shown below [4].

3.1. Centrality Determination

In particle physics, especially in studying the collision of heavy ions, it is important to estimate the centrality. The classification of centrality is based on the sum of the amplitude of the signals in V0-A and V0-C detector. The Vzero amplitude is fit perfectly based on the Glauber Monte Carlo. The number of the total particles in Vzero detector could be calculated using the following formula:

$$N_{source} = f \times N_{part} + (1 - f) \times N_{coll} \tag{1}$$

where $f = 0.806$, N_{coll} and N_{part} could be obtained by running the Glauber Monte Carlo. The amplitude of Vzero is determined by the following formula:

$$Vzero = NBD(\mu) \tag{2}$$

From 0 to N_{source} where μ is the mean number of particle sources, where in this case, is 29 [3].

3.2. *the dependence of* $\boldsymbol{\Delta\phi}$ *and* $\boldsymbol{\Delta\eta}$

In order to determine whether there is a relationship between $\Delta\phi$ and $\Delta\eta$, we use the 2D histogram, a nested function in Spyder using the library matplotlib. The results shown below better illustrate that there is no relationship between $\Delta\phi$ and $\Delta\eta$ [5]. (Figure 2)

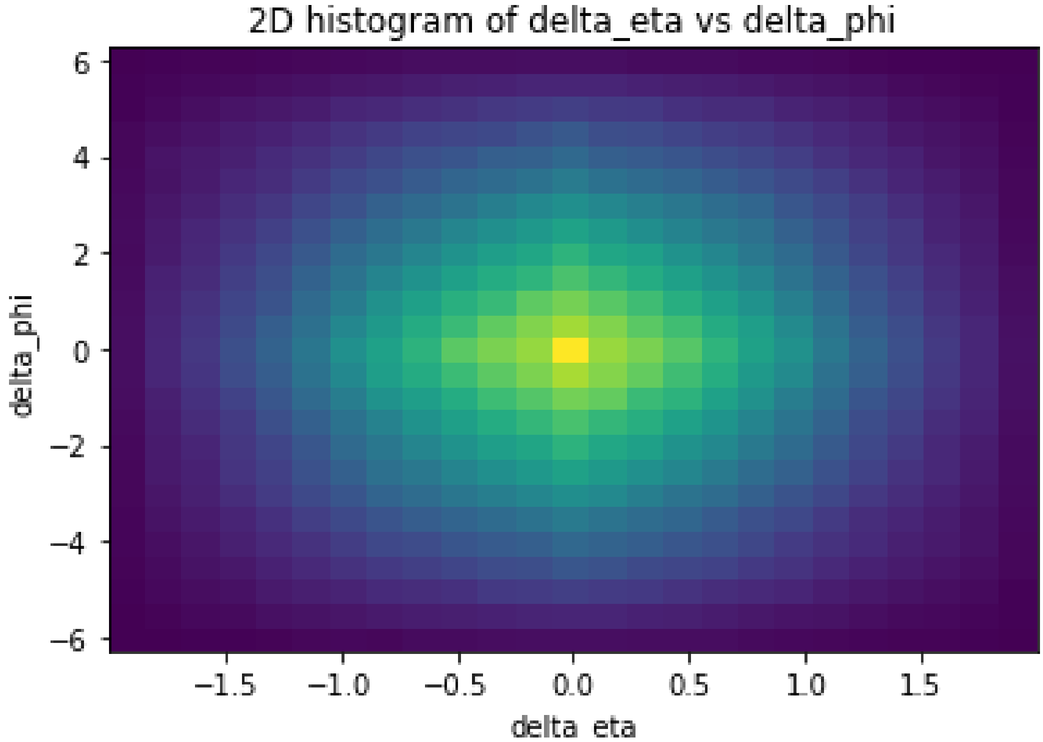

Figure 2. The 2D histogram of Δϕ and Δη indicates that there is no linear or exponential relationship between the two parameters.

3.3. *Data Analysis Part*

Let N be the number of events. In the part, $N = 20000$.

Centrality is from $VZERO$.

For Glauber fit, $\langle N_{part}\rangle$ and $\langle N_{coll}\rangle$ and $VZERO$ ($VZERO = (\frac{4}{5}\langle N_{part}\rangle + \frac{1}{5}\langle N_{coll}\rangle) \times 26$) of a event is from TGlauberMC ($sysA =$ "Pb" , $sysB =$ "Pb" , $signn = 64(\pm 5)$) v3.2 on https://tglaubermc.hepforge.org/ [6]. (Figure 3)

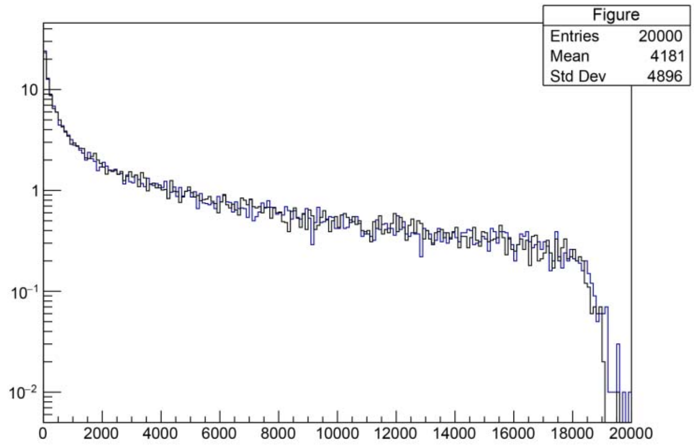

Figure 3. The histogram of VZERO (Glauber fit is black).

4. Data Analysis Part

4.1. $dN_{ch}/d\eta$

4.1.1. $dN_{ch}/d\eta$ *of a event.* Two hits the first and the second hit of which are respectively in the first and the second layer and the mean η of which $\overline{\eta}$ satisfies $-0.5 < \overline{\eta} < 0.5$ is called data. If the two hits of a data are from the same particle, the data is called Signal data. If not, the data is called Background data.

For D as a data, let $diff(D)$ be the difference from (η, ϕ) of the first hit of D to (η, ϕ) of the second hit of D. (Figure 4)

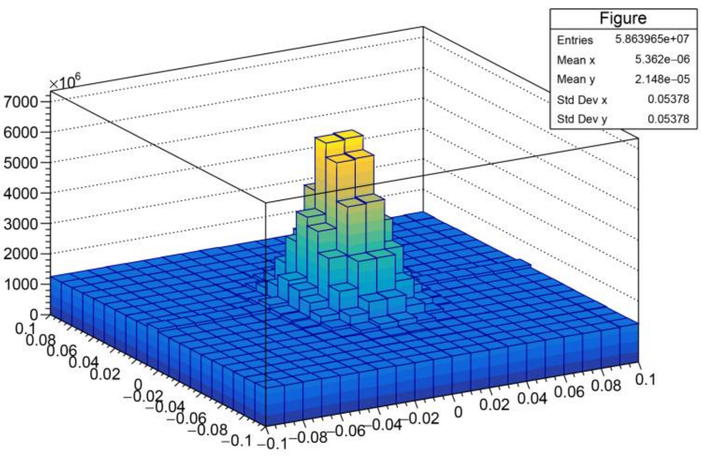

Figure 4. The histogram of diff(D) for D as a data in all datas of all events.

For A as a set of 2D points, let $area(A)$ be the area of A; let $datas(A)$ be the number of datas which each and only data D satisfies $diff(D) \in A$ is in; let $Signal\_datas(A)$ be the number of Signal datas which each and only data D satisfies $diff(D) \in A$ is in; let $Background\_datas(A)$ be the number of Background datas which each and only data D satisfies $diff(D) \in A$ is in.

Let T be the set of all 2D points.

It is assumed, if η is from -0.5 to 0.5, $\mathrm{d}N_{ch}/\mathrm{d}\eta = \Delta N_{ch}/\Delta\eta$, and, if η is from -0.5 to 0.5, $\Delta N_{ch} = Signal\_datas(T)$.

So, $\mathrm{d}N_{ch}/\mathrm{d}\eta = \Delta N_{ch}/\Delta\eta = Signal\_datas(T)/(0.5-(-0.5)) = Signal\_datas(T)$.

Since data is known and data the two hits of which are and are not from the same particle is unknown, for any A as a set of 2D points, $datas(A)$ is known and $Signal\_datas(A)$ is unknown and $Background\_datas(A)$ is unknown.

Let $S_{01} = \{(\Delta\eta,\Delta\phi)|\Delta\eta^2+\Delta\phi^2 \in [0,2\times 0.05^2)\}$.

Let $S_{E0} = \{(\Delta\eta,\Delta\phi)|\Delta\eta^2+\Delta\phi^2 \in [0.05^2,\infty]\}$.

Let $S_0 = \{(\Delta\eta,\Delta\phi)|\Delta\eta^2+\Delta\phi^2 \in [0,0.05^2)\}$.

Let $S_1 = \{(\Delta\eta,\Delta\phi)|\Delta\eta^2+\Delta\phi^2 \in [0.05^2,2\times 0.05^2)\}$.

It is assumed, for any A as a set of 2D points which satisfies $A \subseteq S_{01}$, $Background\_datas(A) \propto area(A)$, and, for any A as a set of 2D points which satisfies $A \subseteq S_{E0}$, $Signal\_datas(A) = 0$.

So, $Background\_datas(S_0) = Background\_datas(S_1)$, and, $Signal\_datas(S_{E0}) = Signal\_datas(S_1) = 0$.

So, $Signal\_datas(T) = Signal\_datas(S_0) + Signal\_datas(S_{E0}) = Signal\_datas(S_0) = datas(S_0) - Background\_datas(S_0) = datas(S_0) - Background\_datas(S_1) = datas(S_0) - (datas(S_1) - Signal\_datas(S_1)) = datas(S_0) - datas(S_1)$.

So, $\mathrm{d}N_{ch}/\mathrm{d}\eta = datas(S_0) - datas(S_1)$.

4.1.2. $\boldsymbol{dN_{ch}/d\eta}$ *of centrality from* $\boldsymbol{b}$ *to* $\boldsymbol{e}$. For $\boldsymbol{a}$ as a number which satisifies $\boldsymbol{a \in Z \cap [0,N)}$, let $\boldsymbol{x_a}$ be $\mathbf{d}\boldsymbol{N_{ch}}/\mathbf{d}\boldsymbol{\eta}$ of event $\boldsymbol{a}$ which has been sorted from the most central to the most peripheral.

For b and e as two numbers which satisfy $b \in [0,1)$ and $e \in (0,1]$ and $b < e$, let $x_{(b,e)}$ be $\mathrm{d}N_{ch}/\mathrm{d}\eta$ of centrality from b to e.

So, for b and e as two numbers which satisfy $b \in [0,1)$ and $e \in (0,1]$ and $b < e$, $x_{(b,e)} = (\sum_{i\in Z\cap[N\times b,N\times e)} x_i) \times (\sum_{i\in Z\cap[N\times b,N\times e)} 1)^{-1}$.

4.1.3. The uncertainty of $\boldsymbol{dN_{ch}/d\eta}$ *of centrality from* $\boldsymbol{b}$ *to* $\boldsymbol{e}$. The total systematic uncertainty on $\mathbf{d}\boldsymbol{N_{ch}}/\mathbf{d}\boldsymbol{\eta}$ amounts to $\mathbf{7.0}\%$ in the most peripheral and $\mathbf{3.8}\%$ in the most central class [1].

For a as a number which satisifies $a \in Z \cap [0,N)$, let $x\_uncertainty_a$ be the uncertainty of $\mathrm{d}N_{ch}/\mathrm{d}\eta$ of event a which has been sorted from the most central to the most peripheral.

So, it is assumed, for any a as a number which satisifies $a \in Z \cap [0,N)$, $x\_uncertainty_a = (0.0000016a + 0.038) \times x_a$.

For b and e as two numbers which satisfy $b \in [0,1)$ and $e \in (0,1]$ and $b < e$, let $x\_uncertainty_{(b,e)}$ be the uncertainty of $\mathrm{d}N_{ch}/\mathrm{d}\eta$ of centrality from b to e.

So, for b and e as two numbers which satisfy $b \in [0,1)$ and $e \in (0,1]$ and $b < e$, $x\_uncertainty_{(b,e)} = (\sum_{i\in Z\cap[N\times b,N\times e)} x\_uncertainty_i) \times (\sum_{i\in Z\cap[N\times b,N\times e)} 1)^{-1}$.

4.2. $\boldsymbol{\langle N_{part}\rangle}$

4.2.1. $\boldsymbol{\langle N_{part}\rangle}$ *of a event.* $\boldsymbol{\langle N_{part}\rangle}$ is known.

4.2.2. $\boldsymbol{\langle N_{part}\rangle}$ of centrality from $\boldsymbol{b}$ to $\boldsymbol{e}$. For $\boldsymbol{a}$ as a number which satisifies $\boldsymbol{a \in Z \cap [0,N)}$, let $\boldsymbol{y_a}$ be $\boldsymbol{\langle N_{part}\rangle}$ of event $\boldsymbol{a}$ which has been sorted from the most central to the most peripheral.

For b and e as two numbers which satisfiy $b \in [0,1)$ and $e \in (0,1]$ and $b < e$, let $y_{(b,e)}$ be

$\langle N_{part} \rangle$ of centrality from b to e.

So, for b and e as two numbers which satisfiy $b \in [0,1)$ and $e \in (0,1]$ and $b < e$, $y_{(b,e)} = (\sum_{i \in Z \cap [N \times b, N \times e)} y_i) \times (\sum_{i \in Z \cap [N \times b, N \times e)} 1)^{-1}$.

4.2.3. The uncertainty of $\langle \boldsymbol{N_{part}} \rangle$ *of centrality from* $\boldsymbol{b}$ *to* $\boldsymbol{e}$. The systematic uncertainty in the $\langle \boldsymbol{N_{part}} \rangle$ values is obtained by varying the parameters entering the Glauber calculation as described above [1].

For b and e as two numbers which satisfiy $b \in [0,1)$ and $e \in (0,1]$ and $b < e$, let $y\_uncertainty_{(b,e)}$ be the uncertainty of $\langle N_{part} \rangle$ of centrality from b to e.

So, for b and e as two numbers which satisfiy $b \in [0,1)$ and $e \in (0,1]$ and $b < e$, $y\_uncertainty_{(b,e)} = \frac{1}{2} \times (y_{(b,e)}|_{signn=64+5} - y_{(b,e)}|_{signn=64-5})$.

4.3. $(\mathbf{d}\boldsymbol{N_{ch}}/\mathbf{d}\boldsymbol{\eta})/(\langle \boldsymbol{N_{part}} \rangle/\mathbf{2})$

4.3.1. $(\boldsymbol{dN_{ch}}/\boldsymbol{d\eta})/(\langle \boldsymbol{N_{part}} \rangle/\mathbf{2})$ *of centrality from* $\boldsymbol{b}$ *to* $\boldsymbol{e}$. For $\boldsymbol{b}$ and $\boldsymbol{e}$ as two numbers which satisfiy $\boldsymbol{b} \in [\mathbf{0}, \mathbf{1})$ and $\boldsymbol{e} \in (\mathbf{0}, \mathbf{1}]$ and $\boldsymbol{b} < \boldsymbol{e}$, let $\boldsymbol{z_{(b,e)}}$ be $(\mathbf{d}\boldsymbol{N_{ch}}/\mathbf{d}\boldsymbol{\eta})/(\langle \boldsymbol{N_{part}} \rangle/\mathbf{2})$ of centrality from $\boldsymbol{b}$ to $\boldsymbol{e}$.

So, for b and e as two numbers which satisfiy $b \in [0,1)$ and $e \in (0,1]$ and $b < e$, $z_{(b,e)} = x_{(b,e)}/(y_{(b,e)}/2)$.

4.3.2. The uncertainty of $(\boldsymbol{dN_{ch}}/\boldsymbol{d\eta})/(\langle \boldsymbol{N_{part}} \rangle/\mathbf{2})$ *of centrality from* $\boldsymbol{b}$ *to* $\boldsymbol{e}$. For $\boldsymbol{b}$ and $\boldsymbol{e}$ as two numbers which satisfiy $\boldsymbol{b} \in [\mathbf{0}, \mathbf{1})$ and $\boldsymbol{e} \in (\mathbf{0}, \mathbf{1}]$ and $\boldsymbol{b} < \boldsymbol{e}$, let $\boldsymbol{z\_uncertainty_{(b,e)}}$ be the uncertainty of $(\mathbf{d}\boldsymbol{N_{ch}}/\mathbf{d}\boldsymbol{\eta})/(\langle \boldsymbol{N_{part}} \rangle/\mathbf{2})$ of centrality from $\boldsymbol{b}$ to $\boldsymbol{e}$.

So, for b and e as two numbers which satisfiy $b \in [0,1)$ and $e \in (0,1]$ and $b < e$, $z\_uncertainty_{(b,e)} = \frac{\partial z_{(b,e)}}{\partial x_{(b,e)}} x\_uncertainty_{(b,e)} + \frac{\partial z_{(b,e)}}{\partial y_{(b,e)}} y\_uncertainty_{(b,e)} = 2y_{(b,e)}^{-1} x\_uncertainty_{(b,e)} - 2x_{(b,e)} y_{(b,e)}^{-2} y\_uncertainty_{(b,e)}$.

4.4. Results

Results are from data analysis. (Table 1) (Figure 5)

Table 1. The table of centrality,$\mathrm{d}N_{ch}/\mathrm{d}\eta$,$\langle N_{part} \rangle$,$(\mathrm{d}N_{ch}/\mathrm{d}\eta)/(\langle N_{part} \rangle/2)$.

centrality	$\mathrm{d}N_{ch}/\mathrm{d}\eta$	$\langle N_{part} \rangle$	$(\mathrm{d}N_{ch}/\mathrm{d}\eta)/(\langle N_{part} \rangle/2)$
$0-5\%$	1598 ± 62	381.4 ± 2.4	8.4 ± 0.3
$5-10\%$	1304 ± 53	327.8 ± 4.4	8.0 ± 0.2
$10-20\%$	958 ± 41	259.8 ± 3.3	7.4 ± 0.2
$20-30\%$	633 ± 29	184.6 ± 3.1	6.9 ± 0.2
$30-40\%$	406 ± 20	128.3 ± 1.9	6.3 ± 0.2
$40-50\%$	249 ± 13	85.4 ± 1.4	5.8 ± 0.2
$50-60\%$	140 ± 8	52.8 ± 0.9	5.3 ± 0.2
$60-70\%$	73 ± 4	29.8 ± 0.5	4.9 ± 0.2
$70-80\%$	35 ± 2	14.9 ± 0.3	4.7 ± 0.2

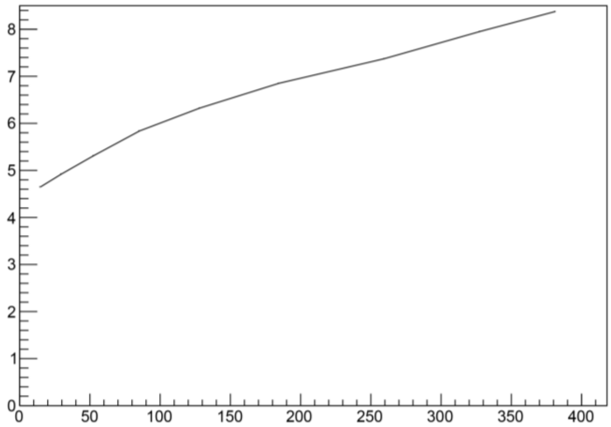

Figure 5. The graph of $(\langle N_{part}\rangle, (\mathrm{d}N_{ch}/\mathrm{d}\eta)/(\langle N_{part}\rangle/2))$.

5. Conclusion

In summary, in hadron Pb Pb collisions at a collision energy of 2.76 TeV per nucleon pair, the relationship between charged hadron diversity and centrality is presented in our research. The graph demonstrates that each normalized charged particle density of participating nucleon pair grows from the centrality of $70-80\%$ to $0-5\%$. The data calculation reveals that it increases by about twice.

Acknowledgement

All authors are the first authors. Zhang Hanwen writes the parts of Methods and Determination of parameters (including figures). Wang Chengchenyu writes the parts of Abstract and Introduction. Mu Yuanyuan does all the preperation work before writing, including categorizing the reference essays and daily research summarization, editor the draft. Data Analysis Part: Shi Xuanyu writes all (including figures and tables) . Shi Xuanyu creates all ways of all data analysis and does all data analysis.

References

[1] Kenneth Aamodt et al. Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Phys. Rev. Lett., 106:032301, 2011.
[2] Serguei Chatrchyan et al. Centrality dependence of dihadron correlations and azimuthal anisotropy harmonics in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Eur. Phys. J. C, 72:2012, 2012.
[3] Serguei Chatrchyan et al. Dependence on pseudorapidity and centrality of charged hadron production in PbPb collisions at a nucleon-nucleon centre-of-mass energy of 2.76 TeV. JHEP, 08:141, 2011.
[4] Georges Aad et al. Measurement of the centrality dependence of the charged particle pseudorapidity distribution in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector. Phys. Lett. B, 710:363–382, 2012.
[5] Georges Aad et al. Measurement of the distributions of event-by-event flow harmonics in lead-lead collisions at = 2.76 TeV with the ATLAS detector at the LHC. JHEP, 11:183, 2013.
[6] Constantin Loizides, Jason Kamin, and David d'Enterria. Improved Monte Carlo Glauber predictions at present and future nuclear colliders. Phys. Rev. C, 97(5):054910, 2018. [Erratum: Phys.Rev.C 99, 019901 (2019)].