CERN SUMMER PROJECT

ALICE Femtoscopy Masterclass Instructions

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1 ABSTRACT

The "International Masterclasses" project aims to introduce the cutting-edge particle physics experiments to high-school students all around the world. More specifically, ALICE Femtoscopy Masterclass is designed to teach students about the methods used to characterize the quark-gluon plasma. The masterclass is developed as a website, which provides easy access to the exercise. It aims to teach students about the physics and the research process behind femtoscopy measurement.

2 INTRODUCTION

ALICE is a detector dedicated to heavy-ion collisions. In these high energy collisions, like lead-on-lead (Pb-Pb), very high temperatures and densities are achieved. These extreme conditions give rise to Quark-Gluon Plasma (QGP) [4].

How is it possible to investigate the physical properties of QGP? One way is through femtoscopy [5]. Using two-particle correlations, the size of this system can be studied. When QGP is created, it emits many types of particles which we can study. In this Masterclass, pions are being studied. Since pions are bosons, they obey the Bose-Einstein quantum statistics. This means that there is a higher probability of observing bosons in the same state, and therefore with similar momentum. Therefore, if many random pairs of two pions were to be examined from the collision, there should be more pions whose difference in momentum is smaller. A way to quantify this difference is using the variable k^*, which is represented by the vector equation:

$$k^* = \frac{p_1 - p_2}{2}. \tag{2.1}$$

Therefore, small k^* represents similar momentum, and larger k^* represents more different momentum. Using this quantity, we can infer the size of the system in the following way. Firstly, pairs of pions that satisfy the selection criteria from the same collison are taken and the distribution of k^* is calculated. This is repeated for all the analyzed collisions. Secondly, pairs of pions from different collisions are taken, and the same distribution function is calculated. In essence, pion pairs from different collisions should not be physically correlated, but the ones from the same collision should be.

Therefore, the way to eliminate all the unwanted noise is to divide the first distribution function (same collisions) by the second distribution function (different collisions). This will eliminate all the unwanted correlations and effects, and "isolate" the correlation which comes from the same collision.

Furthermore, dividing the two distributions will also eliminate the noise which can come from limited detector acceptance or detector inefficiencies. This way, the correlation function should be obtained.

This correlation function can further be used to infer the size of the system in the following way. The width of the k^* distribution is inversely proportional to the size of the system (Figure 2.1).

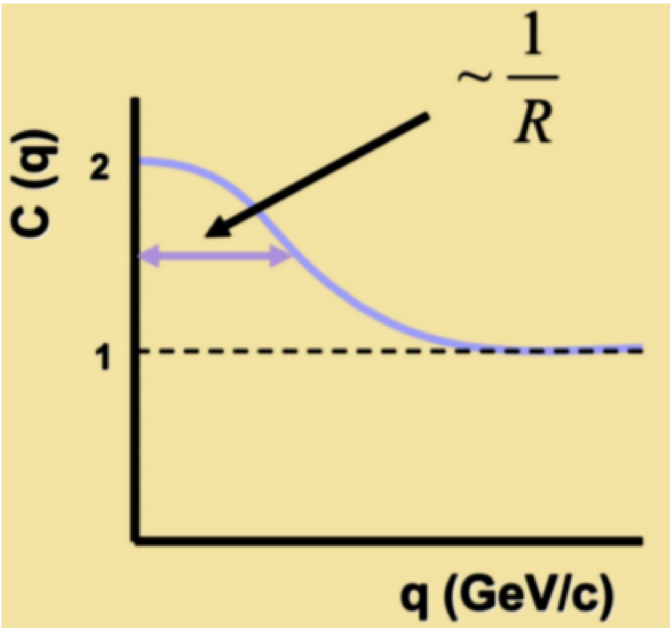

Figure 2.1: The k^* distribution.

How does one obtain the value of R? It is done by fitting the correlation function which should have the value of R as it's free parameter. All the fit functions are of the same form:

$$C = (1-\lambda) + \lambda(K(k^*))(1+\exp(-R^2 k^{*2})) \quad (2.2)$$

where R and λ are the free parameters, C and k^* are the values on the y and x axis, respectively. $K(k^*)$ represents the Coulomb function. Furthermore, the Coulomb function has no analytical formula, therefore it will have to be precalculated. An example of the Coulomb function can be seen in Figure 2.2. More details on the method of this calculation will be given in the website instructions (Section 7). By obtaining this radius value for QGP for all the centralities, it can be observed how the size of the QGP droplet depends on the centrality of the Pb-Pb collision , which is the main goal of this masterclass (more on centraility in Section 7.1).

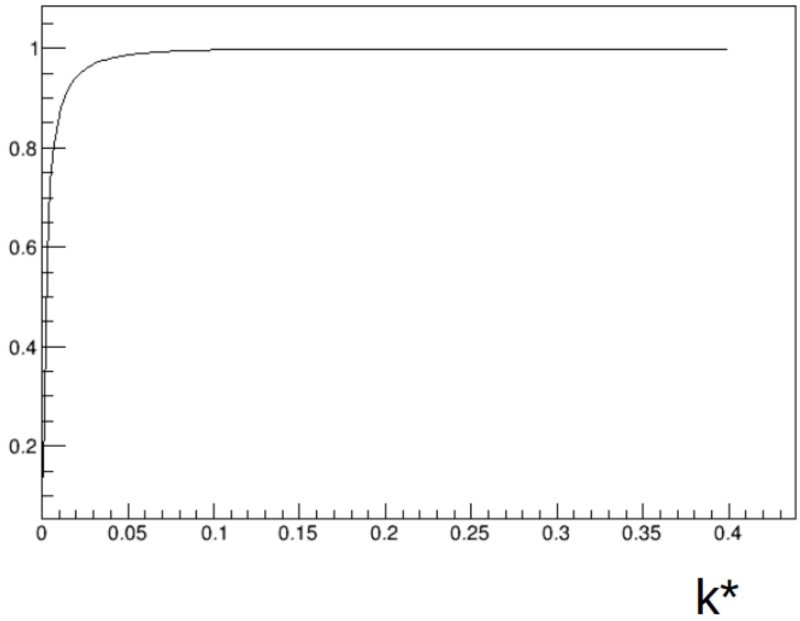

Figure 2.2: An example of the Coulomb function.

3 Tools Used

Angular Application was used to make the website. As a part of Angular, HTML, CSS as well as JavaScript programming languages had to be used. The Masterclass Package has multiple components:

- Introduction,
- About,
- Contact,
- Femto Large Scale Analysis,

- Same Events Histogram,
- Mixed Events Histogram,
- Divided Histogram.

All of these components are crucial to the functionality of the website.

4 The Website Layout

Firstly, the website is accessed by using this link: "https://alice-femtoanalysis-masterclass.app.cern.ch". The first page a user would encounter is the "Home Page". From this page, all other website components can be accessed using the navigation bar, or the designated buttons. Those other pages consist of the "About Page", "Contacts" as well as the main "Data Analysis Page". All these pages and their functions will described in the following sections.

5 Navigation Bar

As mentioned above, the navigation bar can be used to navigate to the various components of the website. It is located at the top of the screen, as shown in Figure 5.1.

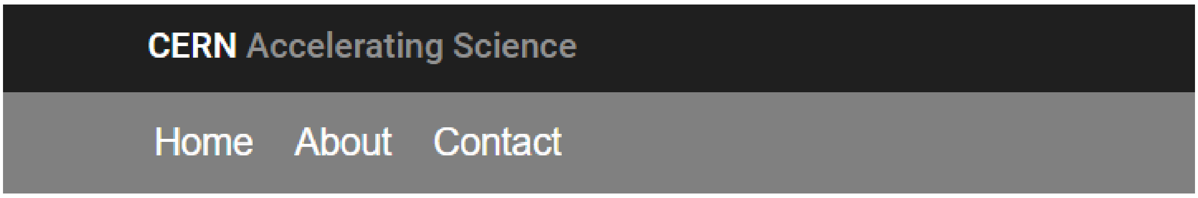

Figure 5.1: The Main Navigation Bar.

6 The Home Page

This is the first page which will be encountered one the website is opened. The page consists of the following:

- The welcome text, along with a short explanation of the purpose of the Masterclass,
- Link to the instruction document,
- Button which leads to the main data analysis page.

This page only serves for introductory purposes, the actual Masterclass tasks will be performed on the following data analysis page.

7 The Data Analysis Page

This is the page where the main Masterclass tasks take place. Initially, the page will only consist of the menu on the left-hand side, which will be used to perform the required tasks. The menu properties and functionalities will now be discussed. Note that the functions of the menu have to be used in the appropriate order, as the buttons for future tasks will be disabled until the necessary current task has been performed.

7.1 Choosing Centrality

In this menu box, shown in Figure 7.1, the user can choose a dataset based on the centrality which they would like to investigate. Centrality is closely related to the impact parameter of the two incoming particle beams. One of the following centralities can be chosen:

- 0-5 %,
- 5-10 %,
- 10-20 %,
- 20-30 %,
- 30-40 %,
- 40-50 %,
- 50-60 %.

All the data is displayed comes from the analysis done by the ALICE collaboration [2]. The smaller the percentage value of this quantity is, the more direct is the collision of the two particle beams. Centrality is also related to multiplicity, which will be important in the following sections [3]. Higher values of multiplicity correspond to lower percentages in centrality, consequently representing a more direct, head-on collision with a smaller impact parameter.

Once the centrality has been chosen, two histograms will appear on the right side of the menu, side by side, labeled as the "Same Event Pairs", or the "Numerator Histogram", and the "Mixed Event Pairs", or the "Denominator Histogram"(Figure 7.2).

7.2 Dividing Histograms

Below the drop-down menu, there is a button titled "Divided Histograms". By pressing this button, the following actions will take place. A graph, called the correlation function, will be displayed in the place of the two histograms (Figure 7.3). The y-axis (vertical) values of the new graph will simply be the y-axis values of the Numerator Histogram, divided by the y-axis values from the Denominator Histogram. Then, these new values will be displayed on the now visible graph.

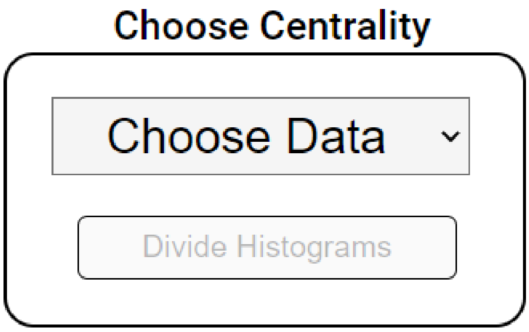

Figure 7.1: Menu For Choosing the Dataset.

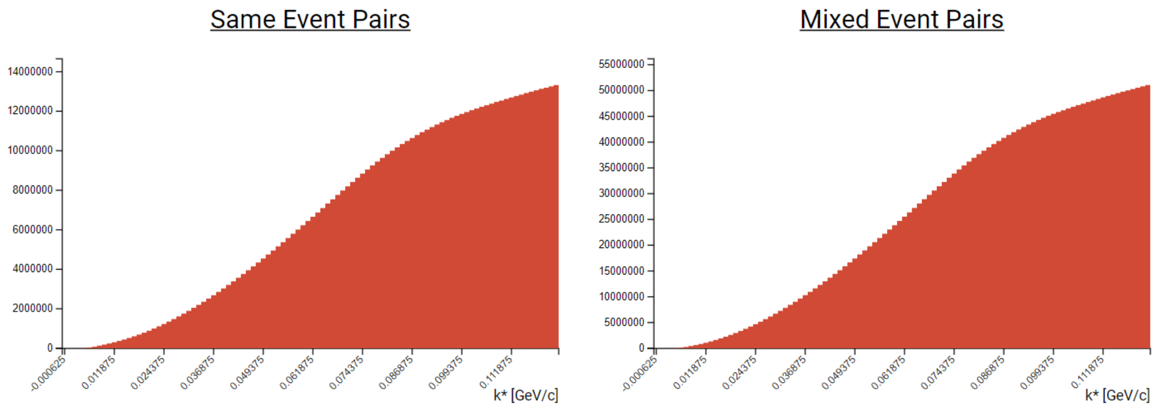

Figure 7.2: Example of the Numerator and Denominator Histograms.

7.3 Normalization

After the new graph has been displayed, the user cannot proceed further without normalizing the correlation function, by using the "Normalization Menu" (Figure 7.4). Normalizing this function requires that high values of k^* for the function are set at $y = 1$. This can be achieved using the main feature of this menu, the range slider. The slider allows the user to select their own preferred normalization range. Once the user is satisfied with the range they have selected, the "Submit" button should be pressed to confirm the selection. Consequently, the function under the selected range will be integrated and will be equal to 1. In simpler terms, whichever range of the function is selected, it will be multiplied so it "goes up" to 1.

A normalized correlation function will have the exact same shape as the non-normalized one, however, the values on the vertical axis will all change by a given constant (Figure 7.5).

7.4 Choosing Coulomb Calculation

The best fit for the correlation function can be chosen using the designated menu shown in Figure 7.6. The menu consists of two different parts: one for choosing the best Coulomb

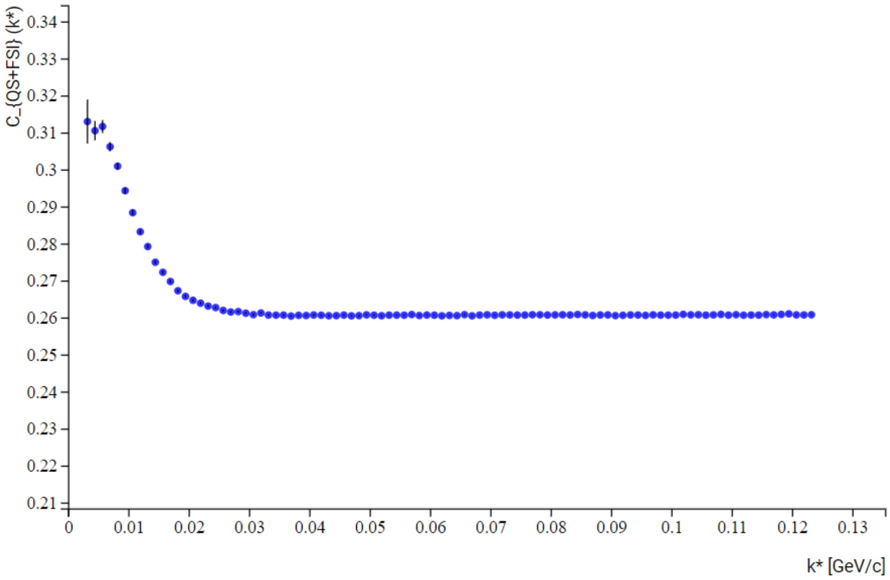

Figure 7.3: An example of the correlation function (Divided Histogram).

calculation for the designated R value, as well as the "Accept" button.

The dropdown menu named "Choose R value" is used to find the best way to calculate the Coulomb function for the fit of the correlation function based on the R parameter, ranging from $R = 2$ fm to $R = 10$ fm. The Coulomb function was introduced in Section 2. The reason why this Coulomb function has to be selected from the dropdown menu is because it has no analytical formula. It is instead numerically calculated for a given value of R, therefore has to be selected separately on the menu. Furthermore, the fit formula has to be multiplied by the speed of light times the plank constant ($h * c$), in goals of unit conversion. An example of the

The best fit for the correlation function can be achieved in the following way. Firstly, a "random" fit should be chosen out of the 8 available options. This fit will have it's respective R and λ parameters, as well as χ^2. These values will be displayed in the upper-right corner of the graph, in a dashed border box (Figure 7.7). Then, by looking at the R value which was obtained as the free parameter of the fit, a new initial R value for the fit should be chosen so it matches the obtained free parameter as much as possible. This process should be repeated until the initial R value for the fit closely matches the free parameter output R.

On the other hand, the free parameter λ is not of great importance in this exercise, and should vary around the value of 0.5.

Finally, once the user is satisfied with the chosen fit, the button "Accept" should be pressed. Next,the parameter R will be recorded and added to a table. More on this in the next section.

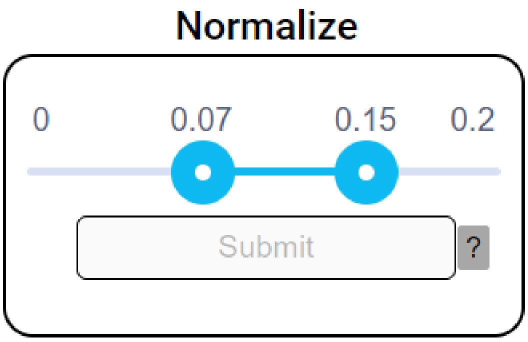

Figure 7.4: Normalization Menu.

7.5 The Data Table

The chosen value of the free parameter R will be passed down to the data table. This table will have two columns. The left column will contain the R values, and the left column will have the value for the multiplicity (centrality), which is dependent on the selected data set, as discussed in the earlier sections. Centrality and multiplicity are related in the following way, as shown in Figure 7.8. Multiplicity is represented by $dN_{ch}/d\eta$.

The table will appear the the right of the correlation function, and will initially only have one row (Figure 7.9). However, once the user repeats the entire process of fitting while using a completely new data set, and accepts the new R and Multiplicity value, another row will be added. This will be repeated until the user chooses an R value for each centrality. Keep in mind that a prior accepted R value CAN be changed, by simply accepting a new fit whose new R value will overwrite the new one, while keeping the multiplicity value the same.

7.6 Radii vs Multiplicity

Once the user is satisfied with the number of data rows in the table, that data can be plotted by clicking on the "Plot" button which is located at the bottom of the data table.

The result will be a Scatter Plot, which will be displayed in the place of the Correlation Function (Figure 7.10). This plot will have the free parameter R on the vertical axis, and the multiplicity value on the horizontal axis. The values for both have been of course taken from the table.

This graph indicates how the size of the source changes with the change in centrality (multiplicity). The user should try and interpret the physical meaning of such result.

8 Conclusion

Overall, the project was successfully completed. The main components of the website are functional, and numerous details were incorporated during the 8 weeks of the summer program. Furthermore, the Masterclass Demo took place on Friday, July 30th 2021 [1], and

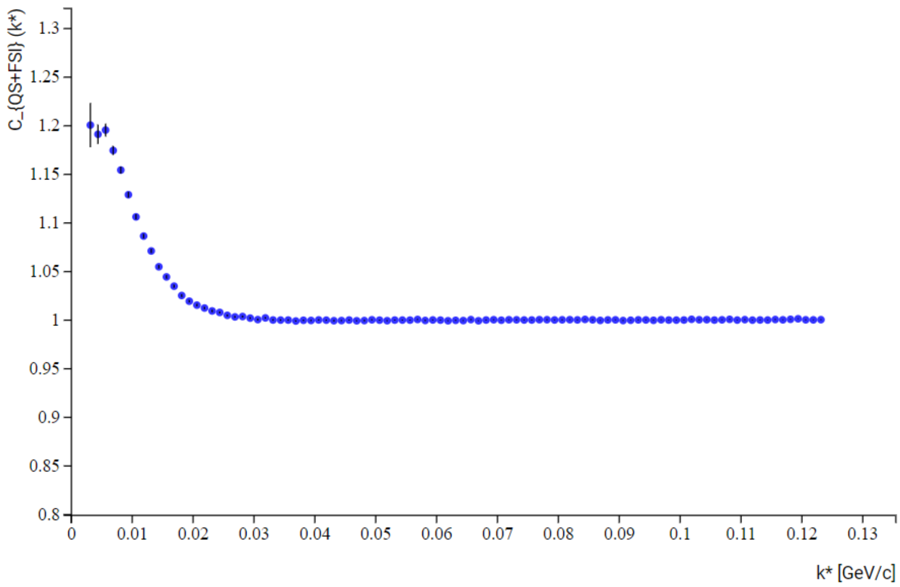

Figure 7.5: An example of the normalized correlation function.

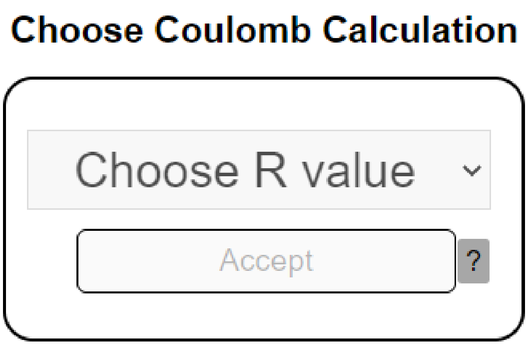

Figure 7.6: Menu for choosing the Coulomb calculation.

according to all those in attendance, the main goal of the website is achieved, as it is easy to use and the main ideas are conveyed clearly and concisely.

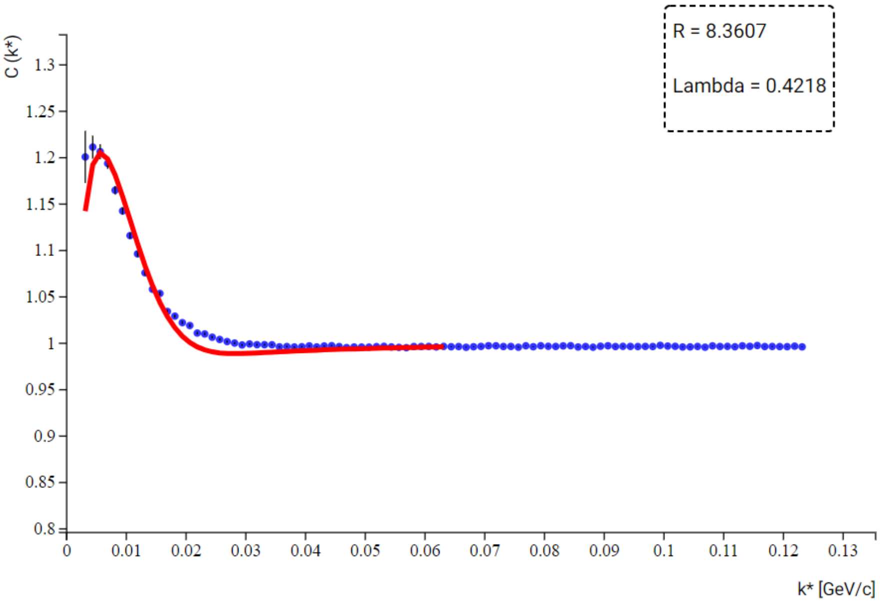

Figure 7.7: An example of a fitted correlation function, with the display of the free parameters.

Centrality	$dN_{ch}/d\eta$	$\langle N_{part} \rangle$	$(dN_{ch}/d\eta)/(\langle N_{part} \rangle/2)$
0–5%	1601 ± 60	382.8 ± 3.1	8.4 ± 0.3
5–10%	1294 ± 49	329.7 ± 4.6	7.9 ± 0.3
10–20%	966 ± 37	260.5 ± 4.4	7.4 ± 0.3
20–30%	649 ± 23	186.4 ± 3.9	7.0 ± 0.3
30–40%	426 ± 15	128.9 ± 3.3	6.6 ± 0.3
40–50%	261 ± 9	85.0 ± 2.6	6.1 ± 0.3
50–60%	149 ± 6	52.8 ± 2.0	5.7 ± 0.3
60–70%	76 ± 4	30.0 ± 1.3	5.1 ± 0.3
70–80%	35 ± 2	15.8 ± 0.6	4.4 ± 0.4

Figure 7.8: Centrality and Multiplicity.

R	Multiplicity
8.3607	1294

Plot

Figure 7.9: The Data Table.

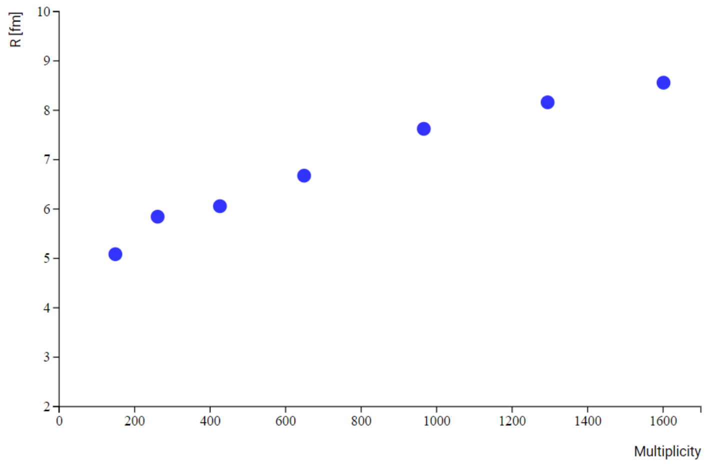

Figure 7.10: An example of the Radii vs Multiplicity plot.

References

[1] Indico page for the masterclass demo, https://indico.cern.ch/event/817585/.

[2] Kenneth Aamodt, A Abrahantes Quintana, D Adamová, AM Adare, MM Aggarwal, G Aglieri Rinella, AG Agocs, S Aguilar Salazar, Z Ahammed, N Ahmad, et al. Centrality dependence of the charged-particle multiplicity density at midrapidity in pb-pb collisions at s nn= 2.76 tev. *Physical review letters*, 106(3):032301, 2011.

[3] ALICE collaboration et al. Centrality determination in heavy ion collisions. Technical report, ALICE-PUBLIC-2018-011, 2018.

[4] Panagiota Foka and Małgorzata Anna Janik. An overview of experimental results from ultra-relativistic heavy-ion collisions at the cern lhc: Hard probes. *Reviews in Physics*, 1:172–194, 2016.

[5] Michael Annan Lisa, Scott Pratt, Ron Soltz, and Urs Wiedemann. Femtoscopy in relativistic heavy ion collisions: two decades of progress. *Annu. Rev. Nucl. Part. Sci.*, 55:357–402, 2005.