Searches for Shock waves in Heavy-ion collisions using Deep Learning

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Abstract

The paper shortly describes my 8th-week summer student program at CERN, where I had the privilege of working in the ALICE team. Over the course of this program, I was engaged in two distinct projects: "Search for Shock Waves Using Deep Learning" and a video project about "Bayesian Estimation of the Specific Shear and Bulk Viscosity of Quark–Gluon Plasma." Both of these projects are centered around Quark Gluon Plasma, a super-hot state of matter that is believed to have existed in the universe's initial moments, occurring just microseconds after the Big Bang. As the titles of the projects indicate, the first project focuses on the investigation of Mach shock waves, which are basically a type of pressure wave that propagates at the speed of sound within a compressible flow. Many experimental trials have been done so far but no proper evidence of the Mach cone has been found. The paper details the diverse aspects of the undertaken projects, discussions, as well as future steps.

1 Objectives

Over the course of the 8-week summer student program, I had the honor of being part of the ALICE team, under the guidance of supervisor Dong Jo Kim. During the program, I collaborated with Pyry Runko, Maxim Virta, and Jasper Parkkila contributing and sharing my work with the team. I was responsible for 2 projects: Search for Shock Waves Using Deep Learning, and the second is a video project about Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma. These projects not only broadened my understanding but also enhanced my skills in scientific research, leadership, and teamwork. Task-sharing, setting deadlines, and collective problem-solving were integral aspects of our daily interactions, creating a productive team dynamic.

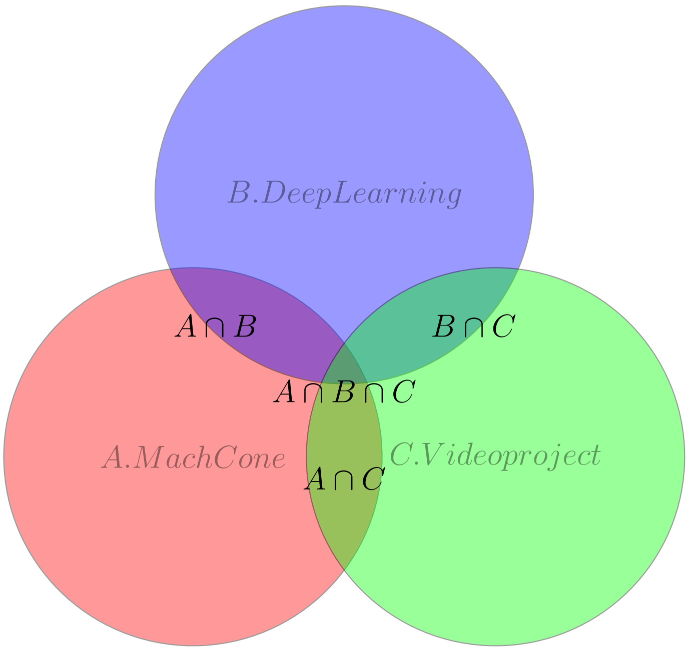

Figure 1: Project overview and Objectives

- Machine Learning: $A \cap B \cap C$
- Enhancing Note-Taking Proficiency through Utilization of Obsidian and Notion: $A \cup B \cup C$
- Time and Project management: $A \cup B \cup C$
- Leadership training: $A \cap B \cap C$

- improvement of presentation skills: $A \cup B \cup C$

As shown in figure 1 aspects of these projects are diverse so they have enriched my understanding of general research methodologies. At the same time, I have realized how important time and project management are correlated to the outcome of the research. Also, these projects helped me a lot in improving my presentation and communication skills.

2 introduction

ALICE Experiment

ALICE (figure 2) is one of the detectors at the LHC, focusing on heavy-ion physics. It studies quark-gluon plasma (QGP) formed at extreme energy densities, where a phase of matter called quark-gluon plasma forms, similar to conditions after the Big Bang. Collisions at the LHC generate temperatures over 100,000 times hotter than the Sun's center, allowing collisions between lead ions to recreate conditions like those after the Big Bang. In these extreme conditions, protons and neutrons "melt," releasing quarks from their bonds with gluons, forming the QGP. ALICE studies this QGP matter as it expands and cools, providing insights into the properties of this early universe phase and its role in the formation of the matter we see today. The research is essential for understanding quantum chromodynamics, confinement, and chiral-symmetry restoration in physics.

Searching for Mach Waves Inside a Perfect Liquid

Scientists create the hottest matter in the universe by colliding heavy ions at almost the speed of light. At such high temperatures, almost 100 000 times hotter than the Sun, nuclear matter melts into a soup of subatomic particles called quarks and gluons. This quark-gluon plasma has almost no resistance to flow which makes it an ideal fluid. The energetic particles generated by the nuclear collisions traverse the quark-gluon plasma, generating Mach shock waves similar to a supersonic jet speeding through the atmosphere. Mach wave is a type of pressure wave that propagates at the speed of sound within a compressible flow. It arises due to a small change in pressure introduced into the flow.

Various stages of the collision model based on [5] are depicted in Figure 2.

First, the system evolves from its initial state through a brief pre-equilibrium phase, followed by the expansion of the Quark-Gluon Plasma (QGP). As the QGP expands, it cools down and - at the critical temperature - undergoes

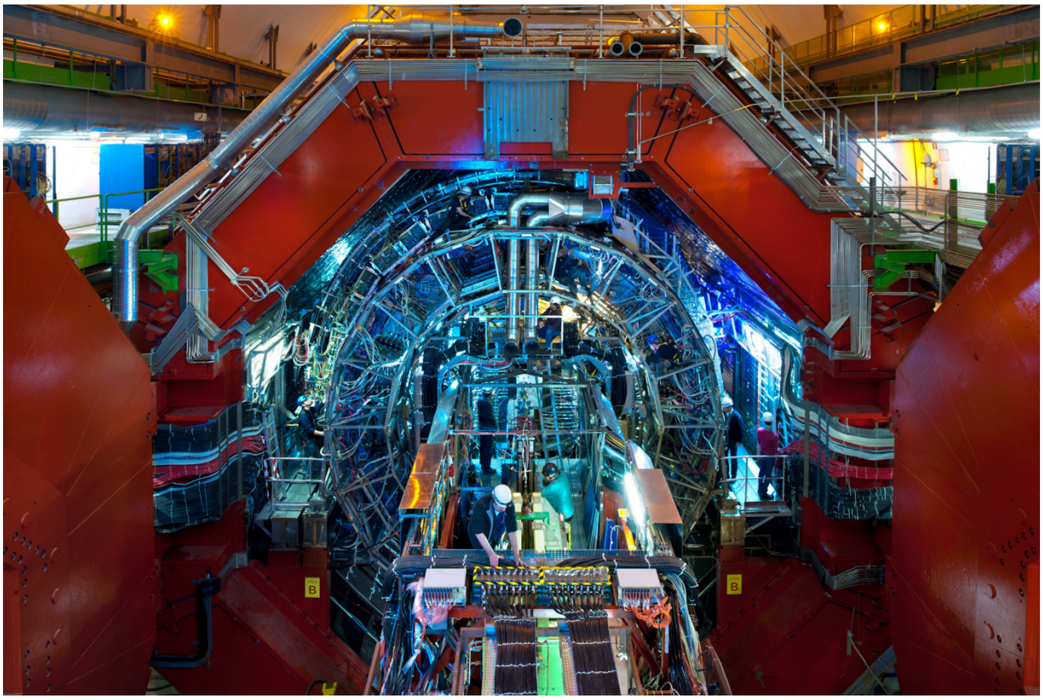

Figure 2: ALICE Detector, add reference

hadronization, where quarks and gluons combine to form composite particles, such as protons and neutrons. These explosively fast initial stages of the collision are typically modeled using relativistic hydrodynamic simulations, treating the system as a collective whole rather than focusing on individual particles. After the hadronization process, the resulting hadrons continue to interact with each other until the system has expanded sufficiently. At this point, only long-lived particles remain, and they are sufficiently separated from each other to minimize further interactions. These long-lived particles are then detected by the experimental detectors.

In this study, QGP formation was carried out once, and several events for the hadronization process. Mach cones created by jets should form right after the QGP formation. The goal of this project is to observe and analyze it.

Elliptic flow, a crucial concept in this study, adds another layer of insight into the quark-gluon plasma phenomenon. This transverse flow is a crucial signature for identifying the presence of QGP. Transverse flow is not uniform, meaning particles are emitted in a non-uniform pattern. This flow's anisotropy is quantified using Fourier expansion coefficients based on the

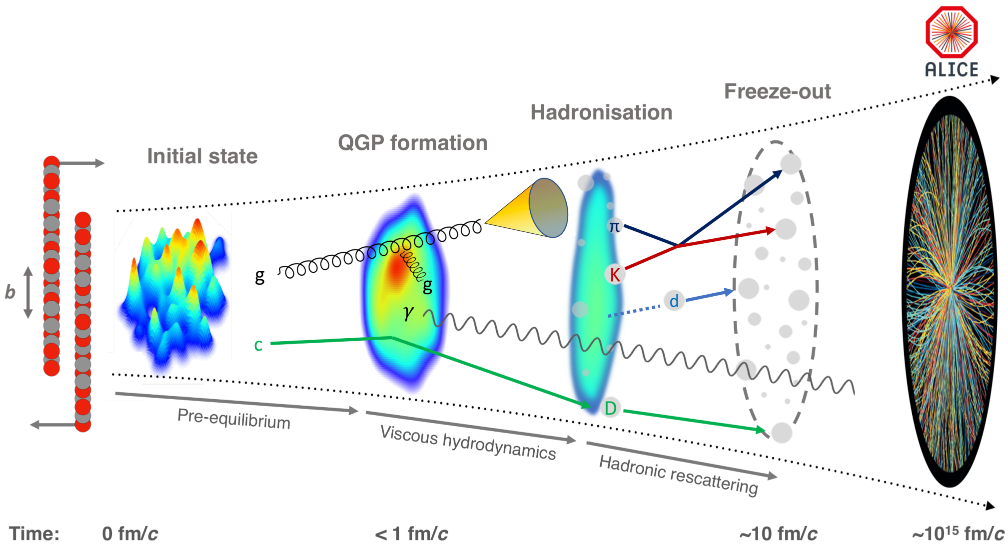

Figure 3: The evolution of a heavy-ion collision at LHC energies. This figure is taken from Ref. [1]

particles' distribution around the collision point. Experimental observations show that anisotropic flow, particularly the elliptic flow (v2), exists in heavy-ion collisions. in our study, we utilized Deep Neural Network (DNN) for calculating elliptic flow coefficients and finally to discover a direct Mach cone signal with the DNN method.

Various model calculations show that the expanding QGP has a small shear viscosity to entropy density ratio (η/s), close to the known lower bound $1/4\pi$ [10]. In such a medium one expects that jets passing through the medium would create Mach cones. Many experimental trials have been done but no proper evidence of the Mach cone has been found [2, 3]. Mach cones were thought to cause double-bumps in azimuthal correlations. However, these were later shown to be the third flow harmonic.

3 Projects

3.1 Research Progress and Deep Learning

In the beginning, I was focused on reading articles ''Estimating Elliptic Flow Coefficient in Heavy Ion Collisions using Deep Learning" [12] and "Pulling Out All the Tops with Computer Vision and Deep Learning" [11]. I aimed to understand the scientific concepts relevant to my project and used the

Obsidian app to make summary posters of the papers, which are given in the references [7], [8] .

The primary objective of this study was to investigate and visualize Mach waves. To achieve this, we employed artificial intelligence (AI) techniques and simulations for analysis.

Our approach involved a two-fold strategy:

1)Flow Analysis in Collisions Without Jets and Hydrodynamic Expansion Simulation: We conducted an in-depth examination of flow patterns in collisions lacking jets and implemented hydrodynamic expansion simulations. These simulations yielded valuable data, allowing us to generate particle information. Subsequently, a machine learning model was trained to predict elliptic flow coefficients

2) Jet Generation using Pythia and Jet Recognition Model Training: The second phase of our research involved the utilization of the Pythia framework to create jets. These simulated jets were then utilized to train a dedicated AI model capable of identifying and distinguishing jets from other phenomena.

First, we developed a code to calculate the elliptic flow coefficients for hadronization events. We created ten samples per event and generated images of particle distribution, as given in figure 4. The elliptic flow coefficients for these samples were then computed using the method described in "Flow analysis with cumulants: direct calculations paper" [4]

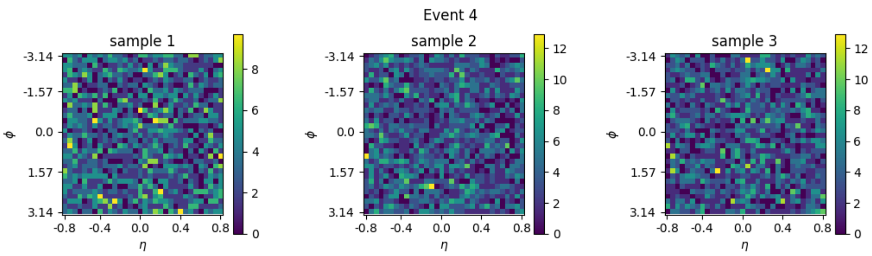

Figure 4: images of particles distributions

The images and computed elliptic flow coefficients were utilized as inputs for training the Deep Neural Network (DNN) model. This DNN architecture comprises several layers, namely the input layer, hidden layers (dense 1, dense 2, and dense 3), and the output layer responsible for predicting the elliptic flow coefficient (v2). The input layer consists of 3072 features derived from particle kinematic properties. Each of the three hidden dense layers contains 256 nodes, as illustrated in Figure 5.

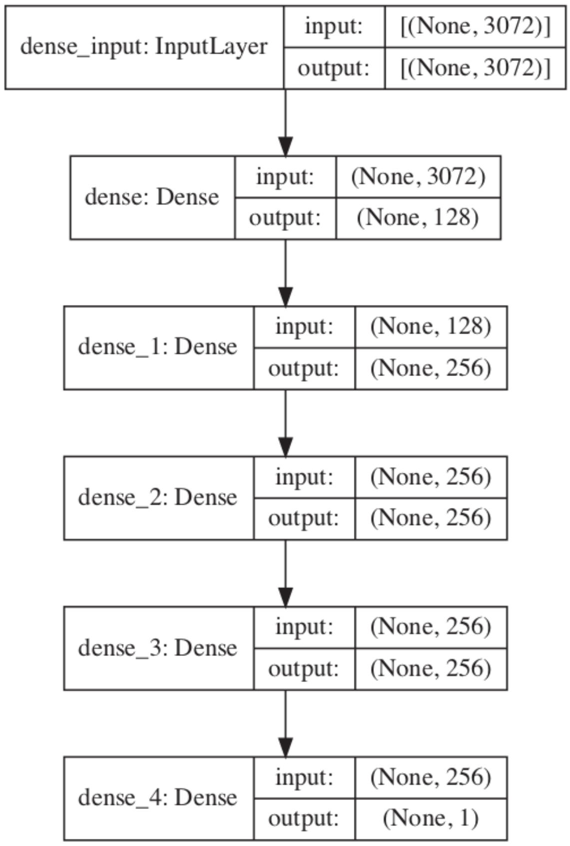

Figure 5: DNN Scheme

Initial attempts to train the DNN resulted in loss values of NaN (Not-a-Number), which can be attributed to the presence of NaN values within the true input values for the elliptic flow. This was likely due to NaN values appearing in the input true values for elliptic flow. It was fixed after removing all Nans from the elliptic flows. The graphical representation provided in Figure 6 illustrates the DNN's predictions for the elliptic flow. However, the graph visually displays the divergence between the predictions generated by the DNN and the actual data points.

Several improvements were done to the mode. Best learning was achieved with the following changes to the previous settings to our model: learning rate was set to 0.001, l2 normalization of input was enabled, all dropouts were removed and the output layer was changed from sigmoid to linear. The graph in Figure 7 illustrated DNN prediction after improvements.

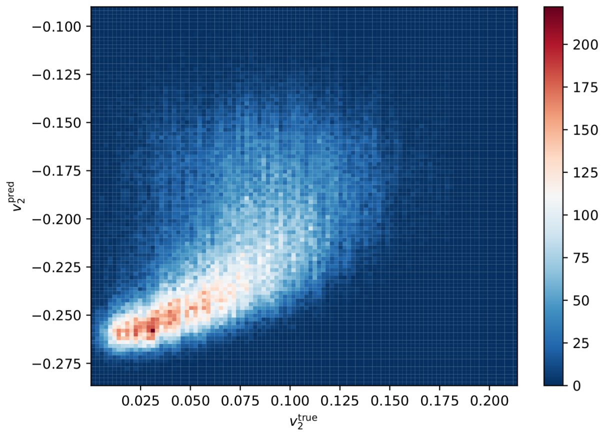

Figure 6: DNN Prediction-1

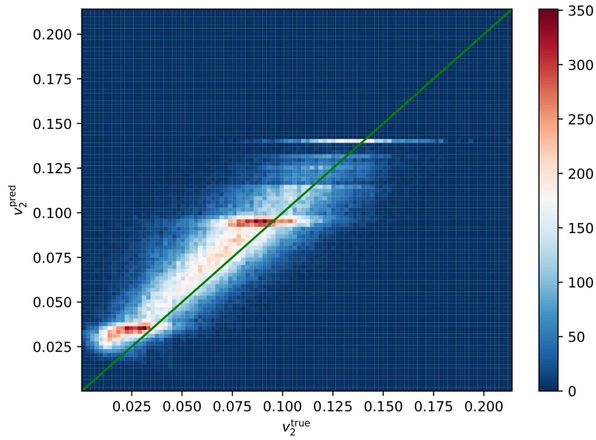

Figure 7: DNN Prediction-2

3.2 Video Project

In parallel with previous work, I was investigating the topic "Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma" [6]. The objective of this project was to create an informative and engaging video presentation on the topic. The content for the video was derived from a summarized article displayed on an Obsidian poster [9]. The goal was to break down complex concepts and provide a clear understanding of the subject matter through a series of concise videos. This video project significantly deepened my comprehension of the Quark Gluon Plasma, which helped me also in the machine learning project. Here is a part from the video project: Input Parameters

The initial step involved the creation of a manuscript designed to present scientific information in an accessible manner, catering to a broad audience. Subsequently, a series of concise videos were produced, utilizing the Obsidian poster as a backdrop.

4 Future Steps

For the machine learning project:

Combine images of particle distributions and Pythia-generated jets to enable AI prediction of both flow patterns and jets. Implement the jetscape framework to explore interactions between jets and plasma.

For the video project:

Enhance the video content through iterative improvements. Collaborate with the authors of the article and poster, and share the video online.

5 Conclusion

In conclusion, this project has provided a fascinating exploration of particle physics, specifically Quark-Gluon Plasma. Through deep learning, hydrodynamic simulations, and Bayesian estimation techniques, we've delved into the complexities of quark-gluon plasma formation, elliptic flow analysis, and the interaction of particles in high-energy collisions. By utilizing innovative techniques, such as Deep Neural Networks, we've made predictions of elliptic flow coefficients, a critical parameter in understanding the quark-gluon plasma's properties. In the future, we are planning to use jetscape framework to look at the interaction between jet and plasma, and try to observe Mach Shock Wave.

Furthermore, the video project served as a catalyst for deepening our understanding of the topic. As we aimed to explain hard scientific concepts in a clear and concise manner, we found ourselves gaining a deeper understanding of the subject matter. The act of teaching and explaining to others often leads to a high level of comprehension.

References

[1] The ALICE experiment – A journey through QCD. 11 2022.

[2] K. Aamodt et al. Higher harmonic anisotropic flow measurements of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV. *Phys. Rev. Lett.*, 107:032301, 2011.

[3] A. Adare et al. Transition in Yield and Azimuthal Shape Modification in Dihadron Correlations in Relativistic Heavy Ion Collisions. *Phys. Rev. Lett.*, 104:252301, 2010.

[4] Sergei Voloshin Ante Bilandzic, Raimond Snellings. Flow analysis with cumulants: direct calculations. 2011.

[5] Jonah E. Bernhard, J. Scott Moreland, and Steffen A. Bass. Bayesian estimation of the specific shear and bulk viscosity of quark-gluon plasma. *Nature Physics*, 2019.

[6] Jonah E. Bernhard, J. Scott Moreland, and Steffen A. Bass. Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma. *Nature Phys.*, 15(11):1113–1117, 2019.

[7] Elina Huseynzade. "obsidian poster for the article estimating elliptic flow coefficient in heavy ion collisions using deep learning". Online, 2023.

[8] Elina Huseynzade. "obsidian poster for the article pulling out all the tops with computer vision and deep learning". Online, 2023.

[9] S.A. Bass J.E. Bernhard, J.S. Moreland. "obsidian poster for bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma". Online, 2023.

[10] P. Kovtun, Dan T. Son, and Andrei O. Starinets. Viscosity in strongly interacting quantum field theories from black hole physics. *Phys. Rev. Lett.*, 94:111601, 2005.

[11] Sebastian Macaluso and David Shih. Pulling Out All the Tops with Computer Vision and Deep Learning. *JHEP*, 10:121, 2018.

[12] Neelkamal Mallick, Suraj Prasad, Aditya Nath Mishra, Raghunath Sahoo, and Gergely Gábor Barnaföldi. Estimating elliptic flow coefficient in heavy ion collisions using deep learning. *Phys. Rev. D*, 105(11):114022, 2022.