Impact Of Strong Electric Field On Z^0 Boson Decay In Ultra Relativistic Heavy Ion Collisions

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Ultra relativistic heavy ion collisions are known to create a state of hot QCD matter known as the Quark Gluon Plasma, which is believed to be the state of matter the early universe consisted of. Collisions of this nature are also predicted to generate a massive electromagnetic field. A direct measurement of the strength and lifetime of the electromagnetic field would allow for a better probe of the dynamics of heavy quarks and an increased understanding of the interactions that occur in hot QCD matter in these types of collisions. A direct measurement of either the electromagnetic field strength and time evolution has yet to successfully be taken for heavy ion collisions. Our team is investigating the possibility of utilizing measurements of the mass shift in Z^0 decay using CMS data as a method of measuring the strength and time evolution of the electromagnetic field in heavy ion collisions. This project focuses on the development of models of particle interactions and decays with the intended use for interpreting data from CMS heavy ion collisions.

I. INTRODUCTION

A. Background

A new state of matter known as Quark Gluon Plasma (QGP) has been created from ultrarealativistic heavy ion collisions at the BNL Relativistic Heavy Ion Collidor (RHIC) and the CERN Large Hadron Collidor (LHC) [3]. QGP is a state of hot Quantum Chromodynamic (QCD) matter that is believed to be the state of matter the early universe consisted of when energy densities were high enough that hadrons such as quarks and gluons were not bound by strong attractions, resulting in a sort of hot 'soup' of quarks and gluons.

During the creation of QGP in heavy ion collisions, a massive electromagnetic field with expected values of $eB_0 \approx 1018$ Gauss is believed to be generated as a result of the collisions [2]. However, a direct measurement of the strength and time evolution of the electromagnetic field has yet to be accurately taken. A direct measurement of the strength and lifetime of the electromagnetic field would allow for a better probe of the dynamics of heavy quarks and an increased understanding of the interactions that occur in hot QCD matter in these types of collisions.

One proposed method of measurement observes the decay of the Z^0 boson into muon-antimuon or dimuon pairs and measures the momentum of the lepton products of the decay [2]. While the Z^0 boson does not interact with the electromagnetic field, the daughter muons are electromagnetically interacting. The theory states the muons will experience a change in momentum due to the massive electromagnetic field and the changed momentum of the muons can be used to reconstruct the invariant mass distribution of the Z^0 boson, which will have a shift in the mean mass and width of the distribution. By comparing the original Z^0 boson unaffected by the electromagnetic field to the Z^0 boson reconstruction using the 4-momentum of the muons, there should be a measurable change due to the electromagnetic field. These resulting changes of the distribution can then be used as a measure of the strength and time evolution electromagnetic field generated by the collision by observing how the distribution changes as the parameters of the electromagnetic field are changed.

B. Project Overview

Our project seeks to explore this proposed method of measurement of the electromagnetic field by developing models to simulate the decay of Z^0 Boson into dimuons to compare against data from the Compact Muon Solenoid (CMS) at the LHC.

The project focused on the development of primarily two components:

- A Monte Carlo Glauber calculation model developed to predict and interpret data from nuclei-nuclei collisions at the Large Hadron Collidor (LHC) using the Compact Muon Solenoid (CMS) Detector.
- A model of Z^0 Boson decay into dimuons under the influence of a magnetic field strength ranging from 0 to 7 GeV/fm.

The ultimate goal of this project is to integrate the two models in order to develop a model representing Z^0 Boson decay into dimuons as a result of heavy ion collisions in CMS. The intention is this model can then be used in comparison to CMS data to identify and interpret Z^0 Boson decay and to measure the momentum of the dimuons.

II. GLAUBER MODEL

Our group developed a Monte Carlo Glauber Model for Pb-Pb nuclei at $\sqrt{s_{NN}} = 2.76\,TeV$ calibrated to estimate collisions for the CMS detector at CERN's LHC. Glauber Models are renowned for their ability to model nuclei collisions in particular for heavy ions [1]. Although this model was originally designed for Pb-Pb collisions, the model is able to be adapted for various nuclei in future use.

To start the model, two Pb nuclei are populated with the xyz coordinates of their respective nucleons populated according to a Woods-Saxon density. The nucleons are offset in the x direction by a randomized impact parameter (b) with the impact parameter in this instance defined as the distance between the center of the two nuclei.

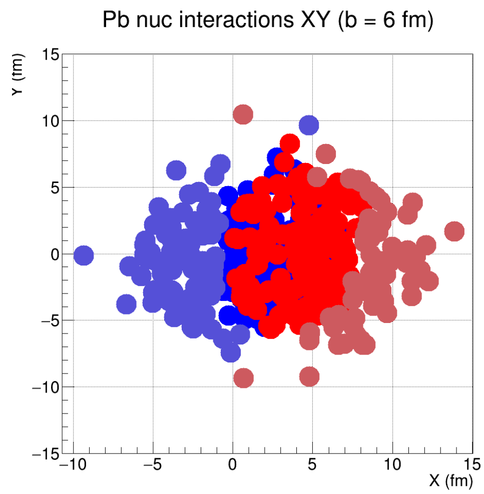

Figure 1: Overlapping Pb nuclei with an impact parameter of b = 6 fm. Nucleus A is in red and Nucleus B is in blue. Light shading denotes the nucleon does not participate in a collision and darker shading denoted the nucleon participates in at least one collision

The nuclear cross section σ can be thought of geometrically as the cross-section of one of the nuclei in the model. If the distance d between any two nucleons is $d \leq \sqrt{\sigma/\pi}$ then the two participating nuclei are considered to be colliding [1].

The nuclei are collided 10^7 times and histograms are generated with the following information for each event: The number of participants, the number of collisions, and the impact parameter.

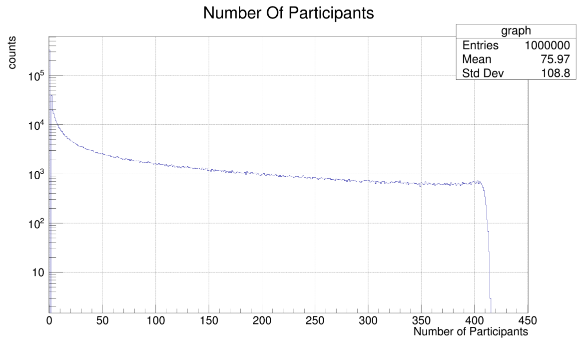

Figure 2: Histogram displaying the number of participants per event for Pb-Pb nucleon collisions.

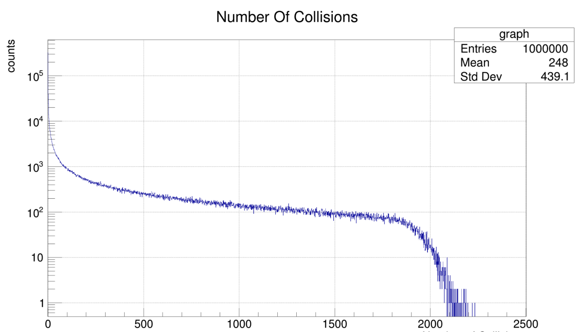

Figure 3: Histogram displaying the number of collisions per event for Pb-Pb nucleon collisions.

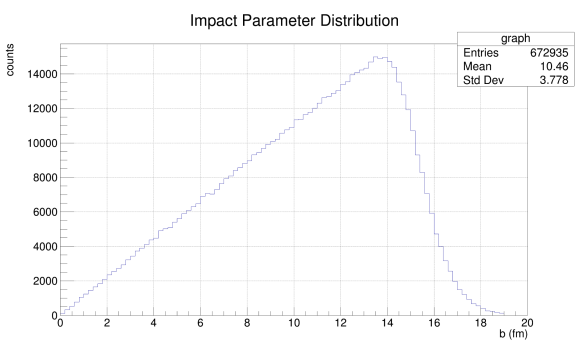

Figure 4: Histogram displaying the impact parameter values randomly generated for each colliding event using Monte Carlo simulations for Pb-Pb nucleon collisions.

The energy of each collision is determined using number of collisions and the energy deposition for each collisions, which is modeled using a negative binomial distribution with parameters k and μ.

The resulting energy for each event is then similarly plotted in a histogram and must be calibrated using CMS data. This is done by conducting a χ^2 test to determine the closest fit between the energy sum distributions. The lowest χ^2 value indicates the k and μ parameters for the closest fit to the accelerator data. For a more refined scan of parameter values, the region of k and μ values is focused on the region of best fit and the test is performed again. This continues for multiple iterations until a low χ^2 value is achieved. This process is demonstrated in Figures 5, 6, 7, and 8 with binning becoming finer for each scan.

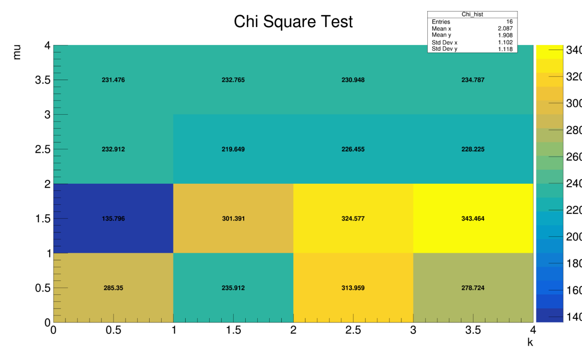

Figure 5: First pass of χ^2 test to determine the best fit of k and μ parameters. The dark blue rectangle denotes the region of k and μ with the closest fit

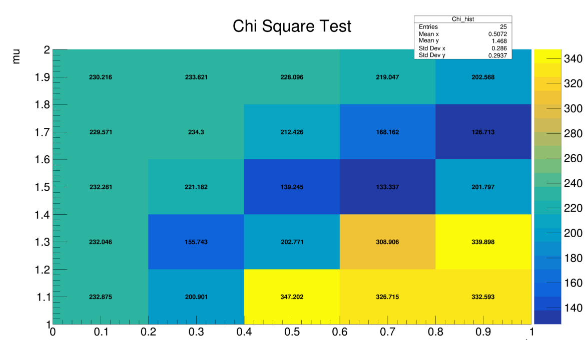

Figure 6: Second pass of χ^2 test to determine the best fit of k and μ parameters

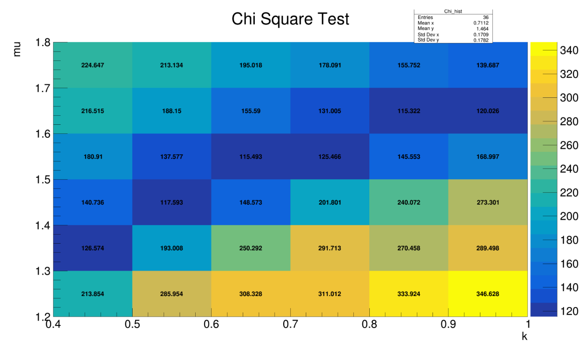

Figure 7: Third pass of χ^2 test to determine best fit of k and µ parameters

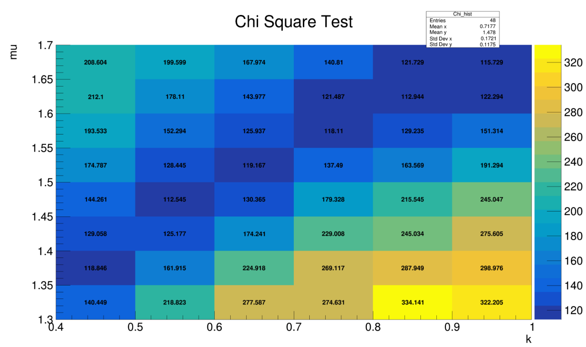

Figure 8: Fourtht pass of χ^2 test to determine best fit of k and µ parameters

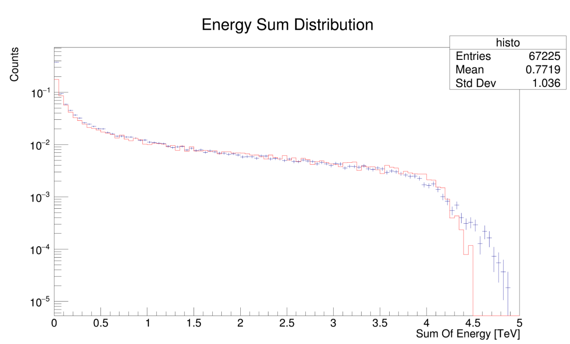

Figure 9: Energy Sum Distribution for Glauber Model (blue) calibrated to the Energy Sum Distribution for CMS data (red)

The resulting model is able to predict the number of participants, number of collisions, impact parameter, and energy of nuclei collisions in the CMS detector as well as the centrality of collisions. In Figure 10 we observed the majority of collisions tend to be low energy with only a few nucleons participating in collisions.

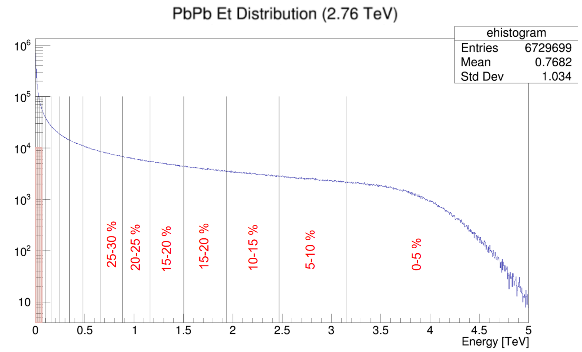

Figure 10: Energy Sum Distribution for Glauber Model Pb-Pb nuclei with centrality classes

Because head-on collisions tend to be rarer, the majority of nuclei collisions contain mostly non-participating nucleons, many of which are electrically charged, moving past each other at ultrarelativistic speeds. This phenomena is what results in the extraordinarily high electromagnetic fields predicted in heavy ion collisions during the creation of QGP [2].

III. Z^0 BOSON SIMULATION

The model used to simulate Z^0 Boson decay into muon-antimuon pairs utilized a general-purpose Monte Carlo event generator known as PYTHIA 8.3. The model used PYTHIA to simulate 10^7 events of proton-proton collisions and sort through the resulting shower particles until an instance of Z^0 boson decay into muon and antimuon daughter particles is identified. The kinematics of the decay for the parent and daughter particles are recorded for each decay event. A magnetic field strength and magnetic field time evolution are then set and used to recalculate the momentum of the muons using the below equation [3]:

$$\overline{\Delta p_x}(p_T, y_z) \propto q \int_0^{y_z} \frac{d\chi}{\cosh\chi}\left[\tau_2 B(\tau_2) - \tau_1 B(\tau_1)\right]$$

The modified momenta of the muons calculated to account for the magnetic field are used to reconstruct the 4-momentum of the Z^0

boson. Rapidity cuts are made on the Z^0 boson such that $|\eta| > 0.5$, mirroring the cuts made in the theoretical predictions [2]. The invariant mass distribution of the reconstructed Z^0 boson to the invariant mass distribution of the original Z^0 boson. The difference in the mean mass and $\Delta\sigma$ of the invariant mass distributions is then calculated and recorded. The strength and time evolution of the magnetic field are both independently changed to identify a correlation between the strength of the magnetic field and the change in mean mass and change in $\Delta\sigma$ of the distribution or a correlation between the time evolution of the magnetic field and the change in mean mass and the change in $\Delta\sigma$ of the distribution.

IV. RESULTS

The predicted changes in the invariant mass distribution include a negative shift in the mean mass of the Z^0 boson of 250 MeV and an increase in the width of the invariant mass distribution of 300 MeV at a magnetic field strength of 7.3 GeV/fm and magnetic field time evolution of 0.4 fm/c as displayed by the red dashed line in Figure 11 [2]. The results of the Z^0 boson event generation simulations conducted by our group displayed in Figure 12 showed no noticable shift in the invariant mass distribution with a calculated difference in original mean mass and reconstructed mean mass of -1.9 MeV. We noted a more significant change in the width of the distribution of 53.9 MeV

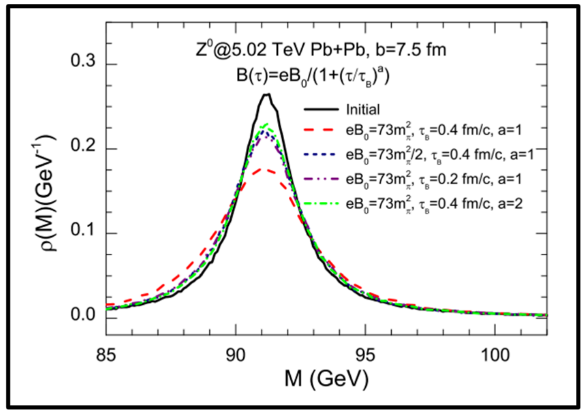

Figure 11: Initial and reconstructed invariant mass distributions from Sun, Y., Plumari, S., & Greco, V 2021 theory paper [2]

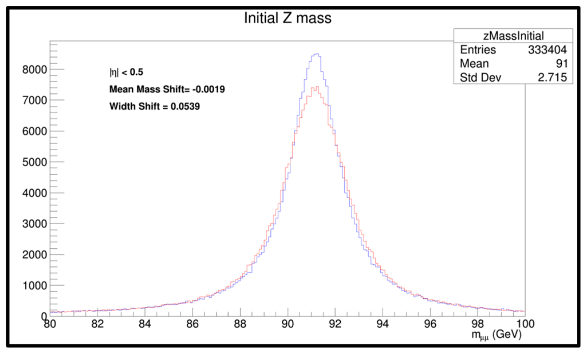

Figure 12: Simulated initial Z^0 boson invariant mass distribution (blue) and reconstructed distribution (red) after a magnetic field with strength 7.3 GeV/fm and time evolution 0.4 fm/c is applied

Upon varying the strength of the magnetic field by increments of 1 GeV/fm from 0 to 7 GeV/fm, we noted no correlation between the strength of the magnetic field and the mean mass of the invariant mass distribution of the reconstructed Z^0 boson. In addition, upon varying the time evolution of the magnetic field by increments of 0.5 fm/c from 0.05 to 0.4 fm/c, we noted no correlation between the time evolution of the magnetic field and the mean mass of the invariant mass distribution of the reconstructed Z^0 boson.

However, our group did observe a correlation between the strength of the magnetic field and the change in $\Delta\sigma$ of the invariant mass distribution as well as a correlation between the time evolution of the magnetic field and the change in Δσ of the invariant mass distribution as predicted by the red dashed lines in Figures 13 and 15.

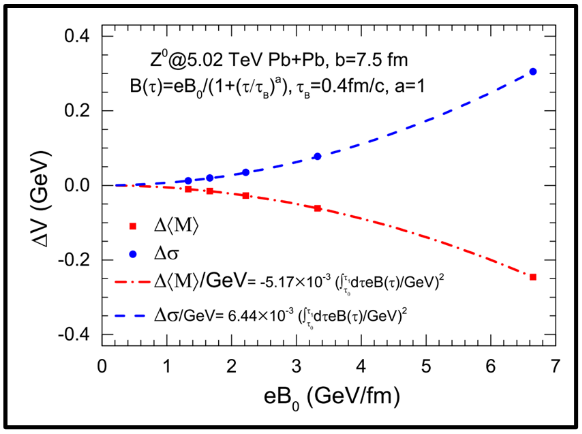

Figure 13: Theory paper predictions of Δσ and Δ<M> as a function of the magnetic field strength [2]

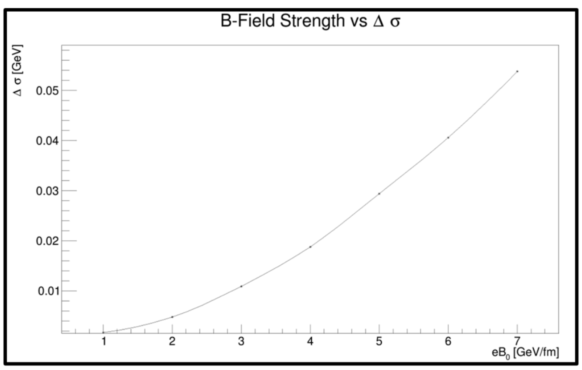

Figure 14: Simulation results of Δσ as a function of the magnetic field strength

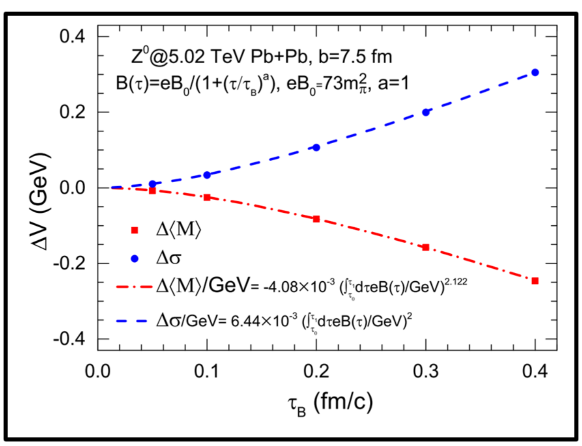

Figure 15: Theory paper predictions of Δσ and Δ<M> as a function of the magnetic field time evolution [2]

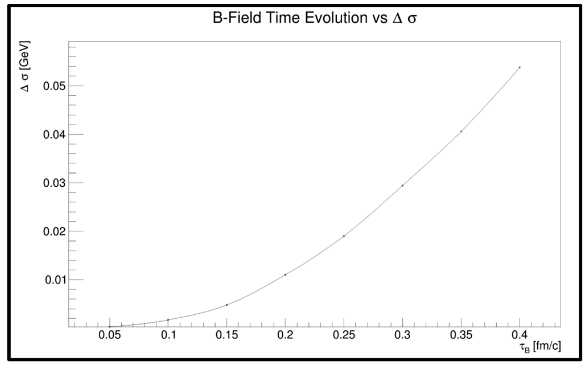

Figure 16: Simulation results of Δσ as a function of the magnetic field time evolution

The change in the width of the distribution is an order of magnitude less than predicted by Sun, Y., Plumari, S., & Greco, V 2021, however, the results of the simulation follow a similar distribution to the predictions as the magnetic field increases in strength and time evolution [2].

V. CONCLUSION

A. Summary

Our group observed a correlation between the width of the reconstructed invariant mass distribution of the simulated Z^0 bosons and both the strength and time evolution of the magnetic field. While the correlation qualitatively resembles the predictions we expected, the magnitude of the change in width is less than predicted. Our group did not see a significant negative shift in the mean mass of the reconstructed invariant mass distribution of the simulated Z^0 bosons. This does not align with our expectations of a negative shift of 250 MeV.

The correlation between the magnetic field and the width of the invariant mass distribution suggests some sort of relationship between the two that may allow for a more accurate measurement of the magnetic field strength and time evolution during heavy ion collisions as our understanding of these results increases.

In response to these results, our group has contacted the authors of the paper we based our simulations on for further clarification concerning some of the mathematical assumptions made when calculating the transverse momentum of the muons and the resulting mass shift.

B. Next Steps

Our next step is to attempt to integrate our current simulations with our CMS Glauber Model, which uses Monte Carlo simulations to randomize the geometric parameters of the collisions, including the distance between the center of the ions and the resulting magnetic field strength. This will create more realistic simulations of the decay process from a heavy ion collision.

In addition, we plan to begin data analysis from CMS 2018 data with the intention of identifying and comparing reconstructed invariant mass distributions from dimuon momentum measurements to simulation results with the goal of identifying any similarities or discrepancies between data and our modeling.

Further action our group may also take as we move forward with data analysis and comparison is to attempt similar PYTHIA simulations with an increased number of events for more statistically significant results.

VI. ACKNOWLEDGEMENTS

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