Research on cluster reconstruction algorithm for the STAR forward electromagnetic calorimeter

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Abstract. The Forward Meson Spectrometer, FMS, is a forward electromagnetic calorimeter at the STAR detector at RHIC, covering pseudorapidity from 2.6 to 4.0. It is an electromagnetic calorimeter comprised of two different types of 1264 lead-glass cells where the two types vary in both composition and size. The FMS was built primarily to unravel the novel spin effects seen in transversely polarized proton collisions. These effects relate to the spin-orbit correlation of the partons in the proton to the spin of the proton, which is a consequence of the confined motion of partons in nucleons. The reconstruction of neutral pions in the FMS is essential to study these effects. The gain calibration of the FMS is solely based on the reconstruction of the invariant mass of neutral pions at a fixed energy – because there is no tracker or hadronic calorimeter around – which poses the complication that the calibration gets intertwined with the reconstruction algorithm. Also, in order to cover the kinematic region of interest, the FMS needs to measure pion energies as high as 80 GeV at pp collisions with center-of-mass energies of 200 and 500 GeV. It was found that there was a strong correlation between the reconstructed neutral pion mass and its energy due to a combination of biases in the photon finding, namely the energy and the opening angle of the decay photons. The impact of the non-linear response of the lead-glass on the energy-scale was verified in detailed simulations of the light attenuation in the lead-glass and it was found that a correction function could be established. The fitting of the electromagnetic shower shape was modified to include non-zero incident angles and non-zero vertex positions. The reconstruction algorithm was optimized for clusters with two showers, especially when the separation of the two photons nears the physical limit in terms of the cell sizes. This article will present details of all these improvements and their impact on the reconstruction of neutral pions with the FMS.

1. The Forward Meson Spectrometer at STAR

The Forward Meson Spectrometer (FMS) is a part of the STAR detector at the relativistic heavy ion collider at Brookhaven National Laboratory. It is an electromagnetic calorimeter made of lead-glass. It is located in the STAR detector facing the blue RHIC beam about 7 meters away from the center of the STAR time projection chamber, covering a pseudo-rapidity of 2.6-4.0. It is composed of two types of lead-glass blocks that are different in size and material-density. The specifications are shown in table 1.
2. Reconstructing the neutral pion mass
The FMS reconstruction algorithm has its limit on getting the right invariant mass for neutral pions. Figure 1 shows the trend of a growing reconstructed $\pi^0$ invariant mass versus the $\pi^0$ energy. This trend appears both in simulation and data, which suggests it is not caused by the poor calibration of the data. If one takes a look at the neutral pion invariant mass at 80 GeV, it is almost 50 MeV above the true mass. This makes it impossible to define the same signal region and side band region for all energy bins. It also causes a lot of trouble to estimate the energy uncertainty and the quality of the calibration. The primary goal of this work was to understand the reason of the growth of the neutral pion reconstructed invariant mass and to integrate modifications in the cluster reconstruction code to correct this behavior.

Figure 1. Growing reconstructed $\pi^0$ invariant mass versus the $\pi^0$ energy.

3. Introduction to the FMS point reconstruction
The FMS reconstruction process [1] includes several steps as shown in Figure 2. The first is the cluster finding. The FMS cell that locally has the highest energy will be chosen as a seed cell. All other cells will be assigned to one of these seed cells based on their distance and energy differences to a given seed cell. These groups of cells are called FMS clusters. After the cluster finding is done, each cluster will be separated into two categories based on its size and shape. One type is for clusters which contain only one photon, the other type is for clusters which contain two photons. The algorithm for this categorization is based on simulations that account for the energy dependence. The hypothetical photon in either type of cluster is called an FMS point. At higher pion energies the decay photons opening angle gets smaller which increases the possibility that the two photons will be merged into the same cluster due to the cell size limit. For instance, most 80 GeV $\pi^0$ decay photons would merge into

| Cell type   | Radiation Length(cm) | Cell Width(cm) | Length(cm) | Attenuation factor |
|-------------|----------------------|----------------|------------|-------------------|
| Small Cell  | 2.50                 | 3.81           | 45.0       | 0.04              |
| Large Cell  | 3.21                 | 5.80           | 60.2       | 0.03              |

Table 1. Specification of the FMS.
Clusters are categorized into 2 types. The next step is to get the position of the FMS points using the shower shape fitting [2,3]. An algorithm compares the energy distribution over the cells of the cluster with the pattern of an ideal shower shape located in different positions. When the pattern matches, an FMS point/photon candidate with its energy and location information is found. For clusters that contain two photons, more degrees of freedom have to be introduced; the algorithm will have to determine the ratio of the energy between the two photons, and also the distance between them. When the position and energy of all the FMS points are determined, they can be used to reconstruct neutral pions.

4. Analysis and solutions

The invariant mass of the neutral pion is calculated by the energy and the opening angle of its decay photons as shown in equation (1). For the case that the decay photons fall into different FMS clusters, only these two factors need to be accounted for. This part of the reconstruction algorithm has been well developed over the years. However, when it comes to high energy pions in which their two decay photons fall into the same FMS cluster, the algorithm does not correctly handle it as shown in Figure 1. For this type of clusters, there are three factors that can contribute to a bias – see equation (2) – the total energy of the cluster, the opening angle $\theta$ and the energy distribution of the two photons, $Z_{gg}$. The definition of $Z_{gg}$ is in equation (3). The neutral pion mass is less sensitive to the last one so the main concern is the energy and the opening angle.

$$m = \sqrt{E_1 \times E_2 (2 - 2 \cos(\theta))}$$  \hspace{1cm} (1)

$$m = \frac{1}{2} E_{\text{total}} \sqrt{(1 - Z_{gg}^2) \times (2 - 2 \cos(\theta))}$$  \hspace{1cm} (2)

$$Z_{gg} = |(E_1 - E_2)/(E_1 + E_2)|$$  \hspace{1cm} (3)

4.1 Energy

The energy of an FMS point is the sum of the energy of the constituent FMS cells, which is calculated from their ADC-information and their gain. There are a few factors that can bias this calculated energy. The first possibility is energy loss due to absorption of the Cherenkov light propagating through the lead-glass. The amount of the energy loss is not linear with the photon energy. High energy photons tend to develop the electromagnetic shower deeper in the lead glass, which results in the photons traveling through less material in the lead glass, thereby losing less energy during the process. Therefore, it requires an energy dependent correction function to get the right energy for the photons.
The solution to account for these dependencies is to include a light attenuation model according to equation (4) in the simulation. In equation (4), \( Z \) is the distance from one end of the lead-glass, and the parameter, \( \beta \), is determined by tests during the construction of the detector. The value of \( \beta \) can be found in table 1. Using this new model, a simple photon only simulation is performed to learn how the energy of a photon should be corrected.

\[
\text{Attenuation factor} = e^{-\beta \cdot Z}
\]  

(4)

The second bias is addressed in the fitting process. For a cluster that contains two photons, the first fit separates the two photons, a second fit is performed to get a better result. The second fit provides freedom for the algorithm to adjust the photon position and energy freely around the result of the first fit. However, due to an imperfect uncertainty estimation, the cells with very low energy have a relatively high chi square, which means the algorithm could adjust the energy to more than it should be. The outer cells of an FMS cluster usually have low energy so when the fitted energies of them are a little bit lower than the measured energies, it would result in a significant increase of total energy in the second fit. This effect happens frequently and can easily be seen from high energy single neutral pion simulations, where the total energy is higher than it should be even after applying the attenuation factor correction. The solution is to fix the energy of the photons before performing the second fit. This procedure limits the freedom to adjust the first fit result, but it prevents the increase in energy from fitting.

The third bias comes from calibration. The FMS calibration is based on reconstructing neutral pions. The modifications of the reconstruction algorithm will definitely effect the calibration. Consequently, the calibration should be redone after all the modifications are determined.

4.2 The opening angle

At pion energies as high as 80 GeV, the distance of two decay photons, projected onto the FMS, is mostly around 3 cm. When compared to the size of the small cells – 3.875 cm – it is most likely that the two photons merge into one cluster, which makes it difficult to separate them. The original algorithm is ideal for neutral pion energies around 40 GeV, where the average distance of the two decay photons is two times larger than for 80 GeV. So, in high energy cases, there are contributions from the reconstructed opening angle to the above discussed biases. There are several other factors that can contribute to the bias and bad resolution of the opening angle.

The first improvement is to account for the extended vertex z-position. Previously, the algorithm assumes all events originate exactly from a z-vertex position of zero. This negatively effects the opening angle calculation as it impacts the distance from the collision point to the decay photons. The size of the effect depends on the z-vertex distribution of the events, which can be different for different trigger setups. In the 2015 STAR data, the average z-position can reach -30 to -40 cm, which can result in a 5% increase of the opening angle. Even with the average z-position being close to 0, the RMS can be up to 30 cm to 50 cm. Correcting for this effect will increase the precision and resolution of the opening angle.

A method was developed to use the beam-beam counters to find the z-vertex position for all the events. The beam-beam counters sit on both sides of the interaction point in STAR. They can provide the time difference between particles passing through each side. This information can be compared with the vertex that is reconstructed by the time projection chamber. A model has been constructed that calculates the z-vertex position of an event based on the time difference recorded by the beam-beam counters. From this the vertex z-position can be calculated for events triggered by the FMS, for which no vertex information is available from the time projection chamber.

The second improvement is accounting for the incident angle of the photon. The original shower shape model is symmetric relative to the FMS surface, which is suitable for photons with a perpendicular incident angle to the FMS surface. For real cases, the shower always develops asymmetrically in the detector due to a non-zero incident angle. Fitting a real shower in the FMS with a symmetric shower shape will introduce a displacement towards the radial direction. The size of this
effect contributes to a bias of the opening angle that depends on the relative position of the decay photons. In the worst case, this could lead to a few percent increase in the opening angle. Although this doesn’t sound like much, some analyses require better positioning of the neutral pion, which makes this improvement crucial.

This issue was resolved by using an asymmetric shower shape model based on a GEANT3 simulation. In the simulation, the detector is divided into 6 segments along the beam direction, each of which is 7.5 cm long and has its own shower shape parameters. This way an asymmetric shower shape is automatically formed when the incident angle is non-zero. This method can be used for both large and small cells, which before used the same set of shower shape parameters.

The third improvement is changing the lower limit for the distance of the two photons during shower shape fitting. The old lower limit is based on a previous study simulating at lower pion energies, which gave good results from low to medium energy. However, when it comes to high energy neutral pions, the lower limit is a little bit too high, which results in the increase of the opening angle. The lower limit was re-set to its theoretical limit or half of the cell width, which is the resolution limit of the FMS detector.

5. Results and Discussion

In the following chapter, all the modifications discussed are used in simulation and analysis of data to see if they work as expected.

5.1 Neutral pion only simulation

A simple but effective test to check our improvements is to see whether the neutral pion invariant mass increases with the measured energy without any interferences from background. The test sample is 75 GeV neutral pions with vertex z-position equal to 0 with a fixed angle (pseudorapidity=2.9/3.7 for small/large cell; phi=0.005). In order to compare with data, the selection cuts are chosen the same as in data, which requires $Z_{gg}<0.7$. First look at the invariant mass distribution (see Figure 3 top left). It shows the mean of the peak is very close to the PDG result 0.1345 GeV, which was before almost 40% higher. Next is to check the three factors that are used to calculate the invariant mass. Figure 3 top right shows the energy is well reconstructed. The two bottom plots of Figure 3 show the differences between reconstructed and generated $Z_{gg}$, and opening angle. All three of them suggest that the biases from before are small, this is a clear sign that the new modifications of the reconstruction algorithm work as expected. The same test is performed for the large cell and the result is similar except that the resolution is worse.

**Figure 3.** Test result of the $\pi^0$ only simulation for the small cells.
5.2 The PYTHIA simulation
The purpose of the PYTHIA simulations test is to see how the reconstruction algorithm behaves in a complex environment and later compares with the data analysis. The vertex-z position is chosen similar to the one in Run11 STAR data. The neutral pion energy is chosen as 75-90 GeV. The statistics of such an energy bin is limited by the whole simulation sample.

The fitted invariant mass peak is a little bit higher than it should be. Some of it can be explained by the energy bias caused by the inseparable background. In Figure 4, the right plot shows the photon energy is around 5% higher than it should be. The other bias can be explained by fluctuations and limitations of the current method.

Figure 4. Test result of PYTHIA simulation for the small cells.

5.3 Data analysis
Finally, we analyse the Run11 STAR data at 500 GeV. These events are triggered by the FMS and therefore most of the events in this energy bin come from the small cells. The neutral pion energy range is chosen as 75-90 GeV.

Figure 5 shows the improvement in the invariant mass after the modifications being applied to the reconstruction algorithm. The fitted lines, red and green, represent signal and background respectively. It can be seen easily that the one after improvement – the left plot – does a much better job in separating signal and background correctly. The fitted mean of the invariant mass is much closer to the book mass. Also, the shape has changed, and the new shape is different from the one in the PYTHIA simulation, which can be explained by the opening angle distribution. The resolution of the opening angle in simulation is much better than that in data, which means in the fitting process the opening angle has more chances of hitting the lower limit. Also, after the smoothing process (the second fit), the reconstructed opening angle distribution in a low mass region is different from that in a high mass region, which results in more skewness in the invariant mass distribution.

Figure 5. Comparison of the invariant mass and fitting result w/o the new improvement.
6. Conclusion

The reconstruction of neutral pions is a crucial part of the FMS physics program. It was found that the algorithm used before could not describe the neutral pion mass correctly as a function of the pion energy. It overestimated the invariant mass by 40% for pions around 80 GeV. This article discussed the possible causes for this bias in detail and proposed that correcting both the energy and opening angle of the decay photons will cure this problem. These multiple modifications have been applied to the old algorithm and were tested in simulation and on data; both show significant improvements.

References

[1] K. Eun 2012 Transverse Single Spin Asymmetries and Cross-Sections for Forward π0 and η Mesons at Large Feynman-x in √s = 200 GeV polarized p+ p Collisions at STAR (arXiv:1205.4771)

[2] A. Lednev, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 366(2) 292 (1995)

[3] L. Bland, A. Ogawa, A. Matulenko, V. Mochalov, A. Morozov, V. Nogach and G. Rakness Instruments and Experimental Techniques, 51(3), 342 (2008).