

UNIVERSITY OF CALIFORNIA  
Los Angeles

**Correlations with Non-Photonic Electrons in  
 $\sqrt{s_{NN}} = 200$  GeV AuAu Collisions in STAR**

A dissertation submitted in partial satisfaction  
of the requirements for the degree  
Doctor of Philosophy in Physics

by

**Lloyd Edward Dunkelberger Jr.**

2015

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# **CHAPTER 1**

## **Introduction**

## CHAPTER 2

### Experimental Setup

2.1 Relativistic Heavy Ion Collider

2.2 STAR Detector

2.3 Time Projection Chamber

2.4 Barrel Electromagnetic Calorimeter

## CHAPTER 3

### Identification of Non-photonic Electrons

We discuss the procedure for identifying electrons in events at STAR and how we remove photonic background. We show the event and track selection criteria and then lastly we will analyze the efficiency for identifying background photonic electrons. The identification of non-photonic electrons (NPE) and efficiency thereof will be critical factors when we construct the NPE-hadron correlations in later chapters.

#### 3.1 Outline of the NPE Identification

This chapter will lay out the general methods for event selection, track selection, electron identification, and the removal of photonic electron background for both Au+Au and p+p collisions.

We start by identifying the dataset and the trigger collections we will use for the analysis. We look at the events and check that the quality of the event is good and that there could be candidate tracks for NPE in the event. We then reconstruct all tracks in the TPC and apply track quality cuts. To identify electrons we rely on the energy loss ( $dE/dx$ ) measured in the TPC and on the hits in the EMC towers and shower max detector.

The background from photonic electrons will be removed by searching for the opposite signed partner electron. If the primary track is from Dalitz decays or photon conversion in the detector, the partner and primary track should have a low invariant mass. We will also investigate, through simulations, the efficiency for determining the background from photonic electrons.

In the end we will have a sample of electrons which we can use as triggers for measuring

NPE-hadron correlations.

## 3.2 Dataset and Event Selection

### 3.2.1 Data and Triggers

In 2011 RHIC collided gold nuclei at  $\sqrt{s_{NN}} = 200$  GeV and delivered  $9.79 \text{ nb}^{-1}$  integrated luminosity similar to what was delivered during the previous year's run (Figure 3.1a). The STAR detector recorded about 1.1 billion events across all triggers with TPC and BEMC information. In 2012 polarized proton collisions were run in RHIC (the polarization of the beams is not relevant to this analysis) at the same 200 GeV beam energy. RHIC delivered  $74.0 \text{ pb}^{-1}$  (Figure 3.1b) which resulted in 1.7 billion triggered events in STAR. Heavy flavor events are rare and detector efficiencies can be low meaning the NPE analysis is typically constrained by statistics, necessitating large data sets. The Silicon Vertex Tracker (SVT) was removed from STAR resulting in less material near the beam line which cuts down on background from conversions in the detector. This combination of low material and high statistics make runs 11 and 12 (prior to run 14) the best datasets available for the analysis of non-photonic electrons.

The STAR data acquisition system handles several different triggers the most commonly used is the minimum bias trigger (minbias) which fires based on the coincidence of the STAR vertex position detector (VPD) and Zero Degree Calorimeters (ZDC) these events are prescaled so that only a fixed fraction of triggers are accepted so that the DAQ's data taking rate is not exceeded. STAR can also trigger on hits in the barrel EMC, these are the high tower (HT) triggers. A high tower trigger requires that a hit in a BEMC tower exceeds an ADC threshold determined such that the transverse energy in that tower is high. In run 11 we use the HT triggers NPE11, NPE15, NPE18, and NPE25 which are in increasing order of  $E_T$ . The NPE11 and NPE15 triggers are also prescaled. In p+p we use the BHT0, BHT1, BHT2, and BHT3 triggers, of these only BHT0 is prescaled.

Due to the large dataset sizes it is in our best interest to cut down on the data we need

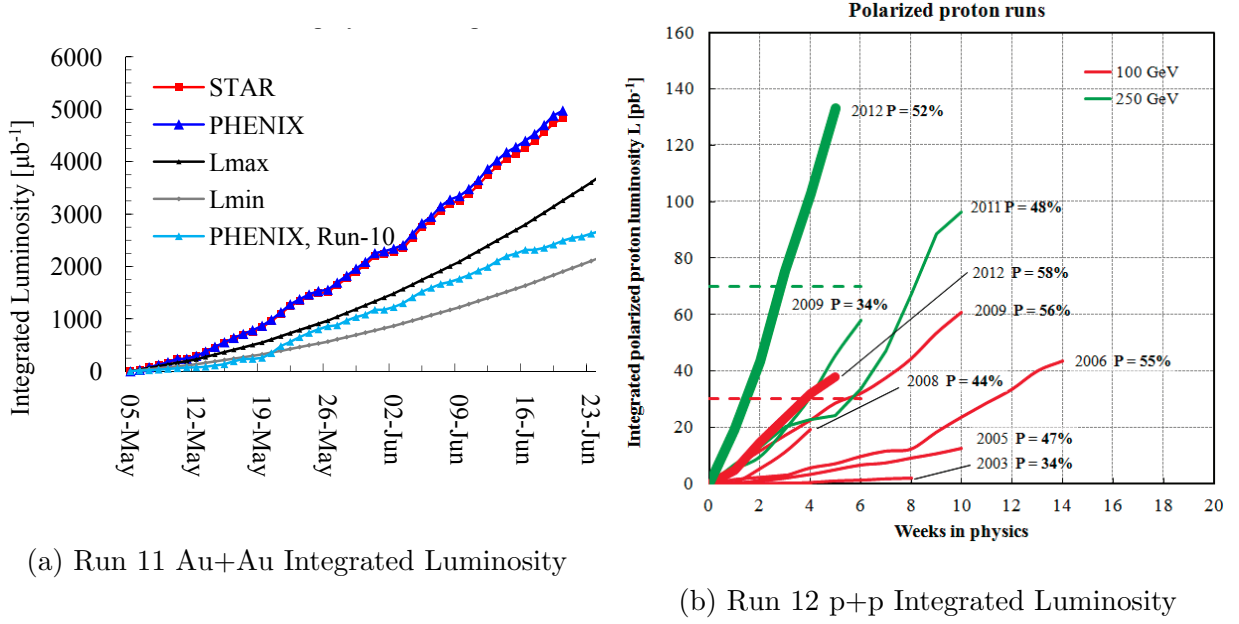


Figure 3.1: Integrated luminosities for run 11 and run 12 in RHIC. Left plot shows Au+Au delivered to STAR and PHENIX as well as run 10 in PHENIX for comparison. Right plot shows all p+p runs, run 12 is shown with thick lines.

whenever possible. We do this first when we read the data to make BEMC points to match to tracks. Here we look through the tracks in the event and search for electron candidates based on the TPC information only. We throw out events without viable electron candidates. Since these cuts are looser than the electron cuts we will apply later we don't remove events we might actually want and we retain the ability to tighten the cuts later if we need to. After limiting ourselves to high tower triggers and keeping only events with electron candidates we are left with approximately 23 million events in Au+Au and 1.1 million events in p+p.

### 3.2.2 Event Level Cuts

At the event level we cut on events with vertex too far out of the center of the detector. We use the tracks in the TPC to reconstruct the vertex, we can also measure the vertex with the Vertex Position Detector (VPD). By convention we have the  $x$  and  $y$  axes as transverse to the beam line. The  $z$  axis then runs along the beam. We require that the vertex be no more than

Variable	Cut
Triggers (Au+Au)	NPE11 NPE15 NPE18 NPE25
Triggers (p+p)	BHT0 BHT1 BHT2 BHT3
$ V_z^{TPC} $ (Au+Au)	$\leq 30$ cm
$ V_z^{TPC} $ (p+p)	$\leq 40$ cm
$ V_z^{TPC} - V_z^{ZDC} $ (Au+Au only)	$\leq 4$ cm

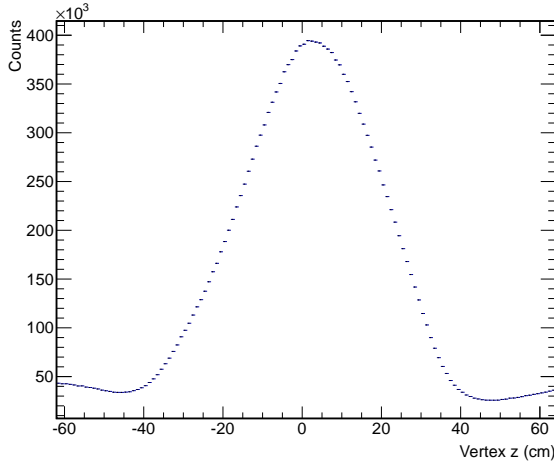
Table 3.1: Datasets used in the analysis as well as the cuts applied at the event level.

2 cm from the center of the beam pipe in the radial direction, i.e.  $\sqrt{(V_x^{TPC})^2 + (V_y^{TPC})^2} \leq 2$  cm. We also cut on the TPC vertex in the  $z$  direction, choosing events with  $|V_z^{TPC}| \leq 30$  cm in Au+Au collisions and  $|V_z^{TPC}| \leq 40$  cm in p+p. Additionally we want to have good agreement between the vertices as measured by the TPC and VPD. We require that the difference between the measured  $V_z$  satisfies  $|V_z^{TPC} - V_z^{VPD}| \leq 4$  cm in Au+Au. Figure 3.2 shows the distribution of  $V_z^{TPC}$  and the difference in TPC and VPD  $V_z$  in Au+Au collisions. In p+p because of lower multiplicity and a wider vertex distribution the measured vertex from VPD is not reliable and thus the cut on the difference of  $V_z$  is not used.

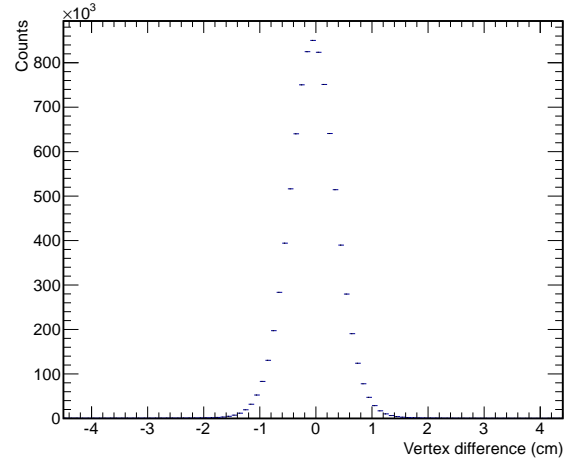
At the event level we also determine the centrality using the STAR `StRefMultCorr` class which calculates the centrality bin based on the reference multiplicity (refmult), vertex  $z$ , run number, and ZDC coincidence rate. Figure 3.3 shows the event by event distribution of refmult as well as the number of events from each centrality bin used in the NPE analysis.

### 3.3 Track Reconstruction and TPC Cuts

The TPC is the primary tracking and particle identification system in STAR. Charged particles traverse the TPC chamber which ionizes the gas inside. Due to the nearly uniform electric field in the TPC these ions drift to the ends of the TPC where the currents are read out by the TPC padrows. The magnetic field in the TPC causes charged particle trajectories to be helical making charge sign distinction possible. We can also use the TPC for particle

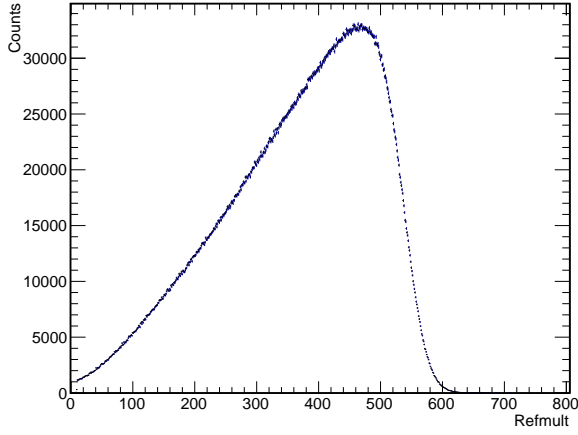


(a)  $V_z^{TPC}$

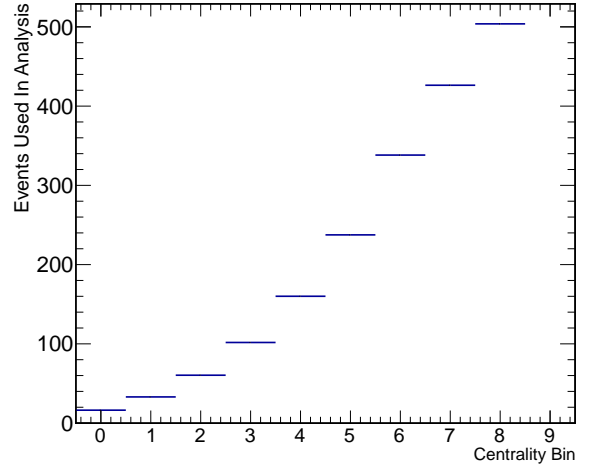


(b)  $V_z^{TPC} - V_z^{VPD}$

Figure 3.2: Vertex  $z$  distribution in run 11 Au+Au. Left plot shows the distribution of the  $z$  vertex (cut at  $\pm 30$  cm), right plot shows the difference between TPC and VPD  $V_z$  (cut at  $\pm 4$  cm).



(a) Reference Multiplicity



(b) Centrality bins

Figure 3.3: Reference multiplicity and centrality bin distributions for HT trigger events in Au+Au.

Variable	Cut
TPC Hits (Primary Tracks)	$\in (20, 50)$
TPC Hits (Global Tracks)	$\geq 15$
$N_{\text{hits}}/N_{\text{possible}}$	$\in (.52, 1.05)$
Primary DCA	$< 2.0\text{cm}$

Table 3.2: Quality cuts used for TPC tracks.

identification by measuring the ionization energy loss in the detector.

In the TPC we consider two types of tracks. The global tracks are those tracks from the fit to hits inside the TPC. If a global track has a distance of closest approach (DCA) to the primary vertex less than 3 cm then the primary vertex is added to the track hits and the track is refit. The resulting track is a primary track, which should represent particles coming directly from the collision.

We impose track quality cuts to make sure the track fits are good and that we get a good measurement of  $dE/dx$ . For primary tracks we require the number of TPC hits used in the track fit is between 20 and 50. For global tracks we only require that the number of hits is above 15. For all tracks we also cut on the ratio of hits fit to the maximum number possible keeping it between .52 and 1.05.

In run 11 and run 12 we have no tracking information near the beam pipe, the Silicon Vertex Tracker was removed before the runs and the new Heavy Flavor Tracker had not been installed. Due to the relatively short decay length (  $100 \mu\text{m}$ ) of  $D$  and  $B$  mesons this means that the decay vertex of these particles can not be distinguished from the primary vertex. For electron candidates we require primary tracks with DCA of less than 2 cm. The corresponding global track for that electron must also be less than 3 cm.

The energy loss ( $dE/dx$ ) in the TPC is modeled by the Bichsel function which also accounts for the spread in values for different particle species. We will be looking at the deviation of the energy loss compared to the Bichsel function value for electrons. This quantity is called  $n\sigma_e$  and is defined as:



$$n\sigma_e = \frac{\log \frac{dE/dx}{B_e}}{\sigma_e} \quad (3.1)$$

where  $B_e$  is the Bichsel function value and  $n\sigma_e$  is the deviation from the mean Bichsel function value for electrons. Analogous values are defined for protons, kaons, and pions but we will only concern ourselves with  $n\sigma_e$ . We will go over the specific  $n\sigma_e$  cuts used when we discuss the details of electron identification.

### 3.4 BEMC Points and Matching

The BEMC is critical to the identification of high  $p_T$  electrons in STAR. In Au+Au and p+p collisions hadrons (mostly pions and protons) greatly outnumber electrons and the  $n\sigma_e$  cuts in the TPC are not enough to give an acceptable electron purity. With the BEMC electron identification is possible at high  $p_T$ , in the calorimeter electrons are much more likely to interact in the first few layers of the calorimeter and they will also deposit their entire energy within the tower.

The barrel information in an event gives us hits for the BEMC towers as well as hits in the  $\eta$  and  $\phi$  directions for the shower max detector. From this information we need to cluster the tower hits as well as find hits in the SMD. Then we need to take the BEMC points (tower cluster and SMD hits) and associate it with a track from the TPC. We want to cluster the tower and SMD hits such that each BEMC point is associated with one electron. With the combined TPC and BEMC information we can identify the high  $p_T$  electrons necessary for our analysis.

We will now describe the UCLA BEMC point making program and will use the following definitions:

- **Tower cluster:** Group of tower hits according to some clustering criterion.
- **BSMD hit:** Signal in a single strip in the BSMD in either  $\phi$  or  $\eta$ .
- **BSMD cluster:** Group of BSMD hits in either  $\phi$  or  $\eta$ .

- **BSMD point:** Pair of clusters, one from  $\phi$ , the other  $\eta$ , which give a spatial point on the detector.
- **BEMC point:** A tower cluster and an associated BSMD point which will be matched up with tracks from the TPC.

To use the UCLA EMC point maker, described in detail in ref, to construct points and associate them with TPC tracks. The first step in reconstructing the BEMC points is to find and cluster the hits in the BEMC towers. To do this we first look for seed towers which have deposited energy above .1 GeV/c. Once we have found a seed tower adjoining towers within the same BEMC module are clustered with the seed, there is no clustering of towers or SMD hits across the modules.

The BSMD uses a similar clustering procedure for both the  $\phi$  and  $\eta$  directions. If EMC towers and BSMD clusters are found then the program will check for multiple clusters and attempt to merge them by relaxing the SMD clustering criteria. If one direction in the BSMD has no hits then clustering is rerun with relaxed criteria to try and find a good SMD point for that module. If neither tower nor SMD clusters are found in a module then the algorithm moves on to the next module.

With clusters in the towers and possibly the SMD found we move on to associating tower clusters to SMD hits. We only use SMD hits adjacent to the tower cluster and if there is only one SMD point associate it with the cluster. For the case of multiple SMD hits adjacent to the tower the tower energy is divided between the SMD points. If there are no points in the SMD but we still have tower clusters then the tower cluster is kept but not used as a BEMC point for matching with the TPC. The SMD info is used as the  $\phi$  and  $\eta$  location of the hit and the tower cluster is used for the point's energy. Figure 3.4 shows the distribution of SMD points in  $\phi$  and  $\eta$ .

From the TPC we only consider tracks with  $p_T$  above 1.5 GeV/c for association with points in the BEMC. When the TPC tracks are reconstructed they are fit to a helix to describe their trajectory through the TPC magnetic field. We then project these helices to the inner surface of the BEMC. After the projection we then associate the track with

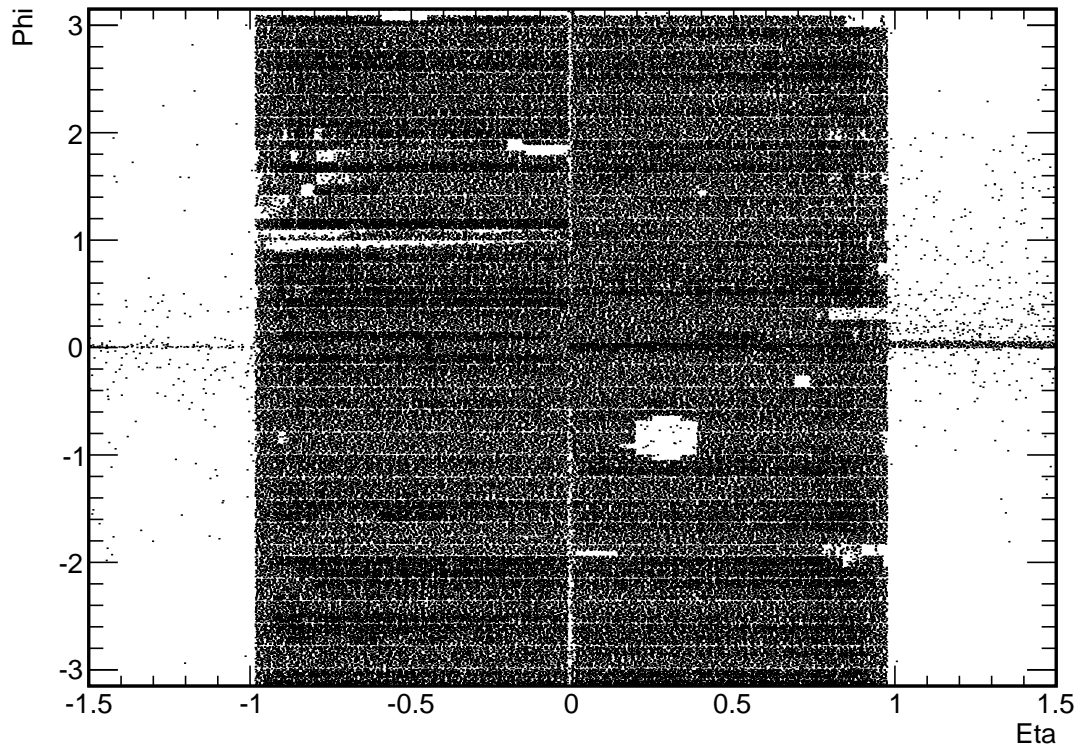


Figure 3.4: SMD points in  $\eta$  and  $\phi$  for the EMC points used in the analysis

a BEMC point. We require that the distance between the points ( $d = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ ) be smaller than .05. If multiple BEMC points are close enough to be matched, then we select the one with the smallest distance. In general tracks from electrons will match better to the points in the BEMC, we will use this to improve the cuts for electron identification which will be discussed in the next section.

## 3.5 Electron Identification

We can now use the matched TPC tracks and BEMC points to identify electrons in Au+Au and p+p collisions. We will use the TPC information to find tracks that originate from the primary vertex, traverse the TPC depositing energy consistent with what we would expect from electrons, then interact in the first few layers of the BEMC leaving a wide shower that terminates within the tower.

### 3.5.1 BEMC Cuts

Our analysis only uses data from high tower trigger events. The only requirement for a high tower trigger is that a tower in the event register a hit above a certain threshold. There is no guarantee that the tower will be matched to a track or that an electron triggered the tower. However we may still find electrons in these events they will just be below the trigger threshold. This effect is called random trigger benefit and it is important to remove in NPE analyses where the production cross-section of NPE is important. It is likely not critical in this analysis because we will be looking at correlations which are normalized per trigger but we still attempt to cut out the random trigger benefit.

When we make the BEMC points we also record the highest tower ADC value in the BEMC cluster and record this as the ADC0 for that point. Figure 3.5 shows the distribution of ADC0 from primary tracks matched to BEMC points. Near 325 ADC counts we see a large rise in the ADC0 of points, this corresponds to the threshold for the NPE18 trigger. Any electrons with ADC0 much below this value can be assumed to come from random

trigger benefits and are not used.

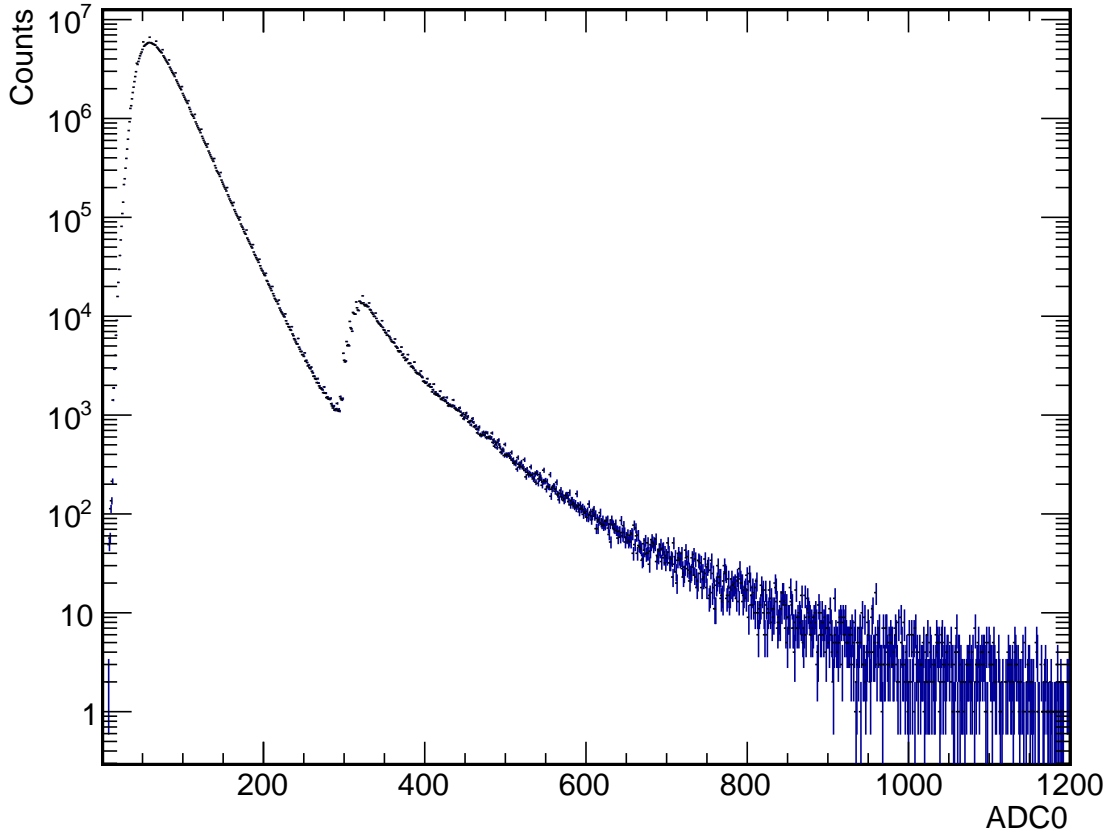


Figure 3.5: ADC0 for primary tracks in NPE18 triggered events. Turn on of the NPE18 trigger is apparent around 325 ADC counts.

For NPE, due to the short lifetime of the parent mesons, we only consider tracks originating from the primary vertex. Further we cut on the DCA of the track to the primary vertex, requiring that that the DCA be less than 1.5 cm. This cut is tighter than the 2 cm cut we used when considering the TPC track quality. We also remove tracks with  $p_T \lesssim 2.0$  GeV/c, generally the tracks coming from triggered electrons will be much higher than this anyway. For our acceptance we want the electron to be  $-0.7 \leq \eta \leq 0.7$  in pseudorapidity. This corresponds to the  $\eta$  acceptance of the BEMC. Run 10 analyses also cut out areas in  $\phi$  which correspond to the position of the SVT support structure. The reasoning behind that cut is

that the remaining structure could cause more photon conversions in those regions, but this cut is not applied here.

Now we apply the BEMC information to select electrons. Electrons begin showering much earlier in the BEMC than hadrons, the SMD sits at  $5.6X_0$  where electromagnetic showers are widest. With more hits in the SMD the spatial resolution of the BEMC points is better as so the BEMC matching for electrons tends to be better. This is illustrated in Figures 3.6 and 3.7 which show the BEMC matching in  $\Delta\phi$  and  $\Delta Z$ . Black points are for all matched primary tracks and red points show the matching for identified electrons (with the matching cuts excluded). We set the  $\Delta\phi$  cut such that  $|\Delta\phi| \leq .013$  and for  $\Delta Z$  we use  $-2.5 \text{ cm} \leq \Delta Z \leq 1.1 \text{ cm}$  (for  $\eta > 0$ ) and  $-1.5 \text{ cm} \leq \Delta Z \leq 1.9 \text{ cm}$  (for  $\eta < 0$ ). Figure 3.7 different cuts on  $\Delta Z$  are applied in the different halves of the TPC due to a discreet jump when crossing the central membrane of the TPC.

The wider showers for electrons also make it possible to cut on electrons based on the number of hits in the BSMD. The strips in the SMD are approximately twice the Moliere radius for electrons in lead, thus for developed EM showers we expect to see hits in multiple strips. Most hadrons will not leave hits in the BSMD, but since we are only considering reconstructed points in the BEMC we know that we will have at least one hit in both  $\eta$  and  $\phi$  in the SMD. Figure 3.8 shows the hits in the SMD for hadrons and for photonic electrons. We show the cuts with photonic electrons because without the SMD cuts the sample of BEMC points is not pure enough to illustrate the difference in behavior between hadrons and electrons. For electrons we require that number of strip hits in both  $\phi$  and  $\eta$  be greater than or equal to 2.

We can also select for electrons by looking at how much energy tracks deposit into the BEMC towers. The towers of the BEMC are around 20 radiation lengths thick meaning electrons will shower and deposit all of their energy within the tower. Hadrons or muons are not likely to develop full showers in the tower and we can use this to pick out electrons. We are interested in the  $E/p$  ratio for tracks hitting the BEMC. For high  $p_T$  electrons, they will deposit all of their energy  $E$  in the tower and since we are at high  $p_T$  ( $> 2 \text{ GeV}/c$ ) we also expect that  $E \approx pc$ . Thus for electrons we should see  $E/p \approx 1$  (ignoring factors of  $c$ ).

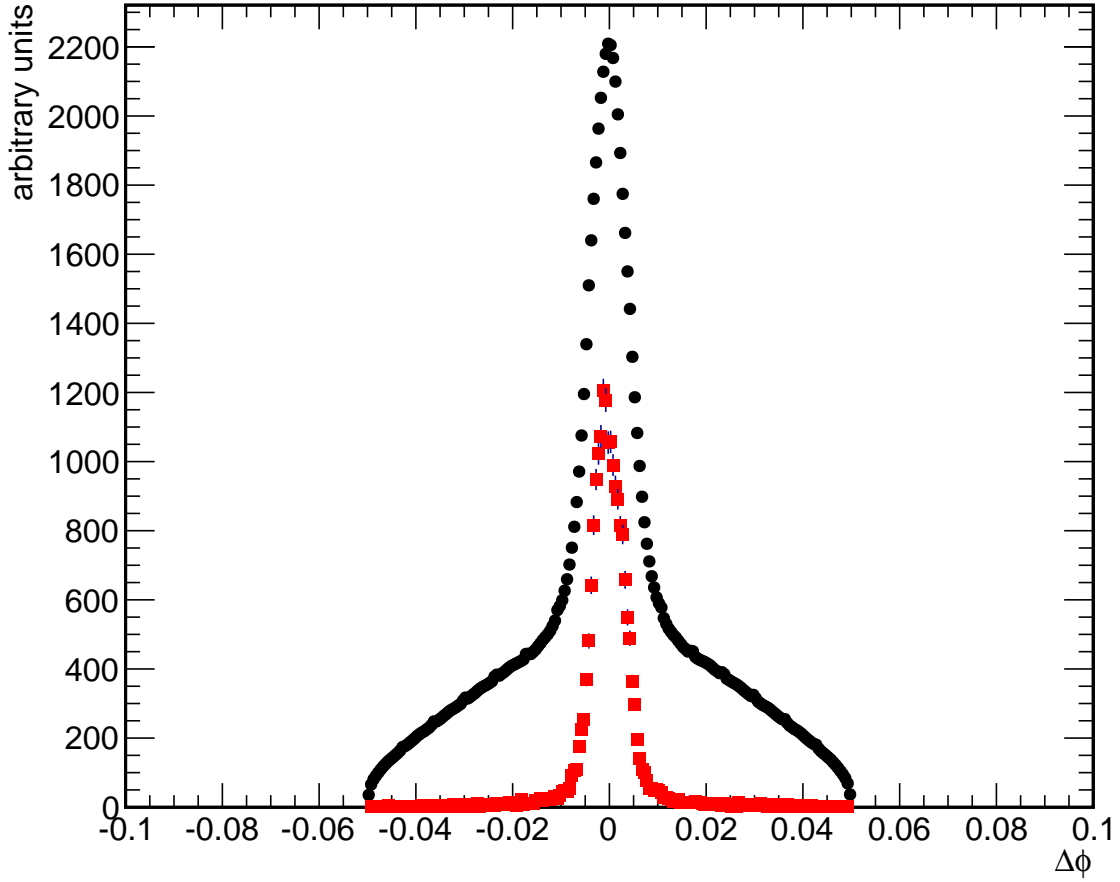
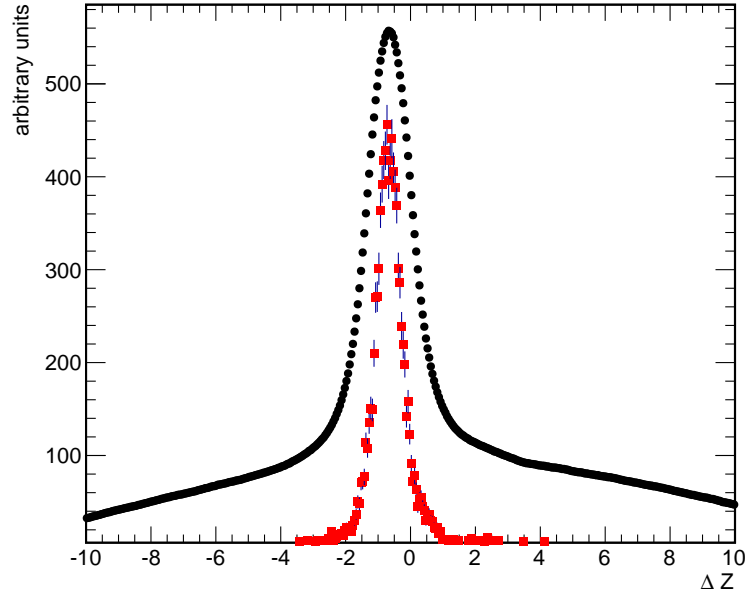
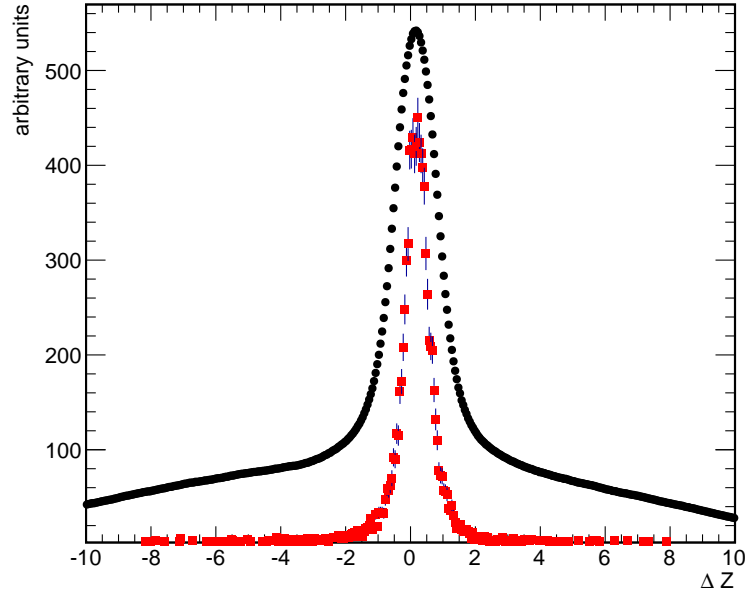


Figure 3.6:  $\Delta\phi$  between the TPC and BEMC for all matched primary tracks (black) and identified electrons (red). Y-axis is arbitrary units scaled to show all tracks and electrons on the same figure. Matching is better for electrons and we cut on such that  $|\Delta\phi| \leq .013$ .



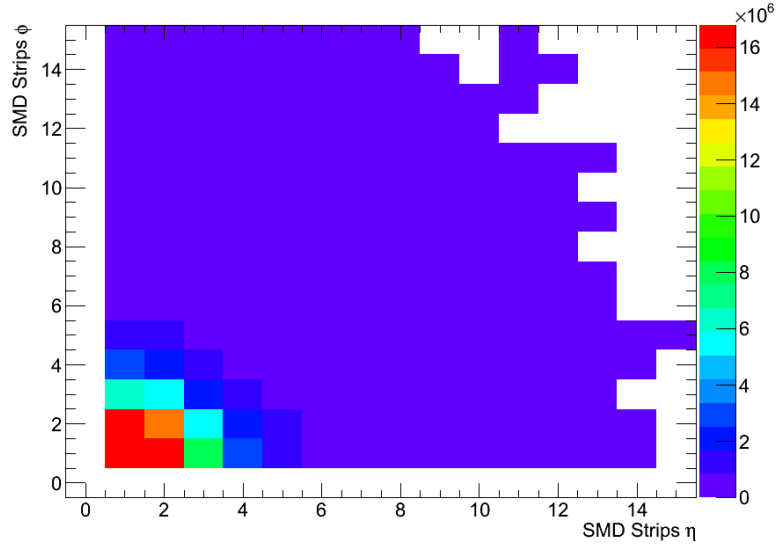
(a)  $\eta > 0$



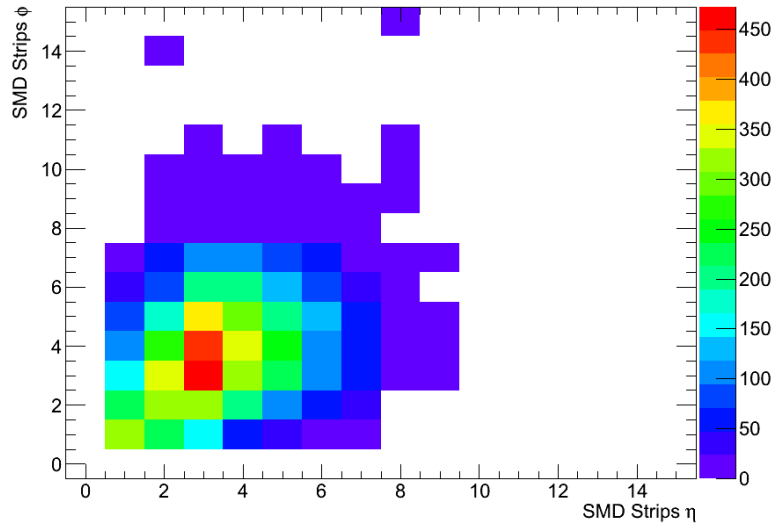
(b)  $\eta < 0$

Figure 3.7:  $\Delta Z$  of the TPC track to BEMC point for all points and for electrons. Different cuts are used in the two halves of the TPC due to a jump when moving from the positive  $\eta$  region to negative.





(a) Hadrons



(b) Photonic electrons

Figure 3.8: SMD strip hits for hadrons and electrons. For the electron sample we take photonic electrons (a relatively pure electron sample) and remove the SMD cuts to see the number of strip hits in each direction.

Figure 3.9 shows the  $E/p$  shape for electrons before applying  $E/p$  cuts and hadrons. Peak is seen for electrons around 1, we set the cut for electrons to be  $.5 \leq E/p \leq 1.7$ .

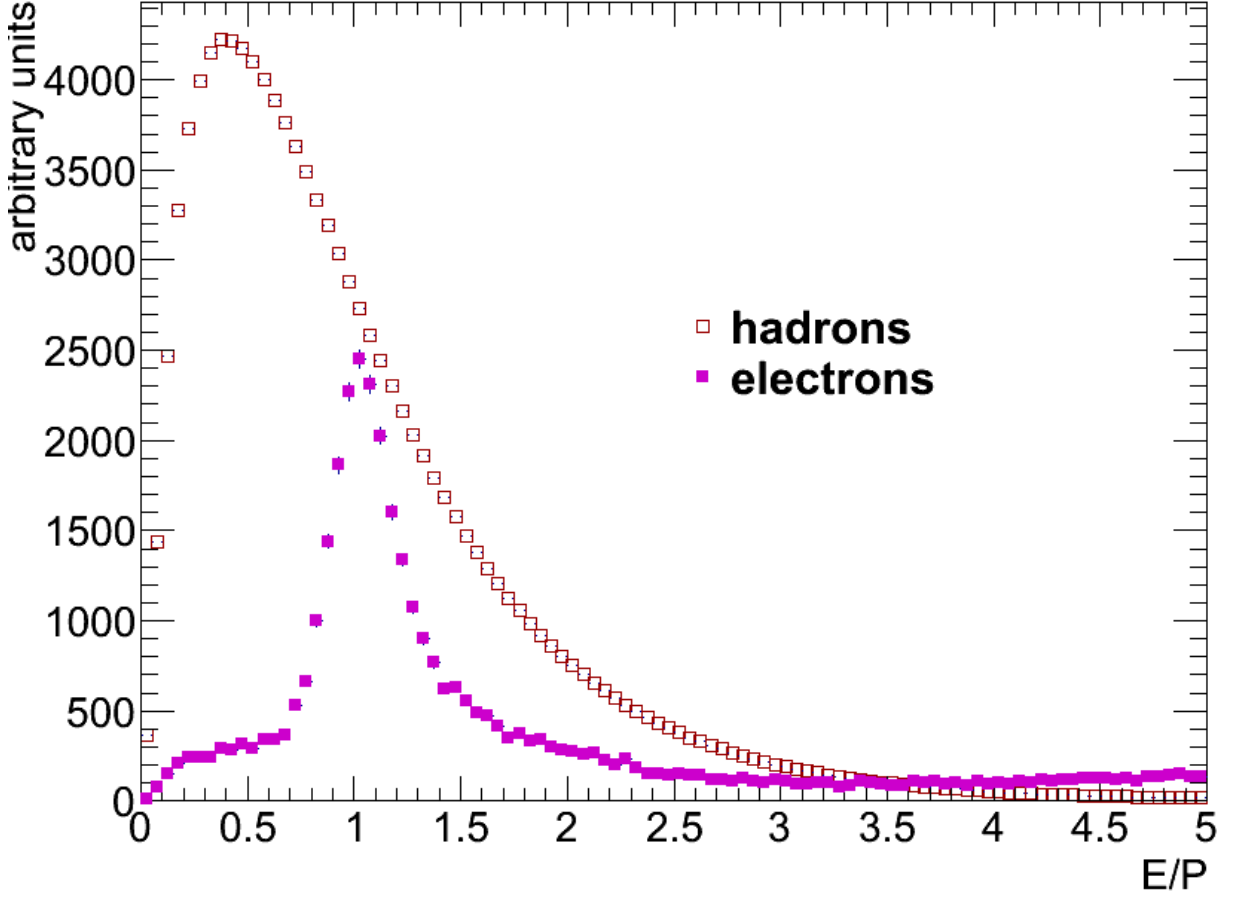


Figure 3.9:  $E/p$  for points in the BEMC for electrons (without  $E/p$  cut applied) and hadrons. Scale is arbitrary to show both cases. Electron cut is set  $.5 \leq E/p \leq 1.7$ .

Table 3.3 summarizes the electron cuts used so far, for the most part these cuts are applied to all tracks equally and do not depend on the track  $p_T$  (the ADC0 cuts being an event-by-event exception). In the next section we will show the  $n\sigma_e$  cuts which will depend on the track  $p_T$  and then later we will look at the overall electron purity that these cuts give to our inclusive sample.

Variable	Cut
Track Type	$< .5$ (Primary)
$\eta$	$\in (-.7, .7)$
Charge	$\pm 1$
ADC0	$\geq 205,270,325,425$ (NPE11/15/18/25)
SMD $\phi$ Strips	$\geq 2$
SMD $\eta$ Strips	$\geq 2$
$E/p$	$\in (.5, 1.7)$
DCA Global	$\leq 1.5$
BEMC $\Delta\phi$	$\in (-.013, .013)$
BEMC $\Delta Z$ ( $\eta > 0$ )	$\in (-2.5, 1.1)$
BEMC $\Delta Z$ ( $\eta < 0$ )	$\in (-1.5, 1.9)$

Table 3.3: Track level electron cuts, excluding  $n\sigma_e$ , cuts for Au+Au collisions.

### 3.5.2 TPC Cuts

The only remaining cuts are those for ionization energy loss in the TPC. The energy loss varies significantly for different particle species as a function of the particle's momentum. Since we are looking for electrons the cuts we will be applying to tracks are based on the calculated  $n\sigma_e$  as defined in Equation 3.1. For electrons  $n\sigma_e$  should be distributed around 0, but for negative values of  $n\sigma_e$  the electrons are overwhelmed by contamination from hadrons. We keep these cuts the same as they are in the run 10 NPE analysis, but they could be further tuned to improve electron purity and efficiency. Table 3.4 summarizes the  $n\sigma_e$  cuts used for electron identification. The cuts are the same for both Au+Au and p+p data.

## 3.6 Electron Purity

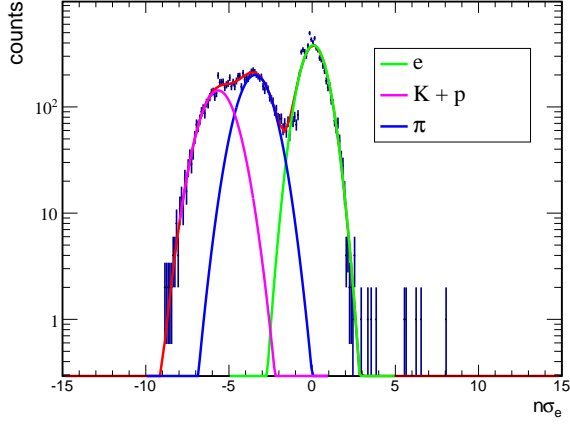
We will now investigate the purity of the electron sample we get from applying our electron identification cuts. To do this we will be relying on the  $n\sigma_e$  distributions we have measured.

$p_T$ Range	$n\sigma_e$ Cut
$1.0 \text{ GeV/c} < p_T < 2.0 \text{ GeV/c}$	$-1.25 < n\sigma_e < 2$
$2.0 \text{ GeV/c} < p_T < 4.0 \text{ GeV/c}$	$-0.75 < n\sigma_e < 2$
$4.0 \text{ GeV/c} < p_T < 6.0 \text{ GeV/c}$	$-0.25 < n\sigma_e < 2$
$6.0 \text{ GeV/c} < p_T < 7.0 \text{ GeV/c}$	$0.25 < n\sigma_e < 2$
$7.0 \text{ GeV/c} < p_T < 8.0 \text{ GeV/c}$	$0.25 < n\sigma_e < 2$
$8.0 \text{ GeV/c} < p_T < 10.0 \text{ GeV/c}$	$0.5 < n\sigma_e < 2$
$10.0 \text{ GeV/c} < p_T < 12.0 \text{ GeV/c}$	$0.5 < n\sigma_e < 2$

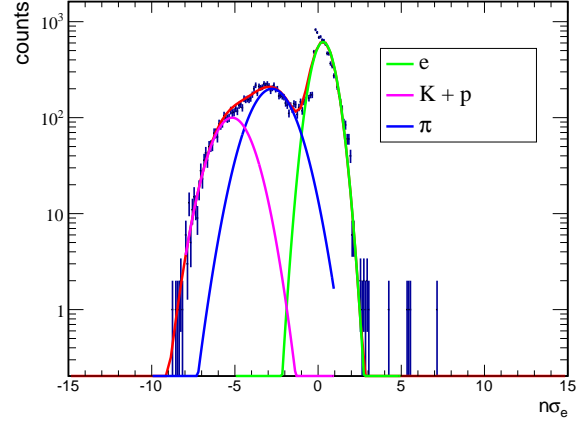
Table 3.4:  $n\sigma_e$  cuts as a function of  $p_T$ .

First we will look at the  $n\sigma_e$  distributions with all of the BEMC and track quality cuts applied. Then we will fit the peaks in  $n\sigma_e$  with gaussian functions, apply the  $n\sigma_e$  cuts as established in Table 3.4, and then calculate the yields from the electron and hadron peaks. This will give us an estimate of the purity of the electron sample we will use in the NPE analysis.

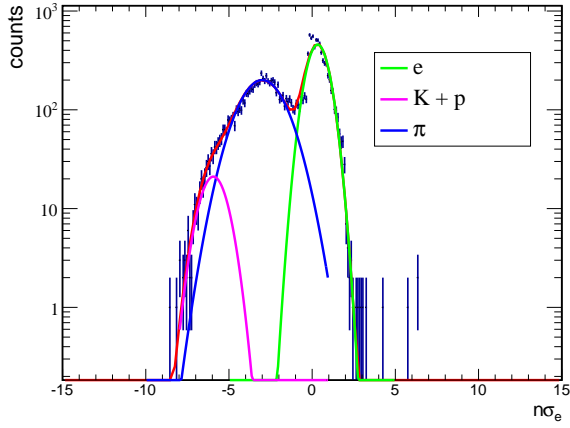
Figure 3.10 shows the  $n\sigma_e$  distributions as well as the fit functions. Each distribution was fit with three gaussian functions, one each for  $e^\pm$ ,  $\pi^\pm$ , and a final function for  $K^\pm + p^\pm$  combined. To estimate the purity we take the parameters (height,  $\mu$ ,  $\sigma$ ) gaussian component of the electron and hadron peaks. Then we integrate the peaks over the range specified by the  $n\sigma_e$  cuts. The purity is then the fraction of the total yield that comes from the electron peak. Table 3.5 lists the purities obtained by this method for a range of electron  $p_T$ . Below 6 GeV/c the purity is quite high between 96% and 100%, it begins to drop for higher  $p_T$  due to narrowing and shifting of the electron peak as well as closer merging of the hadron peaks with the electrons. The peak shape is biased by the fact that we only select events with high  $p_T$  tracks and  $n\sigma_e$  within certain values. This causes the peaks to have non-gaussian features and prevents us from taking the purities obtained at face value. However, in this analysis we will not directly need the electron purity unlike if we were looking at NPE  $v_2$ . We will be normalizing our observations per trigger particle, so we only need to look at purity to



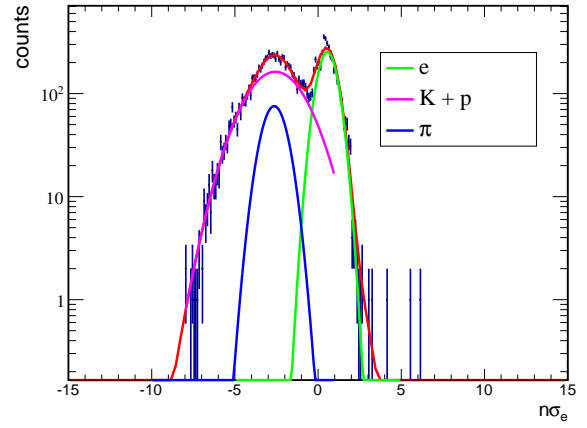
(a)  $3.0 \text{ GeV}/c \leq p_T \leq 4.0 \text{ GeV}/c$



(b)  $4.0 \text{ GeV}/c \leq p_T \leq 5.0 \text{ GeV}/c$



(c)  $5.0 \text{ GeV}/c \leq p_T \leq 6.0 \text{ GeV}/c$



(d)  $6.0 \text{ GeV}/c \leq p_T \leq 8.0 \text{ GeV}/c$

Figure 3.10: Fits to the  $n\sigma_e$  distributions for primary electron candidates (particles that pass all electron cuts excluding the  $n\sigma_e$  cut) as a function of particle  $p_T$ .

Electron $p_T$	Purity
$3.0 \text{ GeV}/c < p_T < 4.0 \text{ GeV}/c$	99.8%
$4.0 \text{ GeV}/c < p_T < 5.0 \text{ GeV}/c$	97.0%
$5.0 \text{ GeV}/c < p_T < 6.0 \text{ GeV}/c$	96.1%
$6.0 \text{ GeV}/c < p_T < 8.0 \text{ GeV}/c$	79.6%

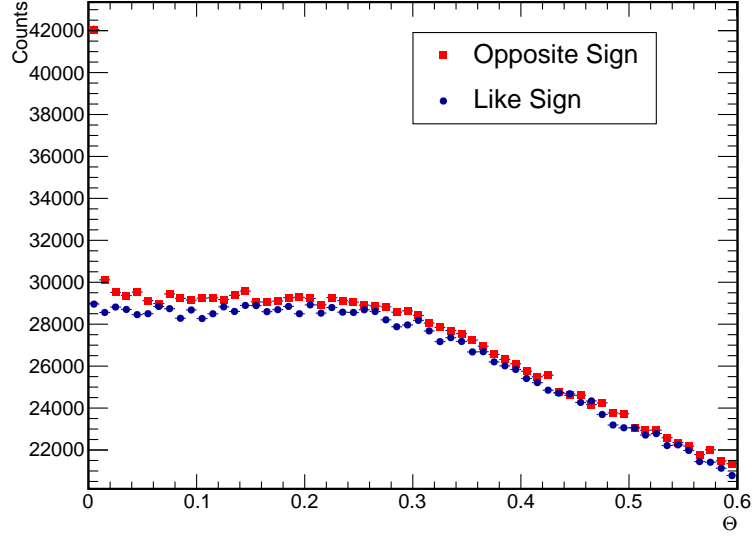
Table 3.5: Purity of electrons obtained from fits to  $n\sigma_e$ .

estimate the contribution of hadron contamination in the NPE sample when we construct NPE-h correlations.

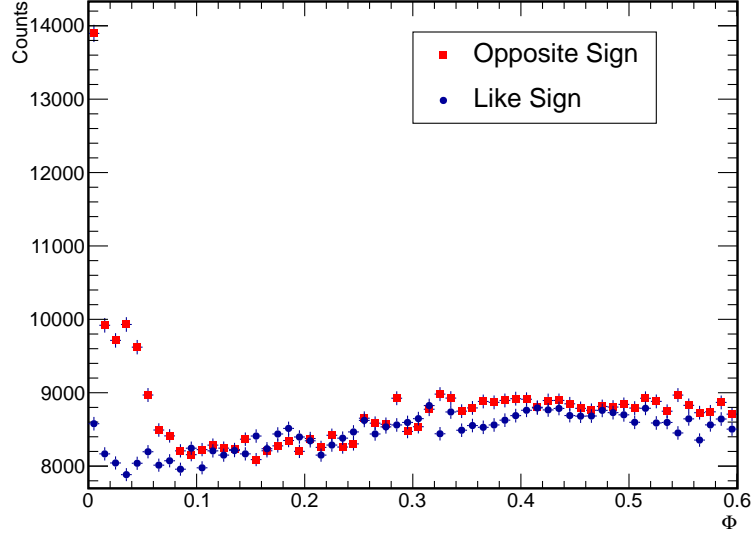
### 3.7 Photonic Electron Identification

The main background to electrons from the decay of heavy flavor mesons comes from photon conversions in the detector and Dalitz decay of  $\pi$  and  $\eta$  mesons. Collectively we refer to these background electrons as *photonic electrons*, and in this section we will summarize how we remove them from our electron sample. When the electrons are produced by these background processes they come in  $e^+e^-$  pairs. To tell whether an electron is of photonic origin we search through the tracks in the event and try to find its partner.

When searching for the partner electron we use very relaxed cuts. We search through all global tracks (rather than primary) within a pseudorapidity of  $-1.3 \leq \eta \leq 1.3$ . To cut out hadrons we require that  $-3 \leq n\sigma_e \leq 3$ . Tracks from photonic background will be very close together in the detector and will have a small opening angle. We apply cuts on the pairwise DCA of the two tracks, requiring the DCA be less than 1.0 cm. Also the opening angle between the tracks should be small, we want the total angle  $\Theta < 0.05$  and the azimuthal angle  $\phi < 0.1$ . Table 3.6 summarizes the track cuts and pairing criteria for reconstructing photonic electrons. The partner for a photonic electron must have opposite charge to the primary track. We look for both opposite-sign as well as like-sign pairs. The like sign pairs which satisfy the photonic partner cuts let us estimate the number of photonic electrons that are misidentified due to combinatorial pairing of tracks.



(a)  $\eta > 0$



(b)  $\eta < 0$

Figure 3.11: Angle cuts for partner tracks used to reconstruct photonic electrons.

Variable	Cuts
TrackType	Global
$\eta$	$\in (-1.3, 1.3)$
$p_T$	$> 0.3 \text{ GeV}/c$
Pair DCA	$< 1.0 \text{ cm}$
Pair $\Theta$	$< 0.05$
Pair $\phi$	$< 0.10$
2D Invariant Mass	$< 0.10 \text{ GeV}/c^2$

Table 3.6: Cuts used for partner tracks and for identifying photonic electrons.

For photonic electrons we expect the pair of particles to have a low invariant mass (exactly 0 for photon conversions and  $< .1 \text{ GeV}/c^2$  for Dalitz decays). However the measurement of the invariant mass is degraded by the finite tracking resolution of the TPC. Reconstructed TPC tracks form helices in the detector volume. The resolution of the TPC effectively means that the helices can shift around relative to each other. Due to this effect, there is a large uncertainty in the location of the secondary vertex where the electrons have their minimum DCA. This causes an uncertainty in the opening angle between the tracks and smears out the invariant mass distribution of the pairs. To correct this we instead consider the 2D invariant mass. The tracks are rotated into the same plane before calculating the mass. The cutoff for photonic electrons is that this 2D invariant mass be below  $.10 \text{ GeV}/c^2$ . Figure 3.12 shows the 2D invariant mass distribution. The 3D invariant mass is not used in identifying photonic electrons but is plotted in Figure 3.13. The peak near 0 is from photon conversions while the peak at  $.05 \text{ GeV}/c^2$  comes from the Dalitz decays. The Dalitz decay is a three body decay and thus the missing photon causes the mass peak to be smeared.

Clearly just pairing up all tracks to look for photonic electrons will not guarantee that we remove all of the background. It is possible for the partner track to be outside of our acceptance or otherwise fail to pass the photonic electron cuts. We will quantify how much background we miss by the parameter  $\epsilon_\gamma$ , the photonic reconstruction efficiency, which is



essentially the fraction of all photonic electrons we are able to reconstruct from searching for partner tracks. The next section will discuss how  $\epsilon_\gamma$  is calculated.

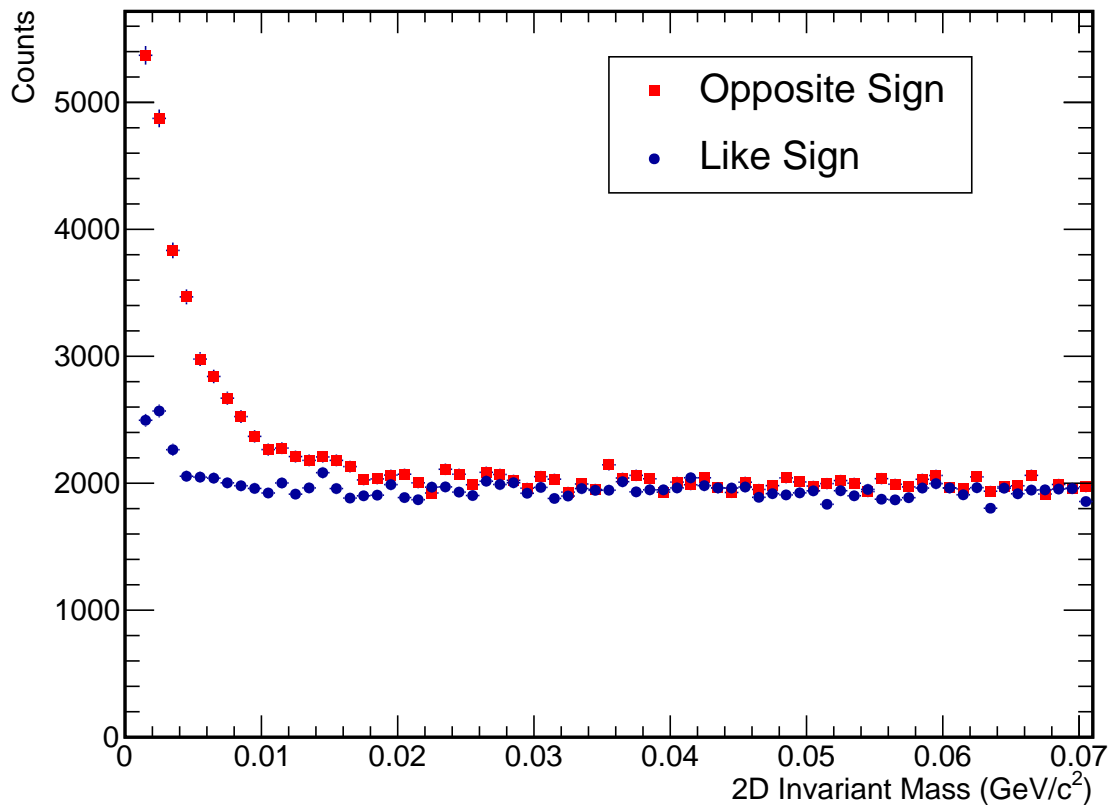


Figure 3.12: 2D invariant mass for opposite sign and same sign pairs. For photonic electron identification we require that  $m_{2D} < 0.10 \text{ GeV}/c^2$ .

### 3.8 Photonic Electron Reconstruction Efficiency

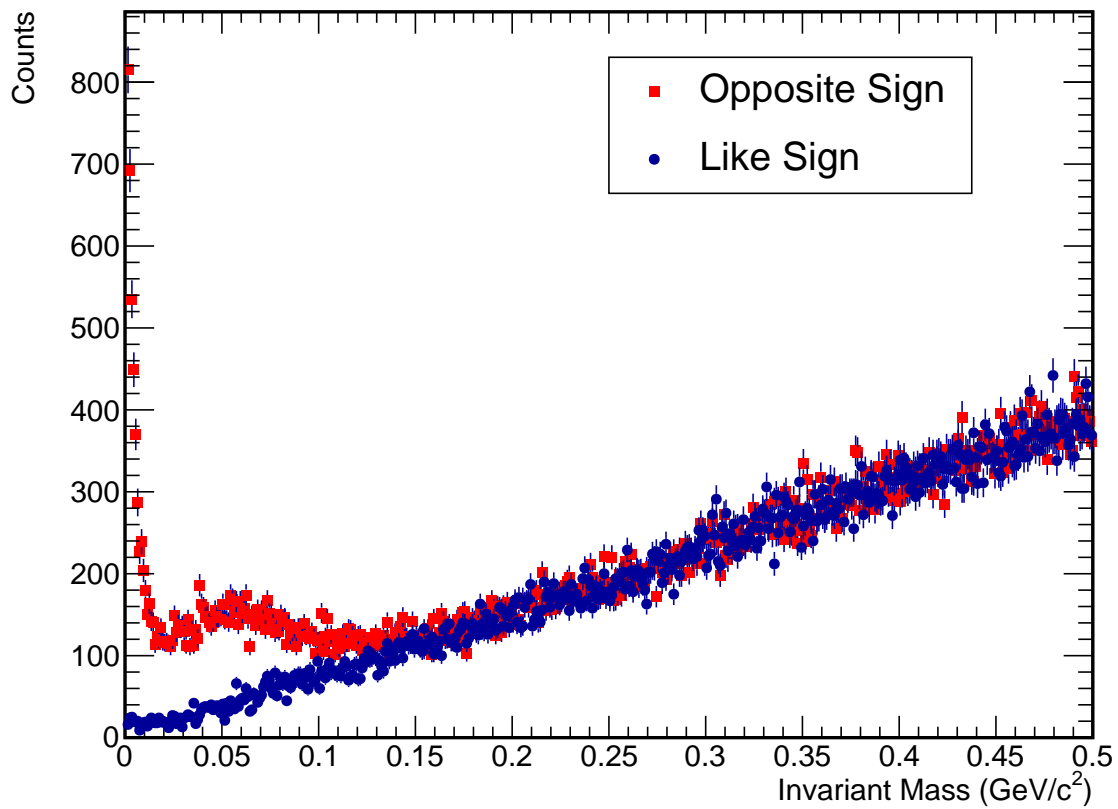


Figure 3.13: Invariant mass distribution for pairs of tracks. Opposite sign pairs show low mass excess which corresponds to the photonic electrons.

## CHAPTER 4

# Azimuthal Correlations of Non-Photonic Electrons to Hadrons

We will now investigate the correlations of triggered non-photonic electrons to hadrons in  $Au + Au$  and  $p + p$  collisions at 200 GeV. Hard processes in these collisions will produce back to back jets in the azimuthal angle  $\phi$ . We search for potential modification of the jet in  $Au + Au$  collisions compared to  $p + p$ .

### 4.1 Overview of Constructing the NPE-hadron Correlation

Several steps are needed to produce the NPE-h correlation. The trigger particle electrons are identified by the procedure described in the previous chapter. The nonuniform acceptance of detector results in false correlations which are not a result of the underlying physics. This is corrected in two ways, the  $\phi$  distribution of all particles is flattened and then the correlations from mixed events are calculated and then a weighting is determined so as to flatten these as well.

In correlations from  $Au + Au$  collisions there is an underlying background correlation from the flow of the both the trigger electron and the associated hadron. In this analysis we only consider the second order harmonic of flow,  $v_2$ . For hadrons,  $v_2$  is very accurately measured across a wide range centralities and  $p_T$ . For non-photonic electrons, the measurements of  $v_2$  are not so precise, thus we can only estimate its contribution to the background. This uncertainty will be reflected in the analysis of systematic error.

We will also look at the dependence of the correlation on the angle between the trig-

gered electron and the event plane. A dependence on this angle could point to path length dependence on the jet suppression in QGP.

## 4.2 Acceptance Corrections

The STAR detector give full  $2\pi$  azimuthal coverage, however there are still regions of the detector which have noticeably poorer efficiency. This causes an uneven azimuthal acceptance which in turn lead to spurious correlations between detected particles. To correct this we need to apply a weighting to each track depending on where it is in the detector.

### 4.2.1 Single Particle $\phi$ -weighting

We begin by correcting for the single particle acceptance in  $\phi$ . The boundaries between sectors produce regions of lower efficiency, also in Run11 one sector of the TPC had noticeably lower efficiency than the rest. These effects are both shown in Figure 4.1.

The dependence of the acceptance on  $\phi$  however is not the same for all tracks. Whether a track crosses a sector boundary or passes through the dead sector will depend on that particular track's geometry. Tracks at low  $p_T$  curve more in the magnetic field and thus the effects of these lower efficiency areas apply to wider regions in track  $\phi$ . The dependence of acceptance on  $p_T$  is shown in Figure 4.2. At low  $p_T$  the dependence is especially strong thus for  $p_T \leq 1$  GeV/c we divide tracks into  $p_T$  bins of .1 GeV/c, which is near the limit of the momentum resolution of the TPC. Above 1 GeV/c the tracks are roughly straight so the effects on acceptance from the sector boundaries and dead sector are consistent bin-to-bin up to arbitrarily large  $p_T$ .

While the dependence of acceptance on track  $p_T$  is by far the largest effect, we still further subdivide the tracks to make acceptance corrections. It is possible for the acceptance to depend on  $\eta$ , and we are especially concerned with edge effects when  $|\eta| \sim 1$ , thus we divide into 4 even bins in pseudorapidity ranging from -1 to 1.

Likewise we account for dependence on the event vertex (in both  $p + p$  and  $Au + Au$ )

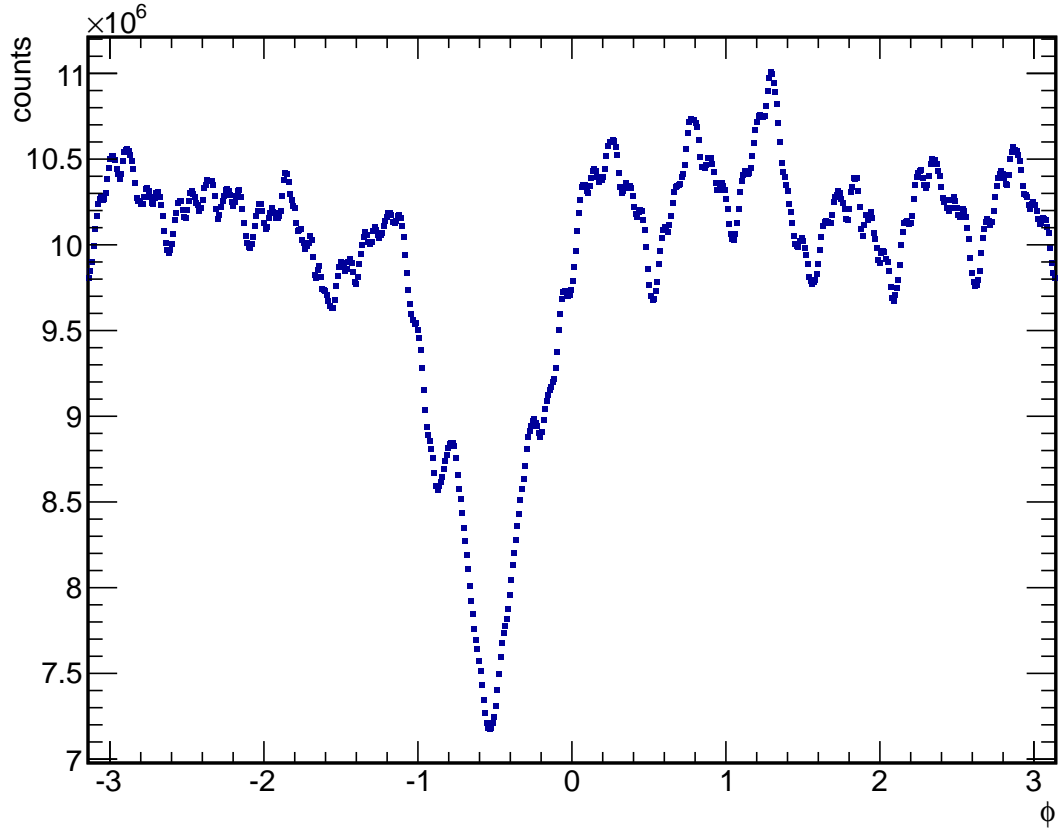
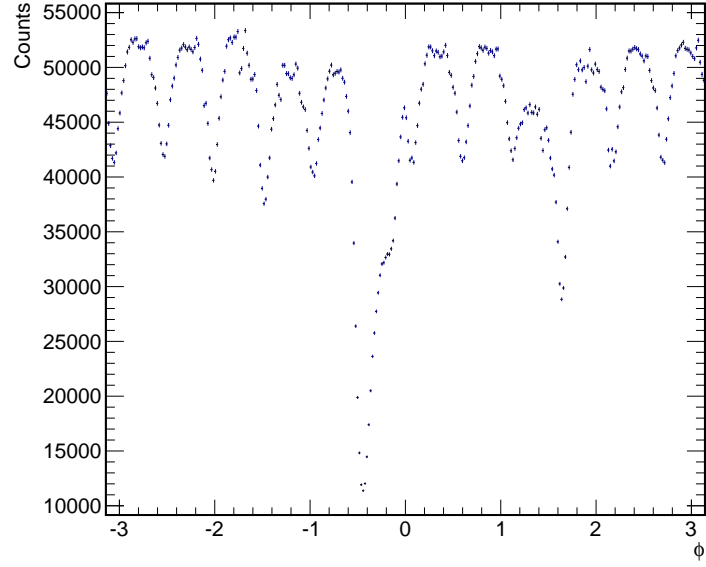
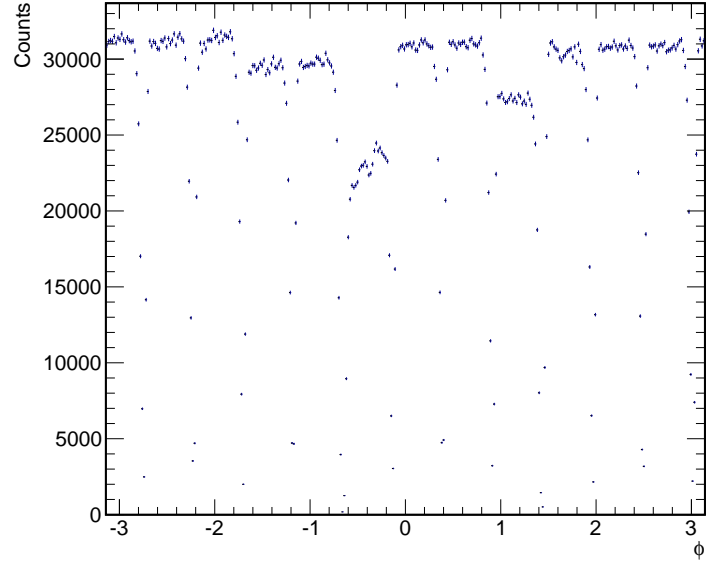


Figure 4.1: The azimuthal angular distribution of all tracks in Run11  $Au + Au$  collisions at 200 GeV. Periodic bumps can be seen from the sector boundaries, as well as a dip in the poorly performing sector.



(a)  $.5 \text{ GeV}/c \leq p_T \leq 1.0 \text{ GeV}/c$



(b)  $1.5 \text{ GeV}/c \leq p_T \leq 2.0 \text{ GeV}/c$

Figure 4.2:  $\phi$  distributions for single particles in different  $p_T$  bins. Strong  $p_T$  dependence is seen especially below  $1 \text{ GeV}/c$  due to the different track geometries.

and multiplicity (only for  $Au + Au$ ) by dividing into bins of vertex-z and centrality. For the centrality bin divisions, all centrality bins from 30% – 80% are taken together since in the peripheral bins the statistics are too low to get a reliable acceptance correction.

Finally, since the tracks in the TPC are curved, there will be a dependence on which direction the track curves. For example, two particles may start on opposite sides of a sector boundary separated by some distance in  $\phi$  but both may cross the boundary if they curve in opposite directions. So we need to take separate weightings based on the product of the magnetic field and the particle’s charge,  $B \cdot q$ .

After calculating the single  $\phi$  correction we apply it to each track in the analysis whenever we calculate event planes or 2-particle correlations. Since some areas of the detector have very low efficiencies they can introduce huge weights for a small number of particles. This can destabilize results, so we cap the weight an individual particle can get at 5.0.

#### **4.2.2 Mixed Event Background**

To further correct for nonuniformities in detector acceptance we use a mixed event weighting. In an ideal detector the correlations of trigger particles to associated hadrons from a different event should be flat, however acceptance effects will result in nonphysical correlations which need to be removed.

Similar to the single particle corrections we divide the mixed event corrections into bins to account for various systematic differences. In mixed event we bin according to associated particle  $p_T$ , triggered particle  $p_T$ , centrality, vertex z position, and  $\eta$ . As in single particle corrections, the most extreme bin to bin variations occur between the low associated  $p_T$  bins.

### **4.3 Background from Flow**

#### **4.3.1 Measurements of Flow**

The motivations behind two-particle correlation studies are typically the investigation of jet modification in QGP and the response of the medium to jets. But even in the absence of jets

we still expect to see some correlation within events from flow. The azimuthal anisotropy resulting from the second order flow harmonic,  $v_2$ , of both the trigger and associated particles produces a background shape with the form:

$$B[1 + v_2^{trig}v_2^{asso} \cos(2\Delta\phi)] \quad (4.1)$$

where  $B$  is an overall constant factor. Higher order harmonics  $v_3$ ,  $v_4$ , etc. can also contribute to the background. Large  $v_3$  in particular is a potential explanation for some of the results in dihadron correlations, but these effects are not considered for this analysis.

Hadron  $v_2$  has been measured to high precision in a wide range of  $p_T$  bins at STAR. Figure 4.3 shows the results of STAR  $v_2$  measurements using an event plane method and illustrates the general dependence on  $p_T$  and centrality. To calculate the hadron  $v_2$  we extrapolate the  $v_2$  measurement to the center of the associated hadron  $p_T$  bin. Then when looking at correlations across multiple hadron  $p_T$  bins we use the weighted average of  $v_2$  based on the number of hadrons in each  $p_T$  bin.

Measurements of electron  $v_2$  at STAR have shown that non-photonic electrons also have large elliptic flow. Because of limited statistics electron  $v_2$  is measured in much larger  $p_T$  and centrality bins. Various measurements of NPE  $v_2$  are seen in Figure 4.4, showing that they tend to fall in a range between .05 and .15 depending on the measurement procedure. For this analysis we assume that NPE  $v_2$  is .1 in all bins, we then vary the NPE  $v_2$  between .05 and .15 and take the difference in final correlations as a systematic error.

### 4.3.2 Background Normalization

Knowing the values of  $v_2$  for hadrons and non-photonic electrons, we then need to determine the overall normalization constant  $B$  as in Equation 4.1. There are two simple ways of estimating this, both relying on the assumption that the jet like contributions to the azimuthal correlation are concentrated in peaks around 0 and  $\pi$ , and that any remaining correlations there are the result of the underlying  $v_2$  background.

In one case we can simply pick a point between the near and away sides and then set  $B$  so



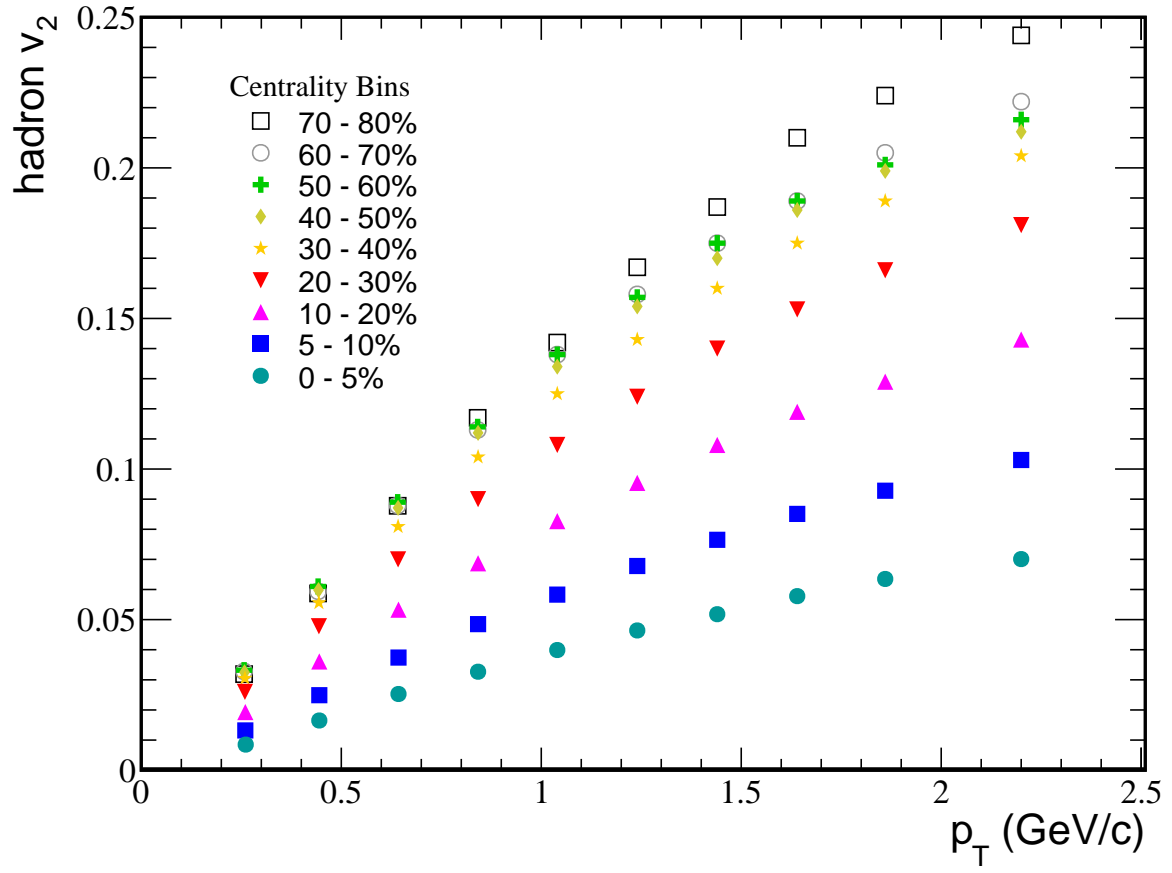


Figure 4.3: Measured  $v_2$  values for hadrons across a range of  $p_T$  and centralities.

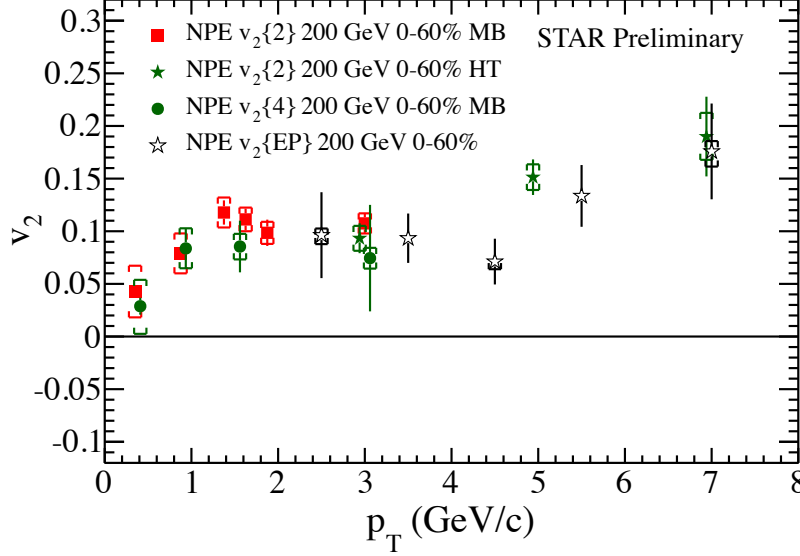


Figure 4.4: Various measurements of NPE  $v_2$  in STAR. Going forward we assume .1 to be the value for NPE  $v_2$  in all bins.

that the overall yield of particles above background at that point is 0. This point is typically taken to be around 1 radian and thus this method is called the zero yield at 1 (ZYA1) normalization. Although when we implment ZYA1 normalization we take the lowest absolute yield of the 3 points closest to 1 radian. Alternatively we can instead pick the point in the raw correlation with lowest value and normalize so that that point produces zero yield. This is the zero yield at minimum (ZYAM) method. These methods tend to coincide in practice and unless otherwise noted we use ZYAM normalization. There is another technique called absolute background subtraction used by PHENIX in their NPE-hadron correlation measurement but we do not use this method.

When using ZYAM or ZYA1 normalization our background subtracted yield can be very suceptible to downward fluctuations of points causing an abnormally high yield. To account for this we also look at the effect of normalizing to the next highest point in the correlation. We then compare the values of  $B$  that we get and then quote the difference as the systematic error of background normalization.

Variable	Cut
Track Type	$< .5$ (Primary)
Global DCA	$< 2.0\text{cm}$
$\eta$	$\in (-1.0, 1.0)$
$p_T$	$\geq .2 \text{ GeV}$

Table 4.1: Cuts for associated hadrons used in e-h correlations

## 4.4 Correlations in Au+Au

We will now look at putting together the results of the previous sections and creating the NPE-h correlation in Au+Au collisions. We will then discuss the results in Au+Au before moving on to p+p and event plane dependent correlations.

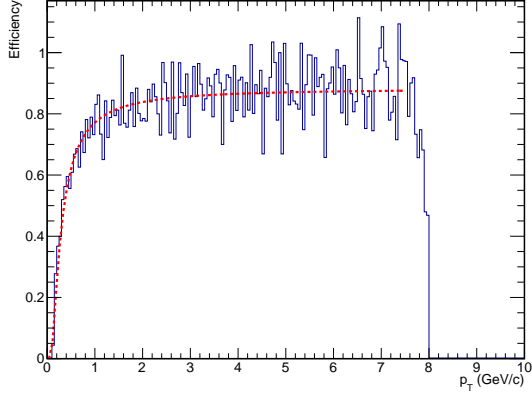
### 4.4.1 Associated Hadrons

The basic quantity we will measure is the yield  $\frac{dN}{d\Delta\phi}$  of associated hadrons at various relative to some triggered electron. For the associated hadrons the cuts we use are summarized in Table 4.1.

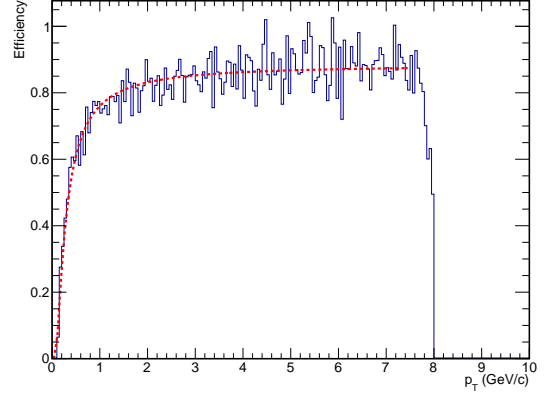
The correlations are further broken up into bins in event centrality and associated hadron  $p_T$ . This is the point at which we apply the acceptance corrections from the single particle  $\phi$  weighting as well as the mixed event weighting. Additionally we also correct the yield for the efficiency of the associated hadron yield. The TPC efficiency is lower for the high occupancy events in central collisions, and efficiency is also significantly worse for very low  $p_T$  hadrons. The efficiency is calculated from embedding and the results are summarized in Figure 4.5.

### 4.4.2 Constructing the NPE-hadron correlation

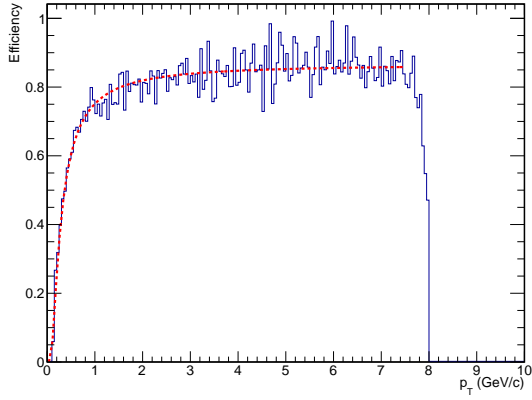
Now with azimuthal electron-hadron correlation functions we look at how we create the NPE-h correlation. The definition of the NPE-h correlation is:



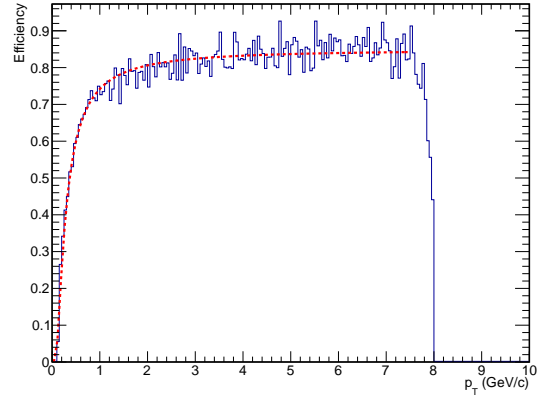
(a) 50-60%



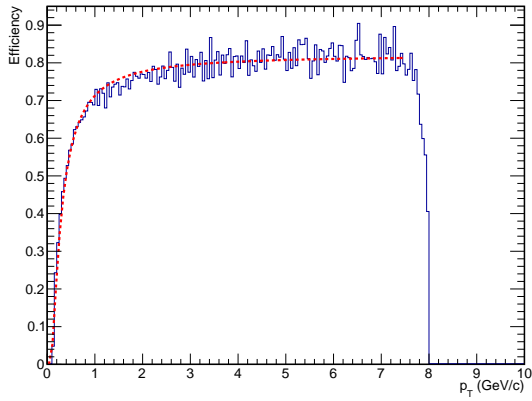
(b) 40-50%



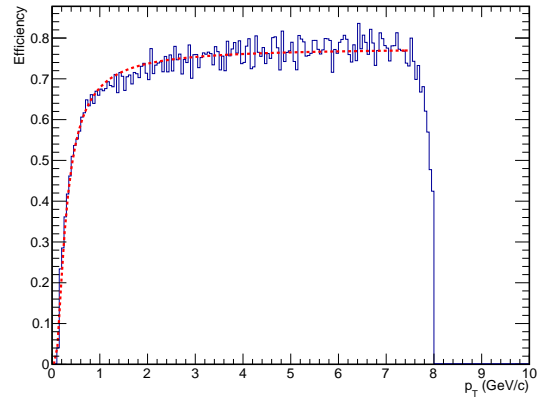
(c) 30-40%



(d) 20-30%



(e) 10-20%



(f) 0-10%

Figure 4.5: The TPC efficiency for hadrons as a function of hadron  $p_T$ . The different plots are for different centralities which correspond to 0-10%, 10-20%, 20-30%, 30-40%, 40-50%, and 50-60%.

$$\frac{dN_{NPE-h}}{d\Delta\phi} = \frac{dN_{semi-h}}{d\Delta\phi} - \left(\frac{1}{\epsilon_\gamma} - 1\right) \frac{dN_{photonic-h}}{d\Delta\phi} + \frac{dN_{same-h}}{d\Delta\phi} \quad (4.2)$$

An explanation of these terms:

- **Semi-inclusive electrons:** This is the correlation of inclusive electrons for which no photonic partner track could be found. This sample will include many non-photonic electrons as well as some photonic background for which we could not find a partner track.
- **Unidentified photonic electrons:** the term:

$$\left(\frac{1}{\epsilon_\gamma} - 1\right) \frac{dN_{photonic-h}}{d\Delta\phi}$$

is intended to remove the remaining photonic background triggers from the semi-inclusive sample. To do this we take the correlation for identified photonic electrons to hadrons and scale it up according to the estimated photonic electrons reconstruction efficiency,  $\epsilon_\gamma$ . The reconstruction efficiency is determined by embedding simulations.

- **Same-sign electrons:** The method for identifying photonic electrons, pairing all tracks and calculating DCAs and invariant masses, will result in some oversubtraction of NPE signal. We account for the combinatorially removed points by looking at the results of same sign pairing tracks, i.e. the tracks which pass all of the photonic partner cuts except that they have the same sign. We add this term back make up for the NPE signal which was removed by the previous two terms.

There is also the potential for contamination of the triggered electrons with hadrons. This would require the subtraction of a dihadron correlation term:

$$\frac{dN_{h-h}}{d\Delta\phi}$$

We expect the purity of our triggered electrons to be high in the relevant  $p_T$  ranges so for this analysis we will not include it.

### 4.4.3 Raw Correlations

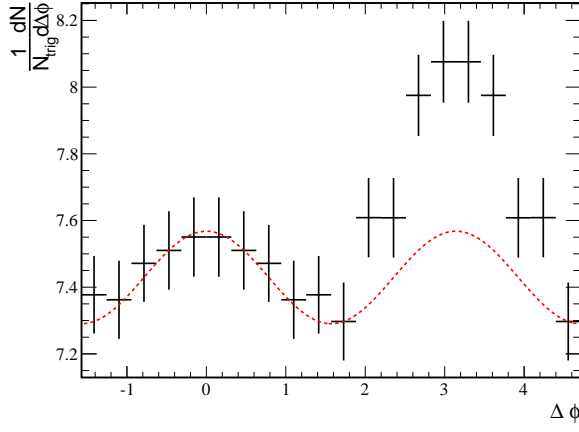
The raw correlation is the distribution  $\frac{dN_{NPE-h}}{d\Delta\phi}$  before we subtract the background from  $v_2$ . The subtraction and correction spelled out in Equation 4.2 has already been performed and what is shown in the following figures is the NPE-h correlation with no background subtraction. The raw correlations serve as an initial check of the correlation method to spot any problems with our procedure.

Figures 4.6, 4.7 and 4.8 show the raw correlations in 200 GeV AuAu collisions and that they conform to our rough expectations. Overall particle yields are also higher at lower  $p_T$  and are much higher in central events where multiplicity is higher. The general trend is for particle yields to be higher around 0 angle relative to the triggered NPE and at  $\pi$ , this is normal dijet distribution which is seen in hard processes. We also see that these dijets sit on top of a modulated background from  $v_2$ . We can see that the calculated backgrounds are reasonable and we also get a sense of the performance and limitations of the ZYAM method. For example in Figure 4.8a we see that a low fluctuation in one bin may have pulled down the normalization causing the near side peak to sit farther above the background. We will account for these types when we estimate the systematic uncertainties.

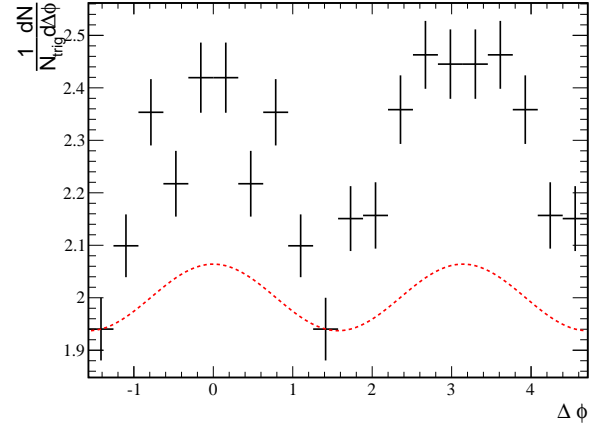
### 4.4.4 Subtracted Distributions and Yields

We now want to look at how the jet-like distributions of particles changes as a function of collision centrality and trigger particle  $p_T$ . We subtract off the background from the underlying event and  $v_2$  to examine effects of the heavy quark fragmentation and propagation through the medium. The subtracted plots are summarized in Figures 4.9, 4.10 and 4.11.

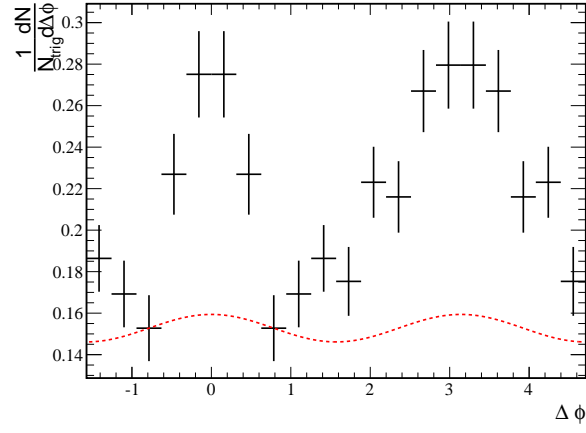
For these NPE-h correlations we also consider three sources of systematic error: Uncertainty from NPE  $v_2$ , uncertainty in photonic electron reconstruction efficiency, and background normalization. Results NPE  $v_2$  are over wide ranges in  $p_T$  and centrality and are roughly around .1 we take that value when calculating the background but we also calculate backgrounds with  $v_2$  of .05 and .15. We then take the difference between these extremes as the uncertainty.



(a)  $0.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$

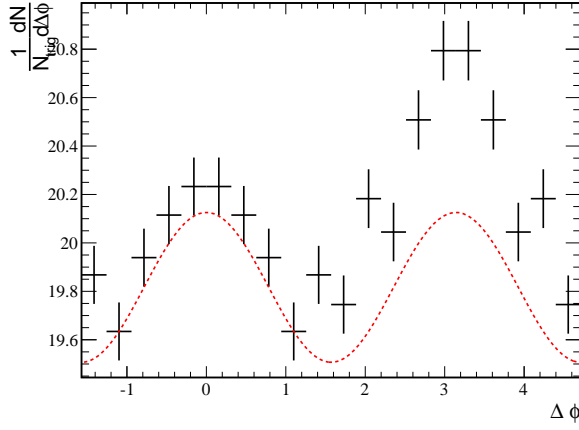


(b)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$

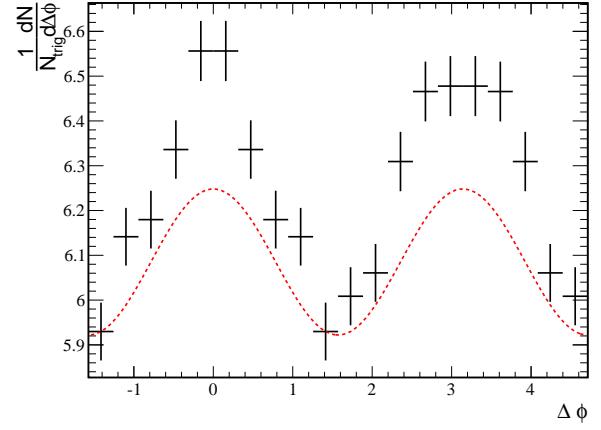


(c)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$

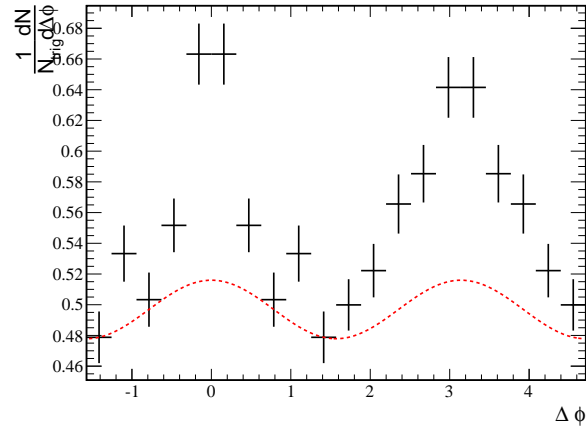
Figure 4.6: Raw NPE-h Correlations for 40-60% centrality events. Trigger  $p_T$  is  $4.0 \text{ GeV}/c \leq p_{T,trig} \leq 6.0 \text{ GeV}/c$



(a)  $.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$



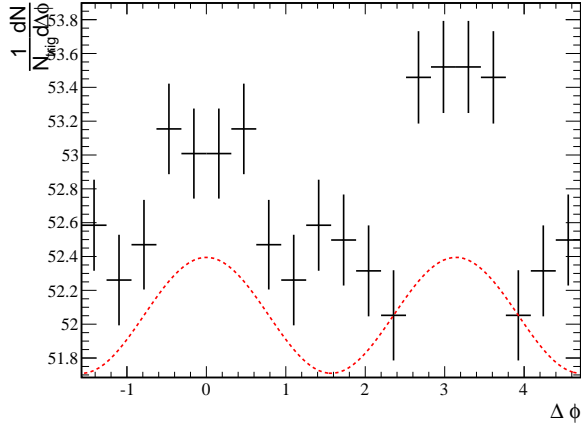
(b)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$



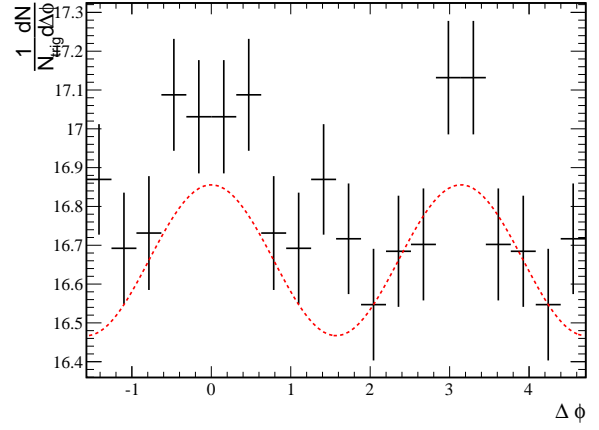
(c)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$

Figure 4.7: Raw NPE-h Correlations for 20-40% centrality events. Trigger  $p_T$  is  $4.0 \text{ GeV}/c \leq p_{T,trig} \leq 6.0 \text{ GeV}/c$

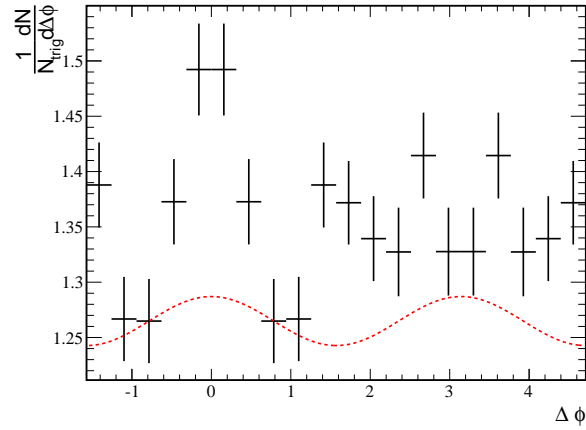




(a)  $.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$

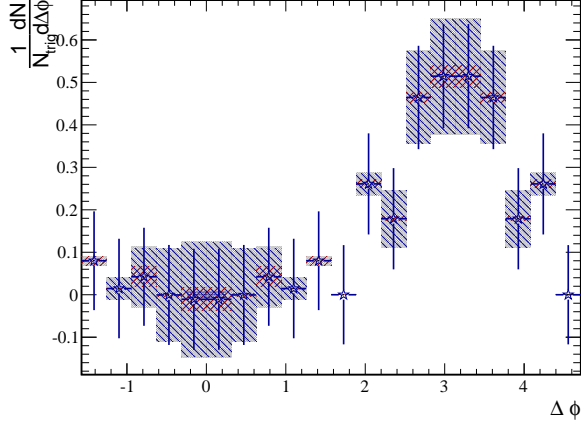


(b)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$

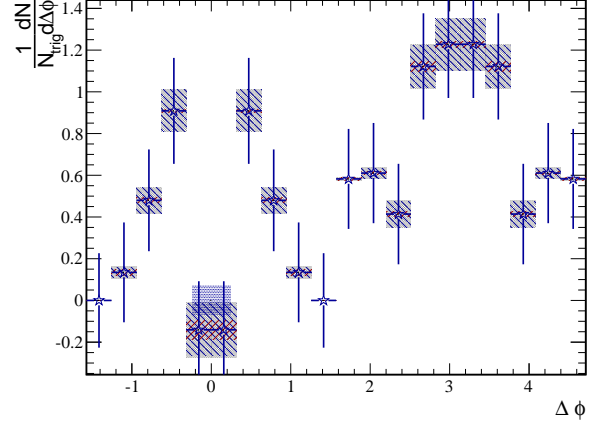


(c)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$

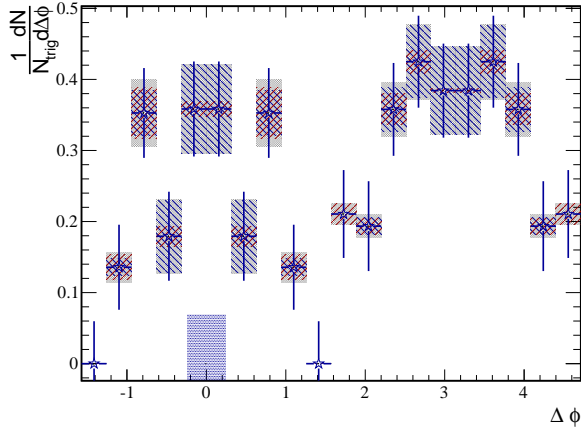
Figure 4.8: Raw NPE-h Correlations for 0-10% centrality events. Trigger  $p_T$  is  $4.0 \text{ GeV}/c \leq p_{T,trig} \leq 6.0 \text{ GeV}/c$



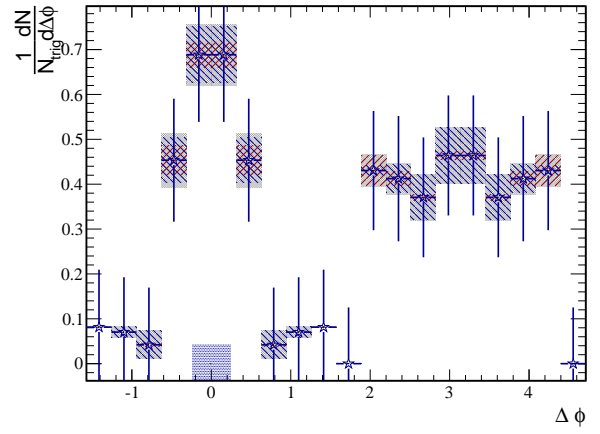
(a)  $.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$



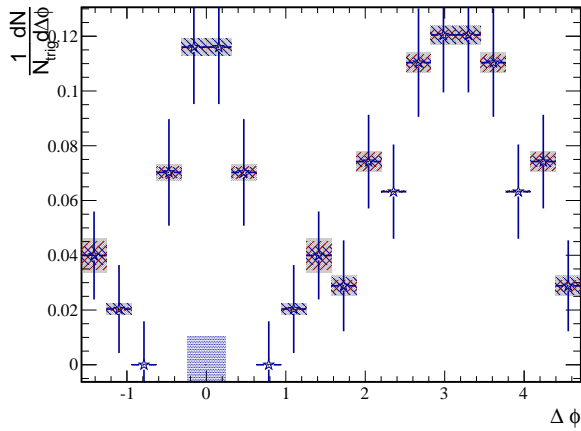
(b)  $.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$



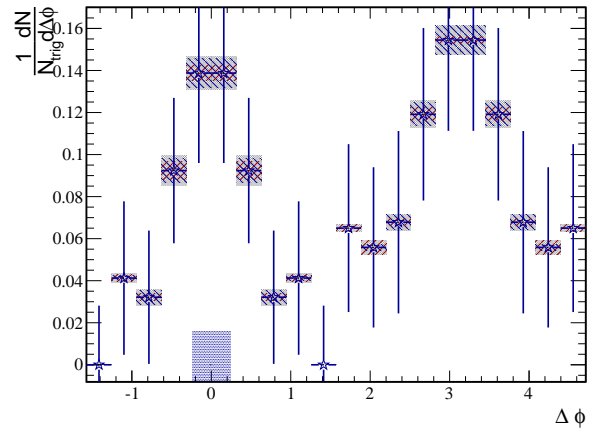
(c)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$



(d)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$

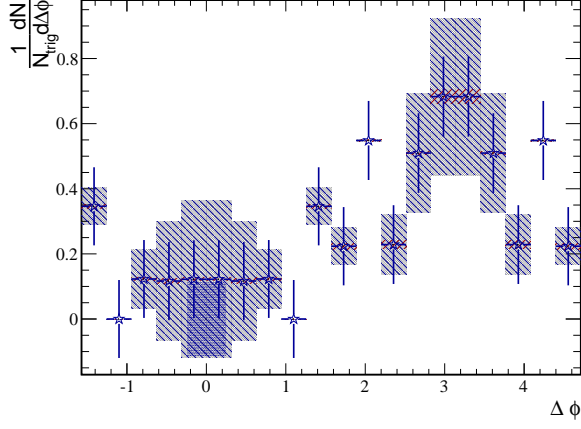


(e)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$

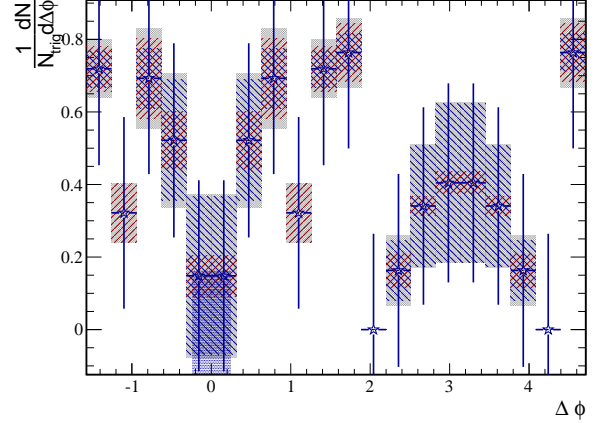


(f)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$

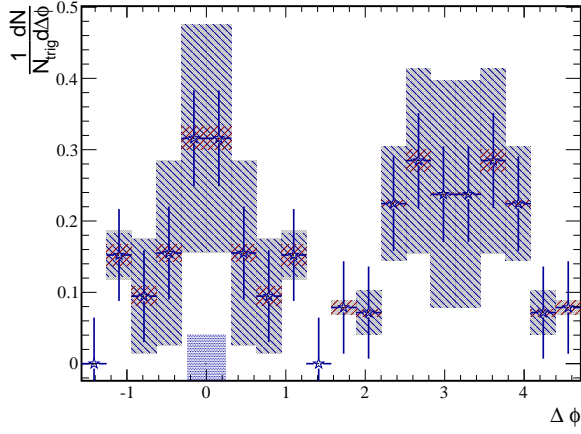
Figure 4.9: Background subtracted NPE-h correlations for 40-60% centrality events. Trigger  $p_T$  is  $4.0 \text{ GeV}/c \leq p_{T, \text{trig}} \leq 6.0 \text{ GeV}/c$



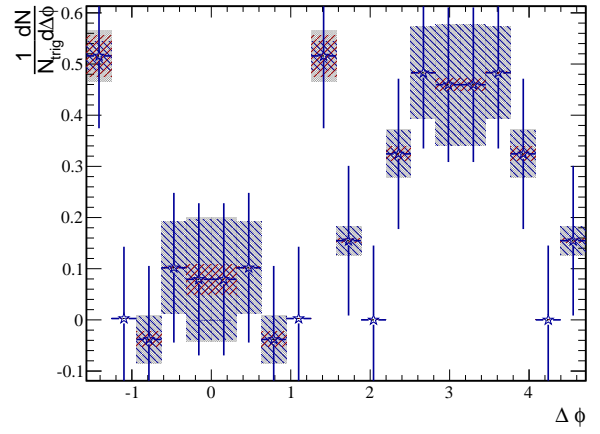
(a)  $.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$



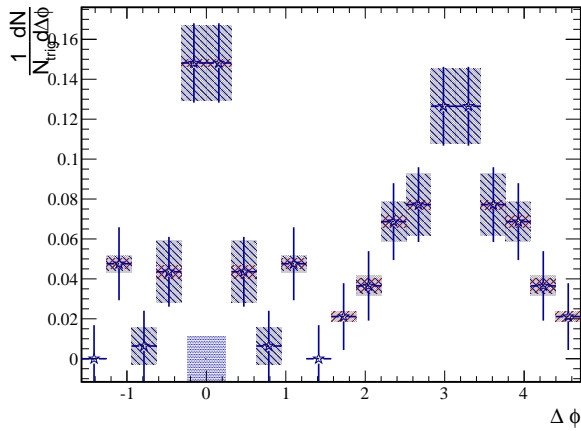
(b)  $.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$



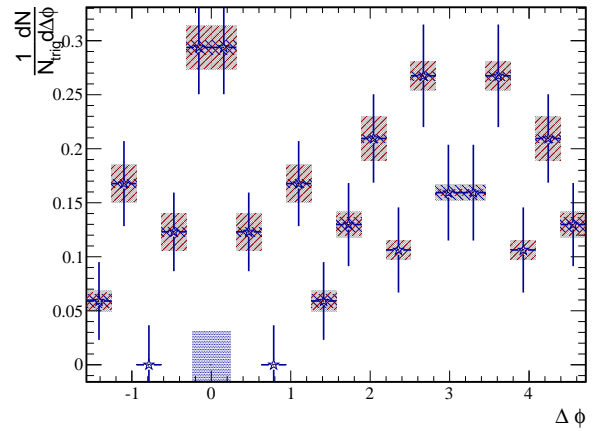
(c)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$



(d)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$

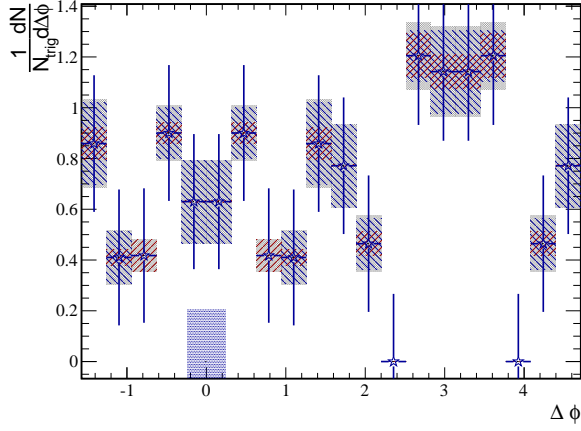


(e)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$

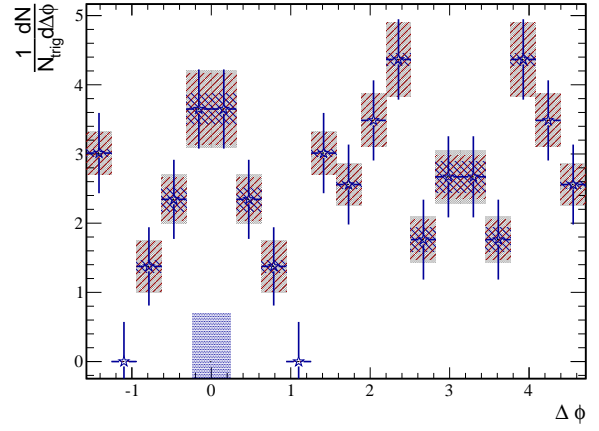


(f)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$

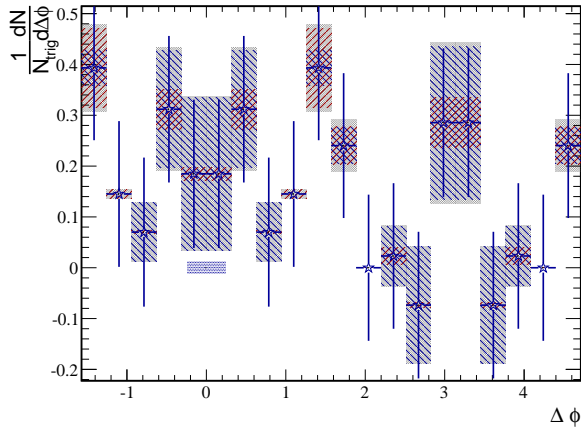
Figure 4.10: Background subtracted NPE-h correlations for 20-40% centrality events. Trigger  $p_T$  is  $4.0 \text{ GeV}/c \leq p_{T, \text{trig}} \leq 6.0 \text{ GeV}/c$



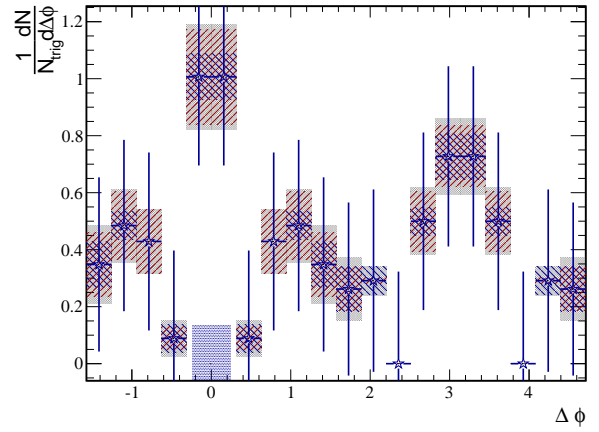
(a)  $.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$



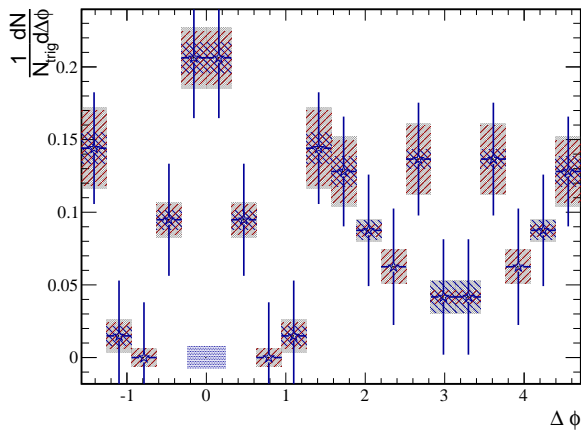
(b)  $.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$



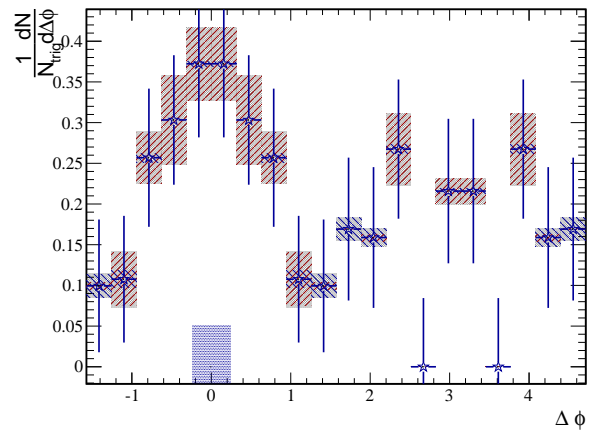
(c)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$



(d)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$



(e)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$



(f)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$

Figure 4.11: Background subtracted NPE-h correlations for 0-10% centrality events. Trigger  $p_T$  is  $4.0 \text{ GeV}/c \leq p_{T, \text{trig}} \leq 6.0 \text{ GeV}/c$

Associated $p_T$	$\Delta\phi$ region	Yield $\frac{1}{N_{trigger\Delta\phi}}$	Stat. Error	Sys. Error
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Near-side	0.0143632	0.0737196	0.0599507
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Head	0.363855	0.0659528	0.0589941
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Shoulder	0.107132	0.063884	0.00917141
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Near-side	0.322385	0.0396921	0.030521
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Head	0.366602	0.0355859	0.0283117
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Shoulder	0.126959	0.0335234	0.00708298
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Near-side	0.0649261	0.0114213	0.00148537
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Head	0.0923857	0.0105544	0.00160527
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Shoulder	0.0449183	0.00902871	0.00252461

Table 4.2: Yields and Errors from NPE-h correlations in 40-60% central Au+Au collisions with trigger  $4.0\text{GeV}/c \leq p_t \leq 6.0\text{ GeV}/c$ .

The photonic electron reconstruction efficiency ( $\epsilon_\gamma$ ) is determined from embedding simulations but the extracted values tend to vary from analysis to analysis. To be safe we allow the efficiency to vary by 10% and then take the difference in distributions as the error. This is done point by point. The combined NPE  $v_2$  and  $\epsilon_\gamma$  systematics are represented on the plots by the shaded region around the points. The NPE  $v_2$  error tends to be the dominant source of uncertainty and the systematics are much larger for lower associated hadron  $p_T$ .

The systematic uncertainty from background normalization is calculated by performing the ZYAM procedure on the two lowest points in the correlation. The difference in normalization factors is taken as the uncertainty and we display this as a shaded bar at 0 yield and 0 angle. This uncertainty would move all points together in a uniform manner.

The subtracted distributions give some insight into the interactions of heavy quarks with the QGP medium. For all trigger  $p_T$  shown the direction of trigger electron is well correlated to the direction of the parent B or D meson. Thus we look to the near and away side yields for clues to the nature of the initially created heavy quarks interactions. We calculate the background subtracted yield for the near side region  $\Delta\phi \leq .942$ , in the away side “head”

Associated $p_T$	$\Delta\phi$ region	Yield $\frac{1}{N_{trigger\Delta\phi}}$	Stat. Error	Sys. Error
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Near-side	0.43422	0.152473	0.0568138
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Head	0.868317	0.136648	0.0549569
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Shoulder	0.37479	0.128162	0.00797441
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Near-side	0.39401	0.0845325	0.0303613
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Head	0.391791	0.0738275	0.0275223
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Shoulder	0.160784	0.0700681	0.0111099
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Near-side	0.0956762	0.0230099	0.00354069
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Head	0.107273	0.0231531	0.00321996
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Shoulder	0.0379724	0.0194678	0.00122931

Table 4.3: Yields and Errors from NPE-h correlations in 40-60% central Au+Au collisions with trigger  $6.0\text{GeV}/c \leq p_t \leq 9.0$  GeV/c.

Associated $p_T$	$\Delta\phi$ region	Yield $\frac{1}{N_{trigger\Delta\phi}}$	Stat. Error	Sys. Error
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Near-side	0.113593	0.0752799	0.0993901
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Head	0.446483	0.0664356	0.0996666
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Shoulder	0.351208	0.0655682	0.0254741
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Near-side	0.225576	0.0410495	0.0702893
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Head	0.234525	0.0363017	0.0692495
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Shoulder	0.0472435	0.035183	0.0101302
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Near-side	0.0771784	0.0115255	0.00835489
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Head	0.0855548	0.0104771	0.00824166
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Shoulder	0.0180967	0.00924105	0.0017841

Table 4.4: Yields and Errors from NPE-h correlations in 20-40% central Au+Au collisions with trigger  $4.0\text{GeV}/c \leq p_t \leq 6.0$  GeV/c.

Associated $p_T$	$\Delta\phi$ region	Yield $\frac{1}{N_{trigger\Delta\phi}}$	Stat. Error	Sys. Error
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Near-side	0.529239	0.16639	0.104476
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Head	0.285343	0.147377	0.0922544
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Shoulder	0.465791	0.144077	0.0391084
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Near-side	0.0457684	0.0909543	0.0497525
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Head	0.398024	0.0809105	0.0490142
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Shoulder	0.21068	0.0785307	0.0177771
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Near-side	0.183656	0.0245176	0.0100624
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Head	0.1675	0.0238689	0.00546355
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Shoulder	0.125145	0.0209576	0.00807931

Table 4.5: Yields and Errors from NPE-h correlations in 20-40% central Au+Au collisions with trigger  $6.0\text{GeV}/c \leq p_t \leq 9.0$  GeV/c.

Associated $p_T$	$\Delta\phi$ region	Yield $\frac{1}{N_{trigger\Delta\phi}}$	Stat. Error	Sys. Error
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Near-side	0.74085	0.167485	0.0727868
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Head	0.737388	0.147269	0.0693534
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Shoulder	0.658026	0.146362	0.0826822
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Near-side	0.223651	0.0911303	0.0636431
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Head	0.0738618	0.078665	0.0643826
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Shoulder	0.199047	0.0777526	0.0314492
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Near-side	0.0992778	0.0245557	0.0086265
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Head	0.0756338	0.0215144	0.00918282
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Shoulder	0.112994	0.0207828	0.0118356

Table 4.6: Yields and Errors from NPE-h correlations in 0-10% central Au+Au collisions with trigger  $4.0\text{GeV}/c \leq p_t \leq 6.0$  GeV/c.

Associated $p_T$	$\Delta\phi$ region	Yield $\frac{1}{N_{trigger\Delta\phi}}$	Stat. Error	Sys. Error
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Near-side	2.31516	0.358503	0.238676
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Head	2.76404	0.316466	0.233436
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Shoulder	2.84518	0.315039	0.180387
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Near-side	0.631058	0.193553	0.0816061
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Head	0.385498	0.172518	0.0558037
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Shoulder	0.283197	0.168621	0.0576901
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Near-side	0.326725	0.052348	0.0266922
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Head	0.151844	0.0469381	0.0147477
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Shoulder	0.134278	0.0464204	0.00730969

Table 4.7: Yields and Errors from NPE-h correlations in 0-10% central Au+Au collisions with trigger  $6.0\text{GeV}/c \leq p_t \leq 9.0\text{ GeV}/c$ .

$\Delta\phi \geq 2.2$ , and in the away side shoulder  $1.25 \leq \Delta\phi \leq 2.2$ . For the separated shoulder and head regions we are looking for signs of away side broadening in the correlation. We might expect to find that the ratio of the shoulder to head yields is larger in more central collisions as a result of jets being diverted or smeared out as a result of interactions with the QGP. We can also look for evidence of medium responses to a heavy quark traversing it. The yields from these plots are listed in Table AAA. We will summarize these results once we have the correlations from p+p as well.

## 4.5 Correlations in p+p

With correlations from Au+Au collisions we can study the effects on observed particles resulting from heavy quark interactions with the medium. By looking across centralities we can select different fireball sizes and durations to see how the presence of QGP affects the formation of dijets. Now we can also look at p+p collisions also at  $\sqrt{s_{NN}} = 200\text{ GeV}$  to see the correlation without any QGP and use this as a baseline for comparison with our Au+Au results.



NPE-h correlations have also been used to study the charm to bottom produced in these collisions. This is done by fitting the observed correlations to Pythia simulations of NPE-h correlations from charm and bottom decays. Those resulting from bottom will have a broader distribution because of the higher mass of the  $B$  mesons compared to  $D$ . We will show a calculation of this as a consistency check with previous NPE-h analyses.

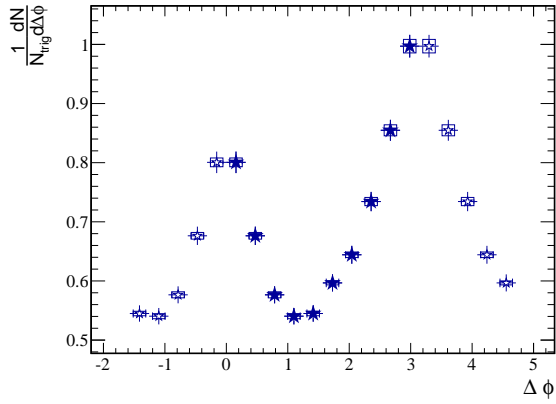
#### 4.5.1 Data and Correlations

The dataset for the p+p correlations is the BHT triggered events in STAR run 12 p+p 200 GeV. The procedure for identifying non-photonic electrons and constructing the NPE-h correlation is nearly identical to Au+Au. We still need to perform the acceptance corrections as in Au+Au, however because of the lower multiplicities in p+p collisions it is difficult to get enough statistics for mixed event correlations so we will rely only on the single particle  $\phi$  weighting. In run 12 the TPC performed much better and has a more uniform acceptance than in run 11 so practically these corrections are far less important.

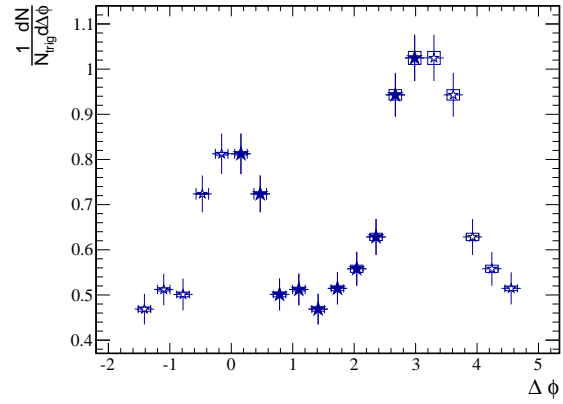
In p+p correlations there is no need to perform the background subtraction as in Equation 4.1 since there is no elliptic flow in p+p collisions. So we no longer need to consider raw correlations, we can just take the results from Equation 4.2 and use those as our correlations. Since there is no NPE-h  $v_2$  and no need to normalize to some background distribution we no longer have to consider 2 of the 3 sources of systematic uncertainty present in Au+Au. We only need to account for uncertainty in  $\epsilon_\gamma$ , the photonic electron reconstruction efficiency. We do this as in Au+Au collisions, allowing the efficiency to vary by 10%. Tables 4.8–4.9 summarize the yields with errors obtained from p+p collisions.

#### 4.5.2 Charm to Bottom Ratios

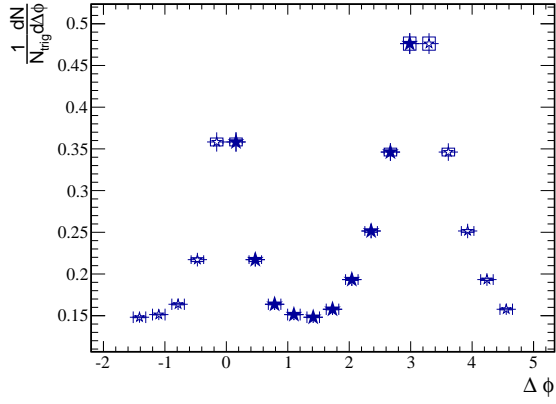
We can use the p+p NPE-h correlations to investigate the relative contributions of charm and bottom to non-photonic electrons by fitting the observed correlations with those from  $B$  and  $D$  to find the ratio as a function of electron  $p_T$ . Several experiments have performed this measurement, making this a reasonable check that our method for constructing NPE-h



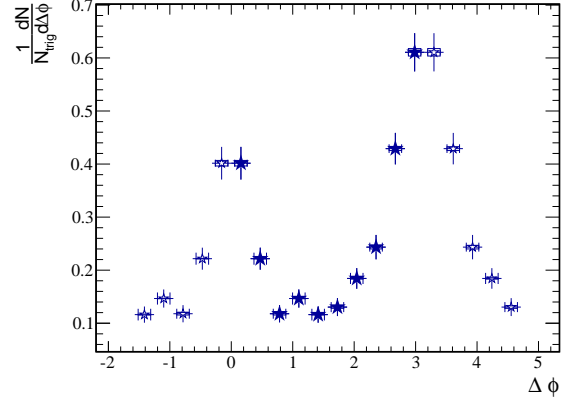
(a)  $.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$



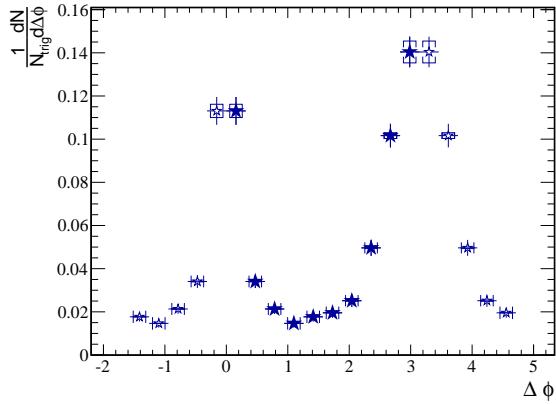
(b)  $.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$



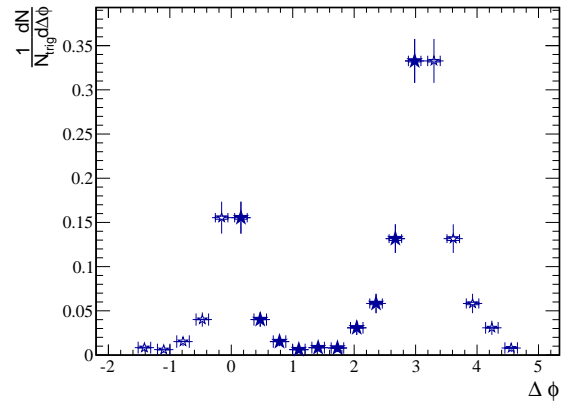
(c)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$



(d)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$



(e)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$



(f)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$

Figure 4.12: NPE-h correlations for p+p collisions at 200 GeV left column shows triggers with  $4.0 \text{ GeV}/c \leq p_T \leq 6.0 \text{ GeV}/c$  and right column is  $6.0 \text{ GeV}/c \leq p_T \leq 9.0 \text{ GeV}/c$ .

Associated $p_T$	$\Delta\phi$ region	Yield $\frac{1}{N_{trigger}\Delta\phi}$	Stat. Error	Sys. Error
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Near-side	0.814888	0.00977926	0.00360017
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Head	0.812439	0.00965688	0.00511522
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Shoulder	0.561056	0.00786714	0.00216749
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Near-side	0.279777	0.00536135	0.00167489
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Head	0.337404	0.00580794	0.00293765
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Shoulder	0.156817	0.00379766	0.000439399
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Near-side	0.057533	0.00242196	0.00096921
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Head	0.0916335	0.0030426	0.00164648
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Shoulder	0.019603	0.00132994	8.75715e-05

Table 4.8: Yields and Errors from NPE-h correlations in p+p collisions with trigger 4.0GeV/c  $\leq p_t \leq 6.0$  GeV/c.

Associated $p_T$	$\Delta\phi$ region	Yield $\frac{1}{N_{trigger}\Delta\phi}$	Stat. Error	Sys. Error
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Near-side	0.801004	0.0245826	0.00217934
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Head	0.815639	0.025429	0.00632914
$p_{T,asso} \in (.5, 1.0)$ GeV/c	Shoulder	0.48424	0.0194036	0.00332109
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Near-side	0.278887	0.0138082	0.00181987
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Head	0.403106	0.0163408	0.00270691
$p_{T,asso} \in (1.0, 2.0)$ GeV/c	Shoulder	0.135421	0.00940179	0.000890293
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Near-side	0.0681146	0.00652803	0.000581799
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Head	0.164206	0.00992462	0.000868219
$p_{T,asso} \in (2.0, 4.0)$ GeV/c	Shoulder	0.0147791	0.00321696	0.000280081

Table 4.9: Yields and Errors from NPE-h correlations in p+p collisions with trigger 6.0GeV/c  $\leq p_t \leq 9.0$  GeV/c.

correlations is working as intended.

The simulations are done with Pythia 8.2 with the standard STAR heavy flavor tune. To get reasonable samples across all electron  $p_T$  and to avoid the low  $p_T$  divergence in heavy flavor processes in Pythia we generate the correlations in several bins in **ptHat** and then piece them together according to a weighting, this closely follows the Pythia example `main08.cc`. For  $\text{ptHat} \leq 3.0$  GeV/c we use the “minbias” process `SoftQCD:nonDiffractive = on` for the bins above this we use the hard QCD processes `HardQCD:all = on`. Then to patch the different bins together we scale each bin by the generated cross section, the raw and scaled **ptHat** spectra can be seen in Figure 4.13.

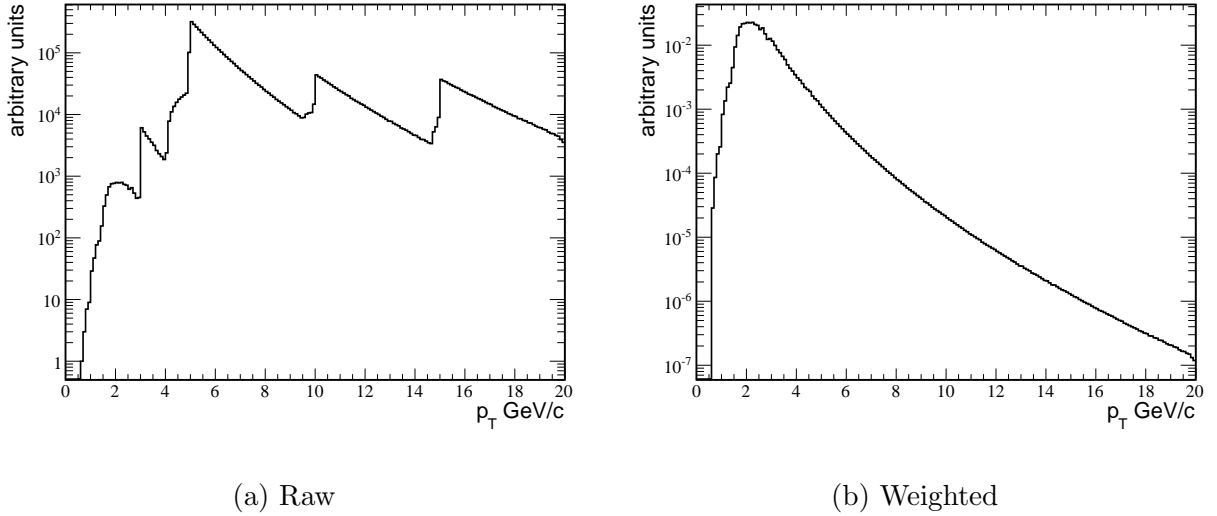


Figure 4.13: The raw and weighted **ptHat** spectra from Pythia.

Then we construct the electron-hadron correlations from the Pythia simulations in two separate cases one for initial  $b$  quarks and one for initial  $c$  quarks. We check that the final state contains an electron and that the electron has a parent  $B$  or  $D$  meson. To increase statistics, if there is no final state electron we pick on of the heavy mesons, undo and then redo the decay until we get an electron effectively setting the branching ratio for semileptonic decays to 100%. Then we apply acceptance cuts that closely match the STAR acceptance:  $\eta_e \in (-.7, .7)$ ,  $p_{T,e} > 2.0$  GeV/c,  $\eta_h \in (1.0, 1.0)$ , and  $p_{T,h} > 0.2$  GeV/c. This gives us the electron-hadron correlation that we use in the fit.

For the fit we compare the correlations for  $p_{T,h} > .2 \text{ GeV}/c$  and vary the  $p_T$  of the trigger particle. We fit the correlation with the function:

$$\frac{dN_{NPE-h}}{d\Delta\phi} = r_B f_B(\Delta\phi) + (1 - r_B) f_D(\Delta\phi) \quad (4.3)$$

Where  $f_B$  and  $f_D$  are the correlations for bottom and charm electron-hadron correlations from Pythia, and  $r_B = \frac{e_B}{e_B + e_D}$ . The fit is done in a range around the near side peak  $\Delta\phi < 1.5$  due to difficulties in Pythia accurately recreating away side behavior. Figure 4.14 shows an example fit, plus the correlations from Pythia.

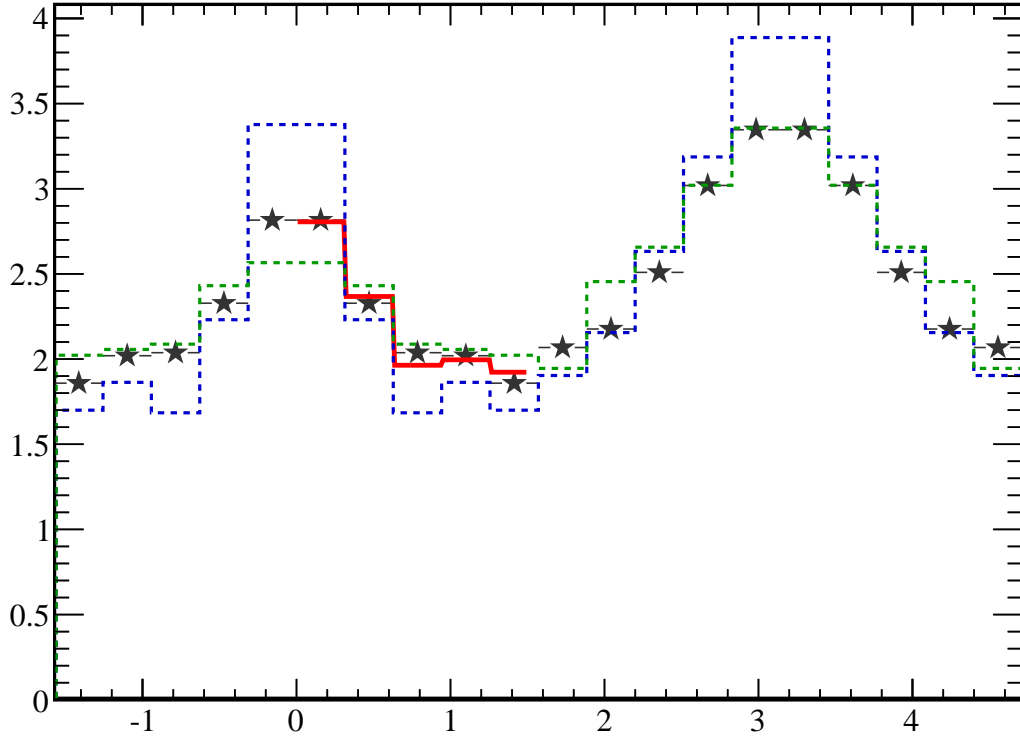


Figure 4.14: NPE-h correlation with  $5.0 \text{ GeV}/c < p_{T,e} < 6.0 \text{ GeV}/c$  and  $p_{T,h} > 0.2 \text{ GeV}/c$ . Pythia distributions are  $f_D(\Delta\phi)$  (blue),  $f_B(\Delta\phi)$  (green), and the distribution with best fit value of  $r_B$  (red).

Figure 4.15 shows the results for obtaining  $r_B$  from fits of the p+p correlation plus

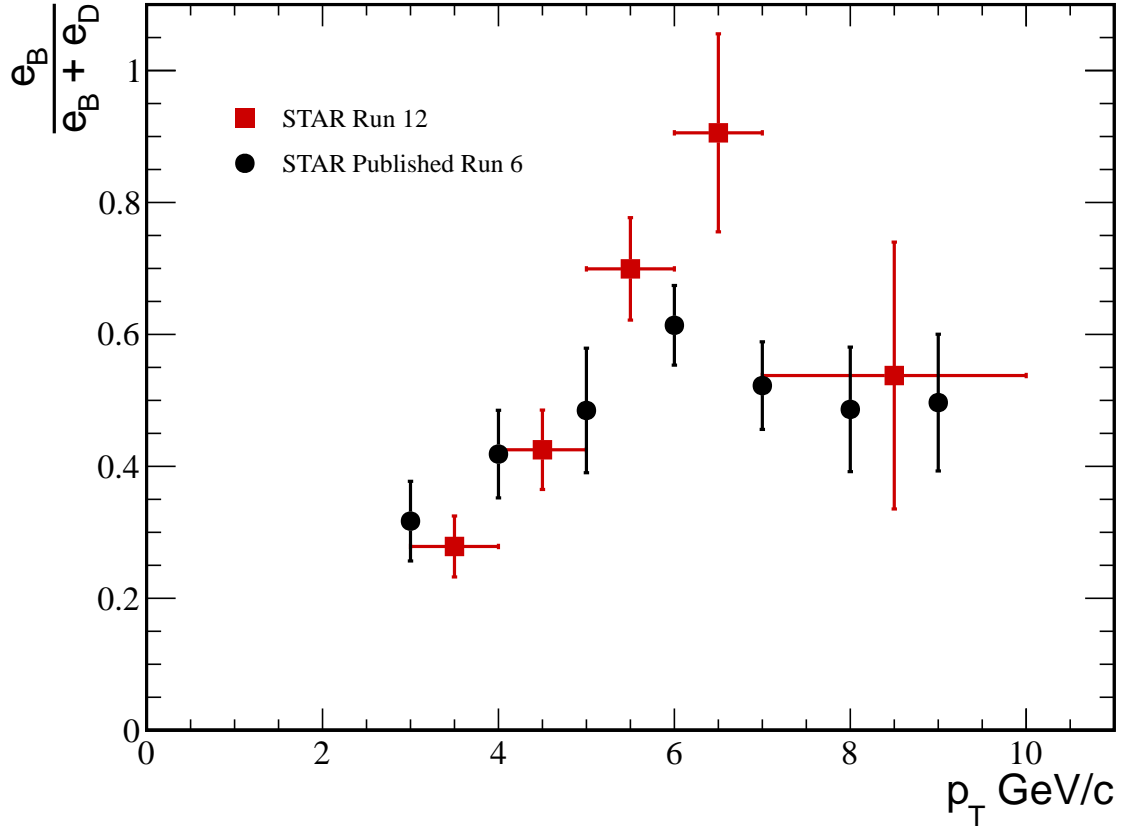


Figure 4.15: Measured value of  $r_B$  as a function of trigger  $p_T$ . Red points are for the current analysis and the black are from STAR published in Ref. Only statistical errors are shown.

a comparison to previous published results. Errors are large at high trigger  $p_T$  due to the distributions from  $B$  and  $D$  becoming similar thus reducing the ability to distinguish between the contributions to the overall p+p correlation shape. Discrepancies in the mid  $p_T$  range may be due to difficulties in patching together the `ptHat` bins in the Pythia simulations and this could be fixed by only using `SoftQCD:nonDiffractive` to generate the simulated correlations, but this would be far more time consuming.

## 4.6 Comparisons of Yields

We can use the yields we measured in p+p and Au+Au collisions to look for evidence of jet modification in the medium. To do this we will examine the away side peak shape by comparing the ratio of yields in the shoulder region to the head region (as defined previously). Interactions with the QGP may cause jets to be redirected or smeared out which would manifest as broader away side correlatins in Au+Au collisions. We will also look at  $I_{AA}$ , the ratio of the integrated yield in Au+Au to p+p. Suppressions of yields in Au+Au could indicate jet suppression in the medium while increased yields may point to medium responses to the jet.

An important thing to note when comparing the yields from p+p and Au+Au is that we subtracted off a background correlation from Au+Au but performed no such ZYAM procedure for p+p. There is no standard way of accounting for this but we calculate a flat underlying event for p+p (essentially the ZYAM coefficient for background with  $v_2 = 0$ ), use this to estimate the oversubtraction of background in Au+Au and add this back to the Au+Au yields. As seen in Figure 4.12, this is not much of a concern at high associated hadron  $p_T$  but for the lower  $p_T$  bins it has a larger effect.

### 4.6.1 Away Side Shape

We define the yield  $Y$  in a region by:

$$Y(\Delta\phi_1, \Delta\phi_2) = \int_{\Delta\phi_1}^{\Delta\phi_2} \frac{dN_{NPE-h}}{d\Delta\phi} d\Delta\phi \quad (4.4)$$

We define the near side yield as  $Y(0, 2\pi/5)$  the head region as  $Y(7\pi/10, \pi)$ , and the shoulder region as  $Y(2\pi/5, 7\pi/10)$ . To see evidence of jet broadening we compare the yields in the shoulder and head regions. In particular we look at the ratio of the yields  $Y(\text{shoulder})/Y(\text{head})$ . We can see from the p+p data that this ratio tends to be below 1 as the away side peaks are narrow and contain most of the yield in the region immediately around  $\pi$ . Figure 4.16 shows the the ratios for p+p data as well as Au+Au collisions with 0-10%, 10-40%, and 40-60% centralities. We see that for the most central bins the ratio is larger indicating wider correlations, but the errors on these yields are large. For the other bins, including the p+p data, the ratios seem to follow a similar trend with increasingly narrow correlations at higher hadron  $p_T$ .

#### 4.6.2 $I_{AA}$

We can also compare the yields in Au+Au collisions to p+p collisions directly to look for jet suppression in heavy flavor correlations. To do this we look at the ration of yields  $I_{AA}$  defined by:

$$I_{AA} = \frac{Y_{AuAu}(\Delta\phi_1, \Delta\phi_2)}{Y_{pp}(\Delta\phi_1, \Delta\phi_2)} \quad (4.5)$$

$I_{AA}$  serves for jets as a rough analogue of  $R_{AA}$  which is typically used to compare particle spectra between heavy-ion and proton collisions. For identical yields in Au+Au and p+p we would get  $I_{AA} = 1$  and we look for deviations from 1, less than 1 indicating suppressed yield in Au+Au and greater than 1 an enhanced yield.

We measure  $I_{AA}$  for the near side as well as in the away side head region. As explained earlier we estimate the level for the underlying event in p+p and then add this back to the Au+Au data to make up for potential oversubtraction of background with the ZYAM normalization. Figure 4.17 show the near side  $I_{AA}$  and Figure 4.18 the away side. The results are largely inconclusive and it appears that with the errors the results are still largely consistent with 1.



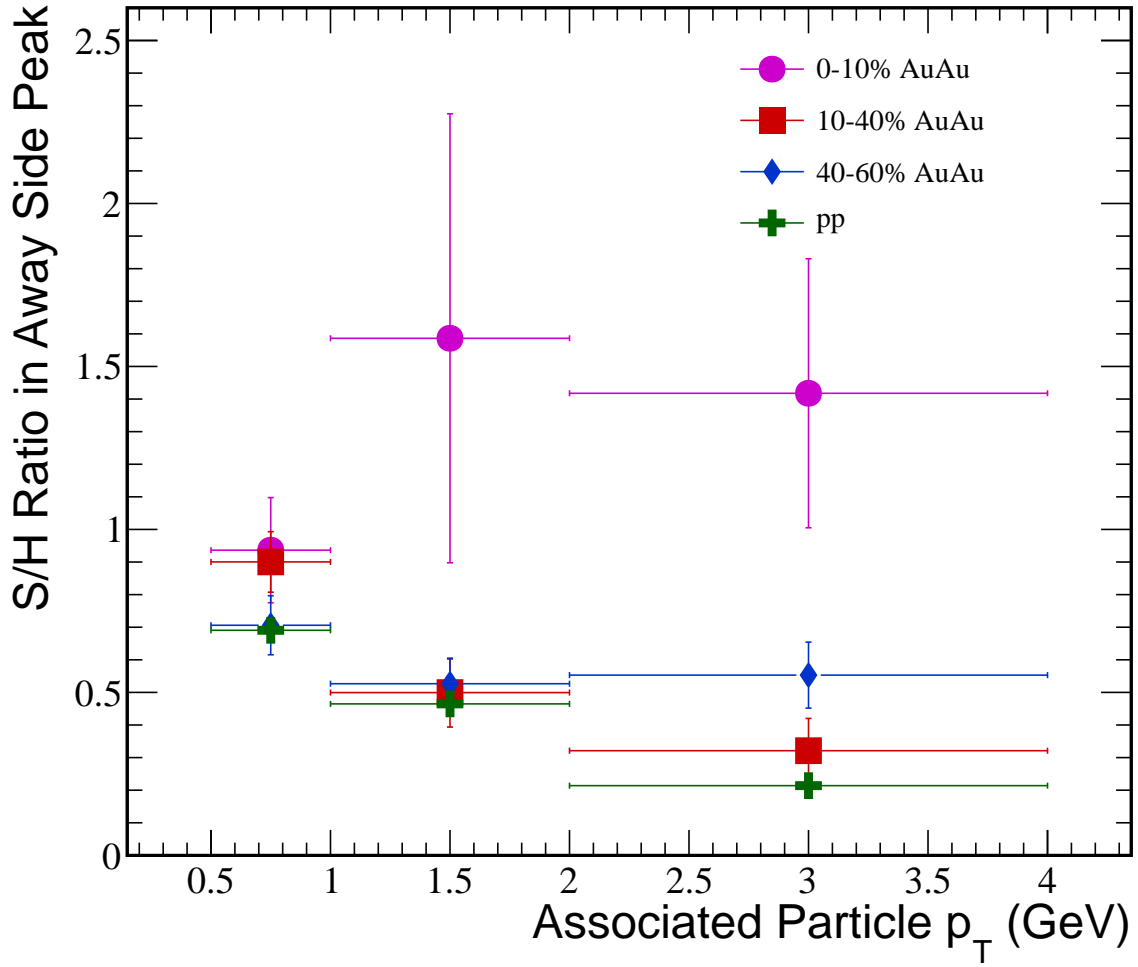


Figure 4.16: Ratio of yields in shoulder region to head region in NPE-h correlations for trigger electrons have  $4.0 \text{ GeV}/c \leq p_T \leq 6.0 \text{ GeV}/c$ . A larger ratio indicates a wider peak.

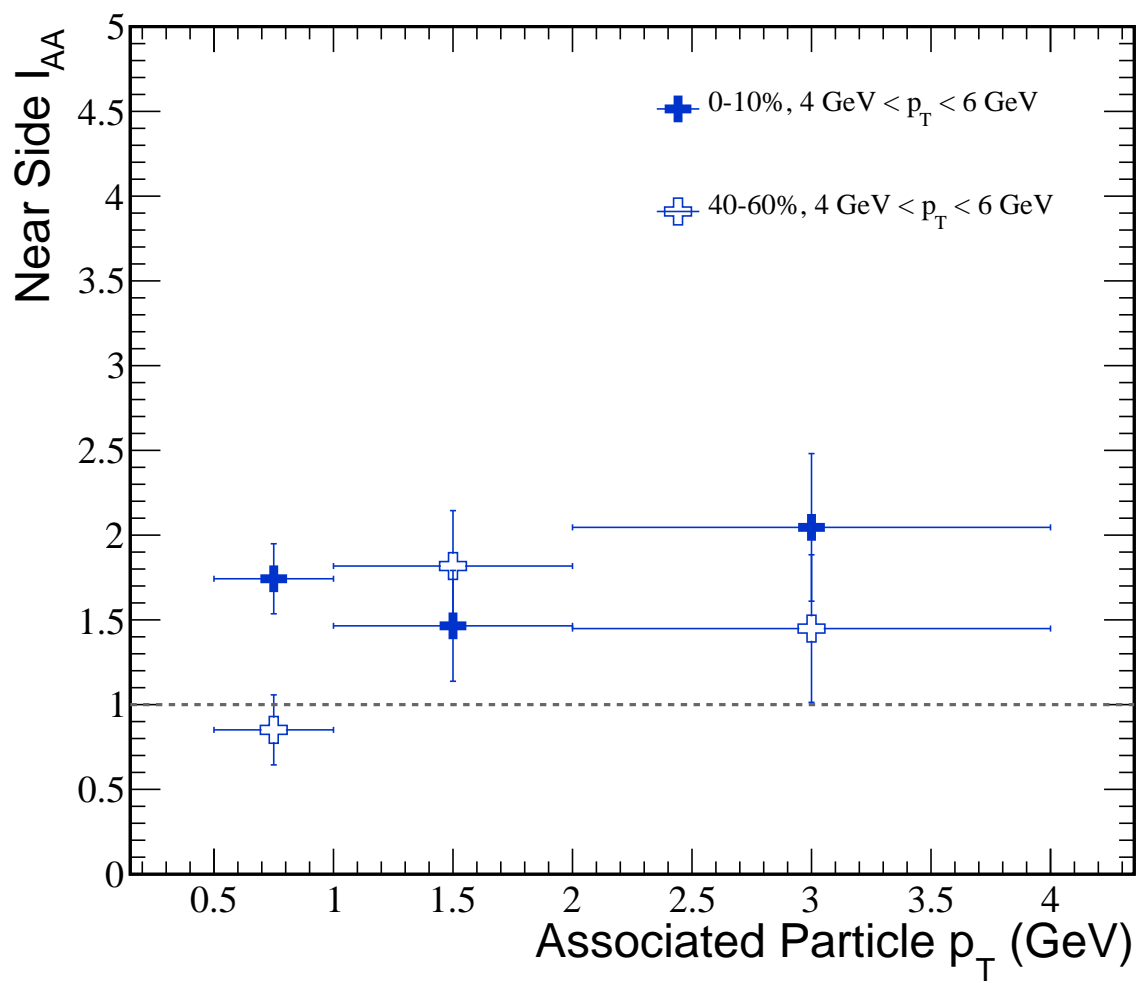


Figure 4.17: Near side

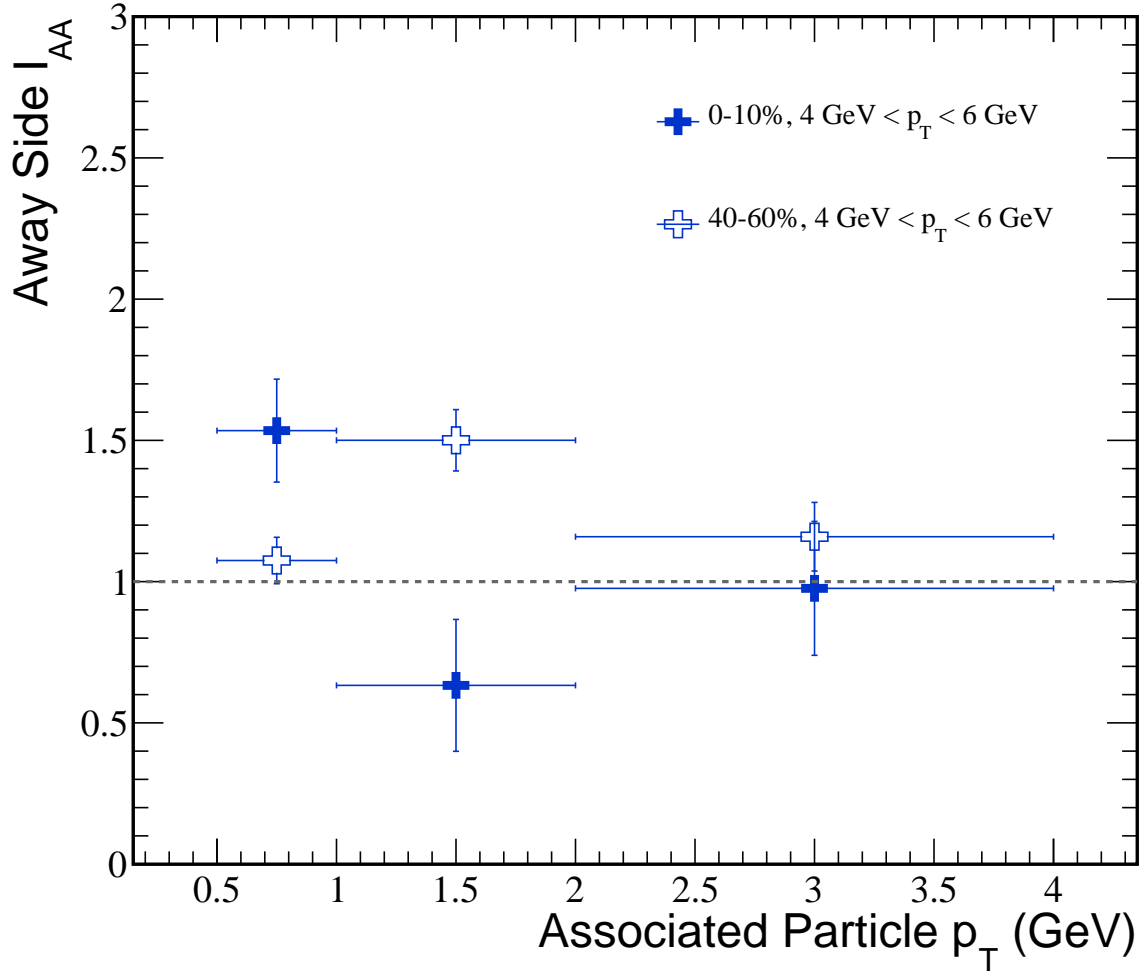


Figure 4.18: Away side

## 4.7 Event-Plane Dependent Correlations

The motivation for measurements of two particle correlations in Au+Au comes from the fact that partons are expected to strongly interact with the color charges present in QGP and that the jet like correlations will depend on the path length traversed by the parton in QGP. Previously we have looked at comparisons between central and peripheral events as well as p+p collisions as a way of investigating the dependence on the presence of QGP. Now we will try to look at a more direct dependence on path length by measuring the correlations relative to emission in or out of the event plane.

In non-central Au+Au collisions the collision region formed from the overlap of the two incident nuclei is ellipsoidal. This initial anisotropy in the medium results in elliptic flow,  $v_2$ , and in the final state we observe anisotropic emissions relative to the reaction plane, defined by the momenta of the initial beam particles (see Figure 4.19).

Elliptic flow is defined relative to the reaction plane, however there is no way to experimentally determine the reaction plane in a given event. Instead we use the azimuthal distribution of observed particles to estimate the reaction plane. We get an angle for the estimated reaction plane which we call the event plane. Due to the fact that we calculate the event plane from a finite number of particles we also have some resolution of our event plane angle.

The event plane angle gives us an estimate for the reaction plane angle, we will then look at our trigger particle's angle relative to the event plane. As seen in Figure 4.19 particles traversing the medium perpendicular to the event plane should move through a larger part of the medium. We might guess that out-of-plane correlations show larger away side suppression compared to in-plane, which has already been observed in dihadron correlations. A large portion of our high tower trigger data comes from mid-centralities (30-60% central) which is useful for this analysis since that is where we have the best event plane resolution, but due to higher hadron  $v_2$  this region also has larger systematic uncertainties which may make drawing conclusions difficult.

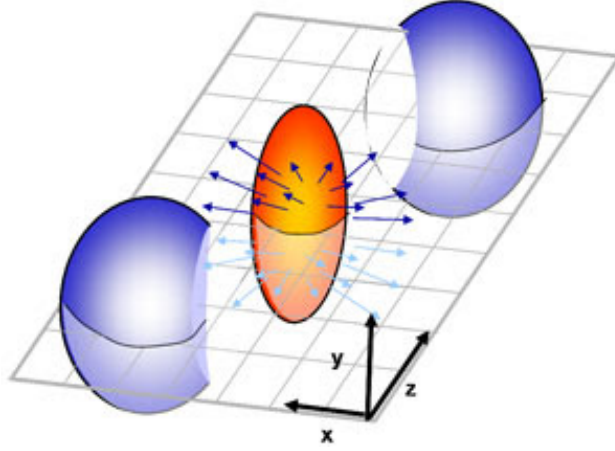


Figure 4.19: Illustration of non-central heavy ion collision and the resulting  $v_2$ . The reaction plane corresponds to the  $xz$ -plane in the diagram.

#### 4.7.1 Event Plane Reconstruction

We use the azimuthal distribution of the particles in an event to calculate the event plane,  $\Psi_{EP}$ . Event planes can be calculated for any order of harmonic in the decomposition of the particle distribution, but since we are interested in  $v_2$  and the second order event plane everything that follows is specifically the  $n = 2$  case. For a more general treatment see ref. First we apply single particle  $\phi$ -weighting to correct for the acceptance of the detector. This is the same procedure as used for the two-particle correlation.

We use the hadrons in the event with  $0.2 \text{ GeV}/c \leq p_T \leq 2.0 \text{ GeV}/c$  in the event plane calculation. Since these events are high tower triggered events there is also a high  $p_T$  leading particle in each event. Since the presence of a jet may bias the calculation of the event plane, we should try to remove this contribution. To do this we exclude the particles in the event with  $|\Delta\eta| < .5$ , where  $\Delta\eta$  is the pseudorapidity difference between the hadron and the leading particle in the event (in events used in NPE analysis this track is usually the electron). This procedure is called the Modified Reaction Plane (MRP) method.

With our sample of hadrons we then construct a flow vector  $\mathbf{Q}$  for the event. The components of this vector are:

$$X = \sum_i w_i \cos(2\phi_i) \quad (4.6)$$

$$Y = \sum_i w_i \sin(2\phi_i) \quad (4.7)$$

where  $w_i$  is some weight given to the particle, in this analysis we use the particle's  $p_T$  as the weight. The second order event plane angle is then given by:

$$\Psi_{EP} = \frac{1}{2} \tan^{-1}\left(\frac{Y}{X}\right) \quad (4.8)$$

The true distribution of the reaction planes should be uniform across all events, however there will still be some distortion in the event plane distribution which we need to correct. To do this we use a shifting method where the harmonics of the uncorrected distribution are used to flatten it. Figure 4.20 shows the distribution of the event plane angle after applying the shifting correction. We see that the resulting distribution is flat to within 1%.

When we calculate the event plane dependent NPE-h correlations we will potentially be correlating the trigger electron with some of the particles used in the event plane calculation. We would like the calculated event plane to be independent of the particles in the correlation so we will actually calculate 5 separate event planes per event. We calculate one for all hadrons in the range  $.2 \text{ GeV}/c \leq p_T \leq 2.0 \text{ GeV}/c$  then we calculate one for each case where the ranges  $.2 \text{ GeV}/c \leq p_T \leq .5 \text{ GeV}/c$ ,  $.5 \text{ GeV}/c \leq p_T \leq 1.0 \text{ GeV}/c$ ,  $1.0 \text{ GeV}/c \leq p_T \leq 1.5 \text{ GeV}/c$ , and  $1.5 \text{ GeV}/c \leq p_T \leq 2.0 \text{ GeV}/c$  are excluded. Each bin with an excluded  $p_T$  range will have a lower resolution due to fewer particles used in the event plane calculation.

Using a finite number of particles to calculate the event plane leaves us with an event plane resolution by which we must scale up our azimuthal anisotropy measurements to get the anisotropy relative to the true reaction plane. This is done to get the correct value of  $v_2$  in flow analyses but we will also need the event plane resolution for calculating the event plane dependent  $v_2$  background for electron-hadron correlations. We calculate the resolution by subevent planes. We divide each event randomly into two equally sized sub events then independently calculate the event plane for each. The differences between the subevent

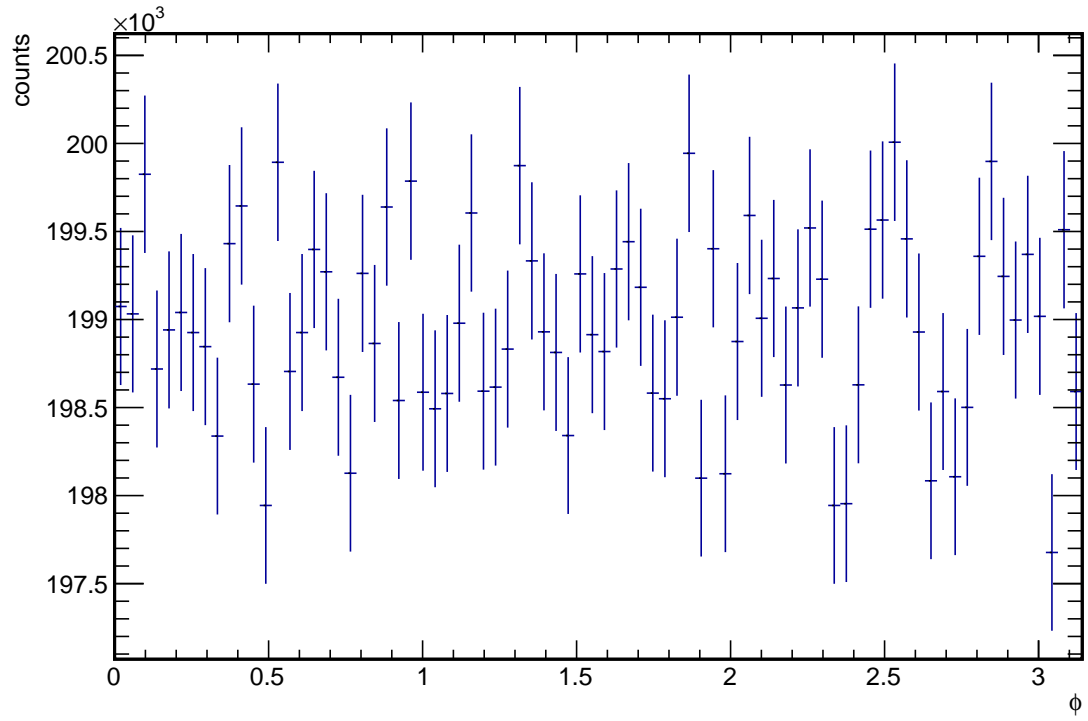


Figure 4.20: The  $\phi$  distribution of the event plane angle  $\Psi_{EP}$  after applying the shifting correction.

planes can be used to measure the event plane resolution. Figure 4.21 summarizes the resolution as a function of event centrality as well for different hadron  $p_T$  slices. Resolution is best around 30% centrality and falls off in central events due to lower azimuthal anisotropy and in peripheral events because of lower multiplicity.

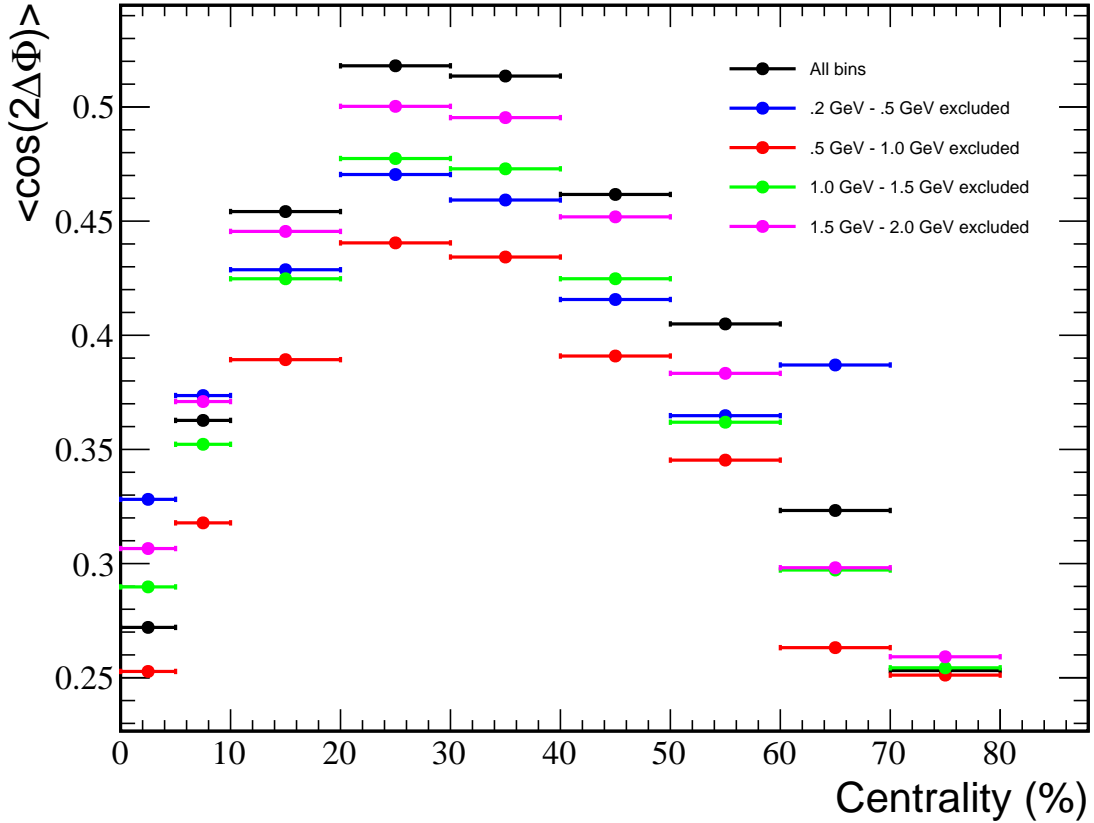


Figure 4.21: Event plane resolution as a function of centrality.

#### 4.7.2 Correlations

Now we would like to calculate the NPE-h correlation and look at the dependence based on how the trigger particle is oriented relative to the event plane. Since for trigger particles which are out of the event plane the heavy quark traversed a longer path in medium, we might wonder if this could effect the correlation.



The correlation is constructed as previously described for Au+Au collisions with one important difference. Before the background from flow assumed no dependence of the trigger particle on the reaction plane. The form of this background resulted from the dependence on the reaction plane cancelling leaving only the difference  $\Delta\phi$  between the correlated particles. Now we are choosing specific orientations of the trigger particle relative to the event plane and thus the background will be different and depend on that orientation.

We use the same functional form for the background, Equation 4.1, as when we originally calculated the NPE-h correlations in Au+Au, but now we replace the  $v_2$  of the electron with an ‘effective’  $v_2$ , denoted  $\tilde{v}_2$ , which will depend on the electrons angle relative to the event plane as well as the event plane resolution. The effective  $v_2$  can be calculated for any arbitrary slice relative to the event plane, but we will only consider the case of two equal slices: in-plane and out-of-plane. For this case  $\tilde{v}_2$  is given by:

$$0 \leq |\phi_{trig} - \Psi_{EP}| \leq \frac{\pi}{4} : \tilde{v}_2 = \frac{\pi v_2 + 2\langle\cos(2\Delta\Psi)\rangle}{\pi + 4v_2\langle\cos(2\Delta\Psi)\rangle} \quad (4.9)$$

$$\frac{\pi}{4} \leq |\phi_{trig} - \Psi_{EP}| \leq \frac{\pi}{2} : \tilde{v}_2 = \frac{\pi v_2 - 2\langle\cos(2\Delta\Psi)\rangle}{\pi - 4v_2\langle\cos(2\Delta\Psi)\rangle} \quad (4.10)$$

where Equation 4.9 is for in-plane triggers and Equation 4.10 is for out-of-plane triggers.

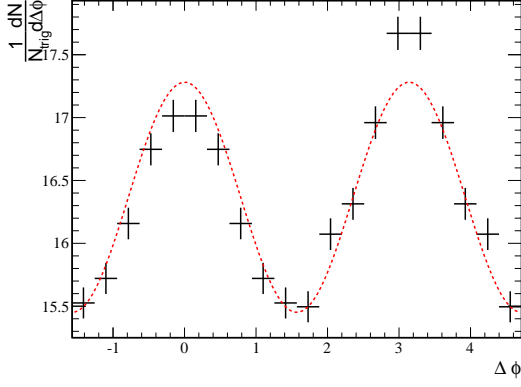
Now we construct the raw correlations for two cases: The trigger particle is in-plane or out-of-plane and then subtract off the appropriate background for that case. We use the ZYAM method to normalize the background to the distributions, calculating each case individually. In principle it is possible to calculate what the normalization for each case should be just from the normalization of the background for all triggers, but we choose not to do this. When combining bins in centrality we calculate  $\tilde{v}_2$  from the average values in each bin, weighted by the number of NPE in each centrality bin.

We construct the raw correlation for 20-60% central events. This is the region with the best event plane resolution due to the large elliptic flow and high multiplicity. It is also similar to the centrality region investigated by previous analyses of event plane dependent dihadron correlations. Figure 4.22 shows the resulting raw correlations for both cases and

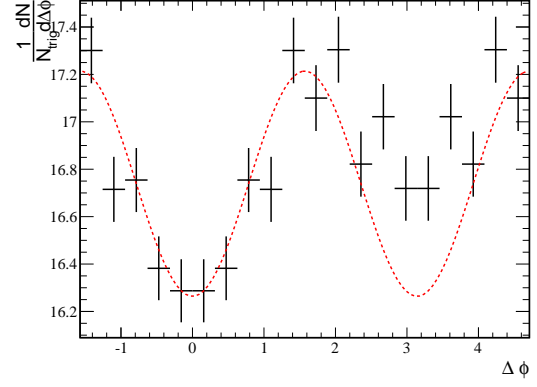
the dependence on the associated hadron  $p_T$ . We can also see how the background changes between in-plane and out-of-plane cases. For out-of-plane triggers the background appears shifted by  $\pi/2$  since the effective  $v_2$  has a negative value. This is not always the case though as for bins with large  $v_2$  but poor event plane resolution we could potentially find that  $\tilde{v}_2$  for out-of-plane triggers is still positive.

We can then subtract the backgrounds to get the correlations and yields to see if there is any significant difference between the in-plane and out-of-plane cases. The systematic errors from photonic electron reconstruction efficiency and background normalization are calculated exactly as before. For the uncertainty in NPE  $v_2$  we again let the value vary between .05 and .15 calculate  $\tilde{v}_2$  for the extreme values and then take the difference between the points when fit with different backgrounds as the uncertainty.

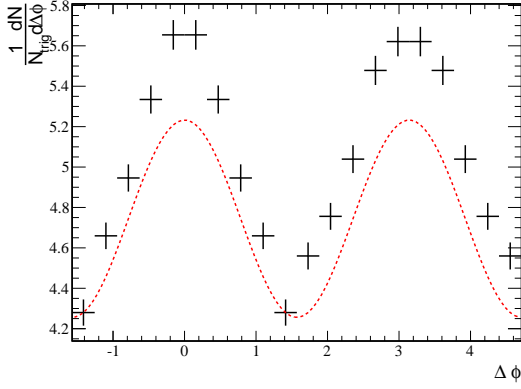
We can see from the subtracted distributions in Figure 4.23 that systematic uncertainties are quite large for lower hadron  $p_T$ . Above 2 GeV/c the uncertainties are less of a problem and this also happens to be the exact region looked at by a previous STAR analysis in dihadron collisions. In Figure 4.24 we show the comparison of in-plane and out-of-plane correlations for NPE-h as well as dihadron correlations, p+p dihadron correlations are also shown. For the dihadron correlations only the statistical errors are shown. We see that while in dihadron correlations there is evidence of greater jet suppression in the out-of-plane correlations, there does not appear to be any discernable difference between in-plane and out-of-plane in NPE-h correlations. In fact, the NPE-h correlations appear comparable to the dihadron p+p data. There are a few possible explanations for this. The NPE-h correlation contains the decay products of the heavy  $B$  or  $D$  meson which happens after the freezeout of the QGP. Also in heavy flavor correlations the connection of the kinematics of the leading particle to the initial heavy quark is more tenuous, and the biases in these correlations may be different. We won't draw any definitive conclusions from these data and instead just present them as potential avenues for further study.



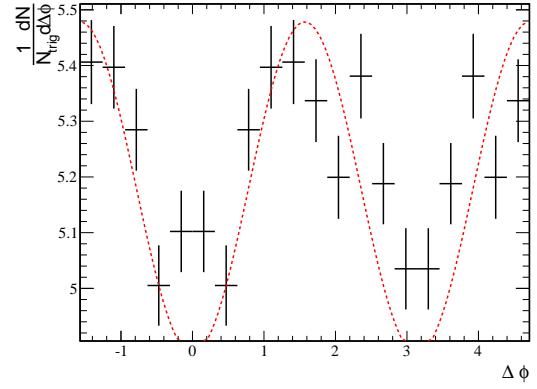
(a)  $.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$



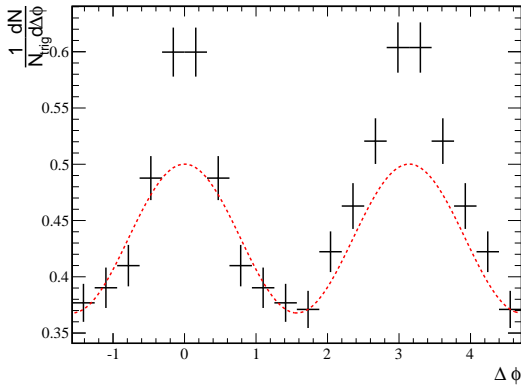
(b)  $.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$



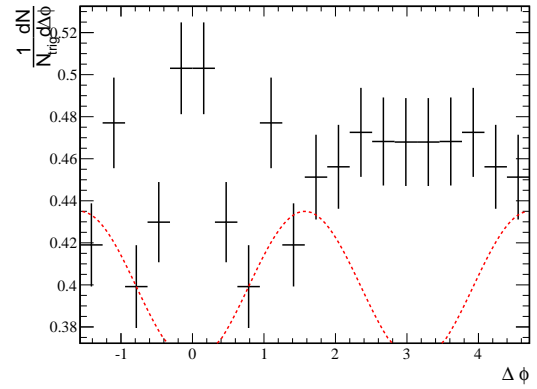
(c)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$



(d)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$

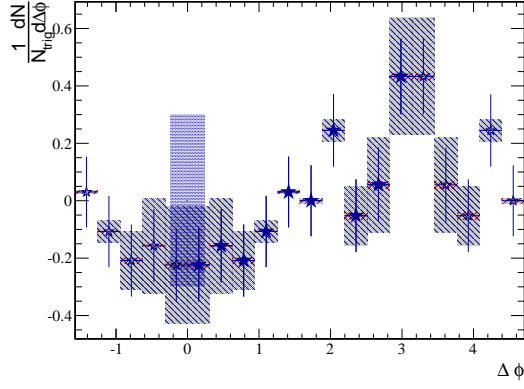


(e)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$

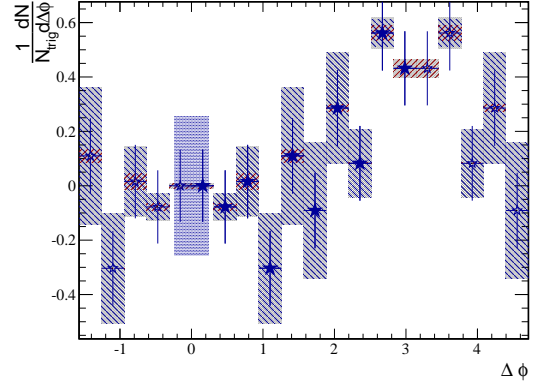


(f)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$

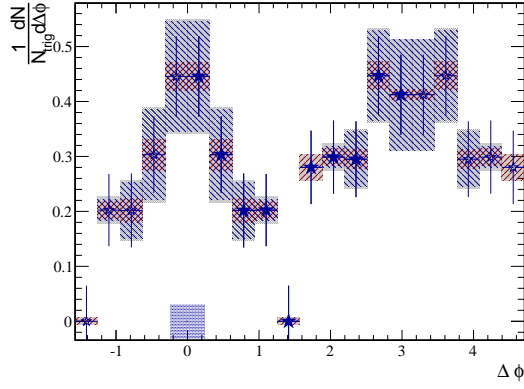
Figure 4.22: Raw NPE-h correlations for 20-60% centrality Au+Au collisions with  $4.0 \text{ GeV}/c \leq p_{T,e} \leq 6.0 \text{ GeV}/c$ . Left column shows correlations for in-plane electrons, right shows out-of-plane electrons.



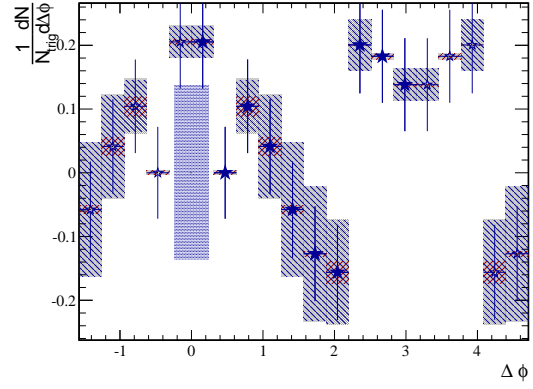
(a)  $.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$



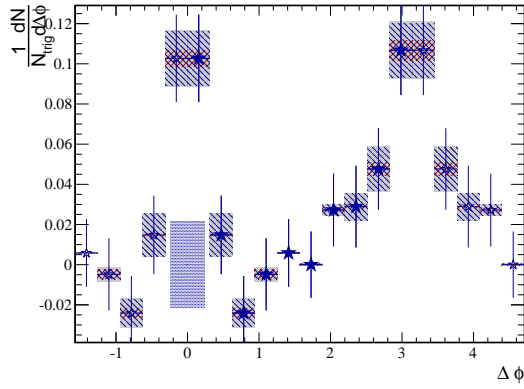
(b)  $.5 \text{ GeV}/c \leq p_{T,h} \leq 1.0 \text{ GeV}/c$



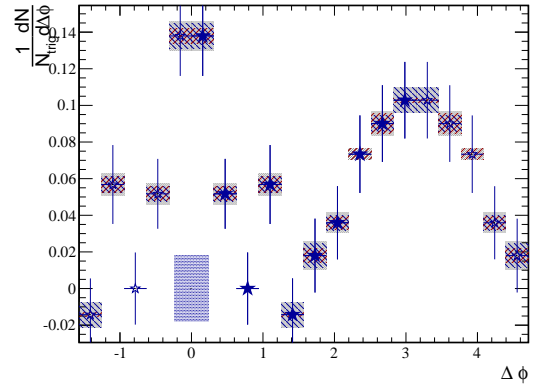
(c)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$



(d)  $1.0 \text{ GeV}/c \leq p_{T,h} \leq 2.0 \text{ GeV}/c$



(e)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$



(f)  $2.0 \text{ GeV}/c \leq p_{T,h} \leq 4.0 \text{ GeV}/c$

Figure 4.23: NPE-h correlations for 20-60% centrality Au+Au collisions with  $4.0 \text{ GeV}/c \leq p_{T,e} \leq 6.0 \text{ GeV}/c$ . Left column shows correlations for in-plane electrons, right shows out-of-plane electrons. Errors from photonic electron reconstruction efficiency and NPE  $v_2$  uncertainty are shown as shaded regions around each point, background normalization uncertainties are the shaded bars around 0.

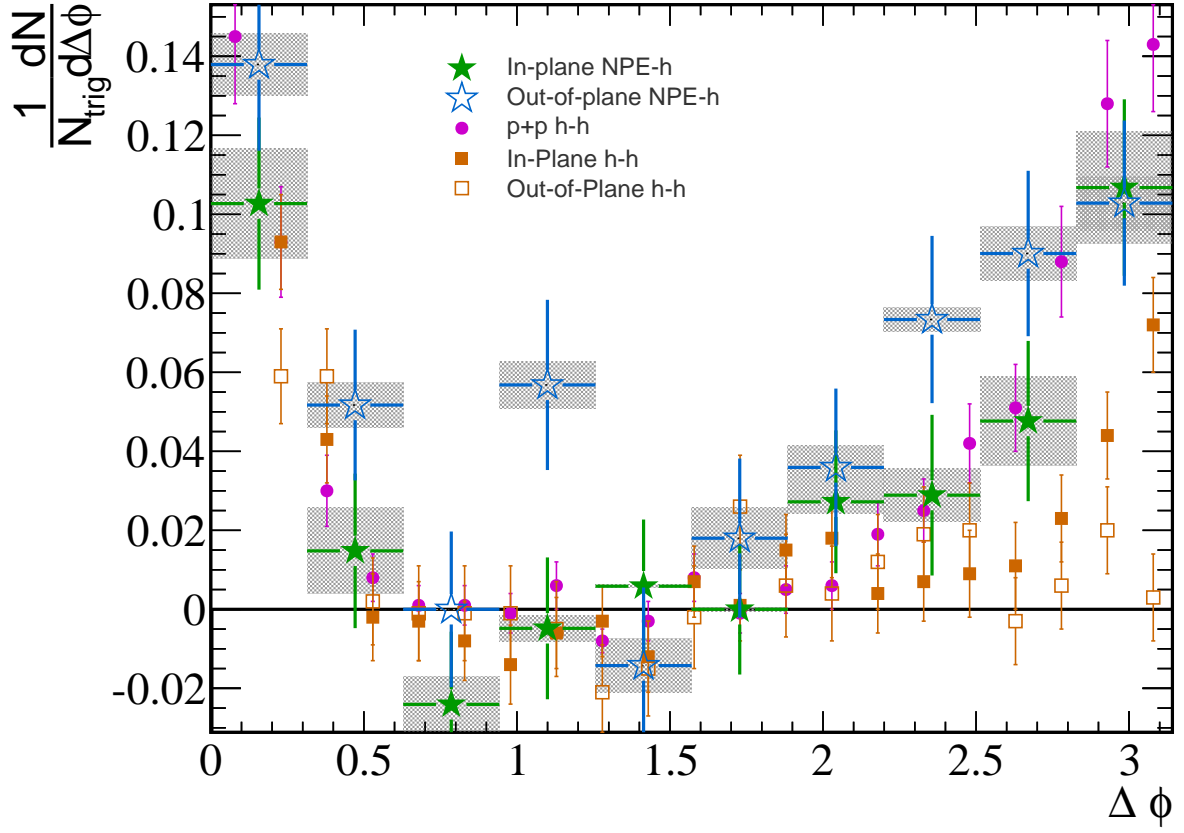


Figure 4.24: In-plane and out-of-plane correlations comparison for NPE-h and dihadron correlations.