This thesis entitled:
v_2 vs p_T and η in p+Au and ^3He+Au 200 GeV at RHIC
written by Theodore Koblesky
has been approved for the Department of Physics

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Prof. Standin

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Date ____________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

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v_2 vs p_T and η in p+Au and ^3He+Au 200 GeV at RHIC

Thesis directed by Prof. James Nagle

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Chapter 1

Analysis

1.1 Direct Observables: Building Blocks of the Measurement

TO DO: ADD A FIGURE OF THE PHENIX COORDINATE SYSTEM

1.1.1 Central Arm Tracks

This analysis use central arm tracks. A central arm track is a charged particle emitted from the heavy ion collision and detected by the PHENIX central arms. There are 2 central arms and each one covers $\eta < |0.35|$ and $\frac{\pi}{2}$ in azimuth. The drift chamber provides momentum information and the pad chambers provide track quality metrics. The RICH provides electron identification. The physics parameters of central arm tracks relevant to this analysis is the momentum vector: $p = (p_x, p_y, p_z)$. The momentum of CNT tracks is defined at the collision vertex. CNT have good momentum resolution (**TO DO: QUANTIFY THIS**). In p+Au collisions, the average number of reconstructed CNT (before cuts) is (**TO DO: QUANTIFY THIS**).

1.1.2 FVTX Clusters

This analysis uses clusters from the forward vertex detector (FVTX). The FVTX detects charged particles traveling through its silicon layers. The intersection between the charged particle and the FVTX detector is recorded in each of the 4 layers the particle goes through. Each intersection is known as a cluster. Each cluster is thought to be produced from a single charged particle. These clusters have a position resolution in x and y (or r and ϕ) (**TO DO: QUANTIFY THIS**) and have a z resolution that is the width of the FVTX layer. The FVTX acceptance is $1 < |\eta| < 3$ and spans the full azimuth.

1.1.3 BBC PMTs

This analysis uses photomultipliers (PMTS) from the beam beam counter (BBC). The BBC detects charged particles traveling through its scintillator material. The BBC acceptance is $3.1 < |\eta| < 3.9$ and spans the full azimuth. The BBC provides position information in x, y, and z and, like the FVTX, the x and y (or r and ϕ) resolution differ from the z resolution in that the z resolution is simply the width of the active area of the BBC. In addition to position information, the BBC provides charge information which is calibrated to roughly correspond to the number of charged particles detected by each PMT per event.

1.2 Event Plane Method

The event plane method is a way of measuring the long range correlations in the spray of particles from a heavy ion collision. The event plane method works by calculating a mathematical object from the data called an event plane. This event plane is defined for each flow harmonic and is sometimes denoted as Ψ_n. The definition for Ψ_n is related to the calculation of the Q-vector:

$$Q_x = \sum(w_i * \cos(n * \phi_i)) \tag{1.1}$$

$$Q_y = \sum(w_i * \sin(n * \phi_i)) \tag{1.2}$$

$$Q_w = \sum(w_i) \tag{1.3}$$

$$\Psi_n = \arctan(\frac{Q_y}{Q_x}). \tag{1.4}$$

The Q_w component of the Q-vector is only used during the event plane calibration. Once the event plane has been calculated, the flow harmonics (v_n) are calculated as

$$v_n = \frac{<< \cos(n(\phi - \Psi_n)) >>}{Resolution(\Psi_n)}, \tag{1.5}$$

where $<<>>$ means averaged over each event and each ϕ value and the resolution of Ψ_n is calculated using the 3-subevent method. It is important to note the the set of particles used to calculate Ψ_n

and ϕ must be different in order to avoid autocorrelations. This is usually done by imposing an η gap between to two particle sets.

For this analysis, the event plane is calculated separately for each of the forward detectors mentioned above, the BBC and the FVTX. For the FVTX, the Q-vector is calculated in each event as

$$Q_x = \sum_{i}^{NFVTXClus} (\cos(n * \phi_i)) \tag{1.6}$$

$$Q_y = \sum_{i}^{NFVTXClus} (\sin(n * \phi_i)) \tag{1.7}$$

$$\phi_i = \arctan(\frac{FVTXClus_y^i}{FVTXClus_x^i}) \tag{1.8}$$

where NFVTXClus is the number FVTX clusters in that event and $FVTXClus_{y,x}^i$ are the x and y components of the ith FVTX Cluster in that event. This Q-vector is calculated with no cluster dependent weight factor as each cluster is taken to be equal weight (since no charge information is available in the FVTX).

For the BBC, the Q-vector is calculated in each event as

$$Q_x = \sum_{i}^{NPMT} (w_i \cos(n * \phi_i)) \tag{1.9}$$

$$Q_y = \sum_{i}^{NPMT} (w_i \sin(n * \phi_i)) \tag{1.10}$$

$$Q_w = \sum(w_i) \tag{1.11}$$

$$\phi_i = \arctan(\frac{PMT_y^i}{PMT_x^i}) \tag{1.12}$$

where w_i is the charge collected on the PMT and NPMT is the number of PMTs that fired (above threshold) in each event.

Finally, the v_n are calculated using a combination of the BBC or FVTX Q-vectors and the CNT tracks as

$$v_n = \frac{\left\langle\left\langle \cos(n(\phi^{CNT} - \Psi_n^{BBC,FVTX})) \right\rangle\right\rangle}{Resolution(\Psi_n^{BBC,FVTX})}. \tag{1.13}$$

In this analysis, I will be exclusively focusing on the second harmonic v_2. The reason for this is two-fold:

(1) The second harmonic is usually the largest and easiest to measure harmonic.

(2) The second harmonic is physically interesting because it is thought to correspond with flow. The first harmonic is thought to correspond momentum conservation.

1.2.1 Event Plane Flattening Calibration

In order for the event plane to be a useful in making a v_n measurement, the event plane must be calibrated. For the event plane method, a physical assumption is made that the true distribution of Ψ_n angles will be uniform. In other words, there is no preferred event plane angle in heavy ion collisions; on average there should an equivalent amount of events where the event plane is oriented at 0 radians and at $\frac{\pi}{2}$. So if the measured Ψ_n distribution is not flat then it could come from a variety of sources such as variations in the efficiency of detecting charged particles as a function of ϕ. Thus, the event plane calibration seeks to restore the Ψ_n distribution to the physical expectation of uniformity.

The method used in this analysis to achieve this is a "re-centering" and "flattening" calibration. In order to better understand this calibration, it is useful to examine an example uncalibrated Ψ_n distribution. The red curve in Fig. 1.2.1 depicts a significant deviation from uniformity in the Ψ_2 distribution which would distort the v_2 measurement. A combination of effects cause there to be a depletion of Ψ_2 values at 0.0 radians and an enhancement at $\frac{\pi}{2}$ radians. The flattening calibration attempts to offset this lack of uniformity by systematically shifting each event's raw Ψ_2 value by an amount corresponding to the amount the Ψ_2 distribution is nonuniform. The more that the raw Ψ_2 distribution is nonuniform, the more significant that the flattening calibration must systematically shift each Ψ_2 value in order to restore uniformity. Thus, it is in the analyzer's best interest to provide the flattest possible Ψ_2 distribution before performing the flattening calibration.

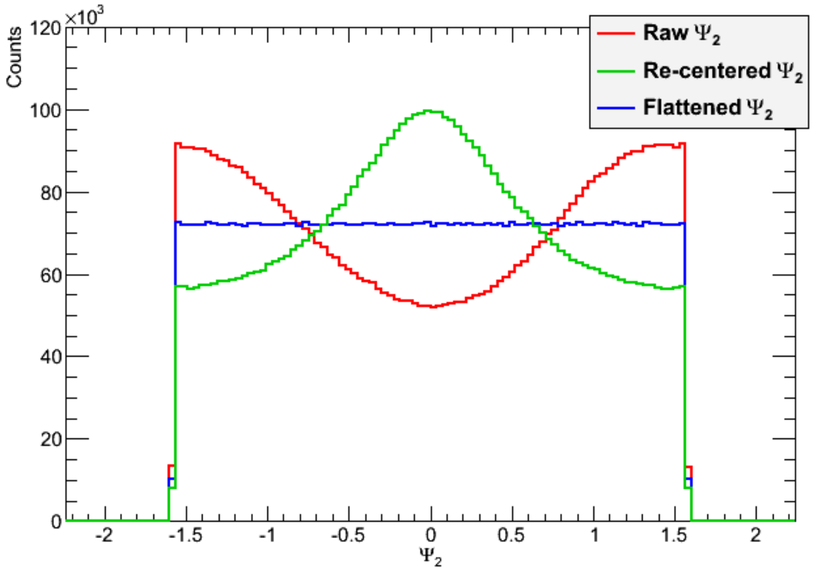


Figure 1.1: This is the FVTX-S Ψ_2 distribution projected over all z-vertex bins at different steps during the calibration. The range of the Ψ_2 resolution is from -$\frac{\pi}{2}$ to $\frac{\pi}{2}$ because of the periodicity. The raw (in red) Ψ_2 distribution has a sinusoidal shape. The re-centered (in green) Ψ_2 distribution moves the peak to 0.0 radians and changes the width. The flattened (in blue) Ψ_2 distribution spread out the counts so that there is uniformity. Each calibration step preserves the integral.

The flattening calibration requires two steps to completely flatten the Ψ_n distribution. The first step of the calibration is to re-center the peak of the raw Ψ_n distribution to be at 0.0 radians and to resize the width of the peak. The second step is to Fourier transform the re-centered distribution and use the transformation to shift the Ψ_n values to a uniform distribution. With flattening, each Ψ_n is transformed to $\Psi_n + \Delta\Psi_n$ where $\Delta\Psi_n$ is defined as

$$\Delta\Psi_n = \sum_{i=1}^{N} \left(\frac{2}{i} \left(\sin(i\Psi) F_i^{\cos}(f(\Psi_n)) - \cos(i\Psi) F_i^{\sin}(f(\Psi_n)) \right) \right), \tag{1.14}$$

where N is the number of components, $F_i^{\cos}(f(x))$ is the ith component of the cosine Fourier transform of $f(x)$, and $f(\Psi_n)$ is the Ψ_n distribution.

For this analysis, N =12 is a sufficient number of components to flatten the Ψ_n distribution. The re-centering and flattening calibration is done 30 z-vertex bins.

1.2.2 Event Plane Resolution Calculation

As mentioned above, the event plane resolution calculation is done using the standard 3-sub event method. The strategy of this method is to leverage the measurement of Ψ_n in different detectors for the same event in order to constrain how well each detector measures Ψ_n. The definition of the event plane resolution is

$$Res(\Psi_n^A) = \sqrt{\frac{\langle\cos(n(\Psi_n^A - \Psi_n^B))\rangle\,\langle\cos(n(\Psi_n^A - \Psi_n^C))\rangle}{\langle\cos(n(\Psi_n^B - \Psi_n^C))\rangle}}, \tag{1.15}$$

where A,B, and C are three detectors measuring the same event, or each detector measuring a "sub event".

In this analysis, the three detectors that are available are FVTX-S, the BBC-S, and the CNT which have η ranges of $-3 < \eta < -1$, $-3.9 < \eta < 3.1$, and $|\eta| < 0.35$ respectively. However, due to the fact that the CNT detector does not have full azimuthal coverage, the CNT event plane is not well defined for a class of events where the event plane doesn't point into the CNT acceptance, therefore the event plane resolution is calculated via a modified yet mathematically equivalent definition to the one mentioned above. This modified method allows the resolution of the FVTX-S and the BBC-S to be calculated using the CNT without having to calculate CNT event plane. It is defined as

$$Res(\Psi_n^A) = \sqrt{\frac{\langle\langle\cos(n(\Psi_n^A - \phi^{CNT}))\rangle\rangle\,\langle\cos(n(\Psi_n^A - \Psi_n^C))\rangle}{\langle\langle\cos(n(\phi^{CNT} - \Psi_n^C))\rangle\rangle}}, \tag{1.16}$$

where there is a double average over each CNT track and each event. (**TO DO: Make a Table of Default Event Plane Resolutions**)

1.3 Correcting for Beam Geometry

As shown above, there is an east west difference observed in the measurement of v_2 when using mid-rapidity particles in the west arm (-1 $< \phi <$ 1) and in the east arm ($2 < \phi < 4$ as see in). The ultimate explanation for this effect comes from beam geometry.

First of all, the collision vertex is significantly offset from the z-axis to which all of the PHENIX detectors are aligned. The other beam geometry effect, and the more significant of the

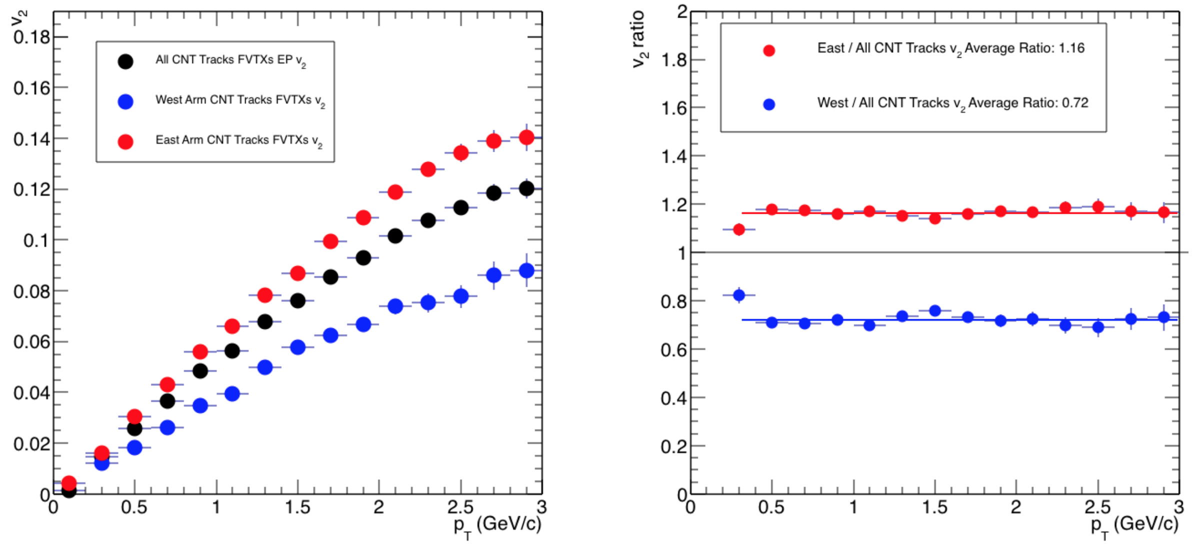


Figure 1.2: The first measurement of v_2 as a function of p_T with the FVTXs event plane for the p+Au @ 200 GeV dataset. The default resolution as shown in table TBA is used. The left panel shows the event plane resolution corrected v_2. The black points show the v_2 measurement measured using all CNT tracks. The blue and red points show the v_2 measurement made with only the west and east arms respectively. It is apparent that there is a significant splitting of the measurement depending on what set of tracks are being used to calculate v_2 which implies there are some systematic errors present. The left panel quantifies the level of splitting by plotting the ratio of the east or west v_2 to the measurement made with all CNT tracks. The blue and red lines are constant fits to this ratio and the numbers in the legend are the constant fit parameter. So the east v_2 measurement is 16% higher on average from the all CNT track measurement and the west measurement is 28% lower on average.

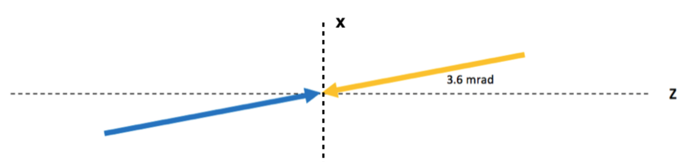


Figure 1.3: A vector diagram illustrating the yellow and blue beam angle.

two effects, comes from the fact that the beams are colliding at an angle of 3.6 milli-Radians in the x-z plane. The reason a non-ideal beam geometry creates an east west v2 measurement difference is because of the assumption that event plane angle is azimuthally isotropic during the event plane flattening calibration. In the translated and rotated frame where the beams aligned with the z-axis the event plane distribution would be uniform, but in the lab frame the event plane distribution in ϕ would have regions of enhancement and reduction.

To correct for the collision vertex offset effect, PHENIX detector elements must have their position calculated with respect to the collision vertex rather than the origin. To correct for the beam rotation effect, PHENIX detector elements must be rotated into the beam frame where the beam is aligned with the z-axis. However, the detector elements being in the right place in the beam frame will not completely correct the event plane bias.

To explain the residual effect, consider a cylindrical disk with a hole in the middle centered in the z-axis (which is the shape of the FVTX layers and the BBC). For any given ϕ value of the detector, the η range spanned by the disk is the same. However, if one were to tilt that disk, the η range spanned by the disk would be ϕ dependent. This tilt would both shift the range in η and increase or decrease the width of the range. The combination of the η range changing and the η distribution of charged particles not being flat means that that the average amount of charge particles going through the disk would be systematically ϕ dependent. If the average charge particle distribution is not uniform in ϕ, the event plane distribution will not uniform in ϕ which will lead to the flatten procedure creating systematic effects such as the east west v_2 asymmetry. Even if the detector elements are in the right frame, the damage has already been done.

In order to correct for this, we increase the weight on hits in ϕ regions with systematically less particles and decrease the weight on hits in ϕ regions with systematically more particles. One can analytically calculate this ϕ dependent weight factor using the geometry of the FVTXs and BBCs as well as using the η distribution of charged particles. Unfortunately, the η distribution of charged particles in pAu @ 200 GeV has not been measured by an experiment so we must rely on models which may be inaccurate. The model that was used during this study was AMPT.

Another way to determine the weight factor is to use the data driven method of inverse ϕ weighting. For this method, the weight factor is determined by plotting all hits in a cylindrical disk detector vs ϕ, normalizing this distribution to one, and then inverting it. When applying this weight factor to the data, it will produce uniform hit distributions in ϕ in the detectors it is applied to. This will, in turn, make the event plane distribution more uniform when measured in those detectors, thus correcting for the effect.

It is apparent when plotting the analytic and data driven weighting together that the analytic method agrees with the data driven method for the FVTX where the η distribution charged particles is better known. The decision was made to use the data driven inverse ϕ weighting method for the FVTXs in part because it isn't model dependent and in part that the method has the added benefit of also correcting for hot and cold ϕ regions in the detector. In order to get rid of significant hot or cold ϕ regions, ϕ regions with weight factors greater than 1.2 or less than 0.8 are set to 0.0. This correction is done for each FVTX layer, in z-vertex bins, and per run.

For the BBCs another data driven method was used to correct for the non-uniform particle distribution. Using the distribution of particles in the BBC from the Run15 pp dataset as a baseline, one can apply an inverse ϕ weighting much like the one described in the previous paragraph. In the Run15 pp dataset, there was no issue with beam colliding at an angle and the average charge across all 64 PMTs in the BBCs is uniform. In this method, the weight for each PMT is calculated as the charge of the PMT times the average Run15 pp charge of the PMT divided by the average Run15 pAu charge of the PMT. This method does not agree with the analytic configuration but this is explained by the fact that the model that was used when calculating the correction may be incorrect for the BBC's η acceptance. One effect of using this weighting method is that not only is the distribution of particles in the BBC uniform in ϕ, the distribution is uniform in η as well.

The combined effect of all these corrections not only makes the east and west arm v_2 measurements using the FVTXs or the BBCs agree to much better degree, it makes the BBCs and FVTXs inclusive v_2 measurements agree as well.

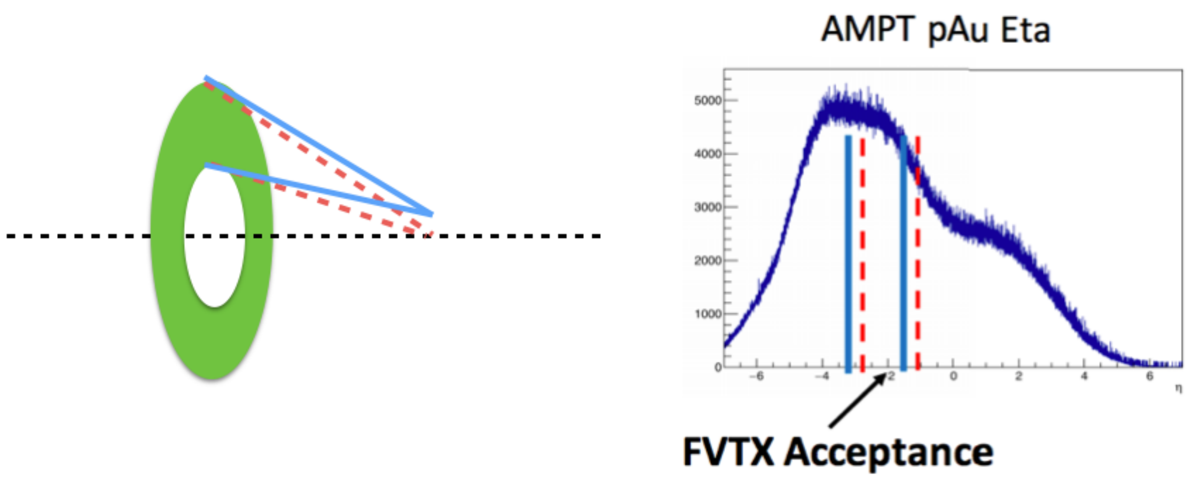


Figure 1.4: On the left is a cartoon diagram illustrating η acceptance shift due to a beam offset in one of the FVTXs layers. The right plot shows the AMPT distribution of particles for pAu @ 200 GeV and the shifted η acceptance.

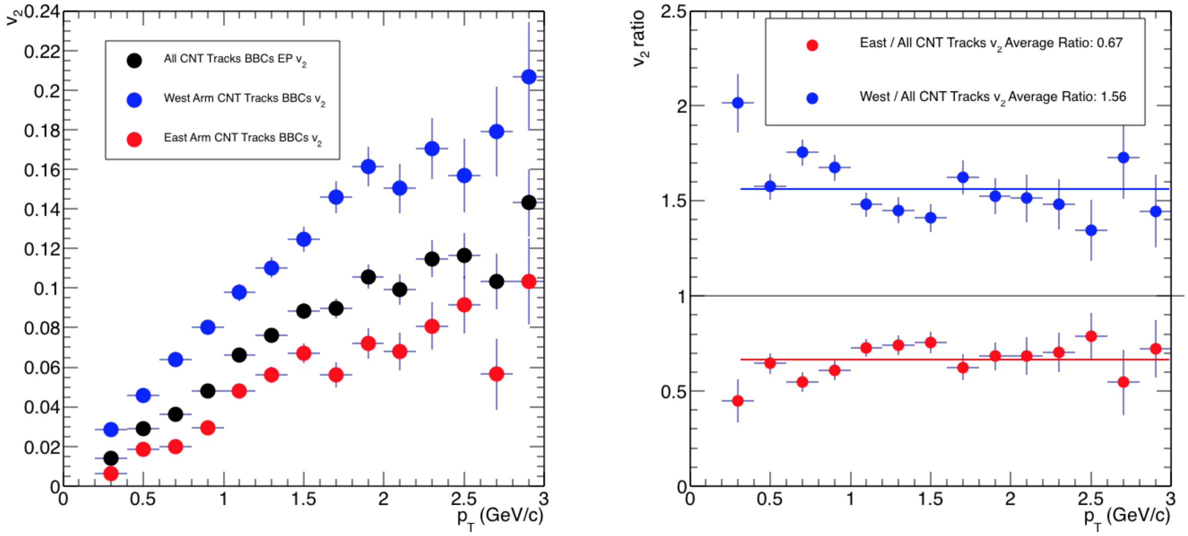


Figure 1.5: The first measurement of v_2 as a function of p_T with the BBCs event plane for the p+Au @ 200 GeV dataset. Along with the FVTXs event plane measurement, the default resolution as show in table TBA is used.

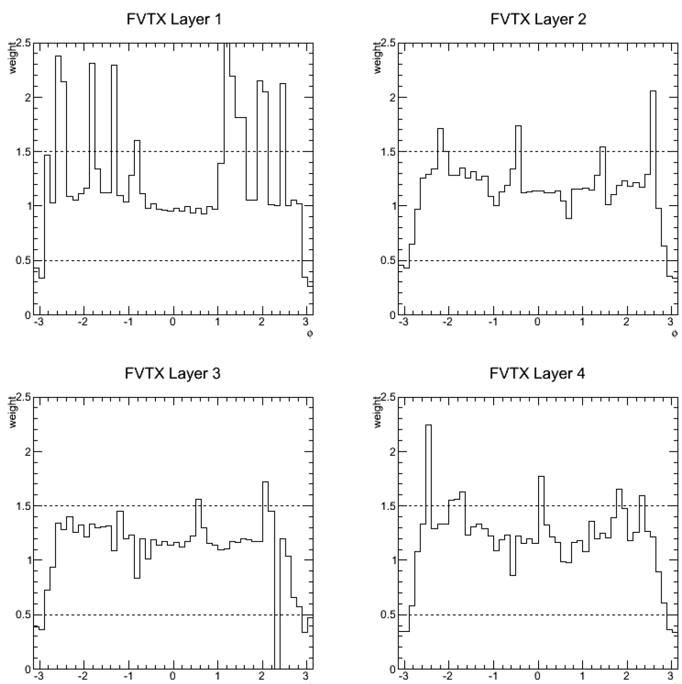


Figure 1.6: These 4 panels show the FVTX ϕ dependent cluster weighting when calculating the FVTX event plane for each layer separately.

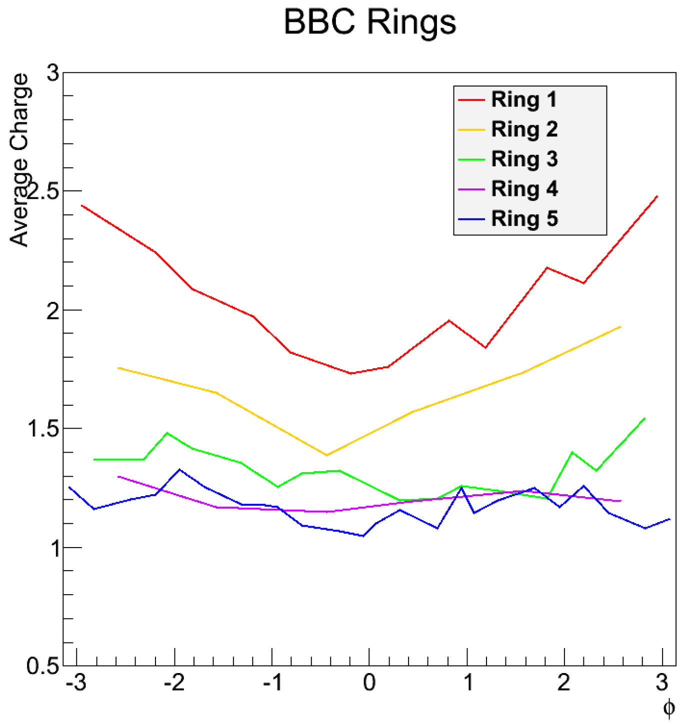


Figure 1.7: These 4 panels show the FVTX ϕ dependent cluster weighting when calculating the FVTX event plane for each layer separately.

1.3.1 BBC Charge Weighting

1.3.2 FVTX Inverse Phi Weighting

1.3.3 Applying Weighting to v2 and EP Resolution

1.3.4 Dataset Quality Assurance

A PHENIX "run" (lower case r) is defined a group of events that were taken over a single timespan of max length 90 minutes. The for p+Au dataset, there are on average 5 million events per run and there are 339 runs.

1.3.5 luminosity over time

RHIC exceeded in delivering its integrated luminosity goals of (**TO DO: Quantify**).

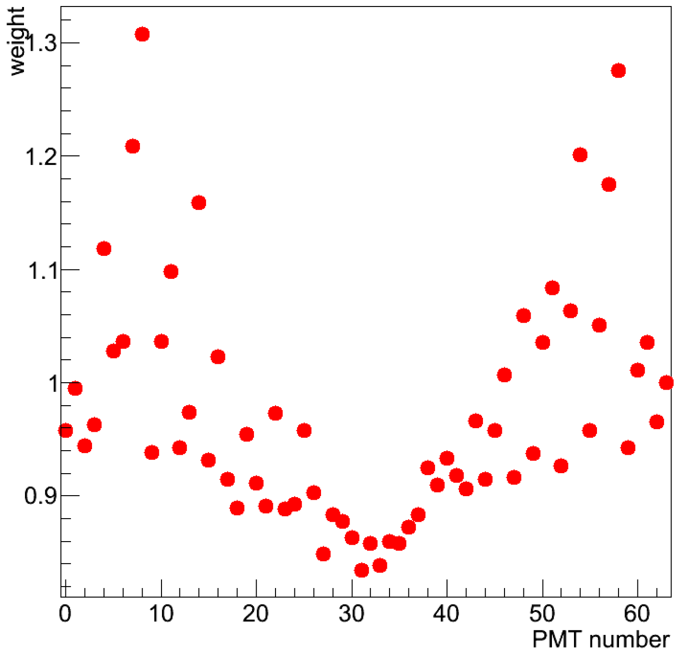


Figure 1.8: These 4 panels show the FVTX ϕ dependent cluster weighting when calculating the FVTX event plane for each layer separately.

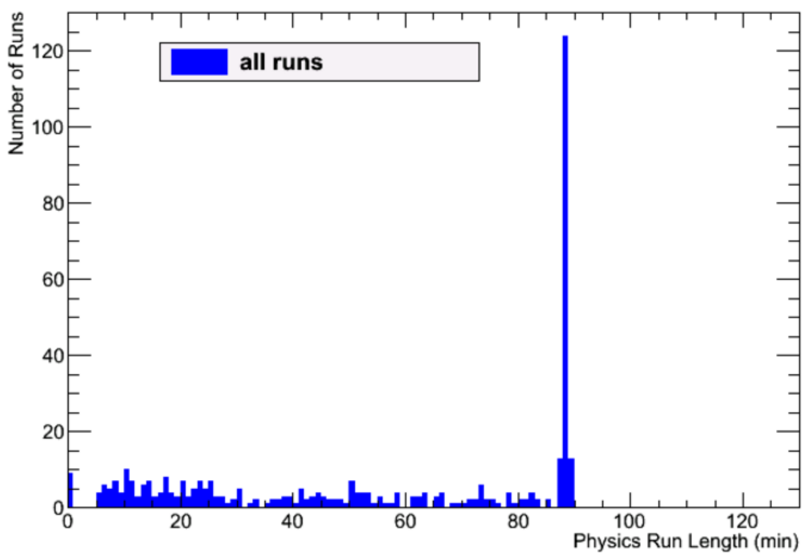


Figure 1.9: The distribution of the length of physics runs.

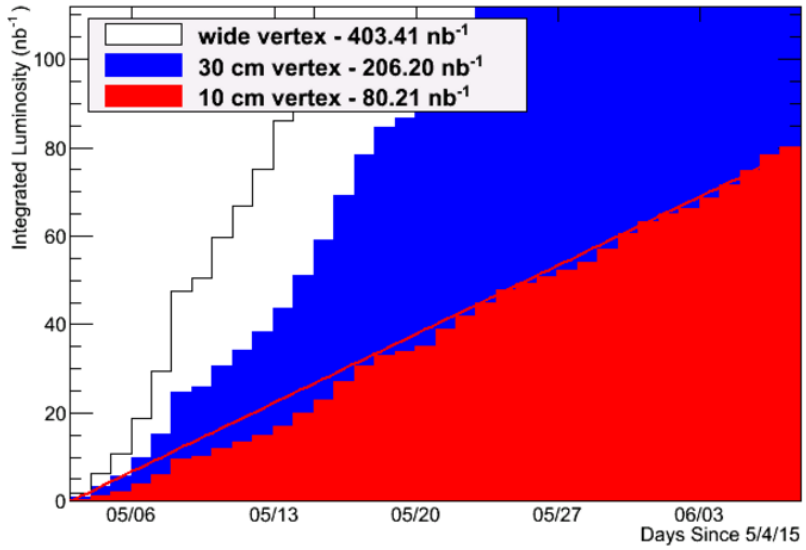


Figure 1.10: Integrated luminosity from the p+Au dataset.

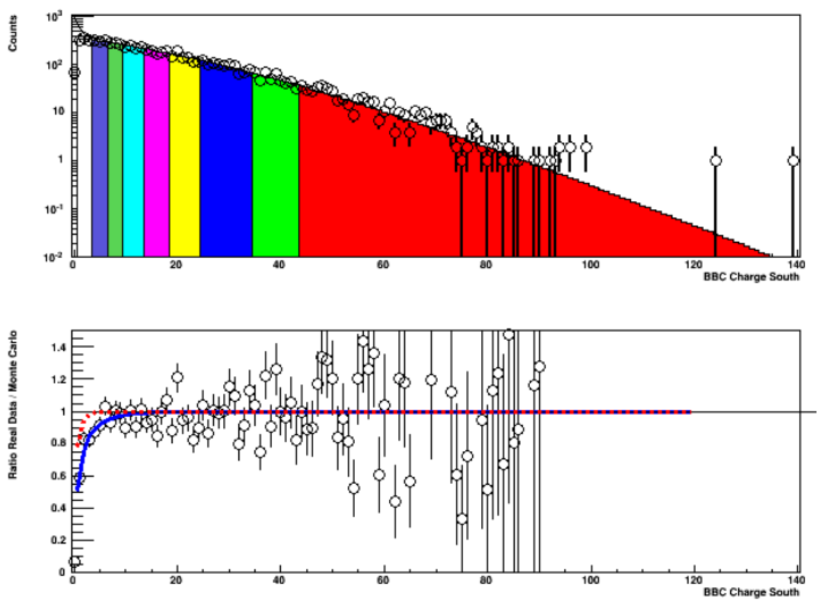


Figure 1.11: Real data for BBC Charge South (Au-going direction) shown as open circles and Glauber Monte Carlo + NBD. The colors correspond to the various percentiles relative to the total inelastic p+Au cross section, the most central 0-5% in solid red. The blue and red curves correspond to the Leve-1 trigger efficiency in all inelastic collisions and inelastic collisions producing a particle at midrapidity, respectively. The best fit NBD parameters are mu = 3.14, k = 0.47 , and the trigger firing on 84 +/- 3% of the total inelastic cross section [sigma = 1.76 barns].

1.4 bbc charge

1.5 Systematic Error Estimate

1.5.1 Non-flow Estimate

1.5.2 Pile Up

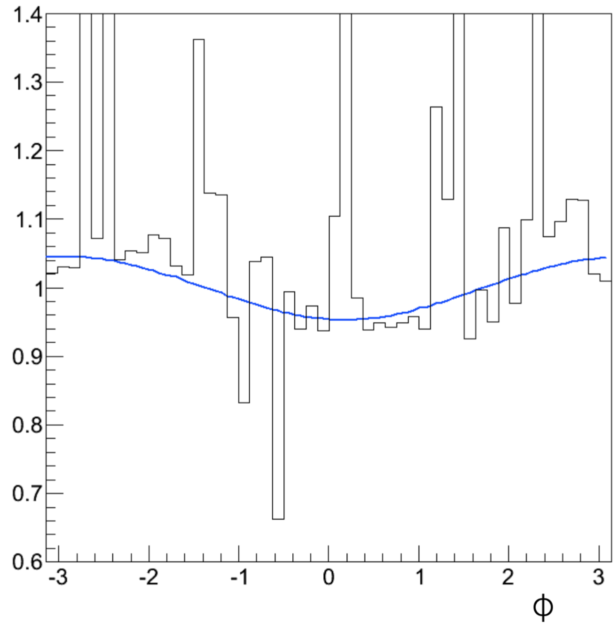


Figure 1.12: TBA

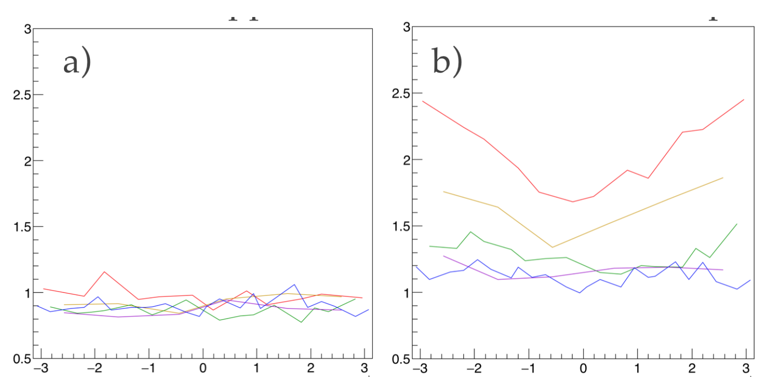
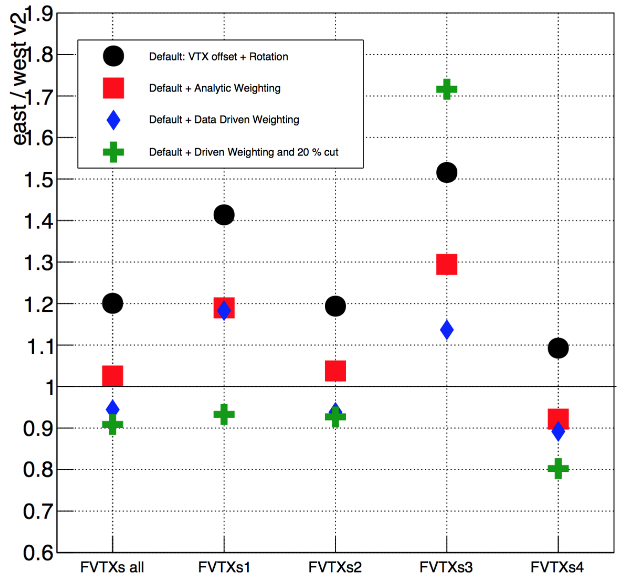


Figure 1.13: These figures show the phi distribution of BBC PMT charge in a) the Run15 pp dataset and in b) the Run15 pAu dataset.



FVTXs All using layers 1, 2, and 4

Figure 1.14: TBA

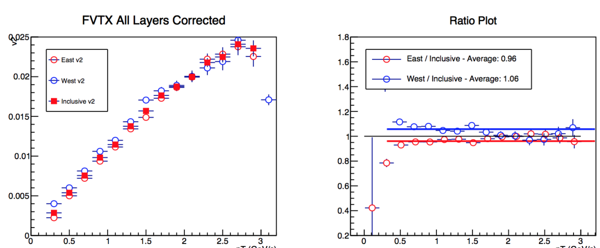


Figure 1.15: FVTX EP corrected with inverse ϕ weighting and 20 % cut.

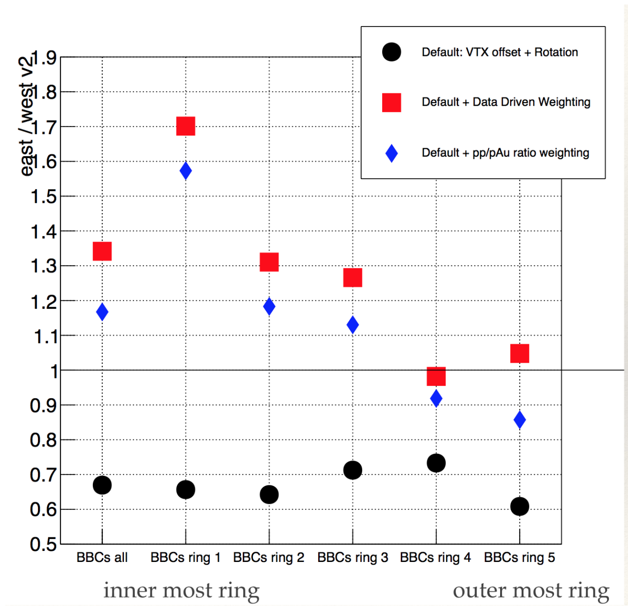


Figure 1.16: TBA

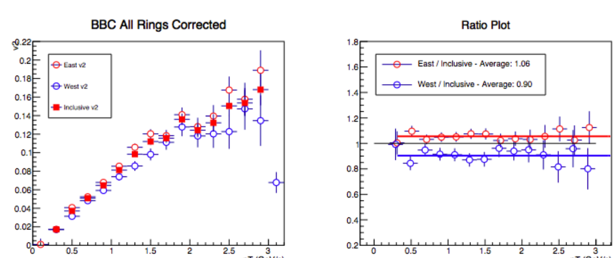


Figure 1.17: BBC EP corrected with pp, pau ratio weighting.

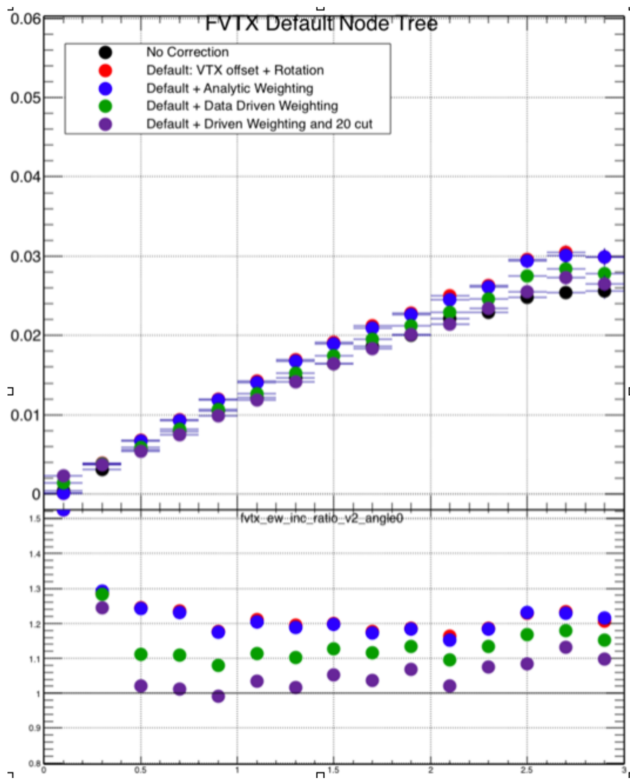


Figure 1.18: A comparison of FVTX EP v_2 corrections on the inclusive measurement.

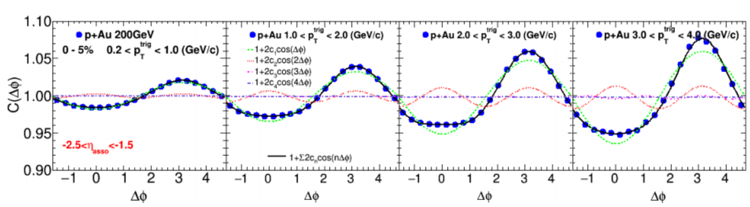


Figure 1.19: TBA

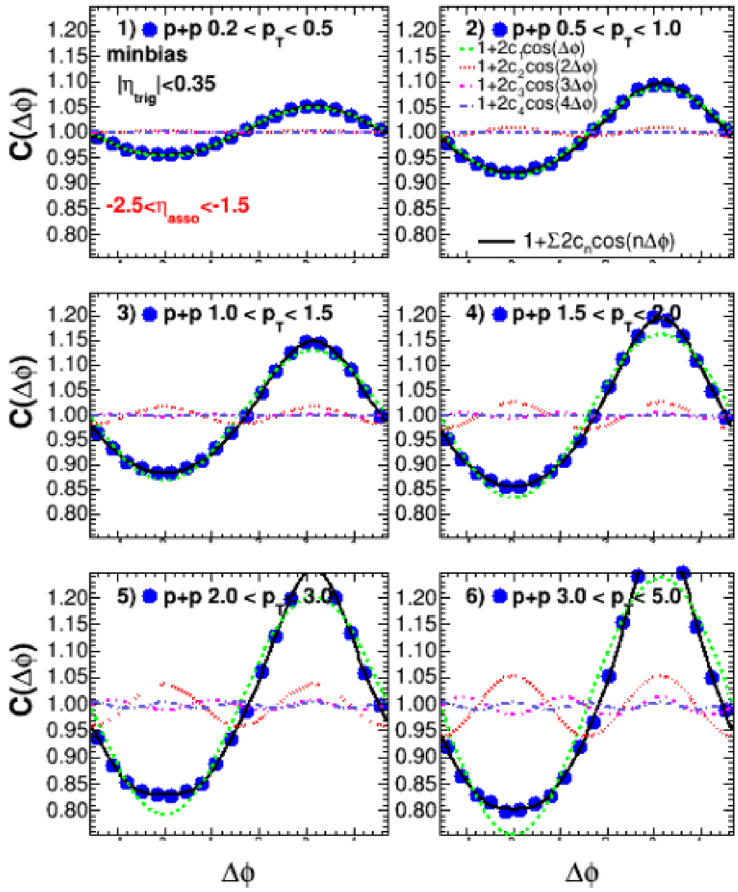


Figure 1.20: TBA

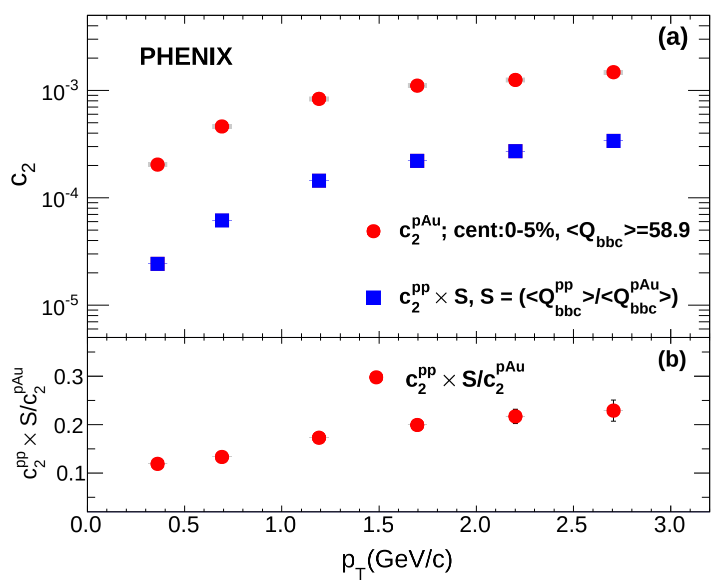


Figure 1.21: TBA

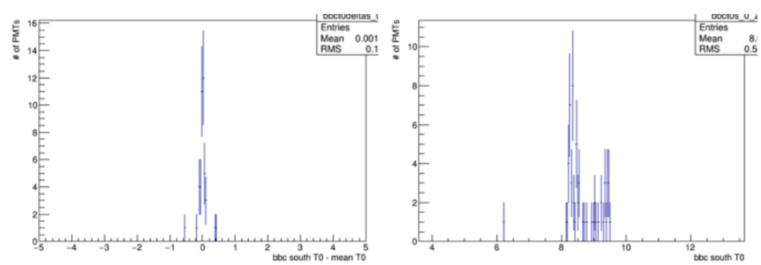


Figure 1.22: The left plot is an example of a normal event, the right plot is an example pile up event.