Vertex finding in pile-up rich events for p+p and d+Au collisions at STAR

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Abstract. Primary vertex finding is an important part of accurately reconstructing events at STAR since many physics parameters, such as transverse momentum for primary particles, depend on the vertex location. Many analyses depend on trigger selection and require an accurate determination of where the interaction that fired the trigger occurred. Here we present two vertex finding methods, the Pile-Up Proof Vertexer (PPV) and a Minuit based vertex finder (MinuitVF), and their performance on the 2008 STAR p+p and d+Au data. PPV had been developed for use in p+p collisions and uses a 1D truncated log-likelihood method to determine the most probable z location of the vertex. MinuitVF had been developed for Au+Au events and finds the vertex by determining the location where the distance of closet approach (DCA) for all tracks is at a minimum. The heart of MinuitVF is the Minuit routine, which is a standard tool that finds the minimum value of a multi-parameter function. We will present the vertex finding efficiency for both forward and mid-rapidity triggers. A comparison to a hardware determination of the vertex will also be included [1], [2].

1. Introduction

An accurate primary vertex location is necessary for the determination of many physics variables in collisions of any species. It is important to reconstruct a vertex in a given event which corresponds to the collision(s) that fired the trigger(s) associated with that event, in order to both properly analyze the results and to determine the integrated luminosity for that trigger. The challenge is that a high luminosity environment coupled with a detector read-out time much longer than the time between bunch crossings, will cause many pile-up vertices to be recorded in each event. In 2008 the Solenoidal Tracker at RHIC (STAR) experiment used two different algorithms, PPV and MinuitVF, for determining the primary vertex location. PPV was optimized for low multiplicity p+p events with a high pile-up rate whereas MinuitVF was optimized for high multiplicity A+A events. Both vertex finders take a collection of tracks from an event, form vertex candidates from the collection of tracks and then rank the vertices in an effort to determine the vertex which corresponds to the collision that triggered the event. The track collection is recorded by a Time Projection Chamber (TPC) that has a read-out time much slower than the bunch-crossing time, causing many of the tracks to be from pile-up collisions. PPV uses a 1D fit to determine the vertex location along the *z* axis, which is more suitable for low multiplicity events. Both vertex finding methods give a greater weight to vertices which have more tracks matched to the electromagnetic-calorimeters (EMCs). PPV gives greater weight to vertices which have a higher multiplicity; whereas MinuitVF gives higher rank to vertices whose average dip angle matches the average dip angle for other vertices at the same *z* location. Tracks are matched to the EMCs as they have a much faster read-out time than the TPC and are not susceptible to tracks from out-of-time collisions. A comparison of both algorithms on p+p and d+Au will be presented [3].

1.1 STAR TPC and EMCs

Three detectors are used in the determination of the vertex location. The first is the TPC, which has an acceptance of $|\eta| < 1.4$ and $0 < \phi < 2\pi$. Particles from each collision travel through the gas of the TPC at nearly the speed of light, leaving ionization trails which drift away from the TPC central membrane to the ends for readout. The curvature and pitch of each track's helix within the TPC allows its momentum to be determined [3]. The other detectors are the Barrel Electromagnetic Calorimeter (BEMC) and the Endcap Electromagnetic Calorimeter (EEMC). The former has acceptance $|\eta| < 1$ and $0 < \phi < 2\pi$, while the latter has acceptance $1.1 < \eta < 2$ and $0 < \phi < 2\pi$. The electronic readout time for TPC is of order 80 μs whereas the EMCs can be read out and reset in 10 ns, which allows them to be read out for every bunch crossing [4], [5], [6].

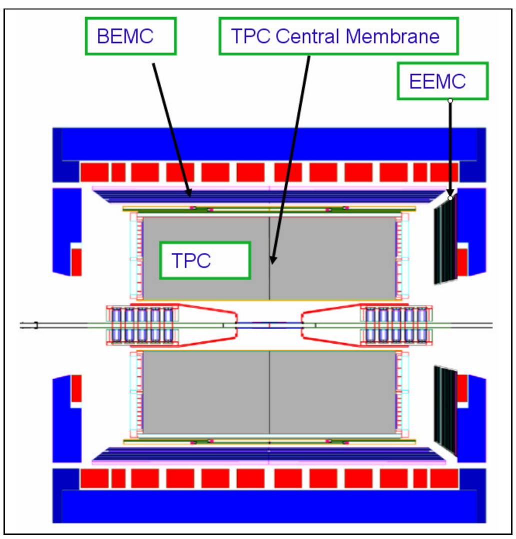

Figure 1. The STAR detector setup. We show the relevant detector components used for vertex finding: the Barrel Electromagnetic Calorimeter (BEMC), the Endcap Electromagnetic Calorimeter (EEMC) and the Time Projection Chamber (TPC). The TPC Central Membrane is also indicated for our arguments.

1.2 Pile-up and Collision rates

In 2008, the peak collision rate for d+Au collisions was roughly 300 kHz. Given the readout time of the TPC, this corresponds to an average of 20 separate minbias collisions in the TPC in any recorded event. The p+p collision rate is higher, and so these events will have an average of 36 different collisions recorded within the TPC data.

There are three types of pile-up; vertices that come from collisions within the same bunch crossing, vertices that come from collisions from earlier or later bunch crossings. The collisions that occur within the same bunch crossing are referred to as within bucket pile-up. The ranking system in both vertex algorithms is designed to remove vertices corresponding to the pre-crossing and post-crossing collisions as these collisions are out of time with the collision that fired the trigger. Tracks from out-of-time events are reconstructed as being shifted along z and broken into two tracks where they cross the TPC central membrane as shown in Figures 2a and 2b. MinuitVF or PPV can not separate within bucket pile-up, as these collisions have all of the same qualities as the collision that fired the trigger. These vertices are separated during analyses when it is determined whether a particular vertex could correspond to a particular trigger. The average number of pile-up vertices is proportional to the instaneous luminosity. In 2008, the p+p peak luminosity was roughly four times what it had been in 2006. RHIC II, a planned upgrade for the accelerator, will further increase the luminosity so the ability of the vertexing algorithms to properly associate a vertex with the collision that fired the trigger given the increased pile-up will be important.

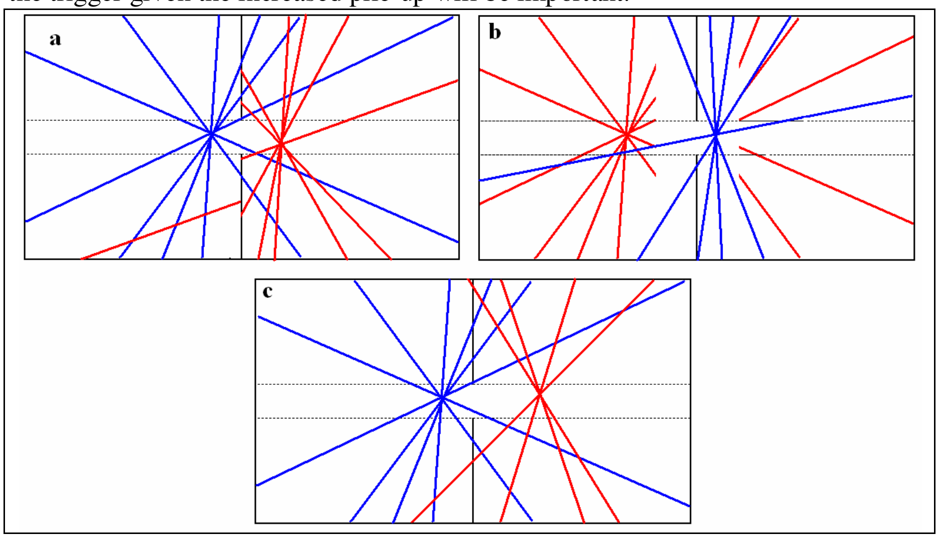

Figure 2. Cartoon events showing the way the three different types of pile-up will be reconstructed for a particular event. In each case, the vertex in blue is constructed from the collision that fired the trigger, while the vertex in red is a pile-up vertex. The pile-up collision for 2a occurred after the triggered collision (post-crossing), which means that the tracks associated with the triggered collision had already drifted away from the TPC Central Membrane. When this event is reconstructed, these tracks are connected properly, but the tracks from the post crossing vertex have discontinuities at the Central Membrane. In 2b the pile-up collision happened before the triggered collision, so the tracks from that collision had already started to drift down the TPC when the trigger was fire. 2c shows within bucket pile-up, where both collisions happen within the same bunch crossing.

2. PPV Method

PPV finds the z position of a vertex. It requires a beam-line constraint to determine the x and y values of the vertex. The beam line constraint is calculated by fitting high multiplicity events with MinuitVF without any constraints on the vertex position. A straight line is fit to the vertex distributions to obtain a relationship between x, y and z. Some of the vertices found in this manner will not be the correct ones for the event; however, there will be enough correct vertices so that the straight line fit is a valid representation of the beam-line. The resolution of the beam-line constraint is dominated by the width of the beams, which is of the order of a few hundred microns.

From each event, tracks are selected based on their quality in the TPC. The tracks should extrapolate to within 3 cm of the beam line and the extrapolated point closest to the beam-line, called the distance-of-closest-approach (DCA), should have $|z| < 200$ cm, which is the longitudinal volume of the TPC. They should have a minimum momentum of 0.2 GeV. The fraction of TPC hit points over the number of possible TPC hit points should be > 0.7. This cut allows many tracks from post-crossing events to be removed. The tracks that pass the quality cuts are then given weights based on the probability that they correspond to the collision that fired the trigger. Each track is given an initial weight based on their DCA to the beam-line and the error in their extrapolation from the TPC to their DCA. If the tracks extrapolate to a point in either the BEMC or the EEMC with a deposit of energy, or cross the TPC central membrane, the tracks are considered matched and their weight is increased. Matched tracks are likely to be tracks from the triggered collision as the calorimeter detectors have a response time which is less than the time between bunch crossings. However, this does not allow the vertex finder to remove pile-up from within-bucket collisions. Tracks which extrapolate to a point in either the BEMC or the EEMC without a deposit of energy are considered vetoed and given reduced weight. The track is not completely removed from the analysis, though it is likely that this track is not from the triggered collision. If the track doesn't extrapolate to the BEMC or the EEMC, or the part of the detector it extrapolates to is unable to be read out, the track gets a "dunno" factor for its weight. If the track does not cross the TPC central membrane it also gets a "dunno" factor for its weight. This factor is set to 1 as we do not have any further knowledge about whether this track belongs to the triggered collision. The total weight for the track is the product of all of the weights.

Detector	Match Factor	Veto Factor	"Dunno" Factor
BEMC	4	¾	1
EEMC	4	¾	1
TPC	5	1/5	1

Table 1. Track weight corrections versus matched detector.

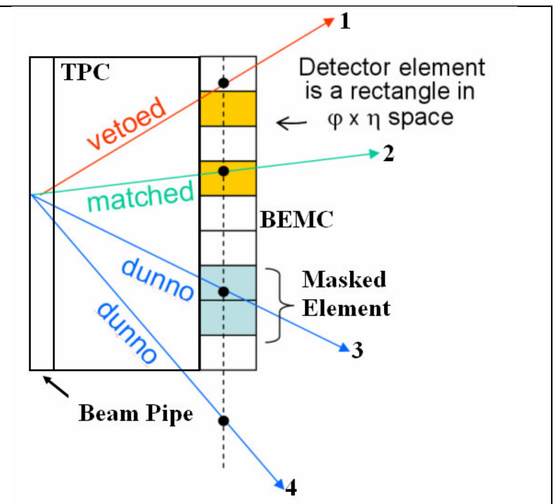

Figure 3. A diagram showing how the weighting scenarios from table 1 would be applied to four different tracks based on how they extrapolate to the BEMC. Track 1 would have a BEMC weight of ¾, track 2 would have a weight of 4 and tracks 3 and 4 would have a weight of 1.

The truncated likelihood of the track belonging to a primary vertex at z, $L_i(z)$, is calculated as:

$$L_i(z) = C_i \exp\left(\frac{-(z_i - z)^2}{2\sigma_i^2}\right) \quad (1)$$

Where z_i is the z value of the track's distance of closest approach (DCA) to the nominal beam-line, C_i is a constant, and σ_i is the error in the extrapolation of the track to the nominal beam-line based on the number of hits within the TPC used to reconstruct the track and the track's transverse momentum. All the likelihoods are combined into a truncated cumulative likelihood, $L^c(z)$, with a truncation value of c = 1.5 cm. This truncation value is the minimal separation between two vertices that PPV is able to find.

$$L_c(z) = \prod_i^{tracks} (L_i^c(z))^{w_i} \tag{2}$$

$$L_i^c(z) = L_i(z)\, for\, |\, z - z_i\, |< c$$

$$L_i^c(z) = L_i(z_i + c) \equiv C_i\ for\, |\, z - z_i\, |> c$$

By setting $L_i^c(z)$ to C_i for z values with no tracks within 1.5 cm, the minimum cumulative likelihood is a constant value. The first vertex candidate is the *z* value with the maximum cumulative likelihood. All tracks which extrapolate to within 3 cm of this location are associated with this vertex and removed from the pool of available tracks. This process is repeated with the remaining tracks until there are not enough tracks left to create further vertex candidates. Ranks are assigned to the vertex candidates based on their likelihood and number of matched tracks. Vertices with two or more matched tracks are given a rank that consists of their cumulative likelihood plus a large offset, vertices with a single matched track are given their cumulative likelihood as their rank and vertices with no matched tracks are given a rank of their cumulative likelihood minus a large offset. This offset allows the different categories of vertices to be easily distinguished from each other, but saves them so that they can be better analyzed in post processing Up to five vertices without any matched tracks are saved as some STAR triggers are forward focused, which means the probability of two tracks pointing to the fast detectors for a real triggered event is low. All vertices with two or more matched tracks are saved.

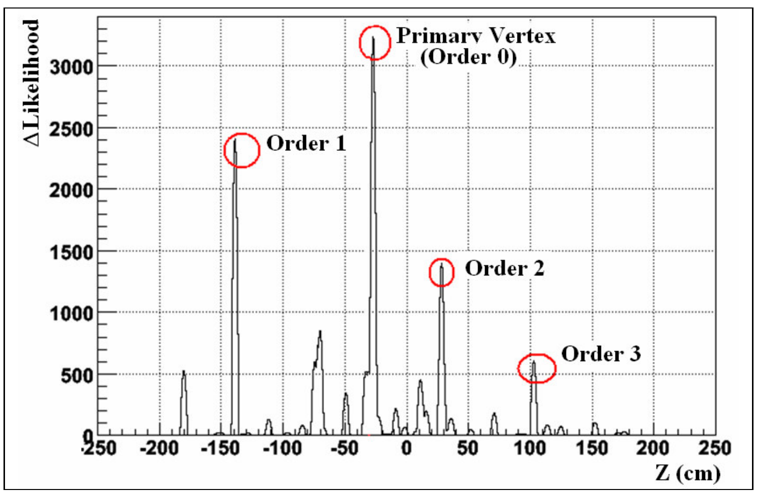

Figure 4. Example Δ cumulative likelihood plot for a single event, where Δ cumulative likelihood is the minimum likelihood subtracted from the cumulative likelihood. The maximum likelihood at -30 corresponds to the primary vertex.

The *x* and *y* values of the vertex position are determined using the beam-line and the *z* position of the vertex. The vertex with the highest cumulative likelihood is set as the default (primary) vertex. All other vertices are saved in order of descending likelihood.

3. MinuitVF Method

As with the PPV algorithim, similar track quality cuts are applied to the collection of tracks used for the vertex finder. Vertex candidates are found by making a histogram of the z-coordinates of the points of closest approach of the selected high-quality tracks to the nominal beam-line. The tracks are also required to have a radial DCA to the beam-line of less than 2 cm. A crude peak-search is then used to find the points with at least 5 tracks with helices that extrapolate back to within 6 cm in *z*.

Next, Minuit is used to minimize the DCA of all the selected tracks and yield a preliminary vertex location in *x, y* and *z*. A robust potential is used in the χ^2 to reduce the contributions from tracks that are many sigma away from the vertex location. The routine iteratively repeats this process with the preliminary vertex position rather than the result of the crude peak search. A vertex candidate is selected when a stable point is reached, or the maximum number of iterations has been cycled through. Each vertex candidate is given a rank based on the average dip angle of the associated tracks versus z, the number of tracks extrapolated to the energy deposits in the BEMC and the number of tracks which cross the TPC central membrane. The dip angle of a track is the angle between that track and the *z* axis. A collision that is near the edge of the detector will have a number of out-going particles that do not have reconstructed tracks in the TPC because the tracks will not leave enough hits in the TPC. The vertices constructed from these collisions will have an average dip angle that is skewed when compared to a vertex constructed for a similar collision in the center of the detector. The primary vertex is the vertex with the highest rank. All other vertices are saved in order of their vertex rank.

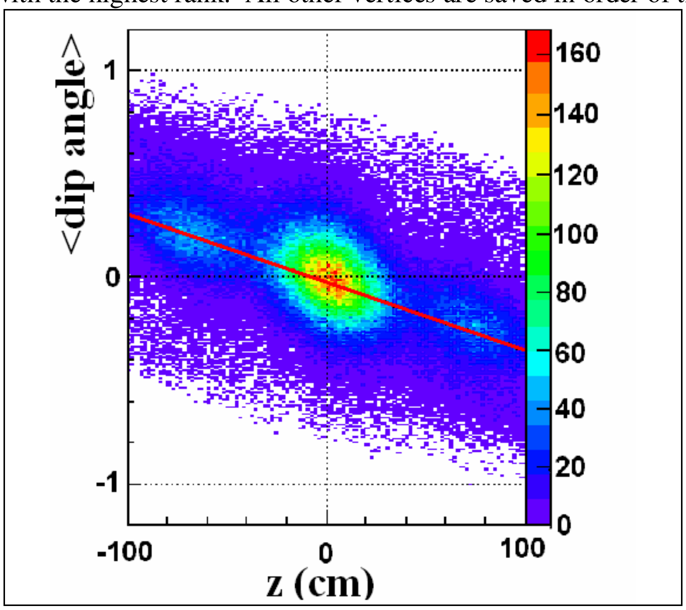

Figure 5. The average dip angle versus the vertex location in the *z* axis for 2008 d+Au events. The shape of this distribution is due to the acceptance of the STAR detector. The rank of a vertex increases as it nears the fit line.

4. Tracking Independent Cross Check

The STAR Vertex Position Detector (VPD), operational for the first time in 2008, was used to independently measure the location of the vertex in order to determine the accuracy of both of the vertex finding methods. The VPD can determine the *z* location of a vertex by measuring the difference in time between the signals that arrive from the East versus the West. However, this method fails if multiple collisions within the same bucket occur. In p+p collisions the VPD found a vertex in 25% of events with a vertex resolution of ~5 cm. This detector gives an independent hardware measurement of the *z* position. The VPDs are not used in the software determination of the vertex due to their small acceptance and efficiency. They are not usable for vertexing as they would introduce a bias hard to reproduce in simulations [7].

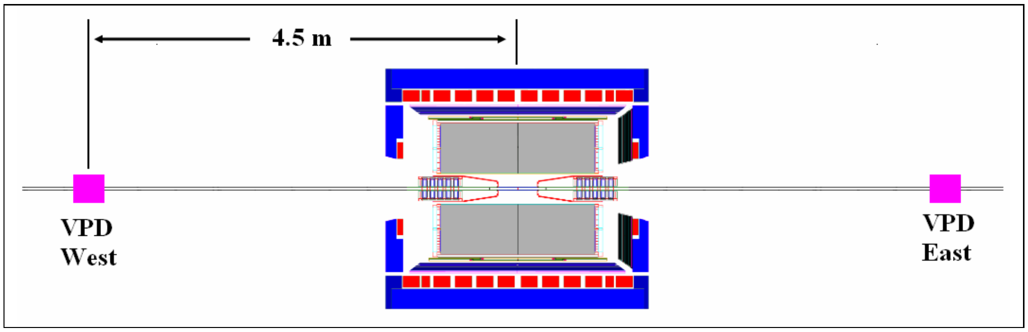

Figure 6. The position of the STAR VPD with respect to the TPC.

Since the STAR trigger set-up changes from year to year depending on the physics goals, a direct comparison between identical triggers is not possible. For year-to-year comparison purposes, several triggers of a similar nature were chosen. A high-tower trigger is one which requires a large amount of energy in one of the towers of the BEMC. A minbias trigger requires that the two ion beams have a coincidental arrival and they leave some energy in one of the forward detectors. Zerobias triggered events are those which only have a requirement that the two ion beams have a coincidental arrival. The number of zerobias events with vertices is a measurement of the probability that a within-bucket pile-up collision will be measured for any given trigger. An increase in luminosity should correspond to an increase in the percentage of zerobias triggered events that contain a vertex. The peak luminosity was four times greater in 2008 than it was in 2006, which is reflected in the change in the vertex finding efficiency in the zerobias trigger. For similar triggers which contain a signal in an electromagnetic-calorimeter, the percentage of events in which PPV found a vertex was consistent between 2006 and 2008, despite increase in peak luminosity.

Trigger	2006 Efficiency	2008 Efficiency	% 2008 matching VPD
Zerobias	3.0 %	12.2 %	80.0 %
Minbias	48.0 %	56.3 %	78.4 %
High tower	95.8 %	96.2 %	69.2 %

Table 2. Comparison of the efficiency of finding a vertex in p+p events from 2006 to 2008 for similar triggers. The exact definition of the minbias and high tower triggers has changed, as the physics analyses change the trigger requirements from year to year. The third column is the comparison between the *z* locations of the 2008 PPV and VPD vertex. To be considered a match, the two vertices were required to be within three sigma of one another.

A subset of 2008 p+p events and d+Au events with VPD vertices were analyzed with both vertexing algorithms in order to determine whether the same vertices were being found in each case. The analysis confined itself to the *z* position of the vertex. In p+p events with both a PPV and a VPD vertex, the vertices were within three sigma of each other ~80% of the time. Of the remaining 20%, most were the result of within-bucket pile-up which causes the VPD to find a vertex midway between the two collisions and thus will not agree with any of the software vertices. PPV rarely saved more than one vertex in a given event as seen in the left hand side of Figure 7. The primary vertex found by MinuitVF disagreed with the VPD vertex more than 20% of the time, though in many events a lower order vertex was found which better agreed with the VPD. MinuitVF currently does not perform as well as PPV in p+p events, as seen in Figure 7. In d+Au, the agreement between the VPD, PPV and MinuitVF was much higher. In d+Au the *z* distribution of the primary vertices found by MinuitVF is nearly identical to that found by PPV, as seen in Figure 8. As in p+p events, PPV rarely finds more than one vertex and this vertex agrees with the VPD vertex ~80% of the time. The similarities between the vertex positions of MinuitVF and PPV in d+Au indicate that either algorithm can be used for d+Au at this luminosity.

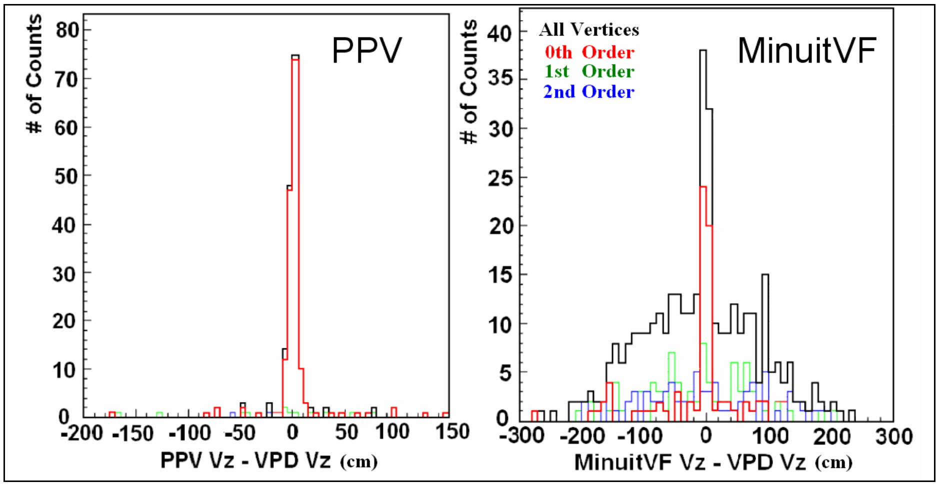

Figure 7. Comparison between PPV, MinuitVF and the VPD for p+p 2008 data. The rank 0 vertex is the primary vertex. MinuitVF does not require that a vertex have at least one track pointing to a fast detector, so it will save more vertices than PPV, though many of these vertices will have a low rank.

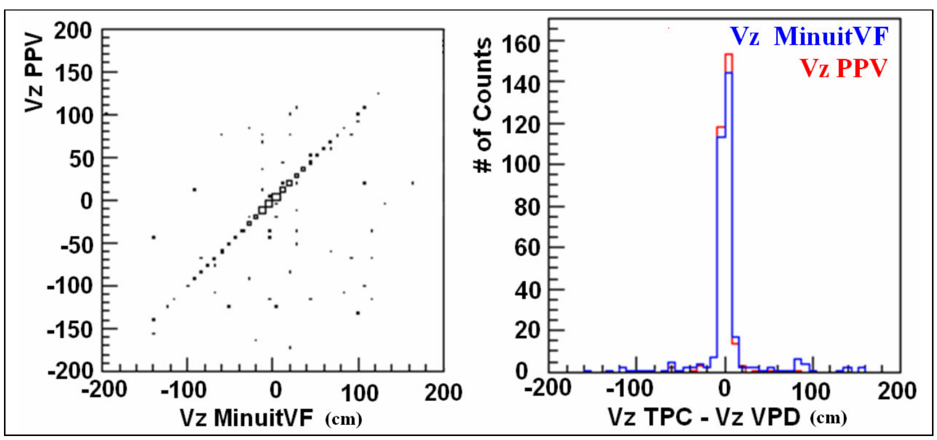

Figure 8. Comparison between PPV, MinuitVF and the VPD for d+Au 2008. The graph on the right compares the primary vertex found for each method with the VPD. The graph on the left shows the strong correlation between the z values given by the primary vertex of each algorithm.

5. Conclusion

PPV had good agreement with the hardware vertex position in both p+p and d+Au, despite the increased luminosity in 2008. MinuitVF also had good agreement with hardware vertex location in d+Au, though it did not perform as well in p+p. This bodes well for their ability to handle the expected increased RHIC II luminosity. While each vertex finder was optimized for a particular ion species, they both appear to have similar efficiencies for d+Au and so either algorithm can be used.

This work was supported in part by the HENP Divisions of the Office of Science of the U.S. DOE and the U.S. NSF.

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