The V-plot, a three dimensional representation of tracking data from HEP experiments

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Contents

1 Abstract

The V-plot is a graphical representation of three dimensional points and three dimensional tracks inside a cylindrical detector surrounded by a solenoidal field.

The position of a point in space can be given by its azimuthal angle ϕ, its distance to the beam axis (z-axis) ρ and the pseudorapidity η, which is a function of the angle θ between the beamline and a line connecting the point to the primary vertex. With ρ_{max}, the outer radius of the cylindrical detector, one defines a further set of coordinates: ϕ, η_1, η_2 where $\eta_1 = \eta - k \cdot (\rho_{max} - \rho)$ and $\eta_2 = \eta + k \cdot (\rho_{max} - \rho)$. The parameter k $\left[\frac{1}{cm}\right]$ is set interactively. For each space point two points are drawn on a picture of the ϕ/η plane: one point at the position ϕ, η_1, the other at ϕ, η_2 .

In this case, space points along a helix segment close to the primary vertex lie on a V like pattern with straight arms. The gradient of the arms is proportional to $\dfrac{1}{P_T}$. Due to the direction of the magnetic field of ATLAS, downward pointing V's belong to positive tracks upward pointing V's to positive tracks. Curved arms indicate that the respective helix does not pass the primary vertex or that its transverse momentum is rather small.

With a well selected parameter k, the distance between points along a V belonging to measured points is very small compared to the total range of ϕ and η and compared to conventional projections. Therefore, the V-plot has a high track separation and a high efficiency to detect deviations from a helix due to kinks or measuring errors.

Tracks represented by V's can be extrapolated easily to the Lego Plot or similar representations of the calorimeters. The V's can be used to associate tracks found in the inner subdetectors to backward extrapolated tracks found in the muon detector.

From the coordinates of a pair of points representing a space point, namely ϕ, η_1 and ϕ, η_2 one can recalculate the carthesian coordinates of the space point. Therefore, the V-plot is a three dimensional picture of the data.

2 Introduction

The ATLAS detector produces data sets (events) which may, depending on the luminosity, contain the data of different interactions and maybe noise. Of those only the triggering interaction is of interest.

It is the role of an event display to visualize such events or only the data of triggering interactions. An event display should be distinguished from a more or less detailed detector display and from the display of single simulated particle trajectories or showers.

When discussing an event display, one deals with two questions:

1. How to bring the data from the data storage to the screen? This means to consider the structure of the data, the program, the basic graphics package etc..

2. **How to show the data on the screen, so that the human observer can best understand them, i.e. how to bring the data from the screen via the eye into the human brain to support human data treatment?**

This article [1] is concerned with the second question.

The data shown in the pictures stem from simulation[1], as real data are not yet available. For simplicity, the true tracks of the triggering interaction and their associated space points are called "**true tracks**" or "**true space points**". The normally heavy **background** is due to noise and **pile up** tracks with their space points. The data used here deliver no association between space points and the **reconstructed tracks**.

The tracking data of the inner tracking chambers of ATLAS are of two types:

1. The measurements of the pixel detector and the SCT, using low angle stereo, deliver three dimensional space points.

2. The tubes of the TRT deliver two dimensional measurements, as the position, where a charged particle crosses a tube, is not known along the fairly long tube.

The V-plot[2] is a three dimensional, non intuitive, abstract, graphical representation of three dimensional space points or tracks. It favours significantly the recognition of helices even in the difficult case that they are represented by their associated space points.

The V-plot can be used[3] for the following tasks:

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[1] The simulated data used in this paper are taken from one event only, which was simulated years ago. At that time the reconstruction program had some bugs. Such bugs are very useful to test the potential of an event display program.

[2] The concept of the V-plot [2], [3], [4], [5] was originally developed for the event display program DALI, where it was used for the representation of three dimensional data from the tracking chamber, TPC, of the ALEPH experiment. It is now used to represent data of the three dimensional tracking chambers of ATLAS in the event display program ATLANTIS.

[3] If the V-plot is used to correct the data, error calculations are biased.

Purpose of the V-plot

1. to identify track patterns from the display of space points,

2. to select tracks or their space points for further investigation,

3. to identify tracks,

   - which might be of special interest,
   - which have problems,
   - which were lost,
   - which were wrongly reconstructed.

4. to extrapolate tracks to three dimensional data of subdetectors further away (e.g. calorimeters),

5. to associate backward extrapolated muon tracks to tracks of the inner detector,

6. to understand interactions by displaying space points or tracks and by extrapolating them to the calorimeters.

The concept of the V-plot will be derived for the first of the tasks above.

It will become clear, that the V-plot is a very powerful tool, which is easy to understand and to use. But it is not self explanatory. This article is meant to teach the interested reader how to work with it.

As the V-plot is a special form of the ϕ/η projection, the V-plot is called ϕ/η projection in the event display program ATLANTIS.

The reader, who just wants to understand the V-plot, should neglect

1. the extensive footnotes, which give supplementary information especially for experts,

2. the appendix, which gives further information for detailed understanding.

Section 5 - applications - gives examples of the use of the V-plot, which may be read in any order or be skipped.

2.1   How to visualize the figures ? - Figure 0

The article discusses the features of the V-plot and compares it to other projections. Practically each chapter is concerned with one colored figure. The reader should be able

to look at the respective figure, while reading the text. This is best accomplished via two independent screens or by displaying the respective picture on a screen and reading the text on paper.

A figure, which contains several subfigures, covers one screen and is stored in one file. Example figure 12 is stored in the file dcv12-ed.pdf[4].

To study the figures on a display, the set of display colors is preferable with black background. If one wants to print the figures, it may be preferable to have a white background[5]. The respective pdf file is named pcv12-ed.pdf. One should make sure, that colors are well visible compared to the figures displayed with the display color set.

Each of these output formats has the disadvantage that the number of pixels per picture generated by the program is different from the one of the original picture, so that small letters, points or lines are less well recognized than on the original picture. Therefore letter-, point- or linesize were set to be fairly large. A very large picture on the screen is preferable. The replay via acroread is fairly good.

Figure 0 allows to test the replay of the figures. It contains equally spaced square points originally drawn with $2 \cdot 2$ pixels. The picture size should be large enough, that the points are not reduced to lines with 1 pixel width.

3 The ϕ/η projection - Figure 1,2

Due to the radial structure of the interactions and the cylindrical structure of the solenoidal field many useful projections are based on polar/cylindrical coordinates (see figure 1a). Instead of the polar angle λ, which varies between $-\frac{\pi}{2}$ and $\frac{\pi}{2}$, one uses also θ , which varies between 0 and π. It is easier to show in drawings as figure 1a. More commonly the pseudo rapidity η is used, which is a function of λ (see figure 1b):

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[4] "dc" for display-color picture, "v" for V-plot, "ed" for event display;
    The pictures are also available in ps format: cv12-ed.ps.

[5] In general white is changed to black, yellow to blue, black to white and blue to yellow.

Polar coordinates used here:

$$\rho = \sqrt{x^2 + y^2} \tag{1}$$

$$\phi = \arctan\left(\frac{y}{x}\right) \tag{2}$$

$$\theta = \arctan\left(\frac{\rho}{z - z_v}\right) \ , \tag{3}$$

$$\lambda = \arctan\left(\frac{z - z_v}{\rho}\right) = \frac{\pi}{2} - \theta \ , \tag{4}$$

$$\eta = \ln\left(\tan\lambda + \sqrt{1 + \tan^2\lambda}\right) \tag{5}$$

The primary vertex lies on the beam axis - the z-axis - at $z = z_v$. The field lines are parallel to the z-axis.

Tracks of charged particles moving in a solenoidal field can be approximated by helices. The difference between tracks and helices is due to multiple scattering.

Helices are commonly parameterized by five perigee parameters:

The perigee parameters

1. R_0, the radius of the helix. R_0 is positive if the helix turns anticlockwise negative if it turns clockwise. In ATLAS R_0 is negative for positive particles and vica versa,

2. ϕ_0, the azimuthal direction of the track at the point of closest approach of the helix to the z-axis (not to the position of the primary vertex !).

3. η_0, which is a function of the angle between the track and the z-axis at the point of closest approach.

4. D_0, the distance between the point of closest approach and the z-axis. D_0 is signed. With the convention used here the distance between the z-axis and the helix axis is given by $|R_0 + D_0|$, i.e. the z-axis is outside of the helix if R_0 and D_0 have the same sign.

5. z_0, the z-position of the point of closest approach.

If $|D_0| \ll \rho$, $|z_0 - z_v| \ll \rho$ and $\rho \ll |R_0|$. helices can be described by linear functions between ϕ, ρ and z, from which follows, that λ and η are constant:

Linear helix equations in polar coordinates

$$linear: \quad \boldsymbol{\phi} - \phi_0 \approx \sin(\phi - \phi_0) = \frac{\boldsymbol{\rho}}{2R_0} \tag{6}$$

$$linear: \quad \boldsymbol{\phi} - \phi_0 = \frac{\boldsymbol{z} - z_v}{2R_0 \cdot \tan\lambda_0} \ . \tag{7}$$

$$linear: \quad \boldsymbol{\rho} \approx \frac{\boldsymbol{z} - z_v}{\tan\lambda_0} \tag{8}$$

$$constant: \boldsymbol{\lambda} \approx \lambda_0 \qquad\qquad \boldsymbol{\eta} \approx \eta_0 \tag{9}$$

The exact helix equations are given in appendix A.3 on page 25.

If helices stem from very low momentum particles or do not pass sufficiently close to the primary vertex the functions between ϕ, ρ and z deviate from linear behaviour and λ and η are no longer constant.

We define a projection by its ordinate, called here vertical axis, and the abscissa, called here horizontal axis. The projection in the direction of the beam axis with y as ordinate and x as abscissa yields the y/x projection. The origin of the carthesian coordinate system is in the center of the detector.

The y/x projection of space points[6] belonging to true tracks with $P_T > 0.6 \ GeV/c$ is shown in figure 1d.

Figure 1c shows the ρ/z projection[7], where ρ is signed:

- $+\rho/z$ for space points with $120^0 - 90^o < \phi < 120^o + 90^o$

- $-\rho/z$ for the others.

The angle 120° was selected interactively.

Figure 1e shows the ϕ/η projection of the space points. In this projection as in the V-plot discussed below, the z-position z_v of the primary vertex must be known to be able to calculate η (see equation 4 and 5).

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[6] In this paper, a space point has the same color on different subwindows of a given figure. The color is often a function of the track number of the respective true track.

[7] In the y/x projection helices are seen from a direction, where track curvature is maximum. A deviation in z-direction of a space point from an ideal position, is not recognized. In the ρ/z pojection helix segments are seen as straight lines. Space point deviations in ϕ direction are not recognized. In this sense y/x and ρ/z are orthogonal projections. If a space point lies on a helix in y/x and in ρ/z, it lies on the helix in space.

As human vision connects close points to lines one recognizes the circular measuring rows of the barrel of the pixel detector and of the SCT in the crowded regions of the y/x projection (figure 1d) and the ρ/z projection (figure 1c), but track identification is only possible for a few sufficiently isolated tracks.

In figure 1e, however, clusters of space points belonging to tracks are easily identified, as they are well separated and as the space points of a given track are close to each other: tracks are compressed.

The space points in the reactangular area on figure 1e are shown magnified in figure 2. The tracks of the jet cannot be identified in y/x (figure 2a) or ρ/z (figure 2b), but the identification is easy in ϕ/η (figure 2c). As a test: it is fairly easy to count the tracks in the ϕ/η projection but impossible in the other ones.

However it is practically impossible to judge charge and transvers momentum[8] in the ϕ/η projection. This problem is solved by the V-plot.

4 The V-plot

4.1 Explanation of the V-plot

There are three approaches to explain the V-plot:

1. The visual approach, where those projections are displayed, which are combined to yield the V-plot. The features of the V-plot are derived from the features of the projections (subsection 4.1.1).

2. The mathematical approach, which gives the variables displayed in the V-plot and derives the features of the V-plot from the helix equations in polar coordinates (subsection 4.1.2 on page 10).

3. The basic approach, which explains, how the V-plot was developed. This is shown in appendix A.1 on page 22.

The reader should select one of these approaches.

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[8] The track length gives a rough estimate of P_T, which is only valid, if the first and last space point of the track is recorded. For tracks with 3 space points of the pixel detector and 4 SCT hits one may guess the track direction i.e. its charge.

4.1.1 Visual explanation of the V-plot - Figure 3, 4

Figure 3a (y/x projection) and 3e (ρ/z projection) show ideal space points of two artificial helices passing through the primary vertex (at $z_v = 0$), i.e. $D_0 = 0$ and $z_0 = z_v$. As these helices are only slightly curved (figure 3a) they are linear in the projections ρ/z (figure 3e), ϕ/ρ (figure 3b) and ϕ/η (figure 3f) according to the equations 6.

The V-plot is based on a combination of the ϕ/η and ϕ/ρ projection:

The basic projections of the V-plot

$$\phi \quad versus \quad \eta - k \cdot (\rho_{max} - \rho) \tag{10}$$

$$\phi \quad versus \quad \eta + k \cdot (\rho_{max} - \rho) \tag{11}$$

These two projections are shown in figure 3c and 3d[9], where ρ_{max} is the outer radius of the SCT detector (ρ_{max} is called ρ" in figure 3).

The real V-plot, as seen in figure 3g, is the superposition of the two projections.

Two points are drawn for each space point. On the vertical axis, they have the same position given by the ϕ value of the space point. Horizontally they are positioned to the left and the right of the η value of the space point at a distance $k \cdot (\rho_{max} - \rho)$. This leads to a V like pattern of the space points of a helix.

The parameter k is interactively chosen with the dimension $[\frac{1}{cm}]$, so that the angle of the V-arms is roughly 45° for tracks above 1 GeV/c. The parameter ρ_{max} may also be varied.

In figure 4 true space points are shown over the total ϕ, η range in the ϕ/η and ϕ/ρ projection and in the V-plot. The narrow figure 4b shows a highly compressed ϕ/ρ projection of the data, which has a high point density due to the small window side. See appendix 4.1 on page 8 [10].

One sees again how a combination of the compressed ϕ/ρ projection with the ϕ/η projection in figure 4a (the same as figure 1e) leads to the V-plot in figure 4c. The V-plot keeps the rather low point density of the ϕ/η projection (figure 4a) and its powerful track separation. It allows for a good track analysis as in the ϕ/ρ projection of figure 4b.

There are two small regions in the V-plot[11] of figure 4c, where the point density is very high. These jet-regions will be shown magnified further below.

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[9] The parameter k was chosen such that the visual gradient of the tracks was the same in figure 3b and 3c.

[10] See also figure 18.

[11] The rather significant scattering of the space points of the SCT is due to the non negligible

4.1.2 Mathematical explanation of the V-plot

From the polar coordinates of a space point - ϕ, ρ, η - the three V-plot coordinates ϕ, η_1 and η_2 are deduced:

The three V-plot coordinates: ϕ, η_1 and η_2

$$\phi \qquad \eta_1 = \eta - k \cdot (\rho_{max} - \rho) \qquad \eta_2 = \eta + k \cdot (\rho_{max} - \rho) \; , \qquad (12)$$

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where the parameter k is set interactively. It has the dimension $[\frac{1}{cm}]$.

If helices pass sufficiently close to the primary vertex and if their bending is not too large, the functions $\phi(\eta_1)$ and $\phi(\eta_2)$ are linear, which follows from equation 6^{12}, 9 and 12:

$$d\phi/d\eta_1 = \frac{1}{2R_0} \propto -\frac{1}{P_T} = constant \qquad d\phi/d\eta_2 = -\frac{1}{2R_0} \propto \frac{1}{P_T} = constant \; . \qquad (13)$$

For each space point two points are drawn on a picture of the ϕ/η plane: one point at the position ϕ, η_1, the other at ϕ, η_2. The pairs of points belonging to space points of the same helix lie on two straight lines which cross at $\phi = \phi(\rho_{max})$. There are no points beyond this point, so that a V pattern is formed.

4.2 The V-plot interpretation - Figure 5

The V-plot, short notation:

$$\boldsymbol{\phi} \quad \boldsymbol{versus} \quad \boldsymbol{\eta \pm k \cdot (\rho_{max} - \rho)} \qquad (14)$$

$$\pm \; stands for \; + \; \underline{and} \; - \; . \qquad (15)$$

The V-plot is only applicable to three dimensional measurements, e.g. space points, as the position of the pair of points on the figure is a function of ϕ, η and ρ of the space point. Vica versa one can deduce from the position of a pair of points in the V-plot[13] the

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distance between the stereo planes.

[12] In equation 13 is $P_T \propto -R_0$ is assumed.

[13] One may connect the pair of points by a line, if it is unclear, which points belong together. An example is shown in appendix A.5 on page 27.

position of the corresponding space point, i.e. ϕ, η and ρ hence x, y and z. Therefore **the V-plot is a three dimensional representation of space points**, i.e. more than a two dimensional projection, in which information is lost. This is discussed in more detail in appendix A.2 on page 24 .

As η is constant for all space points on a given helix the V-plots inherits the features of the ϕ/ρ projection:

The rules of the V-plot

- In the V-plot tracks exit at the tip of the V, where $\rho_{max} - \rho = 0$.

- Due to the ATLAS magnetical field direction, V's of negative tracks are pointing upward, V's of positive tracks are pointing downward.

- the arms of the V are straight lines with a gradient proportional to $\dfrac{1}{|R_0|} \propto \dfrac{1}{|P_T|}$:

  - Low P_T tracks with a large ϕ variation are represented by a very long V with small opening angle.
  - High P_T tracks with a small ϕ variation are represented by a rather short V and have a large opening angle.
  - For very high P_T tracks the ϕ variation may be so small that the arms of the V are horizontal lines.

- Long V's with curving arms at their tip represent low momentum tracks where $\sin(\phi - \phi_0) \neq \phi - \phi_0$.

- For helices which do not pass through the primary vertex the linearity according to the equations 6 is no longer valid, so that the respective V's have curved arms or are assymmetric around their vertical axis. In this way one may detect tracks of secondary interactions.

Figure 5 shows a comparison of the ϕ/η projection with the V-plot. For some V's the P_T value of the associated tracks is displayed to show the correspondance between the angle of the V and P_T.

4.3 The V-plot of true helices - Figure 6

Helices[14] can be drawn in the V-plot by calculating the respective pairs of points for a sufficient number of three dimensional points along the helix[15]. Lines connecting these points are then drawn for each arm separately. True helices through the primary vertex or close to it will form a V.

Figure 6a shows a V-plot of true space points compared to a V-plot of true helices (figure 6b). Due to the small distance between points on the V-plot, the two V-plots are almost identical, which is not the case in the y/x projection (figure 6b and c).

Small discrepancies between the two V-plots are due to the fact that the space points lie on the tracks and not exactly on the helices, which represent the tracks only close to the vertex. Therefore, the representation of tracks, which are different from the helices due to multiple scattering, is better via their space points than via the helices, but not totally exact due to measuring errors.

4.4 The V-plot parameters - Figure 7a,b,c

The parameter k is very small. In order that an operator remembers and changes easily its values, one sets $k = n \cdot k_1$, where $k_1 = 0.00036 \, \frac{1}{cm}$. The value n defined by the operator lies normally between 1 and 20. The width of the V is affected by k and the ratio of the picture scales.

Figure 7a shows a V-plot over the total ϕ, η range with $k = 5 \cdot k_1$ to be compared to figure 4c with $k = 10 \cdot k1$ and a wider window.

The region of the large jet is shown enlarged in figure 7b and c. Between figure 7b and c the parameter k is reduced, which improves track separation. η errors at the tip of the V become more apparent[16].

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[14] In principle also other curves could be drawn.

[15] When drawing a helix a third V-plot parameter ρ_{min} is required, which defines from where the V is drawn outwards. This is necessary as ϕ is not defined at $\rho = 0$.

If $D_0 \neq 0$ and if ρ approaches D_0, the azimuthal angle ϕ changes by 90°, independent how small D_0 is. As this effect complicates the V-plot picture considerably, the minimum distance ρ_{min} must be chosen carefully.

[16] The errors at the tip of the V are mostly due to the non negligible distance of the SCT stereo layers.

4.5 Helix extrapolation to calorimeters and μ - detector- Figure 7d,e

In figure 7d, showing a small part of figure 7c, the true helices are drawn as well. This figure should be compared to figure 7e, where ρ_{max} is changed from 55 cm to 150 cm. In this figure the tips of V's point at a cylinder plane with $\rho = 150\ cm$.

One may assume that this plane is a calorimeter barrel plane with a radius of 150 cm still inside the solenoidal field. If the calorimeter would have isolated calorimeter hits in the direction of the helices, they would lie at the ϕ, η positions shown as open squares in figure 7e. These artificially inserted calorimeter hits can easily be associated to the corresponding helix[17].

In reality the picture is more complicated:

- due to the showering of the respective particles, which give rise to more complicated hit clusters,

- due to the sophisticated structure of the ATLAS calorimeters.

In the simplified picture of figure 7e one recognizes two artificial calorimeter[18] hits with no V pointing to them, which means that they would have been created by neutral particles.

In figure 7d a V was artificially added (1). The data do not contain data from the μ - detector. However, if they would exist, a measured μ - track, could be extrapolated down to the primary vertex and look like the artificial V. In that case it could be associated to the V above, as the two V's are similar in position, charge and transverse momentum. Cases like this are found using the current ATLANTIS event display applied to new simulated data.

4.6 High luminosity events: the filter - Figure 8

When space points are shown via the V-plot, the number of space points may be so large, that the V-plot is overloaded and becomes too difficult to analyse.

The space points presented so far belong to a data set which was simulated for high luminosity and heavy noise leading to 39000 (thirty nine thousand!) space points. It is of

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[17] See appendix A.4 on page 26 for the extrapolation to the calorimeter endcaps, which requires a modification of ρ_{max}. The application of this modification does not change the gradient of the V arms and the rules of the V-plot.

[18] When calculating the ϕ, η position of calorimeter hits it is important to calculate η as seen from the primary vertex at the position z_v on the beam axis, i.e. not as seen from the center of the coordinate system!

no use to show a figure of the respective V-plot, as it is just uniformly filled with points. A significant reduction of the number of space points to be drawn is required.

When drawing all true space points without background space points the V-plot of figure 8a (1110 space points) results, which is still rather difficult to analyse in contrast to the V-plot in figure 8b (241 space points), which contains only true space points from the - more interesting - true tracks with $P_T > 1 \; GeV/c$.

However, it will not be possible to make such a space point selection on real data. A way out would be to show only those space points which were associated to the reconstructed tracks. This implies that the association of space points to the reconstructed tracks is given. However, a space point selection on the basis of the reconstruction is dangerous. It would be impossible to find lost tracks or to correct tracks, where relevant space points were not associated.

Therefore, a method was developed [7] to filter out the space points of tracks of the triggering interaction without taking into account information from the reconstruction. For this technique the primary vertex position z_v needs to be known beforehand[19].

The filter was tuned to lose as few 'good' space points as possible for tracks above 1 GeV/c. Space points of tracks below 1 GeV/c are mostly lost[20]. On the other side some 'bad' space points do pass the filter leading to a total number of 370 space points out of the 39000 space points of the data set. From the simulation one gets 241 space points of simulated tracks above 1 GeV/c.

A V-plot of the filtered space points is shown in figure 8c, which is easy to analyse. It contains some V's which are not seen in the true data of figure 8b. They belong either to tracks below 1 GeV/c or to pile up tracks or are background space points[21].

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[19] A technique to find the vertex positions of interactions with sufficiently many high P_T tracks was developed. The technique, which uses no information from the reconstruction or the simulation, needs for the data set of 39000 space less than 100 msec on a modern Laptop.

The technique makes use of the fact, that two of the perigee parameters are the same for all primary tracks, namely D_0, which is 0, and z_0, which is equal to z_v. For combinations of 4 space points lying on a helix with $P_T > 5 \; GeV/c$ and $D_0 = 0$ the z-position is calculated, where the helix crosses the beam line. A histogram of the z-position gives z_v.

[20] The basic method of the filter consists in keeping only those space points, where at least three more space points are found in the same ϕ, η direction on alltogether four different layers.

The filter needs for the data set of 39000 space points less than 500 msec on a machine with Intel Pentium Centrino M, 1.73 GHz and 2 GB of memory. This is tolerable, when interactively using an event display program.

The effective P_T cut of the filter can be decreased, but the time to run the filter will increase and more 'bad' space points will pass the filter.

[21] These "noisy V's" have in most cases only 4 space points, which was the minimum number of space points for a 'track' to pass the filter.

The filtering process is improved to group the filtered space points into subsets of space points called groups, which contain the space points of single tracks or of very close tracks and eventually some space points due to noise. As each of the space points passing the filter has an unique group number, the space points in figure 8c are colored in dependence of the group number[22]. The coloring by groups confirms human track recognition.

5 Applications

5.1 The V-plot as a tool

5.1.1 Table of tracks and the V-plot - Figure 9

If one makes a list of helices of the triggering interaction, one may order them by their transverse momentum. Such a list of tracks above 10 GeV/c is shown in figure 9a. However, it is difficult to recognize, if helices are close to each other or not.

Figure 9d shows a table where tracks could be recorded horizontally in η and vertically in ϕ. If more than 1 track falls into a single box, the number of tracks falling into the box is recorded and the sum of their transverse momenta.

Another way of a sort of table is shown in figure 9e, where the P_T value is shown at the ϕ,η position of the track. At the center of the picture the numbers overlap each other. However, a region can be selected and shown enlarged in figure 9b.

The V-plot is similar to this table, if one replaces the numbers by symbols, namely V's, where direction and hight of the V's represent charge and P_T. If one calculates the V pattern according to equation 14, the V shows the ϕ variation of the helix and if the helix stems from a secondary interaction, which will be discussed below. In that case space ponts can be drawn instead of helices, which is done for a magnified selected region in figure 9c.

By comparing the figures showing different track representations one recognizes the correspondence between tables and the V-plot.

In the V-plot one may pick a single V to get a write up of the respective helix parameters as in figure 9a. In some event display programs, as in ATLANTIS, it is possible to highlight the helix in other projections, where it is usefull to see the V-plot and the relevant projections side by side.

To use the V-plot in this way no knowledge about the V-plot is required.

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[22] Space points of different groups may have the same color, as there are not enough different colors, which can be distinguished by human vision in case of small screen objects.

5.1.2 Track selection via the V-plot - Figure 10

The selection of space points of one or more tracks is best done by drawing only those space points, which are inside a narrow, sharp pyramid with

- the axis defined by ϕ and η

- and the width defined by $\Delta\phi$ and $\Delta\eta$.

ϕ, η, $\Delta\phi$ and $\Delta\eta$ are best defined in the V-plot by selecting a ϕ/η region. Two examples are shown in figure 10.

The space points inside the selected region (1) containing a single track are displayed in the y/x projection in figure 10b. If one would display all space points the track is hardly identified (see figure 10c) due to a narrow jet with similar ϕ as seen in figure 10a.

The region (2) of space points of two tracks is selected and shown in a ρ/z projection (figure 10d). Without the selection they are hardly identified in figure 10e, due to the large jet which has similar η[23].

In the same way one can select helices instead of space points..

5.2 Use of the V-plot to understand the interaction

5.2.1 The structure of the interaction - Figure 11

True helices with $P_T > 1\ GeV/c$ are shown in the y/x, the ρ/z projection and as V-plot in figure 11. In the V-plot it is easy to identify a narrow and a large jet, with similar, slightly negative η but almost opposite in ϕ. There are furthermore two tracks with a slightly positive η and with very high P_T, so that they look like horizontal lines. They are not belonging to the jets.

The transverse momentum and charge of the particles, can be judged from the y/x projection and the V-plot, but not from the ρ/z projection[24]. It is very difficult to describe the structure of the interaction from the y/x and the ρ/z projection as clearly and easily as it is done via the V-plot.

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[23] The narrow jet falls into the opposite y-x hemisphere. Therefore it is not shown in figure 10e.

[24] If one can neglect the influence of uncharged tracks, the y/x projection of charged tracks shows momentum conservation. However, the ρ/z projection, does not show momentum conservation. The "momentum symmetry" between the upper and the lower part of the projection, depends on how the hemispheres were defined. Even in its pure form without hemispheres the ρ/z projection cannot be used to judge momentum conservation.

Data from the calorimeters, which are further away from the center, are mostly shown in the form of Lego plots (or similar pictures), which are based on the same ϕ/η projection as the V-plot[25]. A presentation side by side of the V-plot and a ϕ/η projection of the calorimeters can be used, to further investigate the structure of the interaction by associating the charged tracks with the deposited energy in the calorimeters.

5.2.2   Triggering interaction with close pile up interactions - Figure 12

Simulated helices from three interactions are shown in y/x, ρ/z and as V-plot in figure 12. One is the triggering interaction at $z_v = -75.6mm$, the others are close pile up interactions[26] at $z_v = -72.1mm$ and $z_v = -76.7mm$.

In the y/x and ρ/z projections (figure 12a and b) the three sets cannot be distinguished.

The V-plot shows clearly different sets of tracks, one with symmetric V's and two others containing V's showing a similar unsymmetry. These sets can be attributed to the different primary vertices.

By changing interactively z_v one can find the z value, where a given V and similar ones are symmetric. In this way one can determine interactively the z-position of the corresponding vertex.

5.2.3   Track with a kink - Figure 13

In the V-plot of figure 13a the selected region contains two V's, one of which looks unsymmetric. This is confirmed via the magnified image in figure 13d, where the right V - track 1 - is rather unsymmetric around a vertical axis through the V.

The two tracks displayed in a ρ/z projection in figure 13b seem to point to the primary vertex. If, however, the area in between the parallelogram is transformed to the square window of figure 13e, so that the aspect ratio is sufficiently high, it becomes obvious that track 1 scatters at the position of the second space point. A straight line through the outer 6 space points would cross the beamline at a distance of 4 to 5 mm from the primary vertex[27].

Similarily the conventional y/x projection shows no scatter of the track (figure 13c). If the track image is linearized by applying the ϕ/ρ projection, and if the ϕ range is sufficiently small, a scatter at the position of the second space point gets visible, too. See figure 13f.

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[25]   This is right as long as η is calculated as a funtion of $\dfrac{z - z_v}{\rho}$ and not as function of $\dfrac{z}{\rho}$!

[26]   As the pile up interactions have tracks of fairly low P_T, helices with $P_T > 0.4\ GeV/c$ are displayed to show more tracks.

[27]   Due to this offset the space points of the track were rejected by the filter.

This example demonstrates the 'visual sensitivity' of the V-plot to small deviations from the ideal helix behaviour, this even if the V-plot is not magnified.

In the overall representation of figure 13a the hits of single tracks are very close to each other, they are compressed, which makes kinks etc. more visible. The magnified picture in figure 13d shows the kink similar to the picture in figure 13c with a large aspect ratio. This demonstrates that compression and large aspect ratio characterize the same concept[28].

5.2.4 Secondary vertices - Figure 14

Starting from the V-plot in figure 14a, which shows true helices, the large jet is magnified in figure 14b. One clearly recognizes, that some of the V's have curved arms. The region containig these V's is shown magnified again in figure 14c.

The helices shown in this region are displayed in y/x in figure 14d with the conventional aspect ratio 1. If one increases the aspect ratio strongly (figure 14e) it is possible to recognize four primary helices (1, 2, 6 and 10) and two secondary vertices the lower one with the helices 7,8 and 9, the upper one with the helicess 3, 4 and 5.

Figure 14c demonstrates how these three sets of helices are identified via the V-plot. The "primary V's" 1, 2, 6 and 10 have straight arms. The V's 3, 4 and 5 have curved arms, which touch[29] in the same point on both sides at the same ϕ position. The two crossing points represent a point in space, the secondary vertex. The arms of the V's 7, 8 and 10 can be extrapolated backwards to two common points with the same ϕ. They represent another point in space.

The track charge cannot be estimated in the y/x projection, as the decays are only visible when magnifying a small area close to the vertex. From the V-plot, however, the charge of the helices can be deduced: the helices 3 and 5 are negative, helix 4 is positive, the helices 7 and 8 are positive, helix 9 is negative. The total charge of the first helix set is -1. It is +1 for the second helix set. To be able to estimate the charge of the helices is important, as a total charge of +3 or -3 would mean, that helices are lost or that the assumption of a secondary vertex is wrong. From the V-plot, however, one cannot decide, if the two secondary vertices are due to a cascade decay or not. This is suggested by the y/x projection in figure 14e.

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[28] In figure 4b the horizontal axis is reduced leading to a compression. If the horizontal axis is not reduced but the vertical axis is enlarged as in figure 13f one speaks of a large aspect ratio.

[29] In all V-plots of this article, ρ_{min} was set to 15mm. Only in the V-plot of figure 14c ρ_{min} was set to 12mm, so that the arms of the three V's touch. If one sets $\rho_{min} = 39mm$, the distance of the innermost space points, the curving of the V arms is just recognized for the tracks 4, 5 and 9. If one sets $\rho_{min} = 5mm$, also the arms of track 7,8 and 10 touch, but then all true primary tracks have slightly curved V arms for small ρ, which indicates that the vertex position was not exactly at $x = 0$ and $y = 0$, as assumed.

With well reconstructed helices instead of true tracks as in figure 14 one should come to the same result

5.3 Check of pattern recognition

The high track separation of the V-plot eases detection of lost tracks.

It was shown in section 4.6, that normal interactions may have too many space points to be easily analysed even using the V-plot. This is aggravated when high luminosity data are available or when one has to deal with heavy noise. Visual analysis of data from the inner tracking detectors for full events is only applicable, if the number of space points can be sufficiently reduced by software. As a consequence, visual checking of pattern recognition means to compare data reduced via different methods, i.e.:

- compare true information and reconstruction data,

- compare true information and the filter,

- compare the filter and reconstruction,

- compare two different methods of reconstruction if these are based on different algorithms or significantly different parameters.

The process of checking pattern recognition consists of two steps:

1. A systematic check of a given interaction for possible errors. This means to 'trigger' the human brain where to look in more detail.

2. A detailed check, where an error is suspected.

In many cases a systemtic check is needed avoiding a random walk through the data being finished when one is bored with continuing.

5.3.1 Systematic check to detect lost tracks - Figure 15

There are two methods to find lost tracks:

1. compare by coloring space points,

2. compare by overlay.

An example of <u>method 1</u> is shown in figure 15a where the filter is checked by comparing it to the true data. Space points belonging to true tracks with $P_T > 1 \ GeV/c$ are selected. Then

- true space points accepted by the filter are displayed in one color (here green),

- true space points rejected by the filter are displayed in another color (white on dark background, *black* on light background)[30]. That means:
  white (*black*) 'space points' are lost by the filter.

There is only one V (1), which is white (*black*), i.e. the respective space points were rejected by the filter. However, the V is rather unsymmetric, i.e. the respective helix is not pointing to the primary vertex, which explains, why it was rejected by the filter. The V was discussed in section 5.2.3 on page 17. In the two jets, which will be discussed below, no white (*black*) V is found when being magnified[31].

Method 2 is applied[32] in figure 15b for the comparison of true with reconstructed tracks. In this case space points of true tracks with $P_T > 1\ GeV/c$ are drawn in yellow on black background, blue on light background. The reconstructed tracks with $P_T > 1\ GeV/c$ are drawn on top of the space points in red. An excess of yellow/blue space points not covered by a red track is visible (2) in the small jet. This is examined in detail in the next subsection.

In figure 15c the space points passing the filter are colored in green and overlayed with reconstructed tracks of $P_T > 0.8\ GeV/c$ in red[33].

As before an excess of space points not covered by a track is seen on top of the small jet. There are some more green V's not covered by reconstructed tracks. The narrow V's (example 3) can be neglected due their low P_T. Some tracks (4) look like fairly high P_T tracks and need to be checked one by one. It turns out that they do not lie on good V's with straight arms. One case is discussed in appendix A.5 on page 27.

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[30] The discovery of objects of a given color through human vision is eased if only very few colors, if possible two, are used.

[31] The good result of the filter may be partly due to the fact, that the filtering constants, i.e. number of ϕ and η bins of the histogram used by the filter, were adjusted using this data set. However the filter works as well for the pile up interactions in the data set. For these the filtering constants were not optimized.

[32] As no association between reconstructed tracks and their space points is available here, method 1 cannot be applied.

[33] The filter is optimized to avoid rejecting space points of tracks with $P_T > 1\ GeV/c$. As no real track reconstruction is done in the filter, space points of tracks below 1 GeV/c may pass as well. Therfore the P_T cut of the reconstructed tracks was set to 0.8 GeV/c.

5.3.2 Examination of the narrow jet in detail: lost track - Figure 16

The narrow jet in figure 16a is magnified in figure 16d, where space points are colored by the filter and reconstructed tracks colored by their track number. A green V without reconstructed helix is clearly recognized[34]. Measuring interactively the opening angle of the V gives a transverse momentum of 10.5 GeV/c.

It is rather difficult to detect the track in the y/x projection (figure 16b) with the conventional *aspect ratio* = 1. It is impossible to find it in the ρ/z projection (figure 16e). Selecting the small jet via a ϕ, η cut and increasing the aspect ratio considerably leads to the representations in figure 16c and f, where the track is easily seen in y/x but still undetectable in ρ/z. The symbol * above the outmost space point of the lost track may help.

In figure 16d, there seems to be another upward pointing V inside the narrow jet without reconstructed track with the symbol + below its outmost space point. The two red lines show direction and position of the arms of the V. To further check this V, one should flag its space points[35] and let reconstruction decide, if there is a real helix[36].

5.3.3 Wrong track - Figure 17

The large jet is magnified in figure 17a showing reconstructed tracks and space points. The space points are selected and colored by the filter. There are two tracks in the upper part of the jet, one of which (red) has curved arms, which means, that the track does not originate from the primary vertex. The two tracks are magnified in figure 17d applying a ϕ, η cut[37].

It is clearly seen, that the track of the V with the curving arms, uses a space point of the other track. There is a space point (red) which was apparently not used by the reconstruction, which would change the V curvature to linear, so that the track would originate from the primary vertex. This is confirmed by the simulation.

When using the conventional *aspect ratio* = 1 in y/x (figure 17b) and ρ/z (figure 17c), the deviation is not detected. Applying the ϕ, η cut and using a large aspect ratio (figure 17e

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[34] The track was reconstructed but lost due to a data transmission error in the reconstruction program.

[35] The V can be isolated by applying a very narrow η cut around the η vaue of the V. See footnote 37.

[36] The true helix data give no hint, as there is an error in the respective true helix parameters and in the space point association.

[37] The cut is on ϕ and η not on $\eta \pm k \cdot (\rho_{max} - \rho)$ (see equation 14). If one defines $\Delta\eta$ for the cut small enough, as done here, the two further V's at the left and right are excluded.

and f) makes the deviation visible in the ρ/z projection.

A warning about the suggestive behaviour of the V-plot, which might lead to a wrong appreciation of cases like this, is discussed in appendix A.6 on page 27.

6   Conclusion

The idea for the V-plot stems from the observation, that tracks are well recognised in the compressed ϕ/ρ projection and that tracks are compressed and well separated in the ϕ/η projection. A combination of these two projections yields the V-plot.

As η depend on the position of the primary vertex on the beam axis at $z = z_v$, the knowledge about the vertex position enters the V-plot representation, which is not the case for conventional projections. This is one reason for the power of the V-plot as compared to conventional projections. In rare cases, this may lead to suggestive but wrong solutions, when using the V-plot.

The V-plot turns out to be a very useful tool to understand the data and to check hardware and software.

Beginners may just use the V-plot to pick a track, in order to list its parameters and highlight the respective helix in other projections on other subwindows.

Somewhat more advanced users will use it as a working tool, to select tracks for further investigation, again visualizing them in other projections.

The advanced user understands most details via the V-plot, without always looking to other projections. In this case he relies on the fact that the V-plot is a three dimensional data representation, through which no information is lost as it is the case in two dimensional projections.

7   Acknowledgments

A   Appendix

A.1   From the ϕ/η and the ϕ/ρ projection to the V-plot - Figure 18, 19

See section 4.1 on page 8 and section 4.1.1 on page 9.

The combination of the ϕ/η and the ϕ/ρ projection comprises three steps

1. The compression of the ϕ/ρ projection,

2. the combination of the ϕ/η and the ϕ/ρ projections to the basic V-plot projection,

3. the overlay of the positive and negative basic V-plot projections.

True space points are shown in figure 18a in a y/x projection. This projection has the problem, that tracks or their space points get very crowded towards the center. They may even cover each other.

This is improved, if tracks or their space points are displayed in the ϕ/ρ projection shown in figure 18b, where the space points on the inner row are expanded in ϕ direction by a factor 4 compared to the y/x projection, whereas the space points on the outer row are closer to each other by a factor 3. Due to the large distance between space points of the same track, it is still difficult to recognize tracks.

Through a horizontal scale change[38] in figure 18c, which reduces artifically the distance between space points - compression - tracks are better recognized as in the uncompressed picture (figure 18b). Except inside the 2 jets, tracks can be well identified. The crossing of tracks, for instance, is well visible.

The high point density of the compressed ϕ/ρ projection in figure 18c (= figure 19a) can be reduced by selecting space points inside a small η region. Fifteen compressed pictures of ϕ/ρ projections showing space points inside consecutive η regions are displayed side by side in figure 19b. This figure consists in reality of 15 discrete figures.

As η is practically constant for space points of the same track, they are found inside a single window. Only in seldom cases they are so close to a border between two neighbouring η regions, that some of the space points fall into the left window and the others into the right one. Such space points close to each other in ϕ and η may hence lie far from each other in figure 19b.

The distance d of a space point image from the center of figure 19b is proportional - neglecting rounding - to $d \approx s_1 \cdot \eta + s_2 \cdot \rho$, where s_1 and s_2 are properly choosen scaling constants.

Therefore one gets almost the same image, if one displays ϕ versus $\eta + k \cdot \rho$ with a properly choosen scaling constant k (see figure 19c).

In order to check 3D objects they must be looked at from at least two properly choosen directions, i.e. projections. A possible candidate to

1. $\phi \quad versus \quad \eta + k \cdot \rho \quad$ is

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[38]   In the y/x projection, the scale change of only one axis transforms the circular images of tracks into ellipses, whereas a change of scale of the horizontal axis of the ϕ/ρ projection, transforms straight lines into straight lines, for which only the inclination changes.

2. $\phi \quad versus \quad \eta - k \cdot \rho.$

The superposition of these two projections leads to the V-plot, which is shown in figure 19d. In this figure ρ is replaced by $\rho_{max} - \rho$. ρ_{max} is the outer radius of the SCT detector. Therefore the two projections of a track touch, where the tracks leave the SCT detector, so that the V points into the direction of the track.

A.2   How to show the position of a point in 3D - Figure 20

See page 11 section 4.2 .

If one assumes that the 3 axes in figure 20a are orthogonal to each other, the carthesian coordinate system is easily interpreted as 3D. This is done intuitively by human vision. However, the positions of the red and the green point are undefined perpendicular to the picture plane, i.e. they remain 2D, as no assumption exists, from which all three coordinates of the points can be deduced, this mathematically and intuitively. Connecting the points by a line to the center (figure 20b) or showing a rotated image[39] (figure 20c), does not help.

If instead of points small rectangular boxes are drawn, one will interpret the boxes as 3D objects. However, the 3D positions of the boxes remain unknown, i.e. they remain 2D.

It is normal practice to connect the points by a vertical line to points on the xz-plane (figure 20d). Human vision assumes

- that lines straight in the projection are straight in space,

- that the lines are parallel to the y-axis

- and that the bottom points lie on the xz-plane.

From these assumptions the 3D position of the points can be deduced intuitively. It is a question, however, if one recognizes immediately, that the two points are far from each other in space, or if this is realized after some thinking.

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[39]   During a smooth rotation around a given rotation axis each of the points moves with a certain speed, which gives three independent variables per point, i.e. the two picture positions of the point and its speed. From these one could in principle find the 3D position of each of the points.

For the human brain it is more easy to find the 3D position of a point, if it is close to another 3D object, the 3d position of which is intuitively known without rotation. As during the rotation the object and the point move with similar speeds, the human brain gives the point a 3D position close to the one of the object. The human brain associates easily objects which have the same speed.

As shown in figure 20e the 3D position can also be found mathematically under the above assumptions.

In general two points on a 2D picture plane connected by a line of variable length but constant direction have three degrees of freedom, i.e. can represent a three dimensional point[40]. The line needs not to be drawn, if the association of the points, one to the other, is obvious.

Similar to this example, two points at the same hight are drawn in the V-plot for each space point. As shown in figure 20f the center point between the 2 points has the coordinates ϕ and η of the space point. From the distance between them ρ can be calculated, i.e. the V-plot is a three dimensional representation of the data.

A.3   Helices not passing through the primary vertex - Figure 21

The exact equations [6] for $\phi(\rho)$, $\phi(z)$, $\rho(z)$ and $\lambda(\rho)$ are given below .

<div style="border:1px solid">

Exact helix equations in polar coordinates
With

$$D_1 = D_0 \cdot \left(1 - \frac{D_0}{2R_1}\right) \qquad\qquad R_1 = R_0 + D_0 \qquad\qquad R_2 = R_0 \cdot \tan \lambda_0 \qquad (16)$$

one gets:

$$\sin(\phi - \phi_0) = \frac{D_1}{\rho} + \frac{\rho}{2R_1} \qquad (17)$$

$$\tan(\phi - \phi_0) = \frac{D_0}{R_0 \cdot \sin \dfrac{z - z_0}{R_2}} + \tan \frac{z - z_0}{2R_2} \qquad (18)$$

$$\rho^2 = D_0^2 + \left(1 + \frac{D_0}{R_0}\right) \cdot 4R_0^2 \cdot \sin^2 \frac{z - z_0}{2R_2} \qquad (19)$$

If $\rho^2 \gg D_0^2$ and $|z - z_0| \ll 2R_2 = 2R_0 \cdot \tan \lambda_0$ one gets:

$$\tan \lambda = \tan \lambda_0 + \frac{z_0 - z_v}{\rho} \qquad (20)$$

</div>

Figure 21a shows the V-pattern of artificial tracks for five different cases of D_0, z_0 and $|R_0|$

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[40]   If the line direction is not kept constant the two points have four degrees of freedom and may represent a four dimensional space point.

for negative (A: $R_0 > 0$) and positive tracks (B: $R_0 < 0$). The V-arms are curved at the bottom of the V, i.e. at the start of the track.

One of the arms of a V may even be straight, if the effects of D_0 and z_0 cancel, but the other arm remains curved as seen for the tracks A4 and A5.

The case A6 shows the pattern of the decay of a neutral particle into charged tracks.

The case B6 shows the pattern of the decay of a negative particle into a negative particle and a neutral one.

For very low momentum tracks the assumption $\phi - \phi_0 \approx \sin(\phi - \phi_0)$ of equation 6 is not more valid, so that the V's curve at the end of the tracks, as shown in figure 21b.

A.4   Extrapolation to the endcap layers

See page 13 section 17 .

Calorimeter hits on the barrel and on the end cap planes are commonly drawn in a ϕ/η projection. To have the respective V's pointing to the calorimeter hits on the end caps, one must modify ρ_{max} to calculate the V's.

Modification of ρ_{max} for the endcaps

A layer with layer number n of a cylindrical calorimeter is composed out of the barrel plane at a distance ρ_b and a left and right end cap plane at $z = z_l$ and $z = z_r$ $(z_l = -z_r)$. The angles of the corners are given by:

$$\lambda_l = \arctan\left(\frac{z_l - z_v}{\rho_b}\right) \qquad\qquad \lambda_r = \arctan\left(\frac{z_r - z_v}{\rho_b}\right) \qquad (21)$$

For a space point with coordinates ρ, z and λ one should calculate ρ_{max} in the following way:

$$left\ endcap: \quad if \quad \lambda \le \lambda_l \quad \rho_{max} = \frac{z_l - z_v}{z - z_v} \cdot \rho \qquad (22)$$

$$barrel: \quad if\ \ \lambda_l < \lambda < \lambda_r \quad \rho_{max} = \rho_b \qquad (23)$$

$$right\ endcap: \quad if \quad \lambda_r \le \lambda \quad \rho_{max} = \frac{z_r - z_v}{z - z_v} \cdot \rho \qquad (24)$$

For z= z_r one gets from equation 24 $\rho_{max} - \rho = 0$ i.e. the tip of the V lies at $z = z_r$. The same for $z = z_l$. In the equations 22 and 24 ρ_{max} is a function of $\dfrac{\rho}{z - z_v}$, which is constant for points on a helix, if $D_0 \approx 0$ and $z - z_v \approx 0$. Therefore the gradients of the arms of the V's are not affected by this modification.

A.5 Check of very high P_T tracks - Figure 22

See footnote 13 on page 10 and page 20 of section 5.3.1 .

Figure 22a shows ϕ / η of true space points of a high P_T track ($P_T \approx 60~GeV/c$ see figure 15c track 6). They have practically the same ϕ and η. The corresponding V-plot is shown in figure 22b. It can only be guessed, which points belong together i.e. represent the space points. In figure 22c the corresponding points are connected by a line, when drawing the V-plot, which gives no amelioration in this case, as the lines overlap. In figure 22d a skewed V-plot is displayed, i.e. the variable of the vertical axis is modified:

$$\phi + k_\phi \cdot (\rho_{max} - \rho) \quad versus \quad \eta \pm k \cdot (\rho_{max} - \rho) \tag{25}$$

If ϕ and η are sufficiently constant the arms of the V must be straight lines. In figure 22d k_ϕ was selected such that the V arms have an angle of $\pm 45^o$. In this picture one recognizes that the track has seven space points on different layers with straight arms of the V.

For comparison figure 22e shows ϕ versus η of a cluster of space points passing the filter. They have almost the same ϕ and η values, and might therefore be a candidate for a high P_T track (see figure 15c track candidate 5). The same four pictures as for the high P_T track discussed above are shown in the figures below. One recognizes four space points, which do not give a good V, as compared to the V in figure 22d. The reconstruction program did not build a track from background points, which is qualitatively confirmed by the picture.

A.6 Suggestive behaviour of the V-plot - Figure 23

The same two tracks as in figure 17d are displayed in figure 23a. As discussed in subsection 5.3.3 on page 21 the point 2 belongs to a track, which is yellow on black background and blue on light background. The magenta track should pass through point 1. This is confirmed by the fact that point 1 is associated to the true magenta track.

If no confirmation from simulation exists, one could argue for this solution, namely that

- it is more probable, that the track originates from the primary vertex

- it is improbable, that a wrong space point is found on the extrapolation of the helix down to the primary vertex.

However, if the vertex position z_v is changed by 1.1 mm (see figure 23c) human pattern recognition might associate point 2 to the magenta track and not point 1, which demonstrates again that the shape of the V depends of the position of the primary vertex.

Human pattern recognition prefers if possible

- symmetric solutions,

- linear extrapolation, if a line starts linear (here from the tip of the V backwards).

That means track extrapolations to the primary vertex are prefered by the human brain, which might lead to wrong decisions, when using the V-plot. This is not the case in the ρ/z projection (figure 23b and d), where z_v does not enter into the calculation of the variables on the two axes.

However, lines connecting points are also very suggestive. To be sure one should be able to recognize a pattern with and without lines, which is a problem for conventional projections.

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