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PHYSICS ASPECTS OF THE DELPHI VERTEX DETECTOR

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ABSTRACT

The contribution of the microstrip silicon vertex detector to the physics from the DELPHI experiment at LEP is presented. The tagging of quark flavour for Z^0 decays to $(d\bar{d}, u\bar{u}, s\bar{s})$, $c\bar{c}$, $b\bar{b}$, $t\bar{t}$, and the spectroscopy of short-lived particles are the most natural initial physics goals for a vertex detector and provide a good introduction to more exotic physics investigations. Results of the Monte Carlo studies show the considerable improvement given by the vertex detector to these fields. The features important for the physics performance such as detector geometry, measurement precision, alignment and pattern recognition are discussed. Finally, some preliminary remarks concerning simple but efficient improvements of the detector geometry for the future are made.

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1. INTRODUCTION

In this paper we present the physics aspects of the silicon microstrip detector being built for the DELPHI experiment at LEP. For a general description of the detector see references [1],[2]. Recent progress in the detector construction is reported at this conference by G. Maehlum [3].

The purpose of the vertex detector is to improve the localization of both the primary e^+e^- interaction vertex and secondary vertices, so that short-lived particles with lifetimes above 10^{-13} sec can be studied directly. The physics motivation is to tag quark flavours and to study the spectroscopy of short-lived particles. For one year of running LEP at the Z^0 mass, assuming an integrated luminosity of 54 pb^{-1} one expects the following yields of quark-antiquark pairs : 640,000 light quark pairs ($u\bar{u}$, $d\bar{d}$, $s\bar{s}$), 180,000 $c\bar{c}$ pairs and 230,000 $b\bar{b}$ pairs. Even assuming $M_t = 30 \text{ GeV}$, which now seems to be an underestimate, only 46,000 $t\bar{t}$ pairs would be anticipated.

The current vertex detector design has been constrained by the very small amount of space between the beam pipe and the inner detector. The optimization of the detector design concentrates on :

- Reduction of the multiple Coulomb scattering by minimizing the effective thickness of the beam pipe and of the vertex detector itself.
- Reduction of the extrapolation error by getting the first detector layer as close as possible to the interaction point.
- High intrinsic detector resolution. This leads naturally to silicon detectors.
- Good algorithms for alignment, pattern recognition and identification of vertices.

The outline of the paper is as follows. In the next section we discuss the present geometry of the detector and its intrinsic precision. Section 3 deals with the use of information from other DELPHI detectors and section 4 with the error in the determination of the impact parameter. The methods and Monte Carlo results concerning primary quark flavour identification are discussed in section 5 and those for secondary vertex search and reconstruction in section 6. Section 7 contains a brief discussion of future improvements. Section 8 summarizes our conclusions.

2. DETECTOR GEOMETRY AND PRECISION

The DELPHI vertex detector will consist of two layers of microstrip Si detectors (Fig. 1). Each layer has 24 modules. A module (about 24 cm long) is parallel to the z axis and covers a little more than 15° in azimuth. The mean radius of the inner layer is about 9 cm and that of the outer layer is about 11 cm. The detector was constrained to fit into the space between the beam pipe of radius of 8 cm and the inner drift chamber of internal radius of about 12 cm.

A module contains 4 Si microstrip detectors with strips parallel to the z (beam) axis. Each detector from the inner (outer) layer contains 1024 (1280) readout strips. The strip pitch is $25\text{ }\mu\text{m}$ with every second strip read out giving a readout pitch of $50\text{ }\mu\text{m}$. The corresponding strips of the two adjacent detectors at $z > 0$ ($z < 0$) are bonded. The readout chips with 128 channels each are located at the ends of the module.

The DELPHI vertex detector provides a precision measurement of the transverse coordinate $R\Phi$ and the sign of the z coordinate for charged tracks. As seen from Fig. 1b the angle between the radial direction and the normal to the detector plane varies from 0° to 15° .

Measurements of the intrinsic detector resolution have been performed at CERN using beams of minimum ionizing particles. The Si detectors used had integrated coupling capacitors and were produced by the Centre for Industrial Research in Oslo [4]. For details about the detectors and the beam test set-up see ref. [5]. Data was taken for angles of 0° , 5° , 10° and 15° with a readout pitch of $25\text{ }\mu\text{m}$ (i.e. from every strip) and also for 0° with a readout pitch of $50\text{ }\mu\text{m}$ (as foreseen for the DELPHI vertex detector). The determination of the transverse coordinate of the particle uses linear interpolation between pulseheights on the individual strips. This method works best when most of the signal is divided between two strips. For single strip hits there is no interpolation while for more than two strips the electronic noise degrades the resolution further. In Fig. 2 we show the distributions of the number of strips per cluster corresponding to angles of 0° , 5° , 10° and 15° . Let us denote by σ_n the rms noise of a single strip. A cluster consists of all adjacent strips with signals above $4\sigma_n$ plus neighbours with signals above $2\sigma_n$. As seen from the figure two strip hits dominate at 5° ; implying maximum resolution for $25\text{ }\mu\text{m}$ readout pitch at about this angle. For $50\text{ }\mu\text{m}$ readout pitch the optimum angle will be larger.

For normal incidence the resolution in the transverse coordinate $\sigma = 3.5\text{ }\mu\text{m}$ for a pitch of $25\text{ }\mu\text{m}$ and $\sigma = 5.5\text{ }\mu\text{m}$ for a pitch of $50\text{ }\mu\text{m}$. At 5° with $25\text{ }\mu\text{m}$ pitch $\sigma = 3.2\text{ }\mu\text{m}$ [5], which is better than expected. At 10° and 15° a preliminary analysis shows that σ is larger but does not exceed $8\text{ }\mu\text{m}$. Further improvement of the resolution can be obtained by including non-linear corrections in the interpolation procedure [6].

3. COOPERATION WITH OTHER COMPONENTS OF THE DELPHI DETECTOR

The final physics analysis uses, of course, data from all the components of the DELPHI detector. For a detailed description of this detector see ref.[7]. The vertex detector, however, being a track detector with acceptance in polar angle ranging from 45° to 135° is linked particularly closely with the three other central track detectors : the Inner Detector (ID), the Track Projection Chamber (TPC) and the Outer Detector (OD). Each of these detectors covers a larger range $30^\circ < \theta < 150^\circ$, and measures all the track parameters, viz. the transverse coordinate $R\Phi$ and the z coordinate, as well as the magnitude p , polar angle θ and azimuthal angle ϕ at the momentum vector. For information concerning the precision of all these measurements cf. [8].

The vertex detector gives by far the most precise measurement of the transverse coordinate $R\Phi$ at small R . For particles with momenta (1-10)GeV/c, the resolution in $R\Phi$ at the beam pipe without the vertex detector is (80-100) μm and with it (5-8) μm . The measurement precision of the silicon detector is not fully exploited because of the small lever arm (~ 2 cm). The inner detector gives the second best measurement of the transverse coordinate $R\Phi$. Its contribution can be described by a single measurement at $R = 17$ cm with an $R\Phi$ precision of 20 μm . As discussed in the next section this additional information greatly enhances the ability of the vertex detector to localize vertices.

The vertex detector does not contribute significantly to momentum measurements. Combining measurements from ID, TPC and OD gives for $\theta = 90^\circ$ the following momentum resolution :

$$\begin{aligned} p > 2 \text{ GeV/c} : \frac{\Delta p}{p} &= [(0.06 p)^2 + (1.5)^2]^{\frac{1}{2}}\% \\ p \leq 2 \text{ GeV/c} : \frac{\Delta p}{p} &= [(0.7 p)^2 + (0.5)^2]^{\frac{1}{2}}\% \end{aligned} \tag{1}$$

The vertex detector needs very accurate alignment in order to maintain its foreseen performance. A study has been done in order to understand the effect of a misalignment of the vertex detector on its capabilities. Z^0 decay events have been generated and tracks have been reconstructed using the ID and the vertex detector. In Fig. 9 we show the impact parameter distribution of high momentum primary tracks with no misalignment (a), with a misalignment of 6 μm in $R\Phi$ plane (b) and of 20 μm in $R\Phi$ plane (c). The positions of the silicon strips in the $R\Phi$ plane need to be known to $\pm 2 \mu\text{m}$ in $R\Phi$ and $\pm 15 \mu\text{m}$ in R , their parallelism to the beam direction to ± 5 mrad. These values are difficult to attain by hardware methods. Software alignment is therefore crucial for the vertex detector, both to relate the vertex detector as a whole to the other tracking detectors and to detect any distortion of the vertex detector that might arise due to the installation procedure or to thermal expansion. The alignment has to be done with tracks, reconstructed in the ID and TPC and extrapolated to the vertex detector, where their predicted and measured positions will be compared. At a LEP luminosity of $6 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$, the alignment would require a few days of data taking. Since

movements due to thermal expansion, etc. are always possible over periods of days, systems to monitor them are planned - capacitive position probes and light spots shining on the detectors.

4. IMPACT PARAMETER RESOLUTION

For the studies reported in this paper the Lund Monte Carlo program JETSET [9] was used to generate particle tracks and the DELPHI simulation program DELSIM [10] to describe the effects of the material and the detector responses.

The impact parameter of a track is defined as the minimum distance of the track from the primary vertex. For error-free extrapolation, a non-zero impact parameter indicates that the track originates from a secondary vertex. In the real detector the extrapolation error modifies significantly the estimate of the impact parameter. The extrapolation error is due to limited accuracies of detector measurements of particle position and momentum, and to Coulomb multiple scattering.

In the DELPHI detector the determination of the $R\Phi$ coordinate is very good, while the determination of the z coordinate is poor. The error in z extrapolated to $R = 0$ is (180-250) μm for particles with momenta above 1 GeV/c. Therefore we consider only the projected impact parameter defined as the minimum distance between the projection of the track in the R,Φ plane and the primary vertex assumed to be in the same plane. The error in the transverse coordinate, $R\Phi$, is of special importance for its determination.

This can be understood from the following simple model (cf. Fig. 4). Suppose that the transverse coordinate y of a straight track generated at the point $x = y = 0$ is measured at two points only : at $x_1 = \alpha d$ with precision σ_1 and at $x_2 = (\alpha+1)d$ with precision σ_2 . Thus d is the lever arm of the detector system. The precision of the extrapolation of the measured track from the detectors to $x = 0$ is given by the formula [1]

$$\sigma_0^2 = (\alpha+1)^2 \sigma_1^2 + \alpha^2 \sigma_2^2 \quad (2)$$

This formula is a straight line approximation, but for the DELPHI magnetic field (1.2 Tesla) it remains valid for most tracks. The formula shows that for given αd the error decreases with increasing lever arm d ; thus the lever arm should not be too small. The error decreases with decreasing α ; thus at given d the first detector should be as close to the vertex as possible.

The Monte Carlo calculations show that formula (2) gives a good description of the track extrapolation from the full DELPHI detector with $x_1 = 9$ cm and $x_2 = 17$ cm, i.e. $\alpha = 9/8$. The first point corresponds to the first layer of the vertex detector with a resolution $\sigma_1 = 5$ μm and the second one to a reference point in the inner detector with resolution $\sigma_2 = 20$ μm . Because of the small lever arm of the vertex detector, the outer layer contributes very little to the extrapolation precision, although it is important for pattern recognition and alignment.

The uncertainty due to multiple Coulomb scattering also can be calculated from formula (2) with the same values of x_1 and x_2 . In this case σ_{1c} is the error introduced by Coulomb scattering in the material between the interaction vertex and the measurement point. Calculation yields $\sigma_{1c} = 12/p \text{ } \mu\text{m}$ and $\sigma_{2c} = 134/p \text{ } \mu\text{m}$, where momentum p is expressed in GeV/c.

The error in the projected impact parameter as a function of particle momentum is shown in Fig. 5 (curve b). This has been obtained using the Monte Carlo program including all effects. The approximate analysis described previously in this section yields

$$\sigma_{\text{imp}}^2 = \left(\frac{153}{p}\right)^2 + (25)^2 + (11)^2 [\mu\text{m}^2] \quad (3)$$

in reasonable agreement with the exact result. The first component in the formula is the contribution to the extrapolation error due to multiple scattering, the second one that of the measurement accuracy of the transverse coordinate $R\Phi$ and the third that due to the absolute momentum measurement error. Errors on the momentum orientation (θ, ϕ) contribute much less.

Also shown in the figure (curve a) is the result obtained without the vertex detector [11]. The improvement due to the vertex detector is better than a factor of 2 over the whole momentum range.

5. QUARK FLAVOUR TAGGING

The flavour tagging described in this section is based on the fact that, if the primary quarks are light ($u\bar{u}$, $d\bar{d}$, $s\bar{s}$), there is very little probability for a secondary vertex close to the primary one, prompt decays of K_S^0 and Λ^0 being the most probable. For heavy quarks, on the other hand, particles with lifetimes $10^{-13} \text{ sec} \lesssim \tau \lesssim 10^{-12} \text{ sec}$ are produced giving such secondary vertices. Moreover, b quarks can in general be distinguished from c quarks because they give about twice as many tracks from secondary vertices (cf. Table 1).

To decide, whether or not there are secondary vertices, the primary vertex must first be reconstructed. This reduces the initial sample of events, because some events are unsuitable for the reconstruction. For instance, the requirement of at least 5 tracks in the detector acceptance region reduces the initial sample of 1,050,000 $q\bar{q}$ events to 673,000.

Figure 6 shows the distribution of the error in the x coordinate (see Fig. 1 for the definition of the DELPHI coordinate system) of the reconstructed primary vertex. The distribution of error in the y coordinate is in our calculation similar. Including however the information about the shape of the beam reduces the width of the y coordinate distribution, while the x coordinate distribution remains practically unchanged. This time the calculation included all the events with three or more measured tracks. The reconstructed vertex is the point at which the sum of the projected impact parameters for the contributing tracks is minimal. The width of the error distribution $\text{FWHM} = 80 \mu\text{m}$. Note, however, that the distribution has non-gaussian tails ; and that the mean square root error is larger than FWHM.

Monte Carlo information about multiplicities, momenta and impact parameters of particles from primary and secondary vertices for the different primary quark flavours is summarized in Table 1 [1]. The average momentum of particles produced at the primary vertex decreases as the primary quark mass increases. Consequently, Coulomb scattering becomes more important and impact parameters increase. Particles from secondary vertices have on average higher momenta and consequently suffer less Coulomb scattering. Their impact parameters are due to the non-zero distances between primary and secondary vertices and the transverse momenta of decay particles. This effect is larger for b quarks, which live longer, give cascade decays and consequently also higher multiplicity of secondary particles. For c quarks the Coulomb scattering effect dominates and in fact the particles from the primary vertex have higher impact parameters than those from secondary vertices. Numbers in the table indicate that the prospects for tagging b-quark events are good while c-quark events are easily confused, both with light-quark and b-quark events.

5.1 Flavour Tagging Using Track Parameters

In this section we describe methods of flavour tagging using impact parameters and momentum measurements only. For the first study all tracks with momenta below a certain p_{cut} were rejected because of their large Coulomb scattering error. Then conclusions are drawn from the sum of the n biggest projected impact parameters in the events. As an example Figure 7* shows the distribution of this sum assuming $p_{\text{cut}} = 2 \text{ GeV}/c$ and $n = 3$. As seen from the figure it is easy to eliminate most of the light-quark events at the expense, however, of losing many heavy-quark events. For example, a cut-off, which reduces the light-quark contamination to about 5% leaves about 40% of c-quark events and about 75% of b-quark events. This simple approach is not very suitable for separating b-quark events from c-quark events.

* This figure is taken from ref.[12] where the calculation was done assuming a somewhat different detector configuration. It is applicable to the present configuration, because the distributions of errors in the projected impact parameter for the two configurations have been compared and found consistent.

Another method uses all the tracks [1]. To each track one ascribes 4 probabilities : P_l - that it belongs to a light-quark event, P_c - that it belongs to a c-quark event, P_b - that it belongs to a b-quark event and P_t - that it belongs to a t-quark event. Each of these possibilities is a function of the projected impact parameter and of the momentum of the track. The probability that the whole event is of type i ($i = l, c, b, t$) is the product of the probabilities P_i of all the tracks. Samples of events of type i are selected by requiring that the probability that the event is of type i is sufficiently larger than all the other probabilities for this event. Stronger requirements on the largest probability improve the signal to background ratio but of course also increase losses of good events.

Figure 8 shows the signal to background ratio as a function of the signal surviving the selection. The continuous curves have been obtained using the method described above and various selection criteria. The point furthest right on each curve is obtained using the weakest reasonable criterion : an event is assumed of flavour i if its probability P_i is bigger than each of the other three probabilities. Imposing stronger requirements one moves along the curves towards higher signal to background ratios and lower fractions of the signal. The dotted (dashed) curves connect smoothly to the value of the ratio for the original generated sample. The loss of events due to the vertex criterion can be seen.

As seen from the figure it is possible to obtain fairly clean samples of light-quark and of b-quark events at the cost of reasonable losses. Obtaining pure samples of c-quark and t-quark events using this method is marginal. However, t-quark events, if produced in Z^0 decays, can be efficiently tagged using the sphericity analysis for example.

5.2 Multidimensional Analysis for Flavour Tagging

The analysis presented in the preceding section indicates that for efficient flavour tagging, all information about the events should be used, especially for c-quark events.

In the following analysis the probability P_i that the event originates from $Z^0 \rightarrow q_i \bar{q}_i$ (q_i = light-quark, c-quark, b-quark or t-quark) is calculated as a function of 14 variables. For more information concerning this method see ref. [13]. The variables are organized into three sets defined below. Information from the vertex detector is crucial for evaluating the variables from the second set and for deciding which tracks should be included for the evaluation of the variables of the third set.

The first set of variables includes : sphericity, aplanarity and $\langle \cos \theta \rangle$ which characterize event shapes, the visible energy and missing momentum, which give information about undetected particles and the multiplicity of charged tracks.

The second set includes 3 variables, each defined from the whole set of detected tracks :

$$\chi_{\perp}^2 = \frac{1}{N-2} \sum \frac{b_{\perp}^2}{\sigma_{\perp}^2} \quad (4)$$

$$\chi_{\parallel}^2 = \frac{1}{N-2} \sum \frac{b_{\parallel}^2}{\sigma_{\parallel}^2} \quad (5)$$

$$b_j = \sum \frac{\vec{b}_{\perp} \cdot \hat{u}_{\perp}}{\sigma_{\perp}} \quad (6)$$

In these formulae, N denotes the number of charged tracks detected in the event, the sums extend over all these tracks . Vector $\vec{b}_{\perp}$ goes from the primary vertex to the point of closest approach to the projection of the track in the xy plane ; $b_{\parallel}$ is the difference in z at the point of closest approach between the track and the primary vertex ; $\hat{u}_{\perp}$ is the unit vector along the jet axis projected into the xy plane ; $\sigma_{\perp}$ and $\sigma_{\parallel}$ are the dispersions of $b_{\perp}$ and $b_{\parallel}$ respectively.

The evaluation of the variables from the third set includes only the tracks with momentum $p > 1 \text{ GeV}/c$ satisfying one of the conditions :

$$\sqrt{2} \sigma_{\perp} < b_{\perp} < 1 \text{ mm} \quad (7)$$

$$\sqrt{3} \sigma_{\parallel} < |b_{\parallel}| < 1 \text{ cm} \quad (8)$$

The lower limits reduce the contamination of tracks from the primary vertex and the upper limits reduce that from long-lived particles, mainly K^0 's and Λ^0 's. Thus the third group of variables is built from a sample of tracks that are potential secondaries. This sample is enriched in tracks originating from decays of short-lived particles containing heavy quarks. The variables of this group, limited to this sample, are : maximal transverse momentum with respect to the jet axis, multiplicity of charged particles, multiplicity of charged kaons, multiplicity of leptons and sum of the absolute values of the momenta.

The set of 14 variables was chosen so as to achieve a good separation of flavours with the additional assumption that the probability P_i for primary flavour i can be expressed as a product of partial probabilities depending each on one variable only. The possibility of improvement by modifying the variables or adding new ones remains of course open.

The results of a tagging using this method for 2000 generated events are shown in Table 2. As an example we show in Fig. 9 the separation between light-quark and b-quark events. A clear separation is visible. As seen from the table for light-quark events and for b-quark events one obtains samples with contamination below 10% with small losses. Let us add that for b-quark events one can reduce the contamination to well below 1% at the cost of losing about 40% of the signal. The selection of t-quark events induces no losses and gives a sample with about 30% impurity. The sample of c-quark events is purer than that described in the preceding section. Furthermore, most of the contamination is by light-quark events which can be eliminated using the method described in the following section.

6. RECONSTRUCTION OF SECONDARY VERTICES AND RELATED PHYSICS

The reconstruction of secondary vertices is very important for two reasons. It can yield valuable spectroscopic information about particles containing heavy quarks. Examples are lifetimes, decay channels, branching ratios. On the other hand, using spectroscopic information as input one can exploit this technique to improve flavour tagging. This is particularly interesting for c-quark events, which as described in the previous section can easily be confused with light-quark events.

For secondary vertex reconstruction c-quark events with a single decay are simpler than b-quark events with their cascade decay. For either process there is a large branching ratio into D mesons. The analysis looks the most promising for the fully reconstructible decays : $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ and their charge conjugates. These decays combine high branching ratios (respectively $(4.2 \pm 0.4 \pm 0.4)\%$, $(9.1 \pm 1.3 \pm 0.4)\%$, $(9.1 \pm 0.8 \pm 0.8)\%$ according to the Mark III measurements [14]) with helpful restrictions from kinematical fitting. The estimated error on the reconstructed D mass is 19 MeV, 15 MeV and 12 MeV for the three channels. For an analysis of B meson decays as measured in the DELPHI detector see ref.[15]. For a recent review of B physics at LEP see ref.[16]. The discussion here is based on the analysis reported first in [12], [1] and on results obtained using the DELPHI vertex reconstruction program.

A first version of the secondary vertex finding and reconstruction program has been written and is currently being tested. It uses a momentum dependent cut on the impact parameter in the transverse plane to separate tracks coming from the decay of short-lived particles. Then a search for vertices is done in this reduced sample of tracks, by forming pairs of tracks which go through (or near) a common point, and then successively matching additional tracks to such pairs, to form vertices with higher prong numbers. The vertex finding efficiency of this approach appears quite satisfactory, and not too far from the limits set by the DELPHI hardware. It is however difficult to give a number for this efficiency, since it depends strongly both on the types of events, and on what one wishes to optimize - efficiency or freedom from contamination.

The average distance between the primary vertex and the D decay vertex is 1.7 mm (3.7 mm) for D^0 (D^+) mesons produced promptly and 3.8 mm (5.0 mm) for those from B decays. The distance between the B decay vertex and the primary vertex is on average 2.8 mm. The error on the distance between two vertices depends on the errors of both their localizations. The error on the secondary vertex dominates and is not isotropic; much larger along the line joining the vertices ($\sigma_{||} \approx 250 \mu\text{m}$) than perpendicular to it ($\sigma_{\perp} \approx 25 \mu\text{m}$). Thus the error on the distance of a secondary vertex from the primary vertex is about 0.25 mm while that on the distance between two secondary vertices is roughly 0.35 mm. Therefore, the prospects for separating secondary vertices from the primary one are good. Since the average distance between the B decay vertex and the D decay vertex is 1 mm (2.2 mm) for D^0 (D^+), the separation of secondary vertices in cascade decays with D^0 's seems difficult. Note that replacing the intermediate D by an F or Λ_c makes the problem even more difficult, since the corresponding lifetimes are shorter. A better resolution in the z coordinate would help.

The precision in the measurement of the transverse coordinate is crucial. Changing the intrinsic detector resolution from $5 \mu\text{m}$ to $15 \mu\text{m}$ makes the localization of the D^0 decay vertices very difficult even for prompt D^0 's [12.]. According to recent results from the secondary vertex program, the efficiency of finding decay vertices for prompt D^0 's drops after this change from 15% to 9%. The corresponding numbers for D^+ 's are 22% and 16.5%. The localization of decay vertices for particles with lifetimes below $5 \times 10^{-13} \text{sec}$ would be out of reach.

For the analysis of the efficiency of reconstruction for D decay vertices, the obvious selections, possible with the DELPHI detector are : the requirement of an identified kaon, the requirement that the reconstructed mass of the D meson agrees within two standard deviations with the true one, the requirement that the D-decay vertex should be sufficiently far from the primary vertex, the requirement that the momentum vector of the D points back to the primary vertex, and a cut on χ^2 for the position of secondary vertex. We found, moreover, that a cut on the energy of the reconstructed D is of great importance. Accepting only the reconstructed D's with energies larger than half the beam energy eliminates, in conjunction with previous cuts, practically all the background mass combinations. Starting from the sample of $c\bar{c}$ events obtained as described in the previous section (containing a contamination of $\sim 50\%$ of light-quark events) one obtains a sample which contains about 2% of the originally generated $c\bar{c}$ events and is almost pure. Since in a c-quark event there are usually two charm particle decays, the fact that we impose our selection criteria on one of the decays, leaves the other one almost unbiased for further analysis.

7. OPTIMIZATION OF THE VERTEX DETECTOR

The present detector has been described in section 2. Its design was constrained mainly by the geometry of the beam-pipe. It is far from optimal and can be easily improved. A reduction of the beam-pipe radius from the present 8 cm to 6 cm allows one to place the inner layer of the vertex detector at 7 cm. It is believed that this will be feasible after having gained some experience with running LEP. The precision in $R\Phi$ will improve as can be seen from (2) to

$$\sigma_{\text{imp}}^2 = \left(\frac{120}{p}\right)^2 + (16)^2 + (7)^2 [\mu\text{m}^2] \quad (9)$$

A more detailed calculation gives $(13)^2$ instead of $(16)^2$ due to the increased contribution from the outer layer. Changing the material of the pipe from Al to Be of the same thickness (1 mm) gives

$$\sigma_{\text{imp}}^2 = \left(\frac{88}{p}\right)^2 + (16)^2 + (7)^2 [\mu\text{m}^2] \quad [10]$$

The improvement is due to reduction of Coulomb scattering in the pipe wall. This simple change in the beam-pipe and detector reduces the error of the projected impact parameter by about a factor 2. Another improvement would be precise z-coordinate measurement at least for the inner layer of the vertex detector. This should enhance the correct assignment of tracks to vertices and is currently under study.

8. CONCLUSIONS

The DELPHI vertex detector will have very good resolution in the transverse coordinate $R\Phi$, but gives only the sign of the z coordinate.

It upgrades the precision in impact parameter, but requires cooperation with other track detectors. This makes the problem of alignment very important.

It considerably improves primary quarks flavour tagging. It is comparatively easy to select good samples of events where the primary quarks are light quarks (uu , $d\bar{d}$, $s\bar{s}$) and where the primary quark pair is $b\bar{b}$. A good sample of events where the primary quark pair is $c\bar{c}$ can be obtained by restricting the analysis to events, where at least one D meson decays into charged particles only and the reconstruction of vertices is possible.

The DELPHI vertex detector has been designed also to localize decay vertices of particles with lifetimes $(1-15) \cdot 10^{-13}$ sec. This is easier for single decays of particles containing a primary c quark than for cascade decays of particles containing a primary b quark. A good measurement of the z coordinates would be helpful here.

The following improvements suggest themselves for the future :

- the radii of the beam-pipe and of the first layer of Si detectors should be reduced as much as possible
- the material of the beam-pipe should be changed from Al to Be
- measurement of the z coordinate at the innermost detector layer should be with similar precision to that of the $R\Phi$.

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Table 1

Mean multiplicity, momentum and impact parameter for primary and secondary particles in events generated by various quark pairs.

	Multiplicity		Momentum (GeV)		Impact (μm)	
	Prim	Sec	Prim	Sec	Prim	Sec
($u\bar{u}, d\bar{d}, s\bar{s}$)	11.8	0.2	2.9		120	
($c\bar{c}$)	8.8	3.5	1.6	5.6	140	100
($b\bar{b}$)	6.3	6.8	1.3	3.7	170	200
($t\bar{t}$)	8.1	7.3	2.1	1.7	140	220

Table 2

Splitting according to the multidimensional analysis of a sample of 2000 generated events.

	Generated as				Purity of the sample
	l	c	b	t	
classified as					
l	893	71	7	0	92.0%
c	247	252	30	0	47.6%
b	7	31	367	0	90.6%
t	18	5	8	64	67.4%
loss	23.3%	29.8%	10.9%	0%	

Figure Captions

Fig. 1 Schematic layout of DELPHI vertex detector in the DELPHI coordinate frame

- a) perspective
- b) projection on the x,y plane.

Fig. 2 Distributions of cluster sizes for various angles between the x,y projection of the particle track and the normal to the detector plane.

Fig. 3 a) Impact parameter distribution for primary tracks

- b) the same with a vertex detector displacement of $6\text{ }\mu\text{m}$ in $R\Phi$ plane
- c) the same with a vertex detector displacement of $20\text{ }\mu\text{m}$ in $R\Phi$ plane.

Fig. 4 Relation between the error on the projected impact parameter (y_{imp}) and the errors on the transverse coordinates (y_1, y_2) at x_1 and x_2 .

Fig. 5 Dependence of the mean projected impact parameter error on the particle momentum :

- a) without information from the vertex detector.
- b) including information from the vertex detector

Fig. 6 Distribution of the difference between measured and generated x-coordinate of the primary vertex.

Fig. 7 Distributions of the sum of the three largest projected impact parameters for $s\bar{s}$, $c\bar{c}$ and $b\bar{b}$ events for $p > 2\text{ GeV}/c$.

Fig. 8 Dependence of the signal/background ratio on the fraction of the signal conserved (see text).

Fig. 9 Distribution of $\text{Log}(P(bb)/P(udo))$, where $P(bb)$ and $P(udo)$ are the probabilities, estimated from the 14 variables as defined in the text. The distribution is given separately for light-quark, c-quark, b-quark and t-quark events.

Fig. 1a

Fig. 1b

**fraction of total
number of clusters**

Fig. 2

Fig. 3

Fig. 4

Fig. 5

of entries / $20\ \mu\text{m}$

Fig. 6

Fig. 7

Fig.8