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THE USE OF THE TWO SIMULTANEOUS COORDINATES IN A SILICON MICROSTRIP DETECTOR

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Abstract

I discuss the relevance of the simultaneous reconstruction of the two coordinates in a silicon microstrip detector when used in high energy colliders experiments. The advantages with respect to more traditional approach, are critically reviewed in terms of hardware and software effort.

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1 Introduction

Detectors with the readout in the two sides have become the most natural choice for the design and the construction of silicon microvertex detectors.

I believe that, given the rapid development of the last years, this has been rather a *blind* choice.

The experience gained now with the construction and the exploitation of double-side and double-side with double metallization detectors, tells us how the choice has often been underestimated in terms of the effort needed for the hardware construction and software reconstruction and simulation.

I show that the experience acquired can be a guidance for the future design of the next generation vertex detectors for the high energy colliders. In most of the cases the conclusions apply even to detectors based on materials different from semiconductors.

The parameters discussed are several, but the constraints they are faced with, are always simply the tight manpower, money and schedule.

2 The hardware effort

After many years of development, only recently, it has been shown ([1],[2]) that the designing and processing of double side silicon microstrip detectors, is reliable for the fabrication in large series. The complexity of the device has required long time of testing and analysis before the technique could be considered reliable for the scale needed at high energy colliders, of few hundreds of detectors.

The difficulties with a double-side choice for the reading of the two coordinates, simultaneously, is not limited to the sensors fabrication and testing. The assembly of the sensors on separate ladders and of these into the full detector structure is an extremely painful task requiring a very complex engineering design [3]. As much as for the construction of special tools for assembly and handling. This brings to lengthen the construction time and to a larger money investment, because, given the innovative design, easy commissioning to the industry was not possible.

Moreover, one of the leit-motiv to adopt the double-side choice is for the reduced radiation length. Later I discuss in detail the limited improvements this brings to the reconstruction performances. To respect the choice on its integrity, it is mandatory to carry out the signal with the least possible amount of radiation length. Any of the envisageble and adopted solutions [4], for the fan out of the strips transverse to the beam direction, brings to nearly doubling the complexity for the assembly, the bonding and the cost.

The electronic readout is more complex as well. The power lines must be independent to avoid ground loops. This implies that they must be decoupled to each other. This must be done for each single readout channel, for its single amplifier power line, for the detector bias, the guard ring or foxfets bias, the multiplexing digital lines and the related power.

An example is the case of the current ALEPH detector [5], in which the detector design imposes additional bias to the detector p^+ guard ring, doubling the bias lines compared to a standard single-side detector.

The similar case is the L3 one for which there are 456 independent switching power lines [6]. Beside the cost, in order to fully exploit the decoupling, one has to be sure that there isn't even electromagnetic coupling between the lines. For the L3 case additional filtering and screening was necessary, requiring further work on the all structure. This was feasible only on site, when the detector was installed. Each single main transformer of each single power line was decoupled explicitly via additional capacitors with respect to its secondary. From that the cables down to the detector and the whole structure, were additionally shielded (figure 1). Although this was a peculiar and unavoidable choice of this experiment, which can eventually be simplified for the future, this is an example of how the simultaneous electronic readout of the two coordinates, brings high hardware complexity.

For the double-side and/or double-metalized microstrip detectors, the same considerations apply. The main difference with respect to the "simple" double-side case, is that here the complexity for bonding, assembling and fabricating the fan-outs are not present. However it has still to be demonstrated that the costs are very much different.

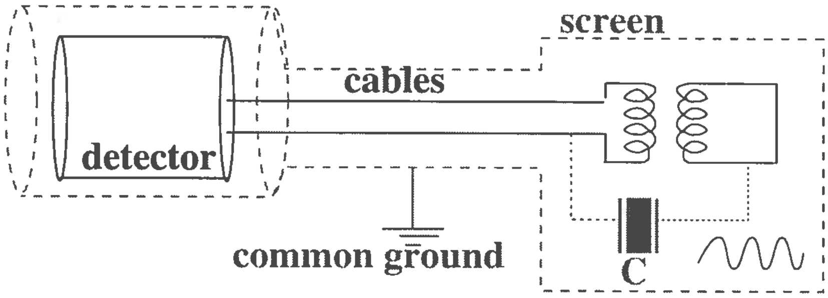

Figure 1: Power lines for the $L3$ microvertex detector.

3 The software effort

In most of the cases a simulation of the vertex detector is done at the starting phase of the project, then refined when the full structure is in place. This gives an indication of the discussion I am going to do on the fact that the detector choice is strictly related to the physics you want to do, the machine performance, the characteristics of the other detectors.

Historically the vertex detectors have been conceived, designed and constructed in a second phase of the collider experiments, beside few cases. Now that they have clearly shown great performance and enormous enlargement on the physics item, they have to become the core of the simulation at the very early design phase and in all the details to enhance the characteristics of the double-side and/or double-metal case.

The experience I am going to present is in fact on the reconstruction, rather than on the simulation. It will then appear clearly the need of an a priori simulation.

3.1 The reconstruction

Here I first deal with the pattern recognition and the improvement the double-side detectors can bring in terms of the ambiguities resolution and in this contest I discuss the charge correlation between the two sides and its use versus its potentiality.

I then discuss the implication of the choice of double-side readout on the momentum resolution, and compare it to the outer detectors performance.

I then attack the problem of the impact parameter resolution, or, more generally, of the single hit resolution and of the influence of the machine performances.

3.1.1 The ambiguities resolution

An example of making use of the double-side detectors for resolving the ambiguities is the L3 detector at CERN.

Because of the little space available when, with all the rest of the detector installed, the vertex detector with microstrips on double side was proposed [7], little redundancy on both coordinates would have been possible within the detector itself, having room only for two layers.

The choice could also fall at that time on single side implanted detectors, orthogonally glued together. The use of those wouldn't have enabled the reconstruction of the z coordinate (orthogonal to the beam direction).

In addition a stereo angle with respect to the beam axis, has been mandatory, not only for the two z layers, but also fto fully exploit the *phi* coordinate.

The Time Expansion Chamber, which follows the microstrip detector in the L3 apparatus, has a single hit resolution of $\simeq 55\mu$m, with a high redundancy on the track points up to 64 wires. All this only in the *r-phi* projections. Therefore, by adding two, although more precise points, wouldn't have helped resolving the ambiguities.

The lever arm and the high single hit resolution of the silicon detectors, could help anyway for improvements on the other measurements, like momentum reconstruction. This I discuss later.

For the applications with relatively high track density, like heavy flavor decays, the resolution on ambiguities is essential for the quality of the selection, in terms of purity and efficiency. The impact of the stereo choice doesn't however stop there. Actually this wouldn't even justify the double-side choice.

To understand the importance of a stereo angle, one can look at the sketch in figure 2.

The impact point of the particle has been found first taking the strip hit in the inner ϕ layer. Then taking the cross point with the corresponding outer ϕ layer, uniquely determined thanks to the stereo position.

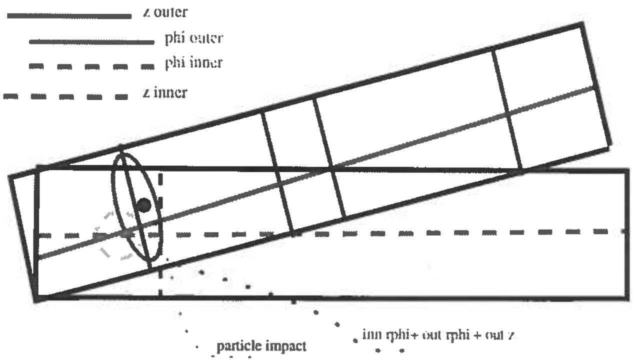

Figure 2: The impact point of a particle in the microstrip silicon layers; the predictions obtained with each layer are indicated.

In figure 2, the angle is $\simeq$2degrees and the consideration above apply for this value obtained through a simulation. It depends on the strip pitch and width and on the length of the detectors, via the equation 1:

$$\theta = arcos\frac{l-(p+w)}{l} \tag{1}$$

with: θ stereo angle; l strip length; p strip pitch; w strip width. For the L3 case: $l \simeq 70400\mu$m; $p \simeq 50\mu$m; $w \simeq 12\mu$m. Then $\theta \simeq$ 2.4degrees. The final exact choice for mechanical constraint was the relative stereo angle of the two layers $\theta = 2.0$degrees [1].

3.1.2 The pattern recognition

Thanks to the stereo angle one can then eventually reconstruct the z coordinate of the particle impact in space. In this case one makes use of the double-side simultaneous hit. First one looks in the inner and outer layer for the strip hit among several, which is closest to the phi_{inner}-phi_{outer} crossing point (the circle in the figure 2). From there one looks for the closest possible z_{outer} strip with a hit.

The full pattern recognition philosophy is similar in most of the detectors for Lep experiments. As illustrated in figure 3, one makes

[1] More general considerations apply, changing accordingly the picture to the detector characteristics. By increasing further the angle, the number of combinatorial tracks left over after reconstruction, stays constant.

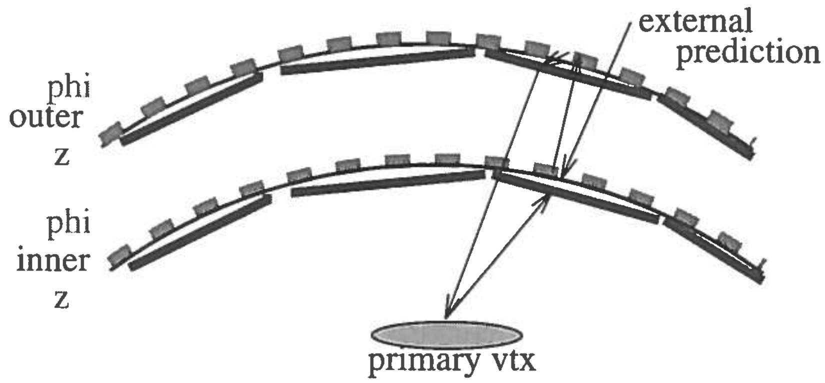

Figure 3: The pattern recognition consecutive predictions.

use of the primary vertex. This is done in this case prior to the z_{inner} strip finding.

The distinctive feature here, for the L3 case, is that the z_{outer} and z_{inner} strips are found only if the corresponding *phi* hits are found. In contrast to most of the detectors at Lep for which a relatively comparably accurate prediction of the z strips, can be obtained already by the external trackers, in the L3 case, the z prediction from the outer tracker is not as accurate. One relies then fully on the consecutive predictions (starting of course from an accurate outer tracker prediction in *phi*) of the silicon microstrip detector only.

Although this procedure can look inefficient, one can see in figure 4, on the contrary that this is not the case. Thanks to the excellent performance of the silicon detectors, the efficiency on the track finding is not limited by the request of the *phi* hits. For a sample of bhabba events, the number of tracks for which z strips contribute to the fits are comparable to the number of tracks the *phi* strips contribute. The fact that the z_{outer} bin is even higher than the corresponding phi_{outer} comes from taking the cases in which even if the *phi* strip is absent, a z_{outer} is taken anyway even if roughly predicted by the outer chamber.

This confirms that the procedure of making pattern recognition based on the double side silicon itself, is efficient as long as it is efficient the single silicon detector layer.

In conclusion, on this respect, the choice for the L3 case of the

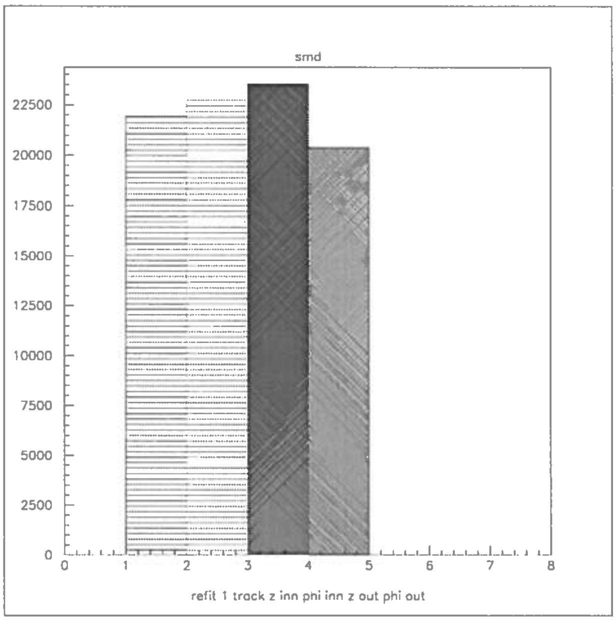

Figure 4: Number of refit tracks; the bins are for z_{inner}, phi_{inner}, z_{outer}, phi_{outer}.

double side, has brought a dramatic improvement on the performance of the tracking by adding the z coordinate and giving the three dimensional reconstruction. It is premature to say if, under these special conditions, the impact on the physics studies is as high. If one looks at the experience of the other detectors, at Lep, it is clear that the 3d reconstruction is the basis for the measurements on b decays, improving the detection and the tagging efficiency [8]. It is not established whether this improvement is due to the contemporary read out of the two coordinates. There are indications only for the L3 experiment that this is the case. This will be confirmed by the next analysis results.

This is the only case to my knowledge, the simultaneous read out has brought improvement on the pattern recognition. In the next section I discuss the impact of the correlated charge deposit on the p and the n side (the phi and z coordinate).

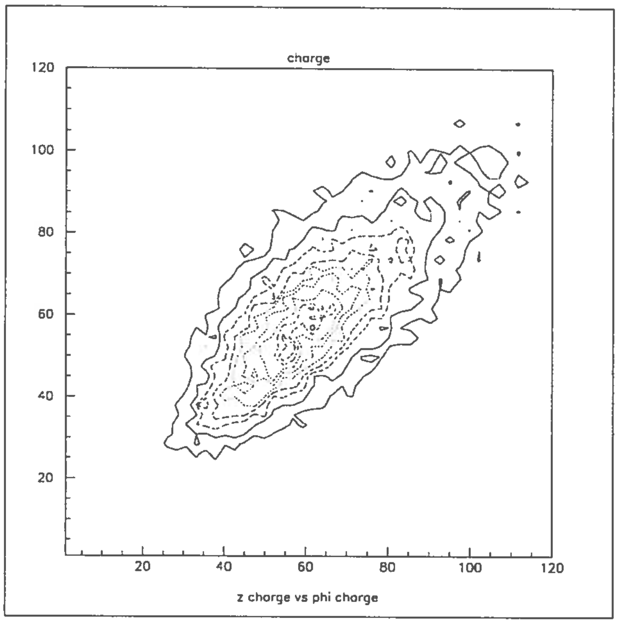

Figure 5: The charge in z versus the charge in the *phi* side for bhabba events.

3.1.3 The charge correlation

Another feature the double side detectors offer in pattern recognition, is the possibility of correlating not only the digital information of the strip hit, but also the analog information of the charge deposit between the *phi* and the z side.

For sake of historical truth, this was actually one of the arguments strongly put forward in favor of the double side detector[9].

To have an idea of the correlation, in figure 5 I show the charge in z (the n) versus the charge in the *phi* (the p) side for bhabba events.

In figure 6it is plotted the charge deposit by a track in one side minus the one on the other, divided by the total, which is the sum of the two.

As already known [10], the correlation is strong. However several conditions must be fulfilled, before one can make a significant use of this.

Given the Landau-like distribution (figure 7) which shows fluctuations with an r.m.s. of 8000 electrons, the spread of the curve in

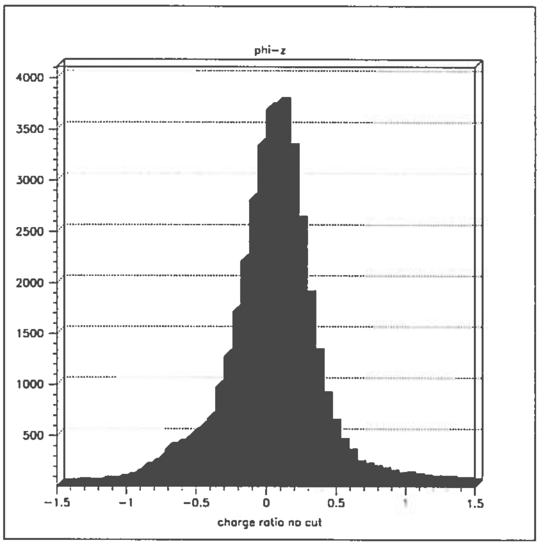

Figure 6: The charge per event in all sides *phi* minus the one in all sides z, divided by the total.

figure 6 should be due to the two Landau curves of *phi* and z only. Actually, as in the example of figure 6, the width is about 3000 electrons more than expected. If one translates this in adc channels [2], it is more evident that this additional gaussian spread is due to additional noise, to which contribute particularly noisy channels, for which the spread of the pedestal distribution is higher than 1 or 2 typical channels, up to 7 adc channels.

All that in the obvious hypothesis of having calibrated the single detector channel to an accuracy at the pedestal level, or that the channels are homogeneously distributed with a spread lower than the pedestal distribution.

The use of the charge correlation is on the rejection of the noise. This improves the quality of the pattern recognition, not the efficiency. It is anyway not essential; it doesn't allow a coordinate reconstruction in case of failure of the other projection, as it was the case of the hit (digital) strip correlation described in section 3.1.2

Results on further noise rejection, after having applied single cluster cut and for already fit tracks, are shown in figure 7. The events in the two plots on the left are for *phi* and z before the cuts, which

[2]For example in the L3 detector 1 channel is about 400 electrons

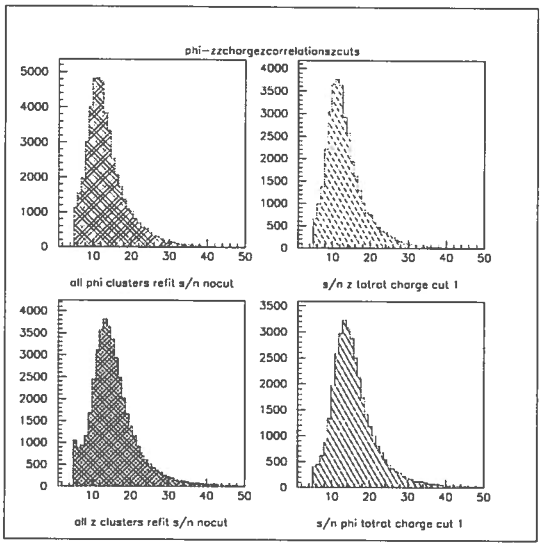

Figure 7: The charge distribution in *phi* (upper plots) and z (lower plots, before (left) and after (right) the cuts on the variable in figure 6.

corresponds to all the events in figure 6. The two plots below are for the events left in the window between -1 and $+1$ in the plot of figure 6. Noisy events which had escaped previous cuts, are rejected. The cut can then be applied more adequately, systematically prior to the track fitting, but after the pattern recognition.

This is the first time it has been proven with real data that charge correlation can eventually improve the track quality. Contrary to what stated in [9], where a selection criteria inapplicable to real data is described, the ambiguities resolution is not feasible via the pure charge correlation.

Before concluding, an additional word of warning also on the fact that to apply the cut described, the response on the two sides should be as symmetric as possible. Not only for the channel calibration as mentioned before, but in particular for the cluster selection algorithm.

As theta increases the charge deposit is higher. The traversed thickness for Lep detectors can more than double the 300μm. This changes the charge deposit.

This is illustrated in figure 8, where the charge is plotted versus the readout pitch, for the L3 detector. The gaps at the edges are

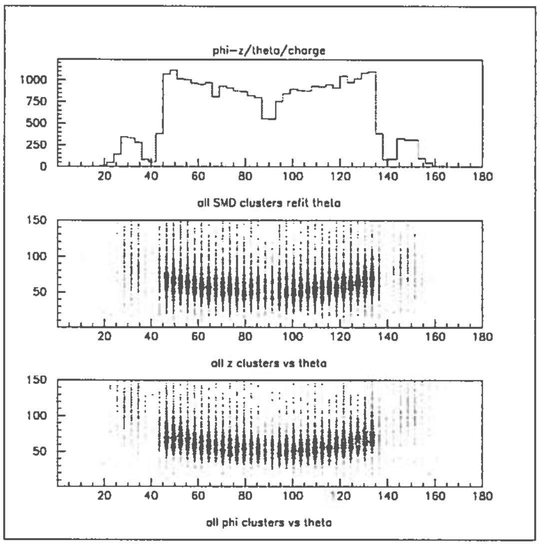

Figure 8: The charge distribution as a function of theta for the *phi* strips (middle plot) and z (lower plot). The upper plot is just all the tracks versus theta.

peculiar of the apparatus. They correspond to the gap between the barrel and the end cap reconstructing the tracks.

The cluster algorithm has to change accordingly, especially if the strip pitch is variable and different from one side to the other. Only the charge can be correlated.

The degree of correlation changes as the fluctuations change, not being described by a simple Landau. This has been taken into account (for example see [11]), but to compensate for this effect, to equalize the charge, one has to know theta with a precision higher than the angular resolution of the silicon layer itself. To do that, there must be at least three layers available or it can a priori, with the same requirement, be determined in test beam.

Further studies are anyway needed to establish more firmly if the charge correlation is a useful quantity for the pattern recognition in the simultaneous double-side readout detectors.

3.1.4 The momentum reconstruction

In this and next section I describe the relevance of the resolution at low momenta, for the momentum itself and for the *dca, the distance of closest approach.*

To have high resolution at low momenta is very important for the heavy quark physics. The choice of the vertex detector is crucial if the machine characteristics follow accordingly. Lep is not the best place to perform these studies, best suited are dedicated factories, but the high statistics available from high cross section at at theZ^0peak, makes these studies feasible. The beam pipe is $\approx$1mm, or 0.3% of the radiation length. Exactly the same relative amount of a standard 300μm silicon detector. It is like as if one has an additional layer of an inert detector, just the closest one to the interaction point. With the others, of the same multiple scattering contribution, one has to perform high precision measurement to compensate for the poor information coming after the beam pipe. This is not the only limitation one has at Lep. The other one, from the large primary vertex uncertainty, is discussed later for the implications on the decay tracks reconstruction and the impact parameter resolution.

Although the cut at very low $p_\perp$ ($\approx$2 Gev/c) is the starting point for most of the b-quark studies, there is neither confidence on going much too low in momentum because of the uncertainty from the multiple scattering[12], nor much interest for the physics channels. This means that, given this beam pipe, it is unnecessary any further saving on the multiple scattering contributions of outer layers after the first one, because anyway the contribution of the beam pipe can't be neglected unless one installs several high precision layers of silicon detectors. In fact in all the apparatuses, there are high precision outer chambers, to do well enough this job.

To profit of working at resonance, the constraint on the total available energy should also help. It is relevant to point out that the momentum is so poorly measured at high energies at Lep, that consequently the low momenta are also affected when imposing the sum. The measurement is dominated by the inaccuracy at low momenta. Taking as an example a simple topology of a bhabba event, closer are the energy of the two tracks (i.e.$\simeq$45Gev/c each), more easily one can use the constraint. This is in fact often done in several other analysis. For the low $p_\perp$ b-quarks physics this is not feasible. To illustrate the inaccuracy this method would have at low $p_\perp$, in figure 9 I plot $1/\Delta {p_\perp}^{diff}$ versus the lowest $p_\perp$ of one of the two tracks. $\Delta {p_\perp}^{diff}$ is the momentum error on the difference between the two $p_\perp$, expressed in percentage. It is clearly seen that the in-

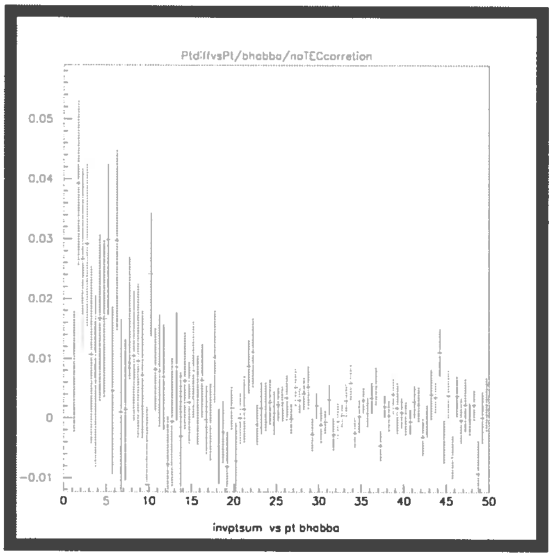

Figure 9: $1/\Delta p_{\perp}{}^{diff}$ versus the lowest $p_{\perp}$ of one of the two tracks for bhabba events.

accuracy is remarkable at low momenta and it tends to a minimum at higher momenta.

In conclusion, also for the momentum measurement, for the most important channel of the present running at Lep (namely the b-quark analysis), there isn't any evidence that having the simultaneous readout of the two coordinates, helps on the momentum reconstruction thanks to the saving of the multiple scattering. I have shown that this saving of the material is inessential for the measurement errors, when doing b-physics at Lep.

3.1.5 The impact parameter

In the case of the impact parameter resolution, the limitations of Lep is well known and so far quantified by several experiments. I will show that these limitations are dominant on the b-quark studies. This doesn't mean that a large variety of measurements can't be done, but again that the use of the double sided simultaneous read out, is marginal.

In figure 10 I sketch the principle of a typical measurement of the τ lifetime. The *distances of closest approach*, *dca* of a one-prong $\tau\tau$ Z^0decay, are summed for each track. The beam spot

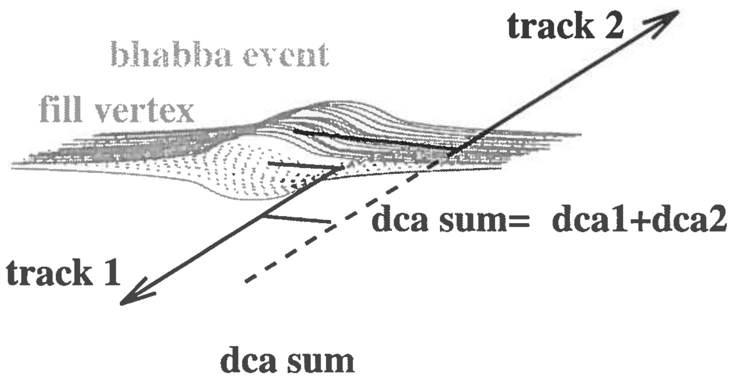

Figure 10: 3-d representation of the beam spot distribution obtained with the fill vertices of the Lep runs and definition of the sum of the dca for two tracks Z^0 decay.

is sketched in its three dimensions distortions. These contribute sensibly to the error on the *dca*. By taking the relative *dca*, each with the sign [13], it is more evident the uncertainty due to the fill vertex. This adds up in quadrature in the lifetime measurement contributing at the level of the percent. This is not marginal at the current level of accuracy for the lifetime measurement to deduce the couplings. This tells that the machine is not designed for such lifetime measurement, given the large uncertainty of the production point. Still this is not the predominant uncertainty. Even if there is, therefore, at the origin an important uncertainty, with respect to the vertex detectors, thanks to the high spatial precision of this, the fill vertex can be determined. In this case the double-side readout doesn't appreciably contribute either. The relevant contribution comes from the multiple scattering on the beam pipe. One sees a width to which contribute the beam pipe multiple scattering and the uncertainty of the beam spot statistical determination. These data are preliminary [3] from L3. The different parts of the dca error, contribute to the width of the curve in figure 11.

One could argue that thanks to the double-side detectors, the measurement can be performed in limited space. This is precisely what is vice versa the main limitation. In fact the limited space,

[3]These data are picked while the process of the intercalibration between the silicon detectors and the TEC is on the progress; a systematic difference of $\approx 33\mu m$ should be subtracted to get the resolution and then divide by $\sqrt{2}$

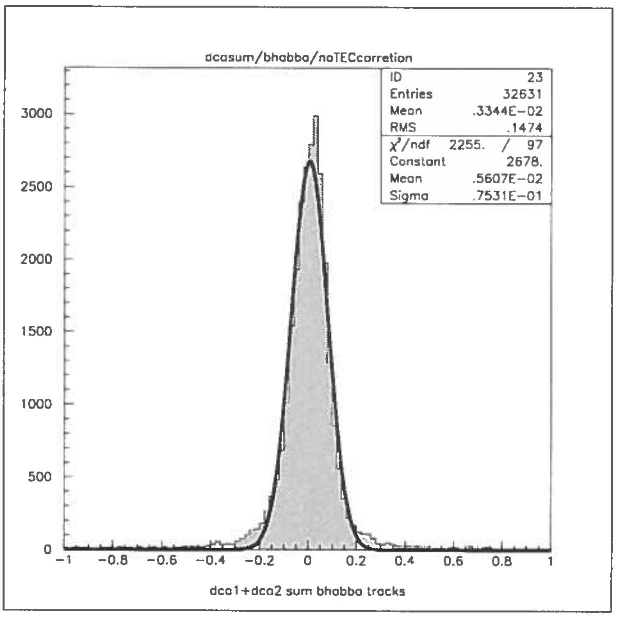

Figure 11: The dca sum distribution for bhabba events. The resolution of the detector is overwhelmed by the TEC systematics (see text) and the multiple scattering of the beam pipe.

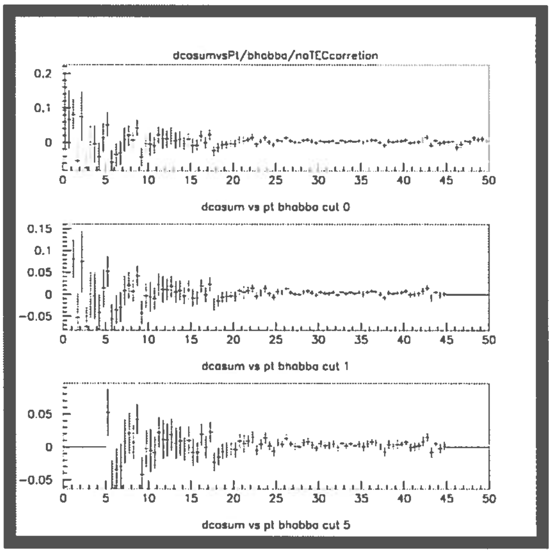

Figure 12: The sum of the dca for bhabba events, versus the $p_\perp$ of one of the two tracks for all the events (top plot); for all but $+p_\perp > 1$ (middle plot) and $p_\perp > 5$ (lower plot). Note the diifferent scale.

doesn't allow [7] a longer lever arm between the consecutive points, (production point included).

Therefore the machine limitation, could call for a looser precision on the single hit (or for a relatively coarser read-out pitch). More redundancy is also useful, but it can be provided only by the outer detectors. This is a consequence of the fact that the 3-dimensional information doesn't come simultaneously in one single spot.

The most striking influence on the resolution, coming from the machine, can be seen by the plot of the sum of the two *dca* versus $p_\perp$, for bhabba tracks, in figure 12. It is clear that at low $p_\perp$, the uncertainty is huge. The three plots are at three different scales. The bottom one are two examples of a cut at low $p_\perp$. It is clear that for any cut one makes, still even around 5Gev/c, where most of the b-quarks physics is at Lep, the relative contribution of the uncertainty on the *dca*, comes from the multiple scattering.

In the case of two layers, the important contribution comes from the beam pipe [11], [14]. In case of more layers, I can understand one needs to suppress the multiple scattering contribution. But, more important, one has to be able to quantify it, in order to parameterize the resolution. For the Aleph detector, the multiple scattering contribution, evaluated in average because it is inhomogeneous, it is 10 times the beam pipe one.

This case again tells that the simultaneous readout of the two coordinates doesn't add anything on the precision. It is much more important not to have the readout electronics in the middle of the detector than the simultaneous readout of the other coordinate. Rather than inessential as for the previous examples, in this case it would have been even better to read the two coordinates independently[4].

4 Results on an example

The arguments brought so far do not tend to discredit the use of the silicon microstrip detector. Here I show an example for the L3 experiment, of the great and fast improvement obtained on a tau lifetime measurement, by the reconstruction of the secondary vertex for the three prongs decay of a τ. With the insertion of two microstrip detector layers, it has been possible to improve the studies on the outer chamber systematics[5] and, after alignment, to have

[4] At the moment of writing a new minivertex detector with a new z readout scheme, like the one adopted in L3, is being installed in the Aleph experiment

[5] The wise man says *...it's better to align with a 4 million(swiss francs) object than with 4 million(Z^0) sample....*

an immediate improvement on the measurement of the decay length. This is due to the addition of the two high precision point in the *phi* coordinates reconstruction, added, with relatively long lever arm, to the 64 points reconstructed along the track with the chamber wires. This was done in the $r - \phi$ projections only. It was possible to make such a fast improvement thanks to the outer chamber precision. Due to the complicated, low redundancy geometry of the z coordinate reconstruction, mainly relying on the microstrip layers, the measurement cannot be extended yet to 3-dimensions (see also the discussion in section 3.1.2).

4.1 Measurement of τ lifetime

In figure 13, it is sketched a decay of a τ in three charged particles. The reconstruction of the secondary vertex is performed via a

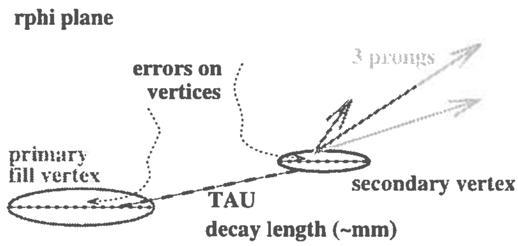

Figure 13: Representation of a 3-prongs tau decays in the $r - phi$ plane, with the error ellipses and the momentum vectors.

minimization using the three momenta vectors. The errors, entering in the decay length determination, are represented by ellipses in the $r - \phi$ plane ([18] and references therein). In figure 14, they are compared for the two cases: when the reconstruction is done with the outer chamber only and with the addition of the two microstrip detectors layers (fill area). The errors in the second case are much smaller for most of the decay length measurements.

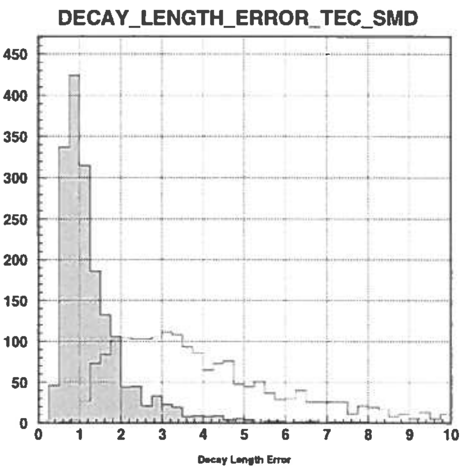

Figure 14: The error on the decay length of a 3-prongs decay of τ on the $r - \phi$ plane; comparison with and without the insertion of the microstrip detector in the track fit. It is not the comparison with the data before and after the physical insertion.

This reflects in the width of the curves. In figure 15, I plot the decay length distribution for three prongs decay on a limited sample (see also footnote[3]) of $Z^0 \to \tau\tau$. The errors are much smaller for most of the decay length measurements. The curve obtained with the TEC chamber only, is much broader and rather symmetric. The one with the addition of the microvertex point is much less broad, and it shows the characteristic asymmetric form of the decay distribution.

This tells that even for a limited sample of data and not ultimately refined alignment constants, the microstrip detector helps a lot to improve physics measurements.

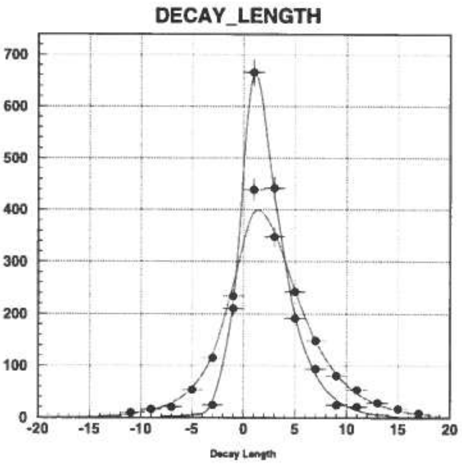

Figure 15: As for figure 14, for the decay length itself, the symmetric curve is for TEC only.

5 Conclusions

I could have given the impression that I criticize both the microstrip detectors or their ability of 3-dimensional reconstruction.

On the contrary. The 3-dimensional reconstruction is crucial, expecially at Lep, for most of the measurements interesting in this phase at high luminosity and for the next one at higher energies.

There are many physics results, obtained at Lep thanks to the insertion of the microvertex. The fact that in most of the cases, even if foreseen at the early technical proposal phase, the detectors have come later than the rest of the apparatus, has pushed for the high redundancy in the tracking and the minimization of the multiple scattering. This has brought to the double sided choice, when possible [7], [15].

I criticize the use of the double side detectors with the simultaneous readout in the two coordinates. I have shown that the effort needed in the hardware, is not justified by the results obtained.

The software effort is huge as well. But for the charge correlation use, no results have been shown so far. For the pattern recognition, only in the case of the L3 detector, the use of the simultaneous information has been crucial as I have demonstrated in section 3.1.2. However this choice has been forced by the later addition of the microvertex and not by a priori motivations.

What I claim is proven by the case of Aleph, for which the overestimated importance of the simultaneous readout has brought to readout choices which even have (although partially) compromise the performance or complicated the simulation, adding inhomogeneous multiple scattering effects to the tracking. This is being now corrected, by the insertion of a new detector ([19] and references therein). This has not been the case for the OPAL detector [16] where the choice had fall, although later, to the single sided solution.

In conclusion, while we are in the process of designing future apparatuses, we have now realized and proved that the microvertex detector are the core for excellent tracking and the outer detectors must follow adequately the choice, rather than adopting the former to the rest. This has also been possible thanks to the developments on this field, from the first proposed detectors.

Finally it has also been acquainted the 3-dimensional reconstruction is a superior tool for the physics analysis, however not necessarily double-side simultaneous readout detectors are the mandatory choice for that. The important recent developments [17]on pixel devices, from which one could build detectors with the immediate 3-dimensional information, should be followed with great care.

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