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Status of Vernier Scan Analysis to Measure Collision Offsets and Dispersion for the 1995 Energy Scan

The LEP Energy Working Group

Abstract

The status of the Vernier scan analysis for the 1995 energy scan is presented. The proceedure to fit the Vernier scan data to obtain the optimal Vernier setting is described. Roughly 35 Vernier scans were performed at each IP and at each off peak energy point for the purposes of controlling collision offsets. The stability of the optimal Vernier setting (at each energy) is found to be $\sim 1\ \mu m$ and collision offsets (at each energy) are estimated to be *on average* less than 0.3 μm over the course of the 1995 energy scan. Difference dispersion measurements were performed at each IP and at each energy point and found to be $\sim$ 2mm at each IP. Combining the results for the collision offsets and dispersion measurements leads to a preliminary estimate of the uncertainty of the center of mass energy of 0.7 MeV at each off peak point. This includes systematic effects which are discussed.

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1 Introduction

The 1995 energy scan required the control of a new effect associatated with the bunch-train bumps. These bumps generate opposite sign vertical dispersion at the interaction points of LEP. If the beams collide with a collision offset then the center of mass energy is shifted from the nominal by an amount ΔE_{cm} [1]:

$$E_{cm} = E(e^{+}) + E(e^{-}) + \Delta E_{cm} \tag{1}$$

$$\Delta E_{cm} = -\frac{1}{2} \cdot \frac{\delta y}{\sigma_y^2} \cdot \frac{\sigma_E^2}{E} \cdot \Delta D_y^* \tag{2}$$

where δy, the collision offset, is the distance between the center of the positron bunch and the electron bunch in collision at the IP, σ_y the individual beam size, ΔD_y^* the difference in the vertical dispersion ($D_{e^+}^* - D_{e^-}^*$) and E, σ_E are the beam energy and spread respectivly.

As ΔD_y^* is a characteristic of the bunch train bumps and σ_E can not be reduced to zero the only practical control of this effect is to reduce δy as much as possible. In the 1995 energy scan, LEP was operated with 4 trains of 3 bunches per beam (4*3 + 4*3). Under such circumstances it not possible to collide all bunches with zero δy since the residual beam-beam kicks generate transverse distortions of the train [2]. It is shown in [1] that optimization of the total luminosity results in a cancellation of the individual ΔE_{cm} of each collision in the train provided that the difference dispersions are the same for each family (the three collisions in a train will be referred to as families a, b and c).

The strategy for controlling collision offsets [3] was to preform Vernier scans during each off-peak fill (once near the beginning of the fill and once near the end). A Vernier scan is an automatic proceedure [4] which uses the vertical separators to scan the colliding beams across each other. The LEP luminosity monitors measure the luminosity of each family at each separation step in the Vernier scan. The lumonisity as a function of the separation indicates the Vernier setting for maximum luminosity for each family. The average of the three families gives the *optimal* Vernier setting.

Additionally, the opposite sign vertical dispersion must also be measured in order to set the size of the effect. This was also done with Vernier scans. The shift in the optimal Vernier setting when the beam energy is changed is directly proportional to the difference in the vertical dispersion. The LEP beam energy is changed by changing the RF frequency. The difference in the dispersion of the two beams is then given by:

$$\Delta D_y^* = -\frac{\alpha_c \cdot f_{RF}}{\Delta f_{RF}} \cdot \Delta y_{opt} \tag{3}$$

where Δy_{opt} is the observed shift in the optimal Vernier setting when the RF frequency, f_{RF}, is shifted by Δf_{RF}. The momentum compaction factor is denoted by α_c [5].

2 Vernier Scans

This section will describe the proceedure for performing Vernier scans and the status of the Vernier scan fit, stability, and collision offset analyses.

2.1 Online Proceedures

During the 1995 energy scan, the Vernier scans were preformed in the following way:

- Typically, there were 8 steps in the scan each separated by 2 μm. The number of steps and the step size could be changed for special circumstances.
- Three consecutive luminosity measurements (with errors) were recorded for each family for each Vernier setting. The length of each measurement was 9 seconds. The redundancy allowed a test of the errors which is important for understanding the fits to the data.
- Vernier scans were done only at one IP at a time.
- The Vernier scan data were stored in the LEP database for offline analysis.

Vernier scans typically took about 8 minutes to conduct. An online program would fit the data for the three families to a gaussian and return the optimal postion for each family as well as the average optimal position. The operators would use this average optimal postion to adjust the Vernier setting thus controlling the collision offsets. If there was a problem with the scan the operator could choose to perform the scan again. The Vernier settings (either during a Vernier scan or not) were logged for offline analysis. Figure 1 shows the display of a series of Vernier scans as it appeared in the LEP control room.

2.2 Fit Analysis

The Vernier scan data were re-analyzed offline to study quality, stability and other characteristics of the scans. To start, the data were fit as they were online. It was noticed early in the energy scan that the χ^2 of the fits were too high. An analysis of the 3 consecutive measures of the luminosity [6] indicated that there were fluctuations in the measurements beyond the reported error, thus the high χ^2. This was traced to an integer truncation of the data when it was transferred from the IP to the control room. After the problem was corrected (after Vernier scan number 587) the data appear to fluctuate in accordance with the reported error [7] and the χ^2 reduced by a factor of two. Figure 2 shows the difference between two consecutive luminosity measurements divided by the combined error. This should be a gaussian with an rms of 1. The left plot shows the distribution for data taken before the fix with an rms of 1.4 and the right plot shows the same after the fix. The rms in that case is 1.03. Note the quality of the fit indicating that the luminosity measurements and errors are quite reliable.

Vernier scans 380 to 974 comprise those Vernier scans taken during the 1995 energy scan. For each off peak energy and each IP there were $\sim$ 35 ”good” [1)] Vernier scans performed for the purposes of controlling collision offsets for a total of 280 Vernier scans.

The χ^2 per degree of freedom of each fit is shown in figure 3. The number of degrees of freedom is typically 21 and there are 3 fits per Vernier scan for a total of (3×280)

[1)] ”good” here refers to those Vernier scans where the logged data are complete, the Vernier scan did not have other problems (usually given in the logbook), and were not taken for other purposes.

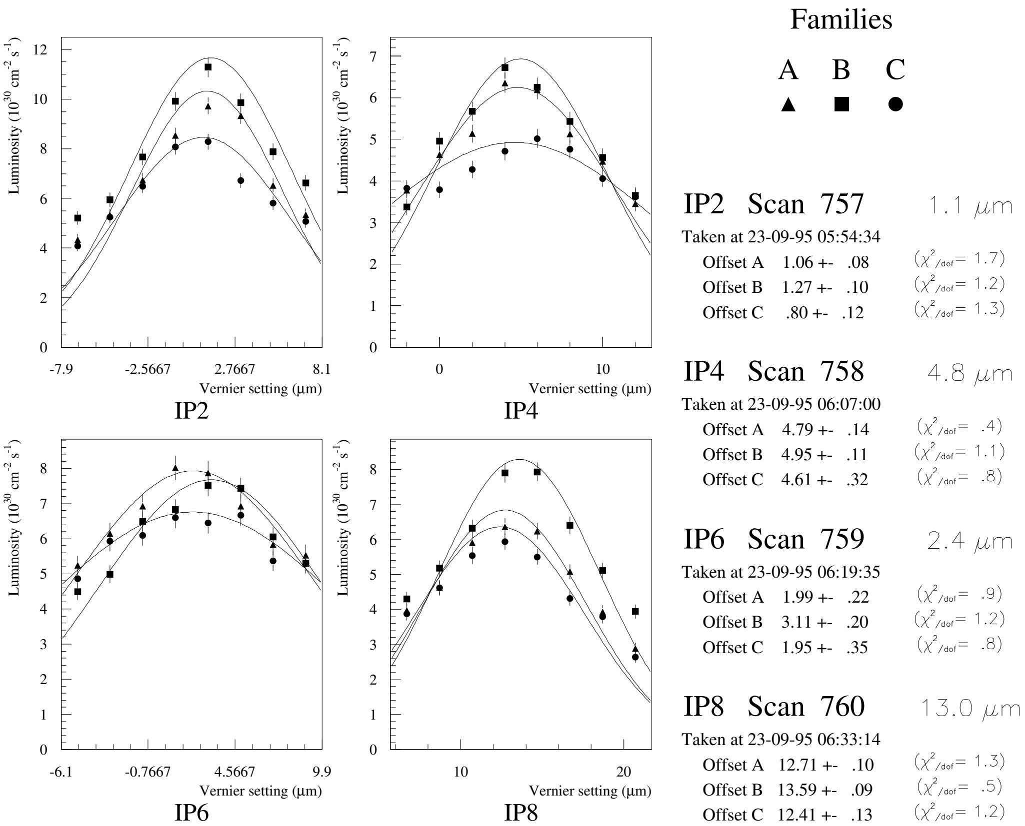

Figure 1: *Typical online display of Vernier scans taken at each IP.*

840 fits. The data taken prior to the data truncation problem have their errors inflated by an amount indicated by their fluctuations (factor 1.4). One can see that when this problem is corrected the fit to a gaussian is quite good. The typical statistical error on the optimal Vernier position per family is 0.2 - 0.3 μm. The χ^2 is observed to average slightly higher than 1 indicating that a gaussian fit is not the exact description of the luminosity vs. separation relation. One possible explanation would be the changing beam size which is sometimes associated with Vernier scans. This effect will be addressed in the section 2.4.

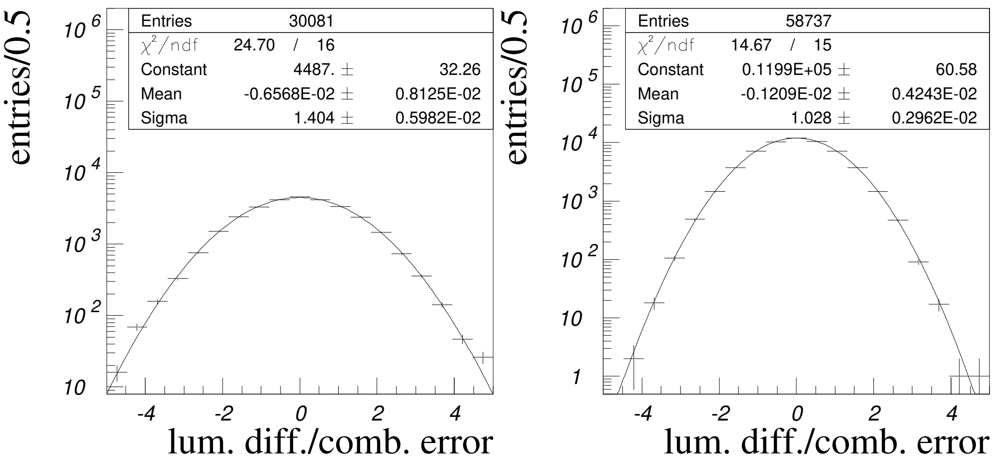

Figure 2: *The difference between consecutive luminosity monitor measurements divided by the combined error. Left: For those data taken with the data truncation problem (Sigma = 1.40). Right: For those data taken after the problem was fixed (Sigma = 1.03).*

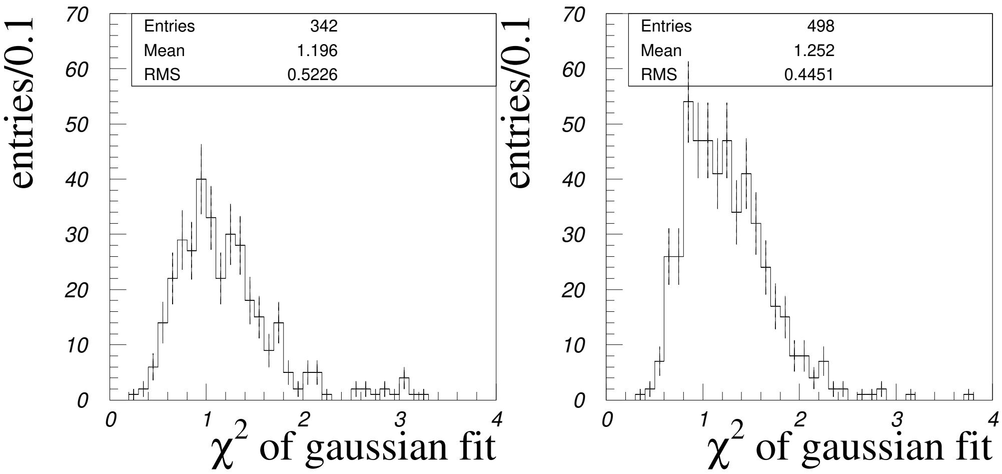

Figure 3: *The χ^2 per degree of freedom distribution for gaussian fits of the Vernier scans used in the analysis of collision offsets. Left: The χ^2 distribution for Vernier scans taken prior to correction of data truncation problem (errors inflated). Right: The distribution for those taken after the problem was fixed.*

2.3 Stability and Collision Offset Analyis

The stability of the optimal position is shown in figure 4 for IP2 as a function of time into the 1995 energy scan running period (time since Aug. 1, 1995). The mean and rms variation of the optimal position for each IP is given in table 1. It is noted that the mean optimal position at each IP is different for the two off peak energies. This fact was noticed early in the energy scan and resulted in different sets of initial Vernier settings for the two off peak points. The error on the mean is simply the rms divided by $\sqrt{N_s}$ where N_s is the number of Vernier scans taken at the IP and energy.

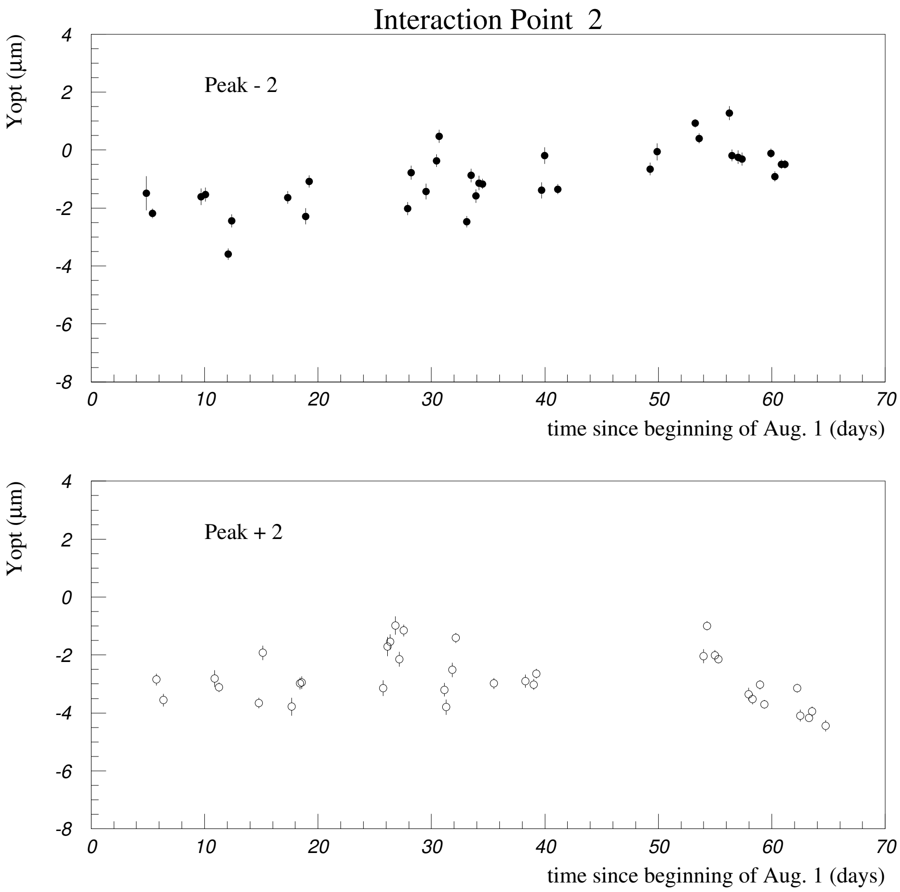

Figure 4: *The stability of the optimal Vernier setting for IP2 during the 1995 energy scan.*

If the Vernier setting had been held constant throughout the running period (unrealistically at the final mean) then the uncertanty on the collision offset would simply be the error on the mean. This of course was not the case. The Vernier setting was adjusted in an attempt to minimize the effects of long and short term drifts.

One way of determining the collision offsets is to take the difference in the Vernier setting just prior to a Vernier scan and the determination of the optimal position from that scan. These results are given in table 2. The mean of this quantity tells us how much *on average* the beams were mis-colliding at the time of a Vernier scan. Not all Vernier scans have been included for reasons of temporary database problems. The rms is another measure of the Vernier stability. One can see that the rms variation is similar to the rms variations in

Table 1: *The mean and rms varation of the optimal Vernier position (using a gaussian fit) for each IP during the 1995 energy scan. L3,ALEPH,OPAL and DELPHI are IP2,4,6 and 8 respectively.*

Optimal Vernier position			
IP	N_s	mean (μm)	rms (μm)
L3 Peak-2	34	-0.88 $\pm$ 0.18	1.07
L3 Peak$+2$	36	-2.91 $\pm$ 0.16	0.93
ALEPH Peak-2	34	6.25 $\pm$ 0.15	0.86
ALEPH Peak$+2$	36	9.67 $\pm$ 0.17	1.01
OPAL Peak-2	34	-0.88 $\pm$ 0.24	1.41
OPAL Peak$+2$	36	-3.16 $\pm$ 0.23	1.39
DELPHI Peak-2	33	14.11 $\pm$ 0.17	0.97
DELPHI Peak$+2$	37	15.75 $\pm$ 0.19	1.17

table 1.

The same table can be made for the difference between the optimal Vernier setting from a scan and the Vernier setting just following the scan. This indicates the performance of the online proceedures to control the collision offsets. These results are shown in table 3. One can see that the mean difference is reduced to the level of $\leq 0.2\mu m$ in all cases. Notice also the general reduction of the rms. The larger values of rms are due to infrequent excursions.

Ultimately, it will be necessary to produce a result which is weighted by luminosity and has some model to "track" the collision offsets in order to more fully understand what is happening when there are no Vernier scans nearby in time. A simple model has been used to produce a luminosity weighted average collision offset for each IP at each off peak energy [8]. In this case the Vernier setting at a given time (15 minute intervals) is compared to the closest available Vernier scan and is weighted by the luminosity accumulated during that interval. The results are shown in table 4.

Table 2: *The mean and rms varation of the difference between the optimal Vernier setting and the Vernier setting just prior to the Vernier scan.*

Difference in prior Vernier setting and Optimal			
IP	N_s	mean (μm)	rms (μm)
L3 Peak-2	18	0.21 $\pm$ 0.20	0.85
L3 Peak$+2$	25	0.09 $\pm$ 0.16	0.82
ALEPH Peak-2	16	0.77 $\pm$ 0.34	1.34
ALEPH Peak$+2$	20	0.21 $\pm$ 0.26	1.15
OPAL Peak-2	17	0.19 $\pm$ 0.34	1.40
OPAL Peak$+2$	20	0.25 $\pm$ 0.37	1.64
DELPHI Peak-2	18	0.27 $\pm$ 0.26	1.12
DELPHI Peak$+2$	21	0.25 $\pm$ 0.26	1.18

Table 3: *The mean and rms varation of the difference between the optimal Vernier setting and the Vernier setting just after the Vernier scan.*

Difference in Optimal and subsequent Vernier setting			
IP	N_s	mean (μm)	rms (μm)
L3 Peak-2	18	-0.22 $\pm$ 0.15	0.62
L3 Peak$+2$	25	-0.01 $\pm$ 0.07	0.37
ALEPH Peak-2	16	-0.14 $\pm$ 0.11	0.43
ALEPH Peak$+2$	20	0.20 $\pm$ 0.24	1.07
OPAL Peak-2	17	-0.10 $\pm$ 0.04	0.15
OPAL Peak$+2$	20	-0.15 $\pm$ 0.08	0.37
DELPHI Peak-2	18	0.00 $\pm$ 0.04	0.17
DELPHI Peak$+2$	21	-0.15 $\pm$ 0.19	0.86

Table 4: *The luminosity weigted collision offsets with a simple model [8].*

Luminosity weighted collision offsets	
IP	mean (μm)
L3 Peak−2	-0.08 ± 0.31
L3 Peak+2	-0.36 ± 0.31
ALEPH Peak−2	0.52 ± 0.22
ALEPH Peak+2	-0.31 ± 0.28
OPAL Peak−2	0.07 ± 0.34
OPAL Peak+2	0.28 ± 0.30
DELPHI Peak−2	0.32 ± 0.22
DELPHI Peak+2	-0.32 ± 0.37