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The Implications for Electroweak Physics of a LEP Scan in 1995 and a Comparison of Different Scanning Strategies.

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Abstract

As a function of the off-peak luminosity to be collected at LEP in 1995, we give estimates of the final accuracy expected for Γ_Z and the other principal electroweak measurements. We conclude that the precision with which these measurements test the Standard Model is maximized if at least 40pb^{-1} is collected off-peak in 1995 in order to reduce substantially the uncertainty on Γ_Z.

Under the assumption that all the 1995 off-peak data will be collected at two and only two energy points we compare various possible scanning strategies. We find that the Γ_Z accuracy achieved when data are taken at ± 3GeV from the Z^0 peak is essentially equal to that achieved if data were to be taken at the ± 2GeV points used in the previous scan in 1993. Measurements in 1995 at ± 3GeV could be combined with the 1993 measurements at ± 2GeV to allow the Standard Model prediction for the shape of the Z^0 resonance to be tested. Therefore, we conclude that it would be highly desirable to collect such data in 1995.

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1 Introduction and Overview

Between 1990 and 1994 each LEP experiment has recorded[1] an integrated luminosity ($\mathcal{L}$) of about 140pb^{-1}. Combining the data from the four experiments will give a sample of about 15 million hadronic and 1.5 million leptonic Z^0 decays. About 25pb^{-1} ($\sim$18% of the total) has been recorded at centre-of-mass energies away from the Z^0 peak. The principal purpose of such 'off-peak' data is to measure the mass (M_Z) and width (Γ_Z) of the Z^0. The final accuracy from the 1990–1993 data is expected to be:

$$\Delta M_Z = 1.7 \oplus 1.4 = 2.2\text{MeV}$$

$$\Delta \Gamma_Z = 2.7 \oplus 1.5 = 3.1\text{MeV}$$

where the first error represents the LEP-combined statistical error and the second error represents the uncertainty arising from the LEP energy scale [1].

The main cost of scanning comes from the smaller cross-section off-peak, which gives a smaller number of collected Z^0s than running on-peak. For the scans performed so far at LEP the average off-peak cross-section is $\sim$12pb — to be compared with $\sim$30pb on-peak (a loss of 60%). From the point of view of the number of Z^0s collected, the off-peak luminosity ($\mathcal{L}^{\text{off-peak}}$) of 25pb^{-1} is therefore equivalent to an on-peak luminosity ($\mathcal{L}^{\text{on-peak}}_{\text{equiv}}$) of 10pb^{-1}.

In section 2 we give a set of fairly conservative assumptions about the performance of LEP in the 1995 run:

- The integrated luminosity recorded per experiment will be 70pb^{-1}.
- The errors on M_Z and Γ_Z from energy calibration will be $\pm$1MeV.
- Commissioning and performing energy calibrations will lead to a loss of 6pb^{-1} recorded luminosity per experiment if there is a scan.

We compare three possible scenarios, in which 0pb^{-1}, 20pb^{-1} and 40pb^{-1} are recorded off-peak per experiment in 1995. In section 3 we give estimates of the LEP-combined errors to be expected for the principal electroweak measurements in each of these scenarios. In section 3.1 the Γ_Z errors are estimated, taking into account the energy calibration and experimental systematic errors. We discuss in some detail the sensitivity to the various assumptions made. The results are summarized in table 2 and figure 1. We find that the error on Γ_Z continues to improve approximately as $1/\sqrt{\mathcal{L}^{\text{off-peak}}}$. The errors on Γ_Z corresponding to our standard assumptions are: 2.9MeV for no scan in 1995, 2.1MeV for a 20pb^{-1} scan and 1.8MeV for a 40pb^{-1} scan. More optimistic assumptions about the energy calibration would give an error of 1.6MeV for the 40pb^{-1} scan. We find that the accuracy with which the peak cross-section is determined has a non-negligible influence on the final Γ_Z error.

In section 3.2 we give the expected accuracy for the measurements of $\sigma^{\text{had}}_{\text{pole}}$, R_{had}, Γ_{lept} and $A^{\text{lept}}_{\text{FB}}$ and in section 3.3 we discuss the principal electroweak measurements from b quarks and taus.

[1] Typical data taking efficiencies of the four experiments are in the range 80–90%. The luminosity delivered by LEP is therefore $\sim$15% higher than that recorded.

In section 4 we discuss the precise tests of the Standard Model that can be performed using these measurements. The lepton pair and b quark forward-backward asymmetries and the tau polarization and its forward-backward asymmetry are all sensitive to the same radiative correction ($\Delta\kappa$). In contrast, the Z^0 lineshape is sensitive to a different correction ($\Delta\rho$). An important test of the Standard Model is to check that these two corrections are consistent with the same value of M_t. If there is no scan in 1995 the precision with which we can perform this check is totally dominated by the error on Γ_Z (for example see table 5 or figure 2). The M_t values extracted from the asymmetries and the lineshape have much more equal errors in the case of a $40pb^{-1}$ scan in 1995 (see figure 4) and so the accuracy of the comparison increases. In addition, when the M_t measurements from the lineshape and asymmetries are combined a smaller overall error on M_t is obtained for a $40pb^{-1}$ scan than for the other scenarios considered. For comparison, we also show the precision on M_t corresponding to the expected future measurements of M_W and A_{LR}. If a direct measurement of M_t with an error in the region of 5GeV becomes available it will be possible to constrain M_H. However, we find that the precision on M_H does not vary much with scan scenario.

In section 5 we consider at which off-peak energy points we should collect data in 1995. In the Standard Model fit to the lineshape three parameters (M_Z, Γ_Z, σ^{had}_{pole}) must be determined. At present, precise cross-section measurements exist at only three energy points and so the fit has no degrees of freedom. Combining the existing measurements at $\pm$2GeV with future measurements at other energy points will allow consistency checks to be made of the Standard Model prediction for the Z^0 lineshape.

We quantify the effect on the measurement of M_Z and Γ_Z of different possible scanning strategies in 1995. In section 5.3 we discuss the contribution of the Z-γ interference term to the hadronic cross-section. We give the precision with which this parameter can be determined in each of the alternative scanning strategies.

We conclude that measurements at either or both of the $\pm$3GeV points could be taken at rather small cost to either the Γ_Z precision or the total number of collected Z^0s. It would therefore seem to be highly desirable to collect such data in 1995.

2 Assumptions about 1995 Running

The LEP schedule for 1995 foresees about 100 days for physics running in the region of the Z^0 peak. This is 20% fewer days than in previous years, because of the high energy run expected for the autumn. However, an increase in luminosity is expected from the bunch train scheme and we take $70pb^{-1}$ to be a rather conservative estimate of the integrated luminosity to be recorded by each experiment in 1995.

If a scan takes place we can expect a reduction in the total recorded $\mathcal{L}$ of about $6pb^{-1}$ (to $64pb^{-1}$). Approximately half of this overhead comes from the time spent calibrating the off-peak fills[2] and half comes from a few extra days machine studies to improve our understanding of the energy calibration.

[2] We assume most of the off-peak fills will be calibrated and that each calibration takes about two hours. If energy calibration is possible during physics data taking then this overhead may be reduced.

Currently, the dominant systematic errors on the energy scale arise from two sources:

(1) NMR measurements are used to monitor the field strength in a reference magnet that is powered in series with the main bending magnets of LEP. The degree to which the strength of the magnetic field seen by the beams circulating in LEP is correlated with the NMR measurements is uncertain.

(2) The energy calibrations show a residual scatter with respect to the predictions of a model that incorporates all known influences on the energy of the machine.

A number of studies are underway that are expected to reduce significantly the uncertainties from source (1). Errors from source (2) affect only the uncalibrated fills. Even if no progress is made in understanding the residual scatter with respect to the model, the systematic errors from this source can be reduced by ensuring that a large fraction ($\sim$ 75%) of off-peak fills are calibrated. Conservatively, we can expect the systematic errors on both M_Z and Γ_Z to be reduced to 1MeV.

In the following we consider three possible scenarios for the running of LEP in 1995:

(1) Data are collected only at the Z^0 peak ($\mathcal{L}$=70pb^{-1}).

(2) A scan is performed with $\mathcal{L}^{\text{off-peak}} = 20\text{pb}^{-1}$, with the remainder of the luminosity (44pb^{-1}) collected on-peak.

(3) A scan is performed with $\mathcal{L}^{\text{off-peak}} = 40\text{pb}^{-1}$, with the remainder of the luminosity (24pb^{-1}) collected on-peak.

For the time being we will assume that any off-peak data in 1995 will be taken at the $\pm$2GeV points used in the 1993 scan. (We will consider other possibilities in section 5.) For simplicity we have assumed the same energy error and overhead for the 20pb^{-1} and 40pb^{-1} scans[3].

In table 1 we summarize the $\mathcal{L}$, $\mathcal{L}^{\text{off-peak}}$ and $\mathcal{L}^{\text{on-peak}}_{\text{equiv}}$ per LEP experiment for the current dataset and the totals expected by the end of 1995 for the various scenarios considered above. The error on Γ_Z is dominated by the off-peak statistics whereas the error on most other quantities is dominated by the on-peak equivalent statistics. With respect to the scenario in which there is no scan in 1995, we give the change in the off-peak ($\Delta^{\text{off-peak}}_{\text{error}}$) and on-peak equivalent ($\Delta^{\text{on-peak}}_{\text{error}}$) statistical errors for the 20pb^{-1} and 40pb^{-1} scans. Because of the small fraction of luminosity collected off-peak ($\mathcal{F}^{\text{off-peak}}$) it is clear that the decrease in the off-peak errors is much larger than the increase in the on-peak equivalent errors for the scans considered. By collecting 40pb^{-1} off-peak in 1995 we recover roughly the same value of $\mathcal{F}^{\text{off-peak}}$ that we had after the 1993 data taking.

[3] A somewhat smaller overhead might be achieved for a 20pb^{-1} scan, but at the likely cost of a larger energy systematic and so the comparison between the two scenarios would not be much affected.

	1993	1994	no 1995 scan	$20\mathrm{pb}^{-1}$ scan	$40\mathrm{pb}^{-1}$ scan
$\mathcal{L}$	80	140	210	204	204
$\mathcal{L}^{\mathrm{off-peak}}$	25	25	25	45	65
$\mathcal{L}^{\mathrm{on-peak}}_{\mathrm{equiv}}$	65	125	195	177	165
$\mathcal{F}^{\mathrm{off-peak}}$	31%	18%	12%	22%	32%
$\Delta^{\mathrm{off-peak}}_{\mathrm{error}}$			0	−25%	−38%
$\Delta^{\mathrm{on-peak}}_{\mathrm{error}}$			0	+5.0%	+8.7%

Table 1: Luminosities (pb^{-1}) recorded per LEP experiment for the datasets 1990–1993 and 1990–1994, and the totals expected by the end of 1995 for various scenarios. Derived from these quantities are: the fraction of luminosity collected off-peak ($\mathcal{F}^{\mathrm{off-peak}}$), the change in the off-peak ($\Delta^{\mathrm{off-peak}}_{\mathrm{error}}$) and on-peak equivalent ($\Delta^{\mathrm{on-peak}}_{\mathrm{error}}$) statistical errors as a result of scanning in 1995.

3 Projected Errors on Electroweak Parameters

In this section we consider the measurements that are of principal interest as precise tests of the theory of the electroweak neutral current. We give estimates of the LEP-combined errors to be expected from the analysis of the 1990–1995 dataset. Predictions are given for each of the 1995 running scenarios considered above. First we discuss in some detail the error expected for Γ_Z in each case and then give the sensitivity to the various assumptions made, e.g., on the energy calibration and experimental systematics. We then consider the errors on $\sigma^{\mathrm{had}}_{\mathrm{pole}}$, $\mathrm{R}_{\mathrm{had}}$, $A^{\mathrm{lept}}_{\mathrm{FB}}$ and Γ_{lept}, where $\sigma^{\mathrm{had}}_{\mathrm{pole}}$ is the pole hadronic cross-section, $\mathrm{R}_{\mathrm{had}}$ is the ratio of the hadronic to the leptonic partial widths of the Z^0, $A^{\mathrm{lept}}_{\mathrm{FB}}$ is the lepton pair forward-backward asymmetry and Γ_{lept} is the leptonic partial width. Finally, we give estimates for the errors on the other major electroweak quantities: A^b_{FB}, the b quark forward-backward asymmetry; R_b, the ratio of the b quark partial width to the total hadronic width of the Z^0; and A_τ and A_e, which are measured by the tau polarization and its forward-backward asymmetry.

3.1 Projected Errors on Γ_Z

The expected Γ_Z errors are derived from fits using the ZFITTER package [2] to data representing the cross-section measurements for each of the years 1990–1995. The energy calibration errors, experimental systematics, and the luminosity statistical and systematic errors are taken into account. The results of the fit are given in table 2 for the 1990–1993 dataset and the 1990–1995 dataset for the various scanning scenarios. The first row of table 2 gives the results for a set of standard assumptions about the systematic errors (which are given below) and the subsequent rows demonstrate how the results change as the assumptions are varied.

The expected Γ_Z errors are displayed graphically as a function of $\mathcal{L}^{\mathrm{off-peak}}$ in figure 1 (solid points). Because of the logarithmic scales for both x and y axes the contribution to the Γ_Z error arising from the statistical uncertainty on the off-peak points appears as a straight line on this plot. This allows the influence of other errors, e.g., energy systematics or the contribution from

assumptions	1990–1993	no 1995 scan	$20pb^{-1}$ scan	$40pb^{-1}$ scan
standard	3.15	2.86	2.07	1.81
optimistic energy		2.86	1.97	1.63
1994 data:				
$\Delta E = \pm 2MeV$		2.85	2.04	1.78
$\Delta E = \pm 10MeV$		2.87	2.10	1.88
$\Delta\mathcal{L}/\mathcal{L} = \pm 0.1\%$		3.05	2.12	1.92
$\mathcal{L}_{1995} = 100pb^{-1}$		2.85	2.04	1.76

Table 2: The Γ_Z errors (MeV) for the 1990–1993 dataset and the 1990–1995 dataset for the various scanning scenarios. The first row gives the results for a set of standard assumptions about the systematic errors and the subsequent rows demonstrate how the results change as the assumptions are varied (see text for details).

errors on the peak cross-section measurement, to be judged more easily. It can be seen that the Γ_Z error does indeed decrease approximately as $1/\sqrt{\mathcal{L}^{\text{off-peak}}}$, but that with our standard assumptions other contributions to the Γ_Z error are significant. For example, it can be seen that the additional on-peak data taken in 1994 and 1995 gives some improvement in the Γ_Z error from the 1993 scan even if there is no scan in 1995[4]. If there is a scan in 1995 the main other contribution to the Γ_Z error comes from the energy calibration systematics. This is demonstrated by the open triangles in figure 1, which show the results of somewhat more optimistic assumptions about the expected energy errors (see below).

The details of the procedure are as follows:

- The integrated luminosities corresponding to the various scenarios are given in table 1.
- For each year, one set of cross-sections is used to represent approximately the LEP-combined dataset. The statistical errors are calculated assuming both hadronic and lepton pair events contribute to the lineshape fit.
- The relative uncertainty between the luminosity measurements of different years is taken to be: 0.05% between 1992 and 1993; and negligible between 1993, 1994 and 1995.
- The energy calibration errors are taken into account by using the known energy error matrix [1][5] for 1990–1993 and estimates for 1994–1995. We assume the error on the 1994 on-peak data is ± 5MeV. We assume that the error matrix for the 1995 scan can be obtained from the error matrix for 1993 by scaling each of the elements by a factor of 1.5^2, which reduces the contribution of the energy systematic on the Γ_Z error to 1MeV for the 1995 data. We assume no correlation among the energy scale uncertainties of the

[4]The accuracy with which the peak point is measured makes a noticeable contribution to the error on Γ_Z from the 1990–1993 data. This is particularly true for ALEPH and OPAL, which have a large relative luminosity error between 1993 and earlier years because of the installation of new forward detectors.

[5]We thus make the, perhaps conservative, assumption that we will not be able to reduce the energy error on the 1993 data in spite of the improved understanding of the energy calibration that is likely to come from the 1995 scan.

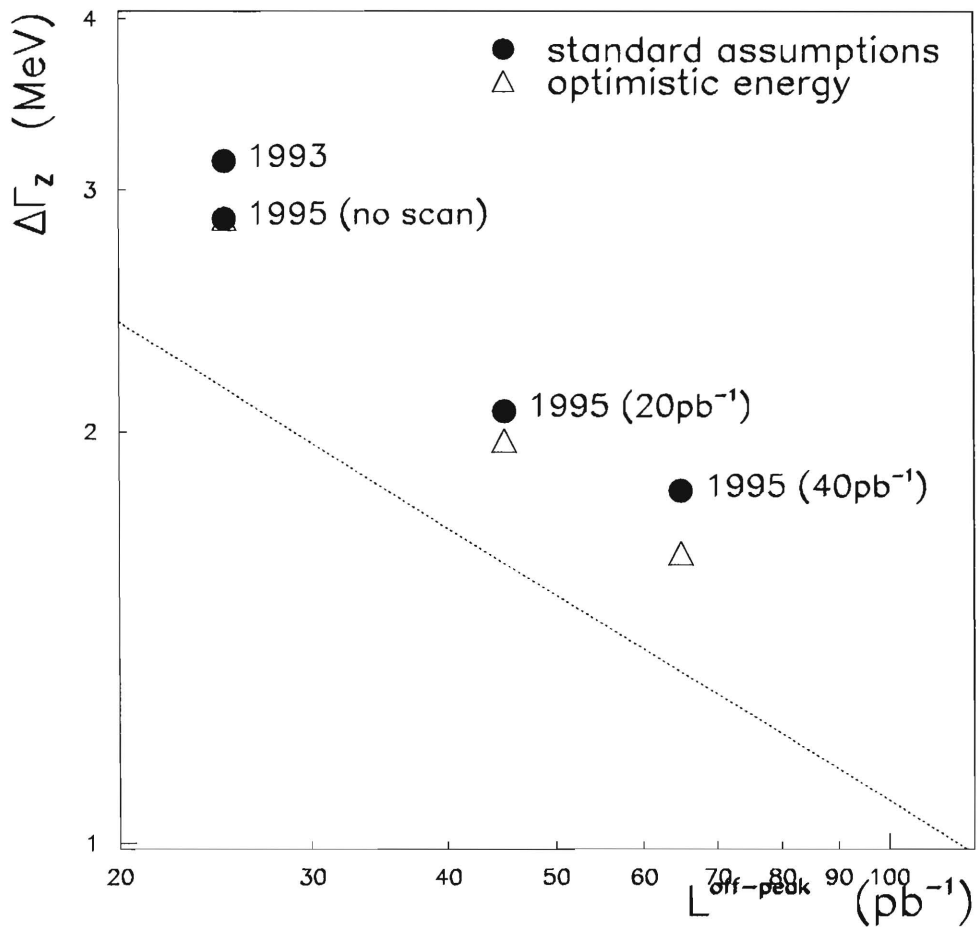

Figure 1: The expected Γ_Z errors displayed as a function of $\mathcal{L}^{\text{off-peak}}$ for various datasets. The solid points (•) give the results for a set of standard assumptions about the systematic errors and the open triangles (△) give the results for a more optimistic set of assumptions about the energy calibration errors (see text for details). The contribution to the Γ_Z error arising from the statistical uncertainty on the off-peak points is shown as the straight line.

different years. As is discussed below in the context of the 1994 data, it is desirable to reduce the sensitivity of the on-peak cross-section to the precise knowledge of the LEP energy. Therefore, it would seem sensible that the 1995 on-peak data be collected at the point of maximum cross-section[6], E_{cm}=91.3GeV, rather than the value E_{cm}=91.2GeV used in the 1993 scan and in 1994. In the fits we assume E_{cm}=91.3GeV for 1995 on-peak data.

- The error on Γ_Z arising from the uncertainty on the non-resonant background to the hadronic event samples is added in quadrature to the results of the fit. It is taken to be $\pm$0.5MeV for the data up to the end of 1993 and is assumed to scale with $1/\sqrt{\mathcal{L}^{\text{off-peak}}}$.

In table 2 we give the results of the following variations in the above assumptions:

More optimistic energy calibration: With the result of new studies on the NMR, the error from this source may become negligible. With the large number of energy calibrations planned for the scan in 1995 it may well be possible that the cause of the residual scatter with respect to the model will be understood. Some of these improvements may also benefit the understanding of the 1993 calibration. We modify our standard assumptions by using a $\pm$0.5MeV energy error on Γ_Z for the 1995 data and a $\pm$1.0MeV error for the data taken in 1993. The accuracy assumed for the 1994 peak data is unchanged. The expected Γ_Z errors are shown by the open triangles in figure 1. The significant improvement in the Γ_Z error, particularly for the 40pb^{-1} scan, provides a real incentive for further improvements in our understanding of the energy calibration.

1994 data: In our standard assumptions the amount of on-peak luminosity in 1995 is not large. For example, in the 40pb^{-1} scan the statistical precision with which the peak cross-section is measured in 1995 is only 0.06%. This will make a non-negligible contribution to the Γ_Z error unless the 1994 on-peak data can be effectively used in the lineshape fits. This fact makes the final Γ_Z error sensitive to the assumptions about the energy error for the 1994 peak data and the relative uncertainty between the luminosity measurements of 1994 and 1995. To set the scale we note that statistical error on the 7M Z^0s collected by the four LEP experiments combined in 1994 is 0.04%. At E_{cm}=91.21GeV, at which the 1994 data were taken, the slope of the cross-section with energy is about 8% per GeV. The $\pm$5MeV energy uncertainty of our standard assumptions therefore corresponds to an uncertainty in the predicted cross-section of 0.04%, which is equal to the statistical precision of the measurement. We consider the following changes to our standard assumptions: the energy uncertainty assumed for the 1994 peak data is varied between $\pm$2MeV and $\pm$10MeV; the relative uncertainty between the luminosity measurements of 1994 and 1995 is degraded to $\pm$0.1%.

Total $\mathcal{L}$ in 1995: Given the very promising performance of the bunch train scheme, our standard assumption that the total $\mathcal{L}$ collected in 1995 will be 70pb^{-1} could be regarded as rather conservative. We modify our standard assumptions by adding an extra 30pb^{-1} recorded on-peak in 1995 to give on-peak luminosities of 100pb^{-1}, 74pb^{-1} and 54pb^{-1} in the no scan, 20pb^{-1} scan and 40pb^{-1} scan scenarios, respectively.

[6] Polarization is not possible at this energy. Therefore, this will require a small change in the energy ($\sim$50MeV) to be made between physics running and the energy calibration by means of a change in the RF frequency, but this introduces a negligible uncertainty.

As expected, the $40pb^{-1}$ scan is found to be most sensitive to the assumptions about the accuracy of the peak cross-section and the energy calibration errors. In the studies that follow the errors on Γ_Z corresponding to our standard assumptions are used: (1) 2.9MeV for no scan in 1995, (2) 2.1MeV for a $20pb^{-1}$ scan and (3) 1.8MeV for a $40pb^{-1}$ scan.

In addition to improving the error on Γ_Z it should be mentioned that a scan in 1995 gives a number of useful by-products:

- The error on M_Z should be reduced to about $1 \oplus 1$GeV.
- The measurement of the energy dependence of the forward-backward asymmetries will be improved substantially.
- The time and effort devoted to an improved understanding of polarization and energy calibration is an excellent investment for LEP2, where the M_W measurement requires a precise energy calibration.

3.2 Projected Errors on σ^{had}_{pole}, R_{had}, Γ_{lept} and A^{lept}_{FB}

The precision of the principal electroweak measurements at LEP is far greater than originally projected. The very large data samples that have been collected have allowed systematic uncertainties to be controlled to a far greater level than expected initially. In looking forward to the results at the end of the 1995 data analysis we feel that a healthy degree of optimism is in order.

We make the following assumptions concerning the likely systematic errors on the *LEP-combined*[7] measurements of cross-sections and lepton pair forward-backward asymmetries:

- Fractional error on the luminosity measurement $= \pm 0.07\%$. This represents the experimental $\oplus$ the theory error and to achieve this will require improvements from the current theory error to the level of $\pm 0.05\%$. Experimental accuracies of this level have already been achieved.
- Fractional error on the hadronic event selection $= \pm 0.03\%$. There is a high degree of motivation for individual experiments to achieve errors of the order of $\pm 0.06\%$ in order to exploit fully the precise new luminosity monitors in the measurement of σ^{had}_{pole}.
- Fractional error on the lepton pair event selection $= \pm 0.05\%$. This level of accuracy should definitely be obtainable for electron and muon pairs, but in the case of tau pairs represents a considerable challenge.
- Error on $A^{lept}_{FB} = \pm 0.0003$.

[7]Except for the luminosity these measurements are likely to be dominated by experimental uncertainties and, therefore, the LEP-combined error is likely to be about one half of the errors expected for a single experiment.

		stat.	syst.	$\Delta\mathcal{L}$	$\Delta\Gamma_Z$	total
σ^{had}_{pole} (nb)	no 1995 scan	.011	.013	.029	.0	.033
	$20pb^{-1}$ scan	.011	.013	.029	.0	.034
	$40pb^{-1}$ scan	.012	.013	.029	.0	.034
R_{had}	no 1995 scan	.014	.012	.0	.0	.019
	$20pb^{-1}$ scan	.015	.012	.0	.0	.019
	$40pb^{-1}$ scan	.015	.012	.0	.0	.020
Γ_{lept} (MeV)	no 1995 scan	.027	.021	.029	.096	.104
	$20pb^{-1}$ scan	.029	.021	.029	.070	.081
	$40pb^{-1}$ scan	.030	.021	.029	.060	.074
A^{lept}_{FB}	no 1995 scan	.00066	.00030	.0	.0	.00072
	$20pb^{-1}$ scan	.00069	.00030	.0	.0	.00075
	$40pb^{-1}$ scan	.00072	.00030	.0	.0	.00078

Table 3: The errors on σ^{had}_{pole}, R_{had}, Γ_{lept} and A^{lept}_{FB} expected for the LEP-combined dataset from 1990–1995 for various scenarios. The total errors are broken down into the components arising from: experimental statistics and systematics, the luminosity uncertainty, and the error on Γ_Z.

Based on these assumptions, table 3 shows the errors on σ^{had}_{pole}, R_{had}, Γ_{lept} and A^{lept}_{FB} expected for the LEP-combined dataset from 1990–1995 for various scenarios. These errors have been obtained using the formulae given in the appendix. The contribution to the error from the various sources is shown explicitly in the table.

In the next section we will be concerned with the precision with which M_t may be extracted from these measurements. In the Standard Model the quantities σ^{had}_{pole} and R_{had} are sensitive mainly to α_s, and Γ_Z is sensitive to both M_t and α_s. It is clear that M_t can be extracted from these parameters as they stand. However, for the purposes of illustration it is useful to perform a parameter transformation to give Γ_{lept}, a quantity that does not depend upon α_s and contains essentially all the M_t information from the lineshape. The errors on Γ_{lept} are therefore also given in the table[8].

One can make the following observations:

- R_{had} and A^{lept}_{FB} remain statistics limited by the total number of collected Z^0s or $\mathcal{L}^{on-peak}_{equiv}$, as long as the required effort is invested to reduce the experimental systematics from their current level. As was expected from table 1, the error on such measurements is not strongly dependent upon whether one scans or not in 1995, since the difference in total statistics between the different scenarios is relatively small.

[8]The error on Γ_{lept} depends explicitly upon the error on Γ_Z since it is determined from the relation $\Gamma_{lept} = \Gamma_Z M_Z \sqrt{\sigma^{lept}_{pole}/12\pi}$.

- $\sigma^{\rm had}_{\rm pole}$ is limited by the systematic error on the luminosity measurement, and thus does not gain significantly from either increased statistics or further scanning.

- The $\Gamma_{\rm lept}$ measurement is limited by the error on $\Gamma_{\rm Z}$, which is itself limited by off-peak statistics, and so can be improved only by further scanning. The physics significance of such an improvement is demonstrated in section 4.

- It can be seen that if the luminosity uncertainty becomes much larger than we have assumed it becomes a significant source of error in the extraction of $\Gamma_{\rm lept}$. This provides an additional motivation for an improvement of the luminosity theory error down to the $\pm 0.05\%$ level.

3.3 Projected Errors on Heavy Quark and Tau Electroweak Measurements

The expected errors on the electroweak measurements with b quarks and taus are even more difficult to estimate, since new analyses techniques can be expected in these areas. Our best estimates[9] are listed in table 4.

Electroweak measurements with b quarks is an area of particular promise. Substantial progress can be expected with these measurements as increasingly sophisticated use is made of the information from silicon vertex detectors. The upgrades that the experiments have made in this regard since the beginning of LEP make the cost in terms of $\mathcal{L}^{\rm on-peak}_{\rm equiv}$ of a scan in 1995 somewhat larger than that naively given in table 1. However, this is not a large effect. For example, if we throw away the data taken in 1990–1991[10] the cost of a 40pb^{-1} scan ($\Delta^{\rm on-peak}_{\rm error}$) increases from the 8.7% given in table 1 to 9.6%.

In the measurement of $A^b_{\rm FB}$ the use of jet charge techniques in vertex tagged events already gives measurements of comparable precision to the more traditional methods using leptons. We can expect further improvements in these techniques to outweigh the cost of having to make harder selection cuts in order to control the systematic uncertainties arising from the charm and light quark backgrounds. In the measurement of $\rm R_b$ we can expect sources of systematic uncertainty common to the four experiments to dominate eventually, but at a level considerably below the current experimental error.

Most published measurements of the tau polarization (which measures A_τ) and its forward-backward asymmetry (which measures A_e), use data only up to 1991. Even preliminary results mostly include data only up to 1992. We can, therefore, expect substantial improvements by the time the analysis of the 1995 data is complete. Because of the cancelation of many systematic uncertainties in the forward-backward asymmetry, A_e will remain statistics limited up to the end of LEP1. Its error can be expected to improve faster than $1/\sqrt{\mathcal{L}^{\rm on-peak}_{\rm equiv}}$ as the number of decay channels analyzed and the geometrical acceptance of the experimental analyses increases. In contrast, the measurements of A_τ will become systematics limited.

[9] We are grateful to Gideon Bella, Roger Jones and Pippa Wells for their advice on these estimates.

[10] The 1990–1991 data correspond to $\mathcal{L}^{\rm on-peak}_{\rm equiv}$=16pb^{-1}.

		error
A^b_{FB}	no 1995 scan	.0016
	$20\mathrm{pb}^{-1}$ scan	.0017
	$40\mathrm{pb}^{-1}$ scan	.0018
R_b	no 1995 scan	.0013
	$20\mathrm{pb}^{-1}$ scan	.0013
	$40\mathrm{pb}^{-1}$ scan	.0013
A_τ	no 1995 scan	.005
	$20\mathrm{pb}^{-1}$ scan	.005
	$40\mathrm{pb}^{-1}$ scan	.005
A_e	no 1995 scan	.0052
	$20\mathrm{pb}^{-1}$ scan	.0055
	$40\mathrm{pb}^{-1}$ scan	.0057

Table 4: LEP-combined errors on tau and b electroweak parameters expected by the end of 1995 for various scenarios.

4 Comparison of the "Standard Model Testing Precision" of the Lineshape, Asymmetries, $\mathrm{M_W}$ and R_b.

Because of the presence of higher order diagrams containing virtual t quarks or Higgs bosons, the electroweak variables discussed in section 3 become sensitive to the unknown masses M_t and $\mathrm{M_H}$. There are four important and different combinations of radiative corrections that arise [3]. These may be ascribed to:

(1) The lineshape Γ_{Z}, $\mathrm{R_{had}}$ and $\sigma^{\mathrm{had}}_{\mathrm{pole}}$ — or alternatively Γ_{lept}: which essentially measures $a^2 + v^2$, the sum of the squares of the axial and vector couplings (giving the radiative correction known as $\Delta\rho$).

(2) Asymmetries $A^{\mathrm{lept}}_{\mathrm{FB}}$, A_e, A_τ, A^b_{FB} and others such as A_{LR}: which measure the ratio $\frac{av}{a^2+v^2}$ (giving the quantity $\Delta\kappa$, which appears in the expression for $\sin^2\theta^{\mathrm{eff}}_w$).

(3) The mass of the W, $\mathrm{M_W}$: which measures the quantity Δr.

(4) R_b: which is sensitive to M_t via radiative corrections to the $\mathrm{Z}^0 b\bar{b}$ vertex.

It is not necessary to go into the detailed definition of each of these, but simply to note that in the Standard Model the leading contribution from the top quark and Higgs boson masses to each of the first three quantities is of the form $a(\mathrm{M}_t^2 - b\log \mathrm{M_H})$. The constant b is approximately universal to all three quantities. Within the Standard Model we can extract a value of M_t from these quantities for a given assumption on $\mathrm{M_H}$, but the quasi-universality of the corrections means that we cannot extract both M_t and $\mathrm{M_H}$ individually. In contrast, R_b is sensitive to M_t alone.

Our principal task is to test the Standard Model by checking the consistency of the above measurements[11]. In order to make such a test, it is illustrative to cast the measurements into a common currency. This may be done by extracting M_t or $\sin^2\theta_w^{\rm eff}$ from each individually. If the Standard Model is valid then all of the values of M_t (or $\sin^2\theta_w^{\rm eff}$) must agree. If they do not then this would be unambiguous evidence for new physics. In order to maximize the accuracy of these comparisons we ideally wish to measure all four quantities with *equally high precision.*

We may compare the relative precision of the lineshape[12], asymmetries, M_W and R_b as tests of the Standard Model by looking at the precision each gives for M_t. The results of this comparison[13] are shown in table 5. These numbers were produced by fitting to the relevant quantities, using ZFITTER , with central values[14] of $M_t = 170$GeV, $M_H = 300$GeV and $\alpha_s = 0.125$. The errors were taken from tables 3 and 4, and the correlation matrices given in [5] were assumed.

The row labeled $A_{\rm FB}^{\rm lept} \oplus A_{\rm FB}^b \oplus A_{e,\tau}$ gives the precision obtained by combining the measurements of the various asymmetries at LEP1. For comparison, we also show the precision on M_t that corresponds to: a measurement of M_W with of an error 30MeV coming from LEP2 and the Fermilab collider; and a measurement of $A_{\rm LR}$ from SLC corresponding to $\sin^2\theta_w^{\rm eff}$ with an accuracy of ± 0.0003.

In table 6 we show the equivalent errors achieved on $\sin^2\theta_w^{\rm eff}$ from the various measurements. The comparison of the M_t ($\sin^2\theta_w^{\rm eff}$) precision from these quantities is shown graphically in figures 2, 3 and 4 for the no scan, $20{\rm pb}^{-1}$ and $40{\rm pb}^{-1}$ scenarios, respectively.

One may make the following observations:

- If there is no scan in 1995 then the precision with which the lineshape determines M_t will be substantially worse than that from the combined asymmetries or M_W.
- If a $40{\rm pb}^{-1}$ scan is performed then the precision from lineshape and combined asymmetries become much more equal although for our standard assumptions the combined asymmetries are still somewhat more precise.
- As mentioned previously, the quantities limited by on-peak equivalent statistics do not depend nearly as much upon whether we scan or not.

[11]There are many approaches to this problem, of which the 'ϵ' parameters [4] are a well-known example.

[12]As far as the lineshape is concerned this is equivalent to using $\Gamma_{\rm lept}$ to determine M_t. We have checked this explicitly by fitting to Γ_Z, $R_{\rm had}$ and $\sigma_{\rm pole}^{\rm had}$ and to $\Gamma_{\rm lept}$ alone. The M_t results were the same. No external constraint on α_s from, e.g., event shapes, has been used in the fits.

[13]In the extraction of all of the M_t errors we have not included the effect of the uncertainty on the fine structure constant (α_{em}). If this gave a equal shift in the value of M_t extracted from all quantities, then it would have no consequence for the arguments presented. In fact the current uncertainty of $\alpha_{em}^{-1} = 128.79 \pm 0.12$ leads to variations of 3, 10 and 3GeV to the values of M_t extracted from lineshape, $A_{\rm FB}^{\rm lept} \oplus A_{\rm FB}^b \oplus A_{e,\tau}$ and M_W, respectively. If the error on α_{em} were to remain at this level, then the precision of the asymmetries would remain completely limited by this effect. However it is likely that the α_{em} error will reduce as a result of experiments currently underway and hence for the purposes of this work we do not consider it a limitation.

[14]The error on M_t is asymmetric and depends upon the central value since the fit is really to M_t^2. In contrast, the error on $\sin^2\theta_w^{\rm eff}$ does not depend upon the central value.

Quantity	no 1995 scan		$20pb^{-1}$ scan		$40pb^{-1}$ scan	
A_{FB}^{lept}	-14.3	+13.3	-15.0	+13.8	-15.6	+14.4
A_{FB}^{b}	-9.2	+8.9	-9.8	+9.5	-10.4	+10.0
$A_{e,\tau}$	-14.9	+14.1	-15.3	+14.5	-15.5	+14.7
$A_{FB}^{lept} \oplus A_{FB}^{b} \oplus A_{e,\tau}$	-6.8	+6.7	-7.1	+7.0	-7.5	+7.3
Lineshape (Γ_{lept})	-12.1	+11.5	-9.4	+9.1	-8.5	+8.3
R_b	-42	+36	-42	+36	-42	+36
M_W			-5.0	+5.0		
A_{LR}			-9.1	+8.9		

Table 5: Precision on M_t (in GeV) arising from the four sets of quantities available at LEP, each measuring a different set of quantum corrections. The central values are M_t = 170GeV, M_H = 300GeV and α_s = .125. For comparison, we give also the result of the expected future A_{LR} measurement at SLC.

Quantity	no 1995 scan	$20pb^{-1}$ scan	$40pb^{-1}$ scan
A_{FB}^{lept}	±4.6	±4.8	±5.0
A_{FB}^{b}	±3.0	±3.2	±3.4
$A_{e,\tau}$	±4.9	±5.0	±5.1
$A_{FB}^{lept} \oplus A_{FB}^{b} \oplus A_{e,\tau}$	±2.2	±2.3	±2.5
Lineshape (Γ_{lept})	±3.9	±3.1	±2.8
R_b	±13	±13	±13
M_W		±1.7	
A_{LR}		±3.0	

Table 6: Precision ($\times10^3$) on $\sin^2\theta_w^{eff}$ arising from the four sets of quantities available at LEP, each measuring a different set of quantum corrections. The central values are M_t = 170GeV, M_H = 300GeV and α_s = .125. For comparison, we give also the result of the expected future A_{LR} measurement at SLC.

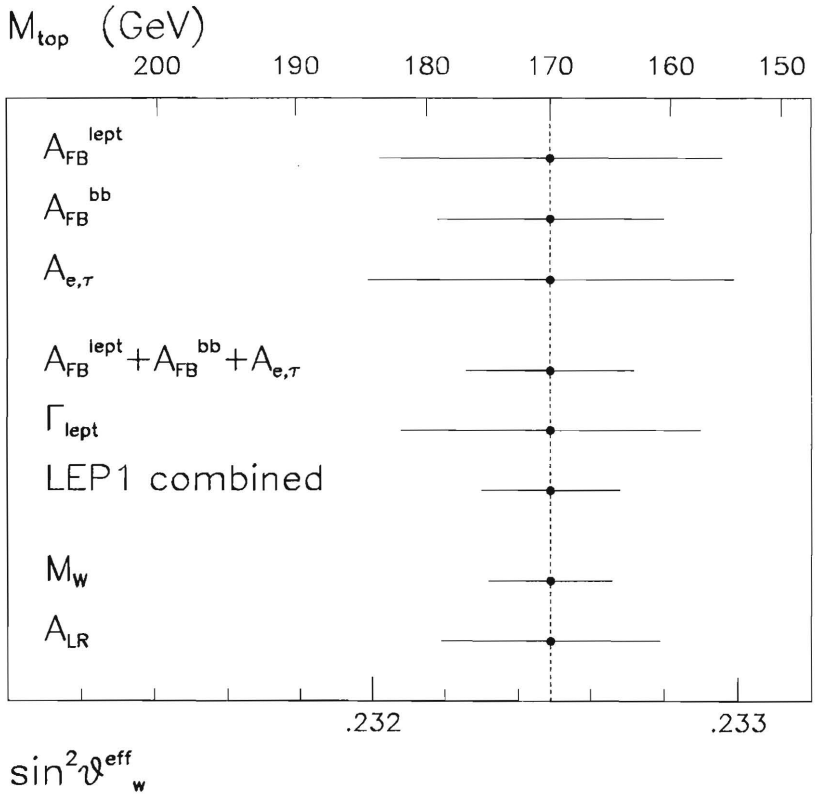

Figure 2: Comparison of the M_t and $\sin^2\theta_w^{\mathrm{eff}}$ precision from various quantities for no scan in 1995.

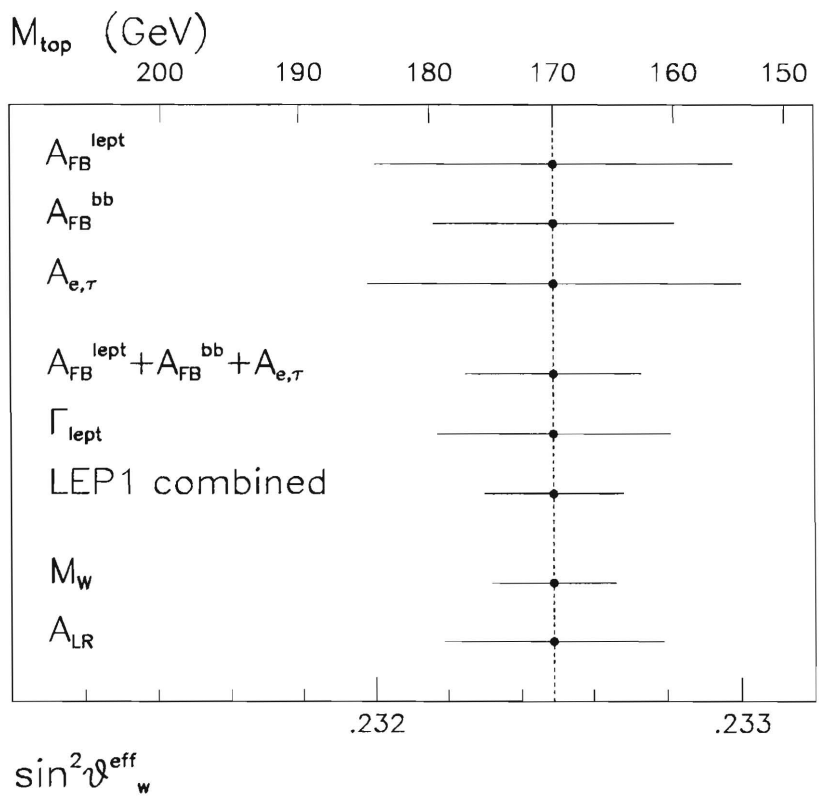

Figure 3: Comparison of the M_t and $\sin^2\theta_w^{\mathrm{eff}}$ precision from various quantities for a $20\mathrm{pb}^{-1}$ scan in 1995.

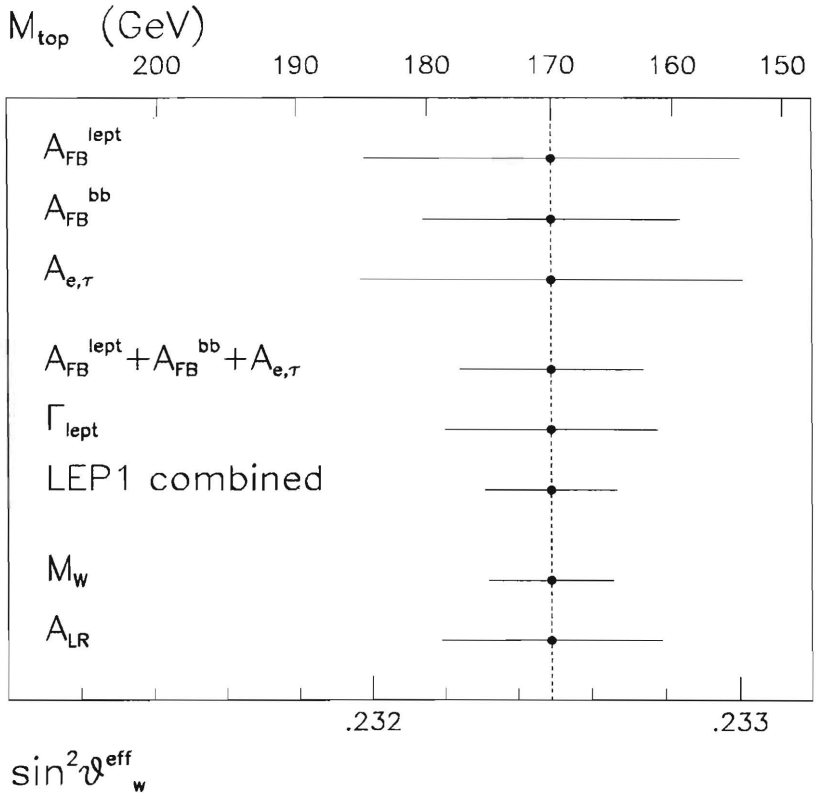

Figure 4: Comparison of the M_t and $\sin^2\theta_w^{\rm eff}$ precision from various quantities for a 40pb^{-1} scan in 1995.

- If only 20pb^{-1} were recorded off-peak in 1995 instead of 40pb^{-1} the error on the $\sin^2\theta_w^{\rm eff}$ value extracted from $\Gamma_{\rm lept}$ would increase by 10.9% whereas the error on the $\sin^2\theta_w^{\rm eff}$ value extracted from the combined asymmetries would decrease by only 4.5%. From the point of view of electroweak measurements the 40pb^{-1} scan is clearly prefered.

- $A_{\rm LR}$ also measures $\Delta\kappa$ and assuming it is consistent with the LEP measurements it can be combined with the $A_{\rm FB}^{\rm lept} \oplus A_{\rm FB}^{b} \oplus A_{e,\tau}$ results. In this case, a scan to improve $\Gamma_{\rm Z}$ becomes an even higher priority and rather more than 40pb^{-1} off-peak in 1995 would be needed to equalize the $\Gamma_{\rm lept}$ and asymmetry errors.

- The error on M_t coming from R_b is much larger than those from the other quantities.

Whilst it is clear that the precise numbers in the tables depend on the detailed assumptions that have been made, we would expect these general conclusions to be rather independent of the assumptions. In table 7 we present the results of combined fits for M_t and α_s to all the LEP1 electroweak quantities. We note a small, but useful improvement in the M_t error with increasing off-peak luminosity. The precision on α_s is improved only slightly by a scan[15].

From these studies we can see that although the precision of the asymmetries is slightly degraded by a scan, this is more than compensated by the substantial improvement in $\Delta\Gamma_{\rm Z}$. We conclude

[15]Given the errors on the input quantities we have assumed, this is because α_s is determined mainly by $R_{\rm had}$. If more pessimistic assumptions were to be made about the expected systematic errors on the hadronic and lepton pair acceptances (and thus $R_{\rm had}$) then $\Gamma_{\rm Z}$ would make a more significant contribution to the α_s determination and a larger relative improvement would result from a scan.

	M_t	α_s
no 1995 scan	± 5.7	$\pm .0023$
$20pb^{-1}$ scan	± 5.5	$\pm .0022$
$40pb^{-1}$ scan	± 5.4	$\pm .0022$

Table 7: Errors obtained from fits for M_t (GeV) and α_s to the combined LEP1 electroweak dataset. The central values are M_t = 170GeV, M_H = 300GeV and α_s = .125.

that a scan in 1995 with at least $40pb^{-1}$ is desirable: most importantly because it gives the most accurate comparison between the two classes of radiative corrections associated with Γ_{lept} and the asymmetries; and secondly because it gives the best overall error on M_t.

4.1 Constraint on M_H

There is some hope that with further running at Fermilab a direct measurement of M_t with an error in the region of 5GeV will become available. In this case the comparison with the indirect measurements of M_t discussed above will provide a very stringent test of the Standard Model. If they are consistent the measurements can be combined in order to constrain the Higgs mass. As explained previously, the predominant sensitivity is through a universal correction depending upon M_t^2 and $\log(M_H)$. It is therefore apparent that since the overall precision on M_t does not vary much with scan scenario, as shown in table 7, then the precision on M_H will also not vary much with scan scenario. We show this explicitly in figure 5, which shows the χ^2 distribution as a function of M_H using all of the electroweak data mentioned above, and in addition a direct measurement of M_t to $\pm$5GeV. The data was generated for a central value of M_H = 300GeV. The solid, dashed, dotted curves represent the no scan, $20pb^{-1}$ scan and $40pb^{-1}$ scan, respectively. As expected the curves are very similar. In fact, the no scan curve is marginally better even though the corresponding M_t error in table 7 is marginally worse; this is due to the small differences in non-universal corrections between the various measurements.

5 Scanning Strategy

We need to decide at which off-peak energy points to collect data in 1995. A number of practical considerations make it desirable to minimize the number of off-peak energy points. In particular, it will be important to maximize the frequency with which energy calibrations are made at each of the off-peak points in order that any variations in their energies can be followed as closely as possible. We therefore restrict our discussion to scans in which all of the off-peak data in 1995 is collected at two and only two energy points. In the following the terms $\pm$nGeV refer to the points above and below the Z^0 by n$\times$0.9GeV; these correspond to the energies at which polarization can be achieved in LEP and which, therefore, can be calibrated.

The reason for considering possible alternatives to the scanning strategy used in 1993, in which data were collected at the $\pm$2GeV points, is as follows. In the Standard Model fit to the

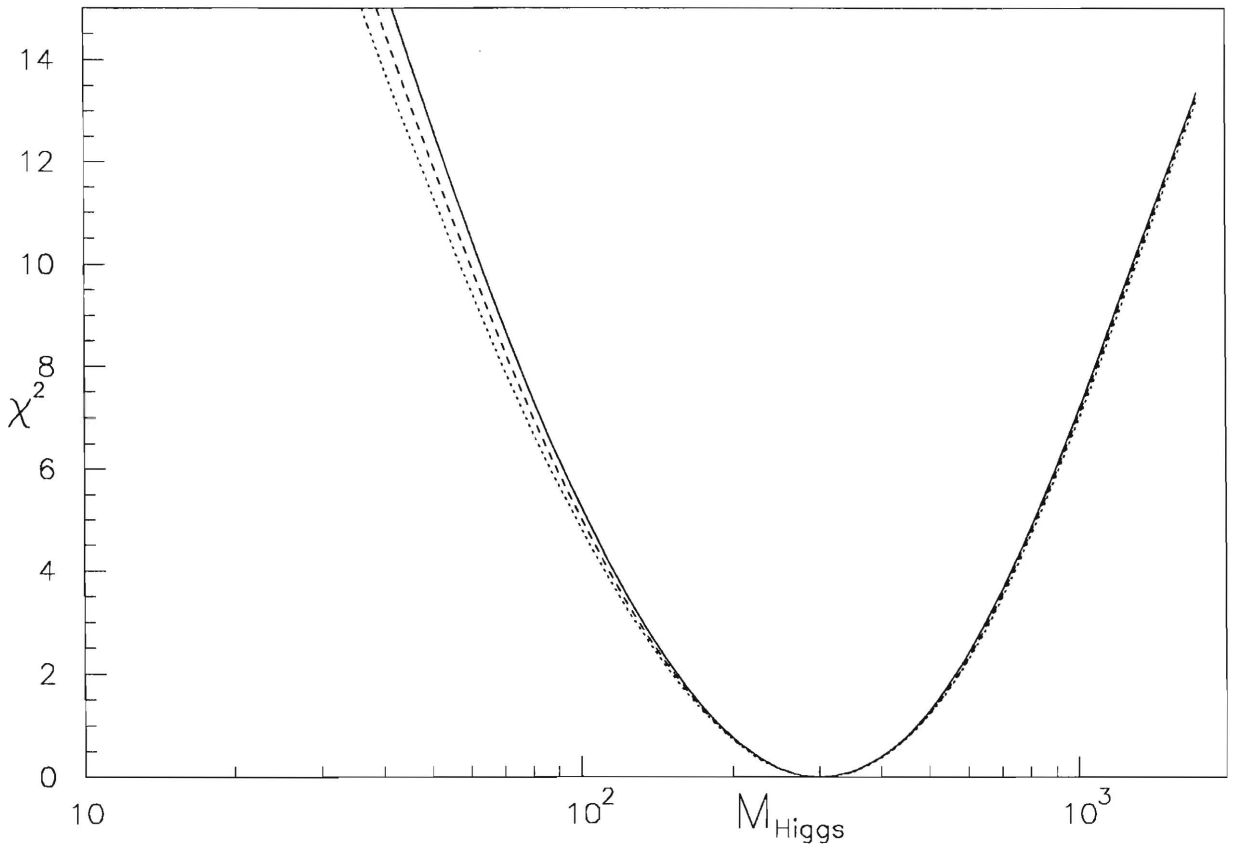

Figure 5: The χ^2 distribution as a function of M_H using all of the electroweak data mentioned above, and in addition a direct measurement of M_t to ± 5GeV. The data were generated for a central value of $M_H = 300$GeV. The solid, dashed, dotted curves represent the no scan, 20pb^{-1} scan and 40pb^{-1} scan, respectively.

lineshape three parameters (M_Z, Γ_Z, σ^{had}_{pole}) must be determined. With precise cross-section measurements at only three energy points the fit has no degrees of freedom. By combining the existing measurements at $\pm$2GeV with future measurements at other energy points the quality of the fit can be tested. This will allow consistency checks to be made of the Standard Model prediction for the Z^0 lineshape and of the experimental and LEP energy scale errors. Such a combination will be possible because the relative error between the experimental cross-section measurements of different years is expected to be small. A careful assessment of the relative errors on the LEP energy scale of the two years will be required. The statistical precision of each of the 1993 and 1995 off-peak points will be 0.1–0.15%. At present such checks of the lineshape fits can be performed only by using the relatively imprecise measurements of the cross-sections at $\pm$1GeV and $\pm$3GeV made in 1990 and 1991.

In this section we quantify the effect on the measurement of M_Z and particularly Γ_Z of different possible scanning strategies in 1995. We first compare various scans in which a fixed off-peak luminosity of 40pb^{-1} is recorded (section 5.1). From the point of view of Γ_Z the most interesting of these scans turn out to be those that include data taken at the $\pm$3GeV points. However, taking data at these points would imply a smaller total number of collected Z^0s than in a $\pm$2GeV scan with the same off-peak luminosity. In a second step we therefore compare a set of scanning strategies in which the amount of off-peak luminosity is adjusted to give the same loss in the number of collected Z^0s as for our standard scan of 40pb^{-1} at $\pm$2GeV (section 5.2).

In section 5.3 we discuss the contribution of the Z-γ interference term to the hadronic cross-section. This provides a quantitative example of a parameter that would lead to a distortion of the Z^0 lineshape if it were to deviate from its Standard Model value. We give the precision with which this parameter can be determined in each of the alternative scanning strategies.

5.1 Fixed Off-Peak Luminosity

We start with the simplest case of a fixed off-peak luminosity for each scan strategy. The results of fits to pseudo data at different scan points are given in table 8[16]. The first error given for Γ_Z and M_Z represents the LEP-combined statistical error and the second error represents the uncertainty arising from the LEP energy scale.

The complete set of assumptions is given below:

- 40pb^{-1} is accumulated off-peak, equally distributed between the two points[17].
- This leaves 24pb^{-1} on-peak in 1995 under the standard assumptions. We assume this data will be collected at the point of maximum cross-section, E_{cm}=91.3GeV.

[16]The number of significant digits given in the table is to allow the small differences among the various scanning scenarios to be seen without being confused by the effects of rounding errors. It is clear that the uncertainties in the assumptions about, for example, the delivered luminosity and energy error that will be achieved in 1995 cause a much larger uncertainty common to all the scenarios than the small differences between them.

[17]We have verified that the accuracy on Γ_Z is not significantly improved or degraded by variations at the 10% level in the sharing of the off-peak luminosity between the two points.

Scan	$\Delta\Gamma_Z$ (MeV)	ΔM_Z (MeV)	$\Delta N_Z \times 10^3$	$\Delta(\partial A_{FB}/\partial E)$
± 1	$3.01 \oplus 1.96 = 3.59$	$0.93 \oplus 0.91 = 1.30$	$+377$	1.41
± 2	$1.88 \oplus 0.98 = 2.12$	$1.19 \oplus 0.91 = 1.50$	0	1
± 3	$1.90 \oplus 0.66 = 2.01$	$1.83 \oplus 0.88 = 2.03$	-184	0.91
$+3, -2$	$1.92 \oplus 0.80 = 2.08$	$1.44 \oplus 0.92 = 1.71$	-98	0.98
$+2, -3$	$1.94 \oplus 0.75 = 2.08$	$1.47 \oplus 0.89 = 1.72$	-86	0.93
$+2, -1$	$2.29 \oplus 1.35 = 2.66$	$0.98 \oplus 0.96 = 1.37$	$+193$	1.21
$+1, -2$	$2.25 \oplus 1.28 = 2.59$	$1.11 \oplus 0.92 = 1.44$	$+184$	1.10
$+3, -1$	$2.29 \oplus 1.05 = 2.52$	$1.12 \oplus 1.00 = 1.50$	$+95$	1.17
$+1, -3$	$2.26 \oplus 0.94 = 2.45$	$1.27 \oplus 0.92 = 1.57$	$+98$	1.01

Table 8: Errors on Γ_Z and M_Z resulting from a 40pb^{-1} scan at various off-peak energy points. The first error represents the LEP-combined statistical error and the second error represents the uncertainty arising from the LEP energy scale. The fourth column gives the difference (ΔN_Z) in the number of collected hadronic Z^0 decays per experiment with respect to the the standard scan at $\pm$2GeV. The final column gives the error on the energy dependence of the forward-backward asymmetry, $\Delta(\partial A_{FB}/\partial E)$, normalized to its value for the standard scan at $\pm$2GeV.

- The fits use the 1995 data points and, in order to constrain in a realistic way the peak cross-section, include also the on-peak data from 1994. The relative luminosity error between 1994 and 1995 is assumed to be negligible. The off-peak data from previous years is *not* used.
- The fit uses the experimental statistical error including the contribution from the luminosity assuming an accepted cross-section of 80pb.
- The uncertainty in the predicted peak cross-section arising from the energy uncertainty of the 1994 on-peak data is taken into account in the fit.
- The errors on Γ_Z and M_Z arising from the uncertainty in the 1995 LEP energy scale are included using an energy error correlation matrix scaled from the 1993 matrix as described in section 3.1. (It is adjusted to give equal uncertainties on the energies of the two off-peak points.)
- The non-resonant background error is ignored in these fits. Currently this adds about 0.5MeV to the LEP-combined error on Γ_Z and will decrease with increased off-peak statistics[18].

It can be seen that the statistical error on Γ_Z from the $\pm$2GeV points is equal to that for the

[18]The non-resonant background forms a larger fraction of the selected event samples for points further from the Z^0 peak. However, it seems likely that with the large increase in $\mathcal{L}^{\text{off-peak}}$ expected in 1995 an improved understanding of the rate and event properties of this background source can be achieved. Therefore, we can probably expect the systematic error from the non-resonant background to be small compared to the other errors on Γ_Z for all the scan scenarios. However, this is certainly a question worthy of more detailed study.

$\pm$3GeV points[19], but once the systematic error is taken into account the $\pm$3GeV points give a slightly smaller error. This is because a fixed LEP energy error has a smaller effect on the Γ_Z error for scan points further from the peak due to the increased "lever arm". Both the statistical and systematic errors on Γ_Z from the $\pm$1GeV points are significantly larger than those for the $\pm$2GeV and $\pm$3GeV points.

Of course, the relative importance of the statistical and systematic errors depends on the detailed assumptions. For example, if a total of only 20pb^{-1} are collected off-peak then $\Delta\Gamma_Z$=2.52$\oplus$0.98=2.70MeV at $\pm$2GeV and $\Delta\Gamma_Z$=2.60$\oplus$0.66=2.68MeV at $\pm$3GeV. On the other hand, the $\pm$3GeV scan points are more robust in the event of unforeseen problems with the energy calibration in 1995. However, the final conclusion — that the overall error on Γ_Z from the $\pm$2GeV points is for all practical purposes equal to that for the $\pm$3GeV points[20] — is not sensitive to these fine details.

It can be seen that the precision on M_Z is rather lower for the points at $\pm$3GeV than $\pm$2GeV. The fourth column in table 8 gives the difference (ΔN_Z) in the number of collected hadronic Z^0 decays per experiment with respect to the standard scan at $\pm$2GeV. It can be seen that the major cost of a 40pb^{-1} scan at $\pm$3GeV is the loss of an extra 184000 hadronic Z^0 decays.

An important by-product of the scan is an improved measurement of the energy dependence of the forward-backward asymmetries ($\partial A_{FB}/\partial E$). This slope is determined by the interference of the Z^0 axial coupling with the γ vector coupling. It is proportional to $Q_e Q_f a_e a_f$ and is therefore well determined within the Standard Model. A deviation from the Standard Model prediction would signal new physics. The error on this quantity, $\Delta(\partial A_{FB}/\partial E)$, depends mainly on the accuracy with which the asymmetry is measured at the two off-peak points and on the amount by which the asymmetry changes between them. The final column in table 8 gives $\Delta(\partial A_{FB}/\partial E)$, normalized to its value for the standard scan at $\pm$2GeV. These results have been obtained by fits to simulated muon pair asymmetries corresponding to the 1995 scan and the 1994 on-peak data. We find that a scan at $\pm$3GeV provides a measurement of $\partial A_{FB}/\partial E$ with a 9% smaller error than that given by the $\pm$2GeV scan.

5.2 Fixed Loss of Events

We now compare a set of scanning strategies in which the amount of off-peak luminosity is adjusted to give the same loss in the number of collected Z^0s as our standard scan of 40pb^{-1} at $\pm$2GeV. We assume that off-peak luminosity is to be shared equally between the pair of off-peak points.

The results of the fits are shown in table 9. The second column gives the total off-peak luminosity for each scan[21]. As before, the first error given for Γ_Z and M_Z represents the LEP-

[19]We note that it is important to take into account the uncertainties on the measured peak cross-section. As might be expected, the effect of these uncertainties on the Γ_Z error is much more important for scan points nearer the peak than for those further away. A more naive treatment would give a higher statistical precision for the $\pm$2GeV that the $\pm$3GeV points.

[20]Note that the numbers given here are the expected results of the 1995 scan. When these results are combined with the measurements from previous years any small differences between them will become even smaller.

[21]One complication which arises is that for the scan at the two $\pm$1GeV points there is no way to achieve a

Scan	$\mathcal{L}^{\text{off-peak}}$ (pb^{-1})	$\Delta\Gamma_Z$ (MeV)	ΔM_Z (MeV)	$\Delta(\partial A_{FB}/\partial E)$
±1	64	$2.58\oplus1.96=3.24$	$0.74\oplus0.91=1.17$	1.11
±2	40	$1.88\oplus0.98=2.12$	$1.19\oplus0.91=1.50$	1
±3	32	$2.09\oplus0.66=2.19$	$2.03\oplus0.88=2.21$	1.02
$+3,-2$	36	$2.00\oplus0.80=2.15$	$1.52\oplus0.92=1.78$	1.04
$+2,-3$	36	$2.01\oplus0.75=2.15$	$1.53\oplus0.89=1.77$	0.98
$+2,-1$	54	$2.05\oplus1.35=2.45$	$0.85\oplus0.96=1.28$	1.04
$+1,-2$	54	$2.01\oplus1.28=2.38$	$0.97\oplus0.92=1.34$	0.96
$+3,-1$	46	$2.17\oplus1.05=2.41$	$1.05\oplus1.00=1.45$	1.09
$+1,-3$	46	$2.14\oplus0.94=2.34$	$1.19\oplus0.92=1.50$	0.94

Table 9: Errors on Γ_Z and M_Z resulting from scanning strategies in which the off-peak luminosity ($\mathcal{L}^{\text{off-peak}}$) is adjusted to give the same loss in the number of collected Z^0s as the of 40pb^{-1} scan at ±2GeV. The first error represents the LEP-combined statistical error and the second error represents the uncertainty arising from the LEP energy scale. The final column gives the error on the energy dependence of the forward-backward asymmetry, $\Delta(\partial A_{FB}/\partial E)$, normalized to its value for the standard scan at ±2GeV.

combined statistical error and the second error represents the uncertainty arising from the LEP energy scale.

A significant difference between the statistical precision of the ±2GeV points and those at ±3GeV is now apparent; this is because of the reduction in the off-peak luminosity needed to compensate for the lower cross-section at ±3GeV. However, once the uncertainty arising from the LEP energy scale is added the precision of the ±3GeV points is again essentially equal to that of the ±2GeV points.

From the fourth column of table 9 it can be seen that, as expected, the precision on M_Z for the points at ±3GeV is degraded with respect to the scenario of fixed off-peak luminosity given in table 8. The final column in table 9 gives the error on the energy dependence of the forward-backward asymmetry, $\Delta(\partial A_{FB}/\partial E)$, normalized to its value for the standard scan at ±2GeV. It can be seen that scans containing any combination of the points at ±2GeV and ±3GeV provide measurements of $\partial A_{FB}/\partial E$ with very similar accuracies.

5.3 Measurement of the Z-γ Interference Contribution to the Hadronic Cross-Section

As was discussed in the introduction to this section, with precise cross-section measurements at only three energy points the fits to the lineshape can determine only three parameters

loss in the number of Z^0s equal to that from the nominal ±2GeV scan. Therefore the off-peak luminosity for this scan is set, somewhat unrealistically, to the total 1995 luminosity of 64pb^{-1}.

(M_Z, Γ_Z, and σ^{had}_{pole}). All other contributions to the cross-section, e.g., that coming from the Z-γ interference, are constrained only by the relatively imprecise measurements of the cross-sections at $\pm$1GeV and $\pm$3GeV made in 1990 and 1991. Such contributions are usually fixed to their Standard Model values in the fits.

As was discussed in [6] and [7], if the Standard Model prediction for the Z-γ interference term is multiplied by a scale factor (C_{int}) that is left as a free parameter in the lineshape fit then it is determined rather imprecisely. In a fit to the 1993 inclusive data we measure it to only $C_{int} = 1 \pm 1.8$. Also the error on M_Z is increased dramatically by an extra 6.5MeV in quadrature [7].

In table 10 we show the improvement in the measurement of C_{int} as a result of the different fixed-loss scan scenarios outlined in section 5.2. For comparison, we also show the effect of 2.5pb^{-1} of data taken at 80GeV, although one should bear in mind that this is outside the fixed-loss scenario.

One can draw the following conclusions:

- Further running at the $\pm$2GeV points does not lead to a substantial improvement in the error on C_{int}.
- Running at *any* points other that $\pm$2GeV does make a substantial improvement in the error on C_{int}.
- Within the fixed-loss scenario, the best error on C_{int} is obtained by running at $\pm$3GeV or the 3, 1GeV combinations.
- For determining C_{int} the $-$3GeV point is more valuable than the +3GeV point; this is because the measurement at $-$3GeV suffers from less 'background' from events with initial state radiation down onto the Z^0 peak[22].
- As pointed out in [7], a similar precision on C_{int} can be obtained by taking 2.5pb^{-1} much further from the peak.

We conclude that measurements at either or both of the $\pm$3GeV points could be taken at rather small cost to either the Γ_Z precision or the total number of collected Z^0s. Since this will allow consistency checks to be made of the Standard Model prediction for the Z^0 lineshape and of the experimental and LEP energy scale errors, it would seem to be highly desirable to collect such data in 1995.

6 Conclusions

In conclusion, 1995 looks like being a very productive year for electroweak physics at LEP. Under our fairly conservative set of standard assumptions a scan with about 40pb^{-1} off-peak is

[22]However, we stress that the Z-γ interference is just one example of a possible deviation from the Standard Model lineshape. Data at +3GeV would provide a better test of the predictions for initial state radiative corrections.

Scan	$\mathcal{L}^{\text{off-peak}}$ (pb^{-1})	ΔC_{int}
1990–1994		1.8
± 1	64	1.1
± 2	40	1.6
± 3	32	0.8
$+3, -2$	36	1.2
$+2, -3$	36	1.0
$+2, -1$	54	1.2
$+1, -2$	54	1.1
$+3, -1$	46	0.9
$+1, -3$	46	0.8
80 GeV point	2.5	0.8

Table 10: Precision on the measurement of the hadronic Z-photon interference term as a function of scan strategy.

desirable to optimize the precision with which we can search for deviations from the Standard Model. If the performance of LEP in 1995 is even better (in terms of the delivered luminosity and the accuracy of the energy calibration) then more than 40pb^{-1} off-peak would bring further improvements in these tests. We conclude that off-peak data should be collected at either or both of the ± 3GeV points.

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A Error Formulae

The following formulae were used to derive the errors on the quantities given in table 3.

$$\frac{\Delta\sigma^{\rm had}_{\rm pole}}{\sigma^{\rm had}_{\rm pole}} = \frac{1}{\sqrt{\rm N_{had}}} \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}} \oplus f^{syst}_{\rm had} \tag{1}$$

$$\frac{\Delta {\rm R_{had}}}{\rm R_{had}} = \frac{1}{\sqrt{\rm N_{lept}}} \oplus \frac{1}{\sqrt{\rm N_{had}}} \oplus f^{syst}_{\rm lept} \oplus f^{syst}_{\rm had} \tag{2}$$

$$\frac{\Delta\Gamma_{\rm lept}}{\Gamma_{\rm lept}} \approx 0.5\frac{1}{\sqrt{\rm N_{lept}}} \oplus 0.5\frac{\Delta\mathcal{L}}{\mathcal{L}} \oplus \frac{\Delta\Gamma_{\rm Z}}{\Gamma_{\rm Z}} \oplus 0.5 f^{syst}_{\rm lept} \tag{3}$$

$$\Delta A^{\rm lept}_{\rm FB} = \sqrt{\frac{1-(A^{\rm lept}_{\rm FB})^2}{\rm N_{lept}}} \oplus f^{syst}_{A^{\rm lept}_{\rm FB}} \tag{4}$$