The Sensitivity to New Physics of a LEP Scan in 1995

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Abstract

We study the implications of possible off-peak measurements in the 1995 LEP run, in regard to probing physics beyond the Standard Model. To do so, we determine the accuracy with which various nonstandard couplings can be expected to be measured in the three different scan scenarios recently discussed by Clarke and Wyatt. We find that each scan scenario allows greater sensitivity to a different set of new physics couplings. Oblique parameters are best measured with the longest scan, while nonstandard fermion couplings to the $Z^0$ tend to be better constrained (albeit only marginally) if all of the 1995 LEP measurements are taken on the $Z^0$ peak.
1. Introduction

With LEP entering into its final period of measurements on the $Z$ peak, the question arises as to how to use the remaining time most efficiently. This involves a basic tradeoff for all experiments that are run in the vicinity of the resonance. On the one hand, longer running on resonance maximizes the number of produced $Z$'s, and so reduces the statistical errors on all quantities which can be measured there. On the other hand, a scan away from the peak is required to better determine the $Z$ lineshape, and so to more accurately determine the $Z$ width. A decision regarding the relative time to be spent scanning or running on resonance during the 1995 run is imminent.

Recently Clarke and Wyatt (CW) [1] have quantitatively analyzed this tradeoff in regard to the expected sensitivity to standard model (SM) parameters such as the top mass $m_t$, and the QCD coupling $\alpha_s$. Our intention in the present note is to similarly analyse the tradeoff that can be expected in sensitivity to potentially ‘new’ physics from beyond the SM. In order to do so we follow (CW) in comparing the following three scanning scenarios:

• **(1) No Scan:** $70pb^{-1}$ collected on peak in 1995;

• **(2) Intermediate Scan:** $44pb^{-1}$ collected on peak and $20pb^{-1}$ collected $\pm 3$ GeV off peak;

• **(3) Long Scan:** $24pb^{-1}$ collected on peak and $40pb^{-1}$ collected $\pm 3$ GeV off peak.

CW conclude that, although observables such as the forward-backward asymmetries — which improve with better statistics — could be better determined by running only on peak, a $40 pb^{-1}$ scan is desirable due to the improved measurement of the total $Z$ width, or its partial width into leptons etc..

We now turn to the implications for new-physics searches of the above three scanning scenarios. To do so we perform fits using the following 14 LEP observables: $A_{FB}(e)$, $A_{FB}(\mu)$, $A_{FB}(\tau)$, $\Gamma_Z$, $\sigma_p^b$, $R_e$, $R_\mu$, $R_\tau$, $A_{FB}(b)$, $A_{FB}(c)$, $R_b$, $R_c$, $A_{pol}(\tau)$ and $A_e(P_\tau)$. For each of the three scan scenarios, we give, in Table I, the precision with which we imagine that these observables will have been measured after the 1995 run. In this table we have taken the expected errors as they are given by CW [1]. For those observables in Table I which are not directly considered by CW, we have scaled the presently-published LEP errors [2], [3] by the improvement predicted in ref. [1]. As shall become clear below, we
need not specify the central values that would be expected for these observables after the 1995 run.

|       | No Scan | 20 pb$^{-1}$ | 40 pb$^{-1}$ |       | No Scan | 20 pb$^{-1}$ | 40 pb$^{-1}$ |
|-------|---------|--------------|--------------|-------|---------|--------------|--------------|
| $A_{FB}(e)$ | 0.00153 | 0.00159 | 0.00166 | $R_\tau$ | 0.033 | 0.033 | 0.035 |
| $A_{FB}(\mu)$ | 0.00095 | 0.00098 | 0.00102 | $A_{FB}(b)$ | 0.0016 | 0.0017 | 0.0018 |
| $A_{FB}(\tau)$ | 0.00117 | 0.00122 | 0.00127 | $A_{FB}(c)$ | 0.0038 | 0.0041 | 0.0043 |
| $\Gamma_Z$ | 0.0029 | 0.0021 | 0.0018 | $R_b$ | 0.0013 | 0.0013 | 0.0013 |
| $\sigma^p_h$ | 0.033 | 0.034 | 0.034 | $R_c$ | 0.0064 | 0.0064 | 0.0064 |
| $R_e$ | 0.032 | 0.032 | 0.034 | $A_{pol}(\tau)$ | 0.005 | 0.005 | 0.005 |
| $R_\mu$ | 0.028 | 0.028 | 0.03 | $A_e(P_\tau)$ | 0.0052 | 0.0055 | 0.0057 |

Table I
Post-1995 Uncertainties in LEP Observables
The expected end-of-1995 standard deviations for some LEP observables considered in this analysis.

In order to infer the implications such improved measurements will have for new-physics searches, we would like to express the implications of such new physics for these observables in a reasonably model-independent way. In what follows, we perform two such model-independent analyses.$^1$ We first consider the widely-studied case for which new physics dominantly enters into LEP observables through the three oblique parameters $S$, $T$, $R$. In this case the theoretical predictions for the LEP observables may be written as a radiatively corrected standard-model piece plus a deviation which is linear in the two new physics parameters $S$ and $T$. Our goal is to determine the accuracy with which $S$ and $T$ will be constrained using the three scenarios for the 1995 run. Notice that since the observables are linear functions of the parameters $S$ and $T$, the precision with which $S$ and $T$ will be measured does not depend on the central values that are assumed to have been found for the observables after the 1995 run. (The same is not true, of course, for the central values for $S$ and $T$.)

In our second analysis, we drop the assumption that new physics is dominantly oblique.

$^1$ Both of these methods have been recently summarized and compared in ref. [4].
Rather, we assume only that the new physics is heavy, so that its effects can be expressed in terms of the low-dimension interactions of an appropriate effective lagrangian. This can be thought of as the lagrangian which would be left after all of the new, heavy particles have been ‘integrated out’. The most general expression for such a lagrangian, subject to the restriction that it contain only the presently observed particles, is given in ref. [9], which also shows how LEP observables depend on its effective couplings. We choose here for simplicity to work with a particularly interesting subset of these effective interactions, namely nonstandard couplings between each flavor of fermion and the $Z$. That is, we focus on effective interactions of the form:

$$\mathcal{L}_{\text{eff}} = \frac{ie}{c_w s_w} Z_\mu \sum_f \bar{f} \gamma^\mu (g^f_{L} \gamma_{L} + g^f_{R} \gamma_{R}) f,$$

where the coupling constants, $g^f_{L,R} = (g^f_{L,R})_{SM} + \delta g^f_{L,R}$, are normalized so that $(g^f_{L})_{SM} = T_3^f - Q_f s^2_w$ and $(g^f_{R})_{SM} = -Q_f s^2_w$. We may now determine the precision with which each of the parameters $\delta g^f_{L,R}$ can be ascertained in each of the three scanning scenarios for the 1995 LEP run.

## 2. Oblique New Physics

The precision which we obtain for the two oblique parameters, $S$ and $T$, when these are fit to the LEP observables using the anticipated experimental errors from Table I are listed in Table II. All of the errors listed in this table represent 2-$\sigma$ allowed ranges. Results are listed for two kinds of fits. The columns labelled ‘Individual Fit’ are performed with only one parameter allowed to vary, the other parameter being set to zero. By contrast, the ‘Global Fit’ column gives the result of a full two-parameter maximum-likelihood analysis. The fits were performed using the correlation matrix given in ref. [10] for the leptonic observables, and the correlation matrix of ref. [3] for the heavy-quark quantities. No correlations were assumed between these two types of observables.

Two points are suggested by the results of Table II.

1 Inspection of the ‘Global’ fit shows that both of the oblique parameters are better measured in the scenario with a 40 $pb^{-1}$ scan.

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2 The $\delta g^f_{L,R}$ correspond to what was denoted $\delta g^f_{L,R}$ in ref. [9].
Table II

Oblique Parameter Fit

The expected sensitivity to electroweak oblique parameters for the three types of scans considered. All error ranges indicate 2-$\sigma$ intervals.

2 An opposite conclusion would have been reached for the parameter $S$ if an ‘Individual’ fit had been performed with $T$ constrained to vanish. This, however, would only be an appropriate fit if the new physics should be known to be dominated by oblique corrections, and if there are a priori theoretical reasons for $T$ to be much smaller than $S$.

3. Nonstandard Neutral-Current Fermion Couplings

We now turn to the case where new physics induces nonstandard neutral-current couplings for fermions. If we count an independent left- and right-handed coupling for each of the eleven light quarks and leptons, then there are potentially 22 couplings to be considered in this case. Happily, not all of these need be considered separately, since not all of these enter into the LEP observables in a linearly-independent way. In particular, the couplings of the three lightest quarks ($u$, $d$ and $s$) only appear through the linear combination

$$\delta_{UD} = \sum_{q=u,d,s} \left[ (g_{SM}^q) L + (g_{SM}^q) R \right].$$

We also choose to ignore the six nonstandard neutrino neutral-current couplings in what follows. This leaves 11 free parameters with which to confront the data.

When the same two types of fits that were performed earlier for the oblique parameters
are repeated, the results in Table III are obtained. All errors again correspond to 2-σ ranges.

|                  | Individual Fit |                                  | Global Fit |                                  |
|------------------|----------------|-----------------------------------|------------|-----------------------------------|
|                  | No Scan 20 pb\(^{-1}\) 40 pb\(^{-1}\) |                                   | No Scan 20 pb\(^{-1}\) 40 pb\(^{-1}\) |
| \(\delta g^e_L\) | 0.000597 0.000607 0.000643 | 0.00109 0.00110 0.00113 | \(\delta g^e_R\) | 0.000603 0.000619 0.000654 | 0.00113 0.00115 0.00119 |
| \(\delta g^\mu_L\) | 0.000625 0.000624 0.000667 | 0.00223 0.00229 0.00238 | \(\delta g^\mu_R\) | 0.000721 0.000721 0.000770 | 0.00257 0.00264 0.00275 |
| \(\delta g^\tau_L\) | 0.000722 0.000722 0.000761 | 0.00121 0.00119 0.00119 | \(\delta g^\tau_R\) | 0.000811 0.000811 0.000853 | 0.00133 0.00132 0.00133 |
| \(\delta g^b_L\) | 0.00148 0.00138 0.00135 | 0.00658 0.00686 0.00712 | \(\delta g^b_R\) | 0.00738 0.00702 0.00694 | 0.0335 0.0352 0.0368 |
| \(\delta g^c_L\) | 0.000811 0.000811 0.000853 | 0.00133 0.00132 0.00133 | \(\delta g^c_R\) | 0.00446 0.00411 0.00402 | 0.0189 0.0201 0.0209 |
| \(\delta u_{UD}\) | 0.000705 0.000645 0.000628 | 0.00513 0.00510 0.00509 |                                  |                                  |

**Table III**

Fermion Coupling Fit

The expected sensitivity to nonstandard neutral current couplings for the three types of scans considered. All error ranges indicate 2-σ intervals.

Several conclusions emerge from these results.

1. For the ‘Global’ fit, all parameters except \(\delta g^\tau_L\), \(\delta g^\tau_R\), and \(\delta u_{UD}\), were best constrained by the no-scan scenario, although the difference between the no-scan and the 40 \(pb^{-1}\) scan are in many cases not large.

2. In the ‘Individual’ fits, the heavy-quark couplings become more constrained in the 40 \(pb^{-1}\) scan. However this conclusion is only applicable if there are reasons to expect all other couplings to be negligible in a particular model. Since it is generically true that most kinds of new physics generate more than one of these effective couplings at once, we take this as a warning against drawing meaningful conclusions from individual fits.

3. The relative improvement or deterioration of the measurement of the neutral-current...
couplings in all three of the scan scenarios appears to be much weaker than was the case for the oblique parameters.

4. Conclusions

Our goal has been to analyse the implications of the three scanning scenarios on the precision with which the LEP experiments can be expected to constrain (or detect!) new physics in their 1995 run. We have done so by parameterizing the assumed new physics in a relatively model-independent way. We have considered two ways of doing so: (i) using the oblique parameters, $S$ and $T$, and (ii) using a set of nonstandard neutral-current couplings for all of the known charged fermions.

Our conclusions as to the relative efficiency of the the various scan scenarios are mixed. We have found that when new physics is well described by the oblique parameters $S$ and $T$, these parameters are best constrained in the scenario with the longest scan. This is because one can profit from the improved accuracy with which the total width and the various leptonic widths are known. The same conclusion holds, although more weakly, if the new physics first shows up in the neutral-current couplings of the light quarks ($u$, $d$ and $s$) or the tau lepton. Otherwise — for new physics in the other neutral-current couplings — the best case is to run continually on resonance. We have also found that whereas measurements of oblique corrections are reasonably sensitive to which scanning scenario is used, the same is not true for exotic fermion-$Z$ couplings.

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