# Chapter 8 Precision Studies at the $Z$ and the $WW$ Threshold

A high-precision program of electroweak and heavy-quark physics provides a natural complement to the direct searches for the Higgs boson and other new particles. The study of loop corrections to the electroweak parameters measured at the $Z$, in $p\overline{p}$ collisions and in neutrino experiments made impressive indirect predictions for the top quark mass, and constrains the mass range for a Standard Model Higgs. Limits on $\mathcal{B}(B \to X_s \gamma)$ provide the tightest mass limits on type II Higgs doublets. Because the new particles appear virtually in loops, the sensitivity extends over a much higher mass range than can be obtained in direct searches, though generally at the expense of some model–dependence.

While the physics program at 500 GeV has the potential to be very rich, it is also possible that at this center-of-mass energy there is only one Higgs-like particle seen, or no such particle at all. Under either scenario, the constraints from the electroweak and heavy-quark studies can be powerful. In the case that we do see a plethora of new particles, the full spectrum of states predicted by any model must satisfy the rules dictated by the precision measurements. In the case that very little is seen directly, the precision low-energy measurements have a good chance of showing deviations from the Standard Model. These deviations will indicate the direction that future studies must take.

There remain open issues with respect to implementing a low-energy program at a linear collider. If only the basic electroweak program is undertaken, the goals may be met by devoting a modest amount of running time at low energy. A single facility for both the high-energy and the $Z$ running, however, requires incorporation of this capability into the design of the accelerator. For a broader program, including running at $W^+W^-$ threshold and extended running at the $Z$ pole for heavy flavor physics, a low-energy facility that can operate in parallel with the high-energy may be required.

## 1 Electroweak observables on the $Z$ resonance

In principle, all measurements done at LEP and SLC can be repeated at the linear collider with much higher statistics. In about 100 days of running, it is possible to collect a sample of $10^9$ $Z$ decays (‘Giga-Z’), about 100 times the LEP or 1000 times the SLC statistics. A high degree of electron polarization seems certain and $\mathcal{P}_{e^-} = 80\%$ will be assumed in the following. Positron polarization is desirable and the R&D to achieve it is under way. Both options, with and without positron polarization, will be discussed. The issue of positron polarization is discussed further in Chapter 12.

### 1.1 Machine issues

In the present designs, the linear collider can deliver a luminosity $\mathcal{L} \sim 5 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at the $Z$ resonance. The energy loss due to beamstrahlung for colliding particles is around $0.05\% - 0.1\%$ and the depolarization in the interaction region is negligible. By sacrificing some luminosity, beamstrahlung can be reduced substantially, for example, by a factor three for a luminosity loss of a factor two [1].

Apart from the beamstrahlung there are several other effects that influence the precision of the measurements:

- The mean energies of the two beams have to be measured very precisely. A precision of $10^{-5}$ relative to the $Z$ mass might be needed to relate $A_{LR}$ to $\sin^2\theta_w^{\mathrm{eff}}$ with the desired precision.
- The beam energy spread of the machine plays a crucial role in the measurement of the total width of the $Z$. If the shape of the distribution is known, the width can be measured from the acolinearity of Bhabha events in the forward region as long as the energies of the two colliding particles are not strongly correlated.
- With the high luminosities planned, the $Z$ multiplicity in a train becomes high. This can influence $Z$ flavor tagging or even $Z$ counting.
- With positron polarization, the positron source must be able to switch polarizations on a time scale commensurate with the stability of the beam conditions.

The two main designs, X-band and superconducting, differ in some aspects relevant for $Z$ running. For the X-band design a bunch train contains 190 bunches with 1.4 ns bunch spacing, for which over half of the $Z$ bosons are produced in the same train as at least one other $Z$. Typical event separation is about 150 ns, but the experimental consequences merit some study. A TESLA bunch contains 2800 bunches with 280 ns bunch spacing. In this case bunch separation is not a problem, but data acquisition system requirements are higher. The smaller wakefields in the superconducting machine should reduce the beam energy spread. The larger bunch spacing may allow sufficient time for energy feedback, resulting in a smaller energy difference between the bunches in a train.

The LC design must accommodate the needs of the precision electroweak program in advance for the program to be viable. Suitable space in the beam delivery system for precise beam energy measurement and for polarimetry must be provided, or the beam energy measurement must be directly incorporated into the Final Focus magnet system. A measurement of these quantities behind the IP is also desirable, though it is difficult. A nonzero crossing angle might be needed.

| | LEP/SLC/Tev [2] | LC |
|---|---|---|
| $\sin^2\theta_w^{\rm eff}$ | $0.23146 \pm 0.00017$ | $\pm 0.000013$ |
| lineshape observables: | | |
| $m_Z$ | $91.1875 \pm 0.0021\,{\rm GeV}$ | $\pm 0.0021\,{\rm GeV}$ |
| $\alpha_s(m_Z^2)$ | $0.1183 \pm 0.0027$ | $\pm 0.0009$ |
| $\Delta\rho_\ell$ | $(0.55 \pm 0.10) \times 10^{-2}$ | $\pm 0.05 \times 10^{-2}$ |
| $N_\nu$ | $2.984 \pm 0.008$ | $\pm 0.004$ |
| heavy flavors: | | |
| $\mathcal{A}_b$ | $0.898 \pm 0.015$ | $\pm 0.001$ |
| $R_b^0$ | $0.21653 \pm 0.00069$ | $\pm 0.00014$ |

Table 8.1: Possible improvement in the electroweak physics quantities for $10^9$ $Z$'s collected at a linear collider. $N_\nu = 3$ is assumed for $\alpha_s$ and $\Delta\rho_\ell$.

## 1.2 Electroweak observables

There are three classes of electroweak observables that can be measured during $Z$-running at a linear collider:

- observables related to the partial widths of the $Z$, measured in a $Z$ resonance scan;
- observables sensitive to the effective weak mixing angle;
- observables using quark flavor tagging.

Table 8.1 summarizes the present precision and the expectations for the linear collider for these quantities.

### *1.2.1 Observables from the $Z$ resonance line scan*

From a scan of the $Z$ resonance curve the following quantities are measured:

- the mass of the $Z$ ($m_Z$);
- the total width of the $Z$ ($\Gamma_Z$);
- the hadronic pole cross section ($\sigma_0 = (12\pi/m_Z^2) \cdot (\Gamma_e\Gamma_{\rm had}/\Gamma_Z^2)$);
- the ratio of the hadronic to the leptonic width of the $Z$ ($R_\ell = \frac{\Gamma_{\rm had}}{\Gamma_l}$).

From these parameters, two interesting physics quantities can be derived: the radiative correction parameter $\Delta\rho_\ell$ that normalizes the $Z$ leptonic width, and the strong coupling constant $\alpha_s$.

The LEP measurements are already systematics-limited, so statistical improvement is not the issue. From LEP, $m_Z$ is known to $2 \times 10^{-5}$, and the other three parameters are all known to $10^{-3}$. To improve on $\alpha_s$ and especially on $\Delta\rho_\ell$, all three measured parameters must be improved. This requires one to understand the beam energy and the beam energy spread for $\Gamma_Z$, the hadronic and leptonic selection efficiencies for $R_\ell$, and the absolute luminosity for $\sigma_0$. With the better detectors and the higher statistics available for cross checks, the errors on the selection efficiency and on the luminosity might be improved by a factor of three relative to the best LEP experiment [3]. It is not clear whether the theory error on the luminosity can be improved beyond its present value of 0.05%. These errors would improve the precision on $R_\ell$ by a factor of four and that on $\sigma_0$ by 30%.

With a Møller spectrometer, one could possibly obtain a precision of $10^{-5}$ in the beam energy relative to $m_Z$. This would give a potential improvement of a factor of two in $\Gamma_Z$. However, because the second derivative of a Breit-Wigner curve at the maximum is rather large, $\Gamma_Z$ and $\sigma_0$ are significantly modified by beamstrahlung and beam energy spread. For illustration, the fitted $\Gamma_Z$ is increased by about 60 MeV and $\sigma_0$ is decreased by 1.8% for the TESLA parameters. The energy spread dominates the effect, so this particularly needs to be understood to about 2% to avoid limiting the precision on $\Gamma_Z$ and $\Delta\rho_\ell$. There is a potential to achieve this precision with the acolinearity measurement of Bhabha events [4] or to extend the scan to five scan points and fit for the energy spread, but both options need further study.

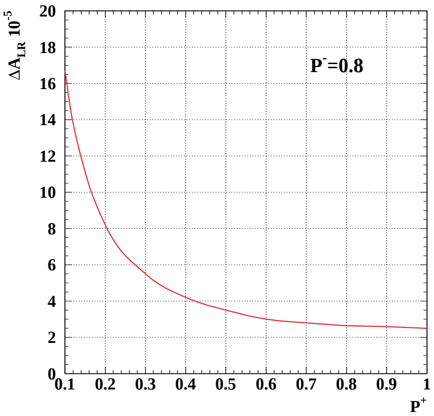
### *1.2.2 The effective weak mixing angle*

If polarized beams are available, the most sensitive quantity by far to the weak mixing angle is the left-right asymmetry:

$$\begin{aligned} A_{LR} &= \frac{1}{\mathcal{P}}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \\ &= \mathcal{A}_e \\ &= \frac{2v_e a_e}{v_e^2 + a_e^2} \\ v_e/a_e &= 1 - 4\sin^2\theta_w^{\text{eff}} . \end{aligned} \tag{8.1}$$

$A_{LR}$ is independent of the final state.

The $A_{LR}$ measurement has been analyzed for the linear collider environment in [5,1]. With $10^9$ $Z$'s, an electron polarization of 80% and no positron polarization, the statistical error is $\Delta A_{LR} = 4 \times 10^{-5}$. The error from the polarization measurement is $\Delta A_{LR}/A_{LR} = \Delta\mathcal{P}/\mathcal{P}$. At SLC, $\Delta\mathcal{P}/\mathcal{P} = 0.5\%$ has been reached [6]. With some optimism a factor two improvement in $\Delta\mathcal{P}/\mathcal{P}$ is possible [1]. In combination with the improved statistics, this leads to $\Delta A_{LR} = 3.8 \times 10^{-4}$. This precision is already more



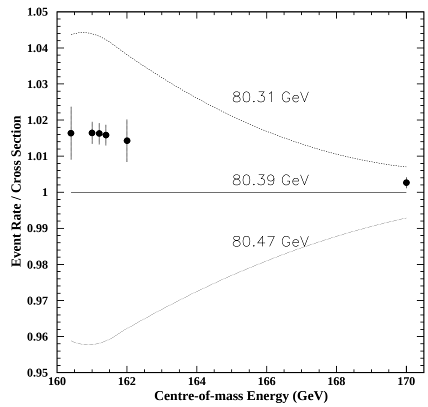




Figure 8.1: Left: Error of $A_{LR}$ as a function of the positron polarization for a luminosity corresponding to $10^9$ unpolarized $Z$'s. The errors assume that switching of the positron polarization can be done on a time scale over which the beam conditions are suitably stable. Right: The ratio of the measured $W^+W^-$ cross section to the predicted cross section for $M_W = 80.39$ GeV (see Section 2). The data were generated using $M_W = 80.36$ GeV. The upper (lower) curves show the ratio of the predicted cross section for $M_W = 80.31$ GeV ($M_W = 80.47$ GeV) to that for $M_W = 80.39$ GeV.

than a factor of five improvement over the final SLD result for $\sin^2\theta_w^{\rm eff}$ and almost a factor of four over the combined LEP/SLD average.

If positron polarization is available, there is the potential to go much further using the 'Blondel scheme' [7]. This method of polarization measurement, and the associated techniques for obtaining polarized positrons, are described in more detail in Chapter 12. To summarize the results, the total cross section with both beams polarized is given as $\sigma = \sigma_u\left[1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-} + A_{LR}(\mathcal{P}_{e^+} - \mathcal{P}_{e^-})\right]$, where $\sigma_u$ is the unpolarized cross section. If all four helicity combinations are measured, $A_{LR}$ can be determined without polarization measurement as

$$A_{LR} = \sqrt{\frac{(\sigma_{++} + \sigma_{-+} - \sigma_{+-} - \sigma_{--})(-\sigma_{++} + \sigma_{-+} - \sigma_{+-} + \sigma_{--})}{(\sigma_{++} + \sigma_{-+} + \sigma_{+-} + \sigma_{--})(-\sigma_{++} + \sigma_{-+} + \sigma_{+-} - \sigma_{--})}}\ .$$

Figure 8.1 shows the error on $A_{LR}$ as a function of the positron polarization. For $\mathcal{P}_{e^+} > 50\%$ the dependence is relatively weak. For $10^9$ $Z$'s, the Blondel scheme with a positron polarization of 20% gives a better result than a polarization measurement of 0.1% and electron polarization only.

Polarimeters are still needed to resolve one remaining question. There could potentially be a difference between the absolute values of the polarization in the left- and right-handed states. If the two polarization values for electrons and positrons are written as $\mathcal{P}_{e^\pm} = \pm|\mathcal{P}_{e^\pm}| + \delta\mathcal{P}_{e^\pm}$, the dependence on this difference is $\mathrm{dA_{LR}}/\mathrm{d}\delta\mathcal{P}_{e^\pm} \approx 0.5$.

One therefore needs to understand $\delta\mathcal{P}_{\mathrm{e}^\pm}$ to $< 10^{-4}$. If polarimeters with at least two channels are available, $\delta P$ can be measured together with other systematic effects intrinsic to the polarimeters in a way that does not increase the statistical error from the Blondel scheme.

Because of $\gamma$–$Z$ interference, the dependence of $A_{LR}$ on the beam energy is $\mathrm{dA_{LR}/d\sqrt{s}} = 2 \times 10^{-2}/\,\mathrm{GeV}$. The difference $\sqrt{s} - m_Z$ thus needs to be known to about 10 MeV to match the measurement with electron polarization only, and to about 1 MeV if polarized positrons are available. For the same reason beamstrahlung shifts $A_{LR}$. The shift is $9 \times 10^{-4}$ for TESLA and is larger for NLC/JLC [1]. The uncertainty can only be a few percent. If beamstrahlung in the $A_{LR}$ running is identical to that in the $Z$ scan used to calibrate the beam energy, the effect is absorbed into the mean energy measured in the calibration. In that case, practically no correction would be needed for $A_{LR}$. How well the beam parameters can be kept constant during the scan and how well the beamstrahlung can be measured still need further study. However, for $A_{LR}$, only the beamstrahlung and not the energy spread matters. If the beamstrahlung cannot be understood to the required level in the normal running mode one can still go to a mode with lower beamstrahlung at the expense of lower luminosity. The cost is an increase in the statistical error or the running time.

Finally, the rate at which the positron polarization must be switched, and the switching rates that are achievable are still unknown.

For the interpretation of the data it will be assumed that $\Delta A_{LR} = 10^{-4}$ is possible. This leads to $\Delta \sin^2 \theta_w^{\mathrm{eff}} = 0.000013$. It must be kept in mind that this error will increase by a factor of four if no positron polarization is available.

### *1.2.3 Observables with tagged quarks*

By the use of quark tagging in addition to the observables discussed above, the partial widths and forward-backward asymmetries for $b$ and $c$ quarks can be measured. These observables are sensitive to vertex corrections at the $Zqq$ vertex and to new Born-level effects that alter the SM relations between quarks and leptons. The $Zbb$ vertex is particularly interesting, since the $b$ is the partner of the heavy top quark, and since the vertex corrections are naturally enhanced with the quark mass.

To date, only the improvement to the $b$-quark observables has been estimated [5]. For the ratio $R_b$ of the $Z$ partial widths to $b$ quarks and to hadrons, an improvement of a factor five to the LEP/SLD average is possible. This improvement is due to the much better $b$ tagging than at LEP. The improved tagging results in a higher purity (over 99% for a 30% efficiency) and a smaller energy dependence, which in turn reduces the hemisphere correlations.

The forward-backward asymmetry with unpolarized beams measures the product of the coupling parameters for the initial-state electrons and the final-state quarks: $A^q_{\mathrm{FB}} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_q$, while the left-right forward-backward asymmetry with polarized beams measures the quark couplings directly: $A^q_{\mathrm{LR,FB}} = \frac{3}{4}\mathcal{P}\mathcal{A}_q$. For this reason a factor 15 improvement on $\mathcal{A}_b$ relative to the LEP/SLC result is possible if polarized positrons are available, and if other systematic effects are relatively small. With polarized electrons only, the improvement is limited by the polarization error to a factor of six. For control of systematics, the improved $b$-tagging capabilities are essential here as well.

Though the SM predicts that $Z$ decays to quarks are flavor-diagonal to a very good approximation, loop effects of new physics can induce flavor-violating rare decays [8]. These could be searched for at a high-luminosity $Z$ factory. For $Z \to b\overline{s}$ decays, the SM predicts a branching ratio of $\mathcal{B}(Z \to b\overline{s}) \simeq 1.4 \cdot 10^{-8}$. To date, the direct experimental bound on this process is relatively weak, at the level of about $10^{-3}$ [9], though bounds from rare $b$ decays such as $b \to s\ell^+\ell^-$ and $b \to s\nu\overline{\nu}$ lead to a bound $\mathcal{B}(Z \to b\overline{s}) \lesssim 5 \cdot 10^{-7}$ [8]. Still, there is room for a new physics contribution that might be revealed in a large sample of $Z$ decays.

## 2 $m_W$ from $WW$ threshold running

The mass $m_W$ of the $W$ boson plays a fundamental role in constraints on the Standard Model via comparison of direct measurement with the prediction based on other electroweak parameters. The electroweak measurements from LEP1 and Giga-Z—combined with the Higgs boson and top quark mass measurements from the linear collider—allow $m_W$ to be predicted to about 3 MeV within the SM. Measurements at the Tevatron and at LEP2 combine to give an $m_W$ precision of 34 MeV [10]. The LEP2 experiments hope to reach a combined precision of 35 MeV. With Run II at the Tevatron, 30 MeV per experiment appears feasible with 2 fb$^{-1}$, though systematics, correlated between experiments, will dominate [11]. The LHC experiments hope to reach an uncertainty of 20 MeV each, for perhaps an overall uncertainty of 15 MeV [12]. Unfortunately, these uncertainties remain significantly larger than that expected for the indirect determination and would limit the power of the electroweak constraints.

A high-luminosity linear collider presents an opportunity to measure $m_W$ with a much higher precision. The two potential approaches [13] are a $W^+W^-$ threshold scan and kinematic fitting of events with $W^+W^-$ production. With expected linear collider luminosities, one could obtain 100 fb$^{-1}$ in one year ($10^7$ s) at $W^+W^-$ threshold and about 1000 fb$^{-1}$ at $\sqrt{s} = 500$ GeV in several years. The threshold scan requires precise determination of the absolute average beam energy and of the distortion of the luminosity spectrum by beamstrahlung. The kinematic fitting method also requires precise knowledge of the beam energy, since it relies on a beam energy constraint. The uncertainty from this parameter will grow with energy, since beam calibration will likely refer back to the $Z$ peak. Furthermore, the energy spread from beamstrahlung grows approximately as the square of the beam energy.

The four-quark ($4q$) channel (46% of the rate) cannot be used in the kinematic analysis because of theoretical uncertainties associated with final-state interactions between the decay products of the $W^+$ and the $W^-$. This uncertainty contributes an error of 40–90 MeV for the current LEP $4q$ measurements [14–17]. Scaling of the LEP2 statistical precision for the remaining channels results in a 5 MeV $m_W$ precision at 500 GeV. However, significant reductions in systematics will be needed. In particular, the difficulties in beam energy calibration disfavor the direct reconstruction method.

### 2.1 $m_W$ from a polarized threshold scan

The extraction of $m_W$ from a threshold scan requires an accurate theoretical description of the cross-section dependence on $m_W$. The main corrections to the Born approximation near threshold come from QED. Fortunately, the dominant Coulomb correction (about 6%) is already known to all orders [18]. To keep the theoretical uncertainty down to 2 MeV, however, the electroweak and QCD corrections to the cross section must be known to 0.12% (about the size of the second-order Coulomb contribution). While work is needed, this goal appears attainable.

Recent studies [19,20] indicate that experimental systematics can be controlled to obtain a 5 MeV $m_W$ measurement with 100 fb$^{-1}$of data *if* a polarization of 60% for the positron beam can be achieved. The strategy capitalizes on the domination of the $W^+W^-$ cross section near threshold by the $t$–channel $\nu_e$ exchange process, which couples only to the $e^+_R e^-_L$ helicity combination. The correct $e^+_R e^-_L$ beam polarization enhances $W^+W^-$ production relative to the background, while the $e^+_L e^-_R$ polarization has almost negligible $W^+W^-$ production and so can constrain the background levels.

A sample scan is illustrated in Fig. 8.1. This study assumes that the absolute luminosity and the reconstruction efficiencies can be determined with a relative (point-to-point) accuracy of 0.25%. This is four times looser than that achieved for the LEP1 $Z$ line-shape scan. Beam polarizations are assumed known to 0.25%, and are further constrained at each scan point by exploring various polarization combinations. About 90% of the luminosity is given to the main $e^+_R e^-_L$ to $e^+_R e^-_L$ configurations, in a 5:1 ratio, with the 10% devoted to the remaining configurations to determine the beam polarization. LEP signal efficiencies and background rates [21] are assumed; this should be conservative for a linear collider detector. The $W$ width $\Gamma_W$ is assumed to have the SM value. Under these assumptions, a precision on $m_W$ of 4.9 MeV is predicted for 100 fb$^{-1}$of data.

To reduce the dependence of the $m_W$ precision on the absolute beam polarization determination, 'radiative return' ($e^+e^- \to \gamma + Z$) events can be incorporated into the analysis. They are sufficiently numerous—$10^7$ in 100 fb$^{-1}$—that the Blondel scheme described in the previous section can be employed to measure the polarization. After fine tuning of the luminosity distribution among various helicity configurations, a scan can still determine $m_W$ to 5 MeV without the 0.25% polarization calibration.

The background from $e^+e^- \to q\overline{q}$ and its polarization asymmetry is neglected in this analysis. It is possible that the polarization asymmetry of the sample of background events that pass the $WW$ event selection cuts will be poorly known. In this case, the scan strategy above may not be optimal for control of the systematics. While further study is warranted, incorporation of a scan point below threshold should control the uncertainties without significantly degrading precision on $m_W$.

The beam-energy and beamstrahlung uncertainties of a $W^+W^-$ threshold scan must be controlled to a few MeV to achieve the desired $m_W$ precision. One method [22] provides a direct measurement of the average $\sqrt{s}$ via reconstruction of $e^+e^- \to \gamma + Z$, $Z \to e^+e^-/\mu^+\mu^-$. This measurement includes the average beamstrahlung effect. A precision of 2.5 MeV may be possible for 100 fb$^{-1}$. Absolute alignment of the detector polar angle to $10^{-5}$ and knowledge of the radiative corrections will be needed. One could also calibrate a precise beam spectrometer using the $Z$ line shape and extrapolate to the $W^+W^-$ threshold. The uncertainty from the LEP1 $m_Z$ measurement will cancel in the $m_W/m_Z$ ratio. Beamstrahlung both reduces the effective $W^+W^-$ cross section at threshold and distorts the shape. To limit the effects to 2 MeV, the absolute induced distortion must be known to 0.1%. Mapping of the distortion to this accuracy appears feasible by measurement of the distribution in the acolinearity angle in Bhabha scattering at forward angles [23]. All of these aspects of the precision energy determination will be challenging if one wishes to achieve a 2 MeV error from this source.

### 2.2 Conclusion

The experimental systematics for an $m_W$ measurement near $W^+W^-$ threshold appear to be under control at the few-MeV level. Issues related to beam energy and beamstrahlung deserve further attention, but cautious optimism is appropriate. Certainly the $m_W$ issues should be considered in the accelerator and interaction region design. Given the one year of running required to reach the order 5 MeV accuracy in $m_W$, consideration of a dedicated low-energy facility seems appropriate. The feasibility of the measurement without positron polarization needs examination. A much longer running period would be necessary just to make up the loss in $W^+W^-$ production. The impact on control of the background level is currently unknown.

## 3 Electroweak tests of the Standard Model

The physics program outlined above opens new opportunities for high-precision physics in the electroweak sector. For reference, Table 8.2 [24] summarizes the present and anticipated precisions for the most relevant electroweak observables at the Tevatron—Run II (2 fb$^{-1}$) and TeV33 (30 fb$^{-1}$), the LHC, and a future linear collider without (LC) and with (Giga-Z) a low-energy program.

| | now | Run II | TeV33 | LHC | LC | Giga-Z |
|---|---|---|---|---|---|---|
| $\delta \sin^2 \theta_w^{\rm eff} (\times 10^5)$ | 17 | 50 [28] | 13 [28] | 21 [28,30] | (6) [28] | 1.3 [5] |
| $\delta m_W$ [MeV] | 37 | 30 [11] | 15 [12] | 15 [12,30] | 15 [32] | 6 [34] |
| $\delta m_t$ [GeV] | 5.1 | 4.0 [28] | 2.0 [28] | 2.0 [28,31] | 0.2 [33] | 0.2 |
| $\delta m_h$ [MeV] | — | — | 2000 [29] | 100 [29] | 50 [29] | 50 [29] |

Table 8.2: The expected experimental precision from various collider programs for $\sin^2 \theta_w^{\rm eff}$, $m_W$, $m_t$ and the Higgs boson mass, $m_h$, assuming $m_h = 110\,{\rm GeV}$. For the LC entry in parentheses, a fixed-target polarized Møller scattering experiment using the $e^-$ beam has been assumed. The present uncertainty on $m_W$ will be improved with the final analysis of the LEP2 data.

The SM predictions for the electroweak precision observables are affected via loop corrections by contributions from the top quark mass, $m_t$, and the Higgs boson mass, $m_h$. The prediction for the $W$ boson mass is obtained from

$$m_W = \frac{m_Z}{\sqrt{2}} \sqrt{1 + \sqrt{\frac{4\,\pi\,\alpha}{\sqrt{2}\,G_F\,m_Z^2}(1+\Delta r)}}, \tag{8.2}$$

where the loop corrections are contained in $\Delta r$ [25]. Beyond one-loop order, the QCD corrections are known at $\mathcal{O}(\alpha\alpha_s)$ [26] and $\mathcal{O}(\alpha\alpha_s^2)$ [27]. The electroweak two–loop corrections have recently been extended to include the complete fermionic contribution at $\mathcal{O}(\alpha^2)$ [35].

The effective leptonic weak mixing angle, $\sin^2 \theta_w^{\rm eff}$, is defined through the effective couplings $g_V^f$ and $g_A^f$ of the $Z$ boson to fermions at the $Z$ resonance,

$$\sin^2 \theta_w^{\rm eff} = \frac{1}{4\,Q_f} \left( 1 - \frac{{\rm Re}\ g_V^f}{{\rm Re}\ g_A^f} \right), \tag{8.3}$$

where the loop corrections enter through $g_{V,A}^f$. The radiative corrections entering the relations (8.2) and (8.3) depend quadratically on $m_t$, while the leading dependence on $m_h$ is only logarithmic.

The current theoretical uncertainties [36] are dominated by the uncertainties in the input parameters $m_t$ and $m_h$, and in the value of the running electromagnetic coupling constant evaluated at the scale $m_Z$. Let $\Delta\alpha = \alpha(m_Z) - \alpha(0)$. This difference results from electromagnetic vacuum polarization corrections due to the charged leptons and light quarks. The hadronic contributions to $\Delta\alpha$ currently give rise to an uncertainty $\delta\Delta\alpha \approx \pm 2 \times 10^{-4}$ [37]. If future low-energy $e^+e^-$ experiments can measure the hadronic total cross section up to the $J/\psi$ to 1%, it is possible to reduce this uncertainty to about $\delta\Delta\alpha = \pm 7 \times 10^{-5}$ [38]. As an estimate for the future theoretical uncertainties in the prediction of $m_W$ and $\sin^2 \theta_w^{\rm eff}$ from unknown higher-order

| | $m_W$ | $\sin^2\theta_w^{\rm eff}$ | all |
|---|---|---|---|
| now | 200% | 62% | 60% |
| Run II | 77% | 46% | 41% |
| TeV33 | 39% | 28% | 26% |
| LHC | 28% | 24% | 21% |
| LC | 18% | 20% | 15% |
| Giga-Z | 12% | 7% | 7% |

Table 8.3: Cumulative expected precisions for the indirect determination of the Higgs boson mass, $\delta m_h/m_h$, taking into account the error projections in Table 8.2 and the theoretical uncertainties of $m_W$ and $\sin^2\theta_w^{\rm eff}$. The first two columns use $m_W$ and $\sin^2\theta_w^{\rm eff}$ constraints alone, while the last column uses the full set of precision observables.

corrections (including the uncertainties from $\delta\Delta\alpha$) we use

$$\delta m_W(\text{theory}) = \pm 3\,\text{MeV}, \quad \delta\sin^2\theta_w^{\rm eff}(\text{theory}) = \pm 3\times 10^{-5} \quad (\text{future}). \tag{8.4}$$

The experimental error on $m_Z$ ($\delta m_Z = \pm 2.1\,\text{MeV}$ [10]) leads to an uncertainty in $\sin^2\theta_w^{\rm eff}$ of $\delta\sin^2\theta_w^{\rm eff} = \pm 1.4\times 10^{-5}$. While this uncertainty can currently be neglected, it will have non-negligible impact given the precision obtainable at Giga-Z. The future experimental error in the top quark mass, $\delta m_t = \pm 130\,\text{MeV}$, induces further uncertainties $\delta m_W = \pm 0.8\,\text{MeV}$ and $\delta\sin^2\theta_w^{\rm eff} = \pm 0.4\times 10^{-5}$.

Comparison of an indirect determination of the SM Higgs boson mass, which would be significantly improved by Giga-Z [39,24,40,5], with a future direct measurement will provide a sensitive test of the SM. Table 8.3 [24] summarizes both today's accuracy for the indirect prediction of $m_h$ and the accuracy available from the prospective improvements at forthcoming colliders listed in Table 8.2. The current accuracies assume $\delta\Delta\alpha = \pm 2\times 10^{-4}$ [37], while the future cases assume $\delta\Delta\alpha = \pm 7\times 10^{-5}$ [38]. The Giga-Z scenario allows an indirect determination of $m_h$ with an uncertainty of $\delta m_h/m_h = \pm 7\%$ (about the level of the current indirect $m_t$ determination). This represents a factor of three improvement over the EW constraints that could be made using LHC measurements, while a linear collider running solely at high energy would provide only a modest gain.

Figure 8.2 compares the potential of Giga-Z for testing the electroweak theory with the present status from both theoretical and experimental standpoints. The SM prediction corresponds to an allowed $m_h$ interval of $113\,\text{GeV} \le m_h \le 400\,\text{GeV}$ and to an allowed $m_t$ interval within its measured uncertainty. The theoretical prediction assumes that the Higgs boson has been found, with masses of 120, 150 and 180 GeV considered. The uncertainty induced assuming $\delta m_t = \pm 200$ MeV and $\delta\Delta\alpha = \pm 7\times 10^{-5}$ is indicated. The figure illustrates that the improved experimental accuracy at Giga-Z will allow tests of the internal consistency of the SM at an unprecedented

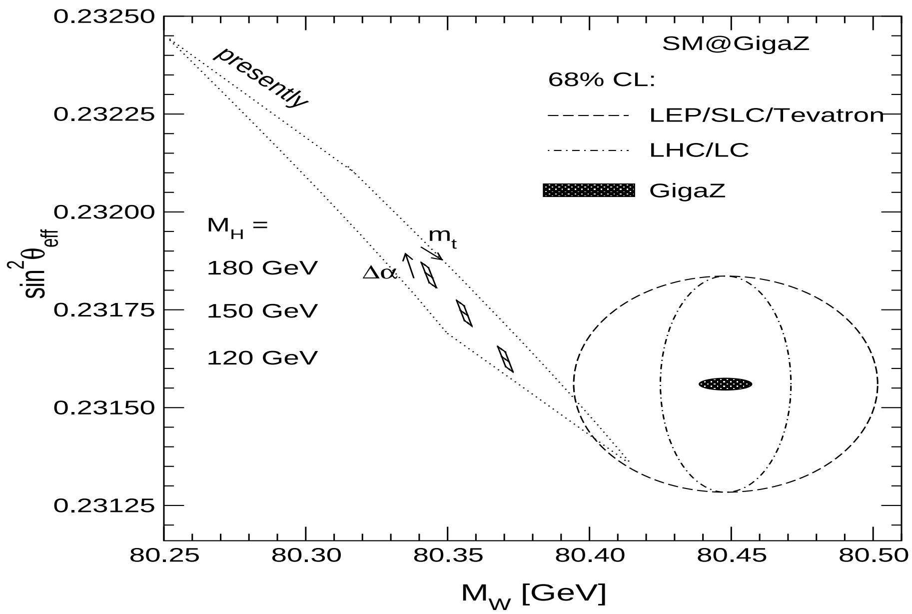



Figure 8.2: The present and prospective future theoretical predictions in the SM (for three $m_h$ values) are compared with the current experimental accuracies and those expected from LHC and Giga-Z (see Table 8.2). The future theoretical uncertainties arising from $\delta\Delta\alpha = \pm 7 \times 10^{-5}$ and $\delta m_t = \pm 200\,\text{MeV}$ are indicated.

level.

### 3.1 Parameterizations of deviations from the Standard Model

The precision achievable at Giga-Z allows for the exploration of possible effects of new physics with great sensitivity. This section is devoted to more general parameterizations of physics beyond the SM through the specific example of the $S$, $T$, $U$ parameters [41]. While these parameters are widely used, considerable confusion exists concerning their meaning and range of applicability. Because it is important to understand precisely how the effects of new physics can be probed in a sensible way given the potential Giga-Z accuracies, we briefly summarize the main points.

By definition, the $S$, $T$, $U$ parameters describe only the effects of new physics contributions that enter via vacuum-polarization effects (*i.e.*, self-energy corrections) to the vector-boson propagators of the SM. That is, the new physics contributions are assumed to have negligible couplings to SM fermions. The parameters can be computed in new models as certain combinations of one-loop self-energies. Experimentally, their values are determined by comparing the measurements, $\mathcal{A}_i^{\rm exp}$, of a number of observables with their SM predictions, $\mathcal{A}_i^{\rm SM}$,

$$\mathcal{A}_i^{\rm exp} = \mathcal{A}_i^{\rm SM} + f_i^{\rm NP}(S,T,U). \quad (8.5)$$

Here $\mathcal{A}_i^{\rm SM}$ contains all known radiative corrections in the SM evaluated at reference values of $m_t$ and $m_h$. The (linear) function $f_i^{\rm NP}(S,T,U)$ describes the contributions of new physics. For most precision observables, the corrections caused by a variation of $m_t$ and $m_h$ at one-loop order can also be absorbed into $S$, $T$, and $U$. A non-zero result for $S$, $T$, $U$ determined in this way indicates non-vanishing contributions of new physics (with respect to the SM reference value).

The $S$, $T$, $U$ parameters can only be applied for parameterizing effects of physics *beyond* the SM. To compute the SM predictions to which these parameters provide corrections, one must take into account the full contributions, which also contain vertex and box corrections, since these effects cannot be consistently absorbed into the $S$, $T$, $U$ parameters. For a more detailed discussion of this point, see [42]. Because the $S$, $T$, $U$ parameters are restricted to the leading-order contributions of new physics, they should only be applied for *small* deviations from the SM predictions. Their application to cases with large deviations from the SM, like extensions of the SM with a very heavy Higgs boson in the range of several TeV, is questionable. The current experimental values [43] (assuming $m_t = 173.4\,\mathrm{GeV}$ and $m_h = 100\,\mathrm{GeV}$) are

$$S = -0.07 \pm 0.11, \quad T = -0.10 \pm 0.14, \quad U = \ 0.10 \pm 0.15. \quad (8.6)$$

Other parameterizations, defined via linear combinations of various observables without reference to the SM contribution, have been suggested (see, *e.g.*, [44,45]). While any new physics model can be explored, it is not in all cases obvious that studying parameters is of advantage compared to studying the observables themselves. For this reason and for brevity, we restrict our discussion to the $S$, $T$, $U$ parameters.

Examples of new physics contributions that can be described in the framework of the $S$, $T$, $U$ parameters are contributions from a fourth generation of heavy fermions or effects from scalar quark loops (see Section 3.2). A counterexample going beyond the $S$, $T$, $U$ framework is given by corrections of the kind that could bring the prediction for the anomalous magnetic moment of the muon in agreement with the experimental value [46,47].

While many SM extensions result in a vanishing or small contribution to the $U$ parameter (see Ref. [43] and references therein), sizable contributions to $S$ and $T$ can be expected from a number of models. For instance, the contribution of a heavy Higgs boson with $m_h = 1\,\mathrm{TeV}$ gives rise to a contribution in $S$ and $T$ of about $S \approx 0.1$, $T \approx -0.3$ [48] (see however the discussion above). In technicolor models one typically expects $S$ and $T$ to be positive and of order 1 [48]. Peskin and Wells [48] have also examined the 'topcolor seesaw' model of Dobrescu and Hill [49], which predicts little or no new physics observable at the LHC or LC. The Giga-Z scenario, however, would reveal a significant departure in the $(S,T)$ plane from the minimal SM with a light Higgs boson.

These additional contributions to the $S,T,U$ parameters have to be compared with the errors with which these parameters can be extracted at Giga-Z [24]:

$$\Delta S = \pm 0.05, \quad \Delta T = \pm 0.06, \quad \Delta U = \pm 0.04. \tag{8.7}$$

These parameters are strongly correlated. Assuming $U = 0$, as justified above, the anticipated errors in $S$ and $T$ would decrease to about

$$\Delta S = \pm 0.02, \quad \Delta T = \pm 0.02. \tag{8.8}$$

The increased precision, compared to the present situation given in Eq. (8.6), will constrain or exclude of many possible extensions of the SM.

### 3.2 Tests of supersymmetry

We now explore the utility of the precision electroweak observables in a scenario with direct observation of new particles, by examining a specific example. Suppose that particles compatible with a MSSM Higgs boson and a light scalar top quark $\tilde{t}_1$ have been discovered at the Tevatron or the LHC, and further explored at an $e^+e^-$ linear collider. With the luminosity expected at a linear collider, the $\tilde{t}_1$ mass, $m_{\tilde{t}_1}$, and the mixing angle in the stop sector, $\cos\theta_{\tilde{t}}$, can be measured in the process $e^+e^- \to \tilde{t}_1\tilde{t}_1^*$ to a level below 1% [50,51].

The precision electroweak variables provide several constraints. First, the measurements and predictions for $m_W$ and $\sin^2\theta_w^{\rm eff}$ provide an indirect test of the MSSM, as they do for the SM. Comparison of the predicted to the measured value of the lightest CP-even MSSM Higgs boson mass, $m_h$, provides a further constraint. In the MSSM, $m_h$ is not a free parameter as in the SM; it is calculable from the other SUSY parameters. Furthermore, because $m_W$, $\sin^2\theta_w^{\rm eff}$ and $m_h$ are particularly sensitive to the SUSY parameters of the scalar top and bottom sector and of the Higgs sector, they provide an indirect probe of the masses of supersymmetric particles that might not be seen at the LHC or LC. In particular, the heavier scalar top quark, $\tilde{t}_2$, and the heavy Higgs bosons $A$, $H$ and $H^\pm$ could be outside the kinematic reach of the initial-stage LC, and background problems could preclude their observation at the LHC. Reference [24] explores this scenario and demonstrates that upper bounds on $M_A$ could be established through the SUSY contributions to $m_W$ and $\sin^2\theta_w^{\rm eff}$, just as the Higgs boson mass can be bounded in the SM.

Finally, we examine the indirect information on the mass of the heavier scalar top quark, $m_{\tilde{t}_2}$, that can be obtained by requiring consistency of the MSSM with measurements of $m_W$, $\sin^2\theta_w^{\rm eff}$, and $m_h$ in addition to those of $m_{\tilde{t}_1}$ and $\cos\theta_{\tilde{t}}$. The SUSY contributions to $m_W$ and $\sin^2\theta_w^{\rm eff}$ include the complete one–loop results in the

MSSM [52] as well as the leading higher-order QCD corrections [53]. The prediction for $m_h$ is obtained with the program *FeynHiggs* [54], based on the Feynman-diagrammatic two-loop result of Ref. [55]. A future uncertainty in the theoretical prediction of $m_h$ of $\pm 0.5\,\text{GeV}$ is assumed.

We examine the scenarios for a LC with and without the Giga-Z option and for the LHC (see Table 8.2), taking $m_{\tilde{t}_1} = 180 \pm 1.25\,\text{GeV}$ for LC/Giga-Z, and $180 \pm 18\,\text{GeV}$ for the LHC. The other parameters have been chosen according to the mSUGRA reference scenario 2 specified in Ref. [56], with the following accuracies: $M_A = 257 \pm 10$ GeV, $\mu = 263 \pm 1$ GeV, $M_2 = 150 \pm 1$ GeV, $m_{\tilde{g}} = 496 \pm 10$ GeV. For $\tan\beta$ a lower bound of $\tan\beta > 10$ has been taken. The central values for $m_W$ and $\sin^2\theta_w^{\text{eff}}$ have been chosen in accordance with a non-zero contribution to the precision observables from SUSY loops.

As one can see in Fig. 8.3, the allowed parameter space in the $m_{\tilde{t}_2}$–$|\cos\theta_{\tilde{t}}|$ plane is significantly reduced in the Giga-Z scenario relative to the others. Using the direct information on $|\cos\theta_{\tilde{t}}|$ from Ref. [51] allows an indirect determination of $m_{\tilde{t}_2}$ with a precision of better than 5% in the Giga-Z case. By comparing this indirect prediction for $m_{\tilde{t}_2}$ with direct experimental information on the mass of this particle, the MSSM could be tested at its quantum level in a sensitive and highly non-trivial way.

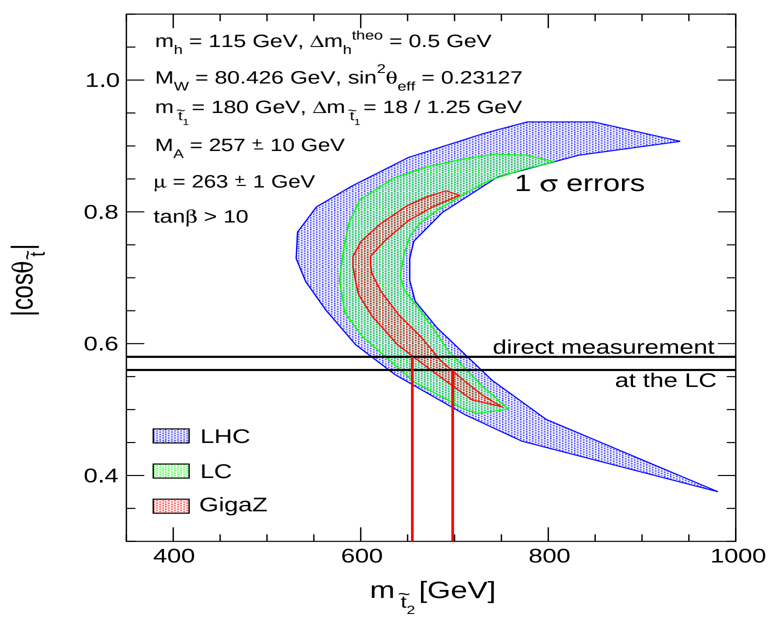



Figure 8.3: Indirect constraints on the MSSM parameter space in the $m_{\tilde{t}_2}$–$|\cos\theta_{\tilde{t}}|$ plane from measurements of $m_h$, $m_W$, $\sin^2\theta_w^{\text{eff}}$, $m_t$ and $m_{\tilde{t}_1}$ at a LC with and without the Giga-Z option and at the LHC. The solid lines indicate the direct information on the mixing angle from a measurement at the LC and the corresponding indirect determination of $m_{\tilde{t}_2}$.

## 4 Heavy flavor physics

The $Z$ pole has already been established as an excellent laboratory for the study of $b$ physics. The large boost and resulting detached vertices for the $b$ decays have amply compensated the relatively modest statistics of the LEP experiments, allowing them to make many competitive and important measurements. SLD, with much smaller statistics, has benefitted greatly from the SLC's beam polarization in the $b$ studies that require production tagging and has produced measurements competitive with LEP. The hadronic experiments, LHC-b and BTeV, will be faced with large backgrounds, with typical signal-to-noise ratios of $S/N \approx 5 \times 10^{-3}$ compared to $S/N \approx 0.21$ at the $Z$ (albeit with $10^4$ to $10^5$ more $b$'s produced).

The $Z$-pole running will result in a very powerful $b$ experiment. With 80% and 60% polarizations for the electron and positron beams, respectively, production flavor tags that include the forward–backward production asymmetry should reach a signal $\times$ purity $\varepsilon D^2$ approaching 0.6. (With 80% electron polarization and no positron polarization, one finds about half of this value.) For comparison, the $B$ factories have achieved $\varepsilon D^2 \approx 0.25$ [57] while the hadronic facilities will have rather lower values. Coupled with the excellent resolution expected from the vertex detector for the linear collider, a reach in $\delta m_s$ of 40 ps$^{-1}$ is possible with $10^9$ $Z$'s, with a resolution limit of around 80 ps$^{-1}$.

The scenario in which $2 \times 10^9$ $Z$ decays are produced, yielding about $6 \times 10^8$ $b$ hadrons, has been investigated. This sample should be compared to the $\Upsilon(4S)$ and hadronic $b$ samples that will be available in the same time period [5,58]. This section is largely based on a review of such work in [58]. With these statistics, $b$ studies at the $Z$ offer a number of measurements that are of fundamental importance for the comprehensive $b$-physics program that is being undertaken worldwide, but which cannot be addressed adequately at other existing or planned facilities. A longer running period at the $Z$ ($10^{10}$ $Z$'s) is necessary to improve upon the sensitivity for the 'canonical' measurements planned at other $b$ facilities, despite the combined advantages of tagging, boost and purity. Such a facility would be quite competitive. A precision on $\sin 2\beta$ of about 0.01 would be obtainable, similar to that obtainable from LHC-b and BTeV. If one translates the studies of $B \to \pi\pi$ to an effective value of $\sin 2\alpha$, the uncertainty would be about 0.02, approaching that of BTeV and somewhat better than that expected from LHC-b.

The topics unique to a polarized $Z$ facility are the following:

1. The quark-level transition
$$b \to q + \nu\overline{\nu} \tag{8.9}$$
could well be affected significantly by new physics in ways quite different from $b \to q + l^+l^-$. Searching for $b \to q\nu\overline{\nu}$ in hadronic colliders appears hopeless. The searches also pose quite a challenge for an $\Upsilon(4S)$ experiment because of

the intermingling of the decay productions from the two $B$ decays [59].

2. The CKM elements $|V(cb)|$ and $|V(ub)|$, determined in semileptonic $B$ decay, suffer from a potentially considerable source of uncertainty due to limitations in the validity of quark-hadron duality, of which at present little is known for certain. Detailed comparisons of semileptonic $B_s$ and $B_{u,d}$ decays would be invaluable in this respect. The $\Upsilon(4S)$ machines will not have $B_s$ samples, while the hadronic machines will have difficulty providing precise inclusive measurements.
3. The availability of polarized beams will allow production of a huge sample of highly polarized beauty baryons whose weak decays can be analyzed. In this way a determination of the handedness of a quark transition becomes feasible.

The canonical measurements for which $2 \times 10^9$ $Z$'s may be competitive include

1. The transition $b \to \tau\nu$ contains multiple neutrinos in the final state, with an experimental situation similar to that for $b \to q + \nu\overline{\nu}$. This measurement determines the product $F_B|V_{ub}|$, and would play a fundamental role in constraints of the CKM matrix. The reach at Giga-Z has not yet been studied.
2. The production flavor tagging from the $Z$ running might offer the most precise measurements of $\mathcal{B}(B^0 \to \pi^0\pi^0)$ and $\mathcal{B}(\overline{B}^0 \to \pi^0\pi^0)$, which are of great significance for extracting the angle $\phi_2$ or $\alpha$ from the measured CP asymmetry in $B^0 \to \pi^+\pi^-$.

The following subsections elaborate on these points.

### 4.1 Measurement prospects for $\mathcal{B}(B \to \pi^0\pi^0)$

One of the promising strategies for measuring the CKM angle $\alpha$ is the study of the CP asymmetry in the decay $\mathrm{B}^0 \to \pi^+\pi^-$. The presence of significant 'penguin' contributions to $\mathrm{B} \to \pi^+\pi^-$ complicates the extraction of $\alpha$ from the measured time-dependent CP asymmetry. The penguin and tree contributions can be separated by measuring the branching ratios $\mathcal{B}(\mathrm{B}^0 \to \pi^+\pi^-)$, $\mathcal{B}(\mathrm{B}^+ \to \pi^+\pi^0)$ and $\mathcal{B}(\mathrm{B}^0 \to \pi^0\pi^0)$ and the charge conjugate modes [60]. The first can be measured as a by-product of the CP-asymmetry analysis, but the other two are more difficult. The need to reconstruct $\pi^0$s makes them extremely challenging for hadron machines. The expected branching ratios are also very small, of order $10^{-6}$, with experimental upper limits of $12.7 \times 10^{-6}$ ($\pi^+\pi^0$) [61] and $9.3 \times 10^{-6}$ ($\pi^0\pi^0$) [62].

The feasibility of measuring these branching ratios at a linear collider was studied [5] using the fast Monte Carlo simulation SIMDET [63]. The reconstructed $B$ mass resolutions were found to be 150 MeV ($\pi^0\pi^0$) and 120 MeV ($\pi^+\pi^0$), dominated by the calorimeter angular resolution. Assuming signal branching ratios of a few

$10^{-6}$ gives signal samples of about 200 events for $2 \times 10^9$ $Z^0$ decays, on top of several hundred events of combinatorial background. This would allow a flavor-independent measurement comparable to that of BABAR or BELLE with about $200\,\mathrm{fb}^{-1}$ [5]. For the separate $B$ versus the $\overline{B}$ branching fractions, which are needed for the $\alpha$ determination, the factor of two or more improvement in $\varepsilon D^2$ at the $Z$ relative to that for the $B$ factories makes these measurements with $10^9$ $Z$'s competitive with, if not better than, those obtainable at the $B$ factories. It should be emphasized that this study was performed with a very crude calorimeter simulation and further background rejection may certainly be possible after more detailed studies.

### 4.2 $B \to X_q \nu\overline{\nu}$

The large backgrounds at hadronic machines make measurement of $B \to X_q \nu\overline{\nu}$ impossible there. In an $e^+e^-$ threshold machine, such transitions could be found only at the cost of reconstructing one $B$ more or less fully. At Giga-Z, however, the relative cleanliness of the $Z$, the hemispheric separation of the $b$ quarks, and the well-defined initial state provide powerful tools for discovering and actually measuring properties of such transitions at the $Z$. This is illustrated by the fact that the current upper limit on this decay mode comes from LEP1:

$$\mathrm{BR}(B \to X_s \nu\overline{\nu}) \leq 7.7 \times 10^{-4} \quad \text{(ALEPH)} \ . \tag{8.10}$$

New physics can affect $b \to q l^+ l^-$ and $b \to q\nu\overline{\nu}$ in quite different way for various reasons [64]. For example, new contributions to an effective $bsZ$ vertex would enhance $b \to q\nu\overline{\nu}$ relative to $b \to q l^+ l^-$ by a large factor, and study of $b \to q\nu\overline{\nu}$ (with contributions from $b \to q\nu_\tau\overline{\nu}_\tau$) in addition to $b \to q e^+ e^-$ and $b \to q\mu^+\mu^-$ can help disentangle new physics scenarios with generation–dependent couplings .

At the $Z$, the statistics will be high enough to make meaningful searches for $B \to X_s \nu\overline{\nu}$. With an inclusive branching fraction in the standard model of about $4 \times 10^{-5}$, and exclusive branching fractions to $K$ and $K^*$ of order $10^{-5}$ [64], one can expect a few times $10^3$ events in exclusive channels and about $10^4$ inclusively. The expected reach, including control of backgrounds such as $b \to \tau\nu$, is not known at this time, but warrants study.

### 4.3 Semileptonic $B_s$ decays

The CKM parameters $V_{cb}$ and $V_{ub}$ play a central role in the prediction of various CP asymmetries in $B$ and $K$ decays. With precision measurements, constraints on new physics scenarios would be obtained by comparison of the predictions with direct measurements. It is crucial for this program to have reliable determination of $V_{cb}$ and $V_{ub}$, obtained from semileptonic $B$ decays through observables in exclusive and inclusive modes.

Inclusive measurements play an important role in these determinations. The known uncertainties are estimated at the 5% level for $V_{cb}$ and at the (10–15)% level for $V_{ub}$. However, there may be an additional significant source of systematic uncertainty, the validity of quark-hadron duality, which underlies almost all applications of the $1/m_Q$ expansions. A large body of folkloric or circumstantial evidence suggests that duality is a useful and meaningful concept. But for a full evaluation of the data from beauty physics it is essential to know with *tested* confidence whether the deviations from exact duality in semileptonic transitions arise at the 10%, the 5%, or the 1% level. It is quite unlikely that this question can be answered by theoretical means alone.

Experimentally, one can probe duality via an independent extraction of $|V_{cb}|$ in $B_s$ decays through measurement of $\Gamma_{SL}(B_s)$. One could also determine the rate for $B_s \to l\nu D_s^*$, extrapolate to zero recoil, and extract the product $|V(cb)F_{B_s\to D_s^*}(0)|$. The form factor can be obtained from the result of the Heavy Quark Expansion

$$|F_{B_s\to D_s^*}(0)| \simeq |F_{B\to D^*}(0)| \tag{8.11}$$

up to $SU(3)$ breaking corrections, which can be estimated.

The physical origin of duality violation would be the accidental presence of a nearby hadronic resonance with appropriate quantum numbers to affect the decay pattern for one of the $B$ mesons. On one hand, this resonance may affect $B_d \to l\nu X_c$ and $B_u \to l\nu X_c$, but not $B_s \to l\nu X_c$; conversely, it may affect $B_s$ transitions while having no impact on $B_{u,d}$ channels. If the same value emerged for $|V(cb)|$ in both cases, we would have verified the validity of duality in this case at least. If not, we would not know which, if any, of the values is the correct one, but we would be aware of a serious problem.

Duality violation could exhibit a different pattern in $B \to l\nu X_u$ channels. Here theory also calls for a detailed comparison of $B_d$ and $B_u$ modes, since one expects a difference in the endpoint region of $B_d$ and $B_u$ semileptonic decays [65]. Hadronic resonances could affect $B_d \to l\nu X_u$ and $B_u \to l\nu X_u$ quite differently. In addition, measurements of $B_s \to l\nu X_u$, both inclusive and exclusive, would provide crucial cross checks.

### 4.4 Weak decays of polarized beauty baryons

The large polarization asymmetry for $Z$ decay to $b$ quarks implies that beauty baryons produced in $Z$ decays are highly polarized. From $2 \times 10^9$ $Z$s, one expects about $3 \times 10^7$ polarized $b$-flavored baryons. The study of the weak decays of these particles offers a whole new field of dynamical information. The existence of initial-state polarization in $\Lambda_b$ decays allows one to analyze the chirality of the quark coupling *directly*; it also leads to a new program of studying observables revealing direct CP violation. Charmed baryons also merit study.

| Mode | Branching Ratio | Number of Events |
|---|---|---|
| $\Lambda_b \to \Lambda_c \ell \overline{\nu}_\ell$ | $8 \times 10^{-2}$ | $5 \times 10^6$ |
| $\Lambda_b \to p \ell \overline{\nu}_\ell$ | $8 \times 10^{-4}$ | $5 \times 10^4$ |
| $\Lambda_b \to X_s \gamma$ | $3 \times 10^{-4}$ | 11000 |
| $\Lambda_b \to \Lambda \gamma$ | $5 \times 10^{-5}$ | 1400 |
| $\Lambda_b \to \Lambda \ell \ell$ | $1 \times 10^{-6}$ | 50 |

Table 8.4: Expected numbers of events for $\Lambda_b$ decays, based on the Standard Model estimates.

A generic analysis of $b \to s\gamma$ results in two transition operators, mediating the decays

$$b_R \to s_L \gamma \ , \ b_L \to s_R \gamma \ . \tag{8.12}$$

While the second operator is highly suppressed in the SM, by a factor $m_s/m_b$, these operators could be of comparable size in new physics scenarios, for example, in Left-Right Symmetric models or the MSSM. While the decays of mesons realistically cannot distinguish between these two transitions, a study of the $\Lambda$ polarization in the decay $\Lambda_b \to \Lambda\gamma$ with polarized $\Lambda_b$ could probe the SM prediction that the ratio of left- to right-handed couplings is $r \lesssim 0.04$. One measures the asymmetry in the angular distribution defined between the $\Lambda_b$ spin and the photon in the parent baryon rest frame. Based on the statistics of Table 8.4, corresponding to roughly 750 fully reconstructed events, the measurement would be sensitive to values of $r$ between 0.5 and 1.9 at the $5\sigma$ level. For comparison, the sensitivity extends from 0.2 and 4.1 with $10^{10}$ $Z$'s [66]. It should be noted that the angular asymmetry is a theoretically very clean observable and the extraction of $r$ is essentially limited only by statistics.

A significant non-vanishing contribution of $b_L \to s_R\gamma$ would signal the intervention of new physics. One can actually undertake an *inclusive* polarization study of $\Lambda_b \to \Lambda\gamma + X$ with large statistics; the clean environment of the $Z$ is crucial here. Corresponding studies can be performed with $\Lambda_b \to l^+ l^- X$ with smaller statistics.

Although theoretically less clean, similar angular asymmetries in rare hadronic 2-body decays such as $\Lambda_\mathrm{b} \to \Lambda\phi$ offer a unique opportunity to probe for new physics contributions to four-quark penguin operators with chiralities opposite to those in the SM [66].

As an advantage over experiments with unpolarized $\Lambda_b$ baryons, spin correlations between the spin of the $\Lambda_b$ and the daughter baryon are fully accessible. It is possible, for example, to distinguish between pseudoscalar and vector transition form factors [67]. This allows for novel, powerful consistency checks of the Standard Model including its CP and chirality properties.

Semileptonic decays of polarized $\Lambda_b$ allow testing of the $V - A$ character of $b$ quarks with unprecedented accuracy and searches for CP asymmetries in the decay spectra. For example, comparison of

$$\Lambda_b \to l^-(p+X)_{\text{no charm}} \quad \text{vs.} \quad \overline{\Lambda}_b \to l^+(\overline{p}+X)_{\text{no charm}}, \tag{8.13}$$

might reveal CP violation from new physics. In final states with at least three particles ($\Lambda_b \to ABC$), one can also form $T$-odd correlations such as

$$C_T \equiv \langle \vec{\sigma}_{\Lambda_b} \cdot (\vec{p}_A \times \vec{p}_B) \rangle \tag{8.14}$$

with $\vec{p}_A$, $\vec{p}_B$ denoting the momenta of $A$ and $B$, respectively, and $\vec{\sigma}_{\Lambda_b}$ the $\Lambda_b$ polarization. A nonzero value of $C_T$ can be due either to $T$ violation or to final-state interactions. Measurement of $\overline{C}_T$ in the CP-conjugate process resolves the ambiguity. If $C_T \neq \overline{C}_T$, one has a signature of direct CP violation. Since these effects are typically quite suppressed in the Standard Model, such studies represent largely a search for new physics. They can be performed in nonleptonic modes

$$\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^0, p\pi^-\pi^0, \Lambda K^+ \pi^- \tag{8.15}$$

as well as in semileptonic channels containing a $\tau$ lepton, since the effect is proportional to the lepton mass [68].

## 5 Summary

A sample of order $10^9$ $Z$'s will provide important and unique tools in the search for and constraint of physics beyond the Standard Model. The program available with polarized positron beams in particular provides dramatic improvement in the measurement precision of the electroweak observables at the $Z$. This improvement leads to markedly more powerful constraints on Standard Model and new physics scenarios. The polarized $b$-baryon program offers a unique window of exploration for new right–handed couplings. With the statistics and $b$-tagging capabilities available with two polarized beams, running for several years ($10^{10}$ $Z$'s) could provide a $b$ physics program rivaling the proposed hadronic experiments in some fundamental CKM measurements.

Without positron polarization, significant gains can still be made. Much of the $b$ physics would suffer only from a decrease in statistics. Impact on the $\Lambda_b$ asymmetry measurements needs to be evaluated. The improvement in $\Delta A_{LR}$ is still significant and useful. The most damaging aspect could be the loss of the $m_W$ determination from threshold running, for which it is unclear that a 5–6 MeV determination would be realistic without positron polarization. This impact still needs study.

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