What is the Case for a Return to the Z-Pole?

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Abstract. The possibilities to run with a linear collider at the Z-pole with high luminosity are examined. Apart from the implications on machine and detector the interest for electroweak and B-physics is discussed.

I INTRODUCTION

In the past LEP and SLC have contributed a lot to our knowledge of particle physics. On one hand the measurements of the Z-mass and couplings near the Z pole and the measurement of the W mass above the W-pair threshold test the Standard Model at the loop level and open a window to new physics at much higher scales through virtual effects. On the other hand the large cross section at the Z pole for all fermions apart from t-quarks provides a rich source for some particles like τ's, D-mesons or B-mesons that can be studies in a rather clean environment.

A linear collider can potentially repeat all the measurements done at LEP and SLC with much higher statistics. It is therefor worth studying in which fields Z-running at such a machine can still contribute in the light of the competition from new machines, namely the e^+e^- B-factories, run II of the TEVATRON and the LHC.

II THE GIGA-Z SETUP

The Linear Collider in the so called Giga-Z scenario should be able to provide about 10^9 recorded Z-decays. As it will be discussed later this is only useful if also a high degree of electron polarization ($\geq 80\%$) is possible. In addition one needs either a very good precision on polarimetry ($\mathcal{O}(0.1-0.5\%)$) or positron polarization of at least 20%.

In addition to Z running also running with similar luminosity at the W-pair threshold should be possible.

In the NLC design [1] the positron source under study is independent of the electron beam. It is thus feasible to start the machine around the Z-pole and upgrade it to higher energies later.

The TESLA design [2] uses the high energy ($> 150\,\mathrm{GeV}$) electron beam to produce the positrons by sending the beam through a wiggler or a helical undulator. To run at the Z-pole one needs one part of the electron arm to produce the 45 GeV physics beam and the other part to accelerate the high energy beam for positron creation. In this design one would therefor prefer to come back to the Z pole only after the basic high energy program is completed.

Table 1 shows the luminosity, beamstrahlung and depolarization for the two designs. The option with low beamstrahlung is shown for the NLC as an example, however it is possible with all designs.

	NLC		TESLA
	norm	low δ_B	
$\mathcal{L}\,(10^{33})$	4.1	2	5
$\delta_B\,(\%)$	0.16	0.05	0.1
$\Delta\mathcal{P}_{\mathrm{IP}}\,(\%)$	0.07	0.02	0.1

TABLE 1. Luminosity, beamstrahlung and depolarisation in the interaction point for the two designs. Beamstrahlung and depolarization are given for the outgoing beam. For the interacting particles they are a factor two to four smaller.

The total hadronic cross section at the Z pole is given by $\sigma \approx \sigma_u(1+\mathcal{P}_{\mathrm{e}^+}\mathcal{P}_{\mathrm{e}^-})$ with $\mathcal{P}_{\mathrm{e}^+}$ ($\mathcal{P}_{\mathrm{e}^-}$) being the positron (electron) polarization and $\sigma_u \approx 30\mathrm{nb}$. 10^9 Zs can thus be be produced in 50-100 days of running with a Z rate of 100-200Hz. If it is found worthwhile also 10^{10} Zs can be produced in three to five years (150days/year) of running time.

The beamstrahl effects seem manageable and the depolarization in the interaction is almost negligible.

III ELECTROWEAK PHYSICS

The interesting quantities in electroweak physics, accessible at Giga-Z are:

- the normalization of the Z axial-vector coupling to leptons ($\Delta\rho_\ell$) which is measured from the partial width Γ_ℓ;
- the effective weak mixing angle measured from the ratio of vector to axial vector coupling of $Z \to \ell\ell$ ($\sin^2\theta^\ell_{\mathrm{eff}}$);
- the mass of the W (m_{W});
- the strong coupling constant from the Z hadronic decay rate ($\alpha_s(m^2_{\mathrm{Z}})$);

	LEP precision
m_Z	$0.2 \cdot 10^{-4}$
Γ_Z	$0.9 \cdot 10^{-3}$
$\sigma_0^{\mathrm{had}} = \frac{12\pi}{m_Z^2} \frac{\Gamma_e \Gamma_{\mathrm{had}}}{\Gamma_Z^2}$	$0.9 \cdot 10^{-3}$
$R_\ell = \frac{\Gamma_{\mathrm{had}}}{\Gamma_l}$	$1.2 \cdot 10^{-3}$

TABLE 2. LEP precision on the minimally correlated observables from the Z-scan [3].

	LEP [3]	Giga-Z
m_Z	$91.1874 \pm 0.0021\,\mathrm{GeV}$	$\pm 0.0021\,\mathrm{GeV}$
$\alpha_s(m_Z^2)$	0.1183 ± 0.0027	± 0.0009
$\Delta\rho_\ell$	$(0.55 \pm 0.10) \cdot 10^{-2}$	$\pm 0.05 \cdot 10^{-2}$
N_ν	2.984 ± 0.008	± 0.004

TABLE 3. Comparison between Giga-Z and LEP for results obtained from a Z-scan.

- the vertex correction to Zbb vertex measured from $R_\mathrm{b}, \mathcal{A}_\mathrm{b}$.

From the parameters listed above $\Delta\rho_\ell$ and α_s are obtained from a scan of the Z-resonance. Table 2 shows the LEP precision on the minimally correlated observables. α_s can be obtained from R_ℓ only. For ρ_ℓ, however, one needs to improve on all parameters apart from m_Z, so that a scan and an absolute luminosity measurement are needed.

A measurement of the beam energy relative to the Z-mass of 10^{-5} seems possible. This would improve the relative accuracy on Γ_Z to $0.4 \cdot 10^{-3}$. The selection efficiency for muons, taus and hadrons should be improved by a factor three relative to the best LEP experiment [4], resulting in $\Delta R_\ell / R_\ell = 0.3 \cdot 10^{-3}$. Also the experimental error on the luminosity might improve by this factor. However if the theoretical uncertainty stays at its present value (0.05%) the possible precision on σ_0^{had} is only $0.6 \cdot 10^{-3}$. It should however be noted that beamstrahlung plus energy spread increase the fitted Γ_Z by about 60 MeV and decrease σ_0^{had} by 1.8%, where the majority comes from the beamspread. For the α_s measurement these effects need to be understood to roughly 10% while for $\Delta\rho_\ell$ one needs 2%. There is the potential to achieve this precision with the acolinearity measurement of Bhabha events [5] or to extend the scan to five scan points and fit for the beamspread, but both options need further studies.

Table 3 compares the parameters that can be obtained from a scan at Giga-Z with the results obtained at LEP. Gains of a factor two to three are generally possible.

Much more interesting are the prospects on $\sin^2\theta^\ell_{\rm eff}$ [6,7]. With polarized beams the most sensitive observable is the left-right cross section asymmetry $A_{\rm LR}$:

$$\begin{aligned} A_{\rm LR} &= \frac{1}{\mathcal{P}}\frac{\sigma_L-\sigma_R}{\sigma_L+\sigma_R} \\ &= \mathcal{A}_{\rm e} \\ &= \frac{2v_e a_e}{v_e^2+a_e^2} \\ v_e/a_e &= 1-4\sin^2\theta^\ell_{\rm eff} \end{aligned} \tag{1}$$

independent of the final state. With 10^9 Zs, an electron polarization of 80% and no positron polarization the statistical error is $\Delta A_{\rm LR}=4\cdot10^{-5}$. The error from the polarization measurement is $\Delta A_{\rm LR}/A_{\rm LR}=\Delta\mathcal{P}/\mathcal{P}$. With electron polarization only and $\Delta\mathcal{P}/\mathcal{P}=0.5\%$ one has $\Delta A_{\rm LR}=8\cdot10^{-4}$. If also positron polarization is available $\mathcal{P}$ in equation (1) has to be replaced by $\mathcal{P}_{\rm eff}=\frac{\mathcal{P}_{\rm e+}+\mathcal{P}_{\rm e-}}{1+\mathcal{P}_{\rm e+}\mathcal{P}_{\rm e-}}$. For $\mathcal{P}_{\rm e^-}(\mathcal{P}_{\rm e^+})=80\%(60\%)$, due to error propagation, the error in $\mathcal{P}_{\rm eff}$ is a factor of three to four smaller than the error on $\mathcal{P}_{\rm e^+}$, $\mathcal{P}_{\rm e^-}$ depending on the correlation between the two measurements [8].

However, with positron polarization a much more precise measurement is possible using the Blondel scheme [9]. The total cross section with both beams being polarized is given as $\sigma=\sigma_u\left[1-\mathcal{P}_{\rm e^+}\mathcal{P}_{\rm e^-}+A_{\rm LR}(\mathcal{P}_{\rm e^+}-\mathcal{P}_{\rm e^-})\right]$. If all four helicity combinations are measured $A_{\rm LR}$ can be determined without polarization measurement as

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

Figure 1 shows the error on $A_{\rm LR}$ as a function on the positron polarization. For $\mathcal{P}_{\rm e^+}>50\%$ the dependence is relatively weak. For 10^9 Zs a positron polarization of 20% is better than a polarization measurement of 0.1% and electron polarization only.

However polarimeters for relative measurements are still needed. The crucial point is the difference between the absolute values of the left- and the right-handed states. If the two helicity states for electrons and positrons are written as $\mathcal{P}_{\rm e^\pm}=\pm|\mathcal{P}_{\rm e^\pm}|+\delta\mathcal{P}_{\rm e^\pm}$ the dependence is $\mathrm{dA_{LR}}/\mathrm{d}\delta\mathcal{P}_{\rm e^\pm}\approx0.5$. One therefor needs to understand $\delta\mathcal{P}_{\rm e^\pm}$ to $<10^{-4}$. To achieve this a polarimeter with at least two channels with different analyzing power to handle effects like polarization dependent e-γ luminosity internally is needed.

Due to $\gamma-Z$-interference the dependence of $A_{\rm LR}$ on the beam energy is $\mathrm{dA_{LR}}/\mathrm{d}\sqrt{\mathrm{s}}=2\cdot10^{-2}/\,\mathrm{GeV}$. The difference $\sqrt{s}-m_{\rm Z}$ thus needs to be known to $\sim1\,\mathrm{MeV}$. For the same reason beamstrahlung shifts $A_{\rm LR}$ by $\sim9\cdot10^{-4}$ (TESLA design), so its uncertainty can only be a few percent. If beamstrahlung is identical in the Z-scan to calibrate the beam energy it gets absorbed in the energy calibration, so that practically no corrections are needed for $A_{\rm LR}$. How far the

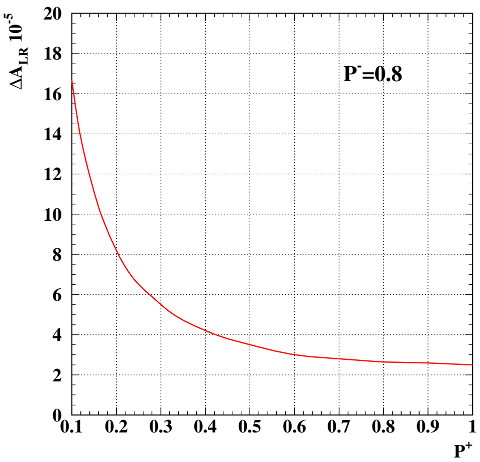

FIGURE 1. Error of $A_{\rm LR}$ as a function of the positron polarization for a luminosity corresponding to 10^9 unpolarized Zs.

beam parameters can be kept constant during the scan and how well the beamstrahlung can be measured still needs further studies. However, for $A_{\rm LR}$ only the beamstrahlung and not the beamspread 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 increasing the statistical error or the running time.

Other systematics should be small. A total error of $\Delta A_{\rm LR} = 10^{-4}$ will thus be assumed, corresponding to $\Delta \sin^2\theta^\ell_{\rm eff} = 0.000013$. This is an improvement of a factor 13 relative to the combined LEP/SLD [3] result.

For the b-quark observables one profits from the improved b-tagging and, in the case of the forward backward asymmetries, also from beam polarization. In summary for $R_{\rm b}$ a factor five improvement and for $\mathcal{A}_{\rm b}$ a factor 15 is possible relative to LEP/SLD [6, 10]. If the present slight discrepancy between the measured and the predicted $\mathcal{A}_{\rm b}$ is real it cannot be missed with Giga-Z.

The cleanest way to measure the W-mass is from a threshold scan where no uncertainties from fragmentation, color reconnection etc. enter. Near threshold the cross section is dominated by the neutrino t-channel exchange with a phase space suppression of β, compared to the β^3 suppressed s-channel. The hard process is thus dominated by the well understood Weν-coupling. However, for the radiative corrections a full one loop calculation is needed, since the double pole approximation [11] is not applicable in this region. To estimate the obtainable precision on $m_{\rm W}$ a scan around $\sqrt{s} = 161\,\text{GeV}$ has been simulated [12] with $\mathcal{L} = 100\,\text{fb}^{-1}$, corresponding to one year of running. Beam polarization has been used to enlarge the signal and to measure the background which requires a polarization measurement of $\Delta\mathcal{P}/\mathcal{P} < 0.25\%$. Assuming efficiencies and purities as at LEP the error on $m_{\rm W}$ will be 6 MeV if the luminosity and the efficiencies are known to 0.25%, increasing to 7 MeV if they are left free in the fit.

Before the precision data can be interpreted in the framework of the Standard Model or one of its extensions the uncertainties of the predictions stemming from the uncertainties in the input parameters need to be discussed. At the moment the by far largest uncertainty, especially for the prediction of $\sin^2\theta^\ell_{\rm eff}$ comes from the running of the electromagnetic coupling from zero to the Z-scale. Using data only, ignoring the latest BES results, the uncertainties on $\sin^2\theta^\ell_{\rm eff}$ and $m_{\rm W}$ are $\Delta\sin^2\theta^\ell_{\rm eff} = 0.00023$, $\Delta m_{\rm W} = 12\,\mathrm{MeV}$ [13]. Using perturbative QCD also at lower energies, these errors can be reduced by about a factor of three [14,15]. Only if the hadronic cross section up to the Υ is known to 1% the errors can be brought down to $\Delta\sin^2\theta^\ell_{\rm eff} = 0.000017$, $\Delta m_{\rm W} < 1\,\mathrm{MeV}$ [16].

The 2 MeV error on the Z mass induces an error of 0.000014 on $\sin^2\theta^\ell_{\rm eff}$ and, if the beam energy is calibrated relative to the Z-mass 1 MeV on $m_{\rm W}$. Unless a new circular collider for Z-pole running is built, where it is easier to measure the absolute energy scale, this error limits even further improvement on $\sin^2\theta^\ell_{\rm eff}$.

A 1 GeV error on $m_{\rm t}$ gives $\Delta\sin^2\theta^\ell_{\rm eff} = 0.00003$, $\Delta m_{\rm W} = 6\,\mathrm{MeV}$. With an error of $\Delta m_{\rm t} \approx 100\,\mathrm{MeV}$ as it is expected from a threshold scan at a linear collider, the contribution from $m_{\rm t}$ on the predictions will be negligible.

If it is assumed that the Standard Model is the final theory the Higgs mass can be determined from the Giga-Z data to a precision of 5% [6,17]. Figure 2 compares the sensitivity of the Higgs fit to the Giga-Z data with the present situation [3].

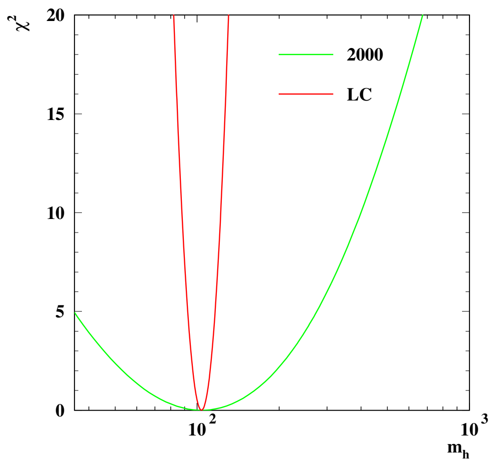

FIGURE 2. $\Delta\chi^2$ as a function of $m_{\rm H}$ for the present and the Giga-Z data.

Also in extensions of the Standard Model the precision data can be used to predict model parameters. As an example figure 3 shows a possible prediction for $m_{\rm A}$ and $\tan\beta$ in the MSSM, once the light Higgs is found and the parameters of the stop sector are measured [17].

The data can also be analyzed within the model independent ε [18] or STU [19] parameters. Figure 4 shows the allowed regions in the $\varepsilon_1 - \varepsilon_3$ (S-T) plane with ε_2

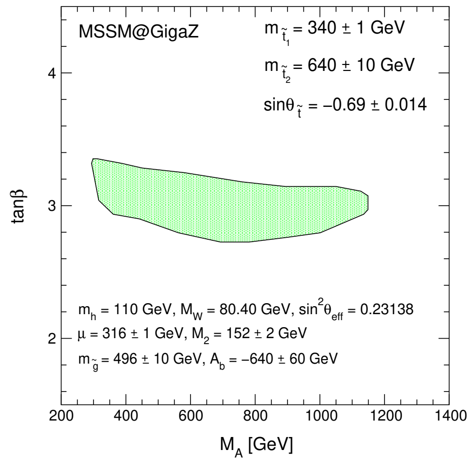

FIGURE 3. The region in the $m_{\mathrm{A}} - \tan\beta$ plane, allowed by $1\,\sigma$ errors by the measurements of m_{W} and $\sin^2\theta^{\ell}_{\mathrm{eff}}$.

(U) fixed to its Standard Model prediction for various configurations compared to the Standard Model. Removing m_{W} from the fit is equivalent to not constraining ε_2 (U). The tight constraint in the direction of the SM trajectory is dominated by the $\sin^2\theta^{\ell}_{\mathrm{eff}}$ measurement, while the orthogonal direction mainly profits from m_{W}.

Figure 5 shows as an application the S,T-predictions from the 2-Higgs doublet model (2HDM) for the cases, where a light Higgs exists, but cannot be seen [20] compared to present and Giga-Z data. Only Giga-Z allows to distinguish the Standard Model with a light Higgs from the 2HDM, but this also needs the precise measurement of m_{W}.

IV B-PHYSICS

Within 10^9 Z-decays about $4 \cdot 10^8$ B-hadrons are produced. This is a sample comparable to the e^+e^--B-factories. Compared to these machines the large boost allows a good separation of the two B's in the event and gives a much better decay length resolution. In addition all B-hadron species are produced, while at the $\Upsilon(4S)$ only B^0 and $B^{\pm}$ are present.

Compared to the experiments at hadron colliders (BTeV, LHCb) the statistics is much smaller. However all events are triggered and the environment is much cleaner.

Due to the large forward backward asymmetry with polarized beams one gets also a very efficient tagging of the initial state flavor from the direction of the event axis only. In all other machines the flavor must be tagged by reconstructing the other B in the event.

Up to now the studies mainly repeat the ones done for the other machines. Only very little exists on reactions that cannot be measured somewhere else.

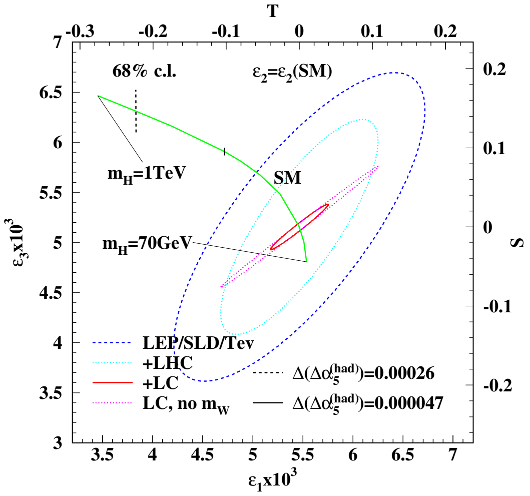

FIGURE 4. Allowed regions in the $\varepsilon_1 - \varepsilon_3$ (S-T) planes for various assumptions compared to the Standard Model prediction. Also shown is the uncertainty in the prediction due to $\alpha(m_Z)$.

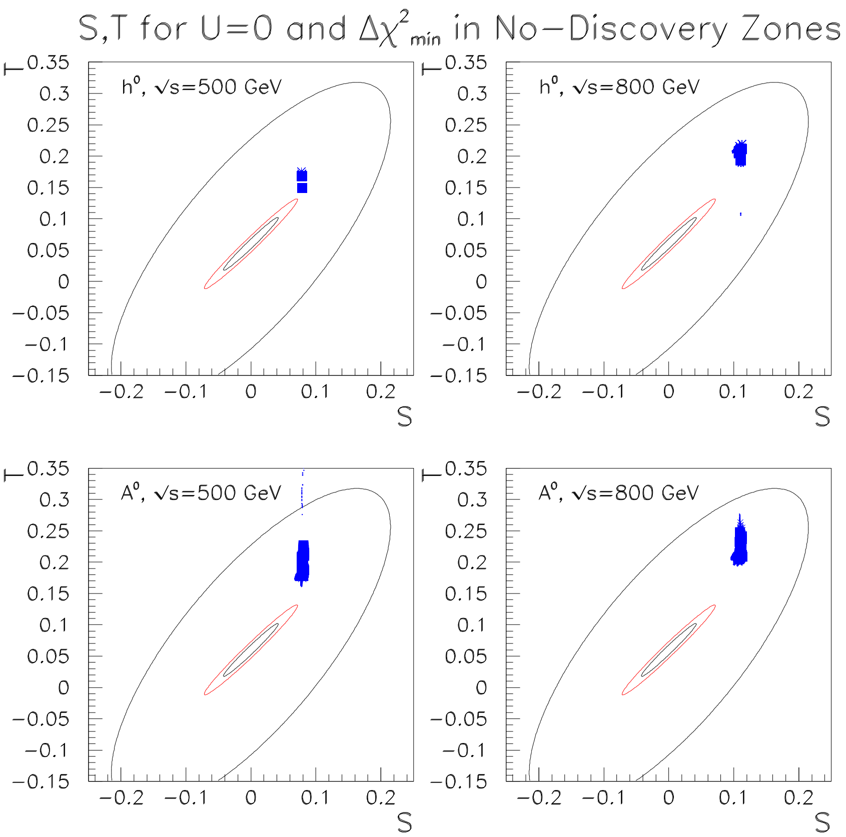

FIGURE 5. Prediction for S and T from the 2 Higgs doublet model with a light Higgs for the cases where no Higgs is found compared to the current electroweak data (95% c.l.) and the projection for Giga-Z (95% and 99% c.l.).

To understand CP-violation in B-decays the time dependent asymmetries in $B^0 \to J/\Psi K_s^0$ have been analyzed to measure $\sin 2\beta$ and in $B^0 \to \pi^+\pi^-$ to measure $\sin 2\alpha$ [6]. The analysis of $B^0 \to J/\Psi K_s^0$ is experimentally relatively easy. For $B^0 \to \pi^+\pi^-$ one needs to separate the mode from $B^0 \to K^+\pi^-$. Figure 6 shows the reconstructed invariant mass for these two modes under the $\pi^+\pi^-$ hypotheses for the TESLA detector. The excellent mass resolution separates the two modes already very well and the remaining background can be rejected using dE/dx in the TPC.

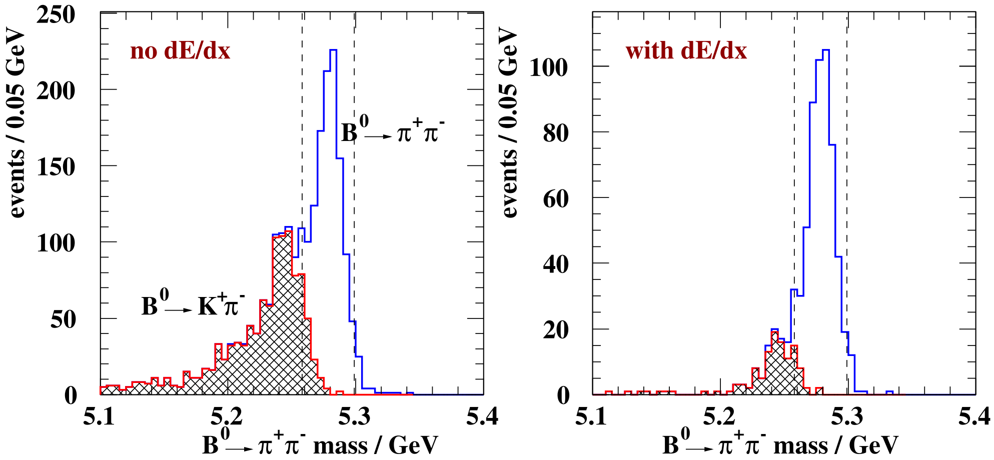

FIGURE 6. $\pi^+\pi^-$ mass resolution for $B^0 \to \pi^+\pi^-$ and $B^0 \to K^+\pi^-$ without and with a cut on dE/dx in the TPC.

Table 4 compares the Giga-Z reach with other machines for $\sin 2\alpha$ and $\sin 2\beta$ under the assumption that the penguin contributions to $B^0 \to \pi^+\pi^-$ are negligible. For 10^9 Zs interesting cross checks are possible while for 10^{10} Zs the linear collider gets highly competitive.

	$\sin 2\beta$	"$\sin 2\alpha$"
BaBar/Belle	0.12	0.26
CDF	0.08	0.10
BTeV/year	0.03	0.02
ATLAS	0.02	0.14
LHC-b	0.01	0.05
Giga-Z (10^9 Zs)	0.04	0.07

TABLE 4. Precision on the angles of the unitarity triangle for the different machines.

To disentangle the penguin contributions to $B^0 \to \pi^+\pi^-$ the branching ratios $\mathrm{BR}(B^0 \to \pi^0\pi^0)$ and $\mathrm{BR}(B^+ \to \pi^+\pi^0)$ can be measured. With 10^9 Zs the precision at Giga-Z is similar to the e^+e^--B-factories.

The large boost and the good vertex resolution also offers the possibility to measure $B_s\overline{B_s}$-mixing [6, 10]. In the fully reconstructed mode $B_s \to D_s\pi$, $D_s \to \Phi\pi, KK$ the detector resolution is about $40\mathrm{ps}^{-1}$. Probably $B_s\overline{B_s}$-oscillations will be discovered at that time, but the good resolution should allow for a precise measurement of the frequency.

There are also some studies which are only possible in the Giga-Z environment. As two examples [21] one can measure the branching ratio $\mathrm{BR(B \to X_s}\nu\bar{\nu})$ or one can test quark hadron duality in B-decays, for example by measuring V_{cb} in B_s-decays. This assumption is essentially untested but is needed for the interpretation of many results.

V OTHER PHYSICS TOPICS

In principle all LEP/SLD analyses can be repeated at Giga-Z. However many of them are already now systematics limited or can be done better at other machines. Not many detailed studies exist beyond the ones already reported.

One field specific to e^+e^- colliders running on the Z pole is the study of flavor violating Z decays. The lepton flavor violating decays $Z \to e\tau, \mu\tau$ have been studied in detail [22]. With 10^9 events Giga-Z is sensitive to the 10^{-8} level. With this precision one would be sensitive to the predictions of models with heavy neutrinos in the TeV mass range or some supersymmetric models.

VI DETECTOR AND MACHINE ISSUES

In the present design NLC plans to run for Giga-Z with 180 bunch trains per second, 190 bunches per train and a bunch spacing of 1.4ns. On the contrary TESLA might run with 5 bunch trains per second, 2800 bunches per train and a bunch spacing of 340ns. In the NLC design the detector basically integrates over a full bunch train, while for TESLA single bunches can be separated. Table 5 shows the Z-multiplicity per NLC train or TESLA bunch.

	NLC-train	TESLA-bunch
0 Zs	0.33	0.986
1 Z	0.37	$1.4 \cdot 10^{-2}$
2 Zs	0.20	$9.7 \cdot 10^{-5}$
$\geq$ 3 Zs	0.10	$4.5 \cdot 10^{-7}$

TABLE 5. Z-multiplicity in a NLC-train and TESLA bunch.

Z counting for the A_{LR} measurement should be possible in both cases. However how much a larger Z multiplicity inside an NLC train affects more complicated

B-physics analyses needs detailed studies.

The presently planned detectors provide excellent momentum resolution, b-tagging and hermeticity and are more or less ideal for the electroweak measurements. The excellent vertexing also helps to separate different Zs within one bunch or train using the different vertex positions along the beam axis.

For some analyses in B-physics a good particle identification is required. Partly this can be replaced by the superb invariant mass resolution and the large magnetic field helps also to separate close-by particles to optimize the dE/dx resolution. Past experience has shown that specialized particle identification devices for this energy region tend to compromise the other features of the detector so that it is not clear in how far a detector optimized for B-physics at Giga-Z would be different from the high energy one.

10^9 Zs can be recorded in 50 to 100 days of running. Since some Z running is required for detector calibration in any case this can be accommodated easily within the normal schedule of the machine.

If however 10^{10} Zs are found a worthwhile goal, which needs several years of running, one might need a specialized interaction region and detector that can run simultaneously with the high energy experiment.

VII CONCLUSIONS

With a relatively modest effort a huge gain in the precision measurements on the Z-pole is possible. Also the W-mass can be improved significantly if one year is spent for it. These measurements allow stringent tests of the then-Standard-Model. By no means the possibility to do these measurements should be excluded by the machine and detector designs.

Some interesting cross check in B-physics can be done with 10^9 Zs and there might be the possibility to improve on the precision from hadron machines with 10^{10} Zs. However this option needs further studies and it is too early to conclude on that.

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