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Third Generation Quark and Electroweak Boson Couplings at the 250 GeV stage of the ILC

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Abstract

The 3rd generation quarks are, due to their large masses, highly sensitive probes for new physics connected to the electroweak symmetry breaking. While top quark pair production requires center-of-mass energies of larger than 350 GeV, the first stage of the ILC at a center-of-mass energy of 250 GeV can perform precision measurements of bottom quark pair production, thereby settling the long standing 3σ tension between the LEP experiments and SLC experiment. For this measurement, polarised beams of the ILC are of special importance as they enable the separation of the vector and axial-vector couplings of the b-quark to Z^0 boson and photon. Another important precision probe for new physics is triple gauge boson couplings. Thanks to the polarised beams and a much higher luminosity, a significant increase in precision beyond past and present experiments is expected at the first stage of the ILC for the TGCs involving $W^{\pm}$ bosons.

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This work was carried out in the framework of the ILD detector concept group.

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PROCEEDINGS OF SCIENCE

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The 3rd generation quarks are, due to their large masses, highly sensitive probes for new physics connected to the electroweak symmetry breaking. While top quark pair production requires center-of-mass energies of larger than 350 GeV, the first stage of the ILC at a center-of-mass energy of 250 GeV can perform precision measurements of bottom quark pair production, thereby settling the long standing 3σ tension between the LEP experiments and SLC experiment. For this measurement, polarised beams of the ILC are of special importance as they enable the separation of the vector and axial-vector couplings of the b-quark to Z^0 boson and photon. Another important precision probe for new physics is triple gauge boson couplings. Thanks to the polarised beams and a much higher luminosity, a significant increase in precision beyond past and present experiments is expected at the first stage of the ILC for the TGCs involving $W^\pm$ bosons.

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1. Introduction

Precision measurements of electroweak couplings is one of the key approaches in indirect searches of the Beyond Standard Model physics. In this contribution we review two of such studies: electroweak couplings of the b-quark and triple gauge couplings (TGCs) measurements, and we describe how these measurements can be done at future e^+e^- colliders, particularly at the International Linear Collider.

The International Linear Collider (ILC) [1] is a linear electron-positron collider planned for high-precision measurements and direct New Physics searches. The linear design of the ILC allow to extend initial center-of-mass energy of 250 GeV to 500 GeV or 1 TeV collisions. Another advantages of the ILC are high luminosity, well-known initial state of the collisions and control of the electron and positron beam polarisation, which plays a key role in measurement of the electroweak physics processes. The ILC will be equipped by two general-purpose detectors, which can be switched by using push-pull technology of the interaction region. This contribution concentrates on one of these detectors, the International Large Detector (ILD). The high-granularity of all ILD subdetectors allows for an individual particle reconstruction using the Particle Flow approach [2]. The central tracker of the ILD is chosen as Time Projection Chamber (TPC) with particle identification capabilities.

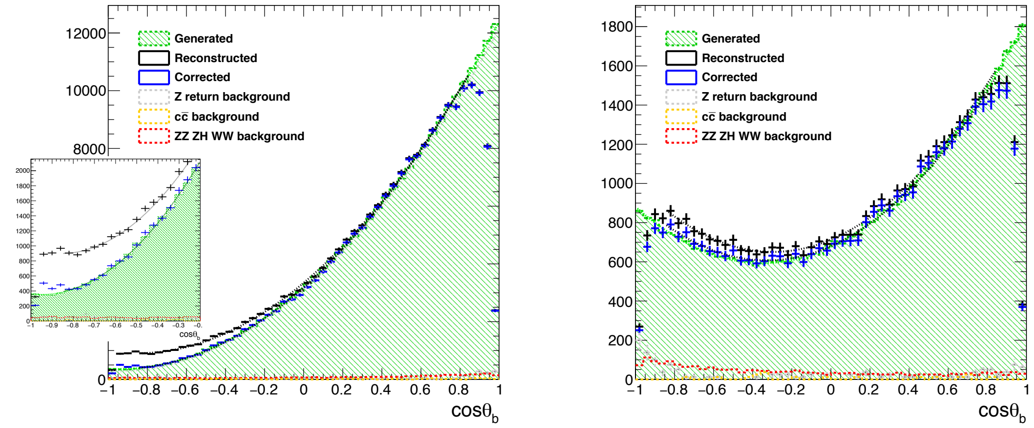
2. Measurement of b-quark electroweak couplings

The LEP collaborations have determined the b-quark couplings to the Z^0 boson by measuring the b partial width and the forward-backward asymmetry called A^b_{FB}. These quantities provide the most precise value of $\sin^2\theta_W$ at LEP I. It turns out that this value is about three standard deviations [3] away from the very precise value from SLD using beam polarisation. Redoing precisely this measurement is therefore a priority for future e^+e^- colliders.

In this study, we intend to prove that the International Linear Collider (ILC) [1], with polarised beams and high luminosity, offers a unique opportunity for precise measurements well above the resonance, where both Z^0 and photon exchanges are present. This additional complexity turns out to be of a great advantage since it allows, through $\gamma - Z^0$ interference, to be sensitive to the sign of Z^0 couplings and fully solve the LEP I puzzle in an unambiguous way. More details are given in [4]. Recall that the LEP I anomaly can be interpreted up to a sign ambiguity for what concerns the right-handed coupling $Z^0b\bar{b}$, referred hereafter as g^Z_R, which shows the largest deviation [5].

In this work, the ILC precision on electroweak b-quark couplings is studied using b-quark polar angle analysis. The b-quark polar angle reconstruction requires an accurate b-quark charge sign assignment. The b-quark charge is identified using two basic signatures: vertex charge, which is defined as a sum of all reconstructed charges, which are associated to the B-hadron vertices and kaon charge, which is the charge of the charged kaons found in b-hadron vertices.

The charged kaons are identified using the specific energy-loss dE/dx in the TPC of ILD. After correcting for the angular dependence of dE/dx [4], the charged kaons from b-hadron vertices can be identified with 97% purity and 87% efficiency, assuming 5% precision on the energy loss value.



(a) (b)

Figure 1: *Polar angle distributions of generated b-quarks and final reconstructed b-quarks in left-handed case (a) and right-handed case (b) with overlaid background processes.*

The reconstructed b-quark polar angle distributions at $\sqrt{s} = 250\,\text{GeV}$ using a combination of kaon and vertex charge signatures are shown in Fig. 1. The integrated luminosity $\mathscr{L}_I = 250\,\text{fb}^{-1}$ is assumed for each beam polarisation.

The events with reconstructed kaon or vertex charges, which are incompatible between jets, allow defining the kaon and vertex charge purity in-situ. Using the in-situ purities, the reconstructed spectrum is corrected using a data-driven procedure [4]. The corrected distributions are fitted by a general cross section function, defined as $S(1+\cos^2\theta)+A\cos\theta$. The extracted precision on the S and A parameters is rescaled to the expected polarisation $e_L^-, e_R^+ = \pm 0.8, \mp 0.3$ and to the luminosity sharing of the ILC physics program. As one can see from Fig. 1, the contribution of the diboson background processes is small.

The relative precisions on the $Z^0 b\bar{b}$ couplings, g_L^Z and g_R^Z, for the LEP I measurements and for the expected ILC performance are shown in Fig. 2. The ILC precision on the g_R^Z coupling is enough to confirm or discard New Physics influence on the LEP I anomaly of the b-quark electroweak coupling measurements.

3. Measurement of Triple Gauge Couplings at the ILC

Lepton colliders are ideally suited to measure electroweak TGCs, like $Z^0W^+W^-$ or γW^+W^-. A precise measurement of TGCs may reveal the presence of additional heavy gauge bosons and it is an important input to the analysis of Higgs couplings in the EFT framework. The measurement of these couplings also has a large sensitivity to the actual beam polarization. Thus, the uncertainty of polarization measurement would significantly affect the precision of TGC determination and vice versa. Therefore, it is necessary to measure TGCs and the beam polarization simultaneously.

In general, $Z^0W^+W^-$ or γW^+W^- vertices are described by 14 complex parameters. Using the $SU(2)\times U(1)$ gauge symmetry constraints and considering only CP conserving parameters, one can reduce the number of considered parameters to 3 TGCs: g_1^Z, k_γ, λ_γ.

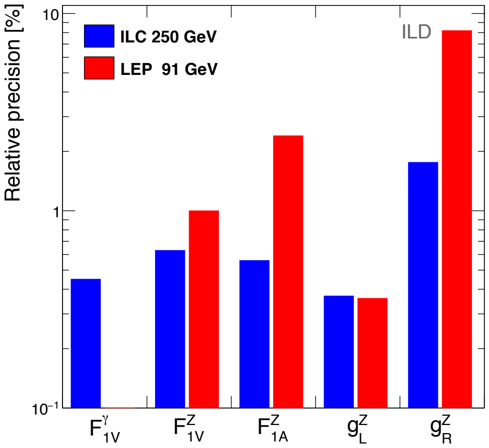


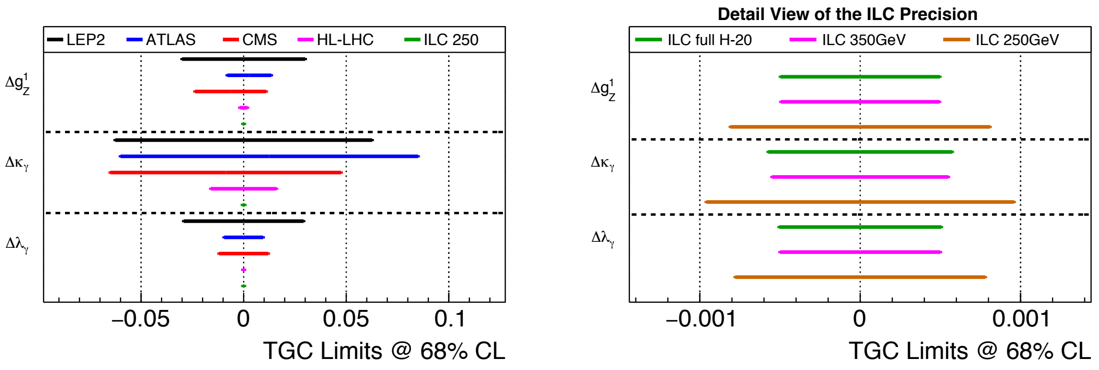
Figure 2: *Comparison of the LEP measurements to the expected precision at the ILC. The results of the ILC assume an integrated luminosity of* $\mathscr{L}_I = 500\,fb^{-1}$ *shared between beam polarizations at* $\sqrt{s} = 250\,GeV$.

At the e^+e^- colliders the TGCs are measured using mainly the $e^+e^- \to W^+W^-$ process. The polarization of the initial state is used to separate the photon and Z^0 boson couplings to W^+W^-. To analyse and separate out the different combination of longitudinally and transversely polarized $W^\pm$ bosons in the final state up to five reconstructed angles can be used: The W^- production polar angle θ and the rest frame fermion polar and azimuthal angles, (θ^*, ϕ^*) and $(\bar{\theta}^*, \bar{\phi}^*)$, associated with the decays of the W^- and W^+, respectively.

For a center-of-mass energy of 500 GeV, the simultaneous measurement of the beam polarization and anomalous TGC was studied using W-pair production in the semileptonic channel [6]. The precision on the three anomalous TGCs g_1^Z, k_γ and λ_γ were determined simultaneously within an Effective Field Theory (EFT) approximation including second order terms. This study was repeated at a center-of-mass energy of 1 TeV [7]. Both studies were performed with a full detector simulation of the ILD detector concept, and, due to the limited MC statistics available in full simulation, used only the information of three out of the five sensitive angles in a binned fit. Nevertheless, all three TGC parameters were determined simultaneaously.

A full simulation study of TGC measurements at $\sqrt{s} = 250\,\text{GeV}$ has not been yet finalised. Therefore, the existing full simulation results at 500 GeV and 1 TeV were extrapolated to lower center-of-mass energies, considering (i) the statistical scaling f_{stat} which is just given by the different cross sections and integrated luminositioes, (ii) the change in actual sensitivity to the TGCs f_{theo}, which is assumed to scale with M_W^2/s, and (iii) a scaling factor f_{det} related to the energy dependence of the detector acceptance. The latter factor has been determined by the comparison between the 500 GeV and 1 TeV results. The final scaling factors are described in [8]. The results of the full simulation studies and the extrapolations are compared to LEP2 and LHC results as well as to HL-LHC prejections in Fig. 3.

The additional relative improvement expected when moving from a 3-angle binned fit to an unbinned fit using all five angles (or an optimal observable technique) was estimated in a toy setup



(a) (b)

Figure 3: *Comparison of the reachable TGC precision of the ILC [8], with the final results from LEP combined from ALEPH, L3 and OPAL results [9] and the LHC TGC limits for* $\sqrt{s} = 8$ *TeV data and an integrated luminosity of* $\mathscr{L} = 20.3\,\text{fb}^{-1}$ *and* $\mathscr{L} = 19.4\,\text{fb}^{-1}$ *for ATLAS and CMS, respectively [10].*

		total error ($\times 10^{-4}$)			correlation		
Exp	N_{par}	g_1^Z	κ_γ	λ_γ	$g_1^Z\ \kappa_\gamma$	$g_1^Z\ \lambda_\gamma$	$\kappa_\gamma\ \lambda_\gamma$
LEP 2	3	516	618	376	-0.17	-0.62	-0.15
ILC 250	3	4.4	5.7	4.2	0.63	0.48	0.35
LEP 2	1	300	626	292	–	–	–
LHC	1	319	1077	198	–	–	–
HL-LHC	1	19	160	4	–	–	–
ILC 250	1	3.7	5.7	3.7	–	–	–

Table 1: TGC precisions for LEP 2, Run1 at LHC, HL-LHC and the ILC at $\sqrt{s} = 250$ GeV with 2000 fb^{-1} luminosity (ILC 250). The LEP 2 result is from ALEPH [12] at $\sqrt{s} \approx 200$ GeV with 0.68 fb^{-1}. The LHC result is from ATLAS[13] at $\sqrt{s} = 7$ TeV with 4.6 fb^{-1}. The HL-LHC estimate is from a 2013 overview of HL-LHC physics [14]. From [11].

to be about a factor of 2. This was confirmed by extrapolating LEP2 results to higher center-of-mass energies. Considering this additional improvement, the currently most up-to-date ILC projections, which are also used in the EFT-based Higgs coupling fit [11] are summarised in Tab. 1, both for simultaneous extraction of all three couplings ($N_{par} = 3$), and for fixing two of them ($N_{par} = 1$) in order to compare to LHC.

Regardless of the exact assumptions in the extrapolation in can be concluded that constraints in the order of 10^{-4} can already be reached in the first stage of the ILC with $\sqrt{s} = 250$ GeV. This is roughly two orders of magnitude better than the current best limit on anomalous TGCs.

Conclusions

In this contribution the ILC precision on electroweak *b*-quark and triple gauge couplings is described. The developed procedure of the b-quark charge reconstruction allows for measuring the b-quark polar angle. The b-quark polar angle fit allows for an independent determination of four electroweak couplings of the b-quark. The relative precision on the right-handed coupling $dg_R^Z/g_R^Z \approx 2\%$ at the ILC is sufficient to confirm at $> 5\,\sigma$ or to discard the LEP I effect, which is at the 25% level. The Triple Gauge Couplings at the ILC will be measured simultaneously with the beam polarization with precisions which will be in the order of 10^{-4}, which is about two orders of magnitude better than current limits.

Acknowledgements

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