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

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The 3rd generation quarks are, due to their large mass, 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 SLD. For this measurement, the 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 are triple gauge boson couplings. Thanks to the polarised beams and the 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.

The LEP I 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 [1] away from the very precise value from SLD using beam polarisation, see Fig. 1. Redoing precisely this measurement is therefore a priority for future e^+e^- colliders.

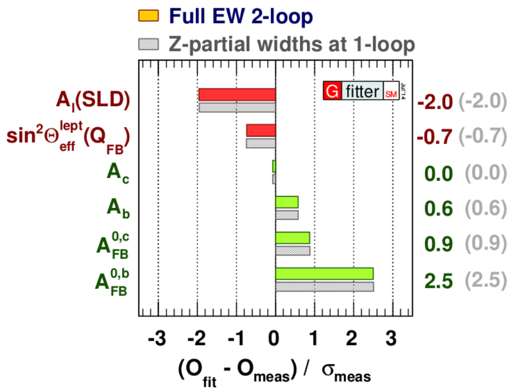


Figure 1: *Deviations of the electroweak precision observables in the Standard Model. Extracted from [1].*

In this study, we intend to prove that the International Linear Collider (ILC) [2], 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 [3]. Recall that the LEP I anomaly can be interpreted up to a sign ambiguity for what concerns the right-handed coupling $Z^0 b\bar{b}$, referred hereafter as g^Z_R, which shows the largest deviation [4].

In this work, the $e^+e^- \to b\bar{b}$ channel is studied at $\sqrt{s} = 250\,\text{GeV}$ using full simulation of the ILD experiment [2], which includes beam spectrum and initial state radiation modelling. The high-granularity of the ILD subdetectors allows for an individual particle reconstruction using the Particle Flow approach [5]. The schematic view of the ILD concept and the subdetector layout is presented in Fig. 2.

Lepton colliders are ideally suited to measure electroweak TGCs, like $Z^0W^+W^-$. The TGC may reveal the presence of additional heavy gauge bosons and their measurement is an important input to the analysis of Higgs couplings in the EFT framework. However, 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 anomalous TGC and the beam polarization simultaneously.

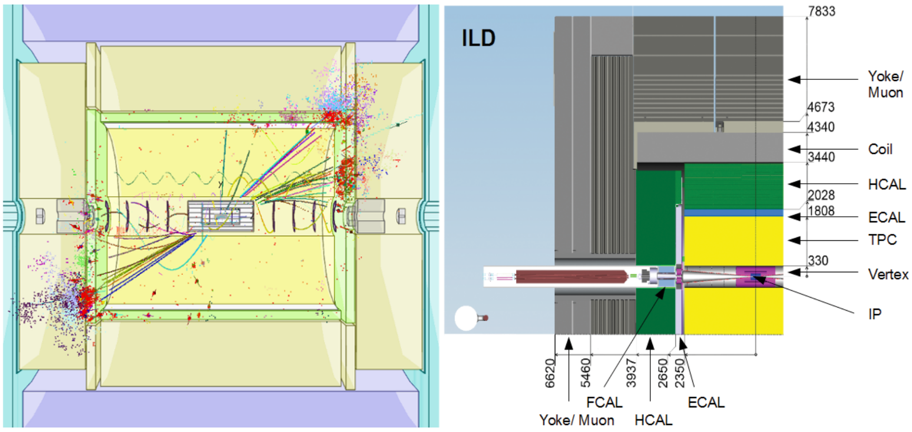


Figure 2: *Example of the event display of the $e^+e^- \to b\bar{b}$ process in a full simulation of the ILD detector (left) and schematic view of the ILD concept [?] (right).*

2. *b*-quark charge sign assignment

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** is a sum of all reconstructed charges, which are associated to the *B*-hadron vertices;
- **Kaon charge** is a charge of charged kaons found in *b*-hadron vertices.

Figure 3 shows a schematic view of a b-hadron decay-chain as seen in the ILD vertex detector.

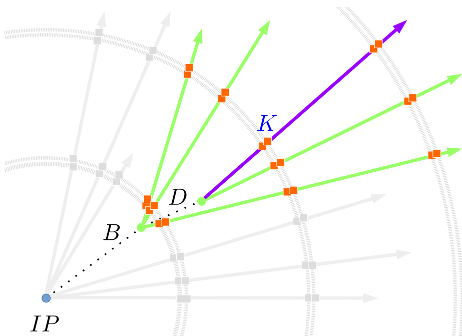
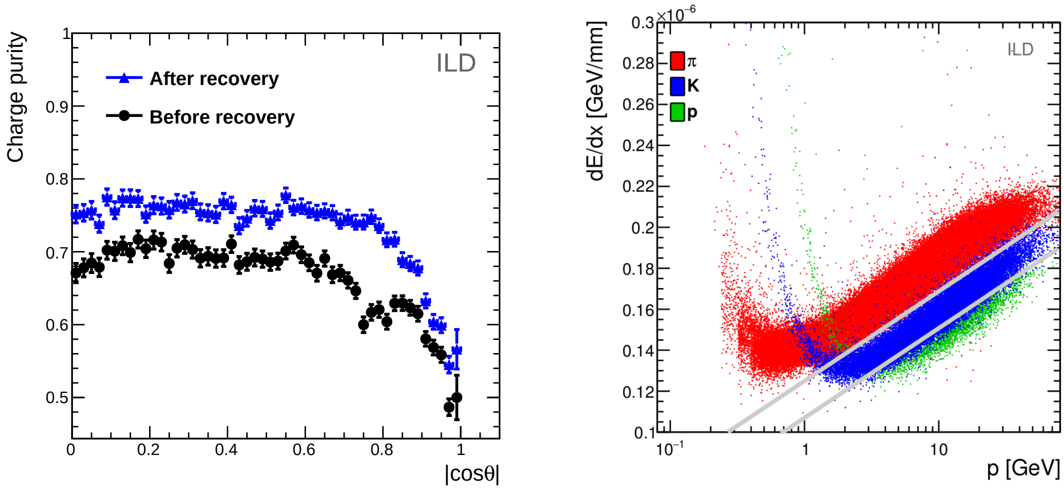


Figure 3: *Illustration of b-hadron decays.*

It was found that vertexing algorithms as currently used in ILD can miss one or more *b*-hadron decay particles from the reconstructed vertices, which decreases the purity of the reconstructed vertex charges. A vertex recovery procedure has been developed to identify the missed tracks and to add them back to the vertices. Figure 4a shows that this improves the vertex charge reconstruction considerably.

The charged kaons are identified using the specific energy-loss dE/dx in the Time Projection Chamber of ILD. After correcting for the angular dependence of dE/dx, the charged kaons from

b-hadron vertices can be identified with 97% purity and 87% efficiency, assuming 5% precision on the energy loss value. The plots of the dE/dx as function of particle momentum for different hadrons are shown in Fig. 4b.



(a) (b)

Figure 4: *Vertex charge sign assignment purity as function of* $|\cos\theta|$ *(left) and energy deposition per unit of length* dE/dx *as function of particle momentum* p *(right).*

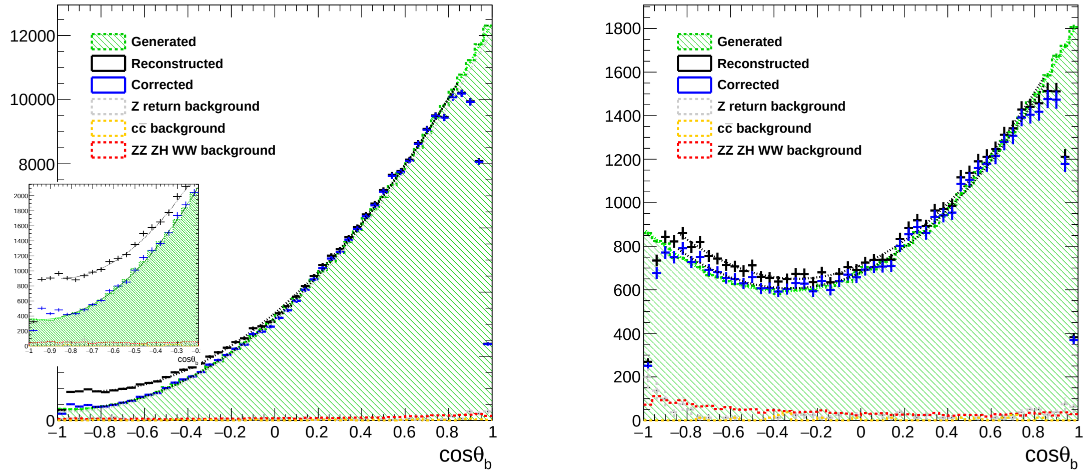
3. *b*-quark polar angle spectrum

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. 5. 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. 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. 5, the contribution of the diboson background processes is small.

4. Interpretation

The relative precisions on the $Z^0 b\bar{b}$ couplings, g^Z_L and g^Z_R, for the LEP I measurements and for the expected ILC performance are shown in Fig. 6. The ILC precision on the g^Z_R coupling is enough to fully confirm or discard any New Physics influence on the b-quark electroweak couplings.



(a) (b)

Figure 5: *Generated b-quark polar angle distribution compared to the final reconstructed b-quarks polar angle in left-handed case (a) and right-handed case (b) with overlaid background processes.*

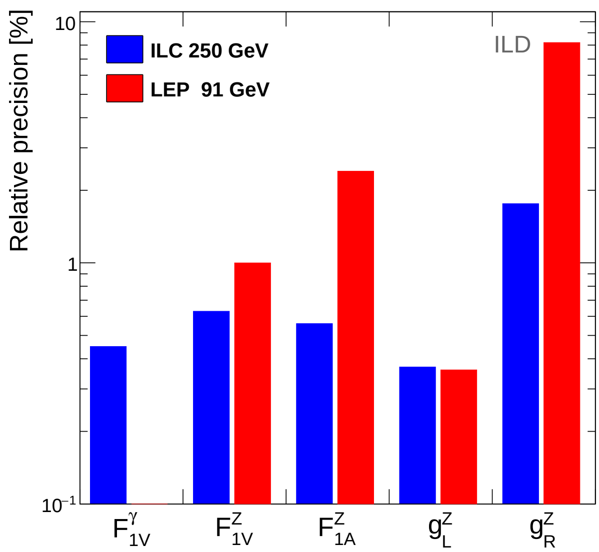


Figure 6: *Comparison of the LEP measurements to the expected precision at the ILC. The results of the ILC assume an integrated luminosity of* $\mathscr{L}_{\mathscr{I}} = 500\ \mathrm{fb}^{-1}$ *shared between beam polarizations at* $\sqrt{s} = 250\ \mathrm{GeV}$.

ILD Full Simulation		Extrapolations		
$E_{c.m.s}$	500 GeV	250 GeV	350 GeV	H-20
g_1^Z	$4.3 \cdot 10^{-4}$	$8.1 \cdot 10^{-4}$	$5.0 \cdot 10^{-4}$	$5.0 \cdot 10^{-4}$
k_γ	$4.4 \cdot 10^{-4}$	$9.6 \cdot 10^{-4}$	$5.5 \cdot 10^{-4}$	$5.7 \cdot 10^{-4}$
λ_γ	$4.1 \cdot 10^{-4}$	$7.8 \cdot 10^{-4}$	$5.0 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$

Table 1: *Achievable precision of the Triple Gauge Couplings measurement for $\mathscr{L}_I = 2\,ab^{-1}$ displayed for different center-of-mass energies and the full benchmark running scenario H-20 of the ILC.*

5. Measurement of Triple Gauge Couplings (TGC) at an e^+e^- Collider

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. These analyses provide two reference points for TGC precision at different center-of-mass energies. The goal is an approximation on the TGC precision at 250 GeV by extrapolating the 500 GeV results to 250 GeV. Therefore, three scaling factors were considered; the first is the statistical scaling f_{stat} which is just given by $1/\sqrt{N}$ and the second f_{theo} is the actual sensitivity to the TGCs which is assumed to scale with M_W^2/s. The third scaling factor f_{det} is related to the energy dependence of the detector acceptance. Such a factor is hard to predict, and thus it is determined by the comparison between the 500 GeV and 1 TeV results. The final scaling factors are shown in Eq. 5.1.

$$\Delta c_i(\sqrt{s}) = \Delta c_i(500\,\mathrm{GeV}) \cdot f_{stat}(\sqrt{s};\mathscr{L}_I) \cdot f_{theo}(\sqrt{s}) \cdot f_{det,i}(\sqrt{s}); \tag{5.1a}$$

$$f_{stat}(\sqrt{s};\mathscr{L}_I) = \sqrt{\frac{500\,\mathrm{fb}^{-1} \cdot \sigma(500\,\mathrm{GeV})}{\mathscr{L}_I \cdot \sigma(\sqrt{s})}}; f_{theo}(\sqrt{s}) = \frac{(500\,\mathrm{GeV})^2}{s}; \tag{5.1b}$$

$$f_{det,\Delta g_1^Z}(\sqrt{s}) = 0.85 + \frac{0.15}{500\,\mathrm{GeV}} \cdot \sqrt{s}; f_{det,\Delta\lambda_\gamma}(\sqrt{s}) = 0.63 + \frac{0.37}{500\,\mathrm{GeV}} \cdot \sqrt{s}; \tag{5.1c}$$

$$f_{det,\Delta k_\gamma}(\sqrt{s}) = 1. \tag{5.1d}$$

The achievable precision of the TGC measurement is shown in Table 1. At the ILC, a subpermille-level on anomalous TGC precision can already be reached in the first stage of the ILC with 250 GeV. This is roughly 2 orders of magnitude better than the current best limit on anomalous TGCs, as shown in Fig 7.

Conclusions

- The developed procedure of the *b*-quark charge reconstruction allows for measuring the *b*-quark polar angle. The residual impurity is corrected by a data-driven procedure;

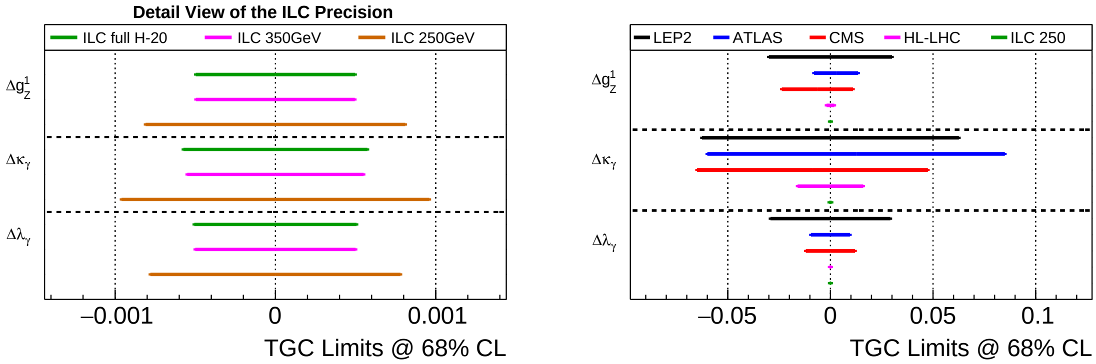


Figure 7: *Comparison of the reachable TGC precision of the ILC, shown in Table 1, with the final results from LEP combined from ALEPH, L3 and OPAL results [8] and the LHC TGC limits for* $\sqrt{s} = 8$ *TeV data and an integrated luminosity of* $\mathscr{L} = 20.3\,\mathrm{fb}^{-1}$ *and* $\mathscr{L} = 19.4\,\mathrm{fb}^{-1}$ *for ATLAS and CMS, respectively [9].*

- The b-quark polar angle fit allows for an independent determination of four electroweak couplings of the b-quark. The fit can be extended to also include a term proportional to $\sin^2\theta$, giving access to an independent determination of the tensorial couplings;
- 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 will be measured simultaneously with the beam polarization
- The ILC precision on TGC will be two orders of magnitude better than at LEP

Acknowledgements

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