LCC Physics Working Group
Electroweak couplings of heavy and light quarks at future linear e^+e^- colliders

Letter of Interest for the Snowmass Study 2021
Energy Frontier – Heavy flavor and top quark physics

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Abstract

The precise measurement of electro-weak couplings in the process $e^+e^- \rightarrow q\overline{q}$ with $q\overline{q} = c\overline{c}, b\overline{b}, t\overline{t}$ at high centre-of-mass energies form a relatively unexplored corner of the Standard Model with an exquisite sensitivity to new physics. This Letter of Interest sketches the state of the art and outlines interesting studies to be carried out during the Snowmass process and beyond.

1 State of the art

The electroweak couplings of the bottom and the top quark are modified substantially in a broad range of new physics scenarios. The most detailed studies have been performed in the context of extra-dimension/composite Higgs scenarios. Measurements in top physics, Higgs physics and gauge boson production provide complementary handles to discover significant signals due to this family of BSM proposals or to constrain the new physics scale well beyond the electro-weak scale [1]. While many models restrict effects of new physics to the heavy quark doublet (t, b) models based on e.g. Grand Higgs Unification predict also modifications of electro-weak couplings of fermions other than (t,b) [2, 3].

In the past years detailed simulation studies of the physics potential of $e^+e^- \rightarrow q\overline{q}$ with $q\overline{q}$ being any of $t\overline{t}$, $b\overline{b}$ and $c\overline{c}$, have been carried out [4, 5, 6]. Beam polarisation at linear colliders supports the disentangling of the different helicity amplitudes and it has been shown that electroweak couplings can be determined to about 0.5% for the t quark and better for the other flavours. LHC can measure the electroweak couplings of the top quark, albeit with 10-100 times less precision, but is incapable to measure electroweak couplings to the Z boson of lighter quarks.

2 Plans

For a complete picture of electroweak couplings to fermions the existing results have to be extended to the light quark flavours uds. Experimental requirements are a clean anti-veto of heavy quarks by the vertex detectors and a deep understanding of particle identification as e.g. π/K/p separation available with the TPC of ILD or alternative methods that may require novel, innovative ideas. Fully simulated samples at a centre-of-mass energy of 250 GeV will

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become available during 2020. One can expect to improve results obtained by DELPHI [7] and SLD [8] by about one order of magnitude.

A revision of the physics potential of the linear collider in 2019 showed that running on the Z-pole adds decisively to the physics potential of the ILC [9, 10]. We propose thus to extend the results for b, c and light quarks using full simulation at the Z-Pole and to apply/adapt the methods developed at 250 GeV. The on average smaller energy of the final state particles may require modifications of the inner part of linear collider detectors. An example is the distance of the first layer of the micro vertex detector to the beam axis.

An exhaustive heavy flavour and in particular top physics programme benefits on the other hand from multiple energy stages above the top quark pair production threshold. This can provide robust bounds in a global analysis of all relevant EFT operator coefficients [11, 12]. It has already been shown in Refs. [4, 13] that the precision measurements of electroweak top quark pair production at future electron-positron colliders provide very competitive bounds on all electroweak top couplings. Further, we note the relevance of four-fermion operators at lepton machines since they drive the sensitivity to compositeness at TeV energies through $\mathrm{e^+e^-} \rightarrow \mathrm{t\bar{t}}$ & $\mathrm{b_L b_L}$.

The potential of the next generation of proton-proton colliders has not been studied at the same level of detail, but several case studies show that the superb energy reach allows providing competitive limits on operators whose effect grows with energy. A detailed assessment of systematic uncertainties is required to provide credible prospects of the FCChh and SPPC potential.

Currently the global analysis is focused on EFT operators relevant for the top quark. A 10-parameter EFT fit that includes the relevant dimension-six operators [14] is envisaged. The fit to current LEP/SLC and LHC Run 2 data is to be compared to realistic prospects for future colliders. This analysis will elucidate the potential in top physics of the different future collider projects, characterize the main strengths of electron-positron and hadron collider projects and identify complementarities in their sensitivity. Futher, it has to be considered how couplings from other quarks can either be integrated into the global EFT fit or in fits to concrete model predictions. These analyses will also take into account the effect of four-fermion contact interactions and $\mathrm{b\bar{b}Z/gg}\gamma$ dipoles.

2.1 The need for precision calculations

The precision measurements described above have to be accompanied and guided by precision theory calculations. As an example may serve here the $\mathrm{e^+e^-} \rightarrow \mathrm{t\bar{t}}$ channel. The electroweak NLO correction to this channel is known to reach to 5-10%. Thus, it has to be included in the future studies. The electroweak NLO correction is sensitive to the initial and final polarisation and the polarised ILC will allow us a more detailed study. Specific theoretical efforts are needed to make progress on the electroweak correction in the future.

3 Conclusions

Studies of the channels $\mathrm{e^+e^-} \rightarrow \mathrm{q\bar{q}}$ bear a considerable discovery potential. A comprehensive program to understand the processes from theory and experimental side is going on since a few years and has to be conducted further in the years to come. The conclusions of the studies will have a considerable impact on the layout of detectors at future $\mathrm{e^+e^-}$ colliders and will sharpen the need for theory calculations. The theory work on $\mathrm{e^+e^-} \rightarrow \mathrm{t\bar{t}}$ has to be extended to other 2-fermion channels to cope with the expected experimental precision. The results have to be interpreted in either global analyses or in the frame of detailed models.

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