Exploring Precision Electroweak Physics Measurement Potential of e^+e^- Colliders

Graham W. Wilson (gwwilson@ku.edu)

Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA

Abstract

The ILC linear e^+e^- collider has been designed with an emphasis on an initial-stage Higgs factory that starts at $\sqrt{s}$ = 250 GeV and is expandable in energy to run at higher energies for pair production of top quarks and Higgs bosons, and potentially to 1 TeV and more. The unique feature of longitudinally polarized electron and positron beams and the higher energies open up many new measurement possibilities that are very complementary to those feasible with e^+e^- circular colliders. An overarching very timely question is how well can ILC running at lower center-of-mass energies, particularly near the Z-pole, perform statistically and systematically for measurements of precision electroweak observables including those already explored at SLC and LEP? Would this offer significant advantages over only running at energies above ZH threshold? A related question is how such running with ILC compares statistically and systematically with the various circular e^+e^- collider proposals? On the one hand, the circular approach now claims enormous luminosity at low energy, but on the other hand, is therefore enormous and expensive, and if ever realized for e^+e^- would likely be on a much longer time horizon than ILC. Whether one can exploit the very large statistics and not be dominated by systematics is at the heart of these questions. A follow-up question is whether, with advances in accelerator designs, there could ever be a physics niche for a SuperLEP? Namely, a high-luminosity circular e^+e^- collider Z-factory of modest size (eg. Tevatron tunnel) that is likely incompatible with use as a Higgs factory. Studies are being undertaken: i) to understand ILC capabilities for a precision measurement of the Z lineshape observables with a scan using polarized beams, ii) to further explore an experimental strategy for $\sqrt{s}$ determination, and iii) to further explore M_W capabilities synergistic with a concurrent Higgs program.

Introduction

As noted above, the ILC design focus has been on polarized e^+e^- collisions at center-of-mass energies of $\sqrt{s}$ = 250 GeV and beyond. There has been long-standing interest in using such a machine to explore with higher precision electroweak observables such as A_{LR}, M_W, $\sin^2\theta^{\ell}_{\text{eff}}$. Early linear collider studies are documented under the term "Giga-Z" where one foresees data-taking at the Z-pole, $\sqrt{s} \approx M_Z$ [1]. Linear collider studies on measuring M_W from data-taking near the WW threshold have also been considered and updated in recent years for ILC [2].

With the new focus of ILC on an initial stage accelerator at $\sqrt{s}$ = 250 GeV, there has been some evolution in the accelerator design. These developments have led to an accelerator parameter set consistent with the ILC baseline design that can achieve an instantaneous luminosity[1] of $4.2 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} \approx M_Z$ once the RF power is upgraded [3]. The design is fully compatible with longitudinal polarization of the electrons and positrons with nominal values of 80% and 30% respectively. This opens up the possibility of using Z-running for a dedicated physics program. It is currently envisaged that one could accumulate 100 fb^{-1} at the Z, and up to 500 fb^{-1} at the W-pair threshold if warranted. It also makes possible running at the Z for short periods for detector calibration and alignment as necessary. This would take advantage of the fact that the multi-hadronic cross-section is much larger at the Z: by factors of 610 and 2420 compared to $\sqrt{s}$ = 250 GeV and $\sqrt{s}$ = 500 GeV respectively.

For Snowmass 2013, contributions were made to the report on electroweak physics [4]. There was a related focus to this LoI. That work concentrated mostly on M_W prospects and an initial exploration of an alternative method

[1] Prior to bunch doubling, the instantaneous luminosity would be half this amount.

for a precision center-of-mass energy determination at an e^+e^- collider. This $\sqrt{s_p}$ method uses di-muon events to measure the center-of-mass energy using simply the muon momenta. It relies on a precision knowledge of the absolute momentum scale, which is best achieved using a plentiful sample of dimuons from J/ψ events. Some aspects are summarized in Ref. [5], and talks this year in the Snowmass 2021 EF04 group and at ICHEP 2020 [6].

Prior studies of J/ψ mass resolution were done by the author using the ILD detector. The current status of ILD is documented in the recent ILD report [7]. Many ILC physics and detector studies could be done as summarized in the ILC Snowmass Study Questions [8]. Particularly relevant to this LoI are Q5.13 (tracker momentum scale), Q10.1 (M_W) and Q11.2 (Z-pole). I very much welcome collaboration including on accelerator and instrumentation aspects.

Proposed Studies

Polarized Z-Lineshape Scan

Prior Giga-Z studies wrote off any prospect at a linear collider for a precision absolute center-of-mass energy scale. However, if the absolute $\sqrt{s}$ scale can be tied to the 2 ppm uncertainty on the J/ψ mass, then there is potential with the $\sqrt{s_p}$ method to improve substantially quantities like M_Z and Γ_Z and the whole suite of SLC/LEP observables. This applies especially to the cross-sections and asymmetries ($A^f_{LR}, A^f_{FB}, A^f_{FB,LR}$) vs $\sqrt{s}$ near the Z-pole. Initial investigations using ZFitter [9] show statistical uncertainties of 35 keV on M_Z and 80 keV on Γ_Z are in reach with a 100 fb^{-1} polarized Z scan. This is already well beyond the systematic limit of any proposed e^+e^- collider for M_Z.

The study will look into scan strategies and assess whether it would be beneficial to take data at many $\sqrt{s}$ values and whether there is merit to frequent scanning (even pulse-to-pulse) to control point-to-point errors as needed for a precision Γ_Z. Work has started on using the more model independent S-matrix approach encoded in SMATASY [10] for describing the $\sqrt{s}$ dependence of the photon, Z, and interference contributions. The longitudinal polarization of the beams, and an extensive scan, should lead to new handles on this problem. An interesting by-product would be a polarized neutrino-counting scan using $\nu\bar{\nu}\gamma$ events where the polarization can be used to disentangle W contributions.

Further Investigation of the $\sqrt{s_p}$ Method for Determining $\sqrt{s}$

When the $\sqrt{s_p}$ method was first proposed the emphasis was on determining $\sqrt{s}$ at center-of-mass energies of 500 GeV, 350 GeV, 250 GeV and 161 GeV and higher. Now that we have the prospect of significant running at $\sqrt{s} \approx M_Z$ for ILC, a critical issue is to look at the limiting systematic effects in the high statistics regime where one uses dimuons collected near M_Z to measure the local $\sqrt{s}$ in situ. Treatment of multiple radiation, incorporation of the crossing-angle and momentum spread will be important. For ILC, the detector conditions with excellent momentum resolution, excellent hermeticity, higher magnetic field, and small crossing angle, should confer significant advantages over a similar measurement using a circular collider. Given that the energy is measured at the IP it is directly what is needed. In contrast, the resonant depolarization method available at low energy at circular e^+e^- colliders, uses an orbit-based average, is restricted to quantized energies, and needs to be extrapolated to the IP [11].

Further Development of M_W Studies Targeted at Higgs Factory Running

Given that all proposed e^+e^- Higgs Factory machines will take most of their data well above the WW threshold, it is particularly important that we understand the capabilities of such continuum running for determing M_W. An overview of potential approaches is given in [12], and work has been on-going on using semi-leptonic WW and lepton-only observables. These are mentioned in [6] and described in talks at LCWS2019 (Sendai).

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