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Precision Electroweak Measurements with ILC250

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We discuss the improvements that the ILC can make in precision electroweak observables based on studies with the ILD detector concept. These include observables from W^+W^- production at a centre of mass energy of 250 GeV and above, and especially from a dedicated stage of running at the Z pole. These improvements take advantage of the ILC capabilities for polarized electron and positron beams, and an accelerator design that accommodates data-taking at a wide range of beam energies. The studies include experimental considerations evaluated in the context of the ILD detector concept and discussion of experimental strategies targeted at controlling especially systematic uncertainties associated with the center-of-mass energy.

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1. Introduction

The proposed International Linear Collider (ILC) [1, 2] presents a tremendous opportunity to advance our knowledge of physics at the electroweak scale using polarized e^+e^- collisions. The international ILC project is now transitioning towards realization in Japan with the announcement of the ICFA appointed ILC International Development Team during ICHEP2020. First collisions are foreseen for the mid-2030s starting at a center-of-mass energy of 250 GeV with an accelerator designed with polarized electron and positron beams. The accelerator will be capable of running at lower energies such as at the Z-pole [3] at luminosities up to $4.2 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ with polarized beams and is expected to be extended to higher energies in future years, in particular to above the top-pair threshold and beyond.

Opportunities exist now to contribute to the design of the experiments and the accelerator, and in further advancing our understanding of the physics capabilities. In this contribution, some of the prospects for improving electroweak physics measurements are highlighted and placed in the context of the International Large Detector (ILD) detector design concept that along with the SiD detector design concept has been under development for the ILC [4]. Recent developments in the ILD detector design are documented in the ILD Interim Design Report [5].

2. Physics and Detector Opportunities

The physics capabilities of ILC are described in many documents. A recent contribution [6] highlights the physics potential of the foreseen initial 250 GeV stage. The benefits from polarized beams and especially the role of positron polarization are detailed in [7] building on [8]. An emphasis on tests of the Standard Model is described in [9]. New physics possibilities are highlighted in [10]. Earlier more expansive documents with an extensive literature include [11–13]. A recent guide to some potential physics and detector study questions for ILC and how to get involved is given in [14].

3. Precision Electroweak Measurements

Studies related to WW production, W mass, and Z-pole observables are highlighted with an emphasis on experimental strategies targeted at controlling otherwise dominating systematic uncertainties. Of particular importance are the control of the center-of-mass energy and the beam polarization as already discussed previously in [15]. With the advent of a better established scheme for physics running at the Z-pole in addition to the possible use of Z-pole running for detector calibration, it is timely to investigate the capabilities for a precision polarized Z-pole scan. Past contributions, dubbed Giga-Z, highlighted the potential for a precision measurement of the left-right asymmetry, A_{LR}, at the Z-pole [16] but discounted the possibility for further improvements in quantities like M_Z and Γ_Z given the presumed insurmountable difficulty of a precision Z independent absolute energy scale. This assumption will be revisited.

4. Center-of-Mass Energy Determination

A key element for a future e^+e^- collider is the ability to determine the center-of-mass energy scale. It is feasible to do this at circular colliders when operating at low center-of-mass energy using the technique of resonant depolarization where the measured spin precession frequencies relate to the energy of each beam averaged over their orbits. This was used at LEP1 [17] and lower energy facilities and is outlined for a potential future circular collider at low energy in [18] where precisions at the 1.0 ppm level are targeted. For a linear collider and for a circular collider operating at higher energies[1], alternative methods are necessary as was already the case for LEP2. Additionally methods that prioritize measurement of the actual center-of-mass energy in collision are especially well motivated.

For an ILC target precision on M_{W} of 2 MeV corresponding to a 25 ppm center-of-mass energy uncertainty, one would want systematic uncertainties on the center-of-mass energy limited to smaller than 10 ppm. This is already beyond the current knowledge of M_{Z} (23 ppm) and so would be a limiting factor for M_{W} target uncertainties below 5 MeV if one needs to rely on M_{Z} for the absolute energy scale such as using the reconstructed di-fermion mass in radiative events [19].

A more promising approach [15] that opens up the possibility of precision measurements of Z observables, as well as sufficient precision for M_{W} measurements independent of M_{Z}, is to base the center-of-mass energy scale determination on the precisely known J/ψ mass (1.9 ppm). Events from $\mathrm{e}^+\mathrm{e}^- \to \mu^+\mu^-(\gamma)$, and potentially $\mathrm{e}^+\mathrm{e}^- \to \mathrm{e}^+\mathrm{e}^-(\gamma)$, can be used to make an *in situ* measurement of the average center-of-mass energy with high statistical precision based simply on the momentum measurements of the leptons. Under the assumption that the recoil mass to the measured muons is zero, an estimate of the center-of-mass energy of such events, $\sqrt{s}_p$, can be formed simply from the measured momenta of the two muons as illustrated in Figure 1

$$\sqrt{s}_p = E_+ + E_- + |\vec{p}_+ + \vec{p}_-| = \sqrt{p_+^2 + m_\mu^2} + \sqrt{p_-^2 + m_\mu^2} + |\vec{p}_+ + \vec{p}_-| \quad .$$

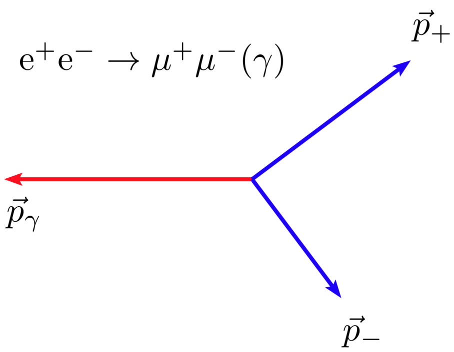

Figure 1: Reconstruction of $\sqrt{s}$ sensitive variable in $\mathrm{e}^+\mathrm{e}^- \to \mu^+\mu^-(\gamma)$ events

This benefits from the typical 0.1% momentum resolution in a detector like ILD. The distribution of this variable and related ones can then be used to deduce relevant parameters including those related to the average absolute center-of-mass energy and the differential luminosity spectrum. Given very good control of the tracking detector absolute momentum scale (2.5 ppm target) using $J/\psi \to \mu^+\mu^-$ collected at the Z with typical mass resolution of 3 MeV, it is foreseen that knowledge of the absolute center-of-mass energy at the few ppm level can be targeted at the Z (with 200M $\mathrm{Z} \to \mu^+\mu^-$) and at the 10 ppm level for higher $\sqrt{s}$.

[1]certainly above 200 GeV center-of-mass energy even for very large ring circumference

5. W Mass

To date no single experiment has measured M_{W} to better than 18 MeV. There are a variety of methods for measuring M_{W} at an e^+e^- collider as detailed in [9]. It is expected that ILC can target M_{W} uncertainties in the 1–3 MeV range. While a dedicated run at WW threshold is feasible such as discussed in [20], the approach that is arguably most promising and deserving of intensive study is to use the primary ILC datasets collected at center-of-mass energies above the ZH threshold.

The primary method used at LEP2 based on kinematic reconstruction of semileptonic WW events took advantage of four-momentum conservation constraints and mass equality of the hadronic and leptonic systems. Shown in Figure 2 is a simulation of the measured hadronic mass for 1.6 ab^{-1} at $\sqrt{s}$ = 500 GeV in semileptonic WW events [21] for favorably polarized e^+e^- collisions with 80% e^- and 30% e^+ beam polarization. This includes experimental effects from backgrounds and beam overlay. The semileptonic channel is also very useful for TGC measurements and beam polarization studies. The fit illustrates a statistical uncertainty based on current ILD reconstruction of 2.4 MeV from the hadronic mass alone. Similar statistical sensitivity is expected at $\sqrt{s}$ = 250 GeV.

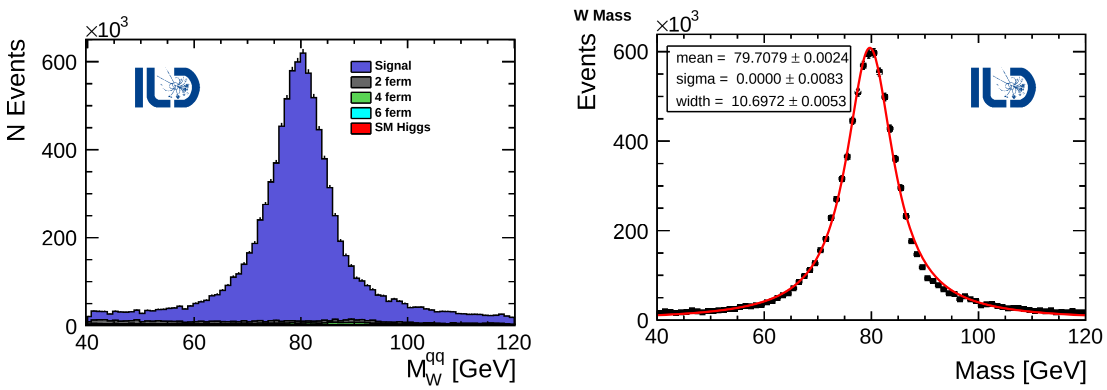

Figure 2: Reconstructed hadronic mass and illustrative fit for semileptonic WW events at $\sqrt{s}$ = 500 GeV [21]

An alternative method that is experimentally very robust, but statistically more challenging, is to base a M_{W} measurement solely on leptonic observables. Four observables of interest are: the lower and upper energy end-points of prompt leptons (in semi-leptonic and fully leptonic WW events), and the so-called pseudo-masses (two solutions) that result from a partial kinematic reconstruction in fully leptonic WW events with prompt leptons based on assuming that the neutrinos are in the same plane as the leptons [22]. Figure 3 illustrates the M_{W} sensitivity. Projected statistical uncertainties amount to 4.4 MeV on M_{W} for 2.0 ab^{-1} at $\sqrt{s}$ = 250 GeV.

6. Polarized Z Scan

Perhaps the most interesting issue is to understand how well one can measure Z lineshape observables using a polarized Z scan now that the ILC accelerator promises substantial luminosity at the Z corresponding to 100 fb^{-1} with polarized beams. Exploiting this fully needs an in-depth study of center-of-mass energy calibration systematics that goes beyond that discussed in Section 4

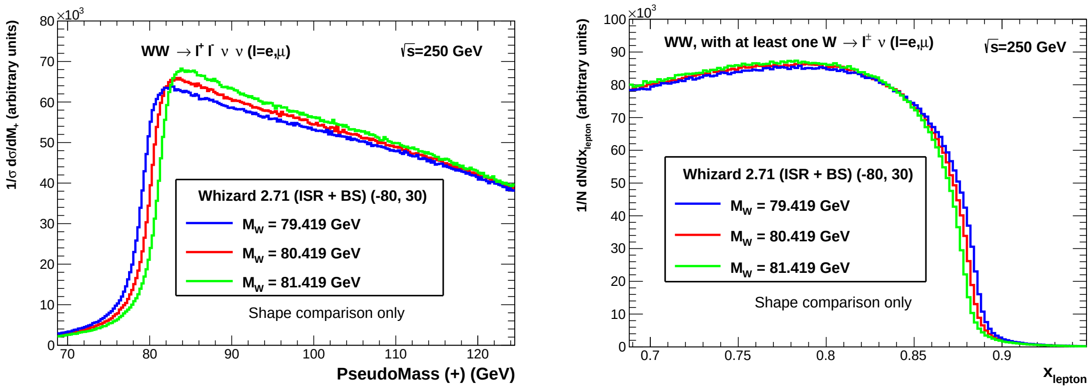

Figure 3: Illustrating the M_{W} sensitivity using the positive pseudomass (left) and upper energy endpoint (right) for collisions at $\sqrt{s}$ = 250 GeV including ISR and beamstrahlung effects.

and is not just an A_{LR} measurement at one center-of-mass energy. It is clear that already 100 fb^{-1} leads to statistical errors on M_{Z} of about 35 keV (0.3 ppm), so the ILC has adequate luminosity at the Z. Even if ultimately the absolute energy scale understanding would be limited to several ppm, there is also the potential to improve on Γ_{Z} where point-to-point systematics are relevant. A particularly appealing feature is the possibility of scanning with polarized beams such that systematics associated with the relative luminosity, absolute polarizations, and center-of-mass energies are controlled in situ.

7. Conclusions

ILC can advance greatly our knowledge of electroweak precision physics including at the Z-pole as now enabled by the accelerator design. There are many opportunities to contribute.

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PoS(ICHEP2020)347