PROCEEDINGS OF SCIENCE

Precision Electroweak Measurements at a Future e^+e^- Linear Collider

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The International Linear Collider (ILC) project aims to build a linear electron-positron collider capable of precision physics measurements at center-of-mass energies ranging from 91 GeV to 1 TeV using polarized electrons and positrons. An overview is presented of the potential of such a facility to advance precision studies of electroweak physics with an emphasis on some opportunities in W and Z physics. Prime targets are complementary and robust precision measurements of the W mass in the few MeV range from data collected both well above and close to the WW threshold, and an ultra-precise measurement of the left-right asymmetry of the Z. In order to take advantage of the high statistics envisioned for ILC, particular attention to the control of systematics associated with the understanding of the initial state experimental conditions is essential. Experimental strategies for controlling systematics associated with the determination of the center-of-mass energy and the beam polarization are highlighted.

38th International Conference on High Energy Physics
3-10 August 2016
Chicago, USA

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[†]Work supported by the National Science Foundation under award PHY-1306953

PoS(ICHEP2016)688

1. Introduction

Our field is eagerly anticipating results from searches for further new particles in the significant datasets at LHC in Run II at $\sqrt{s} = 13$ TeV. Direct discovery of new physics would of course be ideal, but is far from guaranteed.

In the years before the emergence of direct experimental evidence for the production of the top quark and the Higgs boson, precision measurements of the then observable Standard Model (SM) parameters pointed the way. If new physics continues to evade direct detection at present and future facilities, ultra-precise measurements of the fundamental parameters of the SM will become especially compelling. These can probe, albeit indirectly, potentially much higher energy scales and the associated new physics.

The current precision experimental tests of the SM as exemplified by [1] rely on measurements particularly from the previous e$^+$e$^-$ colliders, LEP and SLC. Further significant improvement will need an e$^+$e$^-$ collider such as the International Linear Collider (ILC).

A future high energy e$^+$e$^-$ collider is recognized as essential for a precision study of the Higgs and the top quark [2]. It can also be a very powerful tool for advancing measurements of precision electroweak observables [2–5]. The ILC is well-placed to advance significantly these tests of the SM by measuring m_{t}, M_{W}, $\sin^2\theta^{\ell}_{\mathrm{eff}}$ with much higher precision than can be envisaged at LHC.

The measurement of m_{t} using a threshold scan at an e$^+$e$^-$ collider operating at center-of-mass energies close to 350 GeV is expected to be limited by theoretical uncertainties, and is projected based on current understanding to achieve an overall uncertainty on the top mass of around 50 MeV [6]. Projections for hadron collider based measurements indicate uncertainties at the 500 MeV level [7].

Two of the main experimental observables of interest for a precision test of the SM are the W mass, M_{W}, and the left-right polarization asymmetry, A_{LR}. Both of these are prime targets for the ILC and are the focus of this contribution. A_{LR} is the most sensitive observable at ILC for measuring $\sin^2\theta^{\ell}_{\mathrm{eff}}$. Order of magnitude improvements in these three quantities, m_{t}, M_{W} and $\sin^2\theta^{\ell}_{\mathrm{eff}}$ promise a sterling test of the internal consistency of the SM [1] and a window to new physics. The precision measurement of M_{W} and m_{t} promises to test models beyond the SM such as various versions of supersymmetry where relatively massive supersymmetric particles can affect the W mass [8].

Measurements from LEP2 and the Tevatron of M_{W} have led to a current precision of 15 MeV. Further improvements from long existing hadron collider data-sets at the Tevatron and LHC are possible, but given the predominant systematic uncertainties will constitute major experimental and phenomenological tours de force if and when they are realized.

2. e$^+$e$^-$ Linear Colliders

Linear colliders such as ILC or CLIC are seen as the only practical way to go significantly above the top pair threshold in e$^+$e$^-$ collisions given the limiting synchrotron radiation losses of conventional circular machines. The ILC project is based on superconducting RF accelerating cavities: now a mature technology used in many other projects. The ILC accelerator and detectors have been under study and development for many years. In 2001, the consensus of the world-wide community was to envision the ILC as the next future collider complementary to LHC.

The ILC project envisages an initial stage with center-of-mass energy up to 500 GeV and upgradable to at least 1 TeV with longitudinally polarized electron and positron beams [9]. With the discovery of the Higgs in 2012 and the maturation of the ILC accelerator technology, a construction decision is eagerly awaited. This international project is under extensive consideration in Japan with a decision expected in the next couple of years.

As a baseline scenario for study, one envisages [10] extensive ILC data-taking at center-of-mass energies of 500 GeV, 350 GeV and 250 GeV amounting to 6.2 ab^{-1} and including options for dedicated running with polarized beams at the Z-pole with 100 fb^{-1} and at the W-pair threshold with up to 500 fb^{-1}. The latter options enable a program of precision electroweak physics measurements at the Z-pole as envisaged in [11] and a precison measurement of M_{W} using a polarized threshold scan as discussed in more detail in [12].

3. Experimentation with ILC

Physics experiments with e^+e^- colliders are very different from a hadron collider. Experiments and detectors can be designed without the severe constraints imposed by triggering, radiation damage and pileup. All decay channels can often be used. Perhaps the most important aspect is that the initial conditions can be adjusted. One can adjust the collision energy, longitudinally polarize both the electron and positron beams, and measure precisely the absolute integrated luminosity. No trigger is needed. Last, but not least, theoretical predictions can be brought under excellent control.

4. Experimental Systematics and Strategies

In situ measurements promise excellent control of the absolute beam polarizations, the center-of-mass energy, the absolute integrated luminosity and the differential luminosity spectrum. Here we concentrate on the first two aspects.

4.1 Polarized beams

The cross-section dependence on the longitudinal polarization of the electron and positron beams is given by [13]

$$\begin{aligned}\sigma(P_{\mathrm{e}^-},P_{\mathrm{e}^+}) \;=\; \frac{1}{4}\{&(1-P_{\mathrm{e}^-})(1+P_{\mathrm{e}^+})\sigma_{LR}+(1+P_{\mathrm{e}^-})(1-P_{\mathrm{e}^+})\sigma_{RL}+\\ &(1-P_{\mathrm{e}^-})(1-P_{\mathrm{e}^+})\sigma_{LL}+(1+P_{\mathrm{e}^-})(1+P_{\mathrm{e}^+})\sigma_{RR}\}\end{aligned}$$

where σ_k ($k =$ LR, RL, LL and RR) are the fully polarized cross-sections. The ability to polarize both the electron and the *positron* beam is central to the precision electroweak physics prospects.

In cases where the LL and RR cross-sections are zero, the resulting cross-section simplifies to

$$\sigma(P_{\mathrm{e}^-},P_{\mathrm{e}^+}) \;=\; \frac{1}{4}\{(1-P_{\mathrm{e}^-})(1+P_{\mathrm{e}^+})\sigma_{LR}+(1+P_{\mathrm{e}^-})(1-P_{\mathrm{e}^+})\sigma_{RL}\}$$

which can be rewritten as

$$\sigma(P_{\mathrm{e}^-},P_{\mathrm{e}^+}) = \sigma_u\{(1-P_{\mathrm{e}^-}P_{\mathrm{e}^+})-(P_{\mathrm{e}^-}-P_{\mathrm{e}^+})A_{LR}\} \tag{4.1}$$

where σ_u is the unpolarized cross-section, $(\sigma_{LR} + \sigma_{RL})/4$, and A_{LR} is defined as

$$A_{LR} = (\sigma_{LR} - \sigma_{RL})/(\sigma_{LR} + \sigma_{RL})$$

Equation 4.1 is appropriate for Z production. With both beams polarized it is then straightforward to measure accurately the absolute polarization in-situ by using the 4 cross-section measurements from the $-+$,$+-$,$--$, and $++$ helicity combinations and the 4 unknowns, namely σ_u, A_{LR}, $|P_{\mathrm{e}^+}|$ and $|P_{\mathrm{e}^-}|$. This assumes "perfect spin-flipping": namely that the absolute polarization values, $|P|$, for the positive and negative helicity of the same beam are identical. This assumption can be tested with polarimeters and if necessary, also with dedicated data with one or both beams unpolarized.

4.2 Center-of-Mass Energy Determination

It has been shown [14] that $e^+e^- \to \mu^+\mu^-(\gamma)$ events can be used to make an *in situ* measurement of the average center-of-mass energy with high statistical precision[1] based simply on momentum measurements of the muons. Under the assumption that the recoil mass to the measured muons is zero, an estimate of the center-of-mass energy of such events can be formed simply from the measured momenta of the two muons:

$$\sqrt{s}_P = E_1 + E_2 + |\vec{p}_1 + \vec{p}_2| = \sqrt{p_1^2 + m_\mu^2} + \sqrt{p_2^2 + m_\mu^2} + |\vec{p}_1 + \vec{p}_2|$$

The distribution of this variable can then be used to deduce relevant parameters including those related to the average absolute center-of-mass energy. Given very good control of the tracking detector absolute momentum scale[2] it is foreseen that knowledge of the absolute center-of-mass energy at the 10 ppm level can be targeted.

5. W Mass

M_{W} is an experimental challenge. Especially so for hadron colliders. The three most promising approaches to measuring the W mass at an e^+e^- collider are:

1. **Polarized Threshold Scan.** Measurement of the W^+W^- cross-section near *threshold* with longitudinally polarized beams as discussed in [12] and references therein. The ability to "turn-on" and "turn-off" the signal with polarized beams allows an in-situ precise measurement of the background that is unique to ILC.

2. **Constrained Reconstruction.** Kinematically-constrained reconstruction of W^+W^- using constraints from *four-momentum conservation* and optionally mass-equality as was done at LEP2.

3. **Hadronic Mass.** Direct measurement of the *hadronic mass*. This can be applied particularly to single-W events decaying hadronically or to the hadronic system in semi-leptonic W^+W^- events.

[1] Previous studies were based on the angle technique in $Z\gamma$ events (with $Z \to \mu^+\mu^-$). That method suffers from relatively poor event-by-event statistical precision given the Z width

[2] Can control to 10 ppm through momentum-scale calibrations with at least 12,000 energetic $J/\psi \to \mu^+\mu^-$ events

Method 1 needs dedicated running near $\sqrt{s} = 161$ GeV. A threshold scan with polarized electron and positron beams can yield a precision measurement of M_W at ILC. Errors at the few MeV level can be envisaged. With 100 fb^{-1}, and polarization values of (90%, 60%), the estimated uncertainty is

$$\Delta M_W\,(\mathrm{MeV}) = 2.4\,(\mathrm{stat}) \oplus 3.1\,(\mathrm{syst}) \oplus 0.8\,(\sqrt{\mathrm{s}}) \oplus \mathrm{theory}$$

amounting to an experimental error of 3.9 MeV. Eventual experimental precision approaching 2 MeV can be considered at ILC if one is able to dedicate 500 fb^{-1} to such a measurement, and the physics perspective of the day demands it.

Methods 2 and 3 can exploit the standard $\sqrt{s} \geq 250$ GeV ILC program. Methods for measuring the W mass in e^+e^- colliders were explored extensively in the LEP2 era, see [15,16] and references therein. For ILC, the constrained reconstruction approach will focus on semi-leptonic events thus avoiding the final-state interaction issues that beset the fully hadronic channel. With the large data-sets of WW events expected above threshold, the expectation is that this measurement will be systematics limited. With much improved detectors compared to LEP2 and with much better lepton and jet energy resolution, it is expected that uncertainties in the few MeV level can be targeted.

Method 3 is based purely on the hadronic mass and was not used explicitly at LEP2. With the increased cross-section for singly-resonant events ($e^+e^- \rightarrow \mathrm{We}\nu$) at higher $\sqrt{s}$, the excellent resolution for particles in jets expected from particle-flow detectors, and the availability of control channels with hadronic decays of the Z, an opportunity exists to make a competitive measurement also using this method. However the demands on the effective jet energy scale calibration are very challenging.

6. A_{LR}

The measurement of A_{LR} is essentially a counting experiment where one measures the cross-section for Z production using all visible decay modes except e^+e^- with the four beam helicity configurations discussed in subsection 4.1. The statistical power is diluted by about 46% due to the normalization statistics from Bhabha events and the statistics from Compton events used to check the relative polarization. The main systematics are assumed to be related to the knowledge of the center-of-mass energy and the luminosity spectrum (LS). An overall uncertainty of

$$\Delta A_{\mathrm{LR}}\,(10^{-5}) = 2.4/\sqrt{L(100\ \mathrm{fb}^{-1})}\,(\mathrm{stat}) \oplus 1.8\,(\sqrt{\mathrm{s}}) \oplus 1.8(\mathrm{LS})$$

appears feasible. More details are given in [11].

7. Conclusion

ILC can advance our knowledge of electroweak precision physics. It can deliver a much more rigorous test of the SM and thus explore new physics. This is highlighted by a precision top mass measurement from a threshold scan with uncertainty around 50 MeV, an uncertainty on M_{W} from three different methods with uncertainties below 5 MeV and approaching the few MeV level, and a measurement of A_{LR} targeting an uncertainty of 3.5×10^{-5} with 100 fb^{-1}, which can be intepreted, subject to additional parametric uncertainties, as a measurement of $\sin^2\theta^{\ell}_{\mathrm{eff}}$ to around

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4×10^{-6}. Experimental strategies for controlling systematics associated with $\sqrt{s}$, polarization, and the luminosity spectrum have been worked out. The physics discussed here benefits greatly when the accelerator is designed to include efficient running at lower center-of-mass energies.

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