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Precision Measurements at the ILC

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Abstract.
With relatively low backgrounds and a well-determined initial state, the proposed International Linear Collider (ILC) would provide a precision complement to the LHC experiments at the energy frontier. Completely and precisely exploring the discoveries of the LHC with such a machine will be critical in understanding the nature of those discoveries and what, if any, new physics they represent. The unique ability to form a complete picture of the Higgs sector is a prime example of the probative power of the ILC and represents a new era in precision physics.

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INTRODUCTION

The International Linear Collider (ILC) is an e^+e^- collider proposed by an international community of high-energy physicists to begin operation at up to $\sqrt{s} = 500$ GeV during the next decade, with the potential to upgrade to $\sqrt{s} = 1$ TeV thereafter. Although the maximum parton-parton energy is much smaller than at the LHC, the virtues of colliding electrons for precision measurements are well established. A well known initial-state energy that provides kinematic constraints, small and well-understood Standard Model backgrounds that provide sensitivity to difficult signatures and control of beam polarization that provides additional constraints are the important features of this design.

Given these strengths, comparisons to LEP and SLD are well motivated, and the ILC is indeed designed to complement the LHC just as LEP and SLD have complemented previous hadron colliders. The logical consequences of this analogy are twofold. First, the ILC should probe the discoveries of the LHC in detail. Second, the ILC should continue the mission of LEP in precision measurements sensitive to new physics through minute deviations in Standard Model predictions.

HIGGS AT THE ILC: THE PRECISION FRONTIER

The full range of LHC discoveries are impossible to predict. However, a legacy of the LEP and SLD programs of precision electroweak measurements is a certainty that there is some unobserved physics, most likely a Higgs boson below $\approx$200 GeV/c^2 in mass, responsible for electroweak symmetry breaking that must be accessible at LHC energies. With large production rates ($> 10^3$/day) and sensitivity to Higgs decays throughout the allowed mass range, it appears that the LHC will observe a Higgs. However, in any scenario, the LHC will access only a small fraction of the Higgs width

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FIGURE 1. The dominant Higgs production mechanisms at the ILC.

because backgrounds preclude the reconstruction of most final states. It will therefore be impossible to perform many of the measurements necessary to determine whether a Higgs-like resonance at the LHC is indeed *the* Standard Model Higgs, or instead manifests behavior that indicates some underlying new physics. These measurements include precise determination of the Higgs mass, width and quantum numbers, and the complete set of couplings of the Higgs to itself and all of the Standard Model particles.

The ILC is an ideal environment for this investigation.[1][2][3] The Standard Model Higgs is produced at the ILC primarily through two mechanisms, shown in Figure 1, that are somewhat selectable via collision of polarized beams. The first, radiation of Higgs from a Z boson ("Higgsstrahlung"), dominates near the production threshold and has a cross section that measures the coupling of Higgs to neutral gauge bosons, g_{HZZ}. The second, production from a pair of W bosons ("W-fusion"), becomes more important well above threshold and has a cross section that measures the coupling to vector bosons, g_{HWW}. These processes produce Higgs at the modest rate of ≈10000/year. However, in considering the reconstruction of Higgsstrahlung events, the power of studying the Higgs at the ILC becomes evident. With a knowledge of the center-of-mass energy, the mass of the Z produced in association with the Higgs, and a measurement of the momentum of the recoiling Z, the Higgs mass peak may be reconstructed without detecting any of the Higgs decay products. This provides an unbiased, high-statistics sample of Higgs bosons for detailed investigations of its properties.

The Higgs mass is, in essence, a fundamental constant of the Standard Model and must be measured to the best possible precision. Reconstruction of Higgsstrahlung events where the Z decays to muons can determine the Higgs mass to ≈100 MeV, even in the case that the Higgs decays only to invisible particles. In the case of a Standard Model Higgs, combining these kinematic constraints with the ability to cleanly reconstruct $ZH \to 4$ jets results in a Higgs mass resolution of ≈50 MeV. An anomalously large Higgs width would be a strong indicator of new physics. Measurement of $\sigma_{H\nu\nu} \times BR(H \to b\bar{b})$ in W-fusion production together with a measurement of $BR(H \to b\bar{b})$ in Higgsstrahlung events determines $\Gamma(H \to WW^\star)$, which can be combined with a similar measurement of $BR(H \to WW^\star)$ to calculate the total width $\Gamma_{tot} = \Gamma(H \to WW^\star)/BR(H \to WW^\star)$ to a precision of 5%-15% depending upon the Higgs mass. For $M_H > 2M_Z$, the natural width of the Higgs is resolvable at the ILC and it will also be possible to measure the Higgs width directly. An additional advantage of mono-energetic beams is the ability to perform threshold scans, and the J^{PC} of the Higgs is strongly constrained by threshold behavior of the Higgsstrahlung cross-section. Together with the angular dependence of Higgsstrahlung production and decay angular distributions in fermionic decays, the

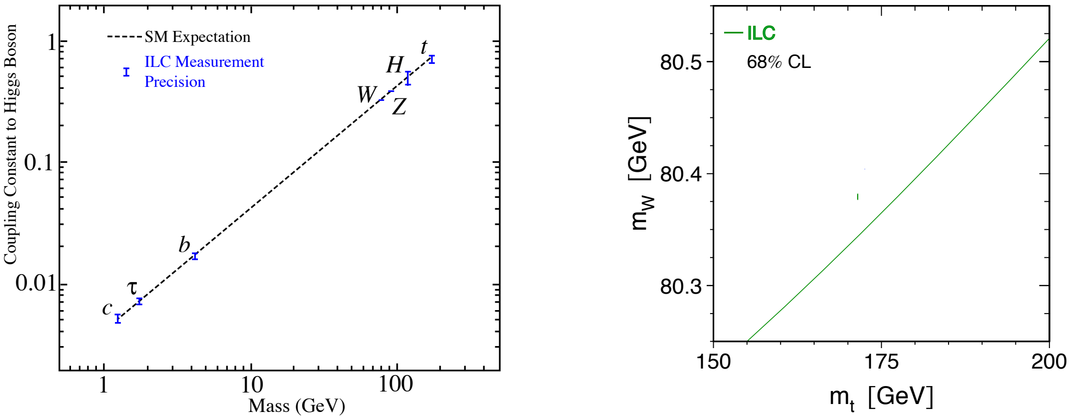

FIGURE 2. At left, the precision with which the ILC can test the coupling-mass relation predicted for the Standard Model Higgs. At right, the precision with which the relationship between the M_t, M_W (tiny point) and M_H (diagonal line) can be constrained by the ILC: a discrepancy is shown for visibility.

quantum numbers of the Higgs may be unambiguously determined.

The hypothesis that the Standard Model particles acquire mass by coupling to the Higgs field is a central question that can be tested at the ILC, since the couplings that generate mass also determine the decay widths to each of the final states. Taking advantage of the kinematic constraints and low-background environment of Higgsstrahlung events, the branching fractions to bb, cc, $\tau\tau$ and virtual W-pairs may be measured to good precision for $M_H < 150 GeV$. In addition, the loop decays to $\gamma\gamma$ and gg, sensitive to couplings to all charged and colored particles respectively, may be measured. For higher Higgs masses, decays through Z pairs will also be measurable. Comparison of the inclusive Higgsstrahlung yield from Z recoil with the sum of the exclusive final states is sensitive to decays of the Higgs to invisible particles with branching fractions as small as 5%. The top Yukawa coupling, unique in being almost unity, can be measured even for $M_H < 2M_t$ using the rate of Higgs radiation from top. Finally, the self-coupling of the Higgs that directly probes the cubic term in the Higgs potential may be measured, and deviations from the SM value can be detected at the 10% level. This complete study of Higgs couplings allows a test of the mass-coupling relation over two decades in mass, providing a precise test of this key hypothesis of the Standard Model, as depicted in Figure 2. Deviations from the expected linear relationship would indicate not only the presence of new physics, but the pattern of deviation would serve as an analyzer for that physics, with clear signatures for SUSY, extra dimensions and other possibilities.[3]

The deconstruction of the Higgs sector provides only a brief illustration of the power of the ILC to analyze new physics. The ability to explore other possibilities such as SUSY[4] is similarly impressive. However, the ILC experiments are not without challenges, as they require detectors with unheard of capabilities.[2][5] Performing $Z \rightarrow \mu\mu$ reconstruction well enough to precisely determine the Higgs mass requires momentum resolution in the tracking system far in excess of any previous collider tracking system: $\delta p_T/p_T < 5 \times 10^{-5}$. The jet-energy resolution required for precise Higgs mass reconstruction and separation of hadronic W and Z decays is approximately $30\%/\sqrt{E(\mathrm{GeV})}$, necessitating new calorimeter technologies and reconstruction techniques. The ability to distinguish the bb, cc and $\tau\tau$ final states requires vertexing of unparalleled precision, with impact parameter resolution on the order of $\delta_{IP} = 5 \oplus 10/p_T \mu$m, calling for a low-mass pixel vertex detector having approximately 1 billion channels and $\approx$0.1% X_0/layer of material. An aggressive R&D program is underway to achieve these goals.

Although precision exploration of the Higgs and new physics are the heart of the ILC physics program, the proposed options for running at the ZZ and WW resonances (GigaZ/MegaW) would refine the previous generation of measurements by LEP, SLD and the Tevatron. In particular, M_W can be measured to $\approx$ 5MeV and $\sin^2\theta^l_{eff}$ to $\approx \mathscr{O}(10^{-5})$, while M_t can be measured to $\approx$ 50 MeV in a threshold scan . Along with precise determination of the Higgs mass, these overconstrain the Standard Model as shown in Figure 2: any inconsistency is a clear sign of new physics. The ILC will also be able to measure the critical couplings of the top quark to gauge bosons to a few percent, and as at LEP, indirect searches would probe and identify new physics such as extended gauge sectors to higher masses than possible even at the LHC.

CONCLUSION

The focus of ILC physics program is the careful examination of new phenomena via precision measurements in order to fully understand the underlying physics. This capability is a necessary accompaniment to the LHC, which has prodigious mass reach but difficult backgrounds that preclude detailed and comprehensive studies. Careful study of the Higgs is prime example and will be central to the ILC physics program, along with similar studies of any surprises that await at the LHC. The ILC will also expand the energy frontier through indirect searches similar to those carried out at LEP. Although the benefits of the ILC are clear, success depends upon the successful development of very aggressive experiments.

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