PROCEEDINGS OF SCIENCE

Higgs Physics with ILC

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The International Linear Collider (ILC) is one of several proposed Higgs factories. In this contribution, we will discuss the potential of Higgs physics studies at the ILC. The pursuit of understanding the fundamental building blocks of the universe continues to be a driving force in the field of particle physics. The Higgs boson has held a central role in our quest to unravel the mysteries of the cosmos. The International Linear Collider (ILC) stands as a cutting-edge tool in this endeavor, offering unparalleled precision and capabilities for exploring the properties of the Higgs boson.

This presentation highlights examples of the most compelling Higgs analyses to be conducted at the ILC. The ILC's unique features, such as its broad energy range and exceptional precision, enable the probing of the Higgs boson with unprecedented accuracy, shedding light on its elusive properties and interactions.

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1. Introduction

The quest to unravel the deepest mysteries of the universe has been an enduring and transformative journey for physicists. At the forefront of this exploration lies the enigmatic Higgs boson, a particle that plays a pivotal role in our understanding of the fundamental forces and particles that make up the cosmos. The discovery [1, 2] of the Higgs boson at the Large Hadron Collider (LHC) in 2012 marked a monumental achievement, validating the existence of a field that endows mass upon other particles and offering insight into the origins of mass itself.

However, the story of the Higgs boson is far from complete, and it is poised to be enriched further by the next generation of particle accelerators. Among them, the International Linear Collider (ILC) [3–7] emerges as a beacon of scientific hope, promising to deepen our understanding of the Higgs sector and extend the frontiers of particle physics.

2. The Higgs Mass

Measuring the Higgs mass using the recoil mass of Z bosons is a crucial technique that is independent of the properties of the Higgs boson's decay modes. This method is particularly relevant at the International ILC due to its clean collision environment and precise knowledge of the initial state. Figure 1 (left) shows the Feynman diagram of the Higgs strahlung process annd the WW-fusion process (right) as dominating Higgs production mechanisms below and above 500 GeV respectively.

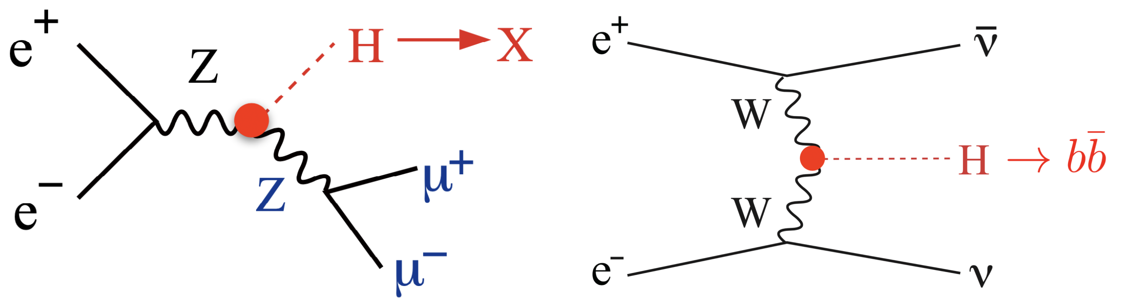

Figure 1: Higgs production in e^+e^- collisions. Left: Higgs strahlung process, right: Vector Boson Fusion process.

Reconstructing the Z boson via its decay products the Higgs mass is given via the Z recoil mass:

$$M^2_{\mathrm{recoil}} = (\sqrt{s} - E_Z)^2 - P_Z^2 \tag{1}$$

where E_Z and P_Z are the energy and the momentum of the Z boson, respectively. The reconstructed recoil mass distributions, calculated assuming the ZH is produced with four-momentum $(\sqrt{s}, \mathbf{0})$, is shown in Figure 2. The recoil mass technique at 250 GeV provides the Higgs mass measurement with absolute statistical precision of 15 MeV [8].

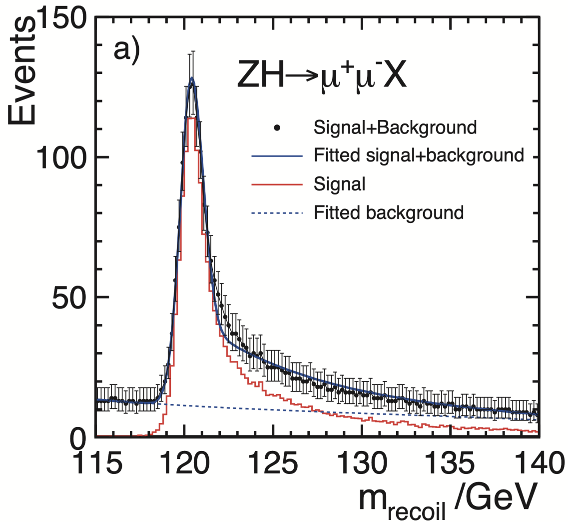

Figure 2: Results of the model independent analysis of the Higgs strahlung process $e^+e^- \rightarrow ZH$ at $\sqrt{s}$ = 250 GeV in which $Z \rightarrow \mu^+\mu^-$. The results are shown for P (e^+, e^-) = (+0.3, -0.8) beam polarization. Taken from [8].

3. The Higgs Width

The determination of the total decay width of the Higgs boson is one of the fundamental physical tasks of investigating its profile. For an Standard Model Higgs of 125 GeV, the expected total width is around 4 MeV, which is far beyond the detector resolution at both LHC and ILC and therefore it cannot be measured directly by reconstructing its line shape. At the ILC, the advantage of recoil mass techniques makes the inclusive measurement possible. It measures the absolute cross section of $e^+e^- \rightarrow ZH$, which is proportional to the square of the HZZ coupling (g_Z^2). With g_Z^2 known, the partial width of $H \rightarrow ZZ^\star$ (Γ_Z) can be given explicitly. Combined with another measurement of the branching ratio of $H \rightarrow ZZ^\star$ (BR_Z), the Higgs total width (Γ_H) can be determined by

$$\Gamma_H = \frac{\Gamma_Z}{BR_Z} \tag{2}$$

In this approach Γ_Z can be measured accurately, however for the SM Higgs the precision of BR_Z is statistically limited by its small branching ratio $BR_Z \sim 2.7\%$. Another approach by utilizing the $H \rightarrow WW^\star$ mode, which has a much larger branching ratio $BR_W \sim 22\%$, gives

$$\Gamma_H = \frac{\Gamma_W}{BR_W} \tag{3}$$

The feasibility of the measurement of the Higgs production cross section through WW-fusion (Figure 1, right side) is investigated for $\sqrt{s}$ = 250 GeV and a beam polarization of P(e^+e^-) = (+0.3, -0.8), assuming 250 fb^{-1} of data. We can extract information on the coupling g_W of the Higgs boson to W-bosons which then provides us the possibility to determine the total decay width of the Higgs boson. The SM Higgs boson with a mass below 140 GeV is expected to decay predominantly into two b-quarks.

Figure 3 gives the distribution of the reconstructed Higgs invariant mass, where both the Higgs peak from the signal and the Z peak from $\nu\bar{\nu}Z$ background can be clearly seen. Eventually, a cut on the Higgs invariant mass is applied to suppress the $\nu\bar{\nu}Z$ background. Ultimately, a 500 GeV ILC can reach a precision of 5% of the Higgs total width [9].

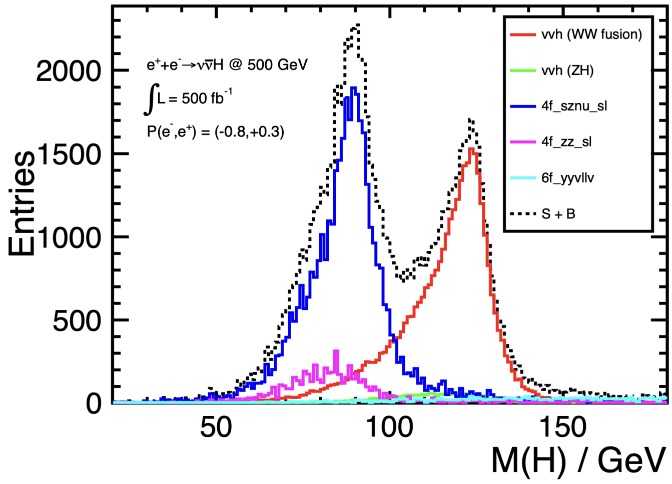

Figure 3: Distribution of the reconstructed Higgs invariant mass using $H \rightarrow b\bar{b}$. Taken from [9].

4. Higgs and a Hidden Sector

The discovery of unexpected properties of the Higgs boson would offer an intriguing opportunity to shed light on some of the most profound puzzles in particle physics. Beyond Standard Model decays of the Higgs boson could reveal new physics in a direct manner. Future electron-positron lepton colliders operating as Higgs factories, including CEPC, FCC-*ee* and ILC, with the advantages of a clean collider environment and large statistics, could greatly enhance sensitivity in searching for these BSM decays.

For future lepton colliders running at the center of mass energy 240 ~ 250 GeV, the most important Higgs production mechanism is Z-Higgs associated production through an off-shell Z boson (see Figure 1, left). The Z boson with visible decays plays the role of Higgs spectator and enables Higgs tagging using above described recoil mass technique (Section 2).

From Figure 4, we can distinctly see the improvement in exotic decays from the lepton collider Higgs factories.

5. Precision Higgs Couplings and the Search for New Physics

The search for new physics beyond the Standard Model is probably the most important goal of particle physics today. Because shifts of the Higgs couplings can be induced by mixing with loop corrections from very heavy particles, the study of these couplings gives a route to new physics that is essentially orthogonal to the methods used at the LHC or direct Dark Matter searches.

The goal of the ILC program on the Higgs boson is to provide determinations of the various Higgs couplings that are both high-precision and model-independent. It is easy to see how this can

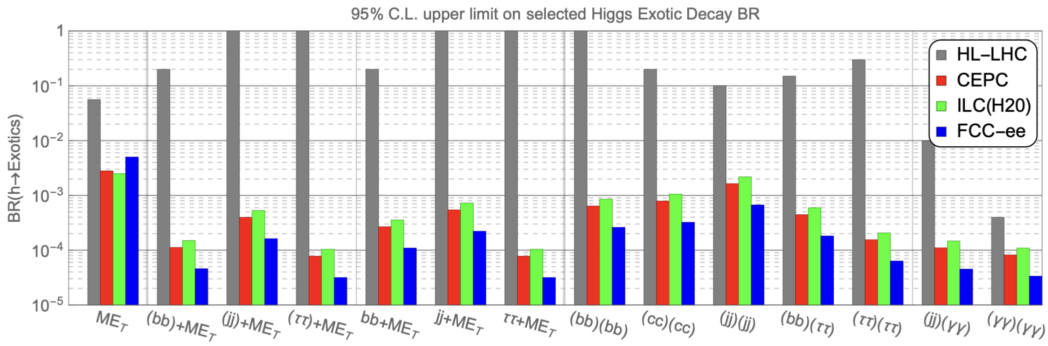

Figure 4: The 95%C.L. upper limit on selected Higgs exotic decay branching fractions at HL-LHC, CEPC, ILC and FCC-ee. We put several vertical lines in this figure to divide different types of Higgs exotic decays.. Taken from [10].

be achieved for some combinations of Higgs couplings. In the reaction $e^+e^- \to ZH$, the Higgs boson is produced in association with a Z boson at a fixed lab-frame energy (110 GeV for $\sqrt{s}$ = 250 GeV). Up to small and calculable background from $e^+e^- \to ZZ$ plus radiation, observation of a Z boson at this energy tags the presence of a Higgs boson. Then the total cross section for $e^+e^- \to ZH$ can be measured absolutely without reference to the Higgs boson decay mode, and the various branching ratios of the Higgs boson can be observed directly.

The difficulty at Hadron Colliders comes when one wishes to obtain the absolute strength of each Higgs coupling. In most of the literature on Higgs boson measurements at e^+e^- colliders, the Higgs couplings are determined using the κ parametrization. One assumes that the Higgs coupling to each species A is modified from the SM value by a mutiplicative factor κ_A. There is a serious problem with the κ formalism: It is not actually model-independent.

There is an attractive solution to this problem. It is suggested to parametrize the effects of the most general new physics on the Higgs boson by writing an effective Lagrangian that consists of the SM Lagrangian plus the most general set of $SU(3) \times SU(2) \times U(1)$-invariant dimension-6 operators. This is called the Standard Model Effective Field Theory (EFT) formalism.

Figure 5 shows graphically the ability of ILC measurements to distinguish the Higgs boson couplings for various BSM models from the SM expectations and from the expectations of other models. Each square shows relative goodness of fit for the two models in units of σ.

6. Conclusions

The physics capabilities of the ILC are formidable. It's a promising and mature Higgs factory proposal. With its clean environment, flexible polarization and energy range it can play a major role in future Higgs studies. As highlighted by examples in this paper, this facility will provide high-precision measurements of various properties of the of the Higgs boson.

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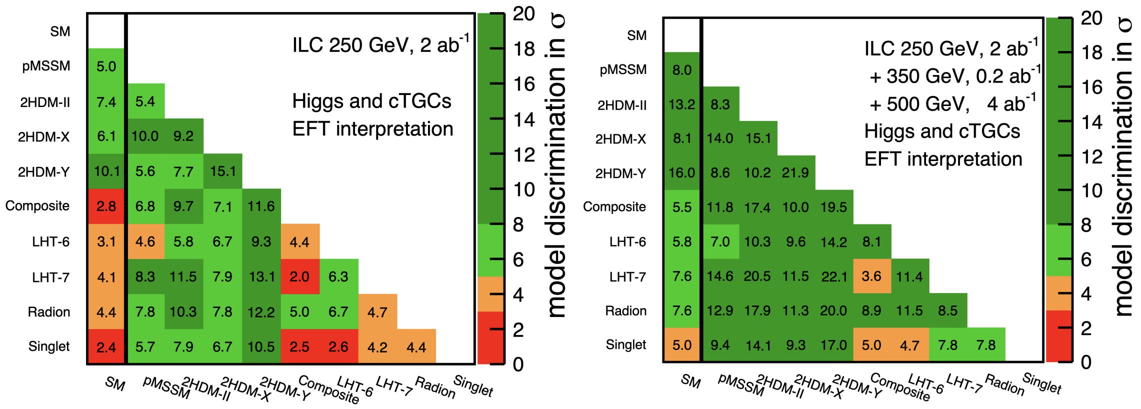

Figure 5: Graphical representation of the χ^2 separation of the Standard Model and the models described in [11]. Left: with 2 ab^{-1} of data at the ILC at 250 GeV; Right: with 2 ab^{-1} of data at the ILC at 250 GeV plus 4 ab^{-1} of data at the ILC at 500 GeV. Comparisons in orange have above 3 σ separation; comparison in green have above 5 σ separation; comparisons in dark green have above 8 σ separation.

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