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Benchmarks for the ILC Physics Studies – 2010

ILC LOI Common Task Groups Physics Panel

1 Introduction

The purpose of this document is to recommend physics analyses that should be carried out by the ILC LOI detector groups in the next round of studies. This note is a revision of the note circulated by the Physics Panel in November 2009. In this document, we will present new tasks for the LOI groups, of two kinds. First, we suggest three sets of processes that should be studied by both LOI groups with full simulation, to test aspects of the detectors and of the machine parameters that were not addressed in the original LOI study. Second, we suggest a number of topics in the ILC physics case that should be revisited for more precise estimates of the ILC capabilities. For these, fast simulation studies informed by the existing full simulation results should be adequate.

The philosophy of this request is that the two LOI groups should *individually* complete the full-simulation studies that fully test their detector capabilities. These require large resources and dedicated manpower, so new requests should be kept to a minimum. At the same time, the two LOI groups should *collectively* work to produce the strongest possible picture of the ILC physics case. This should include attention to the central physics issues around which the ILC is designed, such as the precision study of the properties of the Higgs boson. They should also cover a range of possibilities for new physics beyond the Standard Model, with special attention to new physics models that could actually be discovered in the current run of the LHC.

In Section 2, we review the processes that were studied in full simulation for the 2009 LOIs. In Section 3, we present and motivate new reactions that should be studied in full simulation in the next round of the LOI study. In Section 4, we discuss some open issues for the precision Higgs boson studies at the ILC, for which we encourage the LOI groups to present new estimates. In Section 5, we discuss some additional issues related to new physics models, for which we encourage new work by the LOI groups. We expect that fast simulation, informed by the present set of full-simulation results, will be adequate for the issues in these latter two sections.

2 Benchmarks used in the 2009 LOIs

It will be useful to begin by reviewing the benchmark reactions actually used in the 2009 LOIs. Here are the five reactions studied, together with the questions about these reactions that were answered in the LOIs. These reactions were drawn from an extensive list of benchmark reactions prepared in 2005 [1].

1. $e^+e^- \to h^0 Z^0$ at $E_{\rm CM} = 250$ GeV, where h^0 is a Standard Model Higgs boson of mass 120 GeV, with $Z^0 \to \ell^+\ell^-$. The goal was to measure the mass of the Higgs boson in recoil against the lepton pair.
2. $e^+e^- \to h^0 Z^0$ at $E_{\rm CM} = 250$ GeV, where h^0 is a Standard Model Higgs boson of mass 120 GeV, in the final state $h^0 \to c\overline{c}$, $Z^0 \to \nu\overline{\nu}$ or $q\overline{q}$. The goal was to measure the branching ratio $BR(h^0 \to c\overline{c})$.
3. $e^+e^- \to \tau^+\tau^-$ at $E_{\rm CM} = 500$ GeV. The goal was to measure the forward-backward asymmetry and the final-state τ polarization.
4. $e^+e^- \to t\overline{t}$ at $E_{\rm CM} = 500$ GeV. The goal was to measure the top quark mass and the cross section and forward-backward asymmetry.
5. $e^+e^- \to \widetilde{\chi}_1^+\widetilde{\chi}_1^-$, $e^+e^- \to \widetilde{\chi}_2^0\widetilde{\chi}_2^0$ at $E_{\rm CM} = 500$ GeV, assuming the supersymmetry spectrum of benchmark point 5 [2]. The goal was to determine the two production cross sections and the masses of $\widetilde{\chi}_1^+$, $\widetilde{\chi}_2^0$, and $\widetilde{\chi}_1^0$.

These reactions were intended to test the capabilities of the detectors for tracking (#1,3), jet energy measurement and W/Z separation in the 2-jet final state (#4,5), missing energy measurement (#2,5), and heavy quark tagging (#2,4). At the same time, they allowed to LOI groups to make precise statements about the ILC capabilities in areas important to the physics case.

3 Proposed new full-simulation benchmarks

There are two sets of problems that, in our opinion, are essential to address with new full-simulation benchmarking reactions. The first is to test the performance of the LOI detectors at a center of mass energy of 1 TeV. One must test the basic capabilities of the detectors for tracking and hadron calorimetry at high energy. Some reactions that one would want to study at 1 TeV peak in the forward direction, so it is important to assess the detection capabilities over a wider range in rapidity than is relevant at 500 GeV. Further, the choice of an energy well above the WW and $t\bar{t}$ thresholds allows reactions of great complexity than are treated at 500 GeV. This increased complexity has an impact on b-tagging performance and missing energy resolution. The benchmarking reactions should give a means of assessing this.

The second problem is the precise requirement on the center of mass energy needed for precision Higgs physics. The GDE is now considering design options that limit the luminosity that would be available at energies below 500 GeV. In the LOIs, the precision determination of Higgs couplings was studied at the maximum of the $e^+e^- \to Z^0h^0$ cross section. However, if the available luminosity depends strongly on energy, it might be that an adequate number of Higgs events for precision measurements would be available only at a higher energy, well above the threshold for this reaction. There has been a great deal of debate within our community on how effectively higher-energy events, with boosted Higgs and Z^0 bosons, can be used to make precise measurements of the Higgs properties. We ought to settle at least part of this question with a full-simulation study.

With this motivation, we propose the following three sets of reactions for full-simulation analysis in the next round of the LOI study:

1. $e^+e^- \to \nu\bar{\nu}h^0$ at $E_{\rm CM} = 1$ TeV, where h^0 is a Standard Model Higgs boson of mass 120 GeV, in the final states $h^0 \to b\bar{b}$ and $h^0 \to \mu^+\mu^-$. The goal is to measure the cross section times branching ratio for these reactions.
2. $e^+e^- \to t\bar{t}h^0$ at $E_{\rm CM} = 1$ TeV, where h^0 is a Standard Model Higgs boson of mass 120 GeV, in the final state $h^0 \to b\bar{b}$. The reaction involves final states with 8 jets and final states with 6 jets, lepton, and missing energy. The goal is to measure the Higgs boson coupling to $t\bar{t}$.
3. $e^+e^- \to Z^0h^0$, at $E_{\rm CM} = 350$ GeV, where h^0 is a Standard Model Higgs boson of mass 120 GeV, decaying to hadronic final states. The goal is to measure the *relative* branching ratios of the h^0 to $b\bar{b}$, $c\bar{c}$, and gg.

The reaction (1) tests the basic capabilities of the detectors at 1 TeV for tracking, including the muon system, and for hadron calorimetry. The cross section is forward-peaked, so it also tests the ability of the detectors to cover a large range in rapidity. The reaction (2) tests the ability of the detectors to unravel complex events at 1 TeV. It tests their ability to tag b's and to measure missing energy in a challenging environment. The reaction (3) provides a test of precision calorimetry and heavy quark tagging capabilities in a system with Higgs bosons boosted away from threshold.

A potential problem with requiring analyses at new center of mass energies is the issue of generating full Standard Model background samples for the analyses. Akiya

Miyamoto, Mikael Berggren, and Tim Barklow are in the process of systematizing the procedure for background generation so that it can be carried out efficiently at any center of mass energy with a relatively small amount of human effort. The computer resources required for generating and storing the events are still substantial and need to be identified.

The reaction $e^+e^- \to t\bar{t}h^0$ poses special challenges. A full physics analysis would probably require generating 10- and even 12-parton final states. We agreed that Barklow, Berggren, and Miyamoto would prepare a background physics event sample with up to 8-parton final states that would be used by both LOI groups for this analysis. We expect that the omission of more complex background processes will have an unimportant effect on the conclusions of the study.

4 ILC Physics: Higgs boson

At the same time that the LOI groups are carrying out full-simulation studies of specific reactions, it is important for the proponents of the ILC to consolidate the knowledge that we have gained about the ILC capabilities in preparation for writing the ILC TDR. We believe that the remaining work can be done with fast-simulation studies using detector models tuned to reproduce the currently available full-simulation results. It is not necessary that every process below be studied by both of the LOI groups, but it is necessary that the two groups together can provide a complete and well-argued picture to be presented in the ILC TDR.

There are two main areas in which new surveys of the ILC capabilities should be put together. The first is in the area of precision Higgs studies. The ILC is capable of assembling the complete phenomenological profile of the Higgs boson in a way that cannot be done at hadron colliders. It will be important for the ILC TDR that this be documented with quantitative estimates of the model-independent determination of the Higgs couplings. This should be done both for our canonical model case of a Standard Model Higgs boson at 120 GeV and for the case of a Standard Model Higgs boson of mass 200 GeV that might be discovered in the current 7 TeV run of the LHC.

In particular, we hope that the following questions will be revisited in fast-simulation studies that take advantage of our current knowledge of the LOI detectors. We repeat that new full-simulation, beyond the ones suggested above, should not be needed. The ordering of the questions reflects our priority ranking.

1. $e^+e^- \to h^0Z^0$ at $E_{\rm CM} = 500$ GeV, where h^0 is a Standard Model Higgs boson of mass 200 GeV, in the final states $h^0 \to WW, ZZ$. The goal is to estimate

the ultimate precision on these Higgs boson branching ratios that is achievable at the ILC.

2. $e^+e^- \to h^0Z^0$ at $E_{\rm CM} = 230$ GeV and at $E_{\rm CM} = 350$ GeV, where h^0 is a Standard Model Higgs boson of mass 120 GeV, in the final states $h^0 \to b\overline{b}, c\overline{c}, gg, WW^*, ZZ^*, \tau^+\tau^-, \gamma\gamma$. The goal is to estimate the ultimate precision on these Higgs boson branching ratios that is achievable at the ILC.

3. $e^+e^- \to \nu\overline{\nu}h^0$ at $E_{\rm CM} = 1$ TeV, where h^0 is a Standard Model Higgs boson, addressing the measurement of the tiny and difficult branching fractions $h \to \mu^+\mu^-$ for $m(h) = 120$ GeV and $h \to b\overline{b}$ for $m(h) = 200$ GeV. The goal is to estimate the ultimate precision on these Higgs boson branching ratios that is achievable at the ILC.

4. $e^+e^- \to t\overline{t}h^0$ at $E_{\rm CM} = 1$ TeV, where h^0 is a Standard Model Higgs boson, addressing the measurement of the cross section, for $m(h) = 120$ GeV and for $m(h) = 200$ GeV. The goal is to estimate the accuracy with which the ILC will measure the coupling of the h^0 to $t\overline{t}$.

5. $e^+e^- \to h^0h^0Z^0, \nu\overline{\nu}h^0h^0$ at $E_{\rm CM} = 500$ GeV and at $E_{\rm CM} = 1$ TeV, where h^0 is a Standard Model Higgs boson of mass 120 GeV. The goal is to estimate the accuracy with which the ILC will measure the triple Higgs coupling. Our expectation is that this measurement will be extremely difficult at 500 GeV, but we still feel that a credible estimate of the ILC capability is needed. We expect that an accuracy of 10-20% is achievable at 1 TeV. This should be documented in a complete study including estimates of systematic errors.

There is one further set of issues that needs to be investigated. We have already noted that that proposed ILC machine revisions will decrease the luminosity available at low energies. This means that we must think more carefully about the optimal energy at which to perform precision Higgs studies and the strategy needed in that study. For this, the following study is urgently needed:

1. $e^+e^- \to h^0Z^0$ where h^0 is a Standard Model Higgs boson of mass 120 GeV. The goal is to estimate the accurary with which the total cross section can be determined in model-independent way from observation of the recoil Z^0. This study should be carried out for a range of center of mass energies from 230 to 400 GeV and for the range of accelerator parameters such as beam energy spread and beamstrahlung fraction being considered in the machine revisions. The goal is to determine the systematic dependence on the accelerator energy and parameters

5 ILC Physics: particles from beyond the Standard Model

The ILC will advance not only the study of the Higgs boson but also of other new particles that might be present in the hundred GeV to TeV energy region. Some of these particles might well be discovered in the current run of the LHC at 7 TeV. If a new particle or set of particles is discovered at the LHC, this discovery will launch the investigation of physics beyond the Standard Model. It is likely that ILC will be essential to uncover the nature of this new particle and the new laws of physics that it implies. It will be important for the proponents of the ILC to explain to the broader high-energy physics community the importance of the role that the ILC will play.

In principle, the information needed for this argument already exists in the literature. The case of supersymmetric models with light sleptons or charginos is already explained in some detail in the RDR Physics document. The chargino reactions have been studied with full simulation in the first round of the LOI studies.

For other types of new particles, however, the existing studies are not organized in the most useful way, and new information from the full-simulation studies done for the LOIs has not been fully incorporated. We recommend that the LOI groups assemble estimates of the ILC capabilities in additional areas. Fast simulation studies should be sufficient, and in some cases it will be sufficient simply to collect and reinterpret results from the existing literature.

1. $e^+e^- \to \tau^+\tau^-$, $b\bar{b}$, $c\bar{c}$, at $E_{\rm CM} = 500$ GeV and at 1 TeV. The goal is to measure the pair-production cross section and forward-backward asymmetry and the τ polarization for each beam polarization.

   It is possible that the LHC could discover a Z' resonance with mass below 2 TeV in the current run. Assuming this mass and various hypotheses for the identity of the Z', the measurement sensitivites should be converted to measurements of the Z' couplings to τ, b, and c.

2. $e^+e^- \to t\bar{t}$ at $E_{\rm CM} = 500$ GeV. The goal is to measure the pair-production cross section and forward-backward asymmetry and the top quark polarization as a function of production angle, for each beam polarization.

   If new physics associated with the top quark is discovered at the LHC, for example, a $t\bar{t}$ resonance at 1 - 1.5 TeV, the couplings of the top quark to pointlike currents will be crucial quantities that will discriminate models. The measurements we suggest should be interpreted as measurements of the four top quark form factors $F_{1I}(Q^2)$ defined by the effective couplings

$$\delta\mathcal{L} = eA_\mu \bar{t}[\gamma^\mu P_L F_{1AL}(Q^2) + \gamma_m u P_R F_{1AR}(Q^2) t$$

$$+\frac{e}{c_w s_w} Z_\mu \bar{t}[\gamma^\mu P_L F_{1ZL}(Q^2) + \gamma^\mu P_R F_{1ZR}(Q^2)]t \qquad (1)$$

at $Q = 500$ GeV.

3. $e^+e^- \to \widetilde{\tau}^+\widetilde{\tau}^-$, $\widetilde{e}_1^+\widetilde{e}_1^-$, $\chi_1^0\chi_1^0$ at $E_{\rm CM} = 500$ GeV, in a gauge-mediated model of supersymmetry in which the $\widetilde{\tau}$ is the lightest Standard Model superpartner and is seen as a stable particle, with a lifetime greater than 1 sec. The goal is to determine the masses, quantum numbers, and couplings of these particles to extremely high precision.

   In supersymmetry models of the type described, the lightest $\widetilde{\tau}$ is stable on particle physics timescales, eventually decaying to $\tau\widetilde{G}$, where $\widetilde{G}$ is the gravitino. The Tevatron puts very weak constraints on the pair-production of such stable sleptons. However, if these particles are produced at the LHC in the decays of squarks and gluinos, the parent particles will be produced with large cross sections and the signatures of the stable particles will be striking. The LHC can learn much about these models [3]. These processes suggested here should be used to demonstrate that the ILC can make an additional suite of important measurements.

The 2010-11 run of the LHC might discover new physics of a very different kind from the guesses represented here. We hope that the ILC community will be prepared to lead, rather than follow, the discussion of the implications of this new physics for future accelerator projects.

References

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