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The road towards the international linear collider: Higgs, top/quantum chromodynamics, loops

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Abstract. The international linear e^+e^- collider (ILC) could go into operation in the second half of the upcoming decade. Experimental analyses and theory calculations for the physics at the ILC are currently performed. We review recent progress, as presented at the LCWS06 in Bangalore, India, in the fields of Higgs boson physics and top/QCD. Also the area of loop calculations, necessary to achieve the required theory precision, is included.

Keywords. International linear collider; quantum chromodynamics; top; loop Verein; Higgs.

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1. Introduction

There is a world-wide consensus that the international linear e^+e^- collider (ILC) is the next major project in the field of high-energy physics [1]. This has most recently been confirmed by the EPP2010 report [2]. The decision about the start of construction of the ILC will be taken by the end of this decade. It could go into operation in the second half of the next decade. It will therefore take data several years after the start of the large hadron collider (LHC). The physics case for the ILC, independent of what the LHC will find, has been made in various studies in the past years [3–7]. The complementarity and the synergy of the two colliders and combined physics analyses has been discussed extensively in ref. [6].

A very important consideration with respect to the ILC physics case is the question as to what the ILC can add to the LHC (or what can a combined ILC/LHC analysis add to the LHC). It has been shown [3–7] that in all conceivable physics scenarios the ILC can add valuable and important information. In particular, it can add precision analyses, pinning down model parameters extremely precisely. Moreover, in contrast to the LHC, this can often be done in a model-independent way. Furthermore, in many scenarios the ILC can discover new states that cannot be detected at the LHC. The combination of these three capabilities (precision measurements, model-independent analyses, discovery of new particles) enables the ILC to determine the underlying physics model.

While the physics case for the ILC has been made and the physics potential of the ILC has been analyzed, there are still many tasks that have to be performed until the full potential of the ILC can be exhausted. This concerns the experimental analyses as well as the (corresponding) theoretical calculations. In many scenarios the feasibility of the experimental analyses has to be worked out in detail. Theory calculations at the level of the anticipated ILC precision still have to be performed (see e.g. refs [8–10]). Progress in both directions has to be made over the next years in order to be ready once the ILC operation starts. The status of the field and about recent progress was given at the LCWS06 in Bangalore, India. Here we briefly review the presentations about new experimental analyses and new theory calculations given at the LCWS06. We focus on the fields of Higgs physics, top/QCD and loop calculations. The overview about the other fields is given elsewhere [11].

2. Higgs physics

If a (SM-like) Higgs mechanism is realized in nature, the LHC will find a Higgs boson and measure its characteristics [12–15]. To be certain that the state observed is indeed the Higgs boson, it is necessary to measure the couplings of this state to the W and Z gauge bosons, and to fermions such as the top and bottom quarks and the tau leptons. Consequently, the measurements at the LHC include a mass determination at the per cent level and coupling constant determination at the level of 10–20%. However, in order to do this several assumptions about the realization of the Higgs mechanism have to be made. Analyses could become much more involved if the Higgs boson decay rates are strongly different from the SM rates. Interesting physics could easily hide in the 10–20% precision achievable for the Higgs boson couplings. Higgs self-couplings are extremely complicated if not impossible to measure at the LHC. On the other hand, all these problems can be overcome with the ILC measurements [3–5,7].

The progress that will be necessary to fully exploit the ILC capabilities has been summarized in ref. [7], where the main open issues are:

- analyses with full simulations of the relevant ILC processes have to be performed,
- higher precision in the theory calculations for the relevant processes are needed to match the anticipated ILC accuracy,
- analyses for SM-like Higgs bosons with 'larger' mass ($M_H \gtrsim 150$ GeV) have to be done,
- tools (encoding high-precision calculations) have to become available,
- the LHC/ILC interplay has to be worked out in more detail.

These issues have (partially) been addressed at the LCWS06. Progress has been reported e.g. about the following subjects (more details can be found in the original publications):

- Improvements in the experimental analyses of triple Higgs boson couplings [16].

- Theory calculations for Higgs production at the $\gamma\gamma$ collider in the minimal supersymmetric standard model (MSSM) at the one-loop level [17].
- Higgs production in models with universal extra dimensions [18].
- Experimental analysis for the determination of anomalous Higgs couplings at the $e\gamma$ collider [19].
- Doubly charged Higgs production at the e^+e^- collider [20].
- Measurement of $\tan\beta$ in the MSSM via heavy Higgs boson production [21].
- Progress for the MSSM Higgs tool FeynHiggs [22].

3. Top/QCD

Top and QCD physics are a guaranteed physics case for the ILC. The top quark is deeply connected to many other issues of high-energy physics:

- Is it just a heavy quark, or does it play a special role in/for electroweak symmetry breaking?
- The experimental uncertainty of m_t induces the largest parametric uncertainty in the calculation of electroweak precision observables [23] and can thus obscure new physics effects.
- In supersymmetric (SUSY) models the top quark mass is an important input parameter and drives spontaneous symmetry breaking and unification.
- Little Higgs models contain 'heavier tops'.

The status of the field has been summarized in ref. [24]. Especially the calculations for $e^+e^- \to t\bar{t}$ at the threshold are quite advanced (see e.g. ref. [25] for a review or ref. [26] for a recent update). Also for the process $e^+e^- \to t\bar{t}H$ and the determination of the top Yukawa coupling substantial progress has been made recently (see e.g. refs [27,28]).

Advance in the field of top/QCD has been reported at the LCWS06 in the following subjects (more details can again be found in the original publications):

- Improved calculation of the cross-section $\sigma(\gamma\gamma \to \text{hadrons})$ [29].
- A new theory evaluation on how to use the lepton characteristics in top decays as probe of new physics scenarios [30].
- A calculation of $\gamma\gamma \to H, A \to t\bar{t}$ in the MSSM, including the polarization of the top quarks; this measurement can be used to test the mixing between CP-even and CP-odd Higgs bosons [31,32].

In order to exploit the full ILC capabilities for top quark physics, many improvements are still necessary. This includes a coherent treatment of electroweak effects at the $t\bar{t}$ threshold [24] or the development of tools providing the prediction of $e^+e^- \to 6f$ or $8f$ (see e.g. ref. [34]).

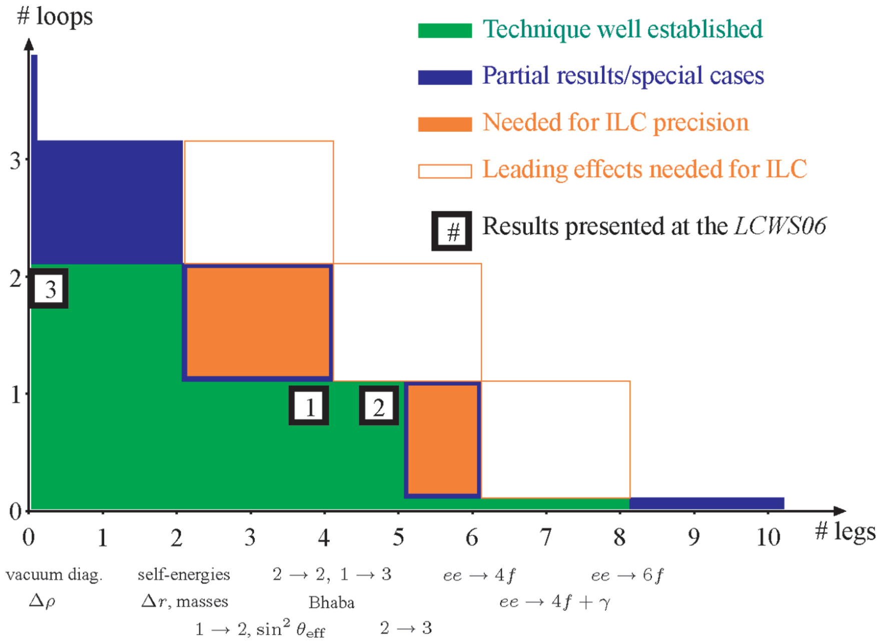

Figure 1. Status of the field of loop calculations. The orange shaded area shows what will be needed to match the anticipated ILC precision. The squares and numbers indicate the contributions presented at the LCWS06.

4. Loop calculations

The ILC will provide measurements of masses, couplings and cross-sections at (or even below) the per cent level [3–5]. A special example is the GigaZ option, which will determine the W boson mass with an error of 7 MeV and the effective leptonic weak mixing angle with a precision of 1.3×10^{-5} (see refs [35,36] and references therein). These anticipated future high precision measurements can fully be exploited only if they are matched with a theory prediction at the same level of accuracy. These theory predictions have to be obtained in the model under investigation (e.g. the SM, or the MSSM, for a recent overview see ref. [37]). The status of the field of loop calculations (including the presentations at the LCWS06) is briefly summarized in figure 1 [37a]. The complication of a higher-order loop calculation increases with the number of loops as well as with the number of external legs. On the other hand, it also increases with the number of (mass) scales appearing in the loop integral. While one-scale integrals (as in QCD) are usually the easiest possibility for a certain loop topology, two or more scales make the evaluation increasingly difficult. This poses a special problem in SUSY, where many independent mass scales can appear in one-loop diagram. In figure 1 on the horizontal axis the number of legs, and on the vertical one the number of loops is shown. Accordingly, the number of scales has to be kept in mind for the individual contributions reviewed below.

The green shaded area in figure 1 displays the number of loops and legs for which the techniques are meanwhile well established, even for an arbitrary number of scales. For these cases often public algebraic computer codes exist that do the main part of the loop calculation itself (for an overview see e.g. ref. [8]). The blue shaded area corresponds to the number of loops and legs for which partial results or calculation for special cases have been performed. This represents today's frontier of the field of loop calculations.

Compared to the situation about two years ago [9] significant progress has been made. Three examples for recent progress in the field of loop calculations are

- a complete $\mathcal{O}(\alpha)$ calculation for $e^+e^- \to 4f$ [38],
- a complete $\mathcal{O}(\alpha)$ calculation for $e^+e^- \to \nu\bar{\nu}HH$ [39],
- the automation of $2 \to 3$ processes at the one-loop level in the SM and the MSSM (including now also NMFV effects) [40].

In order to match the anticipated experimental precision of a future ILC, the field of loop calculations still has to advance substantially. The necessary improvement is indicated in figure 1 as the orange shaded areas, which will have to be under full control for the ILC precision [40a].

Some advances have been presented at this conference, which are shown as black rectangles (and numbers):

1. The GRACE system has been extended to $2 \to 2$ processes at the one-loop level in the MSSM [43].
2. Improvements in the calculation of Q_T spectra for $2 \to 3$ processes at the one-loop level have been obtained [44].
3. Two-loop vacuum diagrams in the MSSM with complex phases have been evaluated [45].

By comparing the necessary level of loop calculations and the current status (including the progress reported at the LCWS06), it becomes apparent that the field of loop calculations deserves a lot of attention in the next years.

5. Conclusions

There are still many tasks that have to be performed until the full potential of the ILC can be exploited. We reviewed the status of the field and the recent progress that was reported at the LCWS06 in Bangalore (India) in the fields of Higgs physics, top/QCD and loop calculations. While progress has been achieved, continuous progress over the next years will be necessary in the experimental analyses as well as the (corresponding) theoretical calculations in order to be ready once the ILC operation starts.

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