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The BSM Physics Case of the ILC

Jürgen Reuter[1a,*]

[a] *DESY Theory Group,*
Notkestr. 85, D-22607 Hamburg, Germany

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ABSTRACT

In this talk I summarize the physics case of the International Linear Collider (ILC) focusing on its potential towards discovery, discrimation or disentanglement of new physics beyond the Standard Model (BSM).

[1] juergen.reuter@desy.de

1 The physics case of the International Linear Collider

For this talk, I was asked to collect material for the physics case of the planned International Linear Collider (ILC) regarding its discovery potential for New Physics beyond the Standard Model. The physics case of a lepton collider with energies up to $\sqrt{s} = 500$ GeV (and beyond) has been outlined many times, starting from workshops during summer 1987 at KEK [1], La Thuile [2] and SLAC [3], following the TESLA Technical Design Report [4,5], towards the ILC Technical Design Report/Detailed Baseline Design [6,7]. Shortly after that, the physics case has been updated for the latest U.S. Snowmass community summer study [8]. In 2015, the ILC Physics Working Group was asked to provide a condensed version of the physics case [9] for the expert committees advising the Japanese Ministry for Education, Science, and Technology, MEXT. Though being a member of this Physics Working Group, this document is no official statement by them. The Physics case document [9] is accompanied by more definite running scenarios for the machine, given both technical machine and physics aspects, which have been worked out [10], and which allow to assess the development in precision of measurements of all parameters with running time of the machine.

The physics programme of any future high-energy lepton collider that reaches at least 500 GeV rests on three pillars, cf. the left-hand side of Fig. 1: its precision Higgs programme, its precision top quark programme and the direct search potential for BSM physics. These are motivated most effectively by the question of the microscopic structure behind the electroweak sector of the SM and its vacuum structure (right hand side of Fig. 1). To determine the stability properties of the electroweak vacuum, precision measurements of the main ingredients, the Higgs boson and the top quark are necessary, and particularly their interplay, namely the top Yukawa coupling. Since this plot has been made under the assumption that there is no BSM up to the Planck scale (at least not with electroweak quantum numbers), this question also depends on the BSM paradigm.

In the field of particle physics, over the years, a paradigm has developed, which I would consider clearly wrong, namely that hadron machines are discovery machines, while lepton colliders are precision machines. First of all, looking particularly at the vast number of impressive measurements on top, W, Z, and Higgs physics from the LHC experiments ATLAS and CMS, it is clear, that also hadron colliders can serve as precision machines. On the other hand, most of the spectacular discoveries, especially the unexpected ones, have been made with lepton beams: starting from the revelation of quark substructure of hadrons in DIS experiements at SLAC in 1969 with electron beams, over the neutral current discovery by the Gargamelle experiment at CERN 1973 using neutrino beams which revealed the group structure of the electroweak SM, to the discovery of the second and third generation (charm and tau) at SLAC 1974/1976 in electron-positron collision which revealed the SM flavor structure. Besides these ground-breaking discoveries, there were more very important discoveries and achievements of e^+e^- colliders: the first jet physics in eletron-positron collisions 1978 at the PETRA ring at DESY which led to the discovery of the gluon, the discovery of $B^0 - \bar{B}^0$ oscillations at the ARGUS experiment at DESY 1987 which for the first time gave proof for a top quark mass beyond 100 GeV, and the electroweak precision data from SLC and LEP at SLAC and CERN 1989-1999 which established a (most likely) light Higgs boson well below 200 GeV.

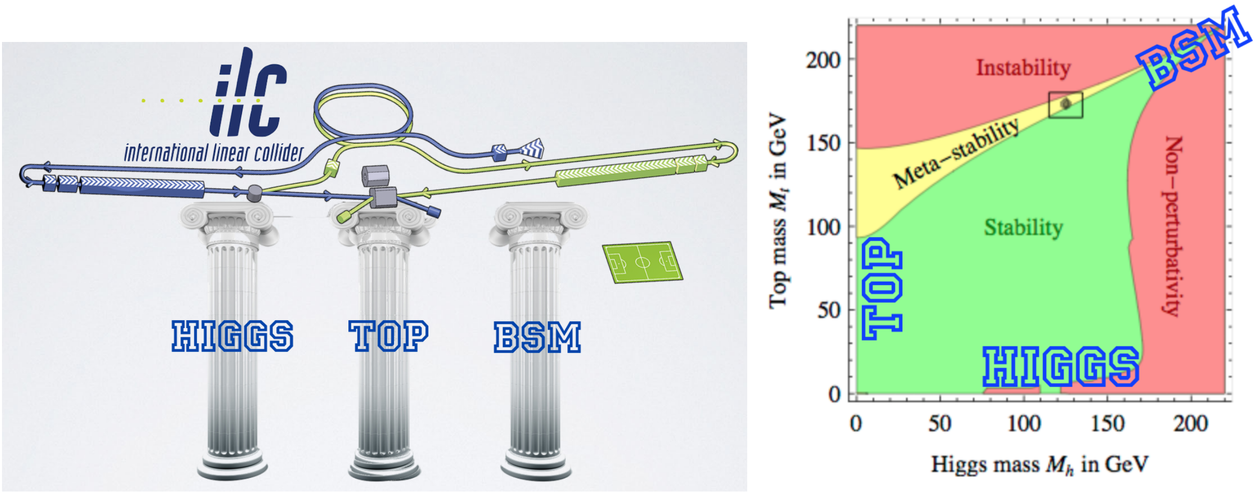

Figure 1: *Left: The physics programme of a high-energy e^+e^- machine like the ILC rests on three pillars: its Higgs physics and top physics programmes as well as its search potential for new physics (BSM). Right: stability diagram of the electroweak vacuum, depending on top, Higgs, and BSM physics, base plot from [11].*

In the history of particle physics, there always was a fruitful interplay between hadron and lepton machines which profited from each other tremendously. Examples are the (guaranteed) discovery of the weak gauge bosons W and Z at the CERN Sp$\overline{\text{p}}$S proton-antiproton collider operating 0.54 TeV which was prepared by many measurements at lepton machines, particularly by neutrino beams. Next, there was the (guaranteed) discovery of the top quark again in proton-antiproton collisions at the Fermilab Tevatron at 1.8/1.96 TeV, prepared by e^+e^- data from DORIS/SLC/LEP at 0.01 TeV and 0.091 TeV. They provided the mass range for the top quark which together with the theory predictions for the QCD cross sections gave the guarantee for a successful discovery. Then, there was the discovery of the Higgs boson at LHC operating at 7/8 TeV (now also 13 TeV) which was prepared by the measurements of SLC and LEP I/II operating at 0.09 TeV and 0.21 TeV. This was not as guaranteed as the two beforementioned discoveries, but assuming the non-existence of vastly different electroweak sectors (which would have led to spectacular, unexpected discoveries at LHC in the first run), it was at the same level of security than the other two.

Particle physics at the moment is at a stage where there is only a single running high-energy collider (for the first time in at least more than 40 years) world-wide, and that there is no guarantee for a future discovery at any technically feasible collider experiment in the near future. There are many preparations for a high-energy hadron collider beyond the LHC that could energies of 60, 80 or even 100 TeV. However, also such a collider should have a preparation by measurements at an e^+e^- collider of energies in the range of 0.35 TeV, 0.5 TeV, or 1 TeV. This would be the ILC with its physics programme. Another issue connected to this which has not been too much stressed up to now, are the benefits of precision QCD measurements at the ILC, which include the strong coupling constants, but more importantly fragmentation functions, especially for bottom and charm.

2 The quest for New Physics

The shortcomings of the SM have been described in great detail in many publications and reports, so I will not repeat them here: the missing dark matter particle(s), the arbitrariness of the flavor sector, the hierarchy and fine-tuning problem, missing CP violation. As stated already above, it is not clear whether any of these questions could be solved at the existing or any planned collider experiments. But clearly, there are good experiments that make it likely that there will be the opportunity to make important discoveries even if there is no solid guarantee as in the cases of the last section.

In the following, I will first list conditions or scenarios or cases for possible discoveries of new physics at the ILC, compare identical or at least similar cases from the past and try to give conditions for possible predictions for such cases:

- **New particle in kinematic reach**
  New particles beyond the SM are in the direct kinematic reach of the ILC. An example from the past of such a scenario is the charm discovery. It is difficult to predict, however, as one needs either a new symmetry principle, together with a coupling strength, or some indirect evidence from elsewhere like e.g. for dark matter. A future example at the ILC would be the discovery of an electroweakino in SUSY models.

- **New physics in (rare) decays of known particles**
  Existing particles will be scrutinized at the ILC, and new physics shows up in their rare decays. Examples from the past are anomalies in rare B decays, future examples of this kind would be anomalies in (rare) Higgs decays. Again, this is difficult to predict because it needs tremendous technical knowledge of known physics.

- **Deviations within existing interactions**
  An example for this would be the anomalies in the $e^+e^- \to$ hadrons at SLC 1973 below the charm threshold, an example in the future would be a modification of two-fermion processes due to a Z'. Again, this is difficult to predict as it needs either a theoretical hint, or an experimental hint from somewhere else.

- **Decipher structure of new but known interactions**
  An example for this is the gluon discovery as a massless carrier of a confining theory, a future example would be the discovery of Higgs self-interactions to decipher the electroweak symmetry breaking. This always has guidance from existing experimental data, but the correct theory framework needs to be known.

- **Discovery of new strong interactions**
  This clearly only works in the case of non-perturbative physics. Prime example from the past is the discovery of quark substructure, future examples would be discovery of (Higgs) compositeness. As this depends on non-perturbative physics, predictions are not easy or straightforward.

The first scenario might sound trivial, but highlights another very important for a lepton collider: namely the only guaranteed way to discover (or exclude) any kind of weakly interacting

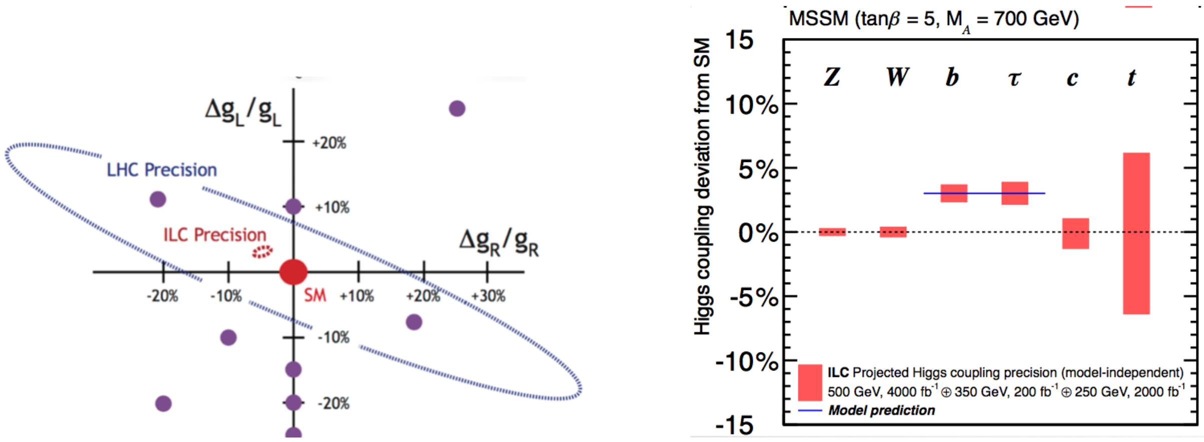

Figure 2: *Left plot: Collection of predictions from several BSM models on the left- and right-handed ttZ coupling, and the projections with which they will be measured at LHC and ILC. Right plot: deviations of Higgs couplings from their SM values in a typical BSM scenario (composite Higgs), overlaid with the projected ILC precision for their measurement.*

particles up to the scale of (half) the collider energy. This is not possible at a hadron collider, where electroweak production processes are suppressed sometimes even by orders of magnitude compared to strong production processes. Furthermore, all searches at hadron colliders are subject to model assumptions that come from trigger constraints, fiducial phase space volume constraints to suppress tremendous backgrounds, and also large(r) theoretical uncertainties from PDFs and missing higher-order calculations. The scan for new weakly interacting particles is the closest to a no-lose theorem for any upcoming collider given our present knowledge on particle physics, that I am aware of.

The two first main pillars of lepton collider physics, the top quark and the Higgs boson, both serve as indirect tools for new physics searches. Using an effective-field theory setup, anomalous top quark couplings and anomalous Higgs couplings parameterize new physics in both sectors most relevant for electroweak symmetry breaking in a way as model-independent as it can get. Constrained by electroweak precision data and direct measurements from Tevatron and LHC, deviations from their corresponding SM values are expected to be in the range of up to 10 or 20 per cent for top couplings and up to five per cent for Higgs couplings. Fig. 2 (from [12]) shows on the left-hand side a collection of typical BSM models and their deviations for the left- and right-handed top couplings to the Z boson. The ellipses mark the projections for the final LHC precision and the expected ILC precision on these parameters. Hence, though a deviation from the SM might have been already established at the LHC, only the resolution power of the ILC can reveal which is the underlying theory of Nature. In certain models, a sensitivity towards new physics scale of the order of 50-60 TeV is reached. The right plot in Fig. 2 denotes a typical BSM scenario, namely one of the so-called minimal compositeness models, and its influence on the Higgs couplings normalized to their SM value. Again, this shows that a resolution power is needed that allows for a determination of the Higgs coupling at the per cent level at least, as it is provided at the ILC.

Both the measurements of the coupling of the Higgs boson to top quarks and to itself are among the most crucial measurements as searches for new physics in the electroweak sector. The ILC will reach higher precision in their measurements than the LHC even in its high-luminosity phase.

In principle, at the same footing are the measurements of the properties of the electroweak gauge bosons, W and Z. Also there measurements at lepton colliders can trade precision frontier into energy frontier, but this usually demands for special setups like running at the Z or WW thresholds or high-energy runs at 1 TeV or beyond [13,14]. New physics in the pure electroweak gauge/Higgs sector is not much constrained from LHC data at the moment, and the reach at the LHC is limited as these measurements are complicated [15].

Turning to direct searches for BSM at the ILC, the main driving horse are searches for dark matter particles, in the form of mono-photon searches similar to the mono-jet searches at the LHC. Polarization of both electron and positron beams are inevitable tools to both enhance the signal and suppress severe backgrounds (W exchange for the $e^+e^- \to \nu\nu\gamma$ SM background). The signal will be visible in the structure of the high-energy part of the recoil spectrum of the photon, cf. e.g. [16]. A nice complementarity in coverage between LHC and ILC have been found, in the sense that LHC covers higher masses for dark matter particles, while ILC in general covers far smaller couplings or higher mediator masses [9]. In Ref. [17], studies showed how regions of supersymmetry parameter space that are inaccessible at the LHC (because they have e.g. almost degenerate LSP and NLSP states with a mass difference of the order 1 GeV or below). The ILC could nicely resolve such a degenerate spectrum and would allow in such a case the reconstruction of high-scale SUSY parameters with a precision of the order of five per cent. That the ILC can cover the whole SUSY spectrum possibilities have been proved in a scan over all most likely NLSP candidates ($\tilde{\mu}$ and $\tilde{\tau}$) in [18], where it is again obvious that the ILC can make use of its whole phase space and detect LSP/NLSP particles very close to the kinematic limit (as close as 2 to 10 GeV in the LSP-NLSP mass plane). This works even for NLSP particles like sneutrinos that are themselves invisible [19].

One prime example for new weakly interacting particles that are difficult or even impossible to detect at hadron machines like the LHC are light scalar or pseudoscalar pseudo-Nambu-Goldstone bosons of spontaneously broken global $U(1)$ symmetries. They decay predominantly to the heaviest possible SM fermions, while having only anomaly-induced couplings to diphotons or digluons (the 750 GeV anomaly at the LHC from December 2015 has fostered interest in these particles again). At the LHC these particles (which have similar properties than light Higgs singlet admixtures) are only detectable if they are heavier than approximately 200 GeV, as they cannot couple as strongly to diphotons and -gluons as the SM Higgs boson due to light constraints and precision data. At the ILC they can be searched for as resonances in the $ttbb$ invariant mass spectrum as they are radiated from top quarks, even if they are in the mass range of 10-200 GeV [20,21].

As a last topic let me mention the search for new neutral current, which was one of the reasonings for high-energy lepton colliders since the 1980s. Z' bosons from $U(1)$ or also non-Abelian extensions of the electroweak gauge sector can be detected in two-fermion processes at lepton colliders, cf. [22]. This allows a sensitivity to new physics scales reaching as far up as 100 TeV [23]. Using the interference between Z and Z', even some information on the structure of possible GUT groups at scales of $10^{12} - 10^{13}$ TeV can be gained (cf. e.g. [24]). Again, from the left- and right-handed couplings extracted from forward-backward asymmetries and charge asymmetries in two-fermion processes, different high-scale models can be discriminated (cf. e.g. [25]).

One final remark: if something similar like the 2 TeV anomaly in $WW/WZ/ZZ$ at the end of the 8 TeV run or the 750 GeV anomaly in diphotons will remain at the end of run II or the high-lumi run, then the ILC is the only option in the near future to comfirm or refute such a signal.

3 Summary

In this talk I tried to collect the facts in favor of a future high-energy lepton collider (that is capable to reach at least 500 GeV) with the focus lying on new physics beyond the SM. Both the two main SM pillars, the Higgs boson and top quark measurements serve as indirect tools for new physics searches, but there is also a plethora of direct search opportunities at such a machine. Most prominent examples are dark matter searches, searches for other light weakly coupling particles, and a scan over all weakly interacting particles. The interplay of the ILC with the LHC, but more importantly with future hadron machines is elucidated. Conditions, or better, scenarios for possible BSM discoveries at the ILC have been given. Several prime examples for the BSM potential of the ILC have been highlighted.

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