# The LHC early phase for the ILC

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With the startup of the Large Hadron Collider LHC in 2008, exciting new phenomena at the TeV energy scale may be discovered. I describe first ideas concerning the implication of the potential discoveries for the planning of the International Linear Collider ILC. These ideas are based on the results of an initial workshop held at Fermilab in April 2007 [2].

## 1 LHC-ILC Interplay

High energy physics is entering a new era when, in 2008, the Large Hadron Collider LHC will provide access to particle collisions with 1 TeV partonic centre-of-mass energy an beyond. At this energy and with sufficient integrated luminosity, the important question how the electro-weak symmetry is broken can most likely be answered. Beyond that, the LHC experiments are sensitive to a broad spectrum of signatures that may indicate phenomena whose explanation lies beyond the Standard Model (SM). Such beyond-SM (BSM) models are generally motivated by fundamental theoretical questions: the apparent hierarchy of mass scales, the quest for a unification of forces and the absence of explanations for the observed dark matter and dark energy in our universe.

The predictions of BSM models which address the above questions often encompass new fundamental particles with masses in the TeV regime. The particles lead to signatures which involve jets and leptons with high transverse momenta $p_t$, in some cases accompanied by large missing transverse energy from high-$p_t$ particles invisible to the detectors. The multi-purpose detectors ATLAS and CMS at the LHC are designed such, that they can discover any excess of high-$p_t$ objects if they are produced with sufficient rate. In particular, signatures of the best-motivated BSM models, e.g. Supersymmetry, models with extra spatial dimensions, new heavy vector bosons, and excited fermions can be detected over large parts of the respective parameter spaces. We thus have any reason to be excited about the possible discoveries that ATLAS and CMS will make in the coming years.

In parallel to the preparations for the LHC and its detectors, a significant amount of work has gone into the preparation of tools which complement the LHC in the future. Most importantly, a new electron positron linear collider in the TeV energy regime has been shown in extensive studies to be the ideal tool to sharpen our view of the phenomena to be discovered at the LHC. Practically is has been shown that – independent of the findings of the LHC experiments – a Linear Collider with 500 GeV initial energy (and upgradeable to 1 TeV) will provide an important addition to the LHC's capabilities. This is mainly due to the fact that the SM without a Higgs boson violates unitarity at slightly above 1 TeV. Such a machine, the International Linear Collider ILC, based on superconducting acceleration technology is well advanced and according to a technically driven schedule can be realized by 2018 [3].

Over the past few years, the interplay of the LHC and the ILC has been studied in great detail [4]. The main focus of these studies was the question how the data from both machines together would yield a more complete picture of the realized new physics scenario compared to that obtained from one machine alone. Also, it was studied how simultaneous analysis of the data may provide feedback and refine the single-machine analyses. Although no clear consensus was reached to which extent simultaneous running of LHC and ILC would be required, it remains evident that a timely construction of the ILC will significantly facilitate the successful interplay of LHC and ILC and thus the best possible exploration of TeV scale physics.

While the physics case for the ILC is to a large extent built on arguments which are independent of the results of the LHC experiments it is obvious that these results which will be available in the near future have to be taken into account, when a solid planning for the ILC's realisation, its initial configuration, and upgrade options is to be made. In this presentation I like to report on a workshop held at Fermilab in April 2007 which laid the ground for a more systematic study of the implications of early LHC physics results for the ILC.

Within the workshop, working groups are being formed around possible signatures seen in the early data of the LHC experiments. The term 'early' is not defined by running time of the LHC rather than by an integrated luminosity of $\mathcal{O}(10)$ fb$^{-1}$ . The chosen signatures are

1. A SM-Higgs-like state at the LHC;
2. No Higgs boson state at the early stage of the LHC;
3. Leptonic resonances and multi-gauge-boson signals;
4. Missing energy signals (and everything else).

In the following, I will briefly sketch these four scenarios, the LHC prospects for early discoveries and possible implications for the ILC.

## 2 A SM-Higgs-like state at the early LHC

Both ATLAS and CMS have demonstrated that with approximately 10 fb$^{-1}$ of understood data a significant signal from a SM-like Higgs boson can be extracted from the expected SM background. While for Higgs boson masses above 200 GeV, a discovery is relatively straight-forward due to the $H \to ZZ \to 4\ell$ decay mode, an early discovery for lower masses possibly needs the combination of several Higgs final states. For low masses below 140 GeV these are the inclusive $H \to \gamma\gamma$ mode, and the weak boson fusion mode $qqH \to qq\tau^+\tau^-$ [5].

While only a limited amount of information about the newly discovered particle will be available at this early stage, it will be probably enough to arrive at a solid decision for the ILC. Its mass will be known better than $\mathcal{O}(1\text{ GeV})$ and its observation in weak boson fusion or in its decay to ZZ will prove that the particle carries a gauge coupling and can thus be produced in the $e^+e^- \to HZ$ Higgs-strahlung process. With 30 fb$^{-1}$ a rough estimate of the partial width ratios $Z/W$, $\gamma/W$, and $\tau/W$ will be possible [6].

What are the consequences of such a discovery for the ILC? The answer to this question depends to some extent on the observed mass of the new particle. If the Higgs boson mass is below approximately 160 GeV, the full program of precision measurements of the Higgs boson properties can be performed at the ILC. In particular, this program comprises precise measurements of the Higgs boson gauge and Yukawa (b,c,t,$\tau$) couplings, its total decay width, and in particular its self-coupling in a completely model-independent way [7].

For a mass above 160 GeV, the phenomenology of a SM-like Higgs boson is less rich since the Yukawa decay modes are highly suppressed (except for $H \to t\bar{t}$ if $m_H > 340$ GeV). In this mass range, which with increasing Higgs mass is increasingly disfavoured by electro-weak precision measurements, the dominant decay modes can be observed at the LHC and furthermore, a model-independent measurement of the total width from the Higgs boson line-shape will be possible for masses beyond approximately 200 GeV.

It is one of the important goals of this working group to assess and compare the potential of the LHC and the ILC for measurements of Higgs boson properties in this mass range more quantitatively than previously done.

## 3 No Higgs (yet) at the LHC

If no Higgs-boson-like signal will be observed with approximately 10 fb$^{-1}$ of well calibrated and understood data at the LHC experiments, there are two different roads of interpretation.

1. There is no Higgs mechanism at work, and thus there is really no Higgs boson.
2. The Higgs mechanism is at work, however its realisation is such that the corresponding Higgs boson(s) are not or not yet accessible with the LHC.

Since the implications of these two interpretations for the ILC are probably different, it is of major importance to study whether the LHC experiments can distinguish between these.

1. Models without Higgs mechanism require a mechanism to unitarize the amplitude for the elastic scattering of longitudinal gauge bosons. In general, the new phenomena associated with this mechanism modify the predictions for electro-weak precision observables. For Technicolor theories [8], this has been a long-standing problem. The more recently constructed Higgsless models [9] which require the existence of towers of new gauge bosons and heavy fermions (as predicted in theories with extra spatial-dimensions) are able to delay the unitarity problem to energy scales beyond those accessible with the LHC while at the same time avoiding too large electro-weak corrections.

In Higgsless models in general new particles should be observable at the LHC since they cannot be too heavy because they have to restore unitarity. The observation of a new $Z'$-like resonance at the LHC clearly calls for its exploration with the ILC as discussed in the next section.

2. The universal signature for the absence of a Higgs mechanism is a deviation of elastic gauge boson scattering. If the LHC could exclude strong vector boson scattering in absence of any Higgs-like signature, this could provide an indirect indication that a Higgs-like signature has been missed at the LHC. This clearly excludes the SM Higgs boson but also standard MSSM Higgs bosons. However, extended Higgs sectors may require higher luminosity at the LHC until at least one state can be observed, as it is the case e.g. in the NMSSM [10]. Also within little Higgs models [11], the discovery of the Higgs sector might be delayed at the LHC [12].

However, it might also be that the presence of the Higgs mechanism may only be revealed by the ILC. Viable models which implement this scenario are e.g. continua of Higgs bosons [13] and Higgs bosons with a very large width decaying into invisible particles [14]. Thus, contrary to some common wisdom, the absence of a Higgs-like state at the LHC may require an ILC to reveal the underlying physics.

## 4 Leptonic Resonances and Multi-Gauge-Boson Signals

New resonances which can be produced via the Drell-Yan process and which decay into $e^+e^-$ and/or $\mu^+\mu^-$ can be seen rather fast by the LHC experiments. The required integrated luminosity to discover e.g. a sequential $Z'$ boson with 1 TeV mass is below 100 pb$^{-1}$ even with imperfect detector calibration [15]. The mass reach for discovery with 10 fb$^{-1}$ is between 3 and 4 TeV, depending on the model.

The implications of such a discovery for the ILC depend on its mass. Given Tevatron exclusion bounds, a resonance within the reach of ILC phase 1 (500 GeV) is not very likely. Should a resonance below 1 TeV be observed, this would clearly call for a fast upgrade path of the ILC to study the new object in s-channel production. However in presence of a light SM-like Higgs boson, also ILC phase 1 remains well-motivated.

If the resonance should occur above the direct reach of the upgraded ILC a precise determination of its couplings structure can still be achieved at the ILC from interference effects with Z/$\gamma$ in SM processes, provided its mass is known from the LHC [16]. Also, for $W'$-like objects, the ILC has sensitivity from the $e^+e^- \to \nu\bar{\nu}\gamma$ process [17].

## 5 Missing energy signals

Signals with an excess of missing transverse energy (MET) at the LHC have extensively been studied. The major motivation to do so are the predictions of low-energy Supersymmetry with R-parity conservation as implemented in the MSSM. However, also other theories which require or postulate the existence of a weakly interacting massive particle like Universal Extra Dimensions or some variants of Little Higgs models predict MET signals.

Understanding MET signals at the LHC experiments is particular difficult, since the proper measurement of MET is very sensitive to detector calibration and modeling. Furthermore, SM contributions to MET have to be simulated to high precision even in tails of distributions and have to be calibrated with real data. It is thus not very likely that a mere excess of events with large MET in the early LHC data can be claimed as a discovery of BSM physics immediately. On the other hand, often, in particular in parts of the MSSM parameter space, the expected excess of large-MET events is huge and furthermore accompanied by additional signatures like multi-jets and/or multi-leptons, which are much easier to control. It is very hard to predict when a clear and significant excess can be claimed.

In view of its implications for the ILC, it is important to infer from LHC data analysis if any signal in $e^+e^-$ collisions is expected and at which centre-of-mass energy. For an MET-excess this questions is not easy to be answered without making too many model assumptions. The main reason for this is that with escaping WIMP-like particles, invariant masses of the decaying BSM particles cannot be reconstructed uniquely. The situation significantly improves if certain assumptions (like they are justified e.g. in mSugra models) about mass hierarchies etc. can be made.

Many different approaches towards mass reconstruction of SUSY-cascades have been worked out [18]. Furthermore global fits of the parameters of SUSY models [19, 20] and generic Monte Carlo tools [21] have been developed to approach this task. However in the course of the workshop new approaches and improvements are necessary.

## 6 Summary and conclusions

I gave a brief sketch of a new aspect of the relation of the LHC and ILC, namely the implications of early LHC data on ILC planning. While the physics motivation for the ILC is independent of the LHC findings, the early LHC data will have an impact on the decision when to build the ILC and on the choice of the parameters. In many possible scenarios, including the discovery of a Higgs boson, a timely construction of the ILC is clearly motivated. Some scenarios including e.g. the observation of an intermediate mass Higgs boson need further studies. A workshop which started in 2007 will study these questions in detail.

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