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Interplay between the LHC and a linear collider in searches for new physics

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Abstract. The LHC / LC Study Group investigates how analyses at the LHC could profit from results obtained at a future Linear Collider and vice versa, leading to mutual benefits for the physics program at both machines. Some examples of results obtained within this working group so far concerning searches for new physics are briefly summarised.

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1 Introduction

Physics at the LHC and a future Linear Collider (LC) will be complementary in many respects, similarly to the situation at previous generations of hadron and lepton colliders. The LHC has a large mass reach for direct discoveries, which extends up to typically ∼6–7 TeV for singly-produced particles. The hadronic environment at the LHC, on the other hand, will be experimentally challenging. Owing to the composite nature of the colliding protons, LHC physics suffers from the presence of an underlying event being related to the interaction of the spectator partons. Kinematic reconstructions are normally restricted to the transverse direction. Since the initial-state particles carry colour charge, QCD cross sections at the LHC are huge, giving rise to backgrounds which are many orders of magnitude larger than the typical signal processes being mostly of electroweak nature.

The envisaged LC in the energy range of ∼0.5–1 TeV provides a much cleaner experimental environment being well suited for high-precision physics. It has a well-defined initial state which can be prepared to enhance or suppress certain processes with the help of beam polarisation. The better knowledge of the momenta of the interacting particles gives rise to kinematic constraints which allow to reconstruct the final state in detail. The signal–to–background ratios at the LC are in general much better than at the LHC. The discovery potential at the LC, on the other hand, is limited by its kinematic reach.

While qualitatively the complementarity between LHC and LC is obvious, more quantitative analyses of the possible interplay between LHC and LC were lacking until recently. In order to investigate this issue, the so-called LHC / LC Study Group [1] has formed as a collaborative effort of the hadron collider and linear collider communities. This world-wide working group investigates in particular how analyses carried out at the LHC could profit from results obtained at a LC and vice versa, leading to mutual benefits for the physics program at both machines.

While the LHC is scheduled to take first data in 2007, the LC could go into operation at about the middle of the next decade. This would guarantee a substantial period of overlapping running of both machines, since it seems reasonable to expect that the LHC (including upgrades) will run for about 20 years. During simultaneous running of both machines there is obviously the highest flexibility for adapting analyses carried out at one machine according to the results obtained at the other machine. The LC results could in this context also give essential input for choosing suitable upgrade options for the LHC.

The results obtained so far in the framework of the LHC / LC Study Group, based on the work of more than 100 contributing authors, will be documented in a working group report [2] which is currently being compiled. Topics under study comprise the physics of weak and strong electroweak symmetry breaking, electroweak and QCD precision physics, the phenomenology of Supersymmetric models, new gauge theories and models with extra dimensions. In this talk some examples of the work carried out in the LHC / LC Study Group concerning searches for physics beyond the Standard Model (SM) are briefly summarised.

2 Some examples of LHC / LC interplay in new physics searches

2.1 Determination of SUSY parameters at LHC / LC

The search for Supersymmetric particles is an example making the need for an interplay between LHC and LC particularly apparent. The production of Supersymmetric particles at the LHC will be dominated by the production

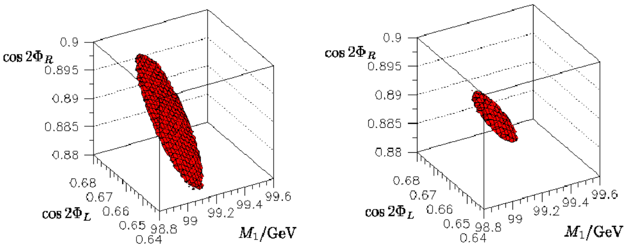

Fig. 1. The $\Delta\chi^2 = 1$ contour in the $M_1, \cos 2\phi_L, \cos 2\phi_R$ parameter space derived from LC data alone (*left*) and from the joint analysis of the LC and LHC data (*right*), from [5]

of coloured particles, i.e. gluinos and squarks. Searches for the signature of jets and missing energy at the LHC will cover gluino and squark masses of up to 2–3 TeV [3]. The main handle to detect uncoloured particles will be from cascade decays of heavy gluinos and squarks, since in most scenarios of Supersymmetry (SUSY) the uncoloured particles are generically lighter than the coloured ones, e.g. $\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}_2^0 \to \bar{q}q\tilde{\tau}\tau \to \bar{q}q\tau\tau\tilde{\chi}_1^0$, where $\tilde{\chi}_1^0$ is assumed to be the lightest Supersymmetric particle (LSP). Thus, the production of Supersymmetric particles at the LHC will normally lead to complicated final states, and in fact the main background for SUSY searches at the LHC will be SUSY itself.

The LC, on the other hand, has good prospects for the production of uncoloured particles. The clean signatures and small backgrounds at the LC as well as the possibility to adjust the energy of the collider to the thresholds at which SUSY particles are produced will allow a precise determination of the mass and spin of Supersymmetric particles and of mixing angles and complex phases [4].

In order to establish SUSY experimentally, it will be indispensable to verify its main predictions, in particular that every particle has a superpartner, that their spins differ by 1/2, that their gauge quantum numbers are the same, that their couplings are identical, that certain mass relations hold, etc. This will require precise measurements of masses, branching ratios, cross sections, angular distributions, etc. A precise knowledge of as many SUSY parameters as possible will be necessary to disentangle the underlying pattern of SUSY breaking. In order to carry out this physics program, experimental information from both the LHC and the LC will be crucial.

Detailed studies of the possible interplay between LHC and LC in SUSY searches have been performed within the LHC / LC Study Group. It has been demonstrated, in particular, that experimental information on properties of uncoloured SUSY particles from the LC can significantly improve the analysis of cascade decays at the LHC [2]. In particular, the precise measurement of the LSP mass at the LC eliminates a large source of uncertainty in the LHC analyses, improving thus the accuracy of the reconstructed masses of the particles in the decay chain [2].

In [5] an analysis was carried out based on the SPS1a benchmark scenario [6] where the measurement of the masses of the two lightest neutralinos, the lighter chargino, the selectrons and the sneutrino at the LC was used to predict the properties of the heavier neutralinos. It was demonstrated that this input makes it possible to identify the heaviest neutralino at the LHC and to measure its mass with high precision. Feeding this information back into the LC analysis improves the determination of the fundamental SUSY parameters from the neutralino and chargino sector at the LC. In Fig. 1 the accuracy in the determination of the parameter M_1 (neutralino sector) and the mixing angles $\cos 2\phi_L$, $\cos 2\phi_R$ (chargino sector) from LC data alone is compared with the LHC / LC combined analyses, showing a significant improvement. This results in a precise determination of the related parameters M_1, M_2, μ and $\tan\beta$ and allows powerful consistency tests of SUSY [5].

LC input on uncoloured SUSY particle properties together with reconstructed sbottom masses from cascade decays can furthermore be used to extend the LHC capabilities in the analysis of the stop and sbottom sector [7], leading to a reconstruction of the stop masses and the stop and sbottom mixing angles [2].

2.2 SUSY Higgs physics

The interplay between LHC and LC will also be crucial for exploring the physics of electroweak symmetry breaking, both in its realisation via the Higgs mechanism and via strong electroweak symmetry breaking. Many detailed investigations can be found in [2].

The LHC will discover a SM-like Higgs over the whole mass range $m_{\rm h} \lesssim 1$ TeV [3]. If the $H \to \gamma\gamma$ decay mode will be accessible, the LHC will be able to perform a first precision measurement in the Higgs sector by determining the Higgs-boson mass with an accuracy of about $\Delta m_{\rm h}^{\rm exp} \approx 200$ MeV [3]. In contrast to the SM, where $m_{\rm h}$ is a free parameter, in SUSY models the mass of the lightest $\mathcal{CP}$-even Higgs-boson mass can be directly predicted from the other parameters of the model. As a consequence of large radiative corrections from the top and scalar top sector of the theory, the prediction for $m_{\rm h}$ sensitively depends on the input value of the top-quark mass. The experimental error on $m_{\rm t}$, which at the LHC will be ~1–2 GeV [3], translates roughly linearly into an uncertainty of $m_{\rm h}$, $\Delta m_{\rm h}^{\delta m_{\rm t}} \approx \delta m_{\rm t}^{\rm exp}$ [8]. In order to match the experimental precision at the LHC, $\Delta m_{\rm h}^{\rm exp} \approx$ 200 MeV, with the accuracy of the theoretical prediction, the precise measurement of the top-quark mass at the LC, $\delta m_{\rm t}^{\rm exp} \lesssim 100$ MeV [4], will be mandatory. A precise measurement of $m_{\rm h}$ and other Higgs sector observables when compared with the MSSM prediction will allow to obtain sensitive constraints on the MSSM parameters. In order to obtain indirect bounds on SUSY parameters in this way, combined LHC / LC information on the other SUSY parameters and a small residual uncertainty from unknown higher-order corrections are crucial [9].

2.3 Higgs and radion searches at LHC and LC

Models with 3-branes in extra dimensions typically imply the existence of a radion, ϕ, which can mix with the

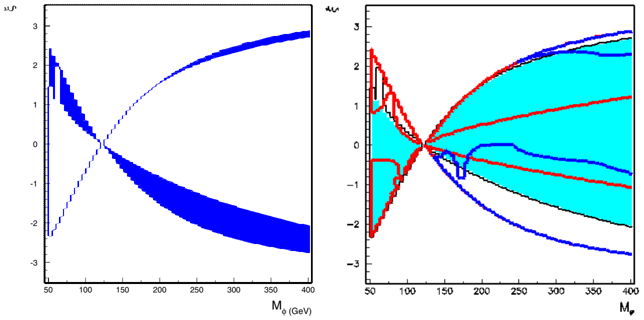

Fig. 2. Parameter regions where the Higgs significance is below 5σ at the LHC for one experiment and 30 fb^{-1} (*left*), regions (indicated by the grey (*red*) lines, which extend also along the edges of the hourglass region) where the precise measurements of the $hb\bar{b}$ and hWW couplings at the LC provide $> 2.5\sigma$ evidence for the radion mixing effect (*right*), from [10]

Higgs boson, thereby modifying the Higgs properties and the prospects for its detectability at the LHC. As a consequence, it might not be possible to observe a Higgs boson at the LHC over a significant region of the parameter space given by the Higgs-boson mass, M_{h}, the radion mass, M_ϕ, the scale Λ_ϕ, and the Higgs–radion mixing parameter, ξ [10]. For most of this parameter region the radion will be observable in the process $gg \to \phi \to ZZ^* \to 4\ell$ [10], leading thus to a situation where one scalar will be detected at the LHC. Disentangling the nature of this scalar state will be a very important but experimentally challenging task.

The LC should guarantee observation of the Higgs boson over the whole parameter region and in addition observation of the radion even in most of the regions within which detection of either at the LHC will be difficult. Furthermore, precision measurements of the Higgs couplings to various types of particle pairs will allow to experimentally establish the Higgs–radion mixing effects. It is demonstrated in Fig. 2 that the parameter regions for which the Higgs significance is below 5σ at the LHC (for $M_{\text{h}} = 120$ GeV, $\Lambda_\phi = 5$ TeV) overlap with the regions where precision measurements of Higgs couplings at the LC establish the Higgs–radion mixing effect [10]. The LHC, on the other hand, will observe the distinctive signature of Kaluza–Klein graviton excitation production over a substantial range of Λ_ϕ in these scenarios.

2.4 New gauge theories and extra dimensions

Many kinds of extensions of the SM lead to an enlarged gauge-boson sector. Determining the nature of the new gauge bosons will require a variety of detailed experimental results which can be provided by the interplay of LHC and LC. The LHC has a large mass reach for direct detection of new gauge bosons, while the LC has a large indirect reach arising from virtual effects of the new states which result in deviations from the SM predictions.

The LC, running at high energy, is sensitive to Z–Z′ interference effects through the fermion pair-production process, $e^+e^- \to f\bar{f}$, yielding in particular the ratio of the $\text{Z}'f\bar{f}$ couplings and the Z′ mass. If $M_{\text{Z}'}$ is known from the LHC, the combined LHC / LC analysis yields a determination of the Z′ couplings with high precision [11]. Furthermore, the measurements of the electroweak precision observables in the GigaZ mode of the LC, i.e. $\sin^2\theta_{\text{eff}}$, the total Z width, the Z partial widths and the W-boson mass, yield important information for distinguishing different models of new physics [12]. This input can be helpful for optimising the search strategies at the LHC.

Careful analyses are required in particular to distinguish a Z′ from the lightest Kaluza–Klein excitations of the SM electroweak gauge bosons [13] and to determine the structure of Little Higgs models from the properties of the new particle states [14]. Also in these cases it has been demonstrated that combined information from LHC and LC can be crucial.

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