Potential LHC Contributions to Europe's Future Strategy at the High-Energy Frontier

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1 - Introduction

Europe's future high-energy frontier strategy is being formulated in the following context.

1) The statement agreed at the July 2004 CERN Council meeting [1]:

Confirms that the first priority for the world particle physics community is to complete the LHC and its detectors in order to unveil, as soon as possible, the physics at the new energy frontier;

Encourages the effort towards the design and development of a linear collider as a unique scientific opportunity at the precision frontier, complementary to the LHC;

Confirms its endorsement of accelerated R&D activities for CLIC;

Recognises the overall value for the world particle physics community of a decision to construct a TeV linear collider, and encourages the efforts of the leading players in that direction;

Takes the view that, in the course of this process, it will be appropriate to take stock of the LHC and accelerator R&D results and produce a new assessment of the physics and the technology by 2010.

2) The ILC GDE Director stresses the need in 2010 to take into account inputs from initial LHC running and from CLIC R&D [2].

This submission to the Zeuthen meeting summarizes some potential LHC contributions to this new assessment of physics, in particular from initial running of the LHC with 10 fb^{-1} of well-understood data, in light of our present physics understanding and information that may become available in the coming years.

2 – Present physics understanding

The Higgs boson is generally expected to weigh less than about 200 GeV [3]. This expectation could be relaxed if there are problems in the interpretation of the precision electroweak data [4] or if there are additional contributions to the electroweak observables [5], and some theorists have recently even been considering models without Higgs bosons [6]. None of these possibilities is mainstream, but they serve as warnings that the existence of a light Higgs boson cannot be taken for granted. Only its discovery will be able to erase this doubt.

There have also been many recent general explorations of the parameter spaces of supersymmetric models and studies of specific benchmark points [7]. Requiring the naturalness of the electroweak mass scale suugest that sparticles should weigh less than about a TeV. Further, postulating that the lightest supersymmetric particle constitutes the dark matter in the Universe imposes upper limits on the masses of the squarks and gluinos. These and other arguments suggest that they are likely to be accessible to the LHC. Depending on their centre-of-mass energies, linear colliders could detect and measure very accurately lighter sparticles such as those with only electroweak interactions.

There is currently no hard information on the energy of the sparticle threshold, though some indications for relatively low masses may be provided by the anomalous magnetic moment of the muon and fine-tuning arguments. As discussed later, initial runs of the LHC are likely to be able to determine whether the threshold for producing sparticles in electron-positron annihilation is below about 1 TeV in the centre of mass.

A multi-TeV linear collider would produce many different sparticle species in all the parameter space studied, would produce higher-level Kaluza-Klein excitations in models with compactified extra dimensions, and would provide additional sensitivity to scenarios with strongly-interacting W bosons [8].

3 – Before the LHC

Our present ignorance may be reduced in the years before initial results from the LHC come available. At the high-energy frontier, the Tevatron will certainly provide better measurements of the properties of the top quark, W and Z bosons. It also has a window of opportunity to detect or exclude a light Higgs boson and supersymmetry over parts of their accessible mass ranges [9]. At low energies, a more accurate measurement of the anomalous magnetic moment of the muon, combined with more accurate measurements of tau decays and low-energy electron-positron annihilation into hadrons, could clarify the need for some new physics at relatively low energies, such as supersymmetry. Likewise, searches for rare processes that are forbidden or suppressed in the Standard Model, such as $\mu \to e \gamma$ decay or rare B and K decays, might provide evidence for new physics at the TeV scale.

Results from these and other possible developments may be incorporated into the new physics assessment envisaged by the CERN Council for 2010.

4 – Initial LHC running

The LHC potential for discoveries in its early years depends crucially on the rate at which the integrated luminosity can be accumulated and the ease with which the CMS and ATLAS detectors will be understood. There have been several recent studies of the LHC discovery potential as a function of the integrated luminosity [10], of which some examples are now given.

A Standard Model Higgs boson could be discovered at the LHC with 5-σ significance with just 5 fb^{-1} of integrated luminosity, whatever its mass, as seen in Fig. 1, and 1 fb^{-1} would be sufficient to exclude a Standard Model Higgs boson at the 95% confidence level [11,12]. However, the signal for a light Higgs boson weighing around 120 GeV would be built up from pieces of evidence in several different channels, including $\gamma\gamma$, $\tau^+\tau^-$, bottom-antibottom, WW and ZZ. Thus, building up this signal will require a good understanding of many aspects of the detectors and backgrounds.

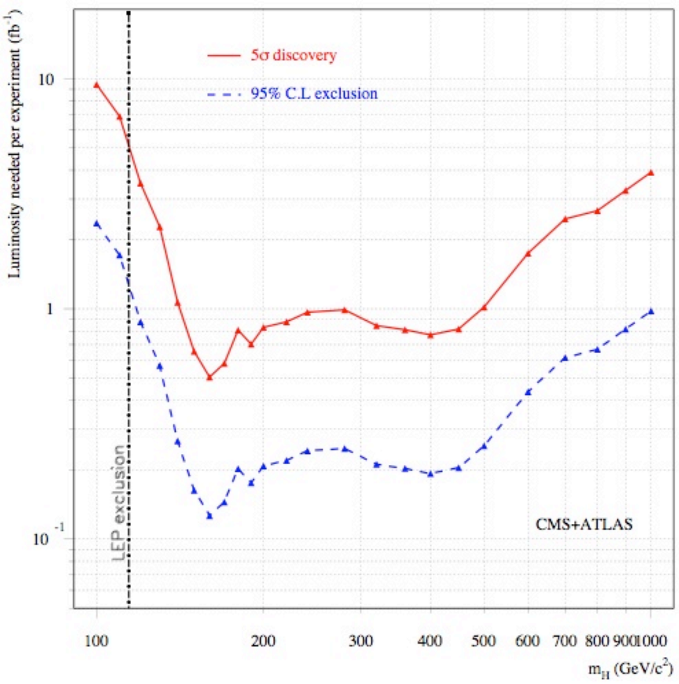

Fig. 1: The prospects for discovering a Standard Model Higgs boson in initial LHC running, as a function of its mass, combining the capabilities of ATLAS [11] and CMS [12].

There may be better chances for the discovery of new physics in some scenarios for physics beyond the Standard Model. For example, just 0.1 fb^{-1} of well-understood data should suffice to discover gluinos weighing less than about 1 .3TeV, a sensitivity to 1.7 TeV would be reached with 1 fb^{-1}, and about 2.2 TeV with 10 fb^{-1}, as shown in Fig. 2 [10,11,12]. This information would immediately provide valuable input on the likely energy of the supersymmetric threshold at a linear collider, at least in simple supersymmetric models.

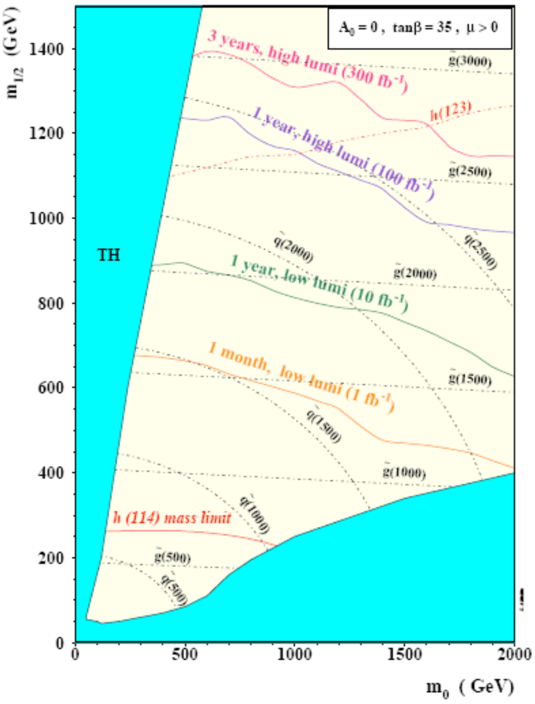

Fig. 2: The CMS reach for supersymmetric particles at the LHC [10,12]: a similar reach is expected for ATLAS [11]. The reach is essentially independent of the assumed values of tan β, A_0 and the sign of μ.

If all the gaugino mass parameters are universal at some high unification scale, the lightest neutralino mass is simply related to the gluino mass. The corresponding threshold for pair production of the two lightest neutralinos in electron-positron collisions is shown in Fig 3. In models where the lightest supersymmetric particle is a neutralino, such as neutralino dark matter models, sleptons must be heavier than the neutralino, though the mass difference is frequently small, particularly in models with universal scalar masses.

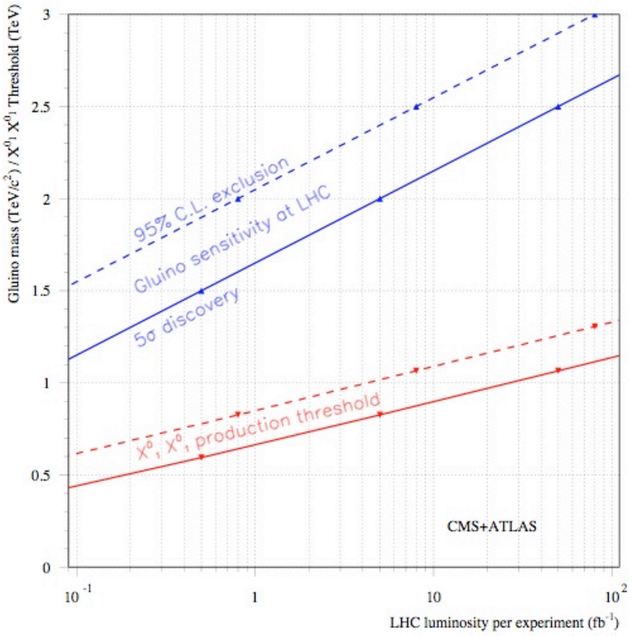

Fig. 3: The reach for gluino detection at the LHC and the corresponding threshold for the production of pairs of the lightest neutralinos at linear colliders, as functions of the LHC luminosity per experiment.

With 0.1 fb^{-1} of well-understood data each, if they do not discover with 5-σ significance a gluino weighing up to 1.1 TeV, the LHC experiments would have the sensitivity to exclude at the 95% confidence level a gluino weighing less than 1.5 TeV. Fig. 3 shows that the latter corresponds to a threshold of 0.6 TeV for the pair production of the lightest neutralinos. The discovery/exclusion reaches for 1 fb^{-1} and 10 fb^{-1} of data would be 1.7/2.0 TeV and 2.2/2.5 TeV, respectively. In the latter case, the LHC would be able to determine/exclude whether there is a supersymmetric threshold below 0.9/1.1 TeV. Thus, the LHC will be able to reveal relatively quickly whether a linear collider with centre-of-mass energy up to about 1 TeV would be able to observe any supersymmetric particles, at least in simple scenarios in which the lightest supersymmetric particle is a neutralino and gaugino masses are universal. Also, some scenarios with sparticles too heavy to be detected at a low-energy collider would be detectable already with initial LHC running.

The rate at which the LHC will accumulate luminosity is difficult to predict, but it seems a reasonable expectation that 10 fb^{-1} will have been accumulated and analyzed successfully by 2010.

5 – Subsequent LHC running

Following an initial Higgs boson discovery, ATLAS and CMS will provide important further information on its properties. For example, if a resonance is seen decaying into γγ or ZZ, which are among the favoured decay modes for a Higgs boson in the Standard Model, it cannot have spin 1. The Z*Z decay mode also provides discrimination between scalar and pseudoscalar decay modes [13].

Fig. 4 compiles the information that could be obtained from the LHC on the couplings of the Higgs boson to different fermion flavours and to the W and Z [14]. The LHC will be able to establish that the couplings track particle masses, but linear colliders can measure them with much greater precision, providing some discrimination between a Standard Model Higgs boson and alternatives such as the lightest Higgs boson in a supersymmetric model. The accuracies on the Higgs boson couplings shown in Fig. 4 are estimated assuming that the Higgs boson has no other important decay modes.

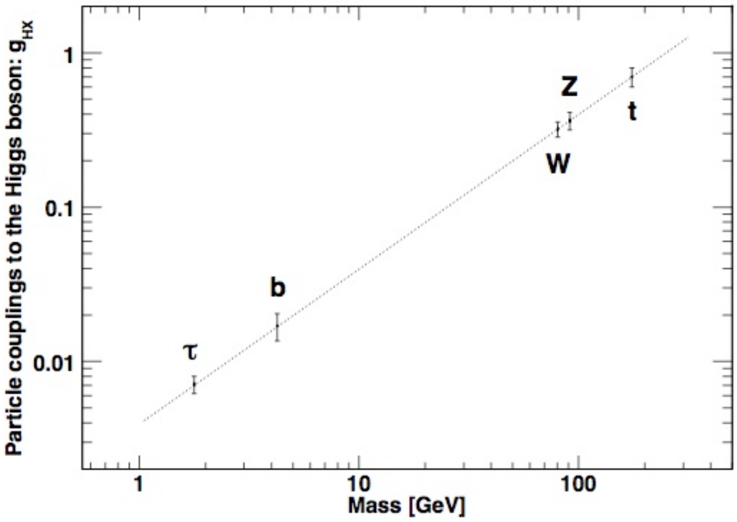

Fig. 4: Expected accuracies in measurements of the Higgs boson couplings attainable at the LHC for a Higgs boson weighing 120 GeV with an integrated luminosity of 300 fb^{-1} per experiment [14].

Recent preliminary studies have shown that the LHC experiments will be sensitive to invisible Higgs boson decays via several production channels, namely in association with the Z or a top-antitop pair, and in vector-boson fusion. With an integrated luminosity of less than 30 fb^{-1}, each experiment should be able to establish a 5-σ signal for a Higgs boson with a 100% branching ratio for invisible decays, or with 10 fb^{-1} of integrated luminosity to establish a 95% confidence-level upper limit on the invisible branching ratio as low as 15 to 30%, for any Higgs boson mass between 115 and 400 GeV [15]. This sensitivity would be sufficient to exclude the possibility that invisible decays could invalidate the analysis shown in Fig. 4.

6 – Final comments

The initial running of the LHC will provide significant physics input for the physics assessment foreseen by Council for 2010. In the case of the Higgs boson, 5 fb^{-1} (1 fb^{-1}) of well-understood data would enable it to be discovered (excluded). As an example of possible other new physics, 5 fb^{-1} would suffice to determine whether supersymmetry exists at an energy low enough to be accessible to a TeV linear collider. Subsequent LHC running will enable many more properties of a Higgs boson and supersymmetry to be measured.

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