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Potential for Higgs Physics at the LHC and Super-LHC

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The expected sensitivity of the LHC experiments to the discovery of the Higgs boson and the measurement of its properties is presented in the context of both the standard model and the its minimal supersymmetric extension. Prospects for a luminosity-upgraded "Super-LHC" are also presented.

1. Introduction

The Large Hadron Collider (LHC) at CERN and the two multipurpose detectors, ATLAS and CMS, have been built in order to discover the Higgs boson, if it exists, and explore the theoretical landscape beyond the standard model [1, 2]. The LHC will collide protons with unprecedented center-of-mass energy ($\sqrt{s} = 14$ TeV) and luminosity (10^{34} cm^{-2}s^{-1}); the ATLAS and CMS detectors will record these interactions with $\sim 10^8$ individual electronic readouts per event. The first collisions are expected in 2007, with a possible luminosity upgrade around 2015.

Observation of the Higgs boson is key to confirming the description of electroweak symmetry breaking in the standard model. The standard model Higgs sector has only one free parameter: the mass of the Higgs boson, m_H. Masses below 114.4 GeV/c^2 have been directly excluded by LEP Higgs searches at the 95% confidence-level [3]. Indirect evidence of the Higgs mass, through electroweak precision measurements, indicate a light Higgs ($m_H \lesssim 185$ GeV/c^2), though the theory remains valid until about 1 TeV/c^2 [4].

For a variety of reasons, it is reasonable to expect that supersymmetry is manifest in nature. The minimal supersymmetric extension of the standard model (MSSM) requires an extended Higgs sector with two Higgs doublets, corresponding to five physically observable Higgs boson resonances. The MSSM Higgs sector is typically parametrized by the ratio of the vacuum expectation values of the two doublets, $\tan\beta$, and the mass of the neutral, CP-odd Higgs boson, m_A. Large radiative corrections extend the upper-bound on the mass of the lightest Higgs from its Born-level value m_Z to about 133 GeV/c^2. Explicit CP-violation in the MSSM complicates matters slightly [5].

At the LHC, production cross-section for the standard model Higgs bosons falls from about 30 pb near the LEP limit to less than 0.1 pb near $m_H \approx 1$ TeV. The production is dominated by the gluon-fusion process, followed by weak boson fusion, and associated production with weak bosons and heavy quarks. The decay is dominated by heavy lepton pairs ($b\bar{b}$ and $\tau^+\tau^-$), for masses less than $2m_W$, and pairs of weak bosons once above threshold [6]. Due to the enormous rate of QCD processes at the LHC, at least one high-p_T lepton or photon or very large missing p_T is needed to trigger the event.[1] Furthermore, due to the high design luminosity of the LHC, an average of 23 soft p-p interactions are expected per bunch crossing – a phenomenon referred to as "pile-up" – which makes the LHC environment particularly challenging. This pile-up effect will be even more severe at the Super-LHC.

2. LHC Discovery and Measurement Potential

The Higgs discovery potential was detailed several years ago by both ATLAS and CMS assuming a total integrated luminosity of 300 fb^{-1} per experiment [1, 2]. Both experiments concluded that they should discover the standard model Higgs with high significance for masses up to 1 TeV and measure the mass of the Higgs boson to within 1%

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[1] The trigger requirement rules out the inclusive observation of $H \to b\bar{b}$, *i.e.* from the dominant gluon-fusion production process.

across the entire mass range (within 0.1% for $m_H < 400$ GeV/c^2). For $m_H > 200$ GeV/c^2, non-standard spin and CP properties of the Higgs can be highly excluded with 100 fb^{-1} [7]. Observation of two or more Higgs bosons would rule out a standard model Higgs sector, and such observations are expected for many, though not all, regions of the MSSM parameter space.[2]

After the original assessments by ATLAS and CMS, phenomenological studies indicated that weak boson fusion Higgs production with decays to W^+W^-, $\tau^+\tau^-$, and $\gamma\gamma$ showed great potential for a discovery of the standard model Higgs [8, 9, 10]. Within the context of the CP-conserving MSSM, the complementary couplings to the light and heavy CP-even neutral Higgs bosons allow the $\tau^+\tau^-$ channel to cover the entire $m_A - \tan\beta$ plane [10]. These weak boson fusion analyses have now been studied by the collaborations and provide for a more robust discovery potential and improved coupling measurements [11, 12].

Prior to the addition of weak boson fusion, the two most powerful analyses for low-mass Higgs came from $H \to \gamma\gamma$ and $ttH \to ttb\bar{b}$. Since their initial study, great advances have been made in terms of the Monte Carlo used to generate the particle-level predictions. More detailed study of the $ttH \to ttb\bar{b}$ channel by ATLAS incorporating the systematic uncertainty on the $b\bar{b}$ invariant mass spectrum indicate that the channel is not as powerful as originally anticipated[3] and is not sufficient for discovery [14]. This loss of sensitivity is found despite the use of multivariate techniques.

By comparing the rates of different Higgs decays, it is possible to measure various properties of the Higgs and how it couples to fermions and bosons. The interpretation of these measurements is tightly coupled to the theoretical assumptions one makes. Ratios of partial widths and (with mild theoretical assumptions) absolute couplings can typically be measured to an accuracy of 10-40% [15]. Some improvements to this result are foreseen by reducing the uncertainty on the rate of $gg \to Hgg$ by taking advantage of its characteristic ϕ_{jj} shape [16] and arguing that certain theoretical uncertainties may largely cancel in ratio [17].

3. Higgs Prospects at the Super-LHC

While the prospects for the LHC are quite encouraging, there are many measurements that are statistics-limited. For example, observation of $H \to \mu\mu$ (a non-third-generation fermion coupling) is straight forward experimentally, but limited by the small branching ratio [18, 19]. Similarly, additional luminosity would increase the supersymmetric parameter space in which two or more Higgs bosons are visible. Also of great importance is the measurement of the Higgs self-couplings, which is largely limited by the integrated luminosity.

For the reasons stated above, a luminosity upgrade to the LHC is being considered. The so-called "Super-LHC", or SLHC, would have a design luminosity of 10^{35} cm^{-2}s^{-1} and would potentially gather 3000 fb^{-1} of data [20]. While details of such an upgrade remain uncertain, it would most likely start around 2015. Significant studies are already underway to assess the requisite modifications to the accelerator, detector subsystems, and trigger and data acquisition infrastructure. Studies of the physics potential of the SLHC by the experimental collaborations are somewhat limited, but they do show the expected gains in coupling measurements and extended discovery potential in the $m_A - \tan\beta$ plane [21]. Additionally, it has been shown in phenomenological studies that the tri-linear Higgs self-coupling could be measured to 20-30%, and both experiments are working to confirm this result [22]. Unfortunately, small variations in the tri-linear coupling will swamp variations in the quartic-coupling, leaving little hope to measure the quartic coupling at any foreseeable hadron collider [23].

The existing studies show an enticing physics program, but with attention turning to the start-up operations of the LHC, additional studies are not likely to be forthcoming. After some experience with pile-up at the LHC design luminosity and potential observations of new physics, the LHC collaborations will undoubtedly embark on more studies germane to the SLHC physics potential.

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[2] CP-violating scenarios have regions of their parameter space in which the current set of search channels are not sensitive.

[3] It is not clear if the ATLAS result is in agreement with the one from CMS [13].

4. Conclusion

If it exists, the LHC should discover standard model Higgs boson, measure its mass accurately, and make various measurements of its couplings, spin and CP properties. In the context of the CP-conserving MSSM, the LHC should be able to discover one or more Higgs bosons over the entire $m_A - \tan\beta$ plane, with two or more observable in many cases. The large number of channels available insure a robust discovery and offer many opportunities for additional measurements.

Observation of $H \to \mu\mu$, measurement of the tri-linear Higgs self-coupling, and various search channels are statistics-limited, and only possible with a luminosity upgrade. A luminosity upgrade would substantially improve some of the coupling measurements and generally extend the sensitivity in the MSSM Higgs plane. Efforts are ongoing to understand the upgrade of the LHC to the Super-LHC.

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