PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 76, No. 5
May 2011
pp. 767–781

Higgs physics at the Large Hadron Collider

ROHINI M GODBOLE
Center for High Energy Physics, Indian Institute of Science, Bangalore 560 012, India
Institute for Theoretical Physics and Spinoza Institute, Utrecht University, 3508 TD Utrecht, The Netherlands
E-mail: rohini@cts.iisc.ernet.in

Abstract. In this talk I shall begin by summarizing the importance of the Higgs physics studies at the Large Hadron Collider (LHC). I shall then give a short description of the pre-LHC constraints on the Higgs mass and the theoretical predictions for the LHC along with a discussion of the current experimental results, ending with prospects in the near future at the LHC. I have added to the write-up, recent experimental results from the LHC which have become available since the time of the workshop.

Keywords. Higgs boson; Large Hadron Collider; electroweak symmetry; spin and CP of the Higgs boson

PACS Nos 14.80.Bn; 12.15.Ji

1. Introduction

It goes without saying that establishing the exact nature of the mechanism of electroweak symmetry breaking is perhaps ‘THE’ most important issue in particle physics at present and arguably the *raison d’être* for the Large Hadron Collider (LHC). The excellent agreement of the LEP data on $\sigma(e^+e^- \rightarrow W^+W^-)$ with predictions of the Standard Model (SM) shown in figure 1 gives us a direct confirmation of the triple gauge boson (ZWW) coupling as predicted by the $SU(2) \times U(1)$ symmetry. At the same time, the observed nonzero mass of the W-boson confirms that the same EW symmetry is broken as well. Higgs mechanism [1,2] is one way of achieving the desired breakdown of the EW symmetry. This predicts the existence of a $J^{\rm PC} = 0^{++}$ state, as the remnant of the $SU(2)_L$ doublet, with precise predictions for the coupling of this state to all the SM particles, but is able to give only very weak theoretical constraints on its mass. Since this is the only particle of the SM [2] still lacking confirmation by direct experimental observation, it is clear that discovery of the Higgs boson and a study of its properties are at the heart of the LHC program which has begun operations since February 2010.

A few remarks are in order here. Theoretical ideas of electroweak symmetry breaking (EWSB) span a large range, beginning from the weakly coupled Higgs to those of strong interaction dynamics which can involve a composite (or worse, no) Higgs boson. All of

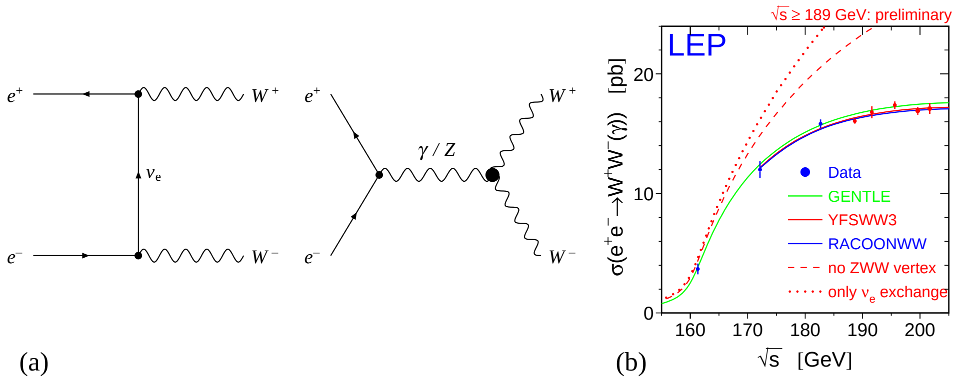


Figure 1. Comparison of the LEP data (taken from LEPEWWG) with the SM prediction (**b**), the contributory processes being shown in (**a**).

these, including the SM, of course have had to pass the acid test of the electroweak precision measurements, at the Z pole at the LEP collider. The latter class of models, involving dynamical symmetry breaking triggered by strong dynamics, have got a new lease of life due to theoretical developments in the context of models with extra dimensions. Needless also to say that the contents of the Higgs sector and the properties of the said particles, both can differ from the SM in the many different proposals of going beyond the Standard Model (BSM). Further, CP violation in the Higgs sector can be the possible BSM physics that is a must for having a quantitative explanation of the baryon asymmetry in the Universe. In addition to this, the dark matter in the Universe, seems to also not consist of any of the known particles in the SM. Interestingly, almost all the extensions of the SM, always have a particle which has all the right properties to be a dark matter (DM) candidate. Since most of the extensions of the SM are introduced to deal with some of the not yet completely understood and/or unsatisfactory features of the EWSB, almost always this candidate DM particle has interesting connections to Higgs physics as well.

We expect the LHC to unravel the secrets of the physics of the EWSB, as well as to provide pointers to the BSM physics which, we hope, in turn will provide the key to the explanation of issues of cosmological importance, viz. the baryon asymmetry in the Universe (BAU) and the DM in the Universe. The discussion preceding these few lines, should then convince us that 'Higgs Physics at the LHC', will indeed touch upon almost all the aspects of active investigation in theoretical and experimental particle physics.

While discussing the 'Higgs Physics at the LHC' the different issues that need be addressed are

- Discovering the spin-0 state(s), measure the mass and the couplings of these states.
- Can these measurements uniquely decide the gauge group representation to which these scalar(s) belong? Can they give information about whether the SM is a strongly coupled theory with (perhaps) a composite Higgs boson or a weakly coupled theory with an elementary Higgs boson?
- Is there a CP violation in the Higgs sector?

LHC is capable of answering these questions to different degree of completeness, some early and some in the far future.

Clearly, a short survey such as this cannot do justice to the enormous amount of work done on the subject [3,4]. The discussion here will hence only focus on a few issues. I shall summarize first the current constraints on the mass and then go on to discuss the status of theoretical predictions for the LHC. I shall then present the current projections for discovery and exclusions made by the two LHC experiments and then discuss briefly the two new developments in the subject: (1) The jet substructure technique which enables use of the $b\bar{b}$ final state arising from the Higgs decay. Due to the large QCD backgrounds this final state could not always be utilized in the analyses hitherto, (2) the possibility of obtaining spin and parity of the observed scalar state even in the early data.

2. SM Higgs: Profile and current constraints

As is well known, theoretical considerations are capable of only giving bounds on the Higgs mass. These bounds arise from considerations of triviality and boundedness of the Higgs potential and are shown in figure 2. These bounds thus indicate that just the mass of the observed scalar state will be able to give information about the energy scale at which new physics must appear. For example, a scalar state with mass in the region of ∼180 GeV will already indicate compatibility with the absence of any new physics upto very high scales.

The radiative corrections to the W/Z boson masses coming from the Higgs boson are $\propto \log(M_H/M_W)$. As a result, the precision measurements of the gauge boson masses already put strong, indirect constraints on the allowed value of M_H. Further, the 'direct' searches at LEP [6] and Tevatron [7] also exclude the existence of a Higgs boson, in certain

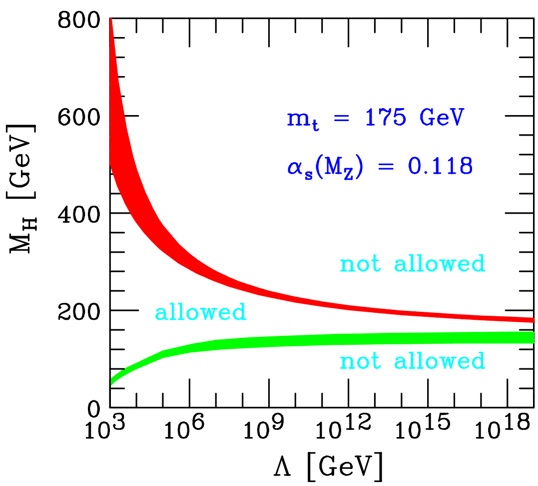
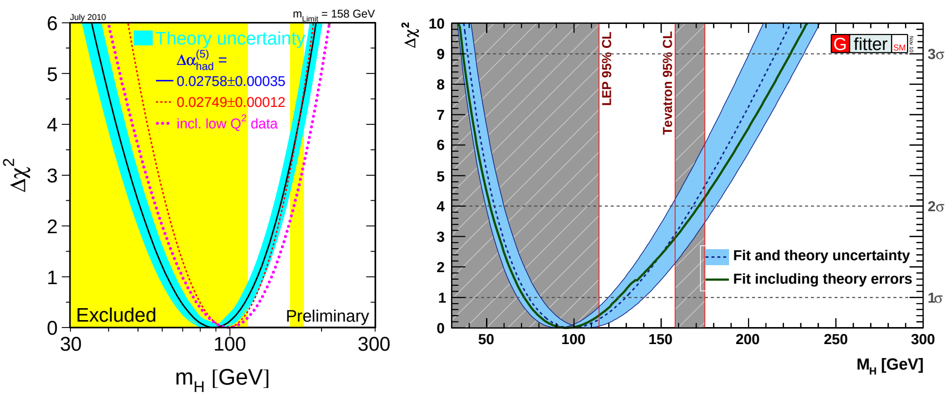


Figure 2. Theoretical upper and lower bounds on the Higgs mass in the SM from the assumption that the SM is valid up to the cut-off scale Λ [5].

mass regions. Figure 3 shows a compilation of these indirect constraints obtained by the LEPEWWG and Gfitter groups, along with the limits from the direct searches. The two panels show $\Delta\chi^2$ as a function of M_H for a SM fit to the various electroweak precision observables. The direct search limit on the heavy mass Higgs, coming from the Tevatron has a nontrivial dependence on the nonperturbative knowledge of the proton [8,9] and I shall comment upon it later.

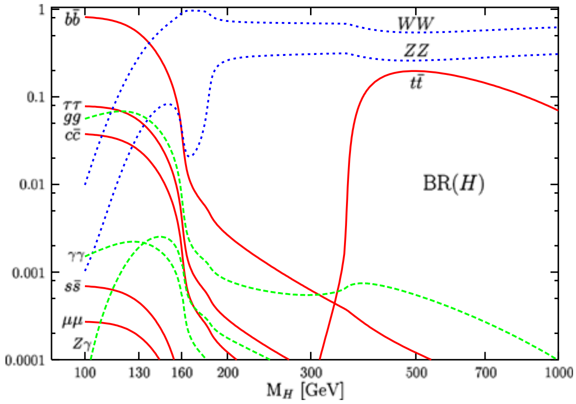
These results shown in figure 3 tell us that in the SM, current data prefer a light Higgs and on inclusion of the direct limits from the collider searches, one gets $M_H < 185$ GeV, at 95% CL. The closeness of this bound with the theoretical analysis presented in figure 2 in fact raises the hairy prospect that we might find only a light Higgs and nothing else at the LHC. It should be mentioned here however, that some of the details of these analyses are quite sensitively dependent on the way the theoretical and experimental errors are accounted for in these analyses. This knowledge thus sets now the stage for the LHC Higgs searches.

Figure 4 shows the branching ratios for the SM Higgs over the entire mass range that is consistent with the theoretical constaints mentioned above. Thus we see that for the light Higgs, such as the one indicated by these constraints, the width of the Higgs boson is expected to be $\lesssim$1 GeV. For the lighter Higgs with mass $\lesssim$130 GeV branching ratio into the $b\bar{b}$ channel is expected to be large, with that in the $\gamma\gamma$ channel $\sim 10^{-3}$. For larger values of the Higgs mass, the VV decay modes are dominant, with WW and ZZ sharing it in the ratio 2 : 1. For the heavier Higgs ($\gtrsim$135 GeV), the four-fermion decay mode is the most important one. Combined QCD and EW corrections can change this by upto a few percent. Due to the large QCD backgrounds, the $\gamma\gamma$ mode is considered optimal for the light Higgs. However, there has been a major change in the attitude since it has been pointed out that the use of $b\bar{b}$ final states can be made possible using jet substructure methods [10]. I shall give a short description of these methods in the later discussions.

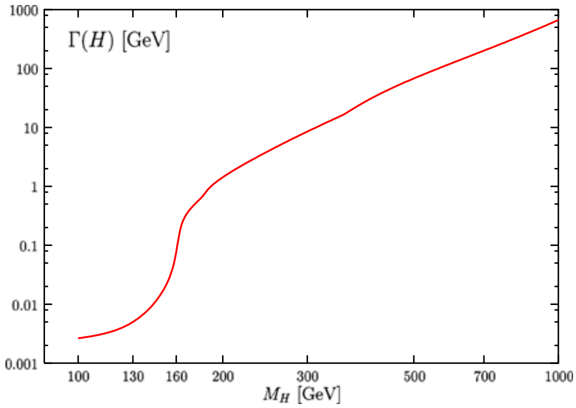


(a) (b)

Figure 3. The two panels show a summary of the current, direct and indirect, experimental constraints on the Higgs mass from the collider experiments, taken from the web pages of the LEPEWWG and the Gfitter group. Both the panels show $\Delta\chi^2$ as a function of M_H for a SM fit to a variety of precisely measured electroweak observables.



(a)



(b)

Figure 4. The decay branching ratios and the total decay width of the SM Higgs boson as a function of its mass taken from [3].

3. Production of the Higgs at the LHC

Since LHC is a hadronic collider, one of the most relevant activity is the accurate predictions of the expected cross-sections as well as differential distributions in important kinematical variables such as, eg., p_T^H for various Higgs production processes. QCD factorization theorem at short distances tells us that this cross-section can be calculated in the following formalism:

$$\sigma(pp \to X + \cdots) = \sum_{a,b} \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 f_a(x_1, \mu_{\mathrm{F}}^2) f_b(x_2, \mu_{\mathrm{F}}^2) \times \sigma(a + b \to X) \left(x_1, x_2, \mu_{\mathrm{R}}^2, \alpha_s(\mu_{\mathrm{R}}^2), \alpha(\mu_{\mathrm{R}}^2), \frac{Q^2}{\mu_{\mathrm{R}}^2}, \frac{Q^2}{\mu_{\mathrm{F}}^2} \right). \quad (1)$$

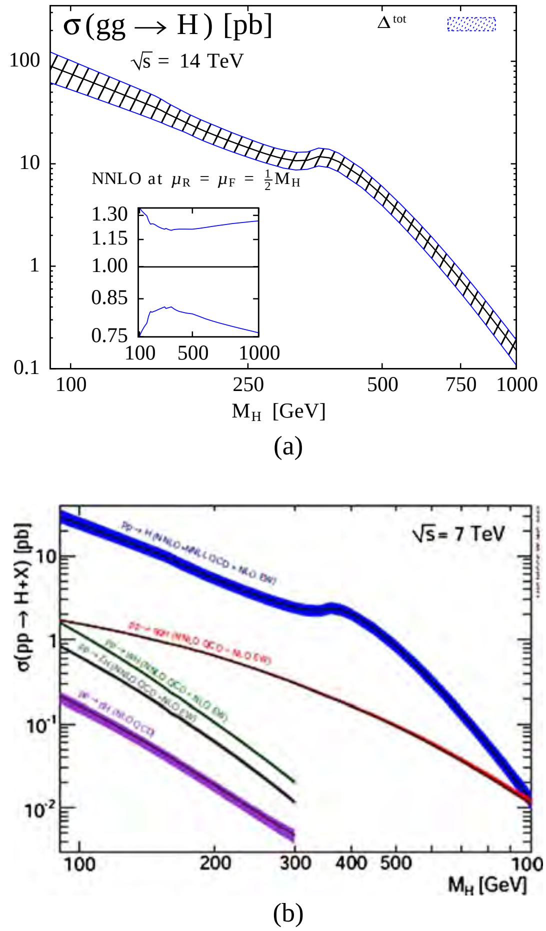


Figure 5. Cross-sections for the gg fusion process with all errors [11] for $\sqrt{s} = 14$ TeV in **(a)** and cross-sections for all the relevant processes for $\sqrt{s} = 7$ TeV [12] in **(b)**.

An accurate calculation requires precise inputs on two nonperturbative quantities α_s and the parton density functions, PDF's, along with an accurate evaluation of the subprocess cross-sections. An enormous amount of work has been done on the subject. An evaluation of the theoretical uncertainties in the predictions for cross-section at the LHC was presented in [11]. In fact, a joint collective effort [12], involving experimentalists and theorists, has been made recently to make the most accurate predictions for total observable cross-sections, taking into account all the current theoretical uncertainties, both in the calculation of production cross-sections and the branching ratios. The next step is to do the same for exclusive distributions. Here, I summarize the main features and refer the reader to [11,12] and references therein for further details.

The most important mode of production at the LHC is the gg fusion, dominated by the top loop. The NLO corrections have been computed both in the effective field theory

(EFT) approach in the limit of infinite top mass and for finite heavy quark mass. Further, the NNLO corrections have been computed doing the three-loop calculation. On top of it, the resummation of soft and collinear corrections has been performed at the NNLL. The nonfactorizable EW and QCD corrections to the process have also been computed and shown to be ∼5%. The K-factor for the dominant gg fusion process, at the LHC, for low Higgs masses, is 1.7 at the NLO and grows to about 2 at the NNLO, thus showing a good convergence of the perturbation series. The NNLO result has small dependence on the renormalization and factorization scale variations, the hallmark of stability of a perturbative QCD calculation. The cleanest prediction is for the WH/ZH production, where both the QCD and EW corrections have been computed and the resulting cross-section has a K-factor ∼1.2–1.3 at NNLO. The *WW*/*ZZ* fusion mechanism has the second largest cross-section at the LHC and would be very important for coupling/quantum number measurements once the Higgs boson has been found. In this case, the extraction of the signal for precision measurements requires extensive cuts on the phase space and hence calculation of higher-order corrections to exclusive distributions is very important. Both the QCD and EW corrections have been computed and the K-factors are found to be modest. Equally important for the measurements of the couplings is the $t\bar{t}H$ production. Use of jet substructure method [13] may yet revive the measurability of this channel. The NLO corrections to this 2 → 3 processes are now available and the scale variation for the NLO result for $\sigma(pp \to t\bar{t}H)$ at the LHC is found to be rather modest (∼10–20%). In figure 5a we show, the predictions at $\sqrt{s} = 14$ TeV for the gg fusion cross-section including all uncertainties, taken from [11] and in figure 5b the cross-section predictions for all the different production processes at $\sqrt{s} = 7$ TeV taken from [12] are shown.

It is worth mentioning here that the situation about the theoretical uncertainties in the production cross-section of the gg fusion process at the Tevatron [8,14] is quite

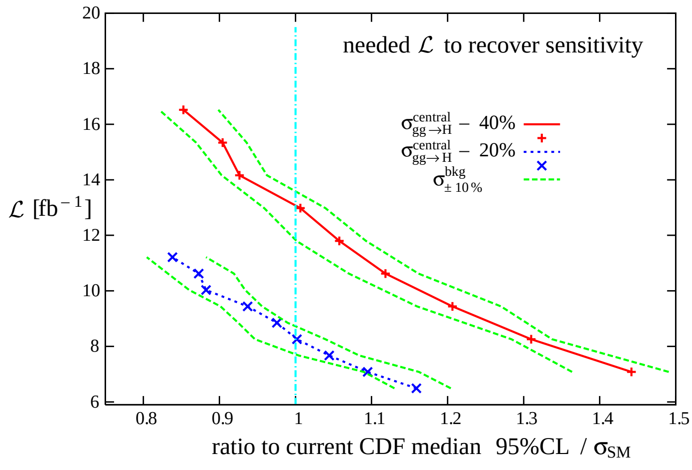


Figure 6. The needed luminosity by the CDF experiment to recover the current sensitivity (with 5.9 fb^{-1} data) when the $gg \to H \to \ell\ell\nu\nu$ signal is lowered by 20% and 40% and with a ±10% change in the dominant $p\bar{b} \to WW$ background (taken from [8]).

different. In fact, this process is observable at the Tevatron only because of the rather large NLO/NNLO corrections it receives corresponding to a K-factor of 2(3) at NLO (NNLO). This thus means that the range of variation of the common factorization and renormalization scales in this case has to be somewhat larger than that for the LHC leading to a larger scale variation uncertainty in the cross-section in this case. Further, the different parametrizations for the PDF's which correspond to different assumptions on these non-perturbative inputs, can differ in the central value of the predicted cross-section [8,9] by upto 40% for Higgs masses where the sensitivity is maximal. If one were to evaluate the theoretical uncertainties for the Tevatron by the method prescribed in [12] one would get about 35% uncertainty in the cross-section as opposed to the 20% and 10% assumed in the CDF and D0 analyses respectively [7]. This raises the somewhat uncomfortable situation that the exclusion bounds from the Tevatron, shown in figure 1, may be dependent on the PDF used and if the true normalization is indeed smaller by 40% than that for the used MSTW parametrization, one might need upto a factor 2 higher luminosity to achieve the same exclusion. This is indicated in figure 6. This underlies the importance of having a complete assessment of the theoretical uncertainties as is presented in [11,12].

4. LHC: Projections and results

As said before, at the LHC, gg fusion is the dominant production mechanism and the final state contributing to the discovery depends on the mass of the Higgs. Figure 7 taken from

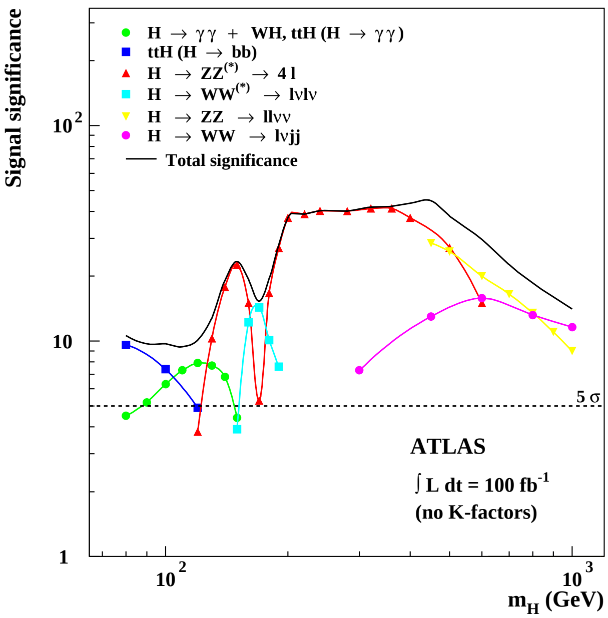
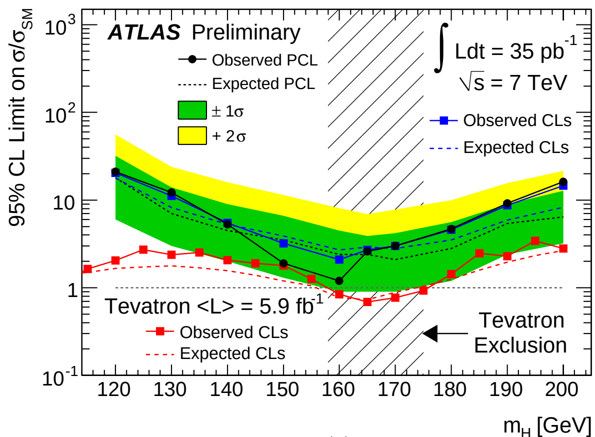


Figure 7. The expected signal significance for different search channels at the LHC with 14 TeV, assuming no K-factors, for 100 fb^{-1} integrated luminosity (taken from ATLAS TDR in [4]).

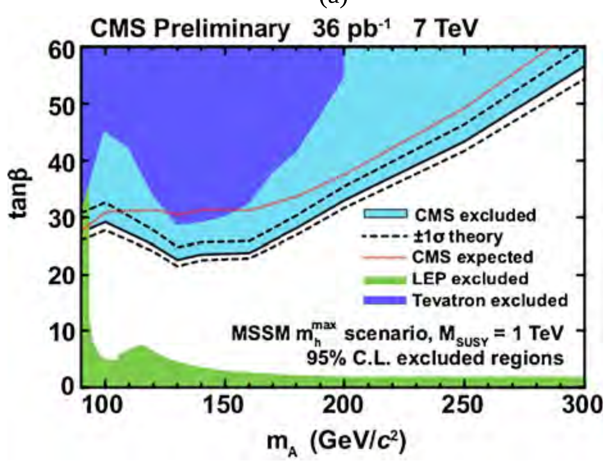
the ATLAS TDR [4], shows the signal significance for an integrated luminosity of 100 fb^{-1} at 14 TeV LHC, neglecting all the K-factors. This corresponds to the assertion that a single experiment can discover the Higgs over the entire mass range allowed by theoretical considerations at 5σ.

Now the LHC has been running at a lower energy of 7 TeV, at a lower luminosity than planned but has already collected 35 pb^{-1} data per experiment thanks to the very good performance of the LHC machine. It will now continue to run at 7 TeV till 2012 end.

Plots in figure 8 show that even with the very small amount of data the LHC has started giving significant results. Figure 8a shows that the ATLAS Collaboration is getting close to being sensitive to the SM Higgs in the heavy mass range and has put limits on the



(a)

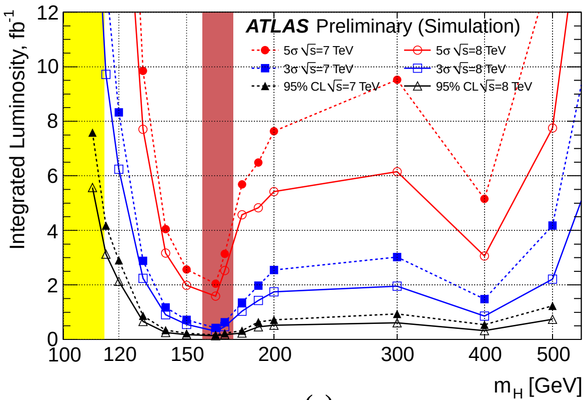


(b)

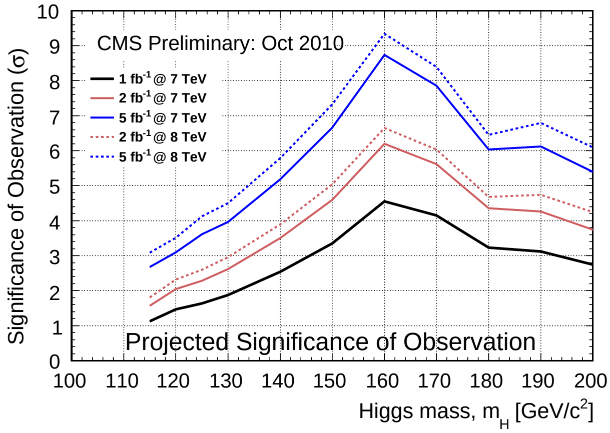
Figure 8. Examples of the results for the SM Higgs and MSSM Higgs available from the data corresponding to an integrated luminosity of 35 pb^{-1} at LHC (taken from [16] and [17] respectively).

cross-section, at 95% CL, at about 1.2 times the SM cross-section, for Higgs mass around 160 GeV. Clearly, one has to watch this space very closely for future news.

For the CMS results, I have chosen the example of the SUSY Higgs about which I have not talked much in §§2 and 3. Supersymmetry is one of the most popular and arguably the best motivated BSM physics candidate. In the MSSM [15] there exist five Higgs bosons, three neutrals and two charged, one of the three neutrals being a pseudoscalar. An important difference from the SM is that the lightest Higgs mass now constrained from above (∼130–140 GeV). The mass bound is pretty robust, even though it depends on some of the details of the specific SUSY model and parameters thereof. The heavier neutral Higgses decay mostly into b and τ's and thus the phenomenology is quite distinct. The production cross-section for the inclusive production of the supersymmetric Higgs in the process $gg \to Hb\bar{b}$ with $H \to \tau\tau$, is considerably enhanced at large $\tan\beta$ [3] and is thus accessible even



(a)



(b)

Figure 9. **(a)** ATLAS simulation for the required integrated luminosity for exclusion at 95% CL and discovery at 3 and 5σ level [19] and **(b)** the expected level of significance of observation at different integrated luminosities from CMS simulation [20], as a function of M_H. Results are shown for both $\sqrt{s} = 7$ and 8 TeV.

with low luminosity. The exclusion for the supersymmetric Higgs achieved by the CMS experiment is shown in figure 8b. However, the ATLAS exclusion for the same seen in [16] is somewhat weaker. These results have already led to theoretical analyses of their implications not just for SUSY searches in general but also for the search of a light, SM Higgs at the LHC [18].

The LHC experiments seem to be performing amazingly well and the time gap between data taking and availability of results is indeed very short. It is therefore important to know what are their projections now for the Higgs searches. For detailed information, I shall refer the reader to the web pages in refs [19,20]. Figure 9a shows the luminosity required for 5 (3) σ discovery and exclusion at 95% CL at the centre of mass energy of 7 and 8 TeV respectively, whereas figure 9b shows the CMS version of the plot of figure 7 but now for $\sqrt{s} = 7$ and 8 TeV, for few selected values of integrated luminosities. These figures show clearly that depending on the luminosity the LHC machine manages to deliver, we would have very significant information on the SM Higgs mass by the end of 2012 run. This makes now for a very agonizing wait indeed.

5. Determination of Higgs properties and couplings

As already stated, just discovering the Higgs at a particular mass and the simultaneous results from the associated searches for BSM physics, will begin to give indicative answers to the second question stated in the introduction of this article. But for a good scrutiny of this question, measurements of its couplings to the other SM particle, determination of its spin and further determination of its CP property is quite essential. The standard wisdom [3] in this respect was that these are usually high-luminosity measurements. For example, the studies of ref. [21] had shown that with an integrated luminosity of about 600 fb^{-1}, at 14 TeV, it will be possible to measure various couplings at a $\lesssim$ 20–30% level for the SM Higgs. These results were confirmed with a more sophisticated analysis recently [22].

Another example is of the investigations of ref. [23] which indicated that at 14 TeV LHC, one would be able to establish some of the anomalous (CP violating) *HZZ* couplings at 3–5σ level, with 100–300 fb^{-1} integrated luminosity, again for $\sqrt{s} = 14$ TeV, if these couplings were of the same order of magnitude as the SM couplings. In figure 10 taken from ref. [23] I show the regions in the $|c|$–a coupling plane that can be probed by just measuring the width of the Higgs boson. Here the *HZZ* vertex has been parametrized in the most general, model-independent way, given by

$$V^{\mu\nu}_{HZZ} = \frac{igm_Z}{\cos\theta_W}\left[ag_{\mu\nu} + b\,\frac{p_\mu p_\nu}{m_Z^2} + c\epsilon_{\mu\nu\alpha\beta}\,\frac{p^\alpha k^\beta}{m_Z^2}\right], \tag{2}$$

in obvious notation for the different quantities appearing therein with p, k standing for the sum and difference of the four momenta of the Z bosons.

It was also demonstrated in [24] that for a Higgs heavy enough to have a reasonable branching ratio in ZZ^* channel, the shape of the distribution in the invariant mass of the $\ell^+\ell^-$ pair coming from the Z^* decay, can give clear information about the spin of the Higgs boson. The plot in figure 11 taken from ref. [24], shows the measurement possible for an integrated luminosity of 100 fb^{-1}, at $\sqrt{s} = 14$ TeV, the histogram showing the expected

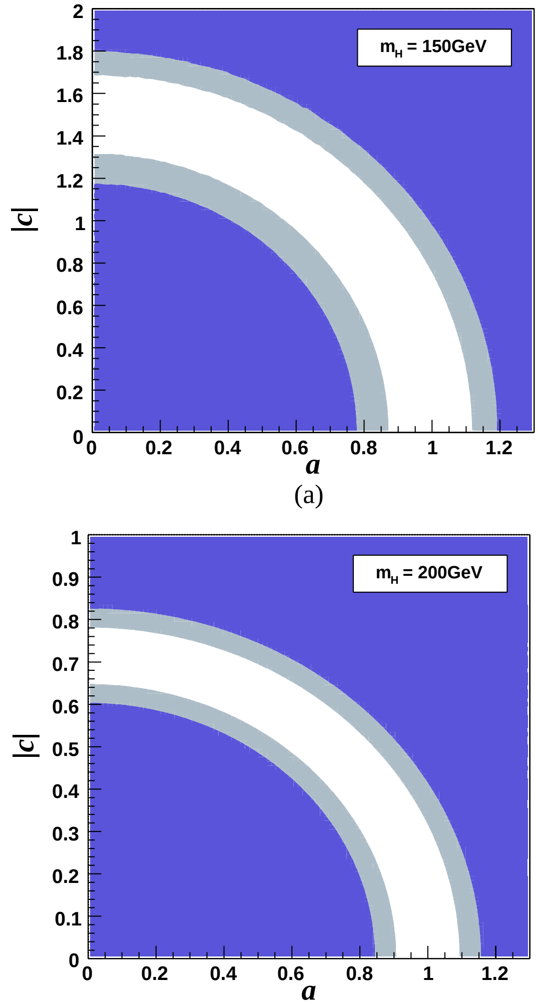


Figure 10. The number of standard deviations from the SM which can be obtained in the process $gg \to H \to Z^* Z^* \to 4$ leptons, as a scan over the $(a, |c|)$ plane. The Higgs mass has been chosen to be 150 GeV **(a)** and 200 GeV **(b)**. The white region is where the deviation from the SM is less than 3σ; in the light blue region the deviation is between 3σ and 5σ; while for the dark blue region the deviation is greater than 5σ for an integrated luminosity of 300 fb^{-1} (taken from [23]).

statistical error. It had also been shown that the distribution in the azimuthal angle between the planes of the two pairs of the decay leptons can also carry information about the spin and the parity of the decaying resonance [25]. Recently there were investigations [26,27] which showed that more complicated, multivariate analyses might be able to do the job of establishing the J^{PC} to be 0^{++} at $\sim 3\sigma$ significance for $\lesssim 10$ fb^{-1} luminosity.

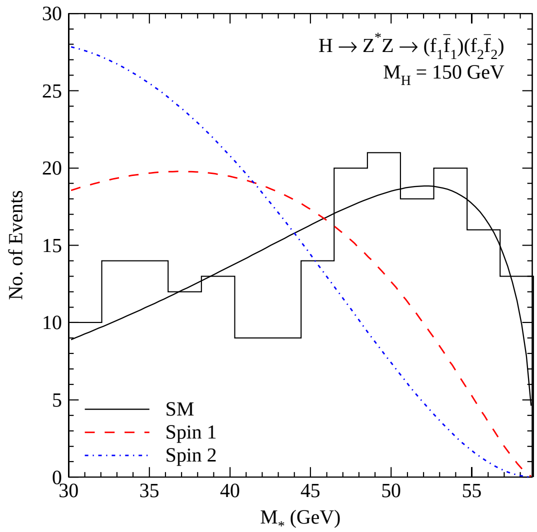
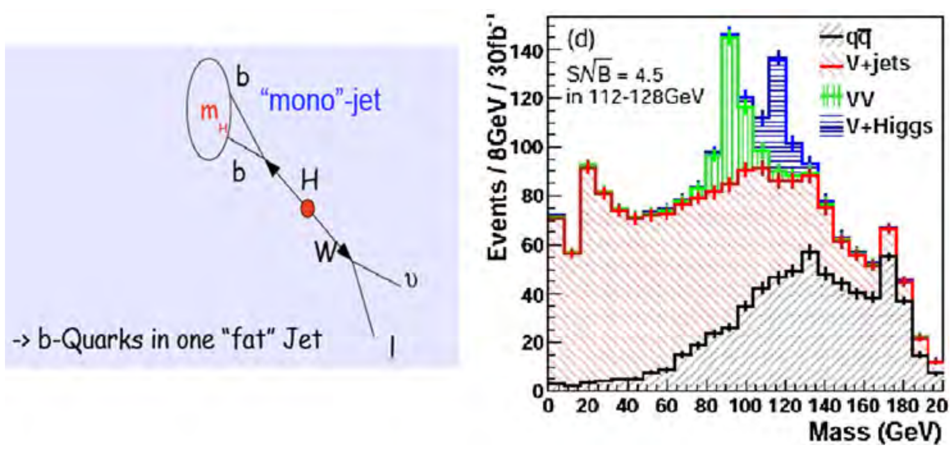


Figure 11. Distribution in M_{Z^*} for $H \to ZZ^*$, taken from [24].

Apart from the high luminosity, for the coupling measurements, using the $b\bar{b}$ final state is also essential and so is the possibility to make a good measurement of the $t\bar{t}H$ process. The $t\bar{t}jj$ background seems to make the use of this channel very difficult [4]. Hence methods to improve the visibility of this channel are welcome. As mentioned before, methods using the substructure of jets have given new hope in both these issues [10,13]. I would therefore describe briefly this method now.



(a) (b)

Figure 12. **(a)** shows a cartoon of a 'fat' jet from the $b\bar{b}$ decay of a large p_{T} Higgs and **(b)** shows how the substructure analysis can help increase $S/\sqrt{B}$ in the WH channel (taken from [10]).

The idea here is based on the fact that for high p_T Higgs bosons the $b\bar{b}$ decay products would emerge close to each other and hence will look in the detector to be a single, fat jet with large invariant mass. The jets produced by QCD emission will not have this feature. Thus, if one can develop an algorithm to see if a fat, heavy jet is made of two fast objects emitted close to each other, one can then reduce the QCD backgrounds to a low level. For the production processes like *WH*, *ZH* where one has to select large p_T Higgs bosons to get rid of the irreducible SM background anyway, this technique seems to work quite nicely. In figure 12a, I show a cartoon which illustrates the kinematical fact and in figure 12b, I show a plot from [10], which indicates the clean way in which the signal can be separated from the background for the *WH* case and $S/\sqrt{B}$ as high as 4.5 can be reached in this channel, with $b\bar{b}$ final state, for 30 fb^{-1} of integrated luminosity, for a 120 GeV Higgs boson. These kinds of studies would be the future of Higgs physics at the LHC once it has been discovered through any channel.

6. Conclusion

Thus we are now at a very exciting stage where in the next two years we should expect either a 3σ signal or a 95% exclusion over the entire range of the Higgs masses at the LHC. As stated already, the mass of the Higgs boson alone can give completely nontrivial indications of the presence or absence of BSM physics. Should the Higgs masses give an indication of the BSM physics, in most cases the corresponding BSM physics, should also reveal itself in the simultaneous direct searches for the integrated luminosity we expect to have. Hence, the next two years of the Higgs physics at the LHC should be very exciting indeed. The measurements of the couplings, spin, parity, CP characteristic all have to however wait for higher luminosities and higher energies and perhaps even for a leptonic collider [28].

Acknowledgement

RMG wishes to acknowledge the Department of Science and Technology for financial support under the J.C. Bose Fellowship Scheme under grant nos SR/S2/JCB-64/2007.

References

[1] P W Higgs, *Phys. Lett.* **12**, 132 (1964); *Phys. Rev.* **145**, 1156 (1966)
F Englert and R Brout, *Phys. Rev. Lett.* **13**, 321 (1964)
P W Higgs, *Phys. Rev. Lett.* **13**, 508 (1964)
G S Guralnik, C R Hagen and T W Kibble, *Phys. Rev. Lett.* **13**, 585 (1964)

[2] J Goldstone, A Salam and S Weinberg, *Phys. Rev.* **127**, 965 (1962)
S Weinberg, *Phys. Rev. Lett.* **19**, 1264 (1967)
S L Glashow and S Weinberg, *Phys. Rev. Lett.* **20**, 224 (1968)
A Salam, *Proceedings of the Nobel Symposium* edited by N Svartholm (Stockholm, 1968)

[3] For a review, see for example, A Djouadi, *Phys. Rep.* **457**, 216 (2008), hep-ph/0503172; *Phys. Rep.* **459**, 1 (2008), hep-ph/0503173 and references therein

A Djouadi and R M Godbole, in: *Physics at the Large Hadron Collider* edited by A Datta, B Mukhopadhyaya and A Raychaudhuri (Springer (India), New Delhi) pp. 47–74, arXiv:0901.2030 [hep-ph] and references therein.

[4] ATLAS Collaboration, Technical Design Report, CERN-LHCC-14 and CERN-LHCC-15
CMS Collaboration, Technical Design Report, CMS-LHCC-2006-21

[5] T Hambye and K Riesselmann, *Phys. Rev.* **D55**, 7255 (1997)

[6] LEP working group for Higgs searches: R Barate *et al*, *Phys. Lett.* **B565**, 61 (2003)

[7] CDF and D0 Collaborations: *Phys. Rev. Lett.* **104**, 061802 (2010); updated in arXiv:1007.4587 [hep-ex]

[8] J Baglio, A Djouadi, S Ferrag and R M Godbole, arXiv:1101.1832 [hep-ph], to appear in *Phys. Lett. B*

[9] S Alekhin, J Blumlein and S Moch, arXiv:1101.5261
S Moch, talk at Kick-off meeting of the LHCPhenoNet, Feb. 2011, Valencia, pp. 8–9 http://indico.ific.uv.es/indico/contributionDisplay.py?contribId=5&sessionId=2&confId=339

[10] One of the pioneering work in this area is J M Butterworth, A R Davison, M Rubin and G P Salam, *Phys. Rev. Lett.* **100**, 242001 (2008), arXiv:0802.2470 [hep-ph]

[11] J Baglio and A Djouadi, *J. High Energy Phys.* **1103**, 055 (2011), arXiv:1012.0530 [hep-ph]

[12] S Dittmaier *et al*, *Handbook of LHC Higgs cross sections*, arXiv:1101.0593 [hep-ph]

[13] T Plehn, G P Salam and M Spannowsky, *Phys. Rev. Lett.* **104**, 111801 (2010), arXiv:0910.5472 [hep-ph]

[14] J Baglio and A Djouadi, *J. High Energy Phys.* **1010**, 064 (2010), arXiv:1003.4266 [hep-ph]; arXiv:1009.1363 [hep-ph]

[15] For a pedagogic introduction see e.g., M Drees, R M Godbole and P Roy, *Theory and phenomenology of sparticles* (World Scientific, 2005)
H Baer and X Tata, *Weak scale supersymmetry: From superfields to scattering events* (Cambridge University Press, 2006)

[16] Atlas Collaboration: ATLAS-CONF-2011-005 for the SM Higgs search. For further information see also https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults#Data_2011

[17] CMS Collaboration: CMS PAS HIG-10-002. For more information see also, https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

[18] J Baglio and A Djouadi, arXiv:1103.6247 [hep-ph]

[19] ATLAS Collaboration, ATL-PHYS-PUB-2011-001. For more information see also, https://twiki.cern.ch/twiki/bin/view/AtlasPublic/PublicHGPlotsAtlPhysPub2011001 and https//twiki.cern.ch/twiki/bin/view/AtlasPublic/PublicHGPlotsAtlPhysPub2010726

[20] CMS-NOTE-2010/008. For more information see also, https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIGStandardModelProjections

[21] M Duhrssen, S Heinemeyer, H Logan, D Rainwater, G Weiglein and D Zeppenfeld, *Phys. Rev.* **D70**, 113009 (2004), hep-ph/0406323

[22] R Lafaye, T Plehn, M Rauch, D Zerwas and M Duhrssen, *J. High Energy Phys.* **0908**, 009 (2009)

[23] R M Godbole, D J Miller and M M Muhlleitner, *J. High Energy Phys.* **0712**, 031 (2007), arXiv:0708.0458 [hep-ph]

[24] D J Miller, S Y Choi, B Eberle, M M Muhlleitner and P M Zerwas, *Phys. Lett.* **B505**, 149 (2001), hep-ph/0102023

[25] S Y Choi, D J Miller, M M Muhlleitner and P M Zerwas, *Phys. Lett.* **B553**, 61 (2003), hep-ph/0210077

[26] A De Rujula, J Lykken, M Pierini, C Rogan and M Spiropulu, *Phys. Rev.* **D82**, 013003 (2010), arXiv:1001.5300 [hep-ph]

[27] Y Gao, A V Gritsan, Z Guo, K Melnikov, M Schulze and N V Tran, *Phys. Rev.* **D81**, 075022 (2010), arXiv:1001.3396 [hep-ph]

[28] ILC Collaboration: G Aarons *et al*, arXiv:0709.1893 [hep-ph]