HIGH STATISTICS STUDY OF THE HIGGS PROPERTIES AS A POSSIBLE CLUE TO NEW PHYSICS

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The paper discusses the implications of a 125 GeV Higgs boson on the search for new physics. Assuming that the intriguing hints reported by ATLAS and CMS in December 2011 could be considered the first evidence of the presence of the Standard Model Higgs boson in LHC data, the paper describes the set of preliminary measurements that could be done to assess the properties of the new particle. Some of these measurements, in particular the measurement of the couplings, could have a crucial role in hinting at the possible presence on new phenomena beyond the Standard Model.

INTRODUCTION

The general purpose LHC detectors, ATLAS and CMS, have been designed to shed light on the mechanism of the Electroweak Symmetry Breaking and to identify all possible signatures of new physics. Results published, so far, by the two collaborations show no sign of new physics but, very recently, they have both reported important progress in the path of understanding the EWSBM.

By analyzing the data collected in 2010 and 2011, the ATLAS and CMS experiments have been able to exclude the presence of the Standard Model Higgs boson in the full allowed mass range below 600 GeV, except for a very narrow region in the low mass end. Between 122 and 129 GeV both Collaborations reported an excess of events, with respect to the expected background, appearing quite consistently in all studied channels, but mostly driven by the high resolution search modes into pair of photons and into four leptons [1–3].

The fact that two independent experiments observed an excess of events with a local significance between 2.6 and 3.6σ at a value of the mass $m_H = (125 \pm 1)$ GeV is an unprecedented coincidence that can be interpreted as the first evidence of the presence of the SM Higgs boson in LHC data. In this hypothesis the observed excess is indeed compatible with the expected signal strength within $\pm 1\sigma$.

Given the low statistical significance of the excess, in particular including the Look-Elsewhere-Effect, the results are not yet conclusive, and only the data we are going to collect within the current year will allow us to make conclusive statements. Let's assume however that indeed "a SM like" Higgs does exist around a mass of 125 GeV and we are going to claim soon its discovery. As of today, at first sight, by putting together the available information from LHC and the Tevatron Collider, it looks like the SM Higgs boson. But there are intriguing hints of possible anomalies that would be worth to check better. For example, both ATLAS and CMS see a larger than expected signal in the decay mode into pair of photons.

In the following I'll describe a preliminary set of measurements on the new particle that could be used to assess its properties. I'll discuss then briefly the implications of a 125 GeV Higgs boson on the quest for new physics and I'll conclude describing some ideas to achieve a preliminary measurement of its couplings.

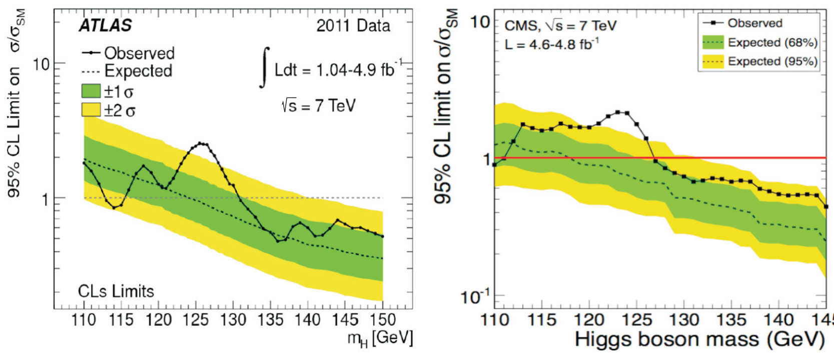

Fig. 1. Exclusion plots in the search for the SM Higgs boson produced by ATLAS (left) and CMS (right). The excess of events around a mass of 125 GeV is clearly visible in both data sets

1. IS IT REALLY THE STANDARD MODEL HIGGS BOSON?

How well could we measure its mass and its quantum numbers? How and when could we conclude that it is really a scalar?

The mass of the Higgs is one of the most important parameters to be measured. Based on the 2011 experience we can expect a <1 GeV accuracy on the measurement using likelihood scans for mass and signal strength in the high-resolution channels: H to $\gamma\gamma$ and H to ZZ in four leptons. On a longer term the decay mode in pairs of photons could hopefully give the best performance. It will be only limited by statistics and by our capability to understand better the systematic in the energy scale of electrons and photons. Achieving the ultimate performance in the calibration of ECAL will be mandatory. Further possible improvements could come from the use of di-jet tagged channels exploiting the good signal-to-noise ratio typical of the Vector Boson fusion production mechanism. Further progress in the ECAL calibration could be envisaged by using the large statistics of π^0, η, W and Z and by implementing a better description of the material in front of the calorimeters, as well as making progress in the understanding of the clusters shape variables. We could envisage to reach an accuracy on the mass ~ 300 MeV with a statistics larger than 30 fb^{-1}and possibly a combination of ATLAS and CMS results. The challenge to understand the systematic errors will dominate the accuracy from then onwards.

The assessment of the quantum number of the new resonance will allow one to establish the nature of the boson. Spin 1 is excluded for the Landau–Yang theorem, since it seems to decay to $\gamma\gamma$. It could be spin 0 or 2. A signal in $\tau\tau$ or bb would imply spin 0 but it will be tough to get enough statistics to claim an observation in this channel with 2012 data. The usual approach is to measure the lepton angular correlations in HZZ4l [4] and Matrix Elements approaches are currently being used in CMS to this purpose, but we might be limited by statistics. It would be worth of exploring also the angular correlations of leptons in WW as recently proposed [5].

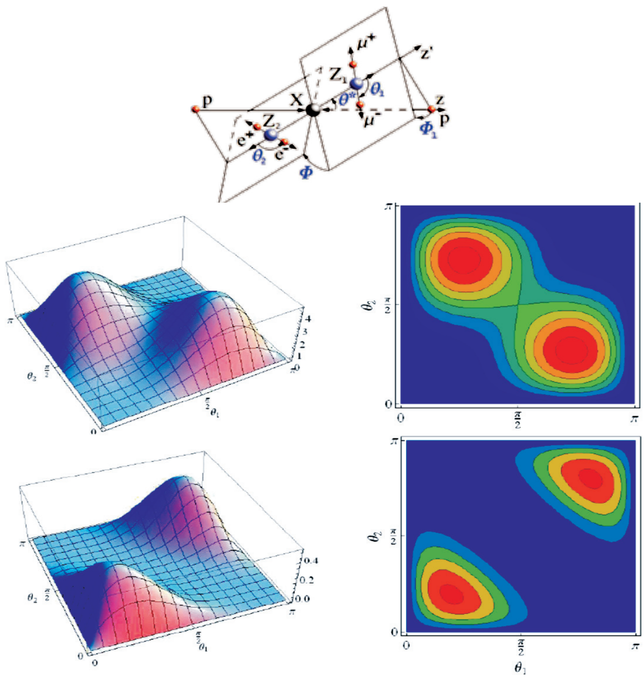

Fig. 2. Assessing the spin properties of the new resonance using the angle between the decay planes in H to ZZ in four leptons (left) and the polar angle distribution in H to WW in $ll\nu\nu$ (right). Upper plots are for a spin 2 particle to be compared with a spin 0 particle in the lower plots

More difficult will be to disentangle scalar from pseudo-scalar although a pseudo-scalar would not decay to WW. Still for the parity determination there will be discriminating power in looking at the angular distributions of the final decay products and again the decay mode in ZZ to four leptons will play a key role. There will be quite some sensitivity to distinguish a pure CP-even behavior of the new resonance with respect to a pure CP-odd one, while a mixture of the two would be difficult to distinguish at LHC.

2. IMPLICATIONS FOR THE SEARCHES FOR NEW PHYSICS

Even including a Higgs boson, we know that the Standard Model is an incomplete theory. It does not account for the presence of dark matter in the Universe; it does not explain neither the dark energy nor the mechanism producing the inflation; and we could add to the list of phenomena hinting at the need of new physics the neutrino masses and hierarchy, the bariogenesis, the asymmetry between matter and antimatter and so on.

A light scalar at 125 GeV has profound implications on the search for new physics. In some sense it will be a turning point forcing us to review some of the mostly used paradigms. A light mass scalar, could in principle rule its self-interaction and the Yukawa interactions with fermions in such a way that the theory could remain weakly coupled up to the Planck scale without any dynamics appearing beyond the Electroweak scale. This would be in itself an outstanding discovery: for the first time we would have observed a phenomenon that could be described by the same theory over 15 orders of magnitude in energy. It could also be that the dynamics responsible for stabilizing the Higgs boson mass might lie at such a large energy scale that it will be practically impossible to check it directly using accelerator based experiments.

Although possible, this scenario would be severely constrained by the need that the couplings of the Higgs boson must be finely tuned to very well predicted values. Therefore precision measurements of the Higgs coupling could lead CMS to unambiguous hints of the presence of New Physics beyond the Electroweak Symmetry Breaking scale.

2.1. Vacuum Stability and a Light Higgs Boson

With a heavy top quark and a light SM Higgs the stability of the Electroweak vacuum in our Universe could be at risk. If the Higgs at 125 GeV is real and we are here discussing about it, that means that the lifetime of our Electroweak vacuum is longer than the age of our Universe. For a Higgs mass in the range 124–126 GeV, and for the current central values of the top mass and strong coupling constant, the Higgs potential develops an instability around 10^{11-12} GeV, with a lifetime still much longer than the age of the Universe [6]. However, taking into account theoretical and experimental errors, stability up to the Planck scale cannot be excluded. It appears that we could be living in a dangerous meta-stable region.

A precise determination of the Higgs mass as well as a new round of measurements of the top mass will be key ingredients of these studies that could have possible implications on the mass of Right-Handed neutrinos, temperature reheating after the inflation, mechanism of the leptogenesis and so on.

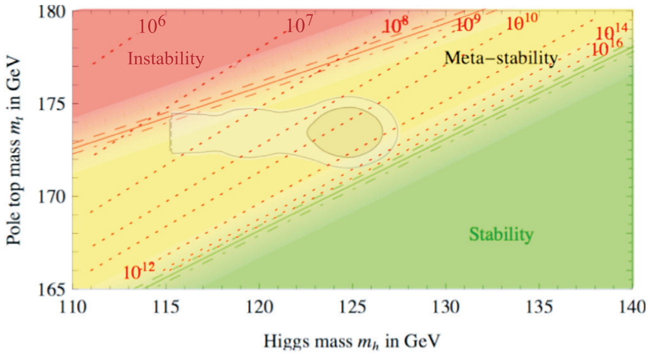

Fig. 3. Diagram of phase of the Electroweak Vacuum versus measured value of the top and Higgs mass (assuming the first hints of a 125 GeV Higgs at LHC would become soon a discovery). Different colors signal the regions corresponding to absolute stability, meta-stability and instability of the SM vacuum. The dotted contour lines show the instability scale Λ in GeV assuming $\alpha_s(M_Z) = 0.1184$

2.2. Dark Matter and a 125 GeV Scalar

The main motivation for an invisible Higgs boson decay width comes from the existence of Dark Matter (DM) in the Universe. Because Higgs boson decays to fermions dark matter are essentially ruled out by direct detection constraints, in this scenario the dark matter is naturally scalar. If the dark matter particles are two times lighter than the Higgs boson, they can lead to invisible Higgs boson width. Light Dark Matter in these models could easily kill the Higgs itself. In this respect a 125 GeV Higgs would be a very sensitive object since its width is very small and there is no much room left for invisible decays. Through a rough measurement of the ratio between the SM modes and the sum between the SM ones and the Dark Matter modes, many models based on scalar particles of masses < 50 GeV could be very likely ruled out even with preliminary data.

2.3. SUSY and a 125 GeV Scalar

Supersymmetry (SUSY) is the most popular extension of the SM invoking new particles at the TeV scale to solve the hierarchy problem.

A 125 GeV scalar will have profound implications on SUSY. In the SM, the Higgs mass is essentially a free parameter. In the Minimal Supersymmetric Standard Model, the lightest CP-even Higgs particle is bounded from above according to the expression

$$m_h^{\max} \approx M_Z|\cos 2\beta| + \text{radiative corrections} \leqslant 110\text{–}135\ \text{GeV}. \quad (1)$$

Therefore, imposing m_h places very strong constraints on the MSSM parameters through their contributions to the radiative corrections. Important parameters entering into the computation of the Higgs mass in the MSSM are $\tan\beta$ and M_A, the SUSY breaking scale, M_S and the mixing parameter in the stop sector, X_t. As a matter of fact, many SUSY models would be simply killed by the discovery of a 125 GeV scalar. For example, it would be too heavy to be accommodated in Minimal Anomaly or Gauge Mediated Symmetry Breaking Models (AMSN, GMSBM) or others that would be compatible only with a Higgs boson with a mass around 120 GeV [7]. Still a not negligible part of other models would survive for large values of the mixing parameter. Small stop masses would be still allowed in these models and all constraints could be compatible with 123 GeV $< m_h <$ 127 GeV but, then, we should also see anomalies in the coupling. The ratio of the decay modes $\gamma\gamma/ZZ$, WW/ZZ could be a powerful tool to further constrain the fraction of models compatible with all experimental data. Additional constraints could come from a precise measurement of the mass since, in this context, measuring 124 or 126 GeV for the mass of the Higgs, would indeed matter.

2.4. A 125 GeV Scalar and Extra-Dimensions

Models with Extra-Dimensions provide an interesting class of scenarios, in which the hierarchy between the Planck and electroweak scales is explained in terms of geometry. The Higgs phenomenology could provide a superb laboratory for probing new physics based on models of Extra-Dimensions.

Much like rare FCNC processes, Higgs production in gluon fusion and Higgs decays into the di-photon final state are loop-suppressed processes, which are very sensitive to not yet discovered, new heavy particles. If we assume that Extra-Dimensions will manifest themselves in a new spectrum of very heavy Kaluza–Klein resonances, we could see spectacular effects on Higgs production via gluon fusion. For Kaluza–Klein masses in the range of several TeV, therefore out of the direct reach at LHC, we could still have visible changes in the coupling of the 125 GeV scalar. For example, with a heavy KK gluon of mass around 7 TeV we could find significant enhancement (suppression) of the $h \to \gamma\gamma$ ($h \to gg$) branching ratios [8]. Again, a careful study of the Higgs couplings could lead to the first indirect evidence of these new states of matter. To disentangle some of these phenomena it will be very important to decouple different production mechanisms (gluon fusion vs VBF) for the $h \to \gamma\gamma$ decay mode; an exercise that CMS has shown already will be able to perform.

3. DETAILED STUDY OF A 125 GeV BOSON AT CMS

The Higgs boson of the Standard Model with a mass of 125 GeV sits in a very special place. It looks like magically placed exactly in the mass range in which we could directly access a large amount of its decay modes. In the low mass region we have already shown that we can study the decay modes in $\gamma\gamma$, $ZZ \to 4$ leptons, $WW \to ll\nu\nu$, bb and $\tau\tau$. For some of these channels we will be also able to study different production mechanisms trying to disentangle the main mechanism proceeding through gluon fusion from Vector Boson fusion or production in association with a Vector Boson.

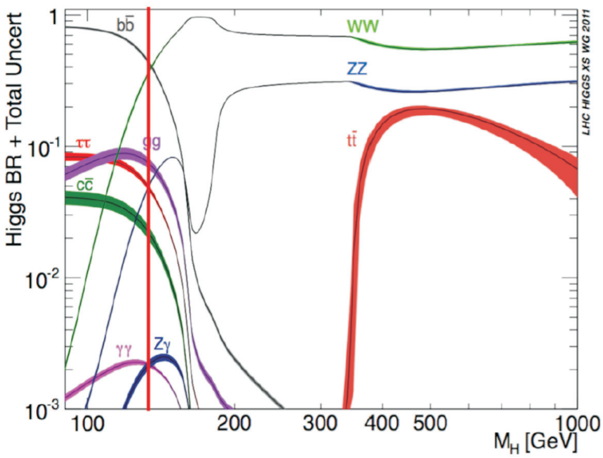

Fig. 4. SM Higgs boson branching ratios vs mass. The red line highlights the mass of 125 GeV

Additional channels and new decay modes are being added in the low mass region (i.e. $H \to Z\gamma$); very important in this respect are the exclusive modes in associated production, in particular $ttH \to ttbb$, that are currently being developed in CMS.

To perform precision measurements of the couplings we'll need also better theoretical predictions on the SM Higgs production cross section at 125 GeV. Gluon fusion mechanism, that is the dominant production mechanism at LHC, is still affected by a significative uncertainty $\sim 15\%$ that will soon become one of the main limiting factors.

The Higgs couplings are studied in CMS by measuring the branching ratios in various decays modes trying to separate different production mechanisms. Table 1 summarizes the current status of the activities for the various modes and the coupling parameters that we might be able to extract. As we can notice, the picture is quite complete and it will be soon possible to make quantitative statements on important quantities like the Higgs coupling to vector bosons, C_V, and on the custodial symmetry characteristics of the Electroweak Symmetry Breaking mechanism as driven by the Higgs field. Measuring the Yukawa coupling to fermions will be more difficult and will depend critically by the available statistics, on further improvements in the analysis and on our capability to study additional channels.

All preliminary studies will be done in the context of the Standard Model Higgs boson. The simplest way to relax this requirement will be to progressively relax the SM constraints assuming floating parameters in front of the SM coupling for fermions and for bosons allowing them to take values differing from 1. The best fit of these floating parameters to

Table 1. Production mechanisms and branching ratios in various decays modes studied by CMS to extract the couplings of the Higgs boson. The squares signal the channels that are currently covered

		BR (ll)	BR (bb)	BR (WW)	BR (ZZ)	BR $(\gamma\gamma)$	BR $(Z\gamma)$
		C_F, C_l	C_F, C_b	C_V	C_V	$f(C_F, C_V)$,$C\gamma$	$f(C_F, C_V)$
gg	C_F, Cg	□		□	□	□	
VBF	C_V	□		□	□	□	
WH	C_V		□	□	□		
ZH	C_V		□	□	□		
ttH	C_F, C_t		□		□		

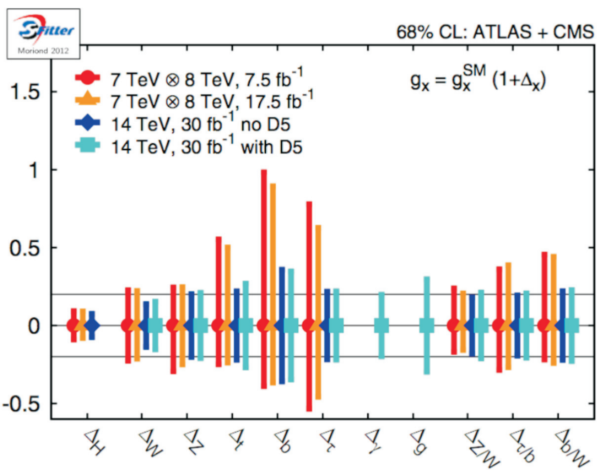

Fig. 5. Projections for an assumed SM Higgs boson at a mass of 125 GeV. The band indicates ±20% variation

the experimental data will be used to check if there is any kind of tension with respect to the SM hypothesis.

The prospects on the accuracy in measuring the Higgs couplings at LHC in the next few years are shown in Fig. 5 [9]. The plot illustrates the accuracies that could be achieved with 25 fb^{-1} of data collected at 7(8) TeV and 30 fb^{-1} at 14 TeV combining together ATLAS and CMS. The accuracy for the coupling to vector bosons is expected to be within 15–20%, while the measurement of the couplings to fermions will be much tougher, ranging between 20 and 40%.

CONCLUSION

Under the working hypothesis that the intriguing hints reported by ATLAS and CMS in December 2011 could be considered the first evidence of the presence of the Standard Model Higgs boson in LHC data, we have described the set of preliminary measurements that could be done to assess the properties of the new particle. We have then discussed the implications of a 125 GeV Higgs boson on the search for new physics and the importance of precision measurements of the coupling to vector bosons and fermions as a powerful tool to discriminate among several models and eventually detect the first evidence at LHC for new physics beyond the SM.

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