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Higgs physics at LHC

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Abstract. The large hadron collider (LHC) and its detectors, ATLAS and CMS, are being built to study TeV scale physics, and to fully understand the electroweak symmetry breaking mechanism. The Monte–Carlo simulation results for the standard model and minimal super symmetric standard model Higgs boson searches and parameter measurements are discussed. Emphasis is placed on recent investigations of Higgs produced in association with top quarks and in vector boson fusion channels. These results indicate that Higgs sector can be explored in many channels within a couple of years of LHC operation, i.e., $\mathcal{L} = 30$ fb^{-1}. Complete coverage including measurements of Higgs parameters can be carried out with full LHC program.

Keywords. Higgs; standard model; supersymmetry.

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1. Introduction

The standard model of elementary particle physics has enjoyed unprecedented success in explaining very precise data acquired in the past several decades of experimentation. However, the electroweak symmetry breaking (EWSB) Higgs sector [1,2], which provides the necessary masses for the vector bosons that mediate weak interactions, remains elusive. The recent limits from direct searches [3,4] and improvements in the measurement precision of the standard model parameters [5] indicate that the Higgs boson must lie just beyond the explored energy range.

Higgs boson searches using the data acquired in e^+–e^- collisions at $\sqrt{s} \approx 200$ GeV LEP-II experiments at CERN are being finalized [3,4]. Those results rule out at 95% confidence level standard model like Higgs with masses up to 114.4 GeV. Combined fits to precision electroweak parameter measurements made by LEP and SLD running at the Z-pole, Tevatron, and fixed target experiments provide an indirect upper limit on the standard model like Higgs at 193 GeV [5]. The initial hopes for early discoveries in the Higgs sector at the Fermilab are now dampened due to revised projections of Tevatron luminosity profile. The quest for Higgs will be resumed in about 4 years time using the large hadron collider which is under construction at the CERN laboratory. The LHC is designed to definitively explore the Higgs sector and the EWSB mechanism. In this report we discuss the simulations of the LHC performance in discovering Higgs boson(s) and measuring

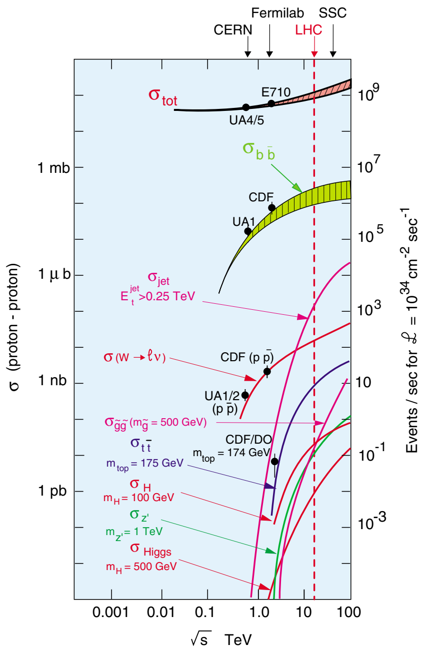


Figure 1. Cross-section vs. center of mass energy and event rates corresponding to full luminosity LHC for various physics processes are shown.

parameters of that sector in various scenarios within and outside the standard model.

The LHC will collide protons on protons at 14 TeV center of mass energy with an initial luminosity of 10^{33} cm^{-2} s^{-1} in 2007, and will ramp up to $\mathcal{L} = 10^{34}$ cm^{-2} s^{-1} by the end of the decade. The standard model processes and any new physics phenomena that may be responsible for EWSB, e.g., super symmetry (SUSY), can be studied in the resultant TeV scale parton–parton interactions. Higgs bosons and super particles with masses up to a TeV can be directly produced. Unfortunately, both the rate of strong interaction physics at electroweak scale, and per event hadron multiplicity are very large. For example, it is seen that at LHC, the event rate is as high as 1 kHz for jets of $E_{\mathrm{T}} = 250$ GeV (figure 1). At high luminosity, $\mathcal{L} = 10^{34}$ cm^{-2} s^{-1}, an average of 17 collisions occur for each 25 ns crossing time, leading to a billion proton–proton interactions per second. The LHC events have an average charge particle multiplicity of about 1000. Extraction of signals, particularly those of the Higgs decays ($< 10^{-3}$ Hz as seen in figure 1), from the profusely produced standard model background requires exploration of low branching fraction ($10^{-2} - 10^{-3}$) leptonic or photonic modes with good energy resolution. Therefore, detectors with good resolution and high degree of segmentation, that can withstand a very high rate environment, are necessary. Further, a trigger and data acquisition system that can weed out the well-understood background, while retaining the interesting high energy physics is required. Recent improvements to the trigger electronics

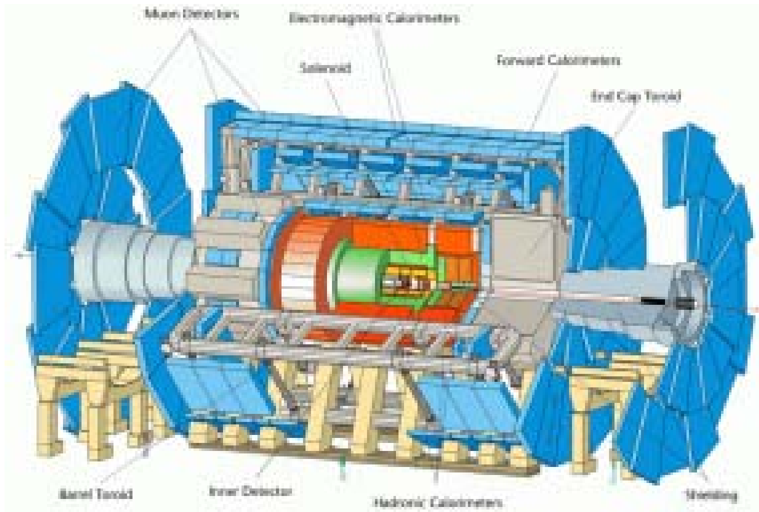


Figure 2. The ATLAS detector showing its subsystems.

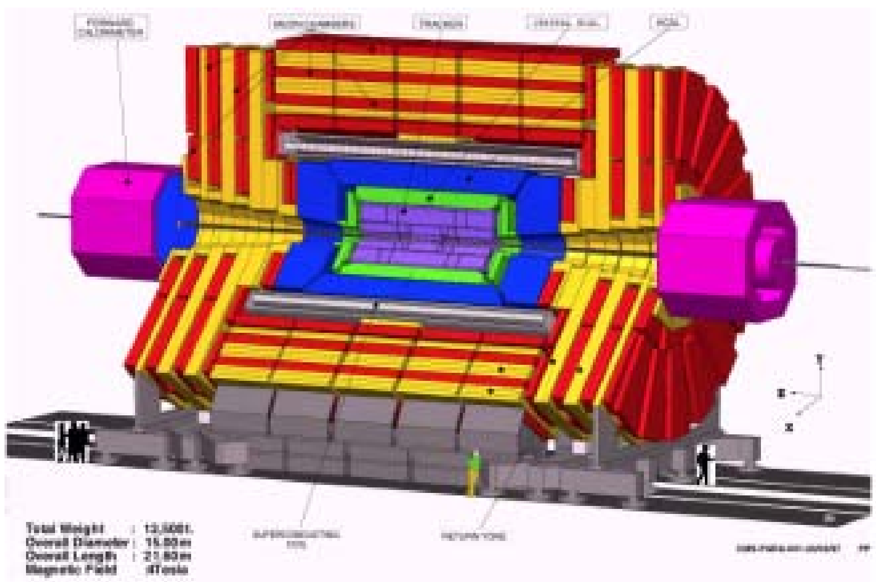


Figure 3. The CMS detector showing its subsystems.

and refinement of the analysis techniques is enabling Higgs sector exploration in hadronic decays of τ leptons and b-quark jets as well. Both ATLAS [6] and CMS [7] detectors (see figures 2 and 3) at the LHC are designed to study the TeV scale physics in this harsh environment. While both ATLAS and CMS are designed to address all aspects of high-$P_{\rm t}$ physics, here we concentrate on their ability to measure the Higgs sector.

Both the detectors have large central charged particle tracking systems immersed in central solenoidal magnetic field. The tracker is surrounded by calorimeters, that are segmented to measure electromagnetic showers with high precision, and jets with large $E_{\rm T}$. Outside the magnetic field return, which also serves as absorber, chambers are placed to detect muons. The extraction of the interesting EWSB and new physics signatures while rejecting the profusely produced strong interaction background, well described by quantum chromodynamics (QCD), is a challenging task for the trigger and event selection systems [7].

2. Triggering LHC physics

Sophisticated triggering is required to save the interesting physics while suppressing the profuse standard model background. The interaction rate is reduced from 40 MHz to 100 kHz using custom electronics at the first level trigger (L1). The high level trigger (HLT) algorithms running in the data acquisition system (DAQ) which includes scalable and programmable computer farms reduces this rate further down to 100 Hz for detailed offline analysis.

The L1 system uses only coarsely segmented data from calorimeter and muon detectors, while holding all the high-resolution data in pipeline memories in the front-end electronics, and produces a decision within 3.2 μs, resulting in a maximum of 100 kHz rate. Efficiencies and rate capability of the L1 triggers are particularly problematic and have been simulated extensively. At high luminosity, trigger energy cut-offs, with 90–95% efficiency, can be maintained at about 30 GeV for single electrons and photons, 25 GeV for single muons, 150 GeV for τ jets, 20 GeV each for double electrons and photons, 10 GeV each for double muons, 80 GeV each for double τ-jets, 300 GeV for missing transverse energy and 300 GeV for single jets down to 100 GeV each for multiple jets, while limiting the background rate within the acceptable DAQ bandwidth. Thresholds can be about 30% lower in the initial low luminosity running period. High efficiencies (>90%) are realized for many physics processes of interest, e.g., Higgs decays to photons, leptons, whereas, acceptance of W decays to single isolated leptons is a modest 70%. Dedicated electronics for identifying narrow jets from hadronic τ decays and improved coverage of multi-jet triggers is now providing access to new channels for Higgs searches that are discussed here.

The HLT software reconstructs the 100 kHz event stream using sophisticated algorithms to identify and classify events, in several steps, making use of as much data as needed, and taking up to several 100 ms, producing 100 Hz event stream for offline storage and detailed analysis. Both ATLAS and CMS have demonstrated several HLT algorithms that are able to retain the L1 efficiencies while reducing the backgrounds to acceptable level. These algorithms are able to significantly improve the resolution of leptons and photons by including the full granularity data and tracker information. Further, HLT algorithms also identify τ lepton and b quark jets. The HLT essentially runs the first stage of physics analysis online.

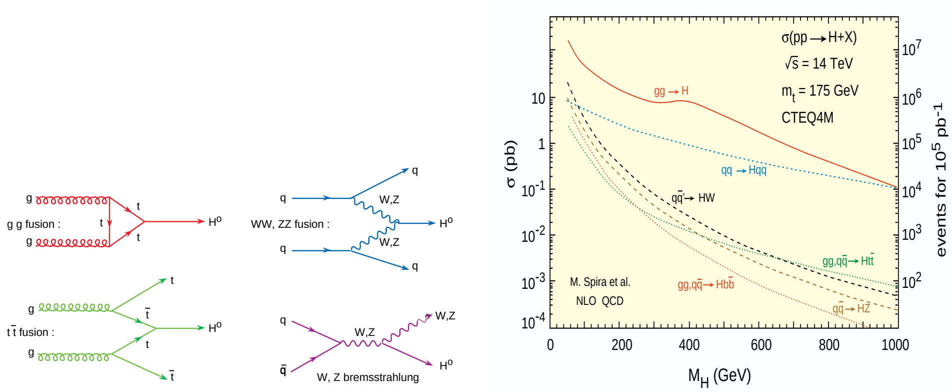


Figure 4. The standard model Higgs production diagrams and their contributions to cross-section (event rate at LHC) are shown as a function of M_H.

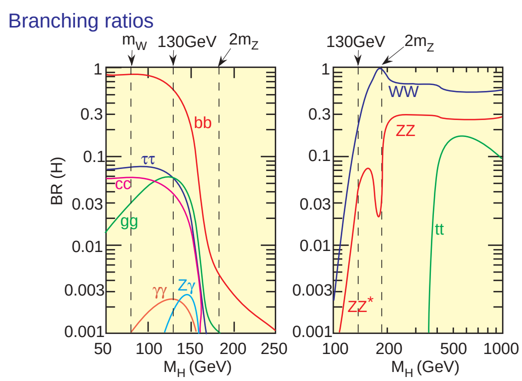


Figure 5. The standard model Higgs decay branching fractions as a function of M_H.

3. The standard model Higgs

The standard model (SM) Higgs boson production (see figure 4) at LHC is dominated by gluon fusion for low masses of Higgs. However, weak boson fusion and associated production with W, Z and top have distinct advantages in being able to suppress QCD background. The production rates [8] at LHC, as a function of Higgs mass, are also shown in figure 4. The SM branching fractions of Higgs decays are shown in figure 5 as a function of M_H. A variety of channels have been simulated by both ATLAS and CMS to cover the entire M_H range allowed. These simulations indicate that not only the SM Higgs will be discovered at LHC, if it exists, but also measure some of its parameters to good accuracy.

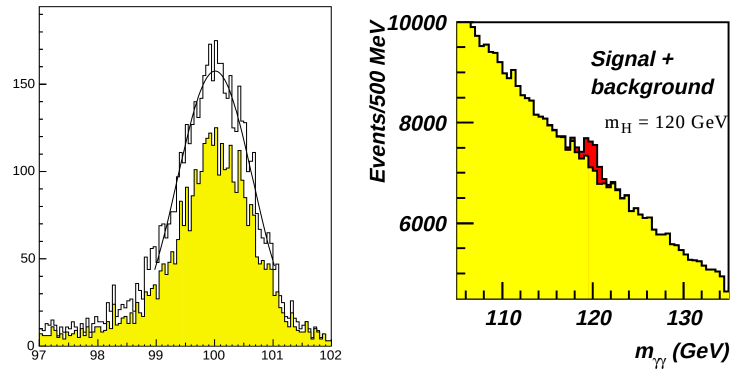


Figure 6. CMS simulations of background subtracted signal, including the recovered photon conversions (left, $M_H = 100$ GeV) and signal+background (right, $M_H = 120$ GeV) for the standard model Higgs decay to two photons are plotted vs. the reconstructed diphoton invariant mass.

3.1 $H \to \gamma\gamma$

The low mass ($M_H \approx 120$ GeV) Higgs decays predominantly to pairs of b quarks and τ leptons. This signal, especially when produced in gluon fusion process, is expected to be swamped by QCD backgrounds. Therefore, both ATLAS and CMS invested greatly in high resolution electromagnetic calorimetry to observe it in two-photon decay. Higgs decay to two photons is the most promising discovery mode for low masses. The crystal ECAL resolutions dominate the signal measurement capability. Figure 6 shows the diphoton invariant mass spectrum, after statistical subtraction of the background. Better than 5σ significance discovery is feasible in the Higgs mass range 80–150 GeV even after including the detector resolutions and reconstruction efficiency with about 30 fb^{-1}.

3.2 $t\bar{t}H(\to b\bar{b})$

Our recent efforts have been focussed on studying the low mass Higgs decays to dominant b quarks and τ leptons (BF = 5%) in top associated production and vector boson fusion channels respectively.

The $t\bar{t}H(\to b\bar{b})$ events are especially rich in b jets. These events are triggered using isolated electron from the t quark decay. The analysis proceeds by identifying the top events at high level trigger. Offline, good b jet tagging efficiency is critical for accessing these Higgs that decay to b quark pairs. Simulated CMS b jet tagging efficiency is also shown in figure 7. Using this detailed analysis we extract the signal for $H \to b\bar{b}$ as shown in figure 7. To observe a 5σ significance signal requires greater than 30 fb^{-1}.

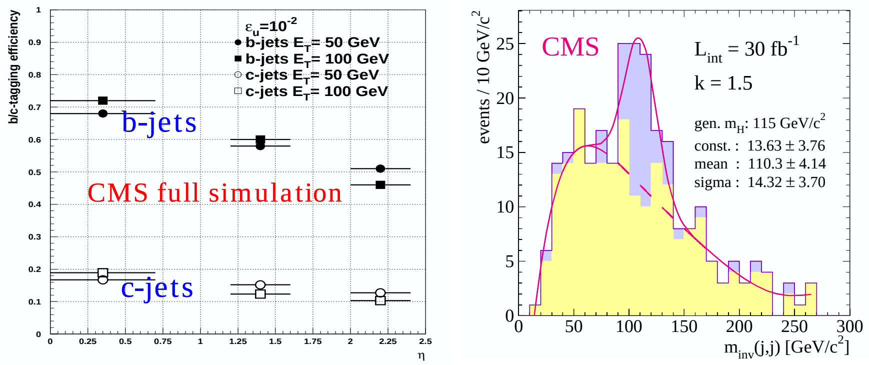


Figure 7. CMS detector b jet tagging efficiency (left) and signal for $pp \to t\bar{t}H(\to b\bar{b})$ (right) are shown.

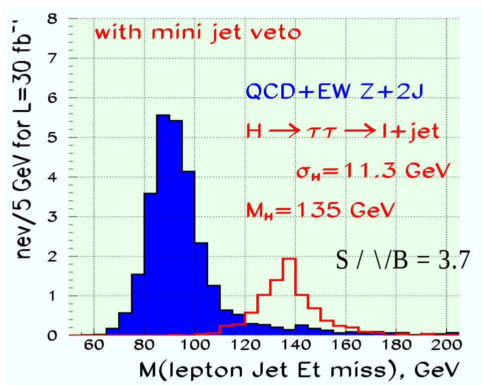


Figure 8. CMS simulation of Higgs decays to τ pairs is shown for the case where one τ decays into a lepton whereas the other decays hadronically.

3.3 $qqH(\to \tau\tau)$

Recent progress in the phenemenology of Higgs production in vector boson fusion mechanism [9] has been followed by both ATLAS and CMS Collaborations. The development of dedicated L1 τ jet triggers and focus on measuring low $E_{\rm T}$ jets in the forward region have enabled substantial gains in access to $H \to \tau\tau$ in hadronic decays of the τ as well. The mass peak, with 8% resolution, for $H \to \tau\tau$ is seen in figure 8.

3.4 $qqH(\to WW^*)$

We have also studied the Higgs decays to WW^* at this low mass, again taking advantage of reduced backgrounds for the vector boson fusion mechanism [9]. We use the tag jets in the forward calorimeters and require that one W decays into $e\nu$

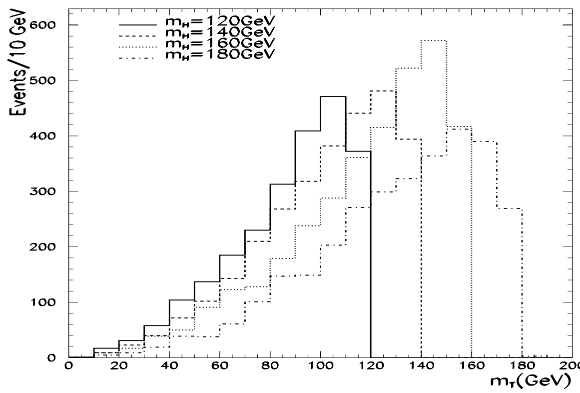


Figure 9. The transverse mass distribution of Higgs that decays to WW^*, $M_H = 120$–180 GeV is shown for the case where W decays into leptons.

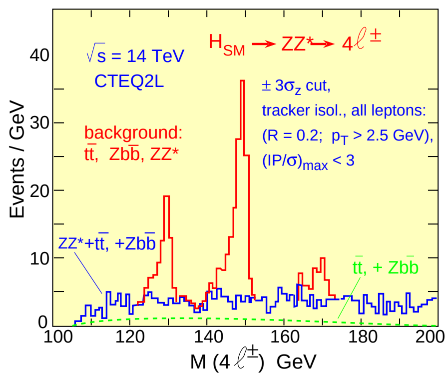


Figure 10. CMS simulation of Higgs decays to ZZ^*. $M_H = 130, 150, 170$ GeV is shown for the case where both the Z bosons decay into leptons.

and the other into $\mu\nu$. The presence of substantial missing transverse energy in the event is also required. Further, we exploit the fact that the spin correlations are such that the two leptons are emitted in the same direction. The lepton momenta and the missing transverse energy are combined to form transverse mass, as shown in figure 9. The backgrounds from $t\bar{t}$, Wt and WW events is estimated to be manageable. Both ATLAS and CMS see that 5σ discovery is possible with as low as 10 fb^{-1}.

For masses $M_H > 130$ GeV, $H \rightarrow ZZ^*$ opens up. The leptonic decays of Z provide excellent signal with very low background as seen in figure 10. The higher cross-section gluon fusion production channel is suitable for this mode.

Higgs bosons with masses greater than twice the mass of the Z boson are well-reconstructed with little background in lepton channels. Neutrino and quark jet modes can also be included to mitigate the substantially reduced cross-section for these high mass Higgs.

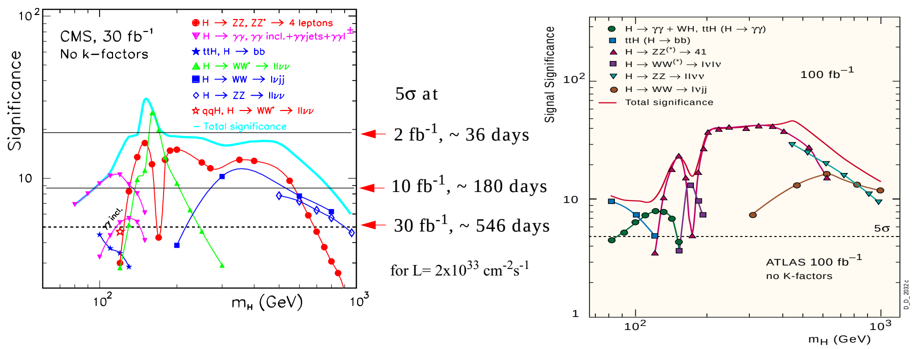


Figure 11. Significance of CMS (left) and ATLAS (right) simulations for various modes and their total is plotted vs. M_H. Horizontal lines are drawn to indicate the significance at various integrated luminosities.

3.5 *SM Higgs reach*

The summary of all the modes studied by both CMS and ATLAS is presented in figure 11. These simulation results indicate that the LHC experiments will begin probing the SM Higgs sector with as little as 10 fb^{-1} and are able to fully cover the range allowed by the precise LEP measurements of electroweak parameters with 30 fb^{-1}.

With the full program of LHC, e.g., 300 fb^{-1}, ATLAS and CMS can not only discover the Higgs but they can also measure its parameters [10]. The SM Higgs mass and the width can be measured to better than 0.3% and 1% respectively, using lepton and photon channels. The production cross-section will be measured to 20% with a systematic uncertainty of 5–10% on the luminosity. Although the absolute couplings cannot be measured well, ratios of couplings can be measured. About 20% accuracy can be achieved on Γ_W/Γ_Z from direct or indirect techniques by using Higgs decays to WW^*, $\gamma\gamma$ and ZZ^*. Yukawa couplings can be accessed using Higgs decays to $\tau\tau$ and $b\bar{b}$ to measure Γ_τ/Γ_W and Γ_b/Γ_W at 20% level.

4. Minimal supersymmetric standard model

The minimal supersymmetric standard model Higgs sector consists of three neutral bosons h, H and A, and two charged bosons $H^{\pm}$. Two independent parameters, e.g., M_A and the ratio of vacuum expectation values, $\tan\beta$, are sufficient to describe the Higgs sector. The LEP 95% confidence level limits on masses of MSSM Higgs are about 91 GeV for neutral and 79 GeV for charged Higgs respectively [3,4]. Further, low $\tan\beta$ is excluded by LEP results.

The light MSSM neutral Higgs can be studied in the same channels as in the standard model. With full data set for ATLAS and CMS, $\mathcal{L} = 600\ \text{fb}^{-1}$ the entire M_A–$\tan\beta$ plane is covered as shown in figure 12.

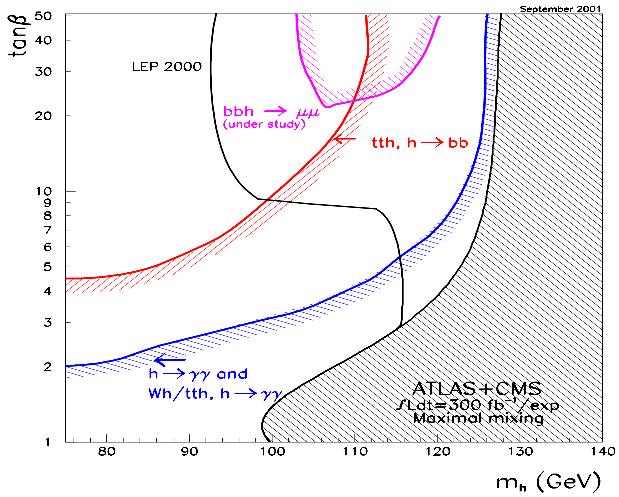


Figure 12. The summary of coverage of MSSM parameter space with various neutral light MSSM Higgs decay modes is shown for full luminosity of ATLAS–CMS.

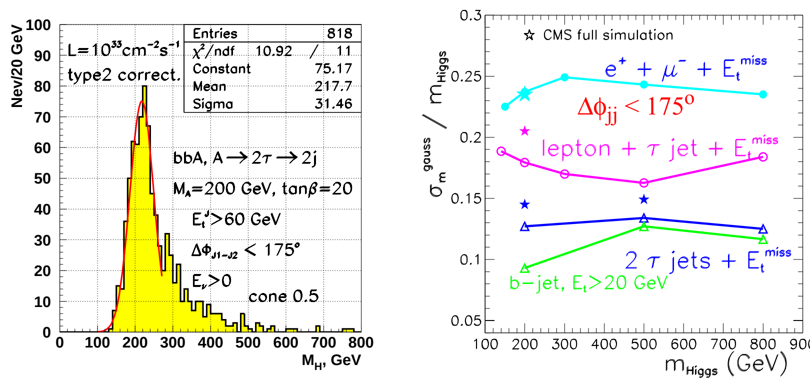


Figure 13. MSSM heavy Higgs mass peak (left) for its decay to τ jet pairs is shown ($M_H = 200$ GeV). Mass resolutions (right) for leptonic and hadronic decays of τ are shown as a function of M_H.

The heavy neutral Higgs bosons H and A have enhanced couplings to b quarks and τ leptons. Therefore, τ jet, forward jet L1 triggers, and HLT b jet tagging are necessary. The CMS simulation of the heavy Higgs decay to τ jet pairs is shown in figure 13.

The lower branching fraction $gg \to b\bar{b}H(\to \mu\mu)$ channel (BR $= 3 \times 10^{-4}$) is accessible as shown in figure 14, and provides excellent mass resolution. The signal is visible even when H mass is close to that of Z. Background from Drell–Yan μ-pair production is suppressed with b jet tagging. Central jet veto suppresses top decay.

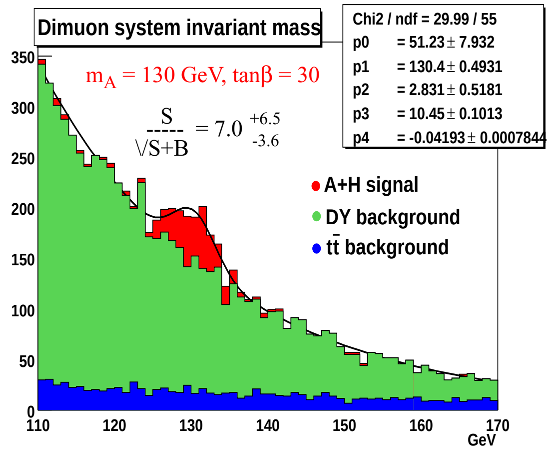
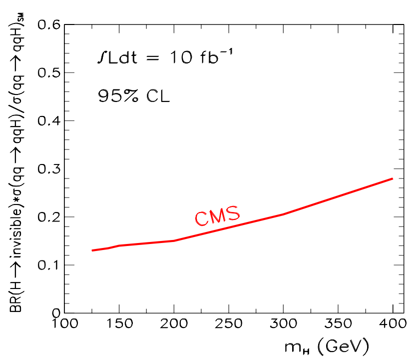


Figure 14. Signal for low mass H and A in $\mu^+\mu^-$ channel is shown above the Drell–Yan background.



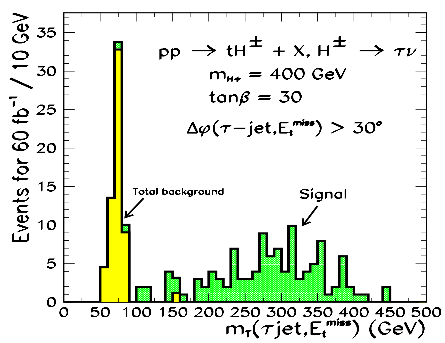


Figure 15. Reach for discovery of neutral heavy Higgs in its potential decays to invisible particles (left) and reconstructed transverse mass spectrum for charged Higgs decay to $\tau\nu$ (right) are shown.

There are regions of MSSM parameter space where the neutral Higgs decays predominantly into non-interacting particles. These invisible Higgs events are studied using vector boson fusion production. The trigger is provided by the missing transverse energy and the forward jets which are not color connected. These forward jets with large $\Delta\eta$ separation also have large invariant mass. Background is further suppressed by vetoing on any events with activity in the central detector. The left plot in figure 15 shows that CMS can find these events when the invisible branching fraction is 10–20% for a wide range of M_H with as low as 10^{-1} luminosity. This study is feasible during low luminosity operation when there are no multiple interactions in beam crossings.

5σ significance discovery contours for these and several other modes for heavy MSSM Higgs in the explorable MSSM parameter space are shown in figure 16 for

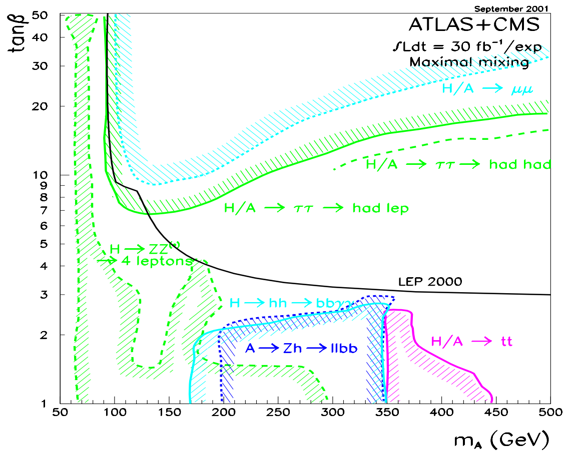


Figure 16. The summary of coverage of MSSM parameter space with various heavy neutral Higgs (H, A) decay modes is shown.

integrated luminosity of $\mathcal{L} = 30$ fb^{-1}. There is a significant moderate $\tan\beta$ and large M_A region for which heavy neutral Higgs (H, A) will not be accessible at LHC. However, in this parameter range, the lighter neutral SM like Higgs (h) will be found.

The charged Higgs decay, $H^+ \to \tau\nu$, is the dominant mode for $M_{H^+} < M_{\mathrm{t}}$. Production of the charged Higgs in top quark decays is the dominant mode for low masses and $\tan\beta$. Most of that region is excluded by the LEP searches. Therefore, associated production with top is the main channel for charged Higgs analysis. Trigger is not a big issue for these channels due to the presence of top quark. The isolated τ jet reconstruction discussed in the context of neutral MSSM heavy Higgs is important. For the latter channel, the single top quark is reconstructed in its purely hadronic channel with b jet tagging. Transverse mass of the charged Higgs ($M_{H^+} = 400$ GeV, $\tan\beta = 30$) reconstructed from the τ jet and the missing transverse energy is shown in the right plot of figure 15. The signal is well-separated from backgrounds.

For very large charged Higgs masses, the decay channel $gb \to tH^+(\to tb)$ opens up. In this case in addition to selecting the event with tag top quark one needs also to reconstruct t and b jets from the H^+ decay. The background for this process is significant but can be measured using the data itself.

5σ significance discovery contours for all these modes in the explorable MSSM parameter space are shown in figure 17 for integrated luminosity of $\mathcal{L} = 30$ fb^{-1}.

These simulations indicated that at least one of the MSSM Higgs will be visible in the entire parameter space at the LHC. In much of the parameter space two or more Higgs bosons will be visible. There is a premium on improving the coverage using new analysis techniques and new decay channels.

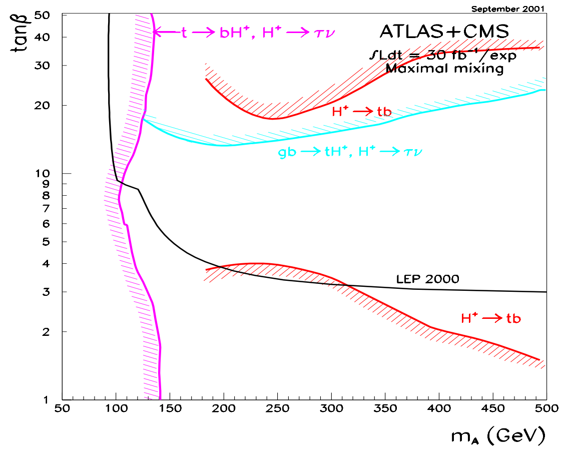


Figure 17. The summary of coverage of MSSM parameter space for charged Higgs decay is shown.

5. Summary

The ATLAS and CMS detectors at LHC are being built to explore exciting TeV physics frontier and expected to be in operation in 2007. The simulation studies indicate that these experiments have the potential to make definitive discoveries in the Higgs sector. Studies discussed here indicate that both the standard model and the minimal supersymmetric model Higgs sector can be fully explored.

Simulation of other new physics processes not discussed here also indicate high potential for discovery. Although, the detector and the trigger systems are optimized with the studies of the benchmark processes in the standard model and MSSM, they are designed to be flexible to enable discoveries in hitherto unexpected fronts.

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