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# Search for Higgs and Supersymmetry

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# Search for Higgs and Supersymmetry

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**Abstract.** The search for the Higgs boson and the search for supersymmetry at the LHC collider are summarized. Particular attention is payed to the LHC potential to study the properties of the Higgs boson as well as the potential of future upgrades of the LHC and the ILC to determine supersymmetric parameters.

## 1. Introduction

The Standard Model of particle physics [1–3] describes successfully matter and its interactions to unprecedented precision. The only missing particle is also the only fundamental scalar: the Higgs boson [4–8] whose mass is not predicted by theory but constrained to the intermediate mass range.

Even with a discovery of the Higgs boson, other questions remain open to which a supersymmetric extension of the Standard Model could provide an answer. Supersymmetry can ensure the unification of the gauge couplings at a high scale. This scale is close to the Planck scale, potentially opening the route to the unification with gravity. Supersymmetry also stabilizes the mass of the Higgs boson at the electroweak scale. Last but not least, many supersymmetric models provide a candidate for dark matter.

The LHC [9] has started operations with the experiments ATLAS [10] and CMS [11] recording roughly 5 $\text{fb}^{-1}$ of data in 2010 and 2011 at a center-of-mass energy of 7 TeV. In 2012 the center-of-mass energy was increased to 8 TeV. The prospects for the discovery of the Higgs boson and/or new phenomena have been summarized in many studies [12, 13].

In the following, first the search for the Higgs will be summarized. Then the determination of the couplings of the Higgs boson with the current data as well as the projection to the future is discussed. Searches for Higgs bosons in models extending the Standard Model are then discussed. Finally the status of the search for supersymmetry will be presented and as outlook the bottom-up reconstruction of supersymmetric parameters will be discussed. All experimental methods are illustrated at a center-of-mass energy of 7 TeV. The results are summarized including 8 TeV.

## 2. Standard Model Higgs boson (low mass)

The search for the Standard Model Higgs is generally separated into a low mass region and a high mass region. In the high mass region the partial widths for decays to pairs of W and Z bosons dominate the total width. A low mass Higgs boson will decay predominantly to b-quark pairs. The precision measurements of the parameters of the Standard Model at LEP and the TeVatron are compatible with a low mass Higgs boson [15]. For the sake of concreteness, in the following only the results for a low mass of $120 - 130$ GeV will be discussed.

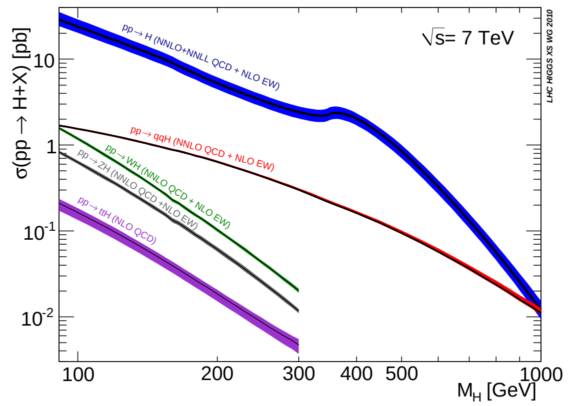


**Figure 1.** The Higgs production cross section is shown as function of the mass for a center-of-mass energy of 7 TeV [14].

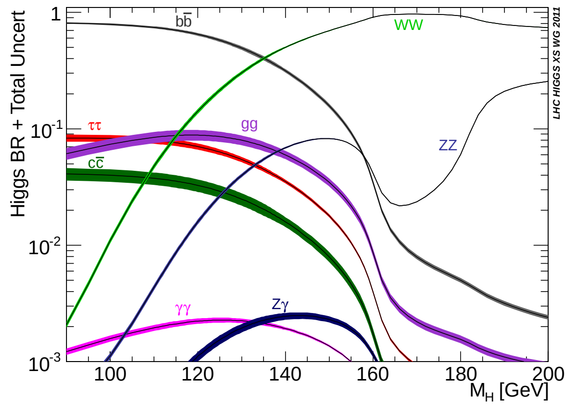


**Figure 2.** The branching ratios of the Standard Model Higgs boson are shown as function of mass [14].

The Standard Model Higgs boson is produced at the LHC predominantly in the gluon fusion process as shown in Figure 1 from [14, 16–24]. The weak boson fusion (VBF) is about an order of magnitude smaller. Higgs-strahlung, the associated production of the Higgs boson together with a weak boson is possible, but suffers from a very large background. The abundant production of top quark pairs opens up the channel $ttH$. This channel however is more promising at higher center-of-mass energies.

The branching ratios of the Standard Model Higgs boson are shown in Figure 2 from [14, 25]. At low mass the largest branching ratio is to pairs of b-quarks. The branching ratio to $\tau$-leptons is about an order of magnitude smaller. Decays to pairs of W and Z bosons also have a non-negligible contribution. At a mass of 125 GeV, rare decays such as the decay to pairs of photons, are typically of the order of $10^{-3}$.

At low mass the QCD background is so overwhelmingly large that the search for the hadronic decays of the Higgs boson is very difficult, unless it is accompanied by a vector boson or a pair of top quarks. Therefore the most promising channels for this mass region are the leptonic decay modes, either via the decay of the vector bosons or through $\tau$ pairs. The golden channels are the decay to a pair of leptonically decaying Z bosons and the rare decay to two photons as the mass of the Higgs boson can be reconstructed with good precision. The general strategy is to devise an analysis dedicated to an inclusive final state and then further enhance the separation between signal and background by separating the selected final state according to the production mode, e.g., gluon fusion with 0-jets, VBF with two jets etc, where further dedicated cuts are applied.

The different production and decay modes which will be discussed in the following are the fruit of a long dedicated effort of theorists and experimentalists. All of the discovery channels shown have been identified and scrutinized for many years, see e.g. [26–31].

The Higgs boson decay to pairs of $\tau$-leptons is difficult because the neutrinos of the $\tau$ decays make the mass information is less precise than in other channels. The presence of a jet recoiling against the Higgs boson such as in the VBF production at LO or in gluon fusion at NLO, improve the information for mass reconstruction. CMS has three event categories and reconstructs the $\tau\tau$ mass with a likelihood technique to improve the mass resolution [32]. However the 0/1-jet channel remains difficult. The situation improves, e.g. shown by ATLAS [33], for the VBF category where two jets are reconstructed. The signal can be separated from dominant background of the Z boson decays, but unfortunately no clear excess is observed.

The Higgs-strahlung process, where the Higgs boson decays to a pair of b quarks and the

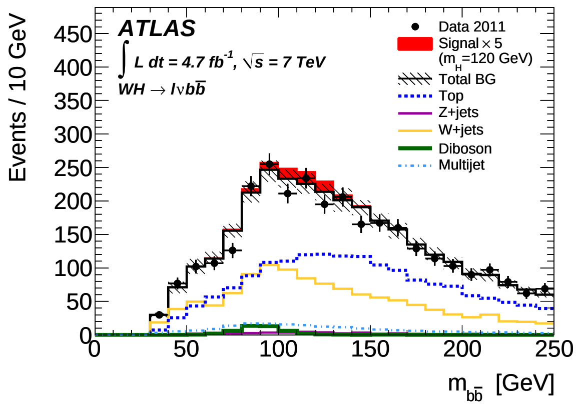


**Figure 3.** The distribution of the reconstructed Higgs boson mass in b-jets is shown for the production in association with a leptonically decaying W boson for ATLAS [35].

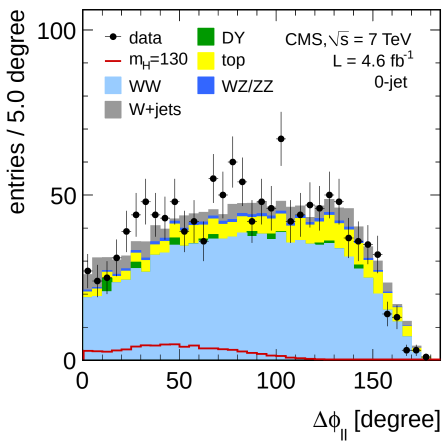


**Figure 4.** The distribution of the azimuthal angular separation between the leptons is shown for the CMS search in the WW final state [39].

weak boson does not decay hadronically, provides access to the main decay channel of a light Higgs boson. In contrast to the $\tau\tau$ channel the mass information can be used directly via the reconstructed b-tagged jets to reconstruct the Higgs boson mass. The channel is nevertheless difficult as the background is very large and the mass resolution for hadronically decaying resonances is less good than for final states with leptons. ATLAS and CMS have searched for this channel in the data [34, 35]. Even after the application of sophisticated methods such as boosted decision trees [34] and requiring b-tagged jets, the background remains dominant and in some of the categories, as shown in Figure 3, it has almost the same form as the signal. This makes the determination of the background from the data challenging. The future will tell whether subjet analyses [36–38] will allow to improve significantly the search for decays to b quarks.

Turning now to the three most promising channels at low mass involving leptons, or photons, the first channel to be considered is the decay to W boson pairs followed by leptonic decays. In the following leptons will be restricted to mean electrons and muons. Here the mass information is very weak as two neutrinos are present in the final state.

As in the other channels the events are divided into different categories as function of the jet multiplicity as well as the lepton flavor by ATLAS and CMS [39, 40]. The background dominating this search is the pair production of W bosons. To differentiate between signal and background one variable is of particular importance, the azimuthal separation of the reconstructed leptons. As shown by CMS in Figure 4 the background is flattish while the signal, due to the scalar nature of the Higgs boson, the angle is small as a result of helicity conservation. Instead of reconstructing the visible mass, inevitably spoiled by the neutrinos, the transverse mass has a peak structure. The peak is not at the nominal mass, but only roughly 5 GeV below as the two leptons are reconstructed close together. For this channel the background is determined from control regions. It is important to have an excellent control of the transverse missing energy.

The decay of the Higgs boson to a pair of Z bosons, one of the golden channels, where one of the Z bosons is off-shell, is intrinsically clean when concentrating on the leptonic decays of the Z bosons. Here only the electroweak production of Z boson pairs (on and off-shell, the latter including a photon) contribute to the background. The main difficulty is to have good lepton identification with a good efficiency and low misidentification down to low transverse momenta

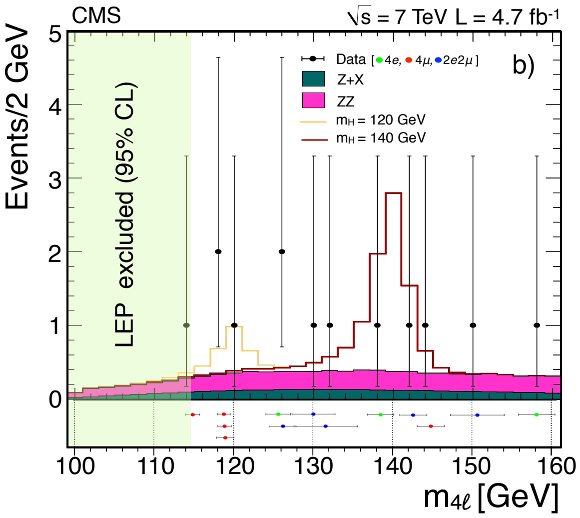


**Figure 5.** The invariant mass of the ZZ final state decaying to leptons is shown for CMS [41].

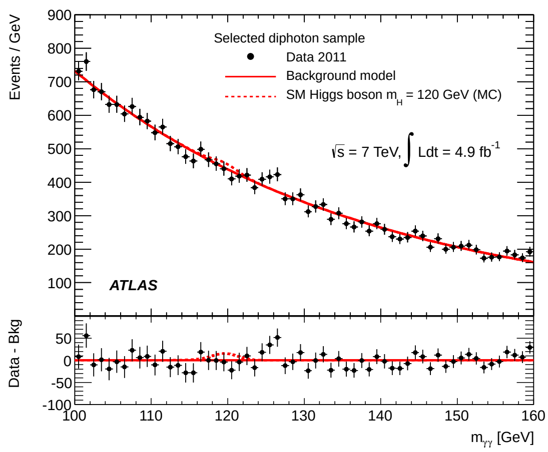


**Figure 6.** The final state $\gamma\gamma$ is shown for [44] together with the line corresponding to the background model.

of order 5 GeV. While the branching ratio of the Higgs boson to Z pairs is large, the leptonic branching ratio of the Z boson is small. At high mass the background is dominated by the leptonic decays of the Z boson pair production, whereas at low mass the relative contribution from the production of a Z boson plus jets is stronger. The ATLAS and CMS results in this channel [41, 42], shown as an example in Figure 5 for CMS, show at low mass an intriguing accumulation of data around 125 GeV. The Standard Model background is well described.

The final channel is a rare decay channel, the decay to a pair photons. The small branching ratio is offset with the excellent mass resolution for this channel which is better than 2 GeV. The calorimeter and tracker information can then be used to reduce the background due to the misidentification of jet as a photon below the level of the background from the Standard Model continuum production of two photons. The resolution of the invariant mass reconstruction is affected by the knowledge of the position of the primary vertex. ATLAS and CMS employ different techniques [43, 44] in this respect. While CMS relies strongly on the tracker, ATLAS uses the directional information in the calorimeter in order to improve the resolution. The material in front of the calorimeters in ATLAS and CMS is not constant as function of the polar angle. This leads to a variation of the resolution of the photons as function of the polar angle. The photons can convert before reaching the detector. It is therefore natural to split the event sample according to the expected resolution and into converted/non-converted photons. This categories differ naturally between the two experiments. The combined spectrum is shown in Figure 6 for ATLAS. As expected for the low branching ratio of this final state, the background is very large with respect to the expected signal. However the use of the data outside the probed Higgs mass allows to determine the background in the Higgs mass window from the data in a theory independent way. Nevertheless the form of the background distribution has also been checked with with the Monte Carlo. Around 125 GeV an intriguing excess of events is observed in the data of the two experiments above the background expectation as expected from the properties of a Standard Model Higgs boson.

The search for the Higgs boson at the TeVatron is complementary to the search at the LHC. Here the dominant channels are the production of the Higgs boson in association with an electroweak boson, followed by the decay of the Higgs boson to a pair of b-quarks. This

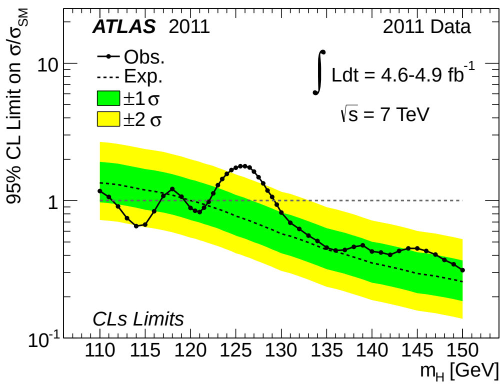


**Figure 7.** The 95% C.L. limit on the excluded Higgs boson cross section normalized to the Standard Model Higgs production cross section from ATLAS is shown as function of the Higgs boson mass [46].

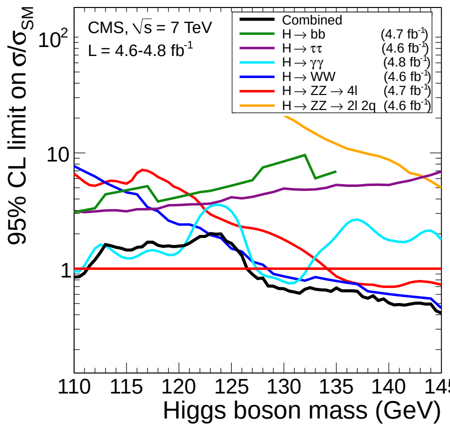


**Figure 8.** The 95% C.L. limit on the excluded Higgs boson cross section normalized to the Standard Model Higgs production cross section from CMS is shown as function of the Higgs boson mass [47].

search is promising as the Standard Model backgrounds for these channels are much lower than at the LHC due to the lower center-of-mass energy. The full combination of the collaborations CDF and D0 for all channels has been performed [45]. In the low mass region, as from roughly 115 GeV to 140 GeV, an excess with respect to the Standard Model background expectation is observed. The maximal (local) excess is 2.5 standard deviations, confirming the results at the LHC.

The combination of the Higgs searches is shown in Fig. 7 for ATLAS collaboration [46] and in Fig. 8 for the CMS collaboration [47] for the full 7 TeV dataset. Even without a combination of the two experiments around 125 GeV the Higgs boson cannot be excluded. Stated differently, around 125 GeV an excess is observed in both experiments which is compatible with the TeVatron excess and compatible overall with the properties expected for a Standard Model Higgs boson. The excess is mainly driven by the ZZ and $\gamma\gamma$ final states. For ATLAS the largest local significance at 126 GeV is almost three standard deviations, taking into account the "look elsewhere effect" (LEE) in a very large window from 110 to 600 GeV, the excess is about one standard deviations. For CMS the largest local significance at 124 GeV is slightly higher than three standard deviations which is reduced to about one and a half standard deviations after inclusion of the LEE effect for the same large mass window as ATLAS.

After the conclusion of the conference on July 4, 2012, ATLAS and CMS announced a local significance each of 5 standard deviations each, compatible with the properties of a Standard Model Higgs boson of mass around 126 GeV [48, 49], including data recorded at 8 TeV. The highest deviations from the Standard Model background expectation in the search for the Higgs boson are within 2 GeV from two independent experiments, each internally compatible with at least two different search channels, and compatible with the TeVatron results.

## 3. Beyond the Standard Model Higgs boson

In a supersymmetric theory the Higgs sector is extended with respect to the Standard Model as two complex doublets are necessary to give mass to up and down type particles [51]. The additional degrees of freedom lead to a richer particle spectrum. There are at least two additional

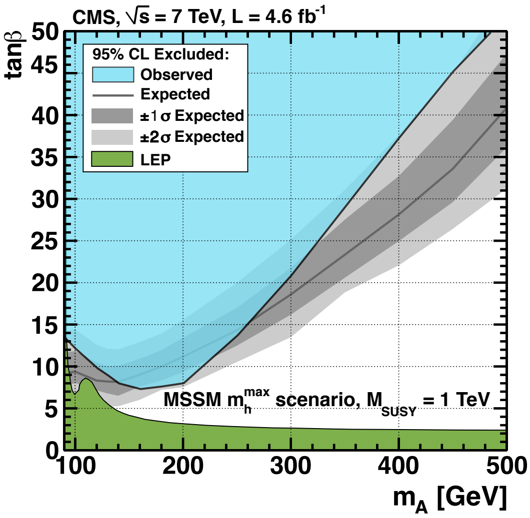


**Figure 9.** The region in the $\tan\beta$-m$_A$ plan excluded in the search for neutral MSSM Higgs bosons by CMS is shown [32].

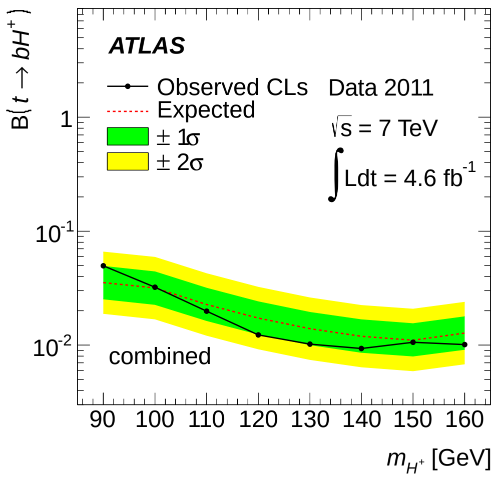


**Figure 10.** The limit on the top quark branching ratio to a charged Higgs boson is shown as function of the charged Higgs boson mass for ATLAS [50].

neutral Higgs bosons H and A as well as a pair of charged Higgs bosons. The ratio of the vacuum expectation values $\tan\beta$ and the mass of the A boson parametrize the Higgs sector to a good approximation. As $\tan\beta$ increases the coupling of the Higgs bosons H and A to the $\tau$ lepton and the b quark increases. Thus the search for the Higgs boson decaying to a pair of $\tau$ leptons as performed by CMS and ATLAS [32, 52] is a probe of the extended Higgs sector. In absence of a signal, a large fraction of the $\tan\beta$ versus $m_A$ plane is excluded by this search when the mass of the A is restricted to less than 500 GeV. The limit gets weaker as function of the mass of the A as the cross section decreases as shown in Figure 9.

The charged Higgs boson, decaying to a $\tau$ lepton and its neutrino, with a mass less than the top quark could manifest itself as a modification of the branching ratio of the top quark. Additionally such events would have a larger transverse mass than the decay of the W boson (from the top quark) to $\tau$ and neutrino. The absence of a signal for charged Higgs boson at the LHC [50, 53] can be used to determine limits as low as 1% on the barnching ratio of the top quark as shown in Figure 10.

## 4. Higgs boson couplings and implications

It is a formidable task to determine the properties of the Higgs boson such as the spin and its couplings experimentally, e.g. [54, 55]. The Higgs boson will be measured in several channels and in each of these measurements several couplings intervene, e.g., for the two photon decay channel on the production side the effective coupling to gluons, on the decay side the effective coupling to photons as well as the total width, dominated by the coupling to b-quarks intervene. The effective coupling to gluons has a large contribution from the tree-level coupling to the top quark while the effective coupling to photons also receives contributions from the tree-level coupling to the W boson.

To measure the couplings a parameter $\Delta_x$ is defined as deviation from the Standard Model value:

$$g_{XXH} = g_x = (1+\Delta_x) g_x^{\mathrm{SM}} \tag{1}$$

where $g_x^{\mathrm{SM}}$ is the Standard Model coupling of particle $X$ to the Higgs boson. As the square of the couplings enters in the observables, $\Delta_x = 0$ as well as $\Delta_x = -2$ will lead to the same prediction. For effective couplings the definition is slightly more evolved with:

$$g_{XXH} = g_x = (1+\Delta_x^{SM} + \Delta_x) g_x^{\mathrm{SM}} \tag{2}$$

where $\Delta_x^{SM}$ is the sum of the contributions of the non-standard tree-level couplings defined in Eq. 1. For example, if $\Delta_t$ is non-zero, the impact of this modification is transported to $g_g$ in the term $\Delta_g^{SM}$ and only a genuine new contribution, e.g., a stop, is measured in $\Delta_g$.

The total width of the Higgs boson enters in all branching ratios in the common denominator. Not all couplings, e.g., the one to charm quarks, can be determined at the LHC. Thus for $\Delta_c > 0$ the total width would be increased, leading to a reduction of the detected events. Determining the non-c-quark couplings such as $\Delta_t$, $\Delta_b$, $\Delta_\tau$, $\Delta_W$ and $\Delta_Z$ from the observed events would result in a determination of anomalous couplings shifted systematically to smaller values. Therefore it is essential to specify the model and the underlying assumptions when determining the couplings.

In Refs. [56, 57] the charm quark coupling is linked to the top quark coupling via: $g_c = m_c/m_t \cdot g_t^{SM}(1+\Delta_t)$. No invisible decays of the Higgs boson are allowed and the total width is restricted to be less than 2 GeV, of the order of mass resolution in the golden channels:

$$\Gamma_{\mathrm{tot}} = \sum_{\mathrm{obs}} \Gamma_x(g_a) + 2\mathrm{nd\,generation} < 2\mathrm{GeV} \tag{3}$$

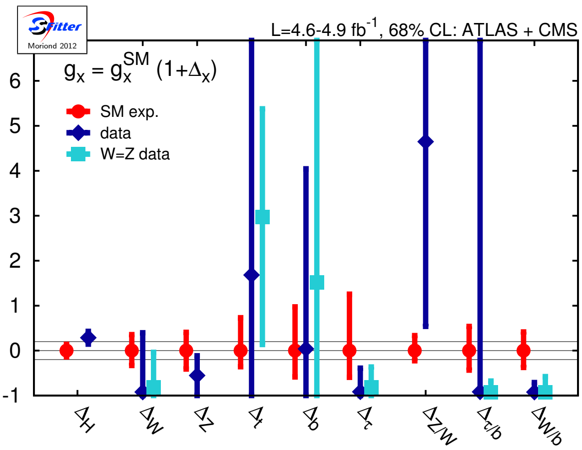


**Figure 11.** The Higgs coupling precision for the data as well as for the Standard Model expectation at 7 TeV is shown for a Higgs boson mass of 125 GeV in different scenarios [57].

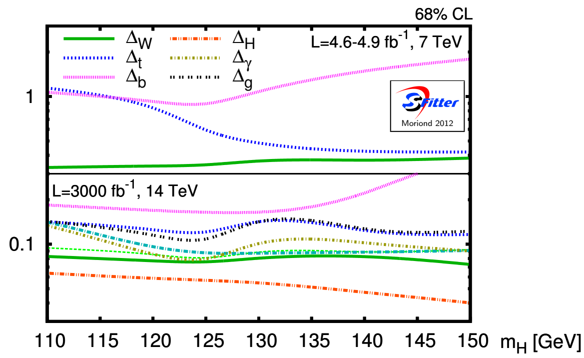


**Figure 12.** The precision of the Higgs coupling measurements at the LHC is shown for the data at 7 TeV as well as for a projection for 3000 fb$^{-1}$ at 14 TeV [57].

In Fig. 11 the result of the determination of the couplings from the 7 TeV data is shown [57]. In red the Standard Model expectation is shown. In dark blue the result for the data are shown. For the light blue points the coupling of the Higgs boson to the weak bosons is forced to be fixed. The central values of the couplings are compatible with the Standard Model expectation of $\Delta_x = 0$. The negative value for $\Delta_W$ can be understood from the data as the channels for the Higgs decay to W bosons is more background like. The overall picture does not change when calculating ratios of couplings. In coupling ratios the correlated systematic errors and theoretical errors cancel, however with the current low statistics the uncorrelated statistical error dominates the coupling determination. A global deviation of all couplings is parametrized with $\Delta_H$ [58–60]. As in this case all measurements are used to determine a single parameter the best possible precision is achieved.

In Fig. 12 two luminosity scenarios are studied for the determination of the Higgs boson couplings as function of the Higgs boson mass. In the first scenario the data at 7 TeV (up to 4.9 fb$^{-1}$) are shown without effective couplings. Here the precision is typically 50%. In the lower half of the figure the expectation for 3000 fb$^{-1}$ at 14 TeV is shown including effective couplings. The coupling precision is improved to roughly order 10%. For the Higgs portal the best precision can be achieved: 5%. This is close to the ultimate precision given by the theoretical error on the cross section.

In addition to the couplings the mass of the Higgs boson can be used to constrain new phenomena beyond the Standard Model. In particular in the supersymmetric models the Higgs boson mass, after including radiative corrections, depends on the mass of the top quark as well as the masses and the mixing of the spin-0 partners of the top quark, the stops. Using the measured mass of the Higgs boson in Ref. [61], the parameter space of the supersymmetric models can be restricted. Some supersymmetry breaking models, such as minimal gauge mediation (mGMSB), are disfavored. In the minimal supersymmetric extension of the Standard Model (MSSM) part of the regions compatible with a Higgs boson mass of 126 GeV are characterized by large mixing which could mean that a light stop could be just around the corner at the LHC.

## 5. Supersymmetric particles

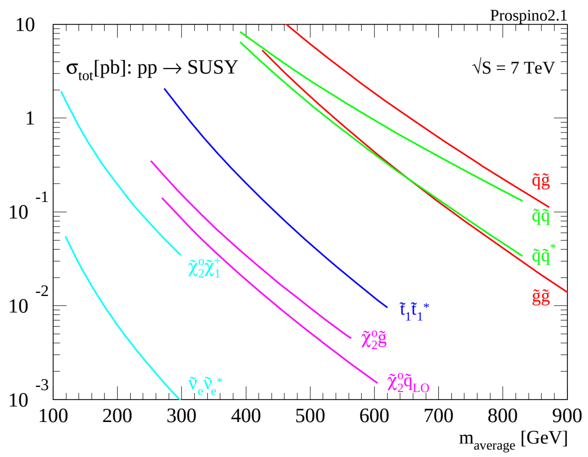


**Figure 13.** The production cross sections for supersymmetric particles at 7 TeV are shown as calculated by Prospino [62–66].

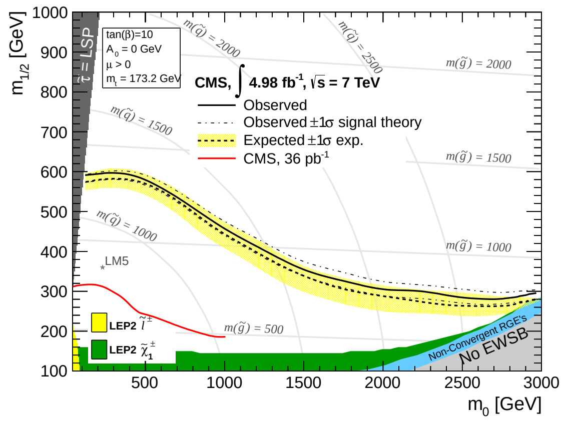


**Figure 14.** The $m_0$-$m_{1/2}$ plane with the exclusion in mSUGRA as obtained by CMS is shown [71].

In supersymmetric theories [67, 68] in addition to the extension of the Higgs sector, the matter particles as well as the carrier of the forces each have a partner differing by a half-unit of spin. In particular gluinos (fermions) are the partners of the gluons and the sleptons (scalars) are the partners of the leptons. In the gauge and Higgs sector, the neutralinos are mixtures of the partners of the neutral Higgs and gauge bosons, the charginos are the partners of the charged Higgs and gauge bosons. The lightest neutralino is the lightest supersymmetric particles, and as a stable weakly interacting particle also a candidate for dark matter. R-parity [69] is defined to be +1 for Standard Model particles and −1 for supersymmetric particles. This new quantum number is assumed to be conserved in the following, so that the sparticles are produced in pairs, decaying to the LSP in possibly long cascades.

The largest cross section for the production of supersymmetric particles [62–66] are those for gluinos and squarks as shown in Figure 13. As the integrated luminosity recorded at the LHC increases, the sensitivity to non-colored particles also increases. An increase of the center-mass-energy is even more powerful.

The search for squarks and gluinos as performed by ATLAS [70] and CMS [71] has not yielded a signal, even though performed in many different channels. The main analysis is the search for multiple jets with large transverse momenta and large missing transverse momentum due to the LSPs escaping the detectors undetected. As the LHC has opened a new large mass regime to be explored, assumptions have to be made about the particle content when presenting the results in terms of limits. An example of a theory with many different final states is mSUGRA. The limits shown in the plane $m_{1/2}$ versus $m_0$, the common fermion and scalar SUSY breaking parameters defined at the unification (=high scale) by CMS in Figure 14 depend only weakly on $\tan\beta$. As an example, for equal gluino and squark masses the limit is at 1.4 TeV by the ATLAS experiment.

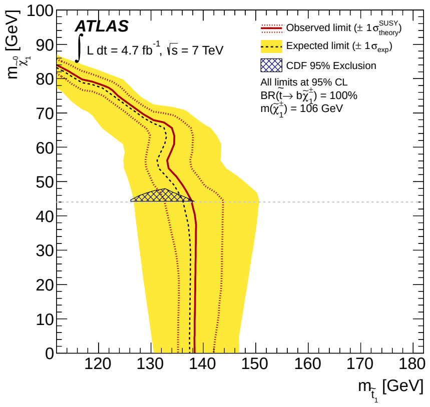


**Figure 15.** The limit on the stop quark mass as function of the LSP mass is shown for ATLAS [73].

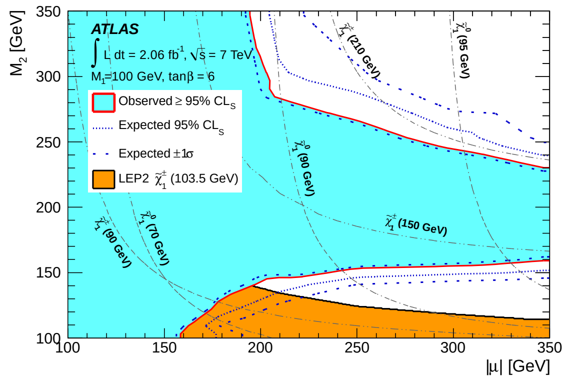


**Figure 16.** The excluded region in $M_2$ versus $\mu$ is shown for the ATLAS tri-lepton search [75].

The third generation plays a special role in supersymmetry. Here mixing effects can be become large due to the large masses of the top quark and the b quark. The mixing can lead to sbottom and stops which are much lighter than the (degenerate) squarks of the first and second generation. While a lower mass increases the cross section, this effect cannot compensate the loss due to the fact that one now probes only a single squark. On the other hand, the use of b-tagging, as the stops and sbottoms will lead to a stronger production of b-jets than first and second generation squarks, will reduce the background.

The search for sbottoms at the LHC has not lead to a signal so far [72, 74]. The search by CMS for the production of gluinos decaying to sbottoms can be interpreted as an excluded region of the gluino mass as function of the LSP mass. Gluino masses up to order 900 GeV can be excluded in this model-dependent scenario.

For the stops ATLAS has performed a search for the direct production of stops [73]. Here the stops decay to a bottom and a chargino. The search yields limits roughly of the order of 137 GeV as shown in Figure 15, depending on the LSP mass. As the mass difference between stop and LSP decreases the limits become weaker.

While the LHC as a proton-proton collider has a natural sensitivity to colored sparticles, it is interesting to note that the search for the production and decay of neutralinos and charginos has started. Typically the most promising channel for such a search are the leptonic decays, i.e., final states with several leptons and missing transverse momentum [75, 77]. As shown in Figure 16 the absence of a signal is translated into a new exclusion domain in the plane of $M_2$, the SUSY breaking parameter associated to the $SU(2)$ group and $\mu$, the Higgs-higgsino mass parameter. Both parameters are defined at the electroweak scale. While it is impressive to see that these searches in the electroweak sector extend significantly the limits from LEP, a caveat must be added: in order to obtain these limits, sleptons are presumed to have a mass between the produced chargino and neutralino and the LSP. Such a hypothesis leads to a strong enhancement of the leptonic branching ratios.

The search for supersymmetry at the LHC goes well beyond mSUGRA or models parametrize supersymmetry breaking via gravity mediation. One example is the search for gauge mediated supersymmetry performed by ATLAS [76]. This analysis is particularly interesting as the final state contains jets, missing transverse momentum and $\tau$ leptons, which are more difficult to identify the electrons or muons. While unfortunately no signal has been found, the excluded region is extended significantly beyond the region excluded by the searches at LEP for the first time.

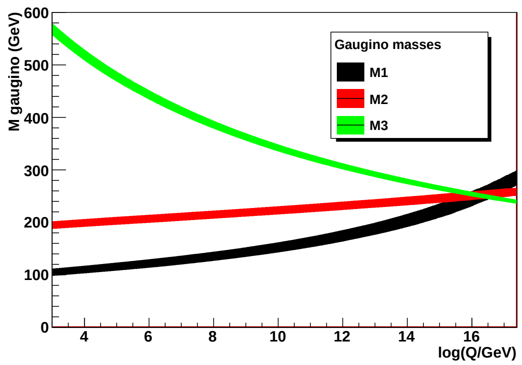


**Figure 17.** The gaugino SUSY breaking parameter unification is it could be measured at the LHC [78] is shown as function of the scale.

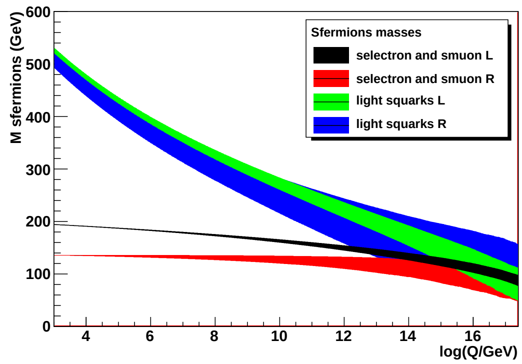


**Figure 18.** The evolution of the scalar SUSY breaking parameters determined at LHC and ILC is shown as function of the scale [78].

While no evidence for supersymmetry has turned up so far at the LHC, it is still interesting to see what information on the fundamental parameters could be obtained from measurements at the LHC. This question was studied in particular in [78–81] among others. In a very optimistic scenario, the gluinos, squark of the first two generations the sleptons, the sbottoms as well as three of the four neutralinos could be measured at the LHC. While this is sufficient information for a highly constrained high scale model such as mSUGRA, the picture changes significantly when going to the more interesting question of reconstructing the parameters of the general MSSM at the low scale. The incomplete information in the neutralino/chargino sector leads to a 12-fold ambiguity when determining $M_1$, $M_2$, $\mu$. However, evolving the MSSM parameters of the gaugino sector, i.e., $M_1$, $M_2$ and $M_3$ via the renormalization group equations to the high scale, leads to unification (in this particular scenario) in only one of the cases. The precision with which the unification can be probed at the LHC is shown in Figure 17. As pointed out in [82] at this conference the Higgs mass from ATLAS and CMS is compatible with light gauginos in SUGRA models. To get a complete picture, an ILC will be necessary to complete the spectrum and resolve the ambiguities. In this case even the unification of the scalar SUSY breaking parameters can be measured from the data as shown in Figure 18.

## 6. Conclusions

ATLAS and CMS have observed a particle compatible with the properties of a Standard Model Higgs boson. It will now be essential to determine its spin and its couplings. Ultimately the couplings can be measured with a precision of about 10% at the LHC.

No significant deviation from the Standard Model has been observed in the search for supersymmetry. This means that easy supersymmetry was easily ruled out. More difficult searches are now being started for supersymmetric processes with lower cross sections. The increase of the center-of-mass energy of the LHC to 14TeV$-\varepsilon$ after a longer shutdown will open up a new mass range to be explored.

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## References

[1] Glashow S 1961 *Nucl.Phys.* **22** 579–588
[2] Salam A 1968 *Conf.Proc.* **C680519** 367–377
[3] Weinberg S 1967 *Phys.Rev.Lett.* **19** 1264–1266
[4] Englert F and Brout R 1964 *Phys.Rev.Lett.* **13** 321–323
[5] Higgs P W 1964 *Phys.Rev.Lett.* **13** 508–509
[6] Higgs P W 1964 *Phys.Lett.* **12** 132–133
[7] Higgs P W 1966 *Phys.Rev.* **145** 1156–1163
[8] Guralnik G, Hagen C and Kibble T 1964 *Phys.Rev.Lett.* **13** 585–587
[9] Evans Lyndon e and Bryant Philip e 2008 *JINST* **3** S08001
[10] Aad G *et al.* (ATLAS Collaboration) 2008 *JINST* **3** S08003
[11] Chatrchyan S *et al.* (CMS Collaboration) 2008 *JINST* **3** S08004
[12] Morrissey D E, Plehn T and Tait T M 2012 *Phys.Rept.* **515** 1–113 (*Preprint* `0912.3259`)
[13] Nath P, Nelson B D, Davoudiasl H, Dutta B, Feldman D *et al.* 2010 *Nucl.Phys.Proc.Suppl.* **200-202** 185–417 (*Preprint* `1001.2693`)
[14] LHC Higgs Cross Section Working Group, Dittmaier S, Mariotti C, Passarino G and Tanaka (Eds) R CERN, Geneva, 2011 *CERN-2011-002* (*Preprint* `1101.0593`)
[15] ALEPH, CDF, D0, DELPHI, L3, OPAL, SLD Collaborations, the LEP Electroweak Working Group, the Tevatron Electroweak Working Group, and the SLD electroweak and heavy flavour groups 2010
[16] Georgi H, Glashow S, Machacek M and Nanopoulos D V 1978 *Phys.Rev.Lett.* **40** 692
[17] Djouadi A, Spira M and Zerwas P 1991 *Phys.Lett.* **B264** 440–446
[18] Dawson S 1991 *Nucl.Phys.* **B359** 283–300
[19] Spira M, Djouadi A, Graudenz D and Zerwas P 1995 *Nucl.Phys.* **B453** 17–82 (*Preprint* `hep-ph/9504378`)
[20] Harlander R V and Kilgore W B 2002 *Phys.Rev.Lett.* **88** 201801 (*Preprint* `hep-ph/0201206`)
[21] Ravindran V, Smith J and van Neerven W L 2003 *Nucl.Phys.* **B665** 325–366 (*Preprint* `hep-ph/0302135`)
[22] Ahrens V, Becher T, Neubert M and Yang L L 2009 *Eur.Phys.J.* **C62** 333–353 (*Preprint* `0809.4283`)
[23] Ciccolini M, Denner A and Dittmaier S 2008 *Phys.Rev.* **D77** 013002 (*Preprint* `0710.4749`)
[24] Arnold K, Bellm J, Bozzi G, Brieg M, Campanario F *et al.* 2011 (*Preprint* `1107.4038`)
[25] Djouadi A, Kalinowski J and Spira M 1998 *Comput.Phys.Commun.* **108** 56–74 (*Preprint* `hep-ph/9704448`)
[26] Richter-Was E and Sapinski M 1999 *Acta Phys.Polon.* **B30** 1001–1040
[27] Dittmar M and Dreiner H K 1997 *Phys.Rev.* **D55** 167–172 (*Preprint* `hep-ph/9608317`)
[28] Ellis R K, Hinchliffe I, Soldate M and van der Bij J 1988 *Nucl.Phys.* **B297** 221
[29] Abdullin S, Dubinin M, Ilyin V, Kovalenko D, Savrin V *et al.* 1998 *Phys.Lett.* **B431** 410–419 (*Preprint* `hep-ph/9805341`)
[30] Kauer N, Plehn T, Rainwater D L and Zeppenfeld D 2001 *Phys.Lett.* **B503** 113–120 (*Preprint* `hep-ph/0012351`)
[31] Plehn T, Rainwater D L and Zeppenfeld D 1999 *Phys.Lett.* **B454** 297–303 (*Preprint* `hep-ph/9902434`)

[32] CMS Collaboration 2012 *Phys.Lett.* **B713** 68–90 (*Preprint* 1202.4083)
[33] ATLAS Collaboration 2012 (*Preprint* 1206.5971)
[34] CMS Collaboration 2012 *Phys.Lett.* **B710** 284–306 (*Preprint* 1202.4195)
[35] ATLAS Collaboration 2012 (*Preprint* 1207.0210)
[36] Butterworth J M, Davison A R, Rubin M and Salam G P 2008 *Phys.Rev.Lett.* **100** 242001 (*Preprint* 0802.2470)
[37] Plehn T, Salam G P and Spannowsky M 2010 *Phys.Rev.Lett.* **104** 111801 (*Preprint* 0910.5472)
[38] Altheimer A, Arora S, Asquith L, Brooijmans G, Butterworth J *et al.* 2012 *J.Phys.* **G39** 063001 (*Preprint* 1201.0008)
[39] CMS Collaboration 2012 *Phys.Lett.* **B710** 91–113 (*Preprint* 1202.1489)
[40] ATLAS Collaboration 2012 *Phys.Lett.* **B716** 62–81 (*Preprint* 1206.0756)
[41] CMS Collaboration 2012 *Phys.Rev.Lett.* **108** 111804 (*Preprint* 1202.1997)
[42] ATLAS Collaboration 2012 *Phys.Lett.* **B710** 383–402 (*Preprint* 1202.1415)
[43] CMS Collaboration 2012 *Phys.Lett.* **B710** 403–425 (*Preprint* 1202.1487)
[44] ATLAS Collaboration 2012 *Phys.Rev.Lett.* **108** 111803 (*Preprint* 1202.1414)
[45] CDF and D0 Collaborations and the Tevatron New Physics and Higgs Working Group (Tevatron New Physics Higgs Working Group, CDF Collaboration, D0 Collaboration) 2012 (*Preprint* 1207.0449)
[46] ATLAS Collaboration 2012 *Phys.Rev.* **D86** 032003 (*Preprint* 1207.0319)
[47] CMS Collaboration 2012 *Phys.Lett.* **B710** 26–48 (*Preprint* 1202.1488)
[48] ATLAS Collaboration 2012 *Phys.Lett.* **B716** 1–29 (*Preprint* 1207.7214)
[49] CMS Collaboration 2012 *Phys.Lett.* **B716** 30–61 (*Preprint* 1207.7235)
[50] ATLAS Collaboration 2012 *JHEP* **1206** 039 (*Preprint* 1204.2760)
[51] Martin S P 1997 (*Preprint* hep-ph/9709356)
[52] ATLAS Collaboration 2011 *Phys.Lett.* **B705** 174–192 (*Preprint* 1107.5003)
[53] CMS Collaboration 2012 *JHEP* **1207** 143 (*Preprint* 1205.5736)
[54] Choi S, Muhlleitner M and Zerwas P 2012 (*Preprint* 1209.5268)
[55] Plehn T and Rauch M 2012 (*Preprint* 1207.6108)
[56] Lafaye R, Plehn T, Rauch M, Zerwas D and Duhrssen M 2009 *JHEP* **0908** 009 (*Preprint* 0904.3866)
[57] Klute M, Lafaye R, Plehn T, Rauch M and Zerwas D 2012 *Phys.Rev.Lett.* **109** 101801 (*Preprint* 1205.2699)
[58] Bock S, Lafaye R, Plehn T, Rauch M, Zerwas D *et al.* 2010 *Phys.Lett.* **B694** 44–53 (*Preprint* 1007.2645)
[59] Englert C, Plehn T, Zerwas D and Zerwas P M 2011 *Phys.Lett.* **B703** 298–305 (*Preprint* 1106.3097)
[60] Englert C, Plehn T, Rauch M, Zerwas D and Zerwas P M 2012 *Phys.Lett.* **B707** 512–516 (*Preprint* 1112.3007)
[61] Arbey A, Battaglia M, Djouadi A, Mahmoudi F and Quevillon J 2012 *Phys.Lett.* **B708** 162–169 (*Preprint* 1112.3028)
[62] Beenakker W, Hopker R, Spira M and Zerwas P 1997 *Nucl.Phys.* **B492** 51–103 (*Preprint* hep-ph/9610490)
[63] Beenakker W, Kramer M, Plehn T, Spira M and Zerwas P 1998 *Nucl.Phys.* **B515** 3–14 (*Preprint* hep-ph/9710451)
[64] Beenakker W, Klasen M, Kramer M, Plehn T, Spira M *et al.* 1999 *Phys.Rev.Lett.* **83** 3780–3783 (*Preprint* hep-ph/9906298)
[65] Spira M 2002 217–226 (*Preprint* hep-ph/0211145)
[66] Plehn T 2005 *Czech.J.Phys.* **55** B213–B220 (*Preprint* hep-ph/0410063)
[67] Golfand Y and Likhtman E 1971 *JETP Lett.* **13** 323–326
[68] Wess J and Zumino B 1974 *Nucl.Phys.* **B70** 39–50
[69] Farrar G R and Fayet P 1978 *Phys.Lett.* **B76** 575–579
[70] ATLAS Collaboration 2012 (*Preprint* 1208.0949)
[71] CMS Collaboration 2012 (*Preprint* 1207.1898)
[72] CMS Collaboration 2012 (*Preprint* 1208.4859)
[73] ATLAS Collaboration 2012 (*Preprint* 1208.4305)
[74] ATLAS Collaboration (ATLAS Collaboration) 2012 *Phys.Rev.Lett.* **108** 181802 (*Preprint* 1112.3832)
[75] ATLAS Collaboration 2012 *Phys.Rev.Lett.* **108** 261804 (*Preprint* 1204.5638)
[76] ATLAS Collaboration 2012 *Phys.Lett.* **B714** 180–196 (*Preprint* 1203.6580)
[77] CMS Collaboration 2012 *JHEP* **1206** 169 (*Preprint* 1204.5341)
[78] Adam C, Kneur J L, Lafaye R, Plehn T, Rauch M *et al.* 2011 *Eur.Phys.J.* **C71** 1520 (*Preprint* 1007.2190)
[79] Allanach B, Blair G, Kraml S, Martyn H, Polesello G *et al.* 2004 (*Preprint* hep-ph/0403133)
[80] Blair G, Porod W and Zerwas P 2003 *Eur.Phys.J.* **C27** 263–281 (*Preprint* hep-ph/0210058)
[81] Lafaye R, Plehn T, Rauch M and Zerwas D 2008 *Eur.Phys.J.* **C54** 617–644 (*Preprint* 0709.3985)
[82] Nath P 2012 (*Preprint* 1207.5501)