

Higgs Physics

Implications of a 125 GeV Higgs for the SM and SUSY

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In the last lecture we will continue the discussion of the Higgs sector in Supersymmetric theory

- Couplings of the SUSY Higgses wrt to SM Higgs couplings.
- Implications of the observed rates as well as non-observation of any other Higgs particle at the LHC for SUSY models.
- Invisible Higgs decays!
- Implications of the observed mass for SUSY models and naturalness!
- Whither from here?

So finally we have two parameters for the Higgs sector:

 $M_A, \tan\beta$

CP even h, H mixture of $\Re h_1^0, \Re eh_2^0$ and A is CP odd.

h, H couplings to VV(V = Z/W) are reduced wrt to those of the SM Higgs. I.e. $a_V < 1$. Depends on the mixing between $\Re eh_1^0$, $\Re eh_2^0$. Call mixing angle α

$$\cos^{2}(\beta - \alpha) = \frac{m_{h}^{2}(M_{Z}^{2} - m_{h}^{2})}{m_{A}^{2}(m_{H}^{2} - m_{h}^{2})}$$

Depends on M_A

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For large $M_A(> 250 GeV)$,

 $m_h \rightarrow M_Z |\cos 2\beta|, \quad \cos^2 2\beta \rightarrow m_h^2/M_Z^2,$

 $m_H^2 \to m_A^2 + M_Z^2 \sin^2 2\beta, \quad |\cos(\beta - \alpha)| \to M_Z^2 |\sin 4\beta| / (2m_A^2).$ $\cos(\beta - \alpha) \to 0$

h is the only state forced to be light, $M_H\simeq M_A\simeq M_{H^\pm}$

Vertex involving at least one vector boson and a heavy Higgs boson vanishes being proportional to $\cos(\beta - \alpha)$. *h* couples to *VV* like the SM Higgs.

H coupling to VV vanishes in this limit. AAH coupling is zero at the tree level any way!

Couplings of h, H relative to those of the SM higgs,

$$hf_d \bar{f}_d: \quad -\frac{\sin \alpha}{\cos \beta}, \quad hf_u \bar{f}_u: \quad \frac{\cos \alpha}{\sin \beta}; \quad Hf_d \bar{f}_d: \quad \frac{\cos \alpha}{\cos \beta}; \quad Hf_u \bar{f}_u: \quad \frac{\sin \alpha}{\sin \beta}$$

ecoupling 1 1
$$\tan \beta \quad 1/\tan(\beta).$$

Large $\tan \beta$ and moderate α , for h, H the down type fermion couplings enhanced wrt those with the up type fermions. For A this is true for all α . That is why you will hear about b quark and τ final states for SUSY Higgs searches.

In the decoupling limit all the couplings of the h (including the self couplings) are the same as that of the SM higgs.



MSSM case

At large $\tan \beta$ large effects are possible. But larger values of $\tan \beta$ now constrained in more than one way!

• Stops will affect both $\gamma\gamma$ and gg couplings.

• Light Charginos and charged sleptons (for masses still allowed by the data) will affect the $\gamma\gamma$ branching ratio without affecting production.

Recall we are beginning to see the Higgs in different, different channels.

 $gg \to \phi \to ZZ, \gamma\gamma, WW, \tau\tau$ and are beginning to see in $q\bar{q} \to V^* \to VH$.

Given m_h and the current constraints on squark and slept on masses, the only decays of the observed state into sparticles are $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$.

So analysis of SUSY scenarios with light stops, light neutralinos and charginos along with the Higgs sector is the most interesting one!

Before commenting on what do we learn for the SM and SUSY from available data let us remind of a few things , some of which were already told by Lian Tao.

With current luminosity a process with cross-section \sim 1 pb or so, giving 2000 events. Cross section for Higgs production for 125 GeV mass is about 20 pb.

Process	$\sigma(nb)$	events for 10 fb^{-1}
Total cross-sections	10 ⁸	10 ¹⁵
$W^{\pm} ightarrow e u$	20	$2 imes 10^8$
$Z \rightarrow e^+ e^-$	2	2×10^7
$t\overline{t}$	0.8	$8 imes 10^6$
$b\overline{b}$	$5 imes 10^5$	$5 imes 10^{12}$
central jets ($P_T > 100 GeV$)	10 ³	10 ¹⁰
Higgs (125 GeV)	0.02	10^{4}



Theorists have made an enormous effort in getting precise predictions for cross-sections and branching ratios to great accuracy

$$\sigma(pp \to X + ..) = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \sigma(a + b \to X) \left(x_1, x_2, \mu_R^2, \alpha_s(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2} \right) (1)$$

An accurate calculation requires two non-pertrubative inputs: Parton Densities (PDFs) and α_s

AND

high precision calculation of subprocess cross-section: of **both** inclusive cross-sections and distributions.

Why the latter? Because we need to make cuts.

Precision predictions put together: S. Dittmaier et al, "Handbook of LHC Higgs cross sections", arXiv: 1101.0593 [hep-ph]



Precision predictions put together: LHC (14 TeV): Djouadi and Baglio : 1012.0530.





Fig: courtesy A. Djouadi.

What do we know for sure about the new state?

It has integral spin.

It can not be spin 1 : Yang's Theorem.

Observed numbers of $\gamma\gamma$ and ZZ events consistent with loop induced coupling to $\gamma\gamma$ and tree level to ZZ. \Rightarrow has to be dominantly CP even.

The analysis of angular distributions of the decay leptons in $ZZ \rightarrow 4\ell$ channel begins to support the spin 0 interpretation. Observation in the WW channel crucially uses the spin 0 nature of the higgs to reduce the background!

Agreement between the WW and the ZZ channel also is a strong indications against spin 2.

The couplings to WW/ZZ, $t\bar{t}$ (indirectly via the gg production) seem to match the SM expectations within 20–%.

Clearly much work is required! lot is going on!

Mass \sim 126 GeV .

Available: mass and rates in different channels:

No SM like state till 600 GeV other than the one we have observed! Exclusions for Heavier Higgs state to the level of $0.3\sigma_{SM}$

This is relevant when we look at constraints on the SUSY Higgs sector!







Consistent with the SM prediction for both ATLAS and CMS with precision about 15% level.

Theory uncertainty (QCD scale $\pm 8\%$ @NNLO and PDF+ $\alpha_s \pm 8\%$) is comparable to experimental and statistical uncertainties on the combined signal strength.

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• The couplings to WW/ZZ, $t\bar{t}$ (indirectly via the gg production) seem to match the SM expectations within 20-%.

• Some 'evidence' for the $b\overline{b}$ coupling as well.



For the first time some information on the fermion higgs coupling. $\lambda_x = m_x/v$ (in the SM) Is it the Higgs? Sample and incomplete list of the papers:

Three batches:

After the December 2011 seminar

After the July 4 2012 announcement

After Moriond Announcement: three or four different groups, different groups assumptions/usage of data slightly different.

1) Giudice, Isidori et al: 1112.2022, 1205.6497 , 1307.3536 $(m_h, m_t \ {\rm and} \ {\rm vacuum} \ {\rm stability}$

2)Moch, Djouadi, Alekhin: 1207.0980 (Effect of uncertainties in knowledge on m_t)

Rates, couplings:

3)Arbey, Djouadi, Battaglia, Mahamoudi : constraints on PMSSM due to m_h information:(1112.3028, 1207.1348,1211.4004)

4) Kraml S. et al, 1212.5214,1302.5694, 1306.2941

5) Ellwanger: 1203.5048 (Diphoton excess and NMSSM),

6)Djouadi, RG, Baglio: 1207.1451 (apparent $\gamma\gamma$ excess : QCD or BSM?)

7)Lykken, Low and Shaughnessy: 1207.1093 (Higgs imposter)

8)Corbett, Eboli et al: 1207.1344 (Anom. Higgs couplings?)

9) Carmi, Falkowski, Kulfik et al: 1207.1718, 1303.1812 (An effective theory appoach to determine general coupling structure)

10)Ellis and You: 1207.1693 (Global analysis)

11)C. Grojean, Muhlleitner, Espinoza et al (How much space for some of the realisation of light, composite higgs, invisible Higgs, Effective Lagrangain analysis) (1202.3697,1205.6790, 1206.7120,1207.1717, 1303.3876)

12) An extensive survey (from January 2012) of connection between the Higgs and the BSM. Les Houches report:1203.1488

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13) Relation between the Higgs signal and DM: light neutralino and invisibly decaying Higgs: T. Hahn et al G. Belanger et al 1308.3735

Spin/Parity:

1208.4018: Bolognesi et al 1208.4311: Boughezal et al 1212.0843: C. Englert et al 1301.4695: R. Godbole et al 1306.2573: A. Djouadi et al 1208.6002,1210.5229,1303.0208: V. Sanz, J. Ellis et al In the global analysis without SUSY it is only the couplings that are fitted. Things generally consistent with SM expectations to within 20-30 %.

In the global analysis with SUSY of course the higgs mass constraint is analyzed. This thus gives relationship between SUSY scales and Higgs mass. fine tuning?

Recall we are beginning to see the Higgs in different, different channels.

 $gg \to \phi \to ZZ, \gamma\gamma, WW, \tau\tau$ and are beginning to see in $q\bar{q} \to V^* \to VH$.

Next I will show a few chosen examples

• m_h^{max} depends on 1) $m_{\tilde{t}}$ 2)mixing in the stop-sector : $X_t = A_t - \mu \cot \beta$.

•
$$M_h^{max} = M_Z |\cos 2\beta| + \epsilon; \quad \epsilon = \frac{3\,\bar{m}_t^4}{2\pi^2 v^2 \sin^2 \beta} \left[\log \frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{2\,M_S^2} \left(1 - \frac{X_t^2}{6\,M_S^2} \right) \right].$$

Observed m_h large and hence we need to maximize.

Observed rates close to that of the SM. We are in close to decoupling regime.

Require large mixing, large $m_{\tilde{t}_1}, m_{\tilde{t}_2}$.

$$X_t = \sqrt{6}M_S = \sqrt{6m_{\tilde{t}_1}m_{\tilde{t}_2}}$$



For high M_S typical mixing possible, for low M_S only maximal mixing possible. Gives some indication of the character of stop. Depending on rates into $\gamma\gamma$ different stop masses allowed. Light stops ~ 500 GeV still allowed. Light Charginos/sleptons allowed.



1112.2200: D. Albornoz Vásquez, Belanger, Godbole. The effect on production in gg fusion and decay into $\gamma\gamma$ channel, relative to the SM. In MSSM difficult to obtain an increase!

Carena et al: can get some increase for light staus. Trieste, Italy

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1112.2200 : D. Albornoz Vásquez, Belanger, Godbole.



Thus we can look for SUSY through the Higgs properties even if other new particles are beyond the LHC reach!

A proposal to look for such a Higgs at the LHC:

1)R.Godbole, D.P. Roy, S. Moretti, M. Guchait: Phys. Lett. B (2006), 2)R. Godbole, D. Ghosh, M. Guchait, Kirtimaan Mohan, Dipan Sengupta: arXiv: 1211.7015 Trieste, Italy August 20-23, 2013. A. Djouadi et al (1303.6591), Kraml et al () Recent global fits which restrict the invisible Branching Ratio: Invisible B.R. <0.52 at 68% c.l





A light neutralino ($\sim 10-15GeV$), along with light stau and light chargino is consistent with all the data

1)on rates 2)right Higgs mass 3)current constraints on invisible Higgs decay widths.

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hep-ph/1308.3735 (G. Belanger, RG et al)
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Looking at the DM through the Higgs 'window'!

Many analyses. I quote from analyses of Djouadi et al. Includes effects of searches for other MSSM Higgses and also flavor physics.



Note: the plot contains also limits from direct search for charged Higgs and other Higgses. Along with flavor constraints allowed only small values of tan β and also larger values of M_A .



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High precision calculation essential and depends on the SUSY breaking mechanism:



In some sense one can say that large SUSY scale is in fact consistent with the large mass of the Higgs.

But many of us do not like this..because this means a fine tuning to Radiative SUSY breaking requires

$$-1/2M_Z^2 = M_{H_u}^2 + |\mu|^2 + \mathcal{O}(\tan \beta^{-2})$$

One has to fine tune the parameters of the theory so as to satisfy this relation.

This causes worries for a lot of us.

This requires quite often at least one light stop OR a light higgsino (lectures by D. Kaplan; X. Tata et al, hep-ph/1207.4846).

Order of the day for SUSY: look for the light stop :-)

Many many phenomenological and experimental investigations.

CMS limit on stops : strong exclusion between 600-700 GeV more or less the edge of the reach of 8 TeV LHC.

Atlas exclusion a little stronger but based on more assumptions.





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Limits depend on assumptions.

1)Branching ratio into the given channel is 1

2)Depends on mass difference.

3)In a given SUSY model all these are interrelated to the SUSY model parameters.

4) The limits depend on the assumed polarization of the top produced in the stop decay

5) And the polarization depends on stop mixing!



Belanger, Godbole, Niessen, Hartring: 1212.3526

One can try to lower the $M_S, M_{\tilde{t}}$ required to get the large M_h in NMSSM.

A lot of interesting work on that. Even accommodates the small mass difference seen by different experiments in different channels by postulating that there are almost two degenerate Higgs states h and H

Kraml, Belanger et al Muellheitner et al



Reconsider the stability bounds given by Giudice et al. They used errors on m_t as measured at the Tevatron/LHC : the so called kinematic mass.

Moch et al : extract the \overline{MS} mass of the top quark from the measurement of the top quark cross-sections at the Tevatron and the NNLO calculation. Led to larger errors!

Estimate: $m_t^{pole} = 173.3 \pm 2.8$ GeV.

Vacuum stability constraint now becomes $m_h > 129.4 \pm 5.6$ GeV.

So the conclusion about the scale up to which SM is valid without getting into conflict with vacuum stability is weakened.



So the precision measurement of the mass at the ILC can really shed light whether higgs mass point to the **NEED** of BSM physics at a **particular scale**.





Higgs has been seen, seems very much SM like! NO evidence for the BSM particles!

Is it now the end?

It is not even beginning of the end !

If at all only the end of a beginning

 \bigcirc

The mass of the observed state very very interesting from a lot of points of view!

Small enough to keep us still thinking of a mechanism like SUSY to stabilize it

and

Large enough to make us wonder whether SM is the ONLY thing all the way to the Planck Scale!

and

A unique value where decays into almost all final states are substantial

Already many BSM ideas constrained strongly. Fourth generation, technicolor ruled out. SUSY constrained heavily, largish fine tuning, specific sparticle predictions for LHC 14.

The first glimpse of the boson seems consistent with the SM.

We need to be patient and hope that we can get a look into the BSM land through the Higgs.

Coupling determination order of the day! Important to understand how to treat the 'systematic' theory uncertainties! In any case the days of Standard Model are coming to an end in some sense!

Hopefully the case will be 'The King is Dead', 'Long live the King'!

Just like the **gauge principle** and the **unitarity** were the guiding principle so far now the **'light' scalar** might be the guiding principle for future developments!

We should get a peek at the BSM land through the 'window' of measurement of the properties of the Higgs!

Exciting days ahead for sure!

If 14 TeV LHC should also fail to find 'direct' evidence for the BSM physics we would really have to understand what is so special about the Standard Model and hopefully that answer won't be Anthropic Principle !



From the talk of Gian Guidice (EPS)

Extra slides

Earlier one thought that determination of J^{CP} of the boson will be a long term prospect.

Distribution in φ ; the angle between the planes of the fermion pairs coming from the Z boson decays.



RG, Miller, Muhlleitner (JHEP 0712 (2007) 31)

In the SM

$$\frac{d\Gamma}{d\varphi} \sim 1 + A\cos\varphi + B\cos 2\varphi$$

A, B are functions of M_H, M_Z . the ϕ dependence will vanish for larger Higgs masses. For CP odd case:

$$\frac{d\Gamma}{d\varphi}\sim 1-\frac{1}{4}\cos 2\varphi$$



If one uses rates alone in fact one delineates a certain region in the |c|-a plane. Djouadi et al. neglects the contribution of c to rates and hence looks only on one axis. Needs to be supplemented by angular analyses.

In fact without looking at the decay products in VBF: vector boson fusion channel and VH channel, one can discriminate against the non-SM structure.

arXiv: 1212.0843 Englert, Plehn et al RG, A. Djouadi, B. Mellado and Kiritmaan Mohan 1301.4965

Experimentalists can isolate the Higgs production via vector boson fusion.

pp – Higgs + 2jets in froward and backward direction.

The BSM vertices have factors involving four momenta. Change the kinematic distributions.



So if the VBF produces a resonance of spin 2 its acceptance to SM cuts will be very different. VBF for spin2 and spin 0 are very different!



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