Higgs Physics

Implications of a 125 GeV Higgs for the SM and SUSY

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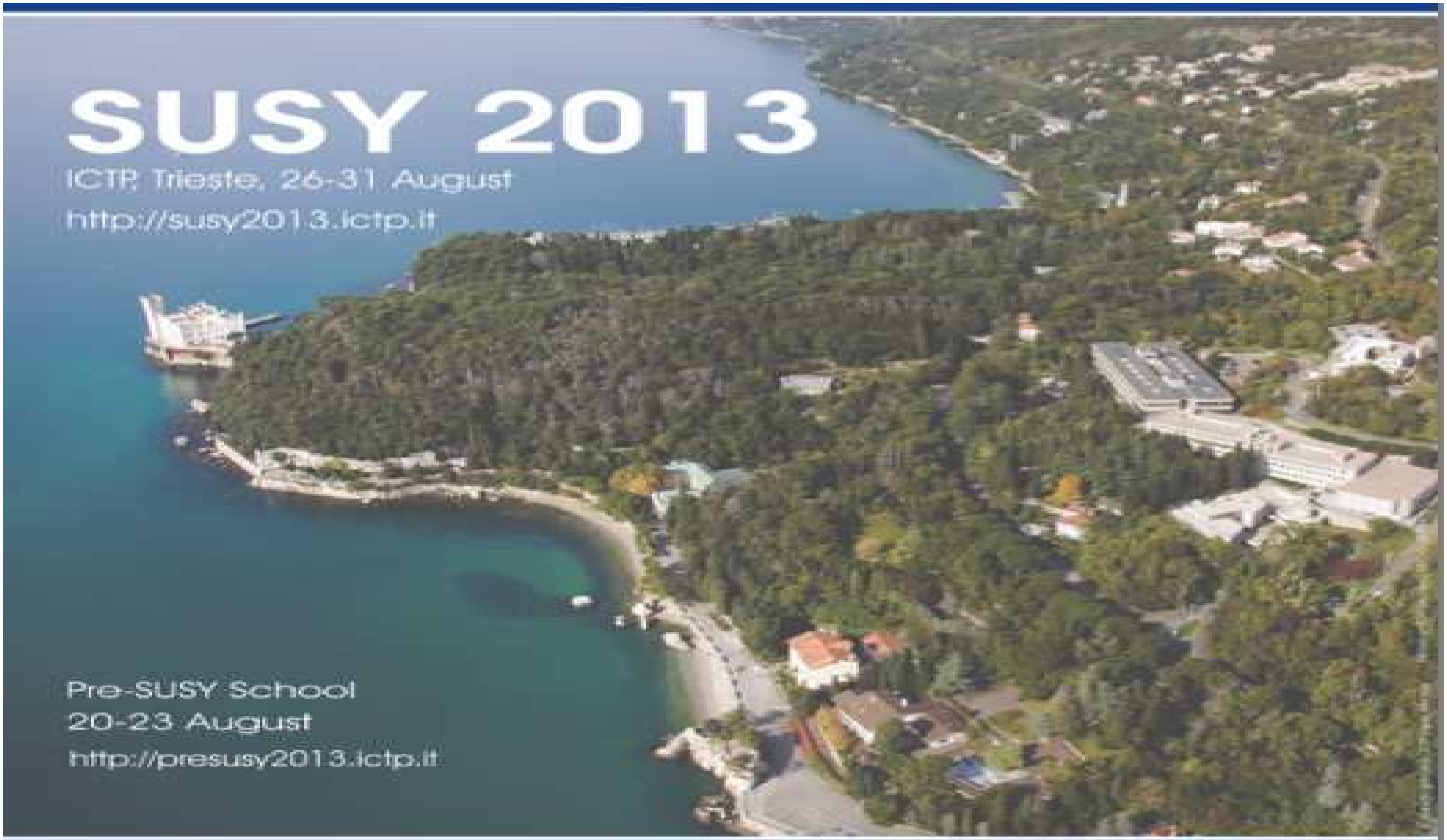
SUSY 2013
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http://susy2013.ictp.it
Pre-SUSY School
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http://presusy2013.ictp.it

In this lecture we will discuss three aspects of the Higgs sector of the Supersymmetric theory

- The Higgs content of the MSSM and NMSSM.

- Mass limits and the couplings for the MSSM Higgses: Recall in the SM λ (and hence m_h) a free parameter. We will see in SUSY, λ related to gauge coupling and hence we have predictivity for masses of some of the Higgses as well.

- EW symmetry breaking is 'natural' in SUSY. Recall $\mu^2 < 0$ was 'ad hoc' in the SM. In SUSY it is not ☺
EW symmetry breaking is triggered by the heavy top quark. SUSY breaking and radiative EWSB intimately connected.

SUSY is aesthetically pleasing and beautiful. The only possible extension of the known space time symmetries of the particle interactions. Supersymmetric quantum field theories 'natural' in spite of scalars.

SUSY breaking is neither beautiful nor easy.
Just like we had no guidance about the Higgs mass in the SM, we have no guidance about what the Supersymmetric breaking scale aught to be.

- The attitude is to assume supersymmetry breaking takes place by some other mechanism, usually involving extensions beyond the MSSM.

- Without knowing the details of this mechanism, we can still discuss the impact of the breaking on the MSSM, in the form of soft supersymmetry breaking terms.

Supersymmetric limit means equal masses for the SM particles (fermions and gauge-bosons) and their super partners the sparticles (sfermions and gauginos).

SUSY is broken, so the masses of particles and sparticles different from each other. We have no 'theoretical' prediction for their masses. 'Naturalness' the ONLY guidance.

ONLY exception: the Higgs sector!

Higgs boson is contained in a chiral superfield.

• A novel feature of supersymmetry: while in the SM a single Higgs doublet gives masses to all quarks and leptons, in the MSSM that is not possible.

• The reason is that chiral superfields couple through a complex analytic superpotential.

Recall the Yukawa interaction term from the SM:

$$\mathcal{L}_{Yuk} = f_e^*(\bar{\nu}, \bar{e})_L \Phi e_R + f_d^*(\bar{u}, \bar{d})_L \Phi d_R + f_u^*(\bar{u}, \bar{d})_L \Phi^C u_R + ..$$

Note that the term giving mass to up-type quarks involves Φ^C and the other two involve Φ. Thus the same Higgs chiral superfield can not be used in the two cases. SUSY generalization of the two types of terms will have to include two separate superfields.

• For this reason there have to be two Higgs doublets in the MSSM (of course there could be more than two, but that would not be the MSSM).

• One gives mass to the down quark (and down squark) while the other gives mass to the up quark (and up squark).

• There is a term in the Superpotential $\mathcal{W}_{MSSM}$ containing $\mu H1 \cdot H2$. A mass parameter which is supersymmetric.

To be specific we have two Higgs chiral super fields :

H_2 is a Higgs chiral superfield of hypercharge $+1$ (like the SM Higgs). It is also called the “up-type” Higgs.

Next, a Higgs chiral super field H_1 of hypercharge -1 which gives mass to the down-type quarks H_1 is also called the “down-type” Higgs.

The Higgs super field contains supersmmetric spin 1/2 partners of the Higgs Higgsinos. The number and the quantum number of the additional fermions is what is needed to cancel the anomalies.

This provides an independent reason for two Higgs doublets, and puts a constraint on extensions of the MSSM.

• Anticipating the Higgs mechanism, the charge assignments of the two Higgs doublets have to be: $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$

• Let the scalar components of the superfields H_1, H_2 be $h_1(x), h_2(x)$. The possible VEV's they can develop, consistent with charge conservation, are: $\langle h_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \quad \langle h_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$

• It is possible to rotate the fields so that both VEV's are real. Then we define:

$$\tan\beta = \frac{v_2}{v_1}$$

and this is the important β -parameter of the MSSM.

For further discussions SUSY breaking terms are essential as the EW symmetry breaking and SUSY breaking intimately connected.

Relevant part for us:

$$\begin{aligned}\mathcal{L}_{soft,Higgs} &= [h_1 \cdot \tilde{\ell}_{iL}(f^e A^e)_{ij}\tilde{e}^{\star}_{jR} + h_1 \cdot \tilde{q}_{iL}(f^d A^d)_{ij}\tilde{d}^{\star}_{jR} \\ &+ \tilde{q}_{iL} \cdot h_2 (f^u A^u)_{ij}\tilde{u}^{\star}_{jR} + \text{h.c.}] \\ &+ m_1^2|h_1|^2 + m_2^2|h_2|^2 + (B\mu h_1 \cdot h_2 + \text{h.c.})\end{aligned}$$

The scalar potential will have contributions from the $\mathcal{L}_{soft,Higgs}$ and from the terms in the super potential. It will involve members of the h_1, h_2 doublets.

The raison de trê of SUSY is to keep the Higgs mass stable under radiative corrections. In spite of the breaking of SUSY there exist **upper** bound for the mass of the lightest Higgs.

This is the only sector of Sparticles where theory has a prediction for **a** *mass* which is robust with respect to the details of Soft SUSY breaking mechanism.

The scalar potential for the Higgs sector is generated from terms in the Superpotential and the quartic coupling is determined in terms of the gauge couplings.

There exist 8 scalars in the MSSM.

Two doublets of complex scalars: 8 fields.

3 Gauge bosons get mass via EWSB. 3 of the scalars are the Goldstone bosons.

Five Physical scalars left h, H, A and $H^{\pm}$. A charged spin 0 particle, if found, would be a great indicator of SUSY.

$\mathcal{L}_{Af\bar{f}} \propto \bar{f}\gamma_5 f A$

$\mathcal{L}_{hf\bar{f}} \propto \bar{f} f h$

In Supersymmetric theories, no EWSB without SUSY breaking.

The scalar potential is given by:

$$V_H = \frac{1}{8}(g_1^2 + g_2^2)(|h_1|^2 - |h_2|^2)^2 + \frac{g_2^2}{2}|h_1^\dagger h_2|^2$$

$$+ m_{1h}^2|h_1|^2 + m_{2h}^2|h_2|^2 + (m_{12}^2 h_1 \cdot h_2 + h.c.),$$

Here, $m_{1,2h}^2 = m_{1,2}^2 + |\mu|^2$ and $m_{12}^2 = B\mu$.

V_H comes from $V_{SOFT} = -\mathcal{L}_{SOFT}$ as well as from $\mathcal{W}_{MSSM}$ (F-terms) and D terms.

Only three parameters compared to the six parameters plus one phase for the general two Higgs doublet potential. The quartic coupling related to gauge couplings.

Scalar potential involves very few (only 2 in the end) of many of SUSY /breaking parameters at tree level. Story is different once we include radiative corrections.

Even then since the parameters involved $m_1, m_2, B\mu$ are arbitrary how can this potential have ANY predictivity?

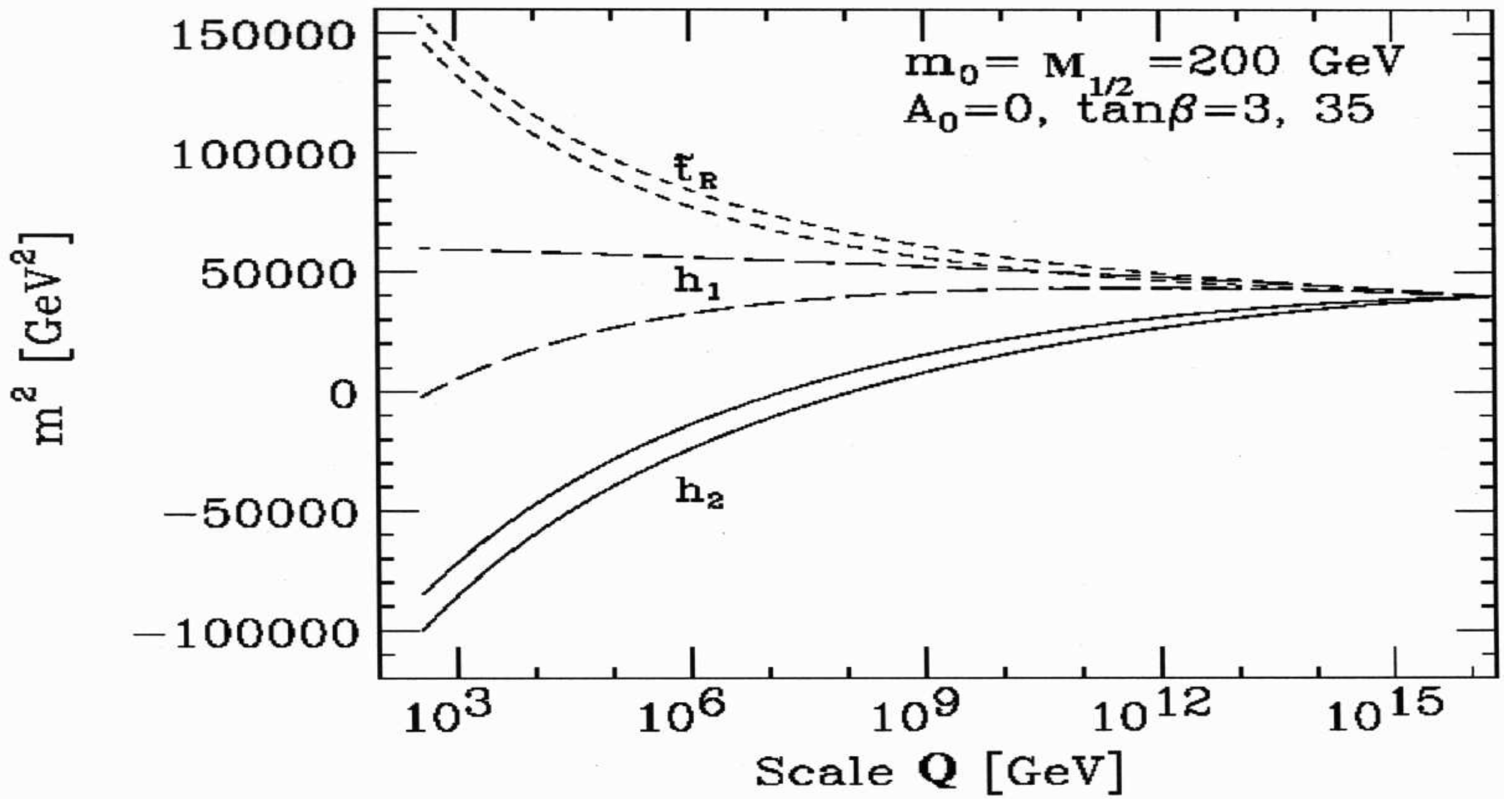
We will find that even then we get a bound for the lightest higgs.

Further the mass bounds for the Higgs not crucially dependent on details of SUSY breaking, but do depend on the breaking scale.

We learnt that masses evolve with scale like the couplings One can write RGE's for m_1^2, m_2^2.

Even if one starts from $m_1^2 = m_2^2$, the RGE for m_2 will receive large contributions from $t\bar{t}$ loops (recall H_2 was the 'up' Higgs) and the corresponding term in the scalar potential can be driven negative triggering EW symmetry breaking. **What we need is a HEAVY top quark** (Hall,Lykken, Weinberg). Nature has given it to us.

Next slide demonstrates this in the cMSSM where all the scalar masses (sfermions and higgses) are the same at high scale. μ then determined by the condition that RGE triggers EWSB.



150000
100000
50000
0
−50000
−100000
m^2 [GeV^2]
10^3
10^6
10^9
10^{12}
10^{15}
Scale Q [GeV]
$m_0 = M_{1/2} = 200$ GeV
$A_0 = 0$, $\tan\beta = 3, 35$
$\tilde{t}_R$
h_1
h_2

The potential involving only the neutrals

$$V_H^0 = \frac{1}{8}(g_Y^2+g_2^2)^2(|h_1^0|^2-|h_2^0|^2)^2+m_{1h}^2|h_1^0|^2+m_{2h}^2|h_2^0|^2-m_{12}^2(h_1^0h_2^0+h.c.)$$

1)V_H^0 must be bounded from below

$m_{1h}^2+m_{2h}^2 = m_1^2+m_2^2+2|\mu|^2 > 2|m_{12}^2|$ (Valid at all scales).

2)EW symmetry breaking should happen:

$m_{12}^4 > m_{1h}^2 m_{2h}^2 = (m_1^2+|\mu|^2)(m_2^2+|\mu|^2)$ (valid at and below the scale where EW breaking is operative).

In the supersymmetric limit $m_{1h}^2 = m_{2h}^2 = \mu^2$, the two conditions are incompatible with each other.

No EW breaking with unbroken SUSY. Intimate connection between SUSY breaking and the EW symmetry breaking in MSSM.

For EW symmetry breaking to occur V_H should have a minimum for

$$\langle h_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \quad \langle h_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}.$$

Consistency conditions that this be a minimum gives two relations and thus constraints on the model parameters:

$$-2B\mu = -2m_{12}^2 = (m_1^2 - m_2^2)\tan 2\beta + M_Z^2 \sin 2\beta$$

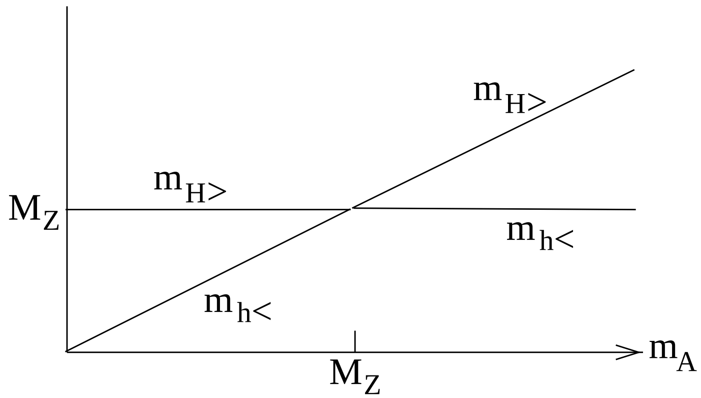
$$|\mu|^2 = (\cos 2\beta)^{-1}(m_2^2 \sin^2\beta - m_1^2 \cos^2\beta) - \frac{1}{2}M_Z^2 \ .$$

Example of the constraints from Higgs sector which reduces number of parameters of SUSY models.

A relation between μ, M_Z and SUSY breaking mass parameters.

Range of $\tan\beta$ values restricted to $1 < \tan\beta < 60$ for radiatively induced symmetry breaking to work.

All the masses $m_h, m_H, m_{H^\pm}$ and their couplings decided in terms of $M_A, \tan\beta$. M_A a good choice rather than the opaque m_1, m_2 etc.



$m_{H^\pm}^2 = m_A^2 + M_W^2 > \max\ (M_W^2, m_A^2)$, $\quad m_h^2 + m_H^2 = m_A^2 + M_Z^2$,

$m_h < \min\ (m_A, M_Z|\cos 2\beta|) < \min\ (m_A, M_Z)$, $\quad m_H > \max\ (m_A, M_Z)$

Absolute (β independent) bound.

$m_{H^\pm} > M_W, \quad m_h < M_Z, \quad m_H > M_Z, \quad m_h < m_A < m_H$

LEP has ruled out existence of a Higgs lighter than M_Z.

Does it mean MSSM is ruled out? no! large radiative Corrections due to large top mass, proportional to m_t^4

For last 15 years radiative corrections have been computed. Two loop results are available.

For $\tan\beta > 1$, the mass eigenvalue of h increases monotonically with m_A, saturating to its maximum Upper bound

$m_h \; < \; (M_Z^2 \cos^2 2\beta + \epsilon_h)^{1/2}$ with $\epsilon_h = \frac{3 G_F m_t^4}{\sqrt{2}\pi^2} \ln \frac{m_{\tilde{t}}^2}{m_t^2}$.

The upper bound is further relaxed when $\tilde{t}_L - \tilde{t}_R$ mixing is included and maximal when $A^t = \sqrt{6 m_{\tilde{t}_1} m_{\tilde{t}_2}}$.

The absolute upper bound is 132 GeV in MSSM for $M_s = 1$ TeV.

The bound can be further relaxed by going to extensions of the MSSM (NMSSM).

NMSSM: enlarge the Higgs sector of the MSSM by adding additional Higgs Singlets.

$$\mathcal{W}_{NMSSM} = \lambda \widehat{S} \widehat{H}_1 \widehat{H}_2 - \frac{k}{3} \widehat{S}^3$$

$$V_F = \lambda^2 x^2 (v_1^2 + v_2^2) + \lambda^2 v_1^2 v_2^2 + k^2 x^4 - 2\lambda k x^2 v_1 v_2,$$

where $x = \langle S \rangle$, $v_{1,2} = \langle H_{1,2}^0 \rangle$ and $\tan\beta = v_2/v_1$.

The upper limit on the lightest Higgs mass is now:

$$M_{H_1}^2 \leq M_Z^2 \cos^2(2\beta) + \frac{2\lambda^2 M_W^2}{g^2} \sin^2(2\beta) + \epsilon,$$

The NMSSM relaxes the LEP bound on M_{H_1}. Due to the second term in red above.

Effect pronounced at moderate $\tan\beta$

The bound is relaxed upto 165-175 GeV.

Experimental information on Higgs mass very close to the theoretical upper bound in MSSM.

This means that the sparticle masses are large! So again some sort of Fine Tuning?