Higgs Physics

Implications of a 125 GeV Higgs for the SM and SUSY

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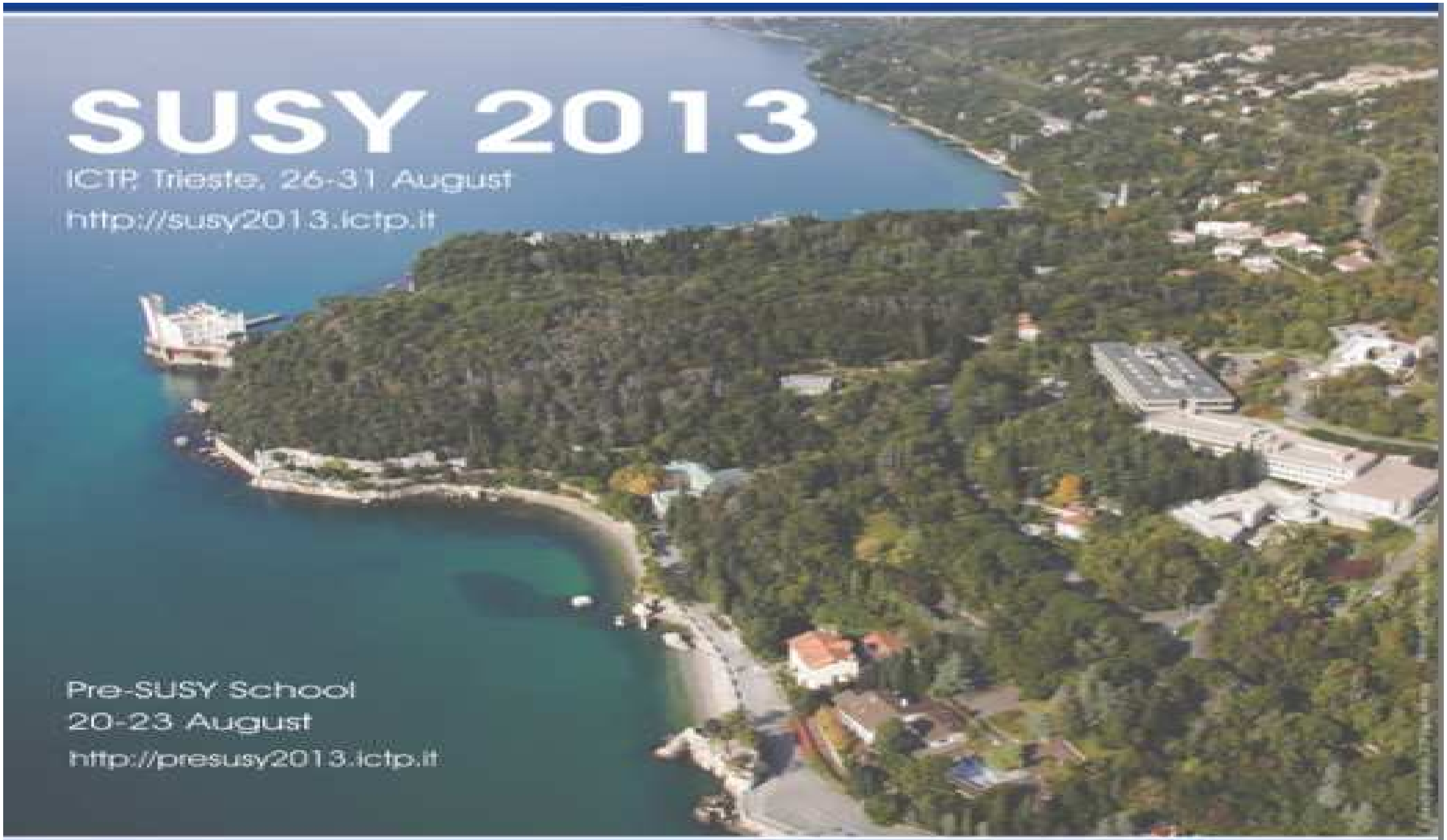
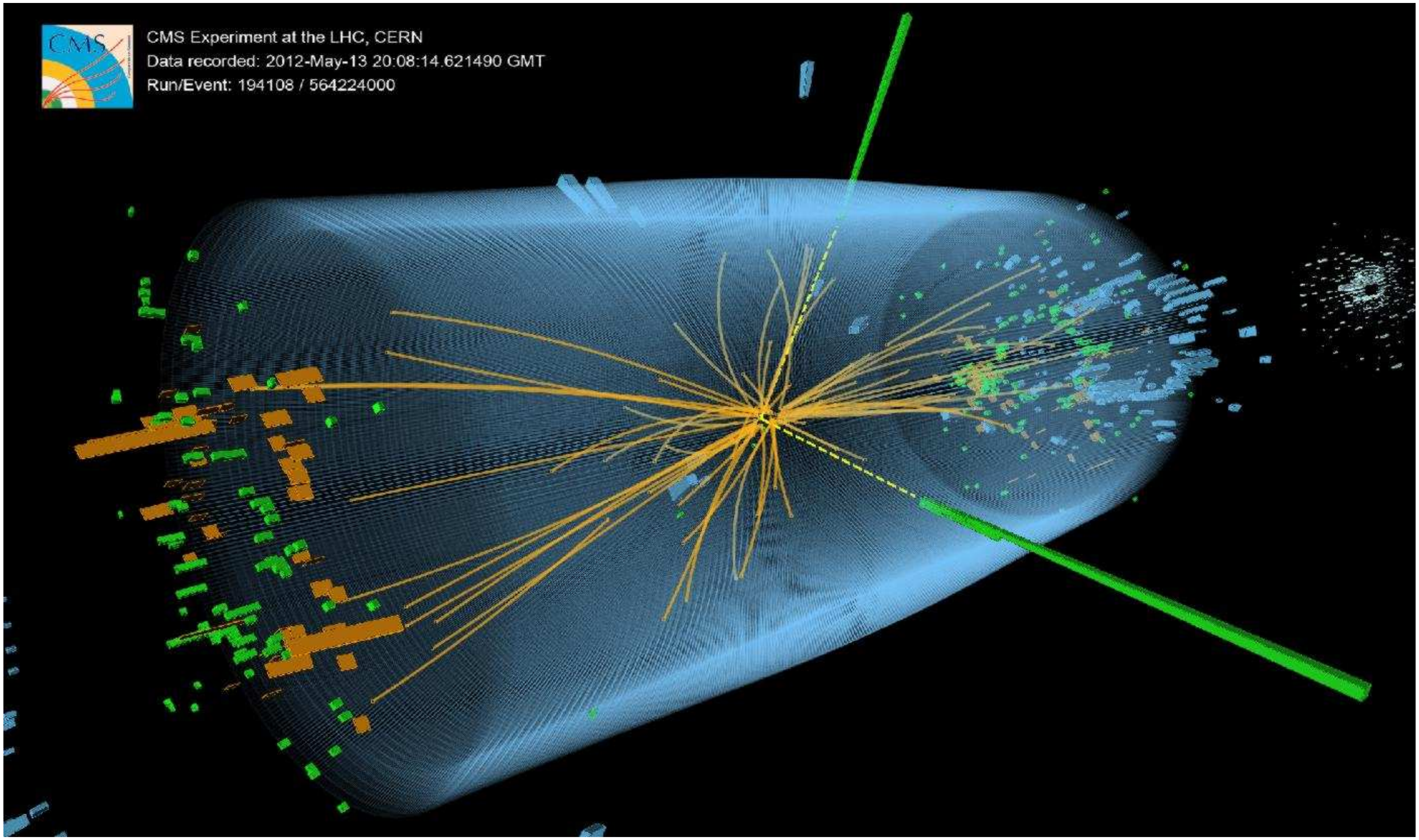
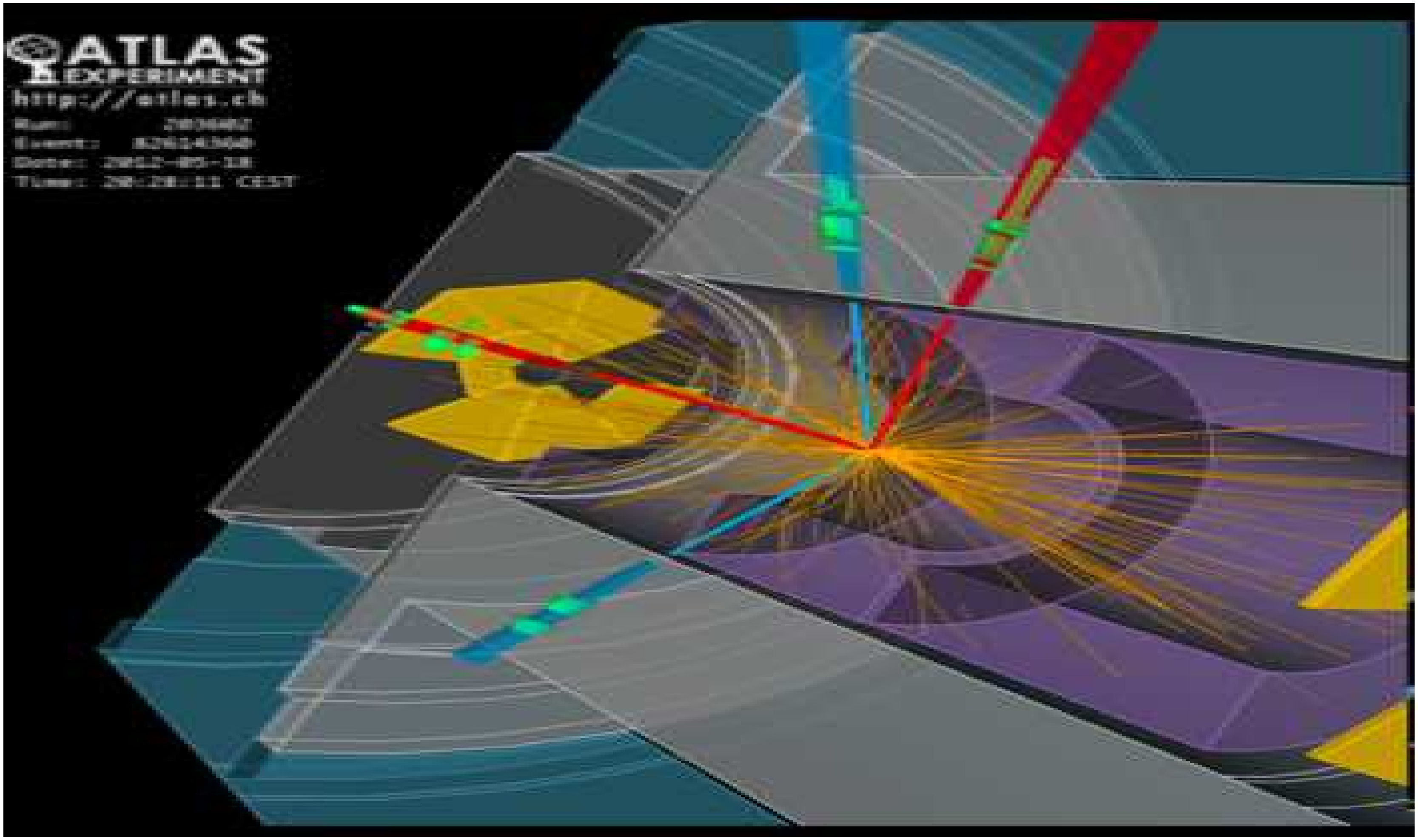
Trieste, Italy August 20-23, 2013.


SUSY 2013
ICTP, Trieste, 26-31 August
http://susy2013.ictp.it
Pre-SUSY School
20-23 August
http://presusy2013.ictp.it

Also happening in the backdrop of

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Signals seen at some level or the other in many channels:

$pp \to h + X \to WW + X$, $pp \to h + X \to \tau\tau + X$ and also in $pp \to VH + X \to Vb\bar{b} + X$.

In fact at 14 TeV hopes for even seeing the $t\bar{t}H$ signal!

One would like to address following questions:

• Is it a Higgs? Are the **tree level** coupling **strengths** proportional to masses of the objects to which it couples?

• Assuming that this is the Higgs what are the theoretical implications of the observed mass and rates? For the SM and BSM physics. In the context of this school implications for SUSY.

• What do we need to do to see if this is the 'standard' scalar or an 'imposter?' What is its spin and CP property? I.e. how to determine the **tensor structure** of its interaction with a pair of fermions and gauge bosons?

• Is it an elementary particle or a composite?

1. Summary of aspects of Higgs couplings which are relevant for the interpretation of the observed signal as A Higgs boson.

2. Theoretical and (pre-July 2012) experimental bounds on the Higgs mass. **Instabiltiy of the Higgs mass against radiative corrections and the hierarchy problem.**

3. Higgs sector in the Supersymmetric theories: MSSM, NMSSM. EWSB induced by RG evolution of masses. Relationship between SUSY breaking and EWSB.

4. Implications of the observed properties of the Higgs boson for the SM and supersymmetric theories..... **Determining Higgs properties? Whither next?**

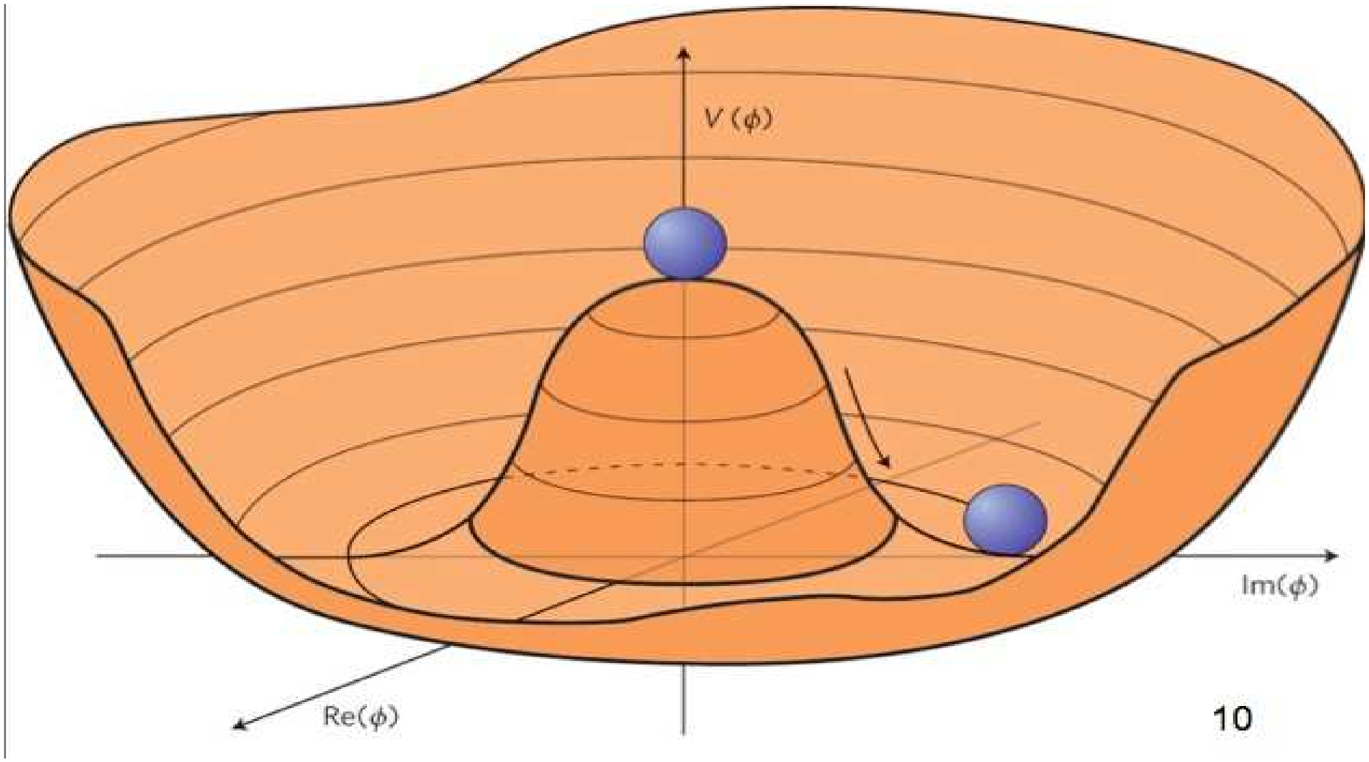
(Use notation of Theory and Phenomenology of Sparticles: Manuel Drees, R.G. and Probir Roy)

It all started with Fermi's theory of β decaywhich was an effective current current interaction.

But we can start at a somewhat later point:

Paper by Weinberg on 'Model of Weak Interactions of the Leptons' : 1967. This when extended to include quarks, Glashow predicted in fact existence of a new quark, charm quark.

This is what we know today as the Standard Model, the 'Gauge Theory' of Weak Interactions



Weinberg-Salam used the Higgs mechanism to make massive gauge bosons consistent with Gauge invariance . But this was ONLY one way of achieving it. It was likely, not necessarily probable, that Weinberg's model was right and still there would be NO elementary Higgs!

Theoretical ideas for the Higgs-boson are from 1960

In 1974 in the so called 'November' revolution, experiments yielded evidence for charm!

Around the same time the weak neutral currents were discovered. Predicted by Glashow-Weinberg-Salam model.

This galvanised interest in Gauge theory of weak interactions with spontaneously broken symmetry as well as the Higgs.

In 1976 Ellis, Nanopoulos, Gaillard wrote a long article in Nucl.Phys. B called 'Profile of the Higgs' but the paper stated that they did not advocate building billion dollar machines to find it, but they thought experimentalists should know what the beast is like if it met them!

But since then phenomenologists started suggesting ways and means of ascertaining whether the Higgs boson exists!

The various experimental discoveries/precision measurements in the intervening period in the end did in fact drive the particle physics and finally led us to LHC to solve the mystery of the EW symmetry breaking!

What was the mystery? How to have massive W/Z and yet have a renormalisable theory of weak interaction.

What is worth noting however, is that this theory would satisfy tree level unitarity ONLY for a light Higgs boson.

Standard Model Lagrangian consists of 'proved' gauge sector, Yukawa sector and **the currently under scanner scalar** sector:

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + i\bar{\psi}\not{D}\psi + f_e^*(\bar{\nu},\bar{e})_L\Phi e_R + f_u^*(\bar{u},\bar{d})_L\Phi^C u_R$$
$$+ \ldots.. + h.c. + |D_\mu\Phi|^2 - \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$$

After spontaneous symmetry breaking ($\mu^2 < 0$)

$$\langle\Phi\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$$

Vacuum not symmetric but the Lagrangian still is. Scattering amplitudes are gauge invariant.

One scalar degree of freedom h left. Mass of W, Z related to g_1, g_2 and v. v can be determined in terms of the μ decay constant G_μ;

$v = \sqrt{-\mu^2/\lambda}$, and $v = (G_\mu \sqrt{2})^{-1/2} \simeq 246$ GeV.

the Lagrangian for the scalar is:

$$\frac{1}{2}(\partial_\mu h)^2 - \frac{m_h^2}{2} - V_1(h)$$

with

$V_1(h) = \lambda v h^3 + \frac{\lambda}{4} h^4$ and $m_h^2 = 2\lambda v^2$.

Note connection between λ and m_h!

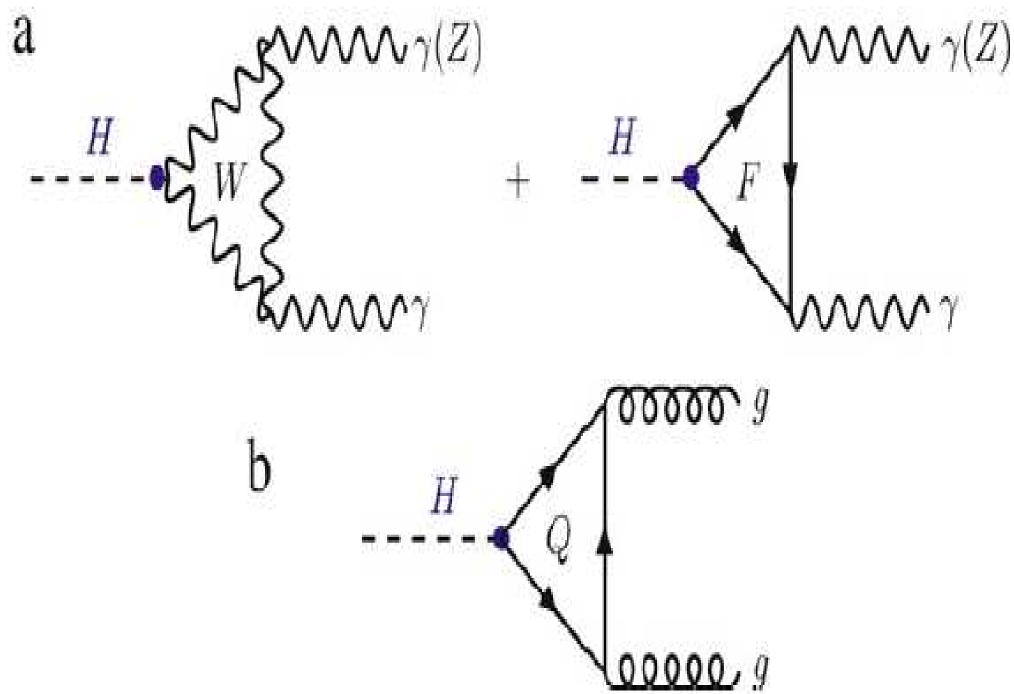
h is J $=$ 0, CP even, Hypercharge Y$=$ 1 and $SU(2)_L$ doublet.

Tree level $\bar{f}fh$, hVV , $hhVV$ couplings $\propto$ mass:

$$\lambda_f = \frac{m_f}{v}; \quad g_V = 2\frac{M_V^2}{v}; \quad g_{hhVV} = 2\frac{M_V^2}{v^2}.$$

Couplings to gg and $\gamma\gamma$ are loop induced!

The most important couplings for the Higgs search at the LHC are $\gamma\gamma h$ and gg-h couplings, which are loop induced.



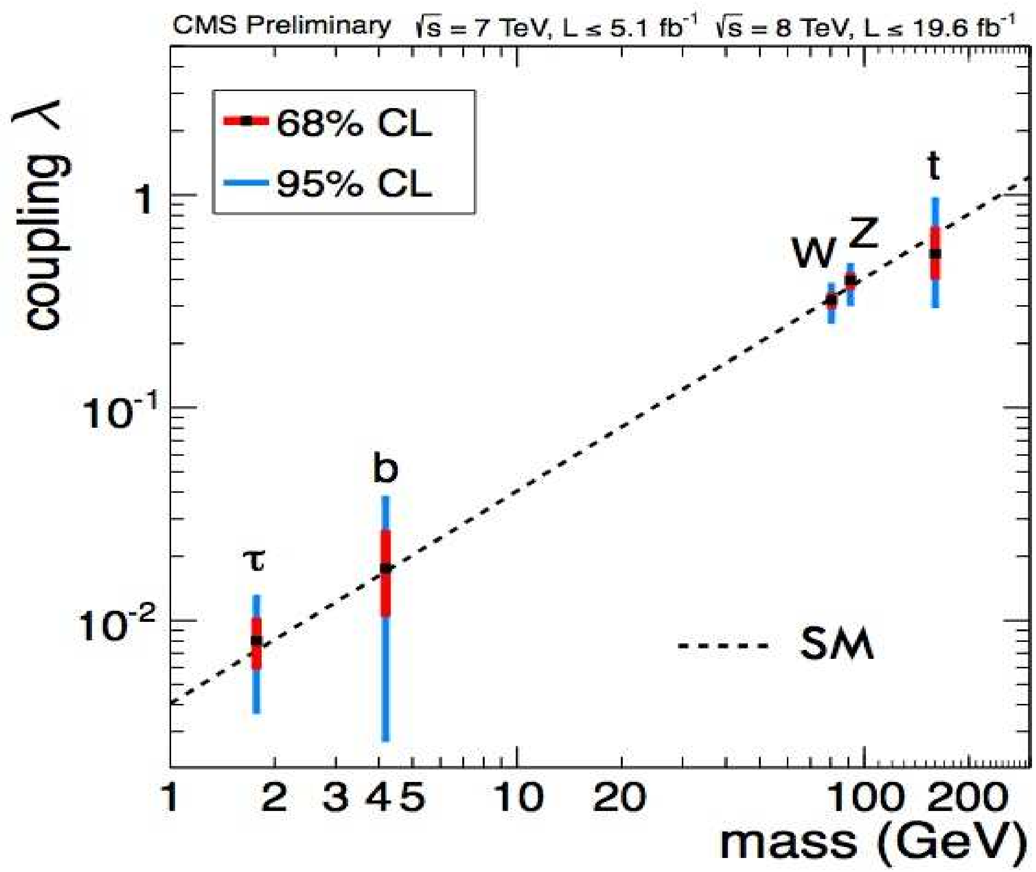
SM case

1) In the SM, the contribution is due to W, t loops for the $h\gamma\gamma$ vertex, whereas for the hgg it is the top contribution. For BSM only strongly interacting new particles can change hgg.

2) New particles beyond the SM contribute in the loops and the contributions are non decoupling for chiral fermions which get their mass from the Higgs mechanism. I.e. they are independent of the mass of the heavy fermions in the loop.

3)For $m_h = 125$ the $\gamma\gamma$ width $\propto |A_W + A_{top}|^2$, is dominated but W contribution: $A_W = -7$ and $A_{top} \sim \mathcal{O}(1)$, about 0.2 of the $W-$ contribution.

4)Can be smoking gun signal for New Physics!



For the first time some information on the fermion higgs coupling.

$\lambda_x = m_x/v$ (in the SM)

Is it the Higgs?

Higgs Couplings with pair of gauge bosons (ZZ/WW) and the pair of heavy fermions (t/τ) are largest.

Study these in a model independent way

$$\phi_i f \bar{f} \;:\; -\bar{f}(a_f + i b_f \gamma_5) f \frac{g m_f}{2 m_W}, \textbf{(mixedCP)}$$

$$V V \phi_i \;:\; c_V \frac{g m_V^2}{m_W} g_{\mu\nu} \quad \textbf{(CPeven)}, \quad (\mathrm{V} = \mathrm{W/Z} \quad \text{tree})$$

$$: \; p_\mu q_\nu / m_V^2 \quad \textbf{(CPeven)}; \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma / m_Z^2 \quad \textbf{(CPodd)}, \text{(loop level)}$$

In more detail:

$$V_{HVV}^{\mu\nu} = \frac{i g m_Z}{\cos\theta_W} \left[a_V \, g_{\mu\nu} + b_V \frac{(p \cdot q g_{\mu\nu} - p_\mu q_\nu)}{m_V^2} + c_V \, \epsilon_{\mu\nu\alpha\beta} \frac{p^\alpha q^\beta}{m_V^2} \right],$$

SM limit: $a_f, a_V = 1$ and $b_V, c_V = 0$

What can give rise to a_f, b_f and a_V, b_V different from those expected in the SM?

1)Multiple scalars (including CP odd) and mixing among them with/out CP violation in the Higgs sector.

3)Higher dimensional operators induced by loops and/or in composite Higgs models.

4) Spin of the resonance different from 0

With the mass of $\sim$ 125 GeV we are very lucky to have all the channels open with significant branching fraction.

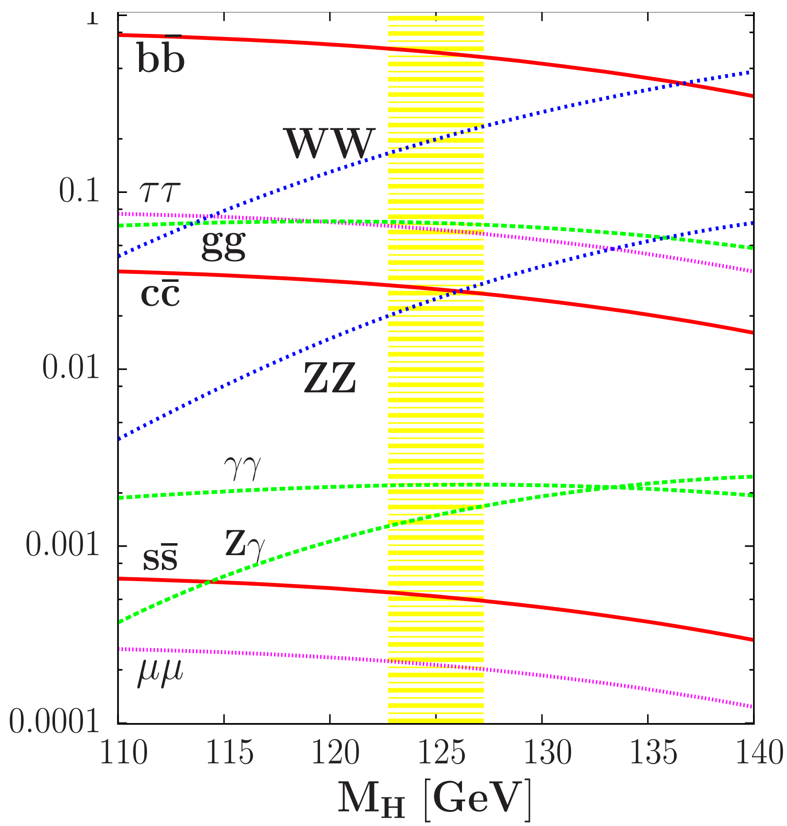


Fig: courtesy A. Djouadi.

Masses of gauge bosons, fermions determined in terms of v, g_1, g_2 and the Yukawa couplings.

One can trade g_1, g_2 and v for α_{em}, G_μ and M_Z.

Two points to remember

- λ is the ONLY undetermined parameter. Hence m_h is undetermined in the SM.

- Choice of $\mu^2 < 0$ ad hoc.

Before July 4, 2012 there existed only mass bounds for the Higgs !

Experimental Bounds:

Indirect by comparing the precision measurements of the Z, W physics at SLC, LEP etc with theory predictions obtained by high precision theory calculation.

Direct by looking for signals of Higgs production.

Theoretical Bounds :

From considerations of consistency of the theory! Quantum corrections to the self coupling λ.

Given α_{em}, M_Z, G_μ one can calculate M_W using tree level relations.

α_{em} = 1/137.0359895(61), G_μ = 1.16637(1) $\times 10^{-5} GeV^{-2}; MZ =$ 91.1875 $\pm$ 0.0021 GeV

Calculate M_W using the tree level relation

$\frac{G_\mu}{\sqrt{2}} = \frac{g_2^2}{8M_W^2} = \frac{\pi\alpha}{2M_W^2(1-M_W^2/M_Z^2)}$

$M_W^{tree} = 80.939$ GeV and $M_W^{expt} = 80.385 \pm 0.015$ GeV.

Loop corrections needed. Can be computed in a renormalizable theory and are finite ONLY for a finite Higgs mass.

- A large number of EW observables measured quite accurately.

- All are predicted in the SM in terms of α_{em}, M_Z and G_μ the **three SM parameters**, M_t *and* M_h.

- Calculate all observables to high precision

- Compare with data, make a SM fit by calculating χ^2.

GAVE AN INDIRECT LIMIT ON THE HIGGS MASS IN THE SM.

Loop corrections can be calculated consistently only in a renormalizable theory.

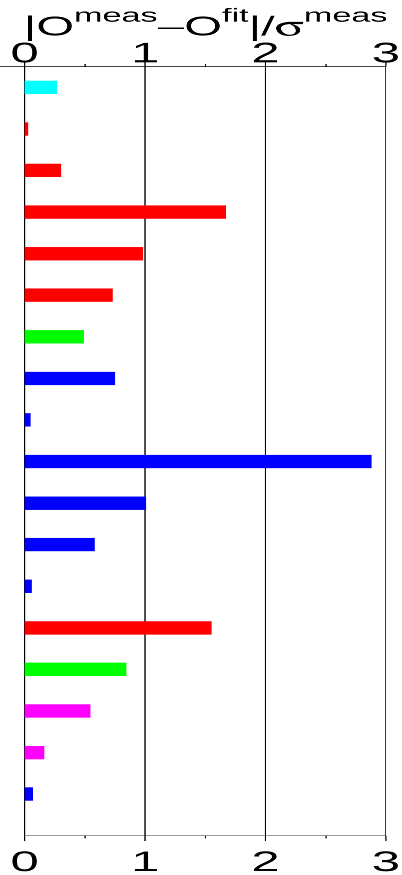
Depend on m_h logarithmically and on m_t quadratically.

Compare measured values of M_W, m_t against calculated from EWPT for different values of m_h.

Precision measurements and precision calculations!

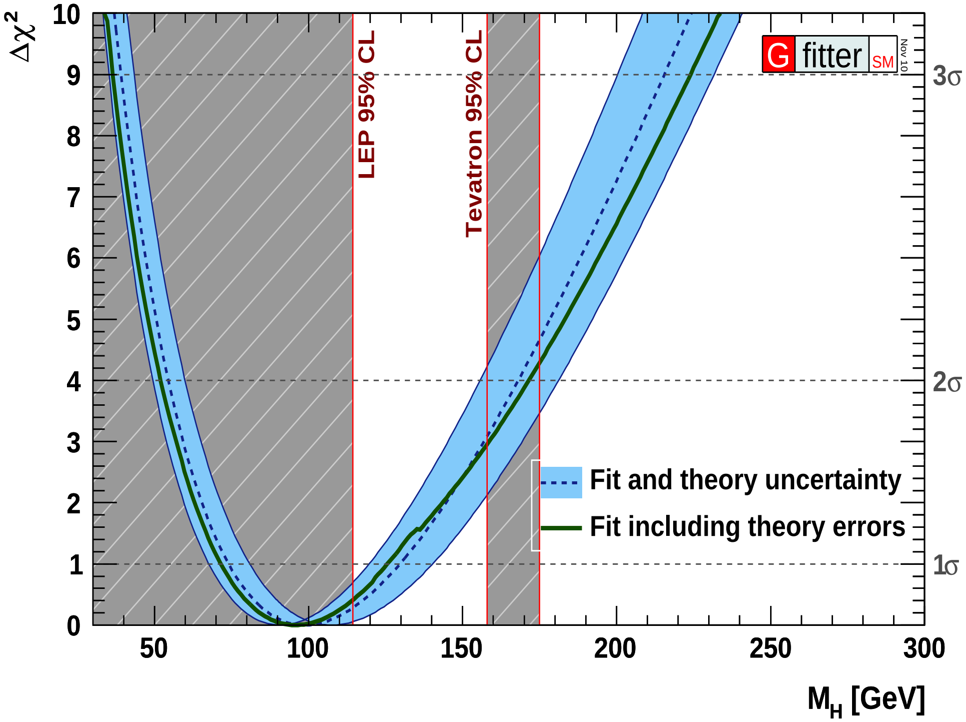
LEP legacy, augmented by Tevatron precision measurements!

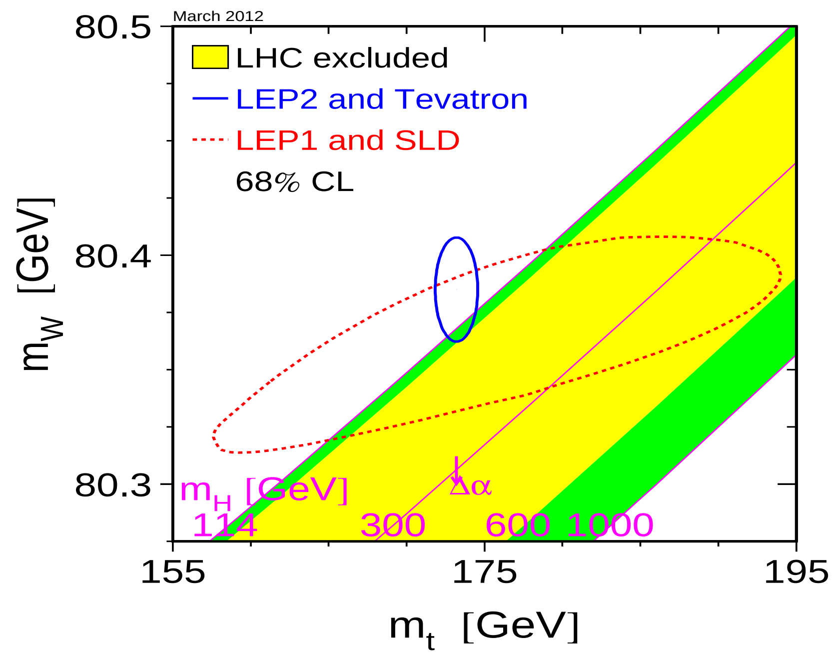
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
$A_l(\mathrm{SLD})$	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



March 2011

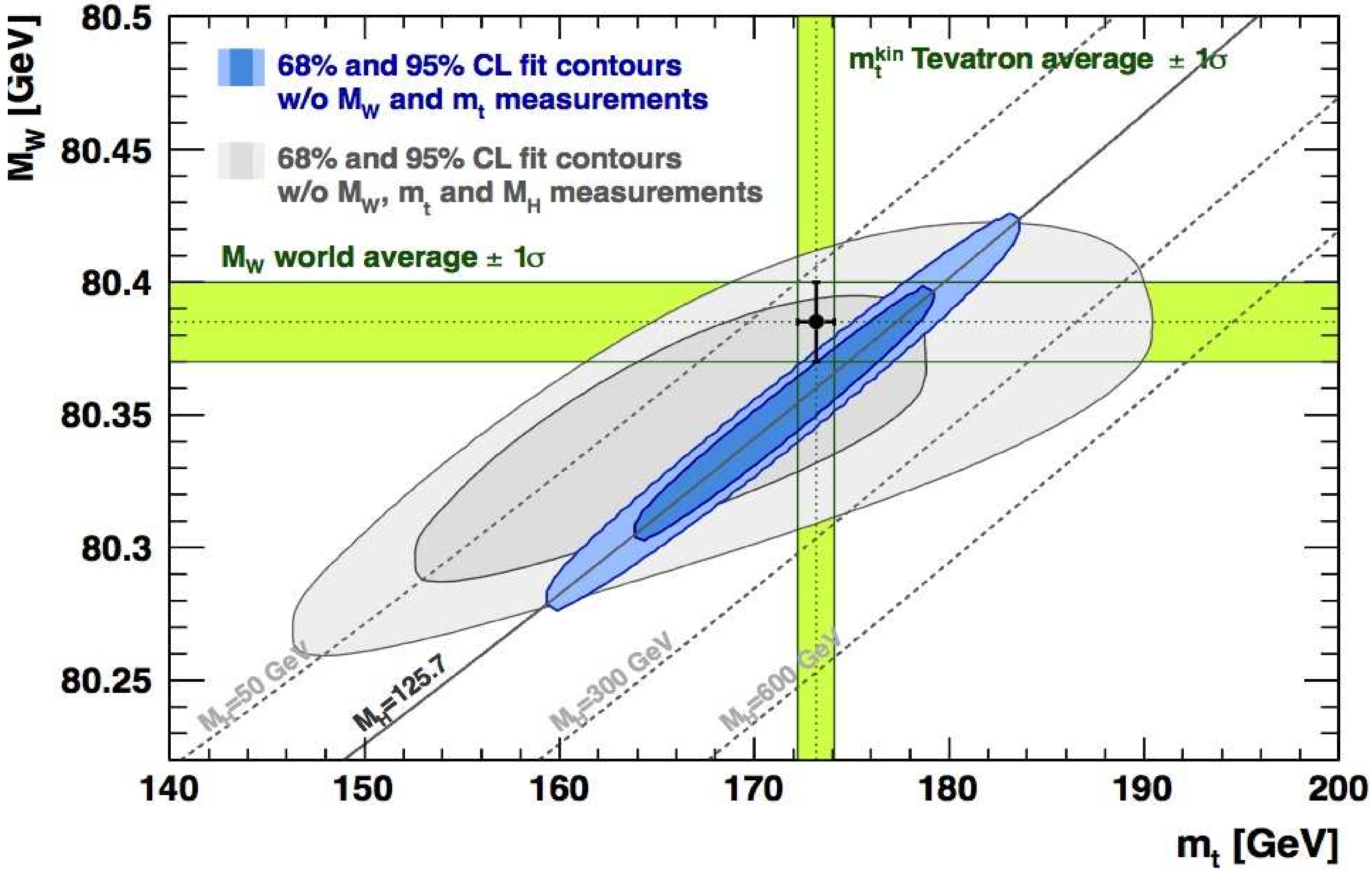
see http://lepewwg.web.cern.ch





Exptal. Limits: from nonobservation of Higgs in direct searches and indirect limits from LEP/Tevatron precision measurements.

Before the observation of signal at the LHC: **Precision EW measurements like LIGHT Higgs**. For the SM to be correct Higgs HAD to be light!



Implication number 1 of the observed m_h value : SM rocks!

Remember: the Higgs mass range allowed by precision measurements can change when one goes away from the SM.

In fact a lot of effort had gone on , in constructing models how one can remove these constraints. Not only that many of these will not be required, but some are now even ruled out, by the observation of the light state.

Implication of the observed light state for BSM:

Model with fourth sequential generation with a single Higgs doublet got ruled out with 126 GeV (low mass) scalar.

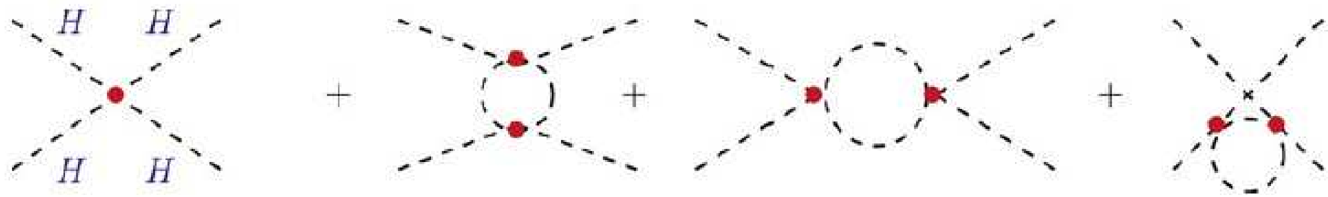
We will come back to this in the last lecture.

Pertubative Uniatrity: Demanding that W^+W^- scattering amplitude satisfy perturbative unitarity in fact one can derive the particle content of one generation of the SM Tiktopoulos, Cornwall as well as S.D. Joglekar $\sim$ 1974

But the unitarity is guaranteed ONLY for $m_h < 780$ GeV B.Lee and Thacker

The small value of the mass of the observed state means that the SM satisfies tree level unitarity!

Triviality and Stability Bounds: demanding that the quartic coupling in the Higgs potential remains perturbative and positive, under loop corrections. The corrections come from:



At large m_h and large λ considerations of triviality give an upper bound. That used to be of great concern !

With the small observed mass it is the stability bound!

Remember: $M_h^2 = \lambda v^2$. For large λ the loop corrections dominated by the $h-$loops.

At one loop running of λ given by:

$$\frac{d\lambda(Q^2)}{d\log Q^2} = \frac{3}{4\pi}\lambda^2(Q^2)$$

Solving this, one gets

$$\lambda(Q^2) = \frac{\lambda(v^2)}{[1 - \frac{3}{4\pi^2}\lambda(v^2)\log(\frac{Q^2}{v^2})]}$$

For large $Q^2 \gg v^2$ then $\lambda(Q^2)$ develops a pole (the Landau pole).

If we demand that λ remain always in perturbative regime, we can ONLY have $\lambda = 0$. Theory will be trivial.

One can take an alternate view:

Demand that the scale at which λ blows up is above a given scale Λ.

For a given M_h the scale at which the pole lies

$$\Lambda_C = v \ \exp\left(\frac{2\pi^2}{3\lambda}\right) = v \exp\left(\frac{4\pi^2 v^2}{3M_h^2}\right)$$

Using $\Lambda_C = \Lambda = 10^{16}$ GeV, we will find $M_h \lesssim 200$ GeV. Upper Bound: called triviality bound

Thus just the mass of M_h can give indication of the scale of new physics beyond the SM

When M_h is small and λ not large, the fermion/gauge boson loops are important. Fermions loops come with a negative sign!

Now the RGE for λ is given by

$$\frac{d\lambda(Q^2)}{d\log(Q^2)} \simeq \frac{1}{16\pi^2}[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4 - \frac{3}{2}\lambda(3g_2^2 + g_1^2) \\ + \frac{3}{16}(2g_2^4 + (g_2^2 + g_1^2)^2)]$$

λ_t is the Yukawa coupling for the top. At small M_h and hence small $\lambda(v)$, at some value of Q, λ can turn negative. Potential will be unbounded. Vacuum will be unstable

The condition is

$$M_h^2 > \frac{v^2}{8\pi^2} \log(Q^2/v^2) \left[12 m_t^2/v^4 - \frac{3}{16}(2g_2^4 + (g_2^2 + g_1^2)^2) \right].$$

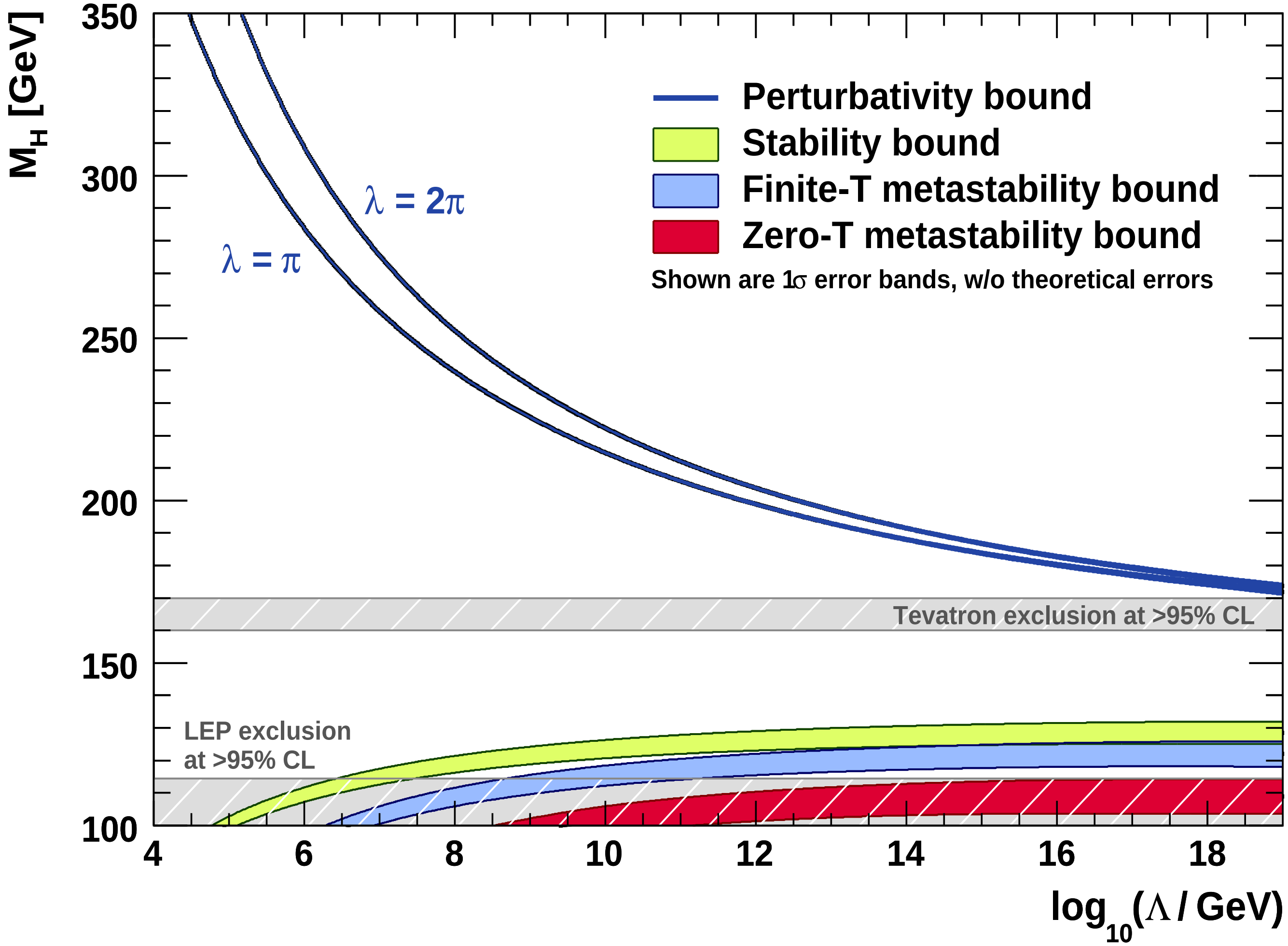
If we demand that the $\lambda(Q)$ is positive upto Λ_C we then get a lower bound.

For example:

$\Lambda_C = 10^3 GeV$, $M_h \gtrsim$ 70 GeV

Earliest calculations of stability bounds by Linde, Weinberg.

Maini et al, Altarelli-Isidori, M. Sher, Quiros...: analysis of stability and triviality bound using RGE, metastability...

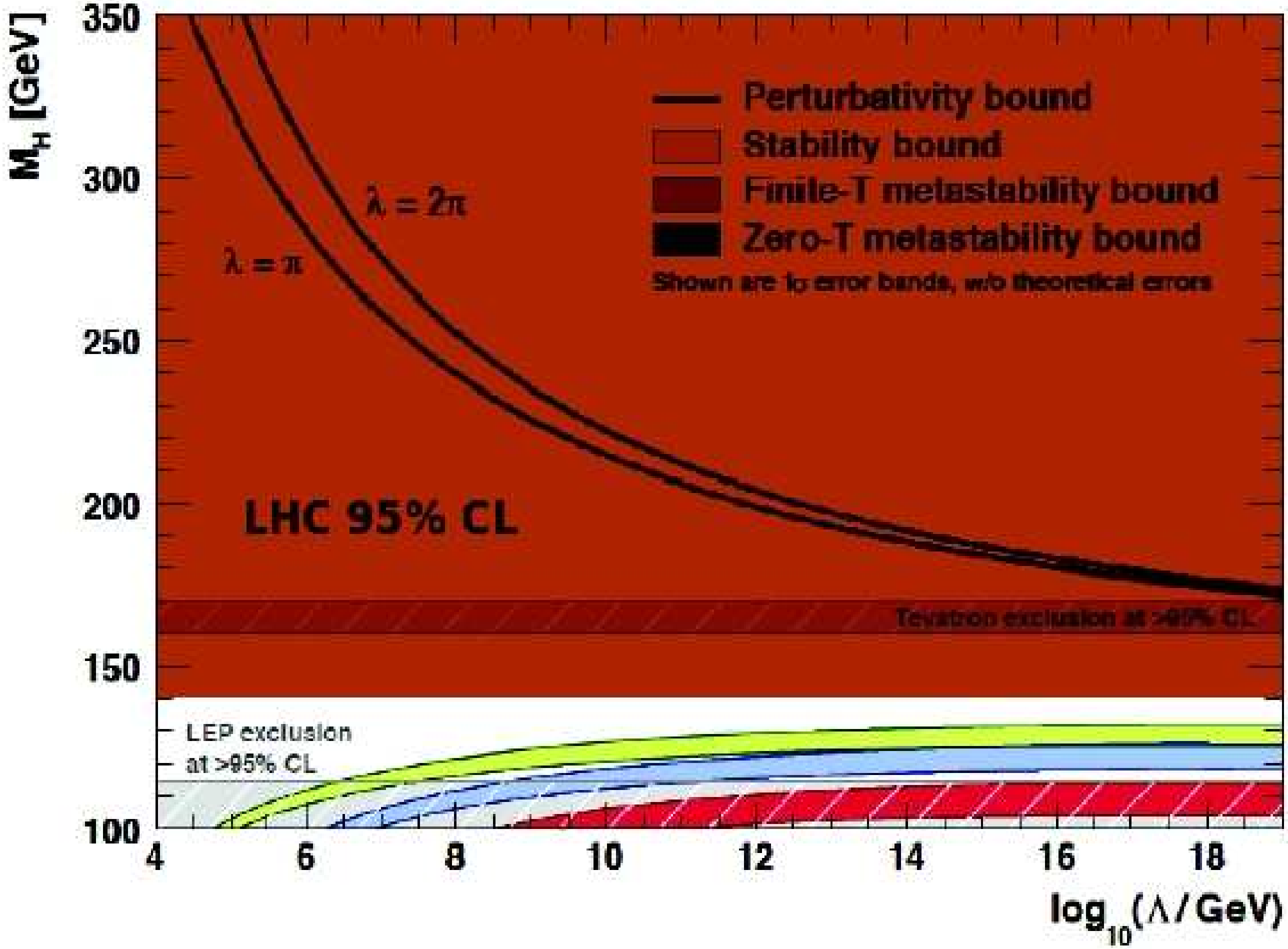


From a paper by Ellis, Giudice et al, PLB 679, 369-375 (2009). Includes higher order effects compared to the formulae here.

In view of the rather small values of m_h indicated by EWPT, need for more accurate calculation of these limits was required.

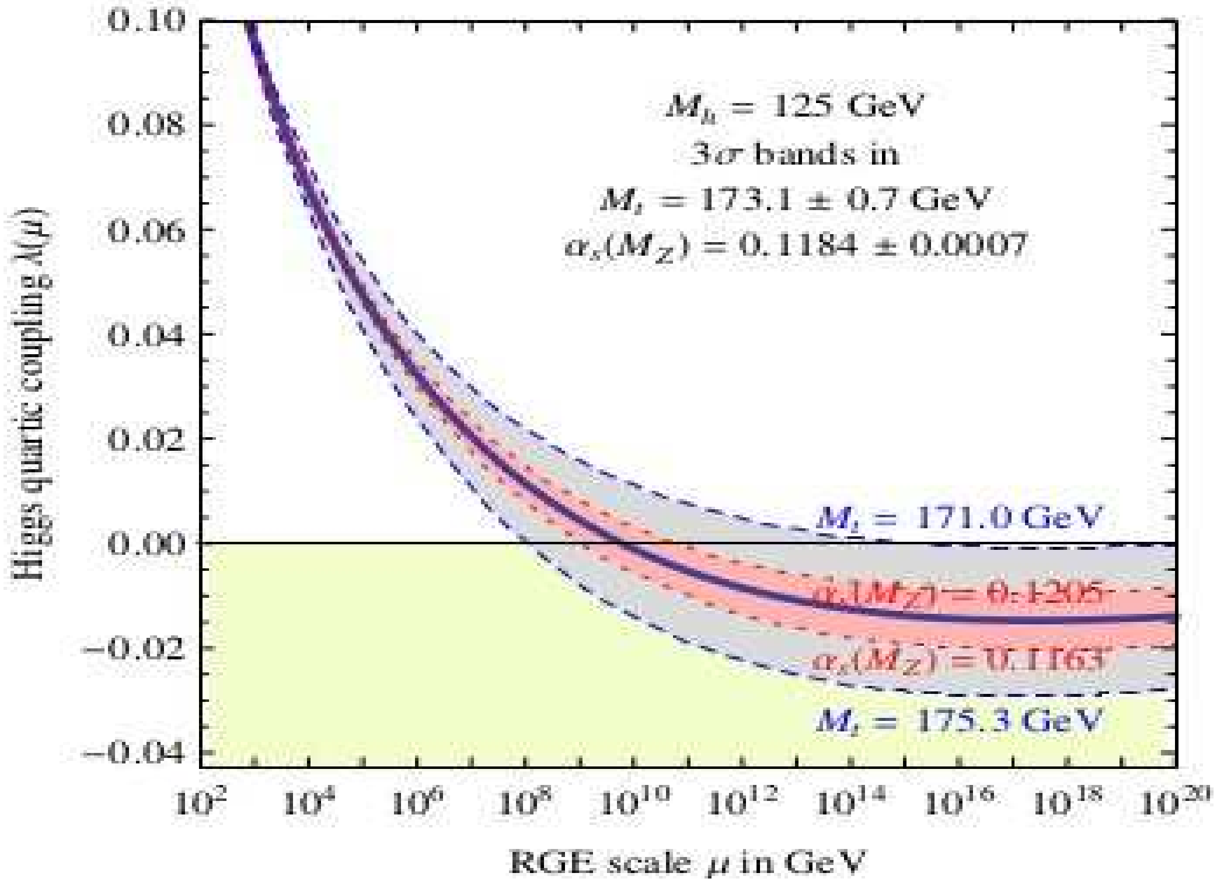
These limits critically depend also on $m_t^{\bar{M}S}$

State of the art in 2009: (Ellis, Giudice et al:0906.0954)



So the reported value around 125/126 GeV is very very special.

De Grassie et al (1205.6497) Complete NNLO analysis. Major progress. Theoretical error on the obtained bounds due to missing higher order corrections reduced to 1 GeV



$$M_h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}$$

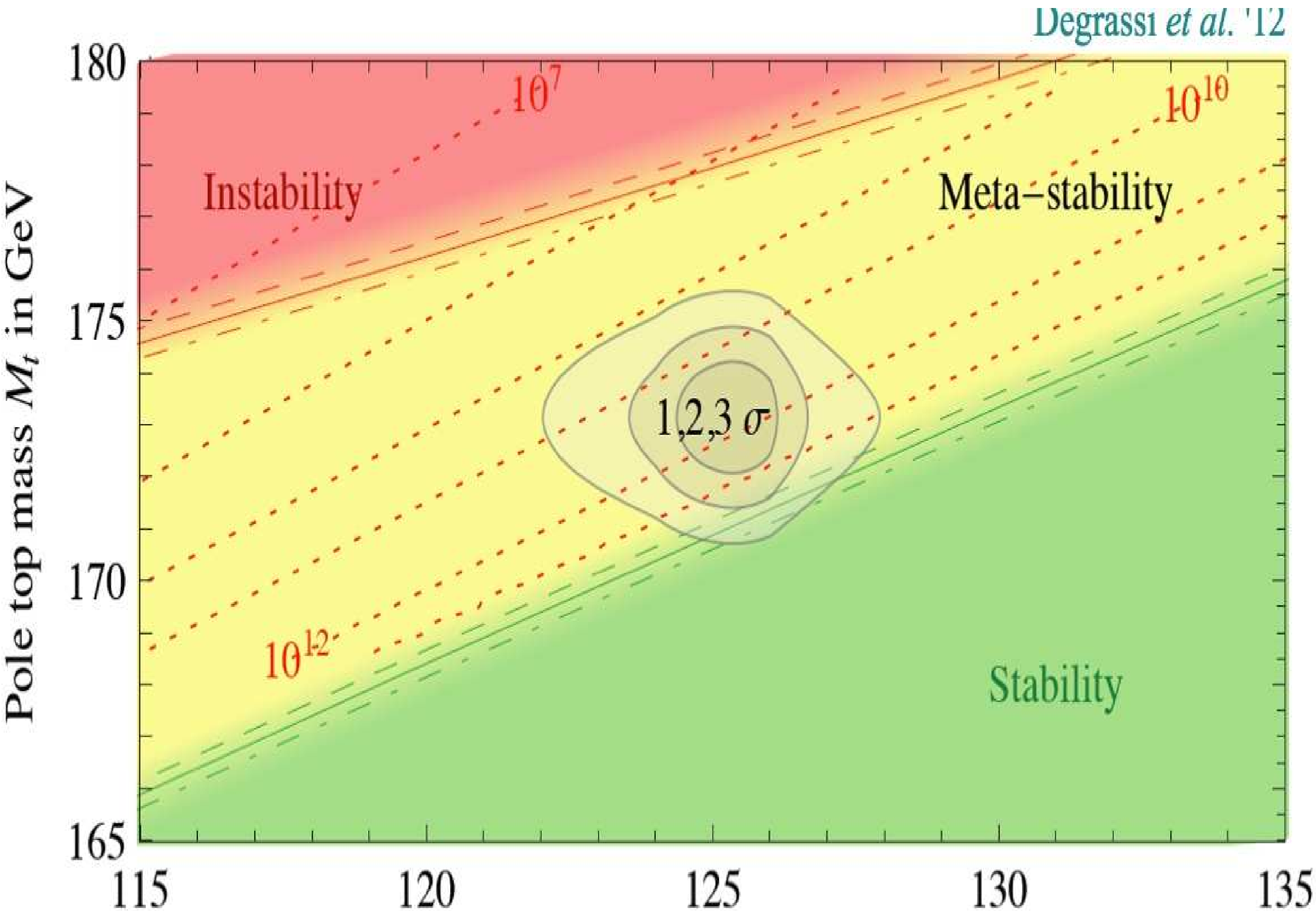
Use errors on pole mass $\Delta m_t = \pm 0.7$ GeV

So for $m_h < 126$ GeV vacuum stability of the SM all the way to Planck Scale is excluded at 98% c.l.

The exact scale where λ crosses zero, though not M_{pl} seems close to it in the SM depending on exact value of m_h.

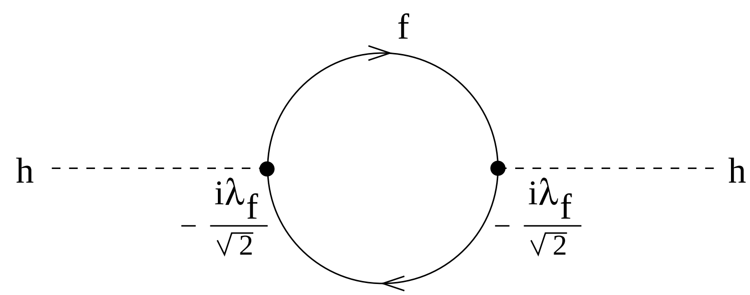
This may be relevant for consideration of BSM or models of inflation etc.

We will come back to this again in the last lecture!


Degrassi et al. '12
Instability
Meta−stability
Stability
1,2,3 σ
10^7
10^{10}
10^{12}
Pole top mass M_t in GeV
180
175
170
165
115
120
125
130
135

Consider $\mathcal{L} = -\lambda_f h \bar{f} f - \lambda_f v \bar{f} f$.

$\Pi^f_{hh}(0)$



$$\Pi^f_{hh}(0) = -2\lambda_f^2 \int \frac{d^4k}{(2\pi)^4} \left[\frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2} \right].$$

First quadratically divergent term independent of m_h. *This is reflection of the fact that* $m_h = 0$ *does not increase symmetry of the theory* and it is an *unnatural parameter*.

Second term $\propto m_f^2 \lambda_f^2/(8\pi)$

If there exist heavy, new fermions (like in GUTS) with mass $M_U \simeq 10^{16}$ GeV ,

$$m_h^2 = m_{\text{bare}}^2 + \delta m_{\text{h}}^2 \simeq m_{bare}^2 + m_U^2 \lambda_U^2/8\pi$$

Since m_h is to be bounded by TeV scale (recall unitarity) this means fine tuning (1 part in 10^{26}) to keep the renormalised mass at the TeV scale.

A light Higgs is not natural. This is the gauge hierarchy problem arising from radiative instability of the scalar mass. (Weinberg & Gildner)

Other way of seeing the same:

The Higgs mass which is a free parameter in the SM, receives large quantum corrections and the mass will approach the cutoff scale of the theory.

If, $m_{\mathrm{h}}^2 = m_{\mathrm{bare}}^2 + \delta m_{\mathrm{h}}^2$ the top loop (e.g.) gives

$$\delta m^2_{\mathrm{h|top}} \sim -\frac{3G_{\mathrm{F}}}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2.$$

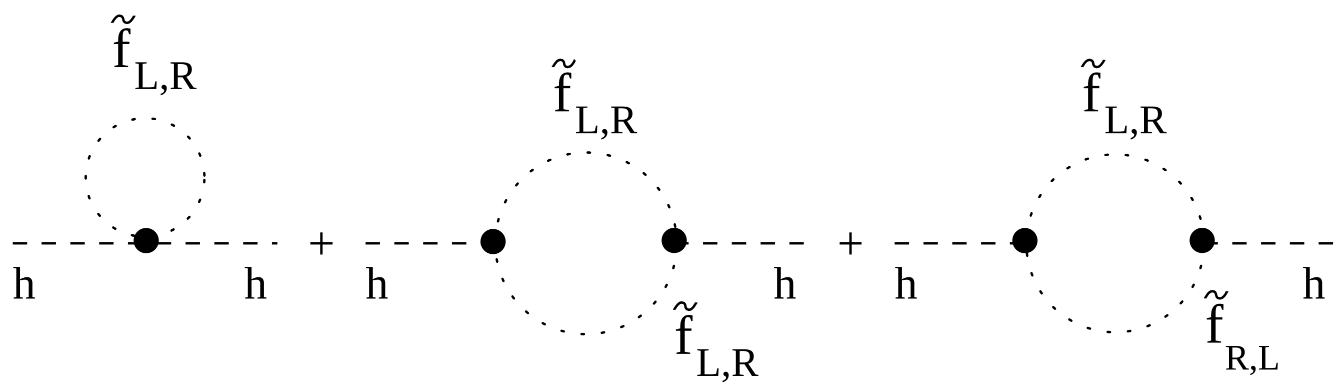
If the light higgs has to be 'natural' then $\Lambda \sim$ TeV.

TeV scale Supersymmetry is one option to keep the higgs light naturally. (Dimopoulos & Georgi, Kaul & Majumdar, Polchsinky, Susskind & Raby..) In SUSY the $\Lambda \Rightarrow m_{sparticle}$ We will see this next.

Add to the earlier Lagrangian two complex scalar $\tilde{f}_L, \tilde{f}_R$ fields and hence additional interaction terms between these and h.

$$\begin{aligned}
\mathcal{L}_{\tilde{f}\tilde{f}\phi} &= \tilde{\lambda}_f |\phi|^2 (|\tilde{f}_L|^2 + |\tilde{f}_R|^2) + (\lambda_f A_f \phi \tilde{f}_L \tilde{f}_R^\star + \text{h.c.}) \\
&= \frac{1}{2}\tilde{\lambda}_f h^2 (|\tilde{f}_L|^2 + |\tilde{f}_R|^2) + v\tilde{\lambda}_f h (|\tilde{f}_L|^2 + |\tilde{f}_R|^2) \\
&\quad + \frac{h}{\sqrt{2}} (\lambda_f A_f \tilde{f}_L \tilde{f}_R^\star + \text{h.c.}) + \cdots .
\end{aligned}$$

$\Pi_{hh}^{\tilde{f}}$:



The qadratically divergent contributions due to fermion loops are cancelled by those from the scalar loops, if , $\tilde{\lambda}_f = -\lambda_f^2$. The logarithmically divergent piece remains of course!

If masses of f and $\tilde{f}_L, \tilde{f}_R$ are equal and $A_f = 0$ and the entire one loop renormalisation of $\Pi_{hh}(0)$ vanishes. You will see that in the MSSM, that SUSY guarantees the coupling equality as well as mass equalities.

SUSY gurantees the equalities and thus Higgs mass will not be destabilised by loop corrections (**non renormalization theorem**)and is 'natural'.

Consider $\Pi_{hh}^{\tilde{f}}$ for the general case:

$$\begin{aligned}
\Pi_{hh}^{\tilde{f}}(0) \;=\; & -\tilde{\lambda}_f \int \frac{d^4k}{(2\pi)^4} \left(\frac{1}{k^2 - m_{\tilde{f}_L}^2} + \frac{1}{k^2 - m_{\tilde{f}_R}^2} \right) + \\
& (\tilde{\lambda}_f v)^2 \int \frac{d^4k}{(2\pi)^4} \left[\frac{1}{(k^2 - m_{\tilde{f}_L}^2)^2} + \frac{1}{(k^2 - m_{\tilde{f}_R}^2)^2} \right] \\
& + |\lambda_f A_f|^2 \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m_{\tilde{f}_L}^2} \frac{1}{k^2 - m_{\tilde{f}_R}^2} \;.
\end{aligned}$$

With $\tilde{\lambda}_f = -\lambda_f^2$, $\quad m_{\tilde{f}} = m_{\tilde{f}_L} = m_{\tilde{f}_R}$

$$\Pi^f_{hh}(0) + \Pi^{\tilde{f}}_{hh}(0) = i\frac{\lambda_f^2}{16\pi^2}\Big[-2m_f^2\left(1 - \ln\frac{m_f^2}{\mu^2}\right) + 4m_f^2 \ln\frac{m_f^2}{\mu^2} + 2m_{\tilde{f}}^2\left(1 - \ln\frac{m_{\tilde{f}}^2}{\mu^2}\right) - 4m_f^2 \ln\frac{m_{\tilde{f}}^2}{\mu^2} - |A_f|^2 \ln\frac{m_{\tilde{f}}^2}{\mu^2}\Big].$$

In supersymmetric limit:

$A_f = 0, m_{\tilde{f}} = m_f$

This implies

$\Pi^f_{hh}(0) + \Pi^{\tilde{f}}_{hh} = 0.$

SUSY broken softly:

If $\delta^2 = m_{\tilde{f}}^2 - m_f^2$ then

$$\Pi_{hh}^{f}(0) + \Pi_{hh}^{\tilde{f}}(0) \simeq -i\frac{\lambda_f^2}{16\pi^2}\left[4\delta^2 + (2\delta^2 + |A_f|^2)\ln\frac{m_f^2}{\mu^2}\right] + \mathcal{O}(\delta^4, |A_f|^2\delta^2)\ .$$

No matter how high m_f the one loop renormalization of m_h controlled by SUSY breaking parameters.

Summary:

1. The introduction of super partners cancelled the quadratic divergence in the Higgs mass identically

2. The value of m_h is shielded from large loop corrections coming from heavy fermions as long as the mass splitting between the fermion and sermon is $\mathcal{O}(m_h)$.

3. Associated with one fermion f we needed 2 sfermions $\tilde{f}_L, \tilde{f}_R$. You will see that in MSSM particle content f_L and f_R each have their supersymmetric partner !

4. If the stops are heavy ($\sim TeV$) then there is still a small hierarchy in that the δm_h^2 and m_h^2 are not quite of the same order. A fine tuning of one part in 100 is perhaps required. I will elaborate on this tomorrow.

5.Standard Model with a light Higgs boson (data seem to indicate that to be the case) is beautiful, it works well but is unnatural. With sparticles in TeV range SUSY with soft breaking renders the v and hence m_h radiatively stable and natural.