Standard Scalar

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1. Theoretical expectations for the standard scalar.

2. Is the new boson announced on July 4 THE Standard Scalar?

3. Implications of the available information on the resonance for the SM and BSM.

The 'Periodic Table' of Fundamental particles and their interactions has arrived!

Pre July 4, it was almost complete.

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	−1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	−1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3

BOSONS

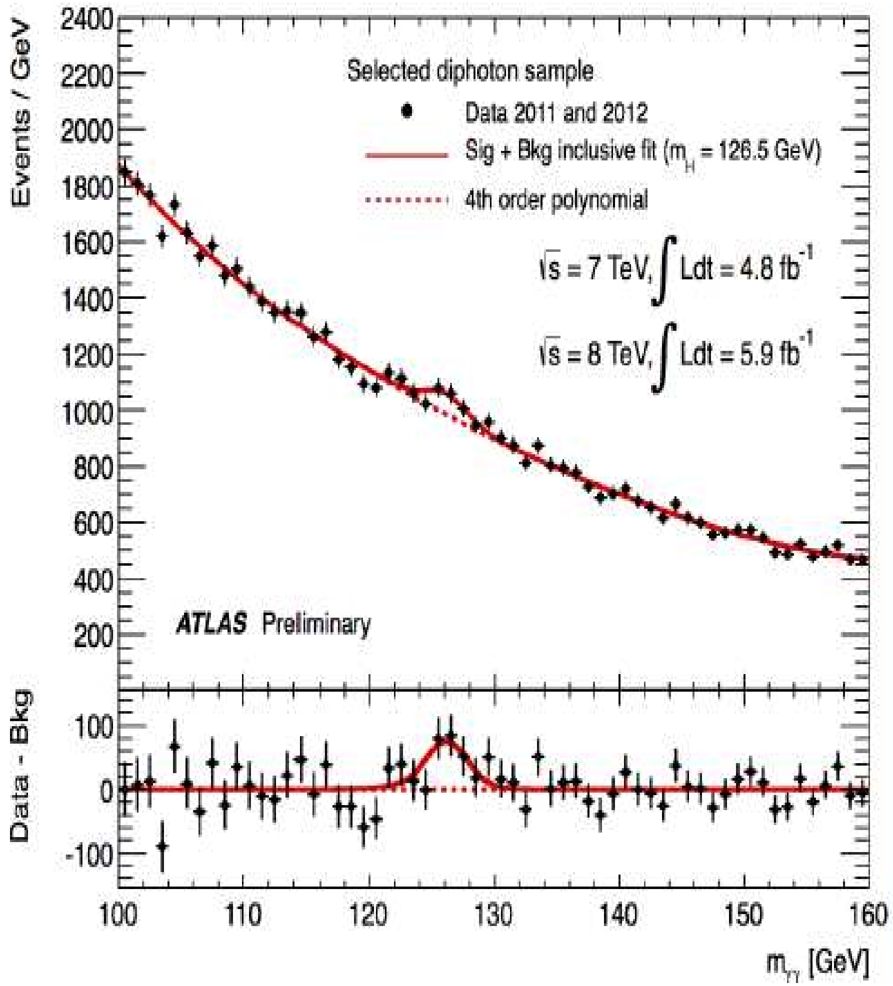
force carriers
spin = 0, 1, 2, ...

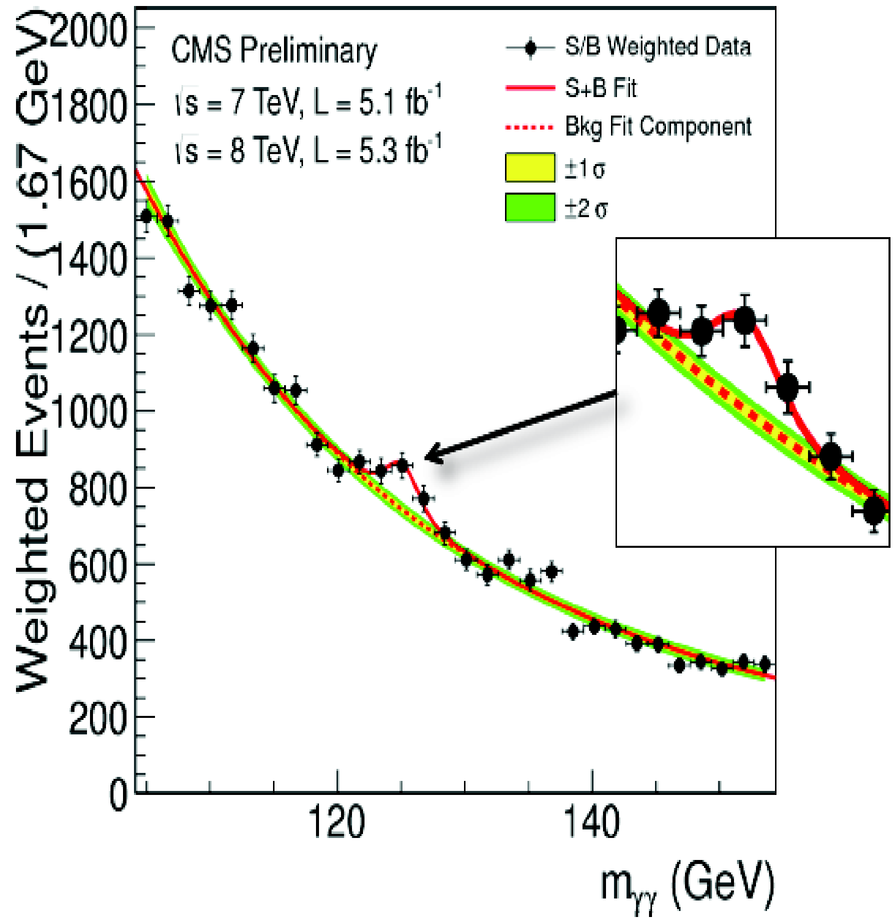
Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

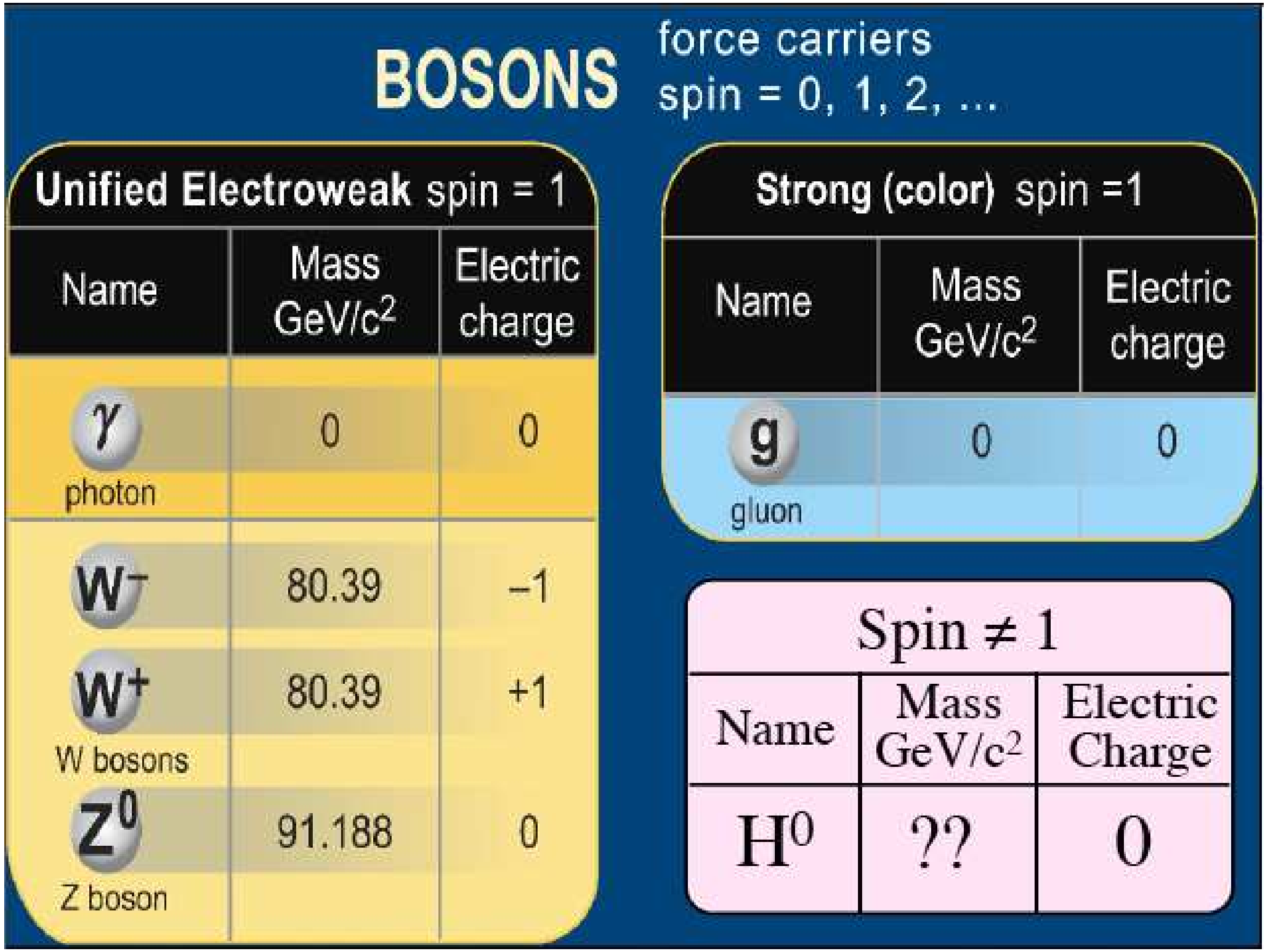
Name	Mass GeV/c^2	Electric charge
g gluon	0	0





Tevatron also has a 3σ result.

The SM periodic table 2013 may well look like this



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Spin $\neq$ 1		
Name	Mass GeV/c^2	Electric Charge
H^0	??	0

What do we know for sure about the new state?

It has integral spin.

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

It couples to $\gamma\gamma$ and ZZ: has to be dominantly CP even.

The analysis of angular distributions of the decay leptons in $ZZ \to 4\ell$ channel mildly supports the spin 0 interpretation. (will come to it later). Clearly much work is required!

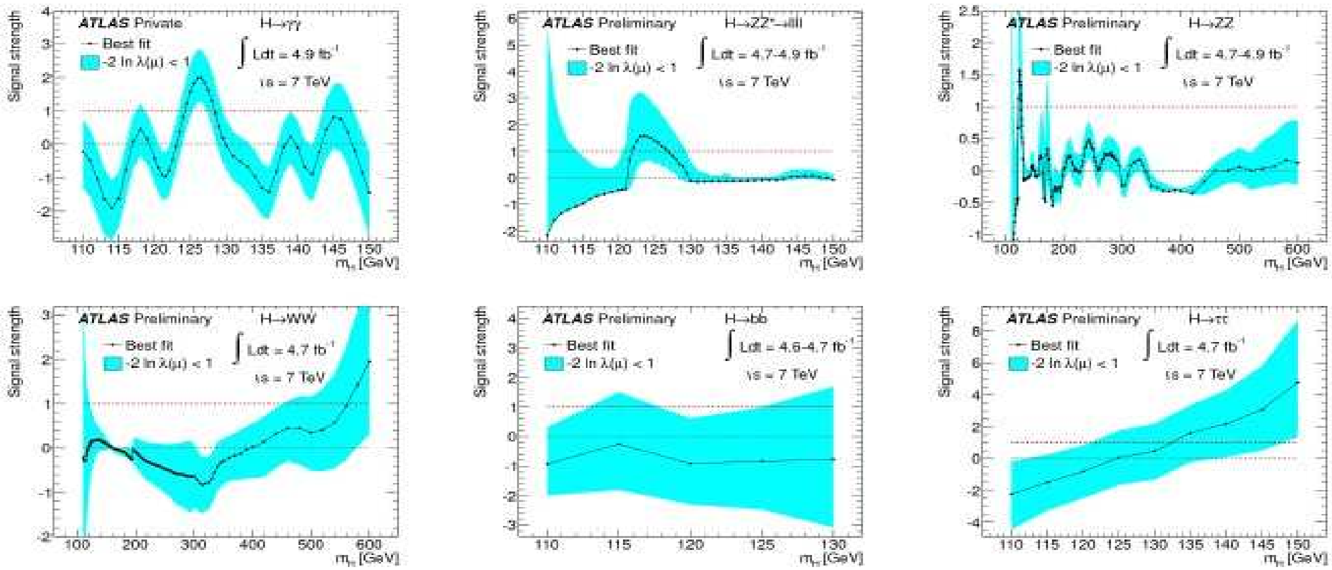
Mass $\sim 125 - 126$ GeV .

Available: mass and rates in different channels:

No SM like state till 600 GeV. Exclusions for Heavier Higgs state to the level of $0.3\sigma_{SM}$

$\widehat{\mu}$ is what is available. (stolen from the talk by C. Grojean at CERN, Implications of LHC workshop).

signal strengths $$\mu_i = \frac{\sum_j \epsilon_{ji}\,\sigma(j \to h) \times \mathrm{Br}(h \to i)}{\sum_j \epsilon_{ji}\,\sigma(j \to h) \times \mathrm{Br}(h \to i)|_{\mathrm{SM}}}$$



Two questions: Assuming that this is the Higgs what are the theoretical implications of this mass? For the SM and BSM physics.

What do we need to do to see if this is the 'standard' scalar or an 'imposter?'

Standard Model Lagrangian consists of 'proved' gauge sector and **yet to be 'completely' proved scalar** sector:

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + i\bar{\psi}\,\not{D}\psi + \psi^T\lambda\psi h + h.c. + D_\mu\Phi|^2 - V(\Phi)$$

After symmetry breaking the Lagrangian for the scalar is:

$1/2(\partial_\mu h)^2 - m_h^2/2 - V(h)$

with

$V(h) = \lambda v h^3 + \frac{\lambda}{4}h^4$

$m_h^2 = 2\lambda v^2$

J = 0, CP even.

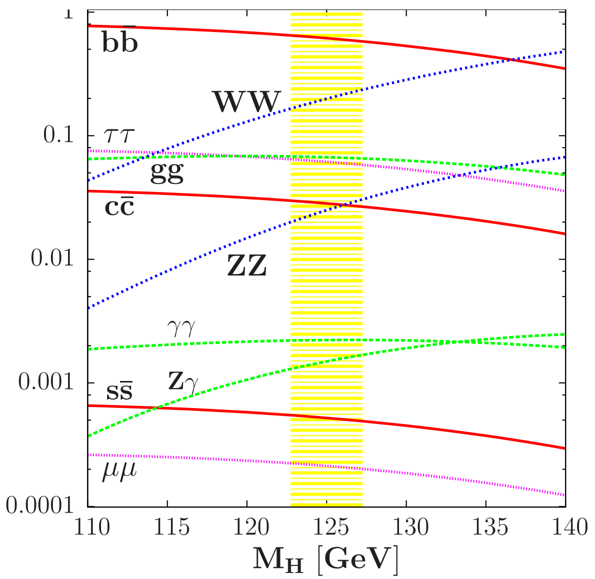
Couplings proportional to mass:

$\lambda_f = \sqrt{2}\frac{m_f}{v}$; $g_V = 2\frac{M_V^2}{v}$.

Higgs field has Hyeprcharge Y= 1, $SU(2)_L$ doublet, with given transformation properties under the Custodial Symmetry and the accidental global symmerty that the $V(h)$ has!

All this needs to be established for it to be called the Standard Scalar.

Theorists have made an enormous effort in getting precise predictions for cross-sections and branching ratios to great accuracy. With the mass of ~ 125 GeV we are very lucky to have all the channels open with significant branching fraction.



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

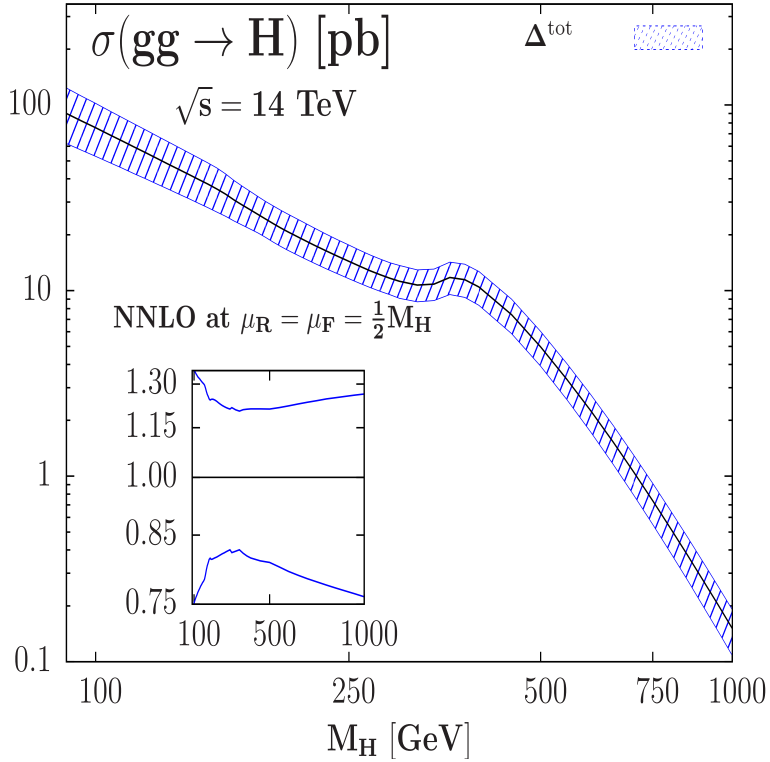
An accurate calculation requires two non-pertrubative inputs: Parton Densities (PDFs) and α_s

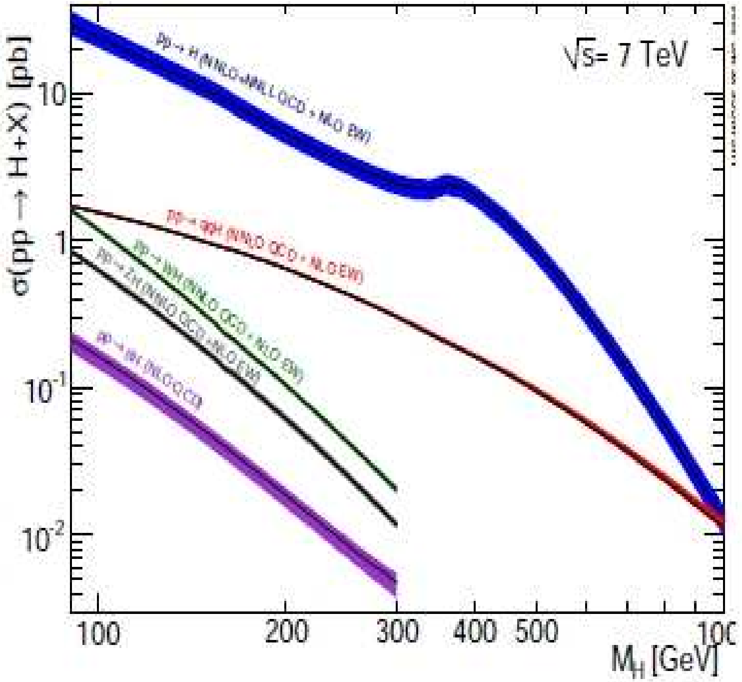
AND

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]





LHC (14 TeV): 1101.0591 ; LHC (7TeV): Djouadi and Baglio : 1012.0530.

1) The QCD scale dependence. NNLO calculation is available. The central value of the scale determined by matching with NNLL results.

2)Dependence on PDF and α_s.

3) Add these linearly (LHCHXWG recommendation)

3)Limitations of EFT (Effective Field Theory) approach.

4)For 7 and 8 TeV the combined PDF + α_s and scale uncertainty is 10% each.

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

Important points about these loop induced couplings:

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.

2) New particles beyond the SM contribute to it, and the contributions are nondecoupling for chiral fermions which get their mass from the Higgs mechanism

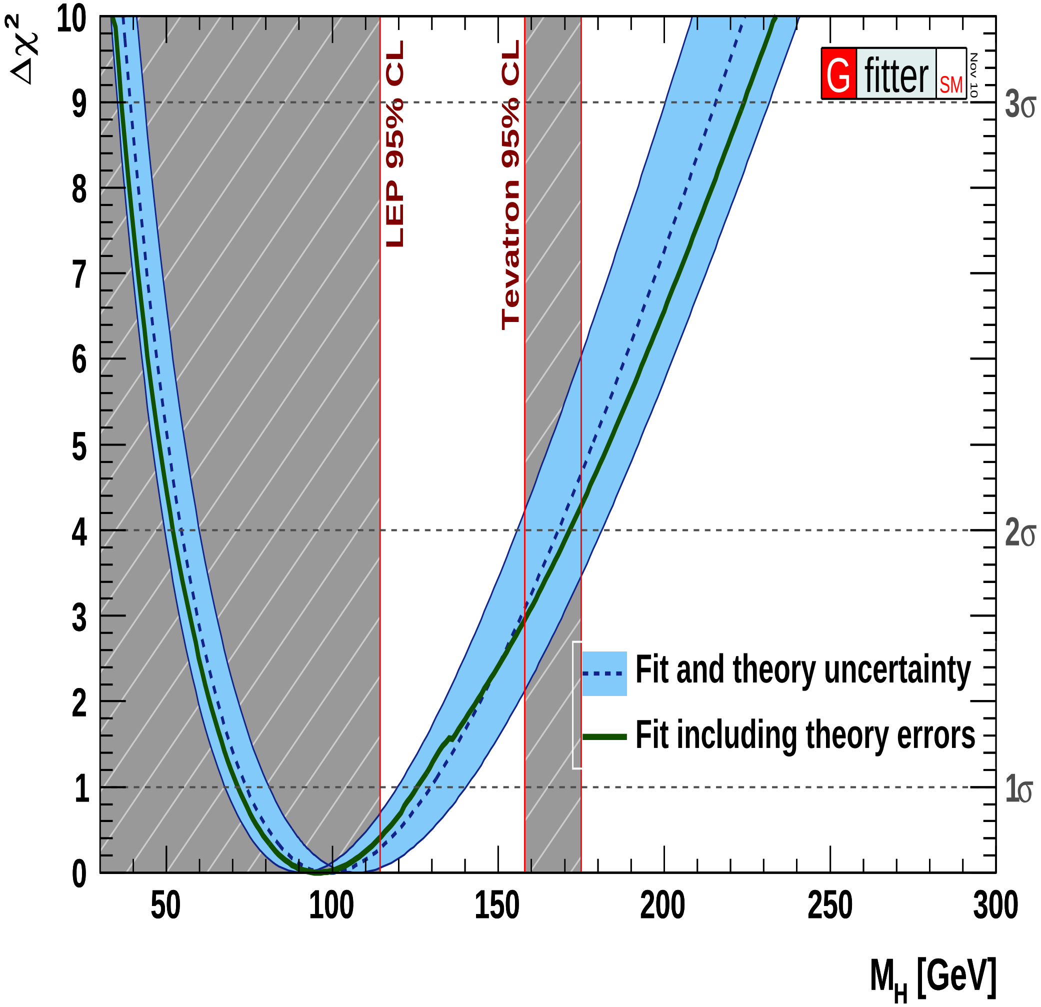
3)For $m_h = 125$ the $\gamma\gamma$ width is $\propto |A_W + A_{top}|^2$, where $A_W = -7$ and $A_{top} \sim \mathcal{O}1$, about 0.2 of the $W-$ contribution.

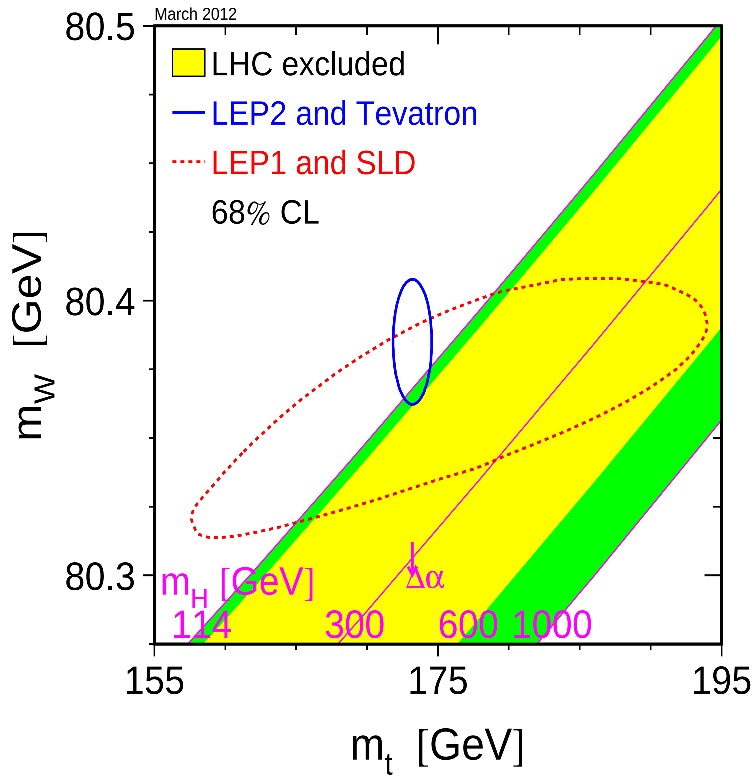
4)For ggh coupling only the strongly interacting heavy particles contribute.

Two types of bounds:

Indirect bounds : Use of the precision EW data.

Theoretical bounds : Come from the quantum corrections to the self coupling λ.





The experiments seem to have found it just in that region.

Remember: the allowed Higgs mass can change when one goes away from the SM.

In fact a lot of effort has 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 a light state.

Example:

Model with four sequential generations with a single Higgs doublet gets severly disfavoured with the discovery of the low mass scalar.

$\frac{d\lambda}{dQ^2} = \frac{3}{4\pi^2}\lambda^2(Q^2)$ + higher orders

λ grows with energy and the scale at which it will become infinite depends on its value at the EW scale, $\lambda(v)$.

$\lambda(v)$ decides the value of m_h.

Demanding that λ should be finite upto a certain scale Λ puts an upper limit on m_h.

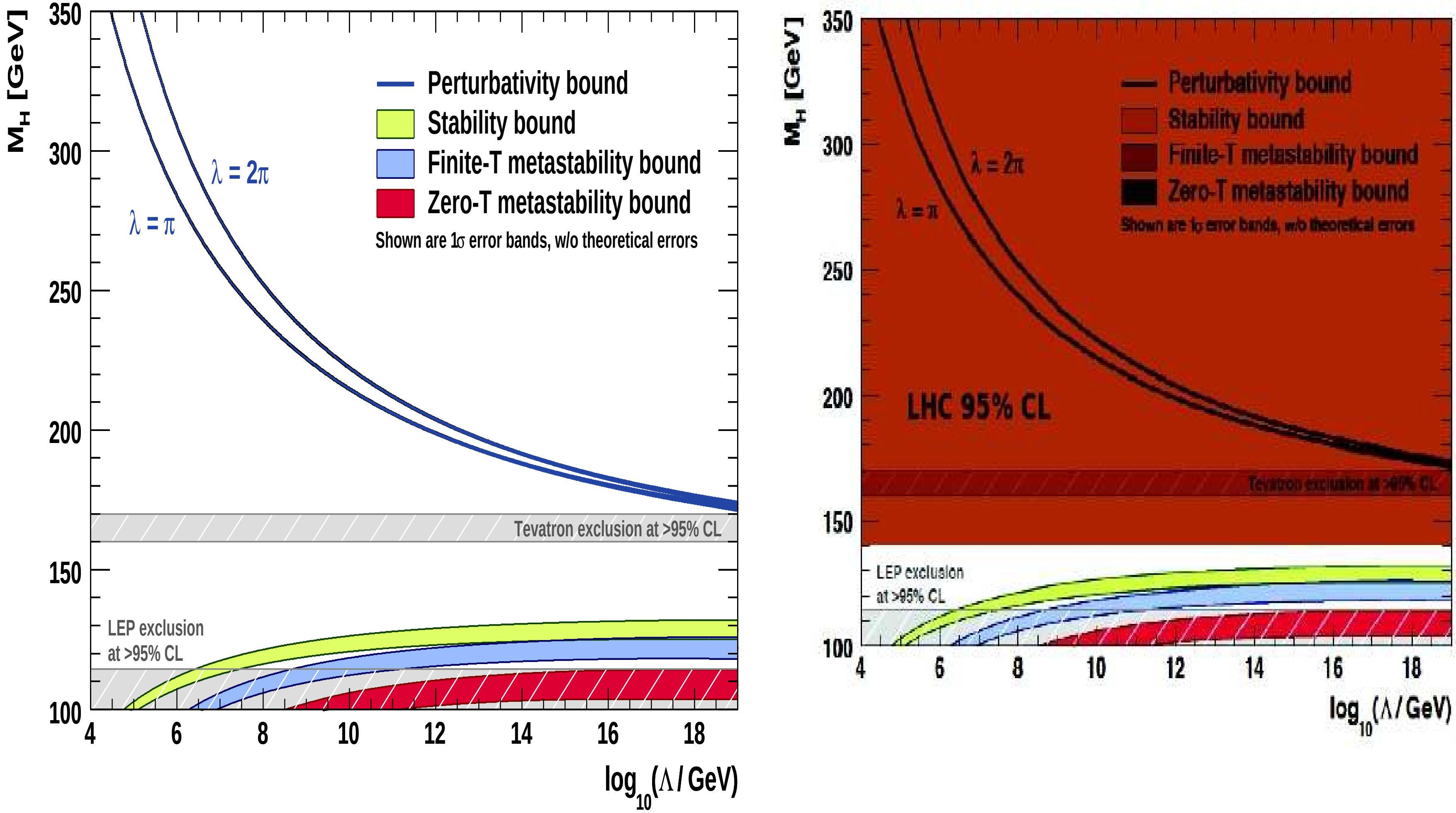
When one includes effects of fermions on the running of λ then unless the value of $\lambda(v)$ and hence m_h is large enough, λ will turn negative at a certain scale and the potential is unbounded from below. Vacumm becomes unstable.

At large scale both the bounds approach each other.

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 from this point of view also.

I will give a sample list of the papers which have come out since July 4.

1)DeGrassie, Giudice, Strumia, Isidori. 1205.6497 (m_h, m_t and vacuum stability: before July 4)

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

3)Battaglia et al: constraints on PMSSM due to m_h information

4)Kraml and S. Sekmen: constraints on PMSSM due to m_h

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 (An effective theory ap-poach 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)

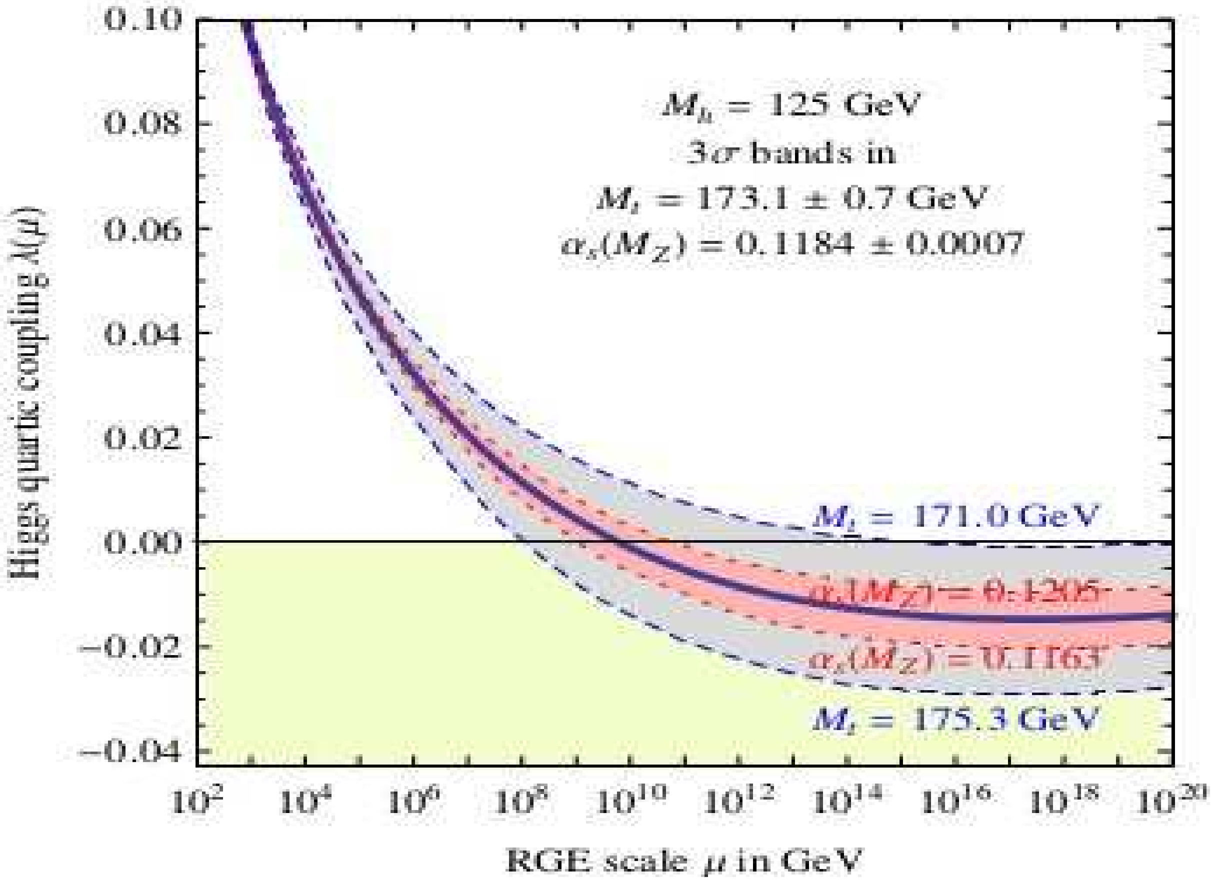
12)An extensive survey (from January 2012) of connection between the Higgs and the BSM. Les Houches report:1203.1488

Most asking one of the two questions:

1) What does the mass value mean for SM and BSM?

2) Do the data already provide indications of deviations from the SM or otherwise?

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



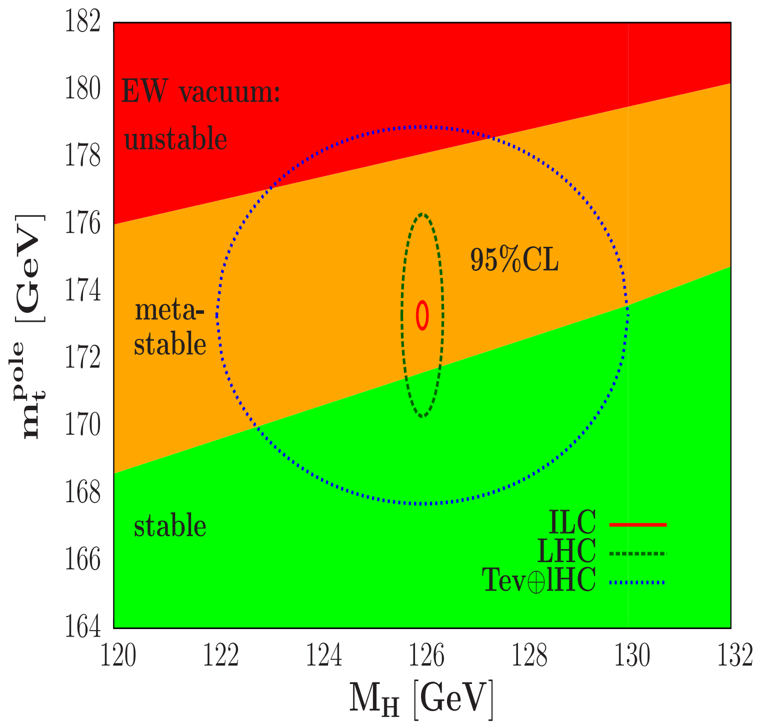
$$M_h\ [\text{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\text{GeV}]-173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z)-0.1184}{0.0007}\right) \pm 1.0_{\text{th}}$$

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.

Moch et al : extract the $\bar{M}S$ mass of the top quark from the measurement of the top quark cross-sections measured at the Tevatron.
Estimate: $m_t^{pole} = 173.3 \pm 2.8$ GeV.
Vacuum stability constraint now becomes $m_h > 129.4 \pm 5.6$ GeV.



Both the collaborations report enhanced $\gamma\gamma$ rate.

In both cases in this channel the expected signficance is less than the actual one.

ATLAS: $R_{\gamma\gamma} = 1.90 \pm 0.5\,, \quad R_{ZZ} = 1.3 \pm 0.6\,,$

CMS: $R_{\gamma\gamma} = 1.56 \pm 0.43\,, \quad R_{ZZ} = 0.7 \pm 0.5\,,$

ATLAS$\oplus$CMS: $R_{\gamma\gamma} = 1.71 \pm 0.33\,, \quad R_{ZZ} = 0.95 \pm 0.4\,.$

Particularly because one would expect effects of heavier, new particles in loops. Not quite very easy to get what one sees if this is interpreted as an excess, but not impossible either.

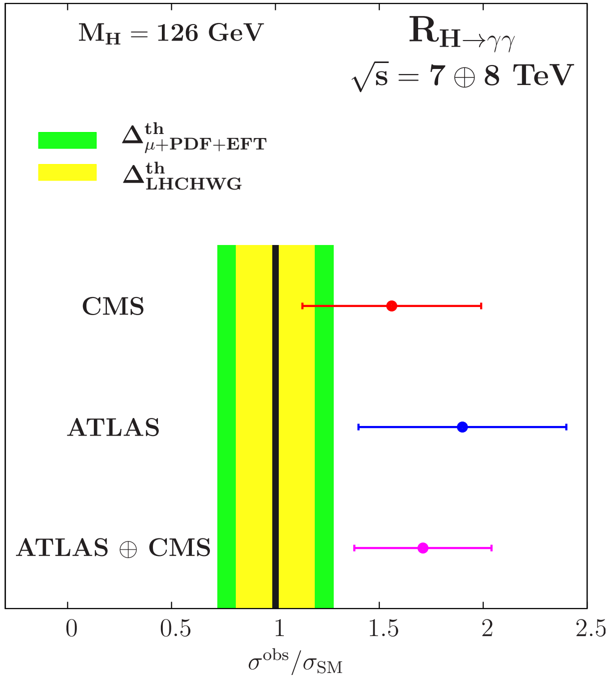
But first can we be sure that this excess is not just due to uncertainities in theory predictions? (1207.1451: Baglio et al)

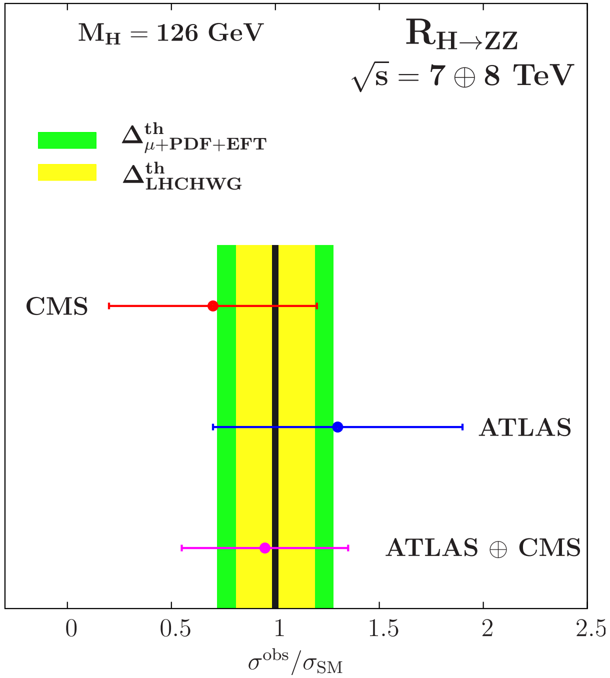
Recall about 20–25% theory uncertainties. The PDF and scale uncertainties have no real statistical basis. In the analysis so far these were added in quadrature

$$\Delta^{\mathrm{tot}}\sigma = \sqrt{(\Delta^{\mathrm{exp}}\sigma)^2 + (\Delta^{\mu}\sigma)^2 + (\Delta^{\mathrm{PDF}}\sigma)^2} \approx \Delta^{\mathrm{exp}}\sigma$$

for $\Delta^{\mathrm{exp}}\sigma \gg \Delta^{\mu}\sigma, \Delta^{\mathrm{PDF}}\sigma$

If $\Delta^{\mathrm{exp}}\sigma \approx 30\%$, then for PDF and scale u ncertainties of 10% each the $\Delta^{\mathrm{tot}}\sigma \approx 33\%$. This means that the theory error is not properly reflected in the reproted ratios $R_{\gamma\gamma}$ etc.





Conclusion: For discovery perhaps it was not so relevant, but for these kind of studies the errors on theory prediction need to be reflected in the extraction.

Mass makes global analysis useful as all the channels are available. Of course CMS made its own global analysis.

In the theory papers, quite often the possible anamolous couplings are parameterised in a manner such that one can analyse various varieties of models such as the light composite Higgs, models with Dilaton/Radion etc. quite easily. Of course, choices made to be consistent with EWPT, which means maintaining Custodial Symmetry etc.

Note also that increasing $\gamma\gamma$ rate, while keeping all the other coulings more or less consistent with the SM expectations is rather difficult.

Indicates then possibly electroweak, lightish particles in loops. If they are fermions you need them in somewhat larger numbers 1206.1082 (Carena , Wagner, Low et al: have such a model)

Falkowski et al:

A top partner which is not too heavy (ie. colour and electromagnetic charge same as the top) does ease the fit.

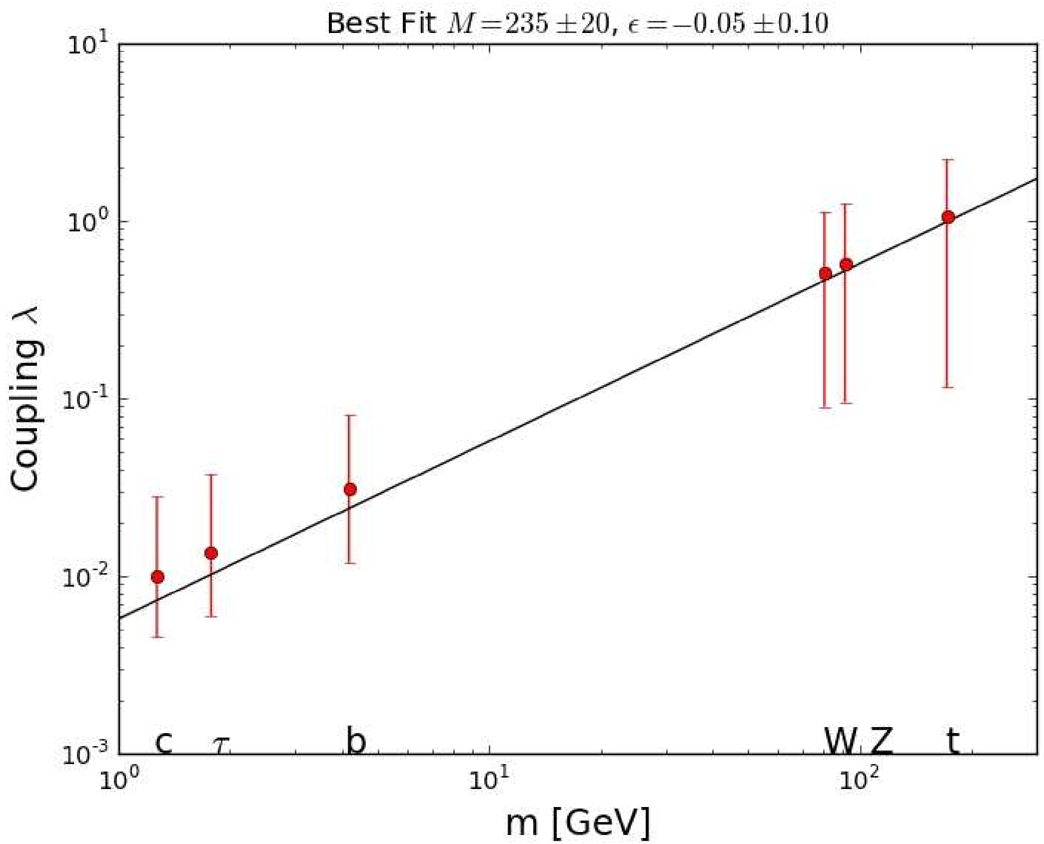
Inlcude possibly an invisible decay channel.

But just an invisible channel does not do the trick.

A top partner, with couplings 'twisted' so that it appears with opposite sign to the top construbution, thus raising the $\gamma\gamma$ but not raising the gg.

SUSY, with two scalars in the loop may work!

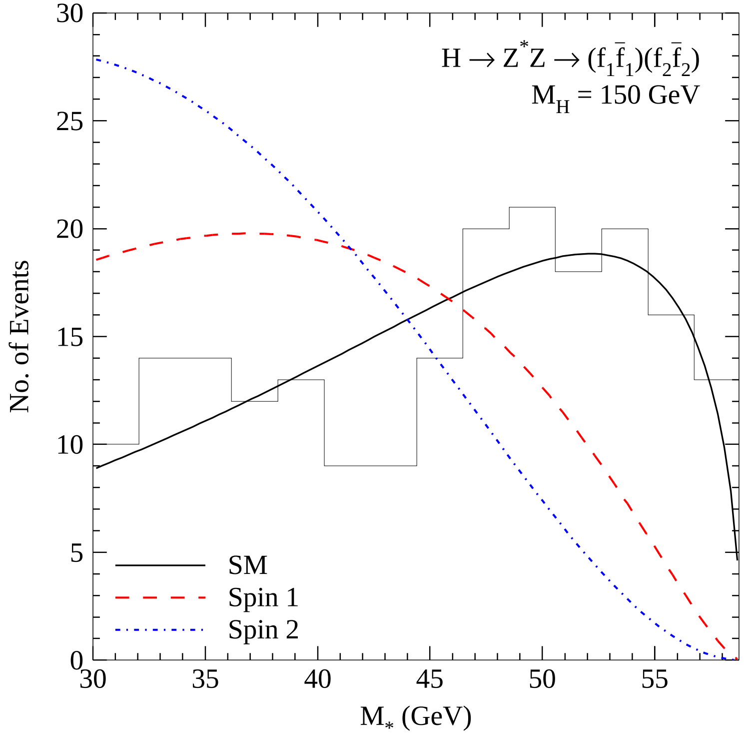
Ellis and You



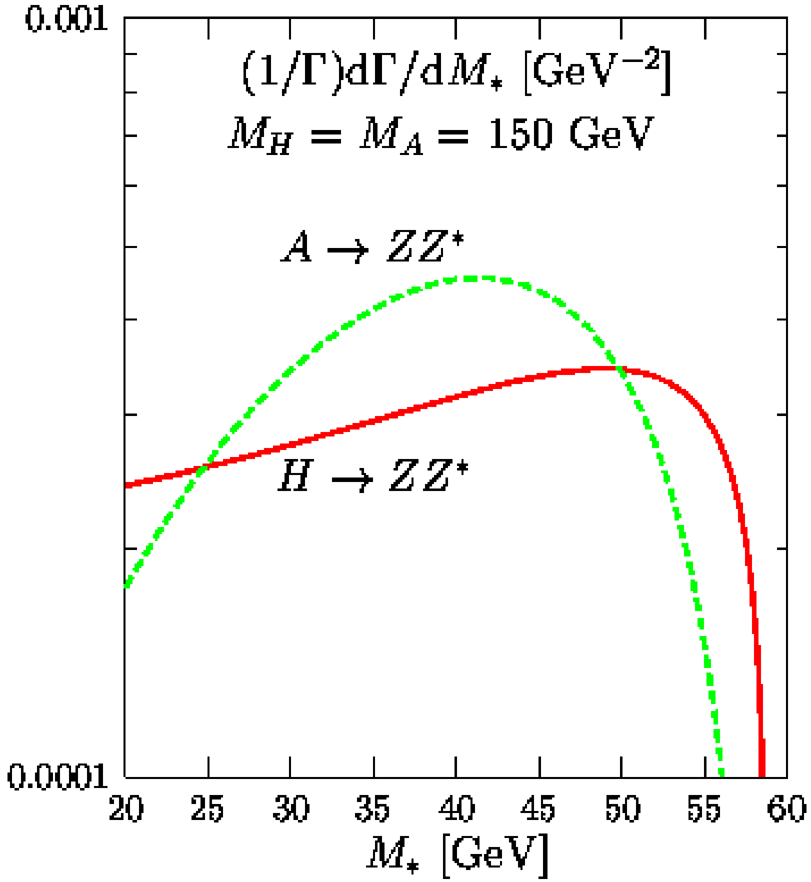
A substantial production rate in ZZ means the state has a large CP even component.

Kinematic distributions of the decay product of the ZZ can probe the CP

Earlier work in the LHC context: Zerwas, Miller, Muhelleitner (PLB 553, 61-71, 2003); Miller, Muhelleitner, Godbole (JHEP 0712 (2007) 031)

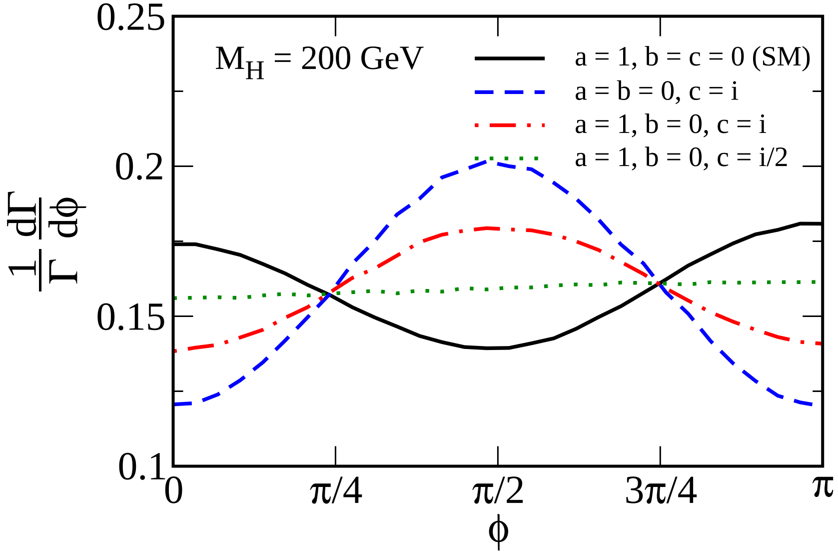


$H \to Z^*Z \to (f_1\bar{f}_1)(f_2\bar{f}_2)$
M_H = 150 GeV
No. of Events
M_* (GeV)
SM
Spin 1
Spin 2



$(1/\Gamma)d\Gamma/dM_*$ [GeV^{-2}]
$M_H = M_A$ = 150 GeV
$A \to ZZ^*$
$H \to ZZ^*$
M_* [GeV]

Distribution in φ ; the angle between the planes of the fermion pai rs 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:

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

hep-ph/1001.3396: Y. Gao et al; hep-ph/1001.5300 A De Rujula et al

A multivariate analysis including correlations among diferent observables possible to get an handle on the spin.

It may be possible to get some information statement about the spin and CP with the 8 TeV data.

The distributions shown at the LHC implications meeting showed already a $\sim 1.6\sigma$ level result.

Already many BSM ideas constrained strongly.

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.