Role of precision predictions in gaining a perspective of 'Higgs' signal and its implications!

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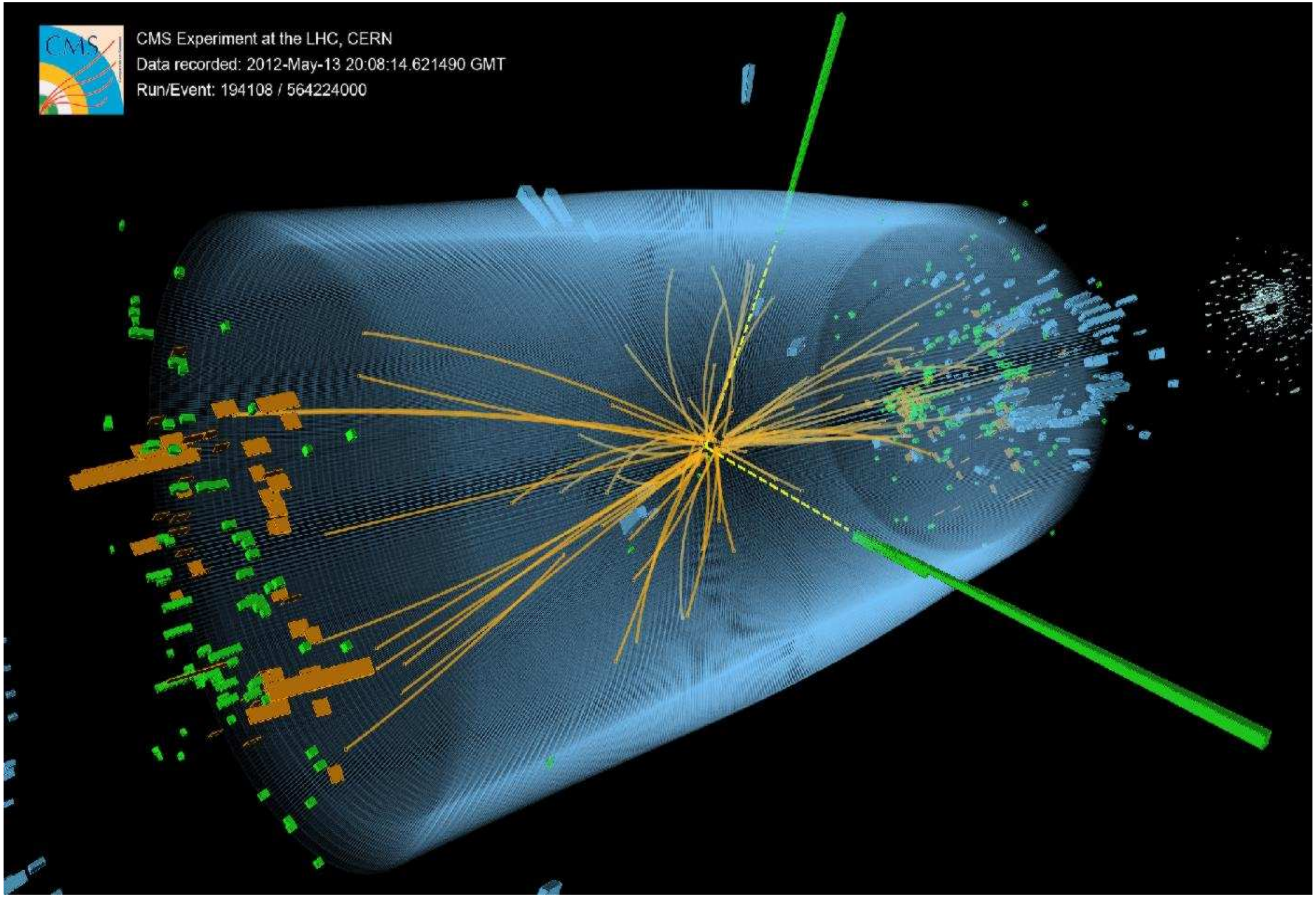
1. Summary of available experimental information on the 'Higgs' signal.

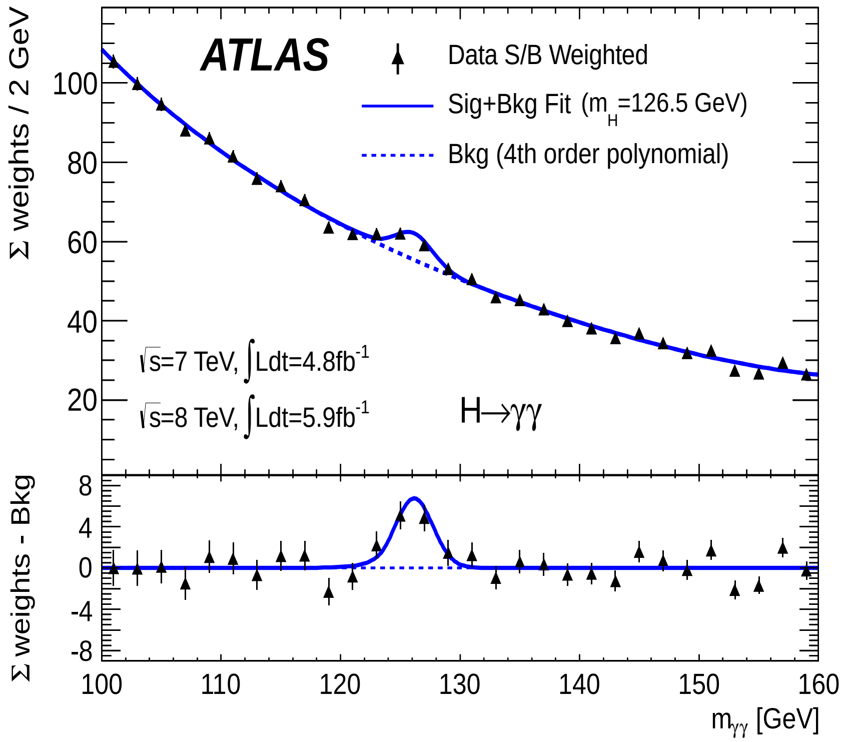
2. What precision predictions?

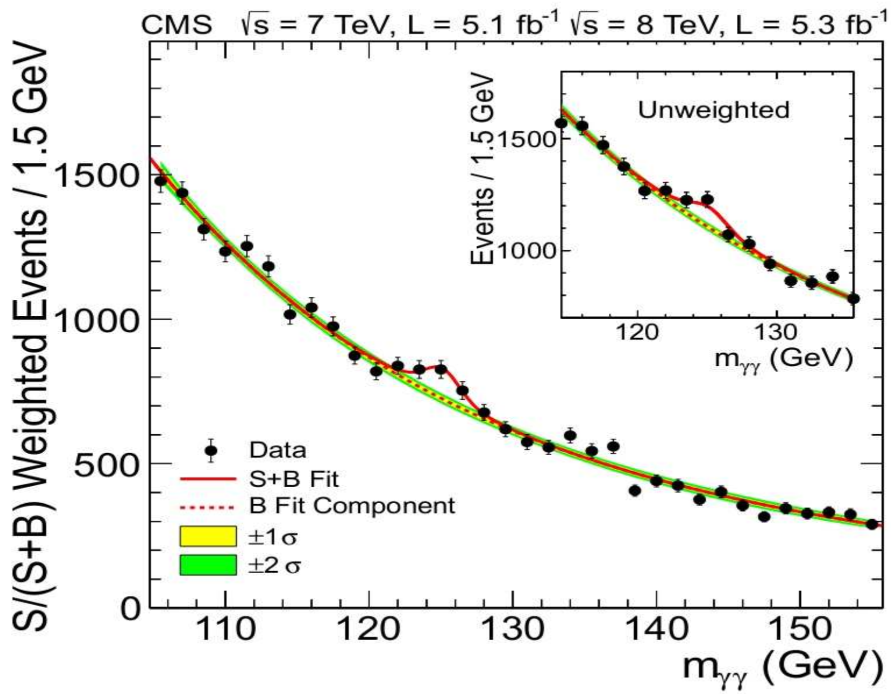
3.How do they affect interpretation and analysis of implications of the signal?

a.Some issues that impact in deciding whether the new resonance is THE Standard Scalar?(Focus on effect of theoretical 'systematic' uncertainties on possible $\gamma\gamma$ enhancement)

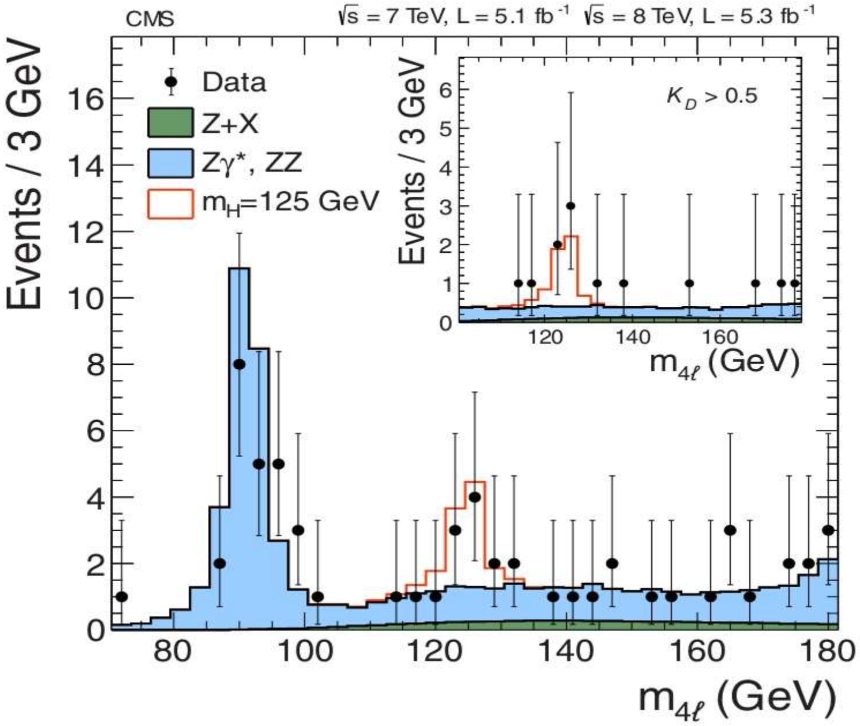
b. Implications of the available information on the resonance for the SM and BSM through vacuum stability bound on its mass.

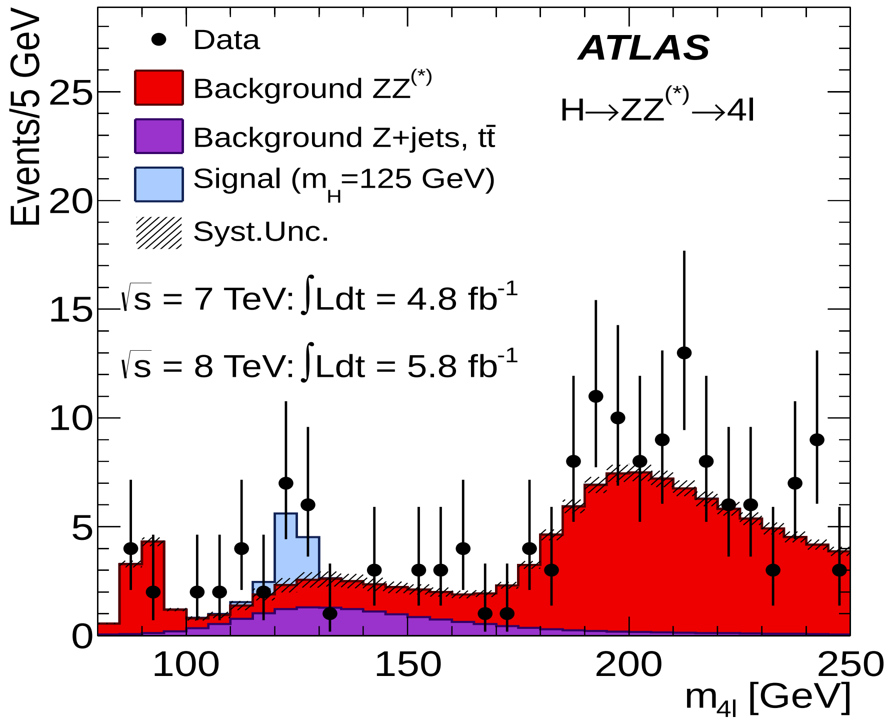

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000





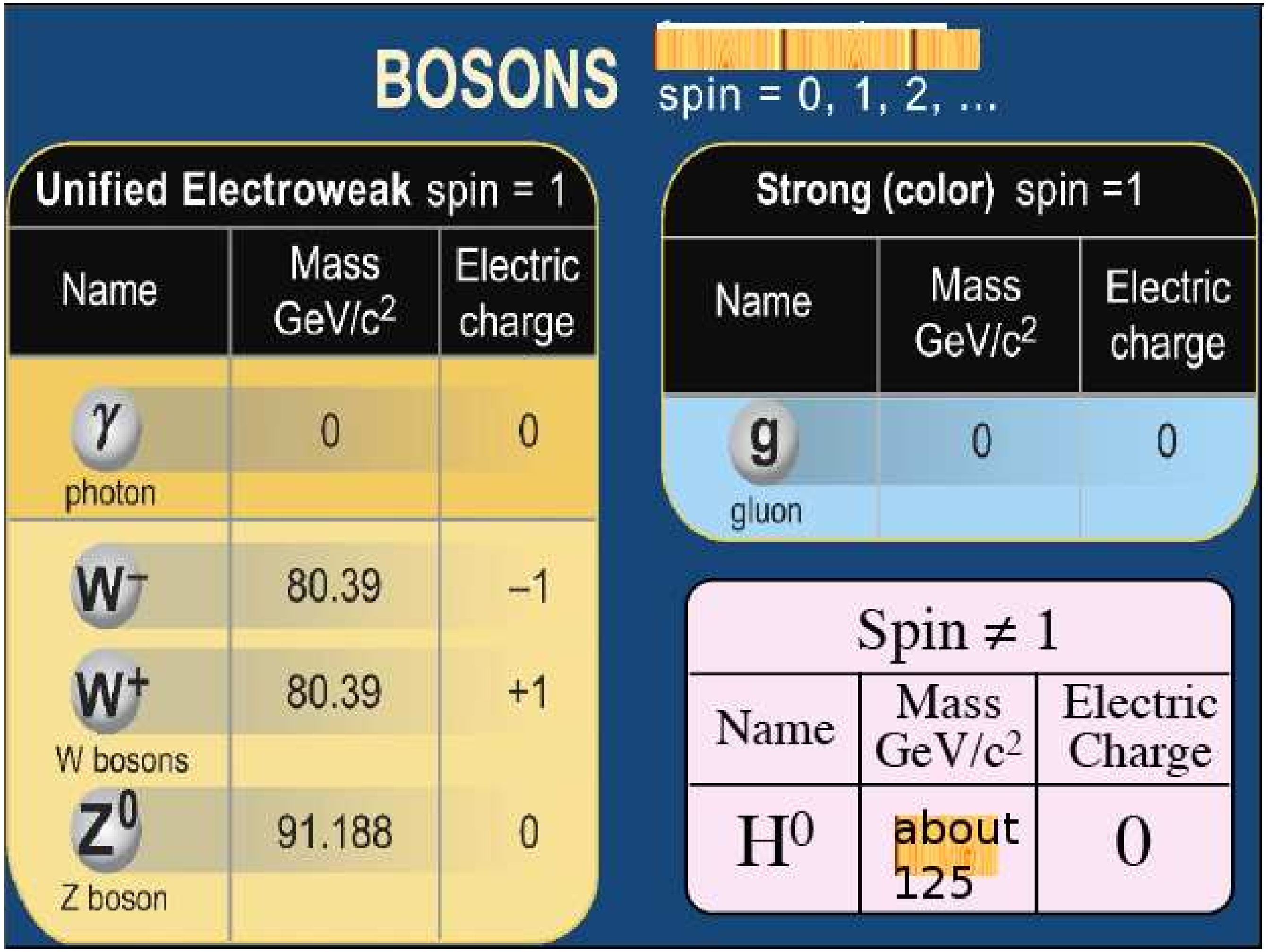
In the $\gamma\gamma$ channel!





Tevatron also has a 3σ result. Signals also in WW.

The SM periodic table 2013 looks like this



BOSONS 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

Spin $\neq$ 1		
Name	Mass GeV/c^2	Electric Charge
H^0	about 125	0

What do we know for sure about the new state?

It has integral spin.

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

Observed information on relative rates of $\gamma\gamma$, ZZ events consistent with loop induced coupling to $\gamma\gamma$ and tree level to ZZ. $\Rightarrow$ has to be dominantly CP even.

Observation in the WW channel crucially uses the spin 0 nature of the higgs to reduce the background!

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

Clearly much work is required! lot is going on!

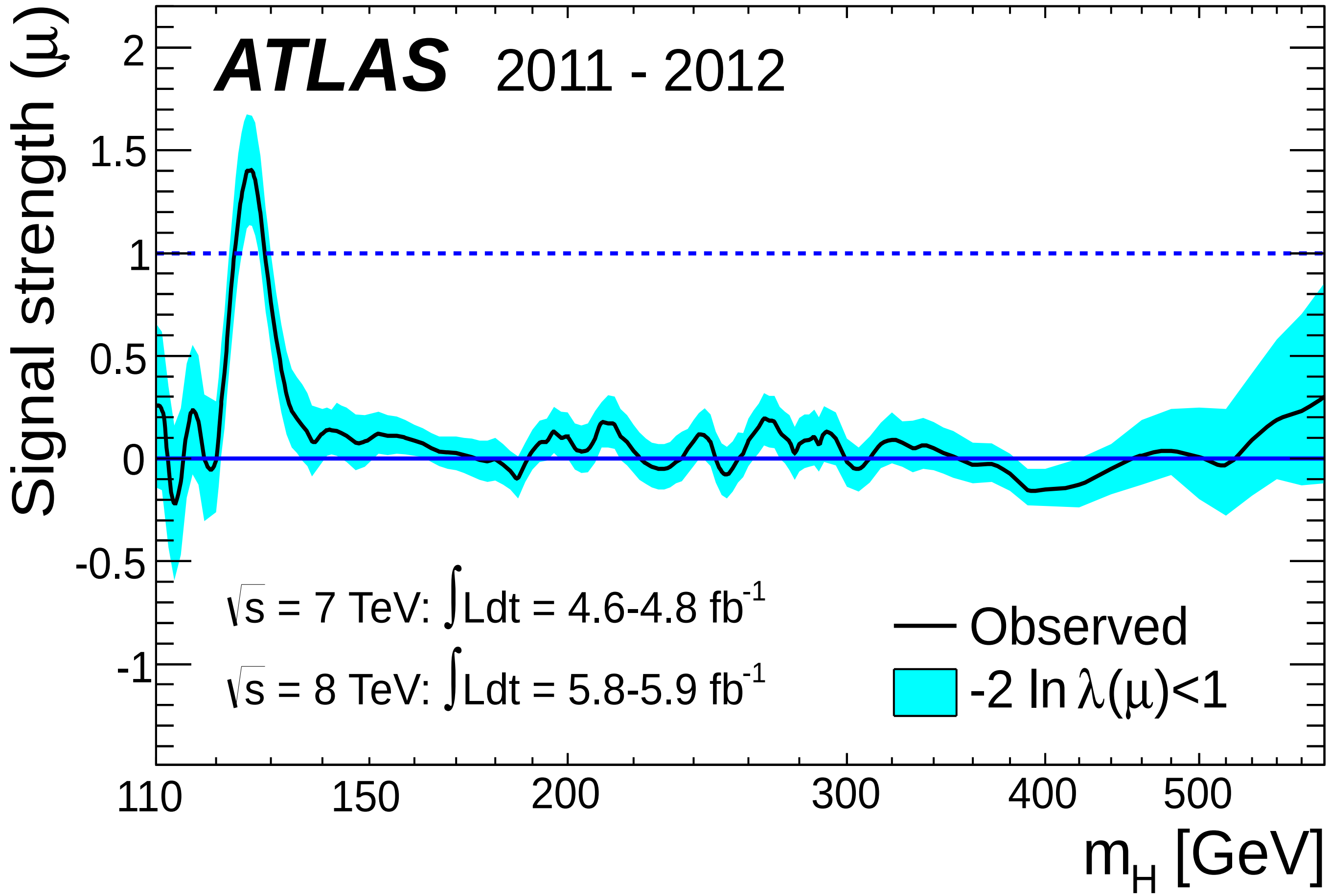
(1208.2692,1208.4018,1208.4311....

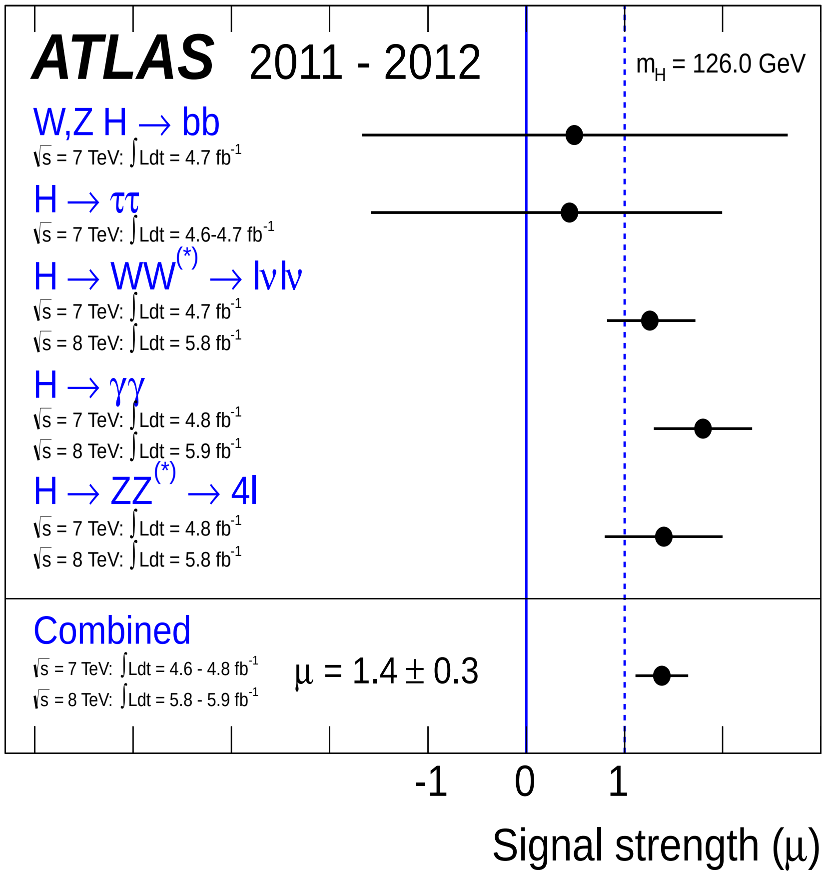
Mass $\sim 125 - 126$ GeV .

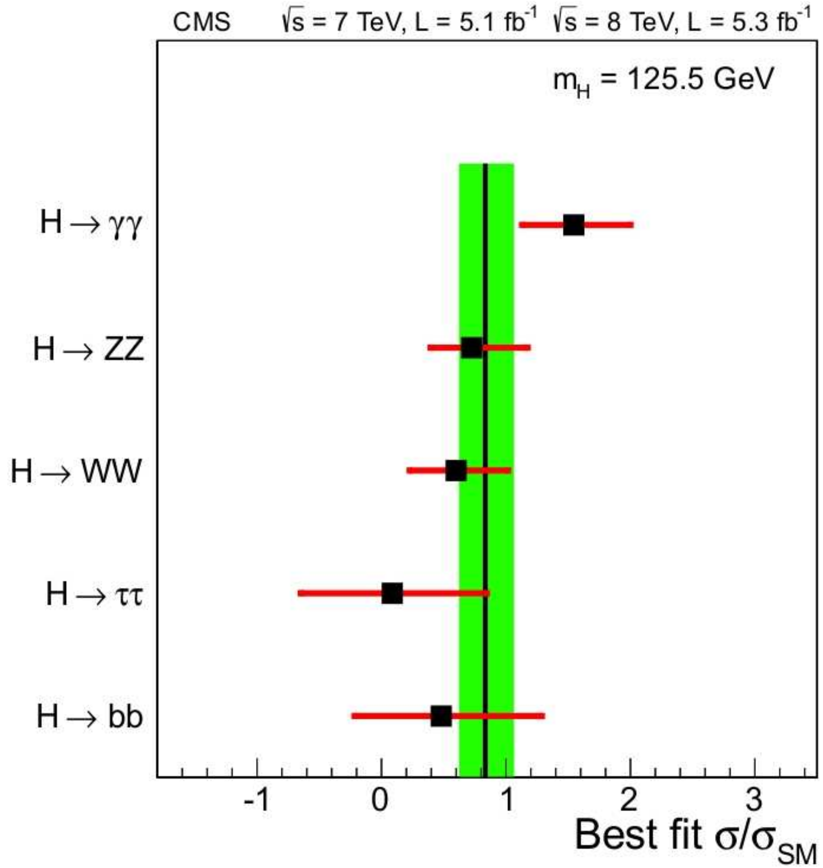
Available: mass and rates in different channels:

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

$\hat{\mu}$ is what is available.




ATLAS 2011 - 2012
m_H = 126.0 GeV
W,Z H → bb
√s = 7 TeV: ∫Ldt = 4.7 fb^-1
H → ττ
√s = 7 TeV: ∫Ldt = 4.6-4.7 fb^-1
H → WW(*) → lνlν
√s = 7 TeV: ∫Ldt = 4.7 fb^-1
√s = 8 TeV: ∫Ldt = 5.8 fb^-1
H → γγ
√s = 7 TeV: ∫Ldt = 4.8 fb^-1
√s = 8 TeV: ∫Ldt = 5.9 fb^-1
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.8 fb^-1
√s = 8 TeV: ∫Ldt = 5.8 fb^-1
Combined
√s = 7 TeV: ∫Ldt = 4.6 - 4.8 fb^-1
√s = 8 TeV: ∫Ldt = 5.8 - 5.9 fb^-1
μ = 1.4 ± 0.3
-1
0
1
Signal strength (μ)


CMS √s = 7 TeV, L = 5.1 fb^-1 √s = 8 TeV, L = 5.3 fb^-1
m_H = 125.5 GeV
H → γγ
H → ZZ
H → WW
H → ττ
H → bb
-1
0
1
2
3
Best fit σ/σ_SM

Theory predicts :

I)Higgs couplings to everything

II)Bounds on Higgs mass

Theorists can provide precise theoretical predictions for cross-sections for the Higgs production and decay as well as for the backgrounds!

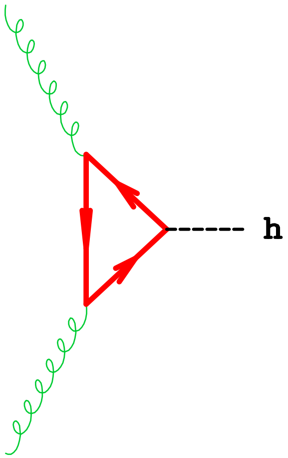
We will see this has played an important role in the discovery and now will play an even more important role when we want to analyse what are the implications of this signal for the SM and BSM.

The observed Higgs mass itself can provide tons of information about SM and BSM.

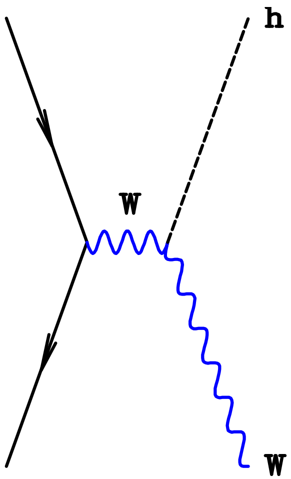
Two questions:

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

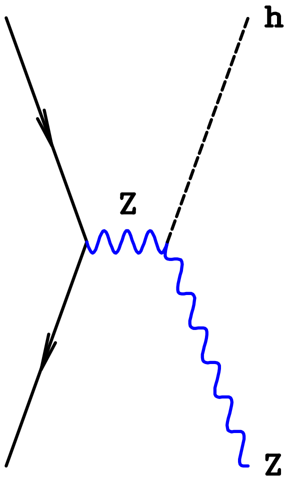
• What do we need to do to see if this is the 'standard' scalar or an 'imposter?'



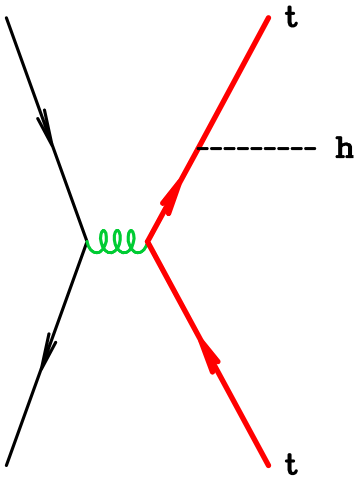
g+g→h



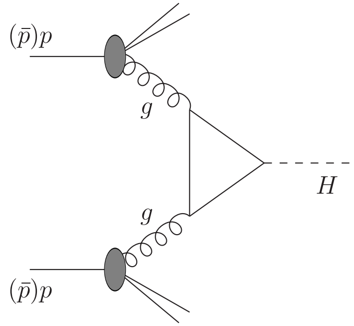
q+q̄→W+h

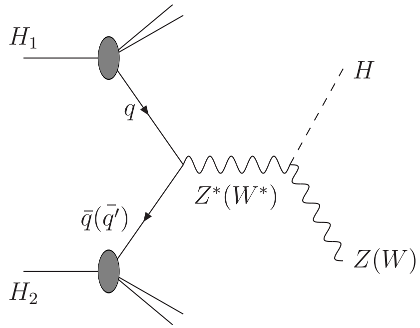


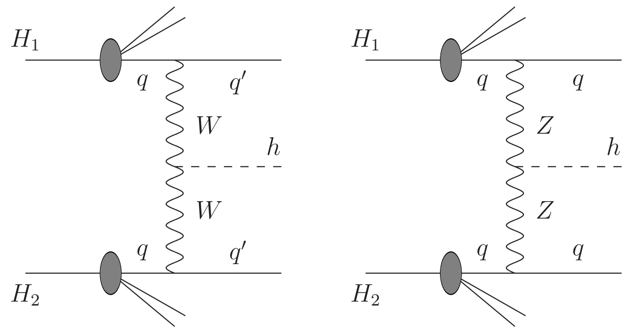
q+q̄→Z+h



q+q̄→t+t̄+h







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

An accurate calculation requires two non-pertrubative inputs: Parton Densities (PDFs) and α_s. Inherent QCD scale dependencies via μ_F^2 for PDF and μ_R^2 for α_s.

AND

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

Why the latter? Because experimentalists need to make cuts. Precision calcualtion of background required too!

The Les Houches Wish List (2005)

Les Houches 2005

process wanted at NLO ($V \in \{Z, W, \gamma\}$)	background to
1. $pp \to VV$ + jet	$t\bar{t}H$, new physics
2. $pp \to H + 2$ jets	H production by vector boson fusion (VBF)
3. $pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
5. $pp \to VVb\bar{b}$	VBF $\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to VV + 2$ jets	VBF $\to H \to VV$
7. $pp \to V + 3$ jets	new physics
8. $pp \to VVV$	SUSY trilepton

The Les Houches Wish List (2010)

2010

process wanted at NLO	background to
1. $pp \to VV + \text{jet}$	$t\bar{t}H$, new physics Dittmaier, Kallweit, Uwer; Campbell, Ellis, Zanderighi
2. $pp \to H + 2$ jets	H in VBF Campbell, Ellis, Zanderighi; Ciccolini, Denner Dittmaier
3. $pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$ Bredenstein, Denner Dittmaier, Pozzorini; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$ Bevilacqua, Czakon, Papadopoulos, Worek
5. $pp \to VVb\bar{b}$	VBF $\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to VV + 2$ jets	VBF $\to H \to VV$ Melia, Melnikov, Rontsch, Zanderighi VBF: Bozzi, Jäger, Oleari, Zeppenfeld
7. $pp \to V + 3$ jets	new physics Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre; Ellis, Melnikov, Zanderighi
8. $pp \to VVV$	SUSY trilepton Lazopoulos, Melnikov, Petriello; Hankele, Zeppenfeld; Binoth, Ossola, Papadopoulos, Pittau
9. $pp \to b\bar{b}b\bar{b}$	Higgs, new physics GOLEM

Feynman diagram methods

now joined by

unitarity based methods

2005 list basically done. Amusingly $W,Z + 4$ jets was not on this list.

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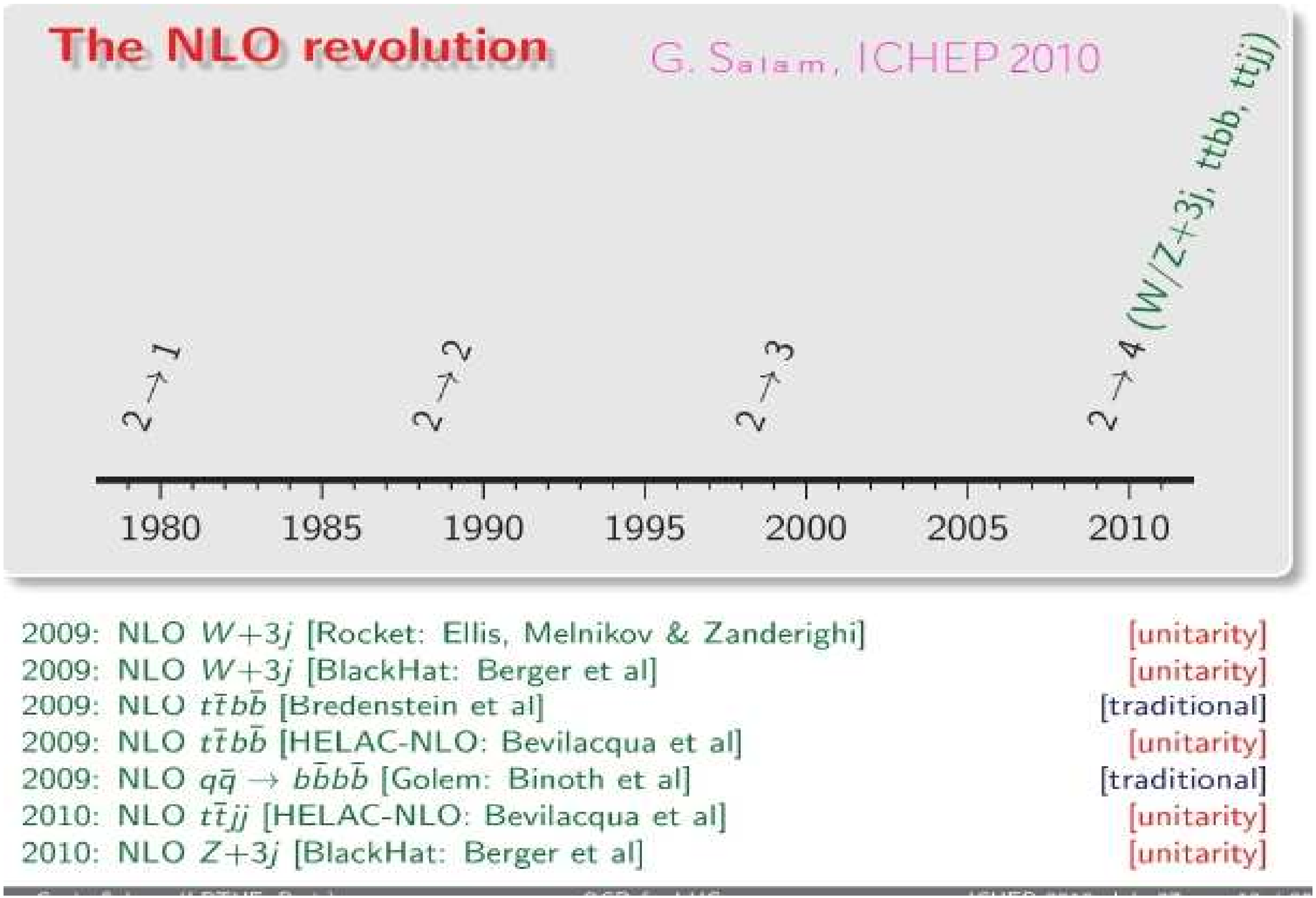
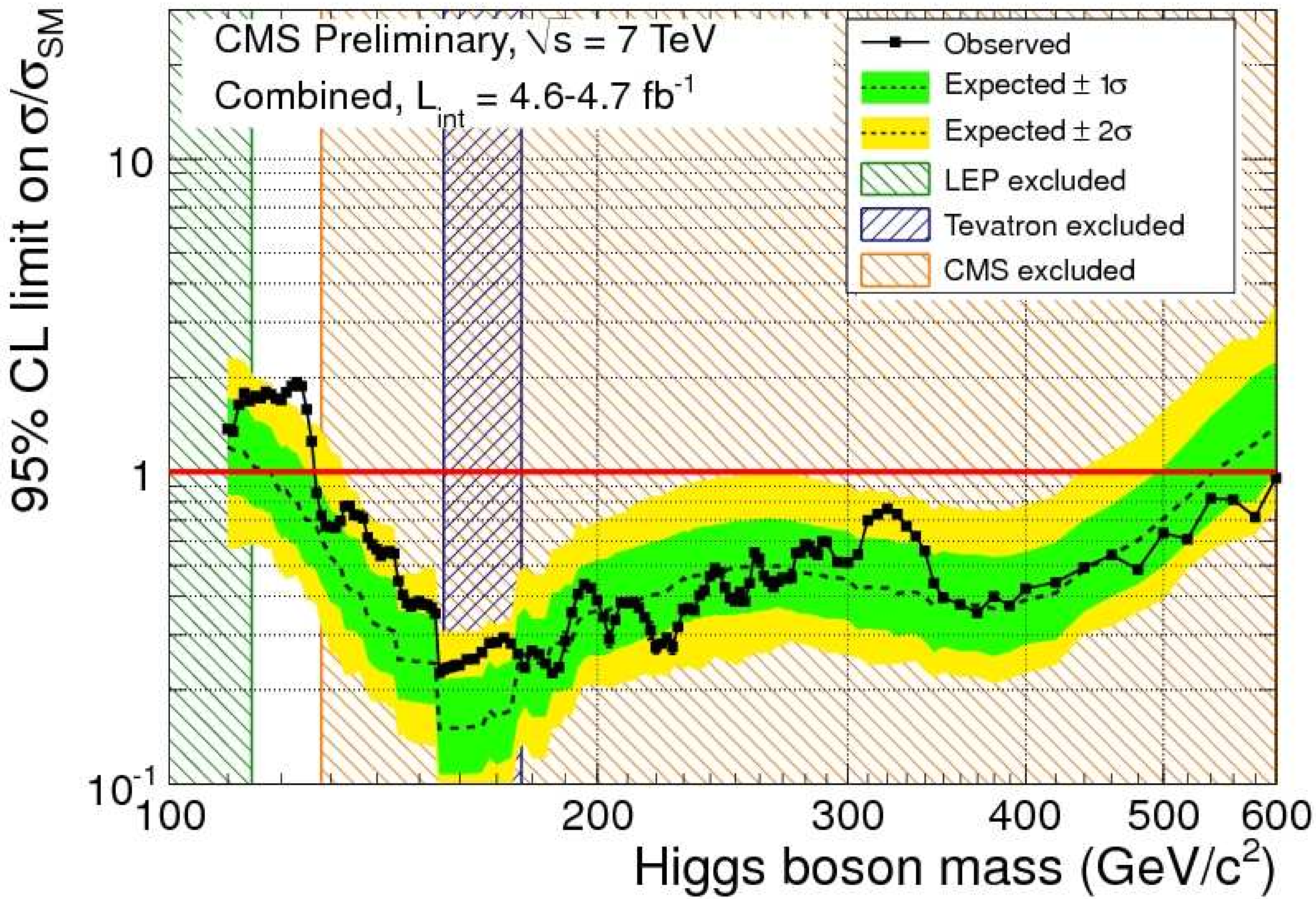
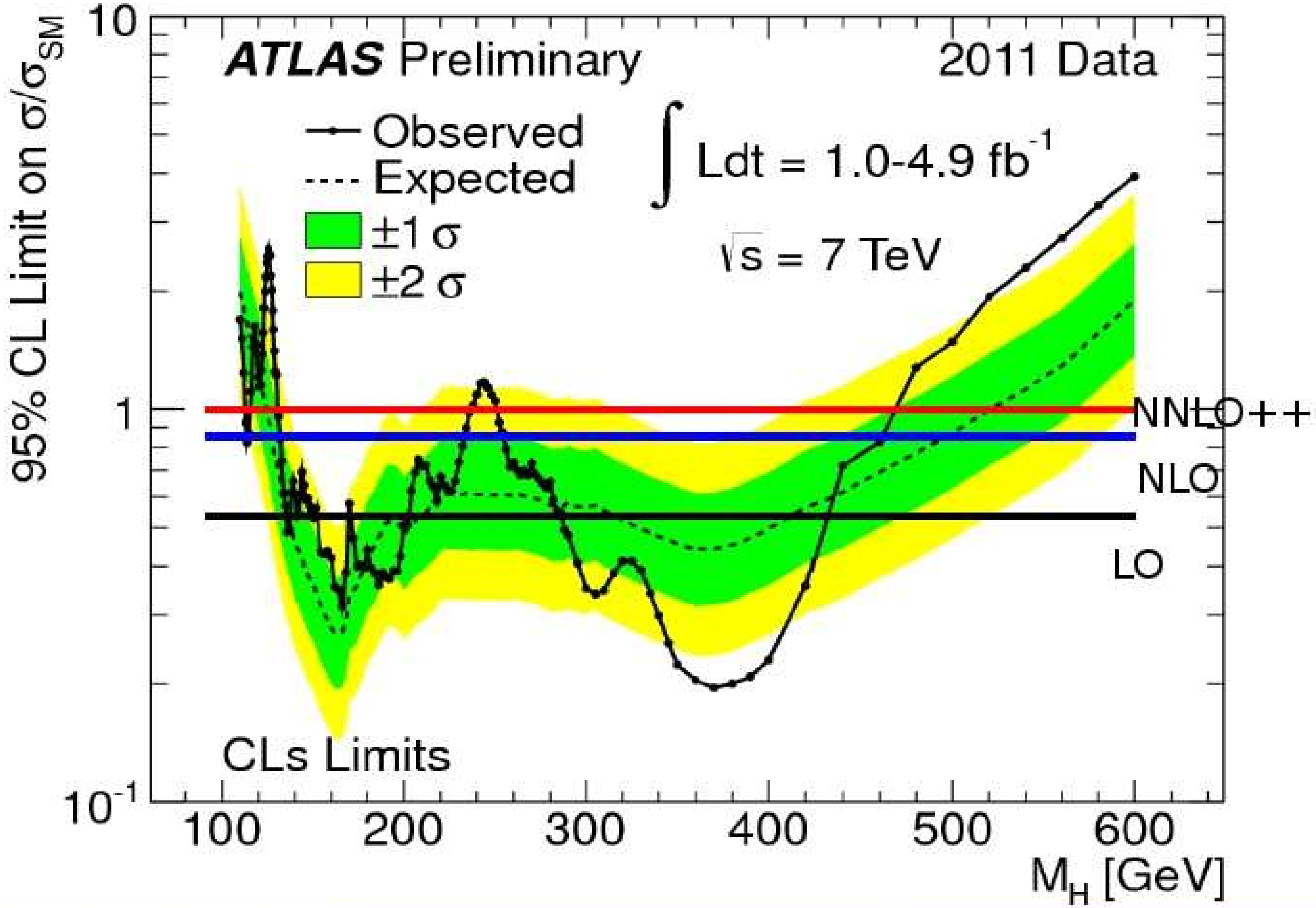
From Zwi Bern's talk.


The NLO revolution
G. Salam, ICHEP 2010
2 → 1
2 → 2
2 → 3
2 → 4 (W/Z+3j, ttbb, ttjj)
1980
1985
1990
1995
2000
2005
2010
2009: NLO $W+3j$ [Rocket: Ellis, Melnikov & Zanderighi] [unitarity]
2009: NLO $W+3j$ [BlackHat: Berger et al] [unitarity]
2009: NLO $t\bar{t}b\bar{b}$ [Bredenstein et al] [traditional]
2009: NLO $t\bar{t}b\bar{b}$ [HELAC-NLO: Bevilacqua et al] [unitarity]
2009: NLO $q\bar{q} \to b\bar{b}b\bar{b}$ [Golem: Binoth et al] [traditional]
2010: NLO $t\bar{t}jj$ [HELAC-NLO: Bevilacqua et al] [unitarity]
2010: NLO $Z+3j$ [BlackHat: Berger et al] [unitarity]


CMS Preliminary, $\sqrt{s}$ = 7 TeV
Combined, L_{int} = 4.6-4.7 fb^{-1}
Observed
Expected ± 1σ
Expected ± 2σ
LEP excluded
Tevatron excluded
CMS excluded
95% CL limit on σ/σ_{SM}
10
1
10^{-1}
100
200
300
400
500
600
Higgs boson mass (GeV/c^2)



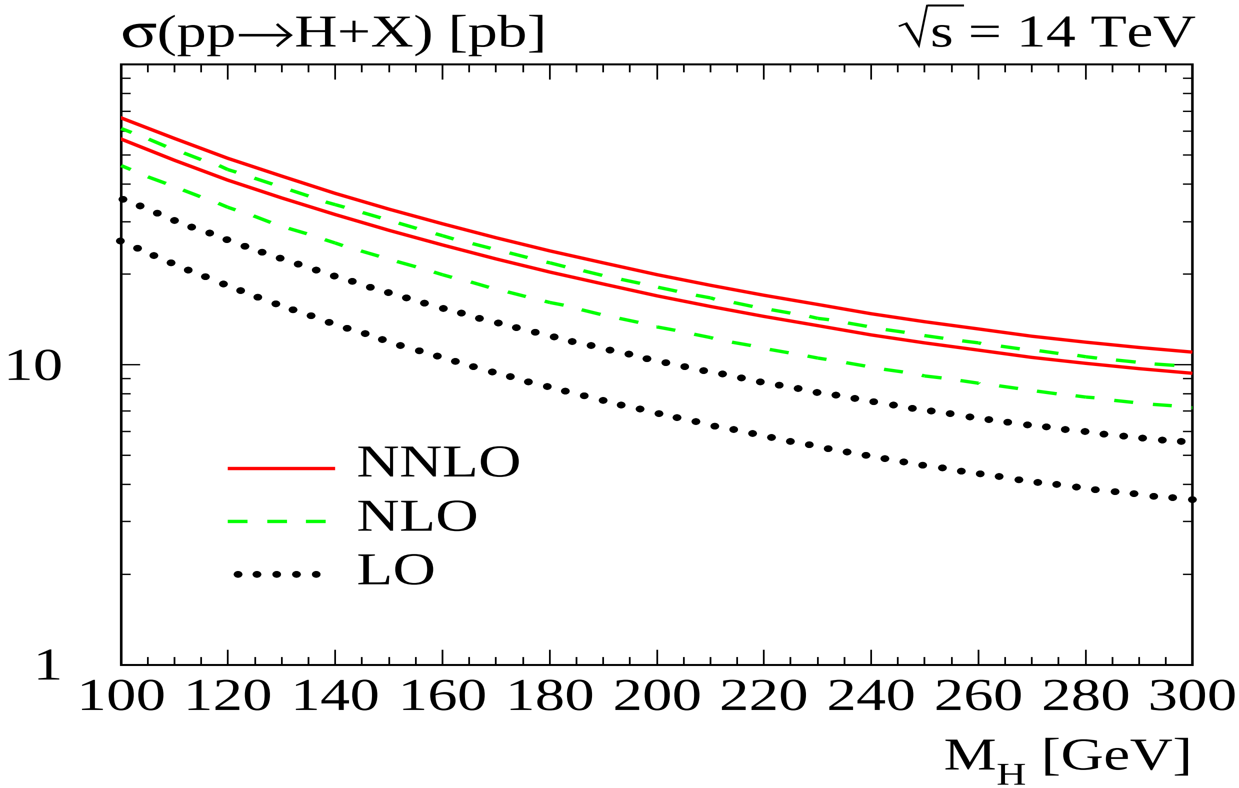
From Haarlander, Lectures at Lake Louise Institute.

We would not have been able to make many of the statements with the luminosity that was available in July.

So when we see that experiments announced limits and/signals much before the projected luminosities in (say) TDR it was because those TDR used LO predictions.

NNLO++ : predictions are stable with respect to inherent scale uncertainties of QCD.

Will discuss this later.



From Haarlander and Kilgore.

Sample and incomplete list of the papers 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:(1207.1348)

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) (1207.1717)

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

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:

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

with

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

Recall connection between λ and m_h!

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

Tree level Couplings proportional to mass:

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

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

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

The hierarchy problem:

The EW theory has been tested at 1-loop level. 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, $m_{\mathsf{h}}^2 = m_{\mathsf{bare}}^2 + \delta m_{\mathsf{h}}^2$ the top loop (e.g.) gives

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

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

LHC:

Seems to have found the light Higgs

BUT

So far no evidence for the different BSM particles.

The mass and the couplings of this light state might be the window through which we can get a view of BSM at present!

• All the masses other than M_h in the SM, predicted in terms of the vacuum expectation value of the Higgs field v. $G_F\sqrt(2) = 1/v^2 \Rightarrow v \simeq 246$ GeV.

• Higgs mass not predicted by the theory in the SM. $m_h^2 = -2\mu^2 = \lambda v^2$. λ undetermined and hence M_h^2 unpredicted.

• In Supersymmetry λ related to gauge couplings and hence Higgs mass is bounded and can be predicted!

Both the collaborations have enhanced $\gamma\gamma$ rate. **(admittedly limited statistics!)**

In both cases in this channel the observed significance is higher than the one that was expected.

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

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

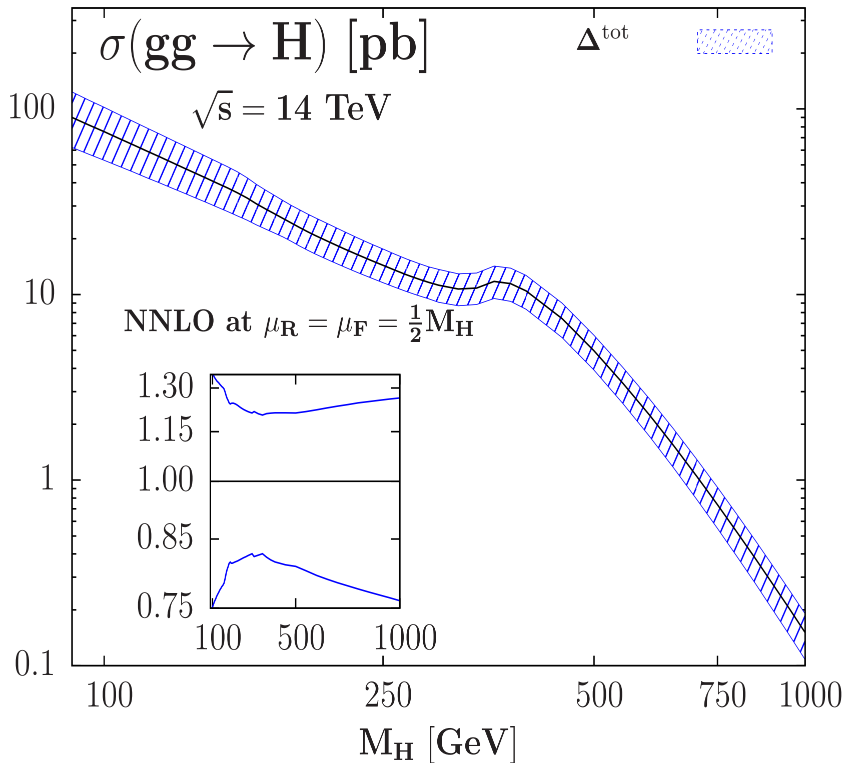
$$\text{ATLAS}\oplus\text{CMS:} \quad R_{\gamma\gamma} = 1.71 \pm 0.33\,, \quad R_{ZZ} = 0.95 \pm 0.4\,.$$

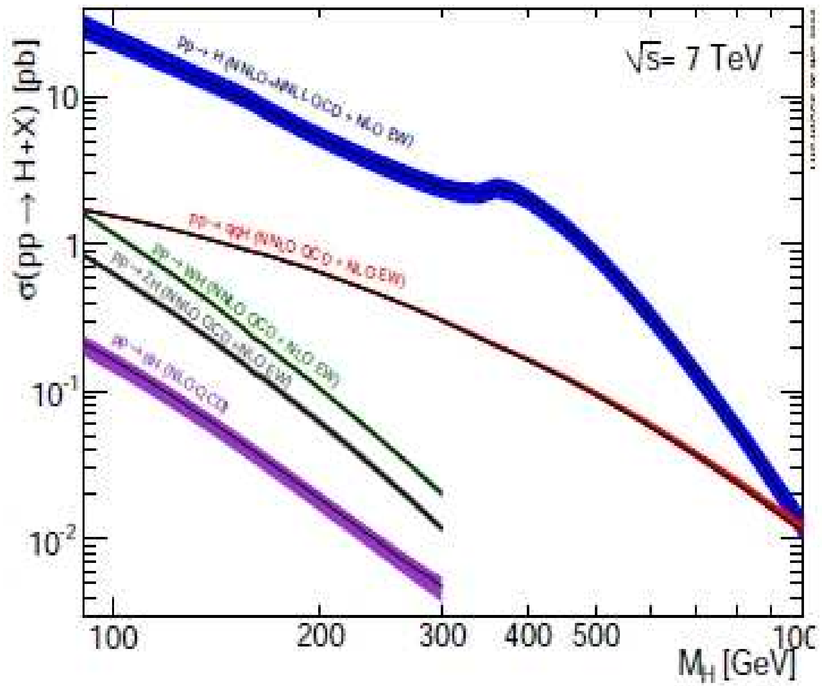
Particularly because hgg and $h\gamma\gamma$ are precisley the loop induced couplings where one would expect effects of heavier, new particles in the loops.

Not quite very easy to get the level of enhancement if this is interpreted as an excess, but not impossible either.

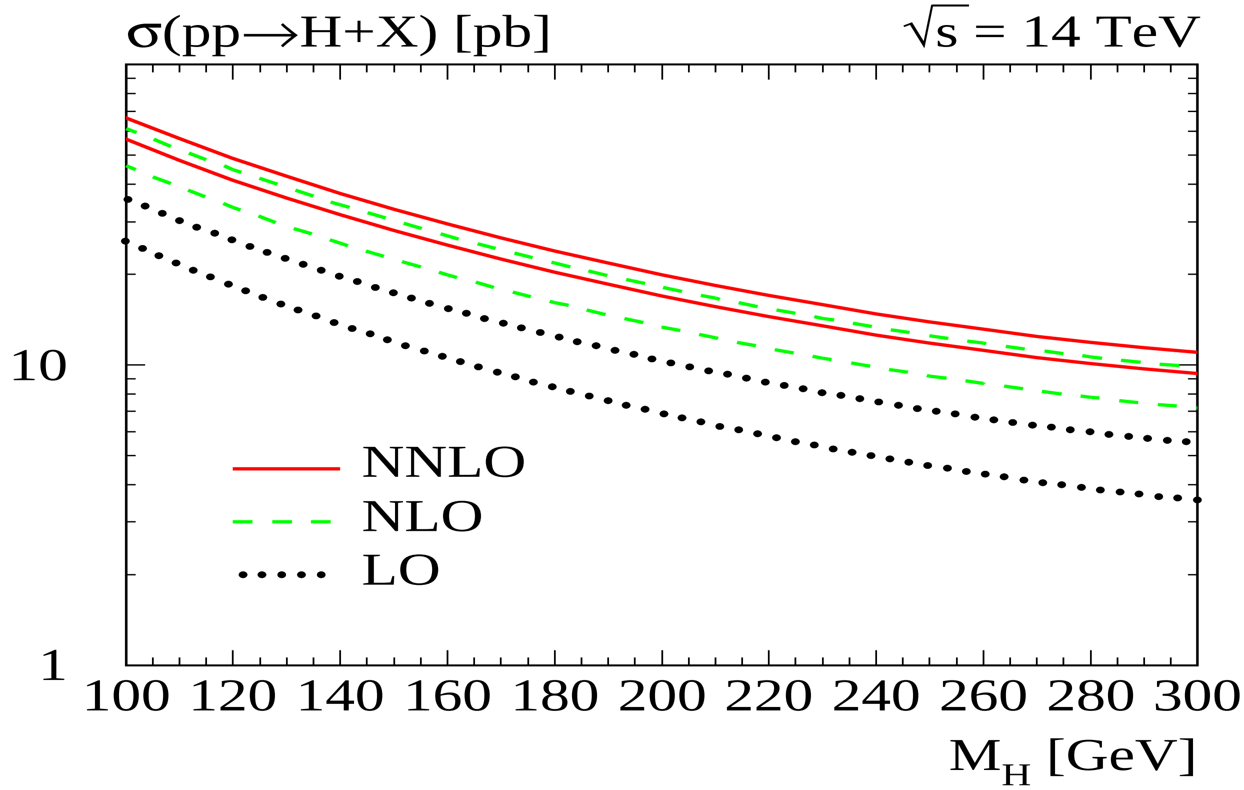
But first can we be sure that this excess is not just due to uncertainities in theory predictions? (1207.1451: Baglio et al)

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





LHC (14 TeV): Djouadi & Baglio : 1012.0530; LHC (7 TeV): 1101.0593



(Reminder) From Haarlander and Kilgore. This is for a fixed PDF.

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)

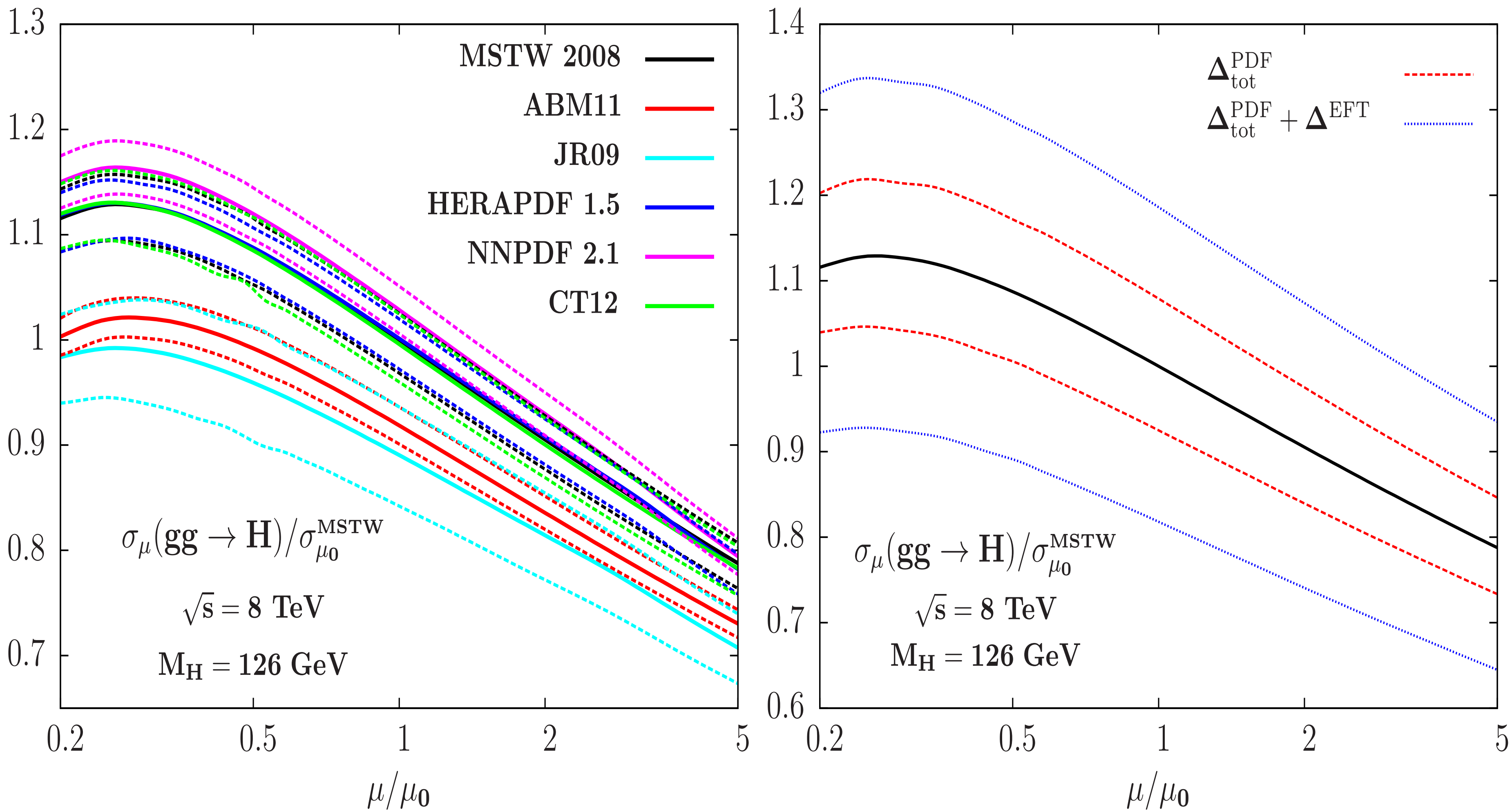
4)Limitations of EFT (Effective Field Theory) approach which shrinks the heavy quark loop to a point. At NLO both exact and approximate answers exist. For NNLO uncertainty has to be estimated.

5)For 7 and 8 TeV the combined PDF + α_s and scale uncertainty is $\sim 10\%$ each.

Plus of course branching ratios.

Note different nature of different uncertainties: The ones due to scale change and/or EFT approximation etc. do not have a statistical interpretation.

A large number of PDF at NNLO available now.



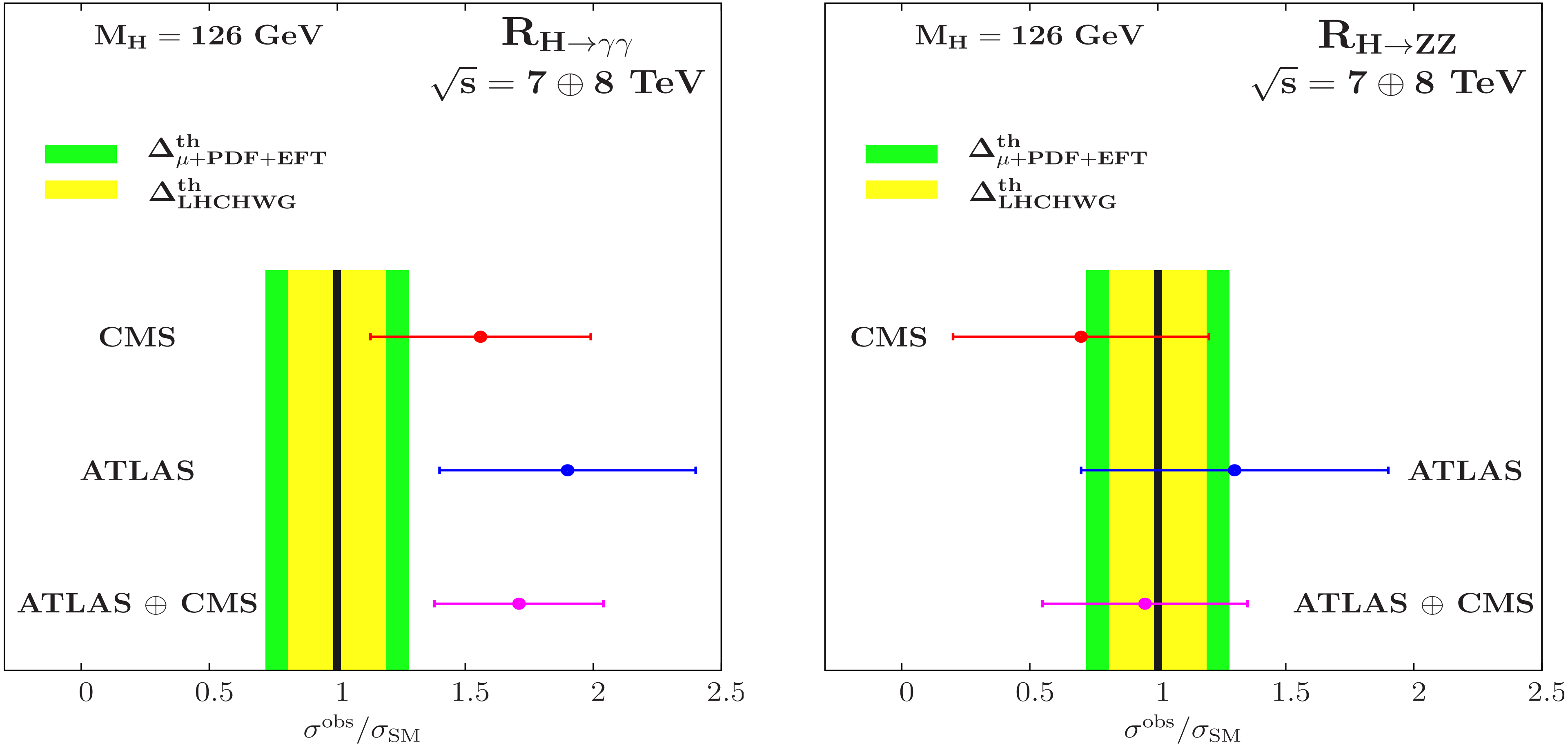
Theory uncertainties $\sim 20\%$.

The PDF and scale uncertainties have no real statistical basis. In the analysis so far these were added in quadrature.

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

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

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



Even without including the additional EFT uncertainty, the procedure reduces the excess from $\sim 2\sigma$ to $\sim 1\sigma$.

Conclusion: For discovery perhaps it was not so relevant, but for the studies of couplings (unless we use ratio of ratios OR ratio of different observed rates !) a discussion of how these errors should be treated in extraction of couplings is important!

In the talk at the 'Implications' workshop at CERN, it was told that the experiments will discuss possibility of including the theory errors with a flat prior in the analysis.

Indeed keeping the higgs light was 'raison d'être' for many Beyond the SM (BSM) models!

Symmetries keeping it light: a) SUSY b) Higgs as the Pseudo Goldstone Boson (Light composite Higgs)!

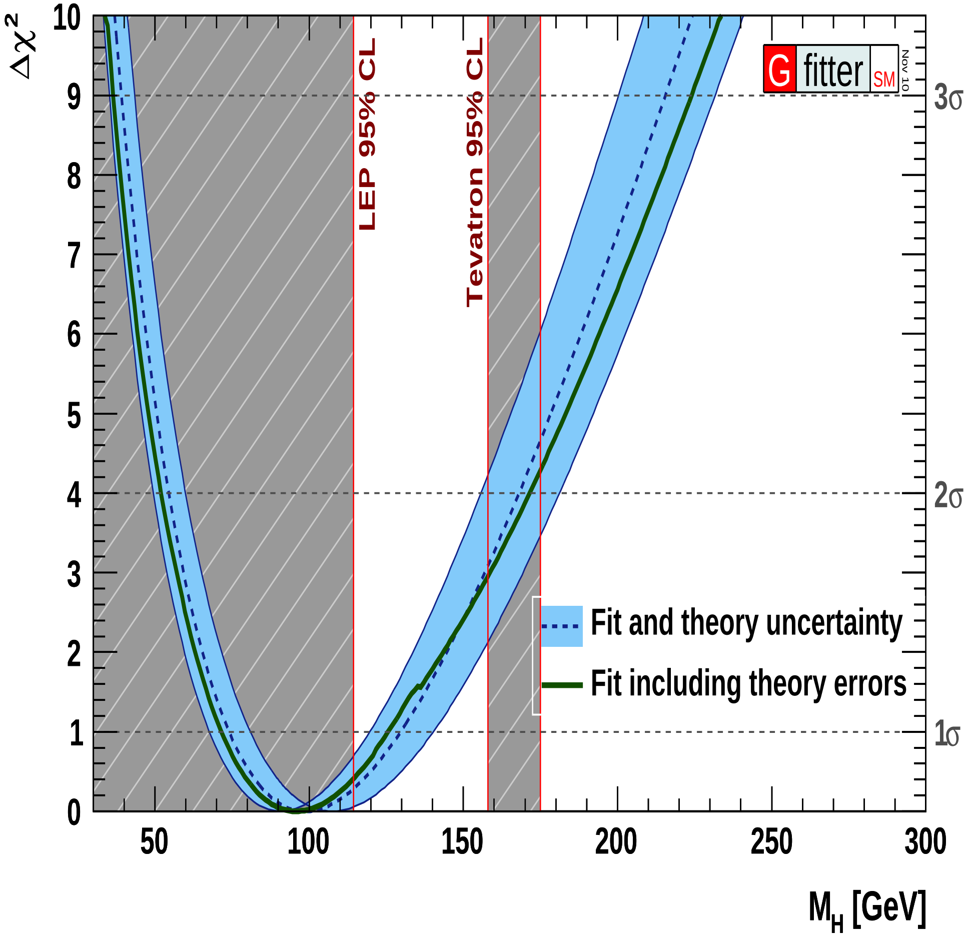
Or removing the need for fine tuning by Extra Dimensions.

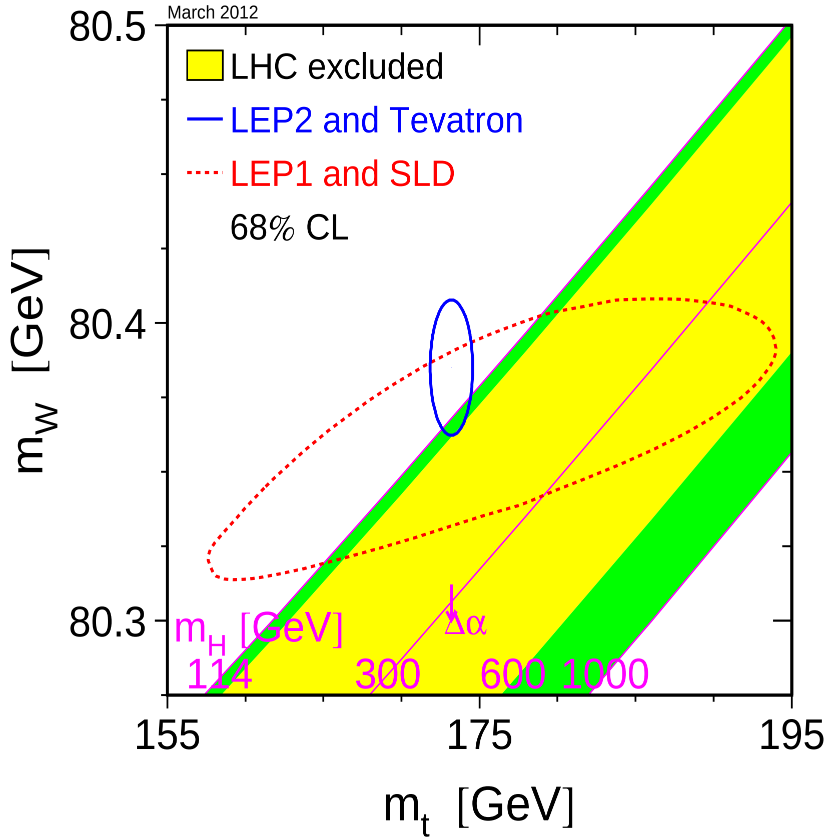
I will focus more on the **lower** theoretical bound than the upper bound!

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 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 a light state.

Example:

Model with fourth sequential generation with a single Higgs doublet gets disfavoured with the discovery of the low mass scalar.

Triviality Bound:

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

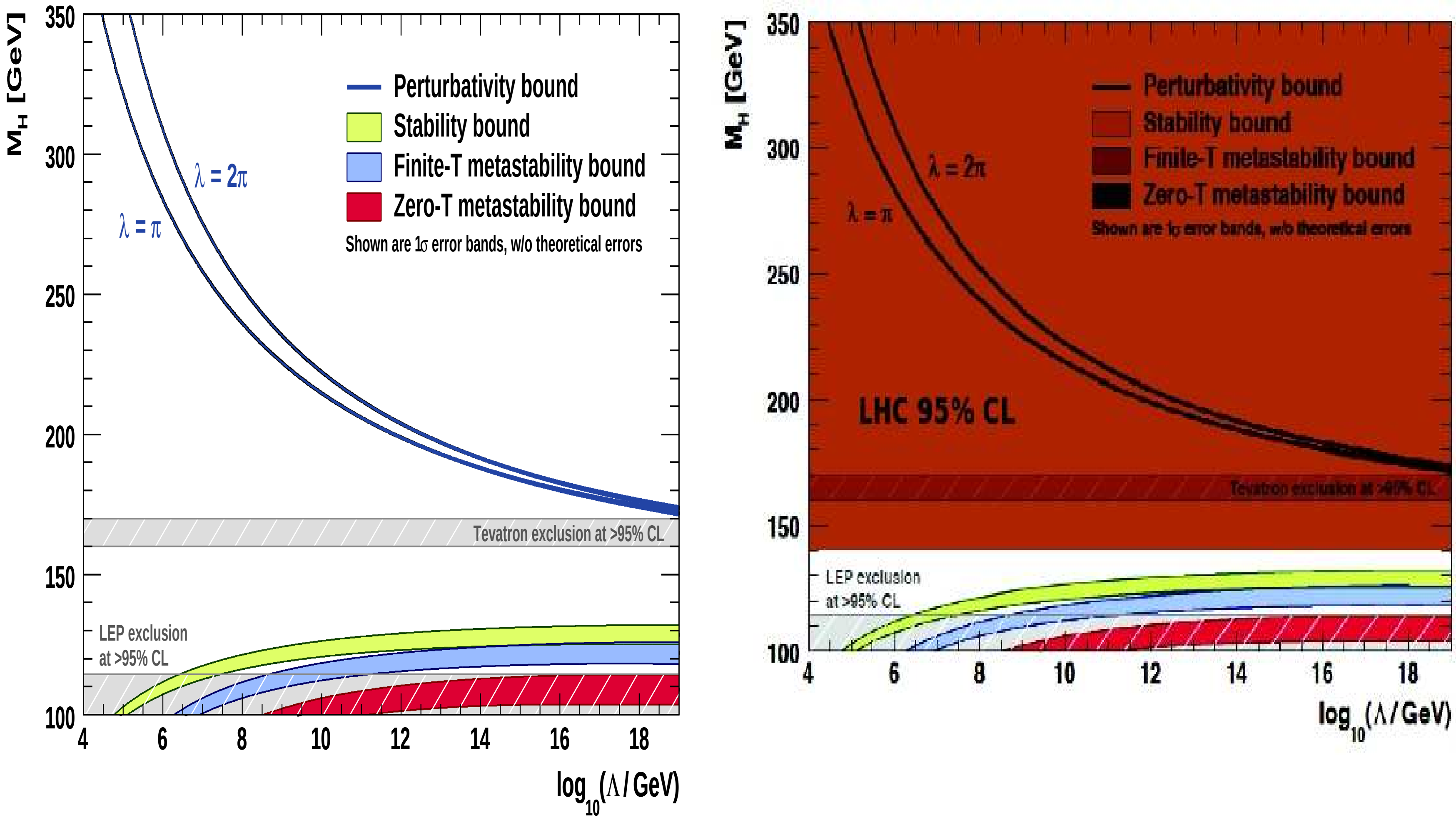
Demanding that λ should be finite upto a certain scale Λ puts an upper limit on m_h.

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. Vacuum becomes unstable.

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

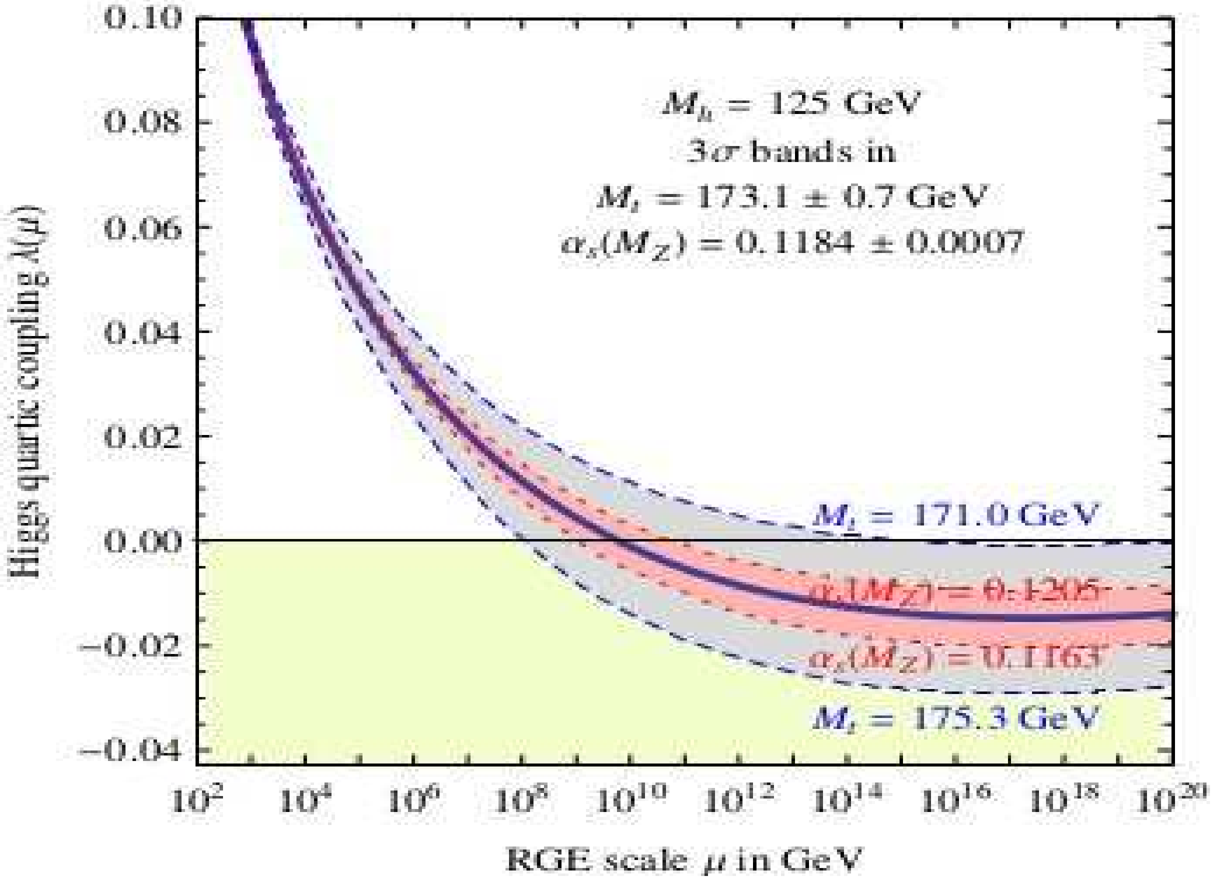
These limits critically depend also on $m_t^{\bar{M}S}$

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.

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



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

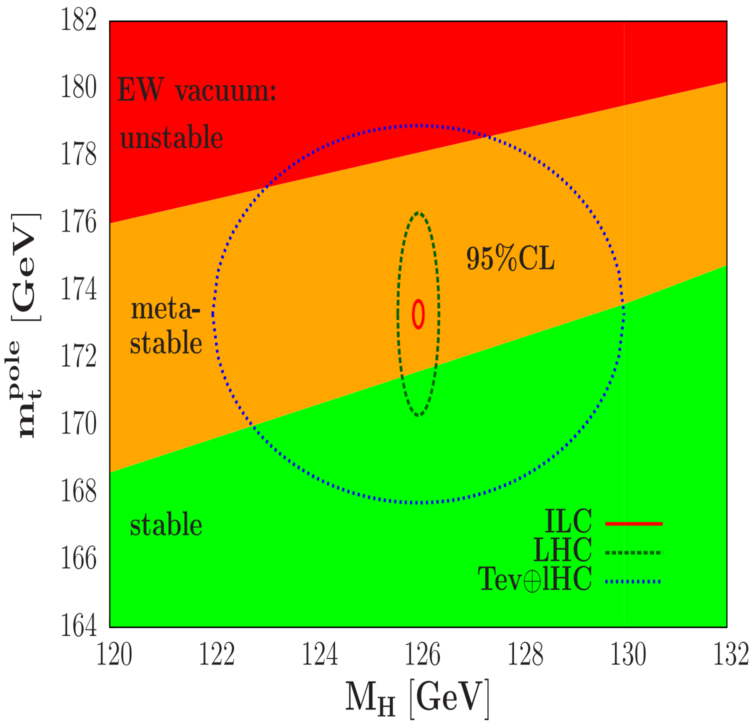
Use errors on pole mass $\Delta m_t = \pm 0.7$ GeV

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 at the Tevatron and the NNLO calculation.
Estimate: $m_t^{pole} = 173.3 \pm 2.8$ GeV.
Vacuum stability constraint now becomes $m_h > 129.4 \pm 5.6$ GeV.



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

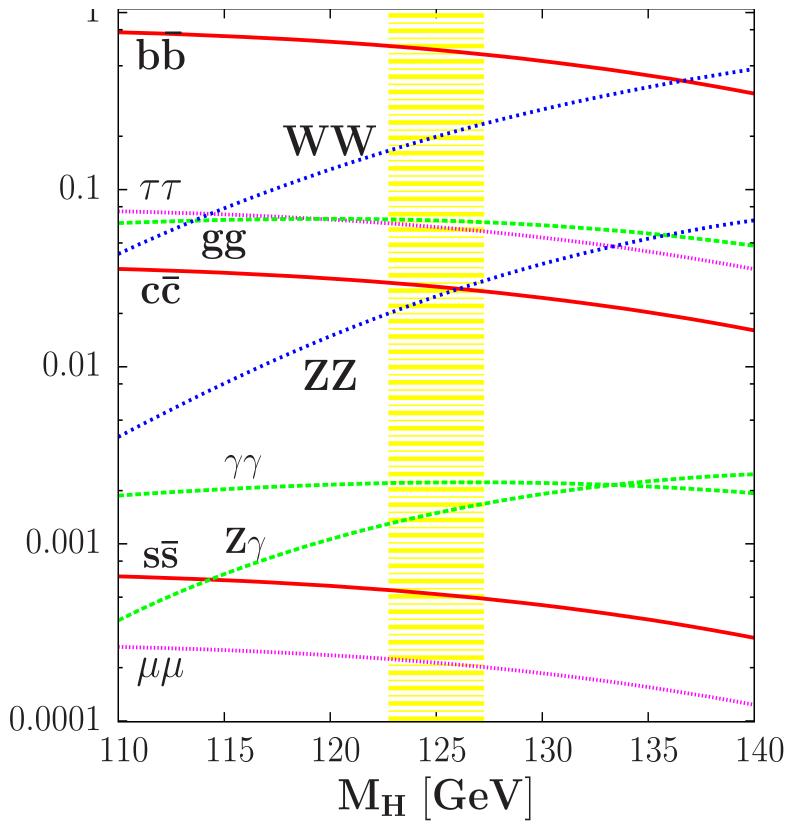


Fig: courtesy A. Djouadi.

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.

The Higgs mass makes global analysis possible 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)

Carmi et al. (1207.1718):

Analyse Higgs decays in terms of higher dimensional operators.

Interpretation in terms of different classes of models which have been proposed to keep the Higgs 'light' and see how many of these are 'natural'!

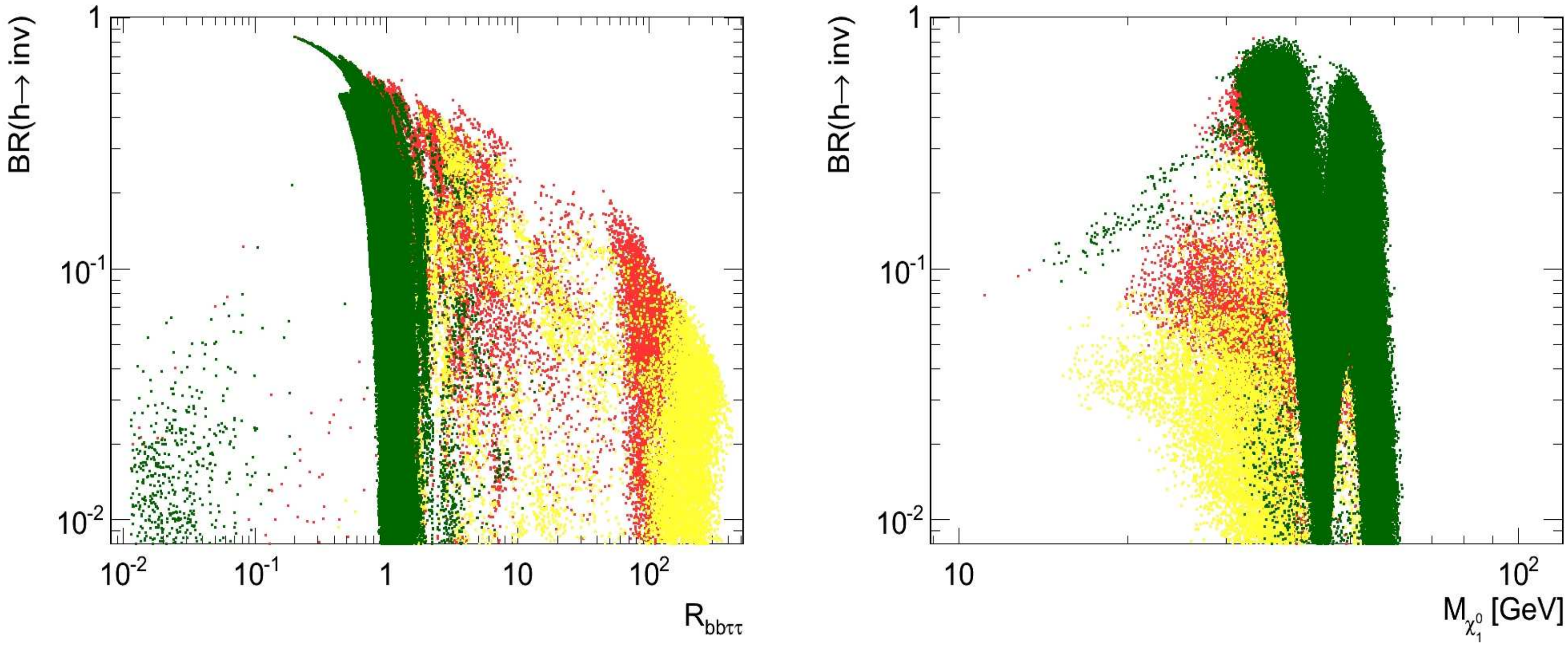
A top partner which is not too heavy (ie. colour and electromagnetic charge same as the top) does ease the fit.

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 conmtribution, thus raising the $\gamma\gamma$ but not raising the gg. May work!

Work by Grojean et al shows that 'invisible' branching ratio upto 0.4 is still allowed!



1112.2200 : D. Albornoz Vásquez, Belanger, Godbole.

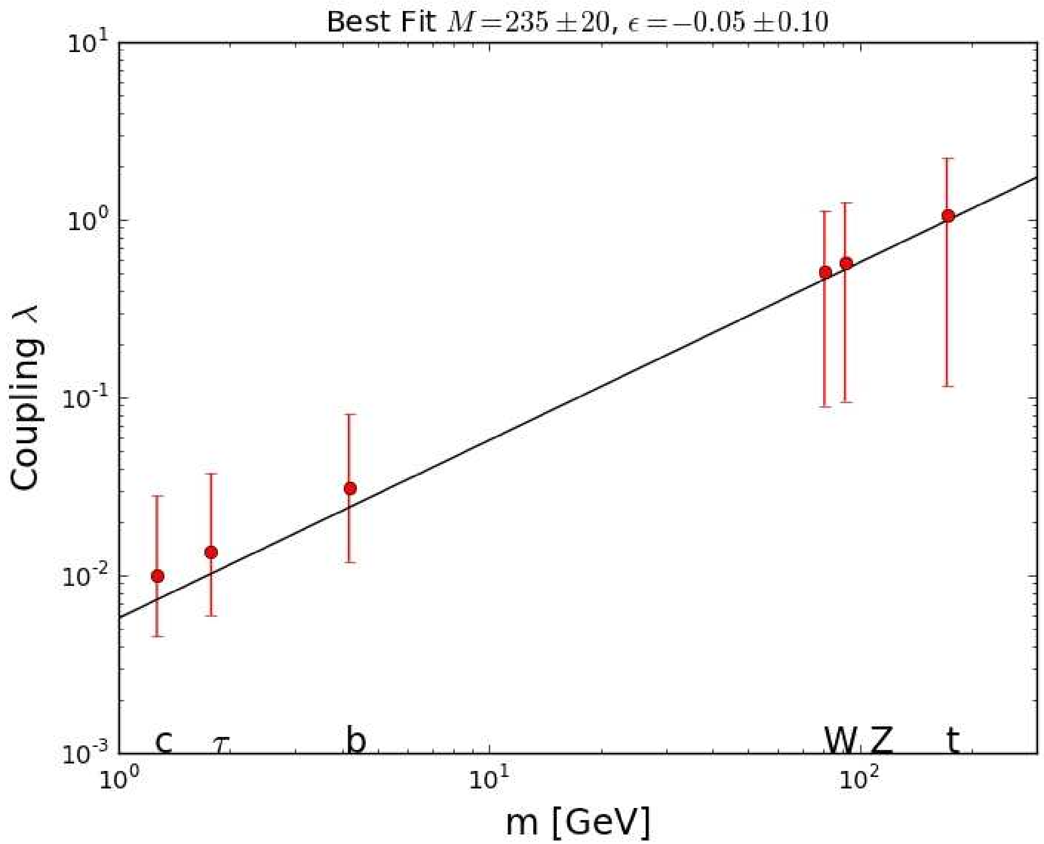
How to look for such a Higgs? (Monoranjan's talk)

The models with coloured particles and with flipped signs of couplings may be constrained due to the Vacuum Stability of the Higgs potential!

The same particles running in the loops will correct the Higgs potential! M. Reece, 1208.1765v1

Has discussed different cases.

Ellis and You:



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

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.

Coupling determination order of the day! Important to understand how to treat the 'systematic' theory uncertainities!

May be possible to get information about 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.

Precision calculations play an important role. Unitarity methods particularly useful for Collider calculations with many legs.

Yet another example of effect of precision calculations is conclusion one draws about the possible existence of a sequential fourth generation from the current LHC data on Higgs!

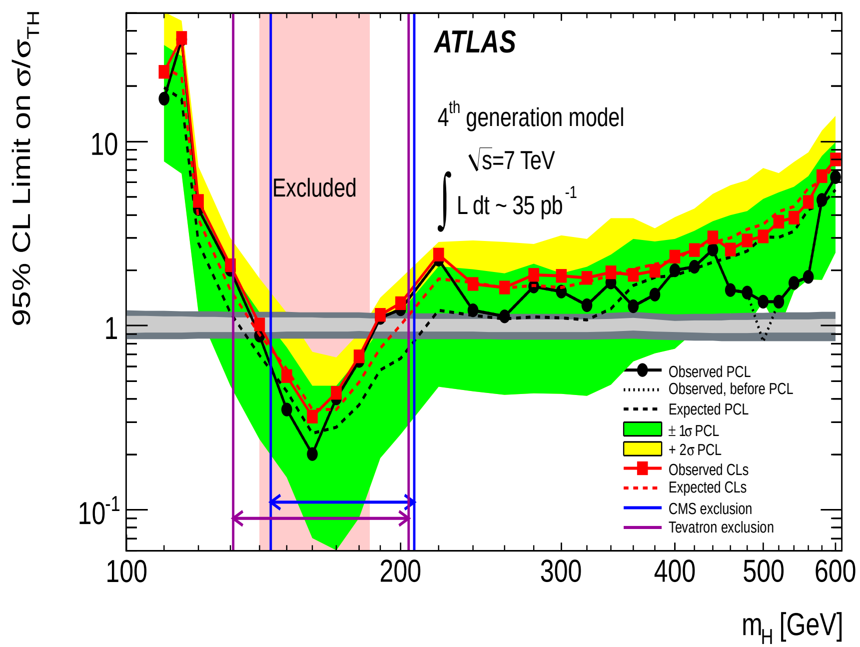
BACKUP SLIDES

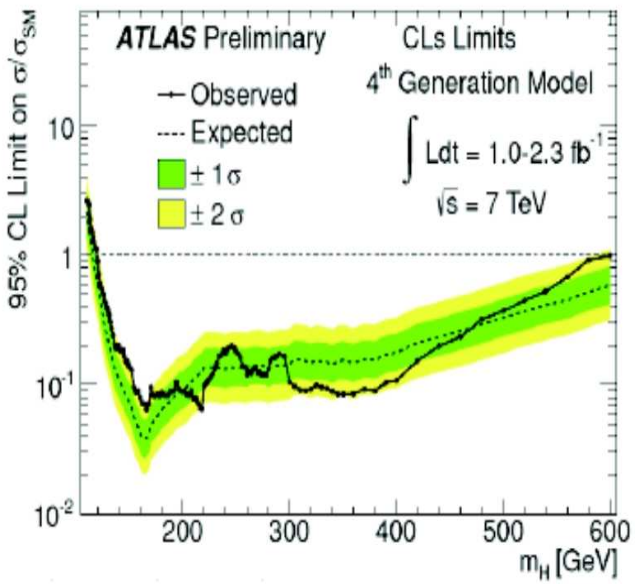
Fourth sequential generation: Chanowitz, Kribbs...

• Fourth sequential generation allows consistency of electroweak precision tests with a Higgs heavier than in the SM_3!

•Provides additional source of CP violation which might help address the issue of Baryon Asymmetry in the Universe.

•For larger values of $m_h > 2M_W$ the $gg \to h \to WW$ rates enhanced by over an order of magnitude.





December 2011: LHC and Tevatron had excluded Higgs with a mass between 124 to 600 GeV in SM_4. A heavy Higgs like this consistent with EWPT. Fourth generation still 'alive'.

With 125 GeV Higgs observation all changed.

A. Djouadi and A. Lenz: 1204.1252v2

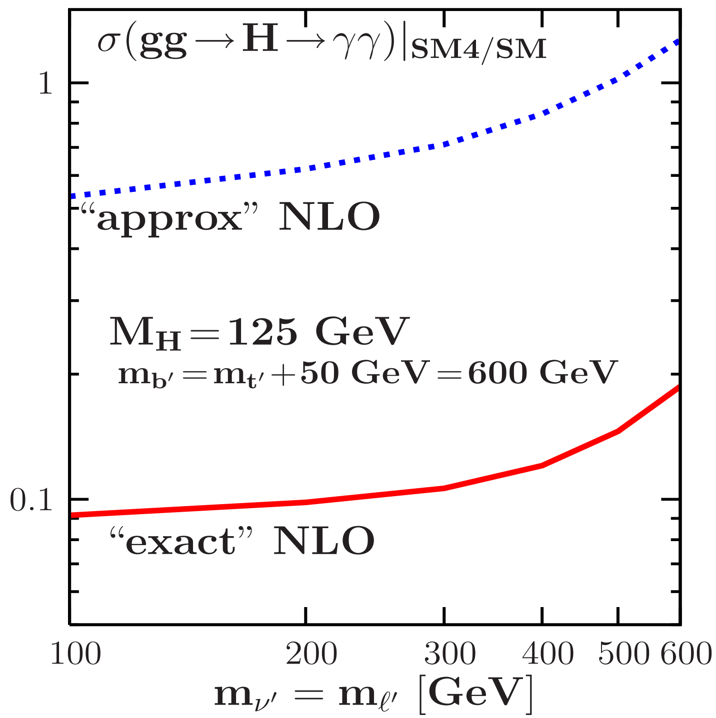
The strong interference effects between W and t', b', l' diagrams lowers $h \to \gamma\gamma$ to compensate the increase in $gg \to h$.

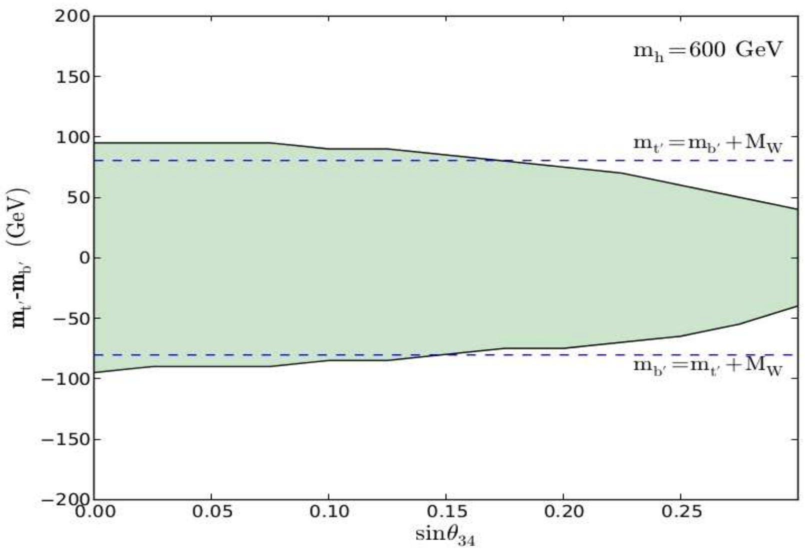
Evaluation of $h \to \gamma\gamma$ with a naive implementation of $\mathcal{O}(G_F m_{f'}^2)$ correction can not rule out SM_4, in fact for $m_h \sim 125$ GeV it can give slight increase in the $gg \to h \to \gamma\gamma$!

BUT

with the exact next-to-leading order EW corrections (Denner et al: 1111.6395) the $h \to \gamma\gamma$ suppressed much below the SM!

For $m_h = 125$ GeV



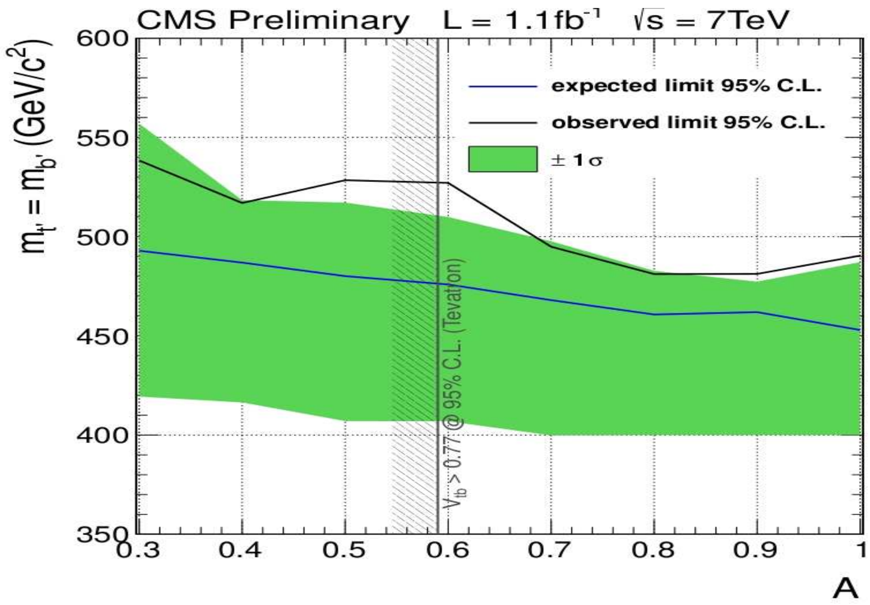


If this were not the case, then fourth generation picture will be still alive AND the LHC results will have interesting imiplications.

$M_{t'} - M_{b'} > m_W$ allowed for M_h for the large m_h and very small θ_{34} !
(Amold Dighe, RG, V. Arunprasath, Diptimoy Ghosh : 1204.3550)

Quite different from what was alwyas assumed in sequential 4 generation picture!

Why is this important?



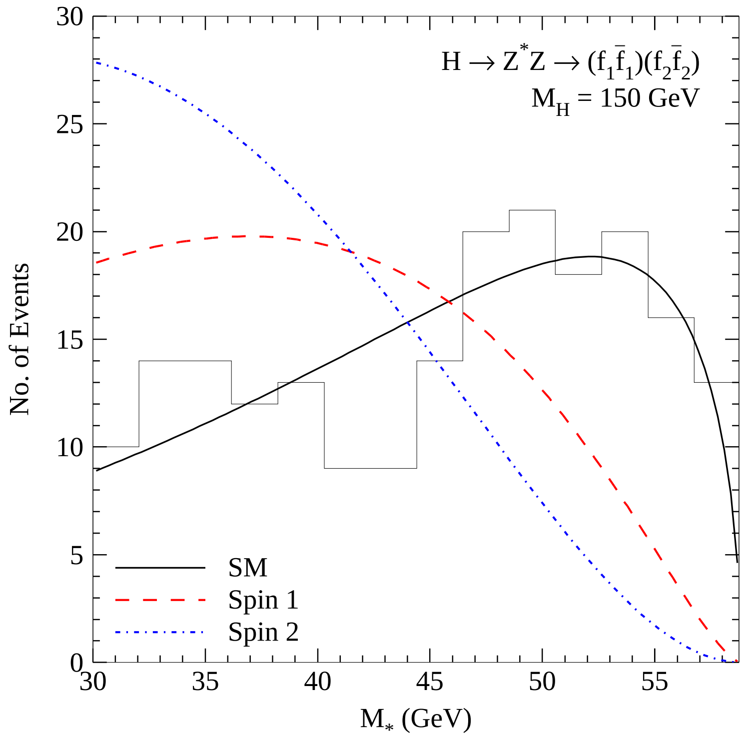
Searches at present use a final state $t' \to bW$ as the channel $t' \to b'W$ was not expected to be open. So the search strategy for fourth generation might have to be revisited.

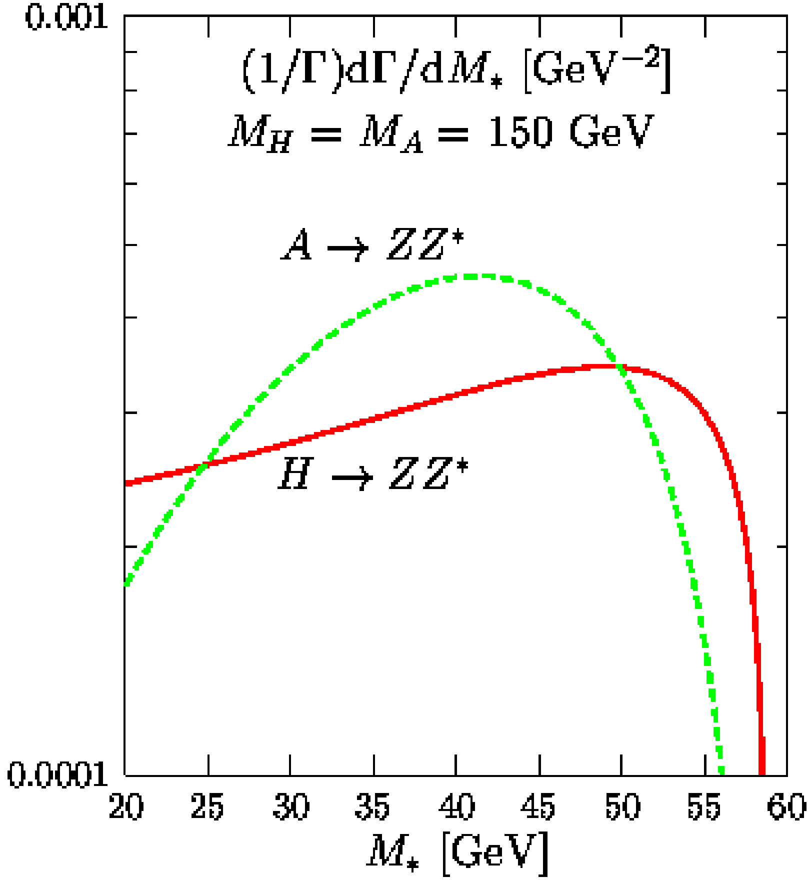
BACKUP SLIDES

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

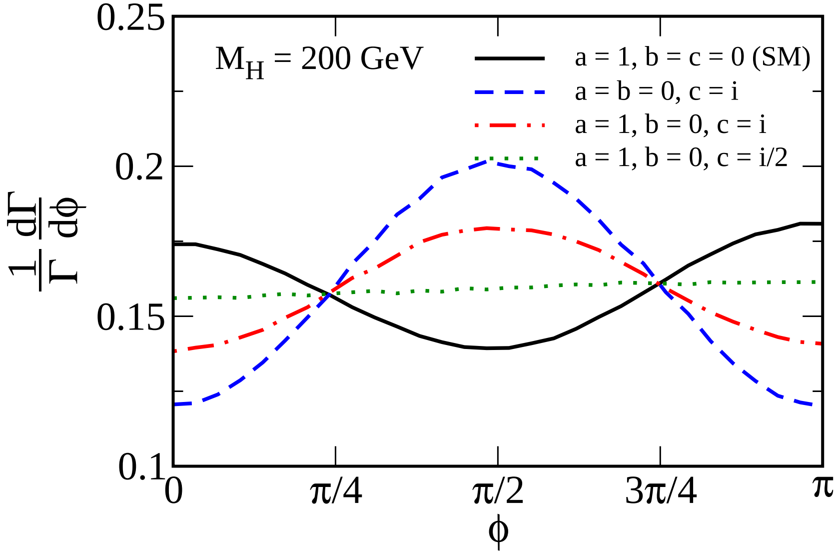
Kinematic distributions of the decay product of the ZZ can probe the CP

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


H → Z*Z → (f1f̄1)(f2f̄2)
MH = 150 GeV
No. of Events
M* (GeV)
SM
Spin 1
Spin 2


(1/Γ)dΓ/dM* [GeV−2]
MH = MA = 150 GeV
A → ZZ*
H → 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.

May be possible to get information about 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.

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

- Tevatron has even provided some 'evidence' for the $b\bar{b}$ coupling as well.

nonabelian nature of the coupling and particle content of the SM including the Higgs particle can be obtained by requiring 'good' high energy behaviour of the amplitude $WW \to WW$ and $e^+e^- \to W^+W^-$

S–matrix derivation of the SM:

Cornwall,Levin, Tiktopoulous (1973,1974) Phys. Rev. Lett. 30, (1973), Phys. Rev. D 10 (1974);

S. D. Joglekar, Annals Phys. **83**, 427 (1974);

Llewellyn Smith (1973), Phys. Lett. B 46, (1973) + Bento Nucl. Phys. B 289 (1987)

These give an upper limit on the Higgs mass too! Lee, Quigg and Thacker: Phys.Rev. D16 (1977) 1519