Some lessons/implications of observed Higgs-like boson

E. Boos
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~ 350 references on
G. Aad et al. [ATLAS collaboration], Phys. Lett. B716 (2012) 1
S. Chatrchyan et al. [CMS collaboration], Phys. Lett. B716 (2012) 30

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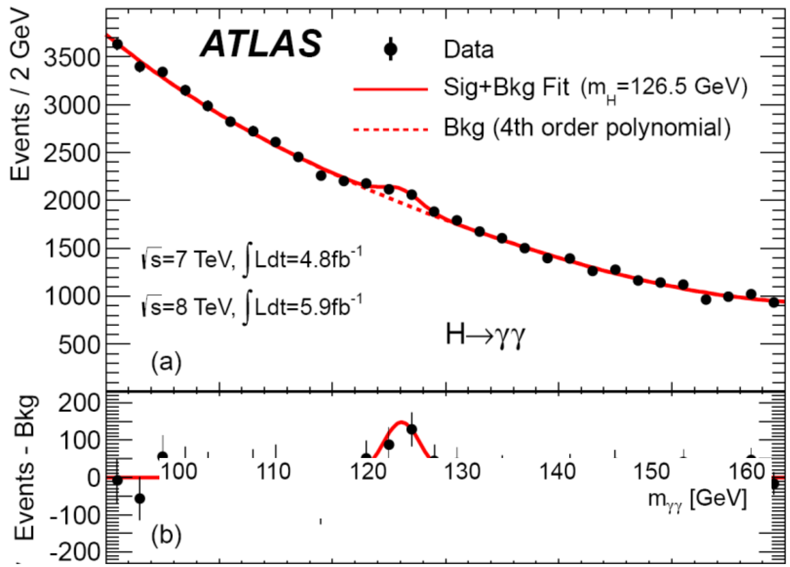
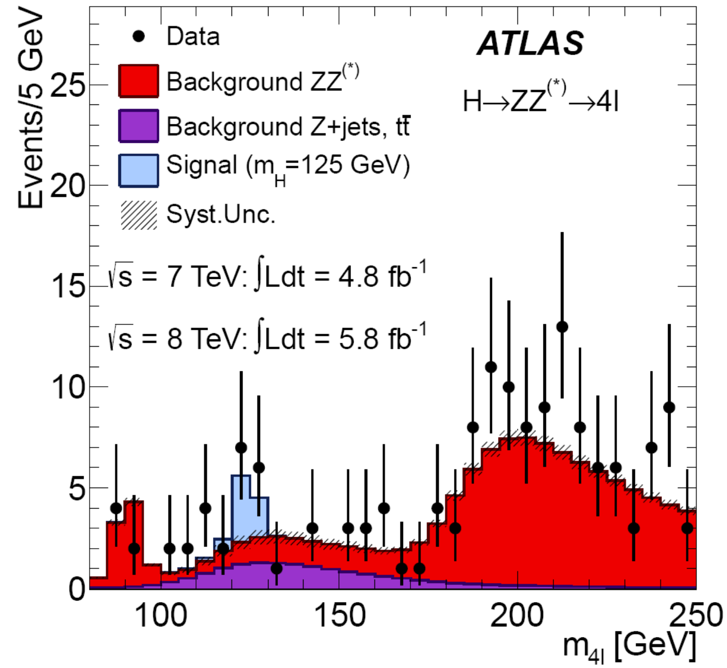
Road map after the discovery

ATLAS results

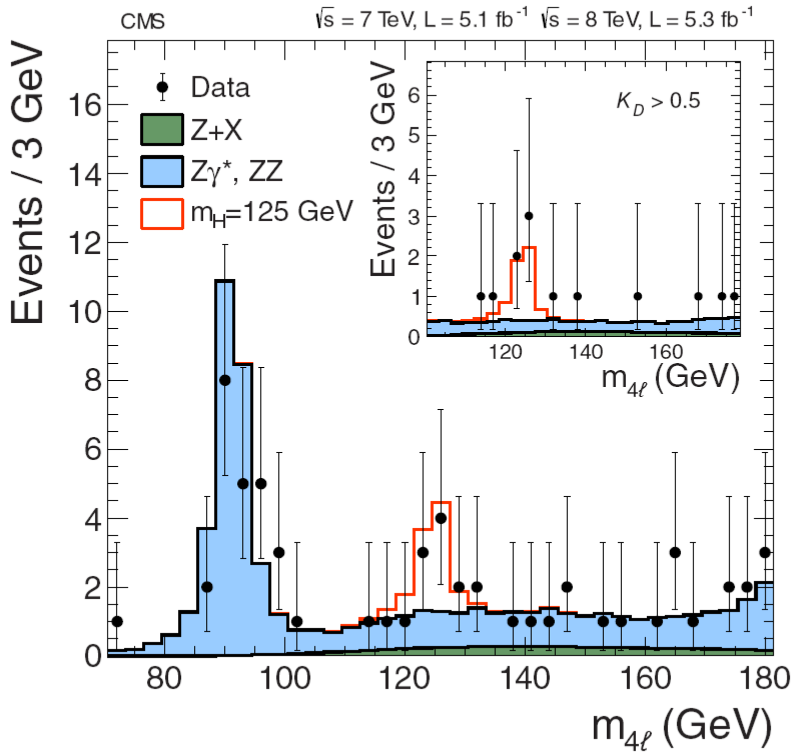


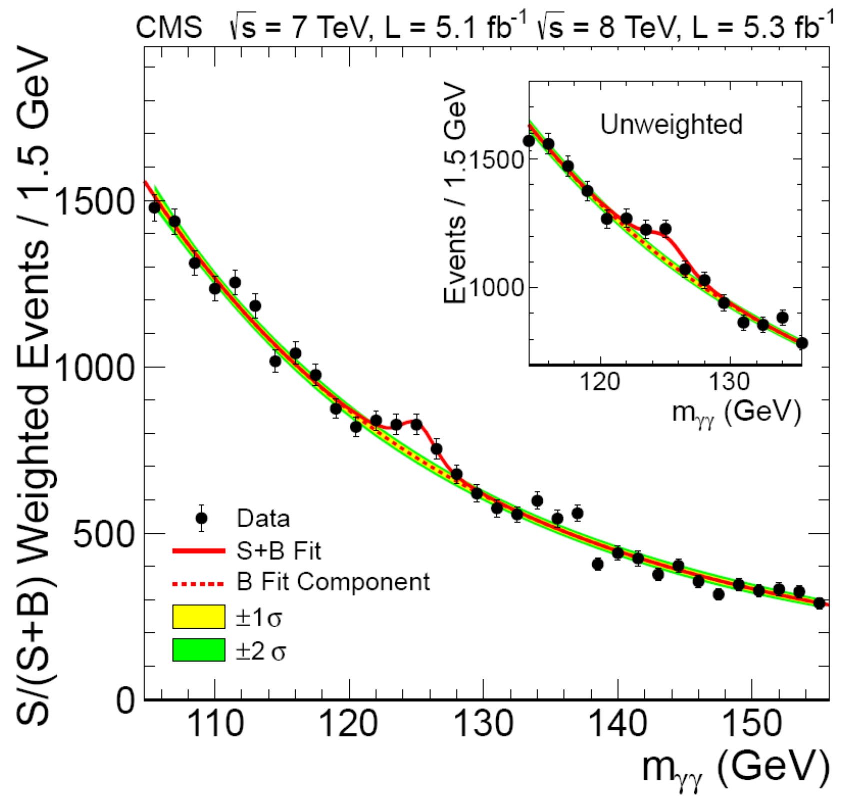


M_H = 126.0 ± 0.4 (stat) ± 0.4 (sys)

5.9 σ significance !

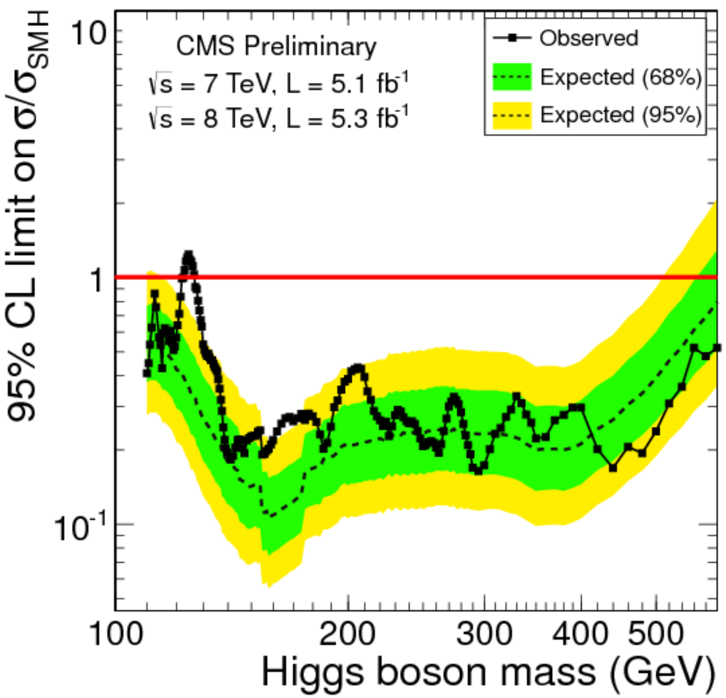
CMS results

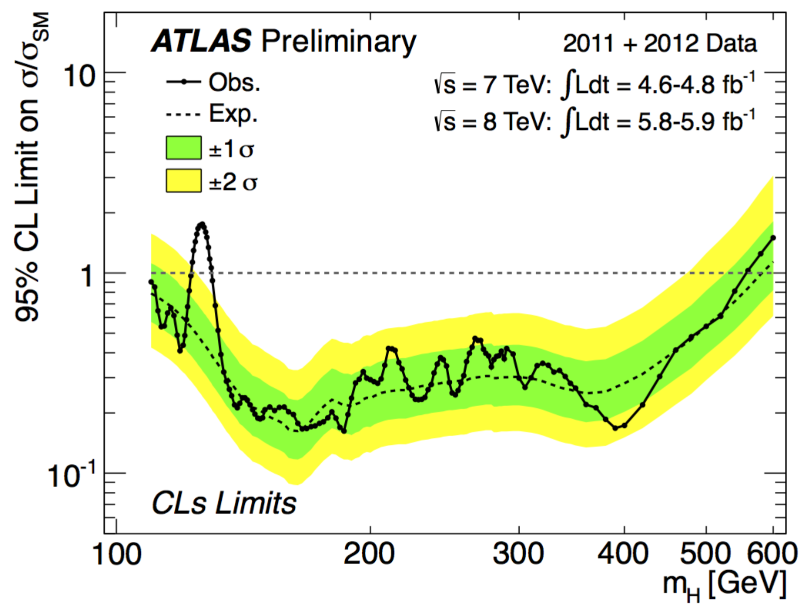




M_H = 125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV

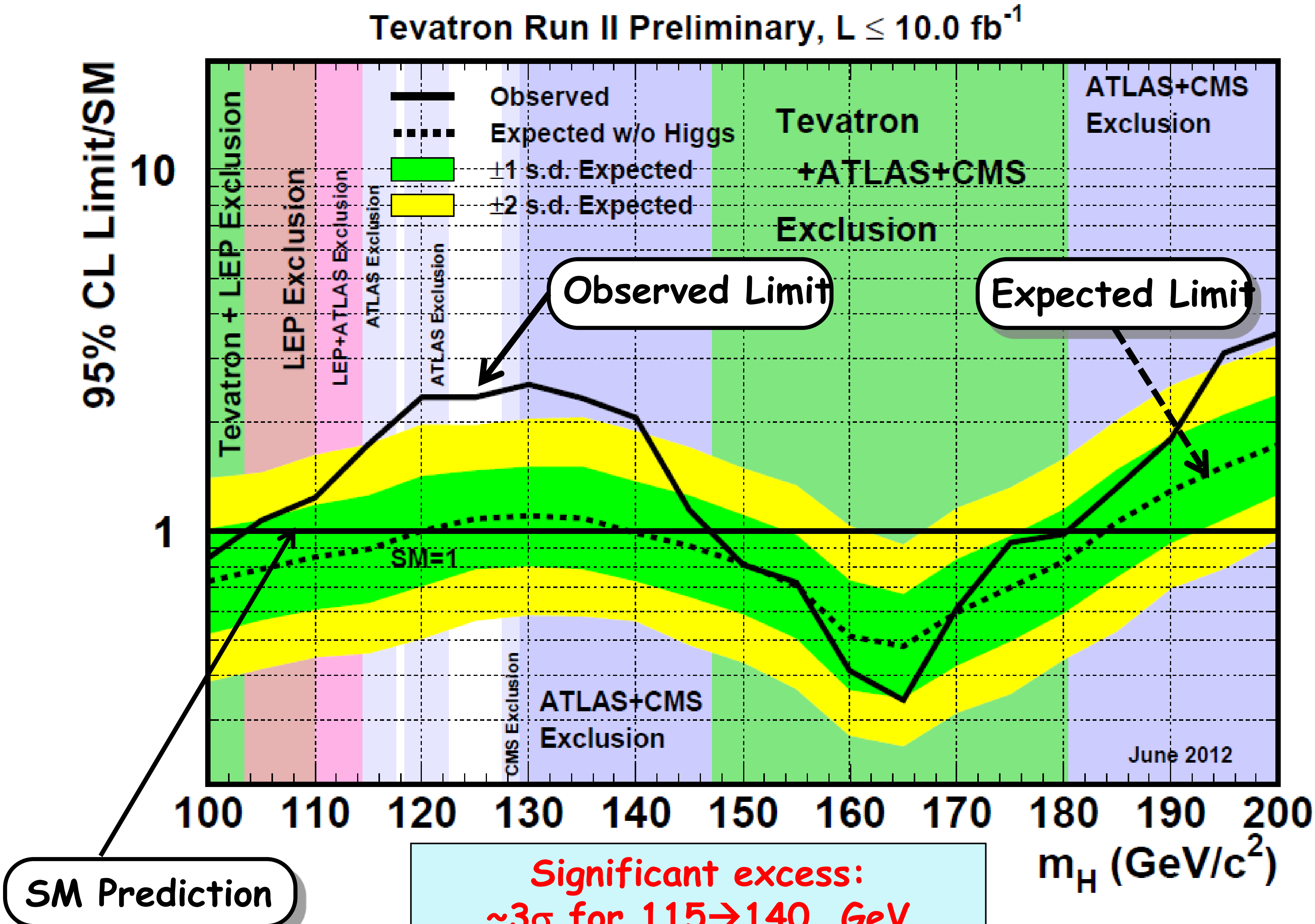
5.0 σ significance !





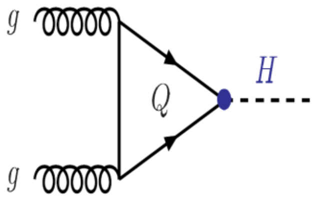
Both CMS and ATLAS have excluded SM Higgs in the mass interval upto about 560 GeV except small interval where the signal was observed

Summer 2012 Tevatron Combination

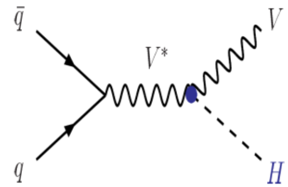


Significant excess:
~3σ for 115→140 GeV

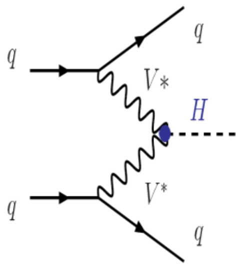
Higgs production modes, decays and signatures at LHC



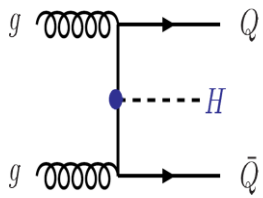
Gluon-gluon fusion



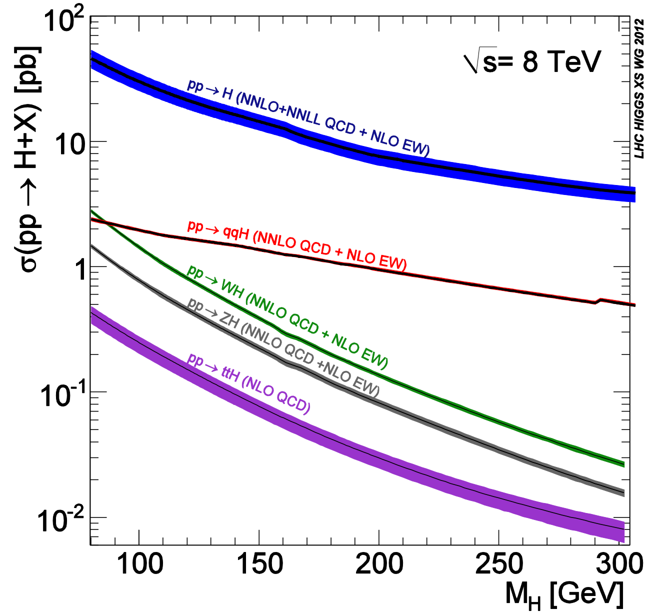
W/Z-Higgs associated

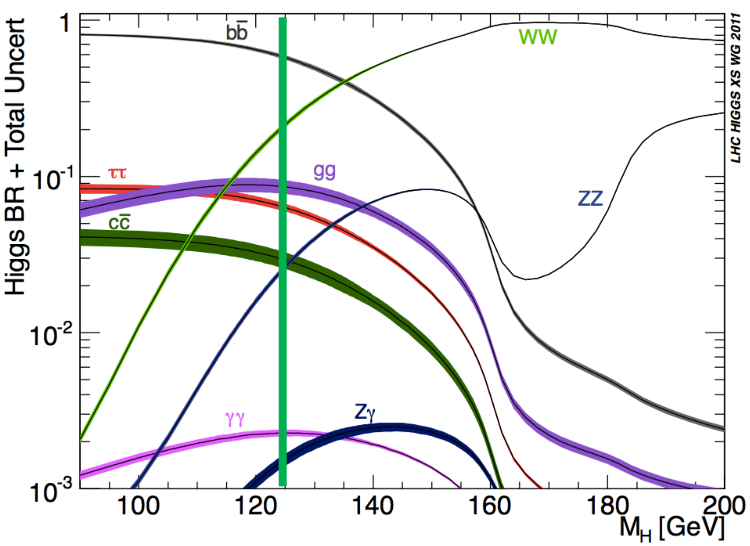


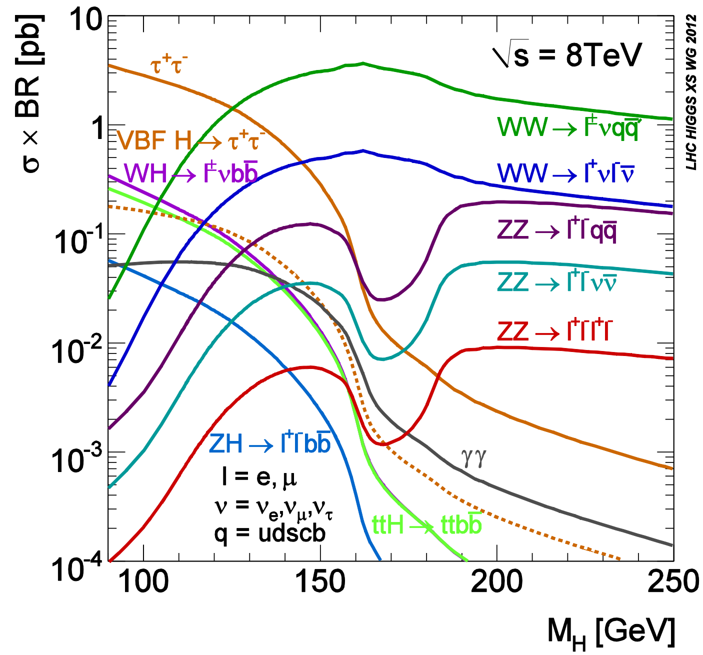
Vector boson fusion



t t-bar Higgs associated





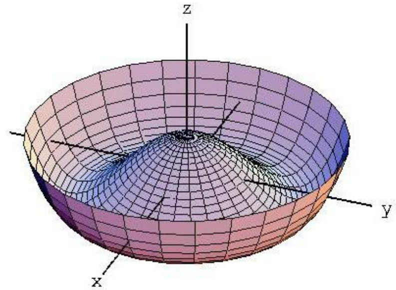


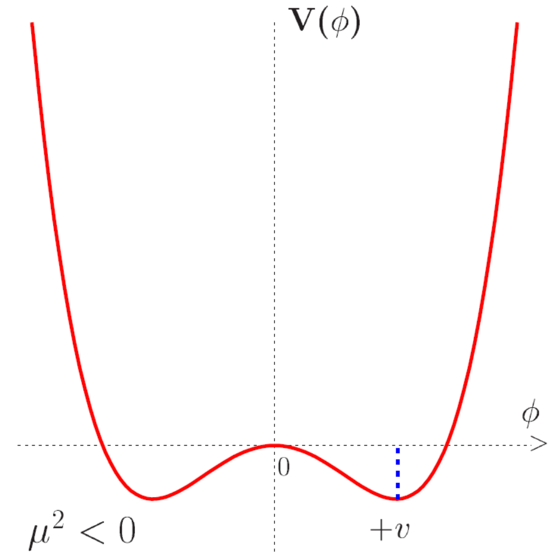
Not only discovery and mass measurement

but also

Very good precision of the mass measurement

Exclusion of large range of higher masses





$$\mathbf{V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2}$$

$$\mathbf{\Phi \rightarrow \frac{1}{\sqrt{2}} \binom{0}{H+v}}$$

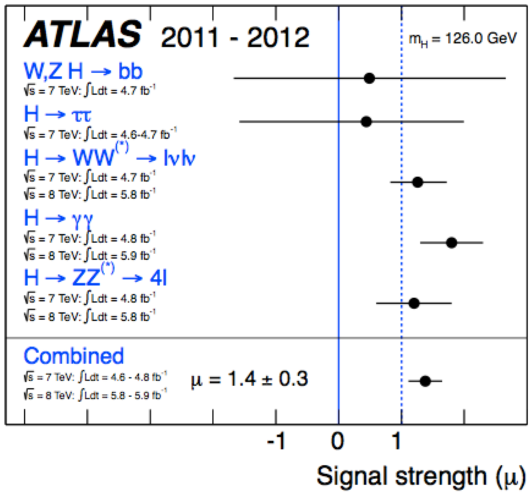
$$\mathcal{L}_{\rm H} = \frac{1}{2}(\partial_\mu {\rm H})(\partial^\mu {\rm H}) - {\rm V} = \frac{1}{2}(\partial^\mu {\rm H})^2 - \lambda {\rm v}^2\, {\rm H}^2 - \lambda {\rm v}\, {\rm H}^3 - \frac{\lambda}{4}\, {\rm H}^4$$

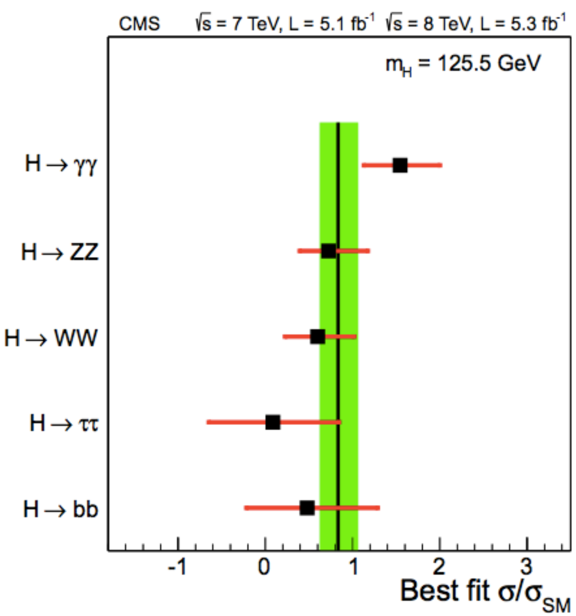
$$\mathbf{M_H^2 = 2\lambda v^2 = -2\mu^2}$$

$$\lambda \cong 0.12$$

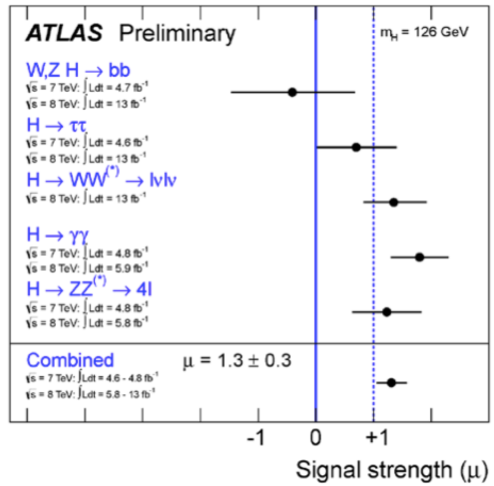
Origin of the EWSB potential → a weakly-coupled theory

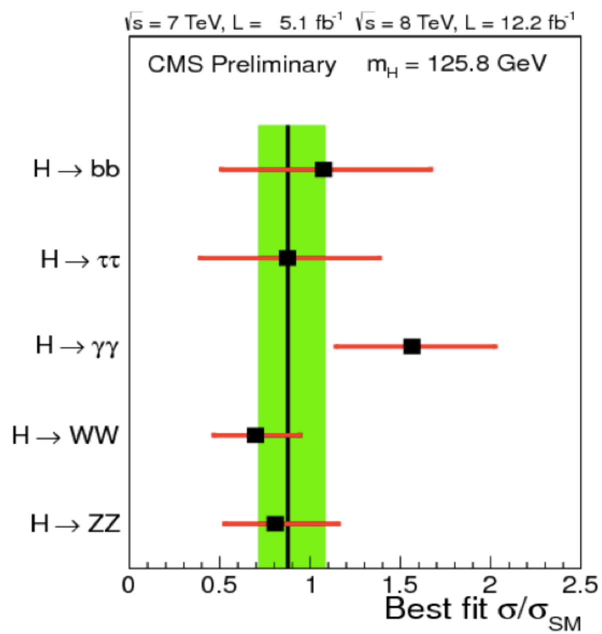
July

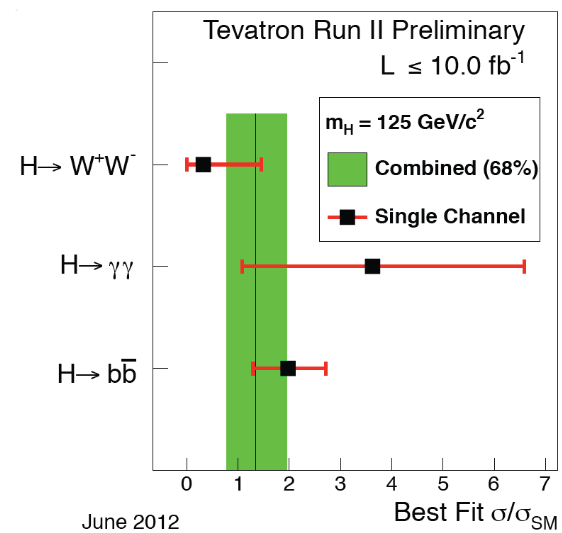




November







1. **How much the observed state corresponds to the SM Higgs ?**

Bezrukov, Shaposhnikov;
Degarssi et al;
Espinosa, Grojean, Meuhlleitner, Trott;
Geardino et al;
Degrandea, Gerardb, Grojeanc, Maltonib, Servant;
Bonnet, Ota, Rauch, Winter;
Plehn, Rauch;
Avery, Bourilkov, Chen, Cheng, Drozdetskiy, Gainer, Korytov, Matchev, Milenovic, Mitselmakher, Park, Rinkevicius, Snowballa;
Carena, Low, Wagner;
Azatov et al
….

2. **What are differences in production and decay for the resonant states with different J^{PC}? How to extract and measure quantum numbers of the new state?**

Ellis, Hwang, Sanz, You;
Ellis, Hwan;
Bolognes et al;
Choi, Meuhlleitner, Zerwas
….

3. **How much the observed state correspond to possible Higgses in various BSM scenarios ? What are implications to various BSM?**

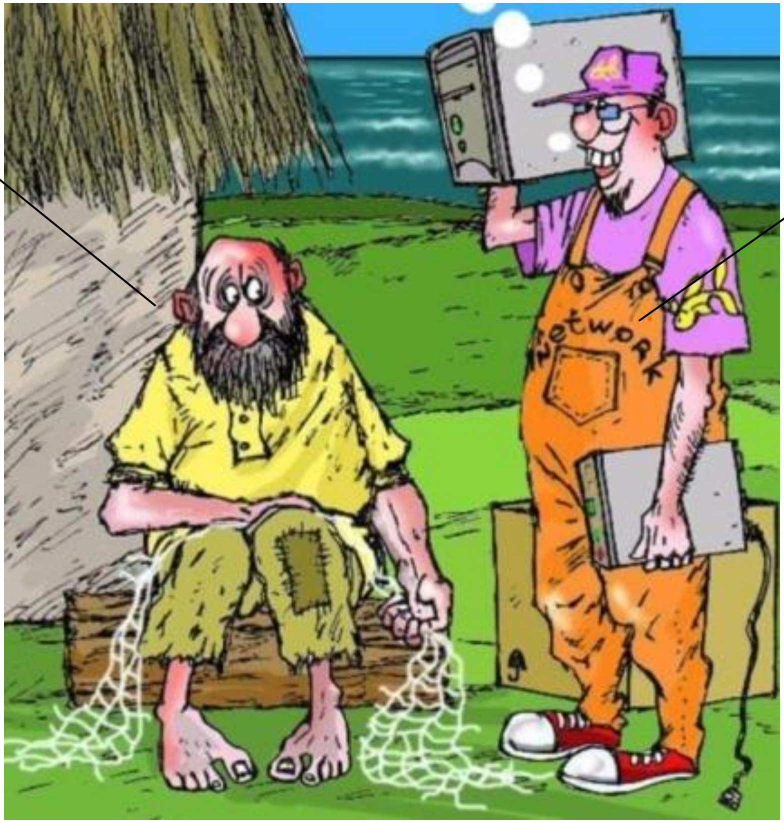
Nath; Peskin; Kuflik et al, Abe et al; Athron et al; Bae et al; Basso et al; Brehmer et al; Ohlsson et al; Belanger et al….

Discovering of new Higgs-like state

Not discovering anything else

"Theorist"

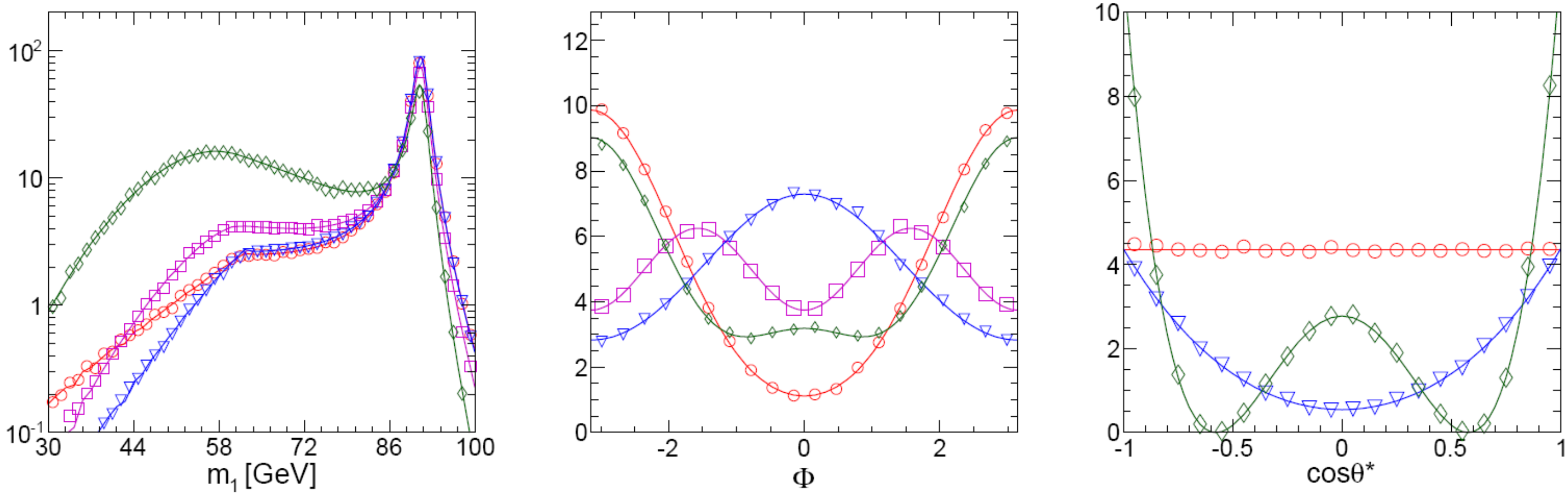
"Experimentalist"



How to measure properties?

Bolognes et al 2012

X -> ZZ*->4l   X -> WW* -> lν lν   X -> γγ



X : 0^+, 0^-, 2^+_m, 2^+_h

Many differences in various kinematic variables

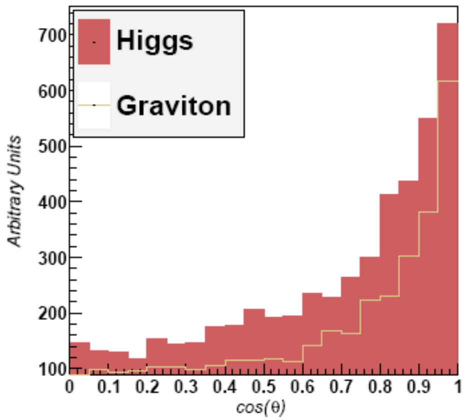
With more realistic simulations:

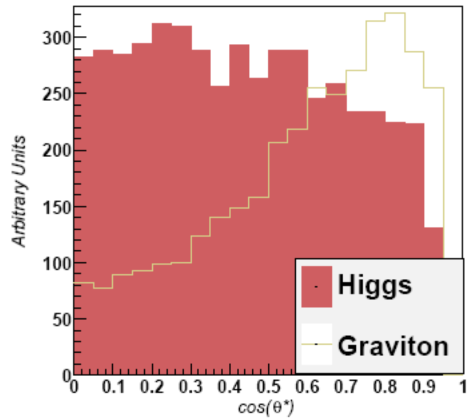
Ellis et al 2012

pp -> $X_{0,2}$ -> $\gamma\gamma$

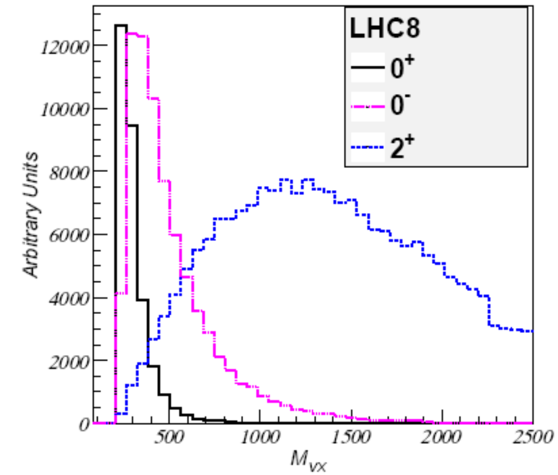
$$\frac{d\sigma}{d\Omega} \sim \frac{1}{4} + \frac{3}{2}\cos^2\theta^* + \frac{1}{4}\cos^4\theta^*$$

M_X = 125 GeV

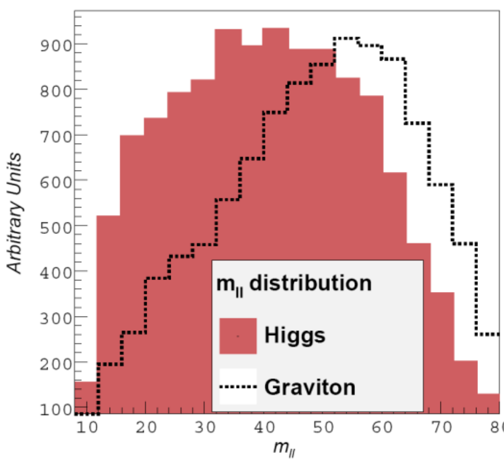


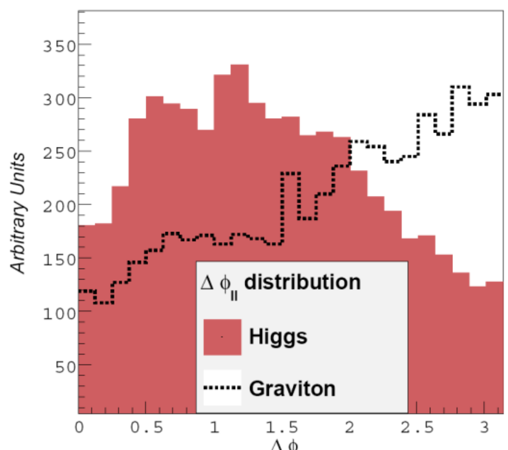


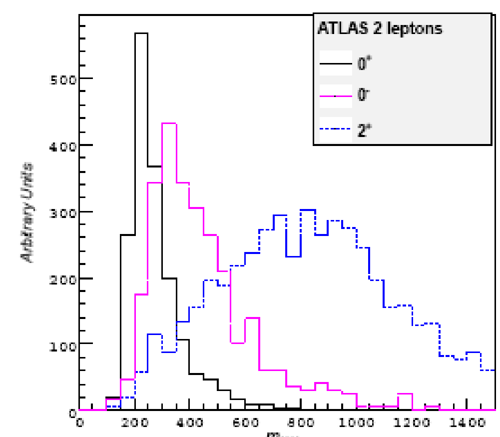
pp -> Z+$X_{0+,0-,2+}$



pp -> $X_{0,2}$ -> WW* -> lν lν



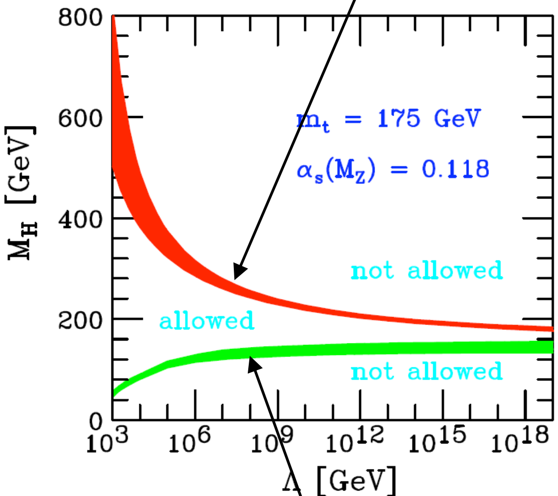


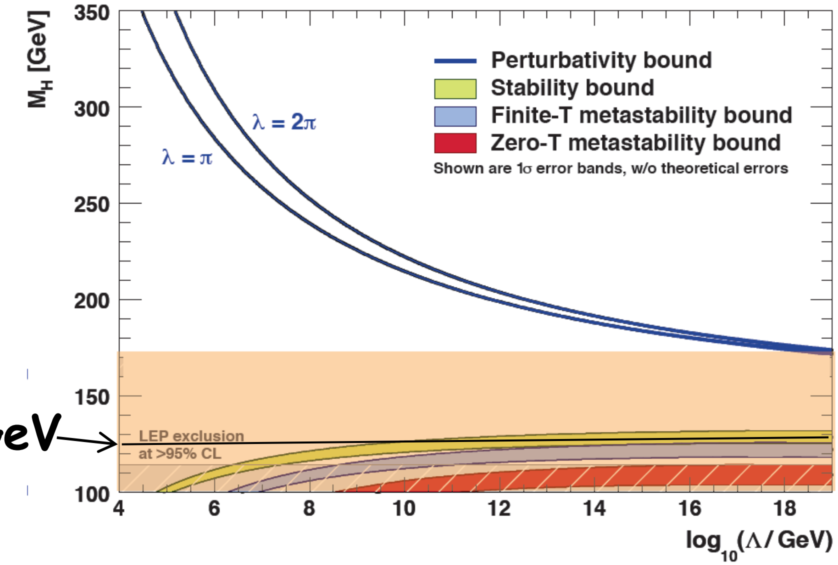


An answer from experiments one might expect soon

May be the SM is the consistent quantum theory till very large scales:

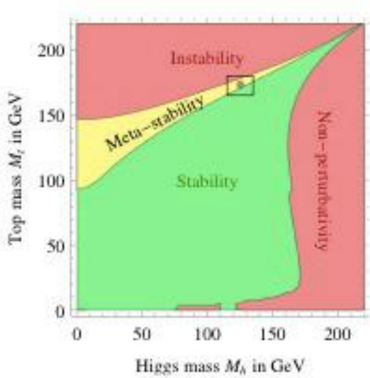
No Landau pole (triiviality)

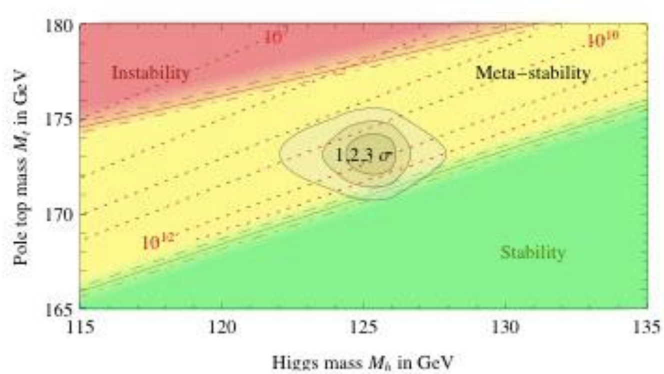




125 GeV

Positive self coupling $\lambda(Q^2) > 0$
(vacuum stability)

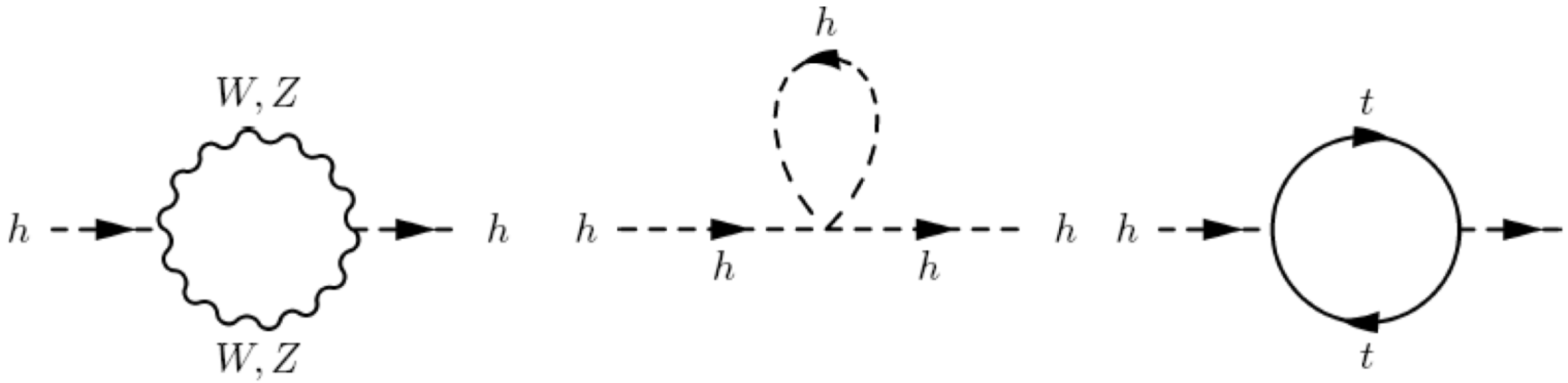




Bezrukov, Shaposhnikov 2012
Degarssi et al 2012

However, the simplest Higgs mechanism SM is not stable with respect to quantum corrections (little hierarchy problem)

Loop corrections to the Higgs mass



$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\Lambda^2 \approx -(0.2\,\Lambda)^2$$

$\delta m_H < m_H$ $\Lambda < 1$ TeV

In SM there is no symmetry which protects a strong dependence of Higgs mass on a possible new scale

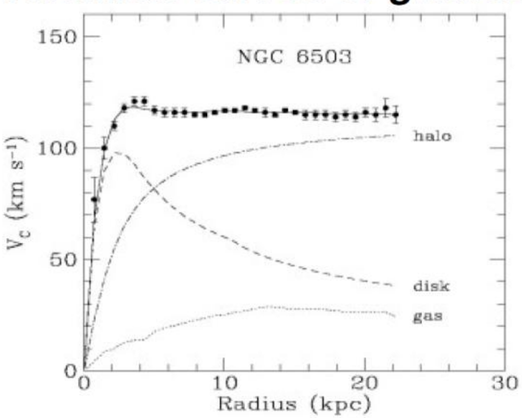
Something is needed in addition to SM…

There is a number of facts which needs to be explained

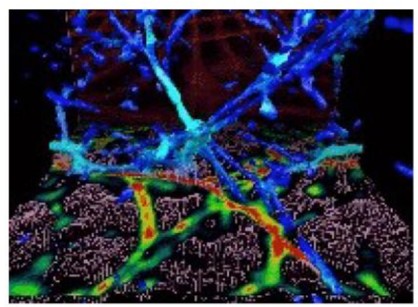
1. EW symmetry is broken – photon is massless, W and Z are massive prticles
Fermions have very much different masses
(Mtop ≈ 172 GeV, Me ≈ 0.5 MeV, ΔMν ≈ 10^{-3} eV)

2. Dark Matter exists in the Universe

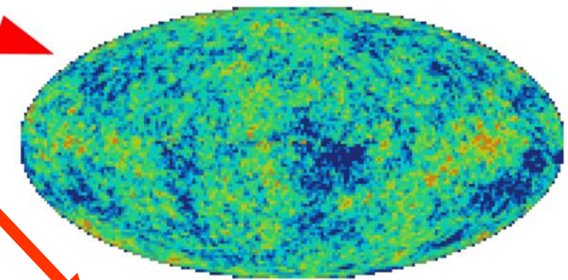
Rotation curves of galaxies



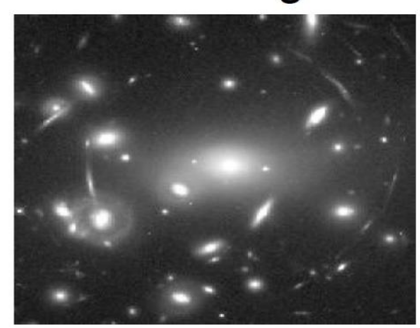
Large Scale Structure

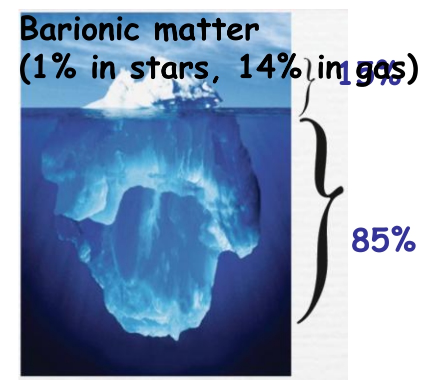


CMB



Lensing





Dark unknown matter

3. (g-2)μ (about 3.5 σ) 4. Neutrino oscillations

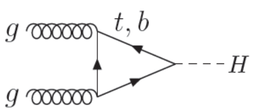
4. Particle – antiparticle asymmetry in the Universe,
CP violation

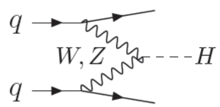
baryon asymmetry: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-10}$

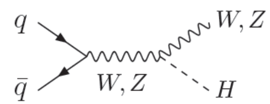
5. Gravity (no connection to EW?). Why gravity is so weak?

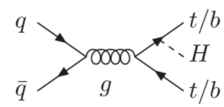
$$\mathcal{L} = \mathcal{L}_h - (M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu)[1 + 2a\frac{h}{v} + \mathcal{O}(h^2)]$$
$$-m_{\psi_i}\bar{\psi}_i\psi_i[1 + c\frac{h}{v} + \mathcal{O}(h^2)] + \ldots$$

Contino et al 2012,
….
Espinosa et al 2012









$\frac{\sigma_{NLO}}{\sigma^{SM}_{NLO}}$ c^2 a^2 a^2 c^2

$$\Gamma(H \to f\bar{f}) = c^2\, \Gamma^{SM}(H \to f\bar{f}),$$
$$\Gamma(H \to VV) = a^2\, \Gamma^{SM}(H \to VV),$$
$$\Gamma(H \to gg) = c^2\, \Gamma^{SM}(H \to gg),$$
$$\Gamma(H \to \gamma\gamma) = \frac{(cI_\gamma + aJ_\gamma)^2}{(I_\gamma + J_\gamma)^2}\Gamma^{SM}(H \to \gamma\gamma)$$

In SM a=1 and c=1

One of the motivation – Effective chiral Lagrangian from golografic viewpoint

Crojean et al 2012

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma)\left[1 + 2\,a\,\frac{h}{v}\right]$$
$$-\frac{v}{\sqrt{2}}\,(\bar{u}_L^i \bar{d}_L^i)\,\Sigma\left[1 + c\,\frac{h}{v}\right]\begin{pmatrix} y_{ij}^u\, u_R^j \\ y_{ij}^d\, d_R^j \end{pmatrix} + h.c. + \cdots$$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 \ldots$$
$$-\left(m_W^2\, W_\mu W_\mu + \frac{1}{2}m_Z^2\, Z_\mu Z_\mu\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right)$$
$$-\sum_{\psi=u,d,l} m_{\psi^{(i)}}\,\bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + c_{2\psi}\frac{h^2}{v^2} + \ldots\right)$$
$$+\frac{g^2}{16\pi^2}\left(c_{WW}\, W_{\mu\nu}^+ W_{\mu\nu}^- + c_{ZZ}\, Z_{\mu\nu}^2 + c_{Z\gamma}\, Z_{\mu\nu}\gamma_{\mu\nu}\right)\frac{h}{v} + \ldots$$
$$+\frac{g^2}{16\pi^2}\left[\gamma_{\mu\nu}^2\left(c_{\gamma\gamma}\frac{h}{v} + \ldots\right) + G_{\mu\nu}^2\left(c_{gg}\frac{h}{v} + c_{2gg}\frac{h^2}{v^2}\ldots\right)\right]$$
$$+\frac{g^2}{16\pi^2}\left[\frac{c_{hhgg}}{\Lambda^2}G_{\mu\nu}^2\frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2}G_{\mu\rho}G_{\rho\nu}\frac{\partial_\mu h\partial_\nu h}{v^2} + \ldots\right]$$
$$+\ \ldots$$

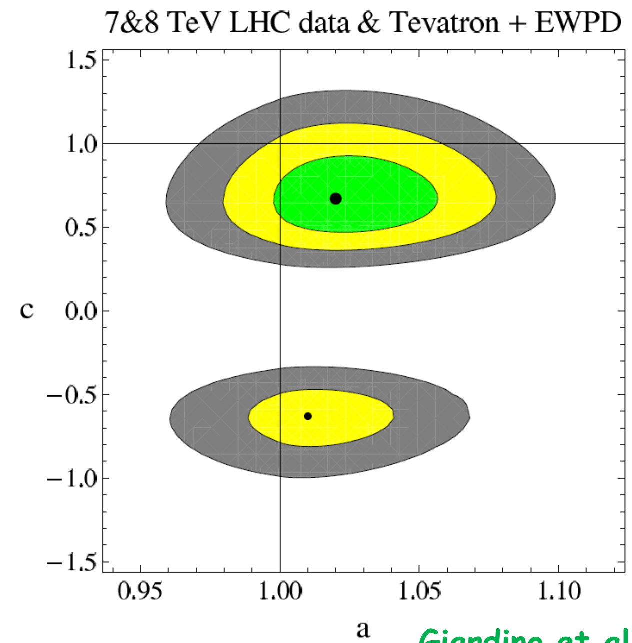
Higgs signal strength parameter:

$$\mu_i = \frac{[\sigma_{j\to h} \times \text{Br}(h \to i)]_{observed}}{[\sigma_{j\to h} \times \text{Br}(h \to i)]_{SM}}$$

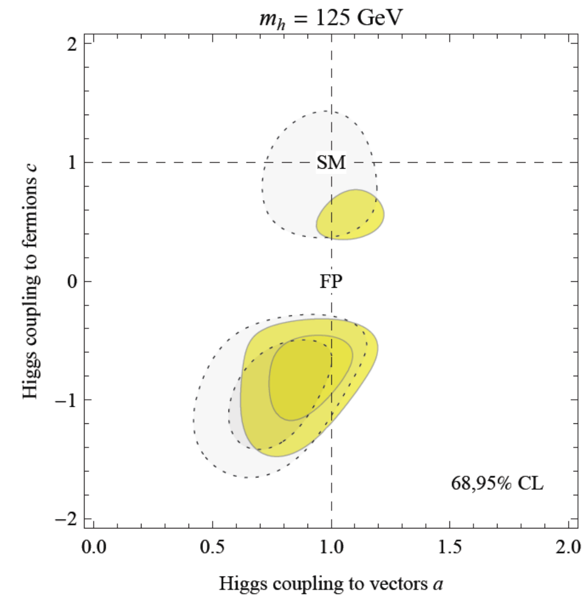
Global χ^2 fit

D0, CDF, CMS, ATLAS data

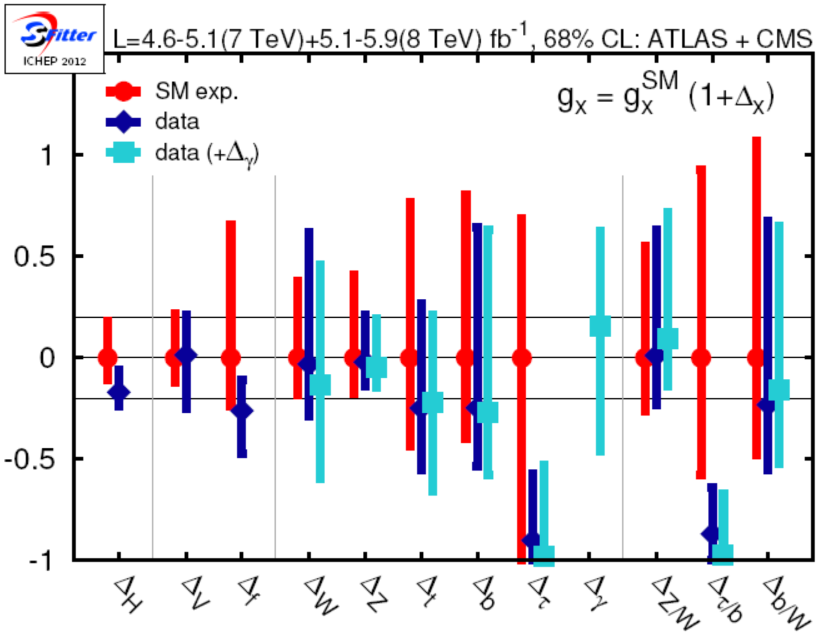
Espinosa et al 2012



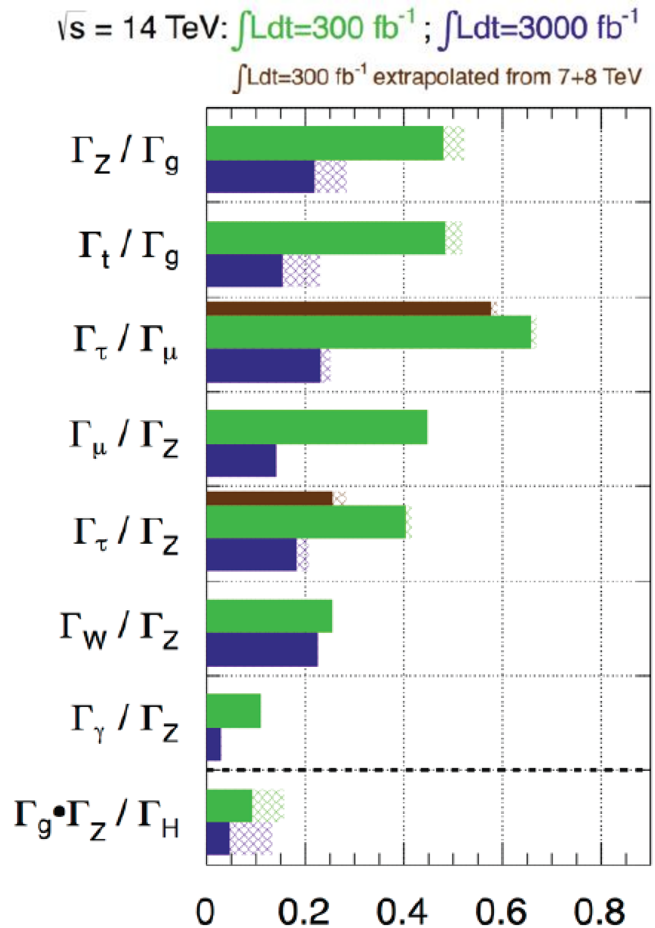
Giardino et al 2012



Plehn et al 2012



ATLAS



Expected uncertaities in CMS

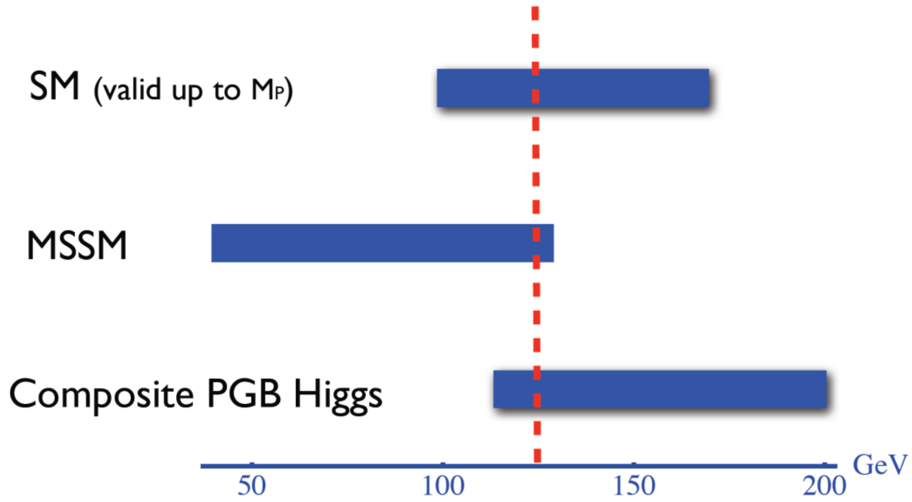
Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Main options beyond SM

1. Fundamental Higgs:
- Supersymmetric models
  (MSSM, NMSSM…)

2. Composite Higgs:
- Models with new strong dynamics
  (Chiral Lagrangians from holography, latest technicolor variants, Little Higgs…)

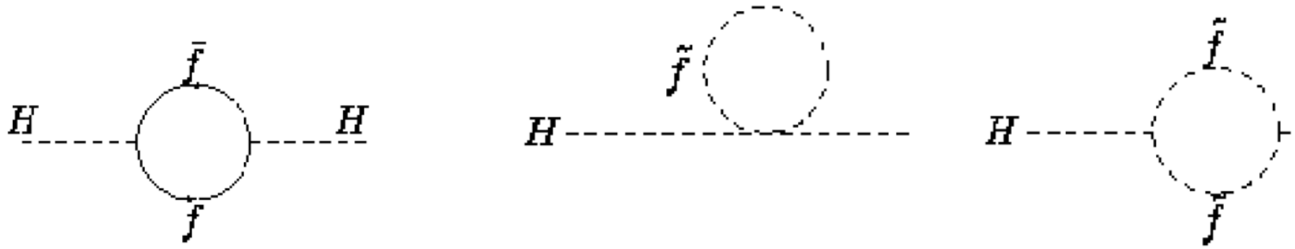
3. Mixed cases:
- Models with extra space dimensions
- Partially composite models…



Pomarol 2012

SUSY

1. Cancellation of Λ^2 dependence



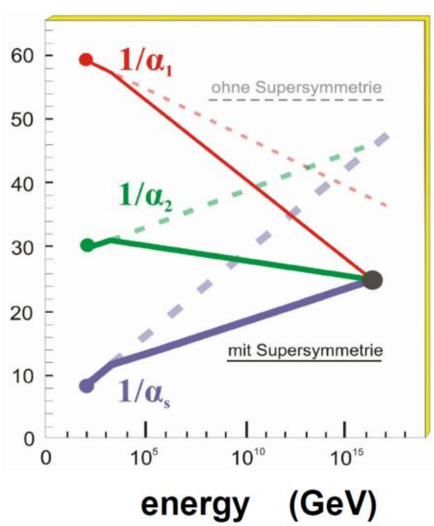
=>

$$\Delta M_H^2|^{tot} = \frac{\lambda_f^2 N_f}{4\pi^2}\left[(m_f^2 - m_S^2)\log\left(\frac{\Lambda}{m_S}\right) + 3m_f^2\log\left(\frac{m_S}{m_f}\right)\right]$$

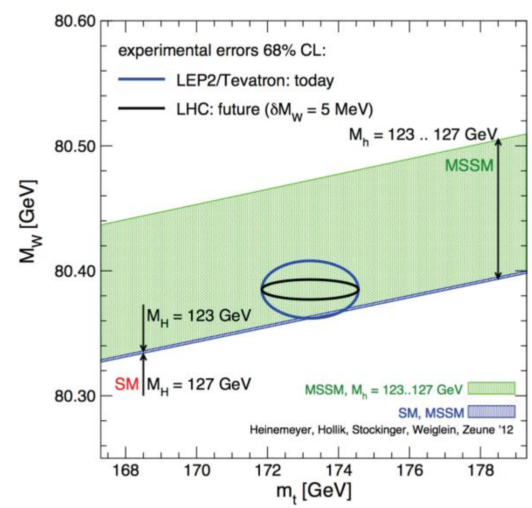
M_H is protected!

2. Lightest SUSY particle is stable (if R-parity) – very good Dark Matter candidate

3. Unification of couplings in contrast to SM



4. Fit of EW precision data



SUSY is one of the most attractive idea for BSM physics

SUSY, if exists, is broken, and there are
many possibilities:

Gravity mediation
Gauge madiation
Gaugino mediation
Anomaly mediation
Hidden sector mediation
…

Many models:
MSSM
CMSSM
mSUGRA
mGMSB
mAMSB
Split SUSY
…
NMSSM
Natural SUSY
…

In general the unconstrained MSSM has 105 parameters
(22 with reasonable assumptions)
(many parameter space points of mSUGRA scenario are rulled out already)

Concrete predictions depend strongly on MSSM breaking scenario.
There are no theory arguments to prefer some of them.

Many nice SUSY feaches are due to additional global symmetry-
R-parity. Tiny deviations of R-parity possible leading to processes
with FCNC, lepton/barion number violation, proton decay…
But what is an origin of R-parity?...

$$\mathbf{M_h^2 \leq M_Z^2 + \Delta m^2}$$

$(125\ \mathrm{GeV})^2$ $(91\ \mathrm{GeV})^2$ $(86\ \mathrm{GeV})^2$

susy breaking term (at one-loop)

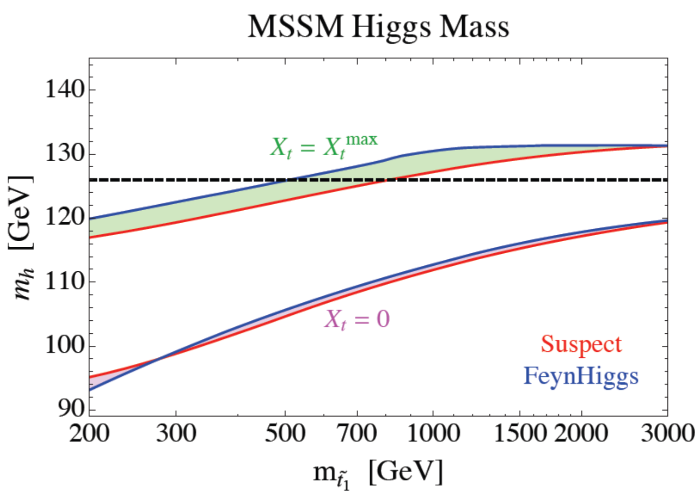
$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\mathrm{SUSY}}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\mathrm{SUSY}}^2}\left(1 - \frac{X_t^2}{12M_{\mathrm{SUSY}}^2}\right)\right]$$

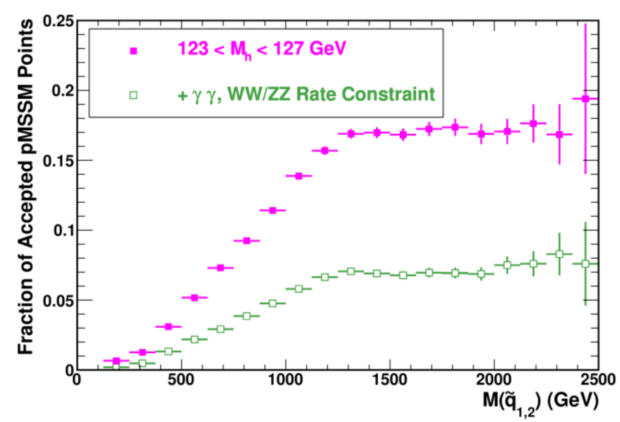
$$M_{\mathrm{SUSY}} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

Heavy stop is needed

Fine tuning:

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$





Mahmoudi et al 2012

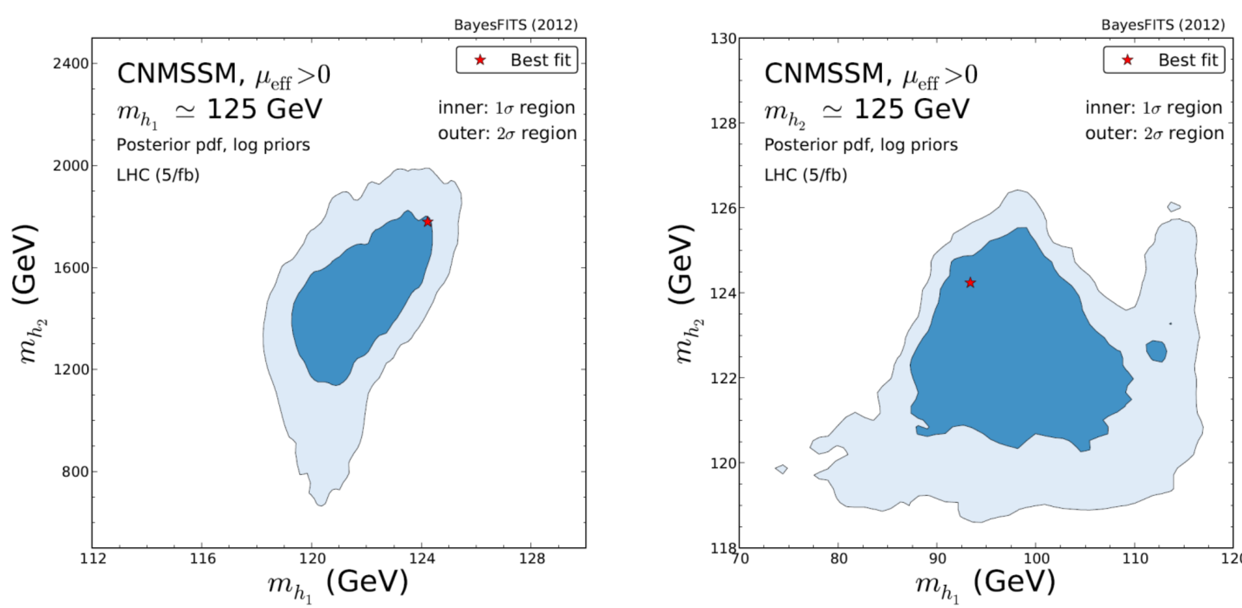
Many options for observed state in the NMSSM

Lightest Higgs   Mh 125 GeV   (most of studies)

Heavy Higgs   Mh 98 GeV, MH 125 GeV   (Drees 2012, Belanger et al 2012)

Denenerate Higgses   (Gunion et al 2012)

The aim is to make better overall χ^2 fit…



(Kowalska et al 2012)

A Higgs Impostor in Low-Scale Technicolor is a technipion

η_T $I^G J^{PC} = 0^+ 0^{-+}$

η_T mixes with 0 component of the isovector π_T^0 giving two physics states

η_L at 125 GeV and η_H in the range 170-190 GeV

$\gamma\gamma$-rate is OK, but ZZ* and WW* should be suppressed

Eichten, Lane, Martin 2012

Natural scale $\Lambda \sim 4\pi v$ with v=246 GeV

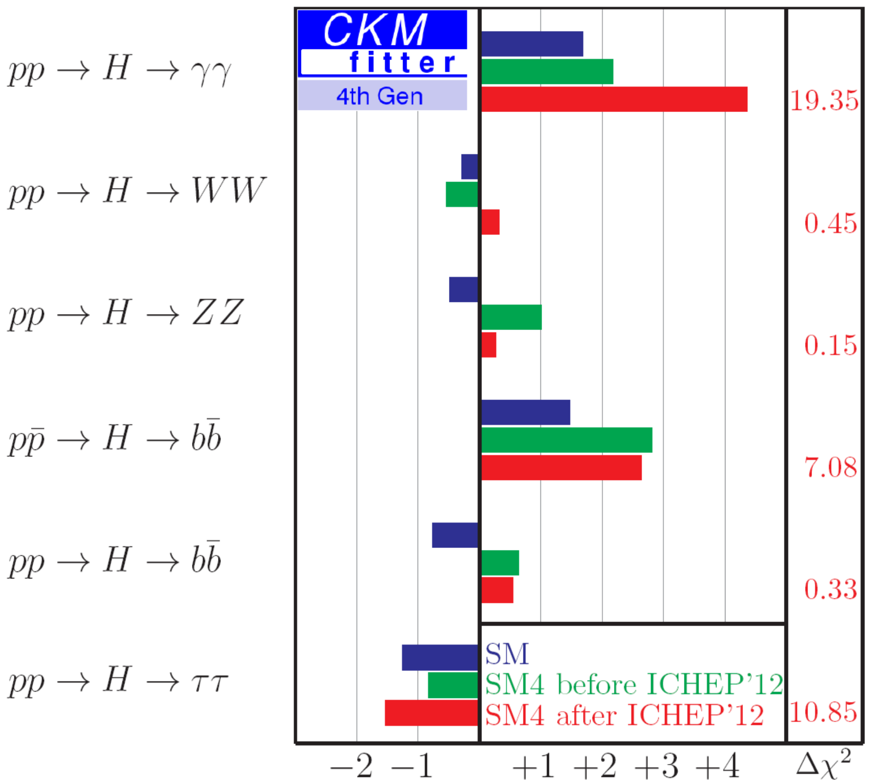
But the mass of the technicolor isosinglet scalar
(the technicolor Higgs) could be much reduced dynamically for large N_{TC}:

$$(M_H^0)^2 = \left[\frac{N_{\rm TC}}{3}\right]^p \frac{3}{N_{\rm TC}} \frac{1}{N_{\rm TD}} \frac{v^2}{f_\pi^2} m_\sigma^2$$

Foadi, Frandsen, Sannino 2012

4^{th} generation

Eberhardt, Herbert, Lacker 2012



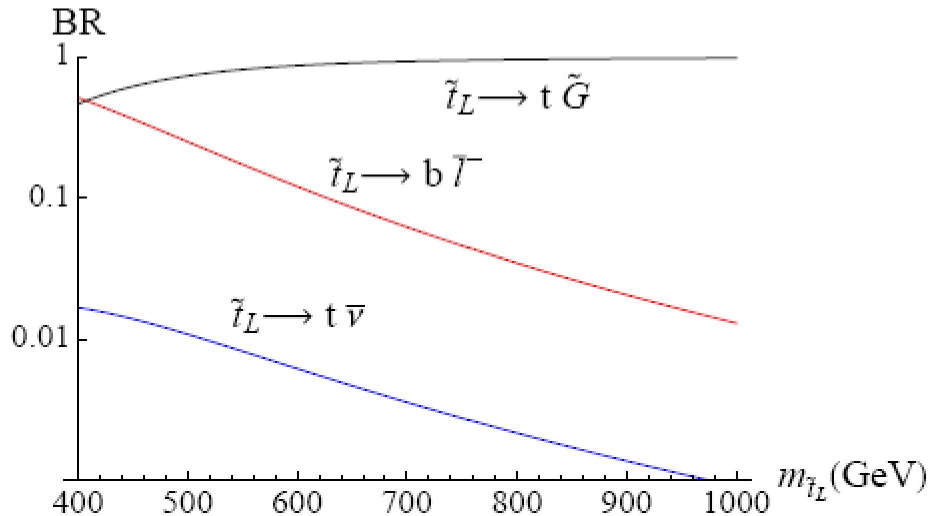
In the SM4 the measured H -> $\gamma\gamma$ signal strength disagrees with the best-fit prediction including all EWPD by more than four standard deviations

Is the 125 GeV Higgs the superpartner of a neutrino?

Riva, Biggio, Pomarol 19/11/12

Approximate R-symmetry acts as a lepton number

New signatures similar to letoquark searches



Conclusions

1. New Higgs-like state is found with very precise mass determination
   M_H = 126.0 ± 0.4 (stat) ± 0.4 (sys) ATLAS
   M_H = 125.3 ± 0.4 (stat) ± 0.5 (sys) CMS

2. The self-coupling is small ($\lambda \cong 0.12$) -> weakly-coupled theory

3. Higgs-like states with the SM signal strength (even about 2 times lager) are excluded up to ~600 GeV

4. Measurements in all channels are compatible with the SM expectations computed for the SM Higgs couplings.
   However, bb-mode is only observed at the Tevatron, $\tau\tau$-mode is not observed

$$\hat{\mu} \equiv \frac{\sigma(pp \to h)_{obs}}{\sigma(pp \to h)_{SM}} = 1.4 \pm 0.3 \text{ (ATLAS)},\ 0.87 \pm 0.23 \text{ (CMS)},$$

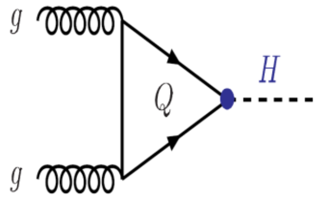
$$R_{\gamma\gamma} \equiv \hat{\mu}\frac{\Gamma(h \to \gamma\gamma)_{obs}}{\Gamma(h \to \gamma\gamma))_{SM}} = 1.8 \pm 0.5 \text{ (ATLAS)},\ 1.6 \pm 0.4 \text{ (CMS)}$$

6. Non of the BSM extensions are excluded completely, however possible parameter spaces for various SUSY, composite, extra dimensional scenarios are much constrained. Enormous number of interpretations is proposed.

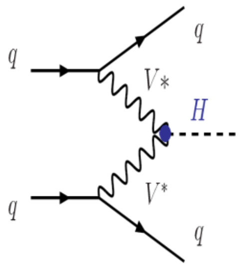
7. Further more precise measurements of production/decay properties and quantum numbers, searches for other Higgs (not SM like) states, and theoretical studies are needed

Many thanks to the organizers!

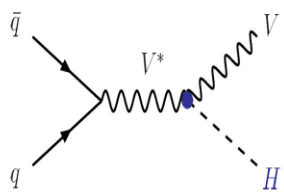
Back up slides



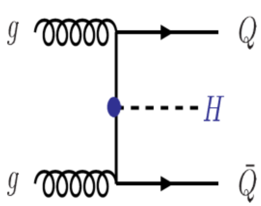
$H \to \gamma\gamma$, γZ (γl^+l^-), ZZ^* (4l), WW^* ($ll\nu\nu$)



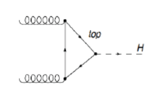
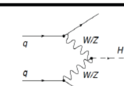
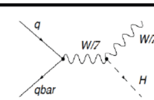
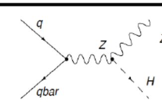
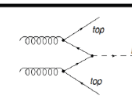
$H \to WW^*$ ($ll\nu\nu$), ZZ^* (4l), $\tau^+\tau^-$



$H \to bb$



$H \to bb$, $\tau^+\tau^-$

Process	Diagram	Cross section [fb]	Unc. [%]
gluon-gluon fusion		19520	15
vector boson fusion		1578	3
WH		697	4
ZH		394	5
ttH		130	15