Implications of the H boson discovery

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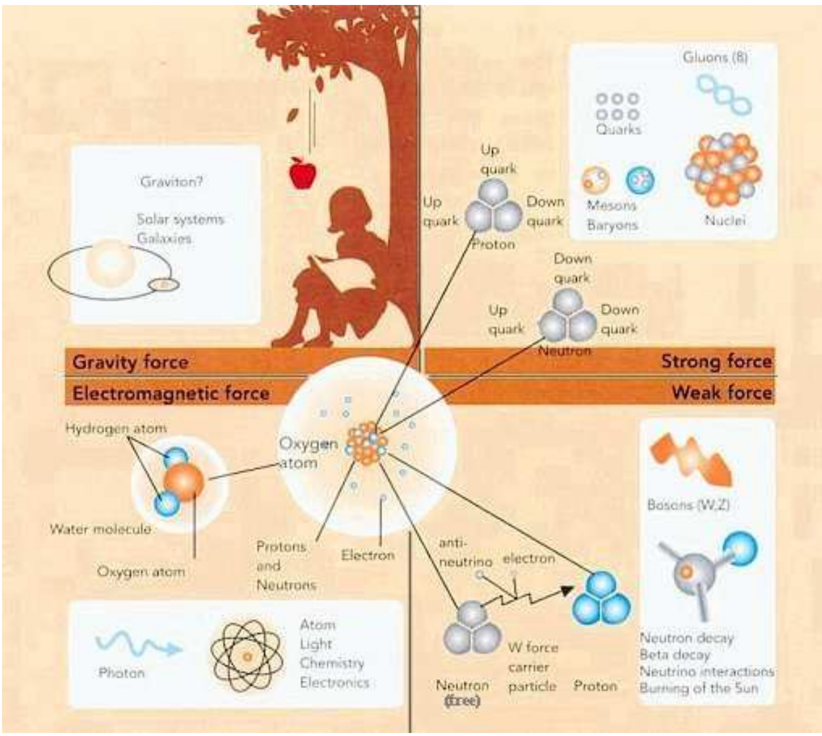
1. The Standard Model and the H boson
2. First, is it really a scalar H boson?
3. Implications of the discovery for the SM
4. Beyond the Standard Model
5. Implications for Supersymmetry
6. What next?

1. The Standard Model and the H boson

We have a theory, the Standard Model, which describes microscopic world:

3 fundamental interactions in Nature (not including the gravitational force):

interactions of $s=\frac{1}{2}$ matter particles via exchange of $s=1$ force particles.



Properties of the Interactions

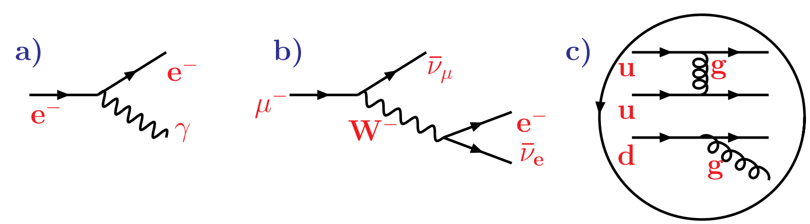
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Particules de: matière (s=1/2) — 3 familles de fermions; force (s=1) — bosons-jauge

(c→ couleur, Q→ charge, m→ masse)

	quark up: ^{3}u, $+2/3$, $\sim$5 MeV	quark charm: ^{3}c, $+2/3$, 1.6 GeV	quark top: ^{3}t, $+2/3$, 172 GeV	gluon: ^{8}g, 0, 0
	quark down: ^{3}d, $-1/3$, $\sim$5 MeV	quark strange: ^{3}s, $-1/3$, 0.2 GeV	quark bottom: ^{3}b, $-1/3$, 4.9 GeV	photon: γ, 0, 0
	neutrino e: ν_e, 0, ~ 0	neutrino μ: ν_μ, 0, ~ 0	τ neutrino: ν_τ, 0, ~ 0	boson Z: Z^0, 0, 91.2 GeV
	electron: e, -1, 0.5 MeV	muon: μ, -1, 0.1 GeV	tau: τ, -1, 1.7 GeV	bosons W: $W^\pm$, ±1, 80.4 GeV



1. The Standard Model and the H boson

The Standard Model of the electromagnetic, weak and strong forces:

- relativistic quantum field theory: quantum mechanics+special relativity,
- based on gauge symmetry: invariance under internal symmetry group,
- a carbon–copy of QED, the quantum field theory of electromagnetism.

Standard Model based on $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry.

- The symmetry group $SU(3)_C$ describes the strong interaction:
  - strong interaction between q, q , q which are SU(3) color triplets,
  - mediated by 8 gluons, corresponding to the 8 generators of SU(3).
- $SU(2)_L \times U(1)_Y$ is for a unified electromagnetic+weak interaction:
  - acts on left (doublets) and right (singlets) handed quarks/leptons,

$$\binom{\nu}{e}_L, \; e_R^-, \; \binom{u}{d}_L, \; u_R, \; d_R, \; \cdots$$

  - mediated by the photon γ and the weak W^+, W^-, Z gauge bosons.

Problem: while the photon is massless, the weak bosons are massive.

Naive M_V and m_f spoils gauge invariance and good SM properties.

Major problem in HEP: how to generate masses in a gauge-invariant way?

$\Rightarrow$ **The Brout-Englert-Higgs mechanism for electroweak symmetry breaking!**

1. The Standard Model and the H boson

Introduce an SU(2) doublet of complex scalar fields $\Phi = \binom{\Phi^+}{\Phi^0}$: 4 d.o.f.
with scalar potential $V_S = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$ with a mass term $\mu^2 < 0$.

The fields and their interactions are still symmetric under SU(2)$\times$U(1)
but, as the minimum of V_S is not at $\langle 0|\Phi^0|0\rangle = 0$, the vaccum is not!

The field Φ develops a non–zero vev

$\langle 0|\Phi^0|0\rangle = v = \sqrt{\frac{-\mu^2}{\lambda^2}}$ ($= 246$ GeV)

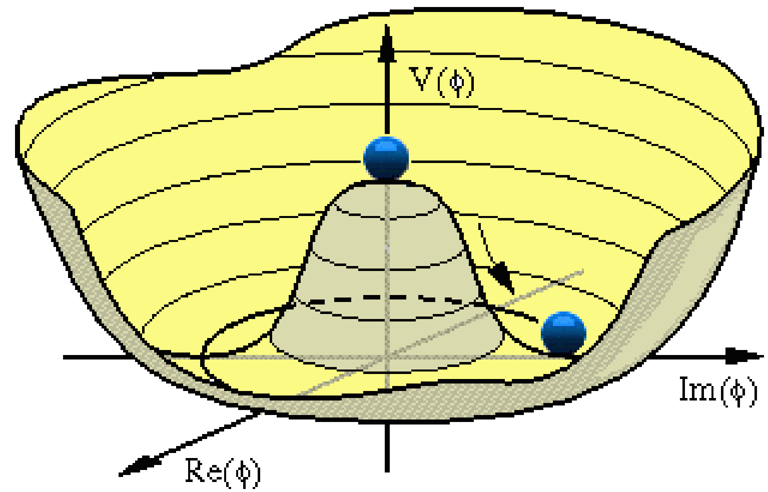
hence vacuum SU(2)xU(1) asymmetric.

Spontaneous EW symmetry breaking.

$\Rightarrow$ three d.o.f. to make $M_{W^\pm}$ and M_Z.

Interaction of fermions with same Φ:

$\Rightarrow$ fermions masses m_f also generated.



Residual d.o.f corresponds to spin–0 H boson: a new type of particle!

- Unique particle: spin zero, not matter particle and not force particle,
- couples to all particles $\propto$ their masses: $g_{Hff} \propto m_f$, $g_{HVV} \propto M_V$,
- couples to itself, $g_{HHH} \propto M_H^2$ with the relation $M_H^2 = 2\lambda v^2$.

Since v is known, the only free parameter in the SM is M_H (or λ).

1. The Standard Model and the H boson

Pré–LHC constraints on the SM scalar sector and on the H boson mass:

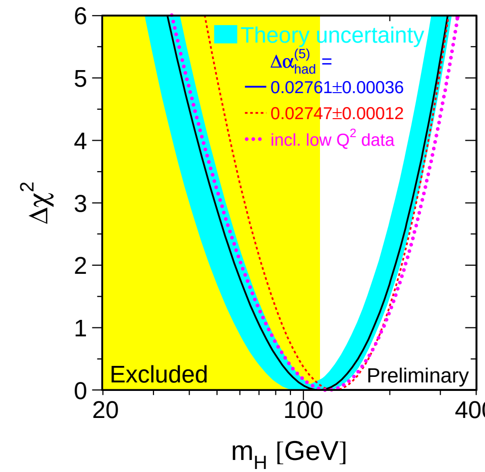
- **Experimental constraints:**

– indirect from global fit of EW precision data:

$M_H = 92^{+34}_{-26}$ GeV $\Rightarrow$ $M_H \lesssim 160$ GeV@95% CL

– Direct searches at LEP and the Tevatron:

$M_H > 114$ GeV@95%CL and $\neq 160-175$ GeV

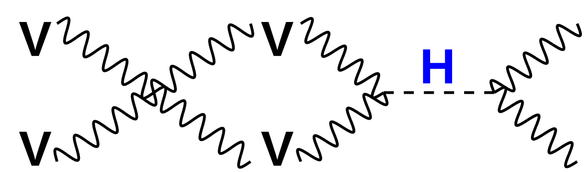


- **Constraints from unitarity at high energies:**

without Higgs: $|A_0(vv \to vv)| \propto E^2/v^2$

including H with couplings as predicted:

$|A_0| \propto M_H^2 \Rightarrow$ theory unitary if $M_H \lesssim 700$ GeV



- **From triviality+stability@high-scale:**

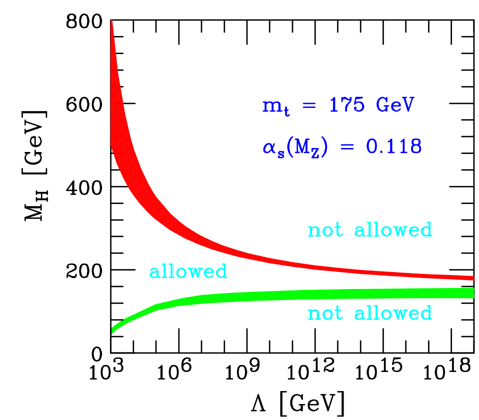
coupling $\lambda = 2M_H^2/v$ evolves with energy

– M_H too large: coupling non perturbative

– M_H too small: stability of the EW vaccum

$\Lambda_C \approx 1$ TeV $\Rightarrow 70 \lesssim M_H \lesssim 700$GeV

$\Lambda_C \approx M_{Pl} \Rightarrow 130 \lesssim M_H \lesssim 180$ GeV



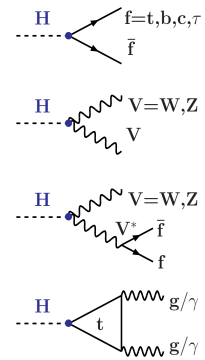
1. The Standard Model and the H boson

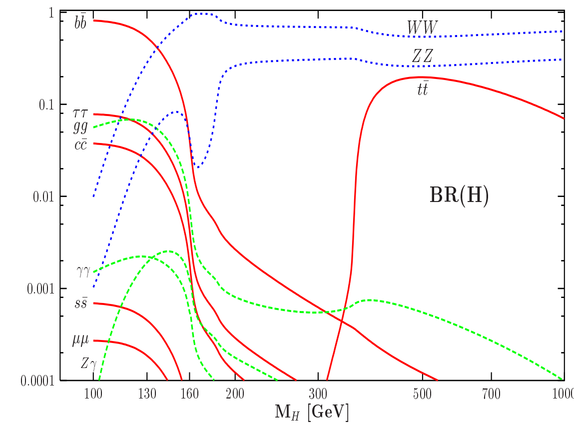
Once M_H known, all the properties of the H boson are fixed in the SM,
and to produce and detect it, take advantage of the fact that $g_{HPP} \propto m_P$.

H boson decays in the SM:

(for $M_H \approx 125$ GeV)

- $H \to b\bar{b}, WW$: dominant
- $H \to cc, \tau\tau, gg = \mathcal{O}(\text{few }\%)$
- $H \to \gamma\gamma, ZZ^* \to 4\ell^{\pm} \propto 10^{-3}$





H production at the LHC:

$gg \to H$ by far dominant.

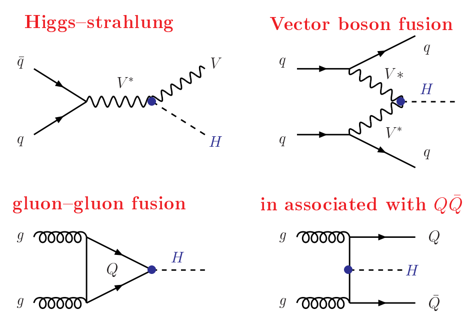
$gg \to H \to \gamma\gamma$

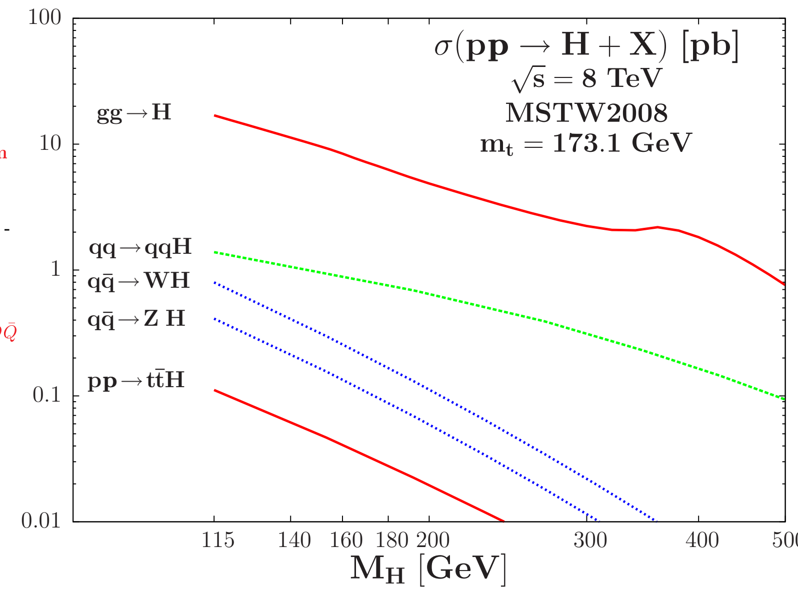
$gg \to H \to ZZ \to 4\ell$

$gg \to H \to WW \to \ell\nu\ell\nu$

also some help from:

$HX \to X\tau\tau$, $HV \to b\bar{b}\ell X$

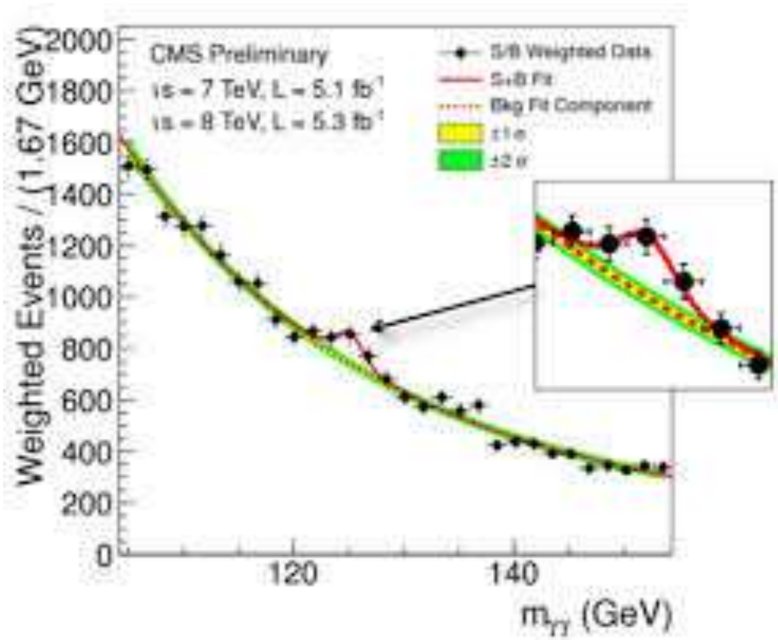


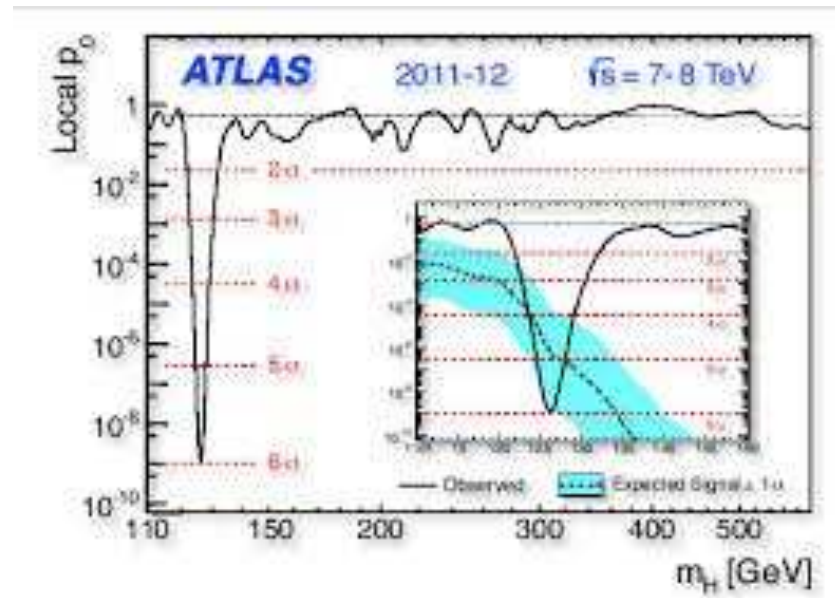


Gigantic theoretical+experimental effort: more than 30 years of hard work to make sure that the H boson will not espace detection at the LHC!

2. First, is it really a scalar H boson?

... a challenge met the 4th of July 2012: a historical day!





2. First, is it really a scalar H boson?

First let's check it is indeed an H boson.

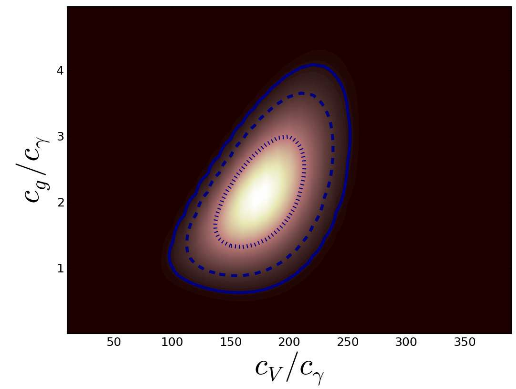
Spin: the new state decays into $\gamma\gamma$

- not spin-1 state: Landau–Yang
- could be spin–2 like graviton? Ellis et al.

– miracle that couplings fit that of H,

– "prima facie" evidence against it:

$$\text{e.g.: } c_g \neq c_\gamma, c_V \gg 35 c_\gamma$$



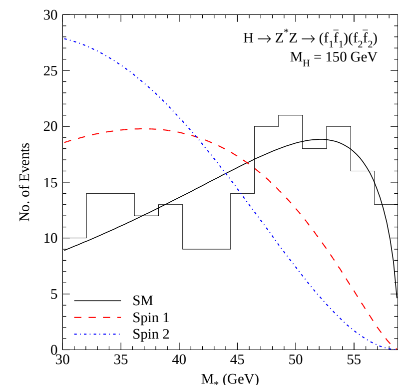
many th. analyses (no suspense...)

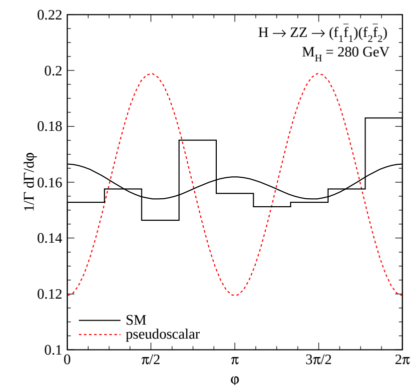
CP no: even, odd, or mixture?

(more important; CPV in H sector!)

ATLAS and CMS CP analyses for

pure CP–even vs pure–CP–odd

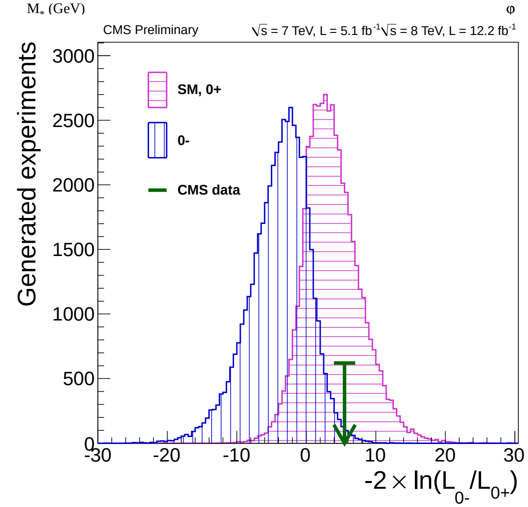




$$\mathrm{HV}_\mu \mathrm{V}^\mu \text{ versus } \mathrm{H}\epsilon^{\mu\nu\rho\sigma}\mathrm{Z}_{\mu\nu}\mathrm{Z}_{\rho\sigma}$$

$$\Rightarrow \frac{d\Gamma(H\to ZZ^*)}{dM_*} \text{ and } \frac{d\Gamma(H\to ZZ)}{d\phi}$$

MELA $\approx 3\sigma$ for CP-even..



2. First, is it really a scalar H boson?

There are however some problems with this (too simple) picture:

– a pure CP odd scalar does not couple to VV states at tree–level,

– coupling should be generated by loops or HOEF: should be small,

– H CP–even with small CP–odd admixture: high precision measurement,

– in H$\to$VV only CP–even component projected out in most cases!

Indirect probe: through $\hat{\mu}_{\rm VV}$

$g_{\rm HVV} = c_{\rm V} g_{\mu\nu}$ with $c_{\rm V} \leq 1$

better probe: $\hat{\mu}_{\rm ZZ} = 1.1 \pm 0.4!$

gives upper bound on CP mixture:

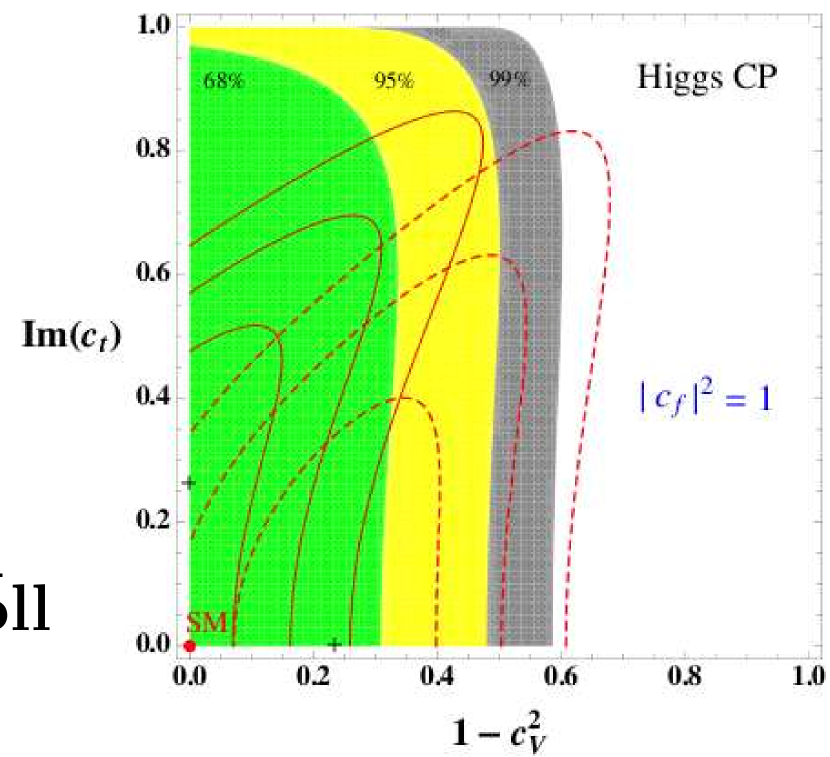
$\eta_{\rm CP} \equiv 1 - c_{\rm V}^2 \gtrsim 0.5 @ 68\% {\rm CL}$

Direct probe: $g_{\rm Hff}$ more democratic

$\Rightarrow$ processes with fermion decays.

spin-corelations in $q\bar{q} \to {\rm HZ} \to b\bar{b}ll$

or later in $q\bar{q}/gg \to {\rm Ht\bar{t}} \to b\bar{b}t\bar{t}$.



Extremely challenging even at HL-LHC... Moreau...

2. First, is it really a scalar H boson?

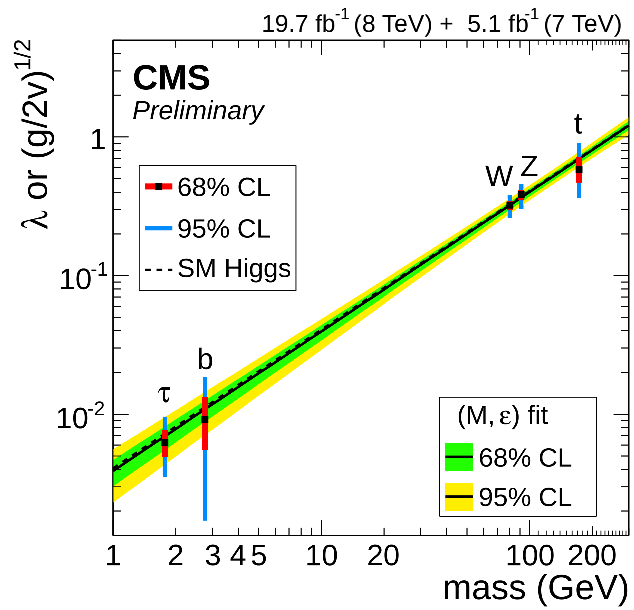
$\sigma\times$ **BR rates compatible with those expected in the SM.**

Fit of all LHC Higgs data $\Rightarrow$
$\hat{\mu}^{\rm signal}_{\rm strength}$ **=observed/SM: agreement at 20–30% level.**

$\hat{\mu}^{\rm ATLAS}_{\rm tot} = 1.30 \pm 0.30$

$\hat{\mu}^{\rm CMS}_{\rm tot} = 1.01 \pm 0.30$

$\text{combined}: \hat{\mu}_{\rm tot} \simeq 1!$



H boson couplings to elementary particles as predicted by BEH mechanism

- **couplings to WW,ZZ,$\gamma\gamma$ roughly as expected for a CP-even scalar,**
- **couplings proportional to masses as expected for the H boson.**

So, it is not only a “new particle”, the “125 GeV boson”, a “new state”...

IT IS A HIGGS BOSON!

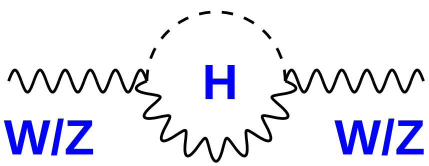
But is it THE SM H boson or AN H boson from some extension?

For the moment, it looks damn SM–like... What are the implications?

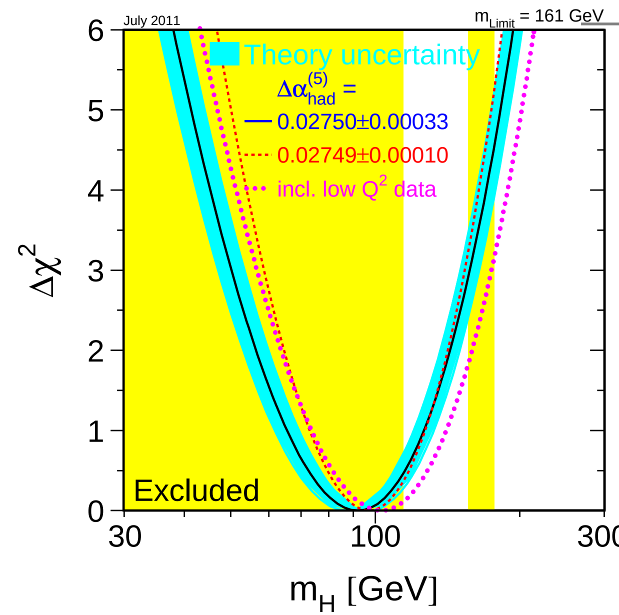
3. Implications of the discovery for the SM

The observation of the new state is a triumph for high-energy physics!

Indeed, constraints from EW data: H contributes to the W/Z masses through tiny quantum fluctuations

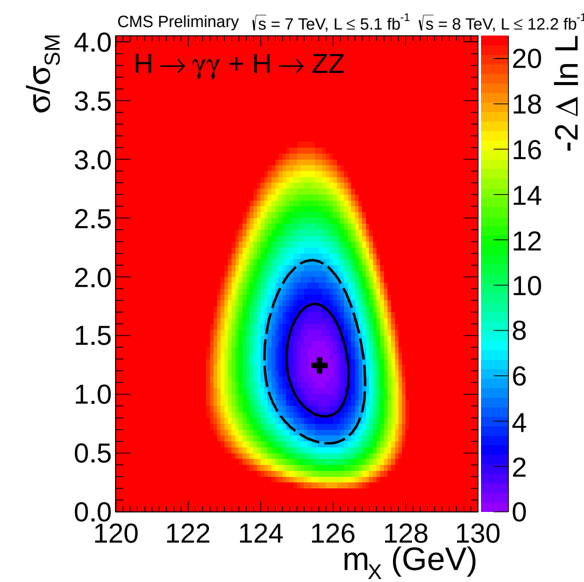


$$\propto \frac{\alpha}{\pi} \log \frac{M_H}{M_W} + \cdots$$



Fit the EW ($\lesssim$ 0.1%) precision data, with all other SM parameters known, one obtains $M_H = 92^{+34}_{-26}$ GeV, or

$M_H \lesssim 160$ GeV at 95% CL



We make an experiment and measure

$M_H = 125$ GeV

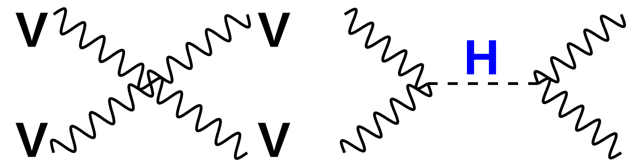
A very non–trivial check of the SM: test at the quantum/permille level!

3. Implications of the discovery for the SM

- For theory to preserve unitarity:

we need Higgs with $M_H \lesssim 700$ GeV...

We have a Higgs and it is light: OK!



- Extrapolable up to highest scales.

$\lambda = 2M_H^2/v$ evolves with energy

– too high: non perturbativity

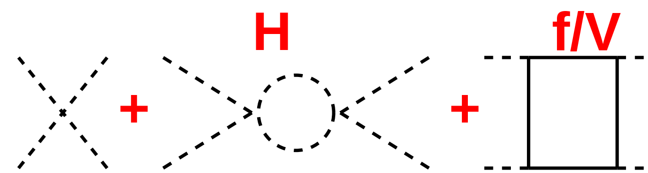
– too low: stability of the EW vacuum

$$\frac{\lambda(Q^2)}{\lambda(v^2)} \approx 1 + 3\,\frac{2M_W^4 + M_Z^4 - 4m_t^4}{16\pi^2 v^4} \log\frac{Q^2}{v^2}$$

$\lambda \geq @M_{Pl} \Rightarrow M_H \gtrsim 129\,\mathrm{GeV}!$

at 2loops for $m_t^{pole} = 173$ GeV.....

$\Rightarrow$ Degrassi et al., Bezrukov et al.

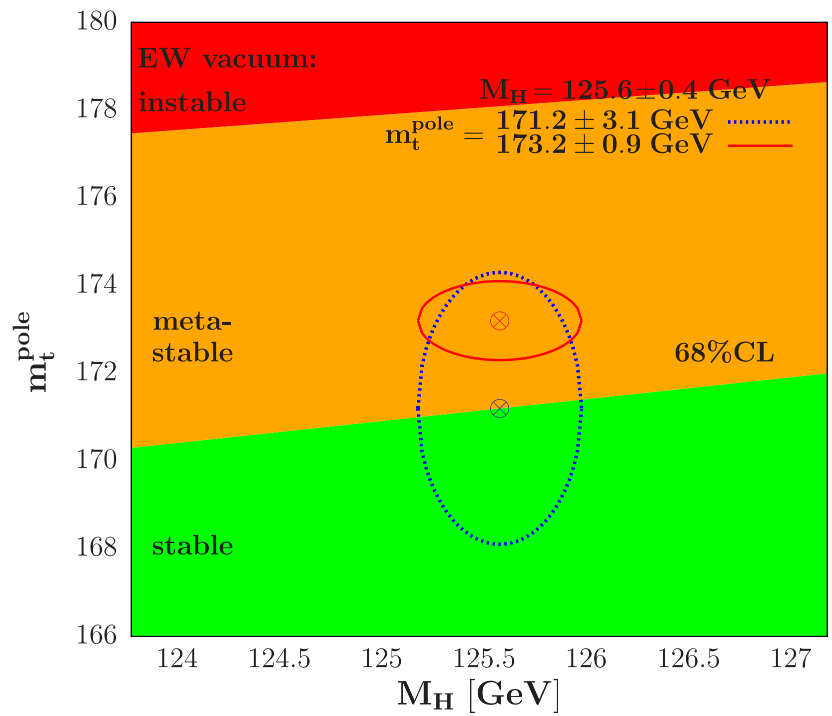


but what is measured m_t at TEV/LHC

$m_t^{pole}?m_t^{MC}?$ not clear; much better:

$m_t = 171 \pm 3$GeV from $\sigma(pp \to t\bar{t})$

issue needs further studies/checks...



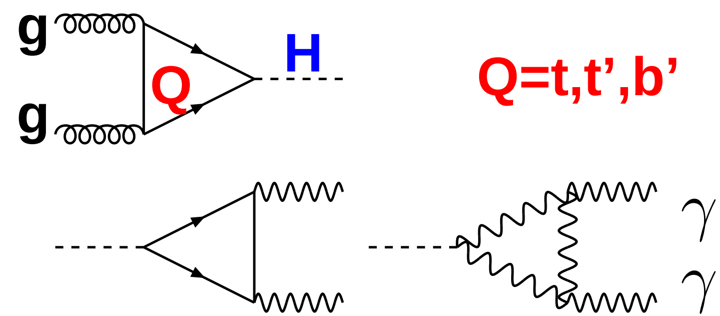
Alekhin....

3. Implications of the discovery for the SM

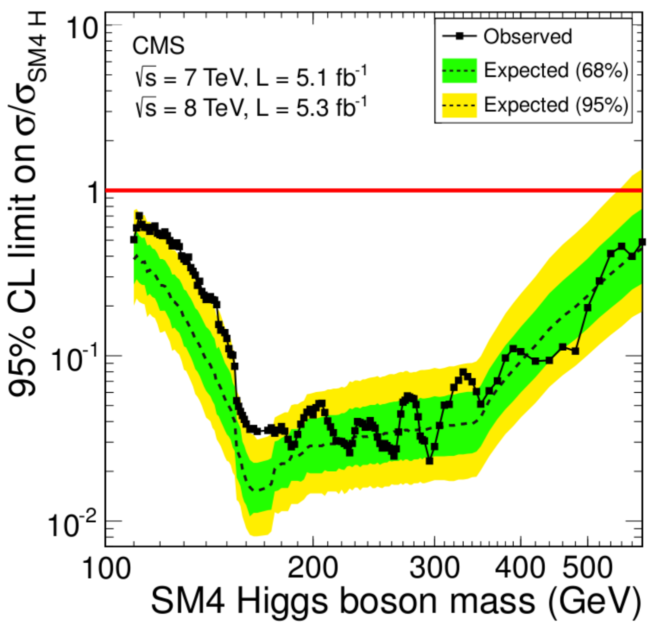
Particle spectrum looks complete: no room for 4th fermion generation!

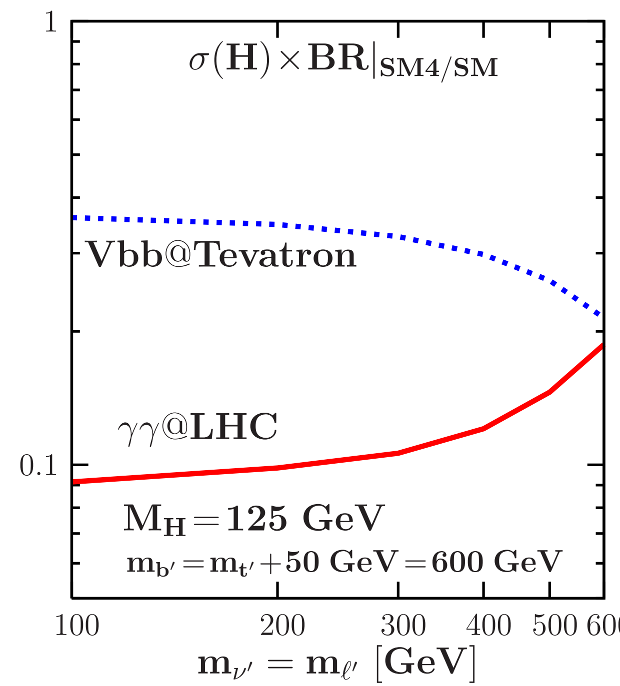
Indeed, an extra doublet of quarks and leptons (with heavy ν') would:

- increase $\sigma(\mathrm{gg}\to \mathrm{H})$ by factor ≈ 9
- H$\to$gg suppresses BR(bb,VV) by $\approx$2
- strongly suppresses $\mathrm{BR}(\mathrm{H}\to\gamma\gamma)$



NLO $\mathcal{O}(\mathrm{G_F m^2_{F'}})$ effects very important:





(Direct seach also constraining..) **Lenz....**

3. Implications of the discovery for the SM

Thus we have a theory for the strong+electroweak forces, the SM, that is:

- a relativistic quantum field theory based on a gauge symmetry,
- renormalisable as proved by ’t Hooft and Veltman for SEWSB,
- unitary as we have now a Higgs and its mass is rather small,
- perturbative up to the Planck scale as again the Higgs is light,
- leads to a (meta)stable electroweak vacuum up to high scales,
- compatible with (almost) all precision data available to date...

Is it the theory of eveything and should we be satisfied with it? No:

The SM can only be a low energy manifestation of a more fundamental theory!

Indeed, the SM has the following problems which need to be cured:

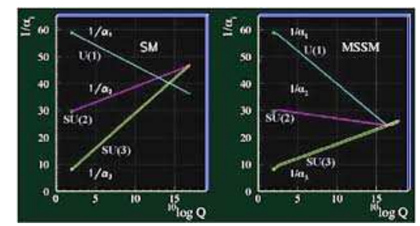
- “Esthetical” problems with multiple and arbitrary parameters.
- “Experimental” problems as it does not explain all seen phenomena.
- ”A theory consistency” problem: the hierarchy/naturalness problem.

All indicate that there is beyond the Standard Model physics.

4. Beyond the Standard Model

There are major theoretical and experimental problems in the SM:

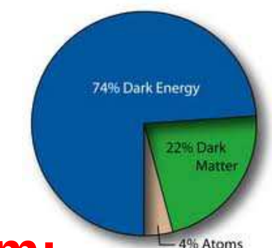
- does not explain why $\mu^2 < 0$ and has too many (19!) free parameters.
- does not incorporate the fourth fundamental interaction, gravity;
- does not incorporate masses for the neutrinos (there is no ν_R in SM);
- does not explain baryon asymmetry (baryogenesis?) in the universe;



- **No real unification of the interactions:**

– $3 \neq$ gauge groups with $3 \neq$ couplings,

– no meeting of the couplings in SU(5).



- **No solution to the Dark Matter problem:**

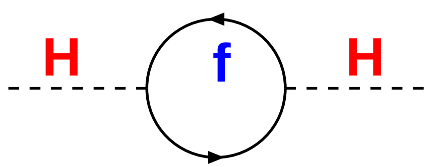
– 25% of the universe made by Dark Matter,

– no stable, neutral, weak, massive particle.

- **Above all: there is the hierarchy or naturalness problem:**

radiative corrections to M_H in SM with a cut–off $\Lambda = M_{NP} \approx M_P$

$$\Delta M_H^2 \equiv$$



$$\propto \Lambda^2 \approx (10^{18}\ \mathrm{GeV})^2!$$

M_H prefers to be close to the high scale than to the EWSB scale...

4. Beyond the Standard Model

Three main avenues for solving the hierarchy or naturalness problems (stabilising the Higgs mass against high scales) have been proposed.

I. Compositeness/substructure:

there is yet another layer in structure!

All particles are not elementary ones.

Technicolor: as QCD but at TeV scale.

$\Rightarrow$ H bound state of two fermions

(no more spin–0 fundamental state).

$\Rightarrow$ H properties $\neq$ from of SM Higgs.

II. Extra space–time dimensions

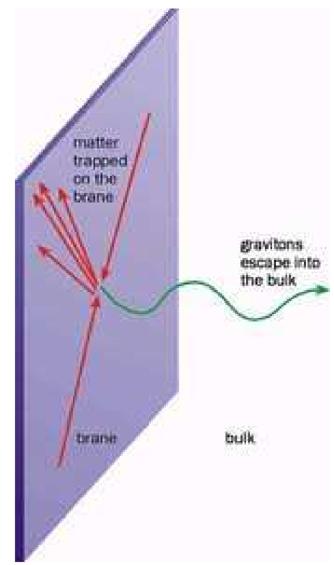
where at least s=2 gravitons propagate.

Gravity: effective scale $\mathrm{M_P^{eff}} \approx \Lambda \approx$ TeV

(and is now $\approx$ included in the game...).

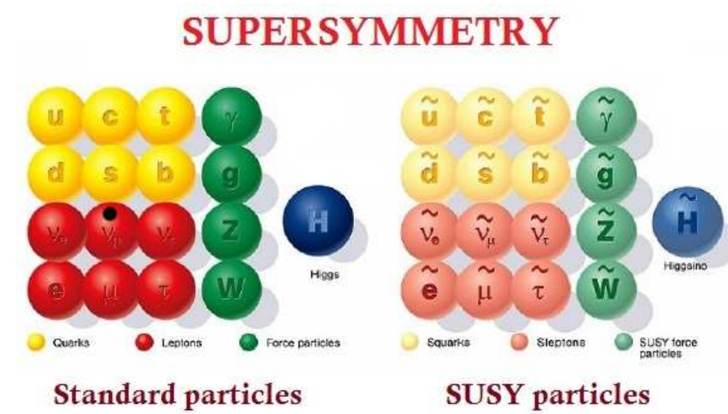
EWSB mechanism needed in addition:

- same Higgs mechanism as in SM,
- but possibility of Higgsless mode!



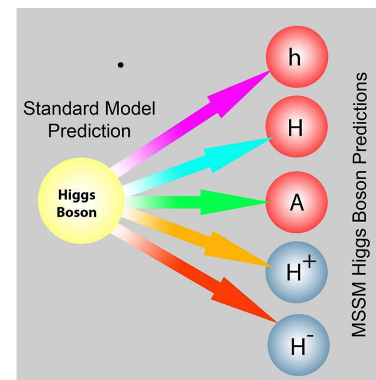
4. Beyond the Standard Model

III. Supersymmetry: doubling the world.



- **SUSY = most attractive SM extension:**

– links s=$\frac{1}{2}$ fermions to s=1 bosons,
– links internal/space-time symmetries,
– if made local, provides link to gravity,
– naturally present in string theory (toe),
– natural $\mu^2 < 0$: radiative EWSB,
– fixes gauge coupling unification pb,
– has ideal candidate for Dark Matter...



- **Needs two scalar doublets for proper and consistent EWSB in the MSSM:**

$\Rightarrow$ extended Higgs sector: $\mathrm{h, H, A, H^+, H^-}$ with $\mathrm{h \oplus H \approx H_{SM}}$,
– SUSY $\Rightarrow$ only two basic inputs at tree-level: $\tan\beta = \mathrm{v_2/v_1}, \mathrm{M_A}$,
– SUSY $\Rightarrow$ hierarchical spectrum: $\mathrm{M_h \approx M_Z}$; $\mathrm{M_H \approx M_A \approx M_{H^\pm}}$.
(SUSY scale $\mathrm{M_S}$ pushes $\mathrm{M_h}$ to 130 GeV via radiative corrections).

- **Most often decoupling regime: $\mathrm{h \equiv H_{SM}}$, others decouple from W/Z.**

4. Beyond the Standard Model

... and along the avenues, many possible streets, paths, corners ...

Just for EWSB, there are dozens of possibilities for the Higgs sector.

Which scenario is chosen by Nature? The LHC gave a first answer!

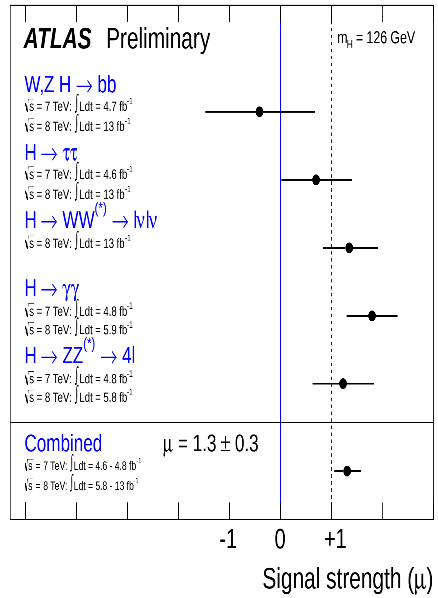
4. Beyond the Standard Model

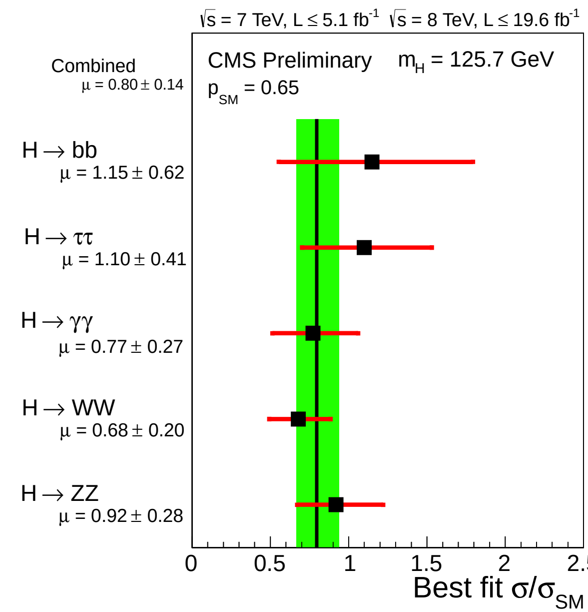
A) We observe a Higgs boson with a mass of 125 GeV and no other Higgs:

$\sigma\times$BR rates compatible with those expected in the SM

Fit of all LHC Higgs data $\Rightarrow$ agreement at 20–30% level

$$\mu_{\rm tot}^{\rm ATL} = 1.30 \pm 0.30$$
$$\mu_{\rm tot}^{\rm CMS} = 1.01 \pm 0.30$$
$$\text{combined}: \mu_{\rm tot} \approx 1!$$





B) We do not observe any new particle beyond those of SM with Higgs:

profound implications for the most discussed BSM scenarios; they are in:

- **“Mortuary”: Higgsless models, 4th generation, fermio or gauge-phobic.**
- **“Hospital”: Technicolor, composite models, ...**
- **“Trouble” and strongly constrained: extra-dimensions, Supersymmetry,**

Here, I discuss the example of Supersymmetry and the MSSM.

5. Implications for Supersymmetry

In the MSSM we need two Higgs doublets $H_1 = \binom{H_1^0}{H_1^-}$ and $H_2 = \binom{H_2^+}{H_2^0}$,
to generate up/down-type fermion masses while having chiral anomalies.
after EWSB, three dof for $W_L^\pm, Z_L \Rightarrow$ 5 physical states: $h, H, A, H^\pm$.
Only two free parameters at tree-level to describe the system $\tan\beta, M_A$:

$$M_{h,H}^2 = \frac{1}{2}\left\{M_A^2 + M_Z^2 \mp \left[(M_A^2+M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta\right]^{1/2}\right\}$$

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

$$\tan 2\alpha = \frac{-(M_A^2+M_Z^2)\sin 2\beta}{(M_Z^2-M_A^2)\cos 2\beta} = \tan 2\beta \, \frac{M_A^2+M_Z^2}{M_A^2-M_Z^2} \quad \left(-\frac{\pi}{2} \leq \alpha \leq 0\right)$$

$$M_h \lesssim M_Z|\cos 2\beta| + RC \lesssim 130 \text{ GeV}\ ,\ M_H \approx M_A \approx M_{H^\pm} \lesssim M_{EWSB}.$$

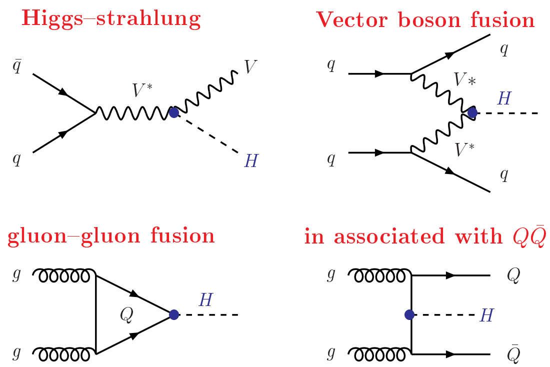
- Couplings of h, H to VV are suppressed; no AVV couplings (CP).
- For $\tan\beta \gg 1$: couplings to b (t) quarks enhanced (suppressed).

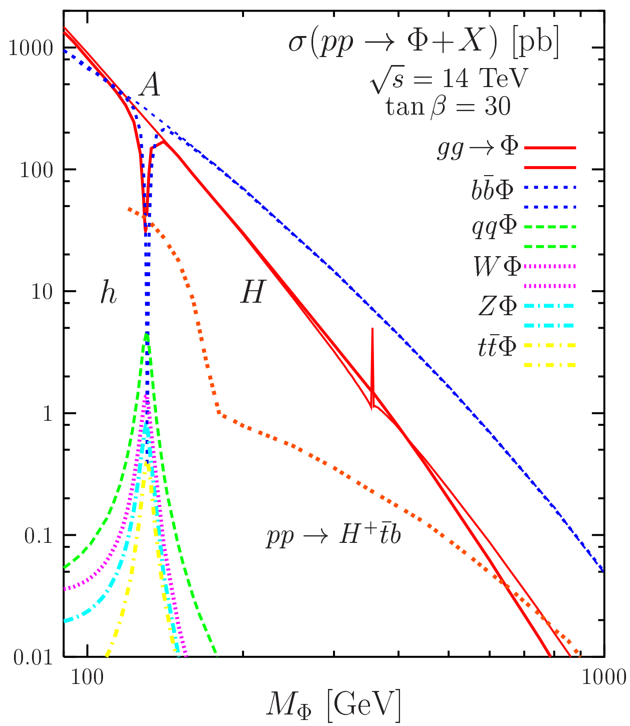
Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$	0

In decoupling limit: MSSM Higgs sector reduces to SM with a light h.

5. Implications for Supersymmetry

Production/decay phenomenology more complicated in the MSSM.





- **More Higgs particles: $\Phi = \mathrm{h}, \mathrm{H}, \mathrm{A}, \mathrm{H}^\pm$:**

– some couple almost like the SM Higgs,

– but some are more weakly coupled.

- **In general same production as in SM but also new/more complicated processes (rates can be smaller or larger than in SM).**
- **Possibly many different decay modes, (and clean decays eg into $\gamma\gamma$ suppressed).**
- **Impact of light SUSY particles?**

$\Rightarrow$ very complicated situation in general!

But simpler in the decoupling regime:

– h as in SM with $M_h = 115-130$ GeV

– dominant mode: $gg, b\bar{b} \to H/A \to \tau\tau$.

It is even more tricky in beyond MSSM, and also in many non-SUSY extensions...

5. Implications for Supersymmetry

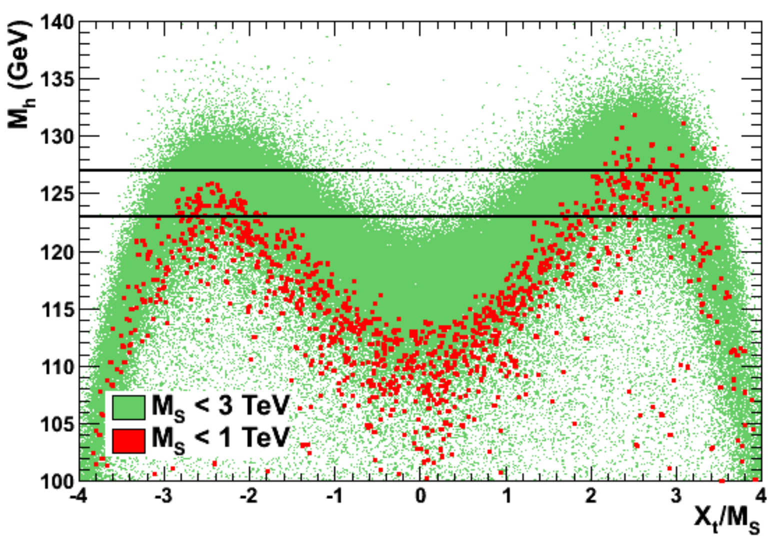
There is a first direct implication from the measurement $M_h = 125$ GeV...

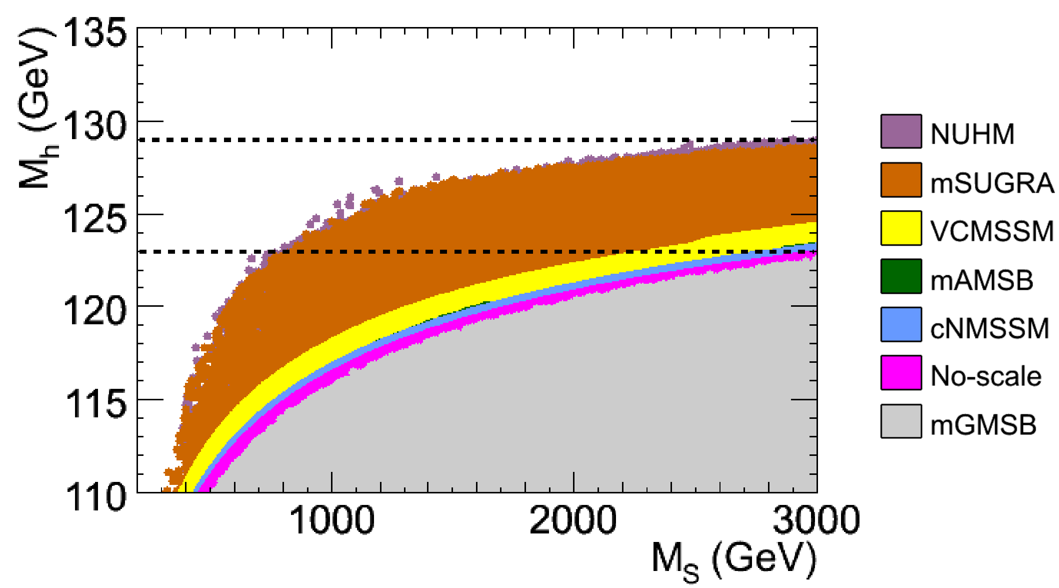
The lightest Higgs boson mass in the MSSM is given (at one-loop) by:

$$M_h^2 \xrightarrow{M_A \gg M_Z} M_Z^2 \cos^2 2\beta + \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right]$$

and M_h=125 GeV is rather high $\Rightarrow$ maximize the radiative corrections:

- decoupling regime with all other H bosons heavy, $M_A \sim \mathcal{O}$(TeV);
- large values of tanβ ($\gtrsim 5$) and the mixing parameter $X_t (\approx \sqrt{6} M_S)$;
- heavy stops, i.e. a rather large SUSY-breaking scale $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$.



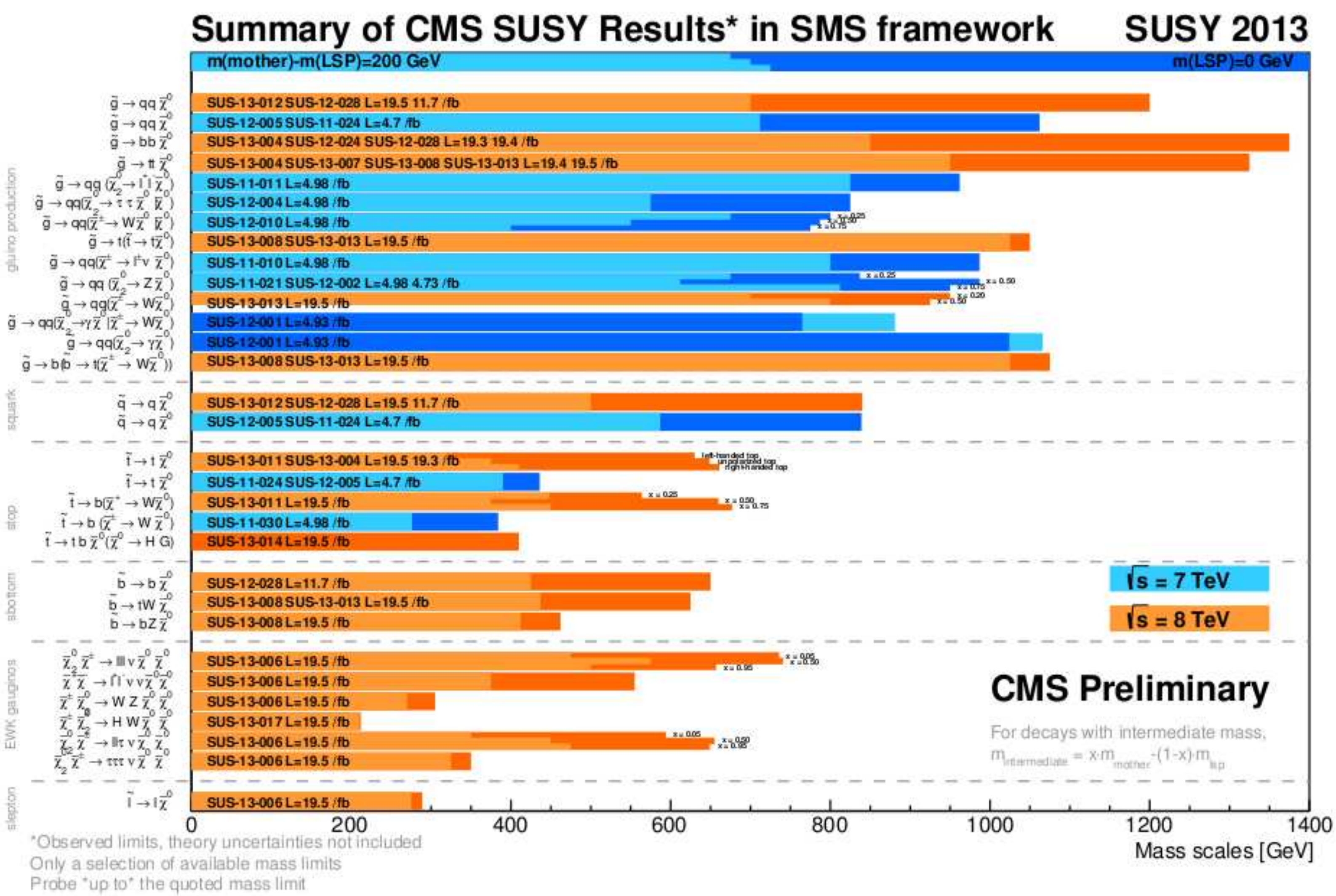


Arbey, Battaglia, AD, Mahmoudi, Quevillon (2012)

5. Implications for Supersymmetry

Hence, one needs a rather large SUSY scale, $M_S \gtrsim \mathcal{O}$(1 TeV).

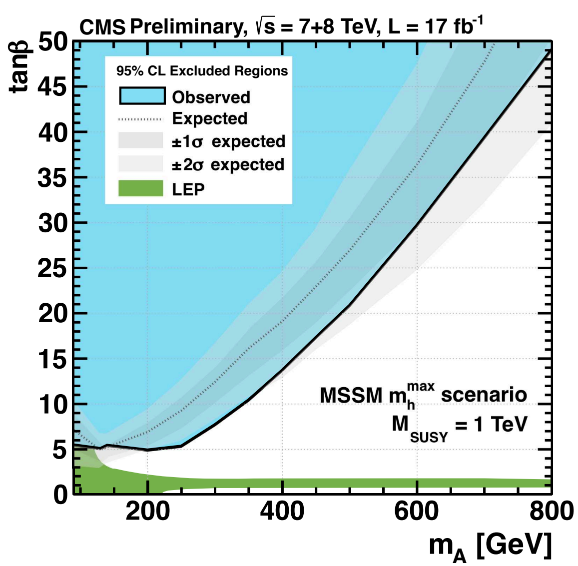
This is backed up by direct searches of SUSY particles at the LHC.

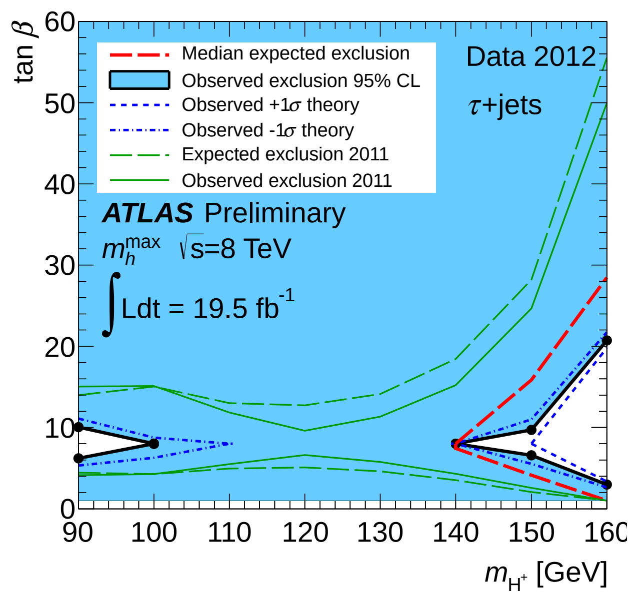


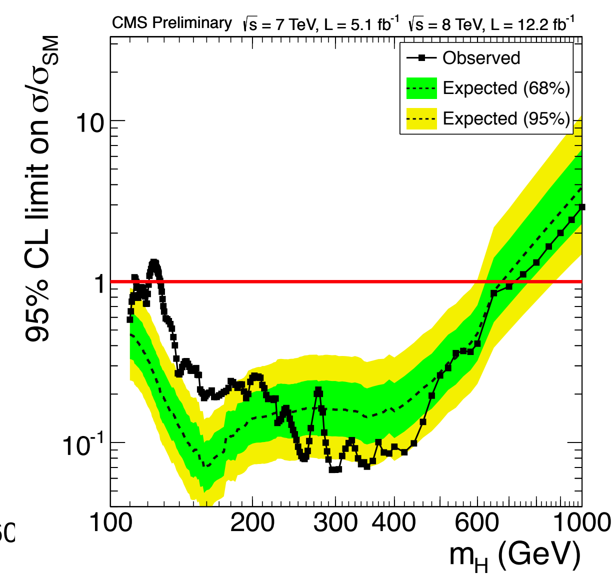
5. Implications for Supersymmetry

What about the other heavier MSSM H states? Need also search for them.

- **Searches for the $pp \to A/H/(h) \to \tau\tau$ resonant process:**
  $\Rightarrow$ rules out high tanβ for low M_A values.
- **Searches for charged Higgs in $t \to bH^+ \to b\tau\nu$ decays:**
  $\Rightarrow$ rules out almost any tanβ value for $M_{H^\pm} \lesssim 160$ GeV.
- **Non observation of heavier Higgs bosons in H$\to$ZZ,WW modes:**
  $\Rightarrow$ no analysis yet!? The width is different from SM-case.
- **Also searches for $A \to hZ$ and $H \to hh$ but not in the MSSM....**
- **Searches for heavy tt resonances but not in the MSSM (KK, Z')...**







5. Implications for Supersymmetry

Constraints on the $[\mathrm{M_A}, \tan\beta]$ plane

- **Fits of the h properties $\Rightarrow$**

can be turned into MSSM constraints

– no important direct SUSY corrections

(no sbottom/sbootom contributions)

– use both signal strengths and ratios

as there is no deviation from SM Higgs:

h SM–like $\Rightarrow \mathrm{M_A} \gtrsim 200 - 500$ GeV

- **Constraints in the high tanβ region:**

– $\mathrm{t \to H^+ b \to b\tau\nu : M_A \gtrsim 140}$ GeV

– $\mathrm{H/A} \to \tau\tau : \mathrm{M_A} \gtrsim 300$ GeV

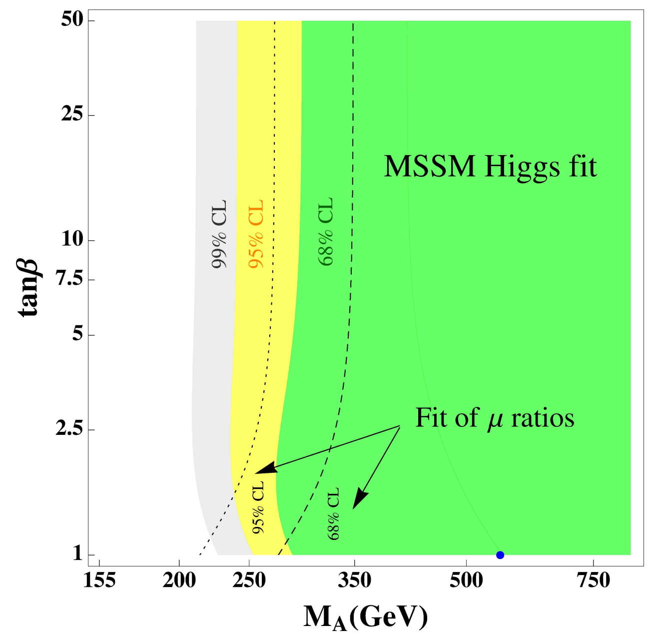
- **Constraints on the low tanβ region:**

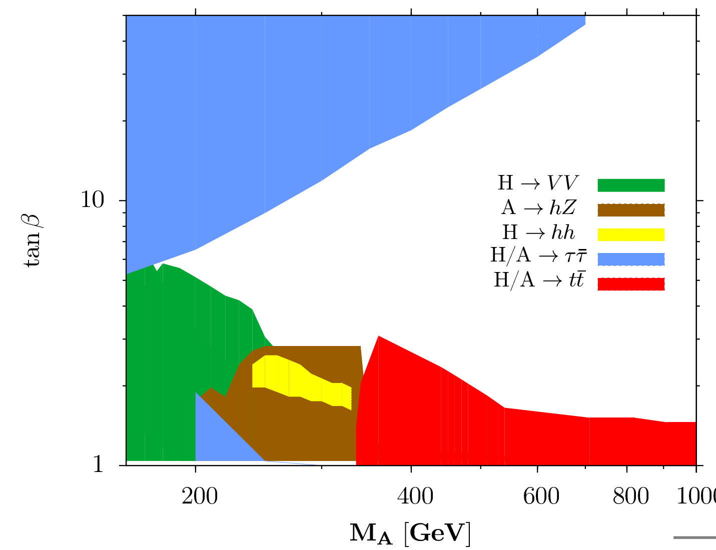
– H$\to$WW,ZZ in SM

– H$\to$tt in BSM scenarios

– H$\to$hh and A$\to$hZ..

Plenty of space probed with current data...





6. What next?

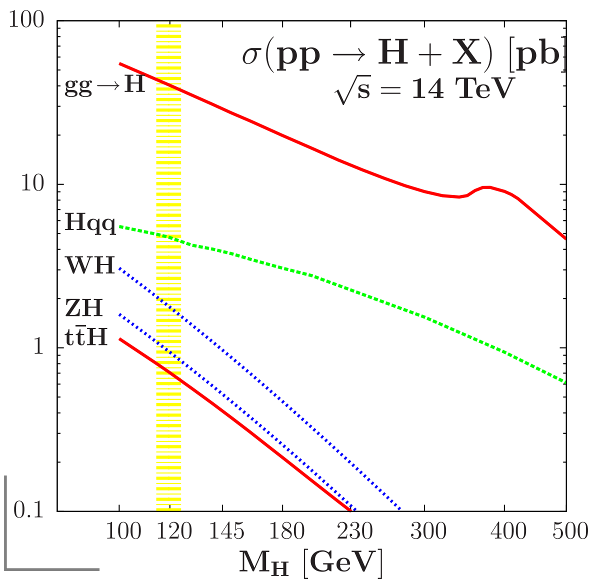
Now that the Higgs boson is found, is Particle Physics "closed"? No!

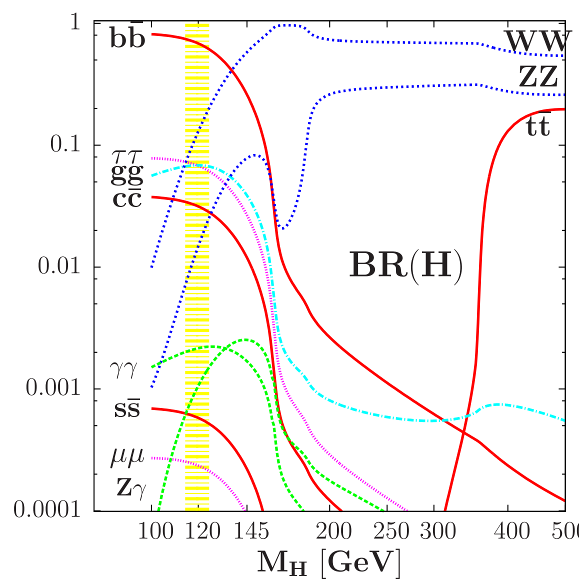
1) Need to check that H is indeed responsible of sEWSB (and SM-like?)

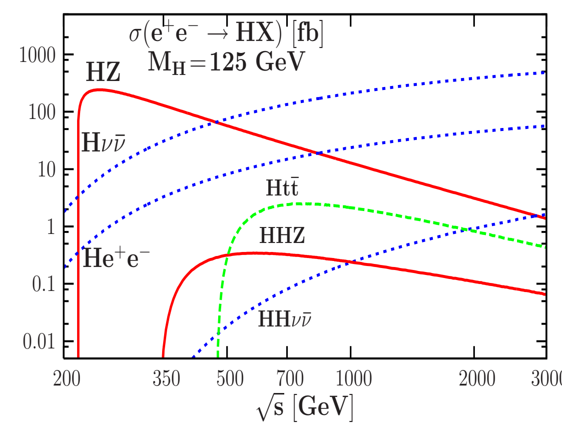
$\Rightarrow$ measure its fundamental properties in the most precise way:

- **its mass and total decay width (invisible width due to dark matter?),**
- **its spin–parity quantum numbers (CP violation for baryogenesis?),**
- **its couplings to fermions and gauge bosons and check if they are only proportional to particle masses (no new physics contributions?),**
- **its self-couplings to reconstruct the potential V_S that makes EWSB.**

Possible for $M_H \approx$ 125 GeV as all production/decay channels useful!







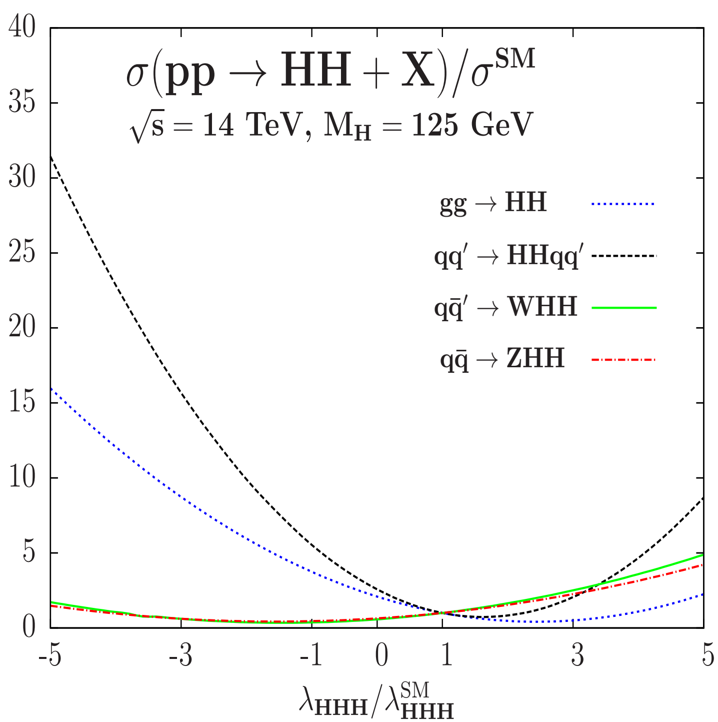
6. What next?

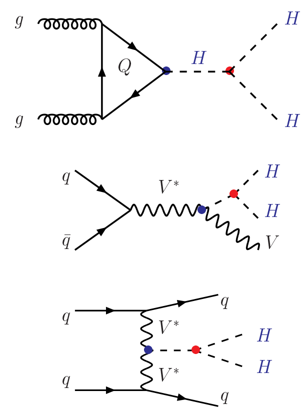
An important challenge: measure Higgs self-couplings and access to V_H

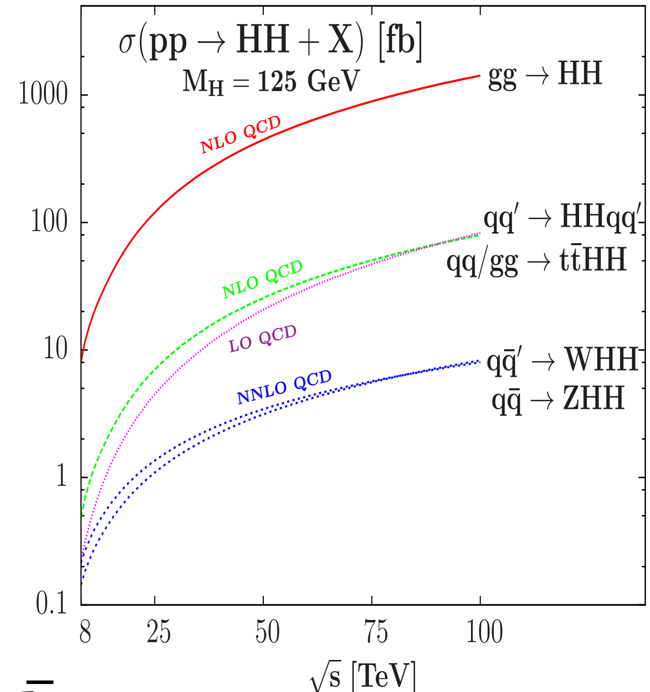
- g_{H^3} **from** $pp \to HH + X \;\Rightarrow$
- g_{H^4} **from pp→3H+X, hopeless.**

Various processes for HH prod:

only $gg \to HHX$ **relevant...**







Baglio et al., arXiv:1212.5581

- $H \to b\bar{b}$ **decay alone not clean**
- $H \to \gamma\gamma$ **decay very rare,**
- $H \to \tau\tau$ **would be possible?**
- $H \to WW$ **not useful?**

– $bb\tau\tau, bb\gamma\gamma$ **viable?**

– **but needs very large luminosity.**

6. What next?

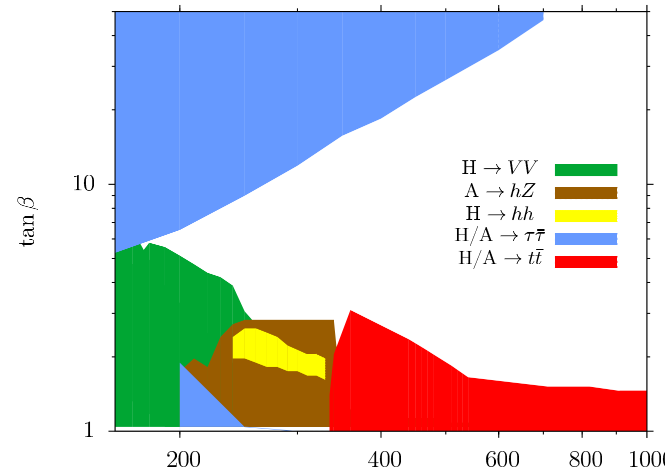
2) Fully probe the TeV scale that is relevant for the hierarchy problem
$\Rightarrow$ continue to search for heavier H bosons and new (super)particles.

- **Search for heavier SUSY H bosons:**

– $\mathrm{pp} \to \mathrm{H/A} \to \tau\tau, \mathrm{t\bar{t}}$
– $\mathrm{pp} \to \mathrm{H} \to \mathrm{WW}, \mathrm{ZZ}, \mathrm{hh}$
– $\mathrm{pp} \to \mathrm{A} \to \mathrm{hZ}$
– $\mathrm{pp} \to \mathrm{H^- t} \to \mathrm{Wb}\tau\nu$

$\Rightarrow$ **extend reach as much as possible.**

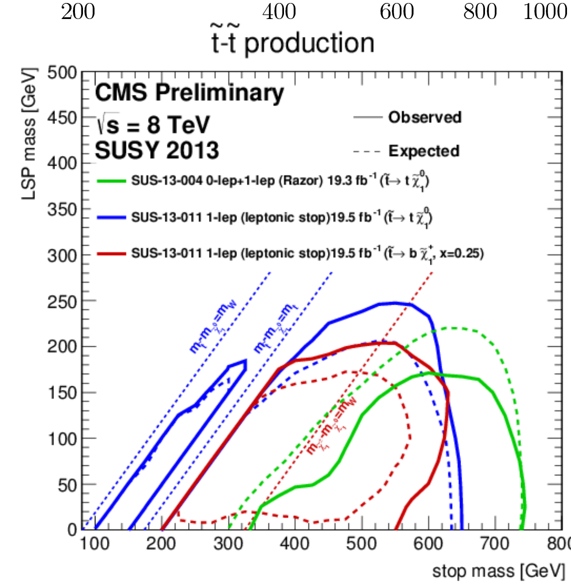
AD, Maiani,Polosa,Quevillon (2013) $\Rightarrow$



- **Search for supersymmetric particles:**

(not only strong but also electroweak)
– squarks and gluinos up to a few TeV,
– chargino/neutralino/sleptons to 1 TeV,
– LSP/DM neutralino upto few 100 GeV.

example of CMS reach in $\tilde{t}/\chi_1^0$ space $\Rightarrow$



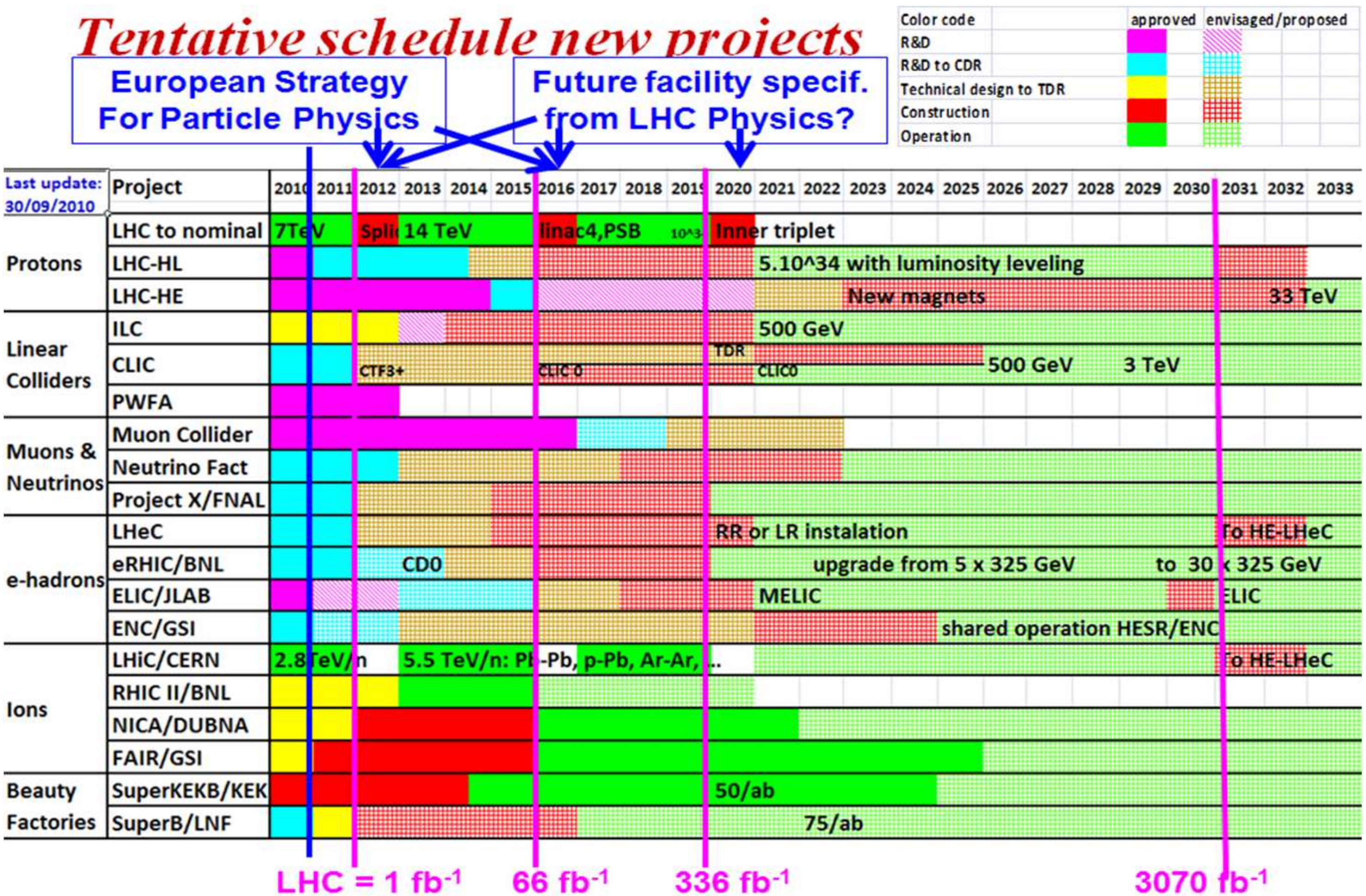
- **Search for any new particle: new $\mathrm{f}, \mathrm{Z'}, \mathrm{V_{KK}}$, etc... at TeV scale!**

6. What next?

Hence, we need to continue search for New Physics and falsify the SM:

- **indirectly via high precision Higgs measurements (HL-LHC, ILC, ...),**
- **directly via heavy particle searches at high-energy (HE-LHC, CLIC),**

and we should plan/prepare/construct the new facilities already now!



6. What next?

The end of the story is not yet told!

"Now, this is not the end.
It is not even the beginning to the end.
But it is perhaps the end of the beginning."

Sir Winston Churchill, November 1942
(after the battle of El-Alamein, Egypt...).

We hope that at the end we finally understand the EWSB mechanism. But there is a long way until then, and there might be many surprises.

We should keep going!