Implications of the Higgs discovery

. . .

Abdelhak DJOUADI (LPT Paris-Sud)

- **The Higgs in the Standard Model and beyond**
- **The Higgs at the LHC**
- **First implications of the discovery**
- **What next?**

1. The Higgs in the Standard Model and beyond

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

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

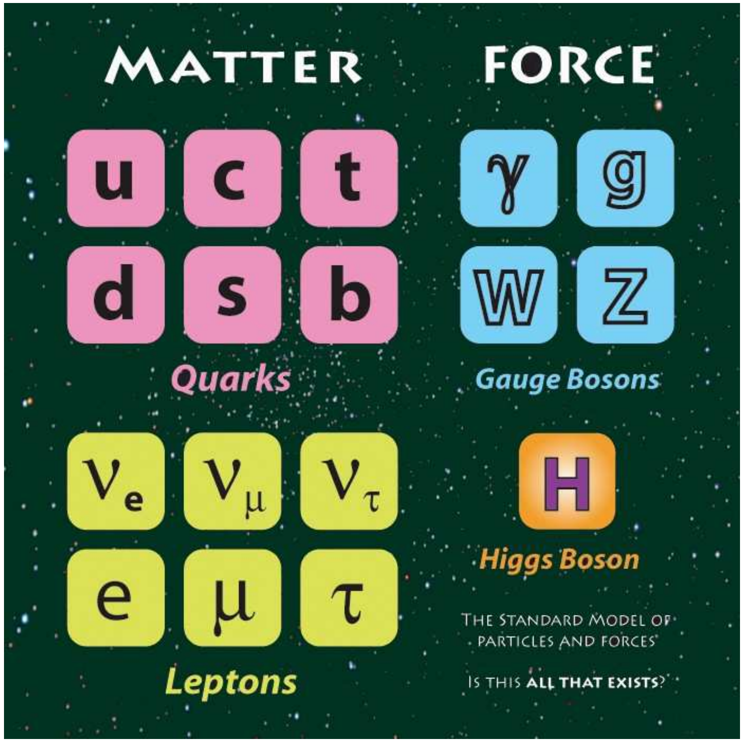
It is based on a gauge symmetry:

$$\mathbf{SU(3)_C \times SU(2)_L \times U(1)_Y}$$

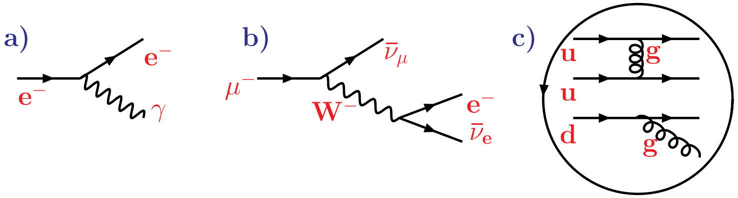
- **relativistic quantum field theory,**
- **perturbative, renormalisable,**
- **and most of all, very successfull:**

⇒ infinitely precise predictions,

⇒ high precision experimental tests.



But true only if particles are massless[a]: **putting naively masses for W/Z/fermions spoils gauge invariance and therefore the nice properties of the theory above.**



Problem: how to generate particle masses in a gauge invariant way?

⇒ the Brout–Englert–Higgs mechanism for EW symmetry breaking!

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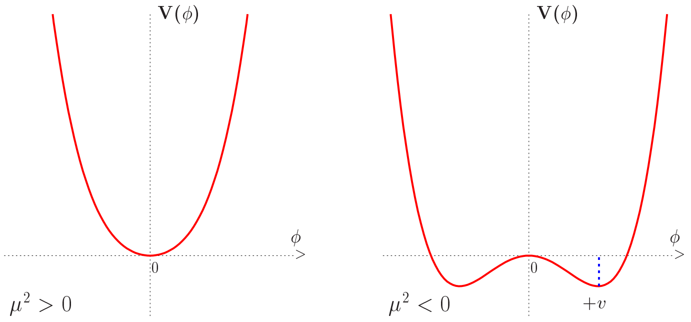
[a] This has nothing to do with mass of macroscopic objects due to binding energy...

1. The Higgs in the Standard Model and beyond

Introduce a doublet of complex scalar fields $\Phi = \binom{\Phi^+}{\Phi^0}$: 4 degrees of freedom.

Scalar potential: $V_S = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$, $SU(2)_L \times U(1)_Y$ invariant.



$\mu^2 > 0$: minimum of V_S at $\langle 0|\Phi^0|0\rangle = 0$:

4 new scalar particles with mass $m_S = \mu$.

$\mu^2 < 0$: (via quantum fluctuations?):

the field Φ develops a non–zero vev

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

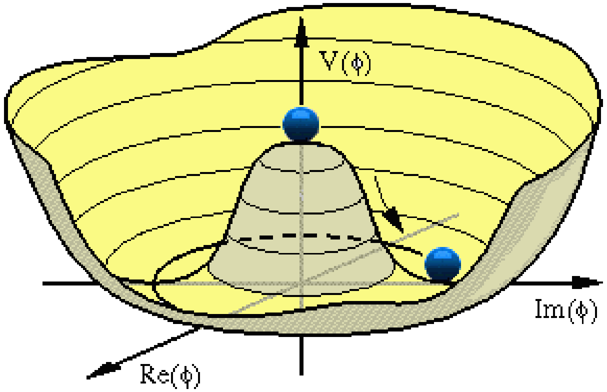
fields/interactions still SU(2)×U(1) symmetric

but vaccum not ⇒ spontaneous EW breaking.

⇒ three d.o.f. for $M_{W^\pm}$ and M_Z.

Introduce interaction of fermions with same Φ:

fermions masses m_f also generated!



Residual d.o.f corresponds to spin–0 Higgs particle.

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

1. The Higgs in the Standard Model and beyond

Since v is known, the only free parameter in the SM is $\mathrm{M_H}$ (or λ).

Pre–LHC constraints on $\mathrm{M_H}$:

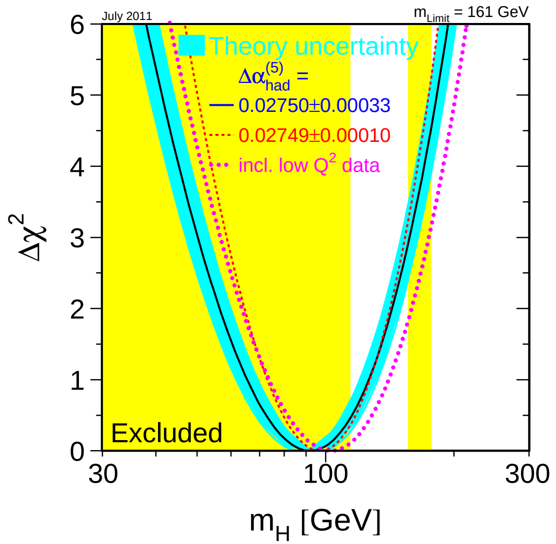
● Experimental constraints:

– direct searches at LEP/Tevatron:

$\mathrm{M_H} > 114$ **GeV,** $\mathrm{M_H} \neq 160$ **GeV**

– quantum effects in EW data:

$\mathrm{M_H} < 160$ **GeV @95% confidence.**

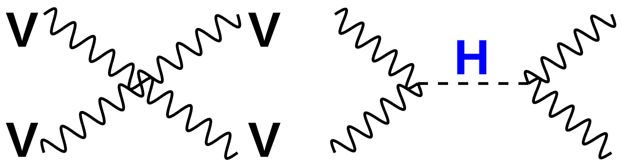


● The Higgs unitarizes the theory:

without H: $|\mathrm{A_0(VV \to VV)}| \propto \mathrm{E^2}$

including H: $|\mathrm{A_0}| \propto \mathrm{M_H^2/v^2}$

theory unitary but $\mathrm{M_H} \lesssim 700$ **GeV...**



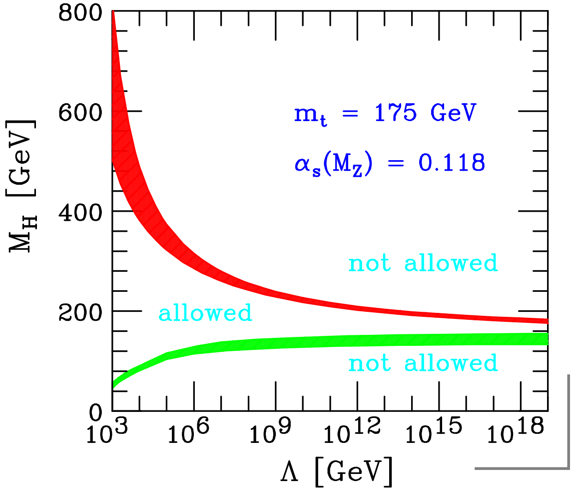
● Triviality and stability bounds:

coupling evolves with energy $\lambda \equiv \lambda(\mathrm{Q^2})$

$\lambda \gg 1$**: becomes infinite (no perturbation)**

$\lambda \ll 1$**: potential unstable (no EWSB)**

$\mathbf{\Lambda \sim M_{Pl} : 120 \lesssim M_H \lesssim 180\ GeV}$**!**

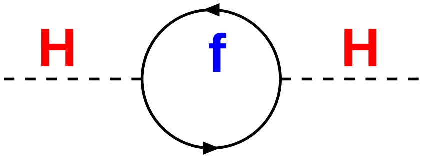


1. The Higgs in the Standard Model and beyond

A major problem in the SM: the hierarchy/naturalness problem.

Radiative corrections to $\mathrm{M_H^2}$ in SM with a cut–off $\Lambda = \mathrm{M_{NP}} \sim \mathrm{M_{Pl}}$

$$\Delta \mathrm{M_H^2} \equiv$$



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

$\mathrm{M_H}$ prefers to be close to the high scale than to the EWSB scale...

Three main avenues for solving the hierarchy problem:

1) Compositness: there is another layer!

all particles are not elementary ones.

Techicolor: like QCD at scale of 1 TeV.

$\Rightarrow$ H bound state of two fermions

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

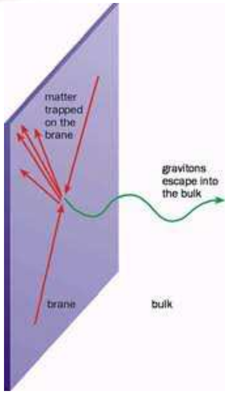
2) Extra space–time dimensions

in which at least gravitons propagate;

effective gravity scale $\mathrm{M_{Pl}^{eff}} \approx \Lambda_C \approx$ TeV

$\Rightarrow$ same Higgs mechanism as in SM,

$\Rightarrow$ but possibility of Higgsless mode!



1. The Higgs in the Standard Model and beyond

3) Supersymmetry: doubling the world.

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

– links $s=\frac{1}{2}$ fermions to $s=1$ bosons

– links internal and space-time symmetry

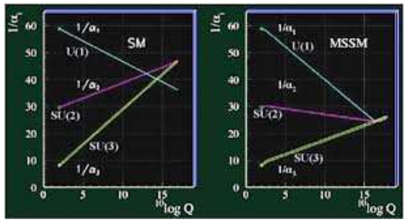
– if made local, it provides link to gravity

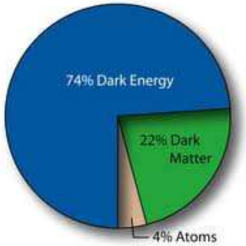
– naturally present in string theory (TOE?)

– natural $\mu^2<0$: radiative EWSB

– fixes gauge coupling unification

– ideal candidate for Dark Matter...





- **Needs two doublets Φ_1, Φ_2 for EWSB:**

$\Rightarrow$ **extended Higgs sector:** $h, H, A, H^\pm$ **with** $h \oplus H \approx H_{SM}$

– **SUSY** $\Rightarrow$ **only two inputs at tree level:** $\tan\beta = v_2/v_1, M_A$

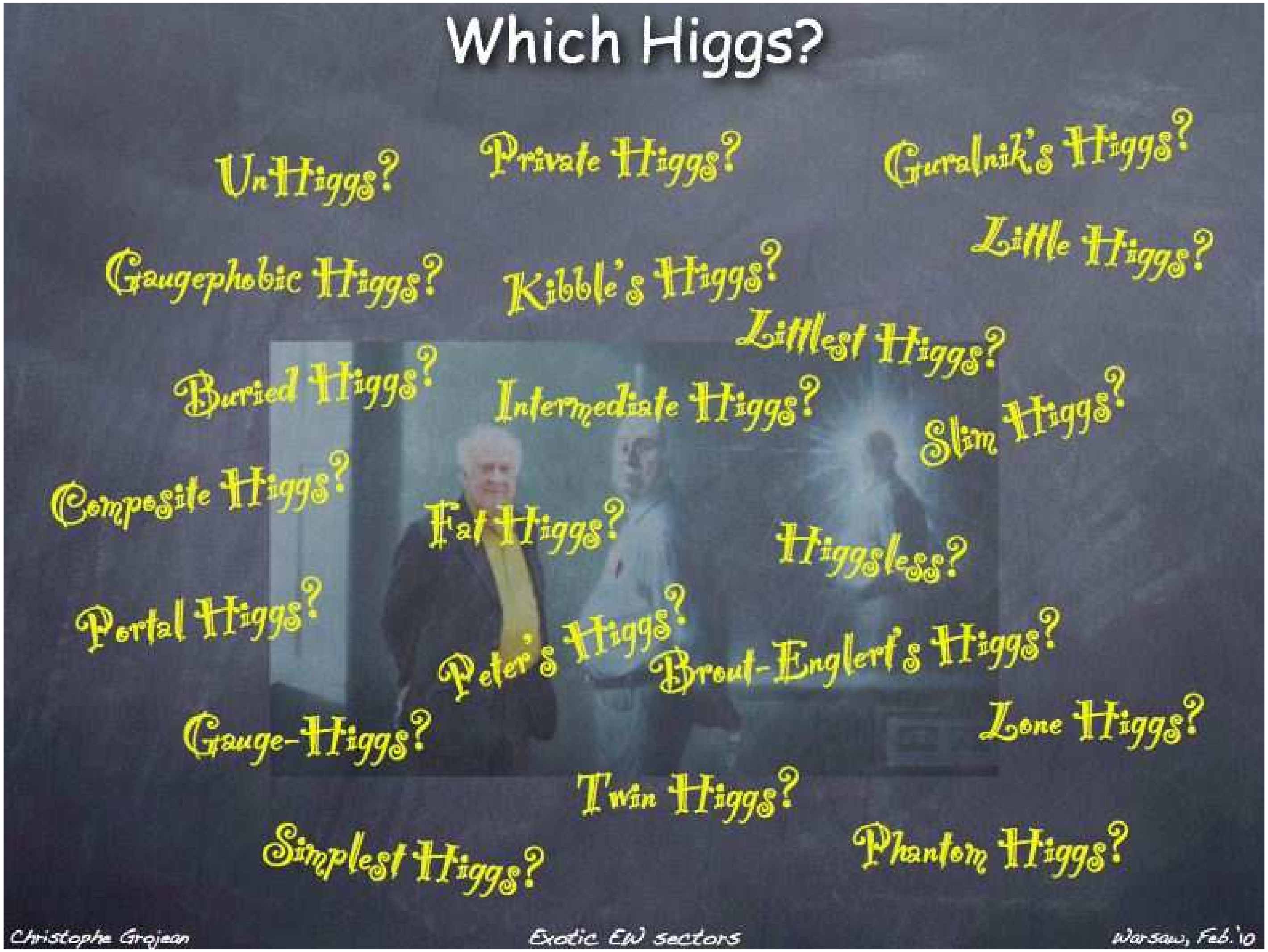
– **SUSY** $\Rightarrow$ **hierarchy spectrum:** $M_h \approx 100$ **GeV,** $M_H \approx M_A \approx M_{H^\pm}$

(SUSY scale M_{SUSY} **pushes via radiative corrections** M_h **to 130 GeV).**

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

1. The Higgs in the Standard Model and beyond

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



Which Higgs?

UnHiggs? Private Higgs? Guralnik's Higgs?

Gaugephobic Higgs? Kibble's Higgs? Little Higgs?

Littlest Higgs?

Buried Higgs? Intermediate Higgs? Slim Higgs?

Composite Higgs? Fat Higgs? Higgsless?

Portal Higgs? Peter's Higgs? Brout-Englert's Higgs?

Gauge-Higgs? Lone Higgs?

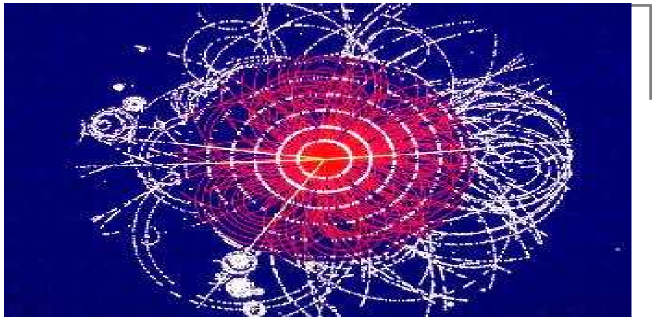
Twin Higgs?

Simplest Higgs? Phantom Higgs?

Christophe Grojean Exotic EW sectors Warsaw, Feb.'10

Which scenario chosen by Nature? The LHC was devised to tell!

2. The Higgs at the LHC



Physics at hadron machines is a nightmare...

- **Protons non–elementary: difficult environment**
- **Huge cross sections for QCD processes**
- **Small cross sections for EW Higgs signal**

  S/B $\gtrsim 10^{10}$ ⇒ a needle in a haystack!

- **Need some strong selection criteria:**

– trigger: get rid of uninteresting events...

– select clean channels: leptons and photons

– use specific kinematic features of Higgs

- **Combine # decay/production channels**

(and eventually several experiments...)

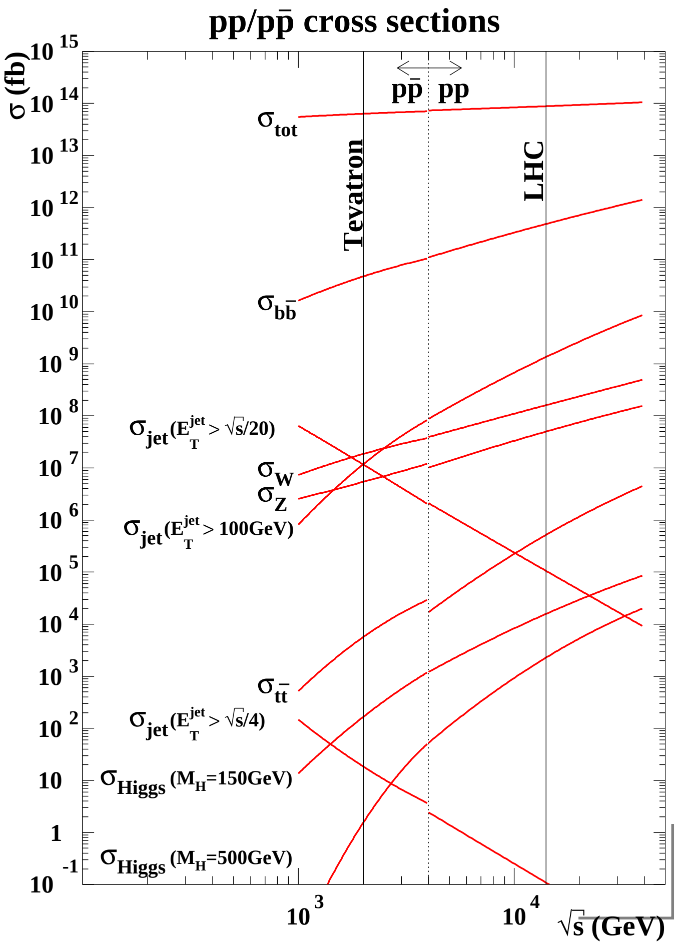
- **Have a precise knowledge of S and B rates**

(higher/quantum effects can be factor of 2!)

- **Gigantic experimental + theoretical efforts**

(more than 30 years of extremely hard work!)

to make sure that the Higgs will not escape!



2. The Higgs at the LHC

Since v is known, the only free parameter in the SM is $\mathrm{M_H}$ (or λ).

Once $\mathrm{M_H}$ known, all the properties of the Higgs boson are fixed.

Example: Higgs decays in the SM

- **As $\mathrm{g_{HPP}} \propto \mathrm{m_P}$, H will decay into heaviest particle phase-space allowed:**

- $\mathrm{M_H} \lesssim 130\ \mathrm{GeV}$:

– $\mathrm{H} \to \mathrm{b\bar{b}}$: **dominant decay**

– $\mathrm{H} \to \mathrm{cc}, \tau^+\tau^-, \mathrm{gg} = \mathcal{O}(\mathrm{few}\ \%)$

– $\mathrm{H} \to \gamma\gamma, \mathrm{Z}\gamma = \mathcal{O}(0.1\%)$

- $\mathrm{M_H} \gtrsim 130\ \mathrm{GeV}$:

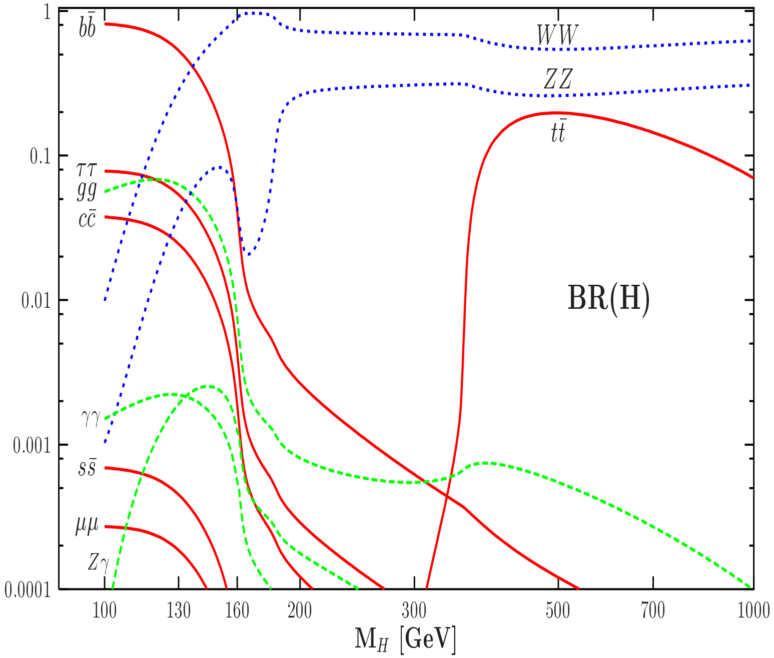
– $\mathrm{H} \to \mathrm{WW}, \mathrm{ZZ}$ **dominant**

– **decays into $\mathrm{t\bar{t}}$ for heavy Higgs**

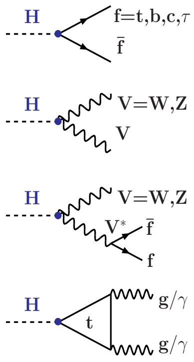
- **Total Higgs decay width:**

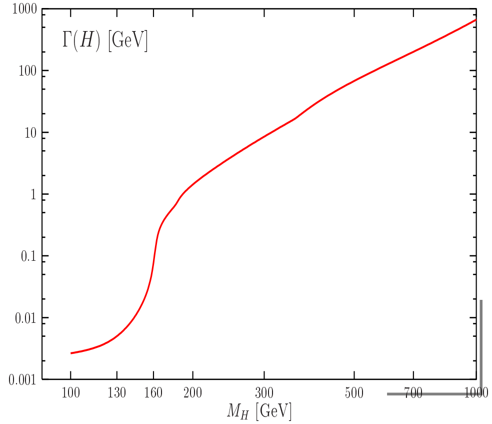
– **very small for a light Higgs**

– **comparable to mass if heavy**



HDECAY ⇒

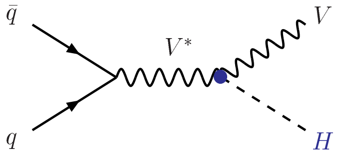




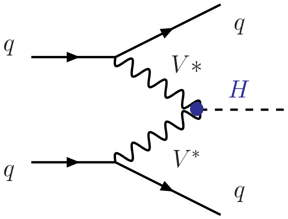
2. The Higgs at the LHC

Main Higgs production channels

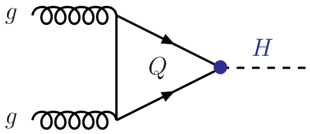
Higgs–strahlung



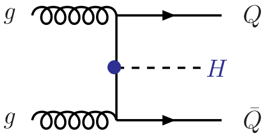
Vector boson fusion

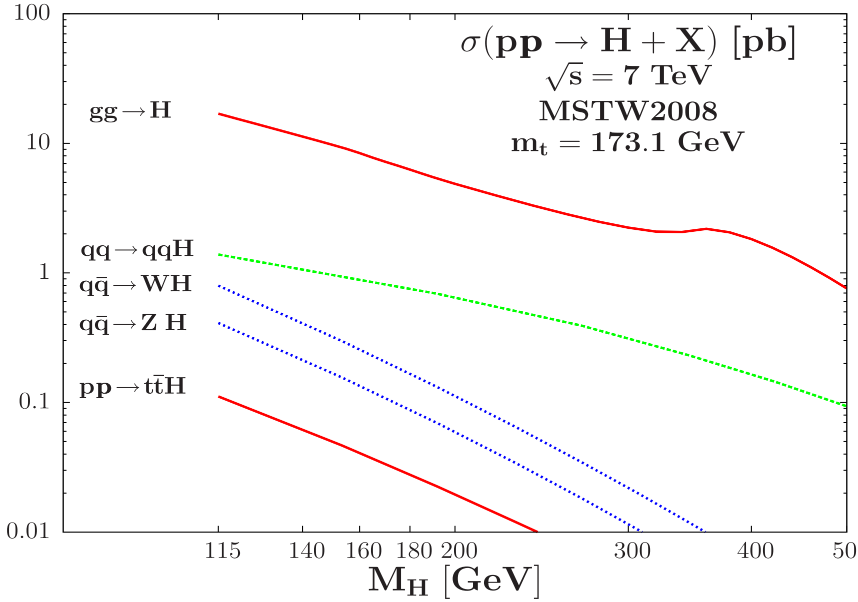


gluon–gluon fusion



in associated with $Q\bar{Q}$





Large production cross sections

with gg$\to$ H by far dominant process

1 $\mathrm{fb}^{-1} \Rightarrow \mathcal{O}(10^4)$ events@LHC

$\Rightarrow \mathcal{O}(10^3)$ events@Tevatron

but eg BR(H$\to \gamma\gamma, \mathrm{ZZ} \to 4\ell) \approx 10^{-3}$

... a small # of events at the end...

with a huge QCD-jet background.

$\Rightarrow$ an extremely challenging task!

Main sensitive channels:

$\mathrm{gg} \to \mathrm{H} \to \gamma\gamma$

$\mathrm{gg} \to \mathrm{H} \to \mathrm{ZZ} \to 4\ell, 2\ell 2\nu, 2\ell 2$

$\mathrm{gg} \to \mathrm{H} \to \mathrm{WW} \to \ell\nu\ell\nu + 0, 1$

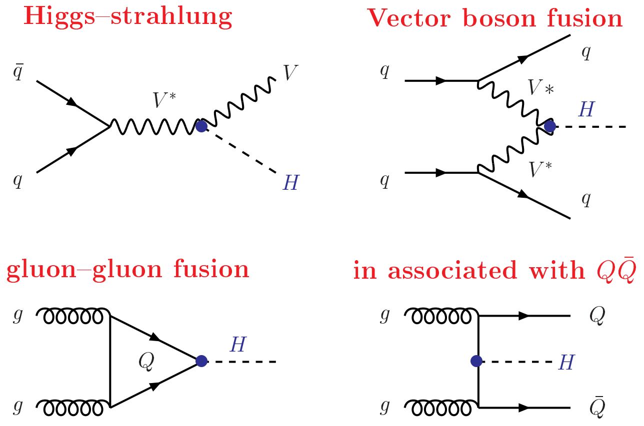
also help from other channels:

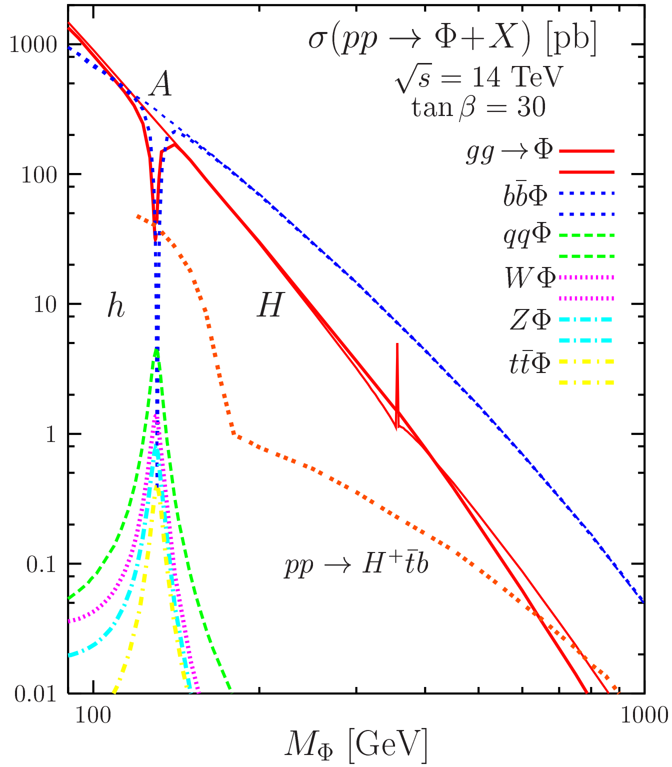
– VBF+$\mathrm{gg} \to \mathrm{H} \to \tau\tau$

– $\mathrm{q\bar{q}} \to \mathrm{HV} \to \mathrm{b\bar{b}}\ell\mathrm{X}$

2. The Higgs at the LHC

Things are even more complicated/challenging in BSM: MSSM case





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

– 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 processs

(rates can be smaller or larger than in SM)

- Possibility of different decay modes

(and clean decays eg into $\gamma\gamma$ suppressed

- Impact of light SUSY particles?

$\Rightarrow$ In general very complicated situation!

But simpler in the decoupling regime:

– h as in SM with $M_h = 115 - 130$ GeV

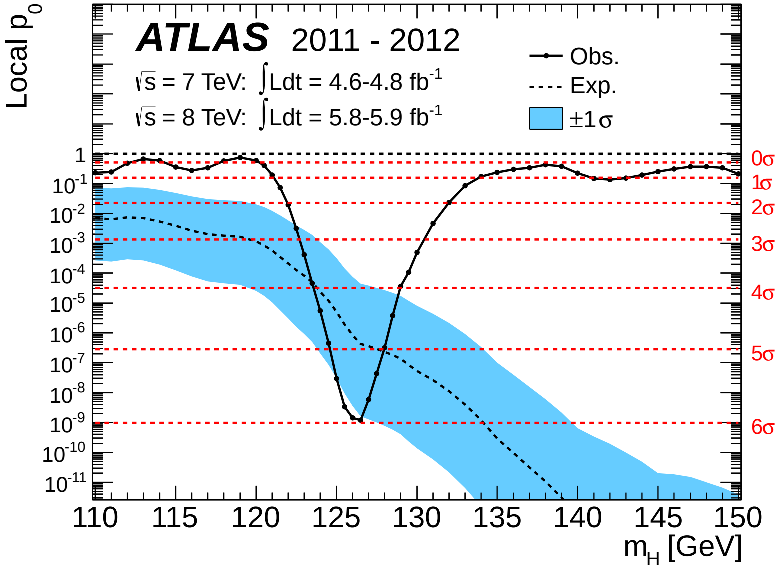
– dominant mode: $gg, b\bar{b} \to H/A \to \tau\tau$

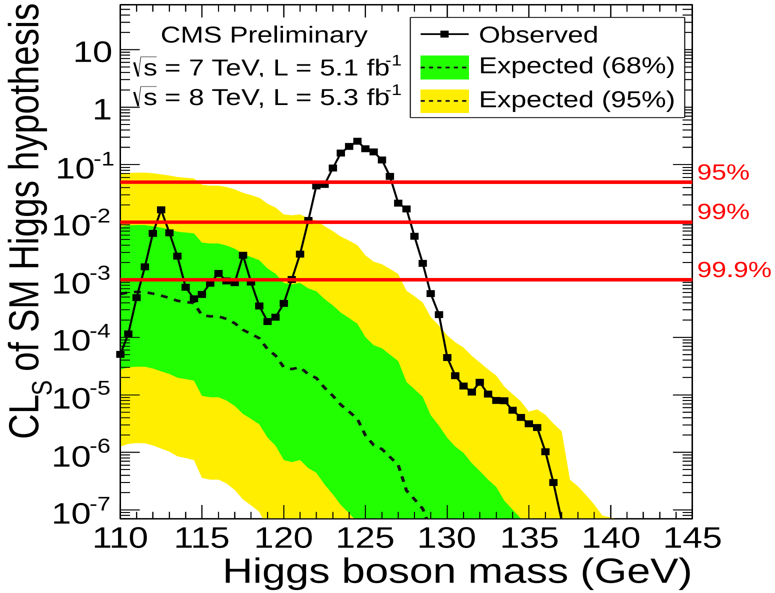
It is even more tricky in beyond MSSM!

and also in some non–SUSY extensions...

2. The Higgs at the LHC

... a challenge met the 4th of July, when the Higgs was discovered at LHC.





3. Implications of the discovery: is it a Higgs?

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

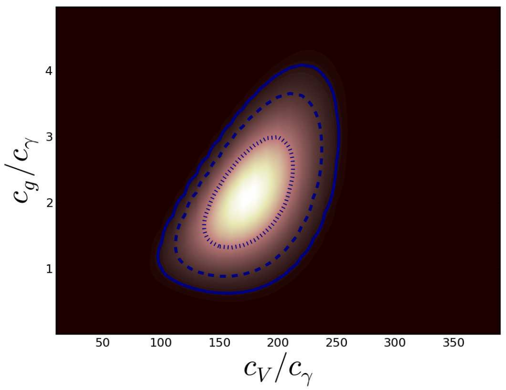
- **not spin–1: Landau–Yang**
- **could be spin–2 like graviton?** **Ellis et al.**

– miracle that couplings fit that of H,

– “prima facie” evidence against it:

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

many th. analyses (no suspense).

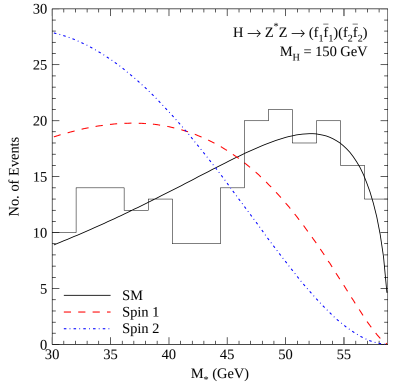


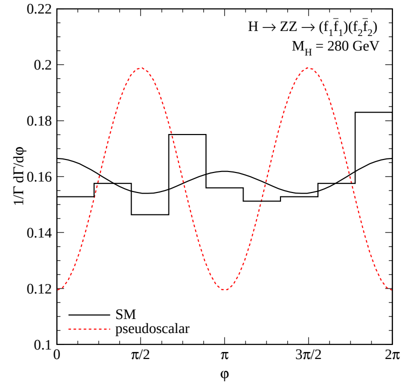
CP: is it CP–even or CP–odd?

$$HV_\mu V^\mu \text{ vs } H\epsilon^{\mu\nu\rho\sigma}Z_{\mu\nu}Z_{\rho\sigma}$$

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

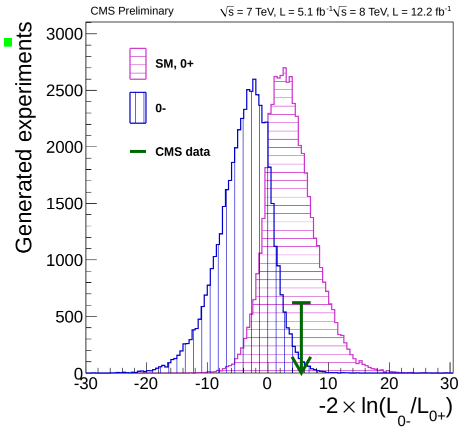
ATLAS/CMS: $\approx 3\sigma$ for CP-even.

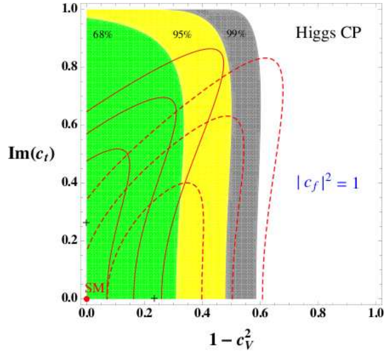




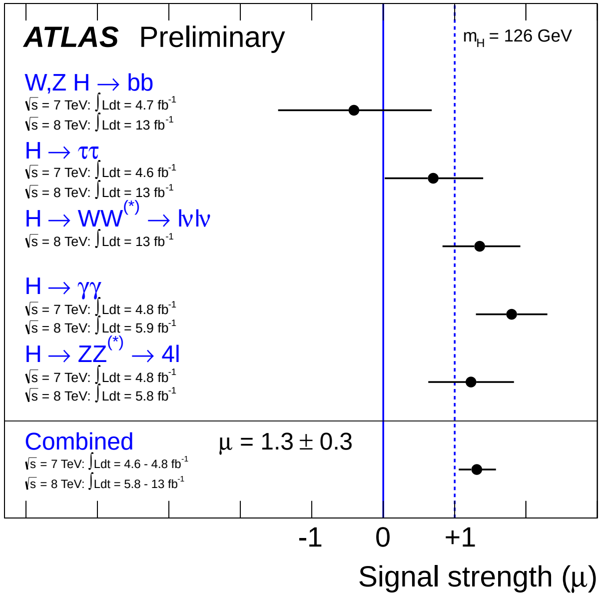
Problem: if H is CP mixture, only 0^+ component is projected out! (or very large 0^-VV loop cplg).

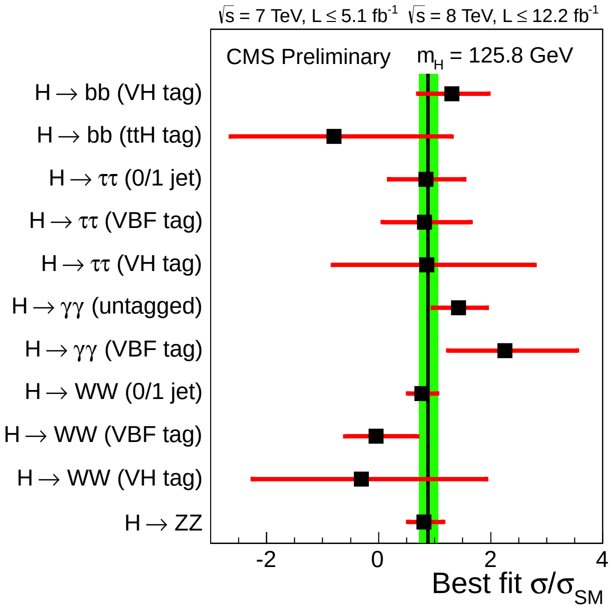
$\Rightarrow$ better probe: $\hat{\mu}_{ZZ} = 1.1 \pm 0.4$!

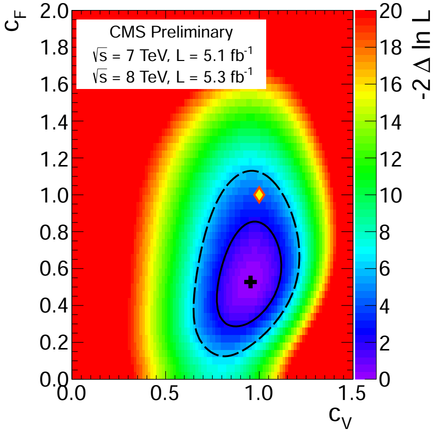


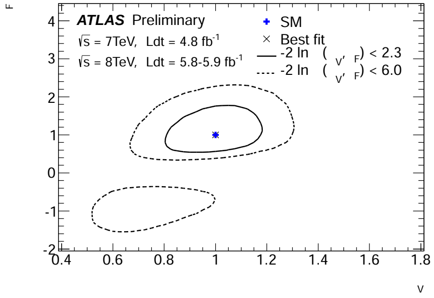


3. Implications of the discovery: is it a Higgs?









From ATLAS/CMS results:

Higgs couplings to elementary particles as predicted by Higgs mechanism

- **couplings to WW,ZZ,$\gamma\gamma$ roughly as expected for a CP-even Higgs**
- **couplings proportionial to masses as expected for the Higgs boson**

So, it is not only a “new particle”, the “126 GeV boson”, a “new state”...

IT IS A HIGGS BOSON!

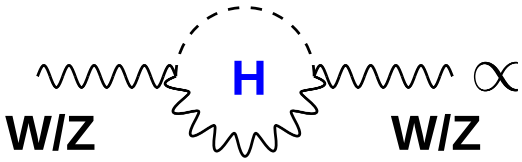
But is it THE SM Higgs boson or A Higgs boson from some extension?
To check this you need very precise measurements to see small deviations...

3. Implications of the discovery: the SM

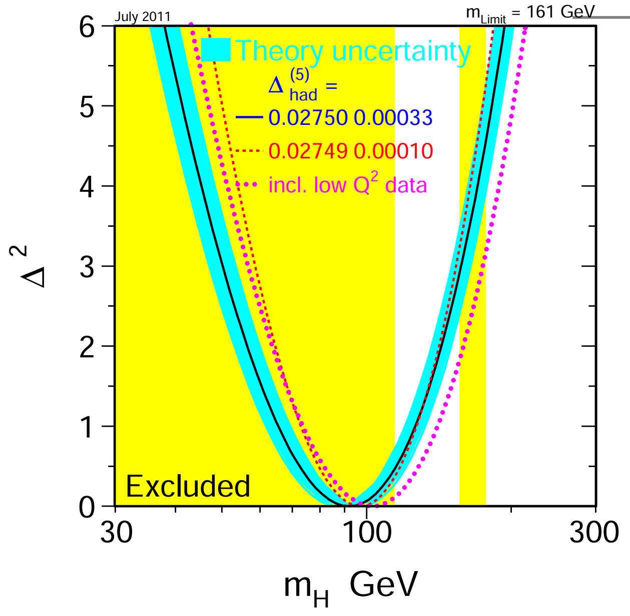
The Higgs looks like expected in SM $\Rightarrow$
a triumph for high-energy physics!

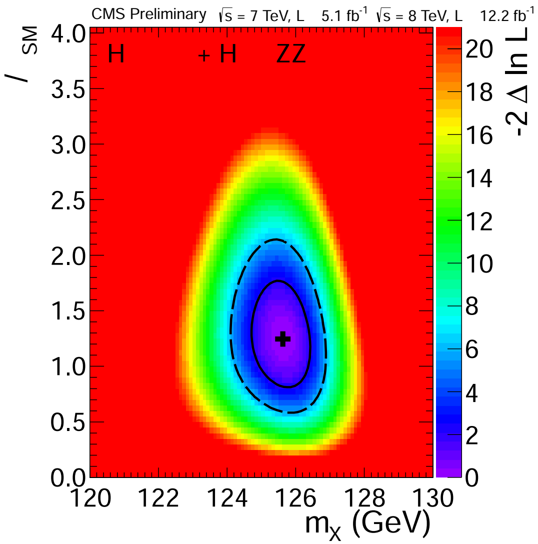
Indirect constraints from EW data [a]

H contributes to RC to W/Z masses:



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





Fit the EW precision measurements,
one obtains $M_H = 92^{+34}_{-26}$ GeV, or

$$M_H \lesssim 160 \text{ GeV at 95\% CL}$$

compared with the measured mass

$$M_H \approx 126 \text{ GeV.}$$

A very non–trivial consistency check!
(remember the story of the top quark!).

The SM is a very successfull theory!

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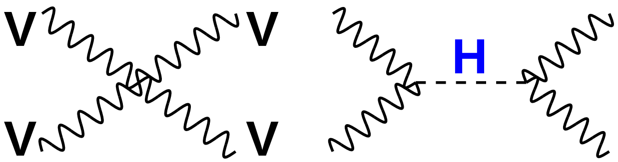
[a] Still some problems with A_{FB}^{b} (LEP), A_{FB}^{t} (TeV) and $g-2$ but not severe...

3. Implications of the discovery: the SM



- **The theory preserves unitarity**

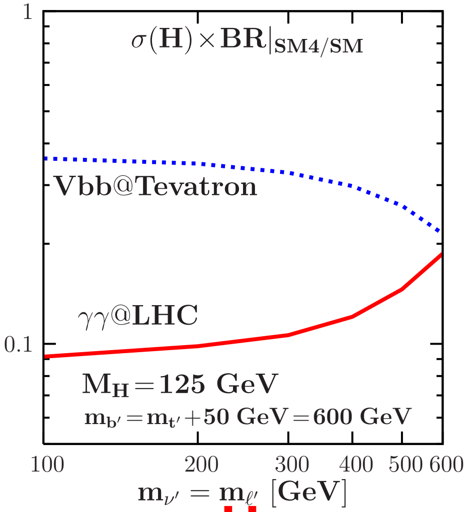
as we have $M_H \ll 700$ GeV...

- **Particle spectrum complete:**

Fourth generation excluded by

$H \to ZZ, WW, \gamma\gamma, bb$ rates...

(as well as by direct searches@LHC...)



- **Extrapolable up to highest scales.**

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

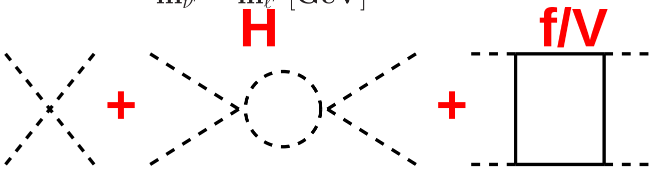
tops make $\lambda < 0$: unstable vacuum

$$\Lambda_C \sim M_{Pl} \Rightarrow M_H \gtrsim 129\,\text{GeV}!$$

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

(Degrassi et al., Bezrukov et al.)

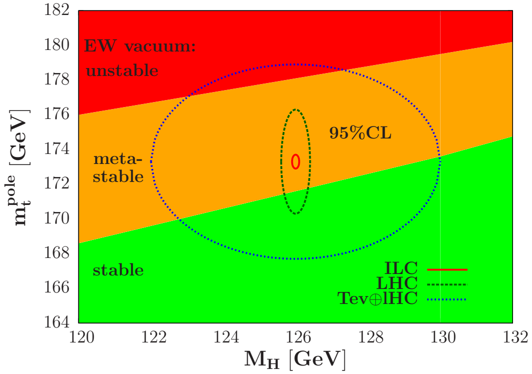
but what is measured m_t value?



- **SM = TOE? Maybe not (?):**

– m_ν, DM, GUT OK with extensions

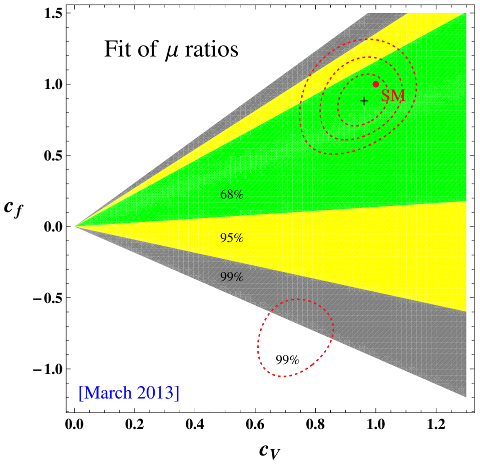
– but about the hierarchy problem?

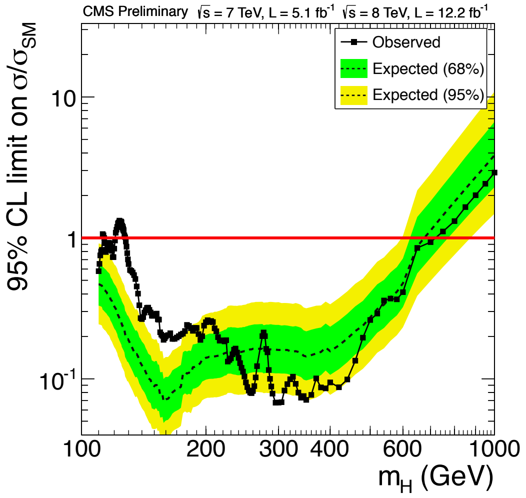


3. Implications of the discovery: beyond the SM

- **Rates compatible with SM**
  fit of all data $\Rightarrow$ OK at $\approx$ 20%
- **No other resonnance found**
  in many search channels....

Huge implications for BSM!





Some beyond the SM scenarios are in ‘mortuary”:

- **Higgsless models, extreme Technicolor and composite scenarios, ..**
- **fermiophobic Higgs, gauge-phobic Higgs, 4th generation, ...**

Some beyond the SM scenarios are in “hospital”:

- **‘light” versions of Technicolor and composite models...**
- **many other extended Higgs scenarios: private, portal, ...**

Other BSM scenarios are strongly constrained...

and the best example is Supersymmetry and the MSSM.

3. Implications of the discovery: the MSSM

In MSSM, two doublets $\mathrm{H_1, H_2} \Rightarrow$ 5 physical states: $\mathrm{h, H, A, H^\pm}$

only two parameters at tree–level: $\tan\beta, \mathrm{M_A}$ but rad. cor. important:

$$\mathrm{M_h} \lesssim \mathrm{M_Z}|\cos2\beta| + \mathrm{RC} \lesssim 130\ \mathrm{GeV}\ ,\ \mathrm{M_H} \approx \mathrm{M_A} \approx \mathrm{M_{H^\pm}} \lesssim \mathrm{M_{EWSB}}$$

126 GeV is large for MSSM: $\Rightarrow \mathrm{M_h}$ needs to be maximal from start...

$$\mathrm{M_h} \overset{\mathrm{M_A \gg M_Z}}{\rightarrow} \mathrm{M_Z}|\cos2\beta| + \frac{3\bar{\mathrm{m}}_\mathrm{t}^4}{2\pi^2\mathrm{v}^2\sin^2\beta}\left[\log\frac{\mathrm{M_S^2}}{\bar{\mathrm{m}}_\mathrm{t}^2} + \frac{\mathrm{X_t^2}}{\mathrm{M_S^2}}\left(1 - \frac{\mathrm{X_t^2}}{12\mathrm{M_S^2}}\right)\right]$$

- decoupling regime with $\mathrm{M_A} \sim \mathcal{O}$(TeV); h is SM–like
- large values of tan$\beta \gtrsim 10$ to maximize tree-level value;
- maximal mixing scenario: $\mathrm{X_t} = \sqrt{6}\mathrm{M_S}$;
- heavy stops, i.e. large $\mathrm{M_S} = \sqrt{\mathrm{m}_{\tilde{\mathrm{t}}_1}\mathrm{m}_{\tilde{\mathrm{t}}_2}}$; but $\mathrm{M_S} \lesssim 3$ TeV....

Scan parameter space with all corrections and full SUSY spectrum

Constrained MSSMs are interesting from model building point of view:

– concrete schemes: SSB occurs in hidden sector $\overset{\mathrm{gravity,..}}{\rightarrow}$ MSSM fields

– provide solutions to some MSSM problems: CP, flavor, etc..

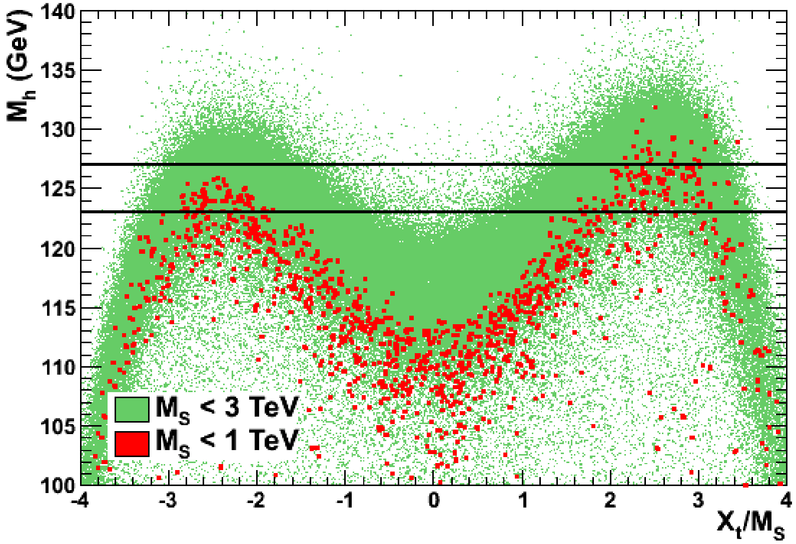
– parameters obey boundary conditions ⇒ small number of inputs...

the protype model is mSUGRA: $\tan\beta\ ,\ \mathrm{m_{1/2}}\ ,\ \mathrm{m_0}\ ,\ \mathrm{A_0}\ ,\ \mathrm{sign}(\mu)$

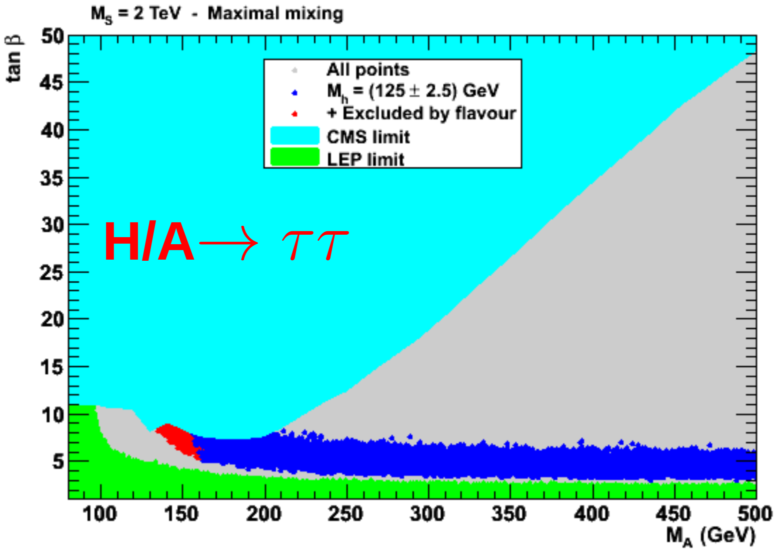
full scan of the model parameters with $123\ \mathrm{GeV} \leq \mathrm{M_h} \leq 129\ \mathrm{GeV}$

3. Implications of the discovery: the MSSM

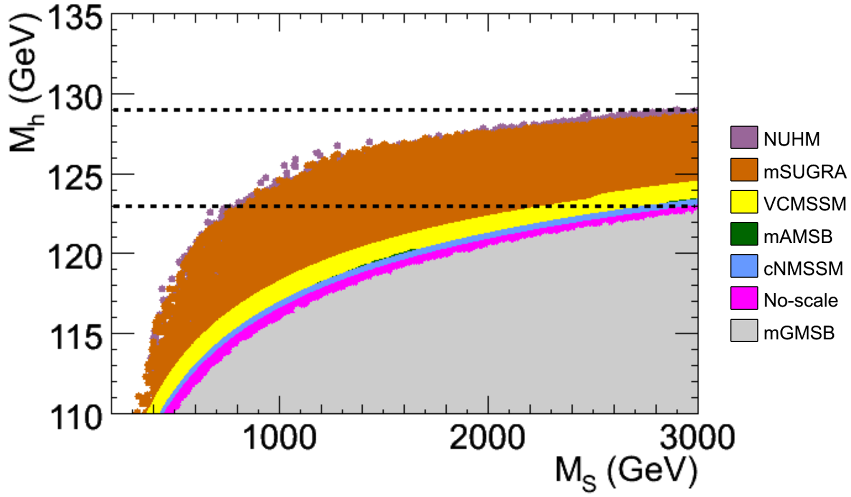
⇒ SUSY scale rather large...



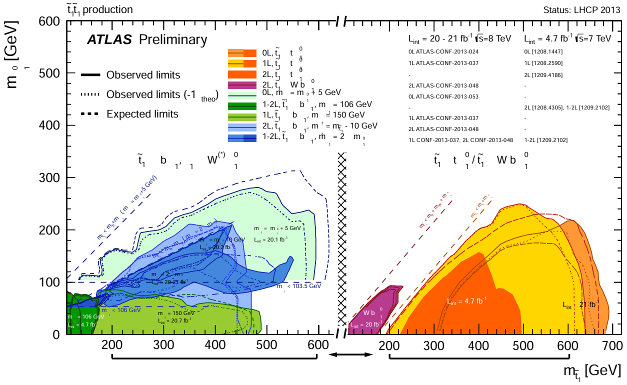
... backed up by direct searches



especially in constrained MSSMs ...



especially squarks/gluinos...



3. Implications of the discovery: the MSSM

A 126 GeV Higgs provides information on BSM and SUSY in particular:

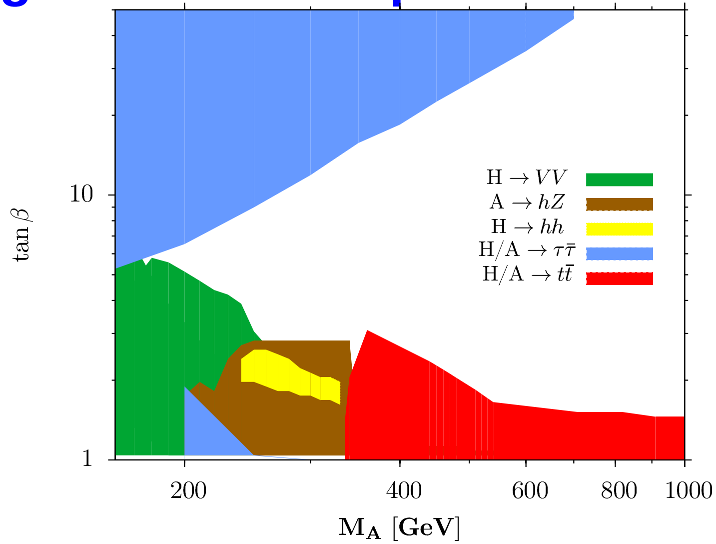
- $\mathrm{M_H = 119}$ **GeV would have been a boring value: everybody OK..**
- $\mathrm{M_H = 145}$ **GeV would be a devastating value: mass extinction..**
- $\mathrm{M_H \approx 126}$ **GeV is Darwinian: (natural) selection among models..**

SUSY spectrum heavy; except maybe for weakly interacting sparticles and also stops $\Rightarrow$ more focus on them in SUSY searches!

One has to refine all other MSSM Higgs searches in particular:

- $\mathrm{gg, bb \to H/A \to \tau\tau, \mu\mu}$
- $\mathrm{t \to H^+b, gg \to tH^-}$
- $\mathrm{H \to WW, ZZ}$ **as in SM**
- $\mathrm{gg, H/A \to tt}$
- $\mathrm{H \to hh, A \to Zh}$**....**

and of course sparticle searches...



7–8 TeV LHC for the lightest h and 13–14 TeV LHC for H/A/$\mathrm{H^+}$?

and maybe some supersymmetric particles will show up?

4. What next?

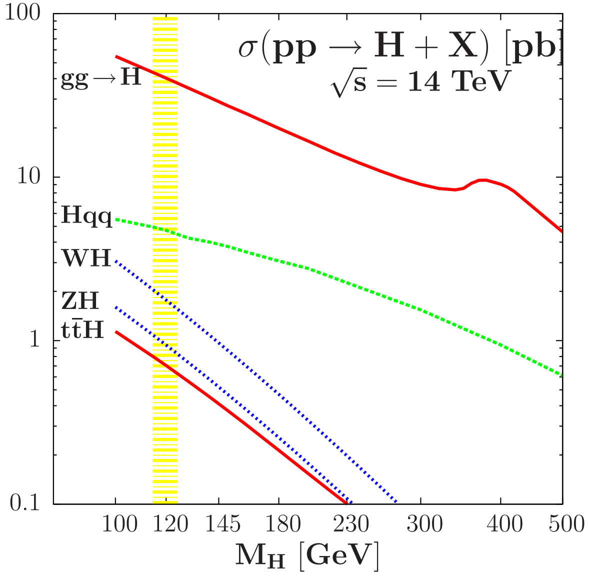
Even if no sign of BSM physics is seen: is Particle Physics “closed”?

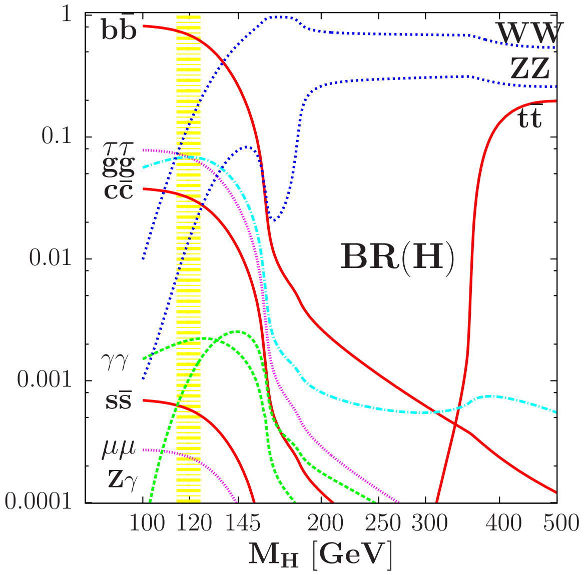
No! Need to check that H is indeed responsible of sEWSB (and SM-like?)

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 and check SM prediction for them,**
- **its couplings to fermions and gauge bosons and check that they are indeed proportional to the particle masses (fundamental prediction!),**
- **its self–couplings to reconstruct the potential V_H that makes EWSB.**

Possible for $M_H \approx$ 126 GeV as all production/decay channels useful!





4. What next? Couplings

- **Look at various H production/decay channels and measure $\mathrm{N_{ev}} = \sigma \times \mathrm{BR}$**
- **But large errors mainly due to:**

– experimental: stats, system., lumi...

– theory: PDFs, HO/scale, jetology...

total error about 20–30% in $\mathrm{gg} \to \mathrm{H}$

Hjj contaminates VBF (now 30%)..

$\Rightarrow$ ratios of σxBR: many errors out!

Deal with width ratios $\Gamma_\mathrm{X}/\Gamma_\mathrm{Y}$

– TH on σ and some EX errors

– parametric errors in BRs

– TH ambiguities from $\Gamma_\mathrm{H}^\mathrm{tot}$

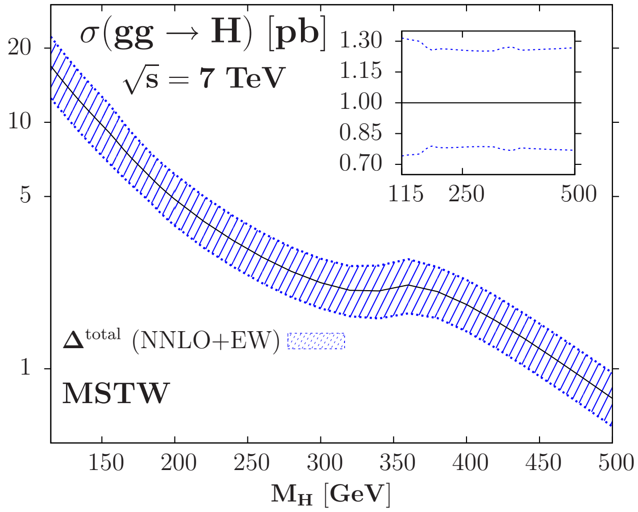
- **Achievable accuracy:**

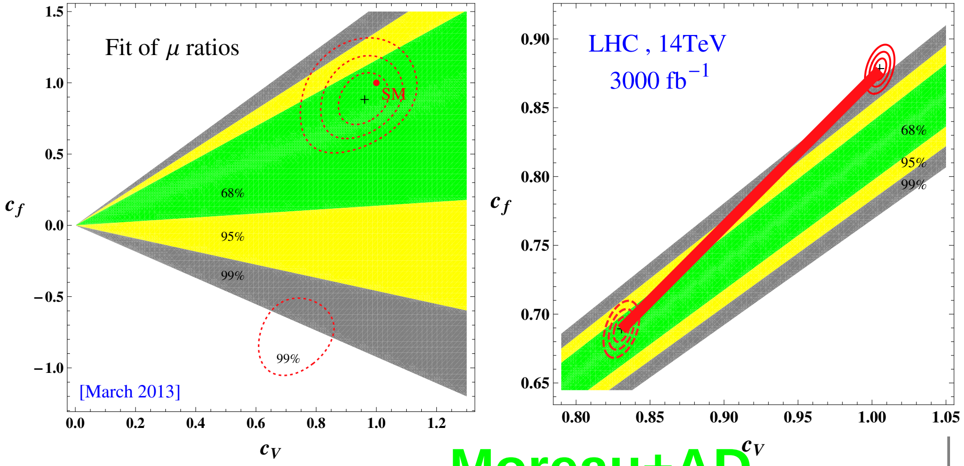
– now: 20–30% on $\gamma\gamma/\mathrm{VV}, \tau\tau/\mathrm{VV}$

– future: few % at HL–LHC!

Sufficient to probe BSM physics?

Baglio+AD





Moreau+AD

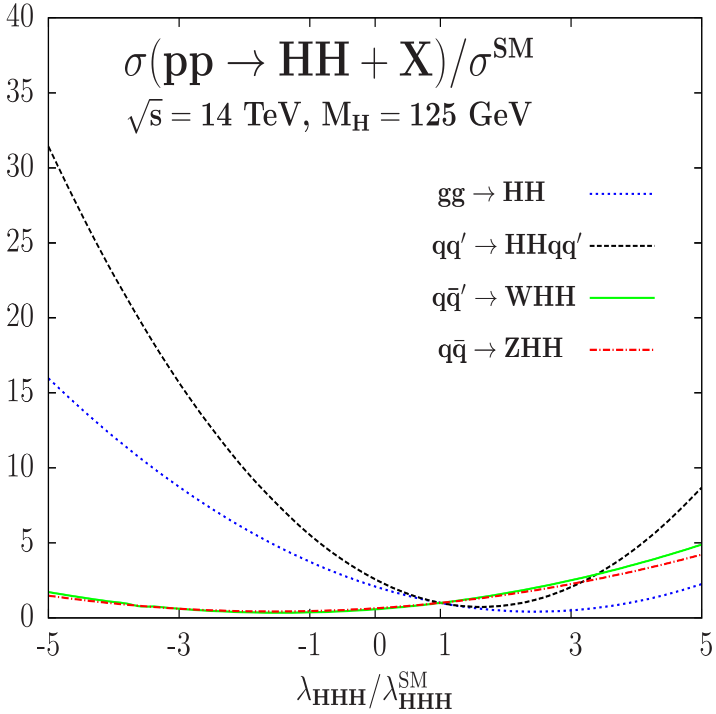
5. What next? Self–coupling

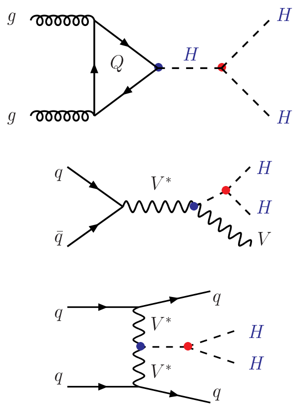
Challenge: measurement of Higgs self-couplings and access to V_H.

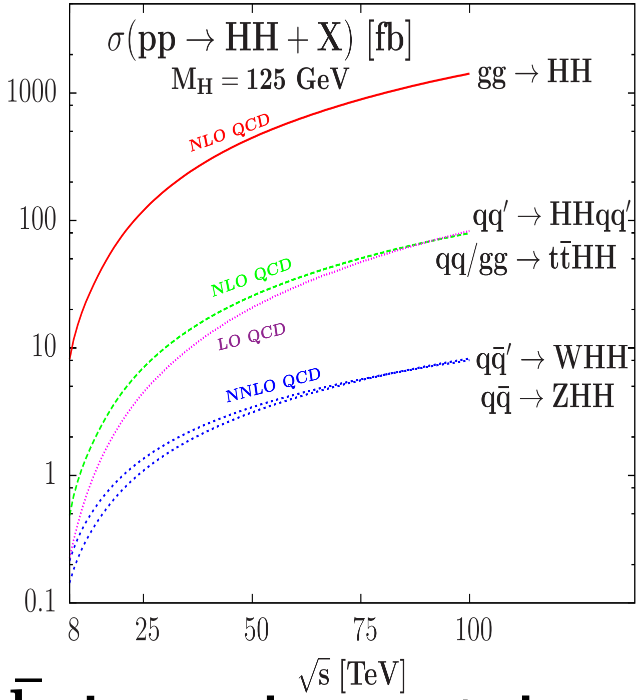
- g_{H^3} **from** $pp \to HH + X \Rightarrow$
- g_{H^4} **from pp→3H+X, hopeless.**

Various processes for HH prod:

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







Baglio et al., arXiv:1212.5581

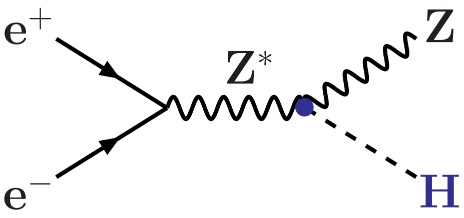
- $H \to b\bar{b}$ **decay alone not clean**
- $H \to \gamma\gamma$ **decay very rare,**
- $H \to \tau\tau$ **would be possible?**
- $H \to WW$ **not useful?**

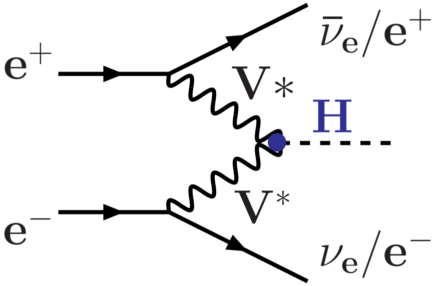
– $bb\tau\tau, bb\gamma\gamma$ **viable?**

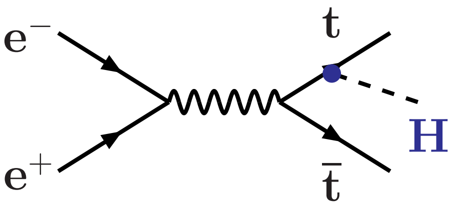
– **but needs very large luminosity.**

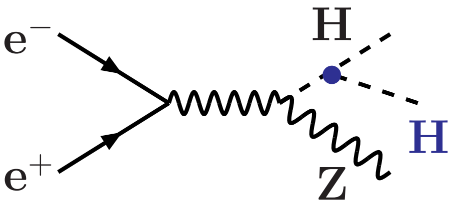
Maybe even needs an ILC.....

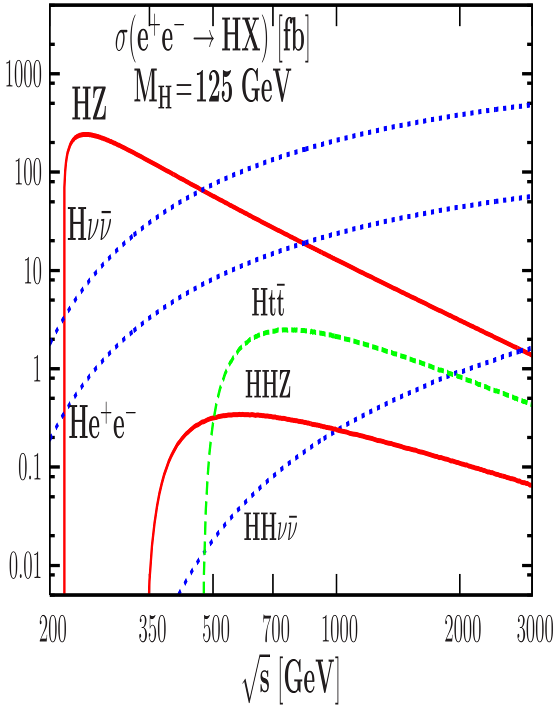
4. What next? ILC











Very precise measurements mostly at $\sqrt{s} \lesssim$ 500 GeV and mainly in $e^+e^- \to ZH$ (with $\sigma \propto 1/s$) and ZHH, ttH

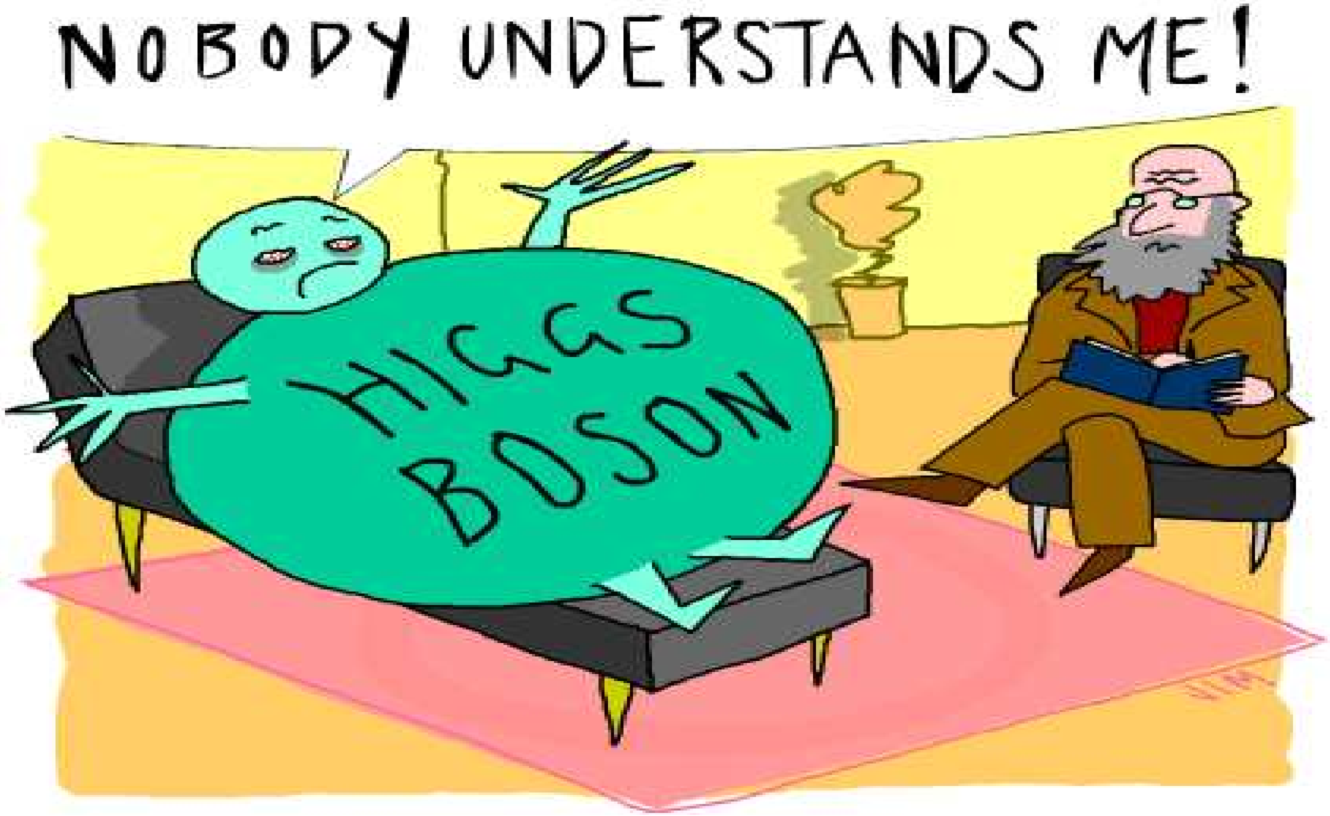
g_{HWW}	± 0.012
g_{HZZ}	± 0.012
g_{Hbb}	± 0.022
g_{Hcc}	± 0.037
$g_{H\tau\tau}$	± 0.033
g_{Htt}	± 0.030
λ_{HHH}	± 0.22
M_H	± 0.0004
Γ_H	± 0.061
CP	± 0.038

⇒ difficult to be beaten by anything else for ≈ 125 GeV Higgs

⇒ welcome to the ILC!

4. What next?

We hope that we will finally understand the Higgs mechanism...



... but there is a long way until we get there....

... and there might be many surprises waiting for us...