

Implications of the Higgs discovery

...



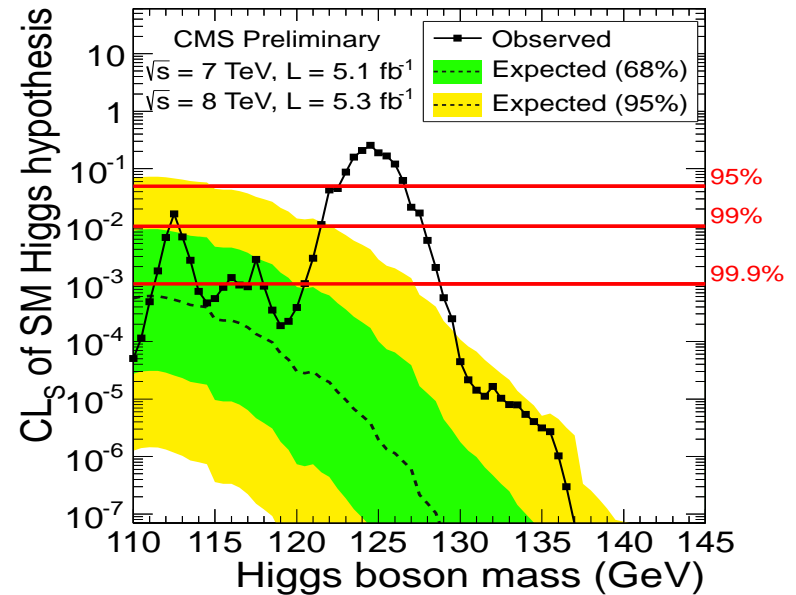
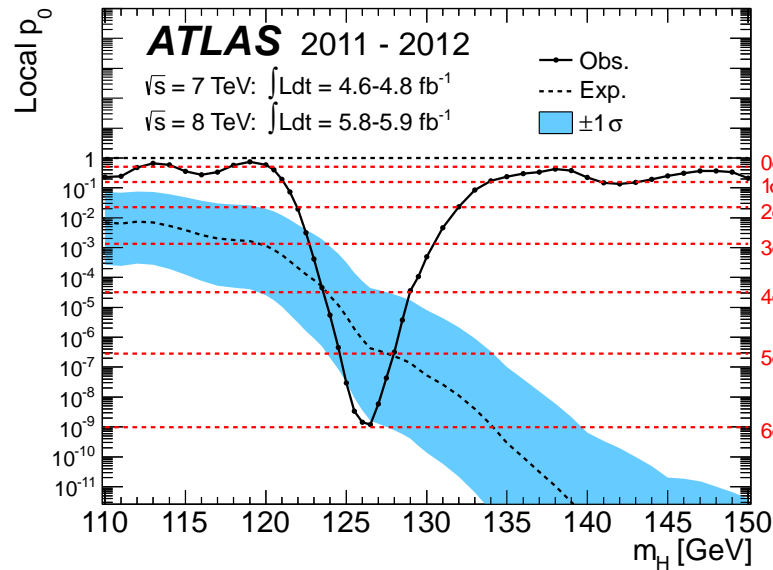
Abdelhak DJOUADI (U. Paris-Sud)



- It is indeed a Higgs...
- 2. Standardissimo!?
- Implications of $M_h \approx 126$ GeV for the MSSM
 - Other implications for the MSSM
 - What next?

1. Is it a Higgs?

After 48 years of postulat, 30 years of search (and a few heart attacks),
“a boson” is discovered at LHC on the 4th of July: Hi(gg)storical day!



1. Is it a Higgs?

The Higgs solves the most crucial problem in particle physics:
how to generate particle masses in an $SU(2) \times U(1)$ gauge invariant way?
in the Standard Model \Rightarrow the Higgs–Englert–Brout mechanism

Introduce a doublet of scalar fields $\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}$ with $\langle 0 | \Phi^0 | 0 \rangle \neq 0$:
fields/interactions symmetric under $SU(2) \times U(1)$ but vacuum not.

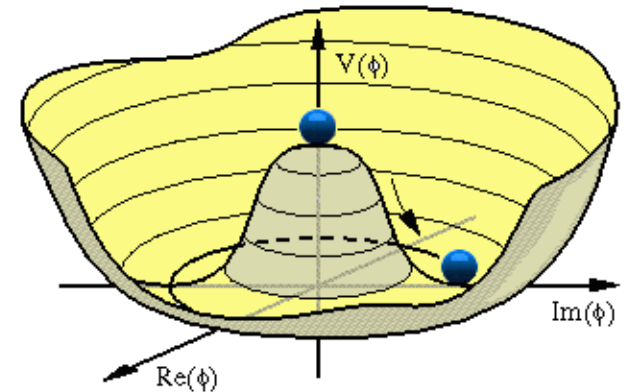
$$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

$$v = (-\mu^2/\lambda)^{1/2} = 246 \text{ GeV}$$

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

For fermion masses, use same Φ :

$$\mathcal{L}_{\text{Yuk}} = -f_e (\bar{e}, \bar{\nu})_L \Phi e_R + \dots$$



Residual d.o.f corresponds to spin-0 H particle.

- The scalar Higgs boson: $J^{PC} = 0^{++}$ quantum numbers (CP-even).
- Mass: $M_H^2 = 2\lambda v^2$ only free parameter; should be $\lesssim \mathcal{O}(v)$
- Higgs couplings \propto particle masses: $g_{Hff} = m_f/v$, $g_{HVV} = 2M_V^2/v$
- Higgs self-couplings from V : $g_{H^3} = 3M_H^2/v, \dots$

1. It is indeed 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.: $c_g \neq c_\gamma, c_V \gg 35c_\gamma$

many th. analyses (no suspense...)

CP no: even, odd, or mixture?

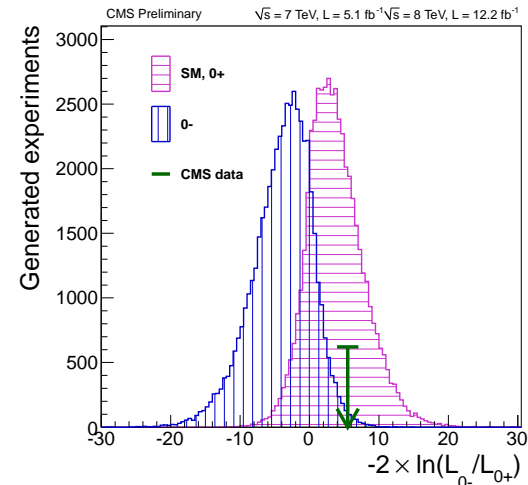
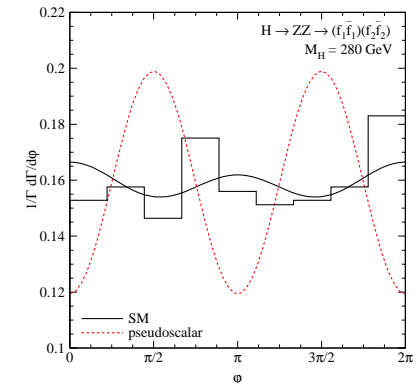
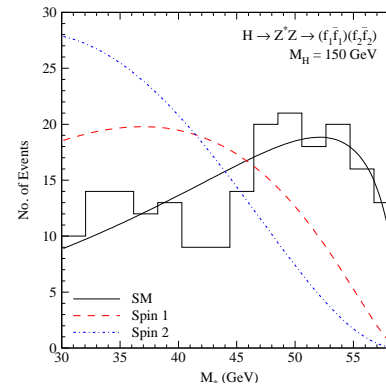
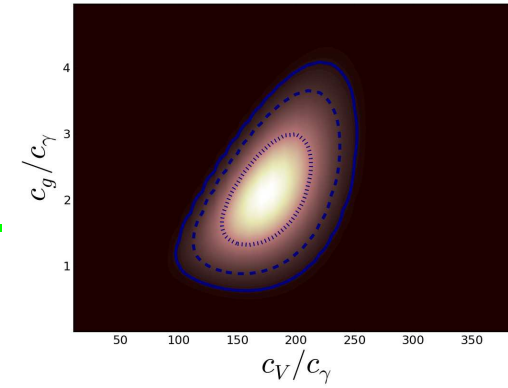
(more important; CPV in Higgs!)

ATLAS and CMS CP analyses for pure CP-even vs pure-CP-odd

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

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

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



1. It is indeed a Higgs...

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

- a pure CP odd Higgs does not couple to VV states at tree-level
- coupling should be generated by loops or HEOF: should be small
- H CP-even with small CP-odd admixture: high precision measurement..
- in $H \rightarrow VV$ only CP-even component projected out in most cases!

Indirect probe: through μ_{VV}

$g_{HVV} = c_V g_{\mu\nu}$ with $c_V \leq 1$

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

gives upper bound on CP mixture:

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

Direct probe: g_{Hff} more democratic

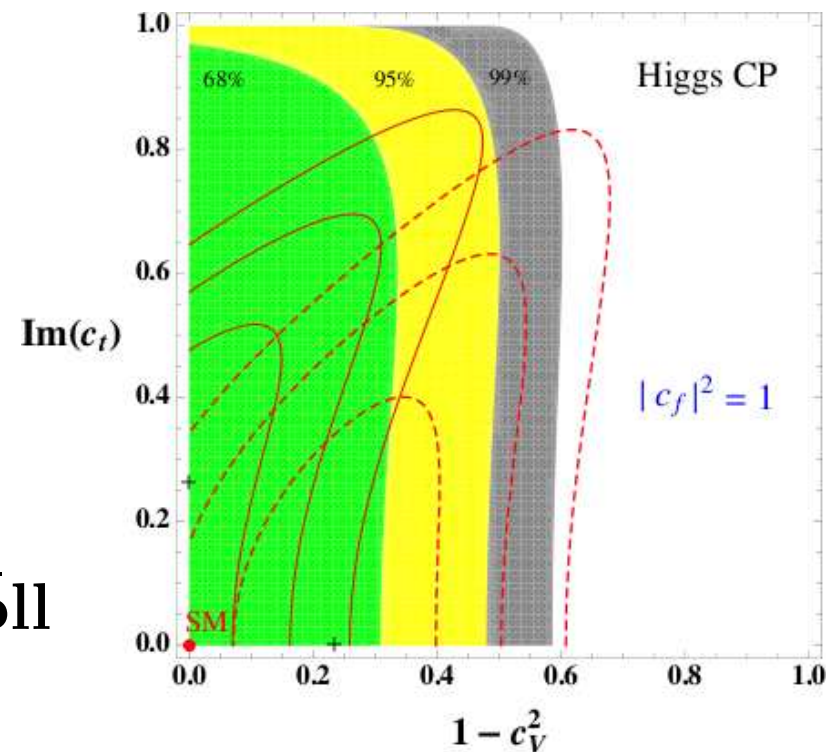
\Rightarrow processes with fermion decays.

spin-correlations in $q\bar{q} \rightarrow HZ \rightarrow b\bar{b}l\bar{l}$

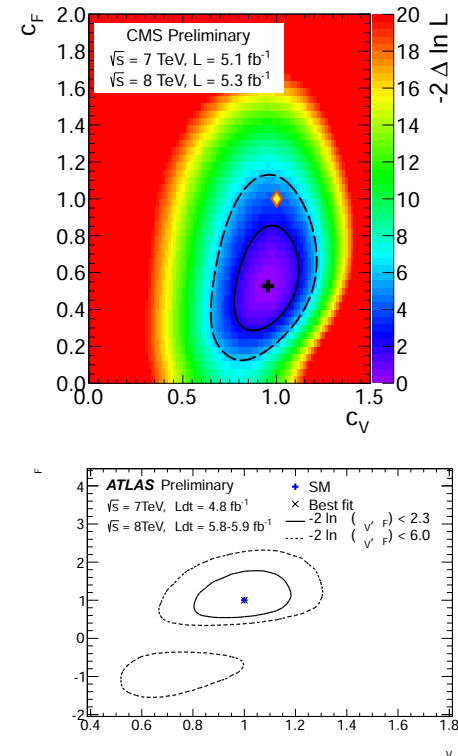
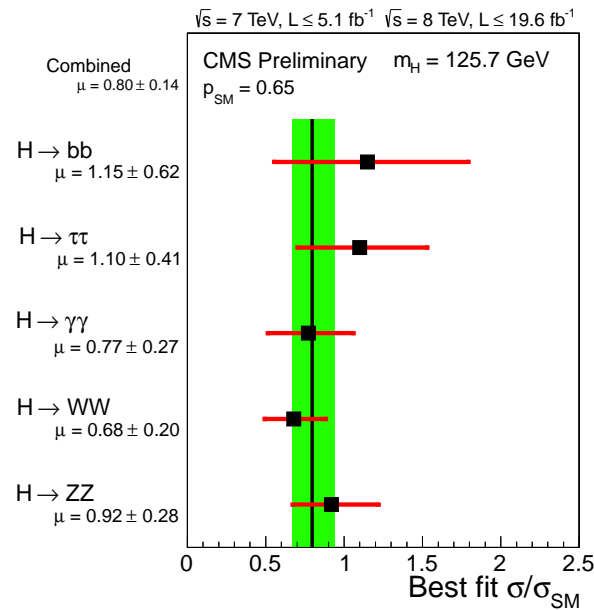
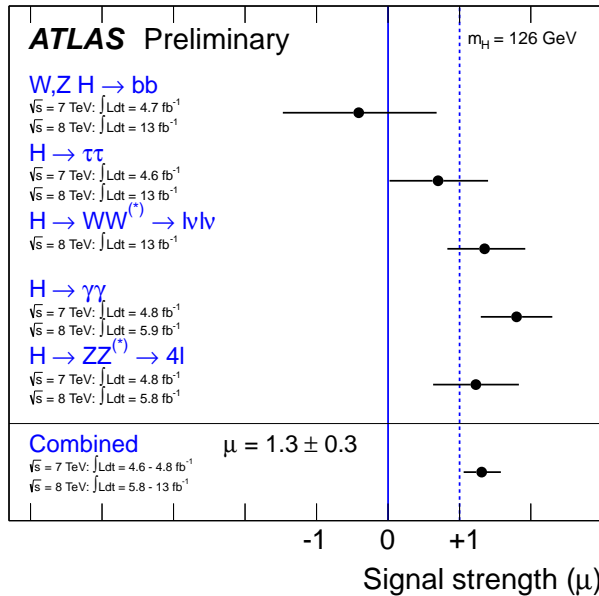
or later in $q\bar{q}/gg \rightarrow Ht\bar{t} \rightarrow b\bar{b}t\bar{t}$.

Extremely challenging even at HL-LHC...

Moreau...



1. It is indeed 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 proportional 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?

2. Standardissimo?!

So it 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:

$$\text{W/Z} \text{ --- } \text{H} \text{ --- } \text{W/Z} \propto \frac{\alpha}{\pi} \log \frac{M_H}{M_W} + \dots$$

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

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

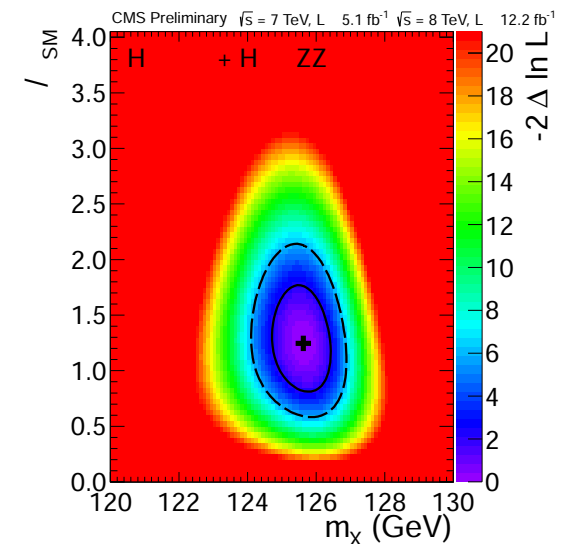
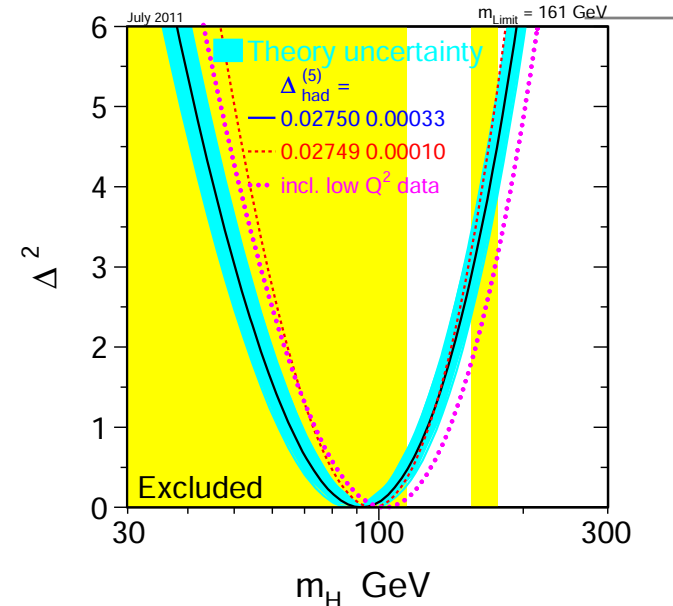
compared with the measured mass

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

A very non-trivial consistency check!
(remember the stop of the top quark!).

The SM is a very successful theory!

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



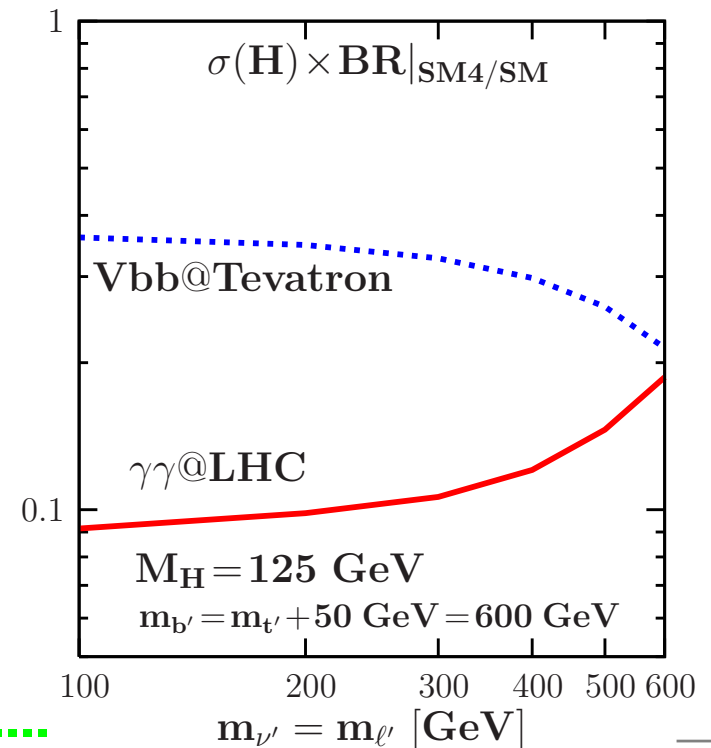
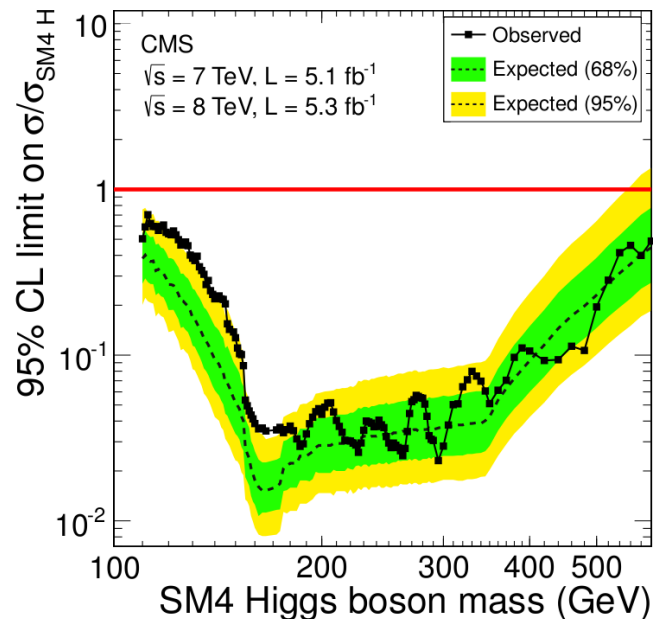
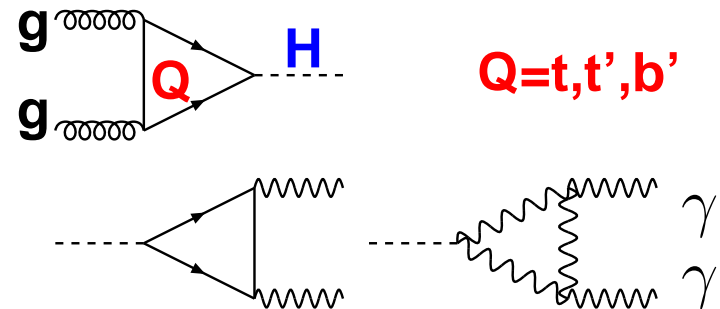
2. Standardismo?!

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

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

- increase $\sigma(gg \rightarrow H)$ by factor ≈ 9
- $H \rightarrow gg$ suppresses $BR(bb, VV)$ by ≈ 2
- strongly suppresses $BR(H \rightarrow \gamma\gamma)$

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



(singlet neutrinos OK)

Lenz....

2. Standardissimo!?

- The theory preserves unitarity:

including H: $|A_0(VV \rightarrow VV)| \propto M_H^2/v^2$

theory unitary if $M_H \lesssim 700$ GeV...

- Extrapolable up to highest scales.

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

– too high: non perturbativity

– too low: stability of the EW vacuum

Cabibbo, Maiani, Parisi, Petronzio

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

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

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

\Rightarrow Degrassi et al., Bezrukov et al.

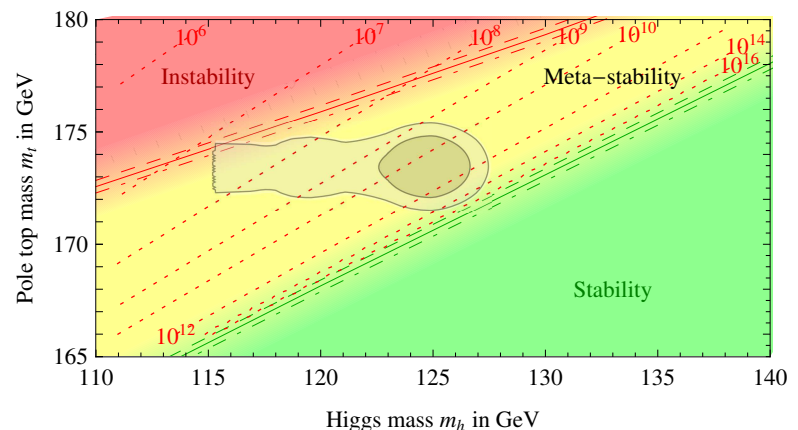
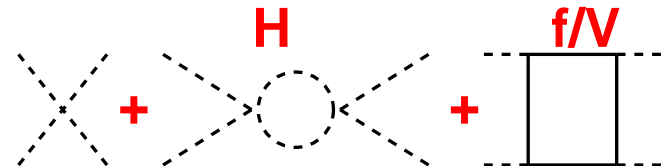
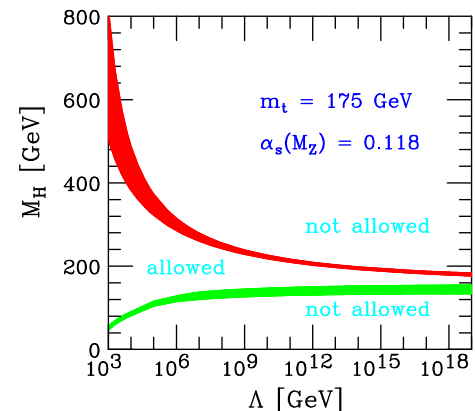
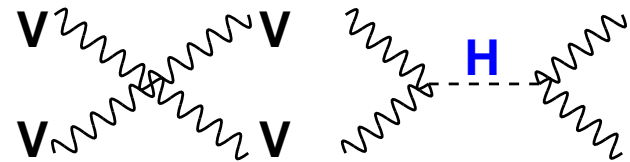
but what is measured m_t at TEV/LHC

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

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

issue needs further studies/checks...

Alekhin....



Degrassi...

2. Standardissimo!?

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

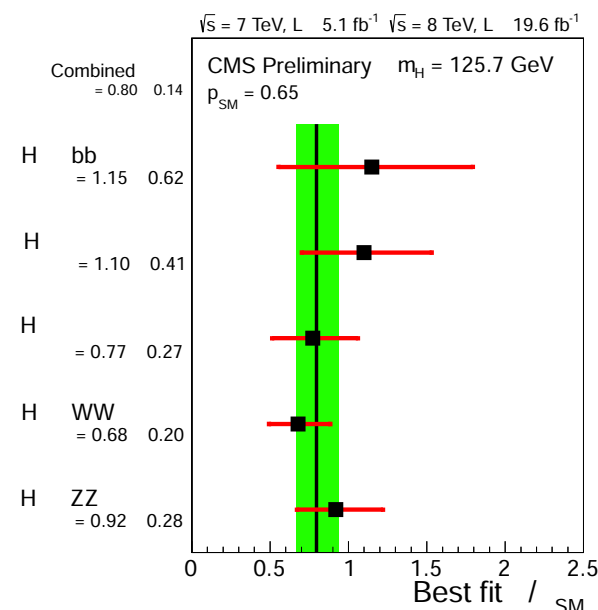
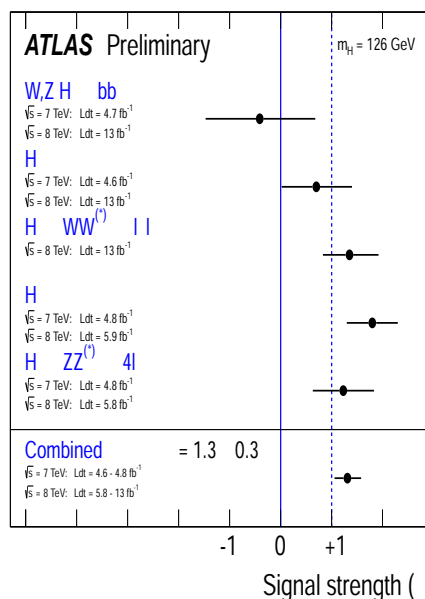
Fit of all LHC Higgs data \Rightarrow agreement at 20–30% level

$$\mu_{\text{tot}}^{\text{ATL}} = 1.30 \pm 0.30$$

$$\mu_{\text{tot}}^{\text{CMS}} = 0.87 \pm 0.23$$

combined : $\mu_{\text{tot}} \simeq 1!$

Standardissimo (TOE)?



• Pros: renormalisable, unitary, perturbative, succesful: OK to M_P ...

• Cons: ν mass, baryogenesis, dark matter, grand unification, ...

\Rightarrow fixed by simple extensions such as SO(10) with ν_{RH} ; ex: Altarelli...

Remains then the hiearchy problem (really?): we need beyond the SM!!

However, the most discussed BSM scenarios 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.

3. Implications of $M_h \approx 126$ GeV for the MSSM

In the MSSM: two Higgs doublets: $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$ and $H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$,

After EWSB (which can be made radiative: more elegant than in SM):

Three dof to make $W_L^\pm, Z_L \Rightarrow$ 5 physical states left out: h, H, A, H^\pm

Only two free parameters at tree-level: $\tan\beta, M_A$ but rad. cor. important

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

– 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	$\frac{\cos\alpha}{\sin\beta} \rightarrow 1$	$\frac{\sin\alpha}{\cos\beta} \rightarrow 1$	$\sin(\beta - \alpha) \rightarrow 1$
H	$\frac{\sin\alpha}{\sin\beta} \rightarrow 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \rightarrow \tan\beta$	$\cos(\beta - \alpha) \rightarrow 0$
A	$1/\tan\beta$	$\tan\beta$	0

In the decoupling limit: MSSM reduces to SM but with a light SM Higgs.

this decoupling limit occurs in many extensions....

At $\tan\beta \gg 1$, one SM-like and two CP-odd like Higgses with cplg to b, τ

$$M_A \leq M_h^{\text{max}} \Rightarrow h \equiv A, H \equiv H_{\text{SM}}, \quad M_A \geq M_h^{\text{max}} \Rightarrow H \equiv A, h \equiv H_{\text{SM}}$$

3. Implications of $M_h \approx 126$ GeV for the MSSM

The mass value 126 GeV is rather large for the MSSM h boson,
 \Rightarrow one needs from the very beginning to almost maximize it...

Maximizing M_h is maximizing the radiative corrections; at 1-loop:

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

- decoupling regime with $M_A \sim \mathcal{O}(\text{TeV})$;
- large values of $\tan\beta \gtrsim 10$ to maximize tree-level value;
- maximal mixing scenario: $X_t = \sqrt{6}M_S$;
- heavy stops, i.e. large $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$;

we choose at maximum $M_S \lesssim 3$ TeV, not to have too much fine-tuning....

- Do the complete job: two-loop corrections and full SUSY spectrum
- Use RGE codes (Suspect) with RC in $\overline{\text{DR}}$ /compare with FeynHiggs (OS)

Perform a full scan of the phenomenological MSSM with 22 free parameters

- determine the regions of parameter space where $123 \leq M_h \leq 129$ GeV (3 GeV uncertainty includes both “experimental” and “theoretical” error)
- require h to be SM-like: $\sigma(h) \times \text{BR}(h) \approx H_{\text{SM}}$ ($H = H_{\text{SM}}$) later)

Many analyses! Here, the one from Arbey et al. 1112.3028+1207.1348

3. Implications of $M_h \approx 126$ GeV for the MSSM

Main results:

- Large M_S values needed:
 - $M_S \approx 1$ TeV: only maximal mixing
 - $M_S \approx 3$ TeV: only typical mixing.
- Large $\tan\beta$ values favored but $\tan\beta \approx 3$ possible if $M_S \approx 3$ TeV

How light sparticles can be with the constraint $M_h = 126$ GeV?

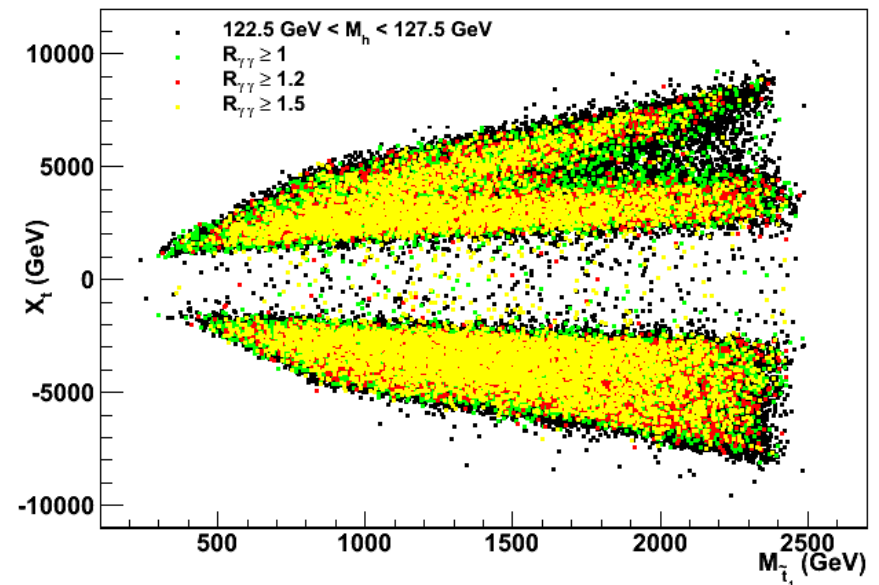
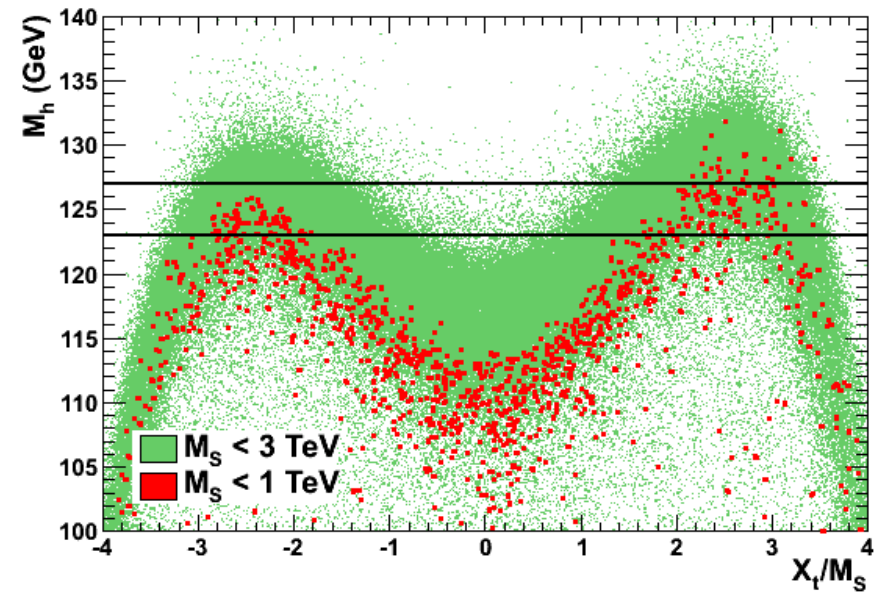
- 1s/2s gen. \tilde{q} should be heavy...

But not main player here: the stops:

$\Rightarrow m_{\tilde{t}_1} \lesssim 500$ GeV still possible!

(see also G. Isidori et al. e.g.)

- M_1, M_2 and μ unconstrained,
 - non-univ. $m_{\tilde{f}}$: decouple $\tilde{\ell}$ from \tilde{q}
- EW sparticles can be still very light but watch out the new LHC limits..

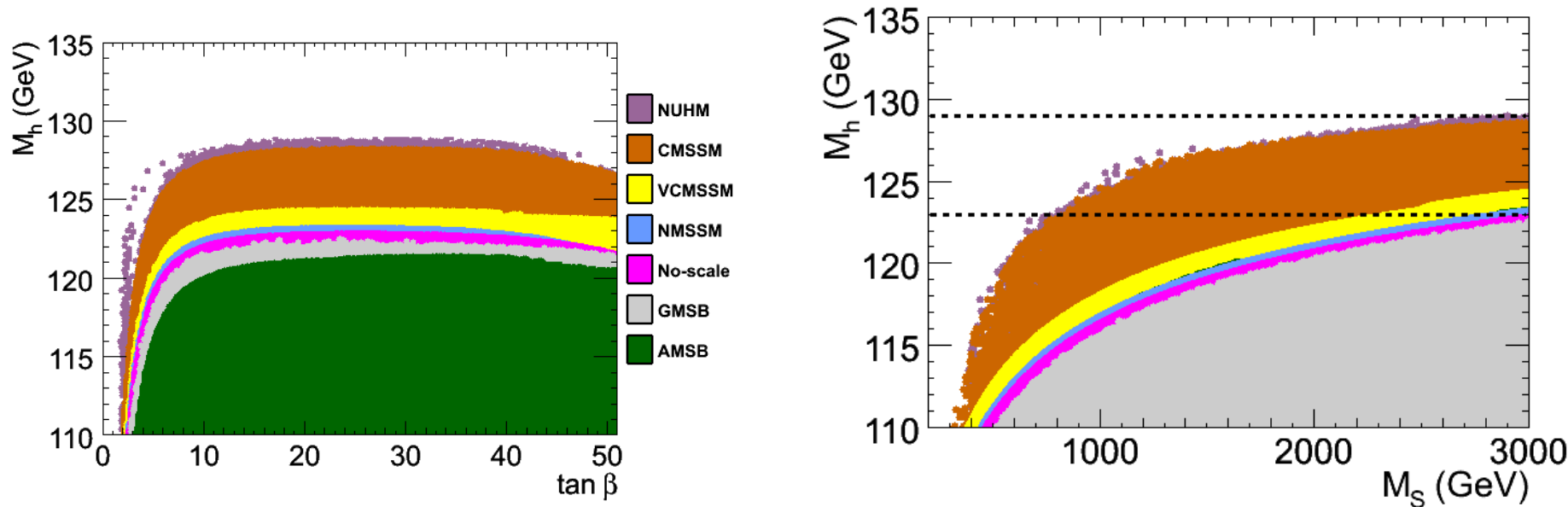


3. Implications of $M_h \approx 126$ GeV for the MSSM

Constrained MSSMs are interesting from model building point of view:

- concrete schemes: SSB occurs in hidden sector $\xrightarrow{\text{gravity, ...}}$ MSSM fields
- provide solutions to some MSSM problems: CP, flavor, etc..
- parameters obey boundary conditions \Rightarrow small number of inputs...
- **mSUGRA**: $\tan \beta$, $m_{1/2}$, m_0 , A_0 , $\text{sign}(\mu)$
- **GMSB**: $\tan \beta$, $\text{sign}(\mu)$, M_{mes} , Λ_{SSB} , N_{mess} fields
- **AMSB**: m_0 , $m_{3/2}$, $\tan \beta$, $\text{sign}(\mu)$

full scans of the model parameters with $123 \text{ GeV} \leq M_h \leq 129 \text{ GeV}$



very strong constraints and some (minimal) models ruled out...

3. Implications of $M_h \approx 126$ GeV for the MSSM: mass

As the scale M_S seems to be large, consider two extreme possibilities

- **Split SUSY: allow fine-tuning** scalars (including H_2) at high scale
gauginos–higgsinos at weak scale
(unification+DM solutions still OK)
 $M_h \propto \log(M_S/m_t) \rightarrow$ large
- **SUSY broken at the GUT scale...**
give up fine-tuning and everything else
still, $\lambda \propto M_H^2$ related to gauge cplgs

$$\lambda(\tilde{m}) = \frac{g_1^2(\tilde{m}) + g_2^2(\tilde{m})}{8} (1 + \delta_{\tilde{m}})$$

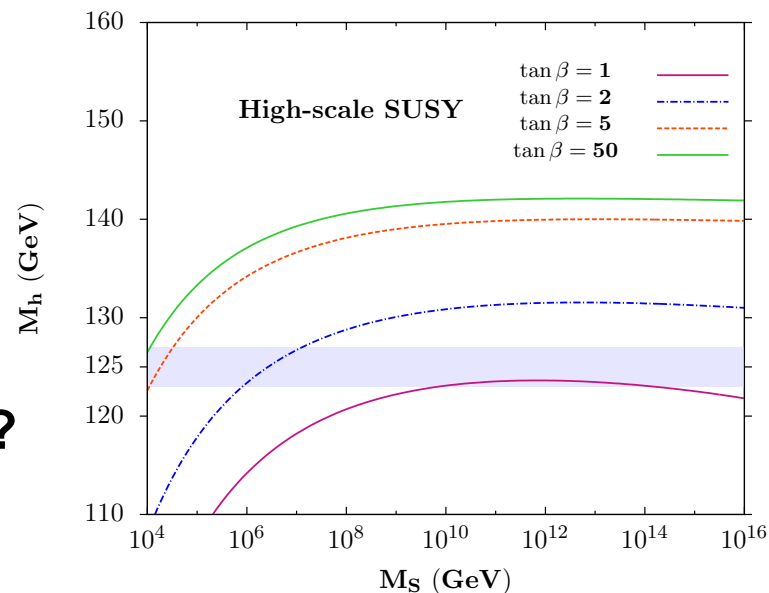
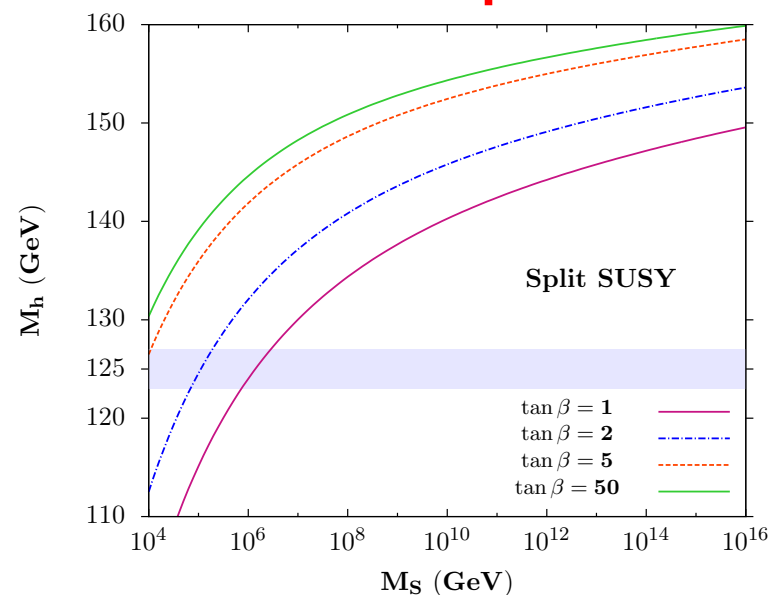
... leading to $M_H = 120\text{--}140$ GeV ...

In both cases small $\tan\beta$ needed...

note 1: $\tan\beta \approx 1$ possible

note 2: M_S large and not M_A possible!?

Consider general MSSM with $\tan\beta \approx 1$!



3. Implications of $M_h \approx 126$ GeV for the MSSM

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

- $M_H = 120$ GeV would have been a boring value: everybody OK..
- $M_H = 150$ GeV would be a devastating value: mass extinction..
- $M_H \approx 126$ GeV is interesting: (natural) selection among models..

Implications in the context of the MSSM:

SUSY spectrum apparently heavy (also backed up by direct searches) except maybe stops and weakly interacting sparticles ($\chi_i^0, \chi_i^\pm, \tilde{\ell}, \tilde{\nu}$).

what does it mean?

- Natural or unnatural? not so easy to quantify/judge...
- Multiverse? almost philosophical question...
- Maybe we simply need to go beyond the celebrated MSSM

to increase $M_h \Rightarrow$ NMSSM and more Higgs structure, more matter...

Personal feeling: it is still action time!

- keep searching for SUSY with more focus on stops and EW states
- another hope: discover the heavier Higgs states...

with an open mind towards more complicated/extended scenarios...

4. Heavy Higgses in the MSSM

Higgs decays in the MSSM:

General features:

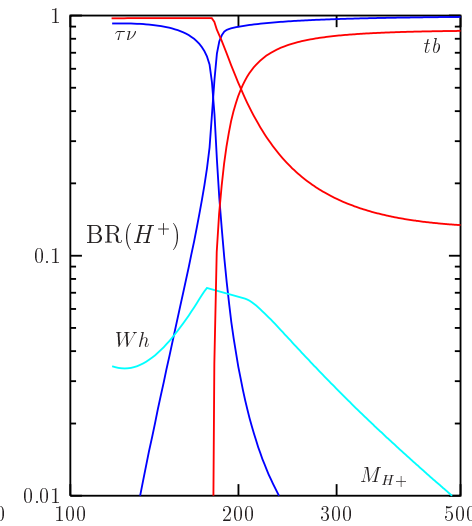
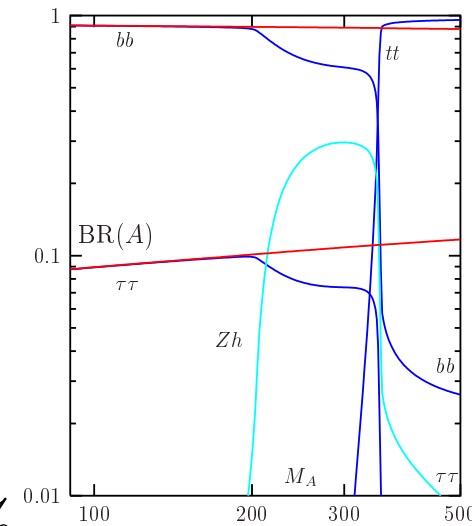
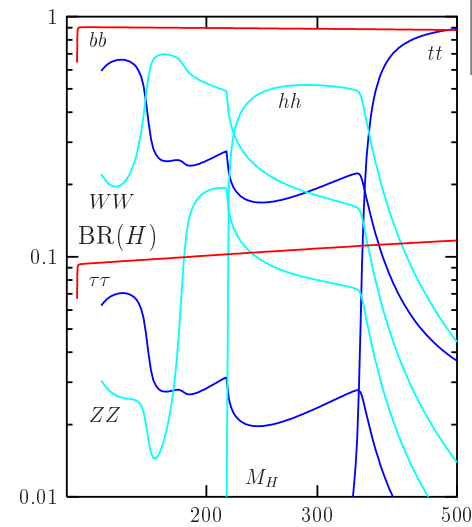
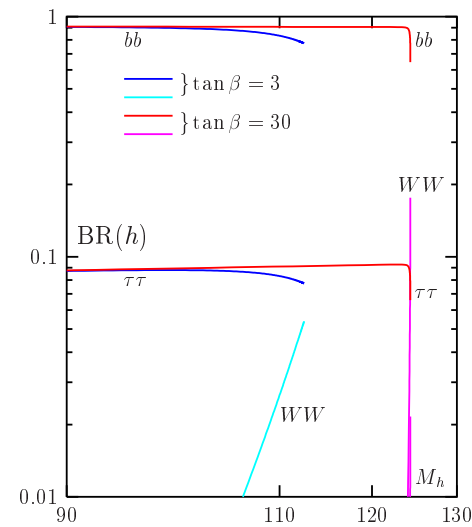
- h : same as H_{SM} in general (esp. in decoupling limit) if not $h \rightarrow b\bar{b}, \tau^+\tau^-$ enhanced for $\tan\beta > 1$
- A : only $b\bar{b}, \tau^+\tau^-$ and $t\bar{t}$ decays (no VV decays, hZ suppressed).
- H : same as A in general; $\tan\beta \gg 1$ WW, ZZ, hh decays suppressed.
- H^\pm : $\tau\nu$ and tb decays (depending if $M_{H^\pm} < \text{or} > m_t$).

Possible new effects from SUSY!!

For $\tan\beta \gg 1$, only decays into b/τ :

BR: $\Phi \rightarrow b\bar{b} \approx 90\%$, $\Phi \rightarrow \tau\tau \approx 10\%$

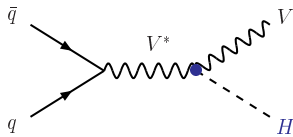
For $\tan\beta \approx 1$, other channels need to be considered too!



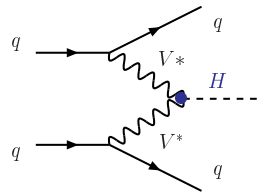
4. Heavy Higgses in the MSSM

SM production mechanisms

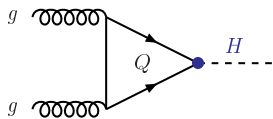
Higgs-strahlung



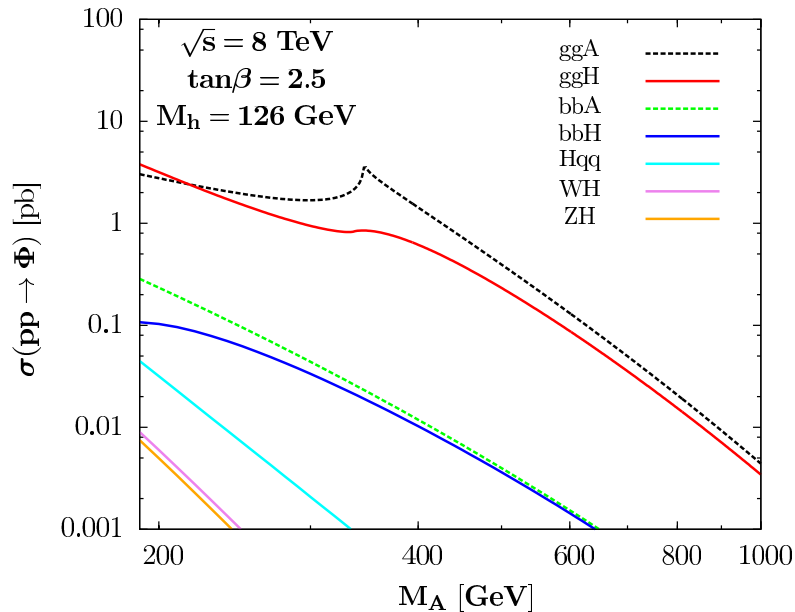
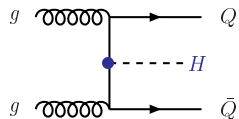
Vector boson fusion



gluon-gluon fusion



in associated with $Q\bar{Q}$



What is different in MSSM

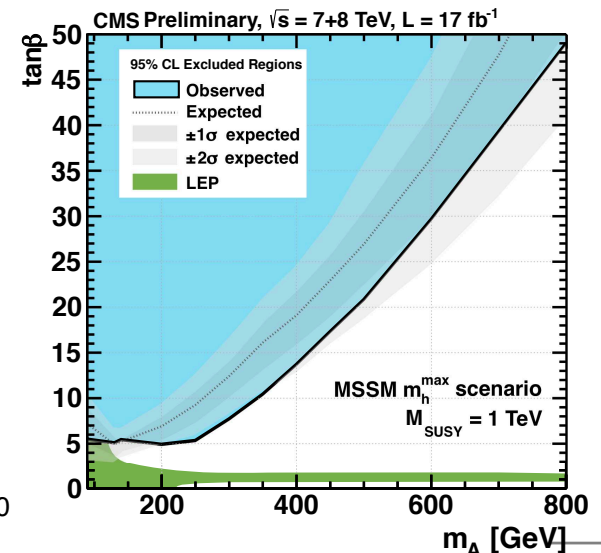
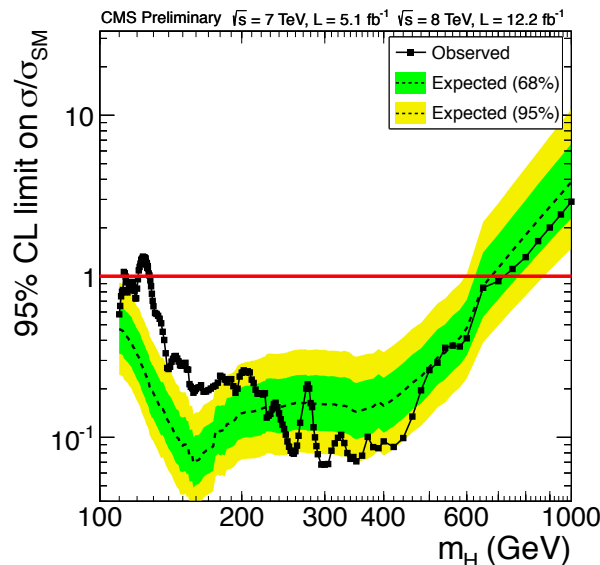
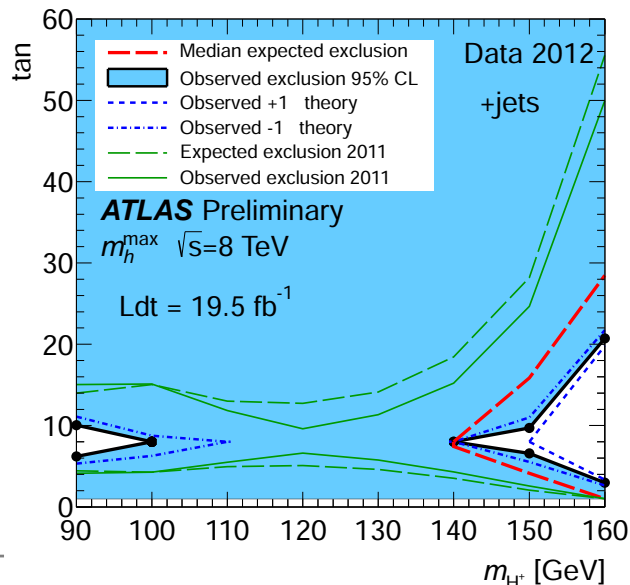
- All work for CP-even h, H bosons.
 - in ΦV , $qq\Phi$ h/H complementary
 - additional mechanism: $qq \rightarrow A+h/H$
 - For $gg \rightarrow \Phi$ and $pp \rightarrow QQ\Phi$
 - include the contr. of b -quarks
 - dominant contr. at high $\tan\beta$!
 - For pseudoscalar A boson:
 - CP: no ΦA and qqA processes
 - $gg \rightarrow A$ and $pp \rightarrow bbA$ dominant.
 - For charged Higgs boson:
 - $M_H \lesssim m_t$: $pp \rightarrow t\bar{t}$ with $t \rightarrow H^+ b$
 - $M_H \gtrsim m_t$: continuum $pp \rightarrow t\bar{b}H^-$
- At high $\tan\beta$ values:**
- h as in SM with $M_h = 115 - 130 \text{ GeV}$
 - dominant channel: $gg, b\bar{b} \rightarrow \Phi \rightarrow \tau\tau$

4. Heavy Higgses in the MSSM

There are other (stringent) constraints on pMSSM to be included (besides the production/decay rates of the observed Higgs)

- Searches for the $pp \rightarrow A/H/(h) \rightarrow \tau\tau$ process;
- Searches for charged Higgs in $t \rightarrow bH^+ \rightarrow b\tau\nu$;
- non observation of heavier Higgs bosons in $H \rightarrow ZZ, WW$;
- one can add searches for resonances in the $H/A \rightarrow t\bar{t}$ channel

Besides: one has constraints from flavor, $B_s \rightarrow \mu\mu$, $b \rightarrow s\gamma \dots$) and constraints from sparticle searches and eventually Dark Matter..



4. Heavy Higgses in the MSSM

Model independent – effective – approach

- $\tan\beta \lesssim 3$ usually “excluded” by LEP2:
 $M_h \gtrsim 114$ GeV for BMS with $M_S \approx 1$ TeV.

Be we can be more relaxed: $M_S \gg M_Z$
 $\Rightarrow \tan\beta$ as low as 1 could be allowed!

- We turn $M_h \approx M_Z |\cos 2\beta| + RC$ to
 $RC = 126 \text{ GeV} - f(M_A, \tan\beta)$

ie. we “trade” RC with the measured M_h

MSSM with only 2 inputs at HO: $M_A, \tan\beta$

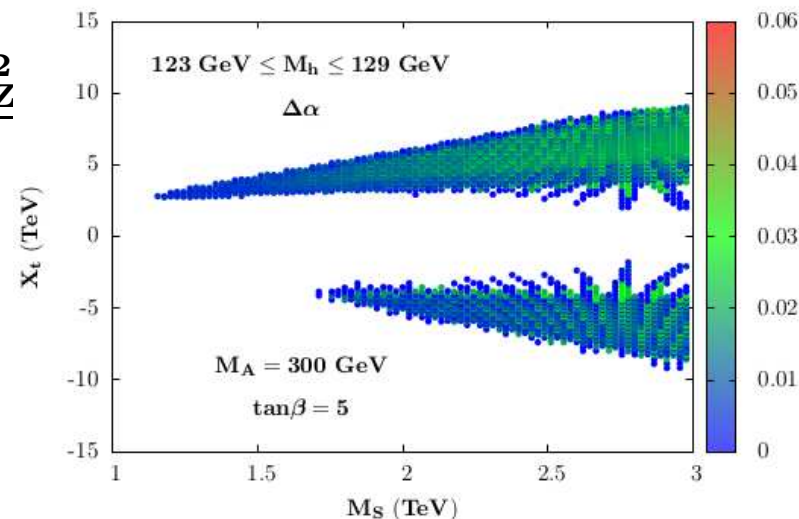
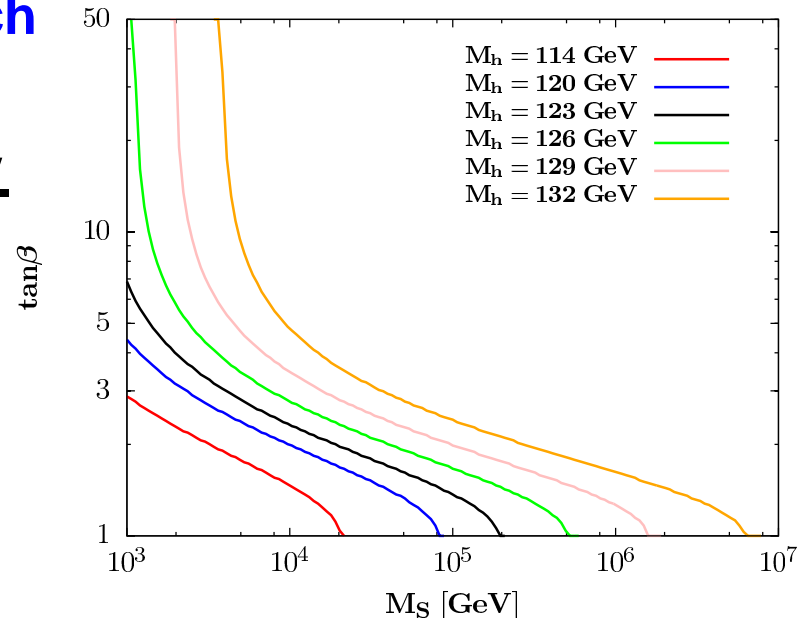
$$M_{H^\pm}^2 = \frac{(M_A^2 + M_Z^2 - M_h^2)(M_Z^2 c_\beta^2 + M_A^2 s_\beta^2) - M_A^2 M_Z^2}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2}$$

$$\alpha = -\arctan \left(\frac{(M_Z^2 + M_A^2) c_\beta s_\beta}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2} \right)$$

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

Habemus MSSM (hMSSM):

AD, Maiani, Polosa, Quevillon, Riquer



4. Heavy Higgses in the MSSM

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

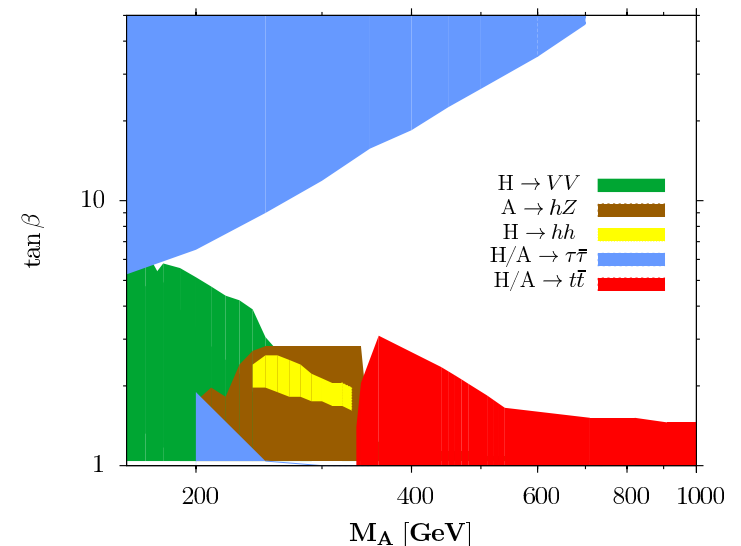
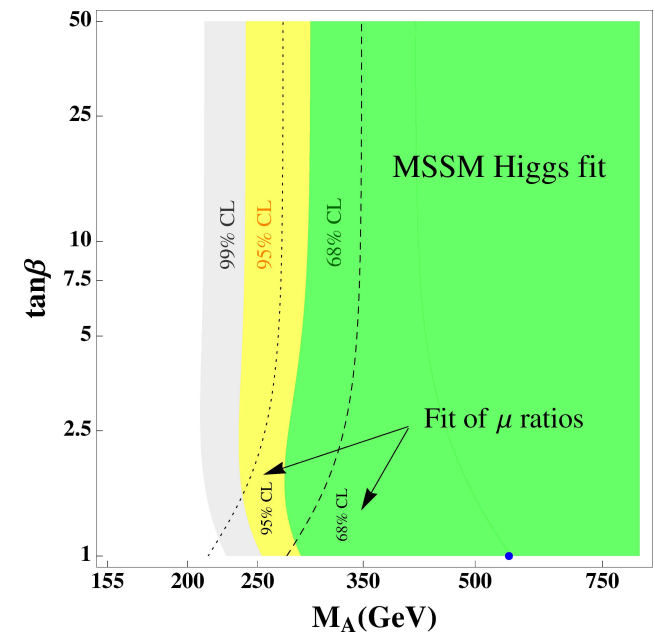
- Fits of the h properties \Rightarrow can be turned into MSSM constraints
 - no important direct SUSY corrections (no sbottom/sbootom contributions)
 - use both signal strengths and ratios

AD, Maiani, Polosa, Quevillon, Riquer

h SM-like $\Rightarrow M_A \gtrsim 200 - 500$ GeV

- Constraints in the high $\tan\beta$ region:
 - $t \rightarrow H^+ b \rightarrow b \tau \nu : M_A \gtrsim 140$ GeV
 - $H/A \rightarrow \tau\tau : M_A \gtrsim 300$ GeV
- Constraints on the low $\tan\beta$ region:
 - $H \rightarrow WW, ZZ$ in SM
 - $H \rightarrow tt$ in BSM scenarios
 - $H \rightarrow hh$ and $A \rightarrow hZ$..

Use current data for constraints...



5. What next?

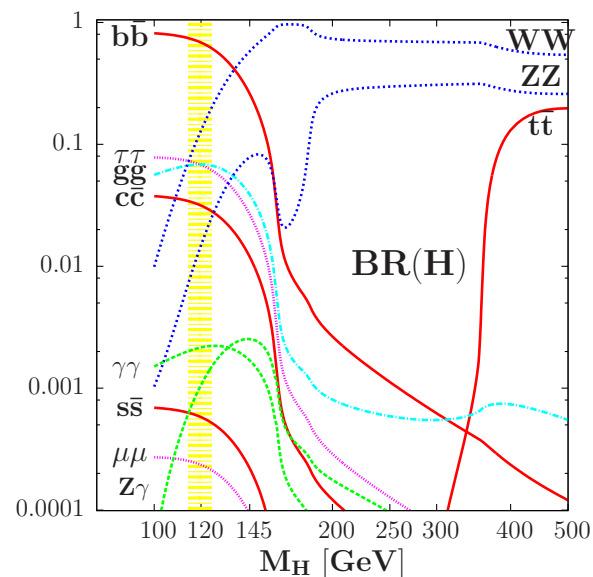
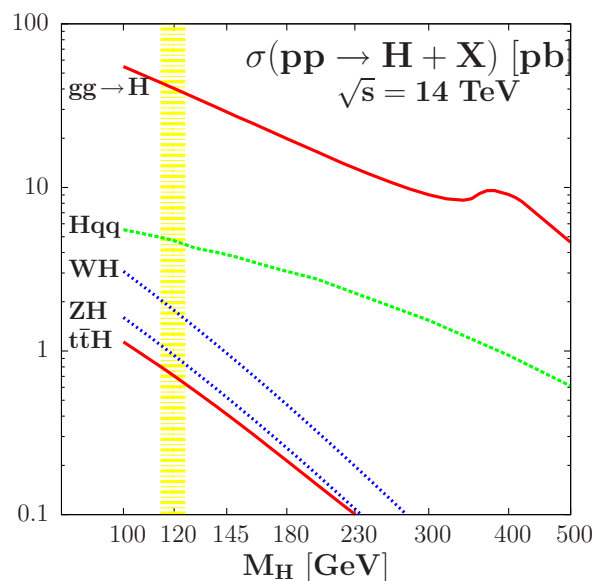
Even if no sign of BSM physics is seen: is Particle Physics “closed”?

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!



5. What next?

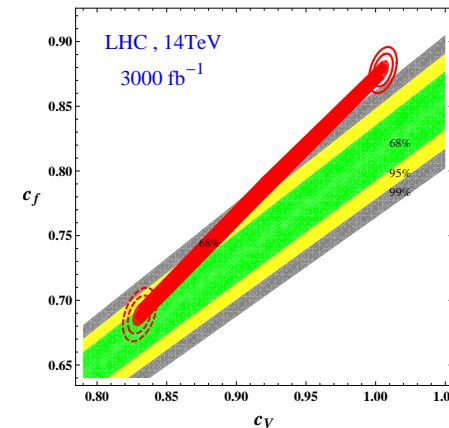
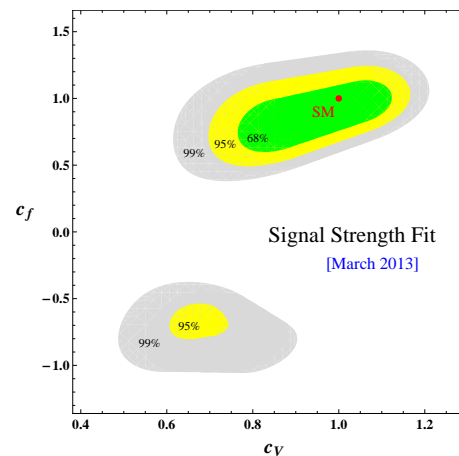
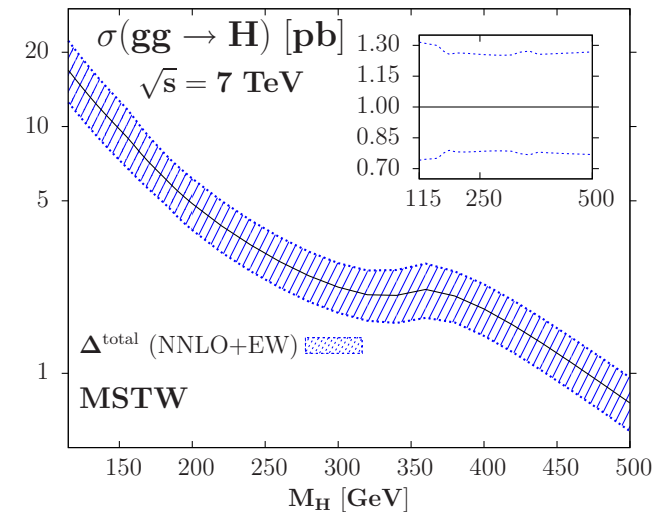
- Look at various H production/decay channels and measure $N_{\text{ev}} = \sigma \times \text{BR}$
 - But large errors mainly due to:
 - experimental: stats, system., lumi...
 - theory: PDFs, HO/scale, jetology...
- total error about 15–20% in $gg \rightarrow H$
 Hjj contaminates VBF (now 30%)..

⇒ **ratios of $\sigma \times \text{BR}$: many errors out!**

Deal with width ratios Γ_X/Γ_Y

- TH on σ and some EX errors
- parametric errors in BRs
- TH ambiguities from Γ_H^{tot}
- Achievable accuracy:
 - now: 20–30% on $\mu_{\frac{\gamma\gamma}{VV}}, \mu_{\frac{\tau\tau}{VV}}$
 - future: few % at HL–LHC!

Baglio...



Moreau...

Sufficient to probe BSM physics?

5. What next?

- **Total width:** $\Gamma_H = 4 \text{ MeV}$, too small to be resolved experimentally.
 - very loose bound from interference $gg \rightarrow ZZ$ (a factor 10 at most..).
 - no way to access it indirectly (via production rates) in a precise way.
- **Invisible decay width:** more easily accessible at the LHC

Direct measurement:

$q\bar{q} \rightarrow HZ$ and $qq \rightarrow Hqq$; $H \rightarrow \text{inv}$

Combined HZ+VBF search from CMS

$BR_{\text{inv}} \lesssim 50\% @ 95\% \text{CL}$ for SM Higgs

More promising in the future: monojets

$gg \rightarrow H + j \rightarrow j + E_T$

Falkowski...

Indirect measurement:

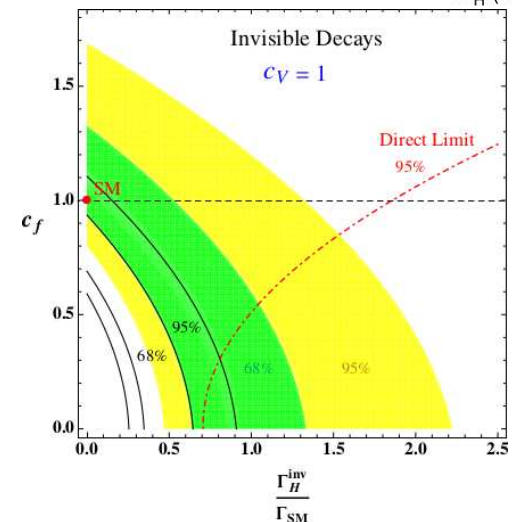
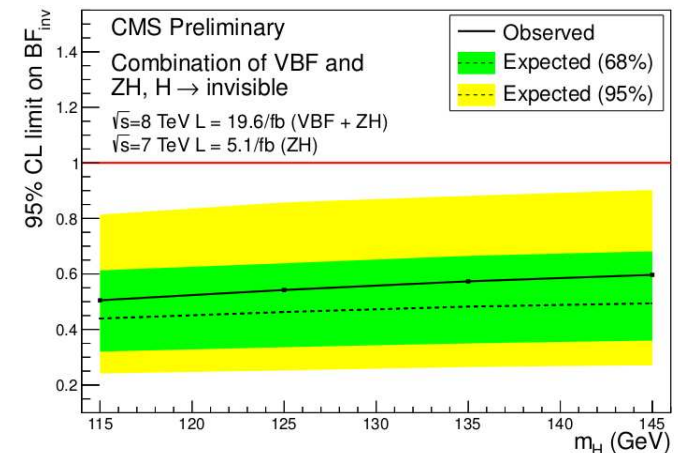
again assume SM-like Higgs couplings

constrain width from signal strengths

$BR_{\text{inv}} \lesssim 50\% @ 95\% \text{CL}$ for $c_f = c_V = 1$

Moreau...

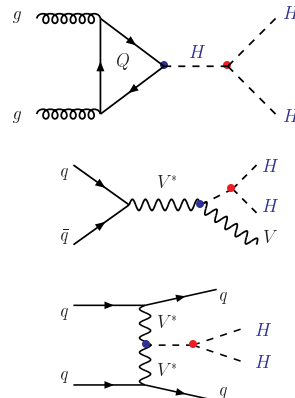
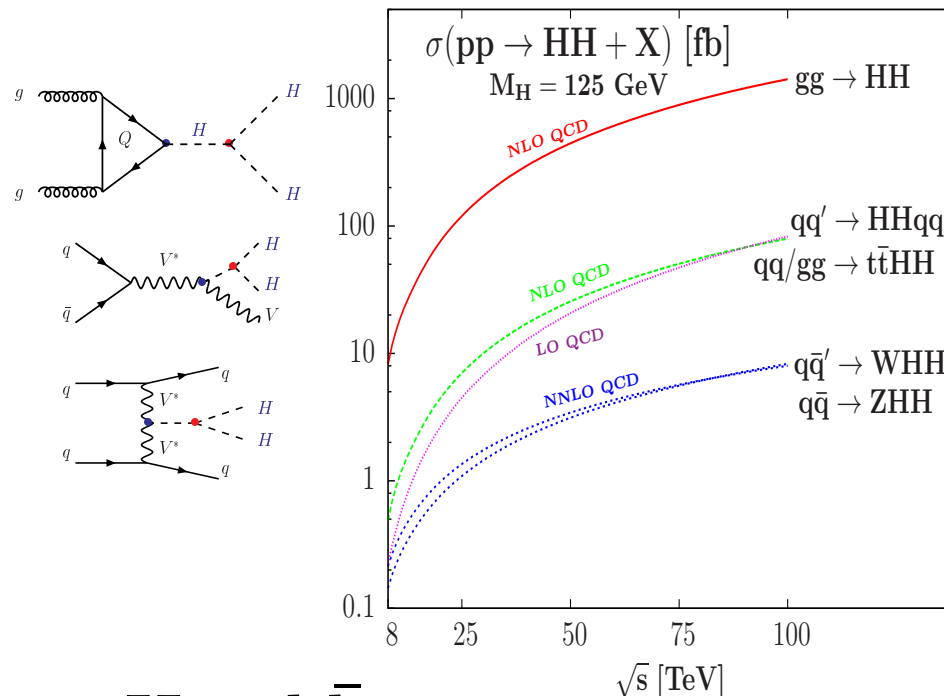
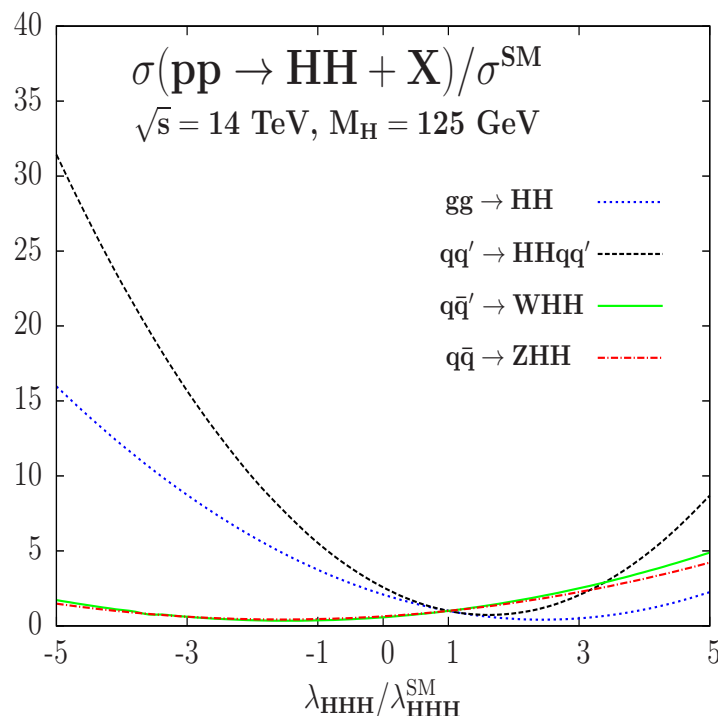
Improvement in future: 10% @ HL-LHC?



5. What next?

Another challenge: measure Higgs self-couplings and access to V_H .

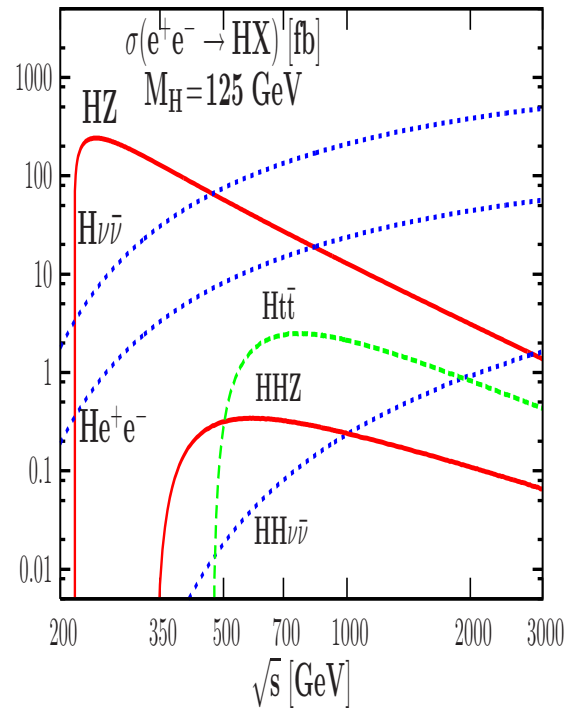
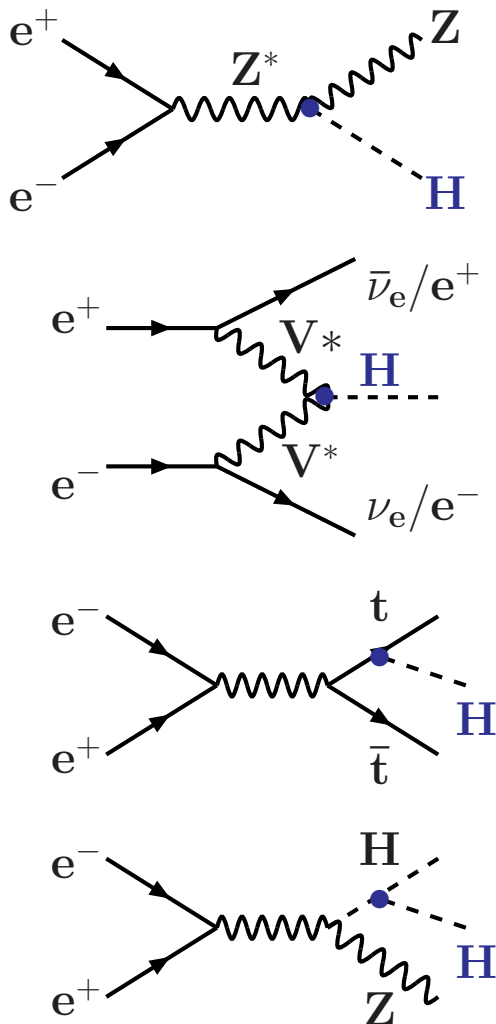
- g_{H^3} from $pp \rightarrow HH + X \Rightarrow$
 - g_{H^4} from $pp \rightarrow 3H + X$, hopeless.
- Various processes for HH prod:
only $gg \rightarrow HHX$ relevant...



- $H \rightarrow b\bar{b}$ decay alone not clean
- $H \rightarrow \gamma\gamma$ decay very rare,
- $H \rightarrow \tau\tau$ would be possible?
- $H \rightarrow WW$ not useful?
- $bb\tau\tau, bb\gamma\gamma$ viable?
- but needs ¹very large luminosity.

Baglio et al., arXiv:1212.5581

5. What next?



Very precise measurements mostly at $\sqrt{s} \lesssim 500$ GeV and mainly in $e^+e^- \rightarrow ZH$ (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

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

\Rightarrow welcome to the ILC!

5. What next?



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

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!

