After the Higgs discovery:

implications for high–energy physics

Abdelhak DJOUADI (LPT Paris-Sud)

- Before the 4th of July
- The 4th of July and the day after...
- Measurement of the Higgs at the LHC
- Further tests at the ILC?

1. Before the 4th of July

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

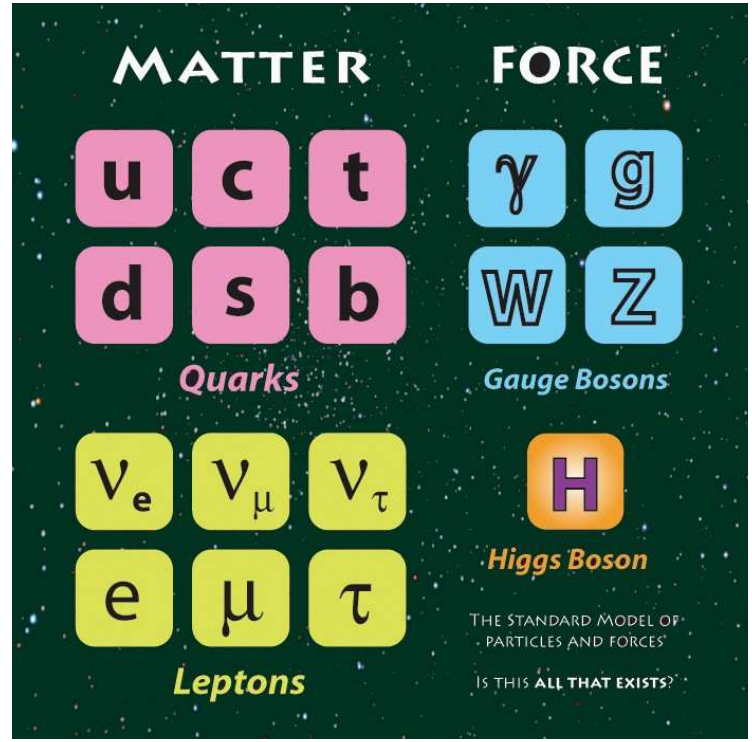
the interaction of $s = \frac{1}{2}$ matter particles
via exchange of $s = 1$ force particles.
It is based on a gauge symmetry:

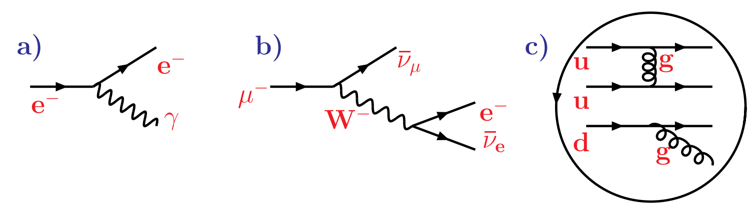
$\mathbf{SU(3)_C \times SU(2)_L \times U(1)_Y}$

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

$\Rightarrow$ infinitely precise predictions,
$\Rightarrow$ high precision experimental tests.

But true only if particles are massless:
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?

$\Rightarrow$ the Brout–Englert–Higgs mechanism for EW symmetry breaking!

1. Before the 4th of July

Introduce a doublet of scalar fields $\Phi = \binom{\Phi^+}{\Phi^0}$ with $\langle 0|\Phi^0|0\rangle \neq 0$:

fields/interactions symmetric under SU(2)×U(1) but vaccum not.

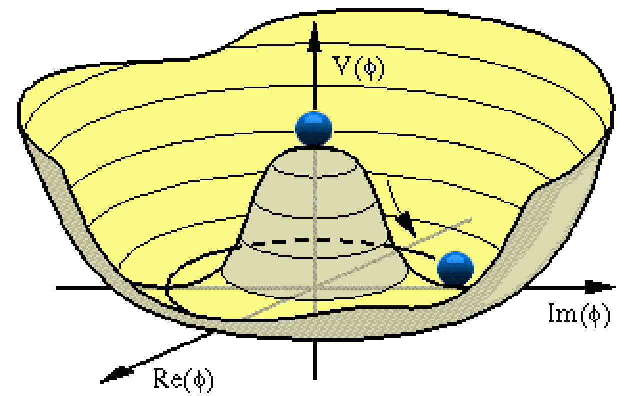
$$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger\Phi)^2$$

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

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

For fermion masses, use <u>same</u> Φ:

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



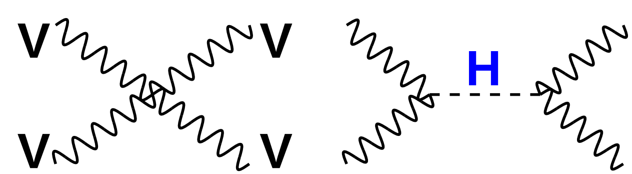
Residual d.o.f corresponds to spin–0 H particle.

- The scalar Higgs boson: $J^{PC} = 0^{++}$ quantum numbers.
- Masses and self–couplings from V : $M_H^2 = 2\lambda v^2, g_{H^3} = 3\frac{M_H^2}{v}, \ldots$
- Higgs couplings $\propto$ particle masses: $g_{Hff} = \frac{m_f}{v}, g_{HVV} = 2\frac{M_V^2}{v}$

The Higgs unitarizes the theory:

without H: $|A_0(VV \to VV)| \propto E^2/v^2$

including H with couplings as predicted:



$|A_0| \propto M_H^2/v^2 \Rightarrow$ the theory is unitary but needs $M_H \lesssim 700$ GeV...

1. Before the 4th of July

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

Once $\mathrm{M_H}$ known, all properties of the Higgs are fixed (modulo QCD).

Example: Higgs decays in the SM

- **As $\mathrm{g_{HPP}} \propto \mathrm{m_P}$, H will decay into heaviest particle phase-space allowed:**
- $\mathrm{M_H} \lesssim 130$ GeV :

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

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

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

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

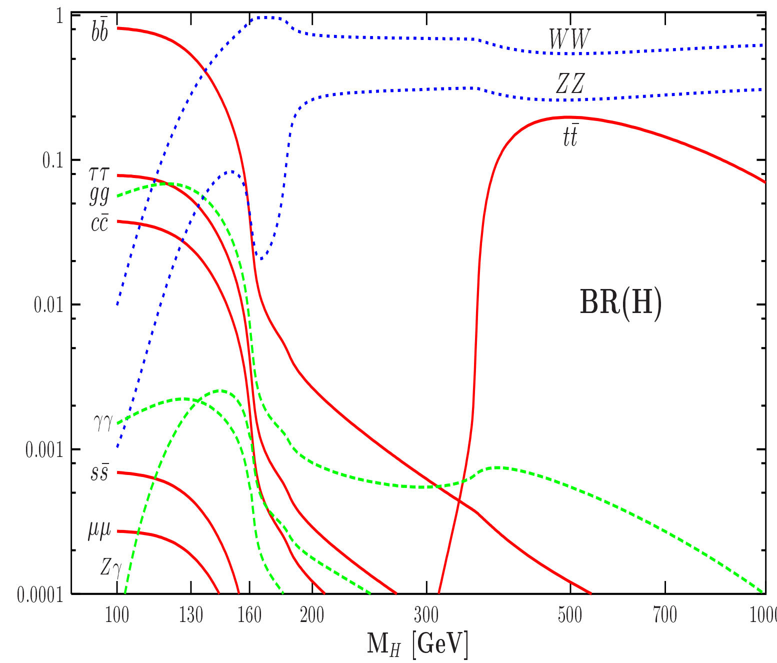
– $\mathrm{H \to WW, ZZ}$ **dominant**

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

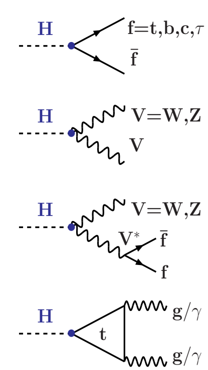
- **Total Higgs decay width:**

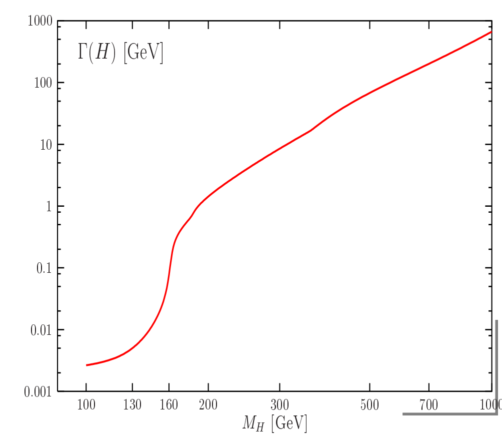
– **very small for a light Higgs**

– **comparable to mass if heavy**



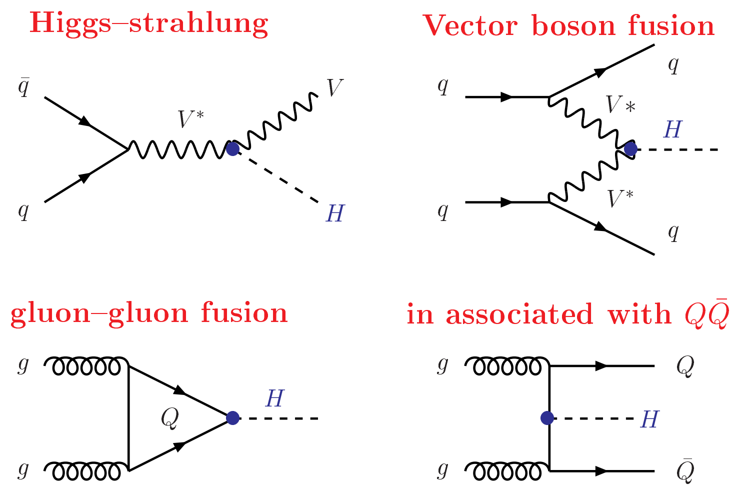
HDECAY $\Rightarrow$

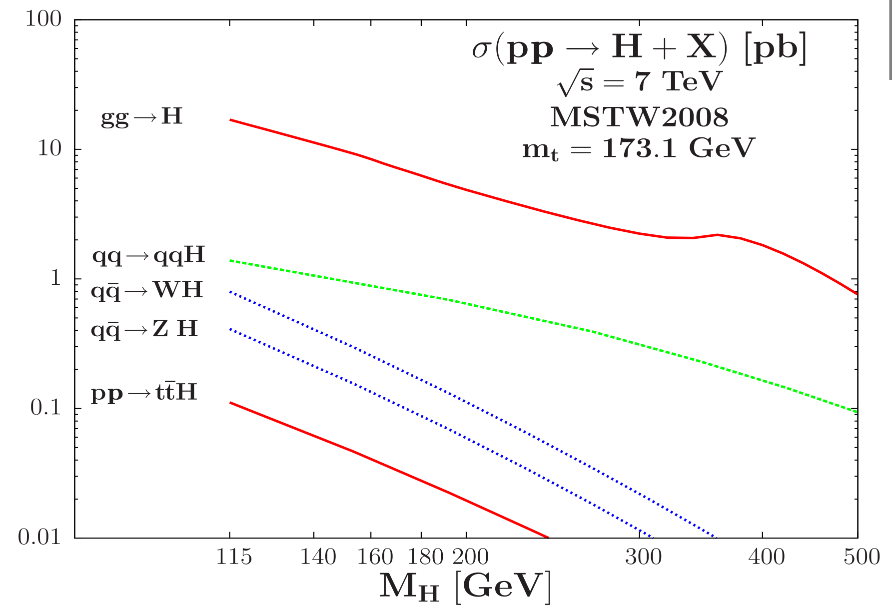




1. Before the 4th of July

Main Higgs production channels





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:

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

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

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

also help from other channels:

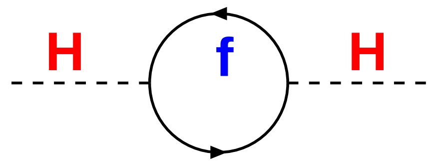
– VBF+$\mathrm{gg} \to \mathrm{H} \to \tau\tau$

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

1. Before the 4th of July

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

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

$\Delta M_H^2 \;\equiv$ 

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

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

Three main avenues for solving the hierarchy problem:

Supersymmetry: a set of new/light SUSY particles cancel the divergence.

– MSSM $\equiv$ two Higgs doublet model $\Rightarrow$ 5 physical states $h, H, A, H^{\pm}$

– very predictive: only two free parameters at tree–level ($\tan\beta, M_A$)

– upper bound on light Higgs $M_h \lesssim 130$ GeV and $M_{H,H^{\pm}} \approx M_A \lesssim$ TeV

Extra dimensions: there is a cut–off at TeV scale where gravity sets in.

– in most cases: SM–like Higgs sector but properties possibly affected

– but in some cases, there might be no Higgs at all (Higgsless models)....

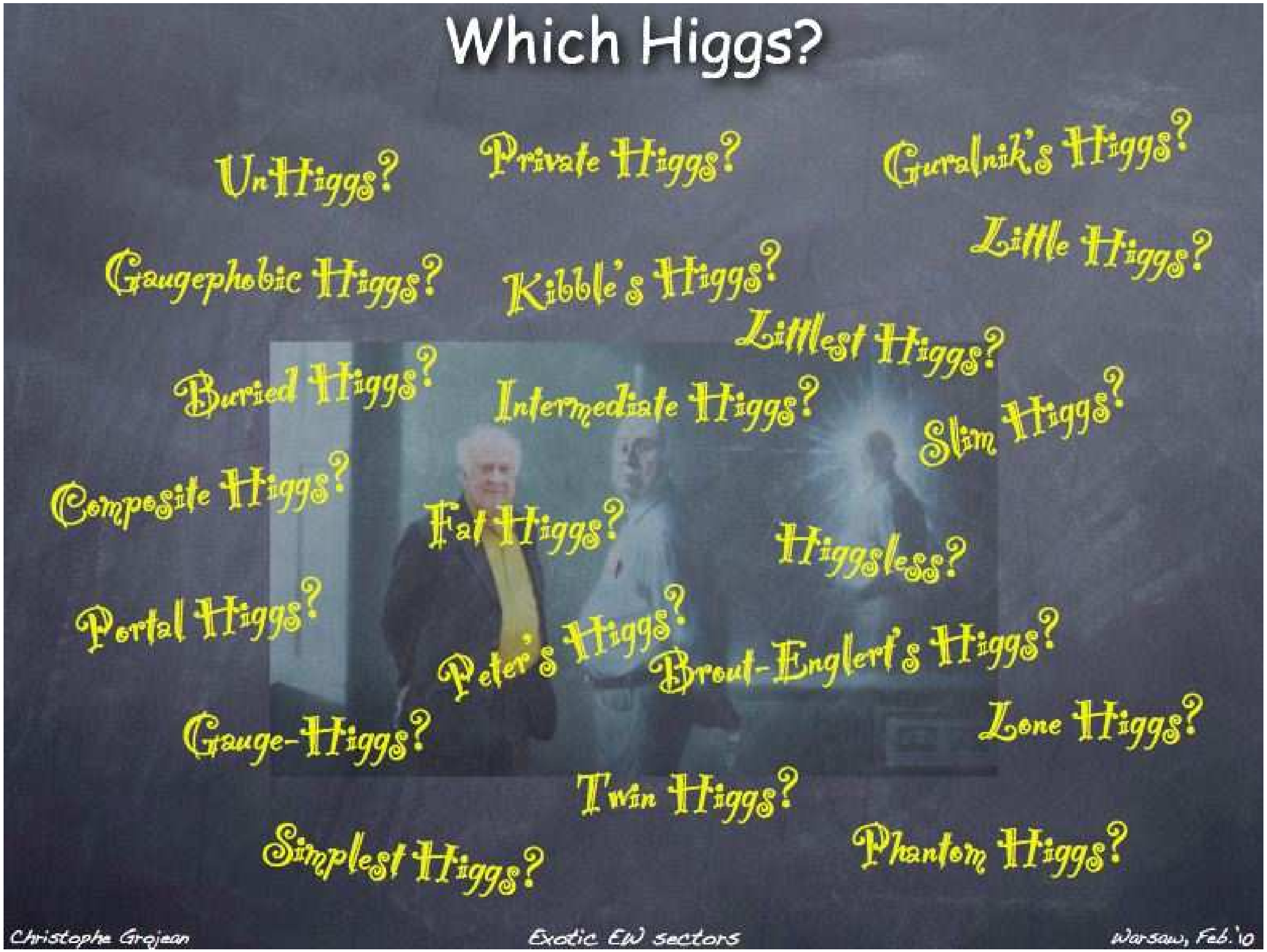
Strong interactions/compositness: the Higgs is not an elementary scalar.

– H is a bound state of fermions like for the pions in QCD...

– H emerges as a Nambu–Goldstone of a strongly interacting sector..

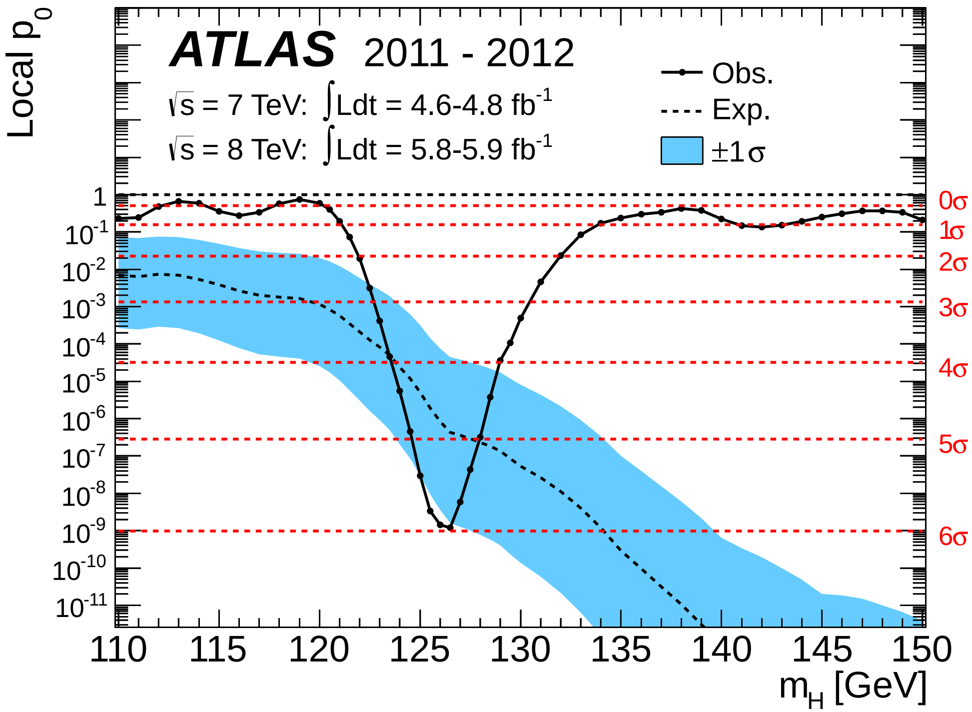
1. Before the 4th of July

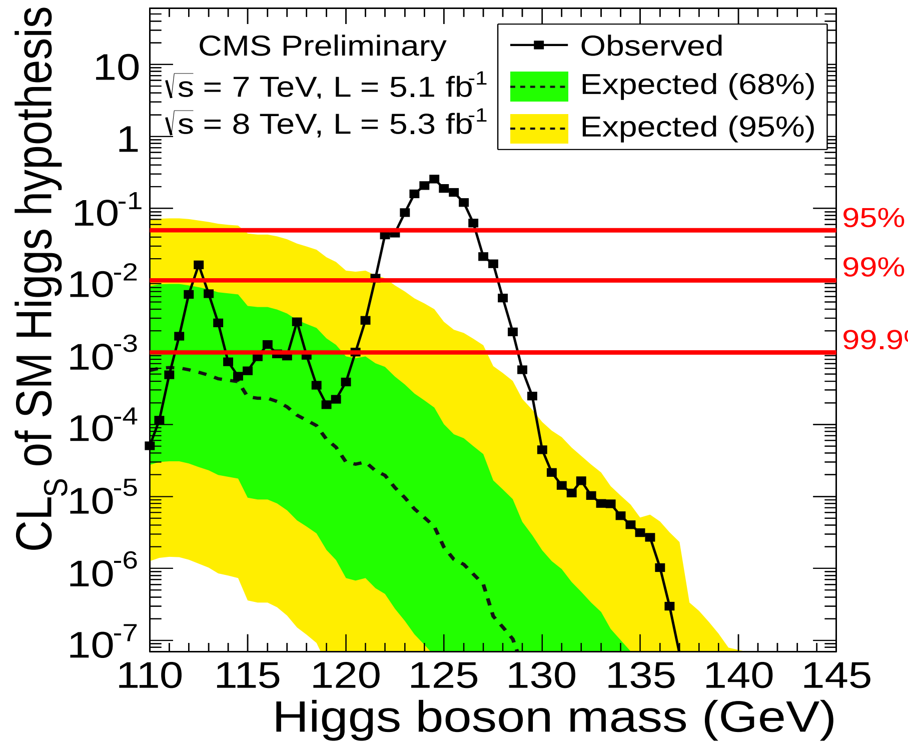
and along the avenues, many possible streets, paths, corners...

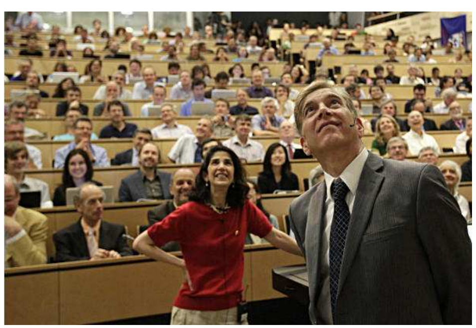


Which scenario chosen by Nature? The LHC supposed to tell!

2. The 4th of July...





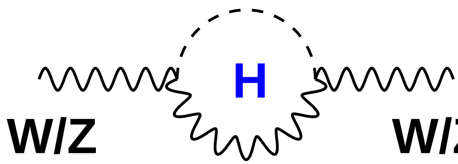


2. The 4th of July...

A triumph for high-energy physics.

Indirect constraints from EW data [a]

H contributes to RC to W/Z masses:



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

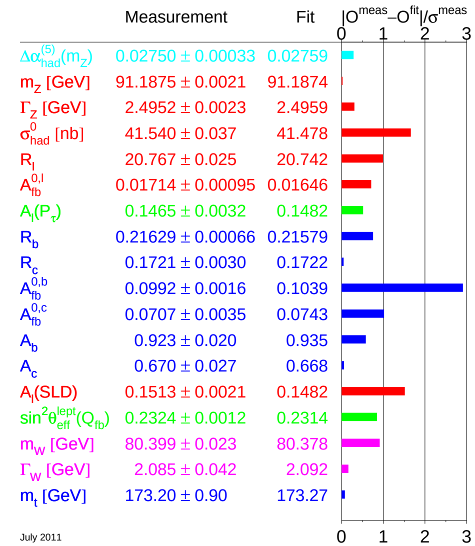
Fit the EW precision measurements, one obtains $M_H = 92^{+34}_{-26}$ GeV, or

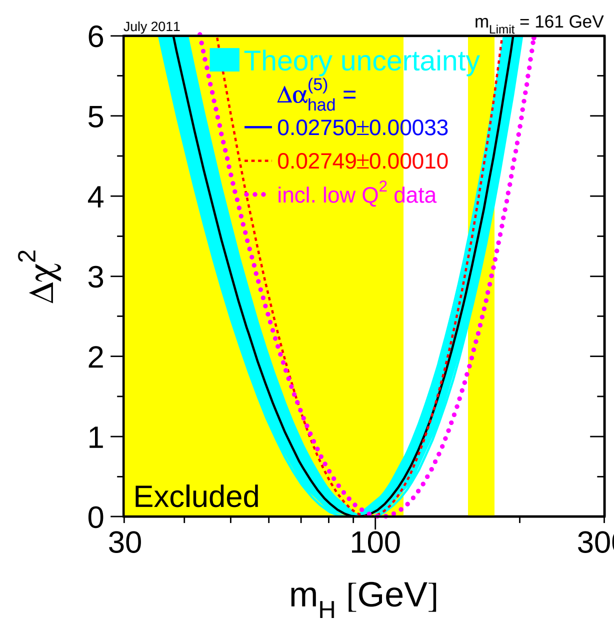
$$M_H \lesssim 160 \text{ GeV at 95\% CL}$$

compared with "observed" $M_H = 125$ GeV

A very non–trivial check of SM consistency!

In 1995: top discovery with $m_t \approx 175$ GeV while best-fit in the SM is for same value: it was considered as a great achievement....





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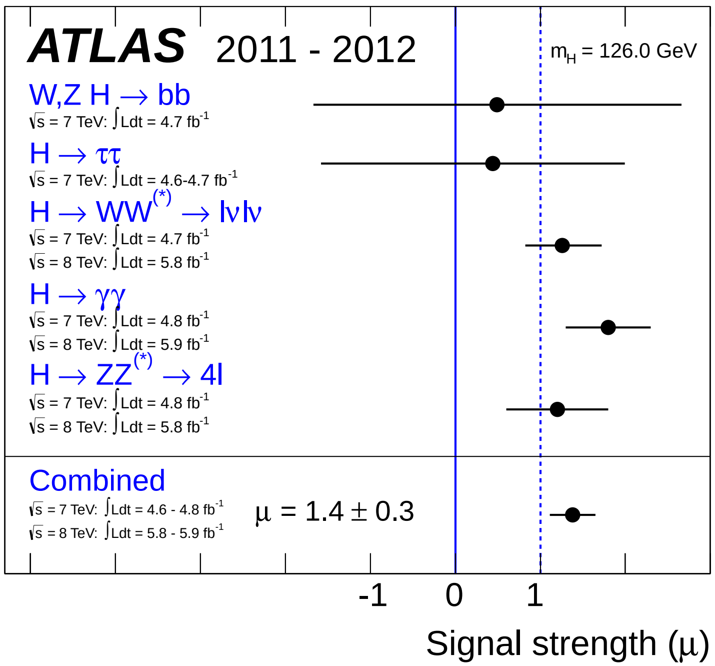
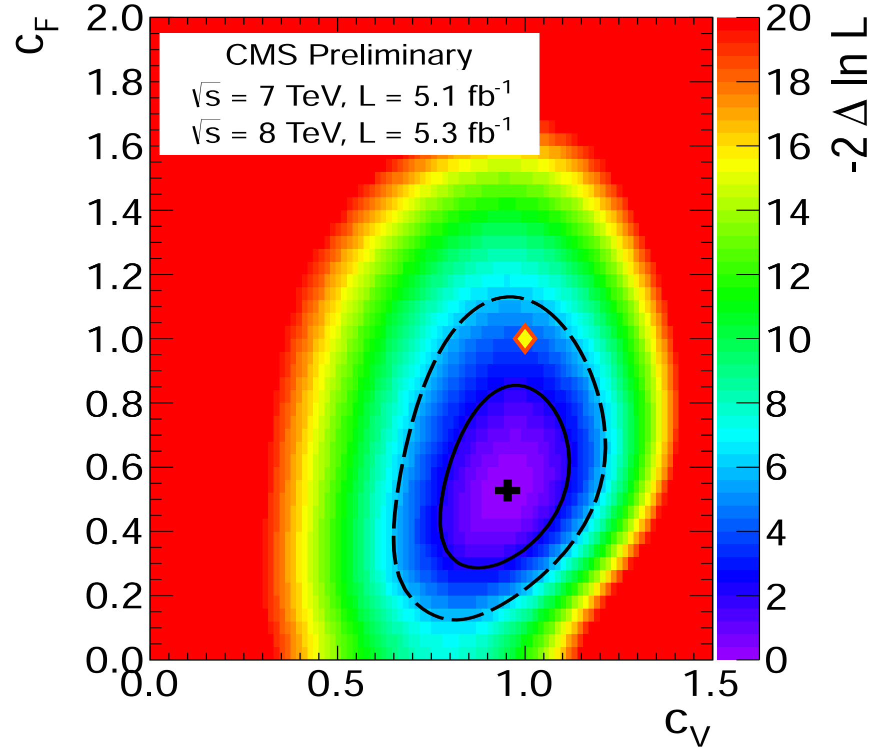
[a] Still some problems with A_{FB}^{b} (LEP), A_{FB}^{t} (TeV) and $g-2$ but not severe...

2. The day after ....

Fit of all the LHC data ⇒ looks like the Higgs is SM–like ....





First/obvious implications (à chaud..):

- **Many scenarios ruled out: Higgsless, gauge/fermio-phobic, 4th gen...**
- **Many others are in great trouble: Techni-Higgs, composite Higgs,...**
- **Other scenarios still OK, but need heavy new particle spectrum:**

example of Supersymmetry and the MSSM....

2. The day after ....

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

- to cancel the chiral anomalies introduced by the new $\tilde{h}$ field,
- give separately masses to d and u fermions in SUSY invariant way.

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: $h, H, A, H^\pm$
SUSY $\Rightarrow$ only 2 free parameters at tree–level ($\tan\beta, M_A$)+constraints:

$$M_h \le \min(M_A, M_Z)\cdot|\cos2\beta| \le M_Z,\ M_{H^\pm} > M_W, M_H > M_A \ldots$$

$M_A \gg M_Z$: decoupling regime, all Higgses heavy except $h \equiv H_{SM}$:

$$M_h \sim M_Z|\cos2\beta| \le M_Z! \ ,\ \ M_H \sim M_{H^\pm} \sim M_A \ ,$$

$\Rightarrow$ Inclusion of radiative corrections to M_h important and necessary:

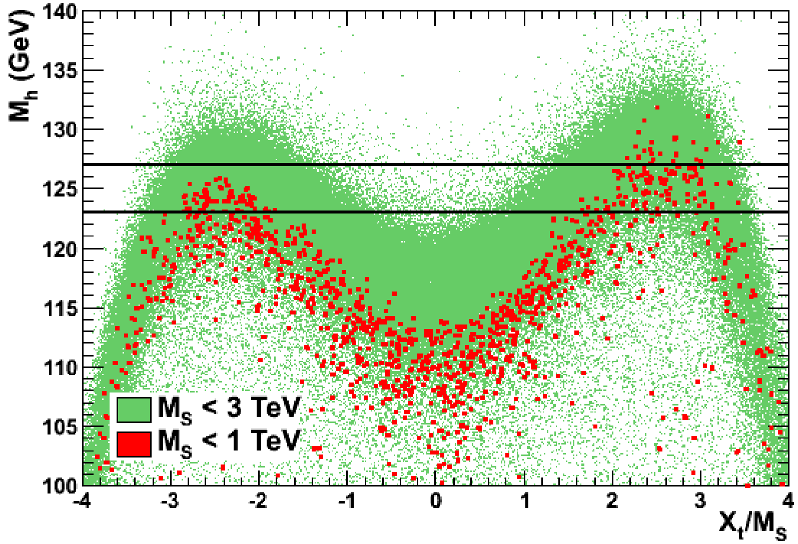
as value $M_h = 125$ GeV large in the MSSM, need to maximize them:

$$M_h \overset{M_A \gg M_Z}{\longrightarrow} M_Z|\cos2\beta| + \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{2M_S^2}\left(1 - \frac{X_t^2}{6M_S^2}\right)\right]$$

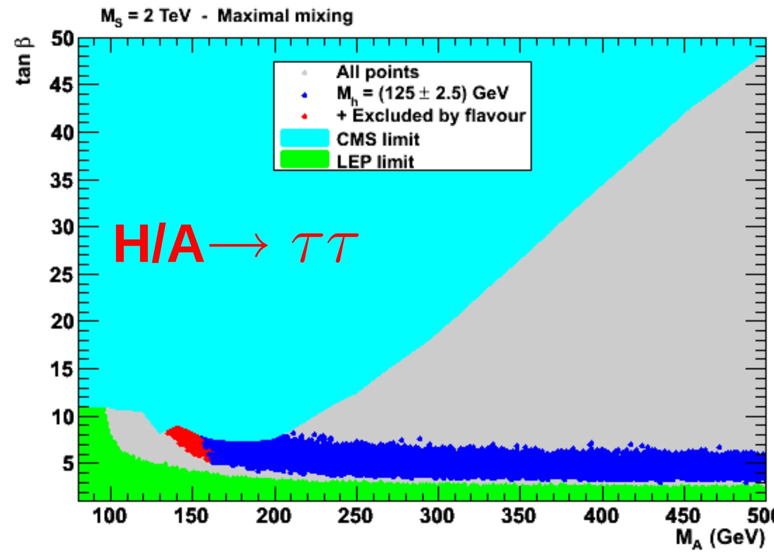
- decoupling regime with $M_A \sim$ few 100 GeV and large tanβ values;
- large $M_{SUSY} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ scale ie heavy stops, with large mxiing;

2. The day after ....

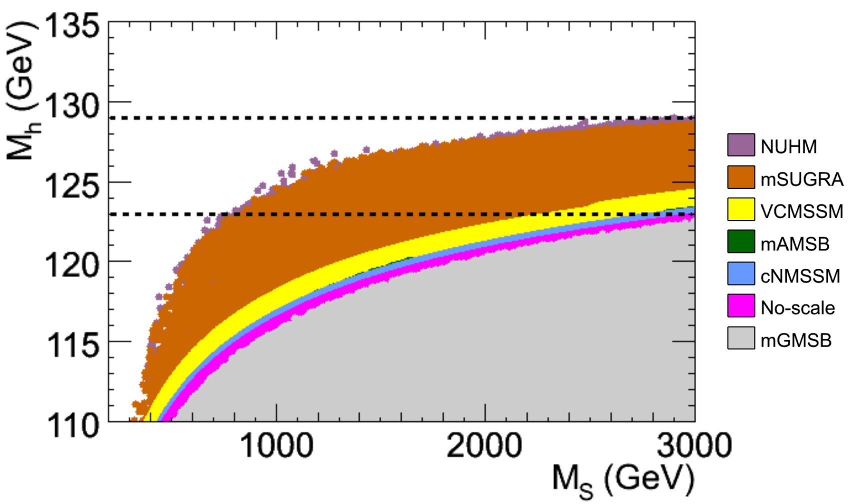
SUSY scale rather large....

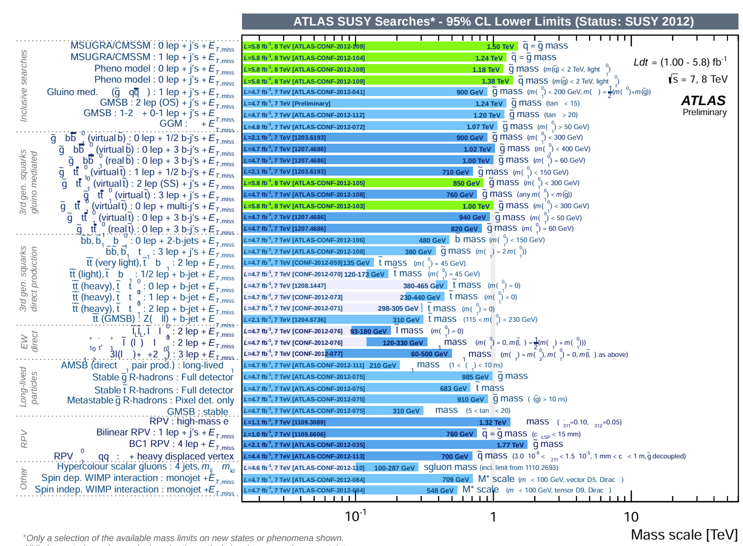


... backed up by direct searches



especially in constrained MSSMs





2. The day after ....

Still one hope: excess in $\mathrm{H} \to \gamma\gamma$!

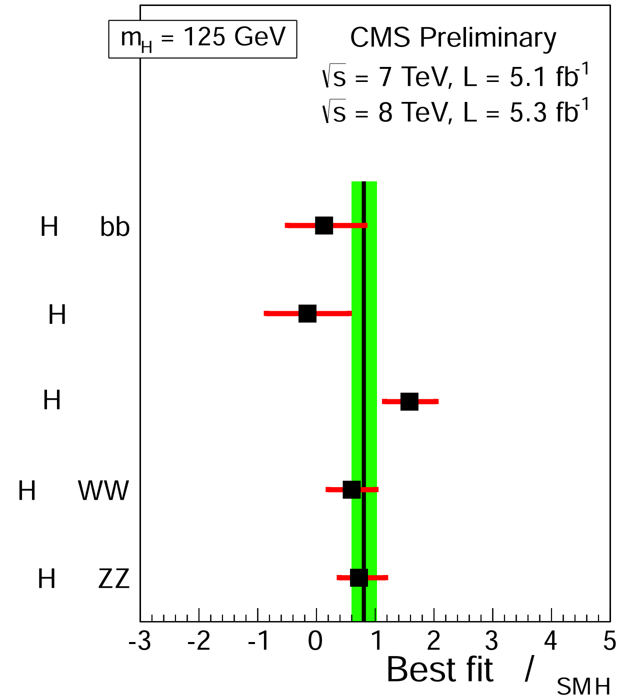
- **light stau's and large $\mu \tan\beta$**
- **light $\tilde{\chi}_1^{\pm}$ in non-univ MSSM**
- **possibility of light $\tilde{\mathrm{t}}$ state:**

$\Rightarrow$ **max-mixing: $\sigma(\mathrm{gg} \to \mathrm{h})$ suppressed.**

$\Rightarrow$ **no mixing: yes, but stops too heavy.**

- **BMSSM? many possiblities (NMSSM)**

Common features: some light sparticles are around the corner!



We need to make sure about the excess and search for the responsibles....

- **Hope something really new will show up in full 2012 data...**
- **If not, at upgraded LHC with 14 TeV energy and 300/fb data?**
- **If not, a high luminosity LHC (3000/fb) will increase sensitivity!**
- **And in case of nothing still, go for the highest possible energy!**

We must make full use of the LHC capabilities!

3. Measurement of Higgs properties at LHC

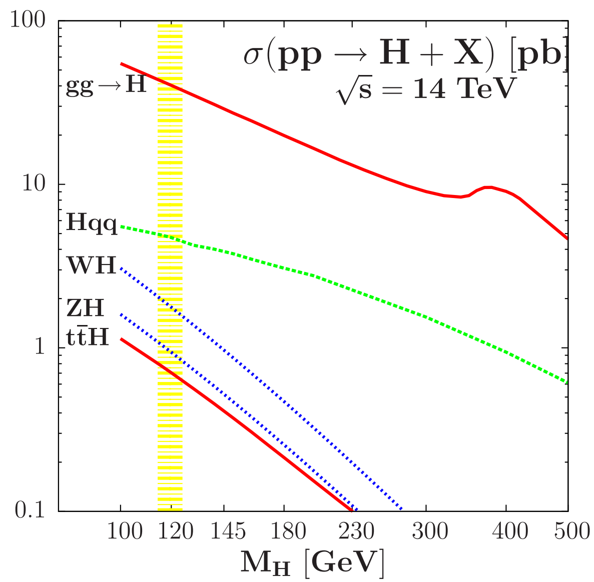
Now that Higgs is found (and nothing else yet): is HEP "closed"?

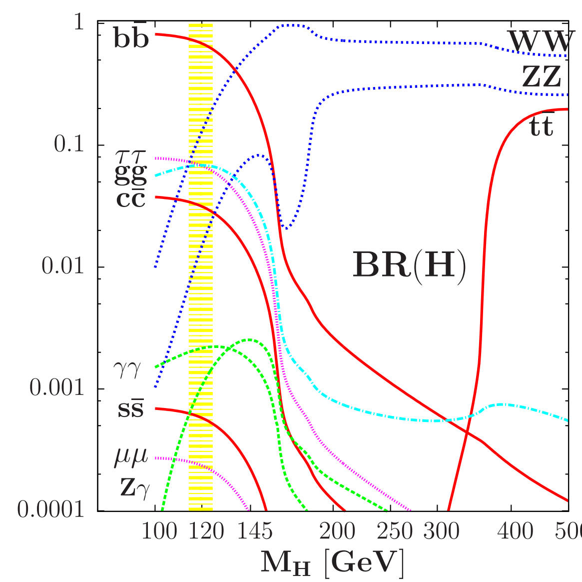
No! Need to check that H is indeed responsible of sEWSB (and SM-like?)

Measure its fundamental properties in the most precise way:

- **its mass and total decay width,**
- **its spin–parity quantum numbers and check $J^{PC} = 0^{++}$,**
- **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 $M_H \approx$ 125 GeV as all production/decay channels useful!





3. Higgs properties: mass and width

Higgs mass $\mathrm{M_H}$ from:

– $\mathrm{H} \to \gamma\gamma$

– $\mathrm{H} \to \mathrm{ZZ} \to 4\ell^{\pm}$

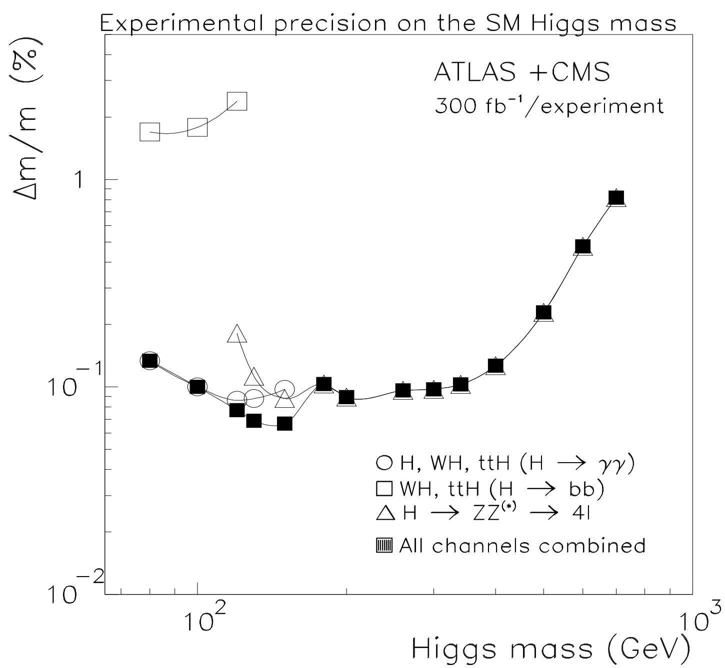
Final $\Delta \mathrm{M_H}/\mathrm{M_H} \sim 0.1\%$.

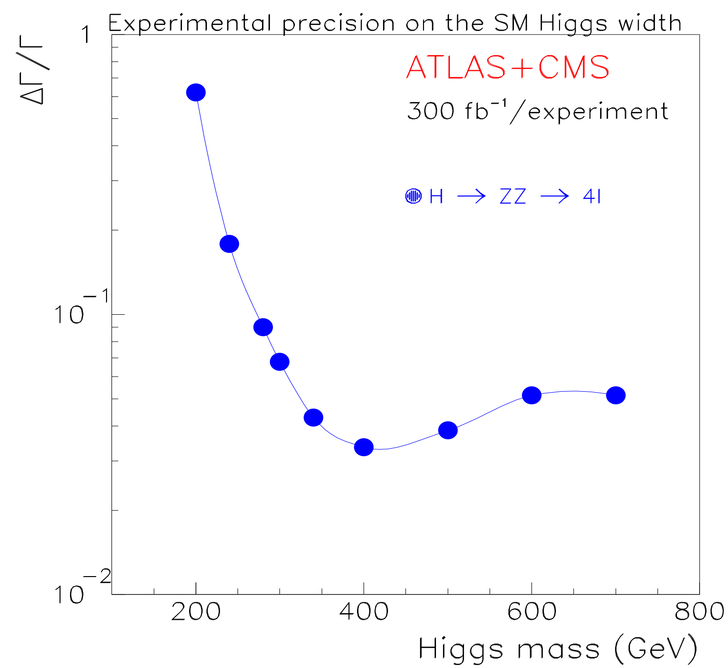
Higgs total width Γ_{H}:

– use $\mathrm{H} \to \mathrm{ZZ} \to 4\ell^{\pm}$

– but too small for $\mathrm{M_H} \lesssim 2\mathrm{M_Z}$

cannot be resolved experiment.





Mass precisely measured but total width out of reach (invisible decays?)

3. Higgs properties: J^{PC} numbers

- **Higgs spin:**

$\mathrm{H}\to\gamma\gamma$: rules out J=1 and fixes C=+.

– not generalizable to $\mathrm{H}\leftrightarrow\mathrm{gg}(\mathrm{g}\approx\mathrm{q})$

– other possibility left, ex: J=2 (radion).

- **Higgs parity:**

– $\mathrm{H}\to\mathrm{ZZ}\to 4\ell^{\pm}$ rules out CP–odd.

– spin–correlations in $\mathrm{gg}\to\mathrm{H}\to\mathrm{WW}^*$.

But need to check that H is pure CP–even

– challenging precision measurement,

– roughly doable in H$\to 4\ell^{\pm}$ correlations.

– also in $\mathrm{d}\Gamma(\mathrm{H}\to\mathrm{ZZ}^*)/\mathrm{dM}_*$

Drawback: If H is mostly CP–even,

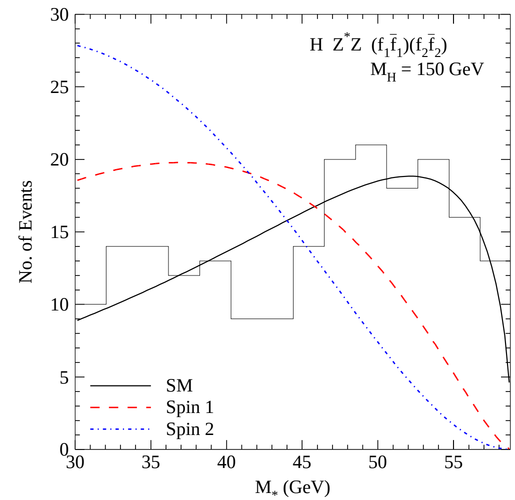
rates for $\mathrm{A}\to\mathrm{VV}$ are too small...

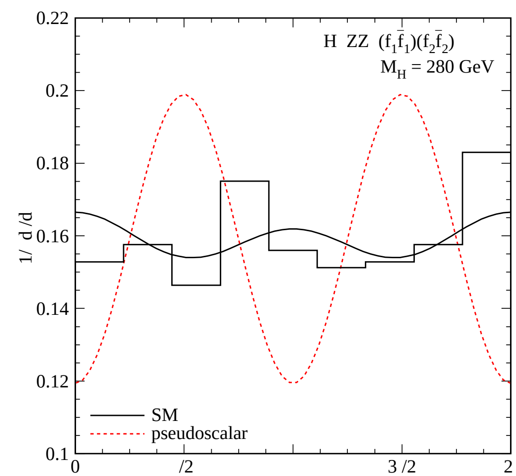
More convincing: look at Hff couplings

Possible but very challenging channels:

$\mathrm{gg}\to\mathrm{H}\to\tau\tau$ or $\mathrm{pp}\to\mathrm{t\bar{t}H}\to\mathrm{ttbb}$

$\mathrm{d}\Gamma(\mathrm{H}\to\mathrm{ZZ}^*)/\mathrm{dM}_*$@thresh





$\mathrm{d}\Gamma(\mathrm{H}\to\mathrm{ZZ})/\mathrm{d}\phi$ azimuth

3. Higgs properties: Higgs couplings

- Look at various H production/decay channels and measure $\mathrm{N_{ev}} = \sigma \times \mathrm{BR}$

LHC with $\mathcal{L} = 300$fb^{-1} (more statistics?)

- Large errors mainly due to:

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

– theory: PDFs, HO/scale, model dep...

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

contaminates also VBF ($\approx$30%)...

$\Rightarrow \sigma \times \mathrm{BR}$ ratios: many errors drop out!

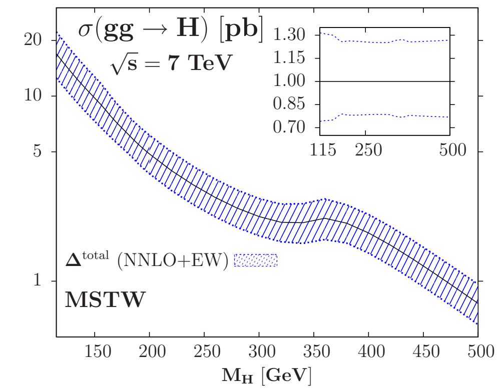
- One obtains width ratios: $\Gamma_\mathrm{X}/\Gamma_\mathrm{Y}$
- Theory assumptions (no invisible, SU(2) invariance, some couplings are known,..)

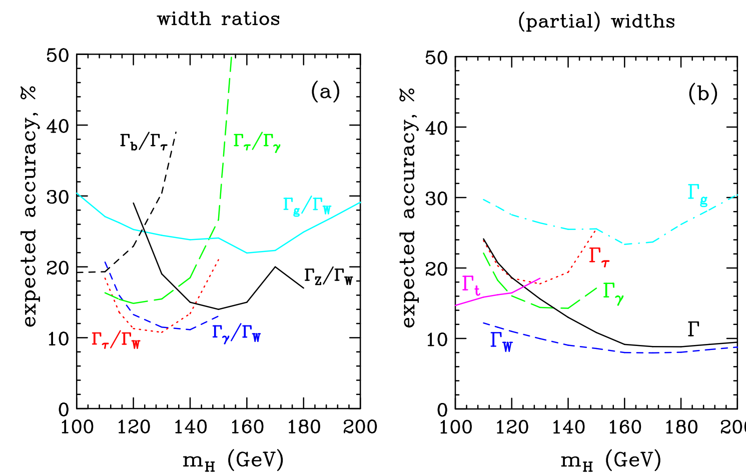
$\Rightarrow$ translate into $\Gamma_\mathrm{X} \propto \mathrm{g}^2_\mathrm{HXX}$ with

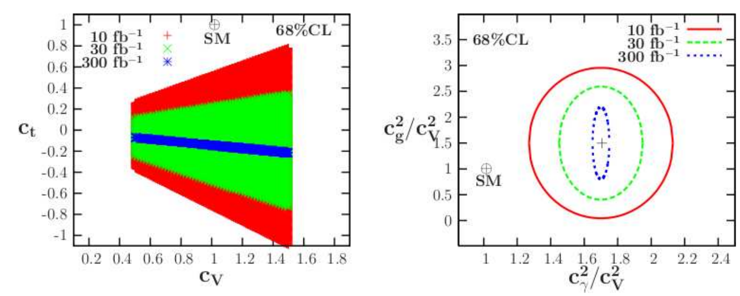
precision: $\Delta \mathrm{g_{HXX}} = \frac{1}{2} \frac{(\Delta^{\mathrm{exp}}\Gamma + \Delta^{\mathrm{th}}\Gamma)}{\Gamma}$

$\Rightarrow$ reasonable precision of order 10%

not too bad... but is it really enough?







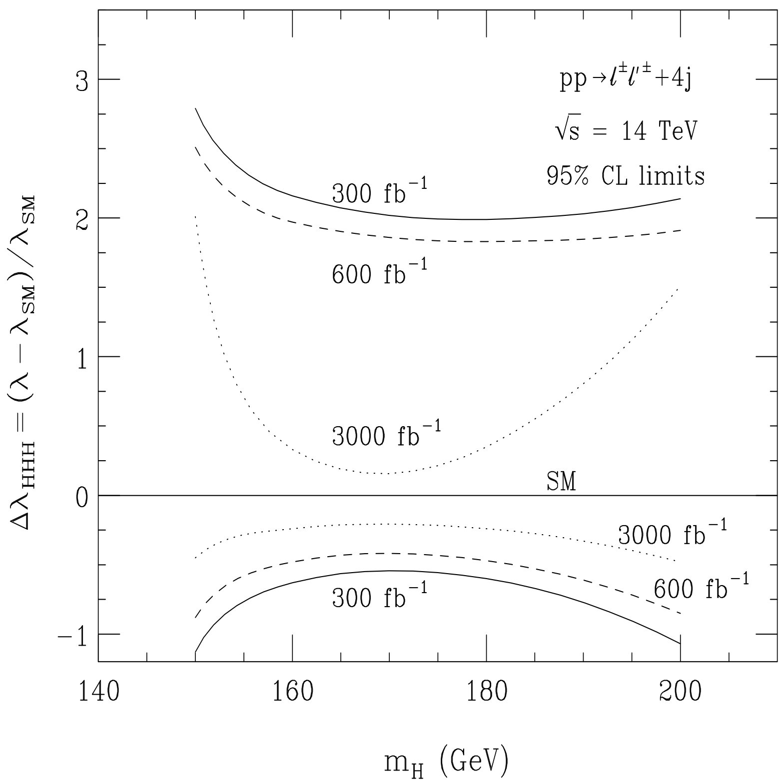
3. Higgs properties: Higgs self-couplings

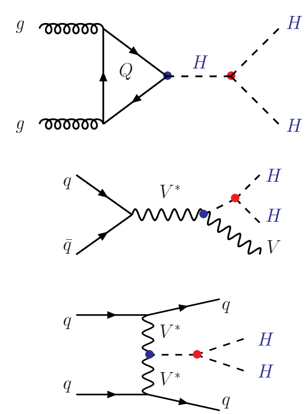
Important couplings to be measured: $g_{H^3}, g_{H^4} \Rightarrow$ access to V_H.

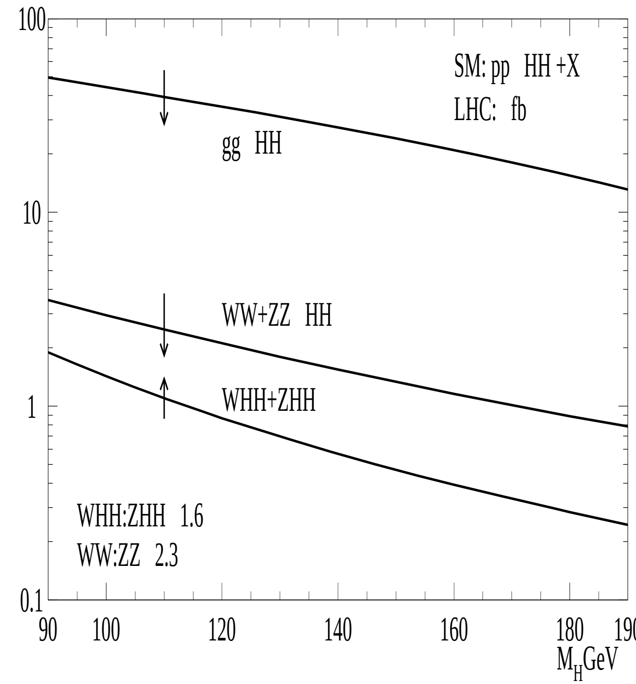
- g_{H^3} from $pp \to HH + X \Rightarrow$
- g_{H^4} from pp$\to$3H+X, hopeless.

Relevant processes for HH prod:

only $gg \to HH$ can be useful...







- $H \to \gamma\gamma$ decay too rare,
- $H \to b\bar{b}$ decay not clean
- $H \to WW$ at low M_H?

most promising possiblity?

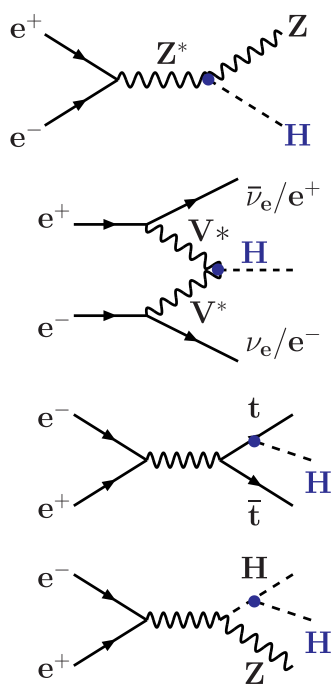
$gg \to HH \to bb\tau\tau$

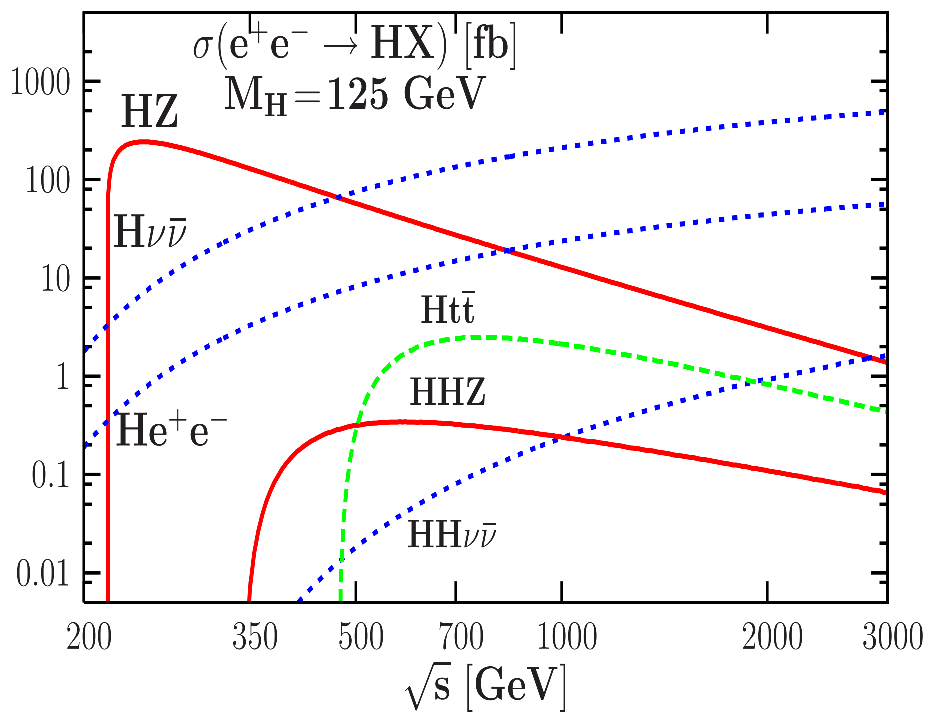
needs very large luminosity.

4. The Higgs at the LC

Ideal machine: clean environment, comparable signal/background, ...

- **High precise tests, mostly at $\sqrt{s} \lesssim$ 350 GeV and mainly in $e^+e^- \to ZH$: measurements of all BRs, $\sigma(HV), \sigma(VV \to H)$, J^{PC}, M_H, Γ_H, ...**
- **Needs upgrade to $\sqrt{s} \approx$ 500 GeV to probe important g_{Htt} and λ_{HHH}.**
- **Very high luminosities, at least a few 100 fb^{-1}, are required...**





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

4. The Higgs at the LC: LEP3?

Some people advocate a (quick/cheap) 250 GeV LC, a kind of LEP3...

– you can indeed precisely measure Higgs couplings to VV and ff,

– but no access to the HHH and Htt couplings: need at least 500 GeV!

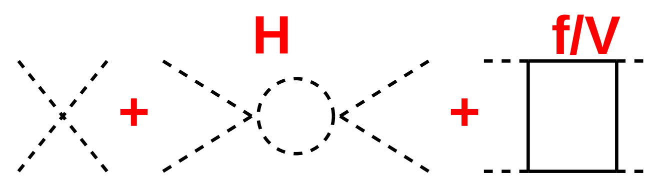
But you cannot produce the top: the other particle to be precisely tested

Why is it so important?? Check the stability of the EW vaccum!

- $\lambda = M_H^2/2v^2$ increases with energy Q;

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

tops make $\lambda(0) < \lambda(v)$: unstable vacuum



- SM valid only if v≡EW-min, ie $\lambda(Q^2) > 0$

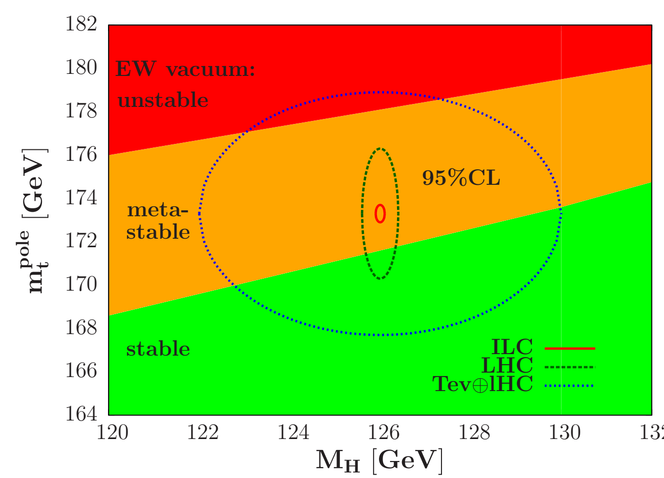
$$\Lambda_C \sim M_P \Rightarrow M_H \gtrsim 129\,\mathrm{GeV}!$$

for $m_t = 173$ GeV; but what is m_t^{TEV}??

- Unambiguous m_t only from $\sigma(tt)$:

– value at TEV/LHC not precise...

– need ILC $\Delta m_t = 200$ MeV!



Only way to check stability/New Physics:

measure the top $\Rightarrow \sqrt{s} \gtrsim 350$ GeV!

4. The Higgs at the LC: CLIC?

Measurements which need the high cross section of $e^+e^- \to H\nu\bar{\nu}$:

- **BR(H$\to \mu^+\mu^-$) $\propto 10^{-4}$**

Higgs couplings to 2d generation

- **BR(H$\to \gamma$Z) $\propto 10^{-3}$**

complementary/same(?) to H$\to\gamma\gamma$

- **Trilinear Higgs couplings**

$e^+e^- \to W^*W^* \to HH\nu\nu$

statistics better than HZ@500 GeV

Scenarios which need high energy:

Search for the MSSM heavy Higgses:

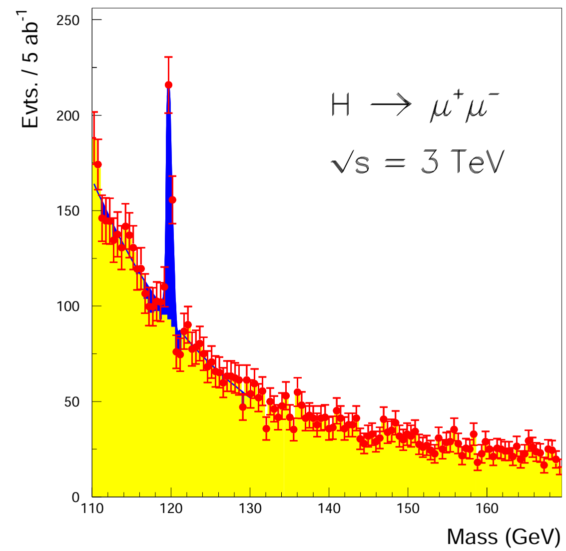
Decoupling: $M_H \approx M_A \approx M_{H^\pm} \gg M_Z$

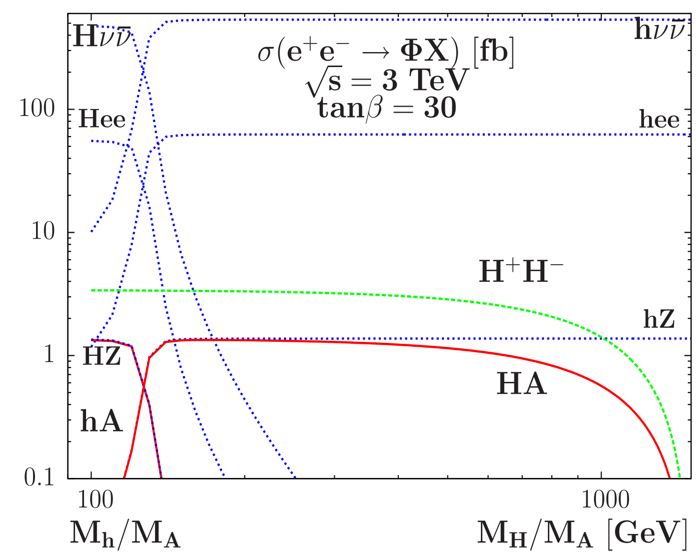
$e^+e- \to HA, H^+H^-$

Kinematical reach: $M_\Phi \approx \frac{1}{2}\sqrt{s}$

At CLIC: $M_\Phi \approx 1.5$ **TeV (beyond LHC).**

also look for EW superparticles....



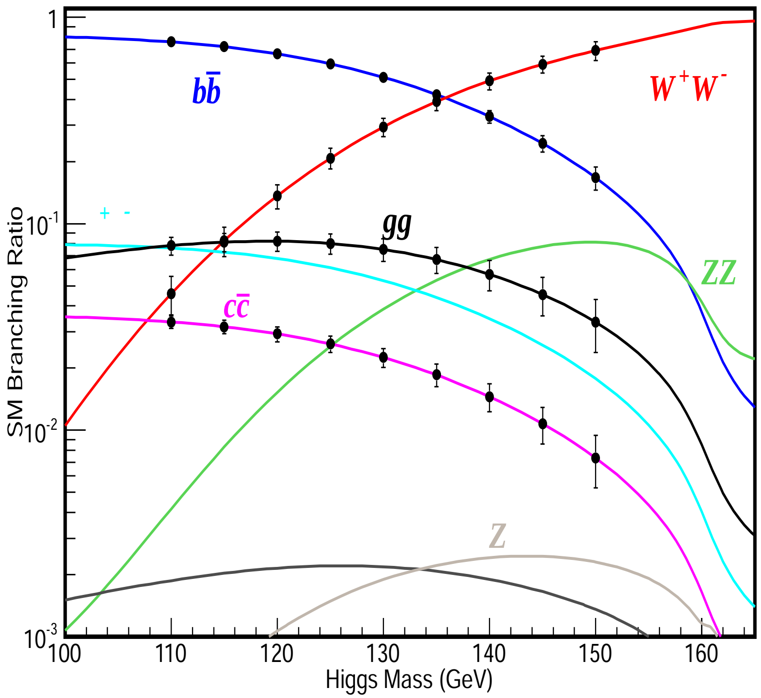


4. Higgs properties: JLC?

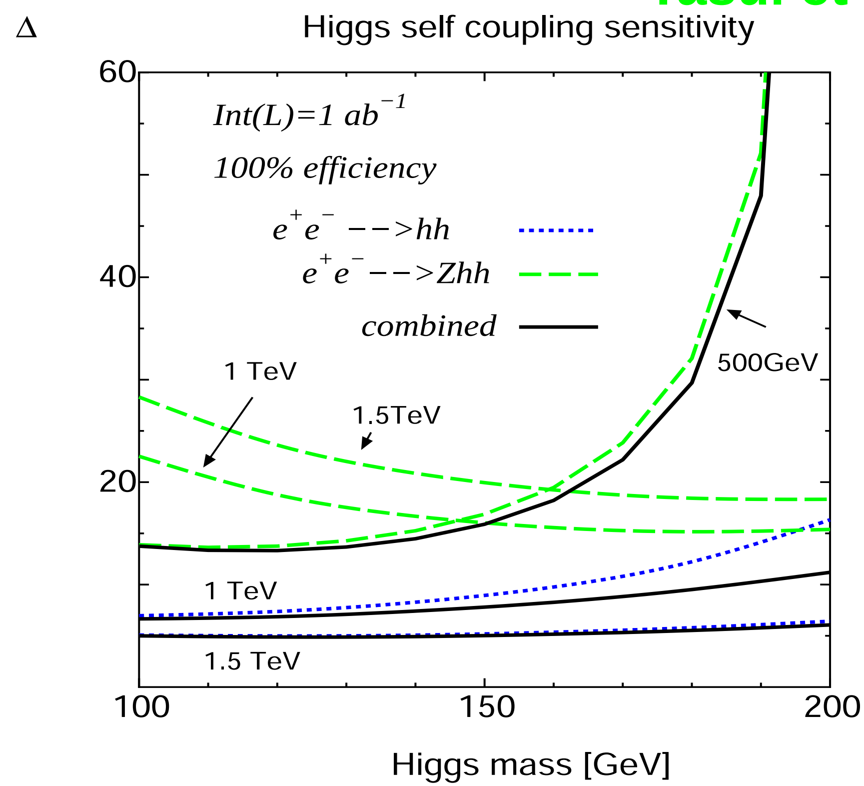
Personal opinion (mais personne n'est obligé d'être d'accord..):

an e^+e^- machine with $\sqrt{s} \approx$ 500 GeV energy will do the best job!

Ono+Miyamoto



Yasui et al.

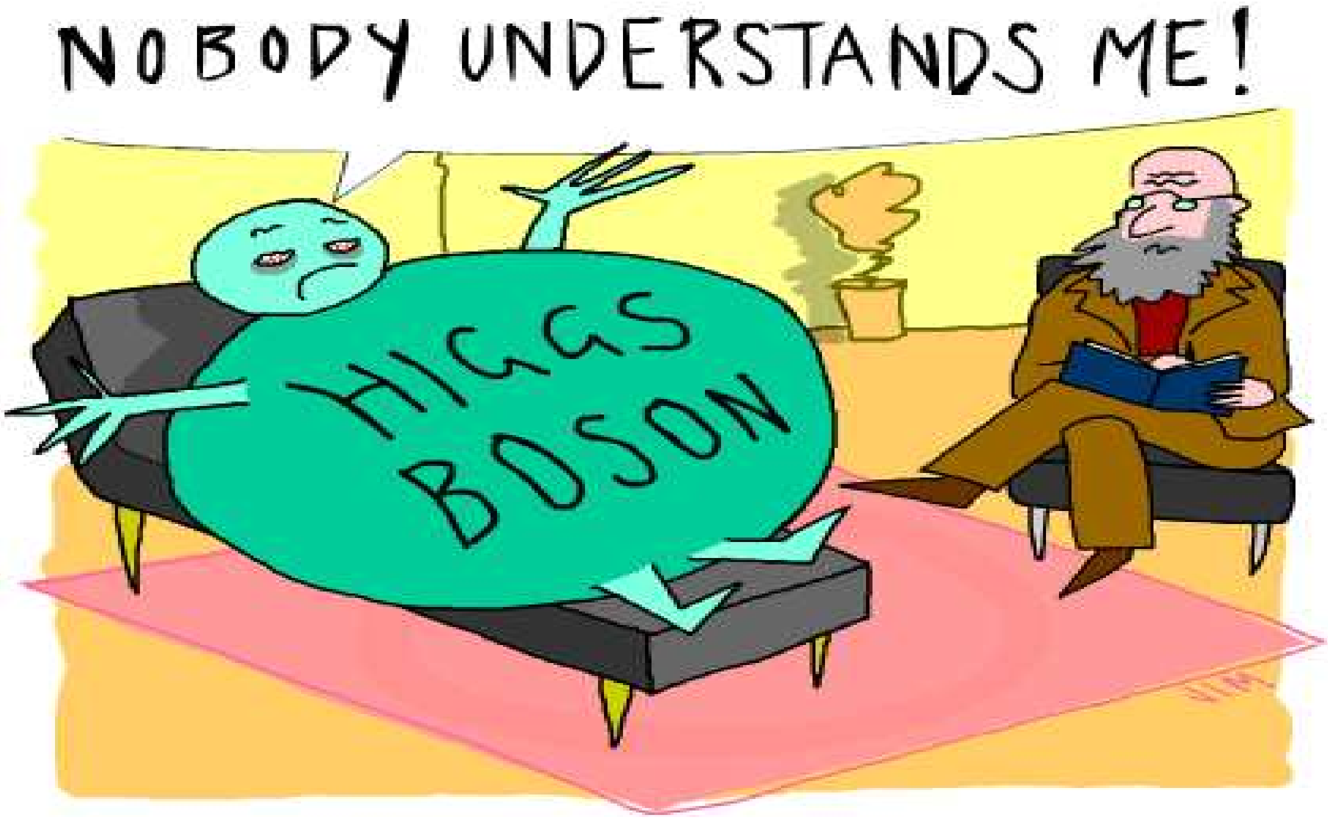


The turn of Japan/Asia to take the lead for a 400–500 GeV LC?

They seem to be rather interested. Il faut leur dérouler le tapis rouge!

5. Conclusion

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...