Physics after the Higgs discovery

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

1. Before the 4th of July

To generate particle masses in an SU(2)×U(1) gauge invariant way:
introduce a doublet of scalar fields $\Phi = \binom{\Phi^+}{\Phi^0}$ **with** $\langle 0|\Phi^0|0\rangle \neq 0$

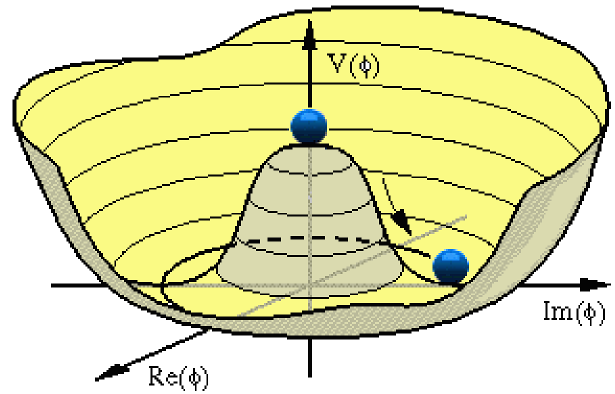
$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2$

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

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

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

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



Residual dof corresponds to spin–0 H particle.

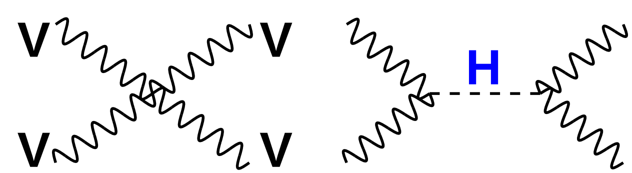
- **The scalar Higgs boson:** $J^{PC} = 0^{++}$ **quantum numbers.**
- **Masses and self–couplings from** V : $M_H^2 = 2\lambda v^2,\ g_{H^3} = 3\frac{M_H^2}{v}, \dots$
- **Higgs couplings** $\propto$ **particle masses:** $g_{Hff} = \frac{m_f}{v},\ g_{HVV} = 2\frac{M_V^2}{v}$

The Higgs unitarizes the theory:

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

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...**



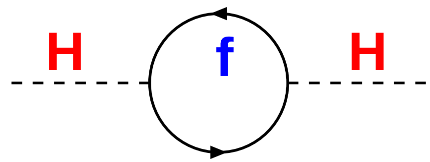
Once M_H **known, all properties of the Higgs are fixed (modulo QCD).**

1. Before the 4th of July

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:

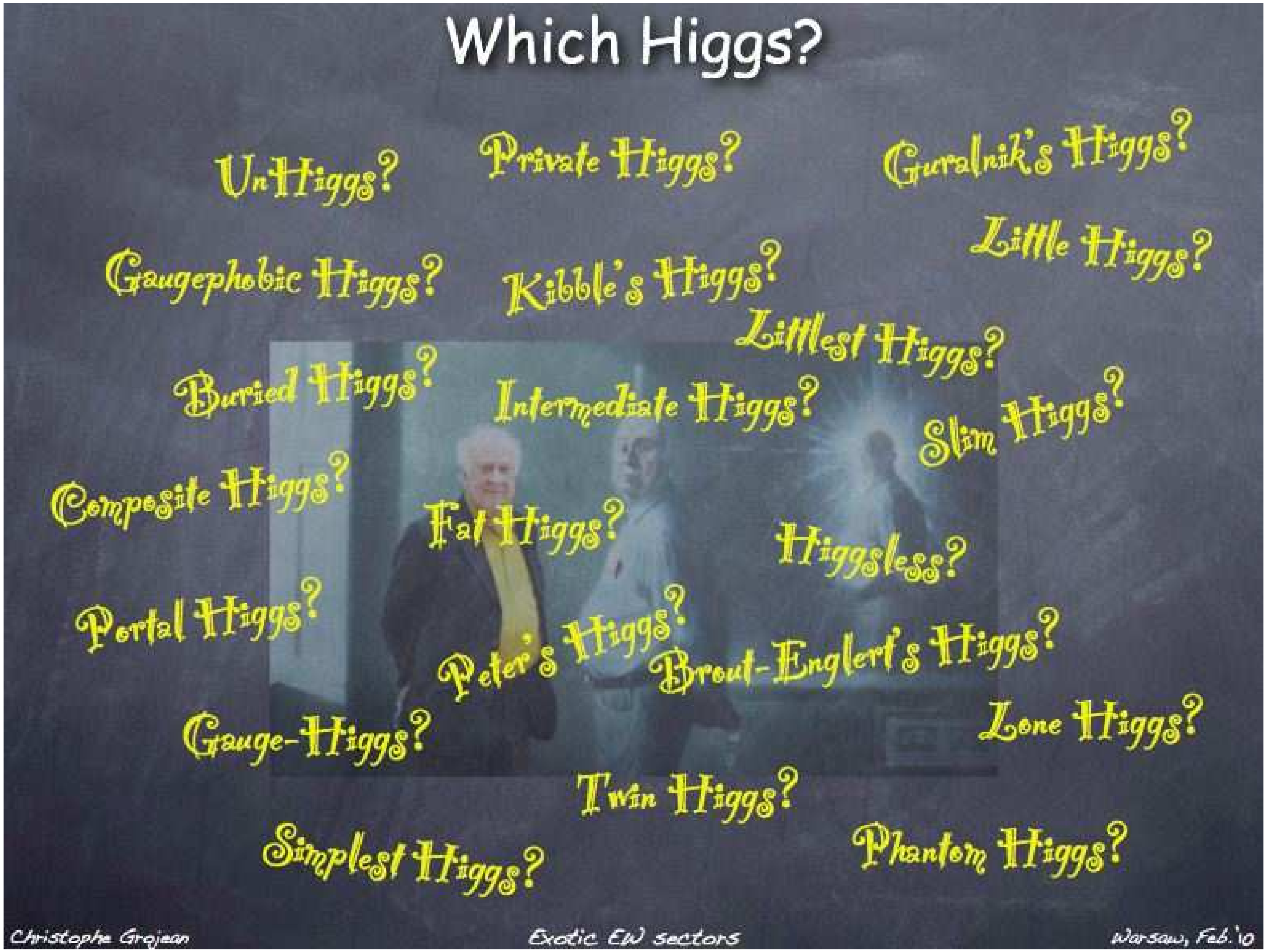
Supersymmetry: a set of new/light SUSY particles cancel the divergence.
– MSSM $\equiv$ two Higgs doublet model $\Rightarrow$ 5 physical states $\mathrm{h, H, A, H^\pm}$
– very predictive: only two free parameters at tree–level ($\tan\beta, \mathrm{M_A}$)
– upper bound on light Higgs $\mathrm{M_h} \lesssim 130\ \mathrm{GeV}$ and $\mathrm{M_{H,H^\pm}} \approx \mathrm{M_A} \lesssim \mathrm{TeV}$

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!

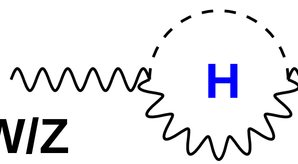
2. The 4th of July...

Higgs observed by ATLAS and CMS!

A triumph for high-energy physics.

Indirect constraints from EW data [a]

H contributes to RC to W/Z masses:



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

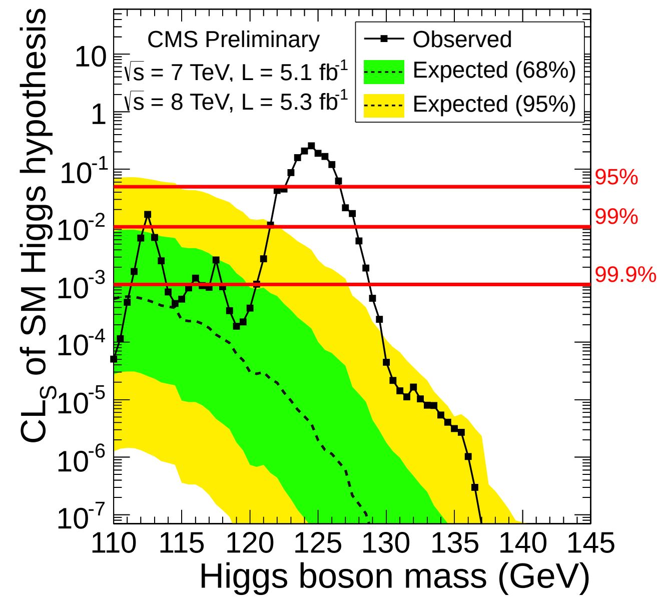
Fit the EW precision measurements, one obtains $M_H = 92^{+34}_{-26}$ GeV, or

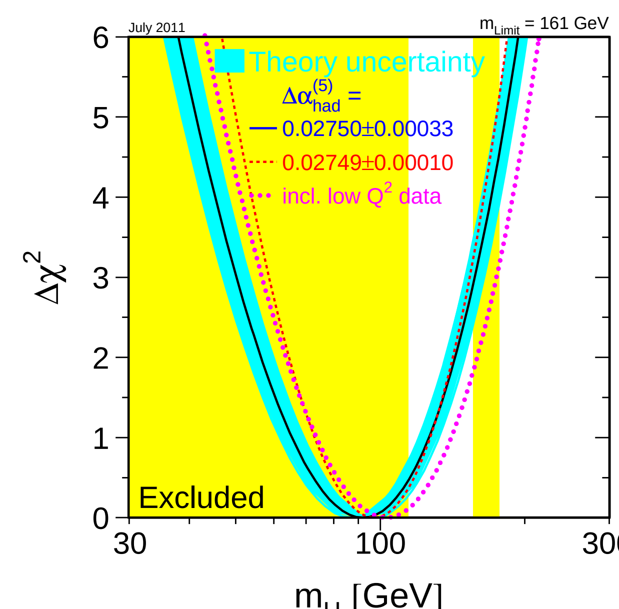
$$M_H \lesssim 161 \text{ GeV at 95\% CL}$$

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....

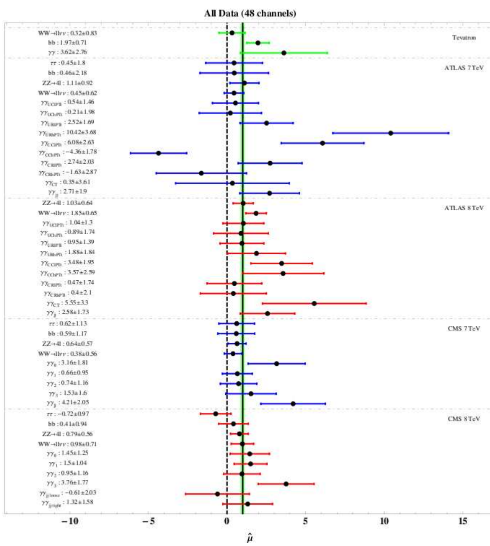


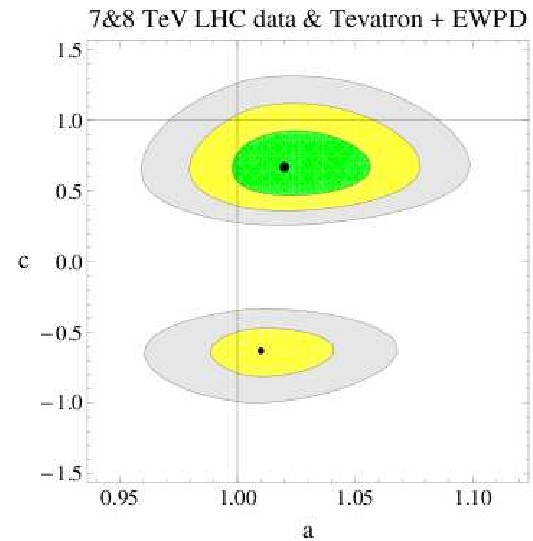


[a] Still some problems with A_{FB}^b (LEP), A_{FB}^t (TeV) and $g-2$ but not severe...

2. The day after ....

Fit of all the LHC data $\Rightarrow$ looks like the Higgs is SM–like ....





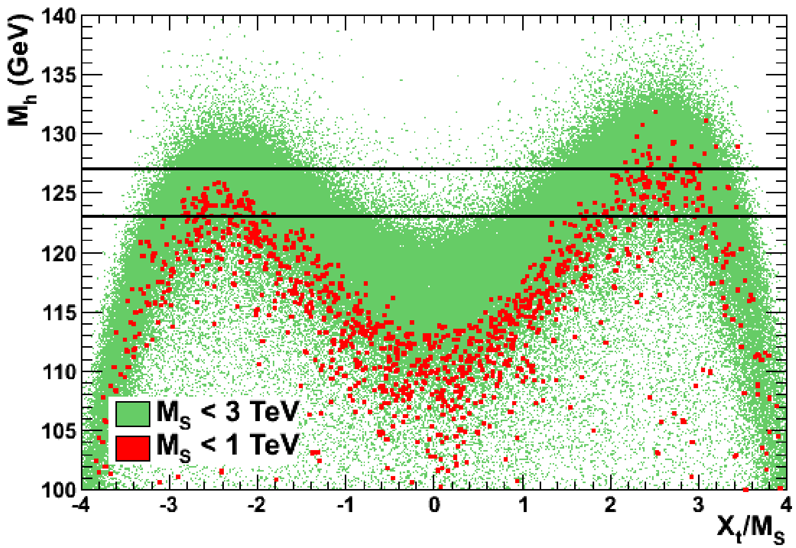
C. Grojean et al. ....

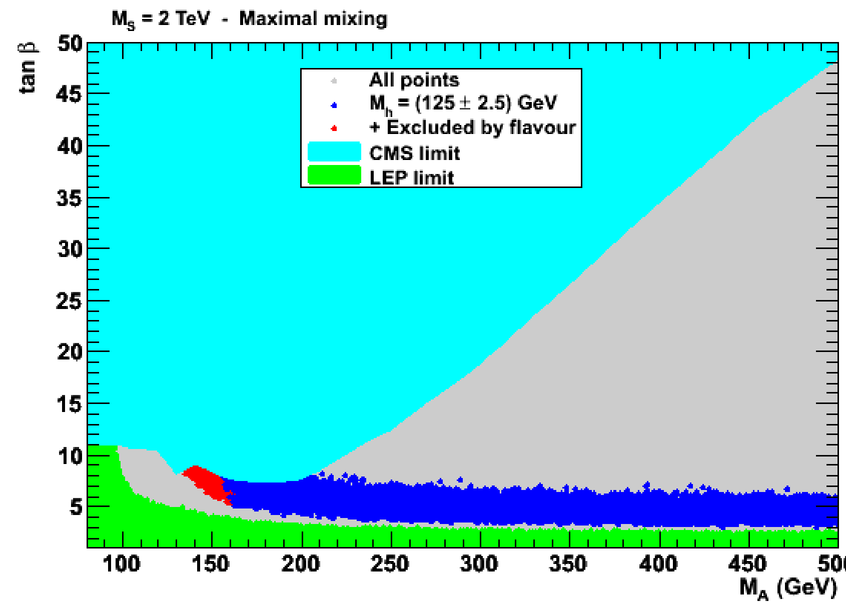
- **Many scenarios are ruled out (Higgsless, gauge/fermio phobic, 4th gen.**
- **Many others are in great trouble: TC Higgs, composite Higgs**
- **Other scenarios OK, but leads to heavy new particle spectrum.**

example of Supersymmetry and the MSSM....

2. The day after ....

Limits for $\mathrm{M_H} = 125 \pm 2$ GeV | **Limits from $\mathrm{H/A} \to \tau\tau$ search**



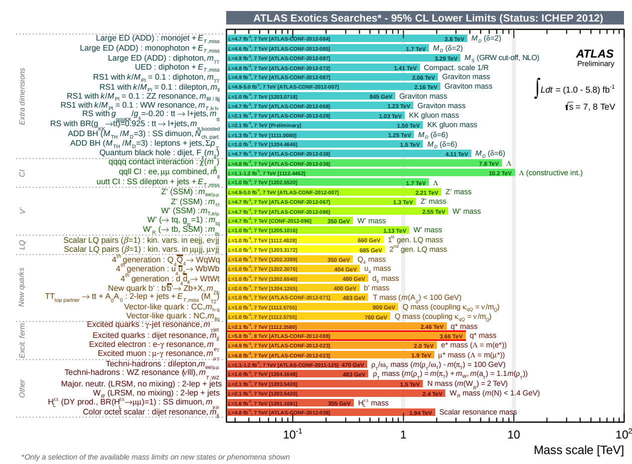


Also backed up by direct searches

$\mathrm{m_{\tilde{m}_q}}, \mathrm{m_{\tilde{m}_g}} \gtrsim 1\ \mathrm{TeV}$. **However:**

– stops might be still light

– no strong bound yet on EW SP.



2. The day after ....

What should one do? Well, there is no choice....

- **Hope someting 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!

One hope: excess in $\mathrm{H} \to \gamma\gamma$ stays!

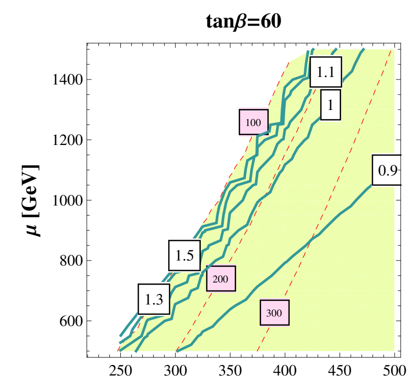
- **light $\tilde{\tau}$'s and large $\mu\tan\beta$**
- **light $\chi_1^{\pm}$ in non-univ MSSM**
- **possibility of light $\tilde{\mathrm{t}}$:**

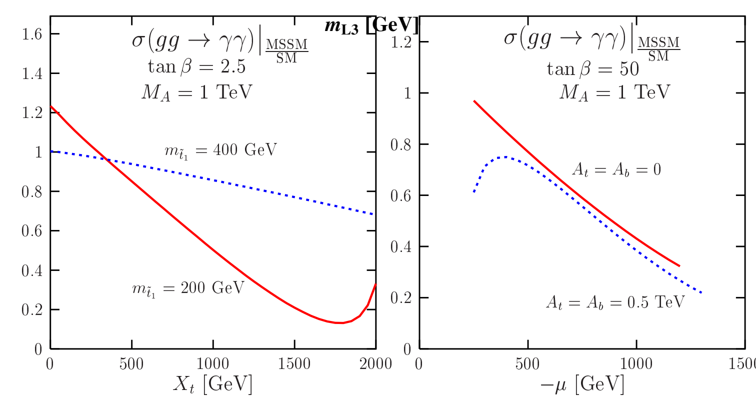
$\Rightarrow$ max-mixing: $\sigma(\mathrm{gg}\to\mathrm{h})$ suppressed.

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

- **BMSSM?** Ellwanger etal, King etal., Kraml+Jiang+Gunion $\cdots$

Common features: some light sparticles are around the corner!





3. Measurement of Higgs properties at LHC

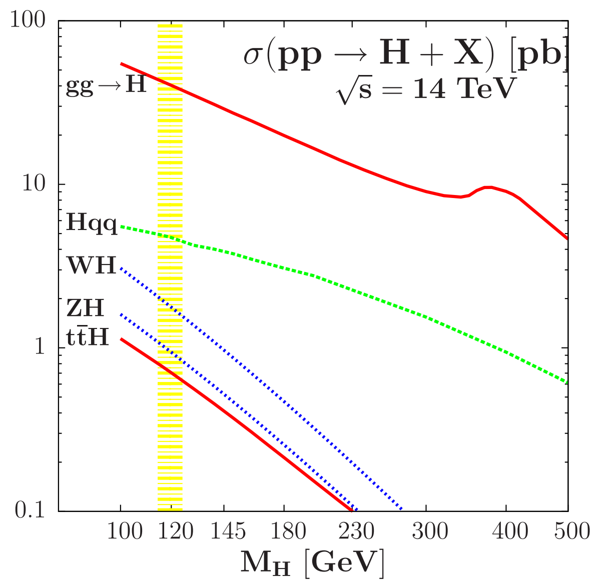
Now that Higgs is found (and nothing else yet): is HEP “closed”?

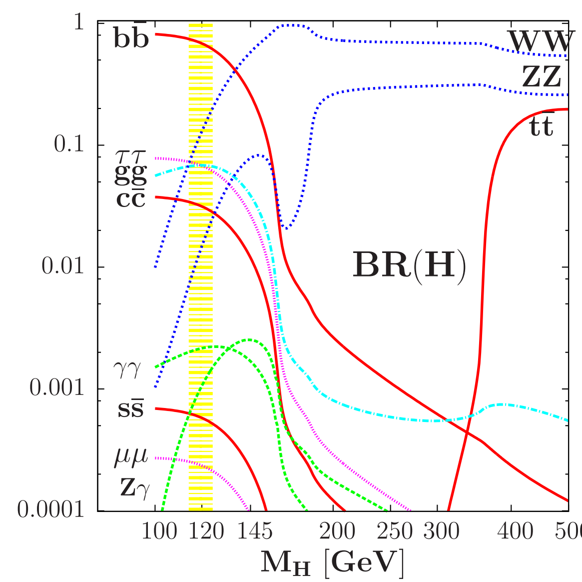
No! Need to check that H is indeed responsible of sEWSB (and SM-like?)

Measure its fundamental properties in the most precise way:

- **its mass and total decay width,**
- **its spin–parity quantum numbers and check $\mathrm{J^{PC}} = 0^{++}$,**
- **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 $\mathrm{V_H}$ that makes EWSB.**

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





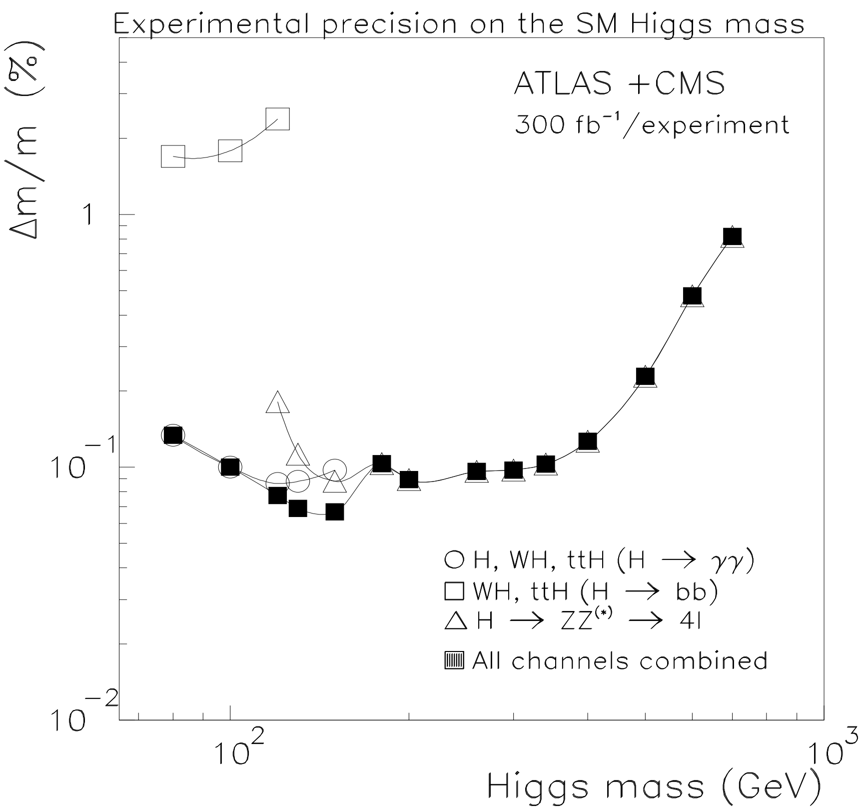
3. Higgs properties: mass and width

Higgs boson mass from:

– $\mathrm{H} \to \gamma\gamma$ for $\mathrm{M_H} \lesssim 130$ GeV

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

Final $\Delta \mathrm{M_H}/\mathrm{M_H} \sim 0.1\%$ to 1%.

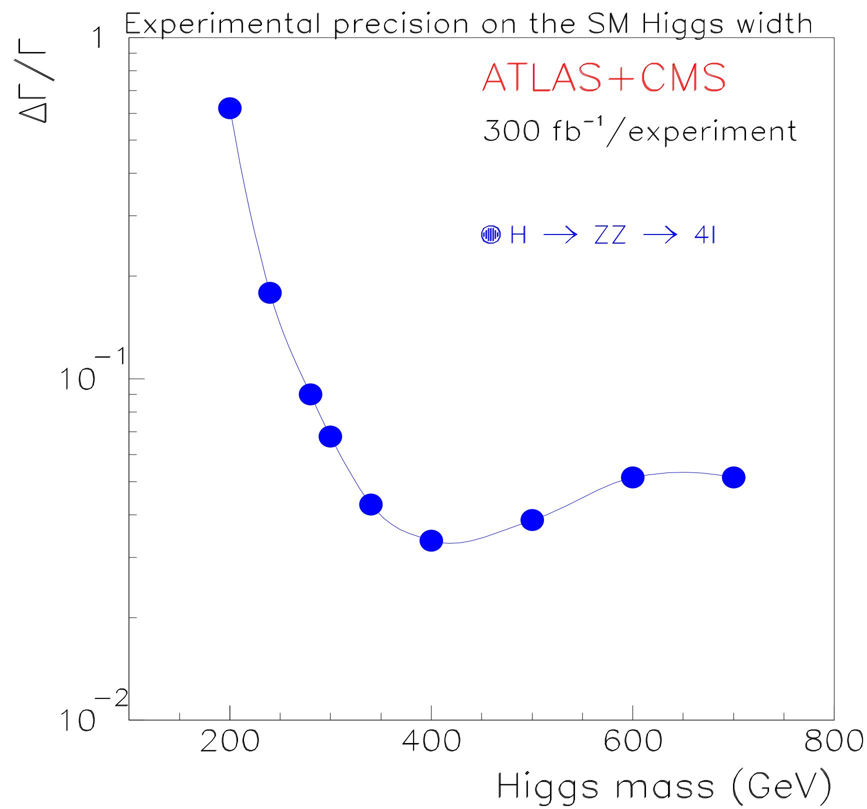


Higgs boson total width:

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

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

Final $\Delta\Gamma_\mathrm{H}/\Gamma_\mathrm{H} \sim$ a few %



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

3. Higgs properties: J^{PC} numbers

• **Higgs spin:**

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

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

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

• **Higgs parity:**

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

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

But need to check that H is pure CP–even

– challenging precision measurement,

– roughly doable in H→VV→ $4\ell^{\pm}$ **correlations.**

– also in $d\Gamma(H \to ZZ^*)/dM_*$

Drawback: If H is mostly CP–even,

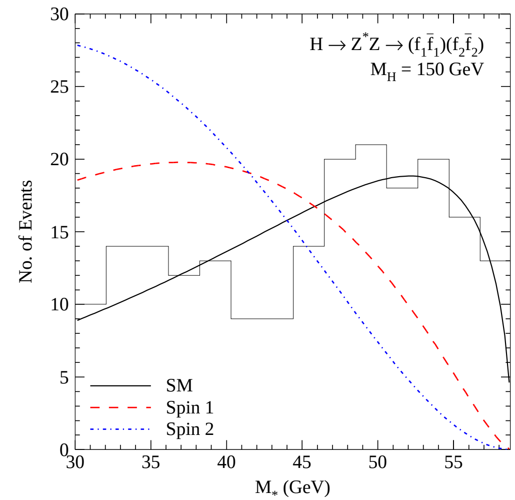
rates for $A \to VV$ **are too small...**

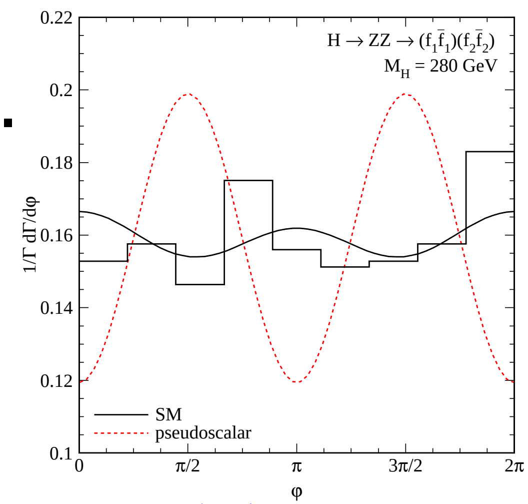
More convincing: look at Hff couplings

Possible but challenging channels:

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

$d\Gamma(H \to ZZ^*)/dM_*$ **@thresh**





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

contaminates also VBF/HZ (30%)...

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

• One obtains width ratios: $\Gamma_\mathbf{X}/\Gamma_\mathbf{Y}$

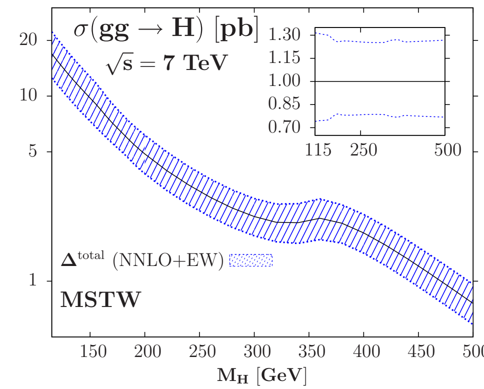
• Theory assumptions (no invisible, SU(2) invariance, some couplings are known,..)

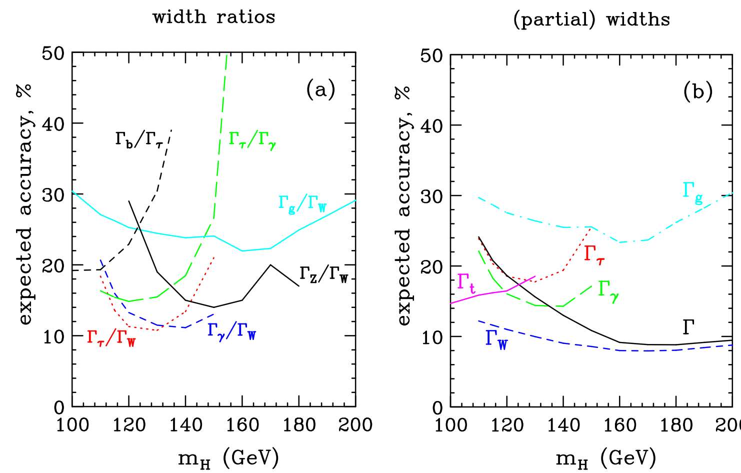
$\Rightarrow$ translate into $\Gamma_\mathbf{X} \propto \mathrm{g^2_{HXX}}$ with

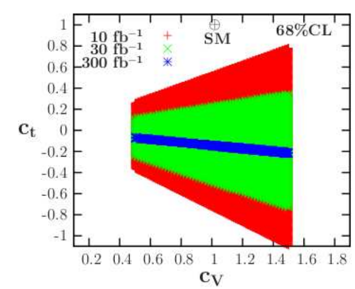
precision: $\Delta \mathrm{g_{HXX}} = \frac{1}{2}\frac{(\Delta^{\rm exp}\Gamma + \Delta^{\rm th}\Gamma)}{\Gamma}$

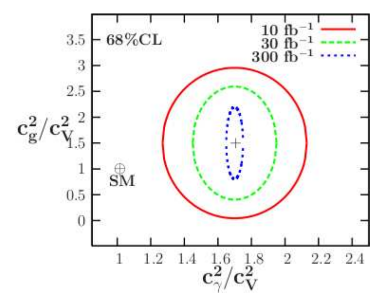
$\Rightarrow$ **reasonable precision of order 10%**

not bad... but is it really enough?









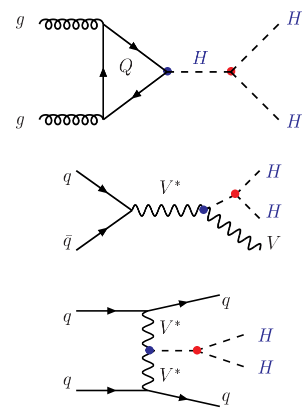
3. Higgs properties: Higgs self-couplings

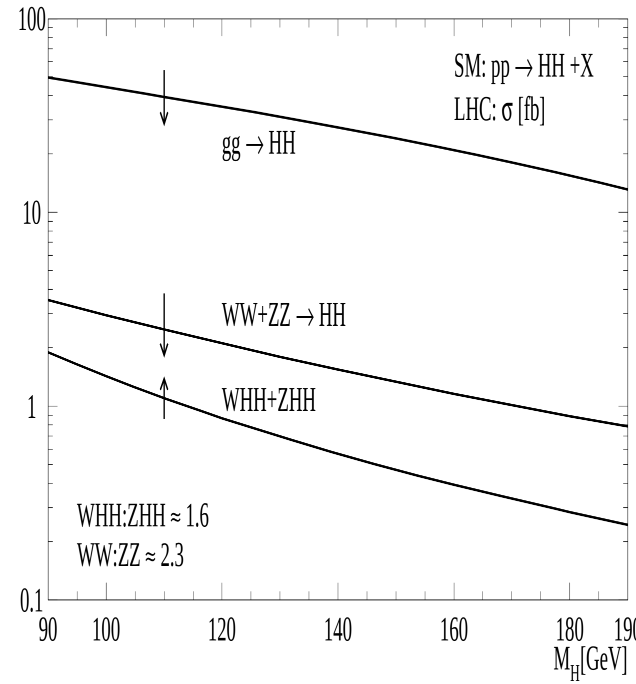
Important couplings to be measured: $g_{H^3}, g_{H^4} \Rightarrow$ access to V_H.

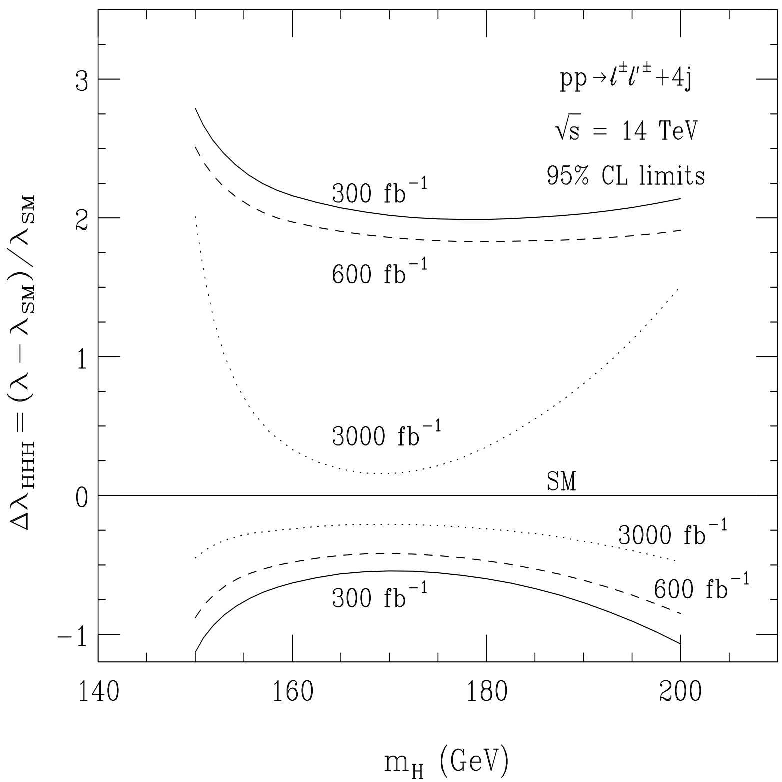
- g_{H^3} **from** $pp \to HH + X \;\Rightarrow$
- g_{H^4} **from pp⟶3H+X, hopeless.**

Relevant processes for HH prod:

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







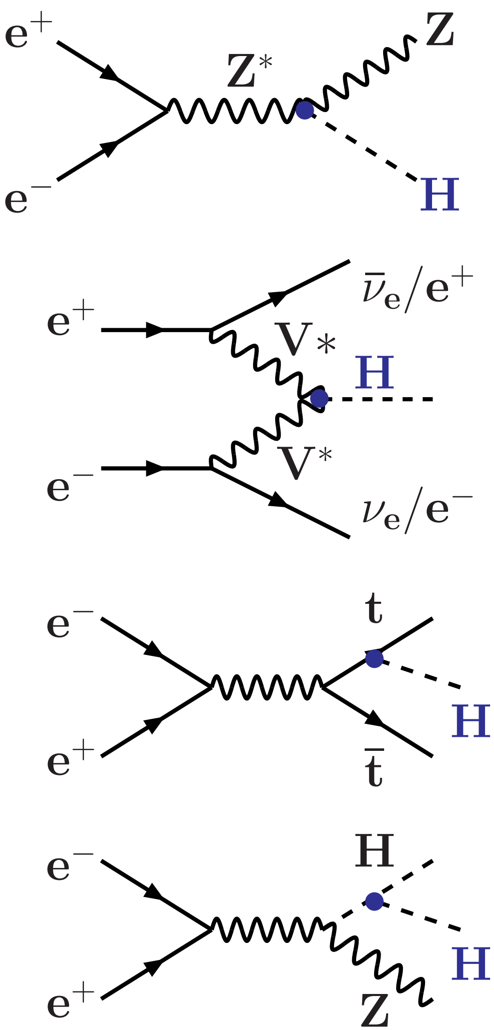
- $H \to \gamma\gamma$ **decay too rare,**
- $H \to b\bar{b}$ **decay not clean**
- $H \to WW$ **at low** M_H**?**

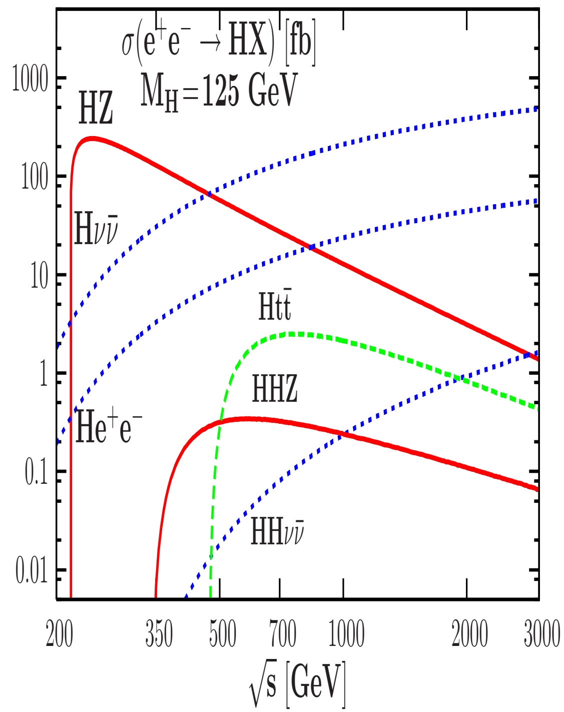
– parton level analysis...

– look for $2\ell^{\pm}, 3\ell^{\pm} + \nu$+jets+

– needs very large luminosity.

4. The Higgs at the LC





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

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 beat**

.. for a 125 GeV Higgs...

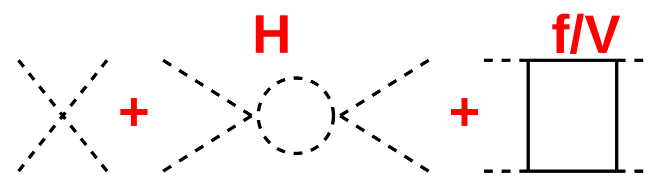
4. Higgs properties: LEP3?

Some people advocate a (quick/cheap) 250 GeV LC, a kind of LEP3...
not a very good idea to my (humble) opinion....
– 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!
And you cannot do top physics! Why is it so important???

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

Small λ: top,W,Z contributions dominant

$$\frac{\lambda(Q^2)}{\lambda(v^2)} \approx s1 + 3\,\frac{2M_W^4 + M_Z^4 - 4m_t^4}{16\pi^2 v^4} \log\frac{Q^2}{v^2}$$

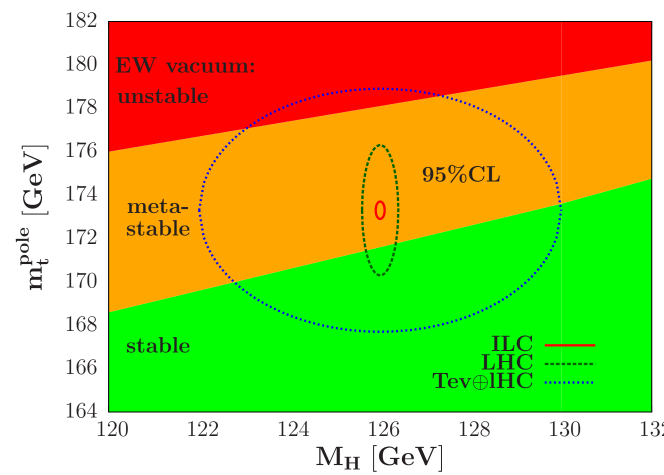


tops lead to $\lambda(0) < \lambda(v)$: unstable vacuum

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 $\Delta m_t = 0.2$ GeV!



Only way to check stability/NP: $\sqrt{s} \gtrsim 350$ GeV!

4. The Higgs at the LC: CLIC?

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

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

Higgs couplings to 2d generation

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

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

– Anomalous Higgs couplings

some (eg. CPV) need high $\sqrt{s}$

- **Trilinear Higgs couplings**

$\mathrm{e^+e^-} \rightarrow \mathrm{W^*W^*} \rightarrow \mathrm{HH}\nu\nu$

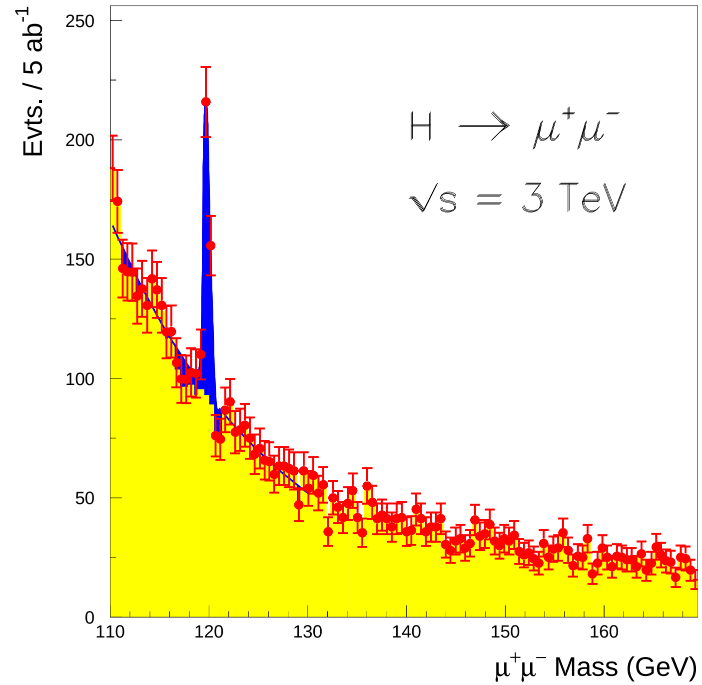
– stats better than HZ@500 GeV

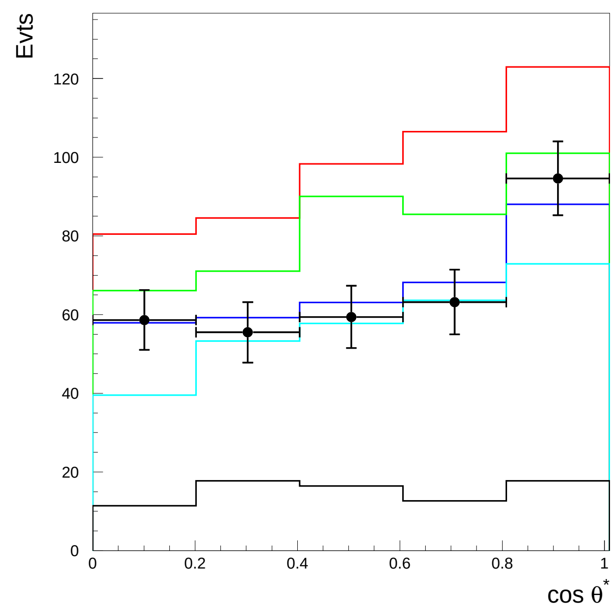
– additional info/separation (θ^*)

with a high lumi needed, a few ab^{-1}

Not much gain compared to ee500 in SM

but what about NP scenarios?



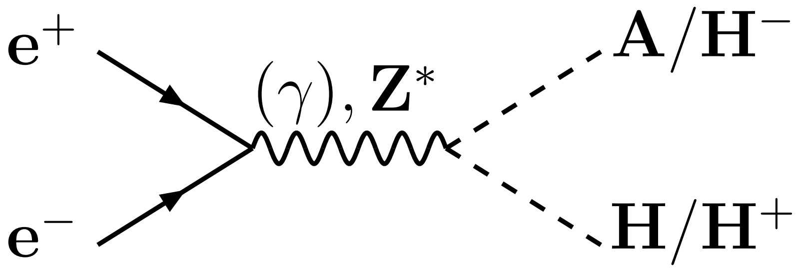


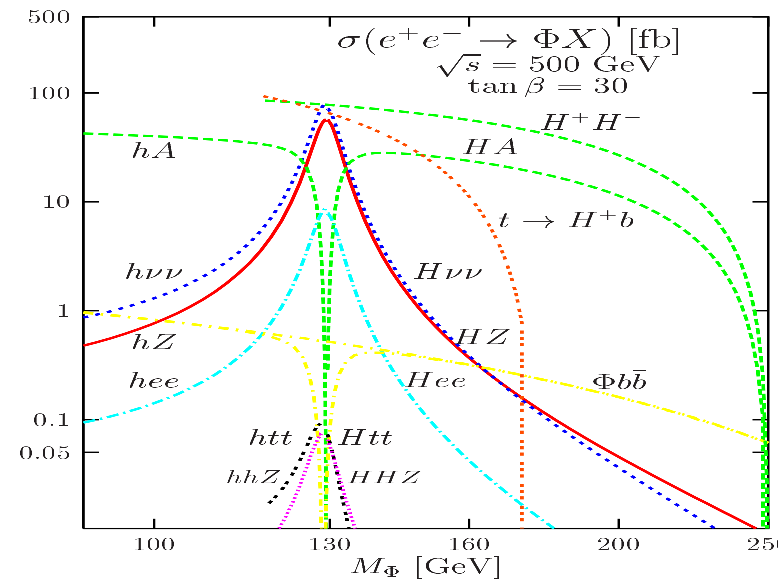
4. The Higgs of the ILC: CLIC

5 Higgs states: $\mathrm{h, H, A, H^\pm}$

- **For** h**, same as SM Higgs**

$\mathrm{H, A, H^\pm}$**: additional channels:**





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

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

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

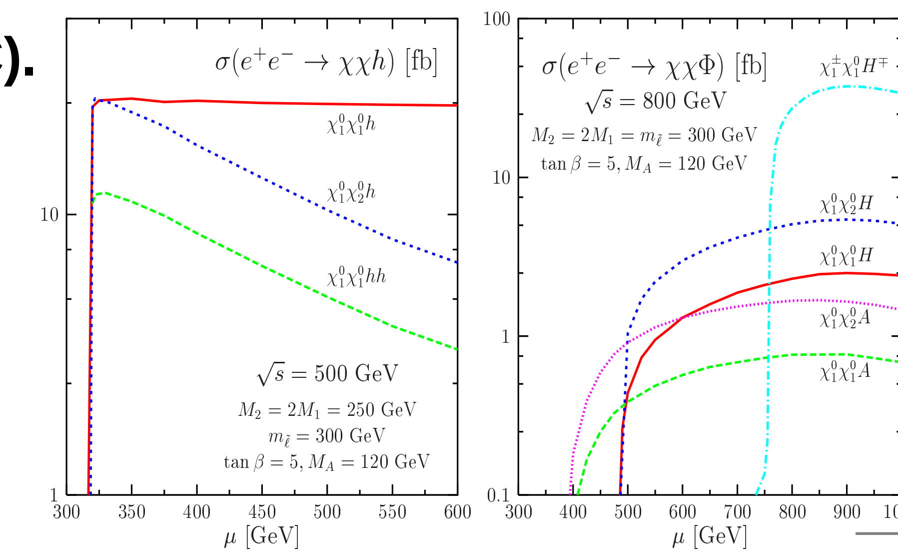
- **Cascade decays of SUSY particles**

– charginos/neutralinos to Higgs

(probes H couplings to sparticles)

– stop2 to stop1 and a Higgs

(good measurement of trilinear $\mathrm{A_t}$**)**

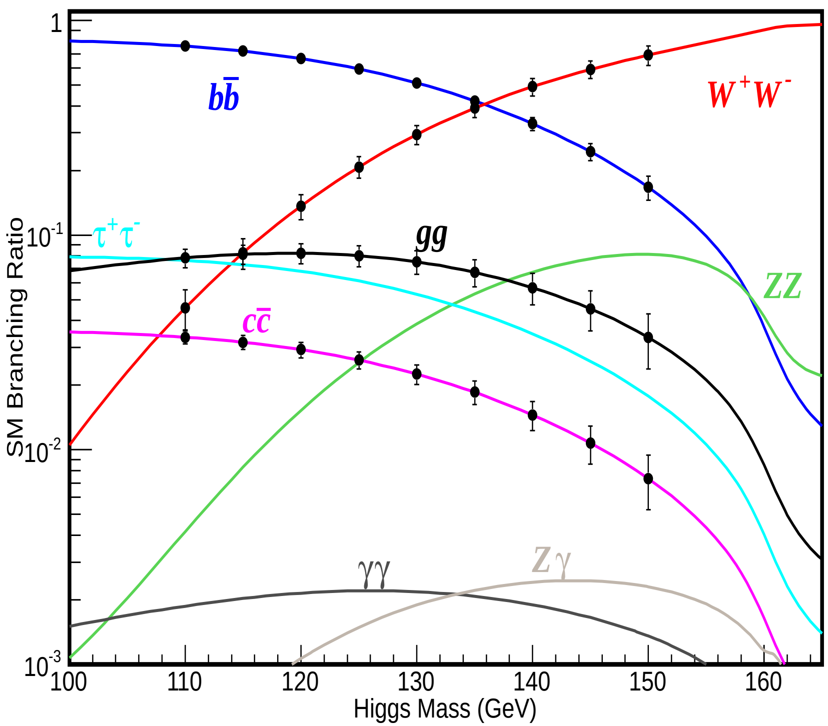


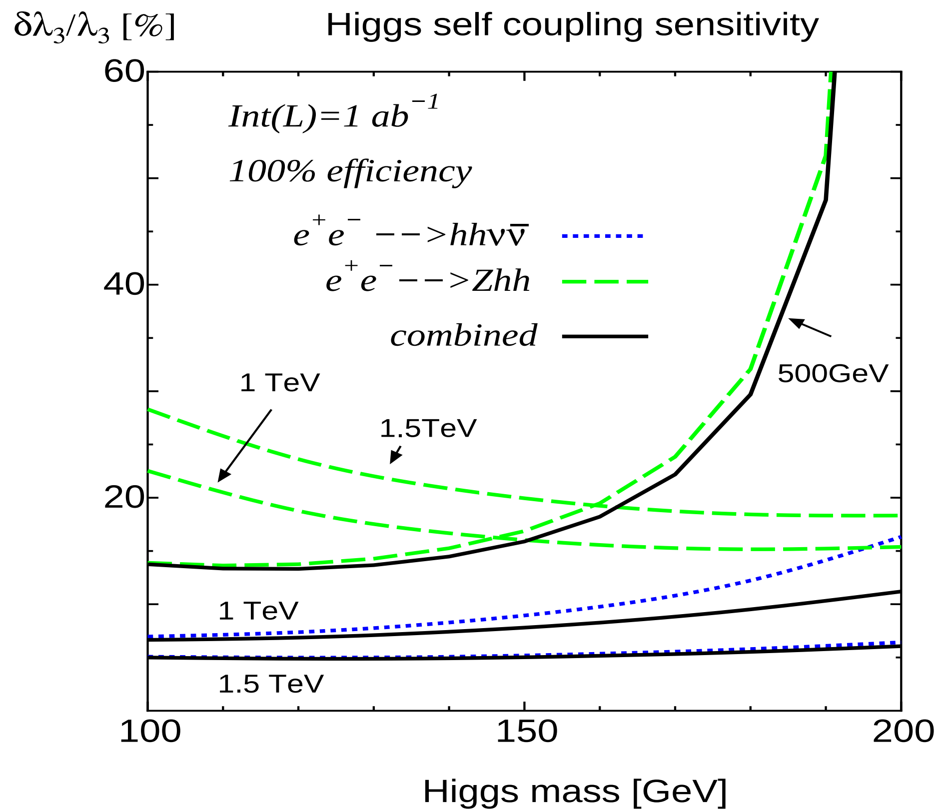
4. Higgs properties: LC?

Personal opinion:

An e^+e^- machine with $\approx$ 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!