Perspectives for Higgs and New Physics

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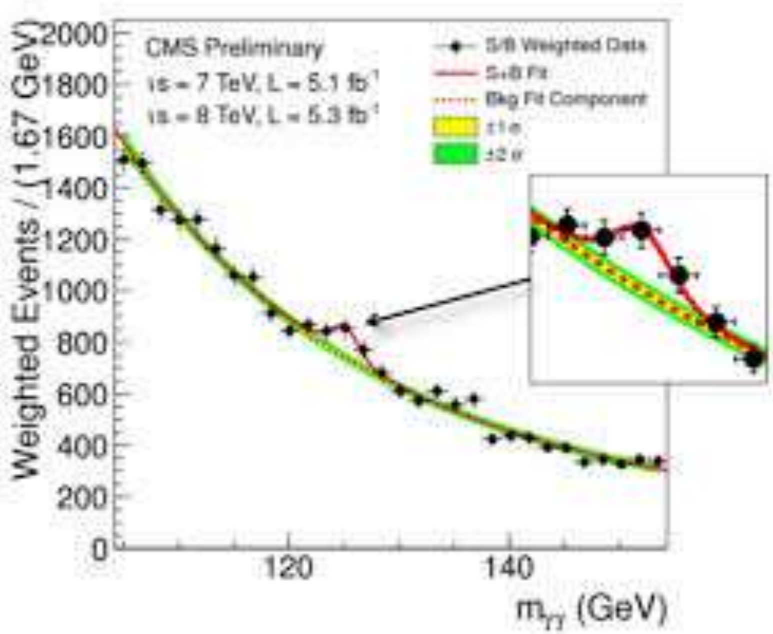
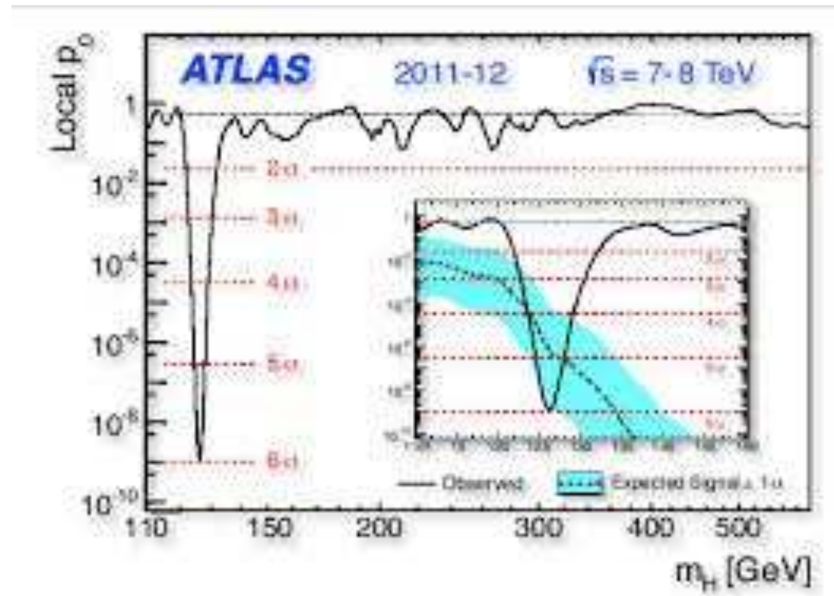
1. The Standard Model and the Higgs boson
2. Beyond the Standard Model
3. Tests of the Higgs properties
4. Search for New Physics
5. Conclusion

1. The Standard Model and the Higgs boson

The 4th of July 2012: a historical day with a Higgstorical discovery!

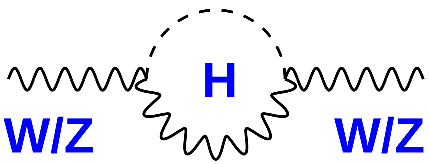




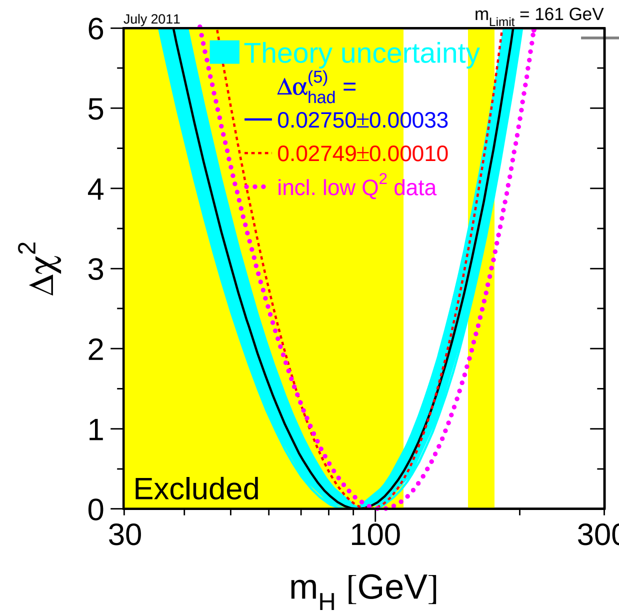
1. The Standard Model and the Higgs boson

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

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



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



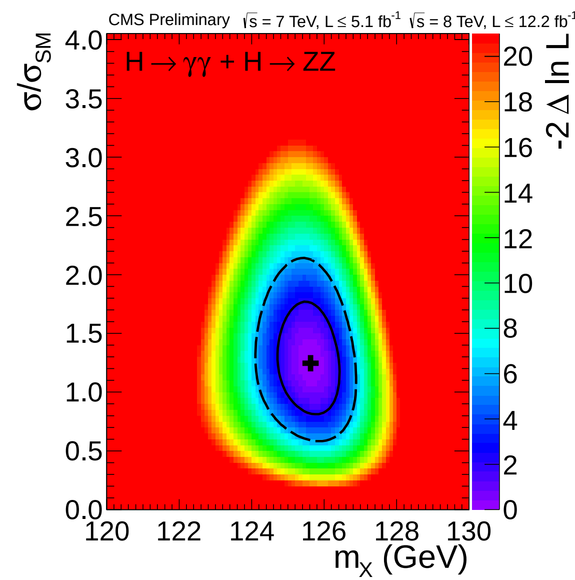
Fit the EW ($\lesssim$ 0.1%) precision data, with all other SM parameters known, one obtains $M_H = 92^{+34}_{-26}$ GeV, or

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

We make an experiment and measure

$$M_H = 125 \text{ GeV}$$

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

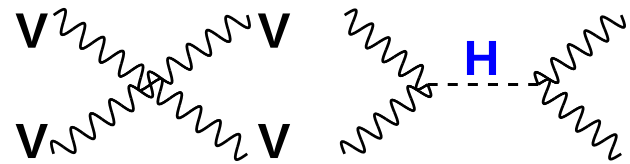


1. The Standard Model and the Higgs boson

● **The theory preserves unitarity:**

we needed a Higgs with $M_H \lesssim 700$ GeV;

we have indeed a Higgs and it is light!



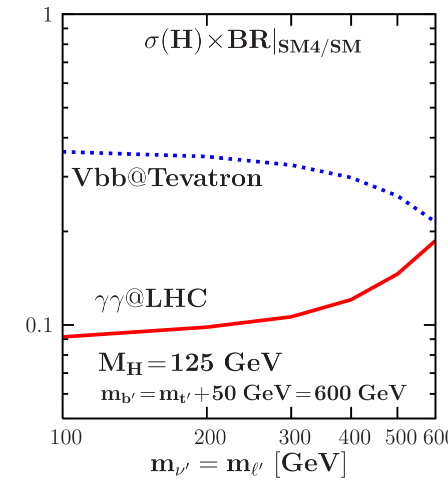
● **Particle spectrum complete:**

no room for 4th fermion generation

from Higgs production/decay rates.

(but still possibility of singlet N...)

$\Rightarrow$ Lenz...



● **Extrapolable up to highest scales.**

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

– too high: non perturbativity

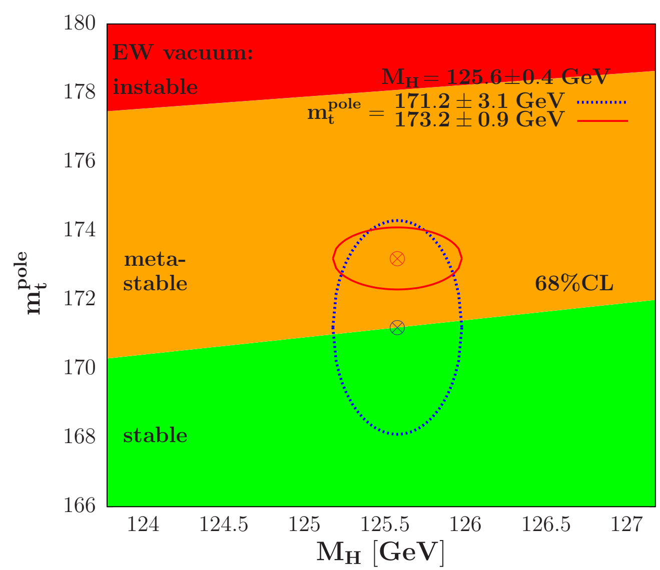
– too low: stability of the EW vacuum

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

$$\lambda \geq 0 @ M_P \Rightarrow M_H \gtrsim 129\ \mathrm{GeV}!$$

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

Degrassi..., Bezrukov...., (Alekhin... $\Rightarrow$)



1. The Standard Model and the Higgs boson

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

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

Is the SM the "theory of everything" and should we be satisfied with it?

No! Low energy manifestation of a fundamental theory that solves:

- "Esthetical" problems with e.g. multiple and arbitrary parameters;

gauge coupling unification: $3 \neq g_i$ which do not meet a high scale.

- "Experimental" problems as it does not explain all seen phenomena:

ν masses/mixing, dark matter, baryon asymmetry in the universe ....

(Note: SO(10) at intermediate $Q = 10^{11}$ GeV and axions cure these pbs!)

- "Theory" (or consistency) problem: the hierarchy/naturalness pbs.

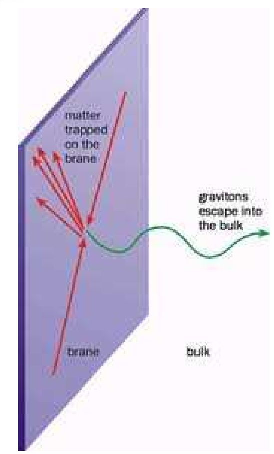
$\Delta M_H^2 \propto \Lambda^2 \approx (10^{18}\ \mathrm{GeV})^2$!: M_H not stable against high scales.

All these indicate that there is beyond the Standard Model physics!

2. Beyond the Standard Model

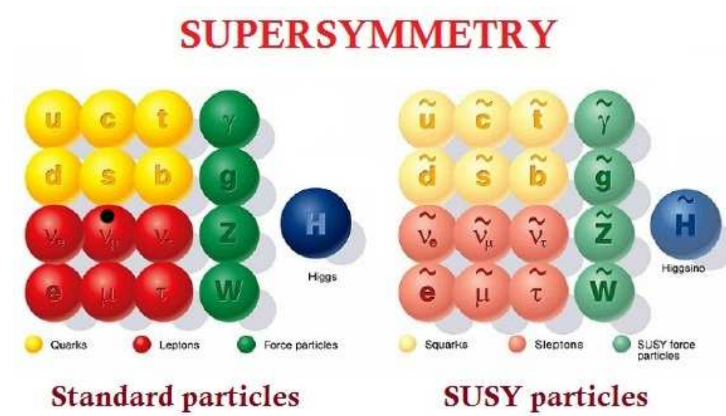
Three main avenues for solving the hierarchy or naturalness problems

I. Compositeness/substructure:
All particles are composite: Technicolor
$\Rightarrow$ H bound state of two fermions
(no more spin–0 fundamental state).



II. Extra space–time dimensions
where at least s=2 gravitons propagate.
$\Rightarrow$ effective gravity scale $\Lambda \approx$ TeV!
EWSB mechanism needed: H or not H!

III. Supersymmetry: doubling the world.
– links s=$\frac{1}{2}$ fermions to s=1 bosons,
– links internal/space-time symmetries,
– if made local, provides link to gravity,
– natural $\mu^2 < 0$: radiative EWSB,
$\Rightarrow$ sparticle loops cancel Λ^2 div!
extend EWSB sector: at least 2 doublets.



2. Beyond the Standard Model

The problem is that:

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

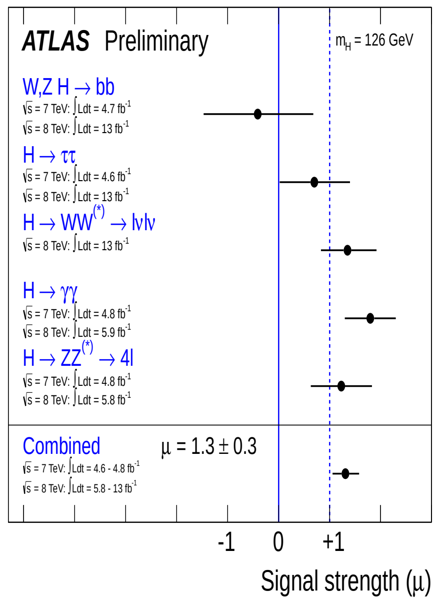
$\sigma\times$BR rates compatible with those expected in the SM

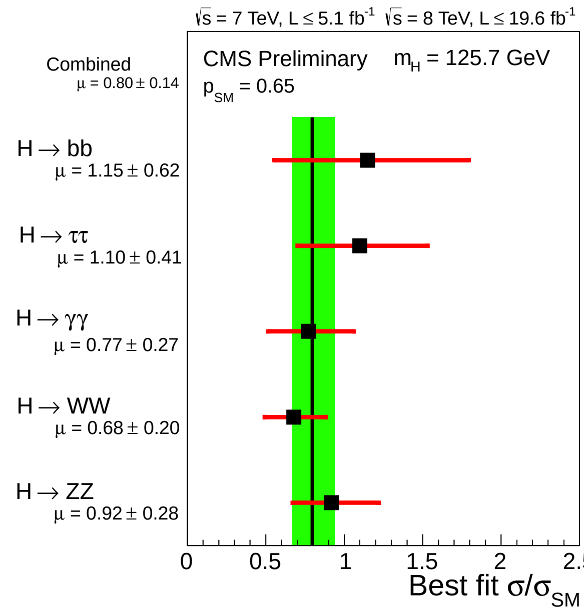
Fit of all LHC Higgs data $\Rightarrow$ agreement at 20–30% level

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

$\mu_{\rm tot}^{\rm CMS} = 1.01 \pm 0.30$

combined : $\mu_{\rm tot} \approx 1$!





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

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

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

As an example, let us see what it implies for SUSY and the MSSM.

2. Beyond the Standard Model

In the MSSM we need two doublets of complex scalar fields $\mathbf{H_1}$ and $\mathbf{H_2}$ to generate up/down-type fermion masses while having chiral anomalies.

after EWSB, three dof for $\mathbf{W_L^\pm, Z_L} \Rightarrow$ 5 physical states: $\mathbf{h, H, A, H^\pm}$.

Only two free parameters at tree-level to describe the system $\tan\beta, \mathbf{M_A}$:

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

$$\mathbf{M^2_{H^\pm}} = \mathbf{M_A^2} + \mathbf{M_W^2}$$

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

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

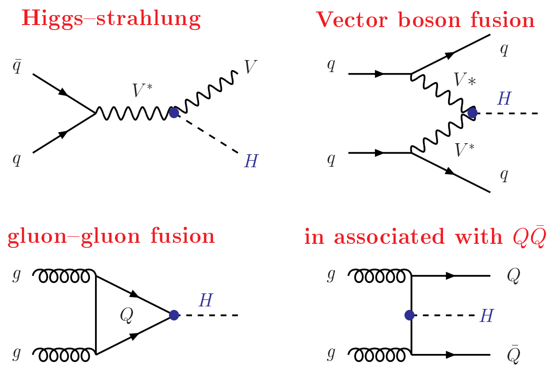
- Couplings of $\mathbf{h, H}$ to VV are suppressed; no AVV couplings (CP).
- For $\tan\beta \gg 1$: couplings to b (t) quarks enhanced (suppressed).

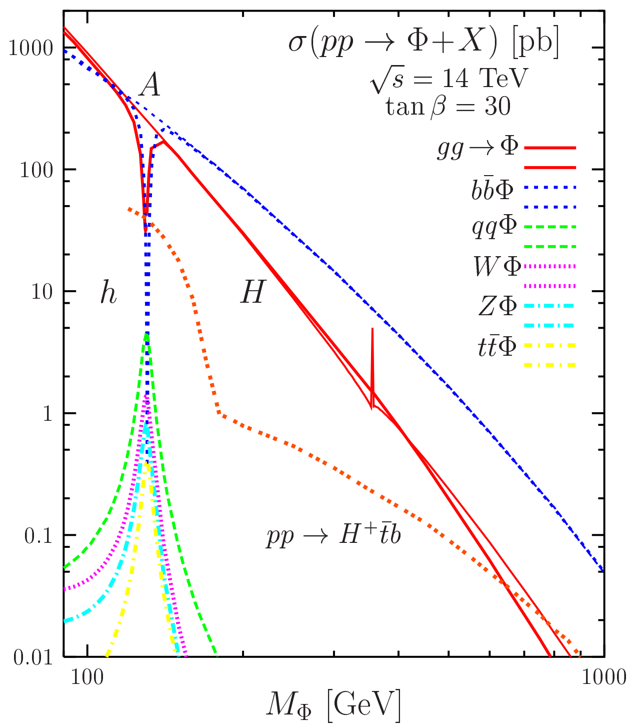
Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$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

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

2. Beyond the Standard Model

Production/decay phenomenology more complicated in the MSSM.





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

– some couple almost like the SM Higgs,

– but some are more weakly coupled.

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

$\Rightarrow$ **very complicated situation in general!**

But simpler in the decoupling regime:

– h as in SM with $\mathrm{M_h = 115-130}$ GeV

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

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

2. Beyond the Standard Model

There is a first direct implication from the measurement $\mathrm{M_h = 125}$ GeV...

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

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

$\mathrm{M_h}$=125GeV high value

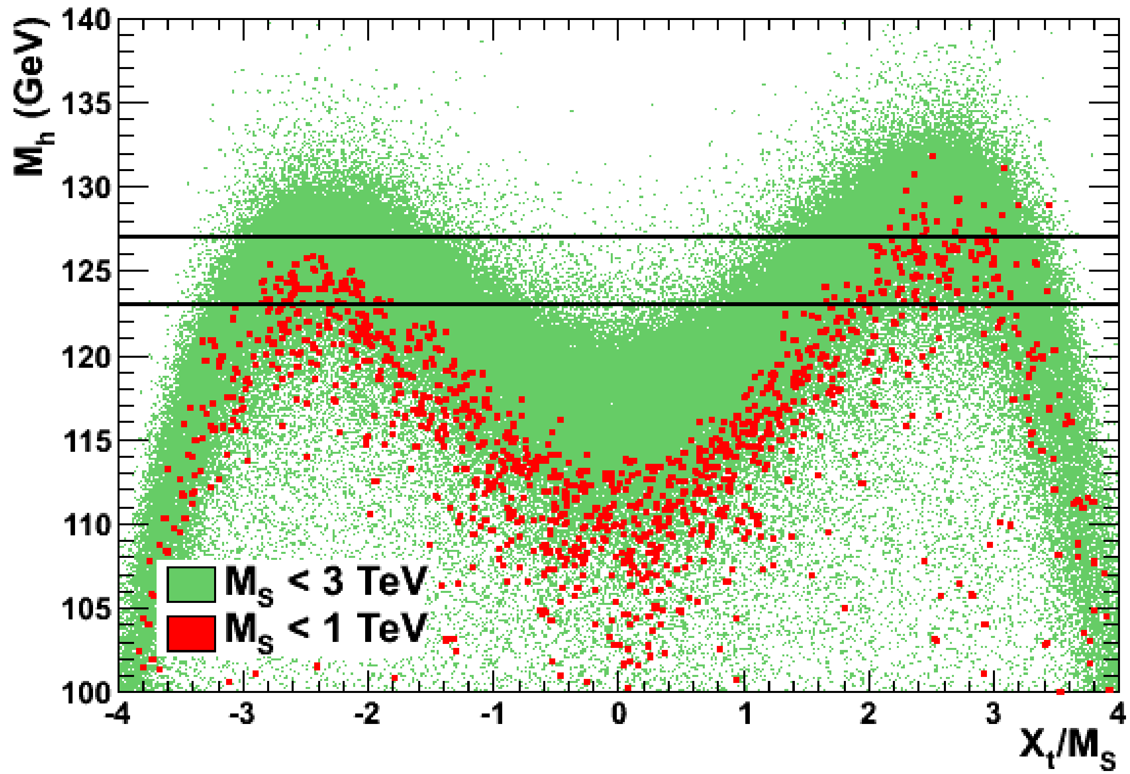
$\Rightarrow$ maximize radiative

and at same time, have:

- decoupling regime:

all other Higgses heavy

- large values of tanβ
- maximal $\mathrm{X_t} (\approx \sqrt{6}\mathrm{M_S})$
- heavy stops, i.e. large $\mathrm{M_{SUSY}} = \sqrt{\mathrm{m_{\tilde{t}_1} m_{\tilde{t}_2}}}$.



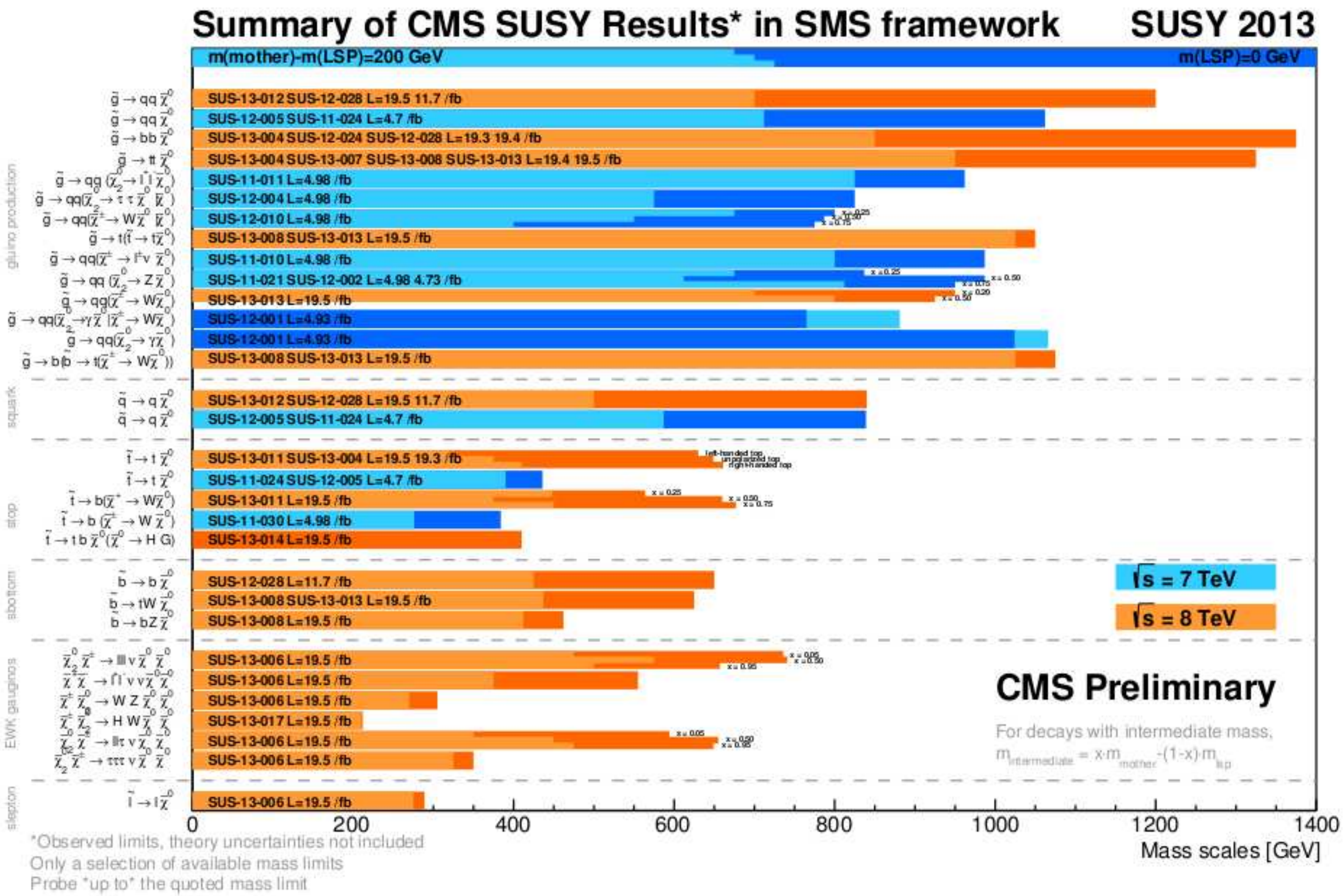
Arbey, Battaglia, AD, Mahmoudi, Quevillon (2012)

$\mathrm{M_{SUSY}} \gtrsim 1$ TeV in general MSSM and even higher in constrained models!

2. Beyond the Standard Model

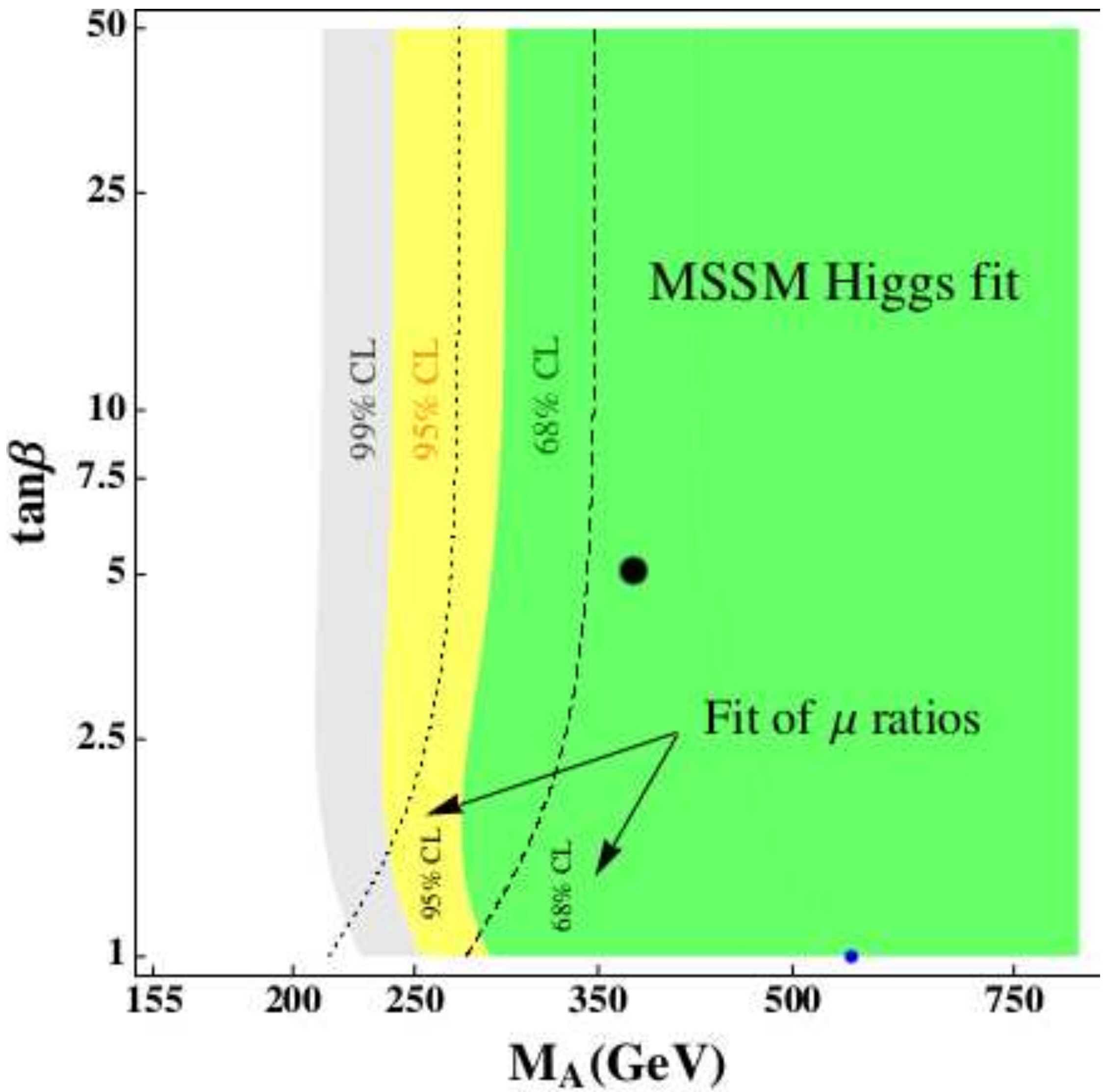
This is backed up by direct searches of SUSY particles at the LHC:

the SUSY scale $M_{SUSY} \gtrsim \mathcal{O}$(1 TeV) in most experimental searches..



2. Beyond the Standard Model

Also backed up indirectly by the measurement of the Higgs properties:
fits of the h couplings $\Rightarrow$ constraints on the MSSM $[\mathrm{M_A}, \tan\beta]$ plane.



AD
Maiani
Moreau
Polosa
Quevillon
Riquer
(2013)

3. What next? Measurement of Higgs properties

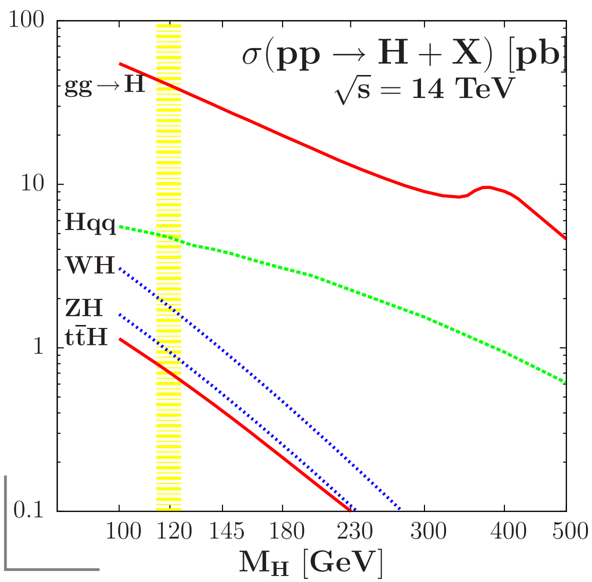
The next question is then: “is Particle Physics closed”? Answer is no!

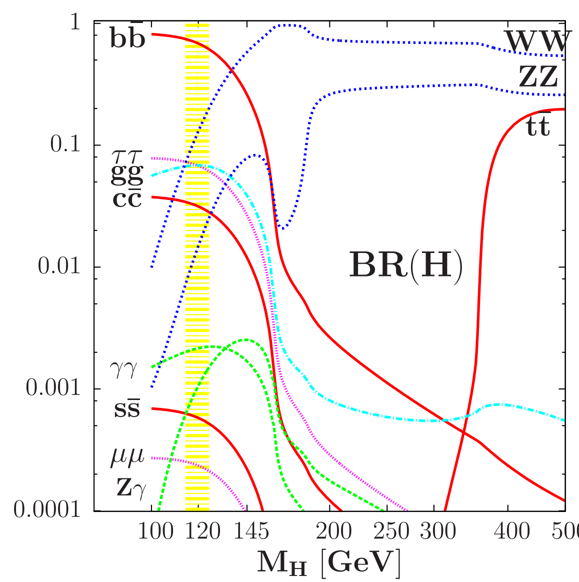
1) Need to check that H is indeed responsible of SEWSB (and SM-like?)

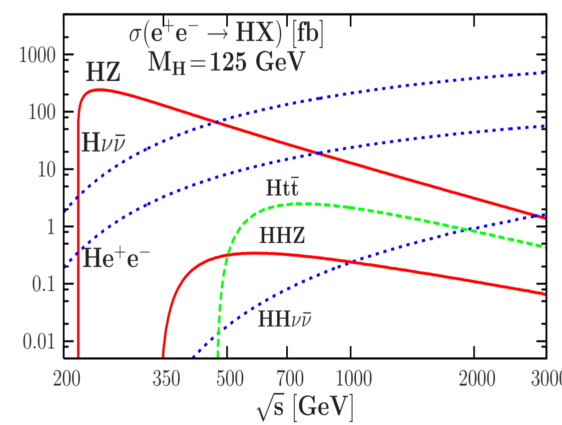
$\Rightarrow$ measure its fundamental properties in the most precise way:

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

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







3. What next? Measurement of Higgs properties

A check of spin–parity quantum numbers.

Spin: clear situation (no suspense) as the new state decays into $\gamma\gamma$
$\Rightarrow$ not s=1 from Landau–Yang theorem and s=2 (KK graviton?) unlikely..

CP numbers: CP-even, CP-odd, or mixture?

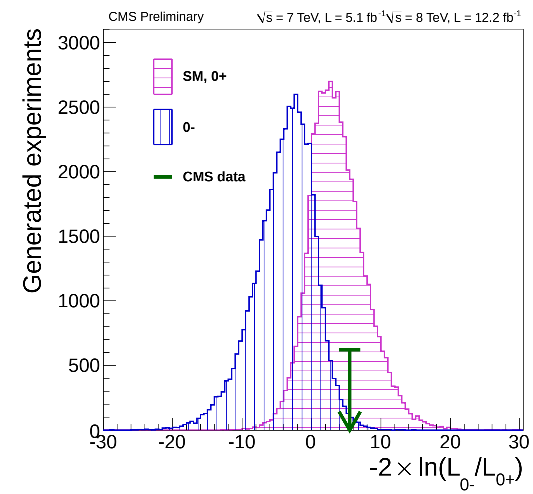
(more important issue: CPV in Higgs sector!)

ATLAS and CMS MELA analyses for pure CP

$\Rightarrow$ pure CP-even favored at $\approx 3\sigma$ level.

But problems with this (too simple) picture:

pure CP–odd does not couple to VV@tree-level.



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

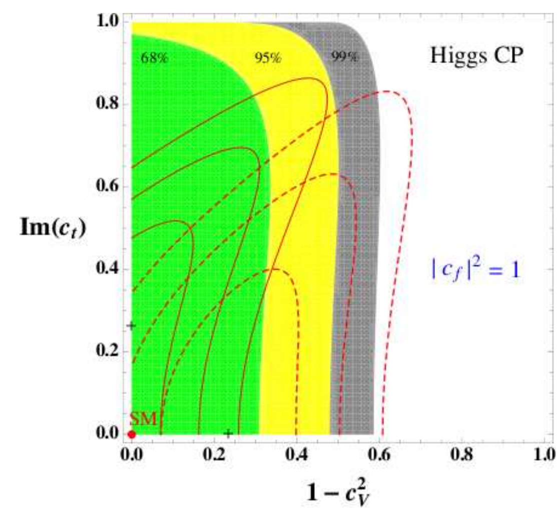
$g_{HVV} = c_V g_{\mu\nu}$ gives upper bound on CP

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

Direct probe: g_{Hff} more democratic!

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

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



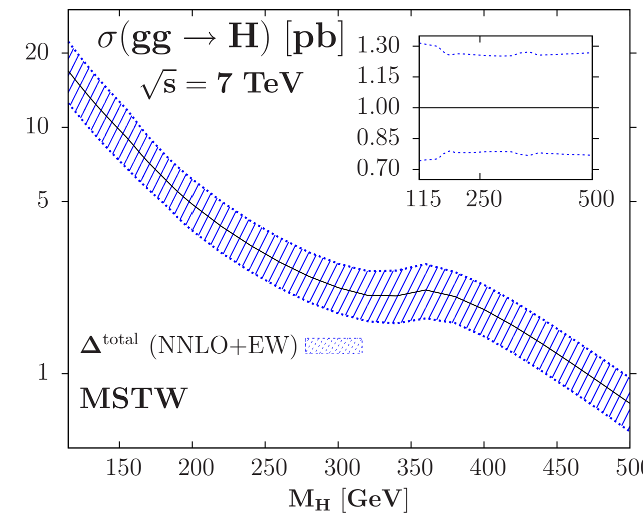
Extremely challenging even at HL-LHC...

3. What next? Measurement of Higgs properties

- **Precise measurement of Higgs couplings**

in various H production+decay channels

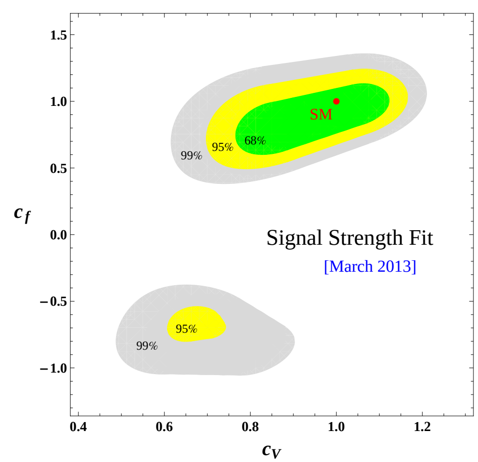
Baglio...

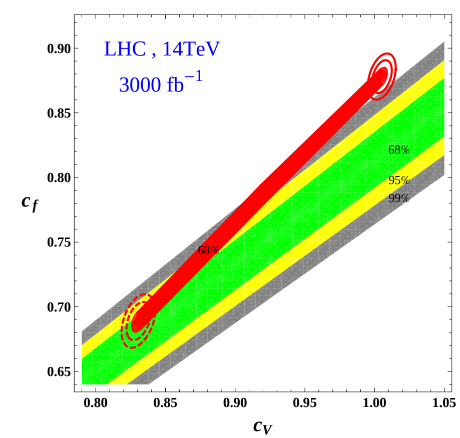


But rather large errors mainly due to:
– experimental: stats, system., lumi...
– theory: PDFs, HO/scale, jetology...
total error about 15–20% in $gg \to H$
Hjj contaminates VBF (now 30%)..
$\Rightarrow$ **ratios of σxBR: many errors out!**
Deal with width ratios Γ_X/Γ_Y
– TH on σ and some EX errors
– 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 % only at HL–LHC.
Sufficient to probe BSM physics?





Moreau...

3. What next? Measurement of Higgs properties

- **Total width**: $\Gamma_H = 4$ MeV, too small to be resolved experimentally.
- – very loose bound from interference gg$\to$ZZ (a factor of a 2–5 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:

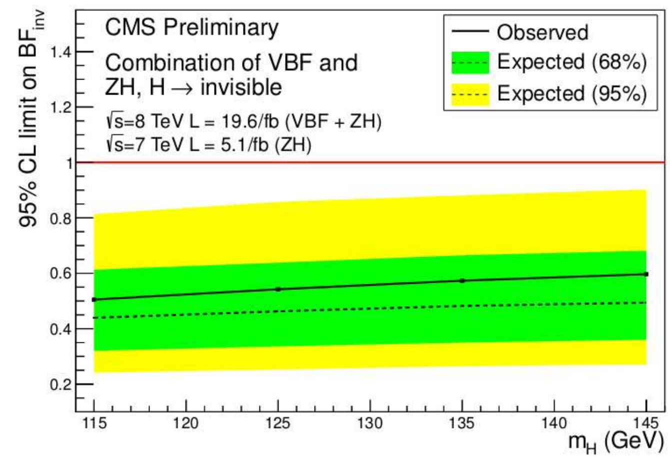
$q\bar{q} \to HZ$ and $qq \to Hqq;\ H \to \text{inv}$

Combined HZ+VBF search from CMS

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

More promising in the future: monojets

$gg \to H + j \to j + \not{E}_T$



Falkowski...

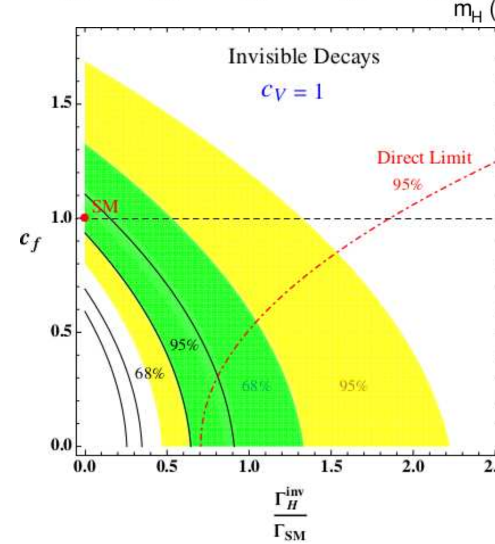
Indirect measurement:

again assume SM–like Higgs couplings

constrain width from signal strengths

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

Moreau...



Improvement in future: 10% @ HL–LHC?

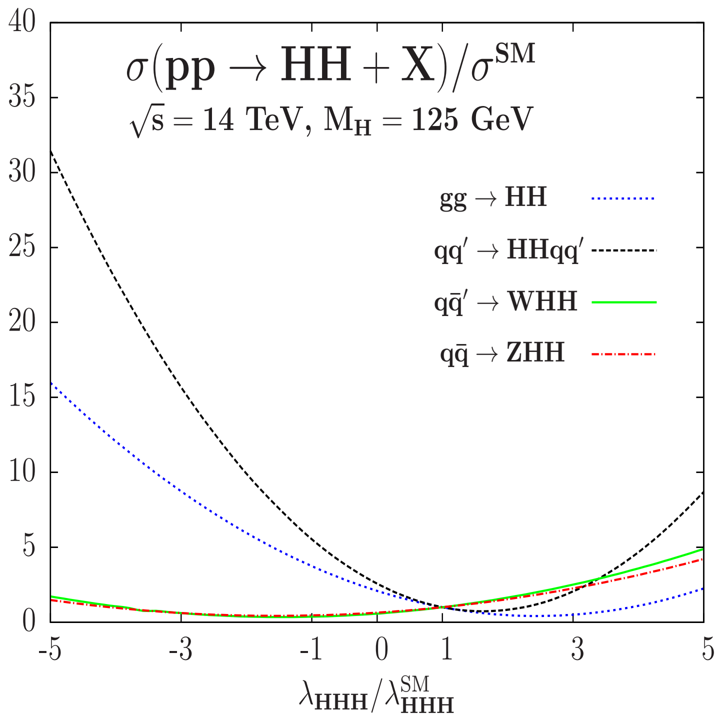
3. What next? Measurement of Higgs properties

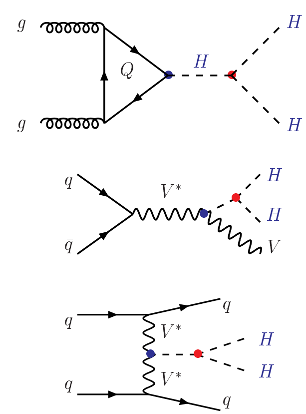
An important challenge: measure Higgs self-couplings and access to V_H

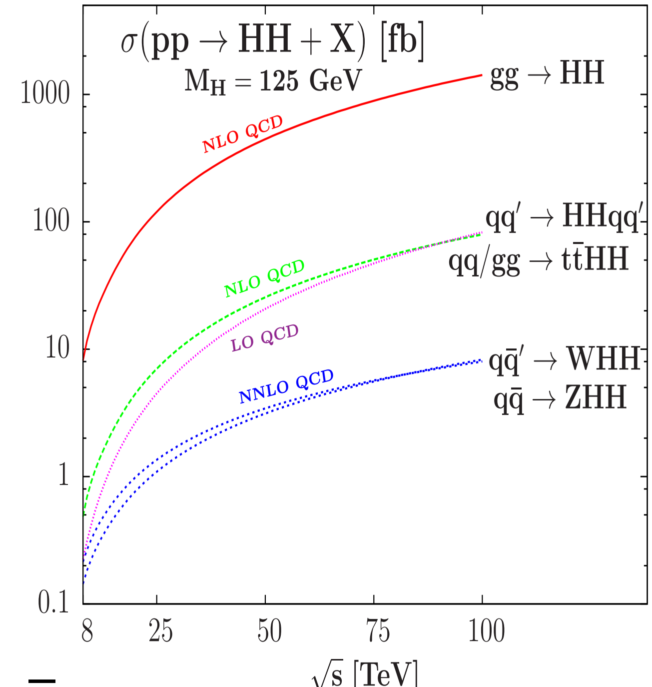
- g_{H^3} **from** $pp \to HH + X \Rightarrow$
- g_{H^4} **from pp→3H+X, hopeless.**

Various processes for HH prod:

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







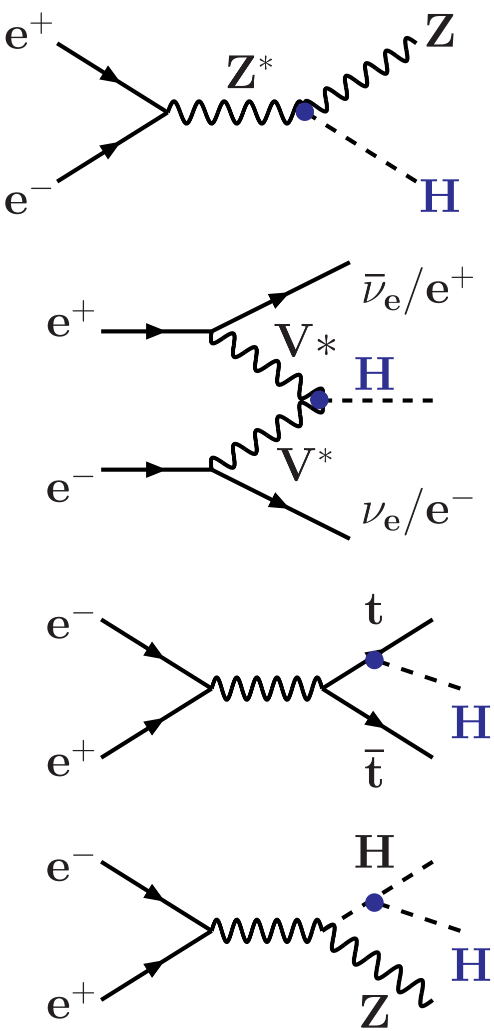
Baglio et al., arXiv:1212.5581

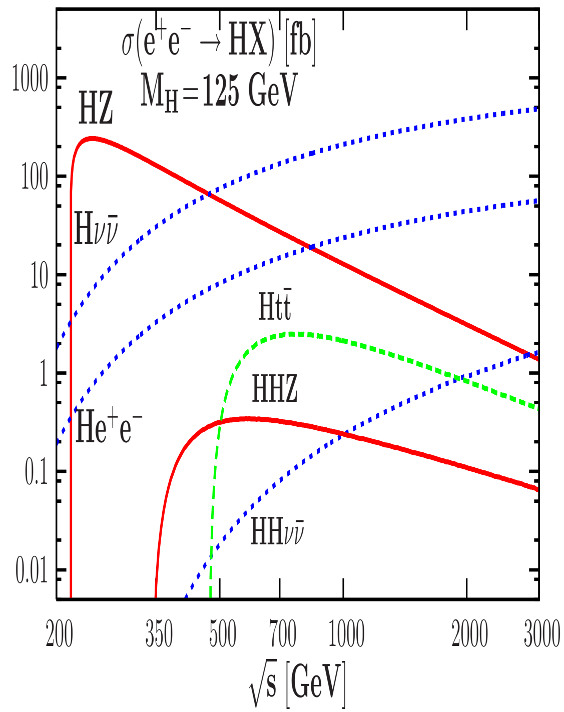
- $H \to b\bar{b}$ **decay alone not clean**
- $H \to \gamma\gamma$ **decay very rare,**
- $H \to \tau\tau$ **would be possible?**
- $H \to WW$ **not useful?**

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

– **but needs very large luminosity.**

3. What next? Measurement of Higgs properties





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

$\Rightarrow$ **difficult to be beaten by anything else for $\approx$ 125 GeV Higgs**

$\Rightarrow$ **welcome to the e^+e^- precision machine!**

4. What next? Search for new particles

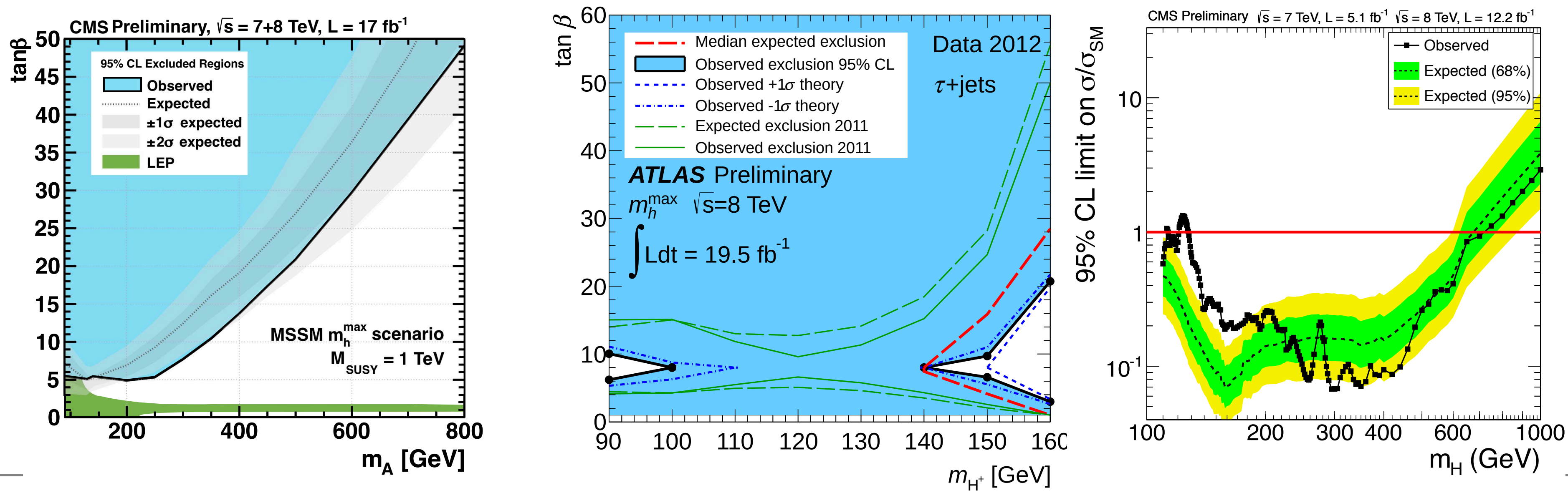
Now that the Higgs boson is found, is Particle Physics "closed"? No!

2) Fully probe the TeV scale that is relevant for the hierarchy problem

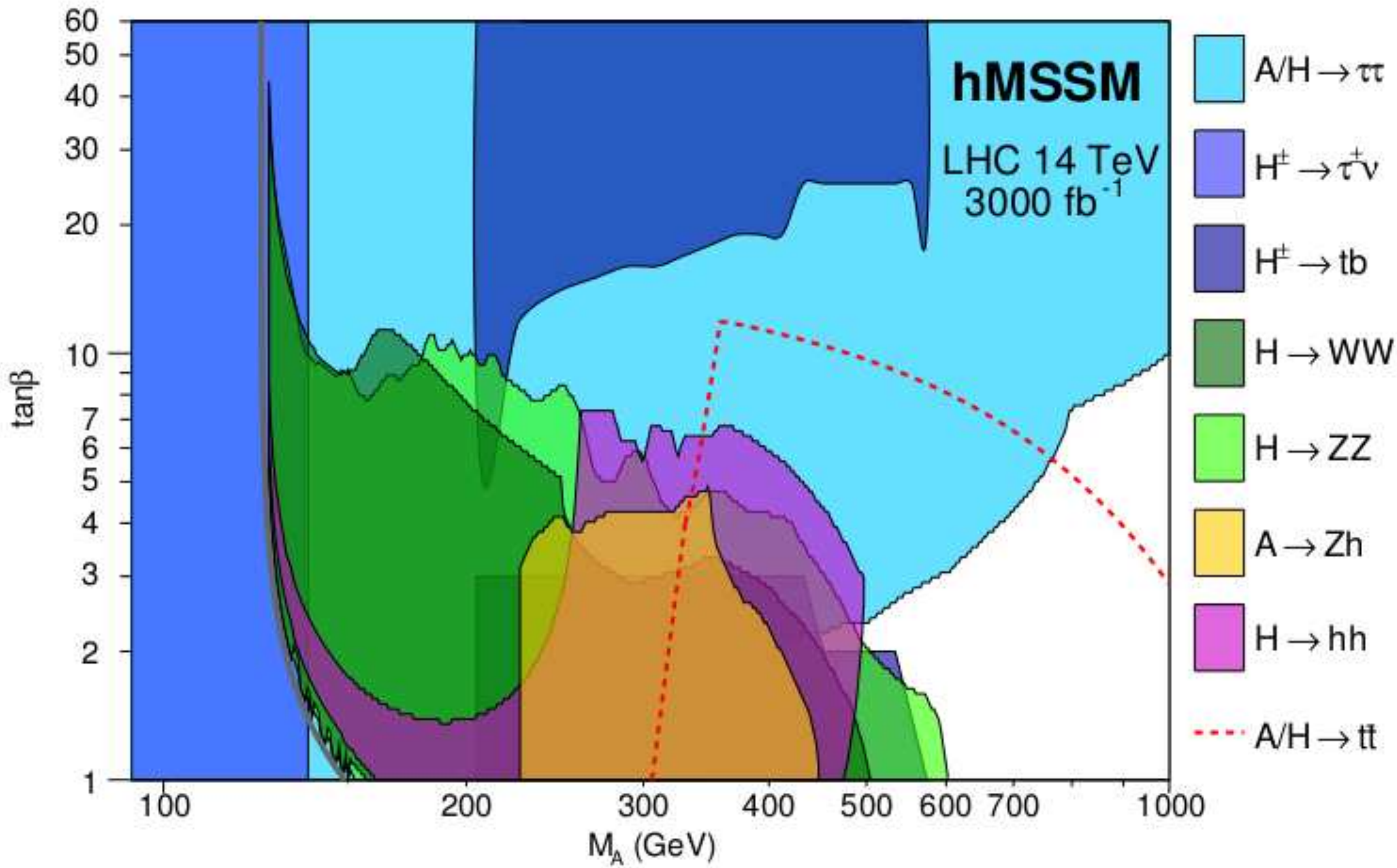
$\Rightarrow$ continue to search for heavier H bosons and new (super)particles.

Search for the heavier MSSM H bosons in all possible channels:

- **Searches for the $\mathrm{pp} \to \mathrm{A/H/(h)} \to \tau\tau$ resonant process:**
- **Searches for charged Higgs in $\mathrm{t} \to \mathrm{bH^+} \to \mathrm{b}\tau\nu$ decays:**
- **Non observation of heavier Higgs bosons in H$\to$ZZ,WW modes:**
- **Also searches for $\mathrm{A} \to \mathrm{hZ}$ and $\mathrm{H} \to \mathrm{hh}$ but not in the MSSM....**
- **Searches for heavy tt resonances but not in the MSSM ($\mathrm{KK}, \mathrm{Z'}$)...**



4. What next? Search for new particles



AD, Maiani, Polosa, Quevillon, Riquer (2015)

4. What next? Search for new particles

● **Search for supersymmetric particles**

(not only strong but also electroweak):

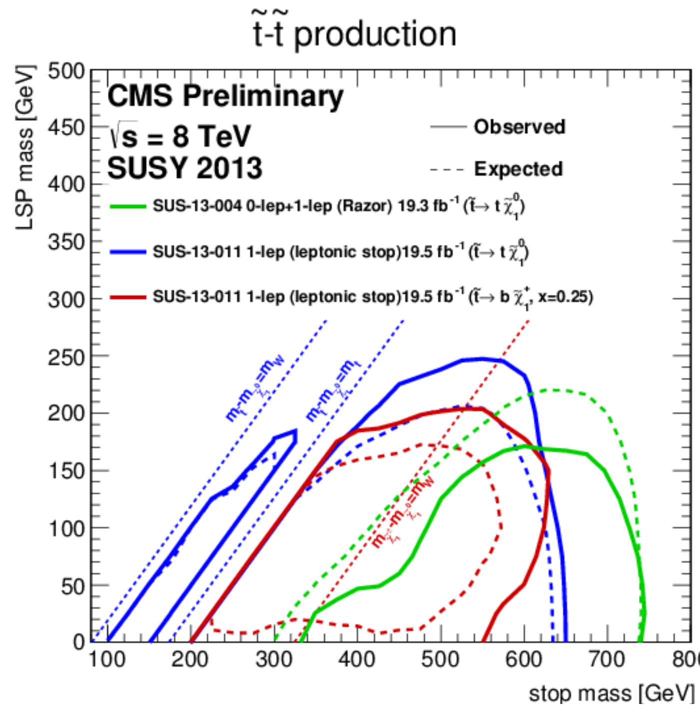
– squarks and gluinos up to a few TeV,

– chargino/neutralino/sleptons to 1 TeV,

– LSP/DM neutralino up to few 100 GeV,

(including in non minimal scenarios).

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



● **Search for any new heavy particle**

(predicted in all BSM extensions...):

– new multi–TeV Z' bosons

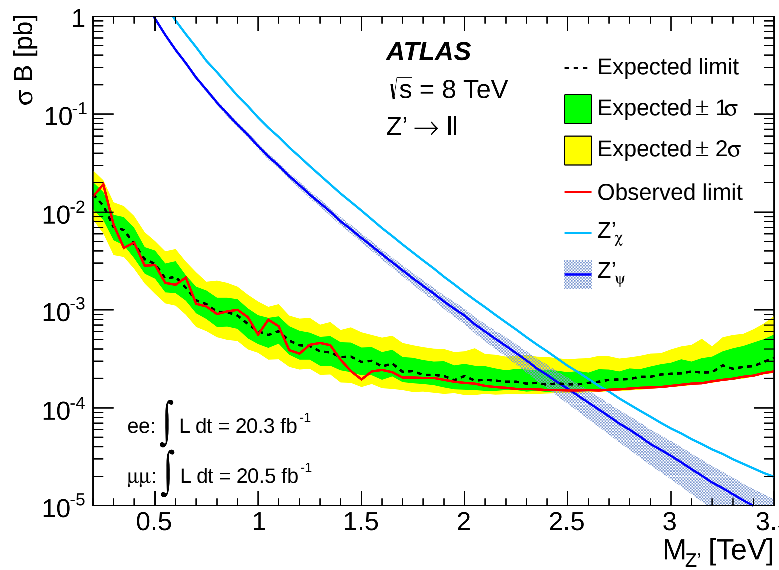
– Kaluza–Klein excitations

– Techni-fermions and bosons

– top (composite) partners

– unexpected ones (LQ, new f, ..)

example of ATLAS reach in $Z' \to l^+l^-$ $\Rightarrow$

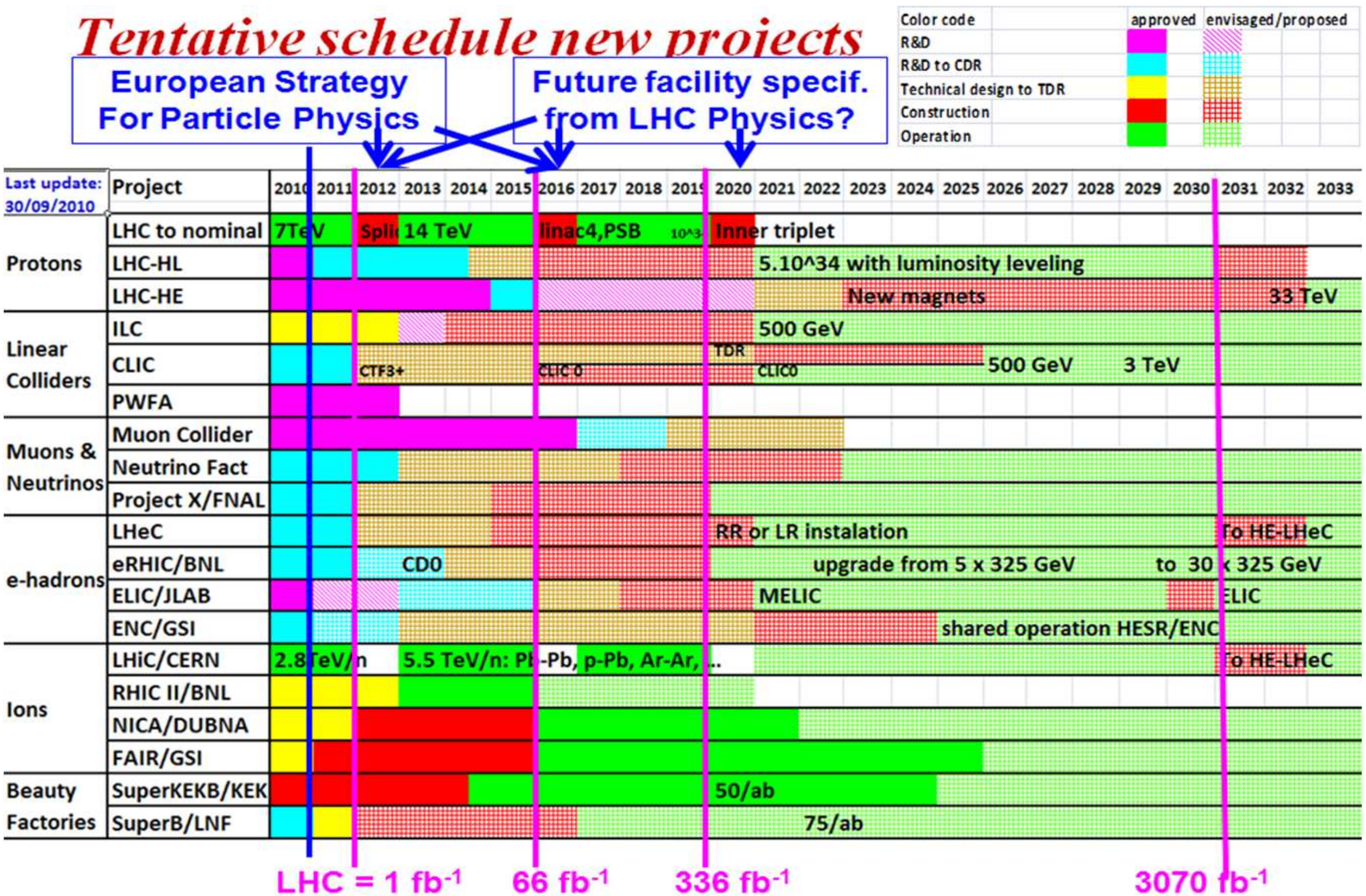


5. Conclusion

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

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

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



5. Conclusion

The end of the story is not yet told!

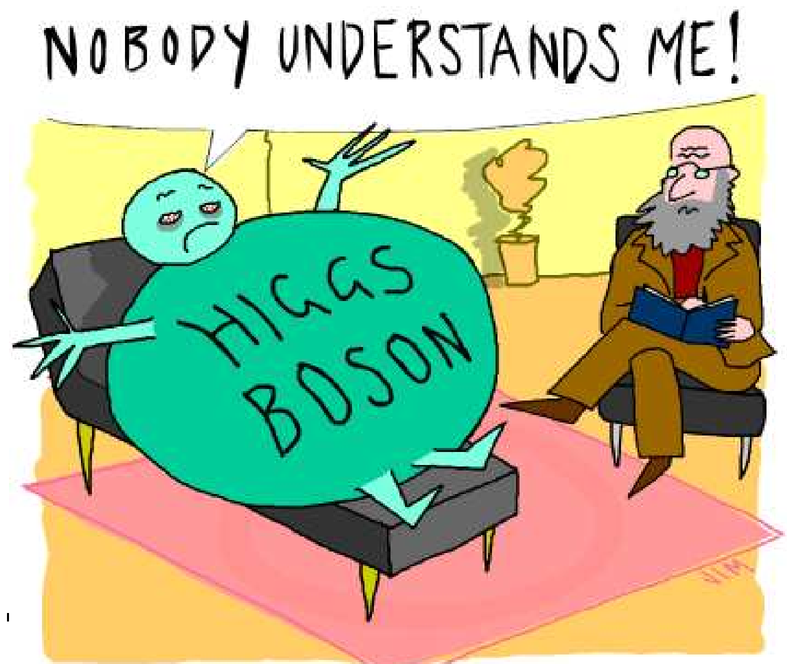
"Now, this is not the end.
It is not even the beginning to the end.
But it is perhaps the end of the beginning."

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

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

We should keep going!

(it's action action time! no philosophy..



5. Conclusion