Electroweak symmeytry breaking and Higgs: status and perspectives

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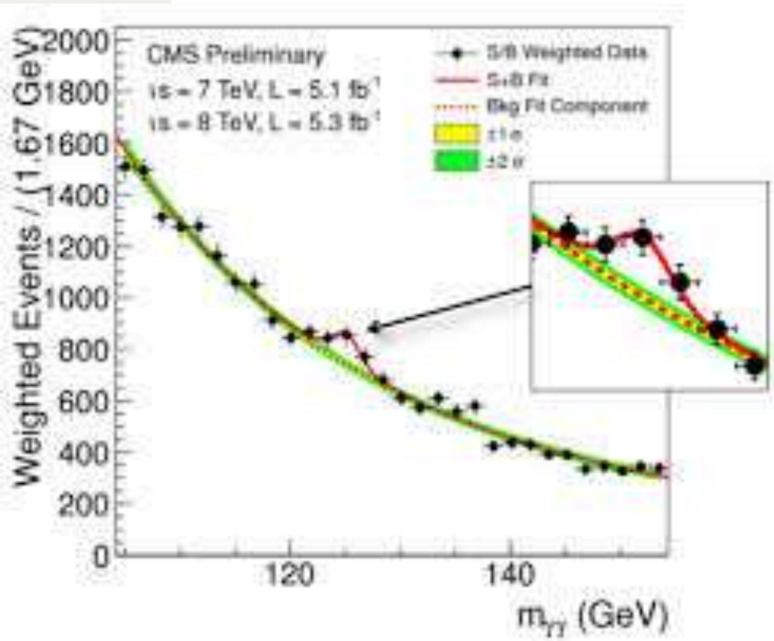
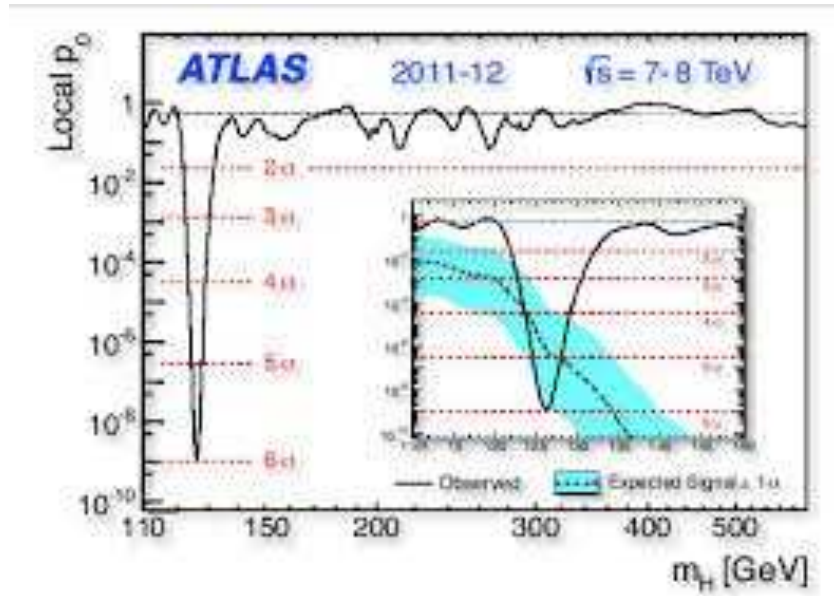
1. **Standardissimo?**
2. **Trouble with minimal beyond the SM?**
3. **Quo vadis? Continue direct BSM searches**
4. **Quo vadis? Further probe of the SM**
5. **Conclusion**

1. Standardissimo?

he Higgs discovery in July 2012: a triumph for high-energy physics.





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

– constraints from data: $\mathrm{M_H} = 92^{+34}_{-26}$ GeV $\lesssim 160$ GeV at 95% CL

– experimentally found to be: $\mathrm{M_H} \simeq 125 \pm 0.2$ GeV (ie within 1σ..)

In addition, it looks as it has the properties of the SM Higgs state:

he triumph of the SM model of particle physics or Standarissimo?!

1. Standardissimo?

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!

1. Standardissimo?

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

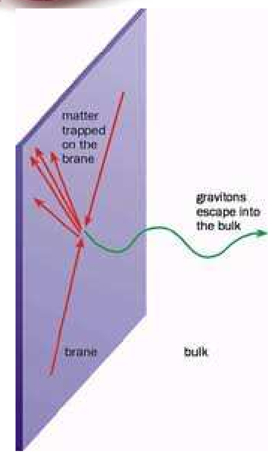
(no more spin–0 fundamental state).

II. Extra space–time dimensions

where at least s=2 gravitons propagate.

$\Rightarrow$ effective gravity scale $\Lambda \approx$ 1TeV.

EWSB mechanism needed: H or not H!

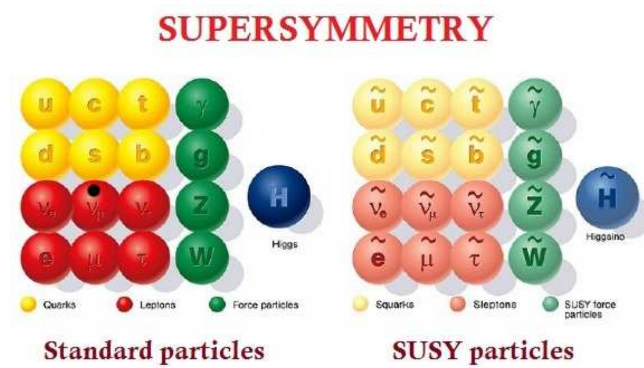


III. Supersymmetry: doubling the world.

– 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 behavior

extend EWSB sector: at least 2 doublets.



1. Standardissimo?

The problem is that:

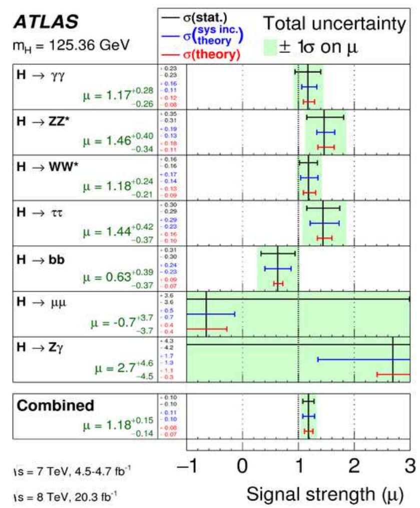
A) we observe a Higgs with a mass of 125 GeV and no other Higgs:

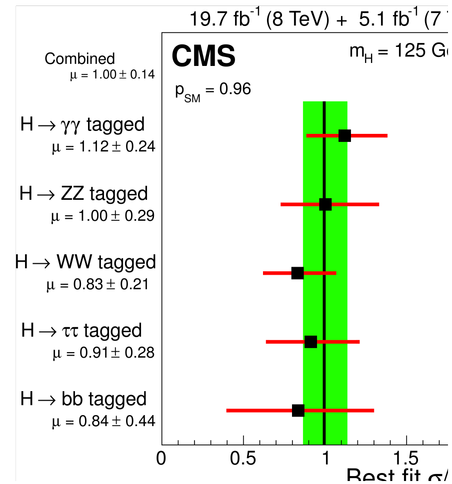
$\sigma\times$BR rates compatible with those expected in the SM

Fit of all LHC Higgs data $\Rightarrow$ agreement at 15–30% level

Results from the LHC run I campaign already give us:

$$\mu_{\rm tot}^{\rm ATLAS} = 1.18 \pm 0.15$$
$$\mu_{\rm tot}^{\rm CMS} = 1.00 \pm 0.14$$





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

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

- **“Mortuary”: Higgsless, 4th generation, fermio or gauge-phobic..**
- **“Hospital”: Technicolor, composite models (but some loopholes) ....**
- **“Trouble” and strongly constrained: extra-dimensions, SUSY, ...**

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

2. Trouble with minimal BSM? The MSSM

In the MSSM we need two doublets of complex scalar fields: $\mathbf{H_1, H_2}$
to generate up/down-type fermion masses and no chiral anomalies.
after EWSB, three dof for $\mathbf{W_L^\pm, Z_L} \Rightarrow$ 5 physical states: $\mathbf{h, H, A, H^\pm}$.
Only 2 free parameters at tree-level to describe the system $\tan\beta, \mathbf{M_A}$:

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

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

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

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

- **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).**

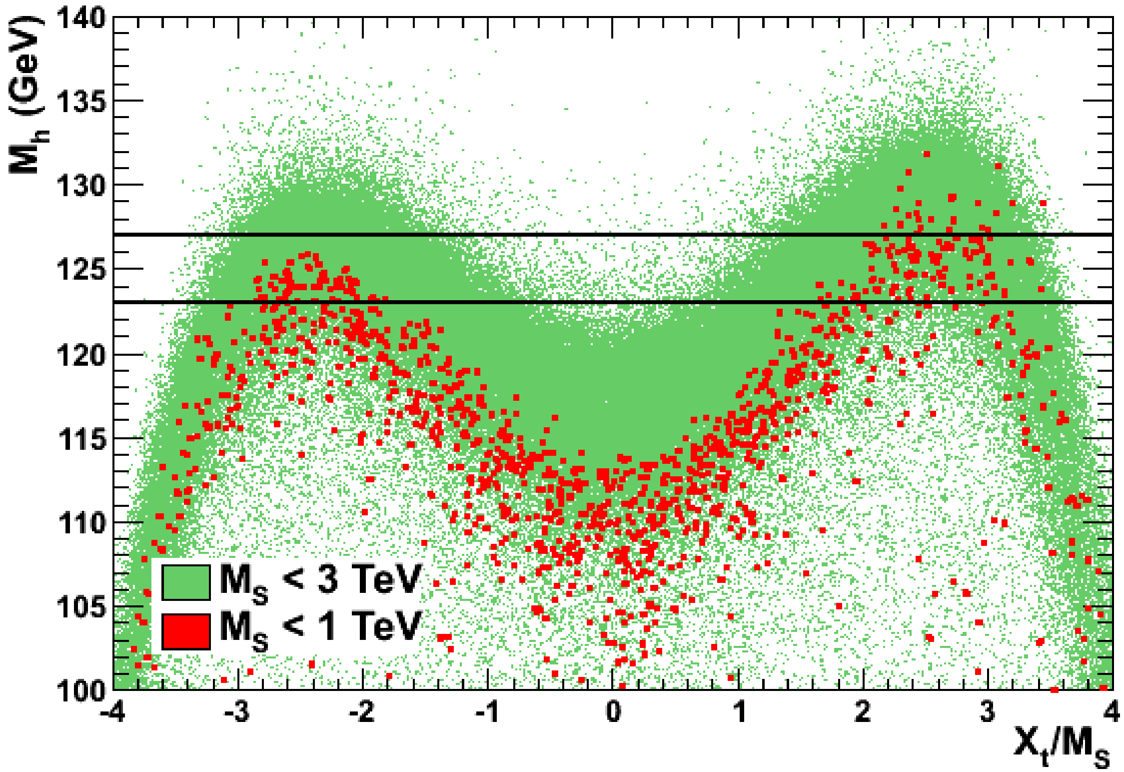
Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$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

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

1. Trouble with minimal BSM? The MSSM

There is first direct implication from the measurement $M_h = 125$GeV.

$$M_h^2 \xrightarrow{M_A \gg M_Z} M_Z^2 \cos^2 2\beta + \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right] = (125)^2$$



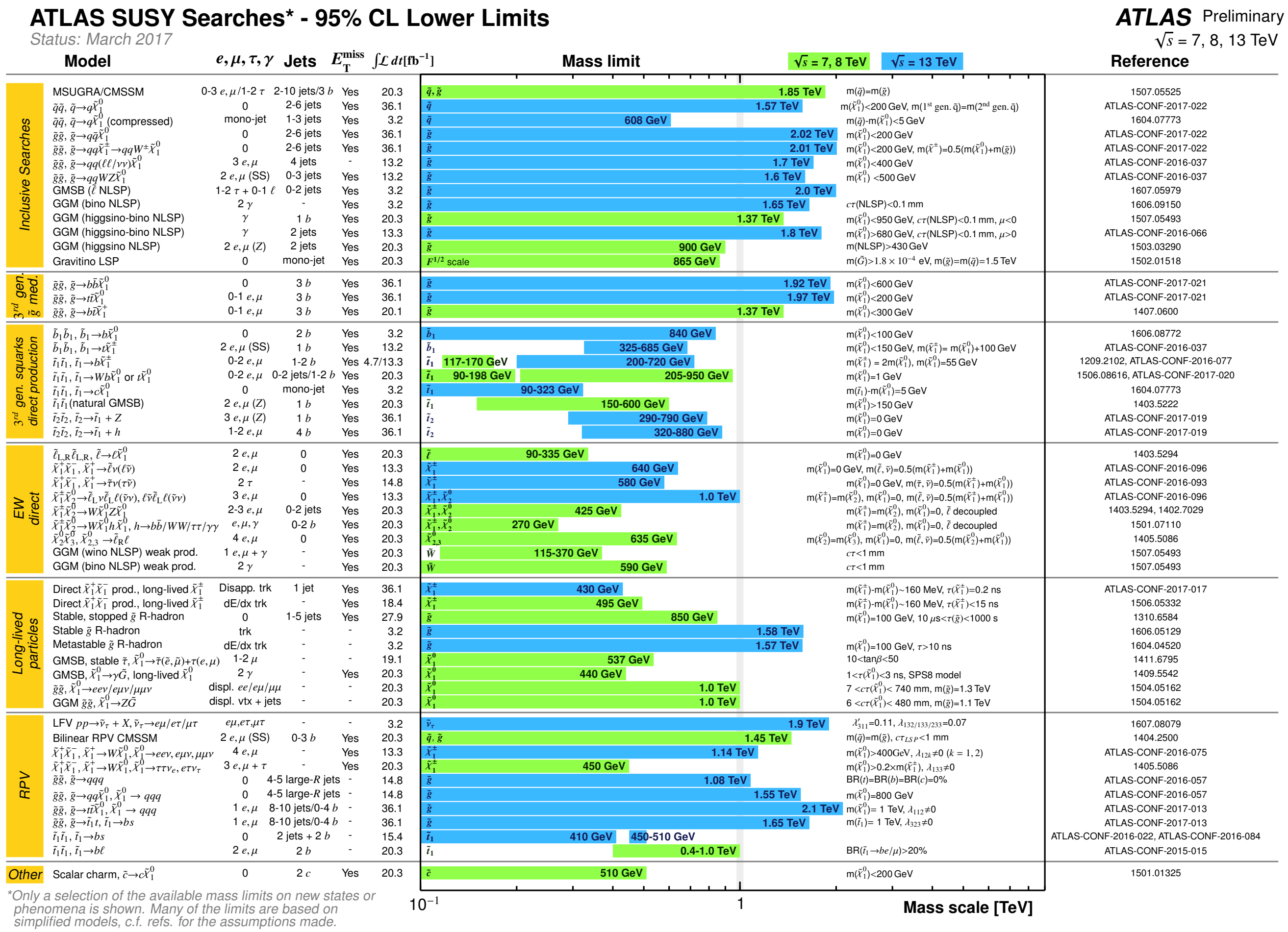
Arbey, Battaglia, AD, Mahmoudi, Quevillon (2012)

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

2. Trouble with minimal BSM? The MSSM

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

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



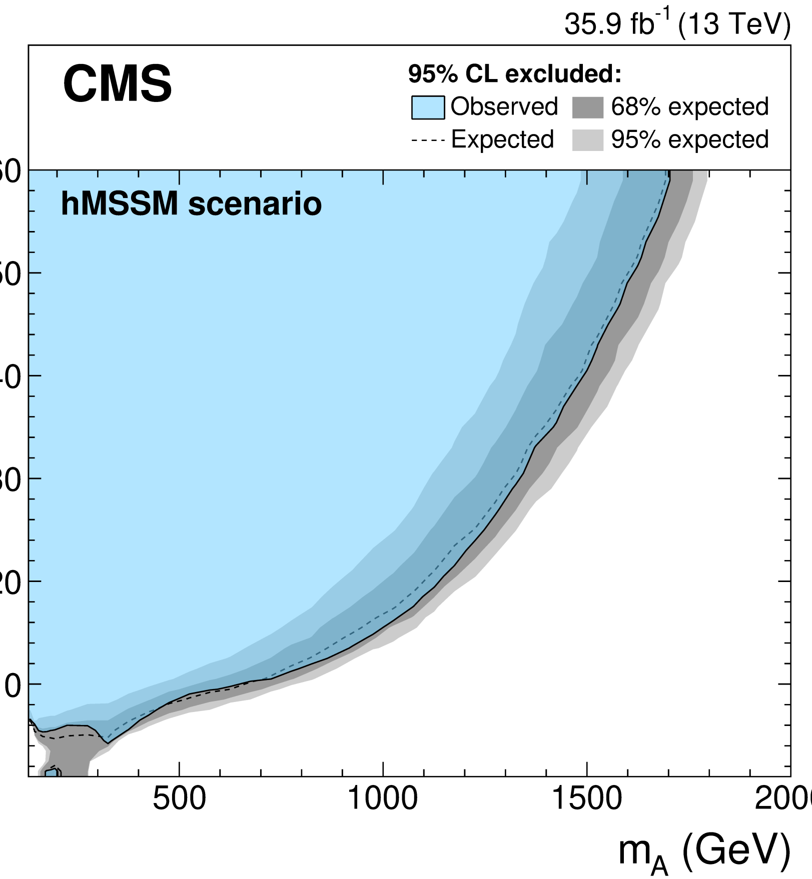
⇒ ATLAS/CMS depressing exclusion tables...

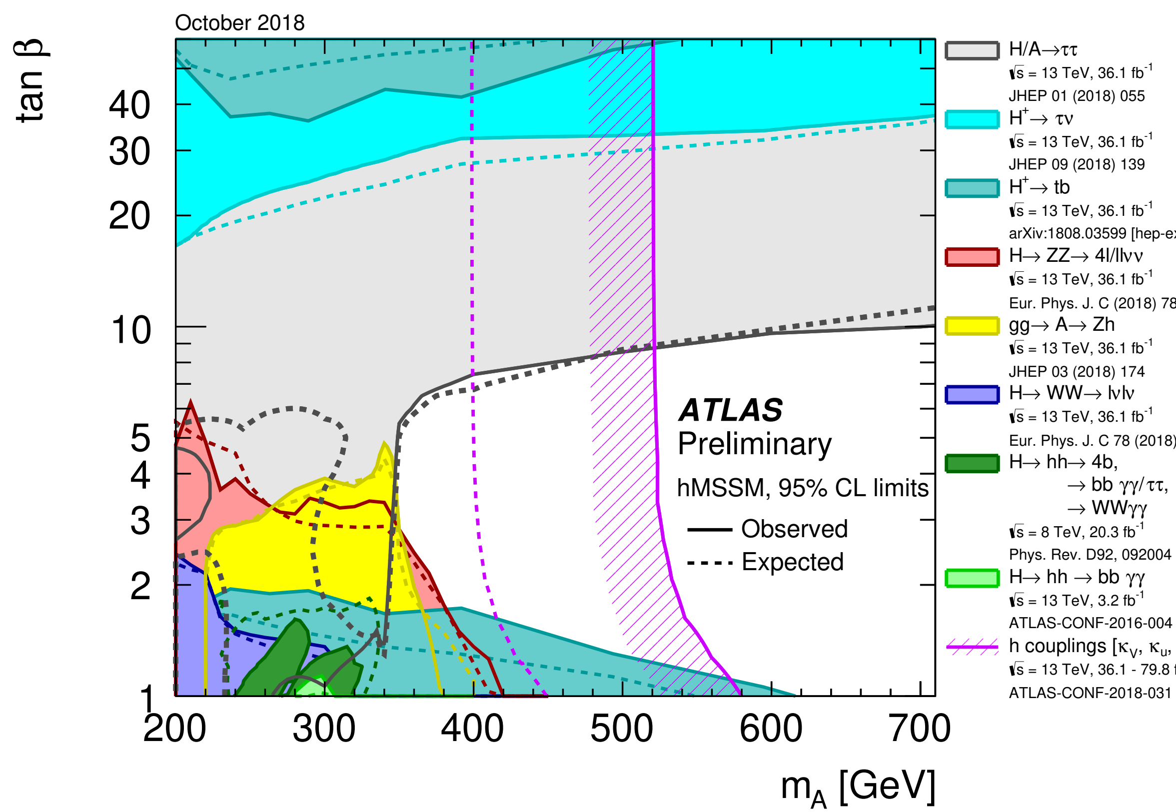
2. Trouble with minimal BSM? The MSSM

Backed up by searches and measurements in the Higgs sector at LHC:

fits of the h couplings ⇒ constraints on the MSSM $[\mathrm{M_A}, \tan\beta]$ plane:

hMSSM: $\mathbf{g_{h\bar{t}t}} = \cos\alpha/\sin\beta$, $\mathbf{g_{h\bar{b}b}} = \cos\alpha/\sin\beta$, $\mathbf{g_{hVV}} = \sin(\beta-\alpha)$



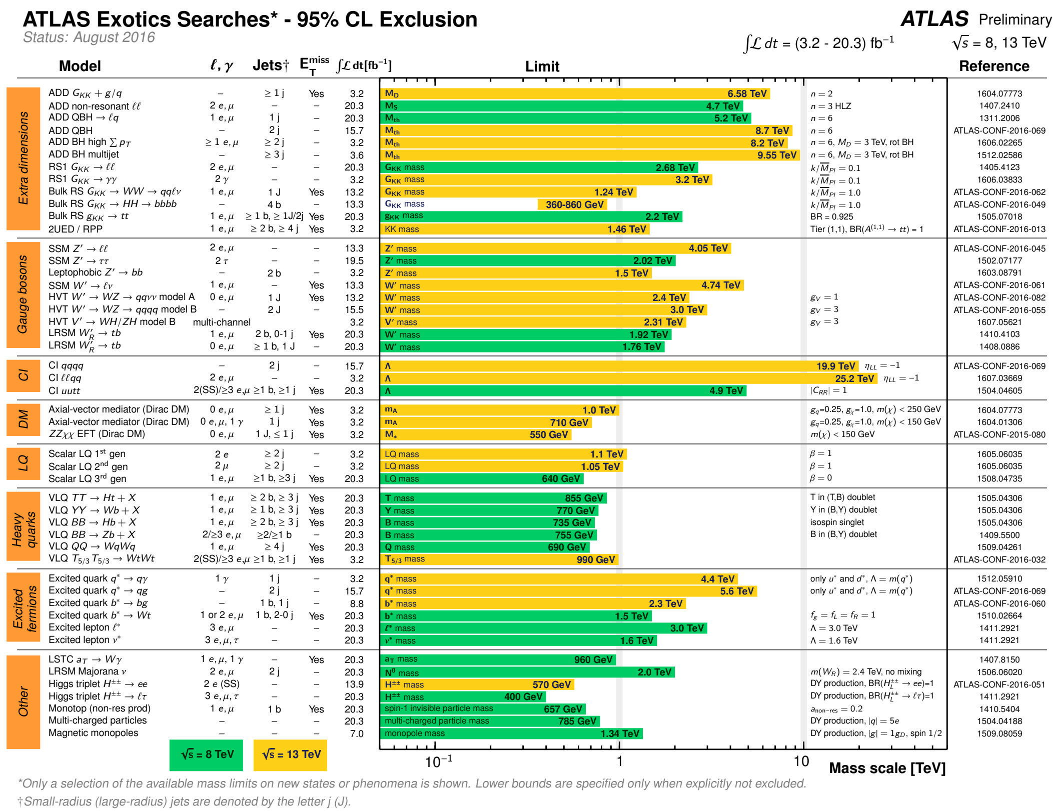


3. Quo vadis? Continue direct BSM searches

So is Particle Physics "closed" and we should all go home? No!

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

$\Rightarrow$ continue searches for new particles in all possible channels.



Should be continued, extended, refined:

new states are simply around the corner and can be found tomorrow!

3. Quo vadis? Continue direct BSM searches

More focus on fined-tuned, non-minimal, more complicated scenarii...

Examples of continued searches for heavier/new (super)particles then:

• Within the plain MSSM:

– heavier $\mathrm{H}, \mathrm{A}, \mathrm{H}^{\pm}$ bosons, especially in non–standard channels,
– keep searching for heavier (3d generation) $\tilde{\mathrm{q}}$ and $\tilde{\mathrm{g}}$ with higher FT,
– more focus on weak sparticles: electroweakinos and sleptons....,
(DM motivated: higgsino–like LSP, stau–co annihilation channels...),
– scenarii with long-lived $\tilde{\mathrm{p}}$: GMSB ($\chi_1^0 \to \gamma \tilde{\mathrm{G}}$), $\tilde{\tau}$ NLSP (displaced..)

• Beyond the MSSM:

– CP and flavor violating MSSM: still possibility of light Higgs states, ...
– Rp violating processes: some are not so severely constrained.
– NMSSM: light Higgs bosons, singlino LSP, long lived particles, etc...

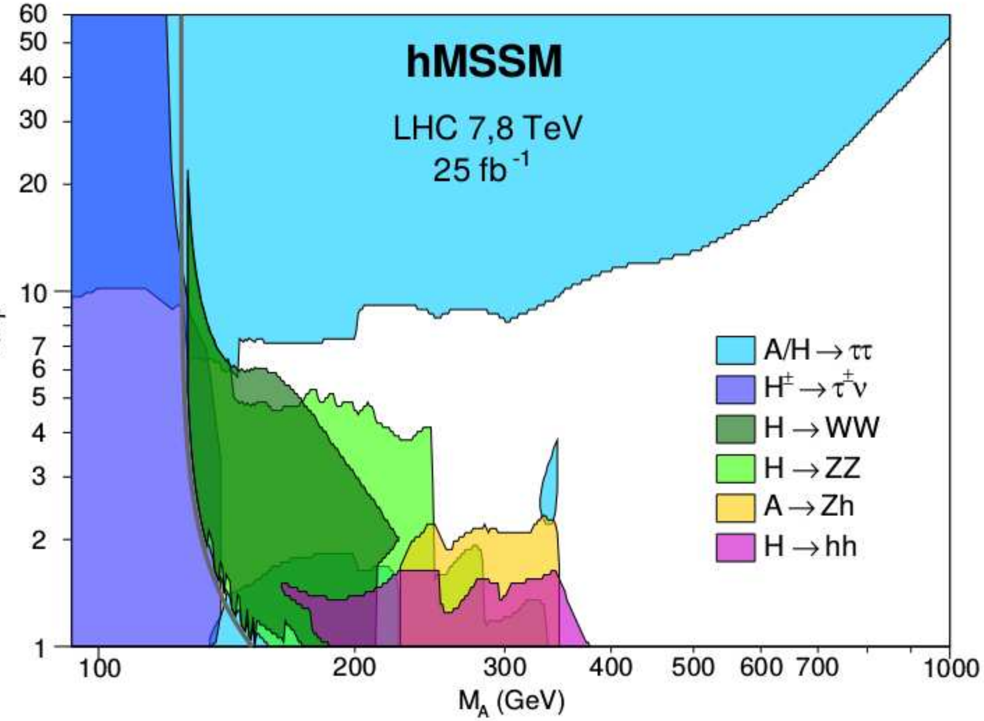
• And anything else:

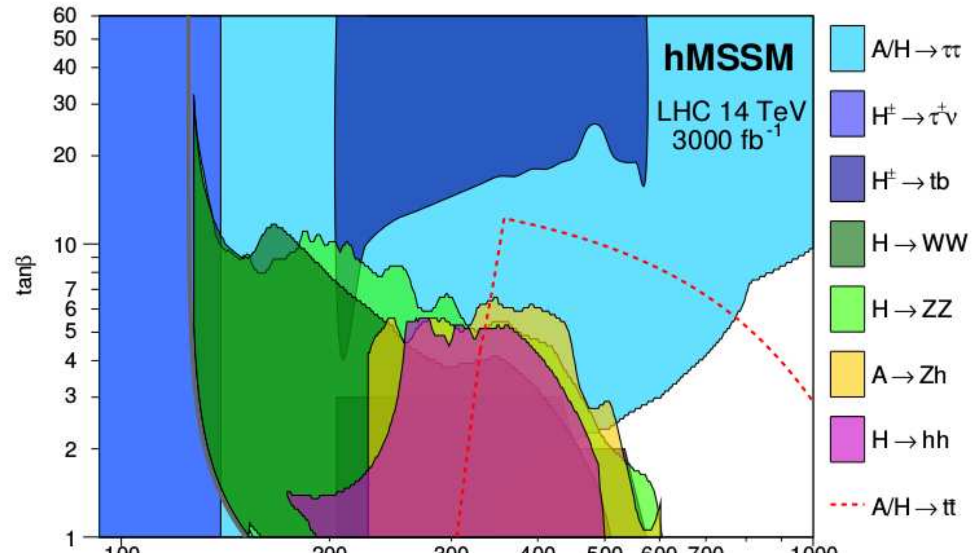
– new gauge bosons: V_{KK} excitations, new Z',W' from GUT, etc...
– new exotic fermions: vector-like, KK fermions, excited fermions, ...
– other exotica: H++ bosons, leptoquarks, diquarks dileptons, etc...

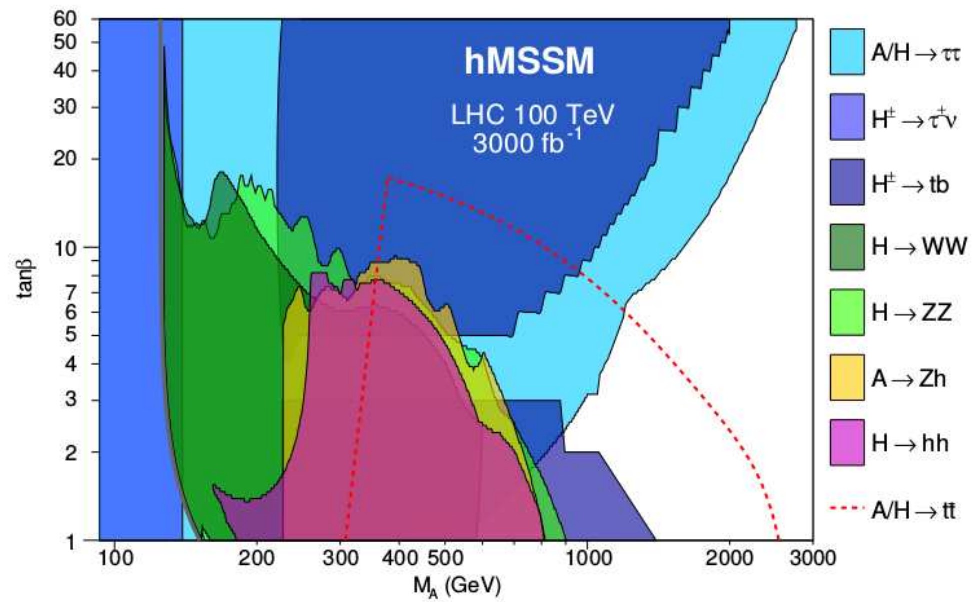
In worst case, one extends the limits on the NP scale....

3. Quo vadis? Continue direct BSM searches

Ex: improved search for heavier MSSM Higgs bosons in all modes



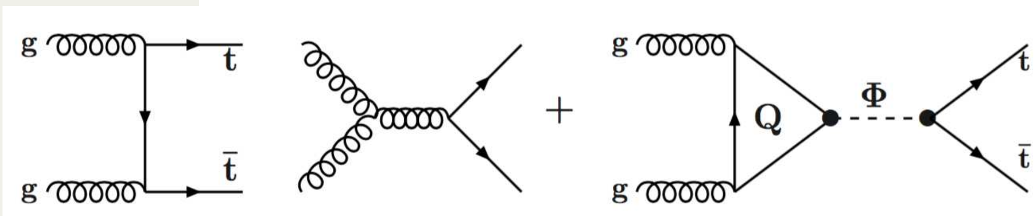


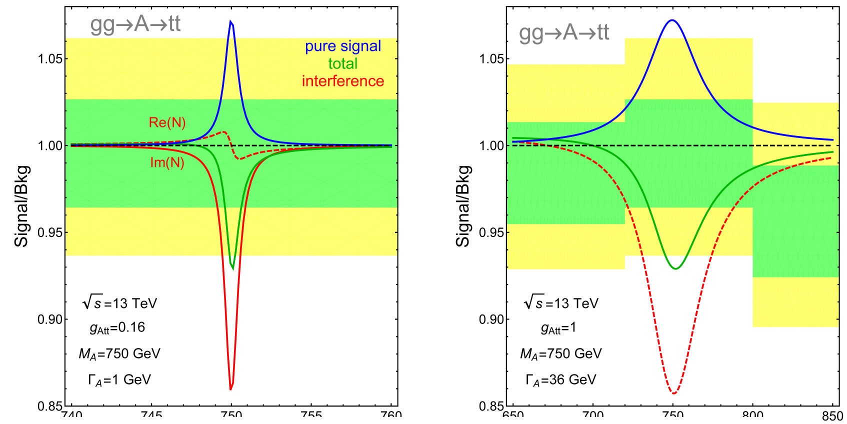


AD, Quevillon, Maiani, ... (2016)

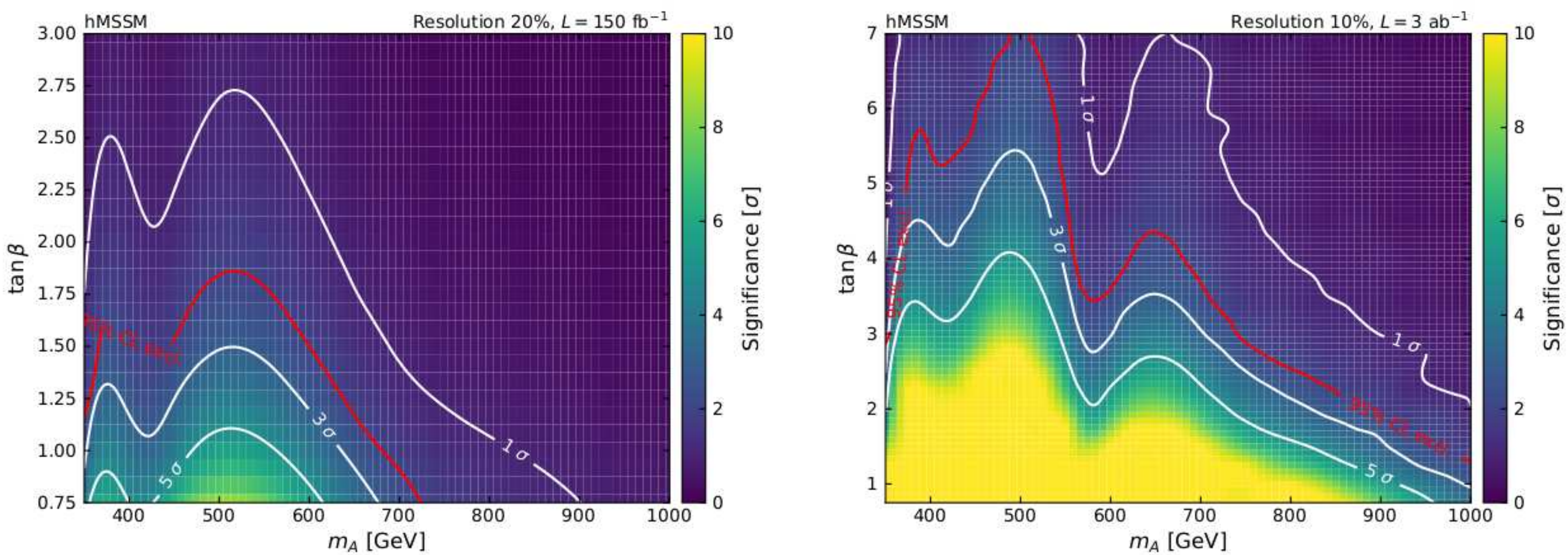
3. Quo vadis? Continue direct BSM searches

Ex: mode not yet probed in heavier Higgs searches: $gg \to H/A \to t\bar{t}$





AD, Ellis,Quevillon,Popov



4. Quo vadis? Further probe of the SM

he next question is then: "is Particle Physics closed"? Answer is no!

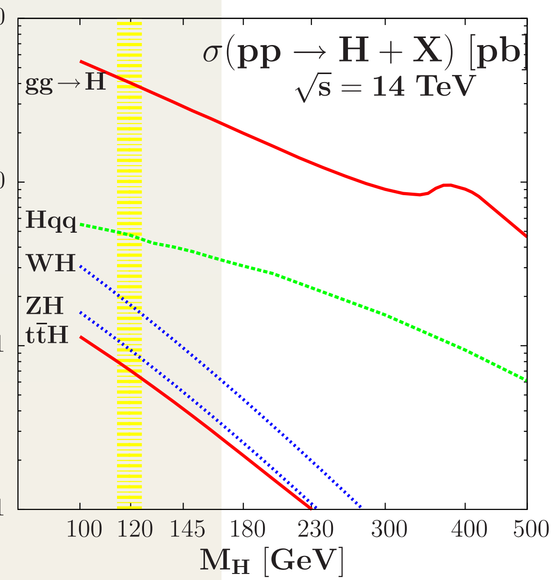
2) Need to check that H is indeed responsible of EWSB (SM-like?)
⇒ measure its fundamental properties in the most precise way:

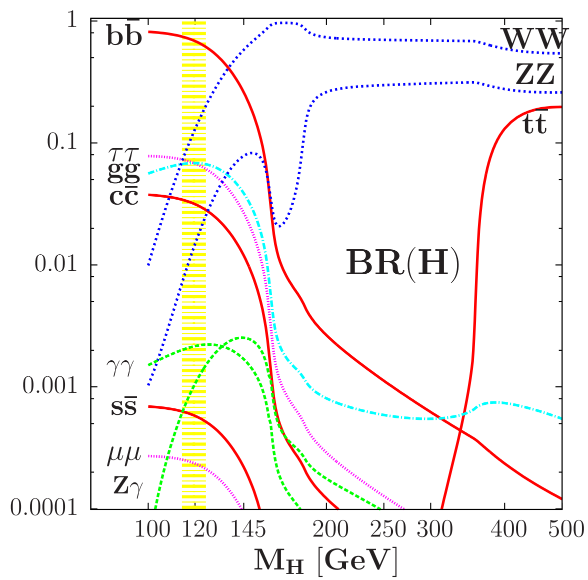
- **its mass and total decay width (invisible width from dark matter?),**
- **its spin–parity quantum numbers (CP violation for baryogenesis?),**
- **its couplings to fermions and gauge bosons and check if they are**

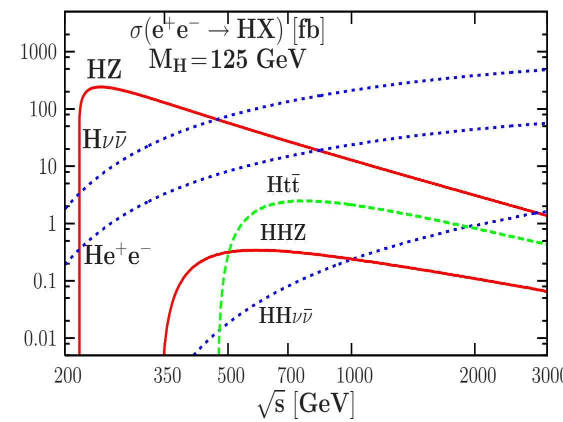
only proportional to particle masses (no new physics contributions?),

- **its self-couplings to reconstruct V_S potential that makes EWSB.**

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





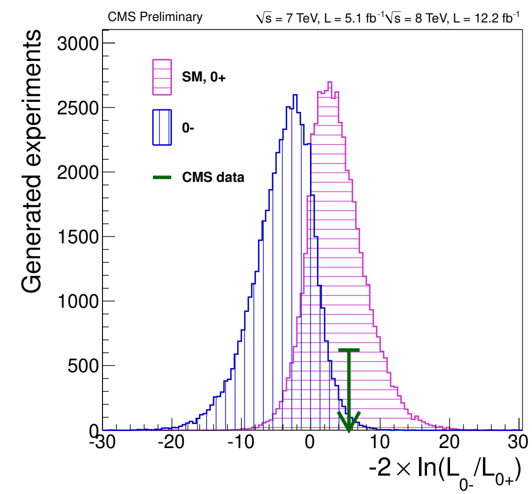


4. Quo vadis? Further probe of the SM

A check of spin–parity quantum numbers and search for CP violation

Spin: clear situation (no suspense) as the new state decays into $\gamma\gamma$
$\Rightarrow$ not s=1 from Landau–Yang 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 $\gtrsim 3\sigma$ level.
But problems with this (too simple) picture:
pure CP–odd does not couple to VV@tree-level;
in $H \to ZZ^*$ only CP-even part is projected out.



- **Direct probe: via production/decays in extensions like C2HDM:**

Ex: Undoubtable signs of CP-violation in Higgs decays at HL-LHC
combined searches of $h_i \to h_j Z$ and $h_i \to ZZ$ with $i, j = 1, 2, 3$.

- **Indirect probe: g_{Hff} more democratic $\Rightarrow$ fermionic decays.**

ex: spin-correlations in $q\bar{q} \to HZ \to b\bar{b}ll$, $q\bar{q}/gg \to Ht\bar{t} \to b\bar{b}t\bar{t}$.

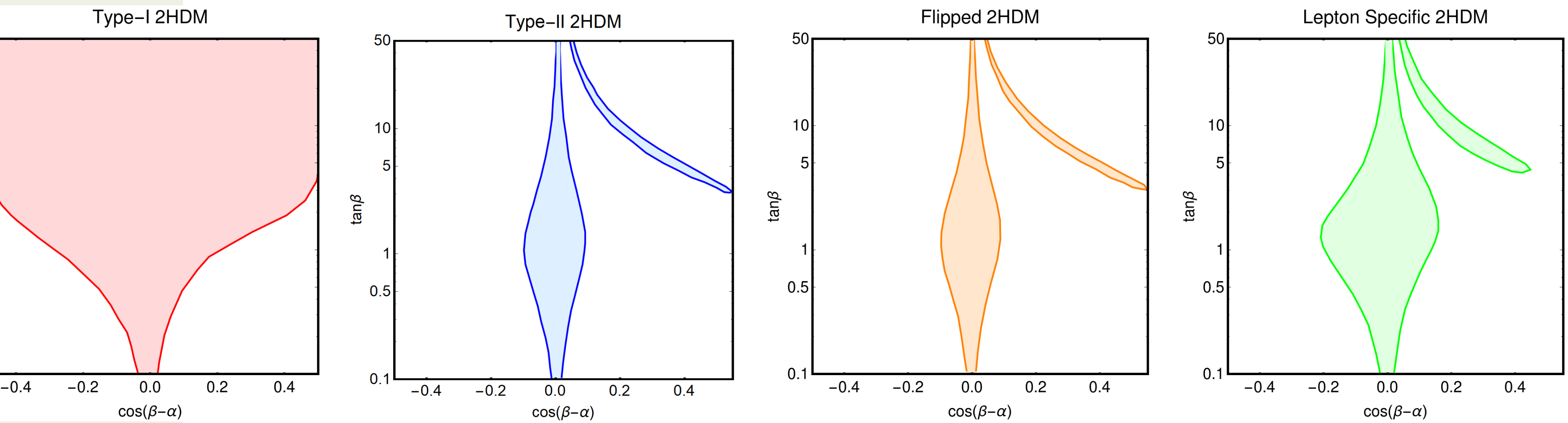
Need to be lucky or is very challenging even at the HL–LHC...

4. Quo vadis? Further probe of the SM

Perform a much more precise measurement of the Higgs couplings
$\Rightarrow$ **would allow a better sensitivity to new physics virtual effects.**

- **In standard production+decay modes as gg $\to$ H $\to$ ZZ, WW, $\gamma\gamma$**

present sensitivity is low in many cases as 2HDM of type I to IV:
Arcadi, AD, Raidal, arXiv:1903.03616



- **In very rare decays that allow additional/unknown information:**

– H $\to \mu^+\mu^-$ to probe second generation fermion couplings,
– H $\to \Upsilon\gamma$ to probe the sign of some fermionic couplings (here b's),
– H $\to Z\gamma$ with information that is complementary to H $\to \gamma\gamma$.

But will this be sufficient to probe BSM physics? (maybe ratios then?)

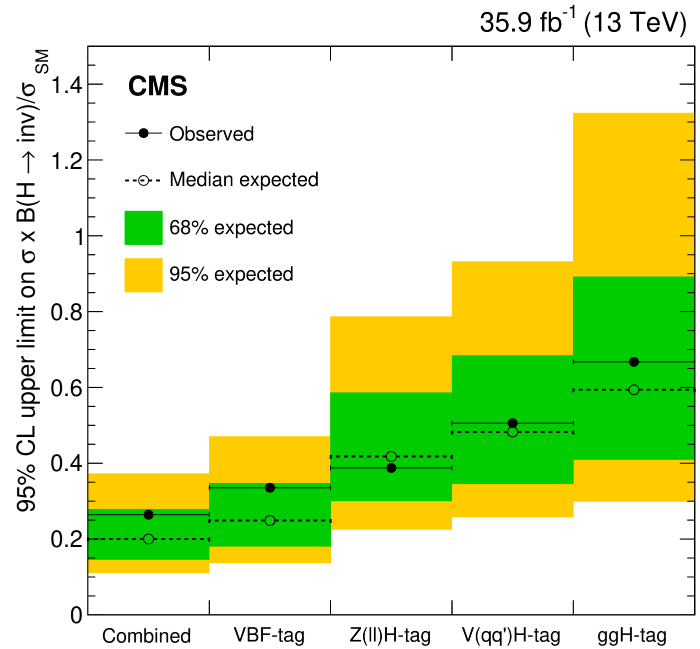
4. Quo vadis? Further probe of the SM

• **Total width**: $\Gamma_H = 4$MeV, too small to be resolved experimentally.
– very loose bound from interference gg→ZZ (100% level).
– difficult to access it indirectly (via production rates) very precisely....

• **Invisible width:** more accessible

Direct measurement of H→inv
- $q\bar{q} \to HZ$ with $Z \to ll$, $H \to inv$
- similar $E\!\!\!/_T$ search in VBF mode
- and also in gg→Higgs+jet

Combined HZ+VBF+ggH now
$BR_{inv} \lesssim 20\%$ @95%CL
assuming a SM Higgs state
few% @HL–LHC possible?



Indirect measurement of H→inv
via Higgs BRs measurement: accuracy of O(few%) at HL–LHC
but with TH assumptions: no other decays, SM-like Higgs, etc...

4. Quo vadis? Further probe of the SM

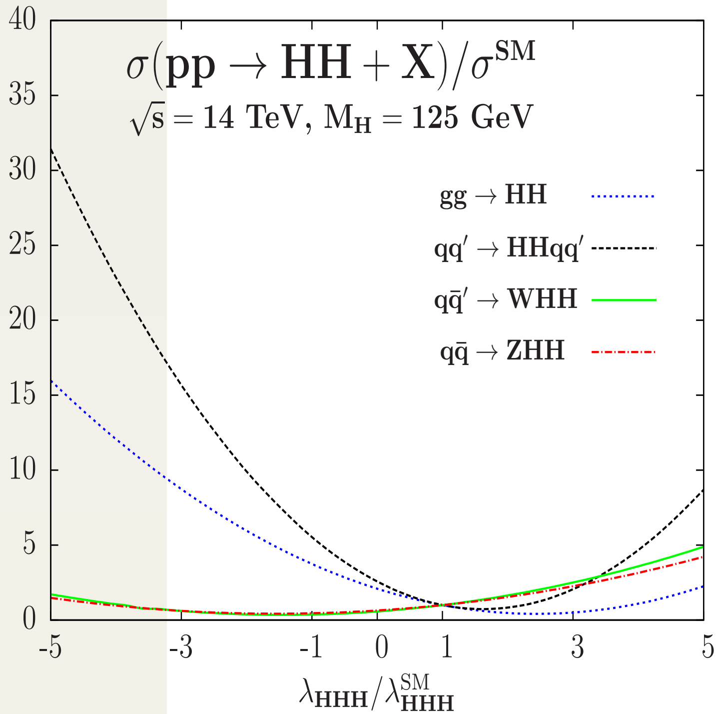
Important challenge: measure Higgs self-couplings and access to V_H.

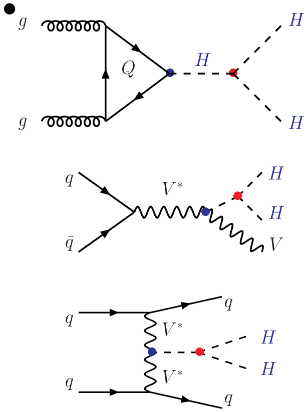
g_{H^3} from $pp \to HH + X$ $\Rightarrow$

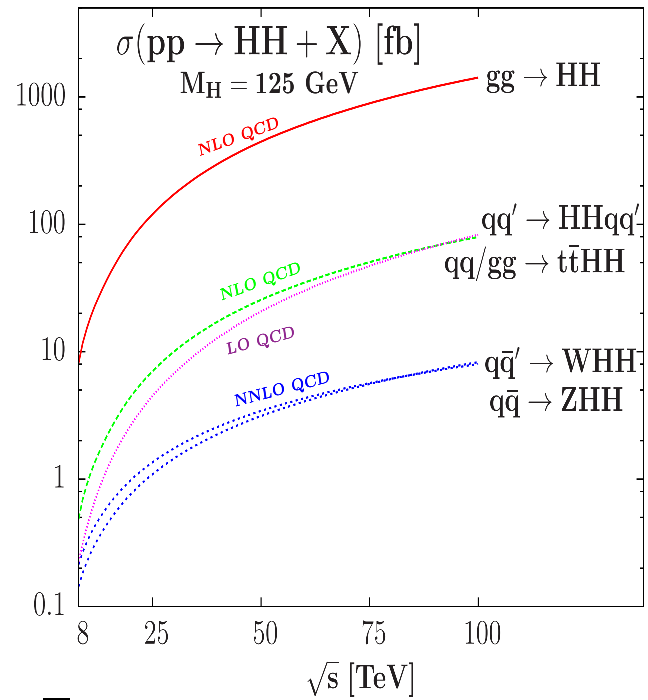
g_{H^4} from pp$\to$3H+X, hopeless.

arious processes for HH prod:

nly gg $\to$ HHX relevant...







- **$H \to b\bar{b}$ 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? Maybe...
but needs very large luminosity.

Baglio et al., arXiv:1212.5581

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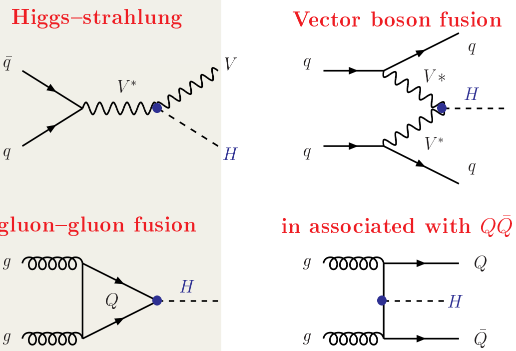
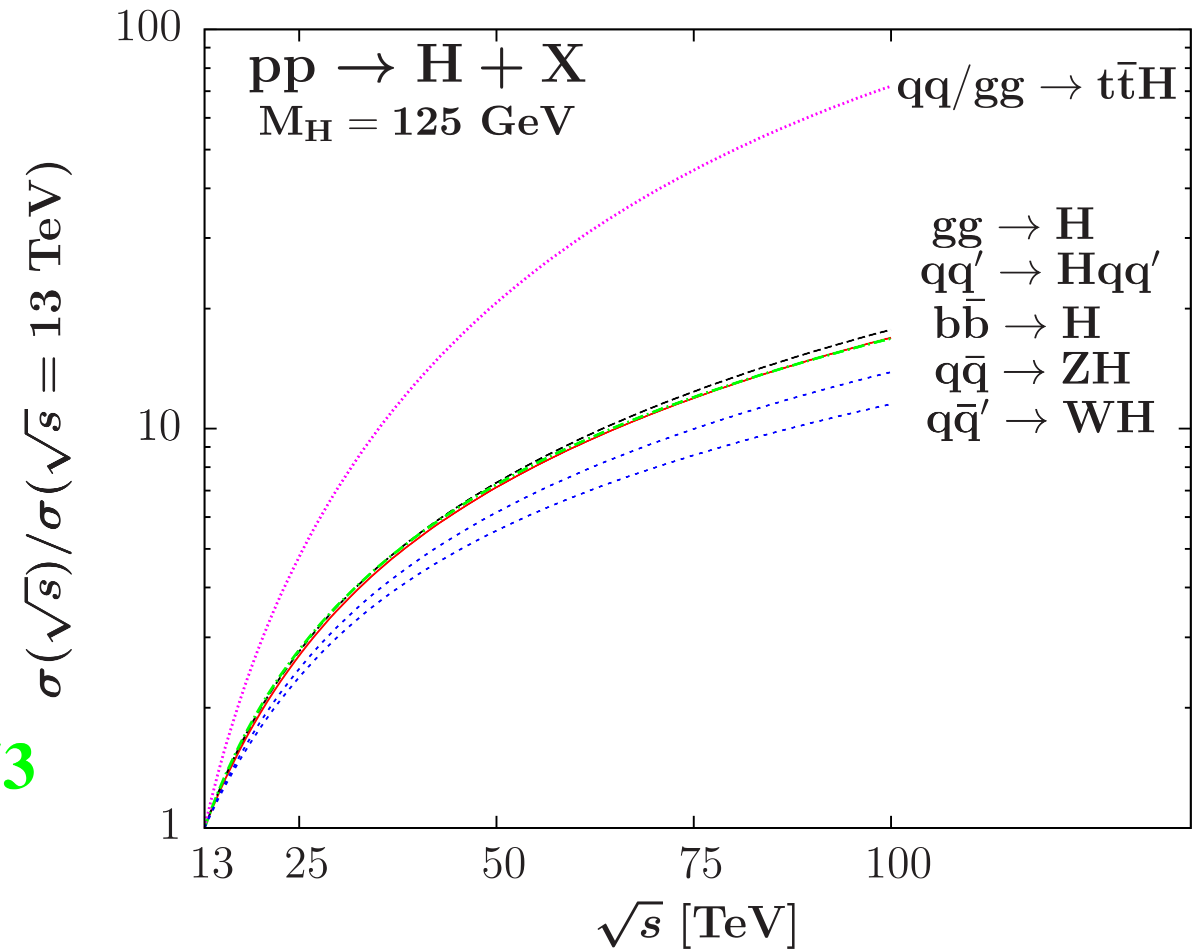
4. Quo vadis? Further probe of the SM

A large increase in sensitivity at high energy machines is possible as production cross section (especially in some cases) are larger

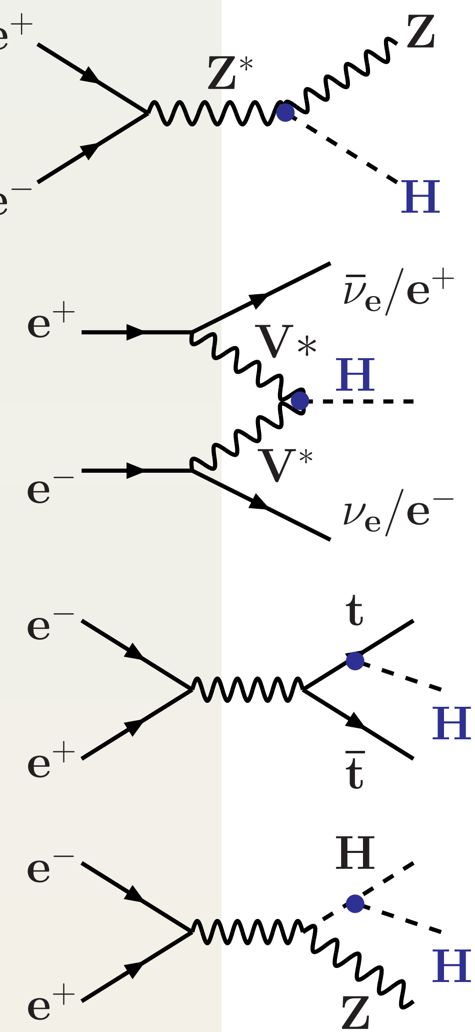


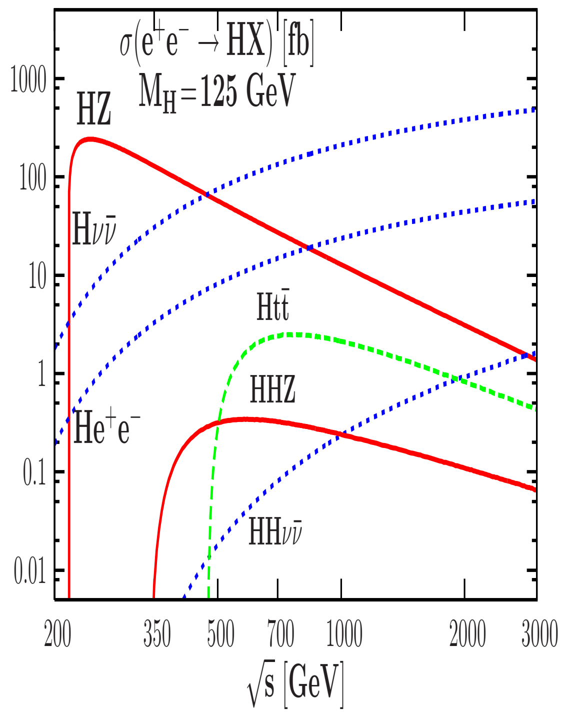


Baglio etal.,1511.07853

Very interesting to move to 100 TeV (not only for this of course)!

4. Quo vadis? Further probe of the SM





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

$\Rightarrow$ best option for ≈ 125 GeV Higgs

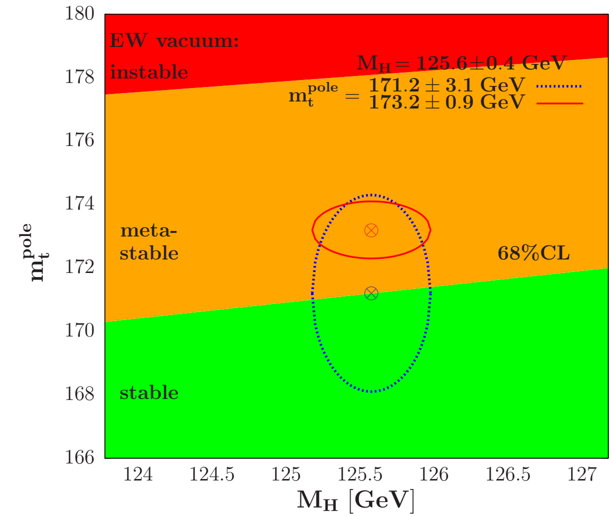
But let's get back to the near future: what can we do at HL-LHC?

5. Conclusion

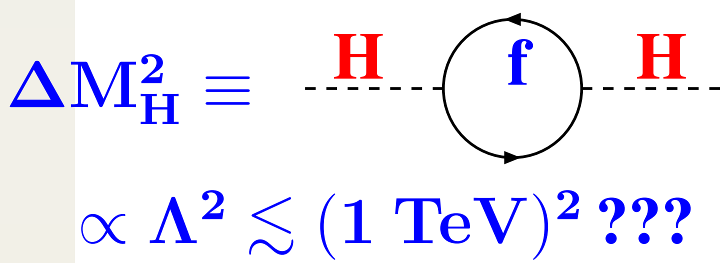
The discovery of the Higgs was historical: and its probe@LHC a remarkable success.

We have now a theory, the SM, which is:

- **theoretically consistent+complete,**
- **compatible with all data (anomalies?).**
- **extrapolable up to ultimate scale $\Rightarrow$**



It is a great success of HEP and we should be proud of it...



We were expecting new phenomena but nothing showed up at the LHC.

Yet still arguments in favor of BSM.

But naturalness guide for BSM no more compelling/successful.

om now on, there is no guarantee for discovery at LHC or elsewhere?!

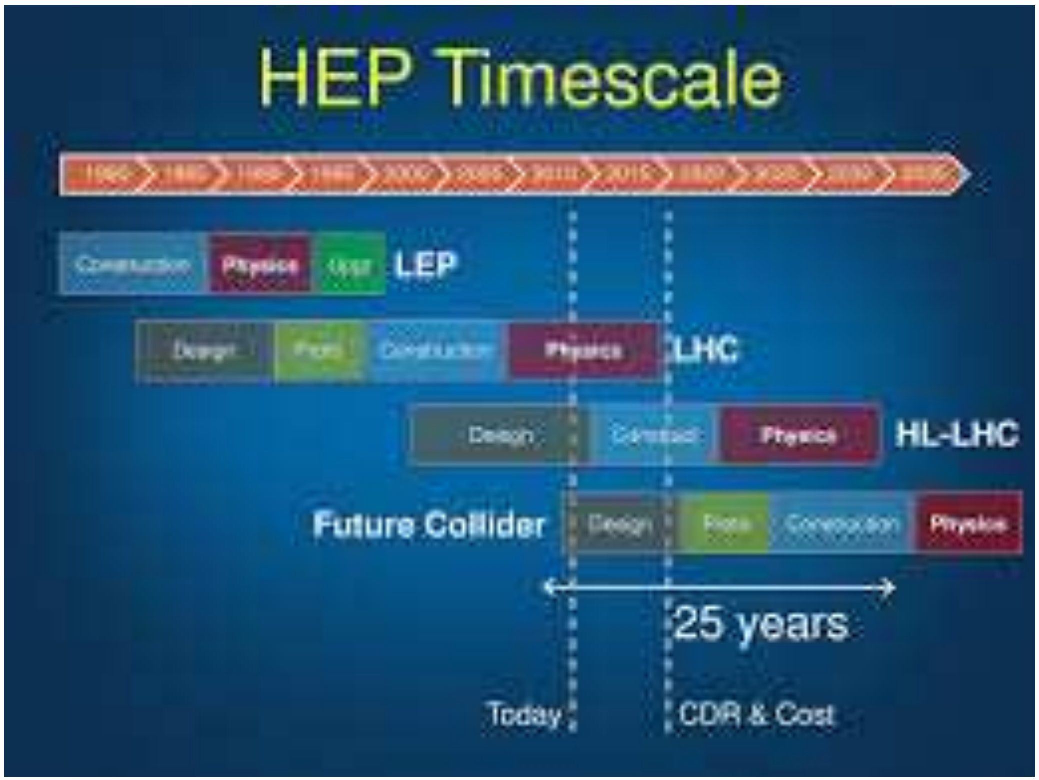
So should we give up and declare that particle physics is closed?

No of course! We should continue our quest (but more modestly).

5. Conclusion

We need to continue to search for New Physics and falsify the SM:

- **directly via new (heavy or light) particle searches with more data.**
- **indirectly via high precision measurements in H/W/Z/top sectors,**



So let's move forward: it is still action time!

or as experimentalists usually say: stay tuned!