Precision measurements in the SM: why and what?

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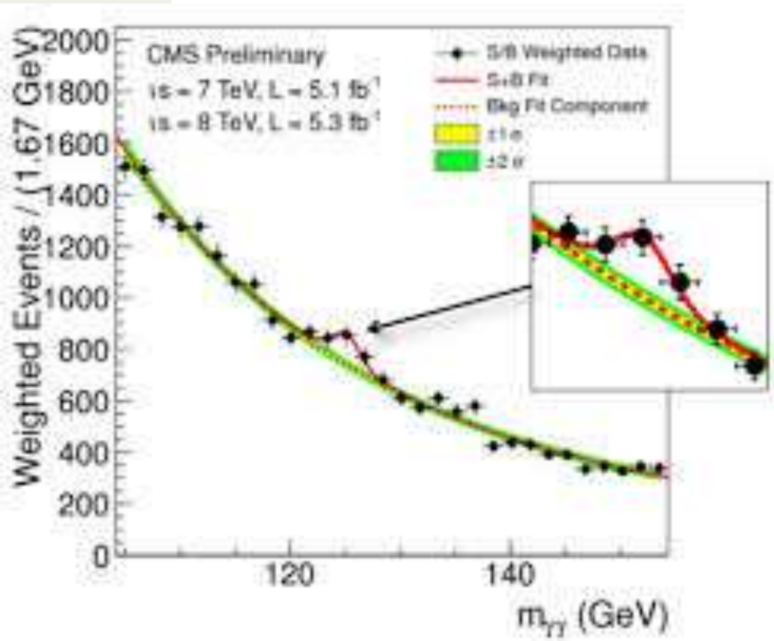
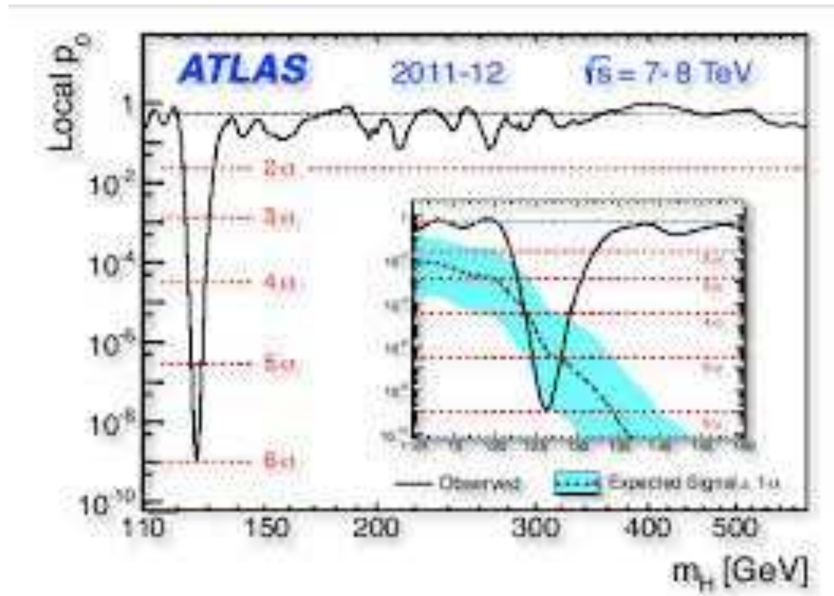
1. **Standardissimo?!**
2. **Trouble with minimal beyond the SM?**
3. **Quo vadis? Further probe of Higgs**
4. **Where and what else?**
5. **Conclusion**

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?

Maybe low energy manifestation of more fundamental theory that solve

- **"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 may indicate that there is beyond the Standard Model.

1. Standardissimo?!

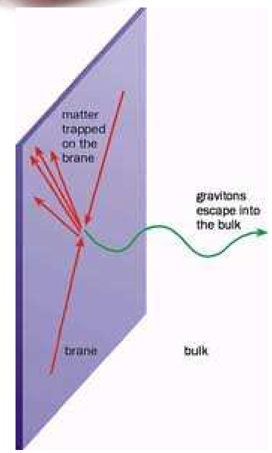
There were 3 avenues for solving the hierarchy/naturalness problem:

I. Compositeness/substructure:

All particles are composite: Technicolor

⇒ H bound state of two fermions

(no more spin–0 fundamental state).



II. Extra space–time dimensions

where at least s=2 gravitons propagate.

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

EWSB mechanism needed: H or not H!

III. Supersymmetry: doubling the world.

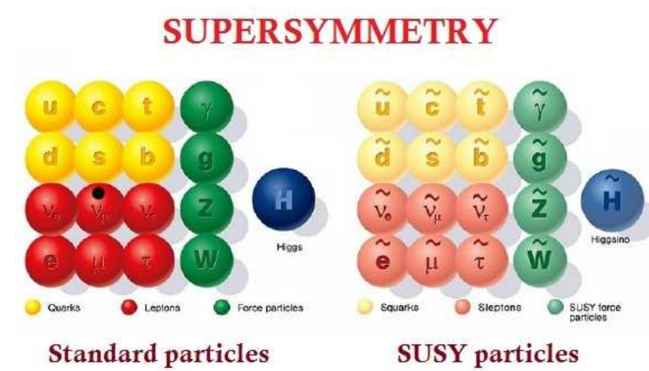
– links s=1/2 fermions to s=1 bosons,

– links internal/space-time symmetries,

– if made local, provides link to gravity,

– natural $\mu^2 < 0$: radiative EWSB,

⇒ sparticle loops cancel Λ^2 behavior



All predicted something at Terascale!

1. Standardissimo?

The problem is that:

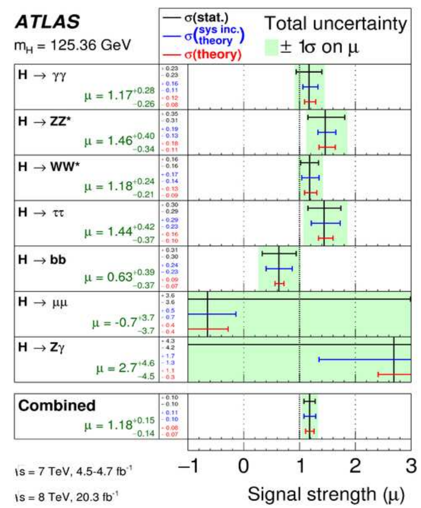
A) we observe a Higgs with a mass of 125 GeV and no other Higgs:

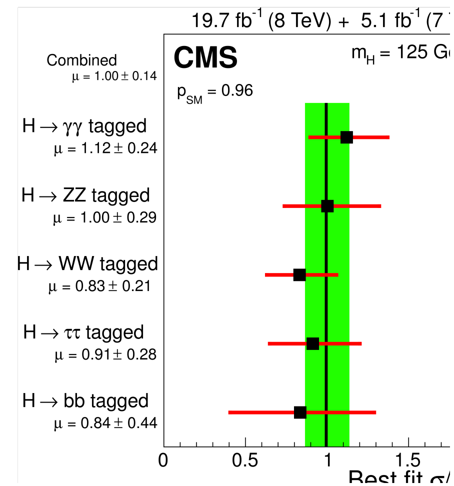
$\sigma\times$BR rates compatible with those expected in the SM

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: H_1, H_2
to generate up/down-type fermion masses and no chiral anomalies.
after EWSB, three dof for $W_L^\pm, Z_L \Rightarrow$ 5 physical states: $h, H, A, H^\pm$.
Only 2 free parameters at tree-level to describe the system $\tan\beta, M_A$:

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

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

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

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

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

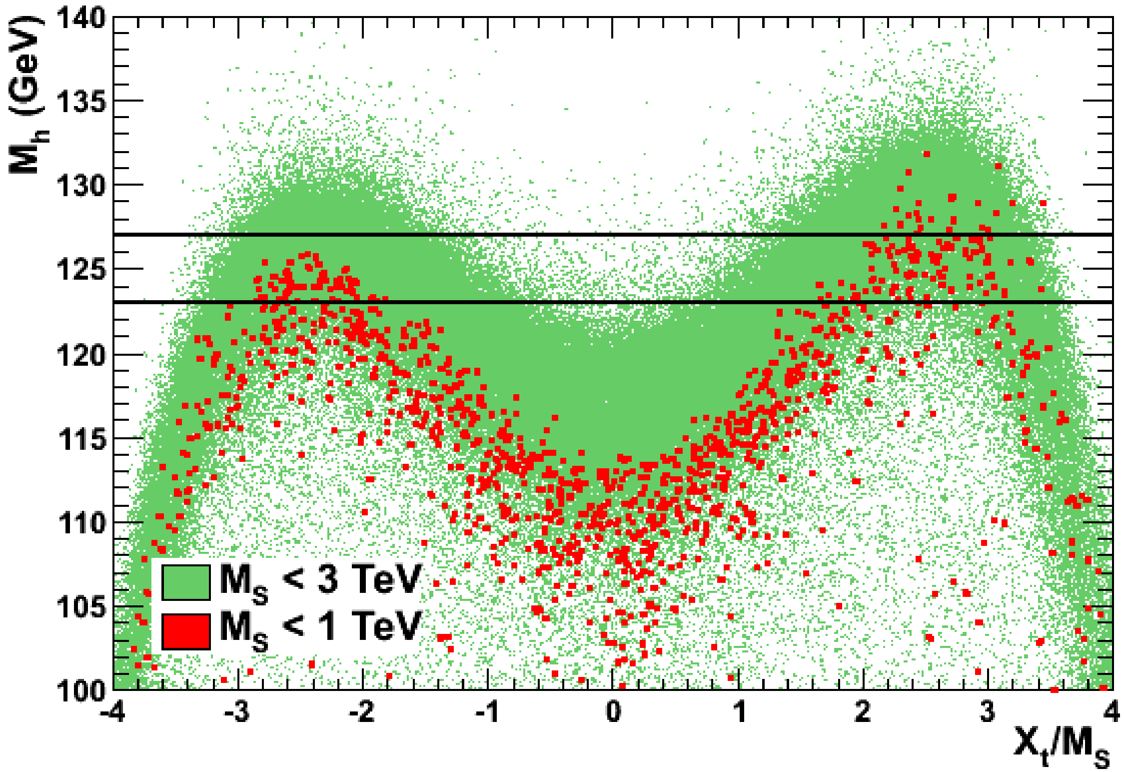
Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$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

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



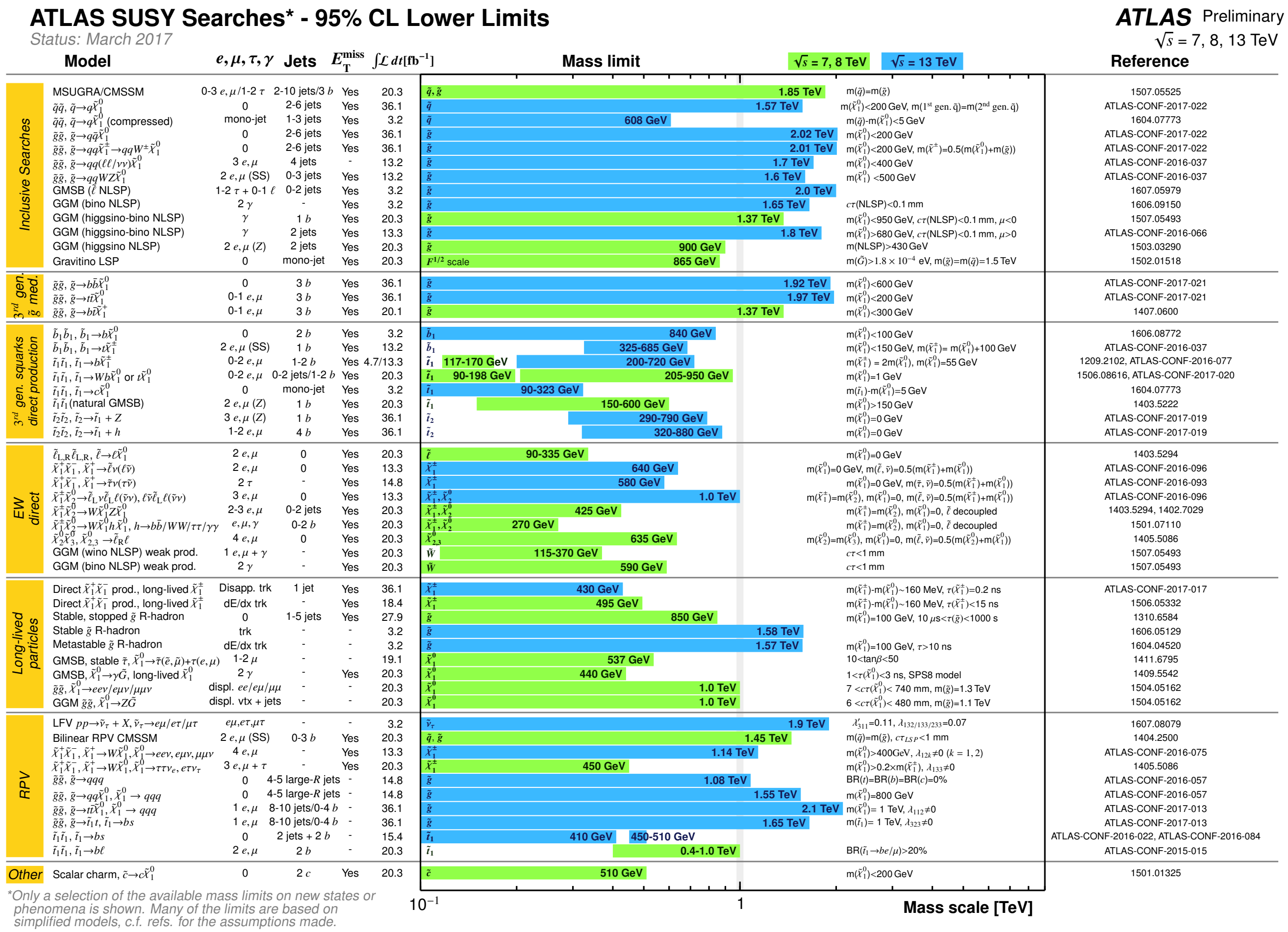
Arbey, Battaglia, AD, Mahmoudi, Quevillon (2012)

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



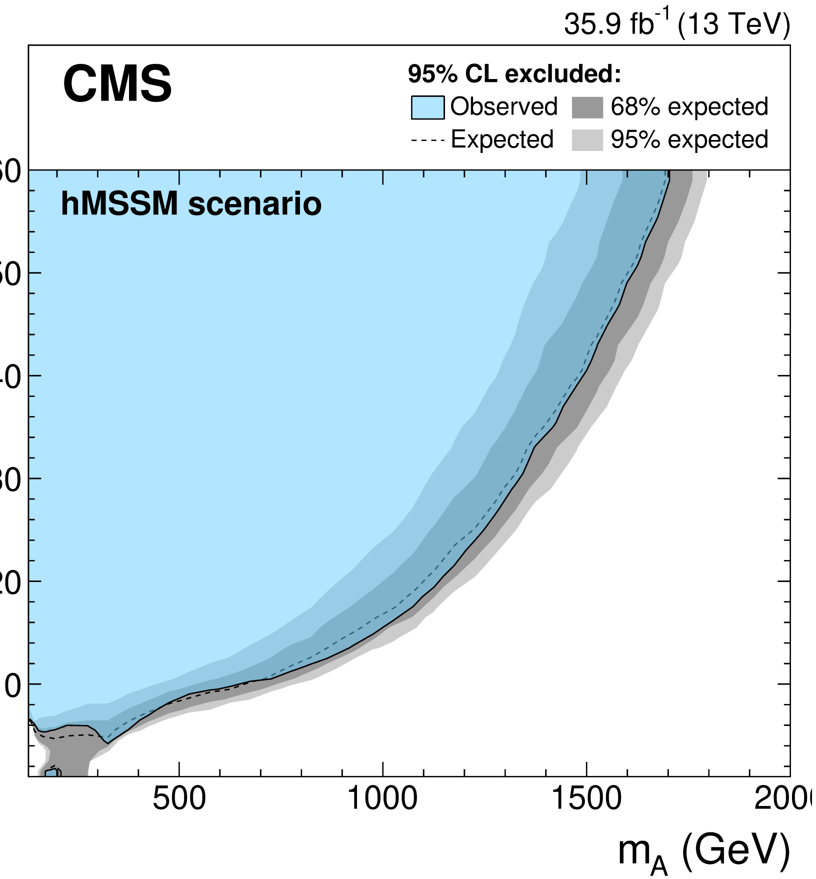
$\Rightarrow$ ATLAS/CMS depressing exclusion tables...

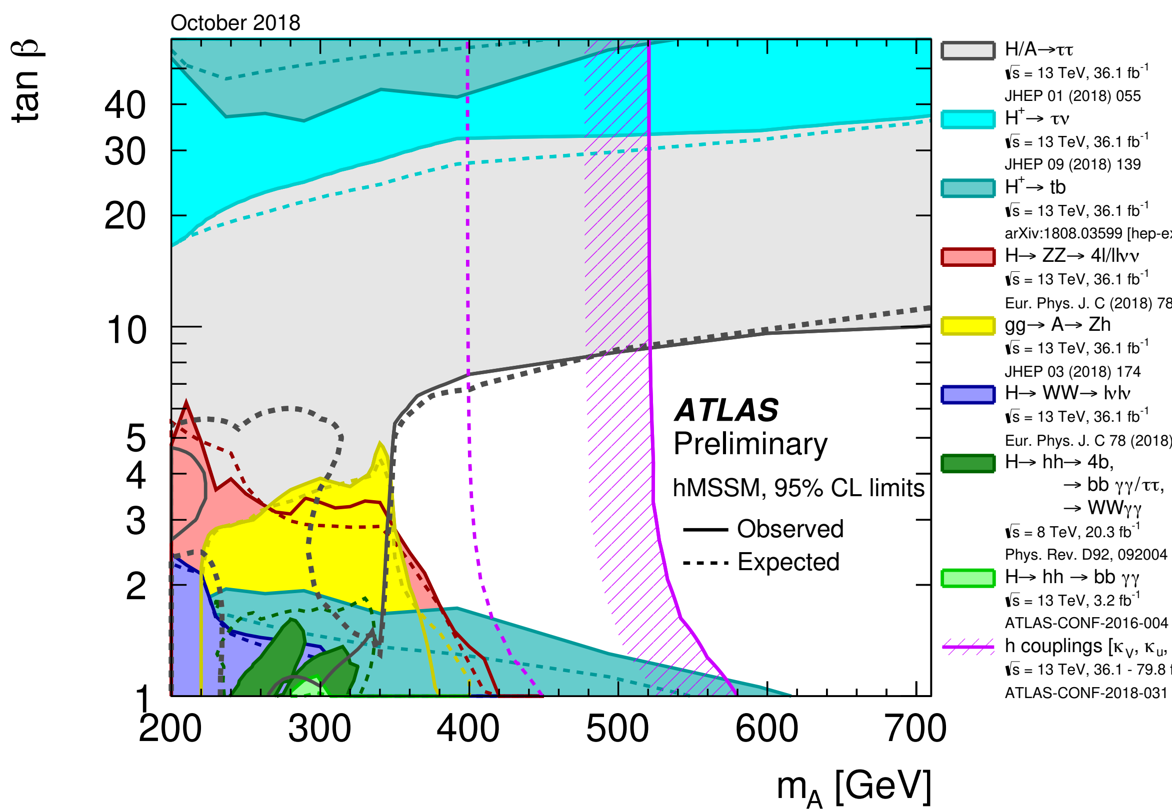
2. Trouble with minimal BSM? The MSSM

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

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

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



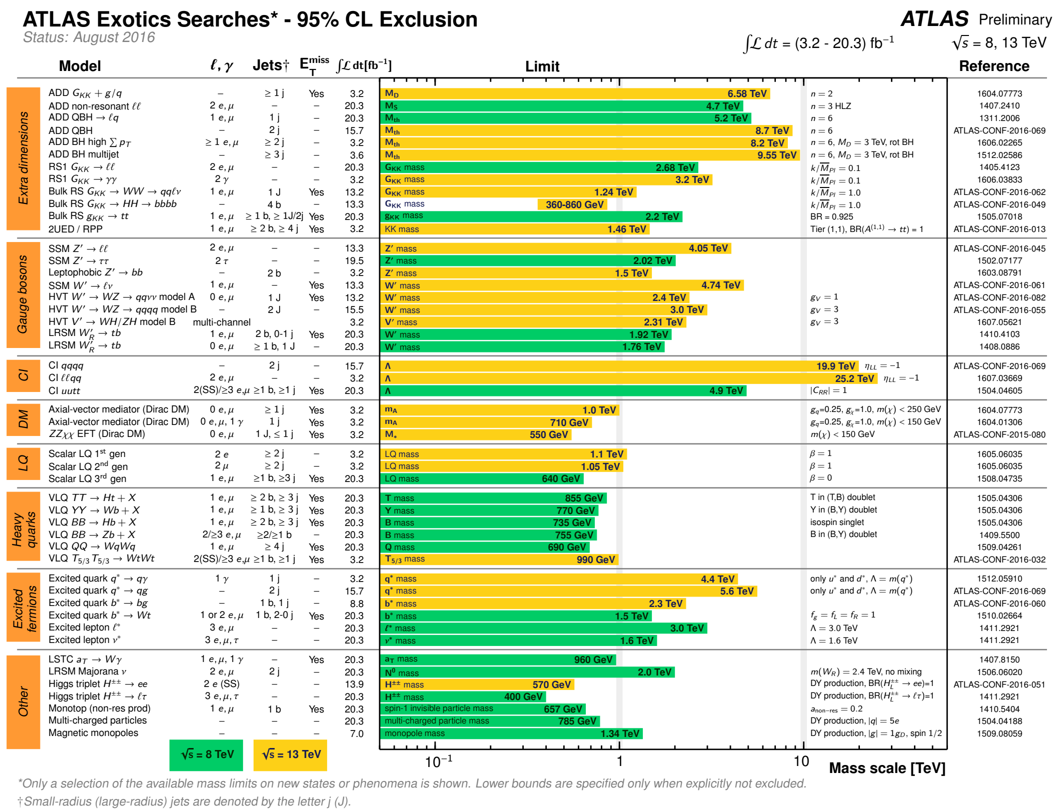


3. Quo vadis? Further probe of Higgs

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? Further probe of Higgs

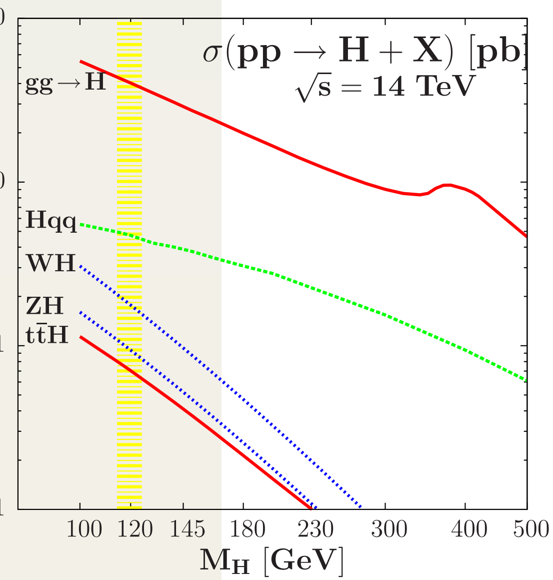
he next question is then: "is Particle Physics closed"? Answer is no!

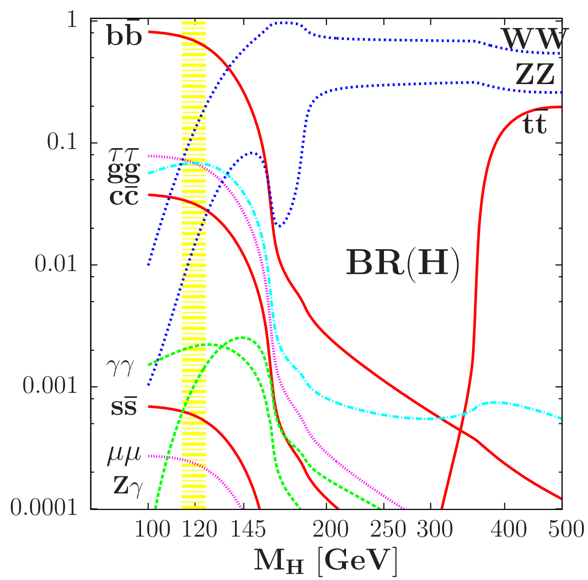
2) Need to check that H is alone responsible of EWSB (SM-like?)

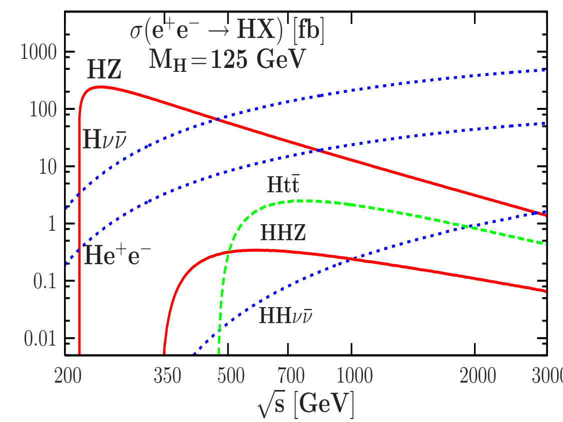
⇒ measure its fundamental properties in the most precise way:

- **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.





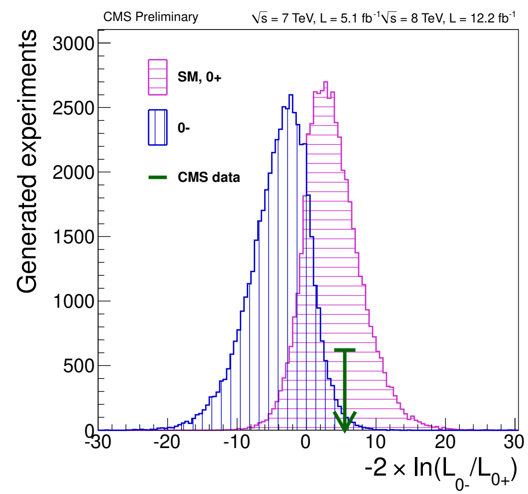


3. Quo vadis? Further probe of Higgs

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.

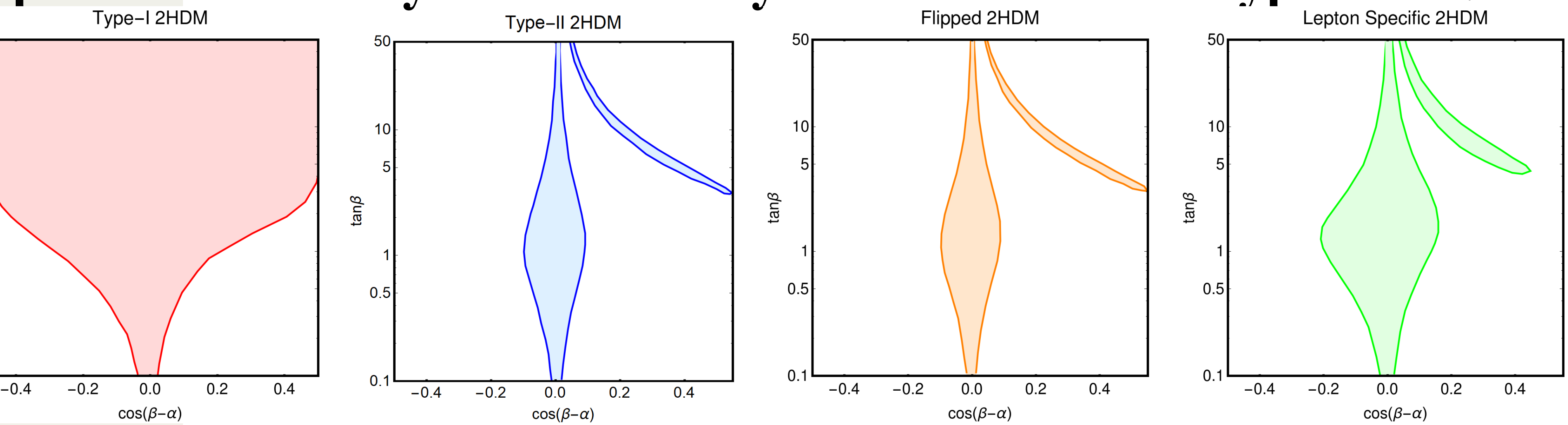
ex: spin-correlations in $q\bar{q} \to HZ \to b\bar{b}ll$, $q\bar{q}/gg \to Ht\bar{t} \to b\bar{b}t\bar{t}$.

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

3. Quo vadis? Further probe of Higgs

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:



• 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?)

3. Quo vadis? Further probe of Higgs

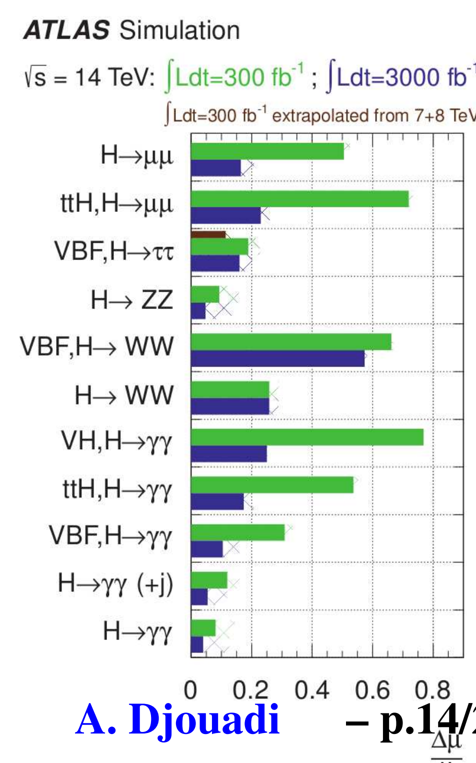
xample of search for New Physics via high precision measurements: the Higgs couplings in cleanest channels $H \to \gamma\gamma, \; H \to 4\ell^{\pm}$

channel	atlas/run1	cms/run1
$\mu_{\gamma\gamma}$	$1.17 \, {}^{+0.23}_{-0.23} \, {}^{+0.16}_{-0.11} \, \left({}^{+0.12}_{-0.08}\right)$	$1.14 \, {}^{+0.21}_{-0.21} \, {}^{+0.16}_{-0.10} \, \left({}^{+0.09}_{-0.05}\right)$
μ_{ZZ}	$1.46 \, {}^{+0.35}_{-0.31} \, {}^{+0.19}_{-0.13} \, \left({}^{+0.18}_{-0.11}\right)$	$0.93 \, {}^{+0.26}_{-0.23} \, {}^{+0.13}_{-0.09}$

Is this enough to probe effects of new physics or BSM?

ot in the case of weakly interacting theories like 2HDM, SUSY, etc...

expect effects at $\approx \frac{C_{new}\alpha_W}{\pi} \approx \frac{M_h^2}{M_{new}^2} \approx 1\%$;



Is 1% accuracy possible at HL-LHC (3ab^{-1})?

- **statistical error:** $20\%/\sqrt{3 \times 100} \lesssim$ **1–2%**
- **systematical error: can be made** $\lesssim 1\%$ **?**
- **theoretical uncertainty is then crucial issue.**

Less ambiguities in ratios of rates! Example:

$$D_{\gamma\gamma} = \frac{\sigma(pp \to H \to \gamma\gamma)}{\sigma(pp \to H \to VV)} = \frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to VV)} = d_{\gamma\gamma} c_\gamma^2 / c_V^2$$

Will $D_{\gamma\gamma}$ be the g-2 of the LHC? Yes, at 1%!

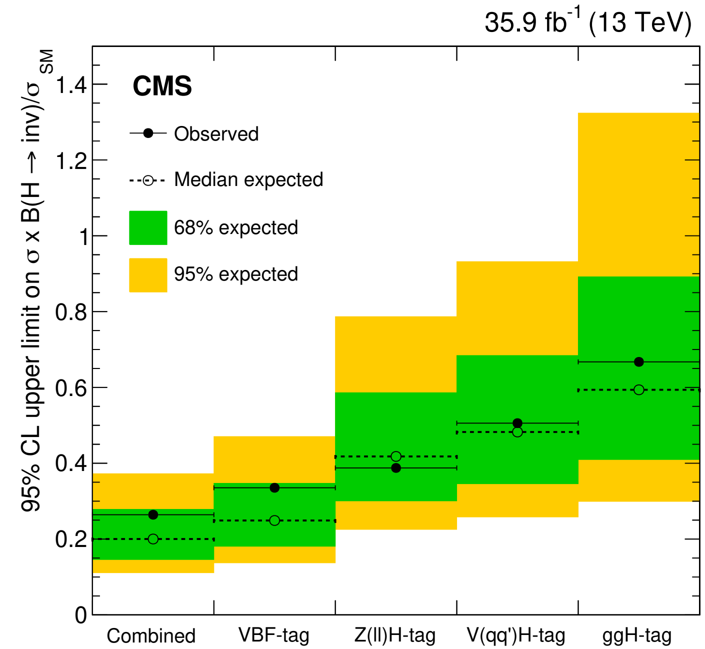
3. Quo vadis? Further probe of Higgs

• **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...

3. Quo vadis? Further probe of Higgs

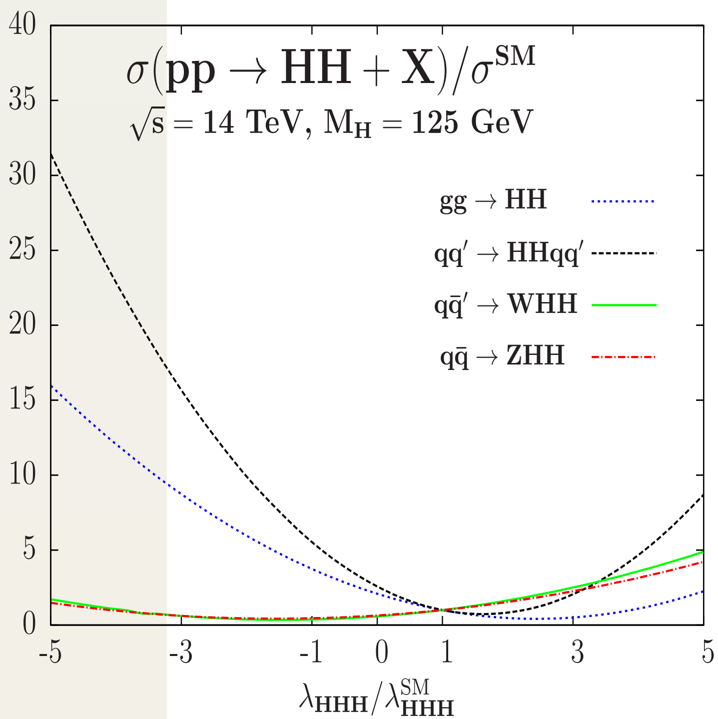
Important challenge: measure Higgs self-couplings and access to V_H.

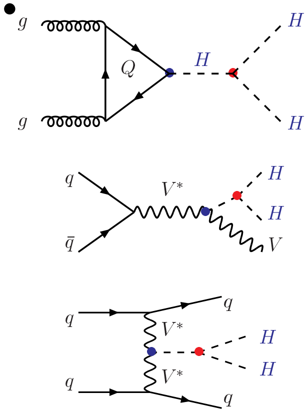
g_{H^3} from $pp \to HH + X$ $\Rightarrow$

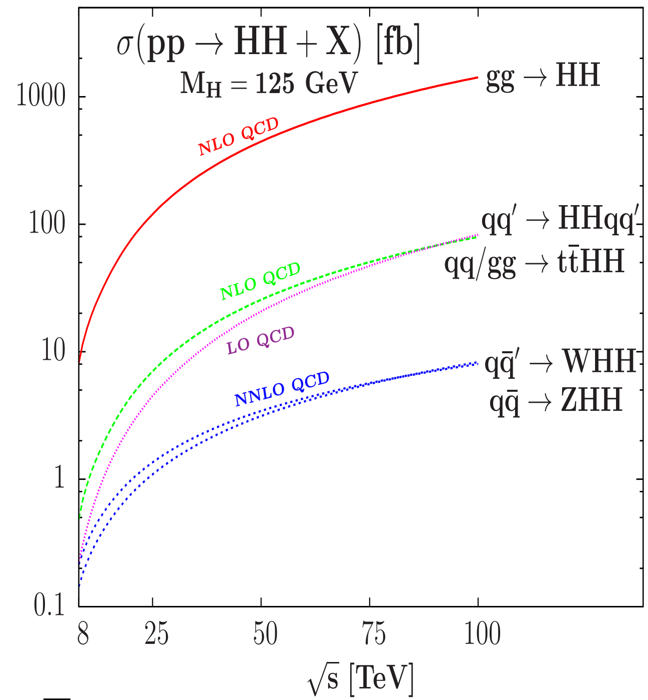
g_{H^4} from pp→3H+X, hopeless.

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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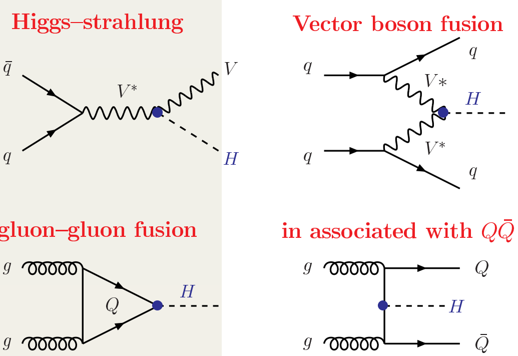
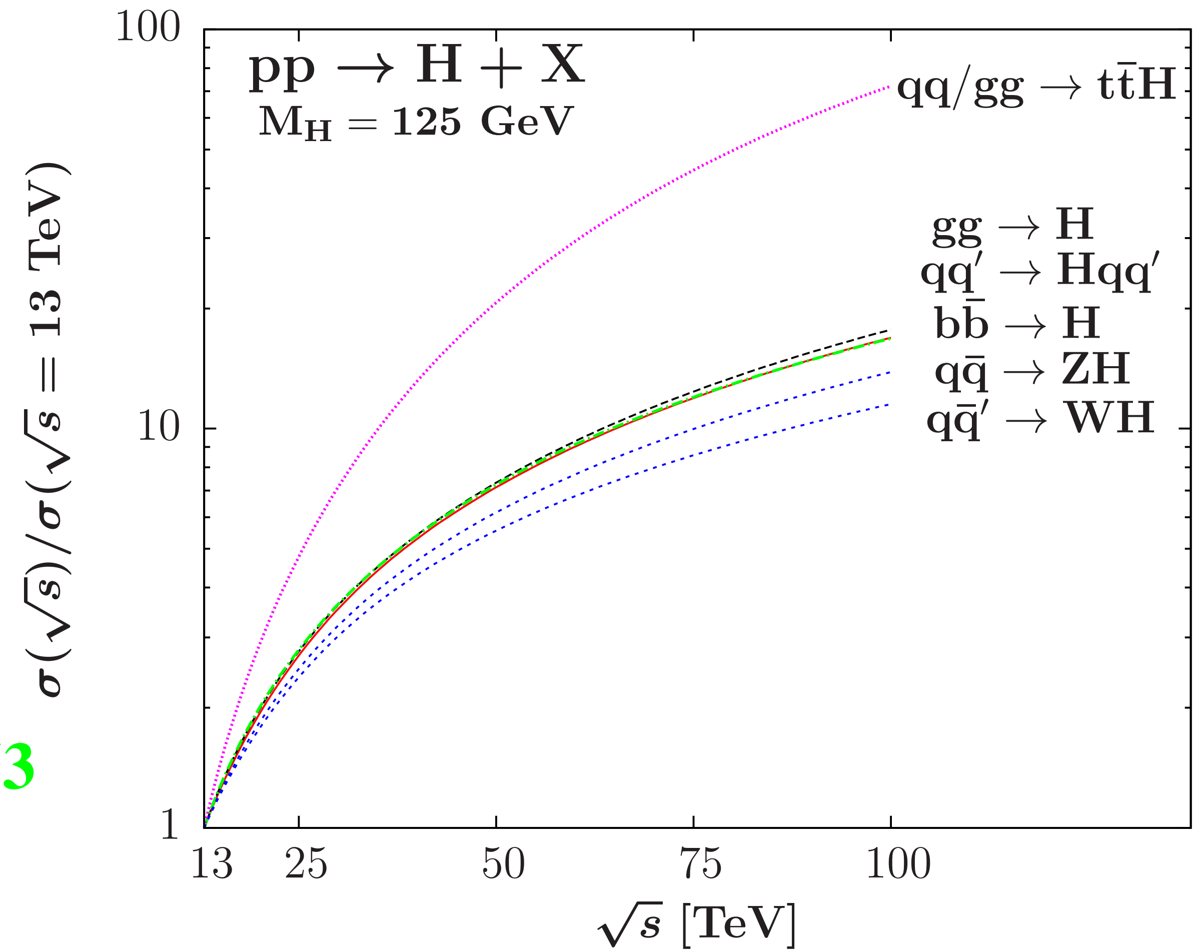
4. Where and what else?

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

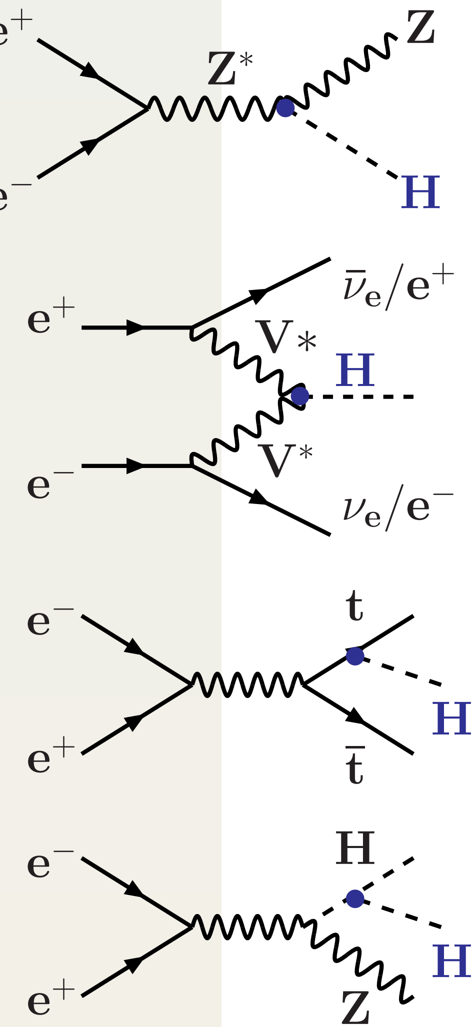


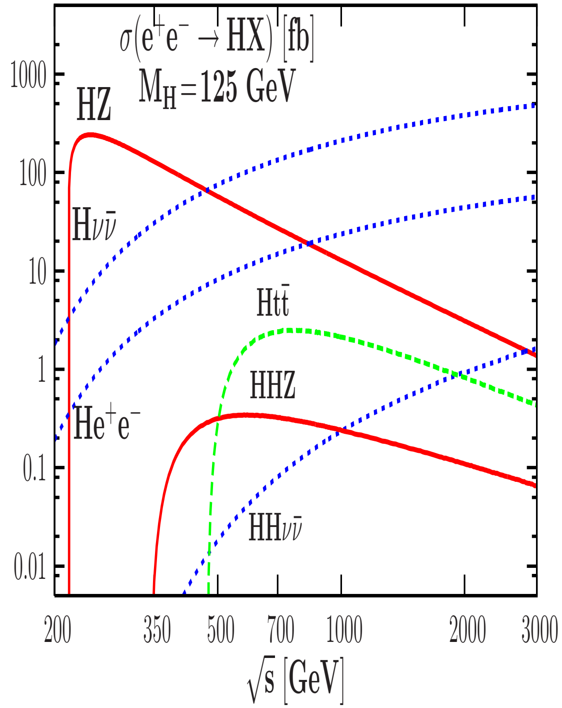


Baglio etal.,1511.07853

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

4. Where and what else?





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

4. Where and what else?

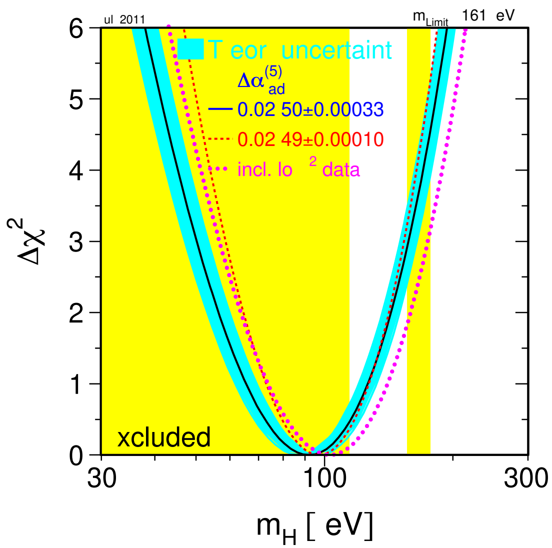
The SM is not only the Higgs, also other domains need to be tested.

A first one is the physics of the Z and W bosons!

emember: pre-LHC constraints on the Higgs boson mass in the SM

- **From various measurements of the Z observables at LEP1, SLC, ...**
- **From the very precise measurement of M_W at LEP2, Tevatron, ...**

constraints on the Higgs mass M_H once we know precisely m_t, α_s, etc...



Global fit: $M_H = 92^{+34}_{-26}$ GeV $\lesssim 160(126)$ GeV at 95% (68%)CL!

Now that the Higgs mass is known, we can really look for New Physics

The GigaZ for $\sin^2\theta_W$ and the MegaW option for M_W are a must!

4. Where and what else?

Another domain is the physics of the top quark! Just one example:

emember again, pre-LHC constraints on the Higgs mass in the SM:

included theory constraints on $\lambda(Q^2)$:

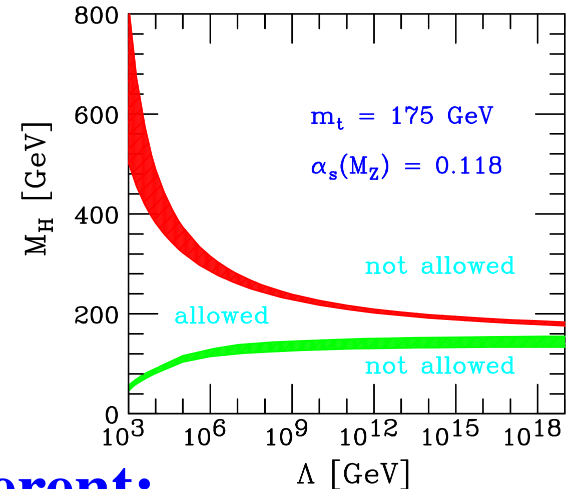
$\lambda \gg 1$: **triviality (non-perturbativity)**

$\lambda \ll 1$: **(un)stability of EW vacuum**

strong constraint depending on cut–off

$\Lambda \sim 1$ TeV $: 70 \lesssim M_H \lesssim 700$ GeV

$\Lambda \sim M_{Planck} : 120 \lesssim M_H \lesssim 180$ GeV



Now that we know M_H, the problem is different:

Depending on m_t (meta)stability!

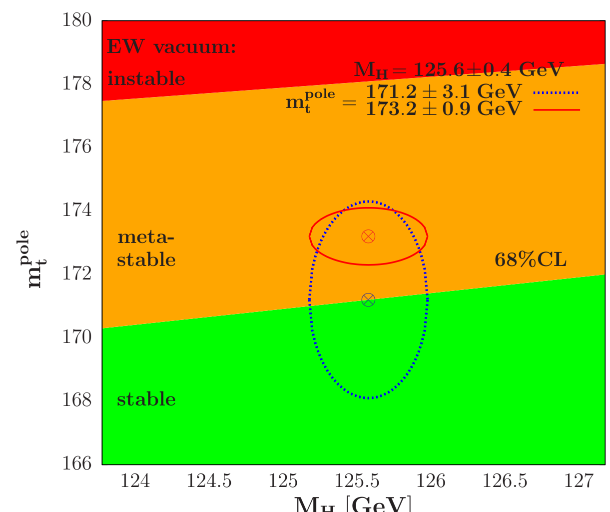
with usual top mass (pole,$\overline{MS}$,MC,?)

vacuum metastable for $\Lambda = M_P$

but with m_t from top cross sections:

vacuum stable up to $\Lambda = M_P$

There are also effects from α_s, ...



We need a better and more "rigorous" determination of m_t, α_s

5. Conclusion

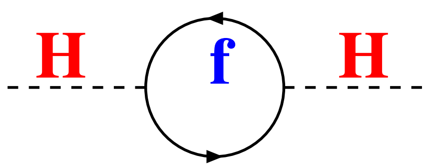
The discovery of the Higgs boson a the LHC was really historical: and the first probe of its basic properties a remarkable success.

We have now a theory, the Standard Modle, that is:

- **theoretically consistent and in principle complete,**
- **compatible with all data (modulo small anomalies?)**
- **it looks extrapolable up to ultimate energy scales**

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

$\Delta M_H^2 =$



$\propto \Lambda^2 \lesssim (1\ \mathrm{TeV})^2$???

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.

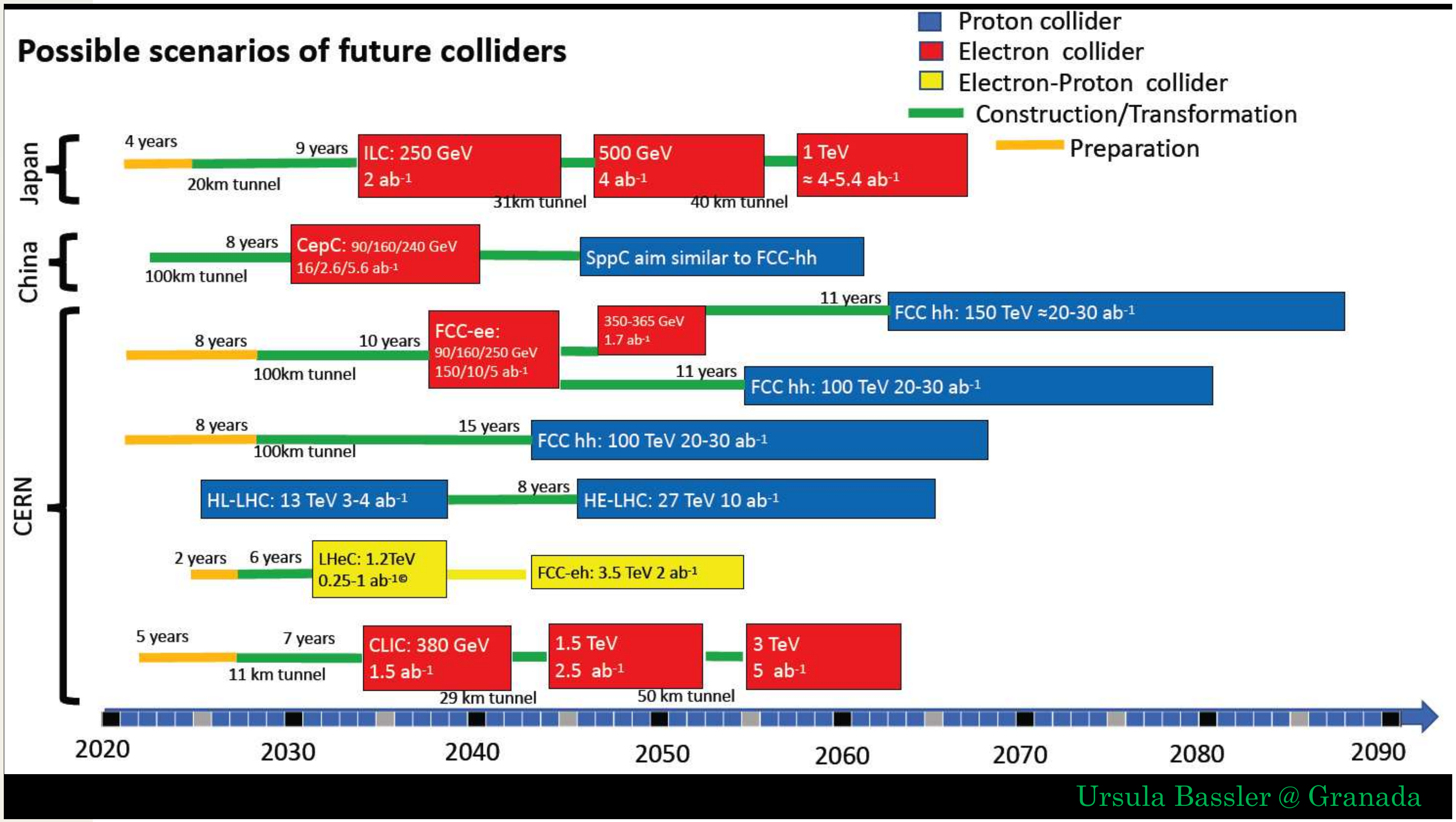
om now on, there is no guarantee for discovery at LHC or elsewhere?!

So should we give up and declare that particle physics is closed?
No of course! We should continue our quest (maybe 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!