

# Particle Physics after the Higgs: status and perspectives



**Abdelhak DJOUADI**  
**(CNRS & LAPTh)**



- 1. The Standard Model before and after the LHC**
- 2. The status of New Physics**
- 3. Quo vadis? Continue searches for BSM**
- 4. Quo vadis? Further probe of the SM**
- 5. Example of further probe:  $D_{\gamma\gamma}$ ?**
- 6. Conclusion**

# Already ten years since adventure started!



**Site LHC-France, 10/09/2008:  
LHC-start:mission accomplie!  
(short) enthusiasm, fever :  
The Guardian, among others:  
'CERN starts LHC with mission  
to make scientific history...'.**



**xtremely high expectations from theorists and also experimentalists!**



**Fabiola Gianotti  
deputy Atlas spoke**

**At "Exploring the Mysteries of the Universe"  
meeting Royal Society, Edinburgh, May 2008:  
"The LHC enables to navigate back in time, may:  
– prove the existence of brand new dimensions,  
– explore SUSY and forces that we don't imagine,  
– the LHC will be a dark matter factory ....."**

**But she also (reasonably and professionally) said:  
"attention will be focused on the search for the  
Higgs boson (God particle). To detect this elusive  
particle would be a major breakthrough...".**

**and spent most time describing how to discover it.**

**Indeed, even then, SM Higgs and BSM had rather different status!**

# 1. The SM before and after the LHC

The theory that describes microscopic world: the Standard Model

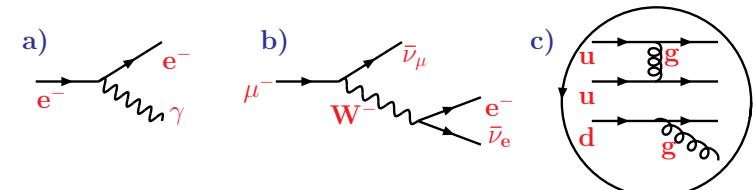
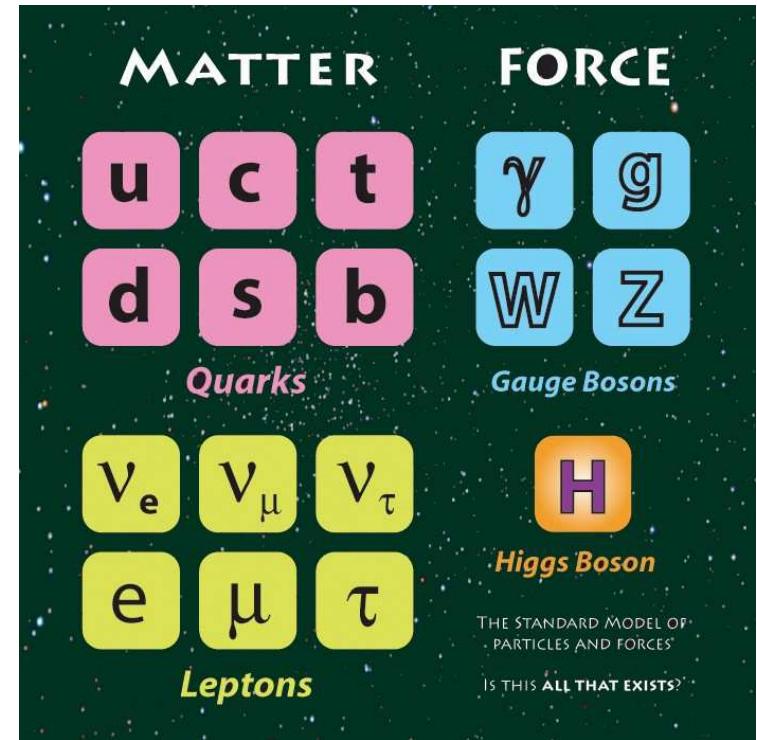
interaction of  $s=\frac{1}{2}$  matter particles via exchange of  $s=1$  force particles.  
It is based on a gauge symmetry:

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

- relativistic quantum field theory,
- perturbative, renormalisable,
- and most of all, very successful:
  - ⇒ infinitely precise predictions,
  - ⇒ high precision experimental tests.

True only if particles are massless:  
putting naively  $W/Z$ /fermion mass spoils gauge invariance and hence nice properties of the theory above.

To generate particle masses in an  $SU(2) \times U(1)$  gauge invariant way:  
⇒ the Brout–Englert–Higgs mechanism for EW symmetry breaking.



# 1. The SM before and after the LHC

► A doublet of complex scalar fields  $\Phi = (\begin{smallmatrix} \Phi^+ \\ \Phi^0 \end{smallmatrix})$ : 4 degrees of freedom.

Scalar potential:  $V_S = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$ ,  $SU(2)_L \times U(1)_Y$  invariant.

$\mu^2 > 0$ : minimum( $V_S$ ) at  $\langle 0 | \Phi^0 | 0 \rangle = 0$ :

four new scalars with mass  $m_S = \mu$ .

$\mu^2 < 0$ : (via quantum fluctuations?):

The field  $\Phi$  develops a non-zero vev

$$\langle 0 | \Phi^0 | 0 \rangle = v = \sqrt{-\mu^2 / \lambda^2} (= 246 \text{ GeV})$$

Fields/interactions still  $SU(2) \times U(1)$  symmetric but vacuum not:

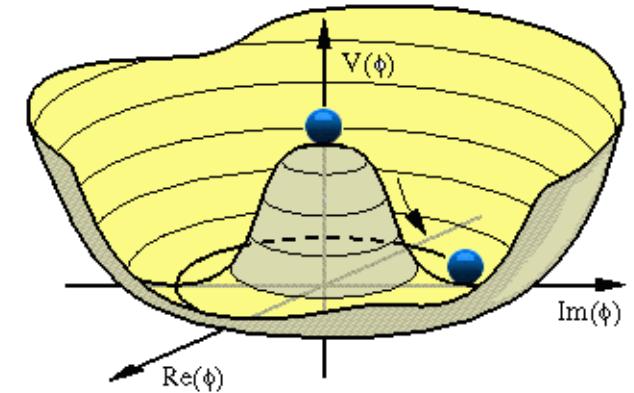
⇒ spontaneous EW symmetry breaking ⇒ 3dof for  $M_{W^\pm}$  and  $M_Z$ .

Introduce fermion interactions with same field  $\Phi$ :  $m_f$  also generated.

Residual d.o.f corresponds to spin-0 Higgs particle.

- Unique particle: spin zero, not matter and not force particle,
- couples to all particles  $\propto$  their masses:  $g_{Hff} \propto m_f$ ,  $g_{HVV} \propto M_V$ ,
- couples to itself,  $g_{HHH} \propto M_H^2$  with the relation  $M_H^2 = 2\lambda v^2$ .

NB: since  $v$  known, the only free parameter in the SM is  $M_H$  (or  $\lambda$ ).



# 1. The SM before and after the LHC

We knew that H (or something else) will be observed at the LHC!

- The Higgs unitarizes the theory:

Without H:  $|A(VV \rightarrow VV)| \propto E^2$

unitarity violated at  $\sqrt{s} \gtrsim 1 \text{ TeV}$

including H:  $|A| \sim M_H^2 / (8\pi v^2)$

theory unitary only if  $M_H \lesssim 1 \text{ TeV}$ !

A discovery was guaranteed at LHC!

- Theory constraints on  $\lambda(Q^2)$ :

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

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

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

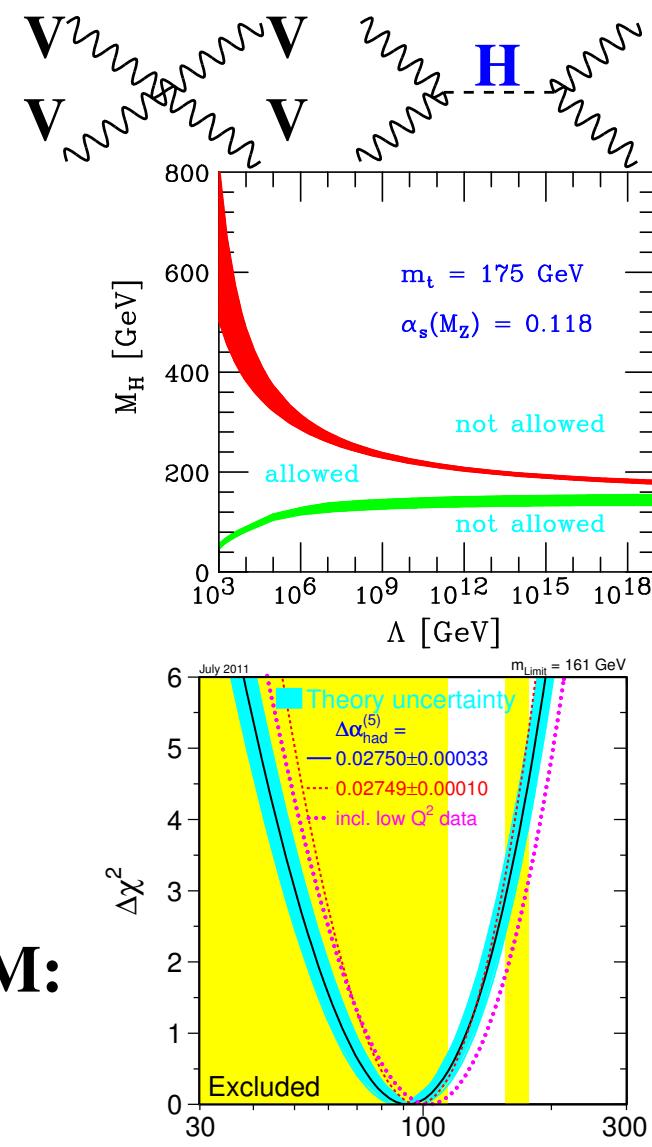
$\Lambda \sim M_{\text{Planck}}$  :  $120 \lesssim M_H \lesssim 180 \text{ GeV}$

- Experimental constraints on  $M_H$

from quantum effects in EW data in SM:

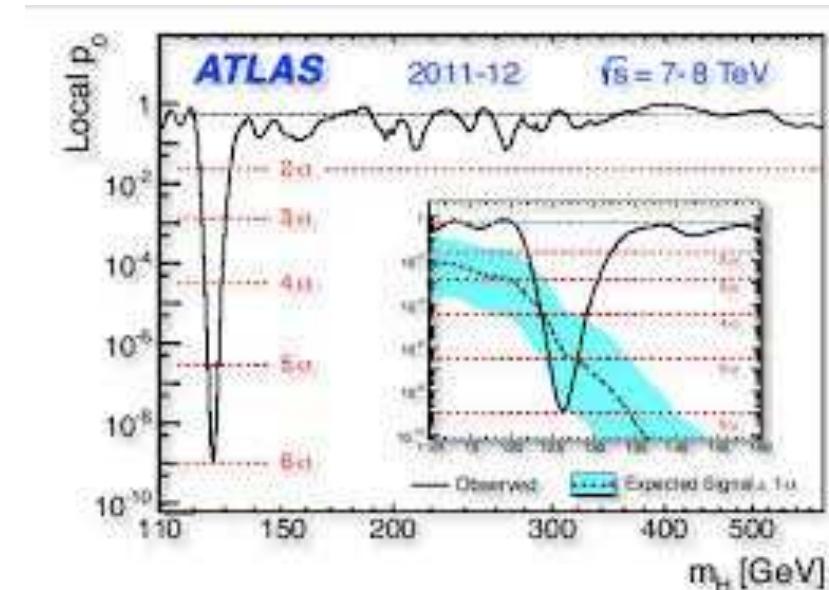
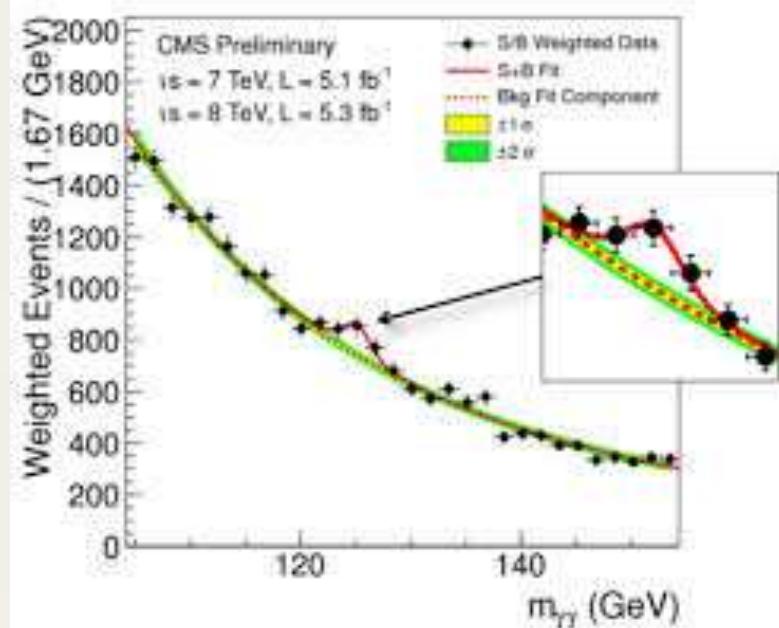
$M_H < 160 \text{ GeV}$  @95% confidence.

The LHC was a no-lose machine!



# 1. The SM before and after the LHC

Hence, the Higgs discovery in July 2012 was not a total surprise!



- A very non-trivial check of the SM: test at quantum/permile level:
- constraints from data:  $M_H = 92^{+34}_{-26} \text{ GeV} \lesssim 160 \text{ GeV}$  at 95% CL
  - experimentally found to be:  $M_H = 125 \pm 0.2 \text{ GeV}$  (ie within  $1\sigma$ ..)
- In addition, it looks as it has the properties of the SM Higgs state:  
The triumph of the Standard Model and Particle Physics!!!?

## 2. Status of beyond the SM

Back to pre-LHC status of HEP: we had a theory (SM) which was:

- theoretically consistent: perturbative, renormalisable, unitary;
- compatible with (almost) all precision data available at that time.

Yet, not the “theory of everything” and nobody was satisfied with it....

Only low energy manifestation of a fundamental theory that solves:

- “**Esthetical**” problems with eg multiple and arbitrary parameters; gauge coupling unification:  $3 \neq g_i$  which do not meet a high scale.
- “**Experimental**” problems as it doesn't explain all seen phenomena:  
 $\nu$  masses/mixing, dark matter, baryon asymmetry in the universe ....

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

- “**Theory**” (or consistency) problem: the hierarchy/naturalness pb: radiative corrections to  $M_H^2$  in SM with a cut-off  $\Lambda = M_{\text{NP}} \sim M_{\text{Pl}}$

$$\Delta M_H^2 \equiv -H \circlearrowleft f \circlearrowright H \dots \propto \Lambda^2 \approx (10^{18} \text{ GeV})^2$$

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

All these ”indicated/convinced” that there is beyond the SM physics!

## 2. Status of beyond the SM

Three BSM avenues for solving the hierarchy/naturalness problems:

### I. Compositeness/substructure:

All particles composite: Technicolor

⇒ H bound state of two fermions

(no more spin=0 fundamental state).

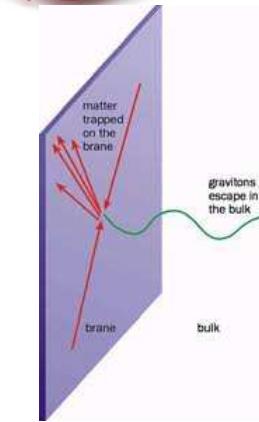


### II. Extra space-time dimensions

where at least s=2 gravitons propagate.

⇒ effective gravity scale  $\Lambda \approx 1 \text{ TeV}$ .

EWSB mechanism needed: H or not H!



### III. Supersymmetry: doubling the world.

– links s=1/2 fermions to s=1 bosons,

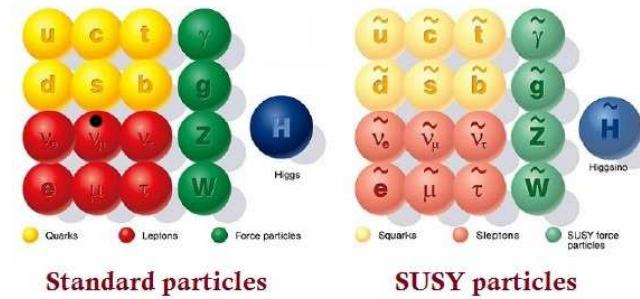
– if made local, provides link to gravity,

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

⇒ sparticle loops cancel  $\Lambda^2$  behavior

extend EWSB sector: at least 2 doublets.

#### SUPERSYMMETRY

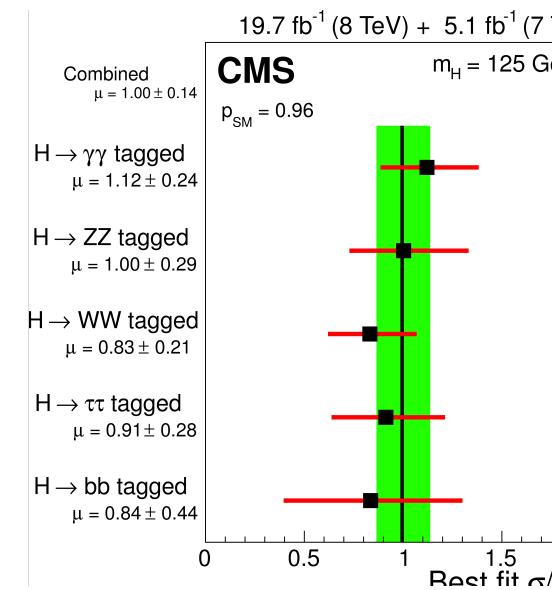
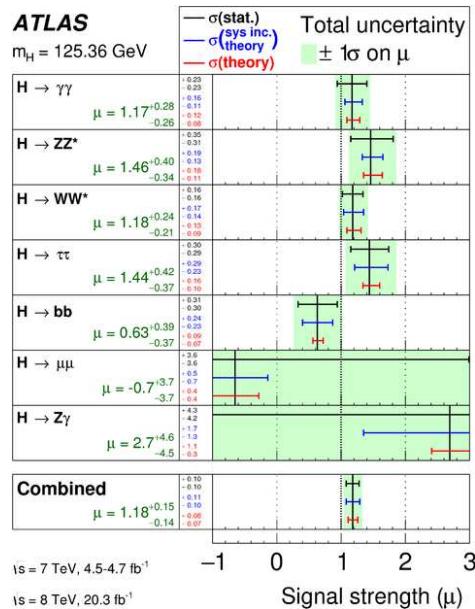


the BSM scale  $\Lambda \gg 1 \text{ TeV}$ , the theory is fine-tuned and not natural!

## 2. Status of beyond the SM

The problem is that at the LHC:

**A) we observe a Higgs with a mass of 125 GeV and it is SM-like:**  
 $\sigma \times \text{BR}(\text{H})$  rates are compatible with those expected in the SM.  
 Higgs results from the LHC 7–8 TeV campaign already give us:



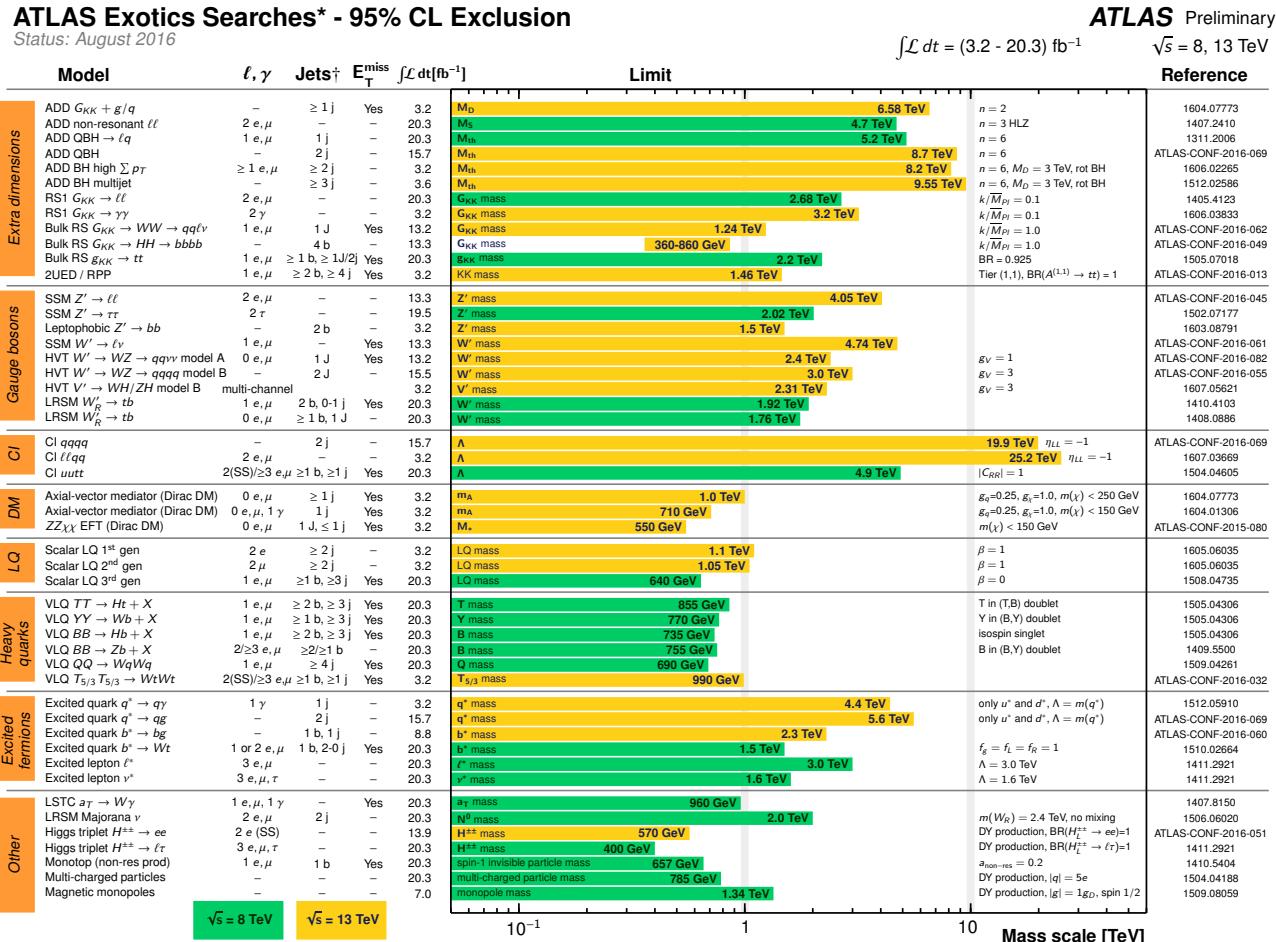
Fit of all LHC Higgs data  $\Rightarrow$  agreement with SM at the 15–30% level,  
 $\mu_{\text{tot}}^{\text{ATLAS}} = 1.18 \pm 0.15$  and  $\mu_{\text{tot}}^{\text{CMS}} = 1.00 \pm 0.14$

Situation is even more clear at 13 TeV with precise fermion modes.

## 2. Status of beyond the SM

The problem is that LHC results/searches tell us that

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



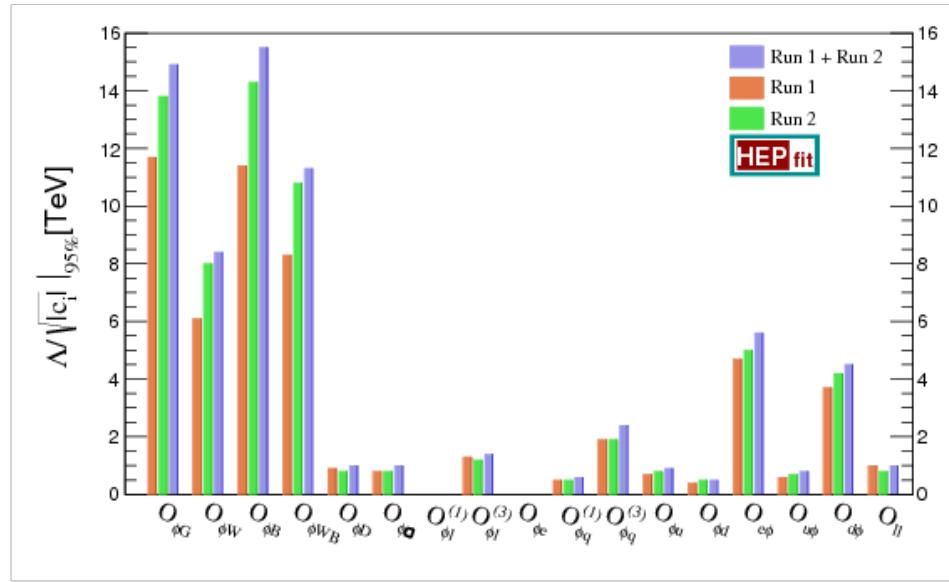
\*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter J (J).

## 2. Status of beyond the SM

**These two observations have profound implications for New Physics.  
Most discussed BSM scenarios, also those addressing hierarchy pb, in**

- “**mortuary**”: Higgsless, 4th generation, fermio or gauge-phobic...
  - “**hospital**” (pve!): Technicolor, standard composite models....
  - “**trouble**”, being strongly constrained and extremely fine-tuned:
    - extra-dimensions: KK excitation masses heavier than  $O(10)$  TeV;
    - Supersymmetry: SUSY scale is above 1 TeV in minimal scenarios.



J. de Blas et al,  
(2017)

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

## 2. Status of beyond the SM

In the MSSM we need 2 doublets of complex scalar fields  $H_1, H_2$   
 (it is a 2HDM of type II but with SUSY constraints)

After EWSB, 3 dof for  $W_L^\pm, Z_L \Rightarrow 5$  physical states:  $h, H, A, H^\pm$ .

2 free parameters at tree-level to describe Higgs pheno:  $\tan\beta, M_A$ :

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

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

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

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

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

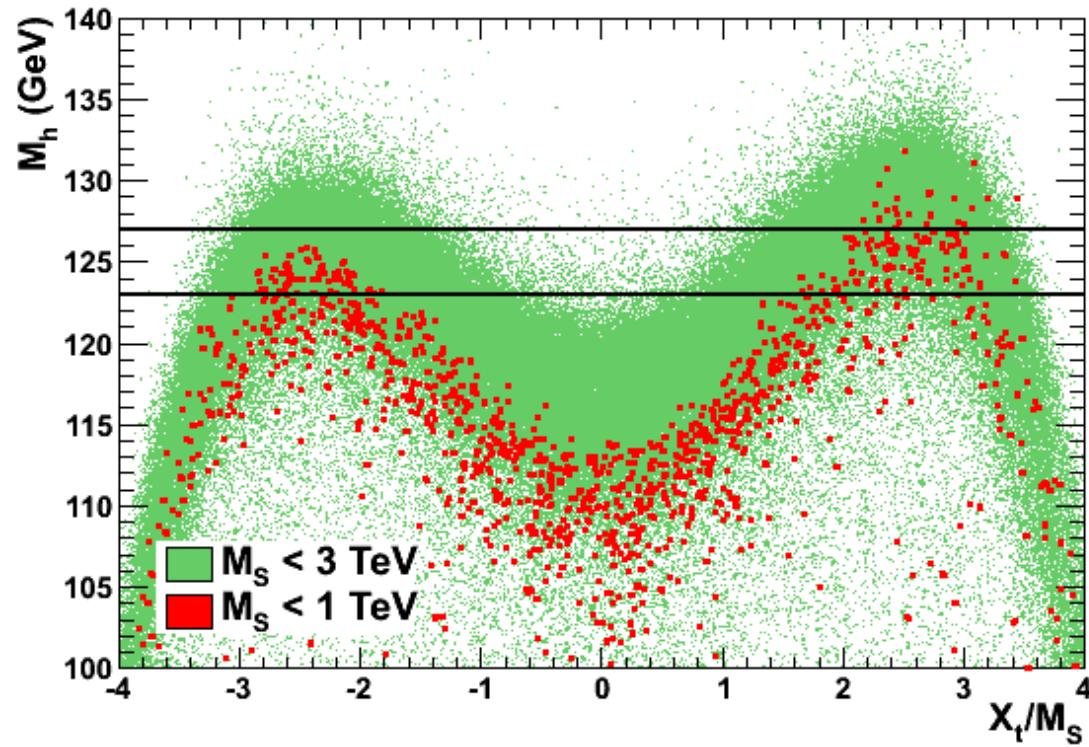
$\Phi$	$g_{\Phi \bar{u} u}$	$g_{\Phi \bar{d} d}$	$g_{\Phi VV}$
$h$	$\frac{\cos \alpha}{\sin \beta} \rightarrow 1$	$\frac{\sin \alpha}{\cos \beta} \rightarrow 1$	$\sin(\beta - \alpha) \rightarrow 1$
$H$	$\frac{\sin \alpha}{\sin \beta} \rightarrow 1/\tan \beta$	$\frac{\cos \alpha}{\cos \beta} \rightarrow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

Decoupling limit: MSSM Higgs sector reduces to SM with a light  $h$ .

## 2. Status of beyond the SM

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

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



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

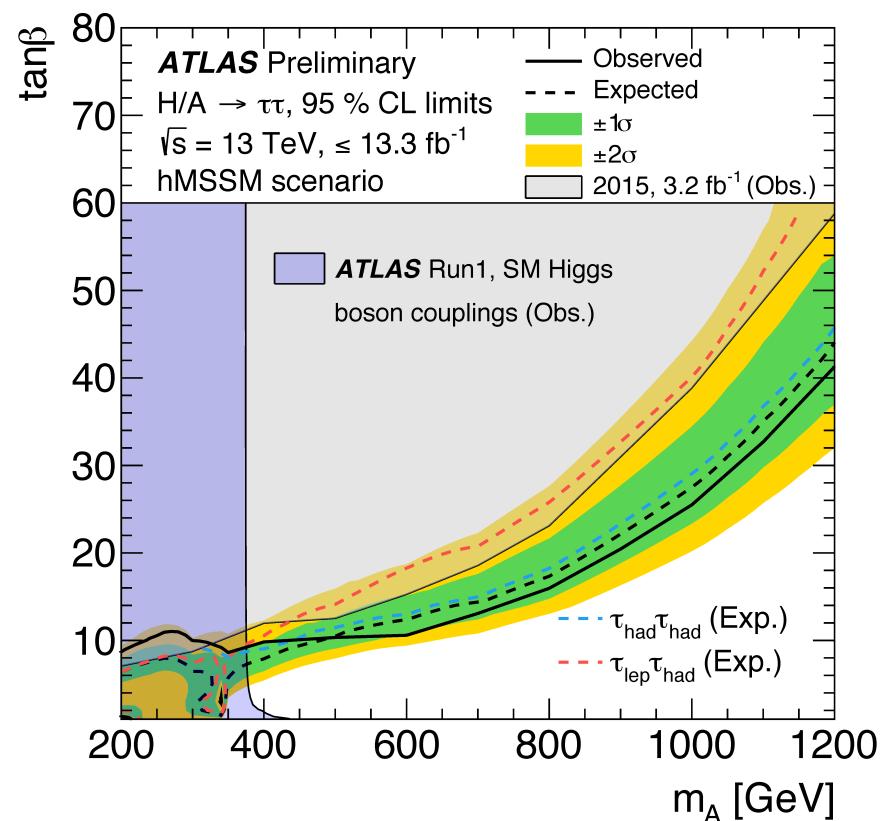
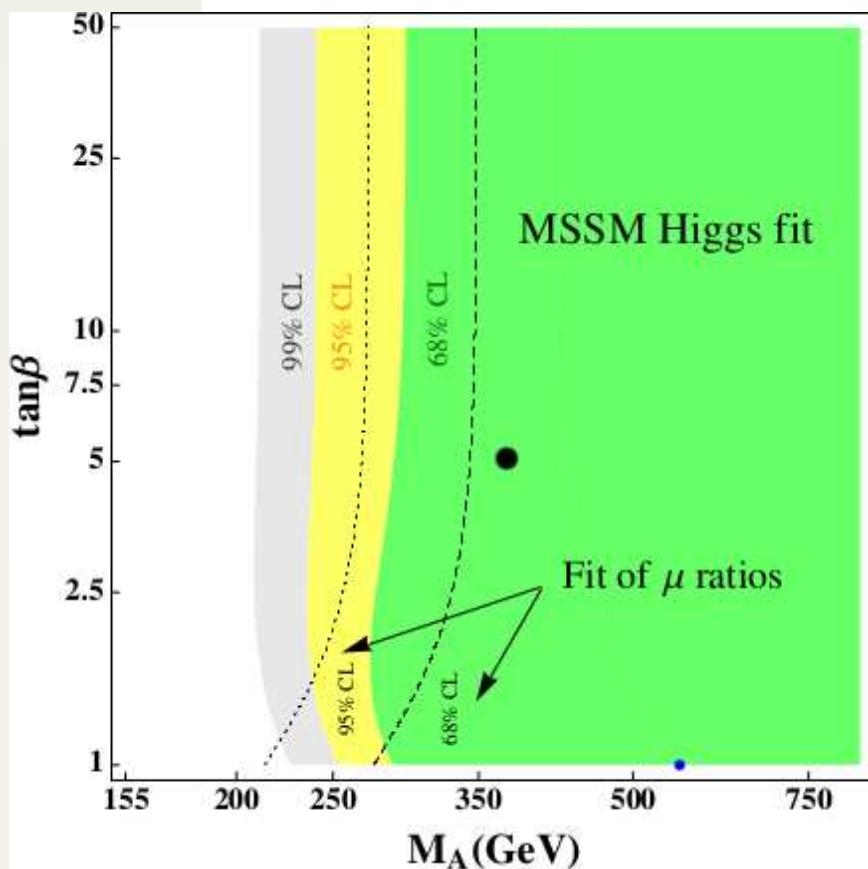
$M_{\text{SUSY}} \gtrsim 1 \text{ TeV}$  in general MSSM and higher in constrained models.

## 2. Status of beyond the SM

**Backed up by measurement of h properties and heavy H/A searches:**  
**fits of the h couplings  $\Rightarrow$  constraints on MSSM  $[M_A, \tan\beta]$  space:**  
**MSSM:  $g_{h\bar{t}\bar{t}} = \cos\alpha/\sin\beta$ ,  $g_{h\bar{b}\bar{b}} = \cos\alpha/\sin\beta$ ,  $g_{hVV} = \sin(\beta - \alpha)$**

**AD, Quevillon, Maiani..(2013)**

**Direct search for  $pp \rightarrow H, A$**

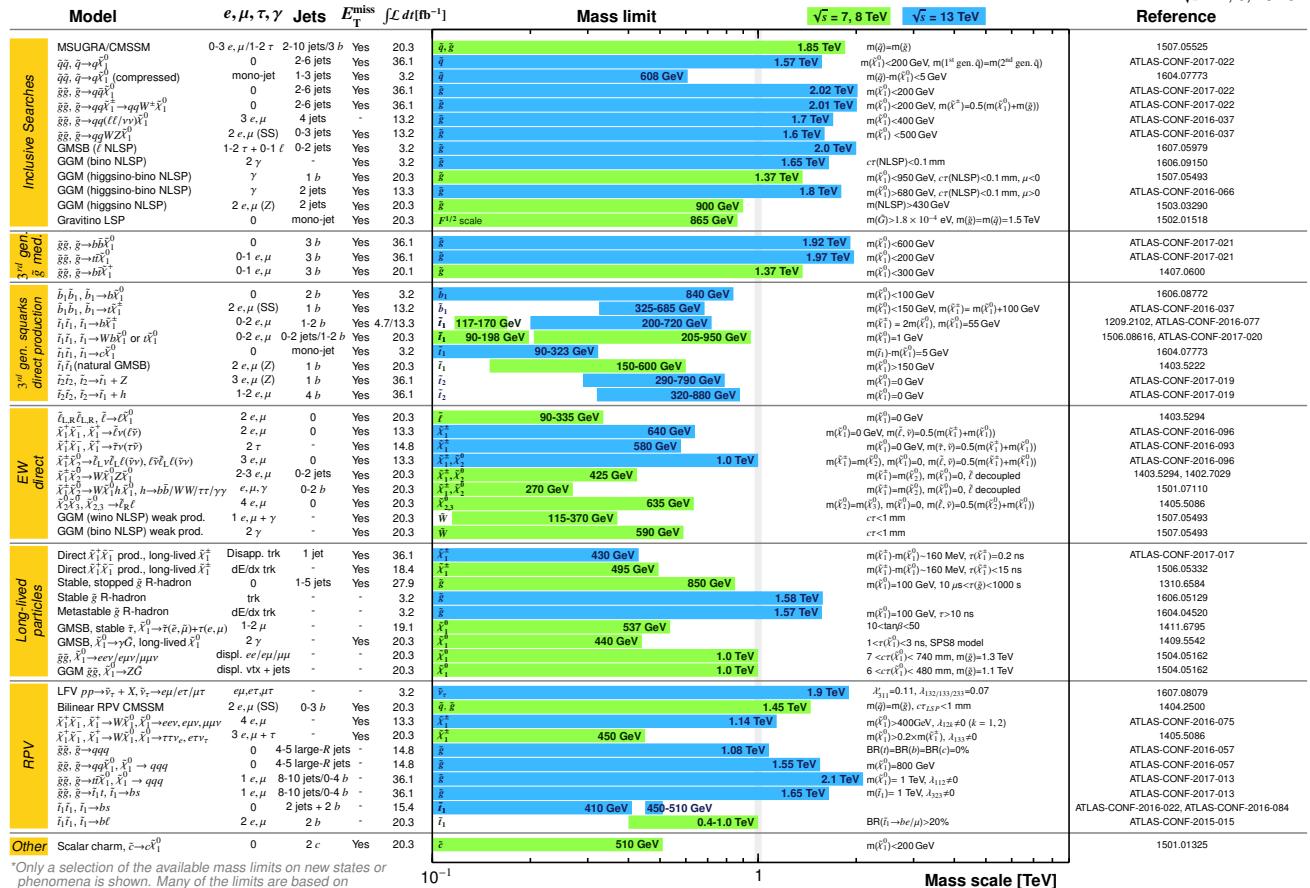


## 2. Status of beyond the SM

Also backed up by direct searches of SUSY particles at the LHC:  
the SUSY scale  $M_{\text{SUSY}} \gtrsim \mathcal{O}(1 \text{ TeV})$  in most experimental searches..

ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: March 2017

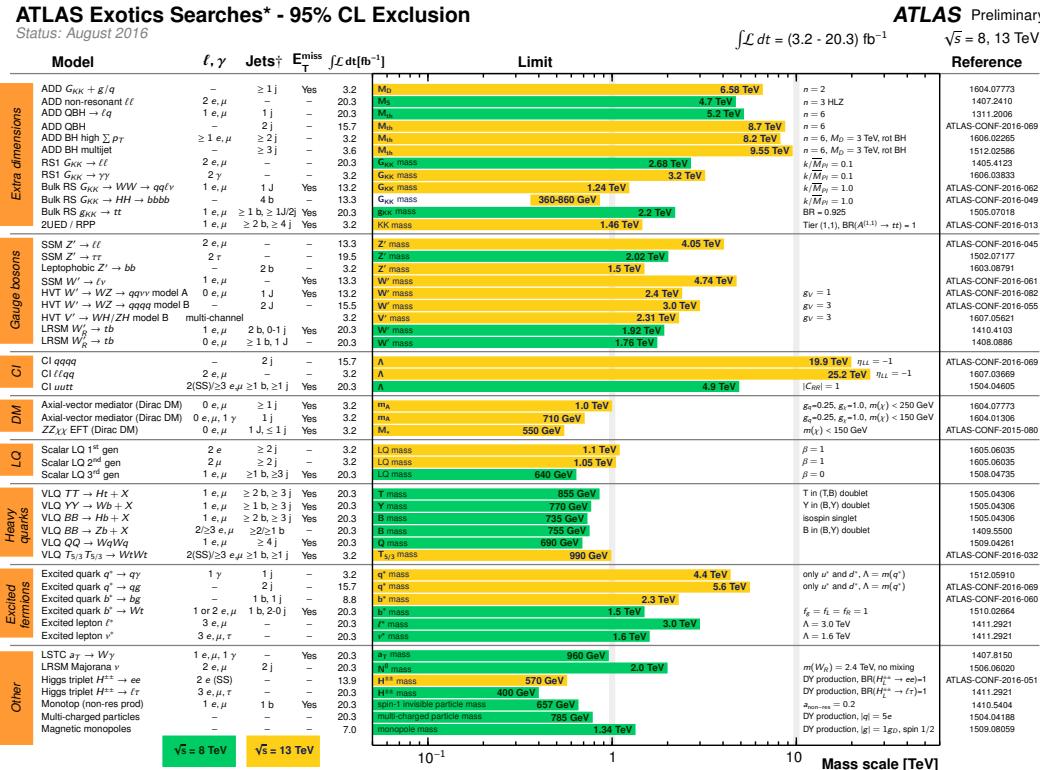


⇒ ATLAS/CMS depressing tables ....

# 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  
 ⇒ continue searches for new particles in all possible channels.

ATLAS Exotics Searches\* - 95% CL Exclusion  
 Status: August 2016



\*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

<sup>†</sup>Small-radius (large-radius) jets are denoted by the letter  $j$  ( $J$ ).

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 fine-tuned, non-minimal, more complicated scenarii...

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

- **Within the plain MSSM:**

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

- **Beyond the MSSM:**

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

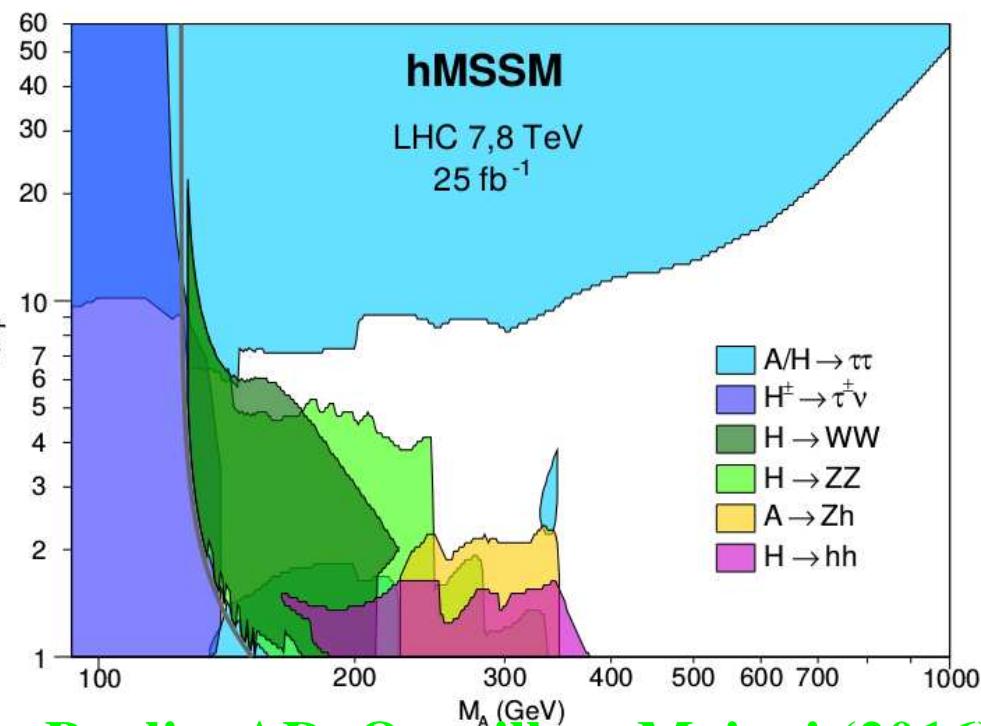
- **And anything else:**

- 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...

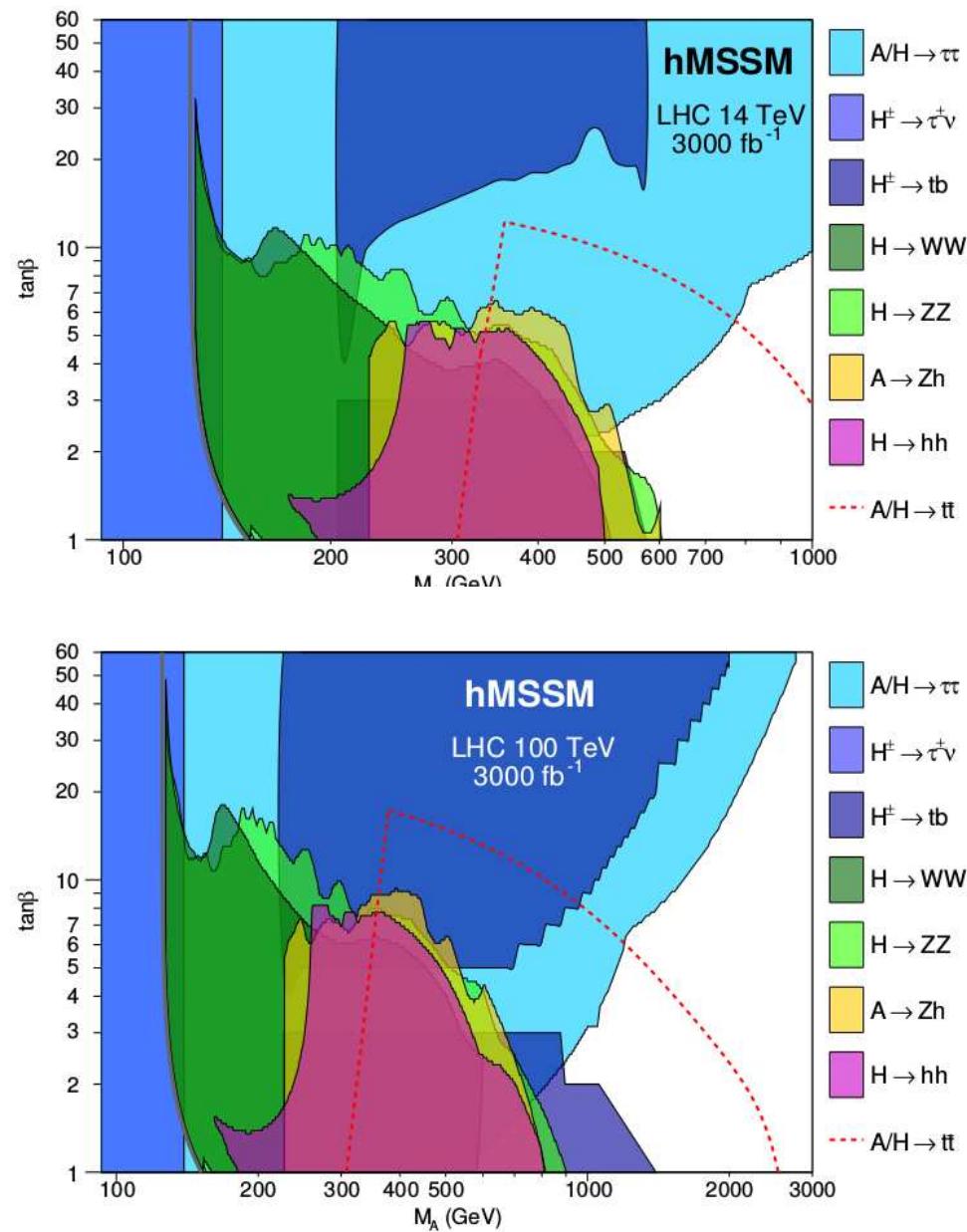
In worst case, one extends the limits on the NP scale....

### 3. Quo vadis? Continue direct RSM searches

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

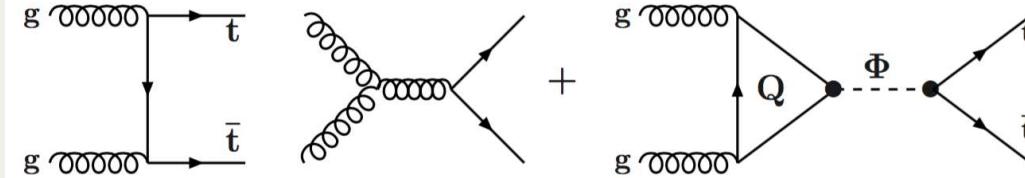


Baglio, AD, Quevillon, Maiani (2016)

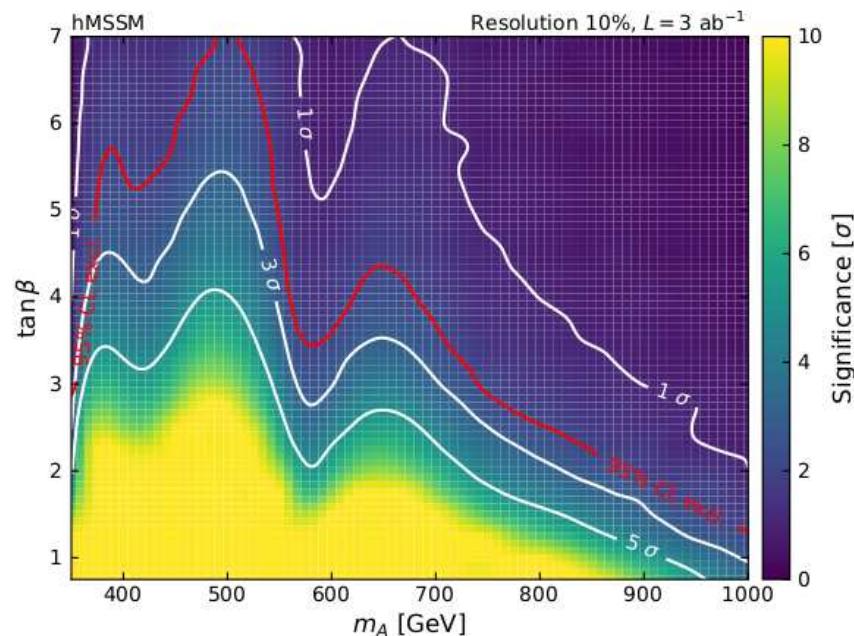
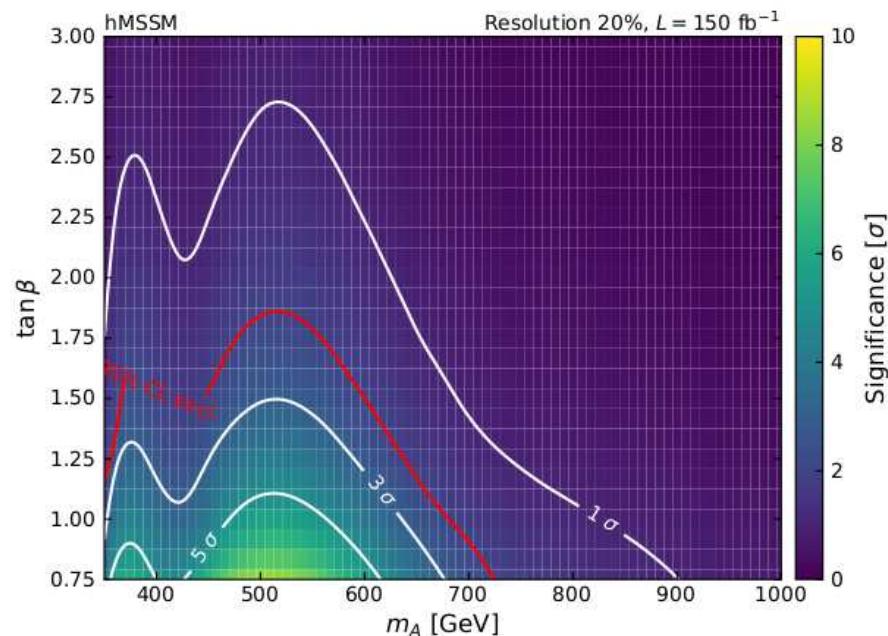
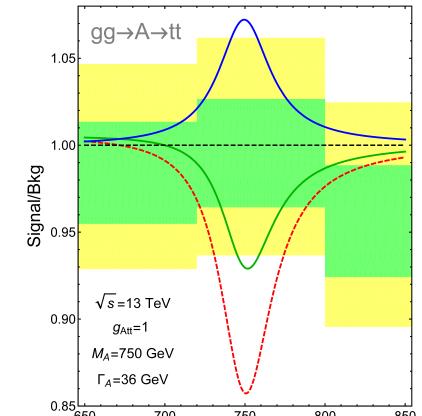
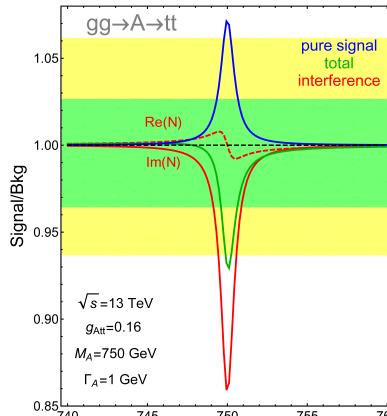


### 3. Quo vadis? Continue direct BSM searches

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



AD, Ellis, Quevillon



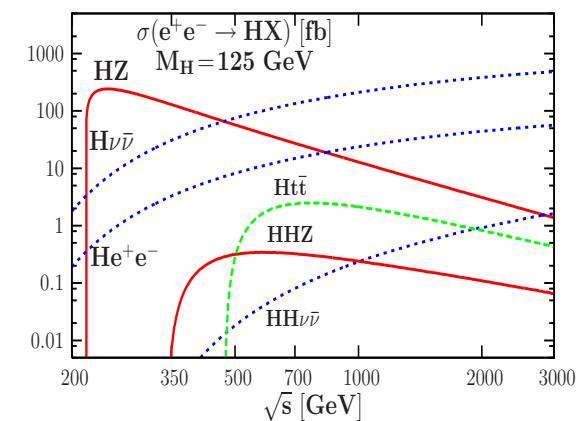
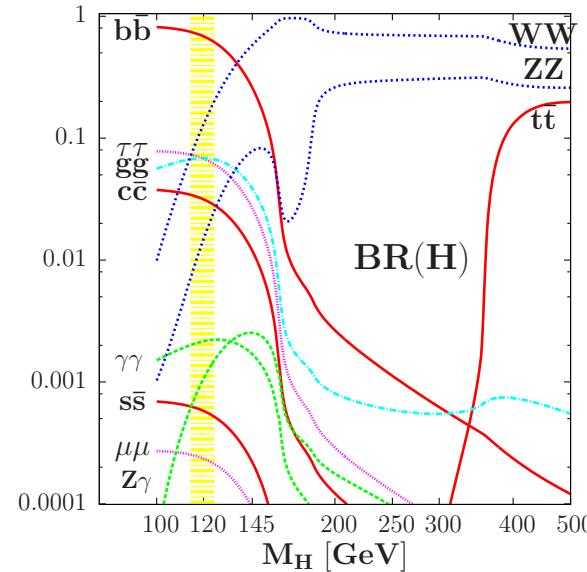
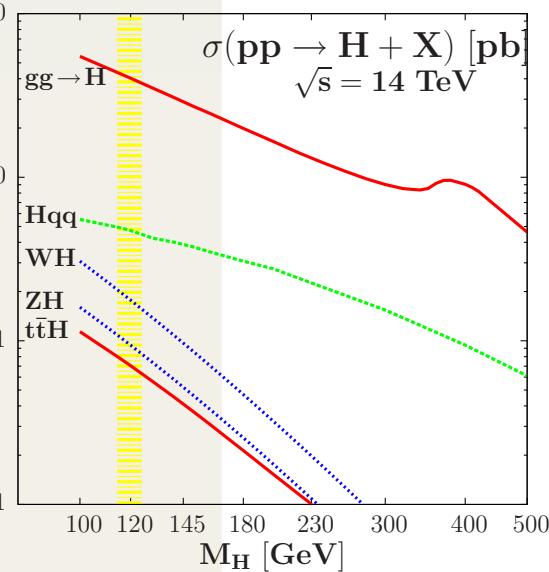
## 4. Quo vadis? Further probe of the SM

The 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

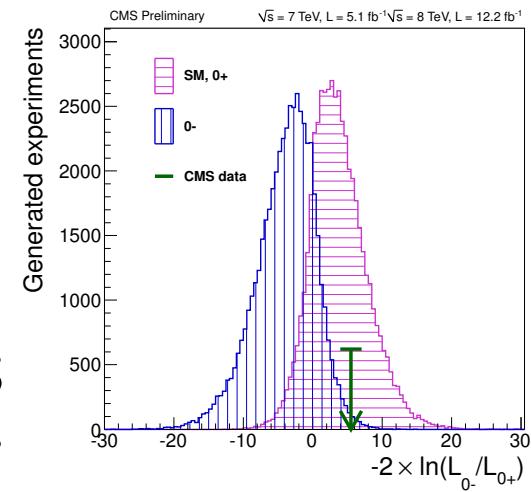
A check of spin–parity quantum numbers and search for CP violation

**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  $H \rightarrow ZZ^*$  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  $h_i \rightarrow h_j Z$  and  $h_i \rightarrow ZZ$  with  $i, j = 1, 2, 3$ .

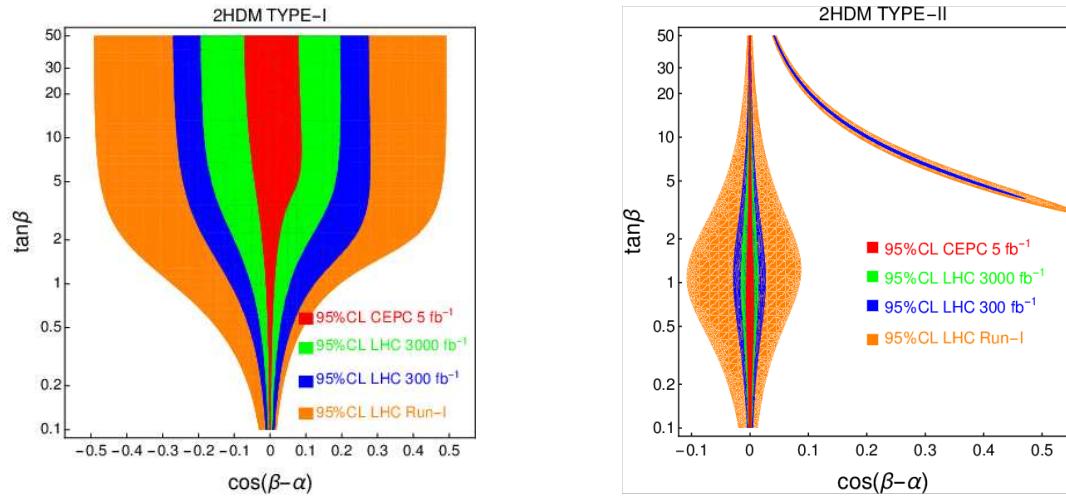
- **Indirect probe:**  $g_{Hff}$  more democratic  $\Rightarrow$  fermionic decays.  
ex: spin-correlations in  $q\bar{q} \rightarrow HZ \rightarrow b\bar{b}ll$ ,  $q\bar{q}/gg \rightarrow Ht\bar{t} \rightarrow b\bar{b}tt\bar{t}$ .

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  
⇒ would allow a better sensitivity to new physics virtual effects.

- In standard production+decay modes as  $gg \rightarrow H \rightarrow ZZ, WW, \gamma\gamma$   
Presently sensitivity is low in many cases as 2HDM of type I and II:  
still large theoretical+experimental errors of about 15–20% each



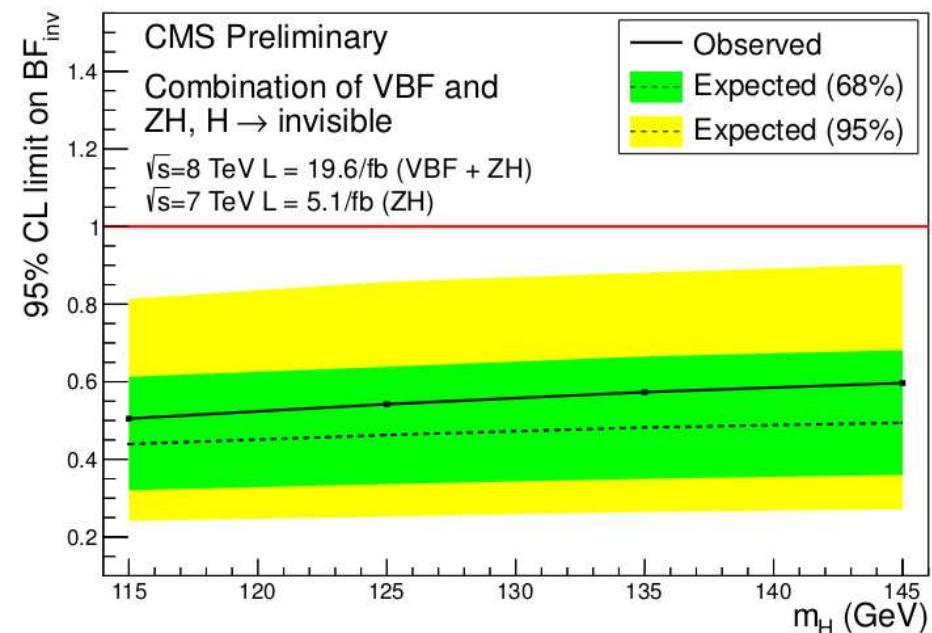
Chen et al.,  
1808.10177

- In very rare decays that allow additional/unknown information:
  - $H \rightarrow \mu^+ \mu^-$  to probe second generation fermion couplings
  - $H \rightarrow \Upsilon \gamma$  to probe the sign of some fermionic couplings (here b's).
  - $H \rightarrow Z \gamma$  with information that is complementary to  $H \rightarrow \gamma\gamma$
- But will this be sufficient to probe BSM physics? (see example later)

## 4. Quo vadis? Further probe of the SM

- **Total width:**  $\Gamma_H = 4 \text{ MeV}$ , too small to be resolved experimentally.
  - very loose bound from interference  $gg \rightarrow ZZ$  (factor 2–5 at most).
  - no way to access it indirectly (via production rates) precisely...
- **Invisible width:** more accessible

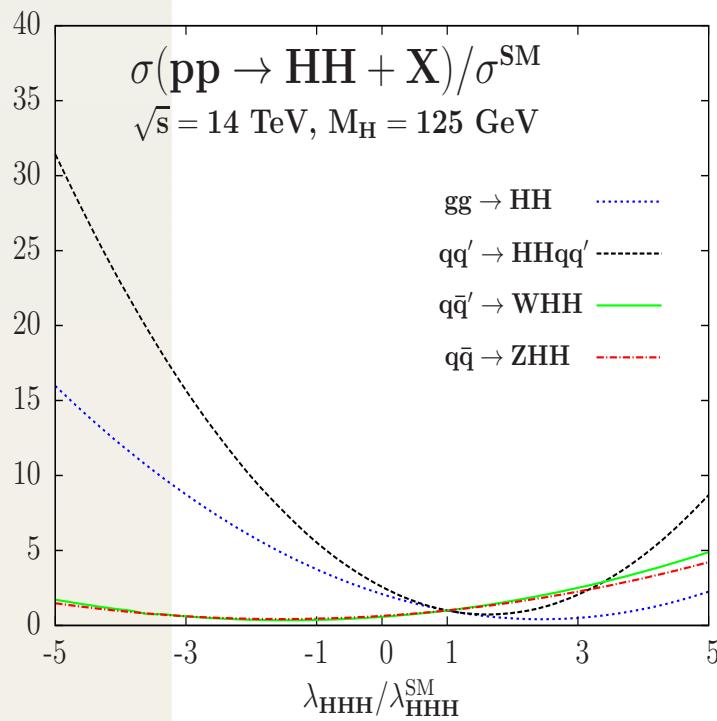
Direct measurement of  $H \rightarrow \text{inv}$   
 $q\bar{q} \rightarrow HZ$  with  $Z \rightarrow ll$ ,  $H \rightarrow \text{inv}$   
similar  $E_T$  search in VBF mode  
and also in  $gg \rightarrow \text{Higgs+jet}$ ...  
Combined  $HZ + \text{VBF}$  in CMS  
 $\text{BR}_{\text{inv}} \lesssim 50\% @ 95\% \text{ CL}$   
assuming a SM Higgs state  
10% @ HL-LHC possible?



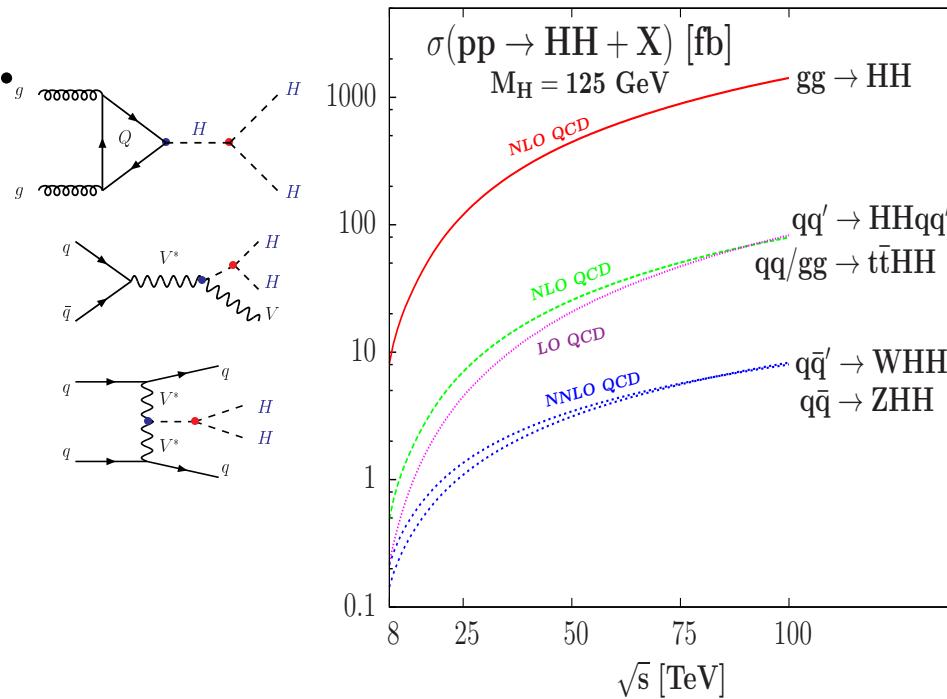
Indirect measurement of  $H \rightarrow \text{inv}$   
via Higgs BRs measurement: again accuracy of O(10%) at HL-LHC  
but with TH assumptions: no other decays, SM-like Higgs, etc...

## 4. Quo vadis? Further probe of the SM

**Important challenge: measure Higgs self-couplings and access to  $V_H$ .**  
 $g_{H^3}$  from  $pp \rightarrow HH + X \Rightarrow$   
 $g_{H^4}$  from  $pp \rightarrow 3H + X$ , hopeless.  
 Various processes for HH prod:  
 Only  $gg \rightarrow HHX$  relevant...



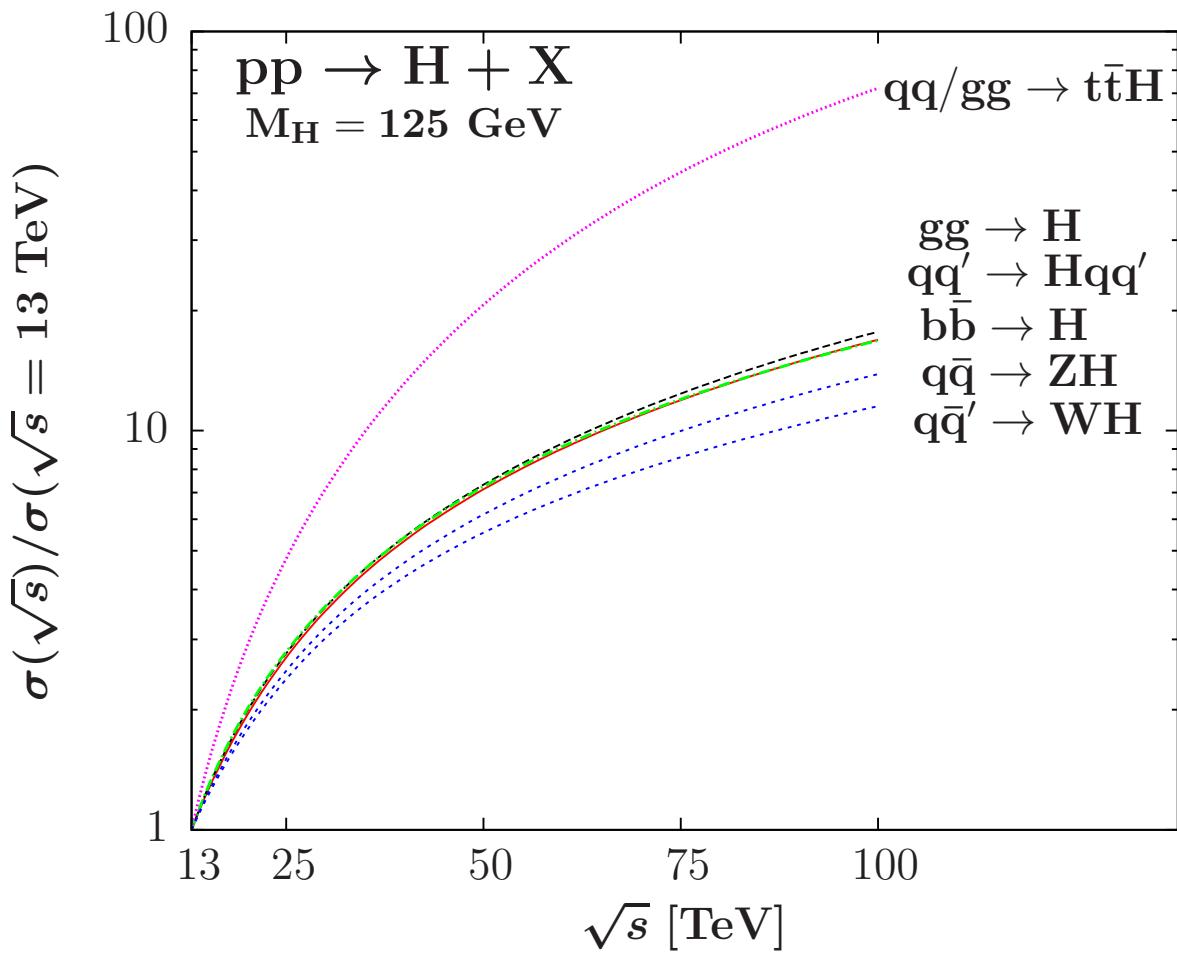
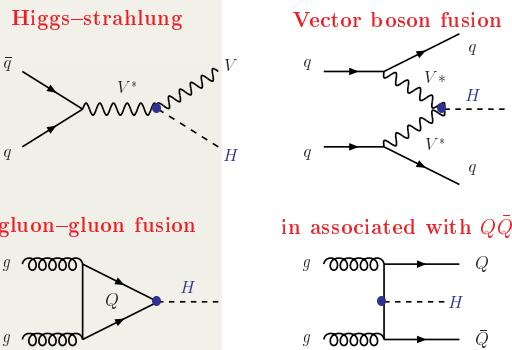
Baglio et al., arXiv:1212.5581



- $H \rightarrow b\bar{b}$  decay alone not clean
- $H \rightarrow \gamma\gamma$  decay very rare,
- $H \rightarrow \tau\tau$  would be possible?
- $H \rightarrow WW$  not useful?  
 $bb\tau\tau, bb\gamma\gamma$  viable? Maybe...  
 but needs very large luminosity.

## 4. Quo vadis? Further probe of the SM

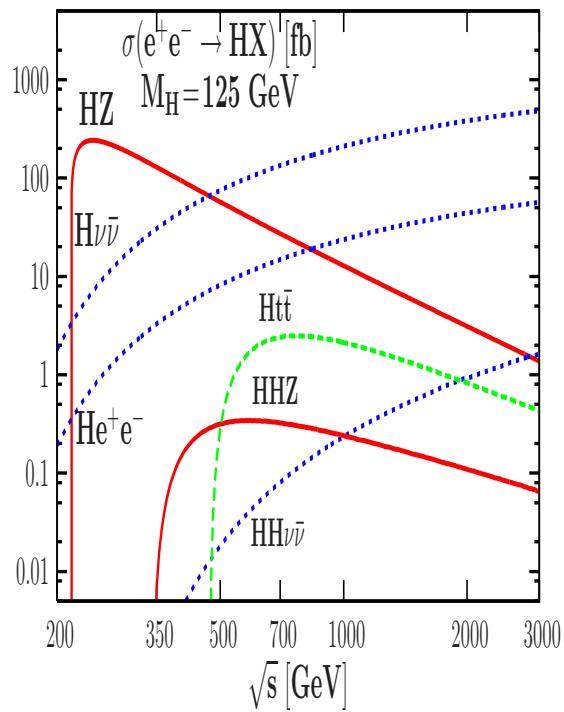
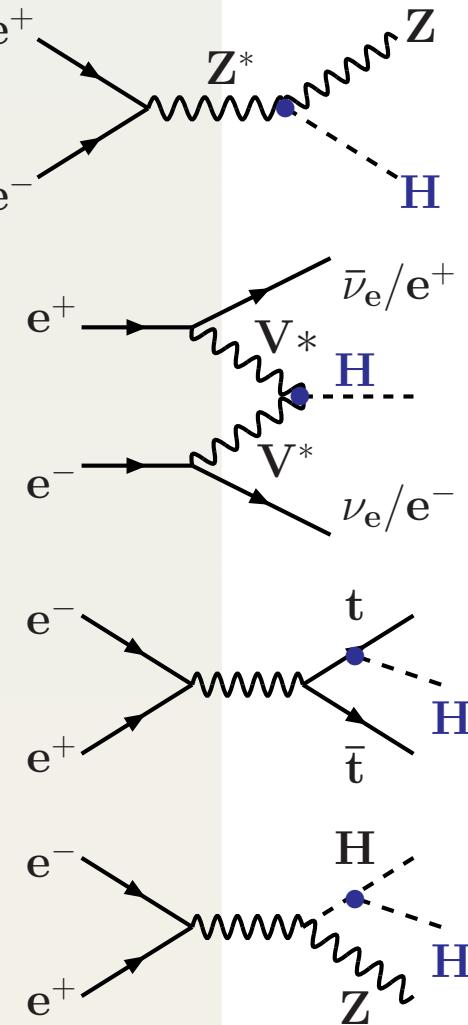
A large increase in sensitivity at high energy machines is possible as production cross section (especially in some cases) are larger



Baglio, AD, Quevillon

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  $\sqrt{s} \lesssim 500 \text{ GeV}$  and mainly in  $e^+e^- \rightarrow ZH$  (with  $\sigma \propto 1/s$ ) and  $ZHH, ttH$**

$g_{HWW}$	$\pm 0.012$
$g_{HZZ}$	$\pm 0.012$
$g_{Hbb}$	$\pm 0.022$
$g_{Hcc}$	$\pm 0.037$
$g_{H\tau\tau}$	$\pm 0.033$
$g_{Htt}$	$\pm 0.030$
$\lambda_{HHH}$	$\pm 0.22$
$M_H$	$\pm 0.0004$
$\Gamma_H$	$\pm 0.061$
CP	$\pm 0.038$

⇒ best option for  $\approx 125 \text{ GeV}$  Higgs

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

## 5. Example of precision measurement: $D_{\gamma\gamma}$ ?

Another way to search for New Physics: high precision measurements.  
 Example: Higgs couplings in cleanest channels:  $H \rightarrow \gamma\gamma$ ,  $H \rightarrow 4\ell^\pm$

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

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

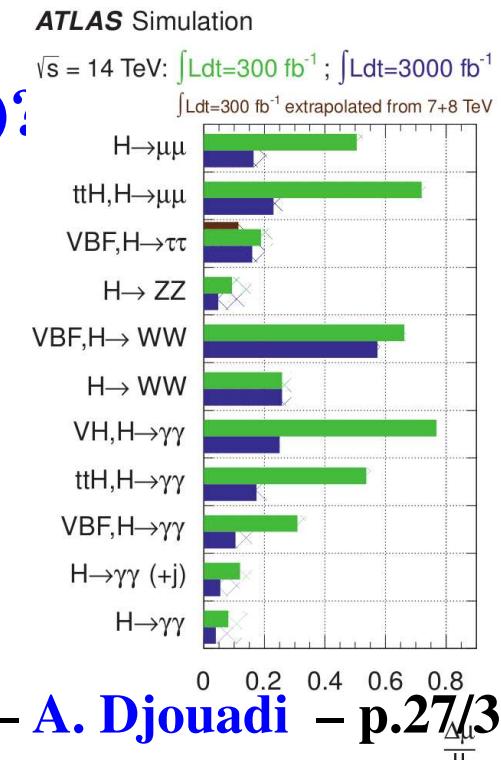
Not in the case of weakly interacting theories like 2HDM, SUSY, etc...

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

Is 1% accuracy achievable at HL-LHC ( $3\text{ab}^{-1}$ )?

- Statistical error:  $20\% / \sqrt{3 \times 100} \lesssim 1\text{-}2\%$   
 (projection OK with ATLAS+CMS combo)
- Systematical error: can be made  $\lesssim 1\%$ ?  
 some errors are common (luminosity, etc....).
- Theoretical uncertainty (if it is  $\gg 1\%$ ):  
 will be then by far the crucial/limiting issue!

⇒ How big is it? Can it be reduced? Removed?



## 5. Example of precision measurements: $D_{\gamma\gamma}$ ?

### Production cross sections

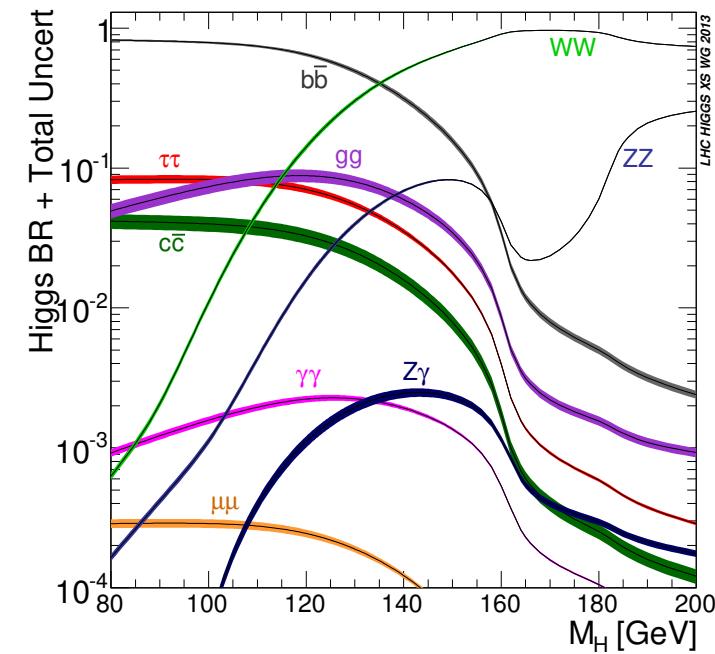
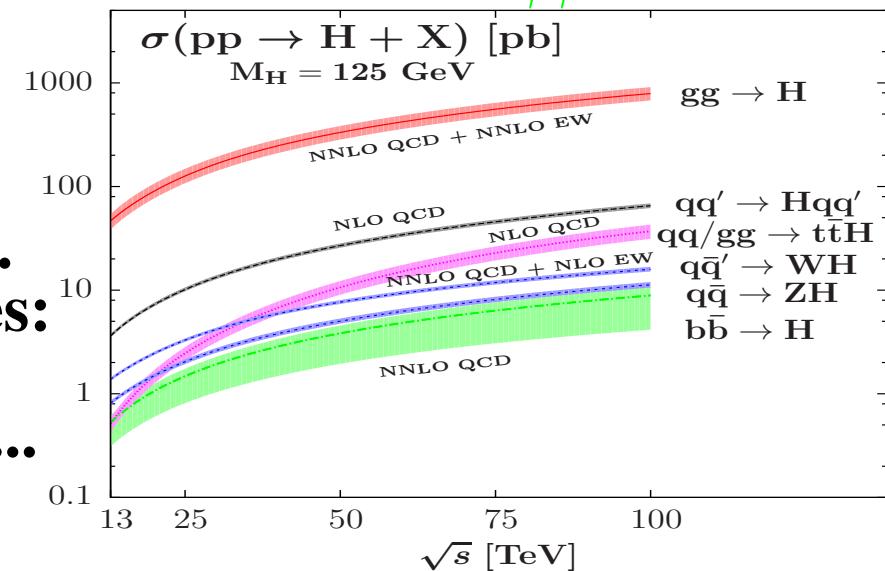
$gg \rightarrow H$  by far dominant process  
 $(\approx 85\%$  of the events before cuts)  
 $\Rightarrow O(10\%)$  total TH uncertainty .....  
 followed by cleaner VBF+VH modes:  
 only  $\lesssim 15\%$  of rate before cuts...  
 smaller TH error only for inclusive...  
 $\Rightarrow O(10\%)$  for total uncertainty?

LHCXSWG (2011), Baglio et al (2015)

### Decay branching ratios

Dominant decay  $H \rightarrow b\bar{b} \approx 60\%$   
 Affected by QCD+parametric errors:  
 from  $m_b$  and  $\alpha_s$  only, a few %  $\Rightarrow$   
 migrate to  $O(5\%)$  error in other modes  
 such as  $H \rightarrow \gamma\gamma, ZZ, WW, \tau\tau$   
 (partial widths very precise  $\lesssim 1\%$ ).  
 $\Rightarrow$  too large theory uncertainties  
 (even if reduced by a factor of 2)...

LHCXSWG + Denner et al. (2011)



## 5. Example of precision measurements: $D_{\gamma\gamma}$ ?

**Best way to eliminate theory uncertainty: use ratios of signal rates.**

$H \rightarrow VV$  with  $V \rightarrow \ell$  as reference and  $H \rightarrow XX$  with  $H$  produced in p:

$$\begin{aligned} D_{XX} &= \sigma^p(pp \rightarrow H \rightarrow XX)/\sigma^p(pp \rightarrow H \rightarrow VV) \\ &= \sigma^p(pp \rightarrow H) \times BR(H \rightarrow XX)/\sigma^p(pp \rightarrow H) \times BR(H \rightarrow VV) \\ &= BR(H \rightarrow XX)/BR(H \rightarrow VV) = \Gamma(H \rightarrow XX)/\Gamma(H \rightarrow VV) \end{aligned}$$

To first approximation:  $D_{XX} = c_X^2/c_V^2$

**Works only if one selects exactly same kinematical configuration (i.e. same "fiducial cross sections") for the two channels X and V!**

- the theoretical uncertainties from the cross sections drop out;
- the parametric uncertainties from the branching ratios drop out;
- the theoretical ambiguities in the Higgs total width also drop out;

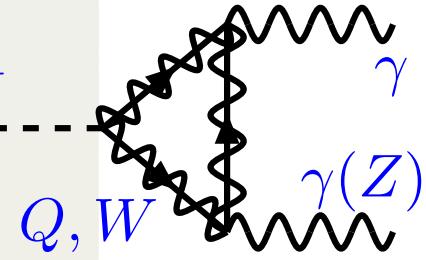
→  $D_{XX}$  measures only the ratio of partial decay widths.

- Extremely clean theoretically, although some information is lost.
- Maybe it has also some advantages from the experimental side?

**Best probe by far is  $D_{\gamma\gamma}$  which measures deviations of the  $\gamma\gamma$  loop**

$$D_{\gamma\gamma} = \frac{\sigma(pp \rightarrow H \rightarrow \gamma\gamma)}{\sigma(pp \rightarrow H \rightarrow VV)} = \frac{\Gamma(H \rightarrow \gamma\gamma)}{\Gamma(H \rightarrow VV)} = d_{\gamma\gamma} c_{\gamma}^2 / c_V^2 \quad \text{AD (2012)}$$

## 5. Example of precision measurements: $D_{\gamma\gamma}$ ?



$$\Gamma = \frac{G_\mu \alpha^2 M_H^3}{128 \sqrt{2} \pi^3} \left| \sum_f N_c e_f^2 A_{\frac{1}{2}}^H(\tau_f) + A_1^H(\tau_W) \right|^2$$

$$A_{1/2}^H(\tau) = 2[\tau + (\tau - 1)f(\tau)] \tau^{-2}$$

$$A_1^H(\tau) = -[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)] \tau^{-2}$$

- Loop decay; SM: only W,top loops are relevant (others small).
  - For  $m_i \rightarrow \infty \Rightarrow A_{1/2} = \frac{4}{3}$  and  $A_1 = -7$ : W loop dominating!
- $\gamma\gamma$  width counts the number of charged particles coupling to Higgs!

Contribution  $A_s^P$  of particle p of spin s with Higgs coupling  $g_{Hpp}$ :

$$A_0^P = -\frac{1}{3}g_{Hpp}^2/m_P^2, A_{1/2}^P = +\frac{4}{3}g_{Hpp}^2/m_P^2, A_1^P = -7g_{Hpp}^2/m_P^2,$$

If  $g_{Hpp} \propto m_p \Rightarrow A_0^P \rightarrow +\frac{1}{3}, A_{1/2}^P \rightarrow -\frac{4}{3}, A_1^P \rightarrow +7$ .

Small/calculated QCD and EW corrections: of order of percent.

+Spira+Zerwas, Vicini et al., AD+Gambino, Actis et al., (ZZ: Denner et al.)

In SM with W,t loops:  $c_\gamma \approx 1.26 \times |c_W - 0.21 c_t|$

Assuming custodial symmetry  $g_{HZZ} = g_{HWW} = c_V$ ,  $D_{\gamma\gamma} = c_\gamma^2/c_V^2$  is

$$c_\gamma^2/c_V^2 \approx 6.5 \times |1 - \frac{1}{5}c_t/c_V|^2$$

with  $c_V = c_t = 1$  in SM. Any new physics effects will alter this value.

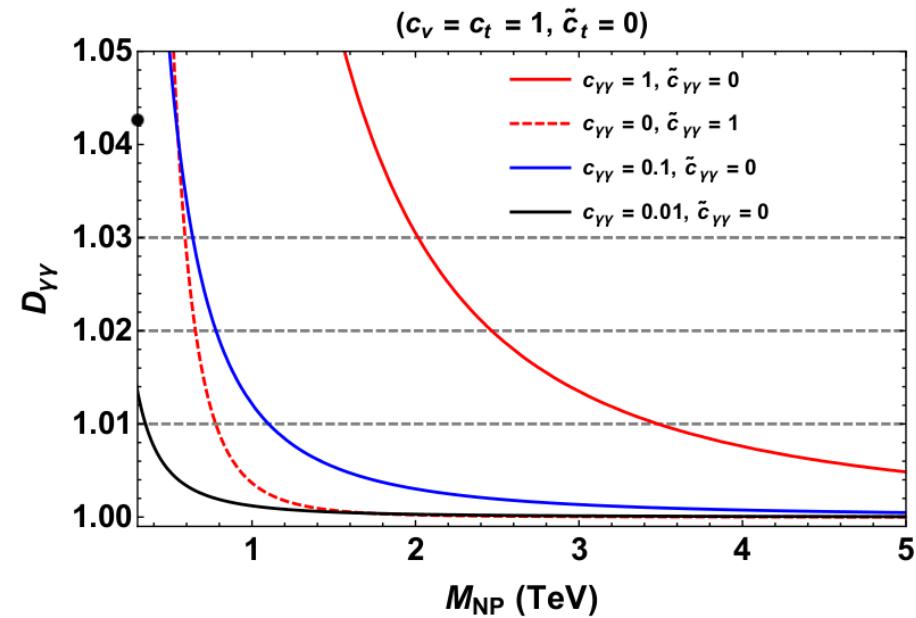
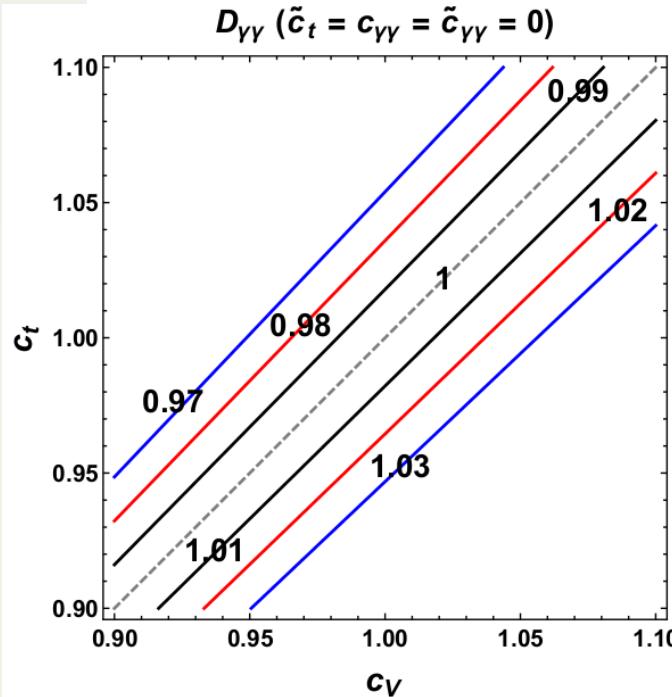
## 5. Example of precision measurements: $D_{\gamma\gamma}$ ?

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

Examples in BSM: AD, Quevillon, Vega-Morales, 1509.03913

Model independent search through an effective Lagrangian approach.

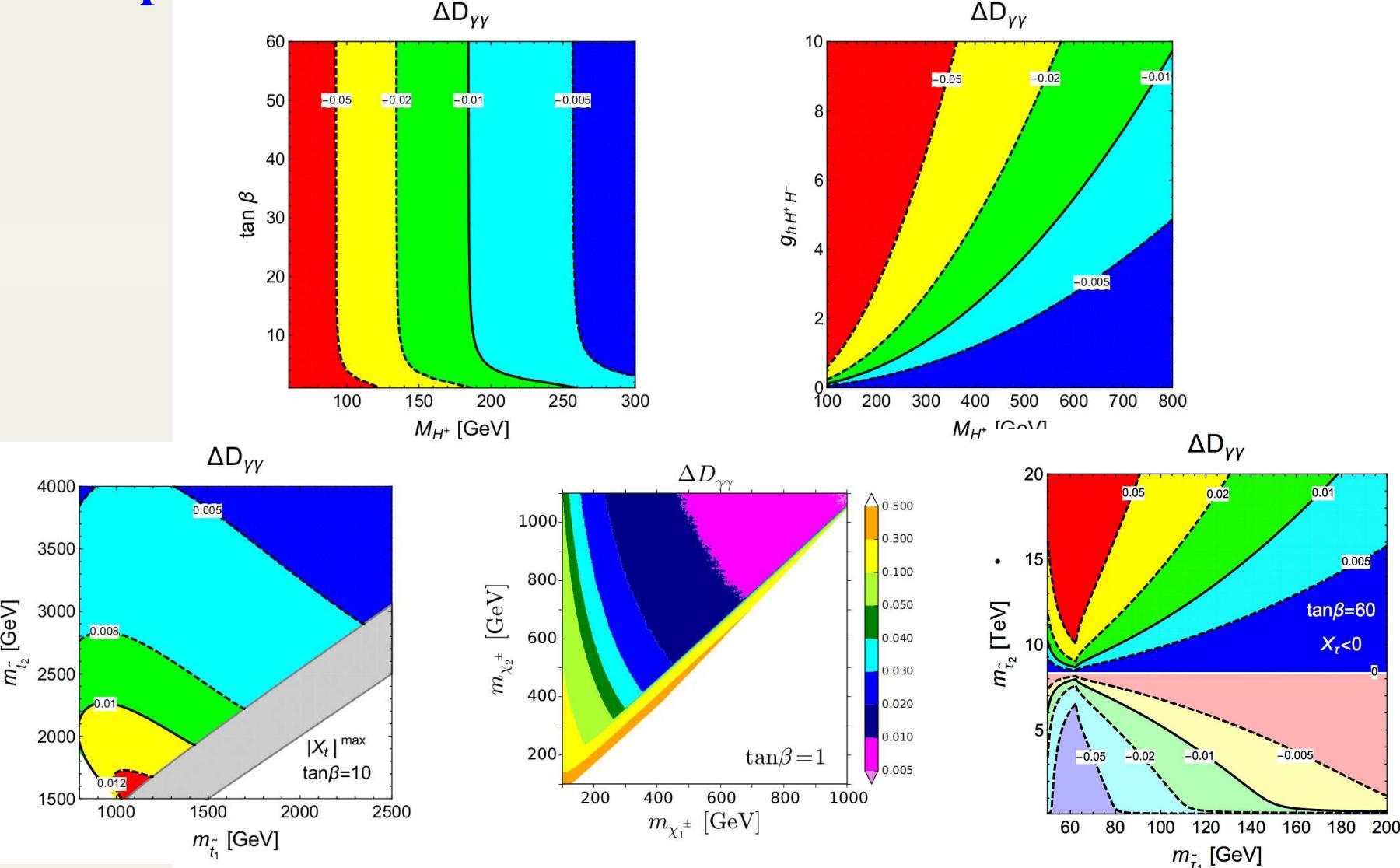
$$\mathcal{L} = \frac{H}{v} \left( c_V (2M_W^2 W_\mu^+ W^{-\mu} + M_Z^2 Z_\mu Z^\mu) - m_t \bar{t}(c_t + i\tilde{c}_t \gamma^5)t \right. \\ \left. + \frac{c_{\gamma\gamma}}{4} F^{\mu\nu} F_{\mu\nu} + \frac{\tilde{c}_{\gamma\gamma}}{4} \tilde{F}^{\mu\nu} F_{\mu\nu} \right)$$



## 5. Example of precision measurements: $D_{\gamma\gamma}$ ?

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

Example in MSSM: AD, Quevillon, Vega-Morales, 1509.03913

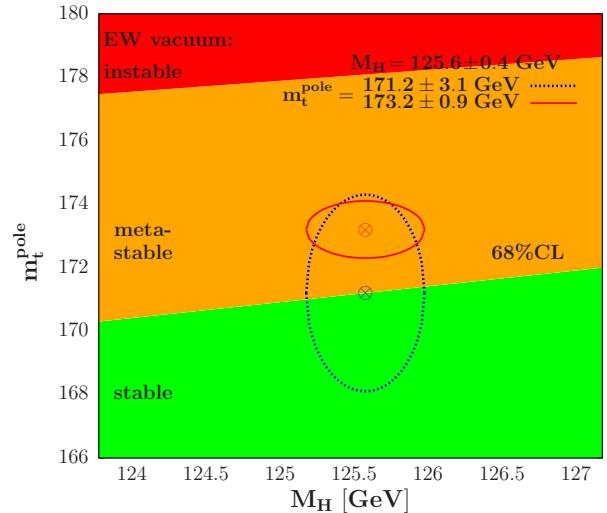


## 6. Conclusion

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  $\Rightarrow$ ADM



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

$$\Delta M_H^2 \equiv \text{---} \overset{\text{H}}{\text{f}} \text{---} \overset{\text{H}}{\text{f}} \text{---} \text{---}$$
$$\propto \Lambda^2 \lesssim (1 \text{ TeV})^2 ???$$

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.

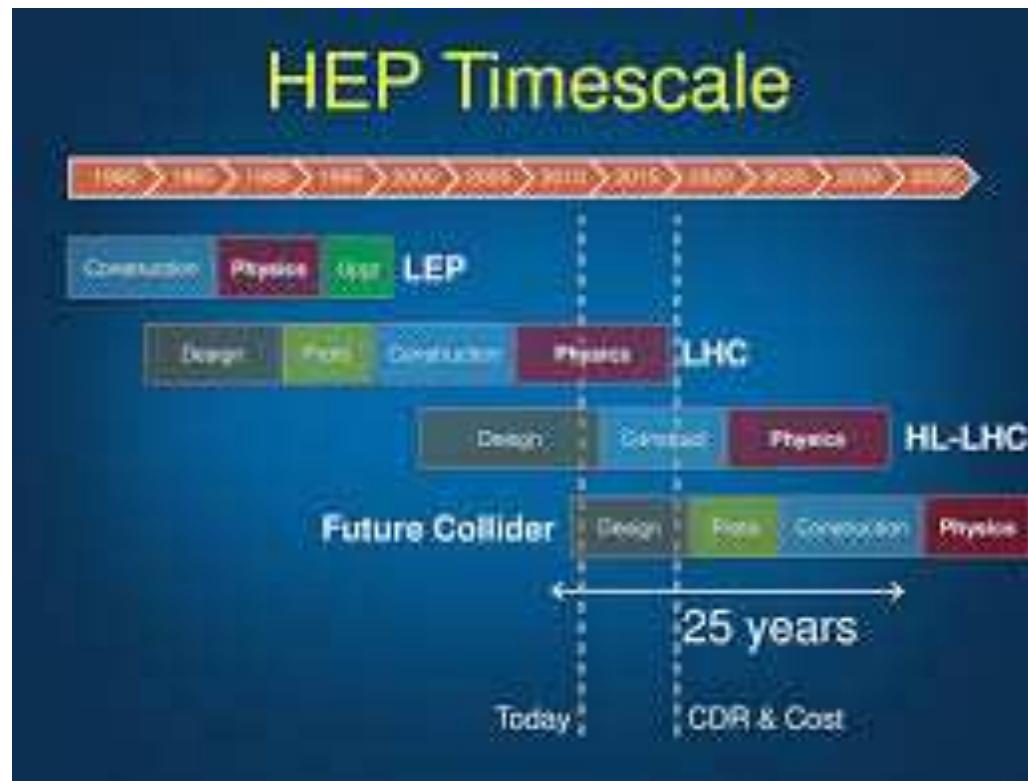
From now on, there is no guarantee for discovery at LHC or elsewhere?!

So should we give up and declare that particle physics is closed?  
No of course! We should continue our quest (but more modestly).

## 6. 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 (pas d'état d'âme!).  
as experimentalists usually say: stay tuned! (mais pas branchés..).