A deeper probe of the Higgs sector

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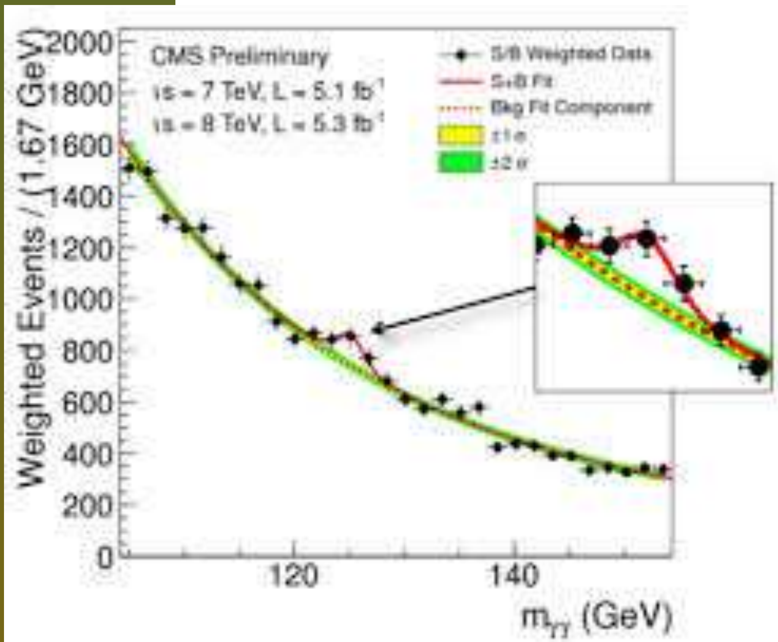
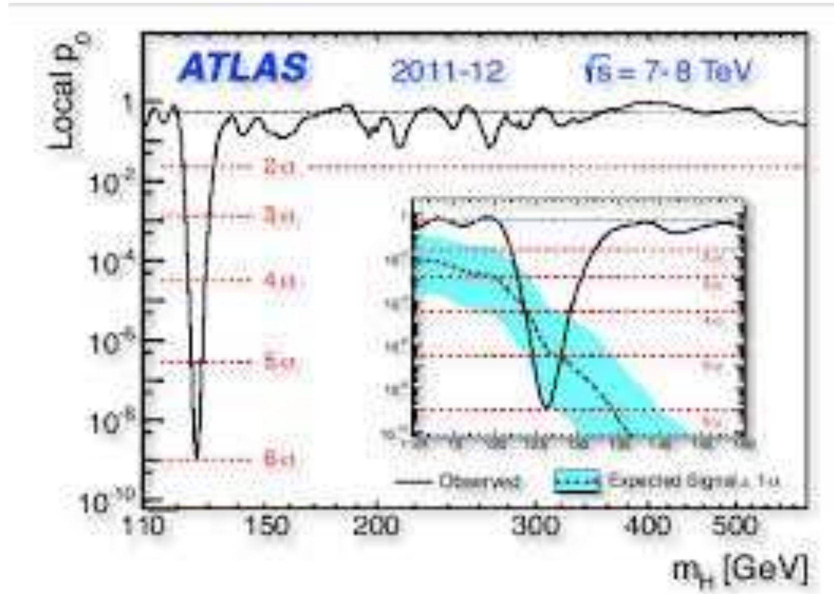
1. The Standard Model Higgs and beyond
2. Tests of the Higgs properties
3. Interludium: $\mathrm{D}_{\gamma\gamma}$
4. Direct search for new states
5. Conclusion

. The Standard Model Higgs and beyond

Higggs discovery in July 2012 was a triumph for high-energy physics.





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

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

– experimentaly found to be: $M_H = 125.1 \pm 0.24$ GeV (ie within 1σ..)

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

The triumph of the SM model of particle physics; Standarissimo?!

. The Standard Model Higgs and beyond

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.

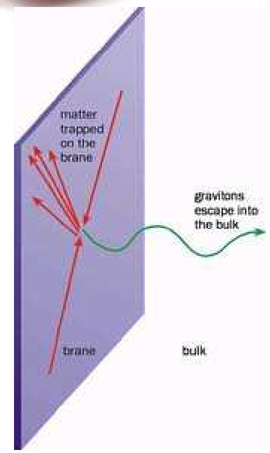
$\Delta M_H^2 \propto \Lambda^2 \approx (10^{18}\ \mathrm{GeV})^2$: M_H not stable against high scales.

All these indicate that there is beyond the Standard Model (?).

. The Standard Model Higgs and beyond

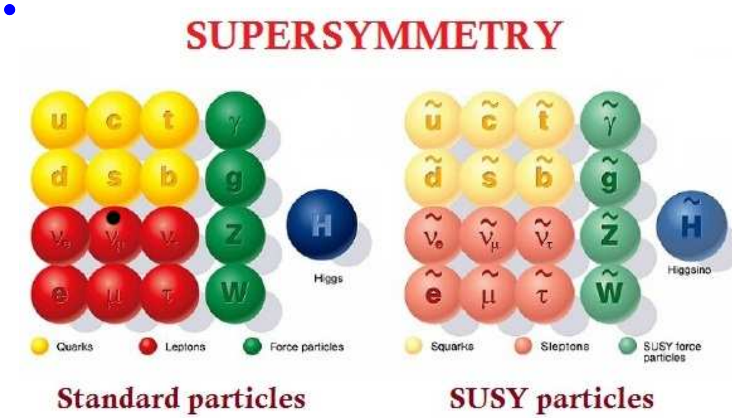
Three main avenues for solving the hierarchy or naturalness problems

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 $\Lambda \approx$.
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.



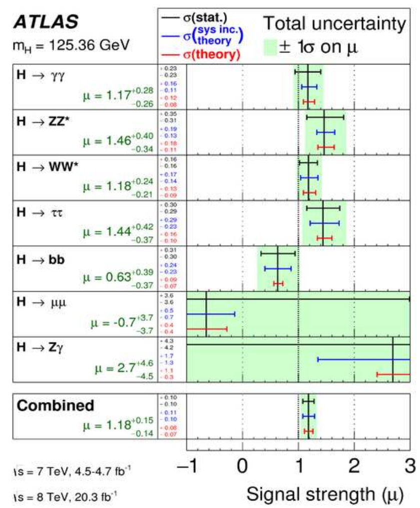
. The Standard Model Higgs and beyond

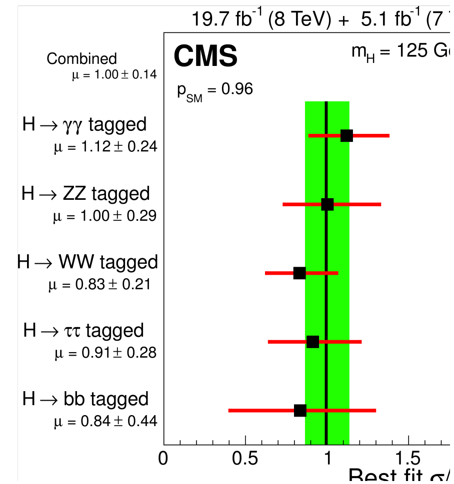
The problem is that:

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 15–30% level
- Results from the LHC 7–8 TeV 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 see Christophe) ....
- "Trouble" and strongly constrained: extra-dimensions, SUSY, ...

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

. The Standard Model Higgs and beyond

In the MSSM we need two doublets of complex scalar fields H_1 and 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 two free parameters at tree-level to describe the system $\tan\beta, M_A$

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

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

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

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

- **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.

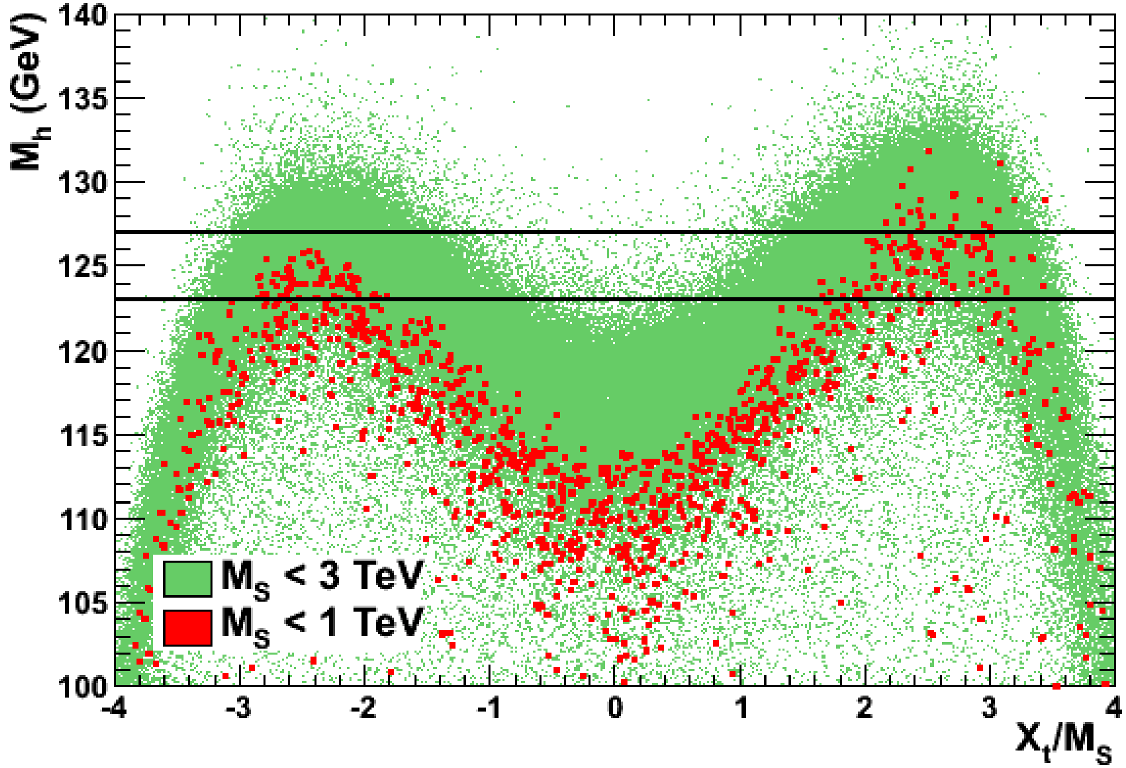
. The Standard Model Higgs and beyond

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

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

See talk by

M. Yamaguchi



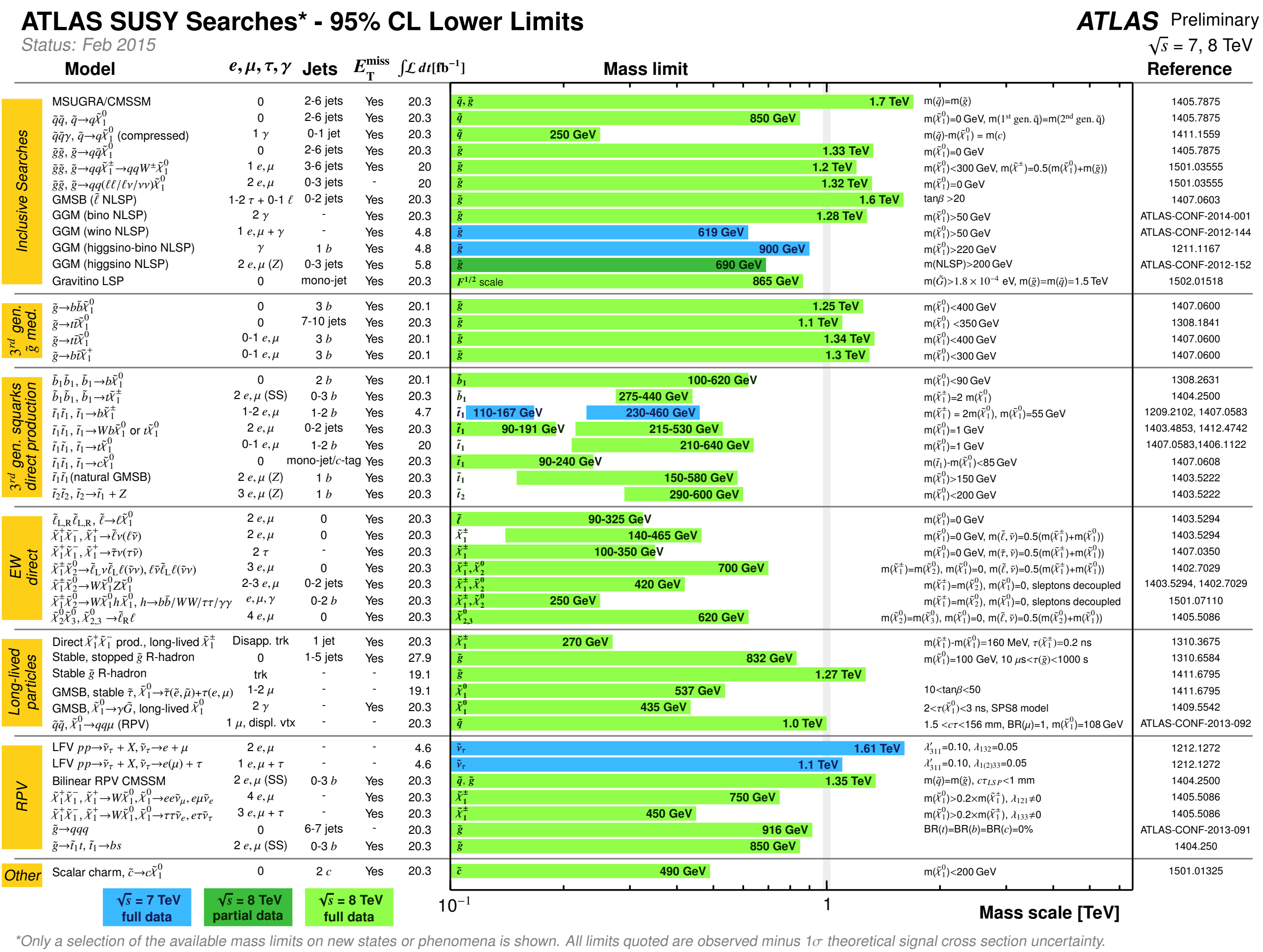
Arbey, Battaglia, AD, Mahmoudi, Quevillon (2012)

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

. The Standard Model Higgs and beyond

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

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

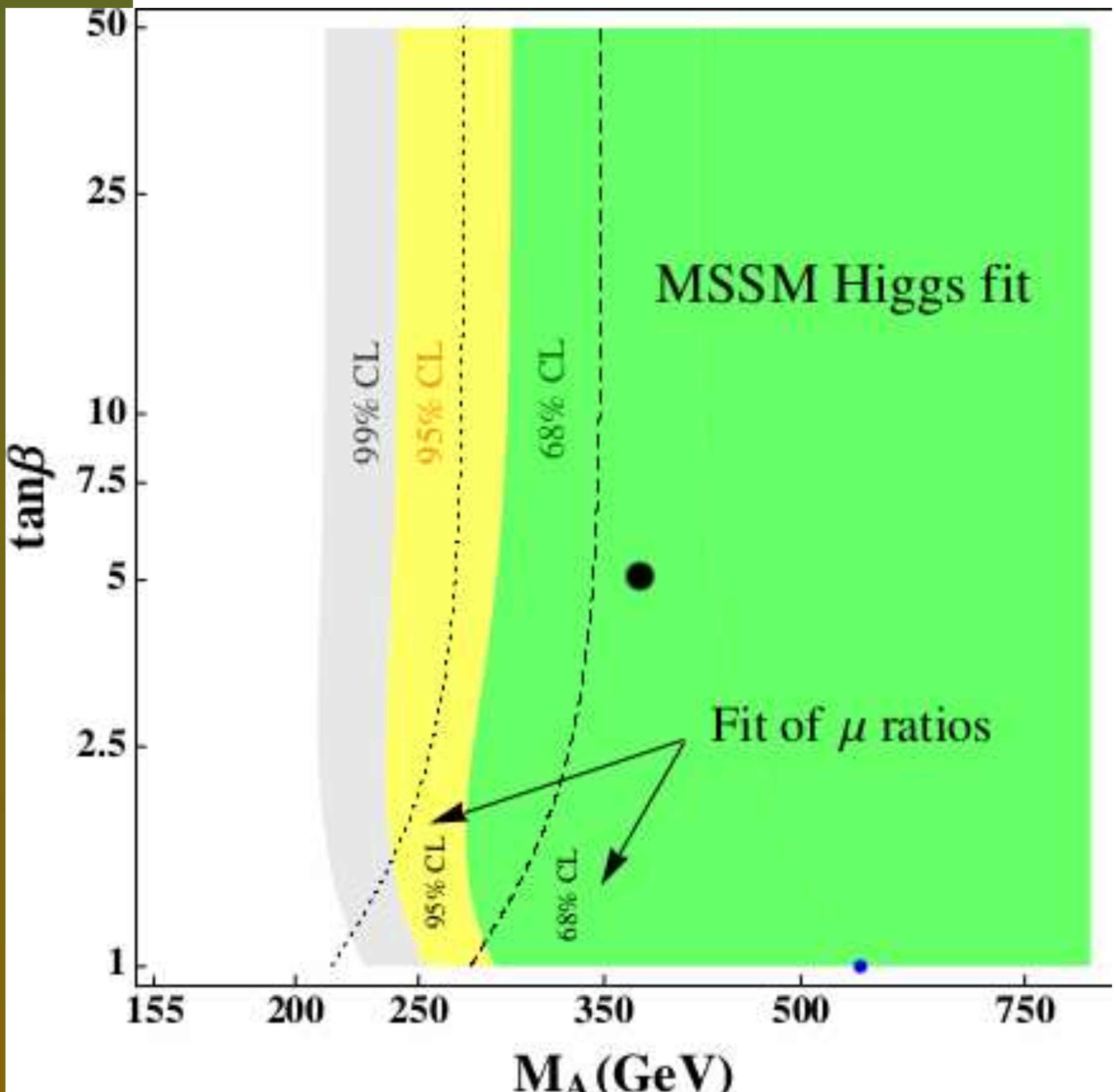


⇒ ATLAS/CMS depressing tables (update: B. Petersen)....

. The Standard Model Higgs and beyond

Also backed up indirectly by the measurement of the Higgs properties:

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



with dominant RC only
(see e.g. above for M_h)
the h couplings read:

$g_{h\bar{t}t} = \cos\alpha / \sin\beta$

$g_{h\bar{b}b} = \cos\alpha / \sin\beta$

$g_{hVV} = \sin(\beta - \alpha)$

$\alpha \approx f(\tan\beta, M_A, M_h)$

like M_H and $M_H^{\pm}$
as in so–called hMSSM
AD, Quevillon, Maiani ... (2013)

. Tests of the Higgs properties

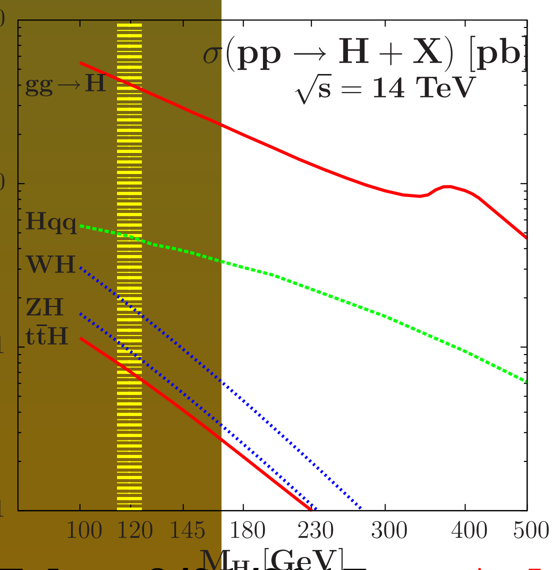
he next question is then: “is Particle Physics closed”? Answer is no!

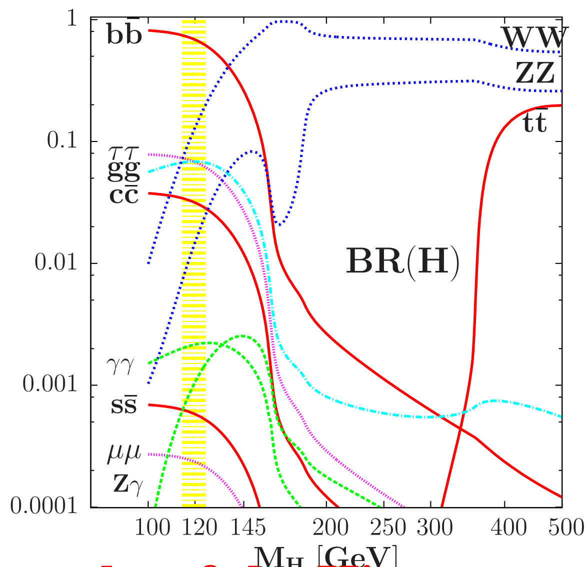
1) Need to check that H is indeed responsible of EWSB (and SM-like?)

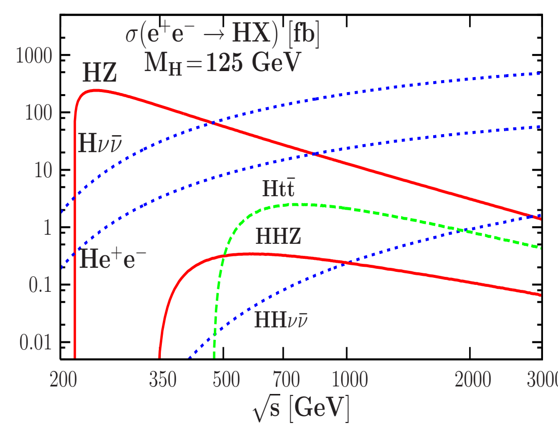
⇒ measure its fundamental properties in the most precise way:

- **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.





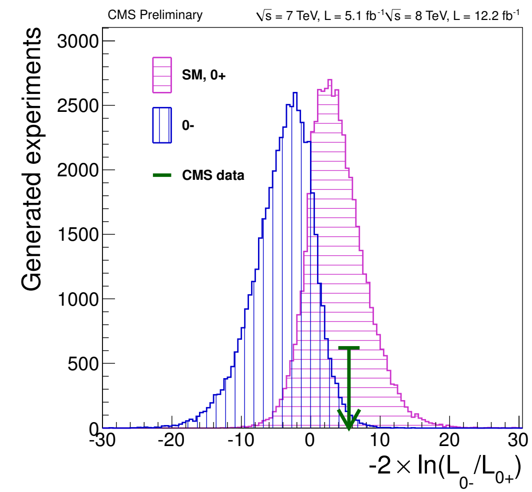


. Tests of the Higgs properties

A check of spin–parity quantum numbers.

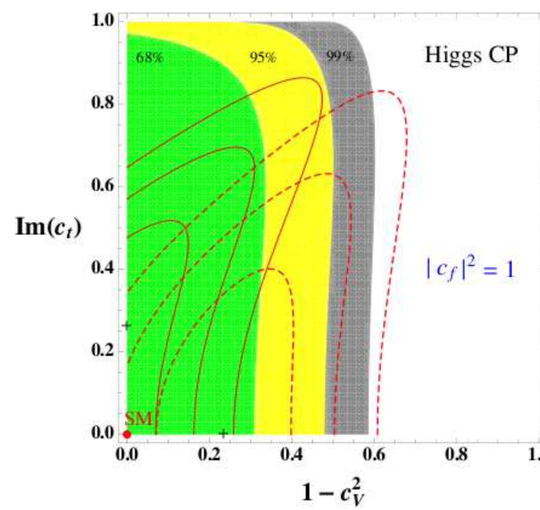
Spin: clear situation (no suspense) as the new state decays into $\gamma\gamma$
$\Rightarrow$ not s=1 from Landau–Yang and s=2 (KK graviton?) unlikely..

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

. Tests of the Higgs properties

• A much more precise measurement of the Higgs couplings

n various H production+decay channels

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

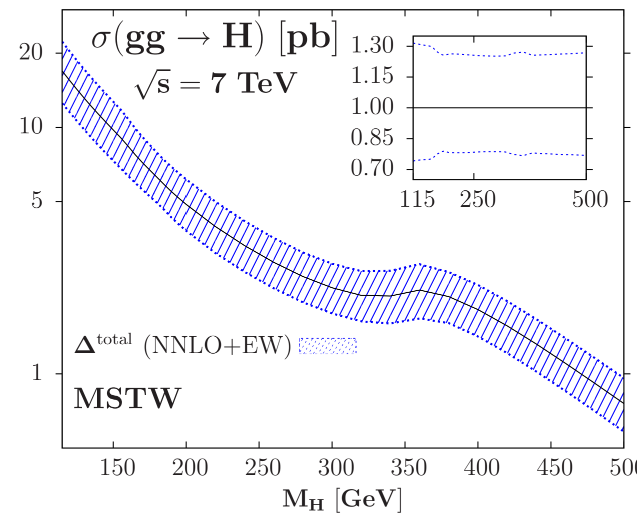
- parametric errors in BRs

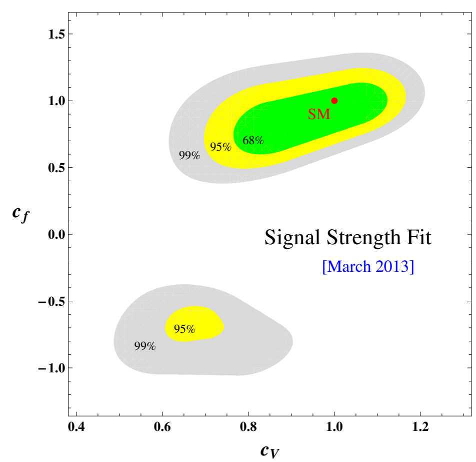
- TH ambiguities from Γ_H^{tot}

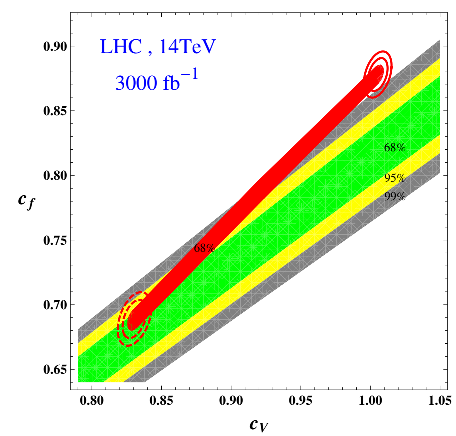
• Achievable accuracy:

- now: 20–30% on some ratios

- future: few % at HL–LHC?





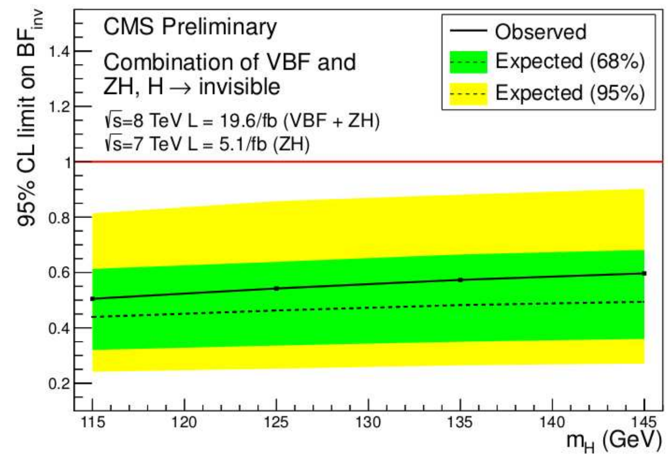


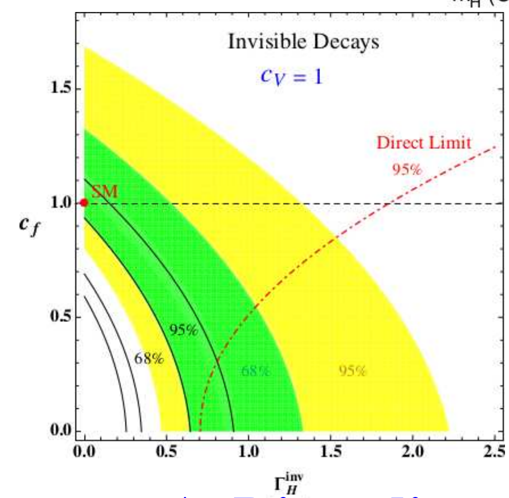
But will this be sufficient to probe BSM physics (at high scales..)?

. Tests of the Higgs properties

• **Total width:** $\Gamma_H = 4$ MeV, too small to be resolved experimentally.
– very loose bound from interference gg→ZZ (a factor 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
$BR_{inv} \lesssim$ 50%@95%CL for SM Higgs
Also promising in the future: monojets
$gg \to H + j \to j + \not{E}_T$
Indirect measurement:
again assume SM–like Higgs couplings
constrain width from signal strengths
$BR_{inv} \lesssim 50\%$@95%CL for $c_f = c_V = 1$
Improvement in future: 10%@HL–LHC?

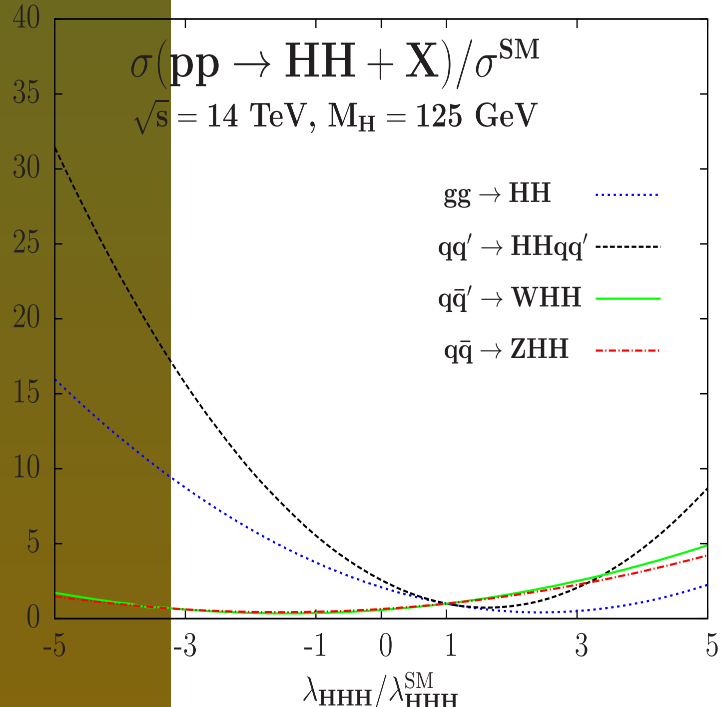


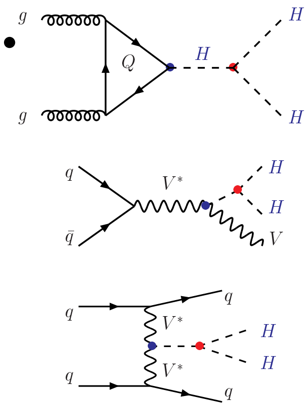


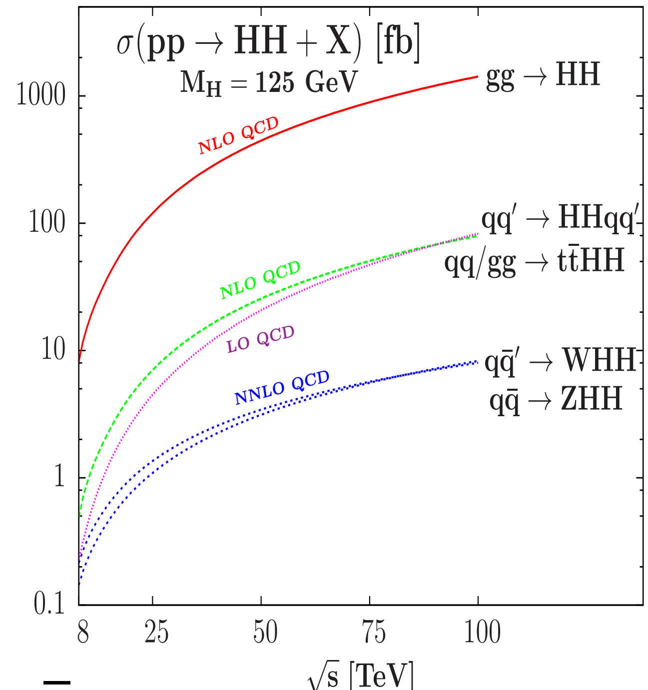
. Tests of the Higgs properties

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

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...





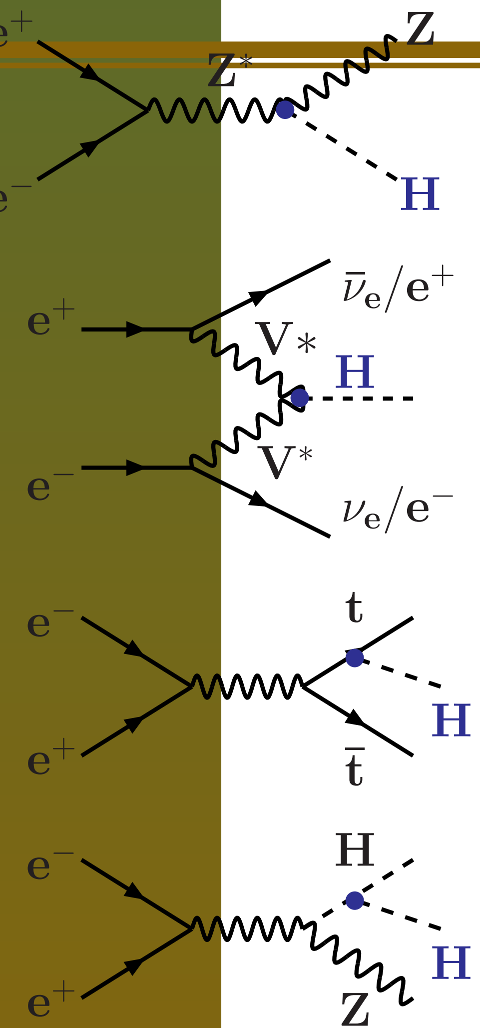


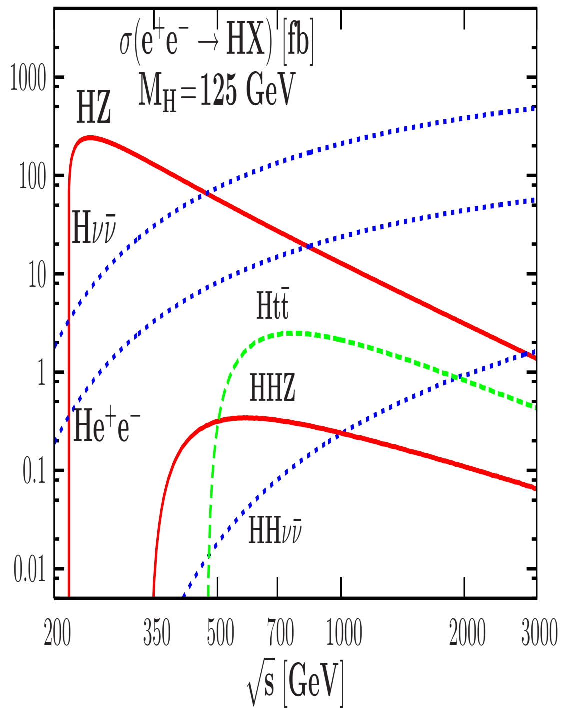
- H $\to$ $b\bar{b}$ decay alone not clean
- H $\to$ $\gamma\gamma$ decay very rare,
- H $\to$ $\tau\tau$ would be possible?
- H $\to$ WW not useful?

– $bb\tau\tau$, $bb\gamma\gamma$ viable?
– but needs very large luminosity.

Baglio et al., arXiv:1212.5581

. Tests of the 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!

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

. Interludium: $D_{\gamma\gamma}$

• **Precise measurement of Higgs couplings in various H channels:**

example of the cleanest detection channels: $H \to \gamma\gamma,\ H \to ZZ^* \to 4\ell^\pm$

channel	atlas	cms
$\mu_{\gamma\gamma}$	$1.17\ ^{+0.23}_{-0.23}\ ^{+0.16}_{-0.11}\ \left(^{+0.12}_{-0.08}\right)$	$1.14\ ^{+0.21}_{-0.21}\ ^{+0.16}_{-0.10}\ \left(^{+0.09}_{-0.05}\right)$
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 achievable at HL-LHC (3ab^{-1})?

• **Statistical error:** $20\%/\sqrt{3\times 100} \lesssim$ **1–2%**

(projection OK with ATLAS+CMS combo)

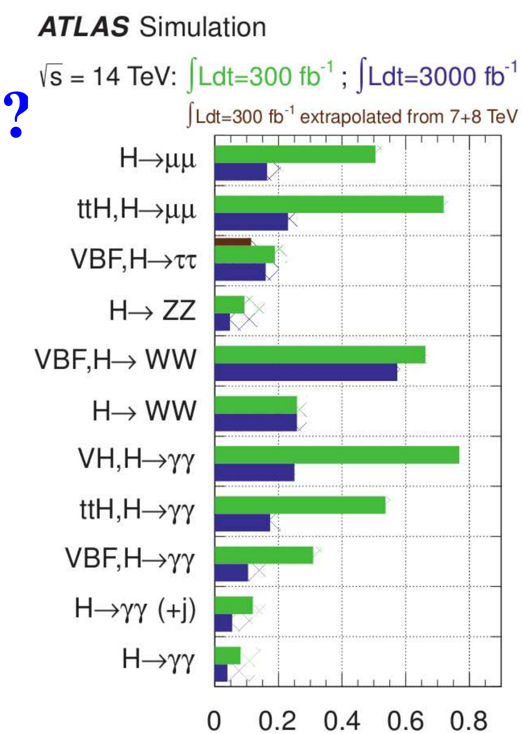
• **Systematical error: can be made** $\lesssim 1\%$ **?**

some errors are common (luminosity, etc....).

• **Theoretical uncertainty (if it is** $\gg$**1%):**

will be then by far the crucial/limiting issue!

$\Rightarrow$ **How big is it? Can it be reduced? Removed?**



. Interludium: $D_{\gamma\gamma}$

LO[a]: already at one loop

QCD: exact NLO[b] : $K \approx$ 1.7

EFT NLO[c]: good approx.

EFT NNLO[d]: $K \approx 2$

EFT NNLL[e]: $\approx +(5\%)$

EFT N3LO[f]: $\approx 3\ \%$.

EW: EFT NLO: [g]: $\approx \pm$ very small

exact NLO[h]: $\approx \pm$ a few %

QCD+EW[i]: a few %

Distributions: a few programs[j]

[a] Georgi+Glashow+Machacek+Nanopoulos

[b] Spira+Graudenz+Zerwas+AD (exact)

[c] Spira+Zerwas+AD; Dawson (EFT)

[d] Harlander+Kilgore, Anastasiou+Melnikov Ravindran+Smith+van Neerven

[e] Catani+de Florian+Grazzini+Nason

[f] Anastasiou et al. (2015)!

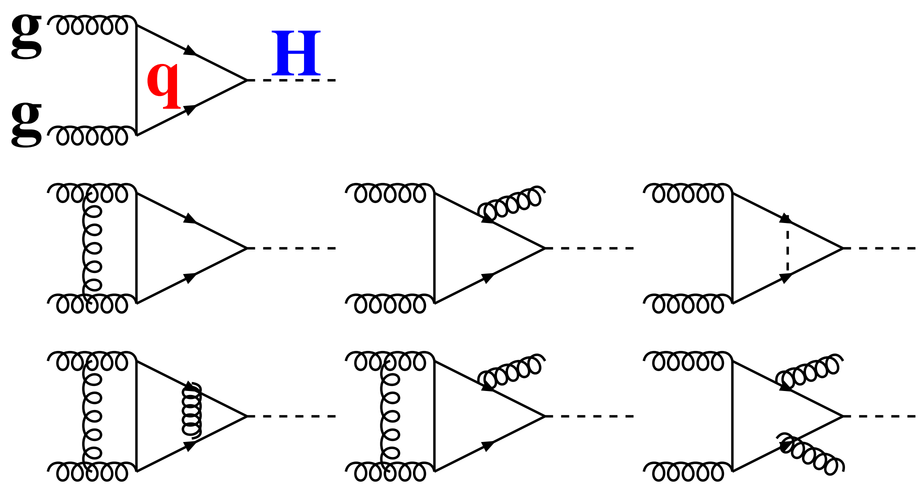
[g] Gambino+AD; Degrassi et al.

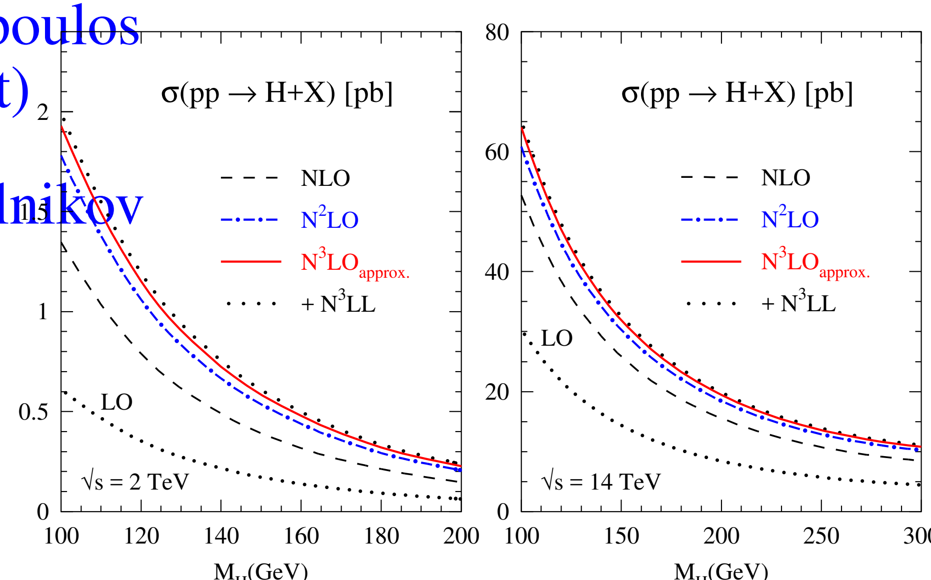
[h] Actis+Passarino+Sturm+Uccirati

[i] Anastasiou+Boughezal+Pietriello

[j] Anastasiou et al.; Grazzini, Nason,...

The $\sigma^{\rm theory}_{gg\to H}$ long story (1978–2016)





Moch+Vogt

. Interludium: $D_{\gamma\gamma}$

Despite of that, the $gg \to H$ cross section still affected by uncertainties

- **Higher-order or scale uncertainties:**

K-factors large $\Rightarrow$ HO could be important

HO estimated by varying scales of process

$$\mu_0/\kappa \le \mu_R, \mu_F \le \kappa\mu_0$$

at lHC: $\mu_0 = \frac{1}{2} M_H, \kappa = 2 \Rightarrow \Delta^{\rm NNLO}_{\rm scale} \approx 10\%$

- **gluon PDF+associated α_s uncertainties:**

PDF(g) at high-x less constrained by data

α_s uncertainty (WA, DIS?) affects $\sigma \propto \alpha_s^2$

$\Rightarrow$ still discrepancies between NNLO PDFs

PDF4LHC recommend: $\Delta_{\rm pdf} \approx 10\%$@lHC

- **Uncertainty from EFT approach at NNLO**

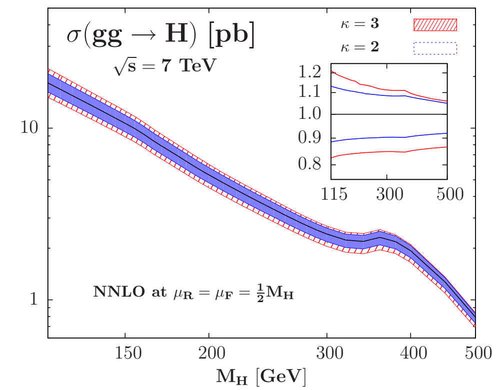
$m_{\rm loop} \gg M_H$ good for top if $M_H \lesssim 2m_t$

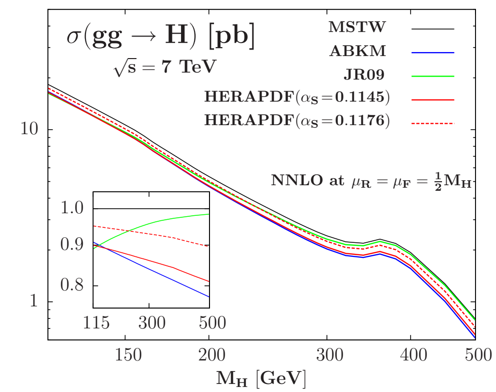
but not for b ($\approx 10\%$) and W/Z loops

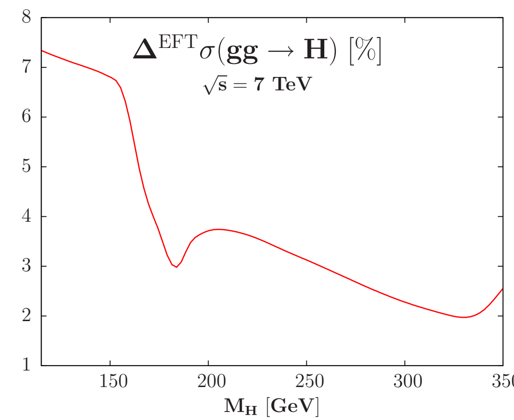
Estimate from (exact) NLO: $\Delta_{\rm EFT} \approx 5\%$

total $\Delta\sigma^{\rm NNLO}_{gg\to H\to X} \approx$10–20% @lHC

LHC-HxsWG: Baglio+AD $\Rightarrow$



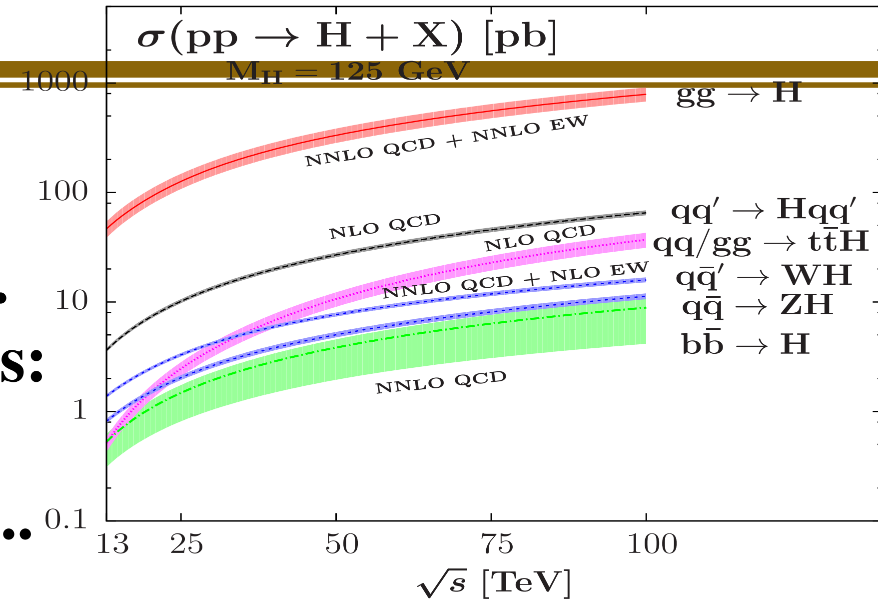




. Interludium: $D_{\gamma\gamma}$

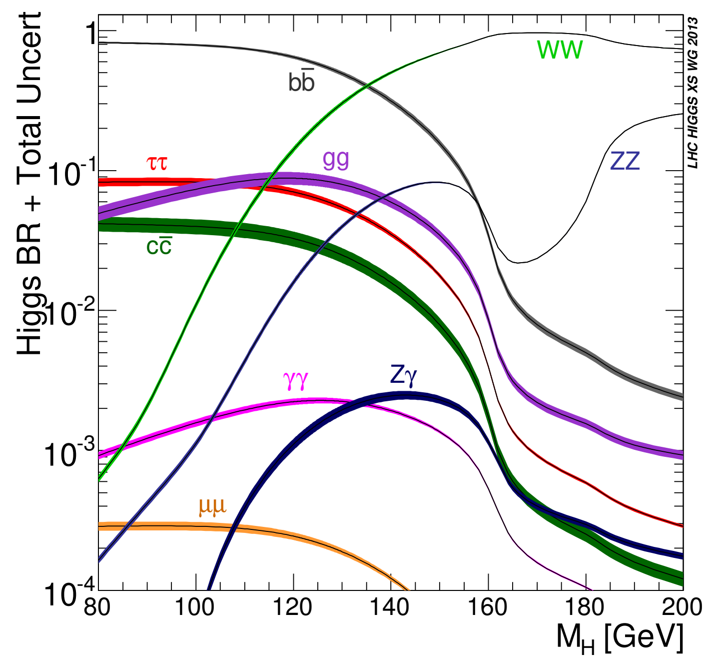
Production cross sections

gg→ H by far dominant process
(≈ 85% of the events before cuts)
⇒ O(10%) total TH uncertainty .....
followed by cleaner VBF+VH modes:
only $\lesssim$ 15% of rate before cuts...
smaller TH error only for inclusive...
⇒ O(10%) for total uncertainty?
LHCXSWG (2011), Baglio et al (2015)



Decay branching ratios

Dominant decay $H \to b\bar{b} \approx 60\%$
Affected by QCD+parametric errors:
from m_b and α_s only, a few % ⇒
migrate to O(5%) error in other modes
such as $H \to \gamma\gamma, ZZ, WW, \tau\tau$
(partial widths very precise $\lesssim$ 1%).



⇒ too large theory uncertainties
(even if reduced by a factor of 2)...

. Interludium: $D_{\gamma\gamma}$

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

H→VV with V→ℓ as reference and H→XX with H produced in p:

$$D_{XX} = \sigma^p(pp \to H \to XX)/\sigma^p(pp \to H \to VV)$$
$$= \sigma^p(pp \to H) \times BR(H \to XX)/\sigma^p(pp \to H) \times BR(H \to VV)$$
$$= BR(H \to XX)/BR(H \to VV) = \Gamma(H \to XX)/\Gamma(H \to VV)$$

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.**

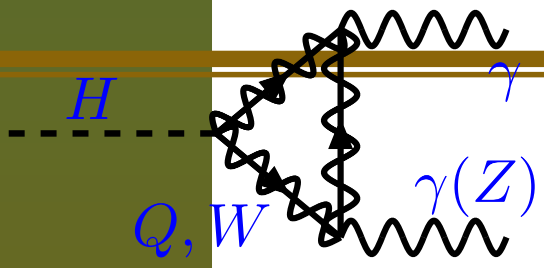
- **Extremely clean theoretically, although some information will be lost.**
- **And maybe it has also some advantages from the experimental side?**

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

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

AD (2012)

. Interludium: $D_{\gamma\gamma}$



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

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

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

- Loop decay. In SM: only W- and top-loops are relevant (others small)
- For $m_i \to \infty \Rightarrow A_{1/2} = \frac{4}{3}$ and $A_1 = -7$: W loop dominating!

(approximation $\tau_W \to 0$ valid only for $M_H \lesssim 2M_W$: relevant here).

$\gamma\gamma$ 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}:

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

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

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

+Spira+Zerwas, Vicini et al., Passarino et al., AD+Gambino, 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

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

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

. Interludium: $D_{\gamma\gamma}$

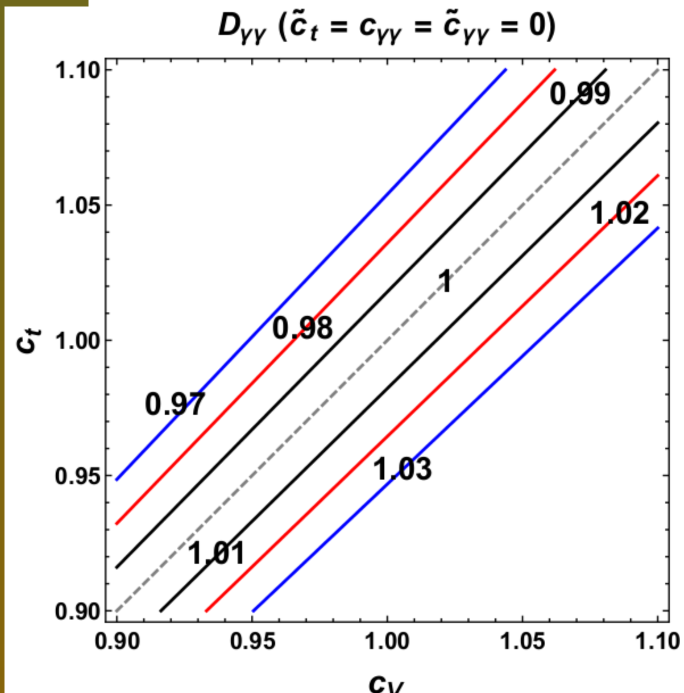
Will $D_{\gamma\gamma}$ be the g-2 of the LHC?

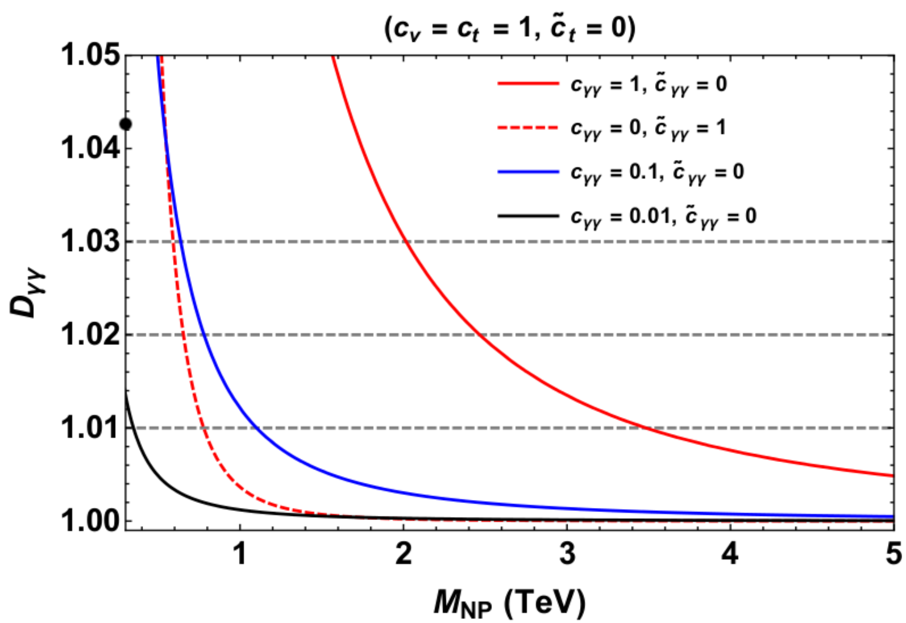
Examples of BSM searches with the observable if measured at 1% level

AD, J. Quevillon and R. Vega-Morales, arXiv:1509.03913

Model independent search through an effective Lagrangian approach.

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



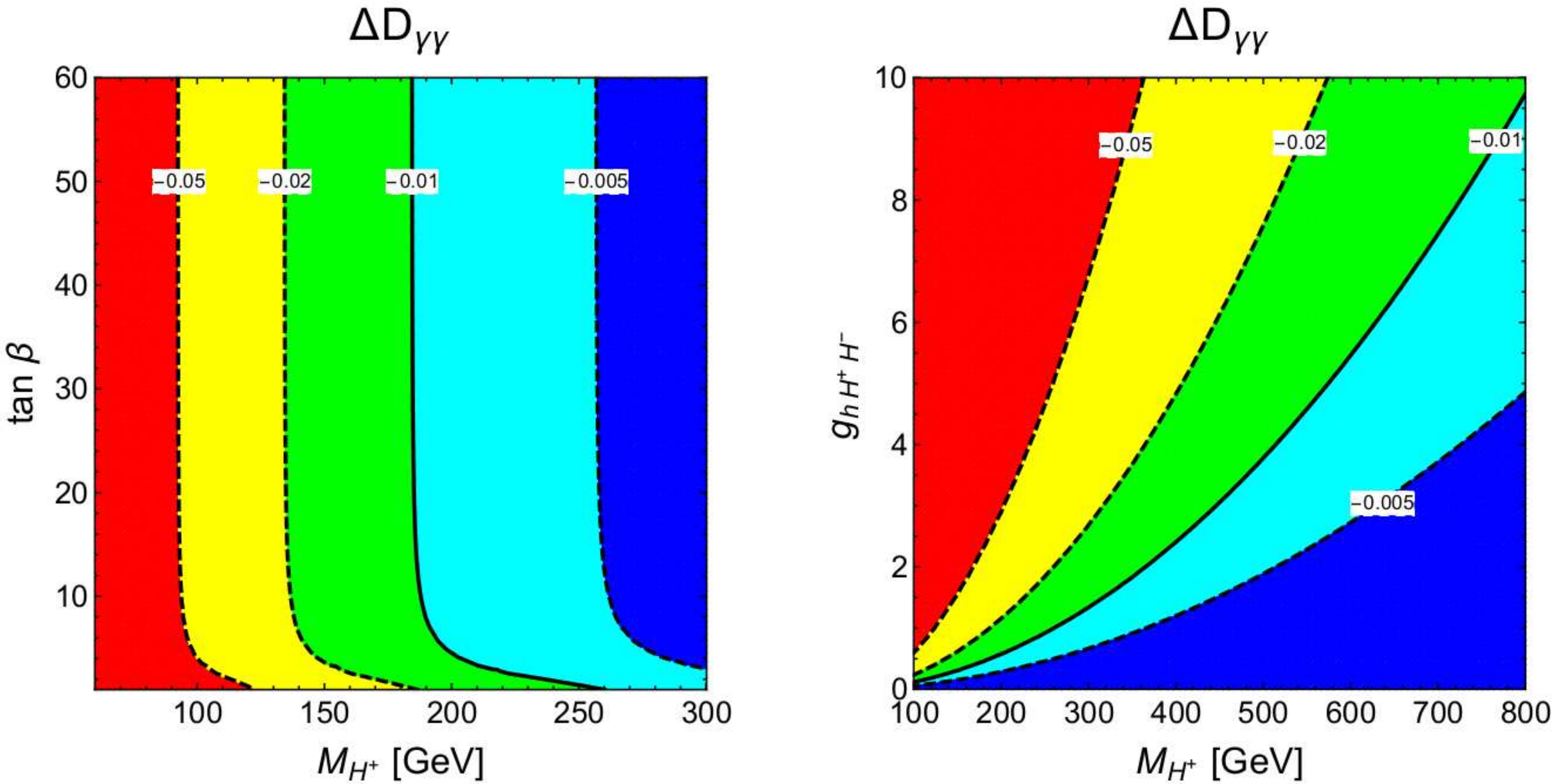


. Interludium: $D_{\gamma\gamma}$

(h)MSSM and 2HDM: charged Higgs contributions

$$g_{hH^+H^+} = \sin(\beta-\alpha) + \cos 2\beta \sin(\beta+\alpha)/(2c_W^2) \overset{M_A \gg M_Z}{\longrightarrow} 1 - \frac{\cos^2 2\beta}{2c_W^2}$$

coupling too small in MSSM but not in a general 2HDM

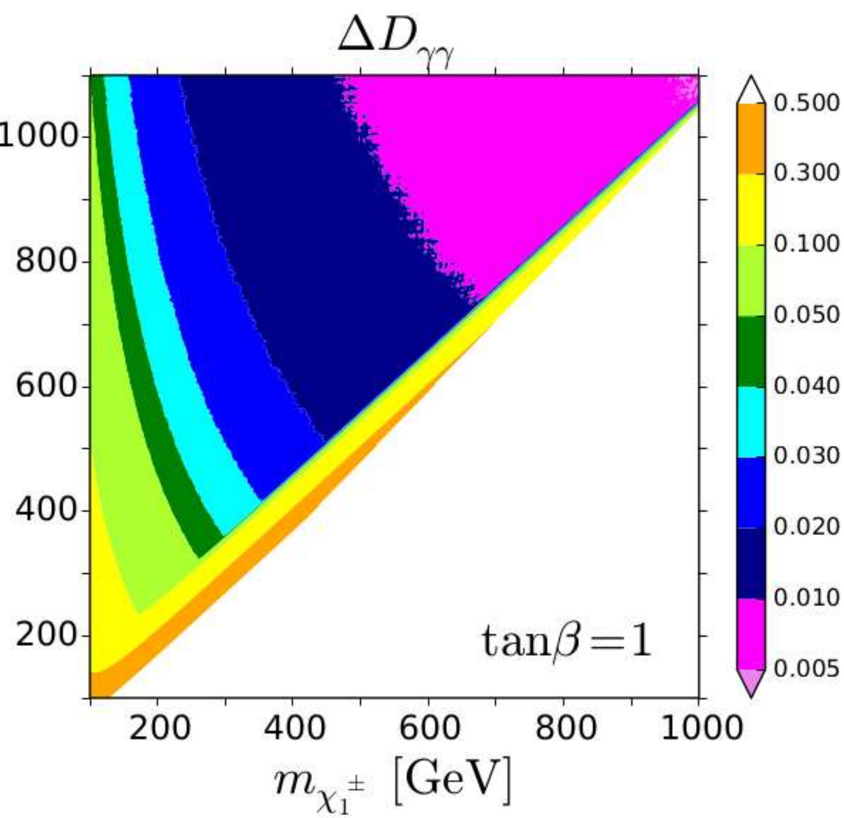


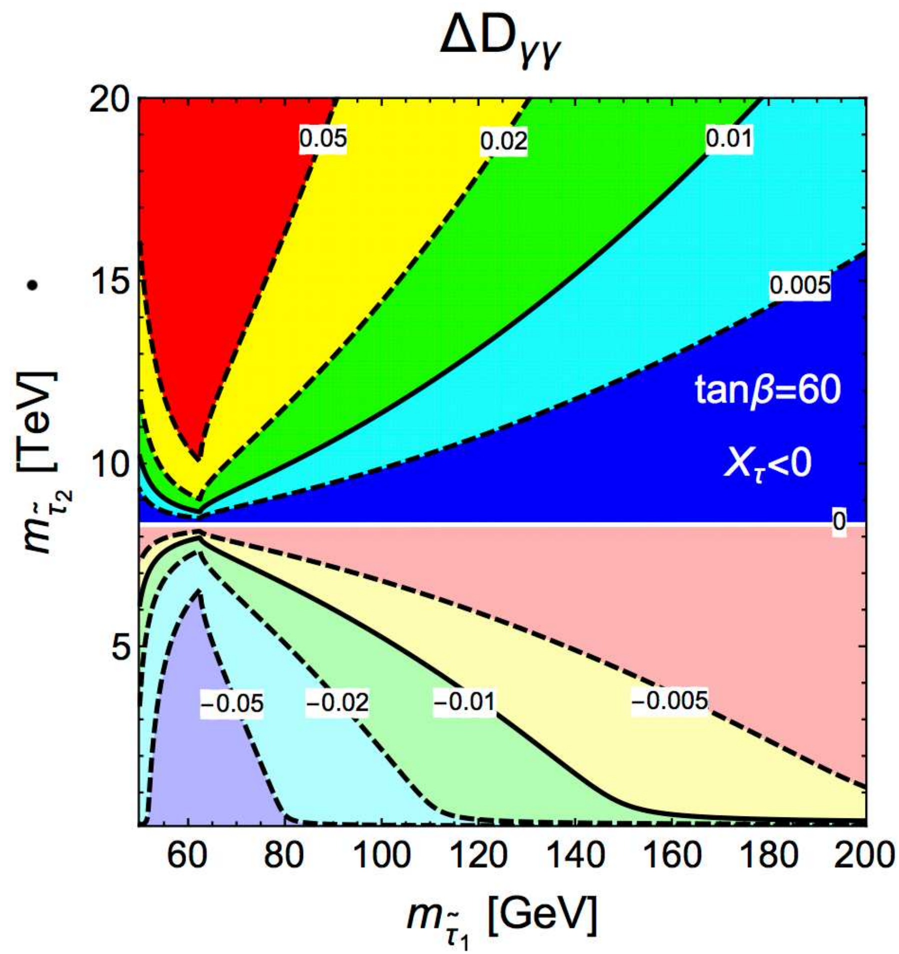
NB: charged Higgs difficult to find for $M_{H^\pm} \gtrsim 200$ GeV at low $\tan\beta$

. Interludium: $D_{\gamma\gamma}$

MSSM: chargino and stau contributions

$\propto \frac{4}{3} \times g_{h\chi_i^+\chi_i^-}/m_{\chi_i^\pm} \propto 1/m^2_{\chi_i^\pm}$ $\propto \frac{1}{3} \times g_{h\tilde{\tau}_i\tilde{\tau}_j}/m^2_{\tilde{\tau}_i} \propto m_\tau X_\tau / m^2_{\tilde{\tau}}$





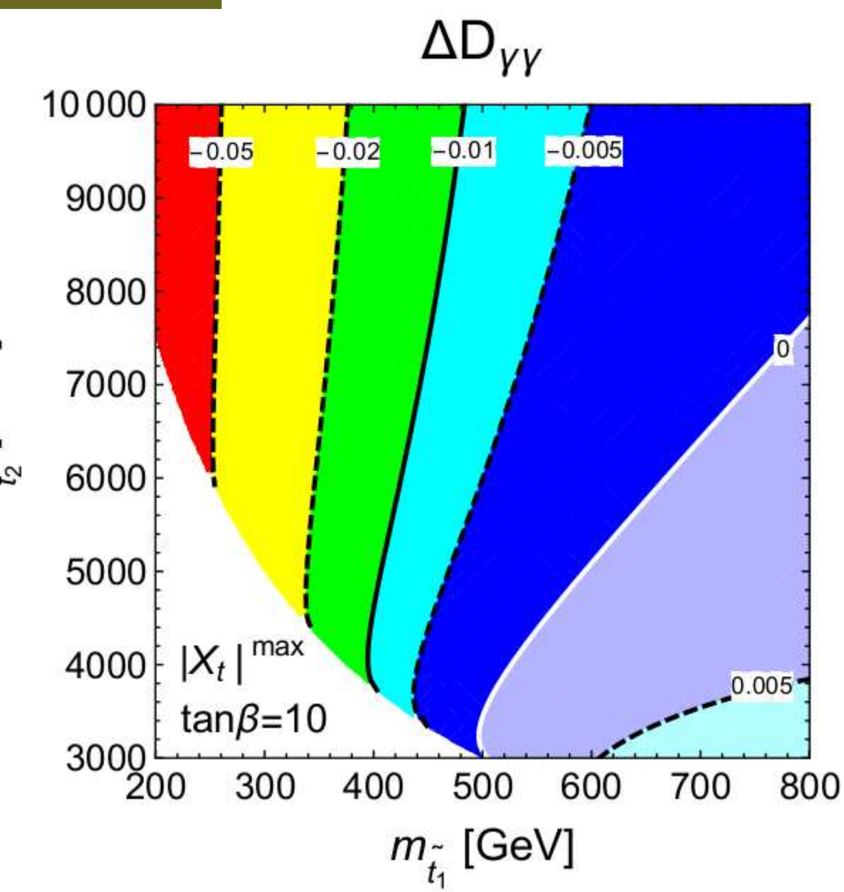
• o limit on charginos and stau's from LHC direct searches in some cases.

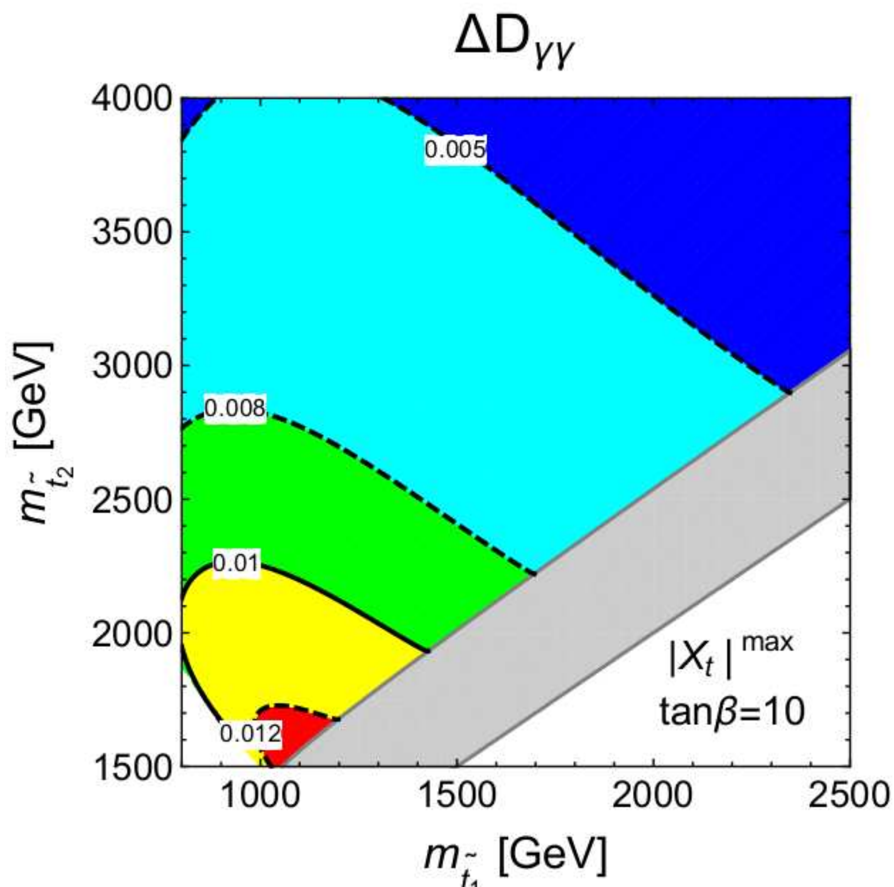
. Interludium: $D_{\gamma\gamma}$

(h)MSSM: stop contributions

$$c_t \approx c_t^0 \times \left[1 + \frac{m_t^2}{4m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - (A_t - \mu\cot\alpha)(A_t + \mu\tan\alpha)\ )\right]$$

$$\Delta M_h^2|^{t/\tilde{t}}_{1\mathrm{loop}} \sim 3m_t^4/(2\pi^2 v^2)[\log(M_S^2/m_t^2) + X_t^2/M_S^2 - X_t^4/(12M_S^4)]$$





NB: loose limits on stops from LHC direct searches in general case.

. Direct search for new states

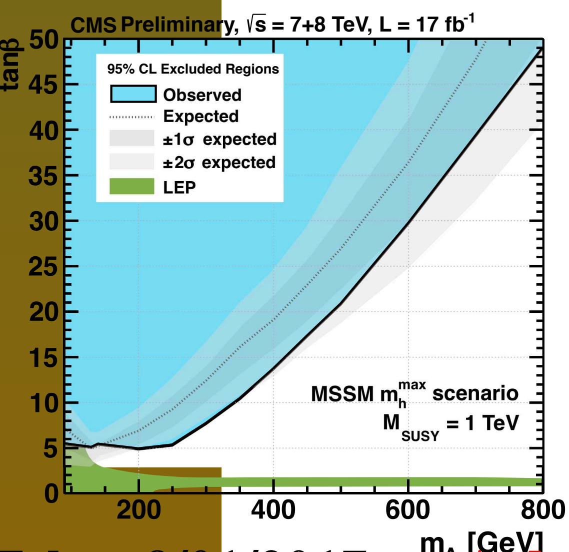
Now that the Higgs boson is found, is Particle Physics "closed"? No!

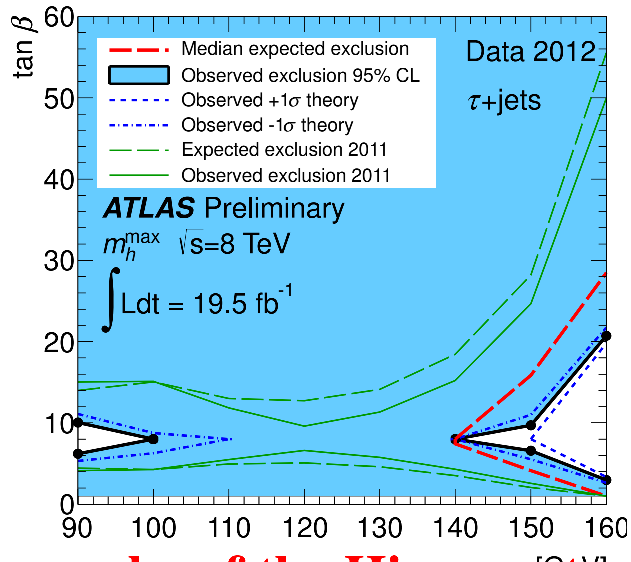
2) Fully probe the TeV scale that is relevant for the hierarchy problem
$\Rightarrow$ continue to search for heavier H bosons and new (super)particles.

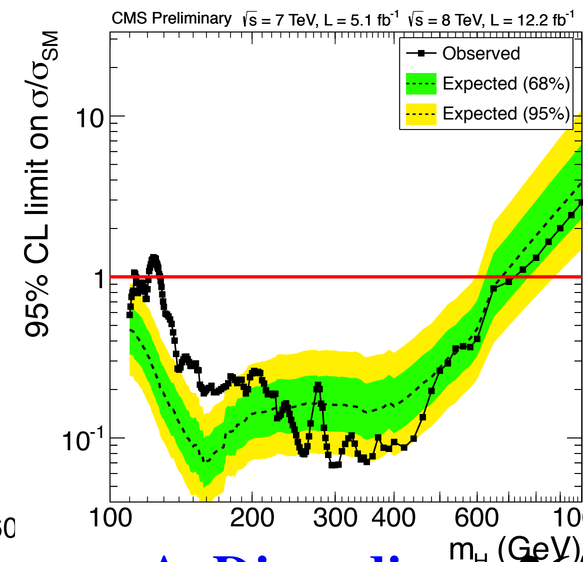
or instance in the MSSM: search for the heavier Higgs bosons: Fig.

) Improve "standard" searches for the heavier MSSM Higgs bosons:

- **Searches for the $pp \to A/H/(h) \to \tau\tau$ resonant process:**
  $\Rightarrow$ constrains high tanβ for low M_A values.
- **Searches for charged Higgs in $t \to bH^+ \to b\tau\nu$ decays:**
- **Search for the heavier Higgsses in H$\to$ZZ,WW (and $\gamma\gamma$!) modes:**

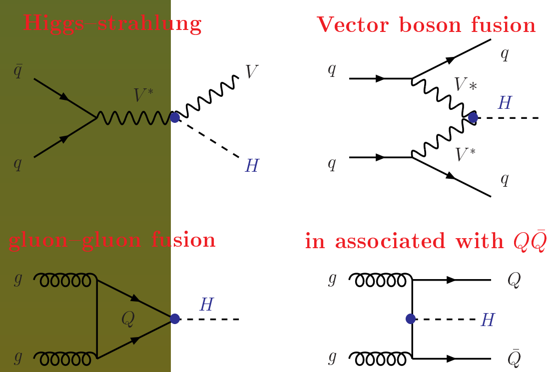


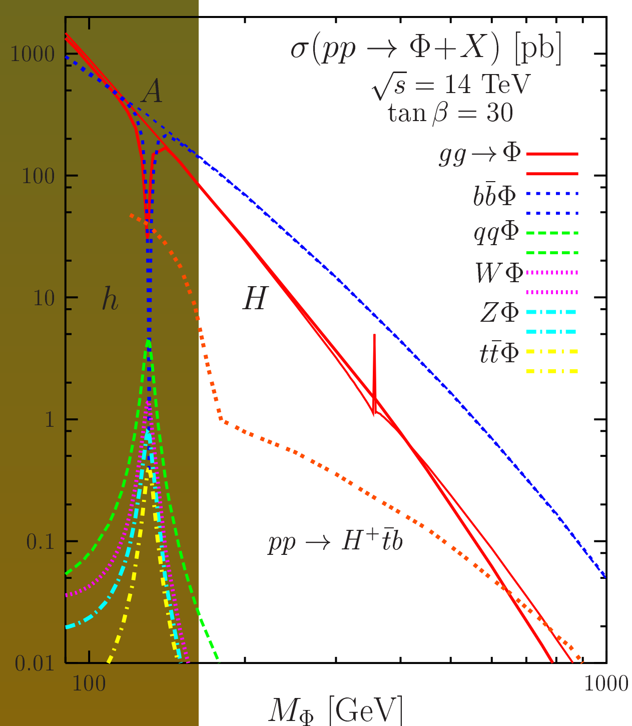




. Direct search for new states

Production/decay phenomenology more complicated in the MSSM.





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

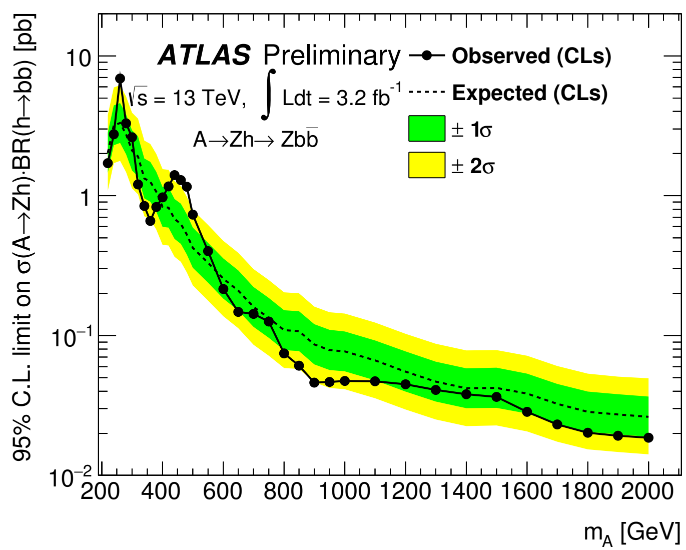
. Direct search for new states

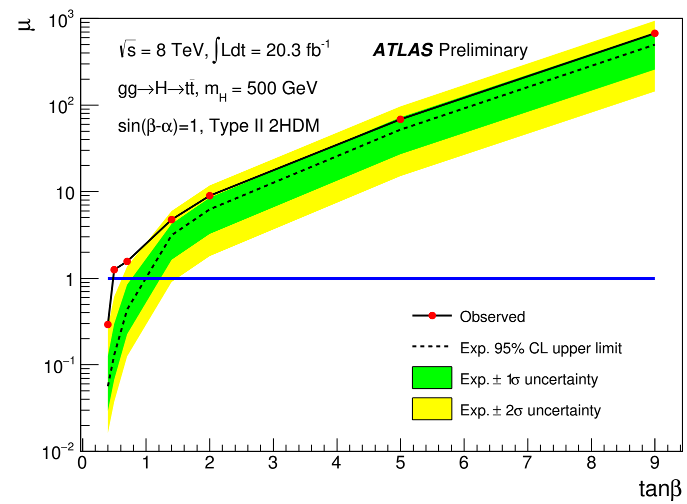
Now that the Higgs boson is found, is Particle Physics "closed"? No!

2) Fully probe the TeV scale that is relevant for the hierarchy problem
⇒ continue to search for heavier H bosons and new (super)particles.
r instance in gtghe MSSM: search for the heavier Higgs bosons: Fig.

B) Look at other channels for H/A not present in the SM case:

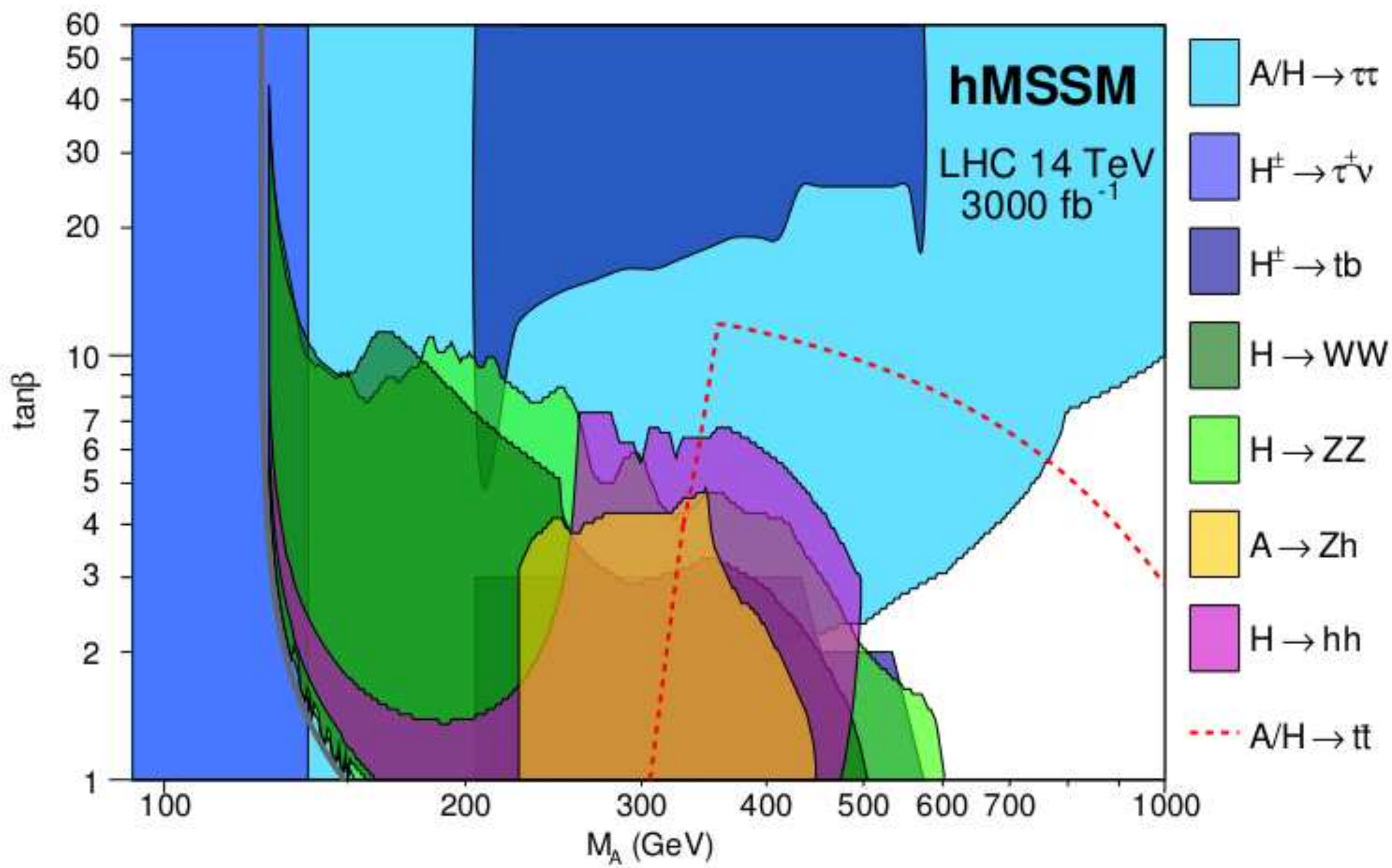
- **Searches for the interesting channels $A \to hZ$ and $H \to hh$ for low tanβ and not too heavy A,H states (below tt threshold)**
- **Searches for heavy $H/A \to t\bar{t}$ resonances (beware of interference) for low tanβ and heavy A,H states (far above the tt threshold)**





. Direct search for new states

The "money Higgs plot" at the end of the LHC could look like:



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

. Direct search for new states

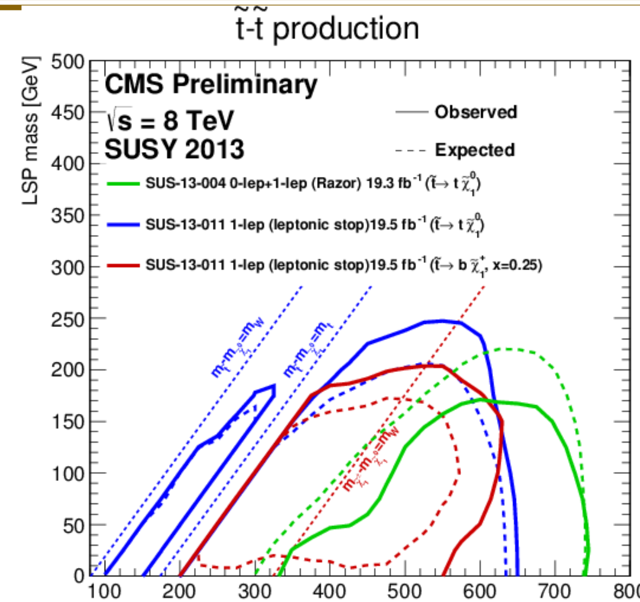
• Search for supersymmetric particles

(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).

See David Shih; example of CMS for $\tilde{t}/\chi_1^0 \Rightarrow$

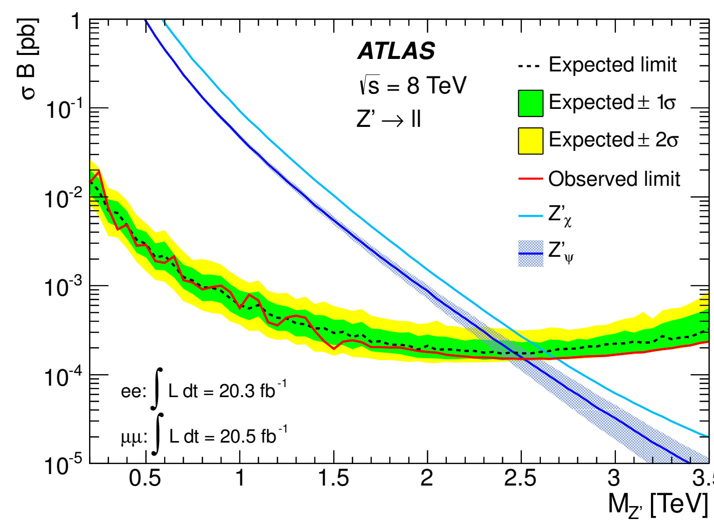


• Search for any new heavy particle

(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, ..)

See Brian; ex: ATLAS for $Z' \to \ell\ell \Rightarrow$

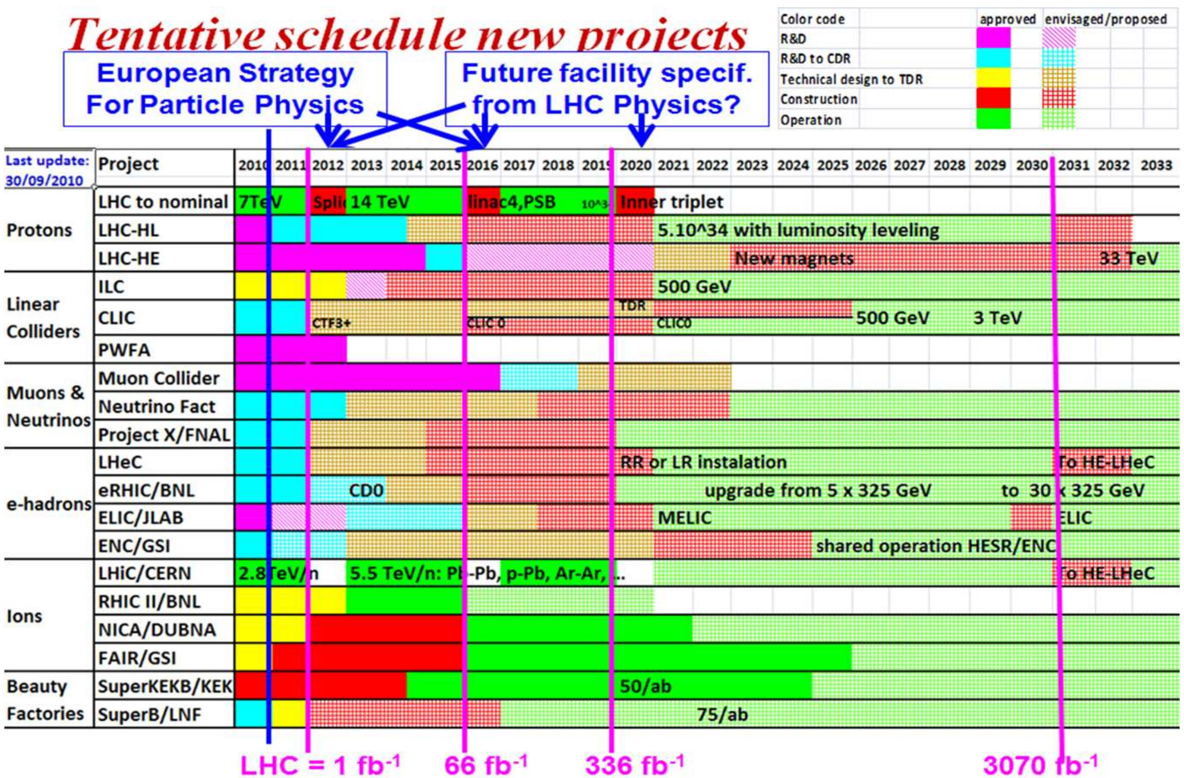


. Conclusion

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.



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

(or as the experimentalists usually say: stay tuned...)