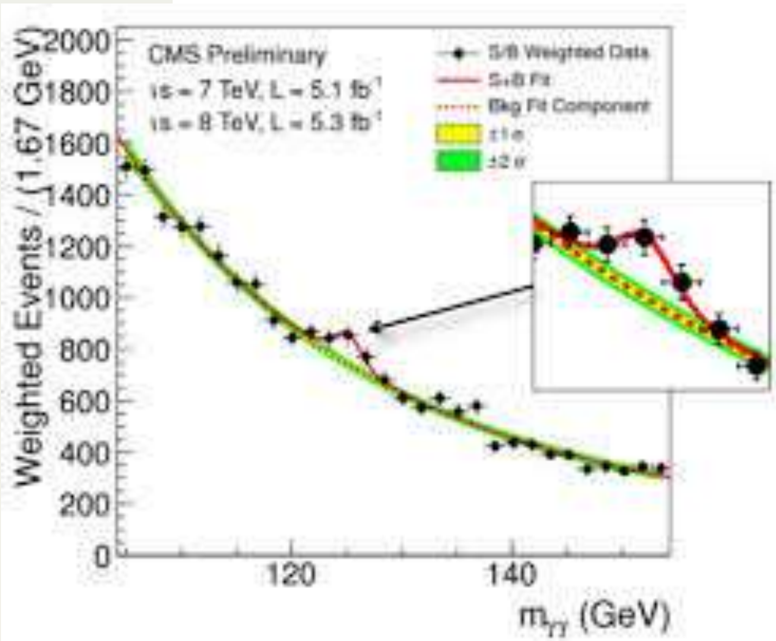
A deeper probe of new physics scenarii at the LHC

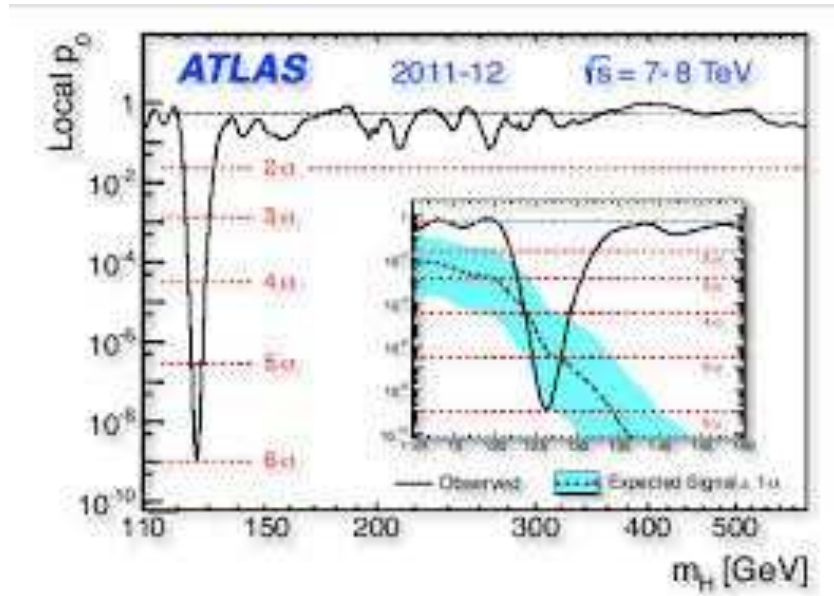
Abdelhak DJOUADI
(CNRS & Université Paris-Sud)

1. Standardissimo?
2. Trouble with minimal SUSY?
3. A deeper probe of new physics
4. Indirect searches for new physics
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: $\mathrm{M_H} = 125.1 \pm 0.24$ 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?

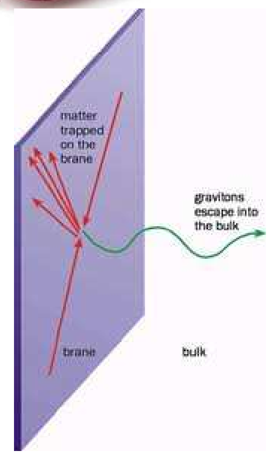
Three main avenues for solving the hierarchy or naturalness problems

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,

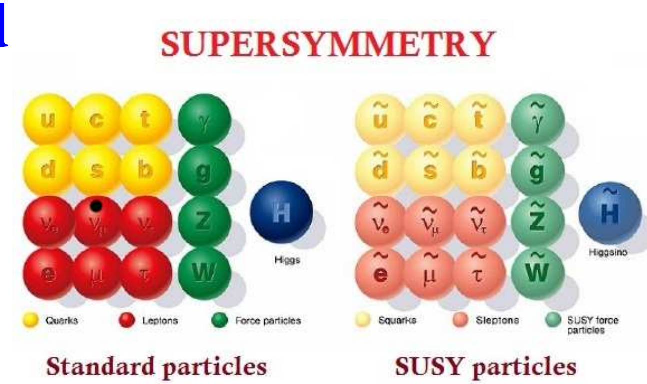
– links internal/space-time symmetries,

– 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:

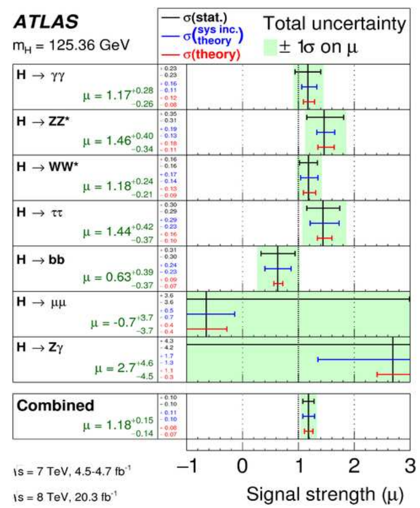
$\sigma\times$BR rates compatible with those expected in the SM

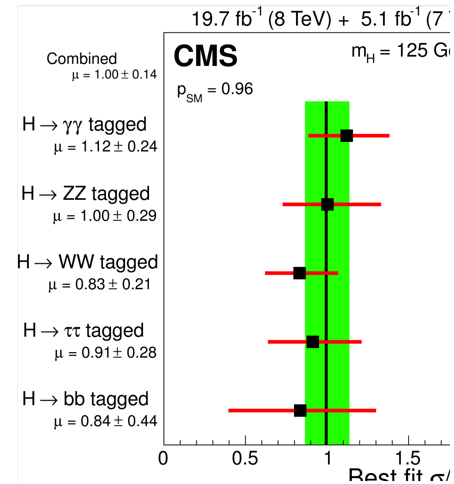
Fit of all LHC Higgs data $\Rightarrow$ agreement at 15–30% level

Results from the LHC 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 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 the MSSM?

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 $\tan\beta, M_A$

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

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

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

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

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

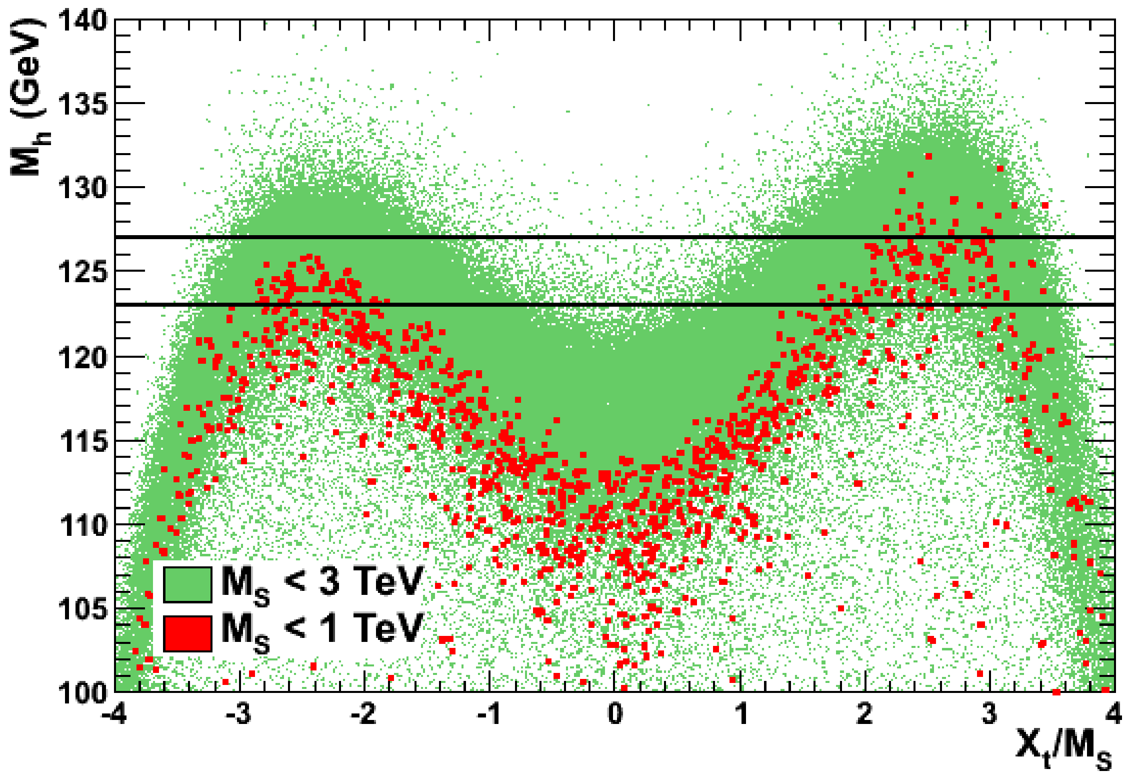
Φ	$g_{\Phi \bar{u} u}$	$g_{\Phi \bar{d} d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$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

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

2. Trouble with the MSSM?

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

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



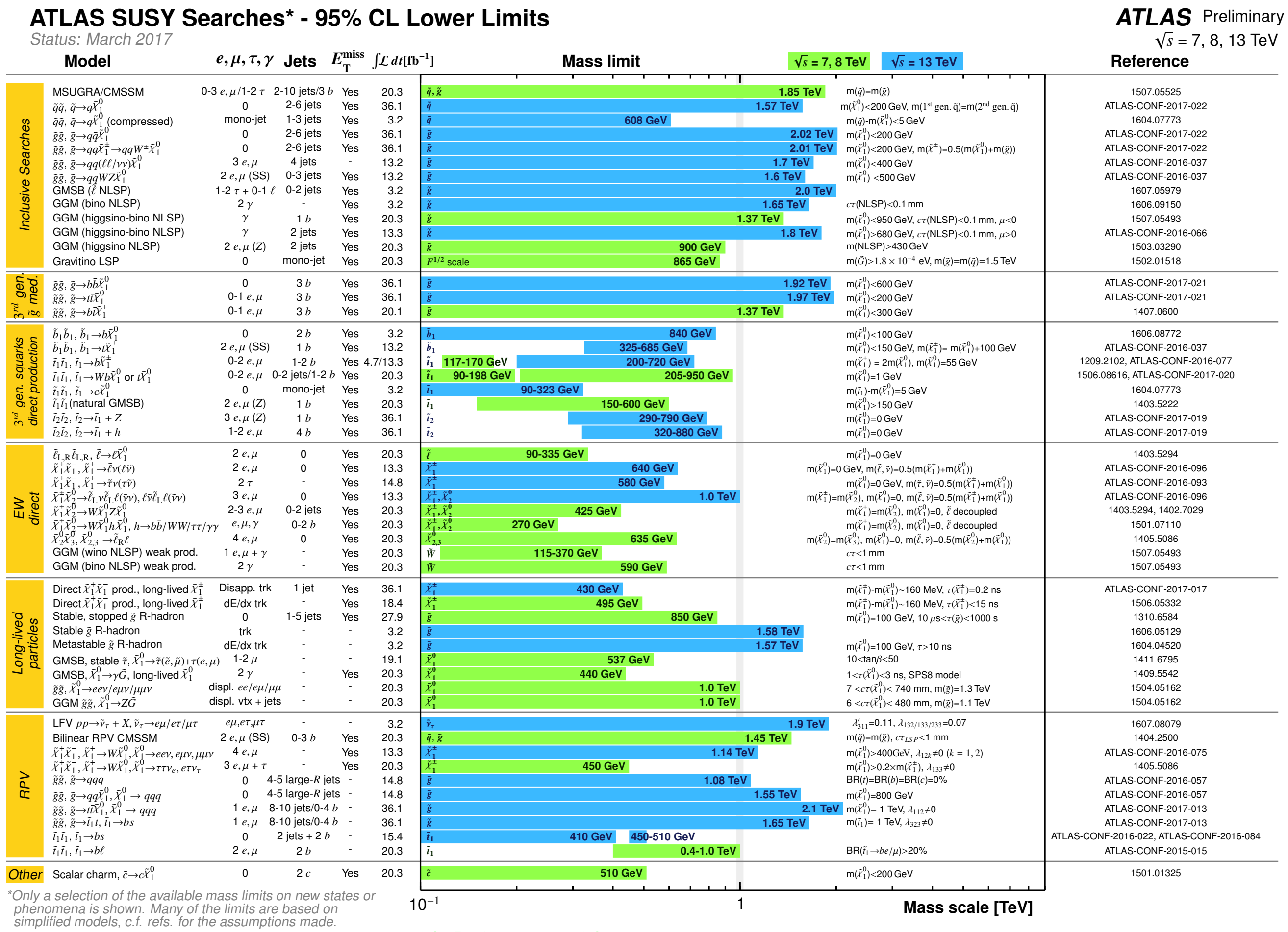
Arbey, Battaglia, AD, Mahmoudi, Quevillon (2012)

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

2. Trouble with the MSSM?

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

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



⇒ ATLAS/CMS depressing tables...

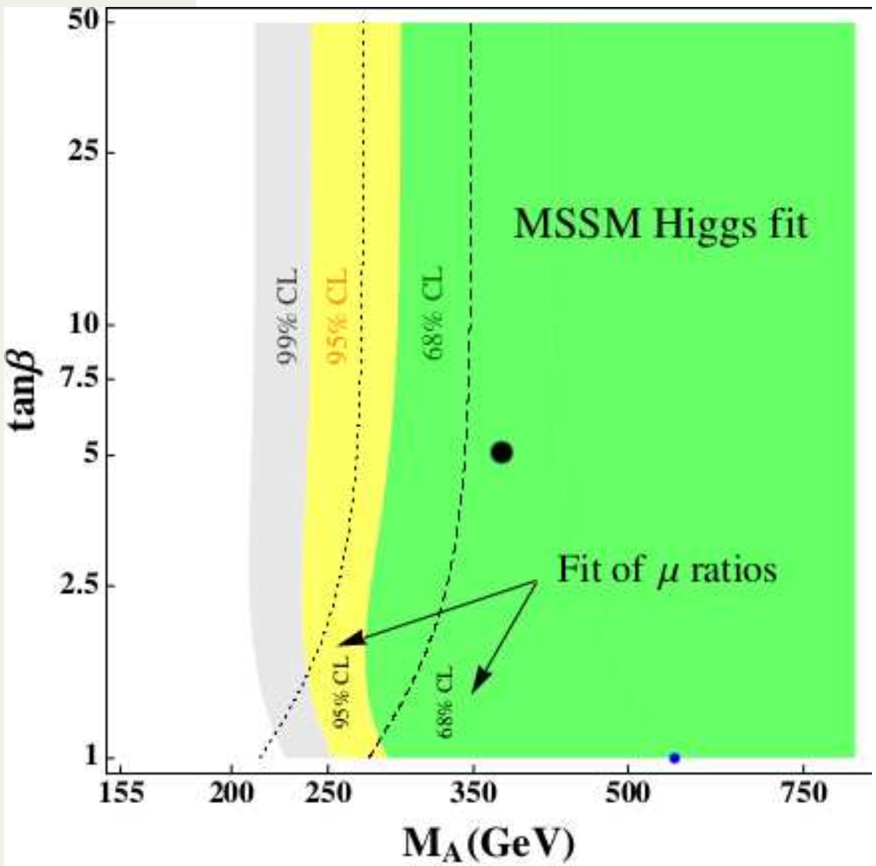
2. Trouble with the MSSM?

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

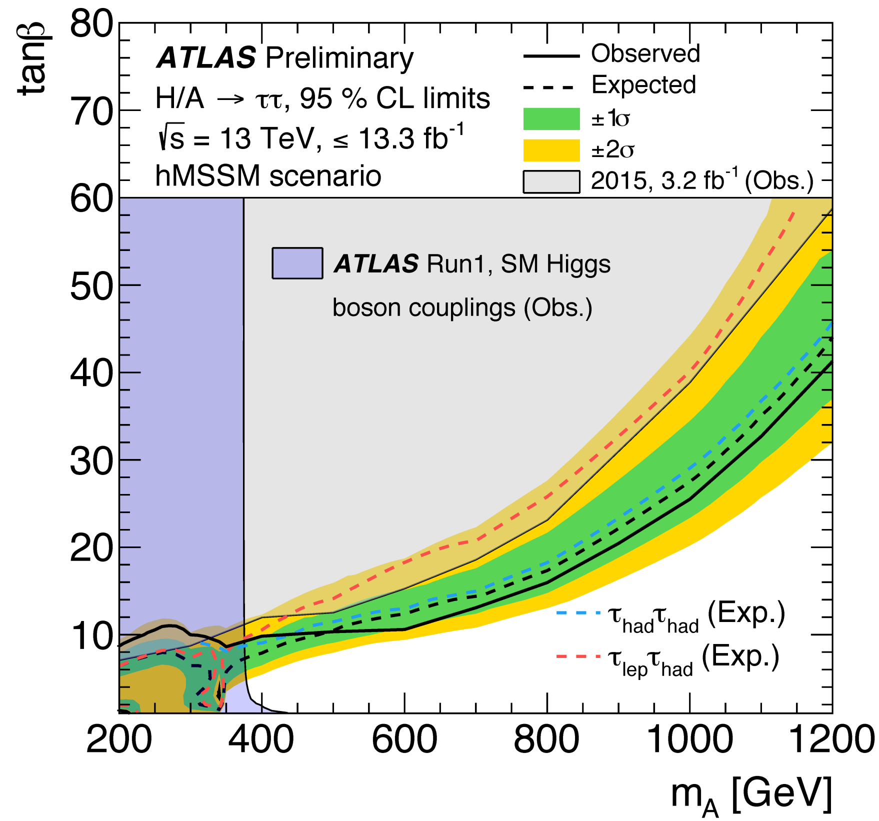
fits of the h couplings ⇒ constraints on the MSSM $[M_A, \tan\beta]$ plane:

MSSM: $g_{ht\bar{t}} = \cos\alpha/\sin\beta$, $g_{hb\bar{b}} = \cos\alpha/\sin\beta$, $g_{hVV} = \sin(\beta-\alpha)$.

AD, Quevillon, Maiani... 2013



Direct search for pp→H,A



3. A deeper probe of new physics

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 to search for heavier Higgs bosons and new (super)particles

• 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...

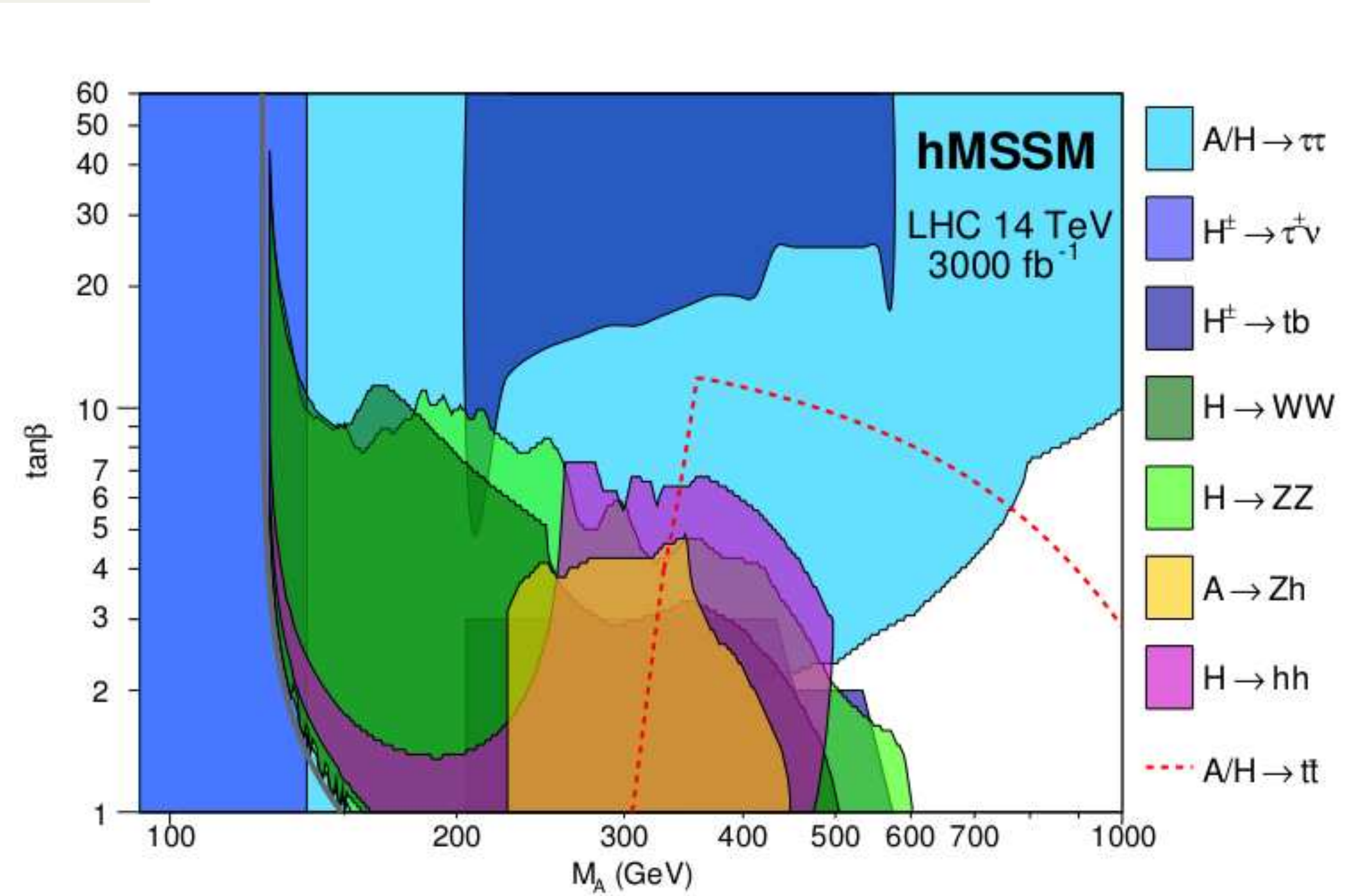
• And anything else:

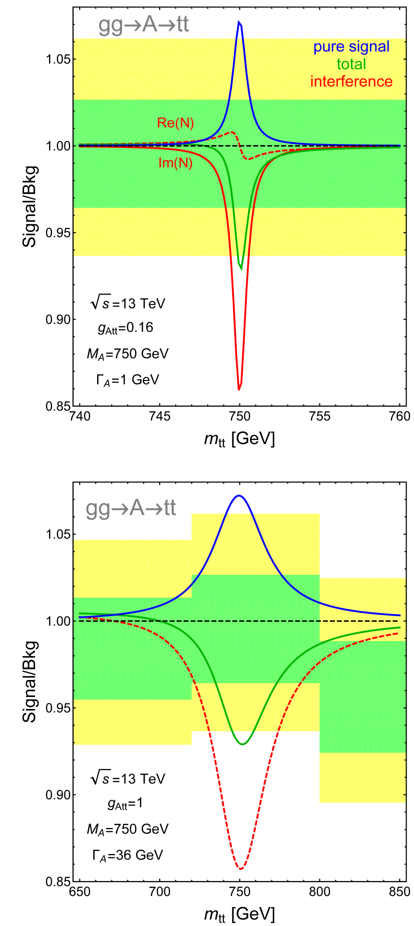
– new gauge bosons: $\mathrm{V_{KK}}$ excitations, new Z',W' from GUT, etc...
– new exotic fermions: vector-like, KK fermions, excited fermions, ...
– other exotica: H++ bosons, leptoquarks, diquarks dileptons, etc...

• ....

3. A deeper probe of new physics

Search for MSSM H, A, $H^\pm$ bosons in non–standard channels,
how the ”money Higgs plot” at the end of HL-LHC could look like:





AD, Maiani,Quevillon, Polosa, Riquer **AD, Ellis,Quev**

3. A deeper probe of new physics

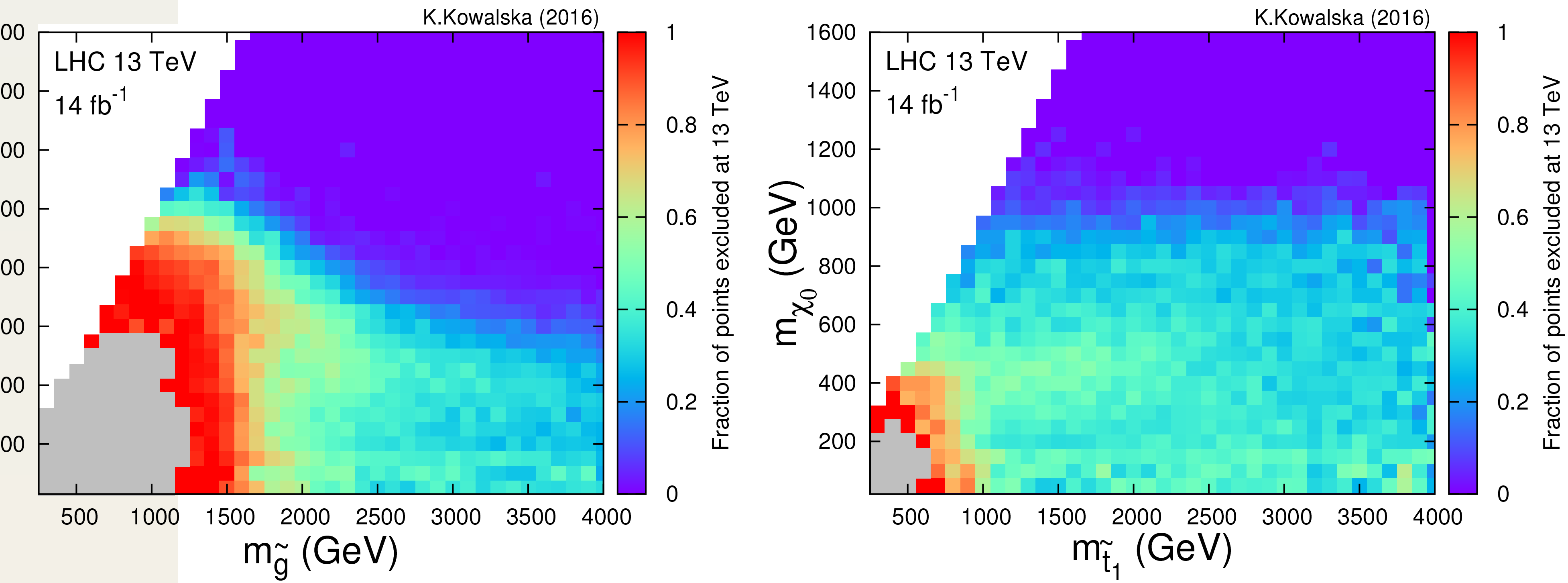
In MSSM: plenty of (natural?) parameter space that is not probed yet!

Example form a recent analysis of Kamila Kowalska, 1608.02489

– analysis of pMSSM with 19 para. and neutralino DM in light of LHC

– recast of 12 ATLAS analyses at 13 TeV with a luminosity of 14 fb^{-1}

– large scan and fraction of points that are not yet excluded by data.



Blue: still some way to go in the parameter space!

3. A deeper probe of new physics

In SUSY, there are several ways to measure naturalness or fine-tuning,
eg Barbieri-Giudice fine-tuning measure: $\Delta_i = \partial \log M_Z^2 / \partial \log M_S^2$
Sensitivity of $m_{H_{1,2}}$ parameters to higgsino, stop, gluino masses @LL:

higgsinos: $\delta m_H^2 = \mu^2$

stops : $\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 m_{\rm stop}^2 \log(\Lambda_{\rm mes}/M_S)$

gluinos : $\delta m_H^2 \sim -\frac{g_3^2 y_t^2}{4\pi^4} |M_3|^2 \log^2(\Lambda_{\rm mes}/M_S)$

with $M_S \approx 1$ TeV and $\Lambda_{\rm mes} \approx$ few 10 to few 100 TeV in GMSB e.g.

$\Delta \leq 10\ (100)$ means that scenario is natural at 10% (1%) level

(scenario is more natural/less fine-tuned with lower messenger scale...).

- Vanilla MSSM: with Rp conservation and flavour diagonal sfermions,

$$\Delta \leq 10 \Rightarrow \mu \lesssim 300\,{\rm GeV}, m_{\tilde g} \lesssim 1.5\,{\rm TeV}, m_{\tilde q} \lesssim 1\,{\rm TeV}$$

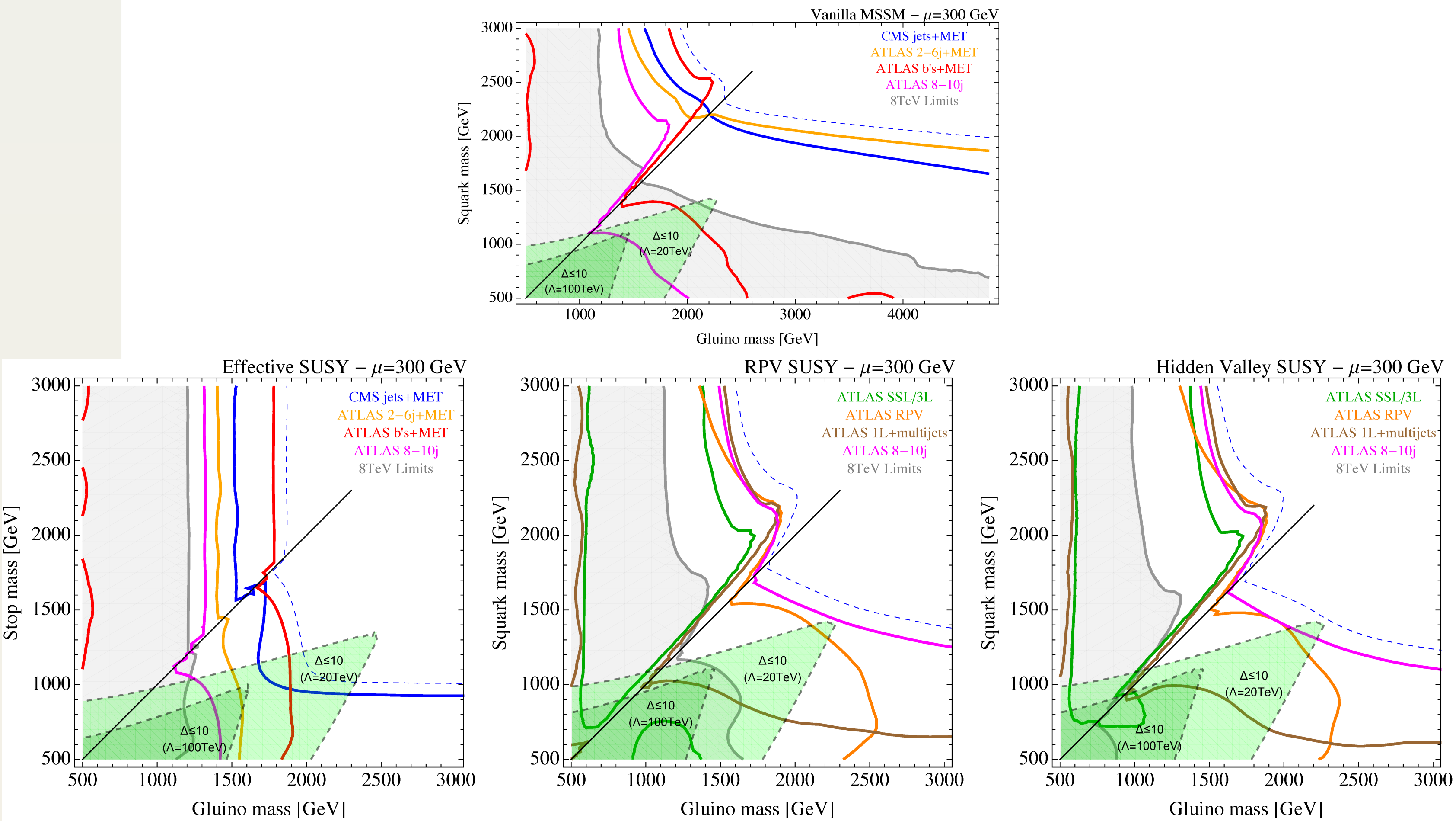
But there are less "constrained" scenarios with less fine-tuning:

- effective SUSY: 1st/2nd generation squarks decoupled to 5 TeV,
- Rp violating SUSY: with e.g. higgsinos decaying into a cds trio,
- adding some sector like Hidden Valley to the MSSM, ...

3. A deeper probe of new physics

Recent (and optimistic?) analysis of M. Buckley et al. in 1610.08059:

detailed reinterpretation of 13TeV ATLAS+CMS searches with 15 fb^{-1} and interpretation in terms of fine-tuning in several SUSY scenarios...

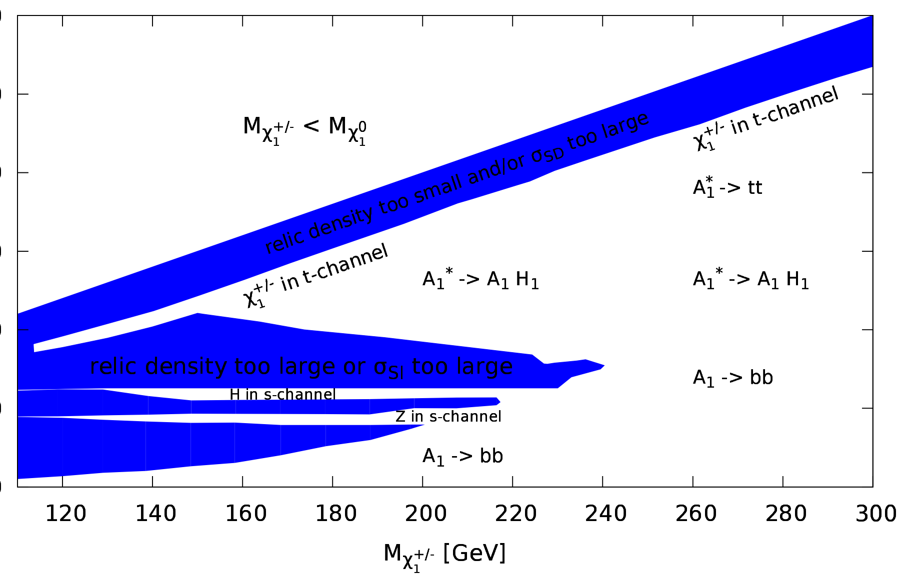


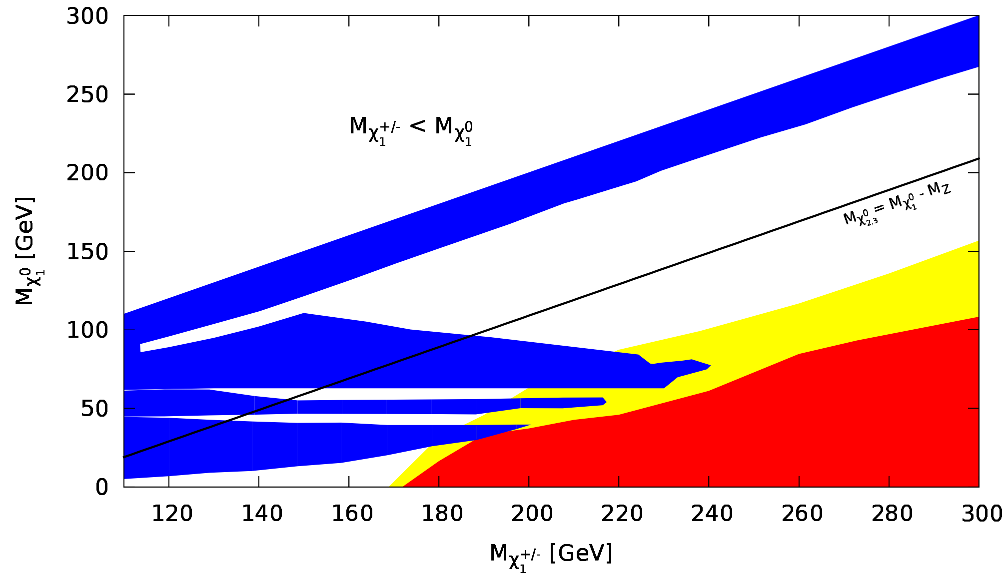
3. A deeper probe of new physics

In the NMSSM: plenty of searches can be made only with more data!

For instance: search for higgsino–singlino states at the HL-LHC (natural with low μ, only weak constraints, yet almost unexplored).

only DM+LEP+Higgs constraints   also direct searches with 3ab^{-1}:





Relevant search channel at THE LHC: $\mathrm{pp} \to \chi_j \chi_j \to \mathrm{n}\ell^{\pm} + \mathrm{E_T^{mis}}$

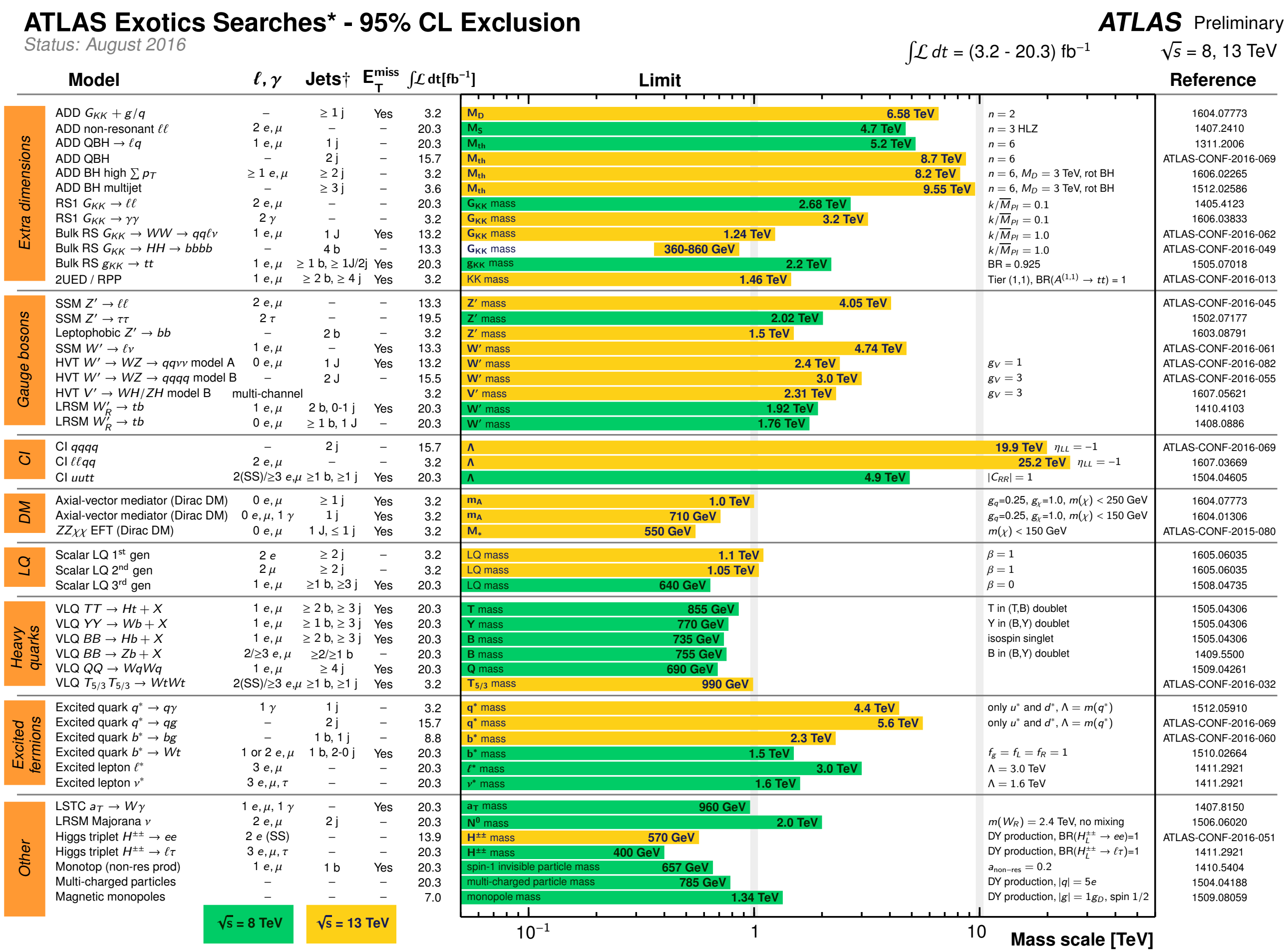
blue: simple recast of ATLAS results but for 3ab^{-1} HL data;

yellow: CHECKMATE analysis including hadronic W decays.

Ellwanger, 1612.06574

3. A deeper probe of new physics

There are searches for exotica in a large number of channels!



*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).

Should be continued, extended, refined:

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

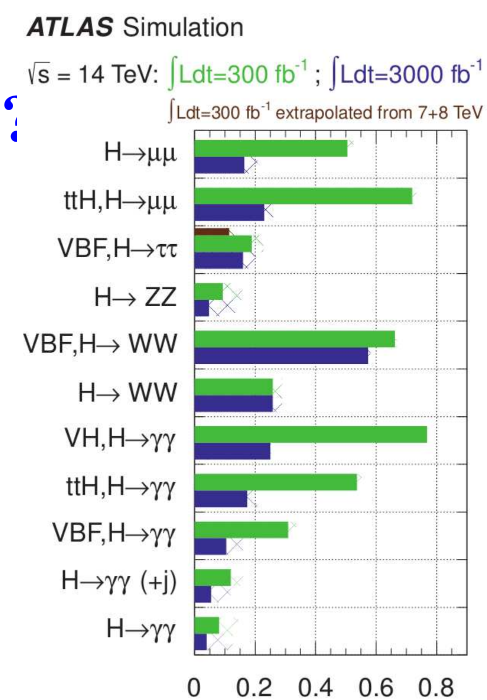
4. Indirect searches for new physics

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

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 $\approx \frac{\mathrm{C_{new}}\alpha_\mathrm{W}}{\pi} \approx \frac{\mathrm{M_h^2}}{\mathrm{M_{new}^2}} \approx 1\%$;



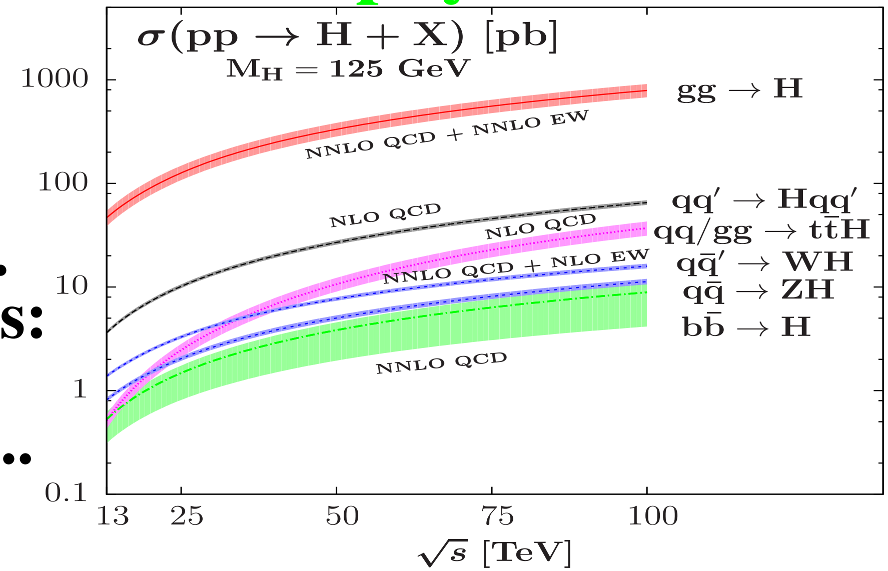
Is 1% accuracy achievable at HL-LHC ($3\mathrm{ab}^{-1}$)?

- **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?

4. Indirect searches for new physics

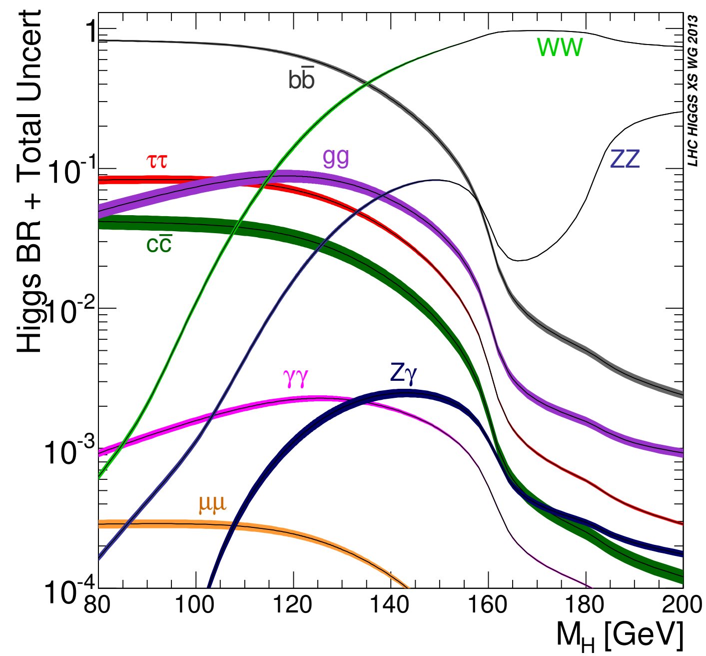
Production cross sections



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

$\Rightarrow$ too large theory uncertainties
(even if reduced by a factor of 2)...

4. Indirect searches for new physics

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;**

$\Rightarrow$ D_{XX} **measures only the ratio of partial decay widths.**

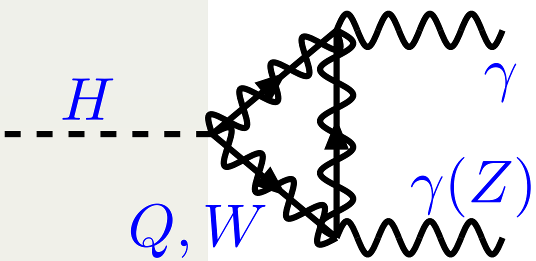
- **Extremely clean theoretically, although some information will be lost.**
- **And maybe it has also some advantages from the experimental side?**

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)

4. Indirect searches for new physics



$$\Gamma = \frac{G_\mu \, \alpha^2 \, M_H^3}{128 \sqrt{2} \, \pi^3} \left| \sum_f N_c e_f^2 A^H_{\frac{1}{2}}(\tau_f) + A^H_1(\tau_W) \right|^2$$

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

$$A^H_1(\tau) = -[2\tau^2 + 3\tau + 3(2\tau - 1) f(\tau)] \, \tau^{-2}$$

- **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!**

$\gamma\gamma$ 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}:

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

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

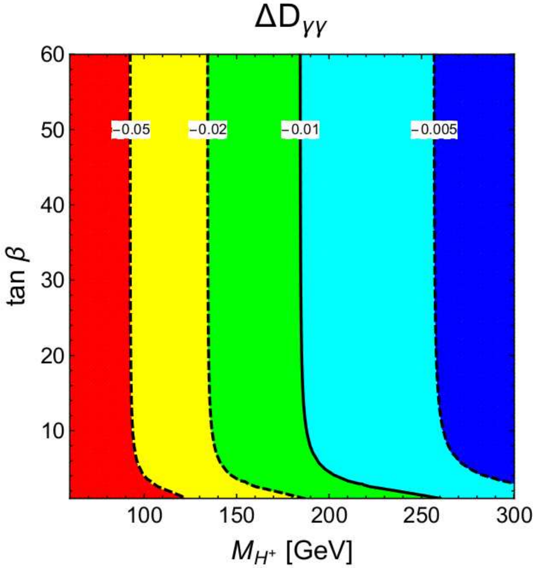
$$c_\gamma^2 / c_V^2 \approx 6.5 \times |1 - \tfrac{1}{5} c_t / c_V|^2$$

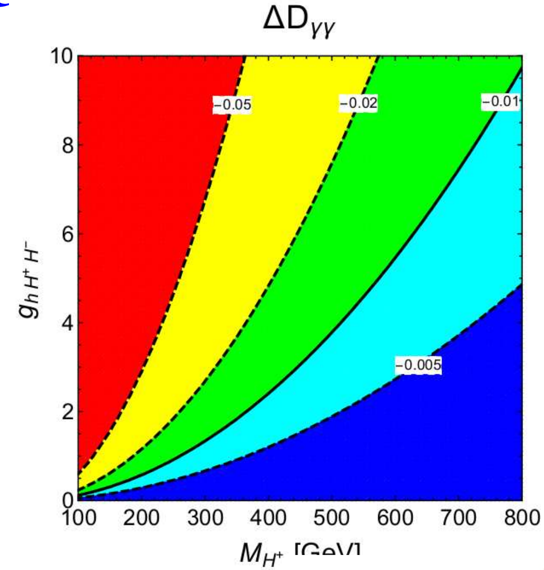
with $c_V = c_t = 1$ in SM. Any new physics effects will alter this value.

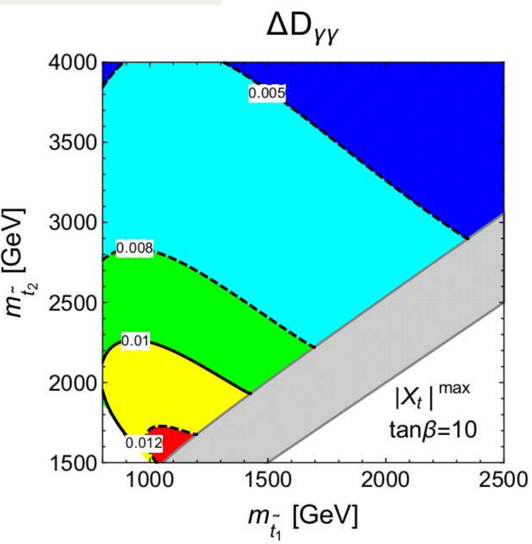
4. Indirect searches for new physics

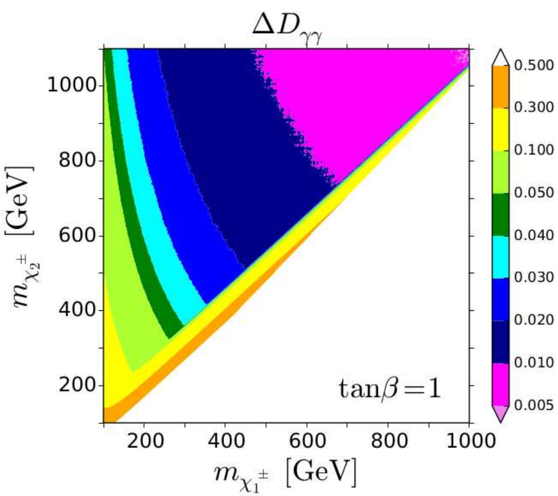
Will $D_{\gamma\gamma}$ be the g-2 of the LHC? Yes, if measured at 1% level!

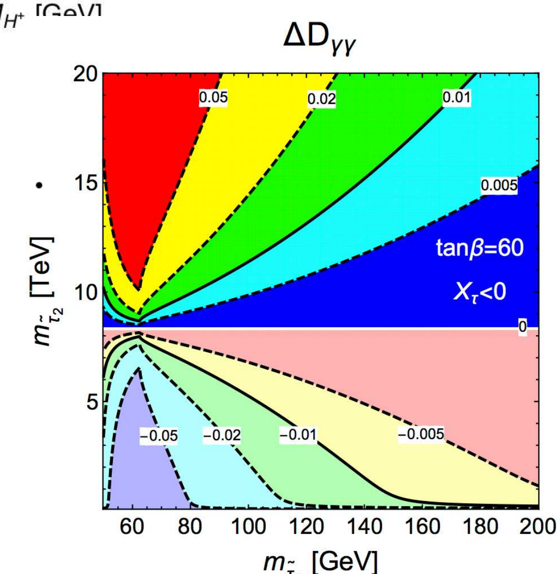
Examples of BSM searches: AD, Quevillon, Vega-Morales, 1509.03913











5. Conclusion

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

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

Now, this is not the end.

It is not even the beginning to the end.

But it is, perhaps, the end of the beginning.

Sir Winston Churchill, November 1942

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

(or as experimentalists usually say: stay tuned!)