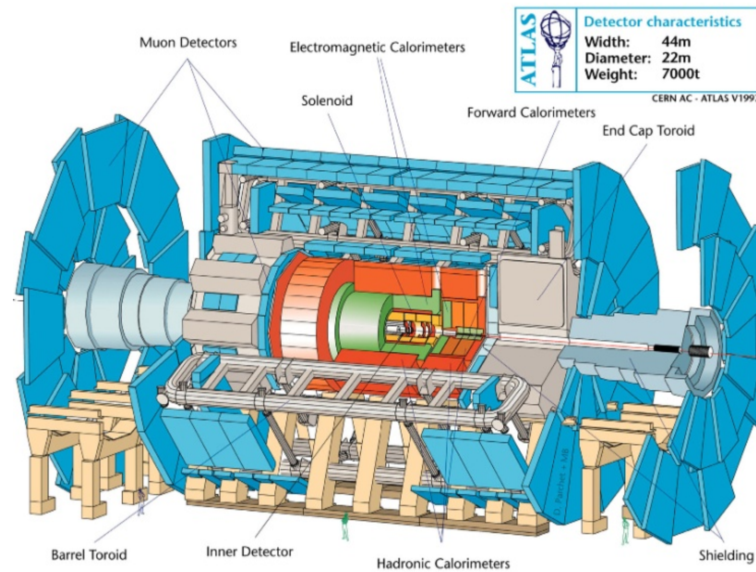
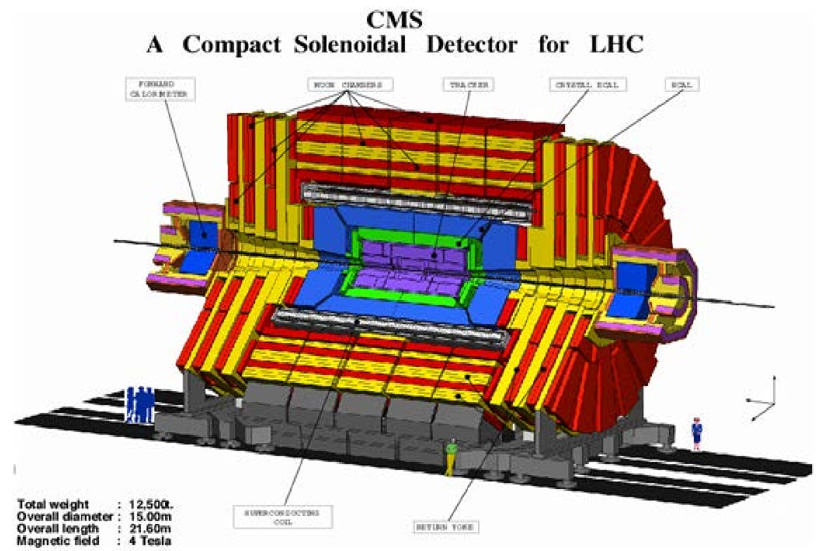
BSM Higgs Physics @ the LHC





NOT your everyday Higgs...

SLAC NATIONAL ACCELERATOR LABORATORY

T.G. Rizzo

10/26/11

Some comments on BSM Higgs
σ's & BF's

Sally is the real expert here...

The LHC Higgs σ Working Group* has been set up to provide the best possible estimates of σ's and BF's for various Higgs in the SM & MSSM, 4GSM, Fermiphobic, ..scenarios at the LHC :

CERN–2011–002
17 February 2011

1101.0593

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Handbook of LHC Higgs cross sections:
1. Inclusive observables

Report of the LHC Higgs Cross Section Working Group

CERN Report went out before the 1st Higgs results of LHC !

Editors: S. Dittmaier
C. Mariotti
G. Passarino
R. Tanaka

64 authors
151 pages
370 references

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2011

CERN–2011–xxx
1 October 2011

12/2011 ?

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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Handbook of LHC Higgs cross sections:
2. Differential Distributions

Contents: (work in progress)
- Results on Higgs production ggF, VBF, WH/ZH, ttH
- Results on Higgs decay $H \to \gamma\gamma/WW/ZZ/\tau\tau/bb$
- Recipe to assess THU+PU for distributions
- Distributions with THU+PU
- BRs: THU+PU
- MSSM: general recipes and specific scenario(s)
- PseudoObs: heavy Higgs M_H/Γ_H, signal-bkg interf.
- NLOMC: tools and error estimates for acceptance
- Specific topics: jet veto, Higgs p_T, etc.

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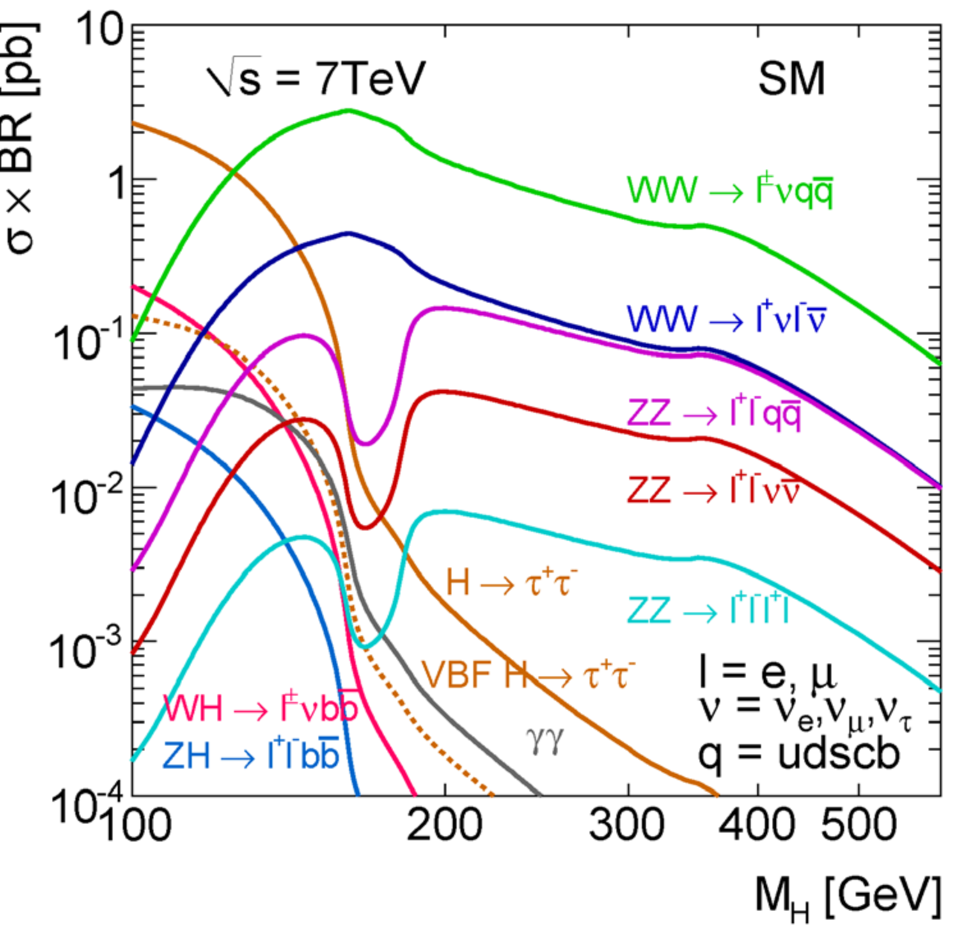
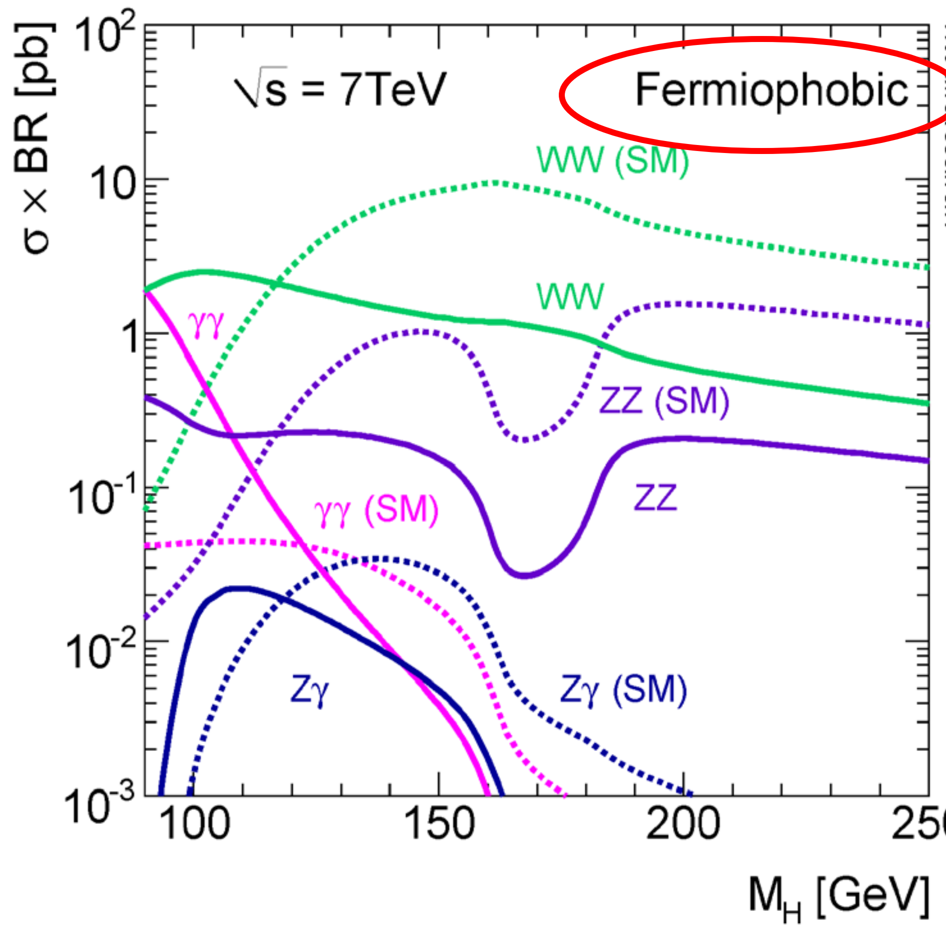
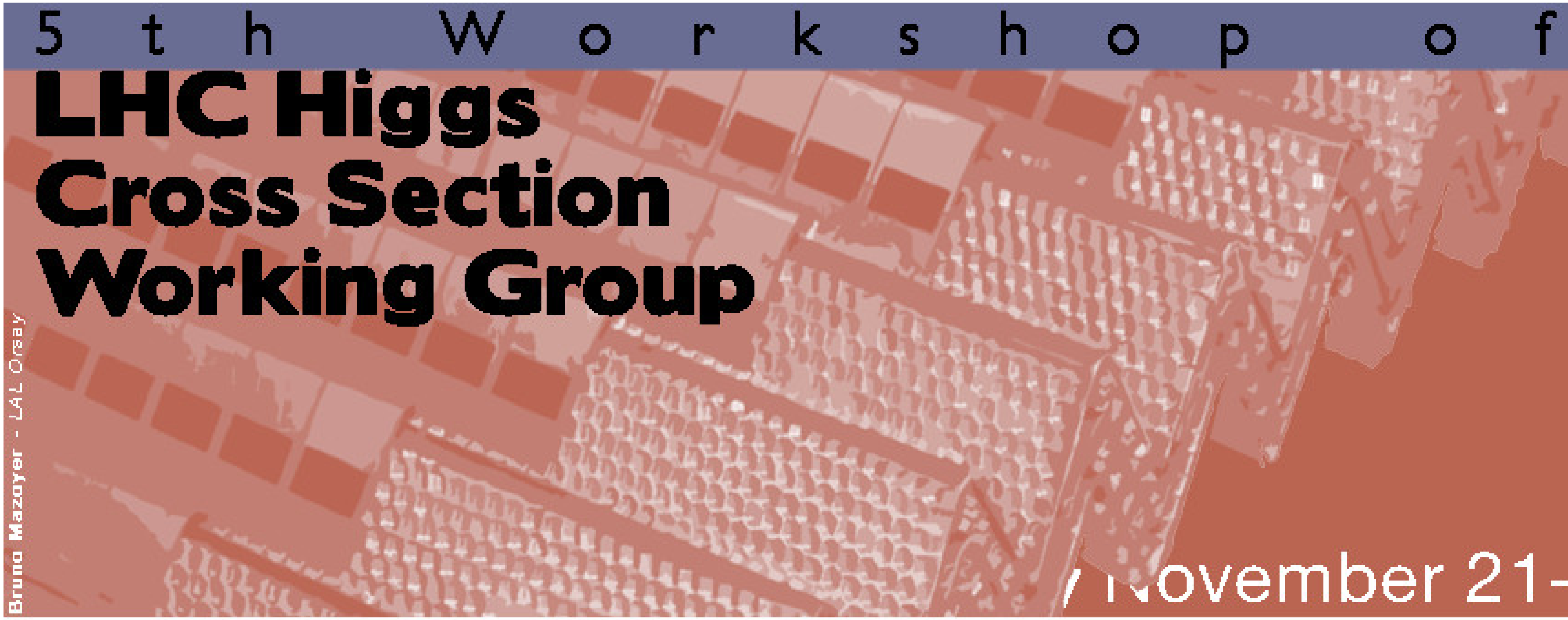
* hpps://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

- This is a work-in-progress .. but results are fairly complete for the SM & are now being expanded to many BSM scenarios. However, lots of work still needs to be done..





- A similarly motivated new working group has just been set up to deal with SUSY & other BSM physics σ's @NLO



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- Participants
- Contact us

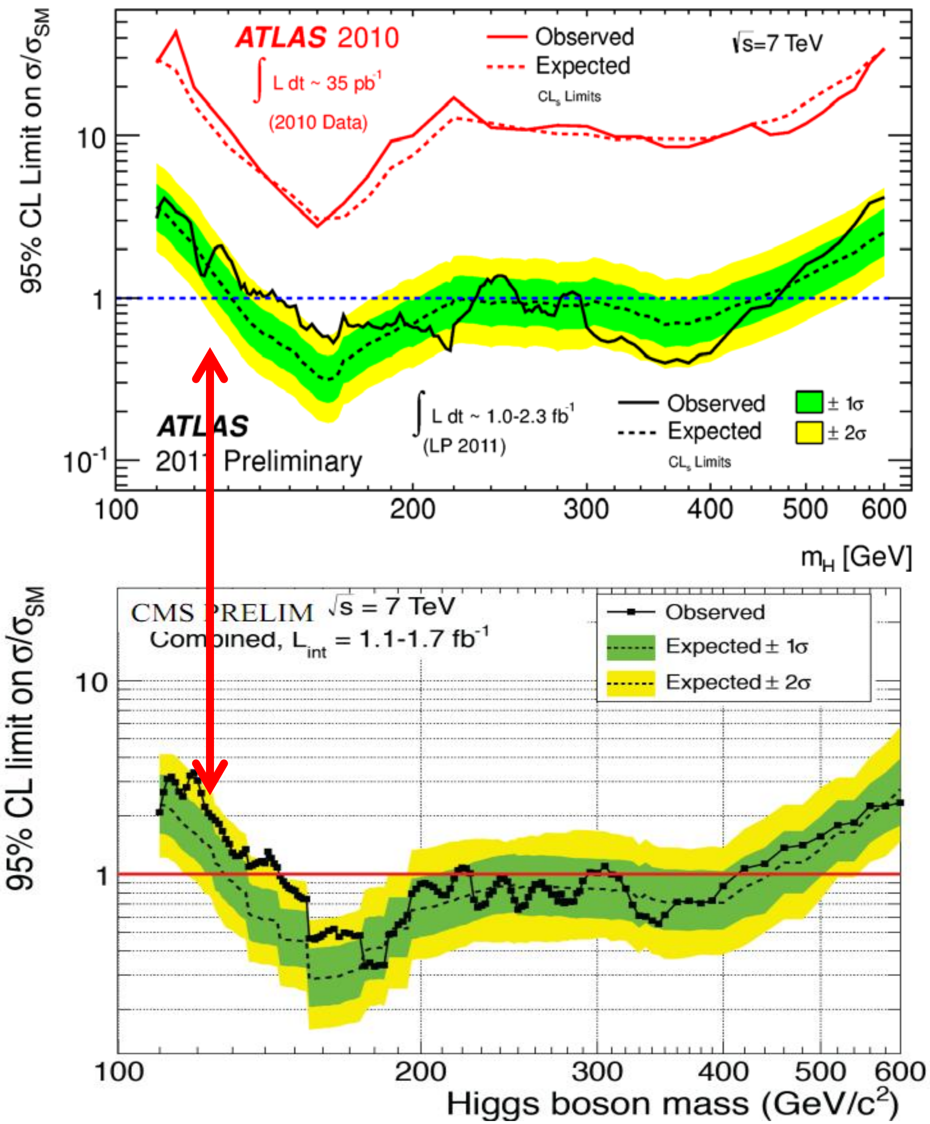
Since January 2010, ATLAS, CMS, LHCb and theory community have been making joint efforts for Higgs cross sections at LHC. Expecting the discovery of Higgs boson(s) in coming years, the current interests are the differential Higgs cross sections as well as the estimation on the Standard Model backgrounds which are relevant to the Higgs search. This meeting will focus on the discussions towards the completion of the second CERN Report on differential distributions by the end of this year. The final session will be devoted to the discussions on the directions for our future activities.

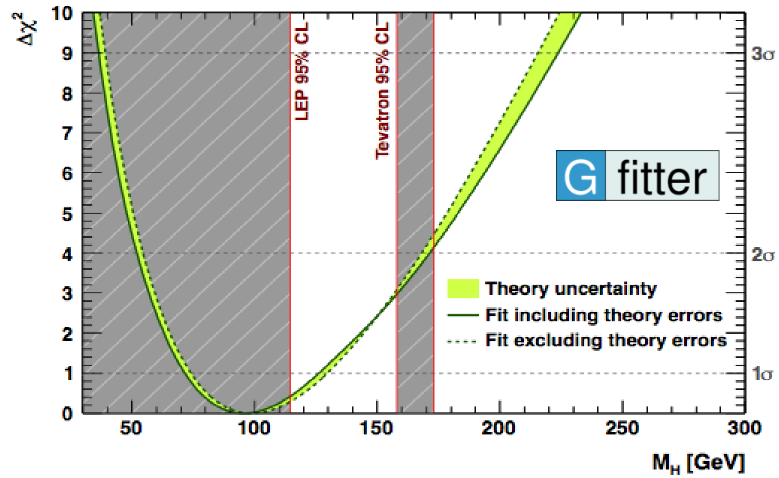
This meeting follows the HCP2011 conference in Paris (Nov. 14-18) and will be followed by the LHC2TSP (LHC to Terascale Physics) workshop in Orsay (Nov. 22-23) which includes the joint session with us on Higgs physics. It is recommended to participate both workshops.

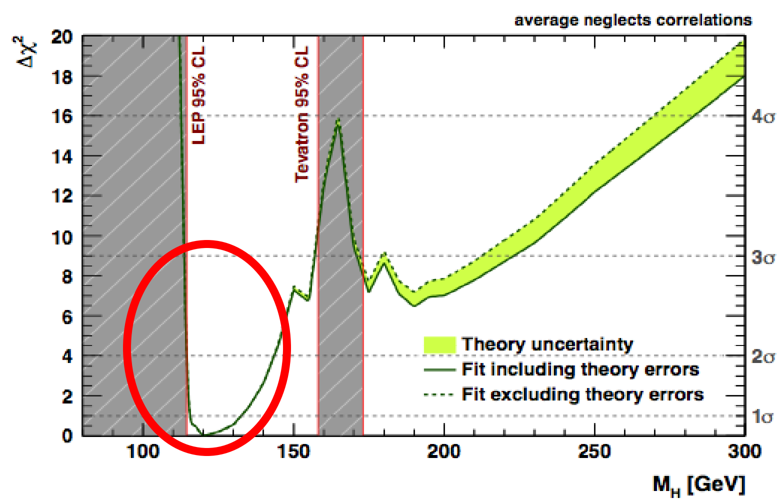
- Social event
- Lodging
- Travel to Orsay
- *LHC to Terascale Physics*
- *HCP2011*

Current Higgs Searches From the BSM Perspective

- **Thanks to you**, if there is no BSM physics, the SM Higgs is running out of places to hide and YOU will 'soon' tell us its mass… More than likely where the SM says it is :







However nature could surprise us due to BSM Physics

Scenarios and exit strategies

Possible scenarios include:

1. A SM-like Higgs boson is discovered. No evidence for BSM physics is evident.
2. A SM-like Higgs boson is discovered. Separate evidence for BSM physics emerges.
3. A light Higgs-like scalar is discovered, with properties that deviate from the SM.
4. A very heavy scalar state is discovered.
5. No Higgs boson candidate is discovered, and the entire mass range for a SM-like Higgs boson below 1 TeV is excluded.

In the last three cases, theoretical consistency implies that BSM physics must exist at the TeV energy scale that is observable at the LHC (with sufficient luminosity). Cases 4 and 5 would likely be incompatible with TeV-scale supersymmetry, whereas cases 2 and 3 would strongly encourage supersymmetric enthusiasts.

Case 1 would strongly cast doubts on the principle of naturalness. Nevertheless, is it still possible to learn about physics at higher mass scales?

From Howie Haber's talk at last week's LBNL SUSY Workshop

- There are many BSM ‘outs’ to the simple SM picture & UNTIL you make any announcements, we’re allowed to speculate.. here in the form of questions. These become more important if ‘nothing’ is seen. Just a few examples:

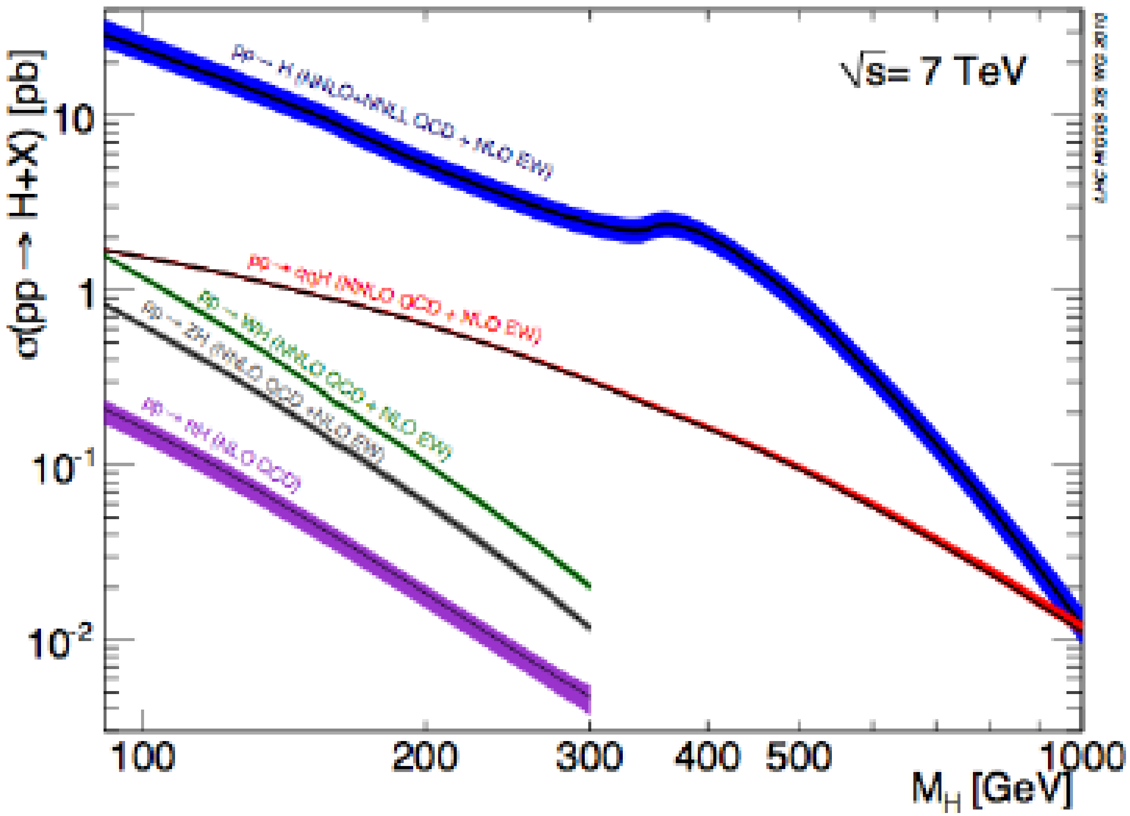
    - Can ‘the Higgs’ be missed at any/all masses?
    - Does ‘the Higgs’ really need to BE light ?
    - Is ‘the Higgs’ alone or does it have partners?
    - What is (the lack of ?) ‘the Higgs’ telling us?
    - If you find ‘it’, is ‘it’ really ‘the Higgs’ ?

- Almost any BSM scenario is likely to lead to changes in some aspect of SM Higgs physics. Are these changes critical for Higgs discovery at the LHC ?

- Furthermore, the Higgs itself provides an important window into the other sectors of BSM scenarios

Within the SM the production mechanisms for h at the LHC are well understood & the uncertainties are under control.

For light-ish Higgs, $gg \to h$ is by far the most important



- The observability of the Higgs then depends on 3 factors:

    1. σ (gg $\rightarrow$ h) must be sufficiently large
    2. The BFs of 'easily detectable' final states must be significant
    3. The SM backgrounds to these final states must, of course, be well understood

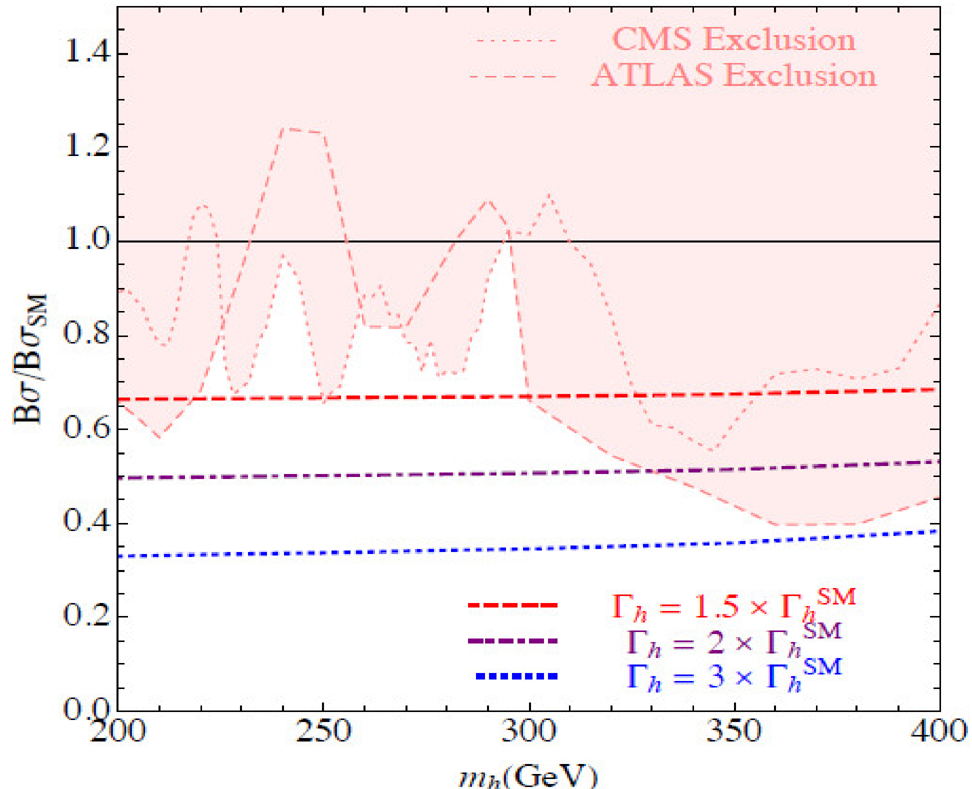
- New physics can certainly change the expectations for 1 & 2 (& maybe 3 as well !) Importantly the Higgs could still be in the mass range that is now 'excluded' (in the SM !) if the relevant $\sigma \cdot$B's are reduced

- There are no shortage of ways to make these alterations even in SUSY models

Alterations to Higgs σ's From BSM Physics

Some Examples

- A Very Simple Example : Couple h to a new singlet which itself does not couple to the SM fields and let h decay into it. Then all partial widths to SM final states are reduced by an overall common factor since the h total width is increased.



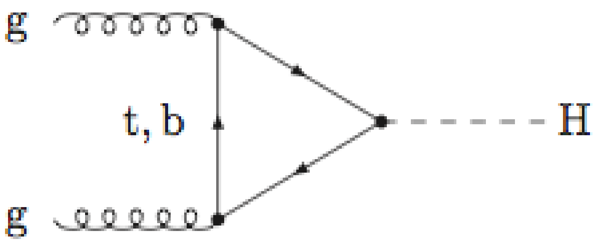
This scenario demonstrates that it is important to go 'deep' into low σ·B values in regions where the SM Higgs is already excluded.

→ Keep looking in excluded regions (no matter what else you find) !

Low etal, 1110.4405

- Instead of tree-level modifications, another relatively easy but still fairly direct way to alter the σ for h production is by adding new colored scalars to the SM top/bottom loops (e.g., the stops & sbottoms in the MSSM)

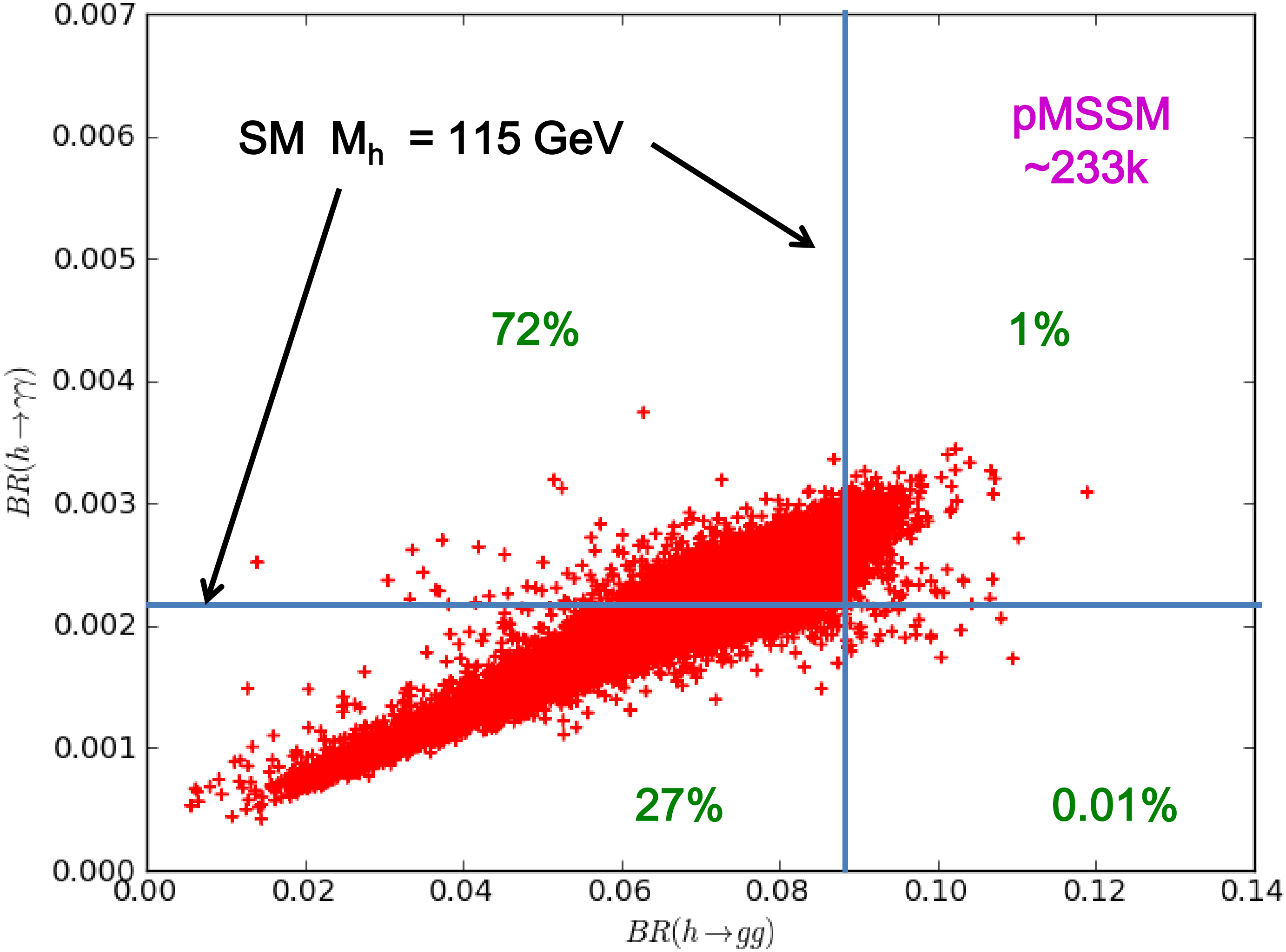
However :



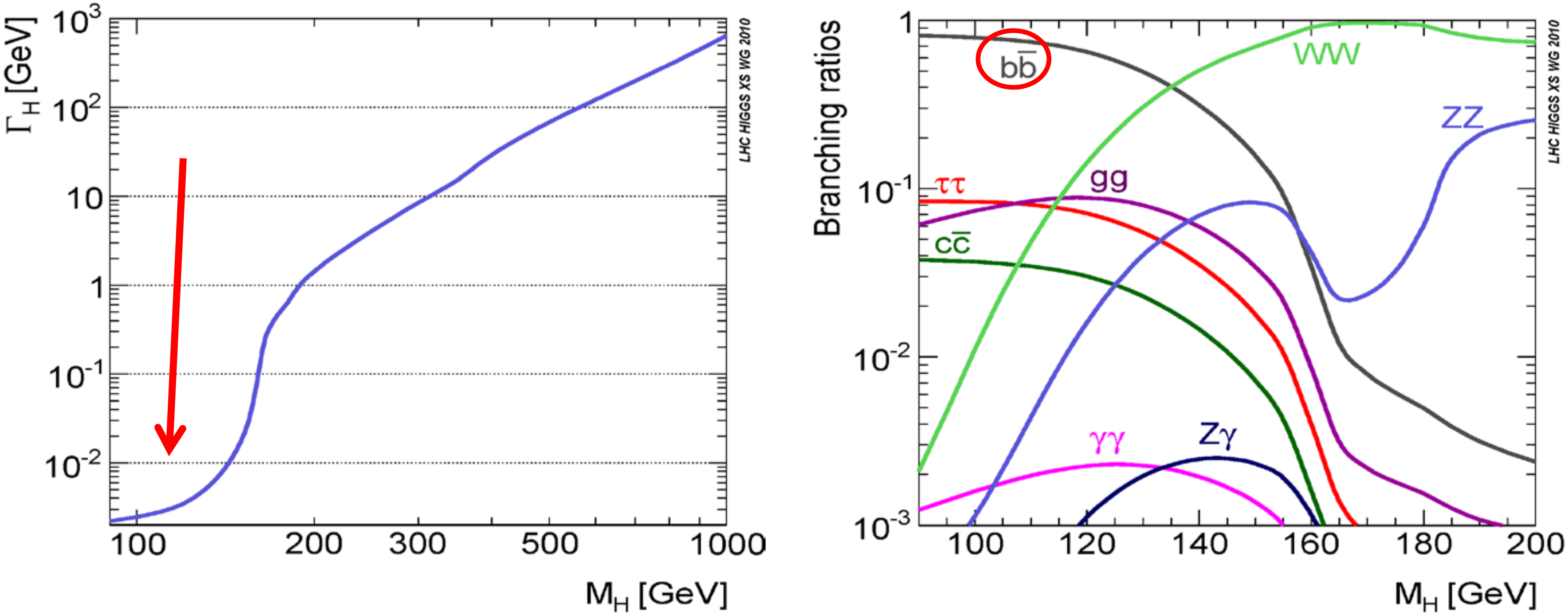
- In the MSSM, both constructive & destructive interference effects are possible depending on the squark masses, μ and the various A-terms

- A scan of the 19-dimensional parameter space of the pMSSM reveals that significant changes in both the SM σ & BFs are possible….

Points surviving spectrum, collider, flavor & DM constraints



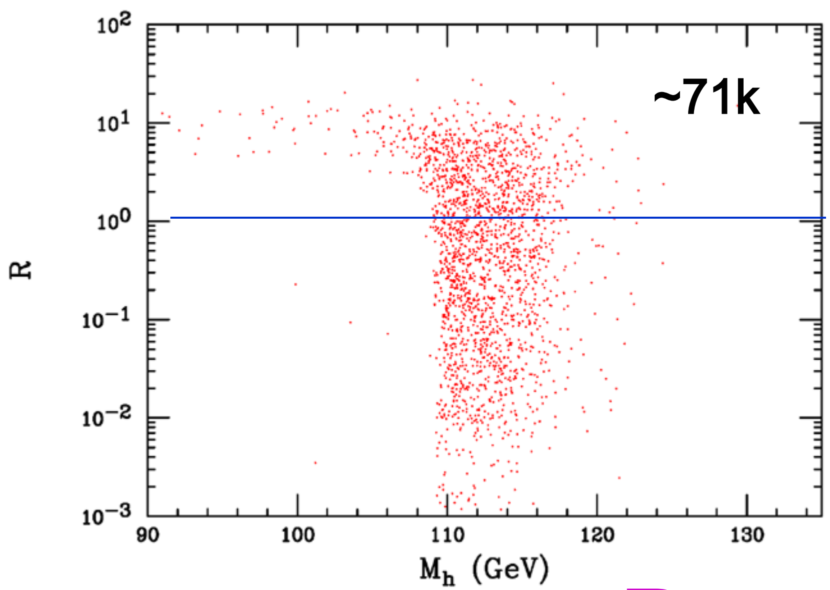
- The observability of a relatively light SM (or SM-like in the MSSM) h may also depend on the relative narrowness of this state due to the helicity suppression in $h \to b\bar{b}$:

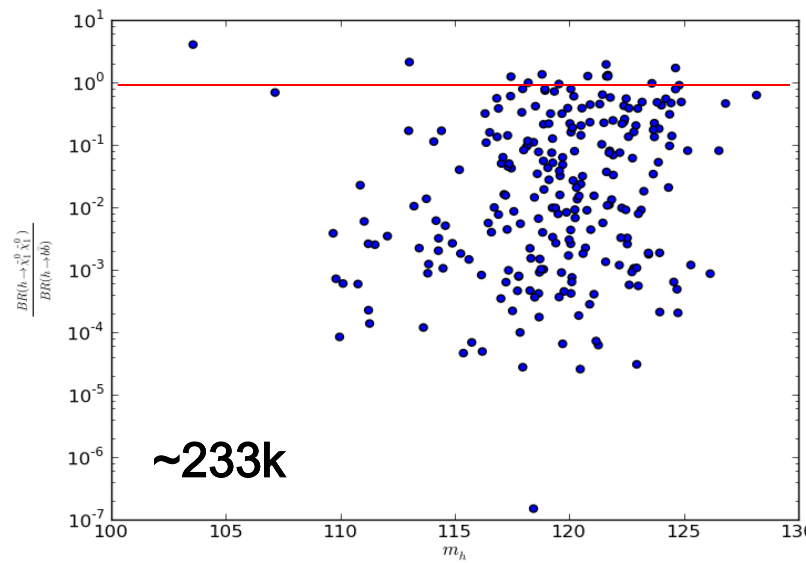


- Below ~$2M_W$ the Higgs is sufficiently narrow that any new decay modes can be very important & may even dominate

- Again, the simplest possibility: add a lighter singlet scalar, S, to the SM (or MSSM → NMSSM) which then can leads to dominant decays such as $h \to aa \to 4\tau$'s or $2b$'s$+2\tau$'s

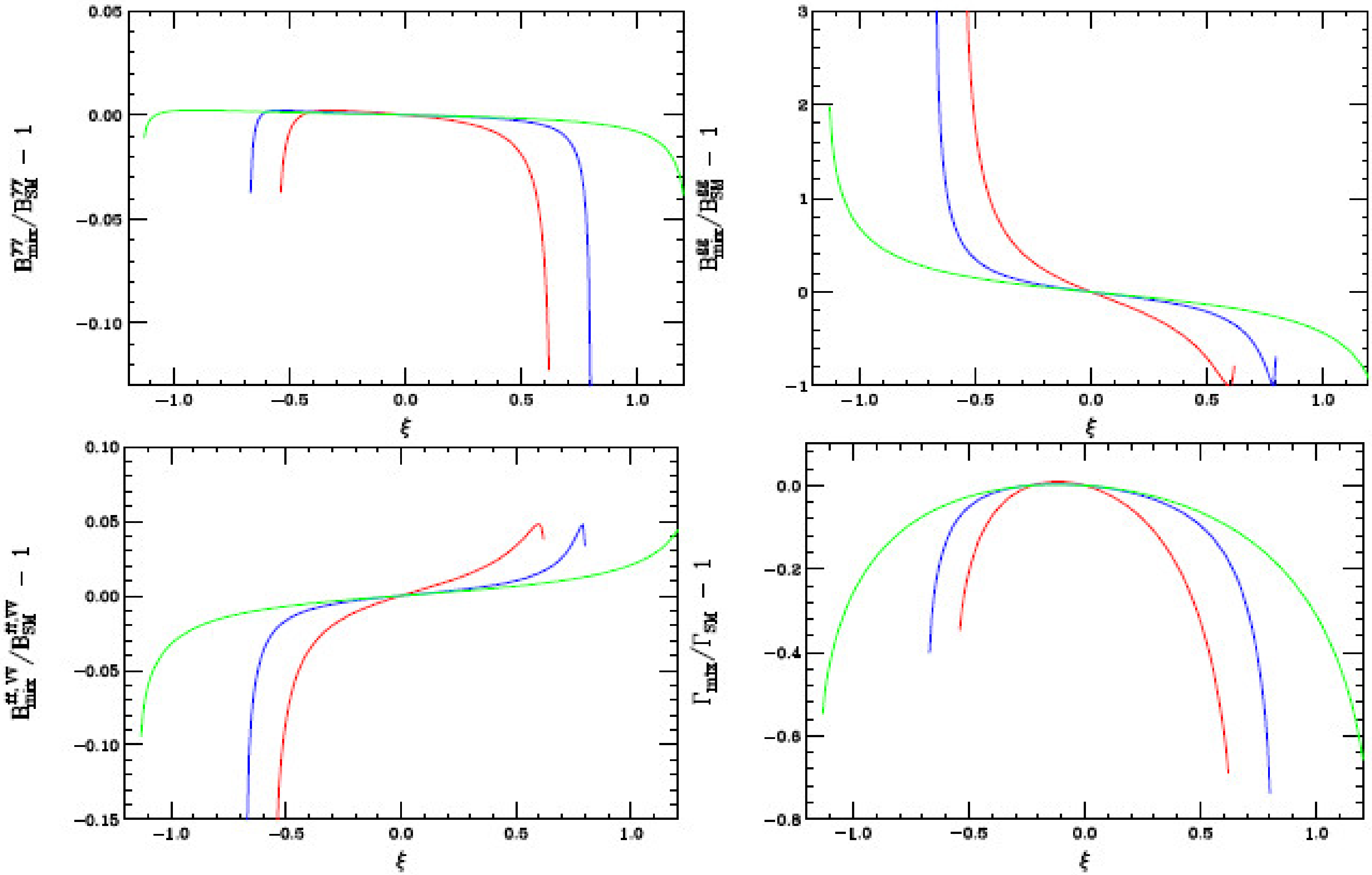
- Even in the (p)MSSM, w/o adding any extra particles, decays such as $h \to \chi\chi$ (i.e., LSPs!) can still be dominant. Here are the results from two different pMSSM scans:





$$R = \Gamma(\chi) / \Gamma(b)$$

- Mixing h with the radion in the RS model can lead to BF alterations .. but mostly to $h \rightarrow gg$

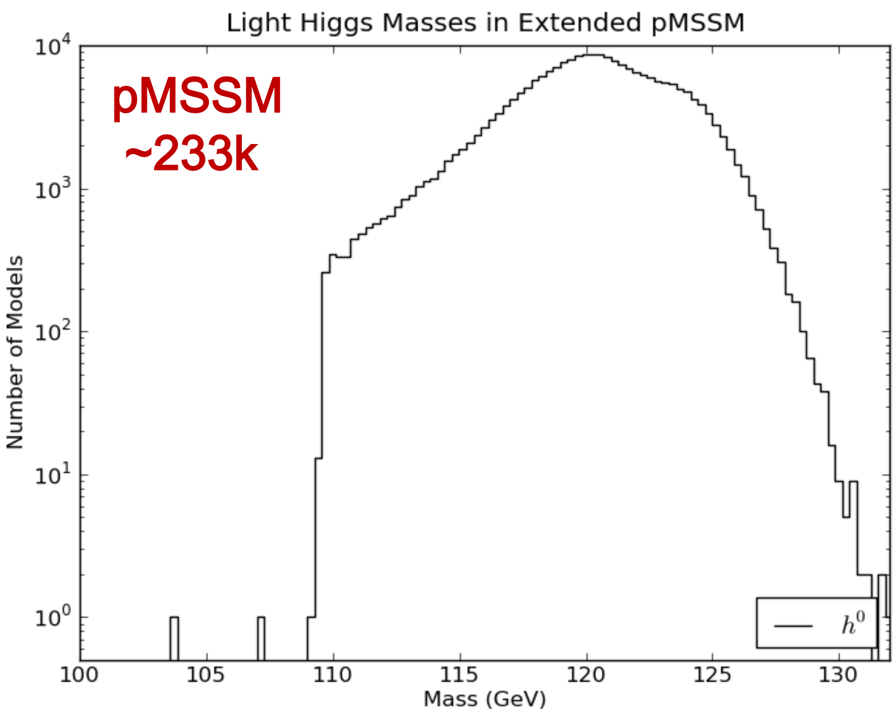


Is ‘the SM Higgs’ necessarily light ?

Heavier Higgs ?

- As we saw, the expected lightness of h (~115-140 GeV) in the SM is the result of data, i.e., the Gfitter EWK results

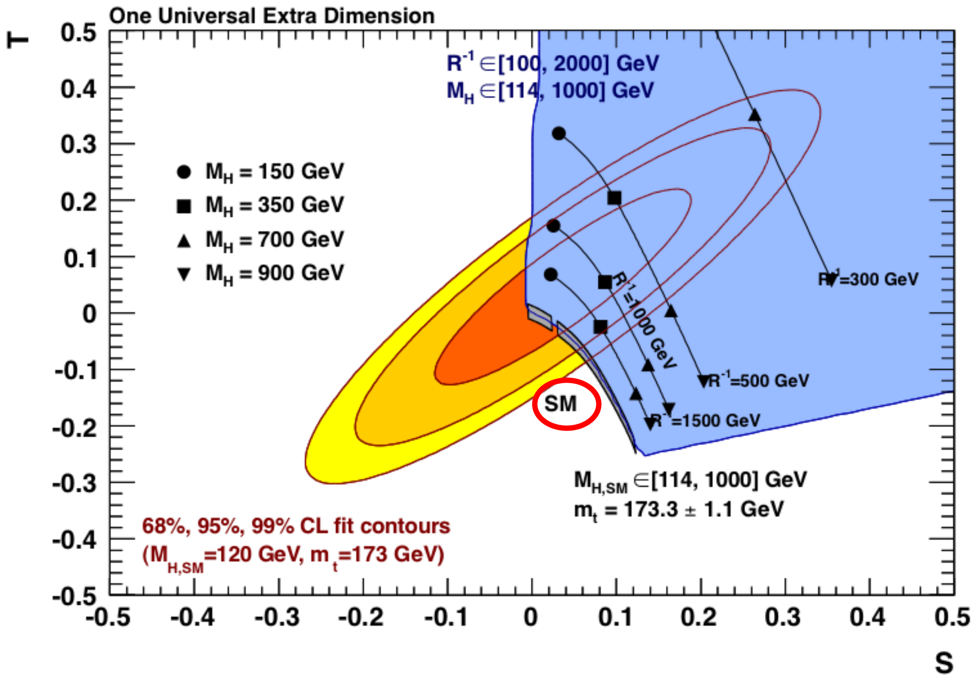
- Instead, in the MSSM, the mass of the h is driven by the RC's generated by top/top squark loops and so < ~ 135 GeV, for top squarks < ~ 3-4 TeV (We'll come back to this…)

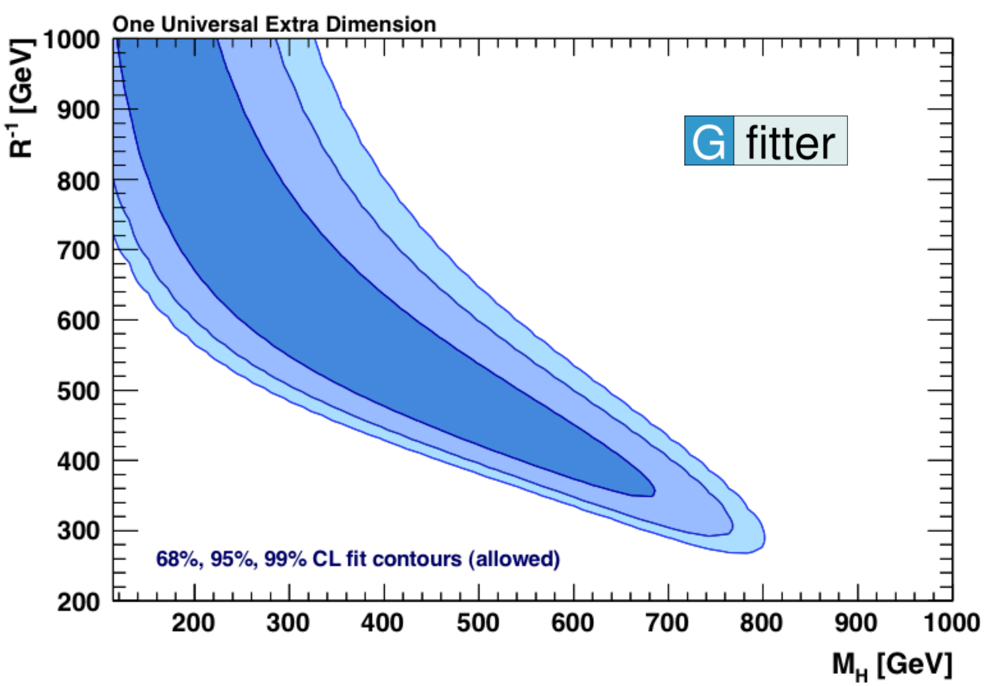


- Both of these expectations are only correct within their specific frameworks

- Adding other new 'stuff' beyond the SM or the MSSM can alter these results

For example….





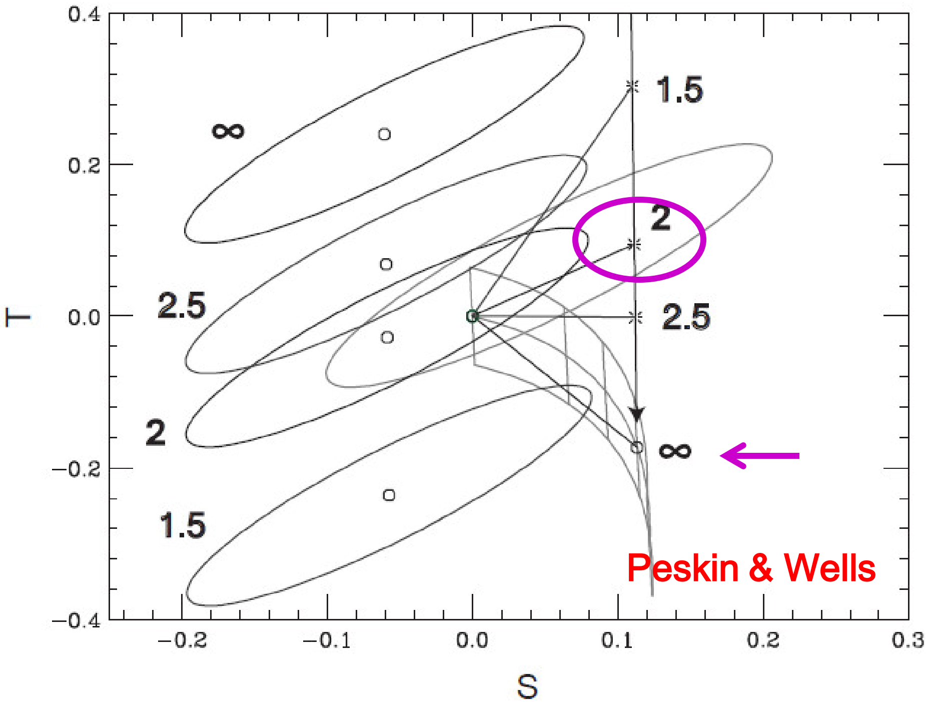
- If the SM h were heavy we could 'move' the prediction 'back' inside the S-T ellipse by adding some new physics

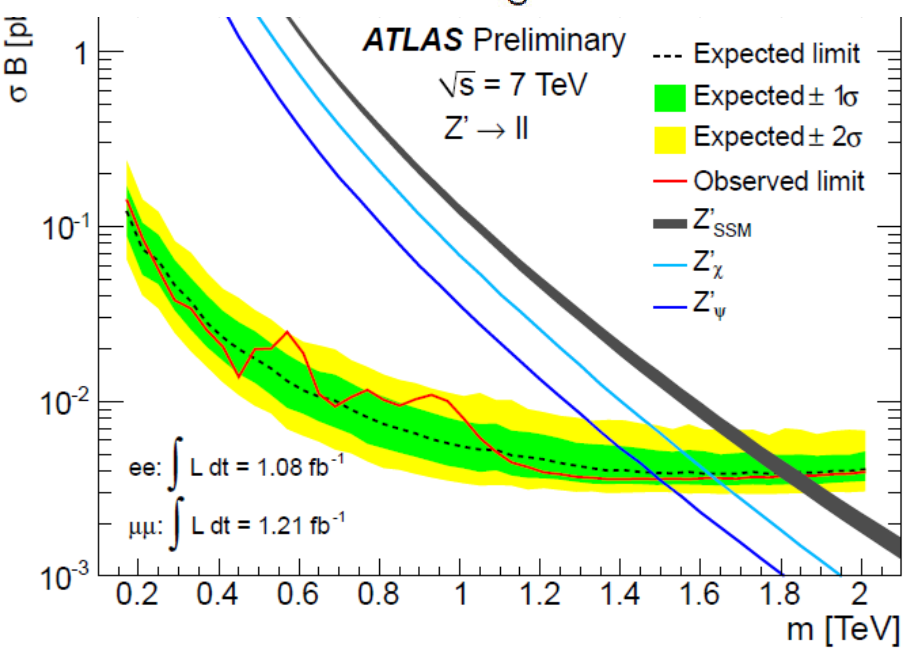
- UED with KK-parity is a perfect example of this.. KK contributions offset those from heavy Higgs. Here the best fit size of the extra dimension is strongly correlated with the h mass

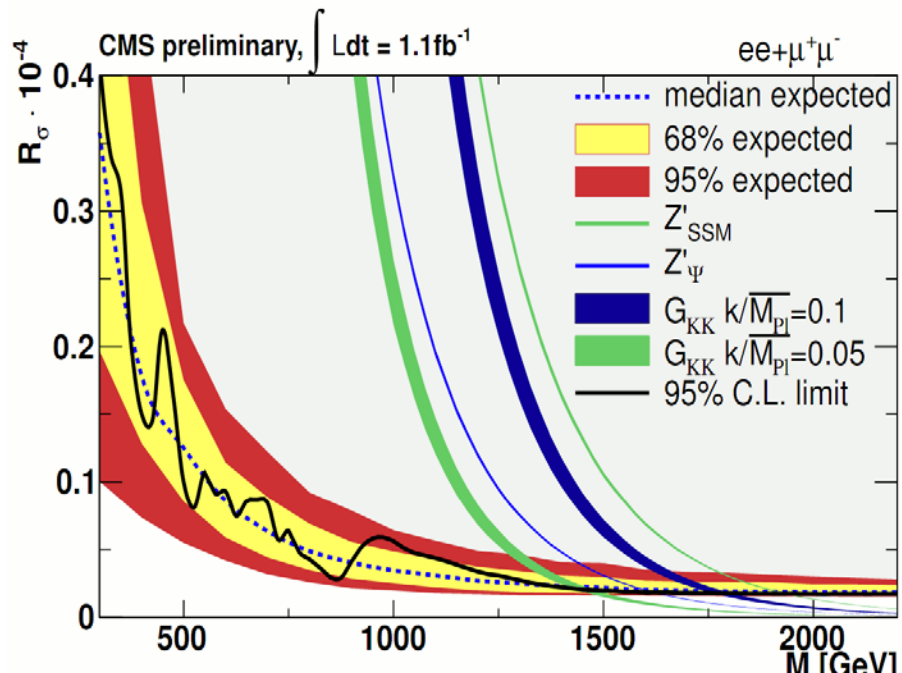
- Qualitatively similar results occur for warped ED

- A new Z’ that mixes w/ the SM Z is another obvious & well-studied example.

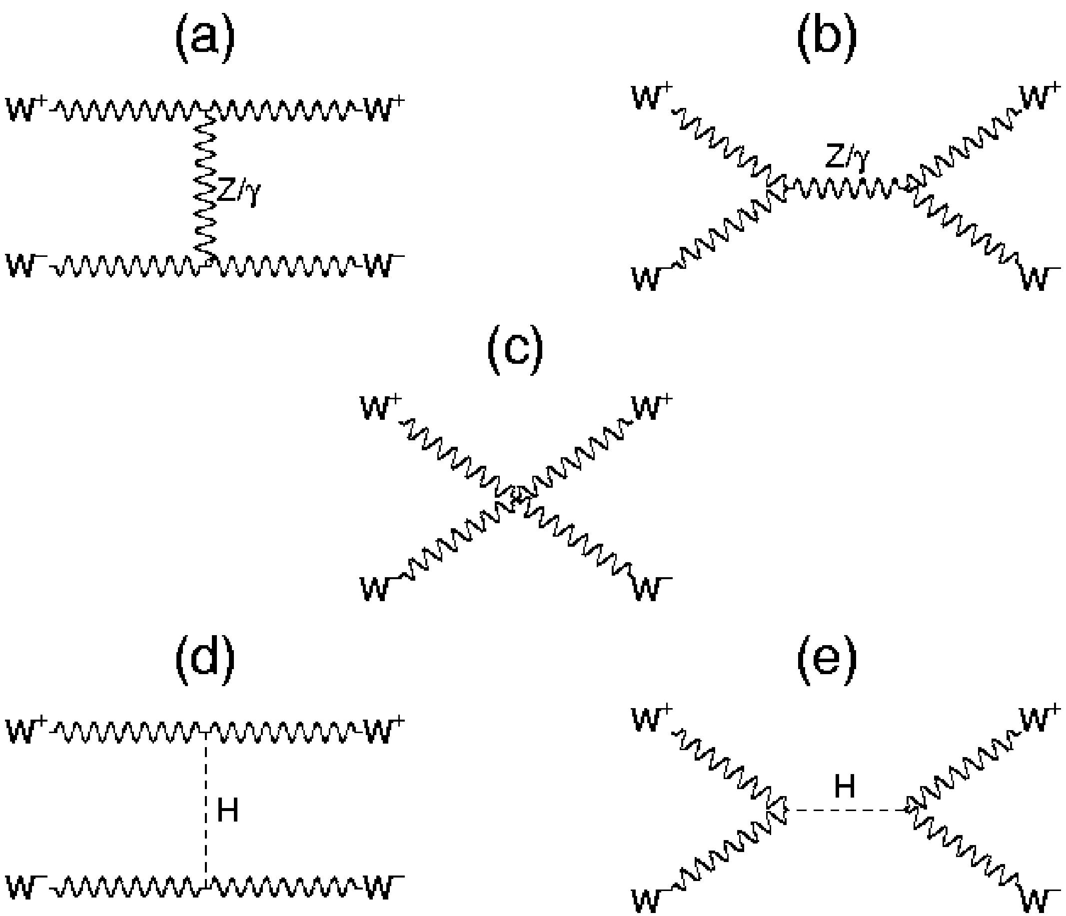
- However for a really heavy h >~500 GeV the Z’ must be <~ 2 TeV..not too far from current LHC bounds







• A reminder: we just can't make the SM h as heavy as we'd like due to partial wave unitarity constraints on 'WW scattering'. However, a 500-600 GeV Higgs, above the current LHC limits, is certainly 'OK'…



- Perturbation theory & lattice studies tell us that the h mass is bounded from above:

  h < ~ 0.8 TeV

  even if the Higgs is strongly coupled

Is h necessarily light in SUSY ?

- In the MSSM, with sparticles below ~ 3-4 TeV, h <~135 GeV is mandatory & is directly calculable from the MSSM input parameters up to Δm_h ~ 2-3 GeV.

It has 2 pieces: one from tree level & another from top & stop loops:

$$m_h^2 \lesssim m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right],$$

$X_t = A_t - \mu/t_\beta$ $\qquad$ $M_S^2 = m_{t1}\, m_{t2}$

- Of course, many SUSY models go beyond the MSSM . The reason that the h mass must be light is that the MSSM + SM gauge inv. + renormalizability @ tree level implies that $m_h \leq M_Z$ & that can only be added to by large, e.g., top/stop, etc., loops. Therefore, we can:

1. Change the tree-level result or
2. Change the gauge symmetry or
3. Put more stuff in the loops or
4. Add power suppressed non-renormalizable terms

(while also still satisfying all of the experimental constraints.)

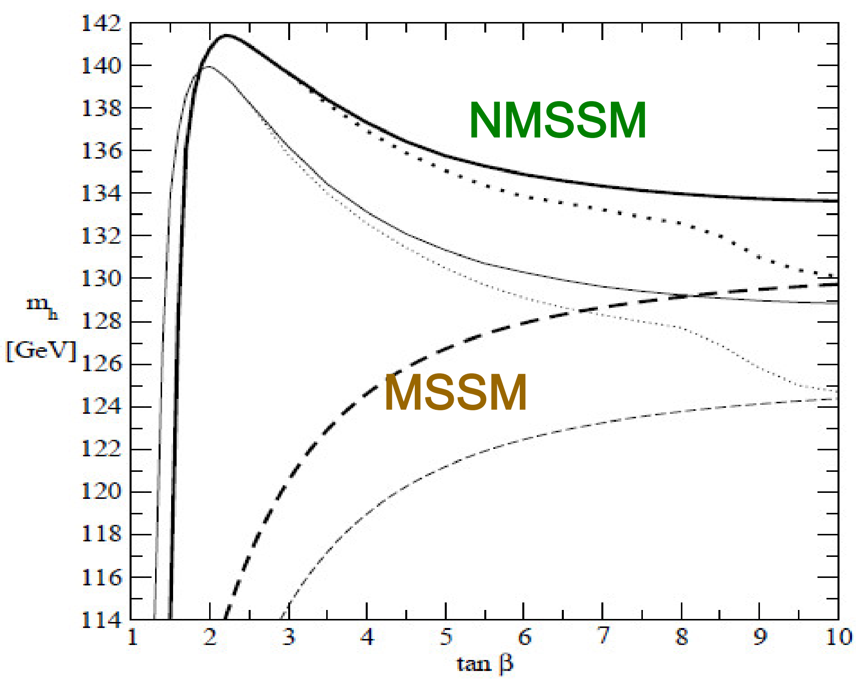
This has sprouted a major industry over the past 2 decades as all these possibilities have been explored at some level

Let's have a (quick) look !

- In the NMSSM the additional singlet alters the Higgs potential & thus the tree-level mass for h :

$$
\begin{aligned}
V = & V_F + V_D + V_{\rm soft} \\
= & \; |\lambda|^2 |S|^2 \left(H_u^\dagger H_u + H_d^\dagger H_d \right) + \left| \lambda (H_u^{\rm T} \epsilon H_d) + \kappa S^2 \right|^2 \\
& + \frac{1}{2} g_2^2 |H_u^\dagger H_d|^2 + \frac{1}{8} (g_1^2 + g_2^2) \left(H_u^\dagger H_u - H_d^\dagger H_d \right)^2 \\
& + m_{H_u}^2 H_u^\dagger H_u + m_{H_d}^2 H_d^\dagger H_d + m_S^2 |S|^2 + \left(\lambda A_\lambda (H_u^{\rm T} \epsilon H_d) S + \frac{1}{3} \kappa A_\kappa S^3 + c.c. \right)
\end{aligned}
$$

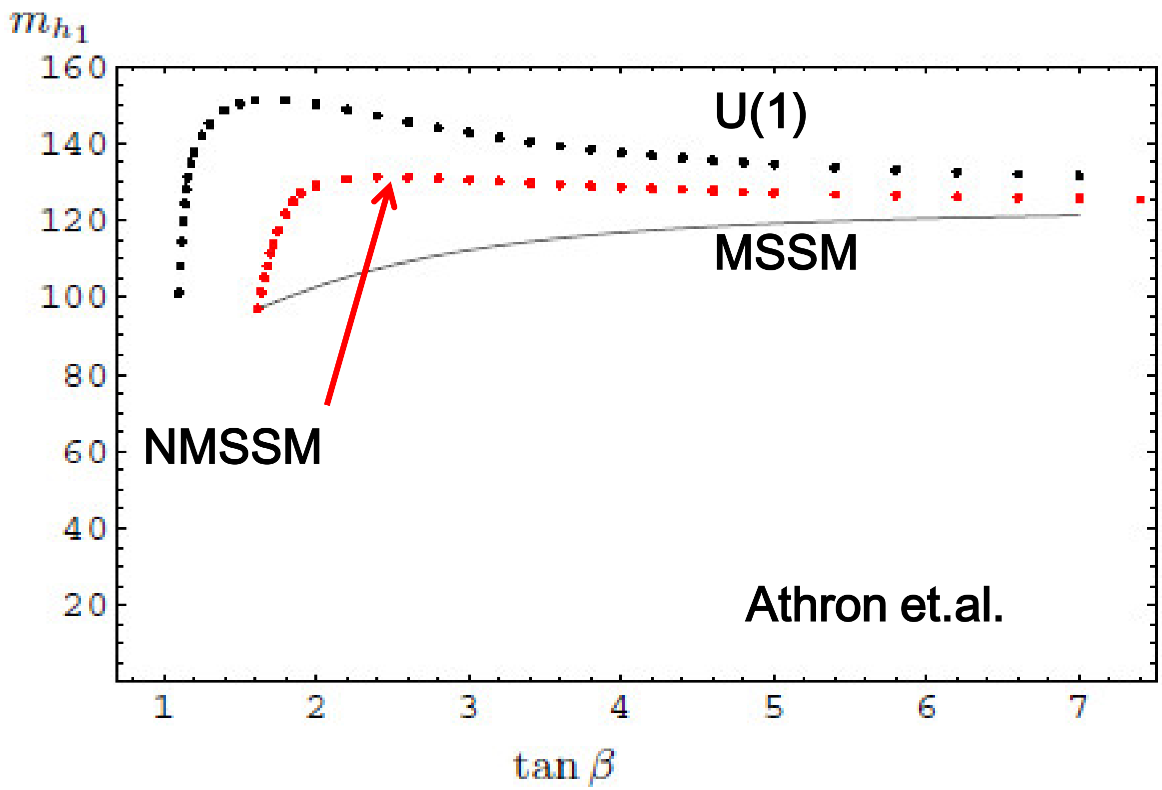
$\longrightarrow$ $$(m_{H_1}^{\rm NMSSM})^2 < m_Z^2 \left(\cos^2(2\beta) + \frac{2|\lambda|^2 \sin^2(2\beta)}{g_1^2 + g_2^2} \right)$$



Still, we only gain ~10 GeV on upper limit on h's mass due to the trade off in tan β dependence

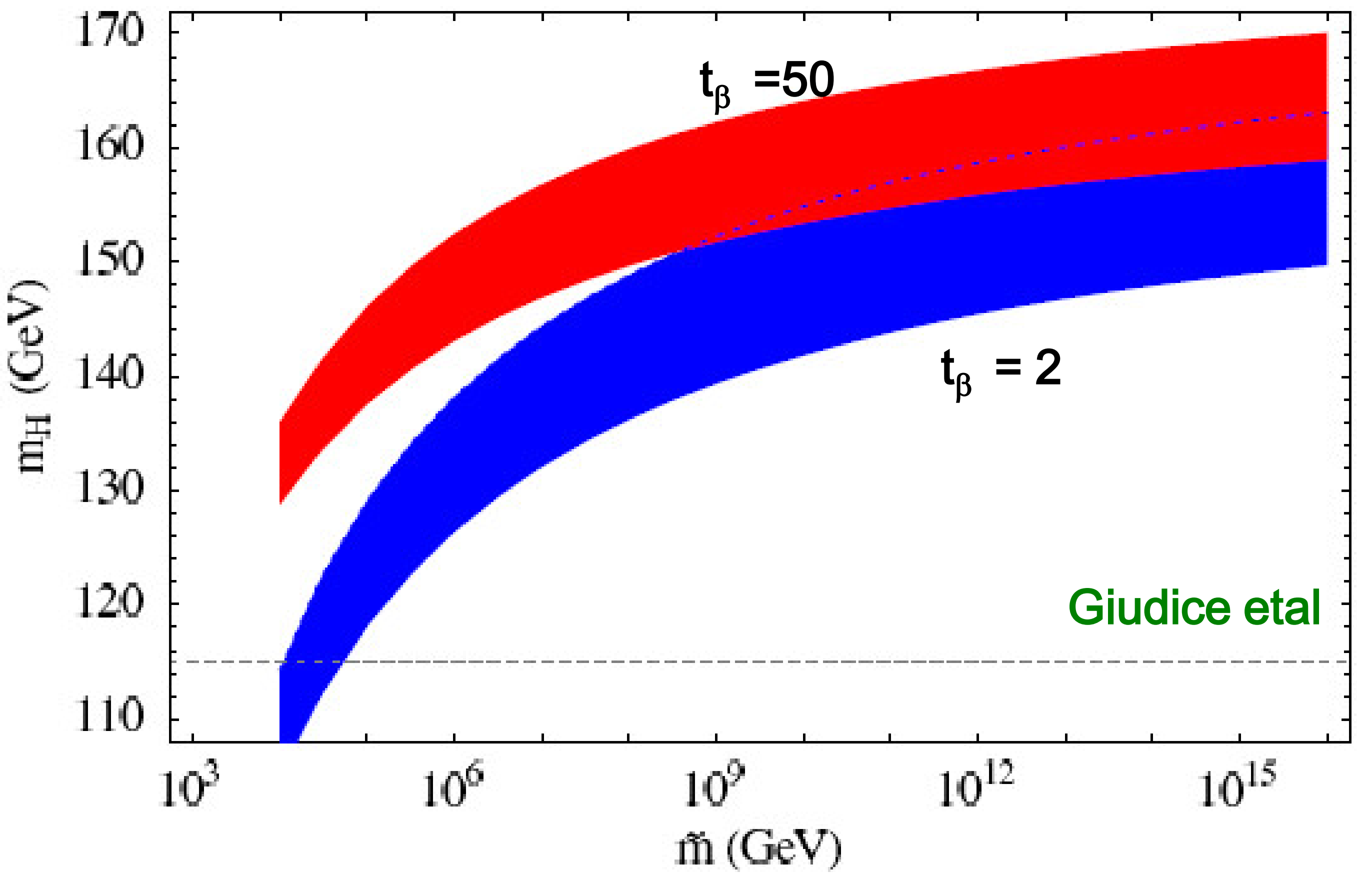
Ellwanger

- What about adding an extra U(1), e.g., from an E_6 gauge symmetry ? This also produces additional terms in the Higgs potential…



For the same input assumptions, the extra U(1) model prediction is only a little larger by another ~10-15 GeV…

• In Split-SUSY we give up trying to address the fine-tuning problem & the associated spectrum assumptions & make all sfermions heavy w/ lighter gauginos. This drives the h mass to larger values due to enhanced loops… but not too large !

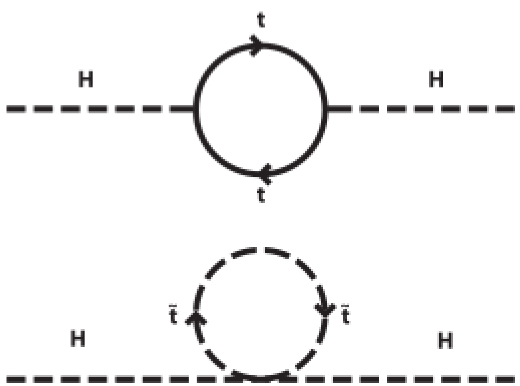


~ $2M_W$!

← MSSM

As an aside on fine-tuning…

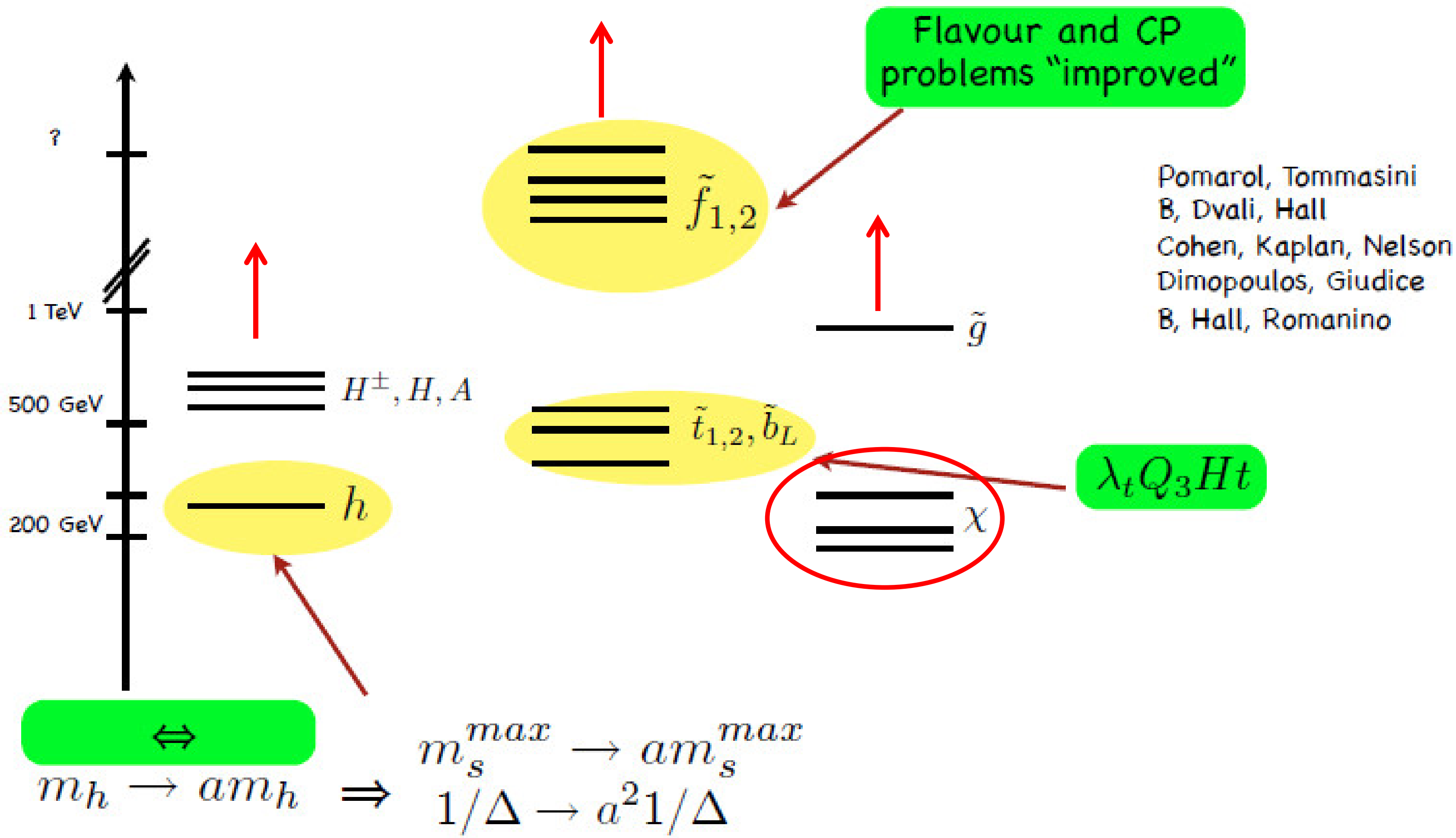
- Within the MSSM it is interesting to turn the tables & ask what the Higgs sector is telling us about the SUSY spectrum if we assume that fine-tuning is THE most important issue …



- To remove the largest amount of fine-tuning due to top/Higgs loops we must (at the very least !) have a stop & Higgsino in the ~few 100's of GeV mass range. The other sq's can be >> ~1 TeV

- This picture tells us we need to look for direct stop & gaugino production at the LHC (& not stops arising from gluino decays)

Two issues (logically almost independent)



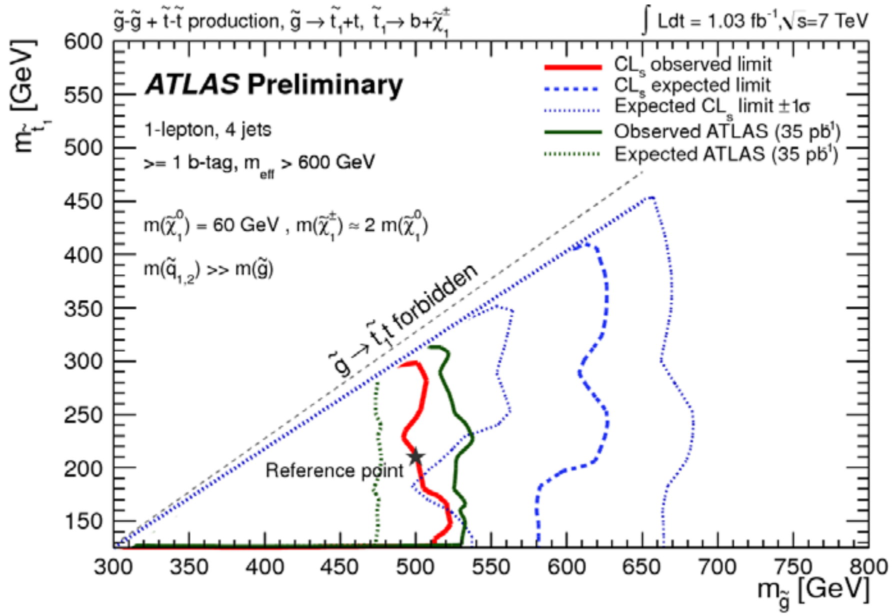
B, Hall, Nomura, Rychkov

Barbieri

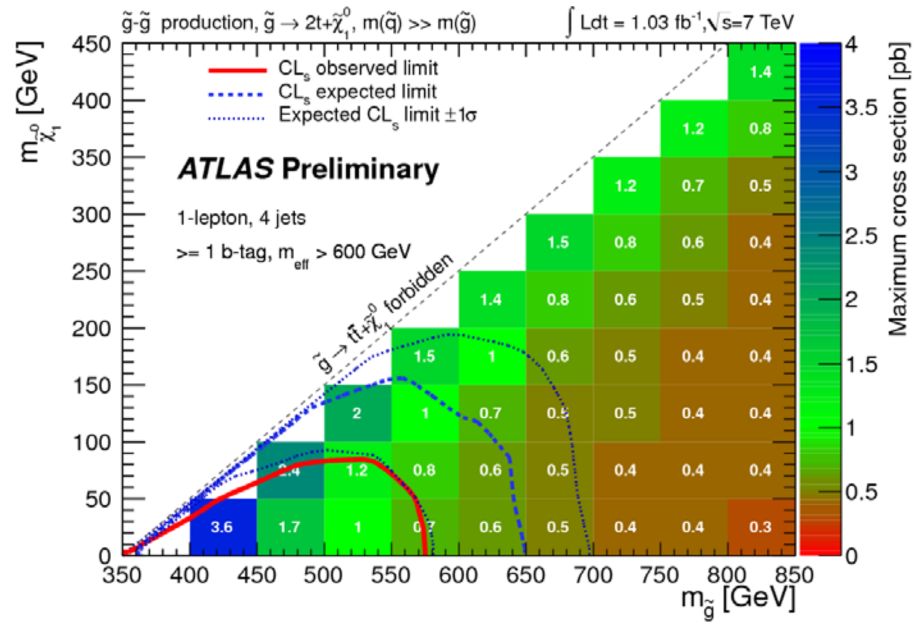
Interpretation of the results

- Two phenomenological interpretations depending on mass hierarchy and stop decay mode

$\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^{\pm}$



$\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$



gluino-stop plane: m(~g)>m(~t1).
Lightest neutralino mass → 60 GeV,
m(chargino) ~ 2 * m(neut)

gluino masses below 520 GeV is excluded @ 95% CL.

gluino masses below 570 GeV (and up to LSP mass 40 GeV) excluded @ 95% CL.

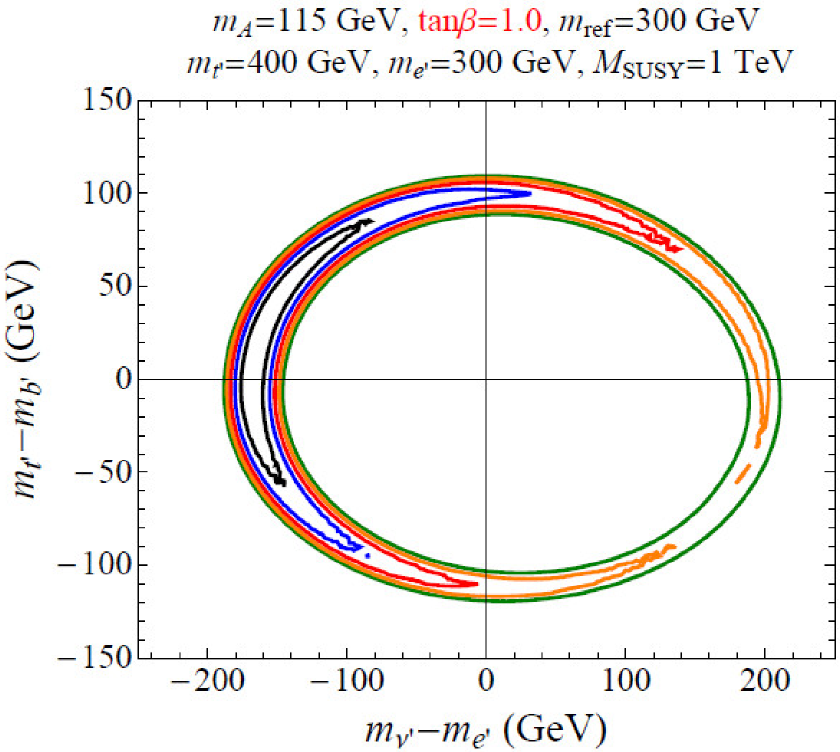
h mass in SUSY cont.

- Add a 4G, i.e., the 4GMSSM. This adds new very large loop corrections $\sim G_F m_{t',b'}^4$ that can make h fairly heavy. 4G quark masses <~ 600 GeV are required by unitarity.

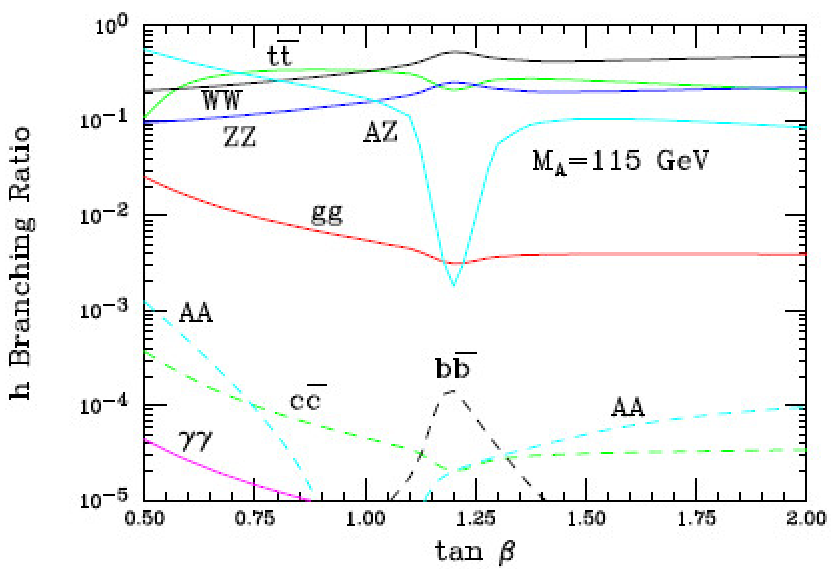
- This model is reasonably restricted by both direct 4G quark (as well as the h, A) searches at LHC. However, apart from a ~35 pb^{-1} ATLAS search, these all rely on b-tags (to reduce backgrounds) & thus assume CKM4 has special structure

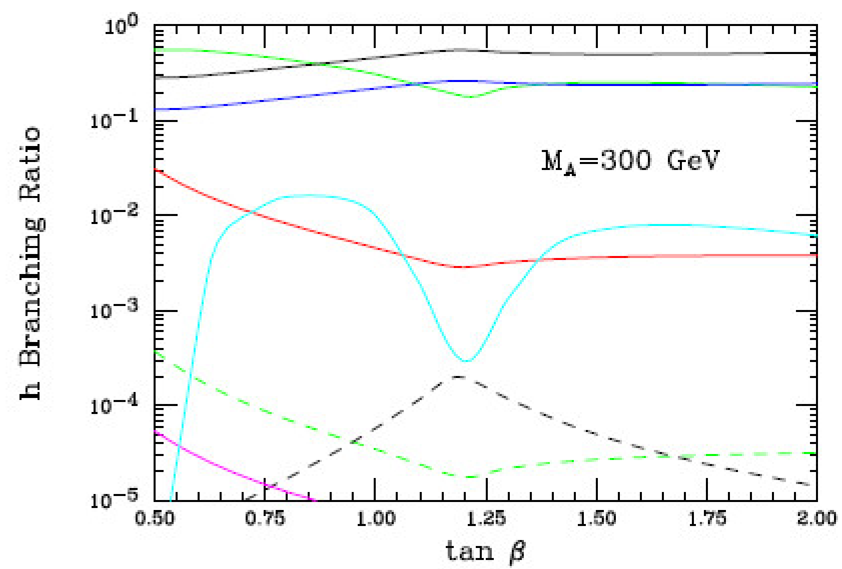
- h cross sections are not necessarily increased by ~ 9 as in the 4GSM due to squark-quark loop cancellations as in the 3GMSSM.

- h BFs can be significantly different than those in the SM or 4GSM

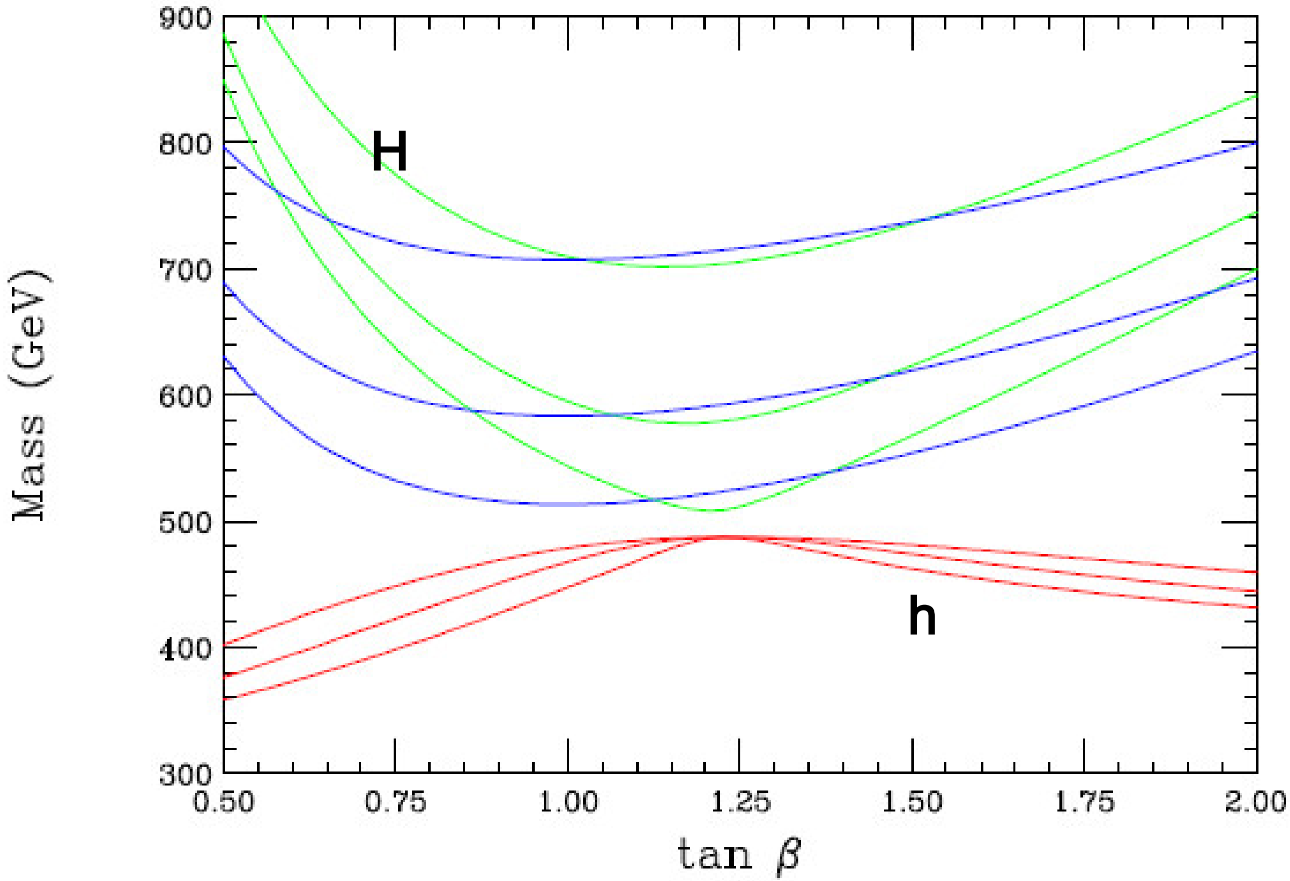


- A dedicated study of the full parameter space, e.g., the influence of off-diagonal CKM & a more realistic SUSY spectrum, has not yet been performed for the 4GMSSM… gives significantly increased flexibility





<u>Bottom Line</u>: I think there is somewhat MORE flexibility here than Sally does… 4GSM ≠ 4GMSSM so more experimental data from LHC plus more work by theorists will tell us soon.



• Add Higher Dim Operators to the Super-& Kahler Potentials:

Carena etal
1005.4887

$$W = \mu H_u H_d + \frac{\omega_1}{2M}(H_u H_d)^2$$

$$K = H_d^\dagger e^{2V} H_d + H_u^\dagger e^{2V} H_u + \Delta K^{\not c} + \Delta K^{c} ,$$

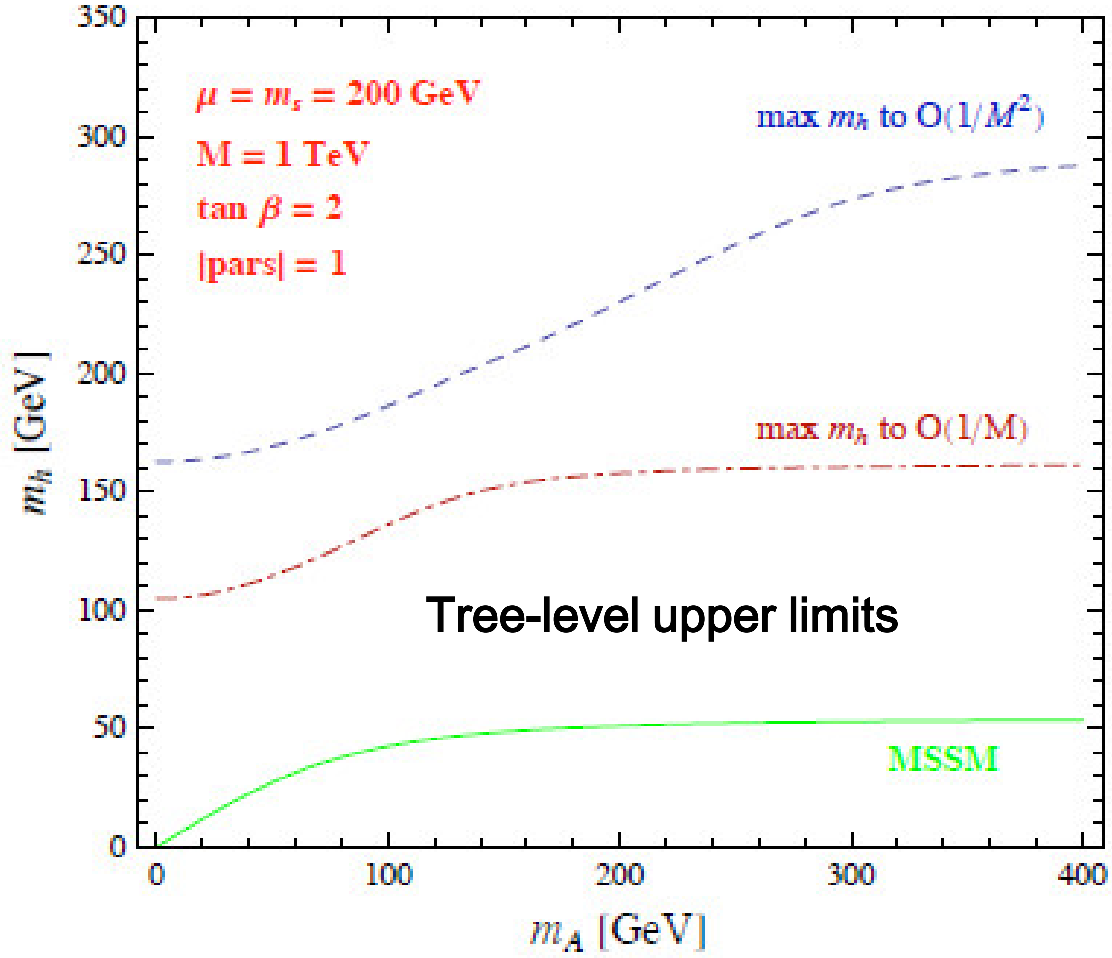
where

$$\Delta K^{\not c} = \frac{c_1}{2|M|^2}(H_d^\dagger e^{2V} H_d)^2 + \frac{c_2}{2|M|^2}(H_u^\dagger e^{2V} H_u)^2 + \frac{c_3}{|M|^2}(H_u^\dagger e^{2V} H_u)(H_d^\dagger e^{2V} H_d)$$

$$\Delta K^{c} = \frac{c_4}{|M|^2}|H_u H_d|^2 + \left[\frac{c_6}{|M|^2} H_d^\dagger e^{2V} H_d + \frac{c_7}{|M|^2} H_u^\dagger e^{2V} H_u\right](H_u H_d) + \text{h.c.}$$

Violates custodial symmetry

Lot's of parameters but even after imposing a reasonable set of constraints a significantly larger tree level h mass is allowed…

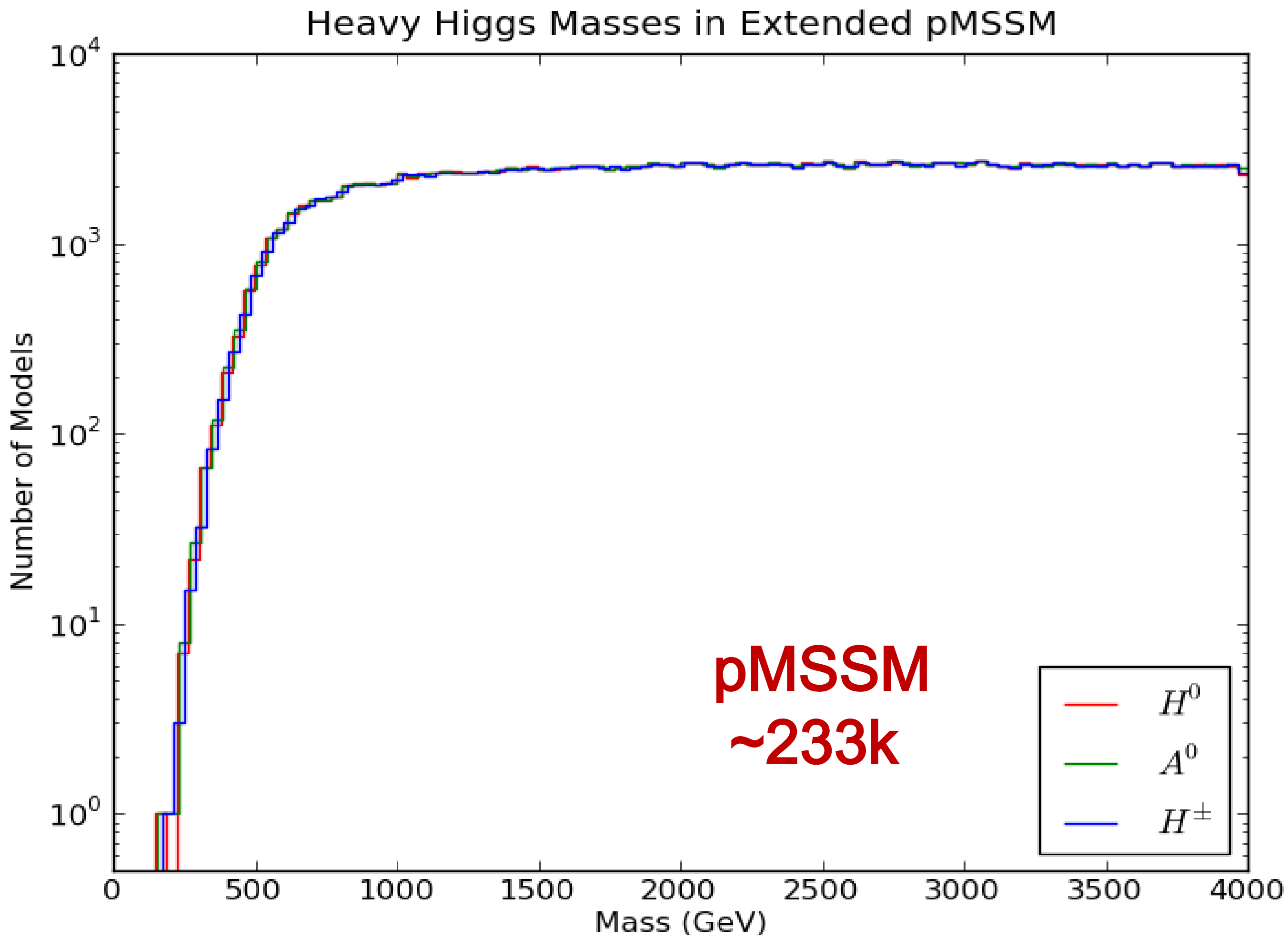


Carena etal

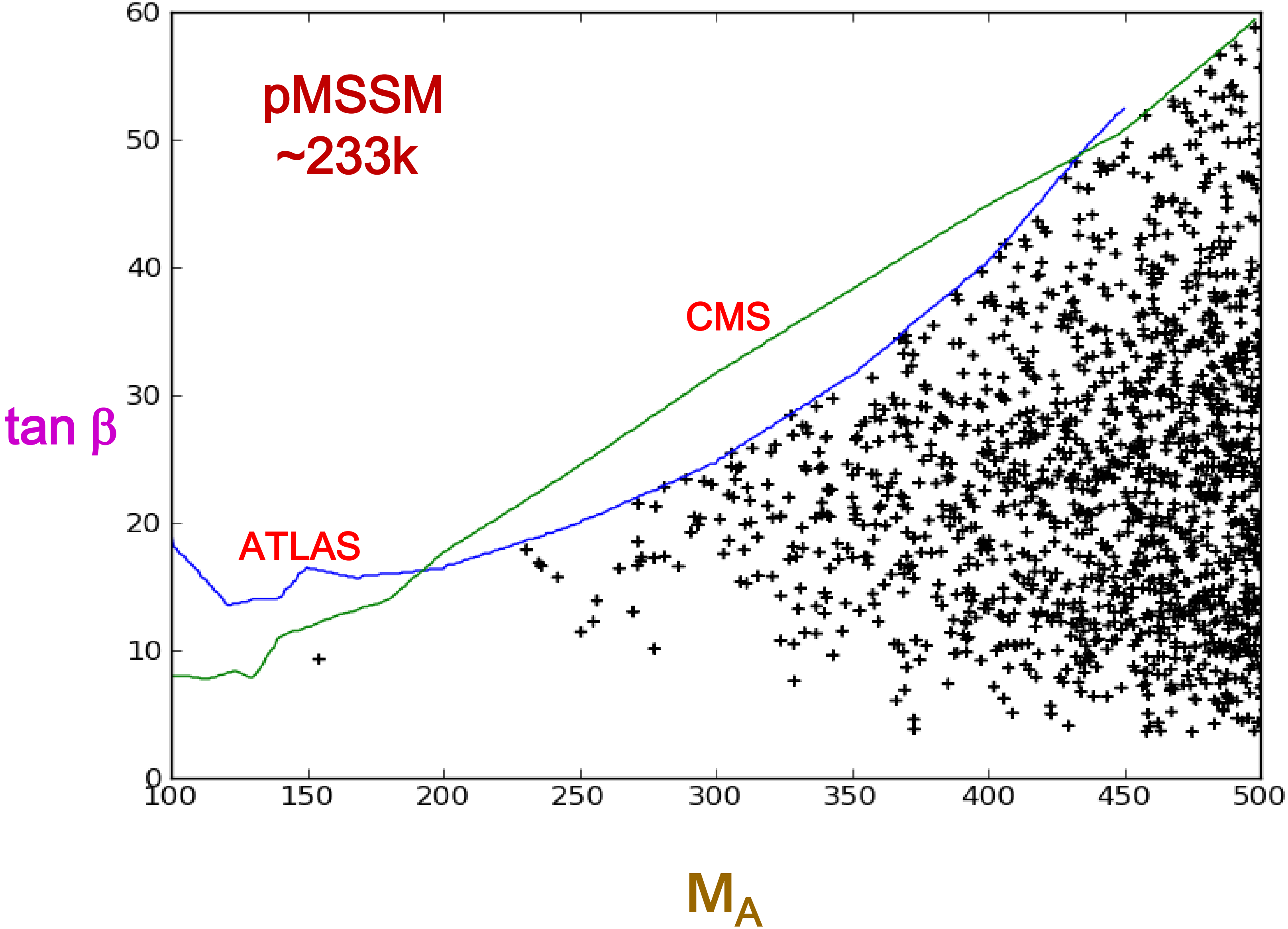
- Couplings & decays can also be significantly affected.

Higgs Partners Play an Important Role in SUSY Searches

Reminder: In the MSSM, H, A & $H^{\pm}$ generally track each other in mass so, e.g., direct searches for $H^{\pm}$ above the top mass are very important . Flavor constraints now rule here



A,H →ττ



pMSSM
~233k
CMS
ATLAS
tan β
M_A
60
50
40
30
20
10
0
100
150
200
250
300
350
400
450
500

Summary & Conclusions

- If a Higgs-like object is found (soon ?) it's properties must be precisely determined. Is it 'the Higgs' ?
- There are many ways to significantly alter the expected Higgs properties in both the SM & MSSM
- No matter what, don't ignore 'excluded' regions..go deep !
- Is there 'Higgs' coverage in the 90-110 GeV mass region ?
- Access to the non-SM part of the scalar sector is important
- Be prepared for surprises

BACKUPS

Aside: watch out using spectrum generator codes as black boxes..