Is (are) the Higgs Boson (s) Hidden?

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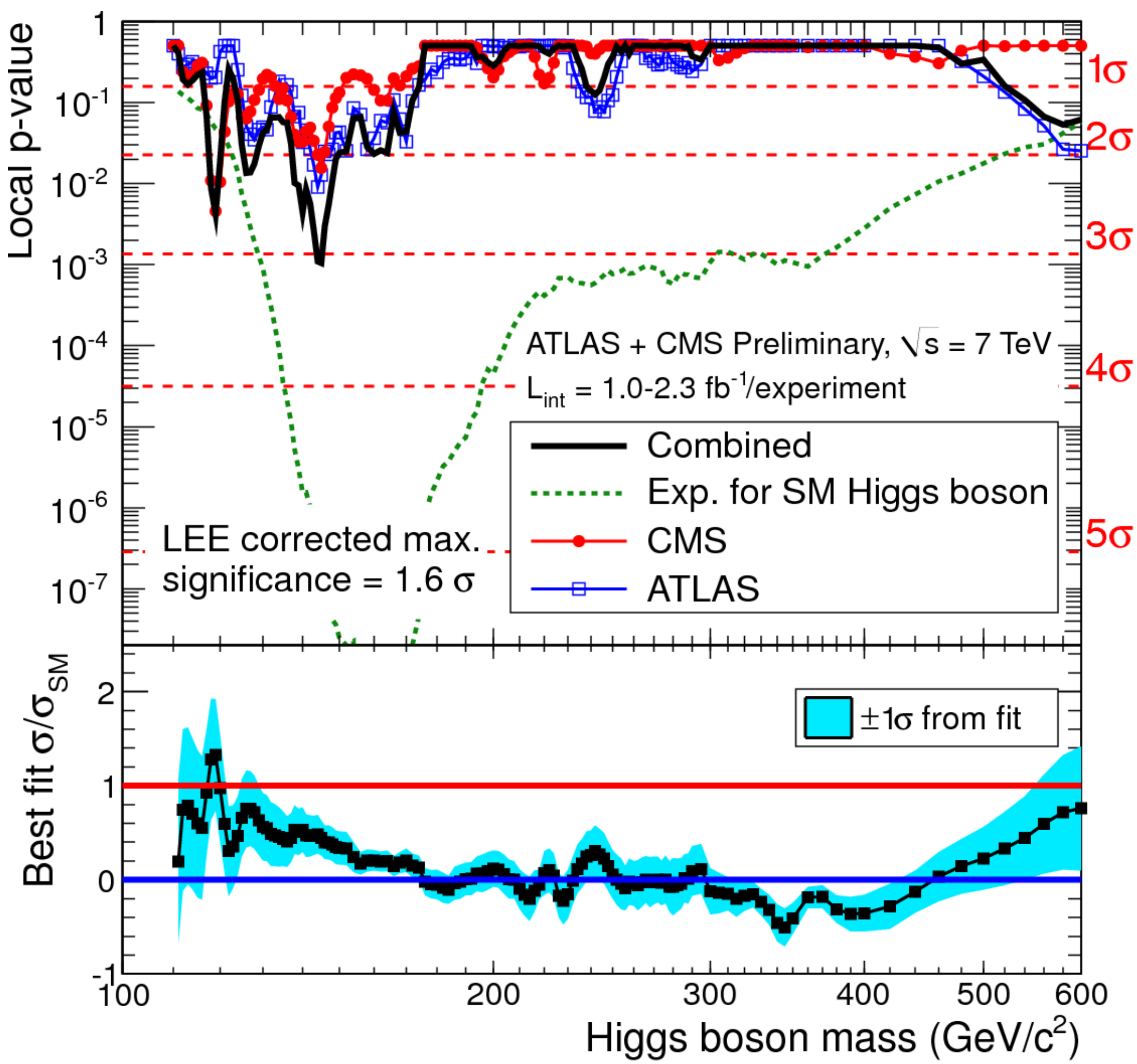
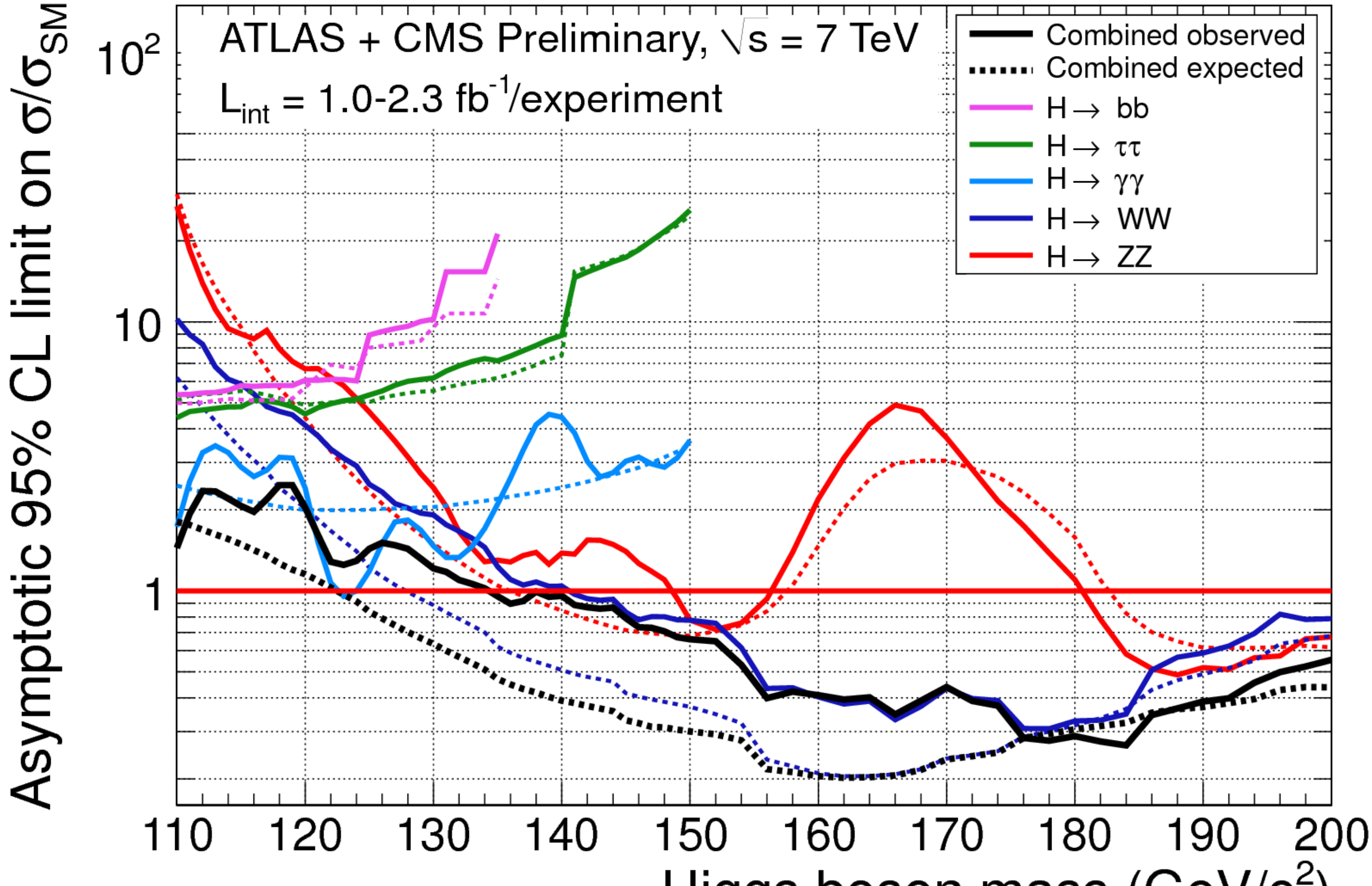
Higgs Combination



Note minimum p values are at $\sim 118 - 119$ GeV and ~ 140 GeV.



Note: Both CMS amd ATLAS have excesses in: $\gamma\gamma$ at $118-119~\mathrm{GeV}$ and at $140~\mathrm{GeV}$; in $ZZ \to 4\ell$ at 118 and $140~\mathrm{GeV}$ but also spread out (in ATLAS analysis, but not in CMS analysis). The $WW \to \ell\nu\ell\nu$ excess is automatically spread out so any m_h might explain if cross section is large enough. In $\gamma\gamma$ the ATLAS excess at $128~\mathrm{GeV}$ is compensated by a CMS deficit at that mass.

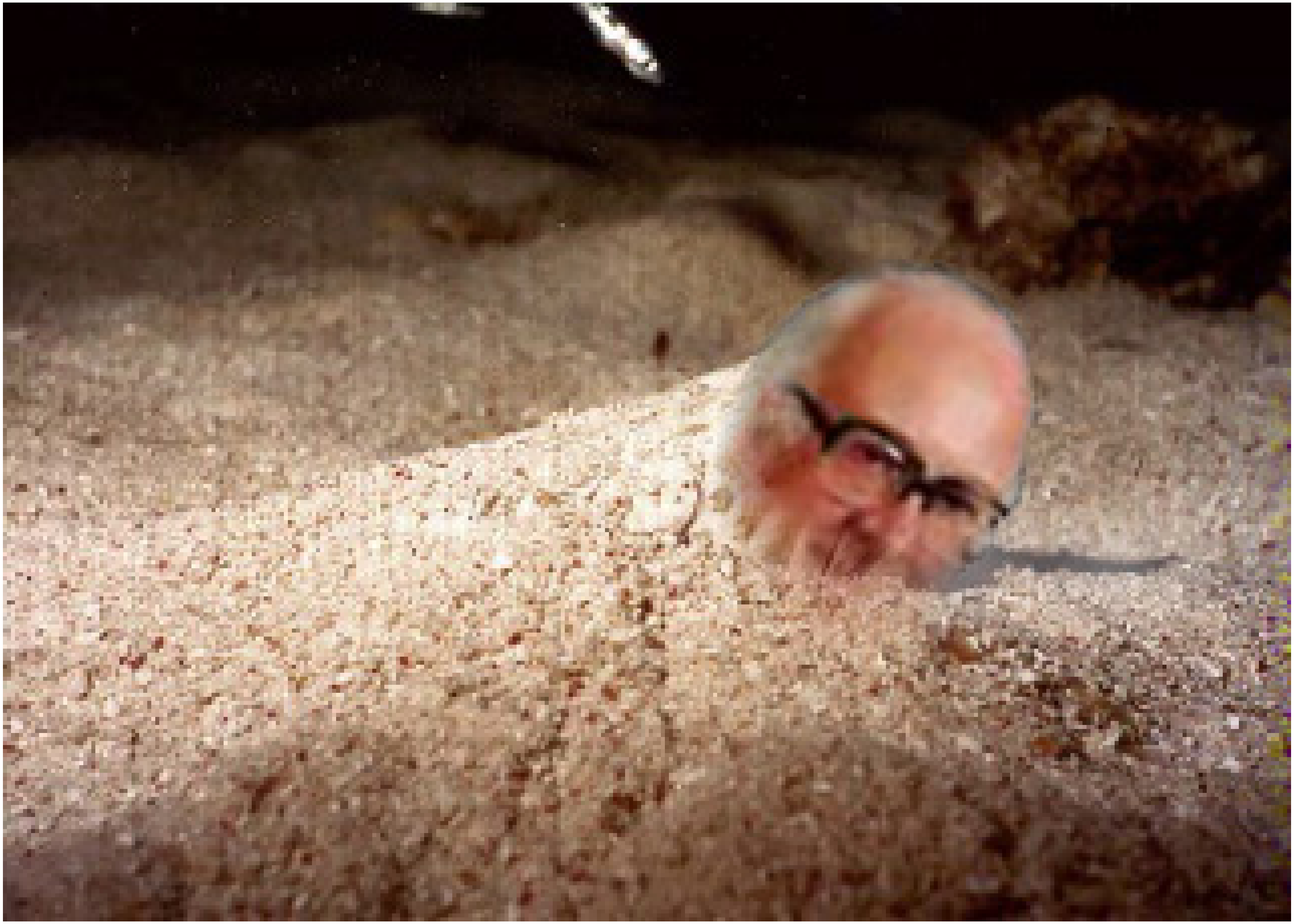
- **Consider the possibility of a Higgs at $118 - 119$ GeV.**

  1. **The $\gamma\gamma$ signal at $118 - 119$ GeV requires $\sigma B \sim 1 - 1.5 \times SM - like$.**
  2. **But, then:**
     (a) **the $\gamma\gamma$ excesses at 140 GeV in CMS and ATLAS would not be explained;**
     (b) **the $ZZ \to 4\ell$ excesses in both ATLAS and CMS at ~ 140 GeV are not explained.**
     (c) **the spread-out WW excess in m_T would be too small.**

- **Inconsistencies with a single Higgs suggest that all excesses are simply statistical flucutations and that with more data one will find local p values below 1 "everywhere".**

  This implies that we should certainly be taking seriously scenarios in which the Higgs has either reduced coupling to the important production modes or reduced branching ratio to the WW and $\gamma\gamma$ final states.

What are the possibilities for emergence of a chameleon-like Higgs boson?



Indeed, there are at least 50 ways to hide the Higgs(es)[1] for now (possibly forever at the LHC) in very reasonable and well-motivated (extreme) models.

Of course, in doing so we should not forget

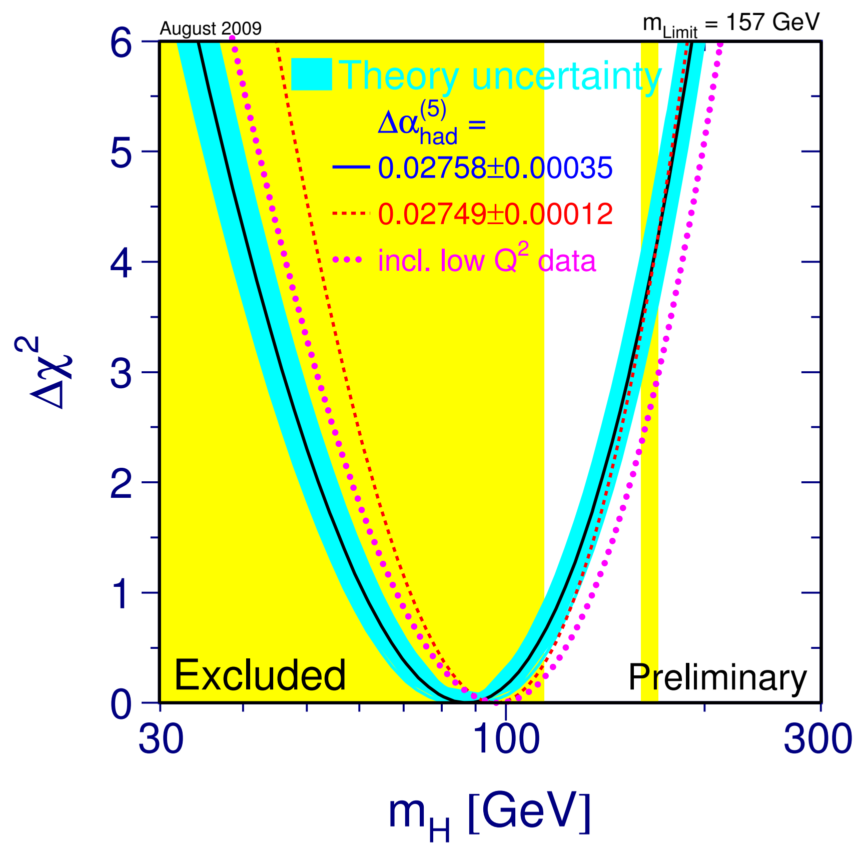


Figure 1: LEP precision electroweak suggests a light Higgs with SM-like WW, ZZ couplings-squared. Or, many light Higgs which cumulatively have SM-like $\sum_k g^2_{VVh_k} = 1$.

[1] "50 ways to leave your lover", Paul Simon: http://www.youtube.com/watch?v=298nld4Yfds

- If the $\gamma\gamma$ LHC signal "evaporates" a very attractive option is to have a light Higgs, $m_h \lesssim 100~\mathrm{GeV}$, with SM-like ZZ, WW couplings (for good PEW) that is "hidden" in that it does not appear in SM-like final states with more than a fraction of SM strength.

- This is supported by the old LEP excess near $95-100~\mathrm{GeV}$:

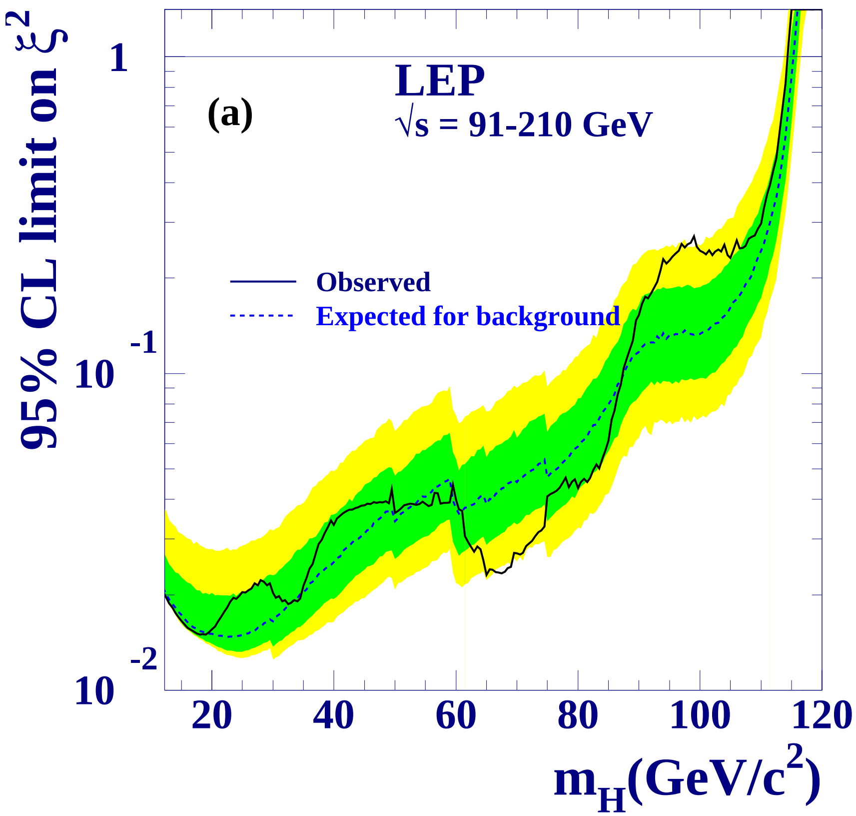


Figure 2: Preference is to retain a $e^+e^- \to Zb\bar{b}$ signal at about $20-30\%$ of SM strength.

Such a scenario is not excluded by the weak LEP limits for model-independent decays of the h:

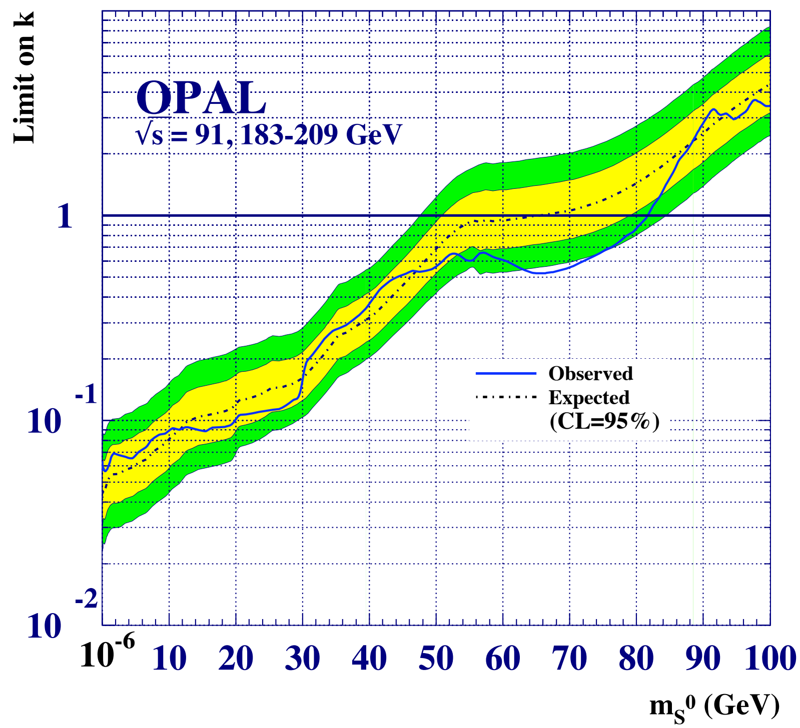


Figure 3: **Limits on $\xi^2 = \sigma(e^+e^- \to Zh)/(e^+e^- \to Zh_{\rm SM})$ from OPAL with no assumption about $h \to X$ decays. m_h as small as $82~{\rm GeV}$ is allowed.**

Let us focus on supersymmetric models. These are ultraviolet complete theories, provide a natural framework for scalars, predict coupling unification, ...

- **A light Higgs, perhaps as light as $100-110~\mathrm{GeV}$ for $m_{\widetilde t_1}\lesssim 700~\mathrm{GeV}$, is then very natural and certainly not yet excluded in the supersymmetric context which provides many escapes from LEP, Tevatron and LHC limits.**

- **Direct limits on $m_{\widetilde t_1}$ are a priority.**

The many ways to hide the Higgs(es)

1. The MSSM

There is a general tendency for Higgs mixing to lead to increased $b\bar{b}$ width of the SM-like Higgs boson at smaller m_A. This suppresses the rates into the most relevant LHC discovery modes, such as $\gamma\gamma, WW^*$.

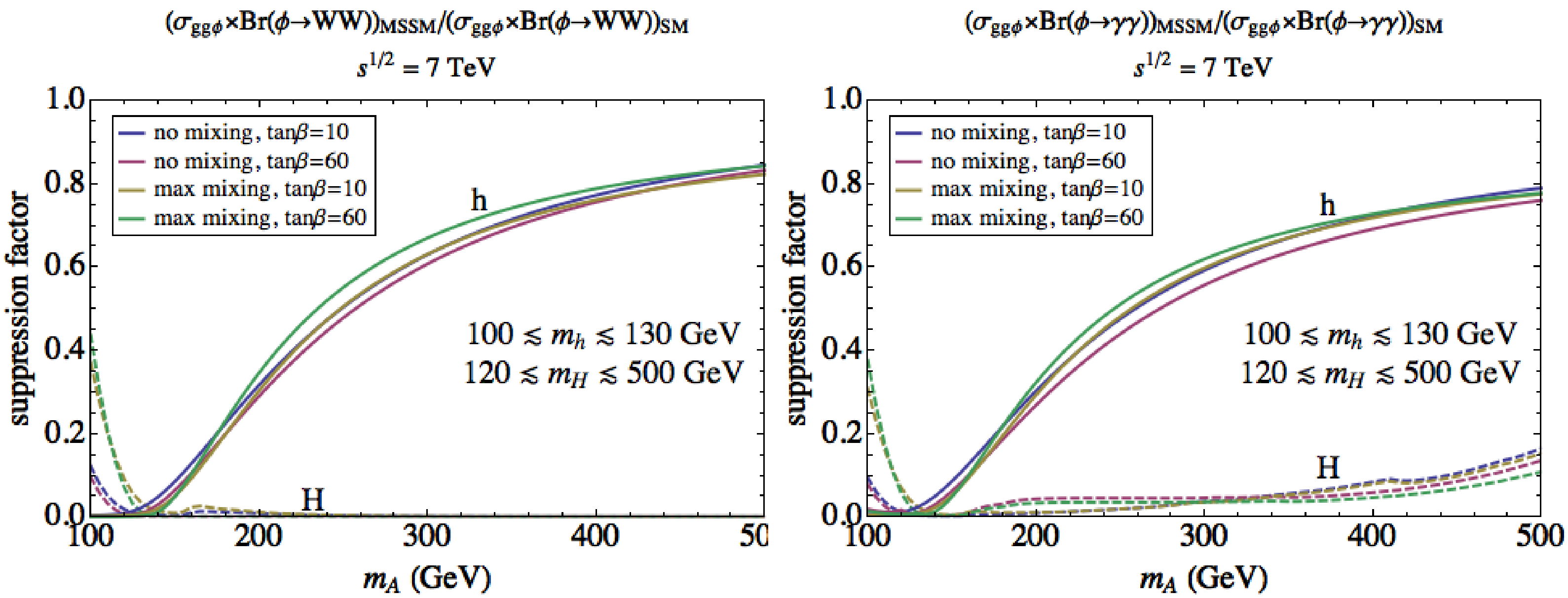


Figure 4: Suppression for the WW and $\gamma\gamma$ final states (Carena, Wagner, *et al.*, arXiv:1107.4354)

There is no need for concern that we have not found the MSSM h for L analyzed so far. But, discovery should not be far off.

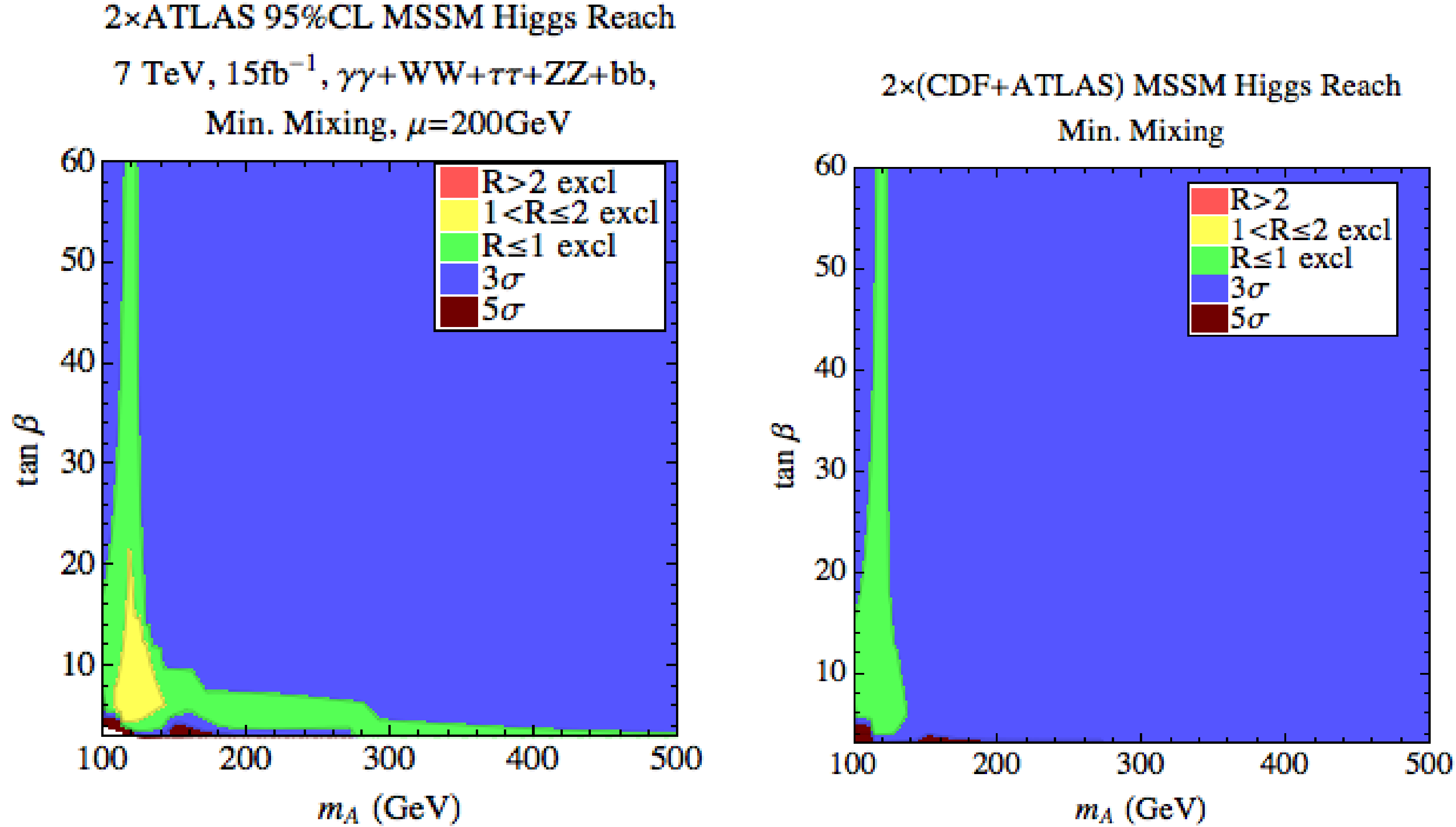


Figure 5: For $L = 15\ \mathrm{fb}^{-1}$ and minimal mixing (the hardest case), most of parameter space is covered at 3σ (left figure). Or (right figure) combine $L = 5\ \mathrm{fb}^{-1}$ LHC and $L = 10\ \mathrm{fb}^{-1}$ Tevatron and do even better. The Tevatron helps at low Higgs mass where the LHC is weak. Do not LHC limits excluding a light H decaying to $\tau^+\tau^-$ for $\tan\beta \gtrsim 15$ eliminate the green "spike".

2. Supersymmetry with Invisible Higgs decays

If $2m_{\widetilde{\chi}_1^0} < m_h$ the Higgs can decay largely invisibly (assuming R parity). For low m_h, the M_1 gaugino mass cannot obey the GUT relation $M_1 = \frac{1}{2}M_2$.

If $m_h > 114~\mathrm{GeV}$, no experimental limit prevents $B(h \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0) = 1$.

Even $m_h < 114~\mathrm{GeV}$ is experimentally acceptable if there is a mixture of $h \to b\overline{b}$ and $h \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0$ decays.

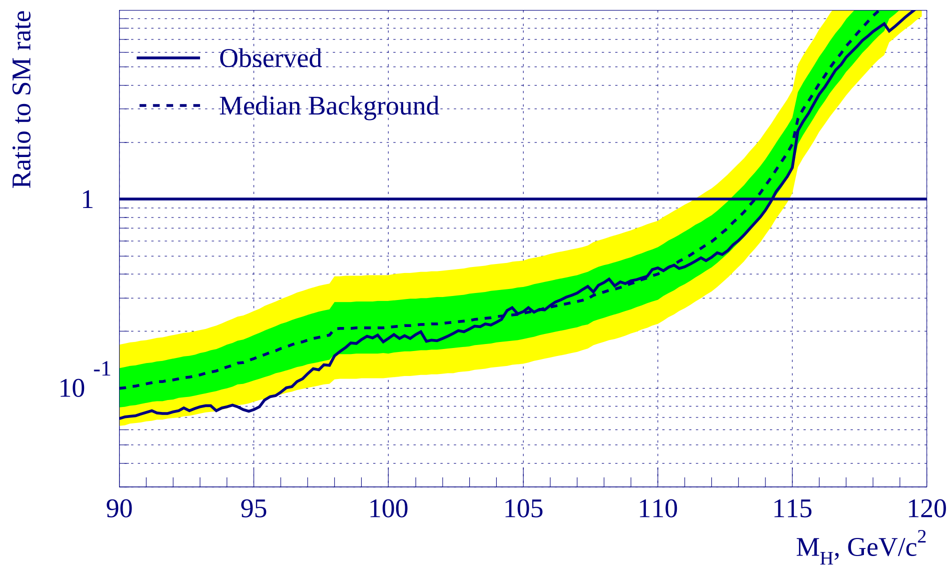


Figure 6: LEP limits on $\xi^2(inv) \equiv [\sigma(Zh)/\sigma(Zh)_{SM}]B(h \to invisible)$ — at $m_h = 112~\mathrm{GeV}$, $\xi^2(inv) = 0.5$ would be ok. Meanwhile, $\xi^2(b\overline{b}) = 0.5$ would also fall under LEP and Tevatron limits. LHC $\gamma\gamma$ rate would be decreased by more than 50%.

The best LHC search channel for an invisibly decaying Higgs is $h \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$ using the $pp \to W^* W^* + 2j \to h + 2j \to invisible + 2j$ mode.

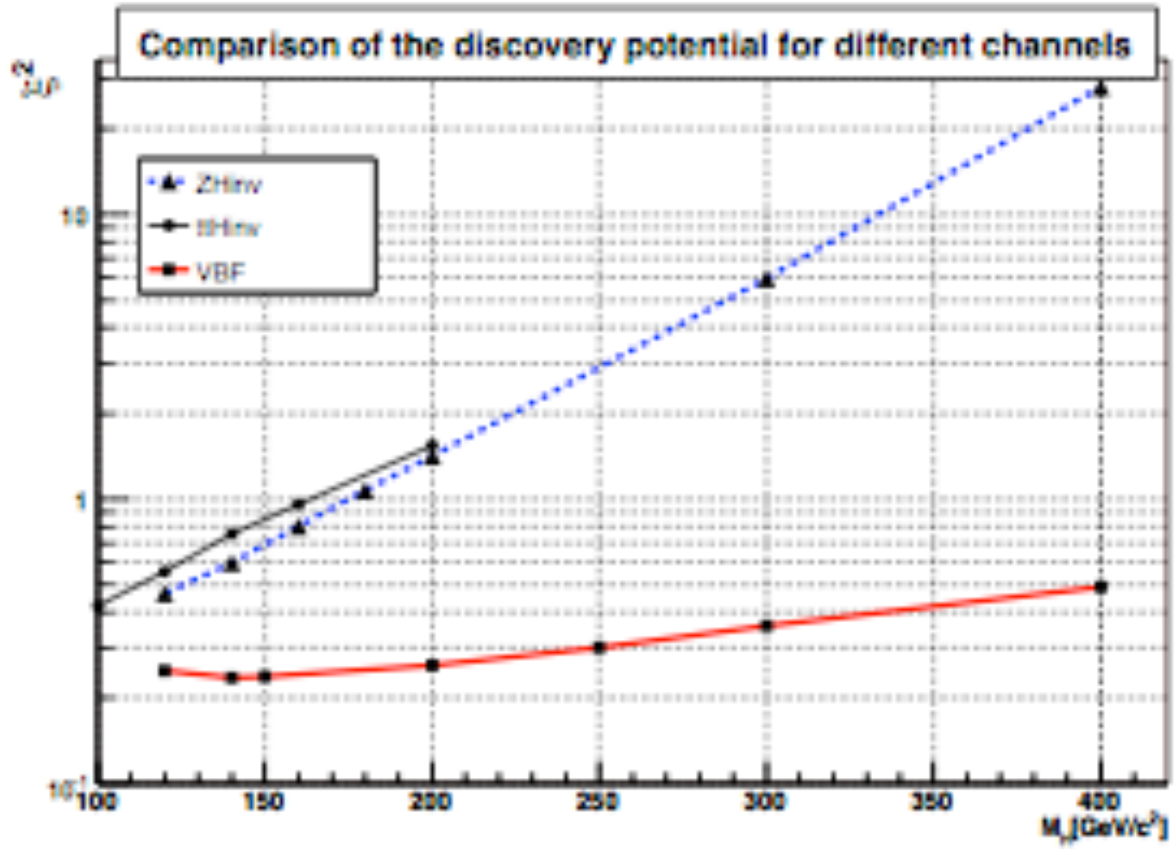


Figure 7: ATLAS-PHYS-PUB-2006-009 95% CL limits on $\xi^2(inv) \equiv [g^2_{hWW}/g^2_{h_{SM}WW}]B(h \to invisible)$ for $L = 30~\mathrm{fb}^{-1}$. Can probe $\xi^2(inv) \sim 0.25$ at low m_h.

Significant invisible decays will soon be visible.

3. Supersymmetry with Baryonic R parity violation

If $B(h \to \widetilde\chi_1^0 \widetilde\chi_1^0)$ is large and $\widetilde\chi_1^0 \to 3j$ (or $5j$ in "collective" RPV) via baryonic R parity violating term(s) in superpotential, $\Rightarrow$ very difficult Higgs detection scenario. (Carpenter, Kaplan, Rhee, arXiv:0804.1581) And, SUSY discovery hard!

Is detection possible in this case, given low $m_{\widetilde\chi_1^0}$ and large QCD background for soft jets?

Could WW fusion with 6 not very hard central jets and two forward jets be separated from background?

Could boosted $\widetilde\chi_1^0$ analysis help in $gg \to h \to 3j + 3j$ when $m_{\widetilde\chi_1^0}$ is not too close to $m_h/2$.

NB: in this scenario one loses the beautiful supersymmetry explanation for dark matter.

4. MSSM with Hidden Sector Decays of $\widetilde\chi_1^0$ $(= \widetilde{N}_1)$

- **This is simply one more option. The idea (Falkowski *et al.*, arXiv:1007.3496) is that there could be a "dark sector" that communicates with our visible sector via kinematic mixing in the Lagrangian.**
  The resulting Higgs decay picture would be:

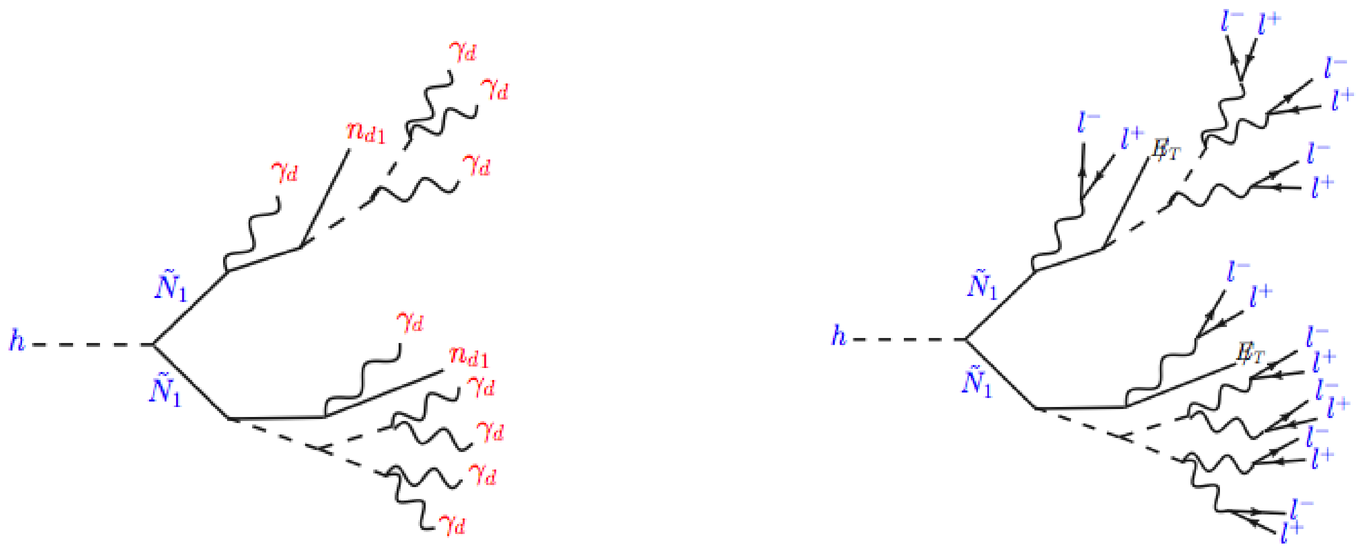
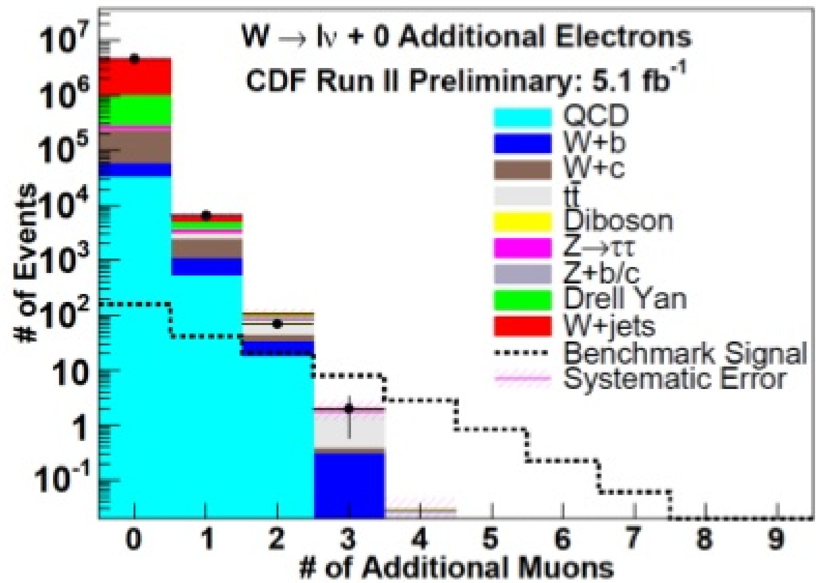


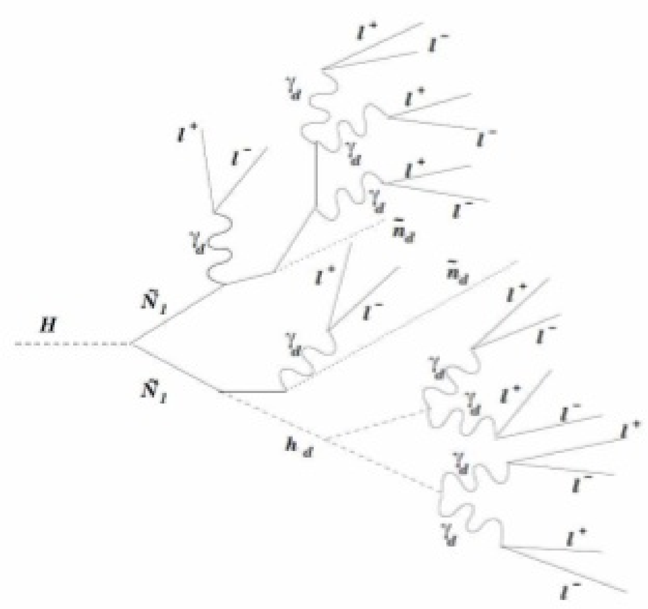
Figure 8: **Picture of h decay to dark sector photons and neutralinos and ultimate final state of two lepton jets. Most likely $m_{\gamma_d} > 2m_\mu$ and the leptons would be μ's.**

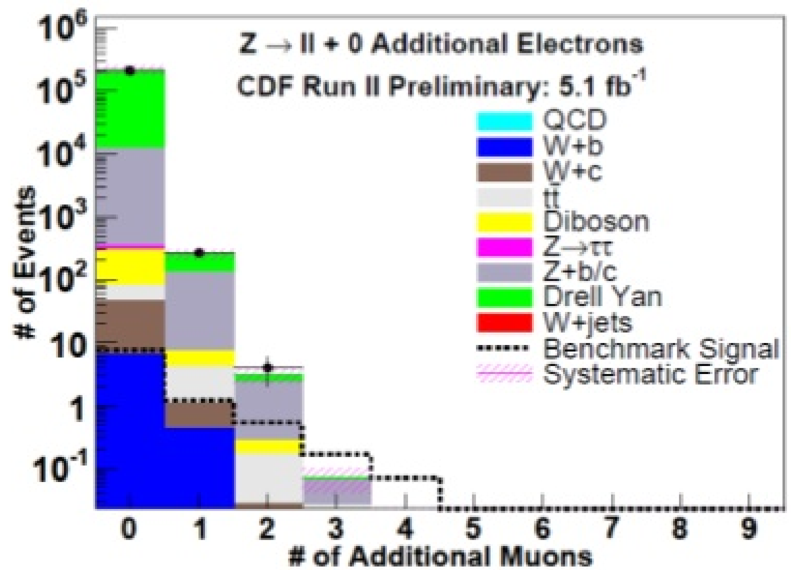
- **At SUSY, Wright showed this transparency which appears to eliminate possibility of muonic lepton jets – assumed $m_h \lesssim 150$ GeV, $m_{\gamma_d} \sim 300$ GeV and prompt decays (delayed decays a possibility in the model).**

Dark Sector Decays

- One of several ways to hide a light Higgs from the LEP limits
  - Decays through neutralinos and dark sector "photons"
  - Falkowski *et al* arXiv:1002.2952
- Search for W/Z+H production, final state containing many soft leptons
- Exclude this particular benchmark scenario at 99.7% CL







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5. Higgs decay via a Hidden Valley

- **Hidden valley again mixes SM sector with a hidden sector** (Strassler, Zurek, Han, arXiv:0712.2041).
- **Much similarity to the lepton jets proposal, but displaced vertices viewed as more likely.**
- **Since final states are more varied, there are no available limits.**

6. MSSM with CPV Higgs sector

If one introduces CP-violation into the MSSM parameters, then CP Violation can be induced in the Higgs sector at the 1-loop level.

Mixing between the CP-even h and H Higgs and the CP-odd A then occurs and one ends up with three neutral Higgs states, h_1, h_2 and h_3, plus the $H^\pm$.

LEP limits are much weaker when substantial CP-violation is present. Such a case is represented by the so-called CPX scenario (Carena, Ellis, Wagner, *et al.*, hep-ph/0211467).

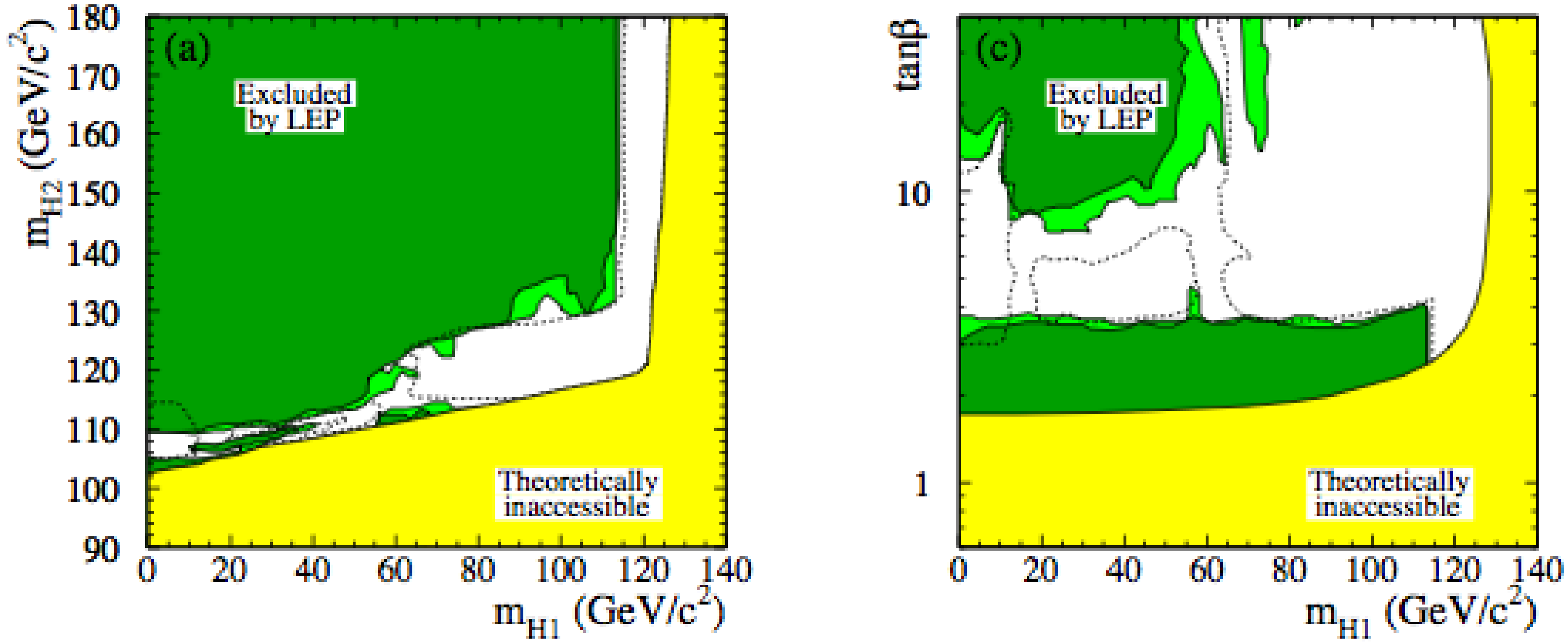


Figure 9: **Exclusions from LEP at 95% CL (light-green) and 99.7% CL (dark-green) for the CPX scenario with $m_t = 179.3~\mathrm{GeV}$. For lower m_t excluded regions expand. Note that unexcluded $m_{h_1} < 2m_b$ cases appear for $m_{h_2} \sim 105~\mathrm{GeV}$.**

The main reason holes develop is that the channel $e^+e^- \to Zh_2 \to Zh_1h_1$ with $h_1 \to b\bar{b}$ (or possibly $\tau^+\tau^-$) becomes important (originally pointed out by Haber, Gunion, Moroi, hep-ph/9610337 In NMSSM context) and, further, the h_2 does not have full ZZ coupling.

The combination of weakened ZZh_2 coupling and the weaker limits on the more complex and less constrained $Z + 4b$ final states lead to regions of parameter space for which LEP cannot exclude the scenario.

These same $h_2 \to h_1 h_1 \to 4b, 4\tau$ decays are considerably more difficult to detect at the LHC than the SM-like final states.

In the $4b$ case, multiple b-tagging is needed. A number of studies by theorists suggest that $10 - 30~\mathrm{fb}^{-1}$ will suffice to reveal the $4b$ final states in $W + Higgs$ events (Kingman Cheung *et al.*, hep-ph/0703149), but full simulations by ATLAS and CMS have not appeared to my knowledge.

Detection of $h_2 \to h_1 h_1 \to 4\tau$ at the LHC is problematical (see later).

7. The NMSSM: = MSSM + extra singlet superfield, $\widehat{S}$

The many attractive features of the NMSSM are well known:

(a) Solves μ problem: $W \ni \lambda \widehat{S} \widehat{H}_u \widehat{H}_d + \frac{1}{3} \kappa \widehat{S}^3 \Rightarrow \mu_{\mathrm{eff}} = \lambda \langle S \rangle$.
(b) Preserves MSSM gauge coupling unification.

(c) Preserves radiative EWSB.

(d) Preserves dark matter (assuming R-parity is preserved).

(e) Like any SUSY model, solves quadratic divergence hierarchy problem.

The Higgs sector is expanded in the NMSSM to two CP-odd Higgs bosons (a_1, a_2) and three CP-even Higgs bosons (h_1, h_2, h_3), as well as the $H^\pm$.

In both sectors, the Higgs are typically a mixture of a singlet component and the doublet components. In particular, we write

$$a_1 = \cos\theta_A A_s + \sin\theta_A A_{MSSM} \,. \tag{1}$$

This Higgs sector expansion leads to some new attractive possibilities:

In particular, a SM-like h_1 with $m_{h_1} \sim 90 - 105~\mathrm{GeV}$ can escape LEP limits because of $h_1 \to a_1 a_1$ decays with $m_{a_1} < 2m_b$ so that $a_1 \to \tau^+\tau^-$ at large $\tan\beta$ or $a_1 \to gg, c\bar{c}, \ldots$ at low $\tan\beta$ (Dermisek, Gunion, hep-ph/0502105 and subsequent).

Typically, LEP escape scenarios correspond to small $|\cos\theta_A| \lesssim 0.1$ for $\tan\beta > 5$, but larger $|\cos\theta_A|$ is possible for small $\tan\beta$.

In terms of the $Z + b\bar{b}$ LEP limits the picture becomes:

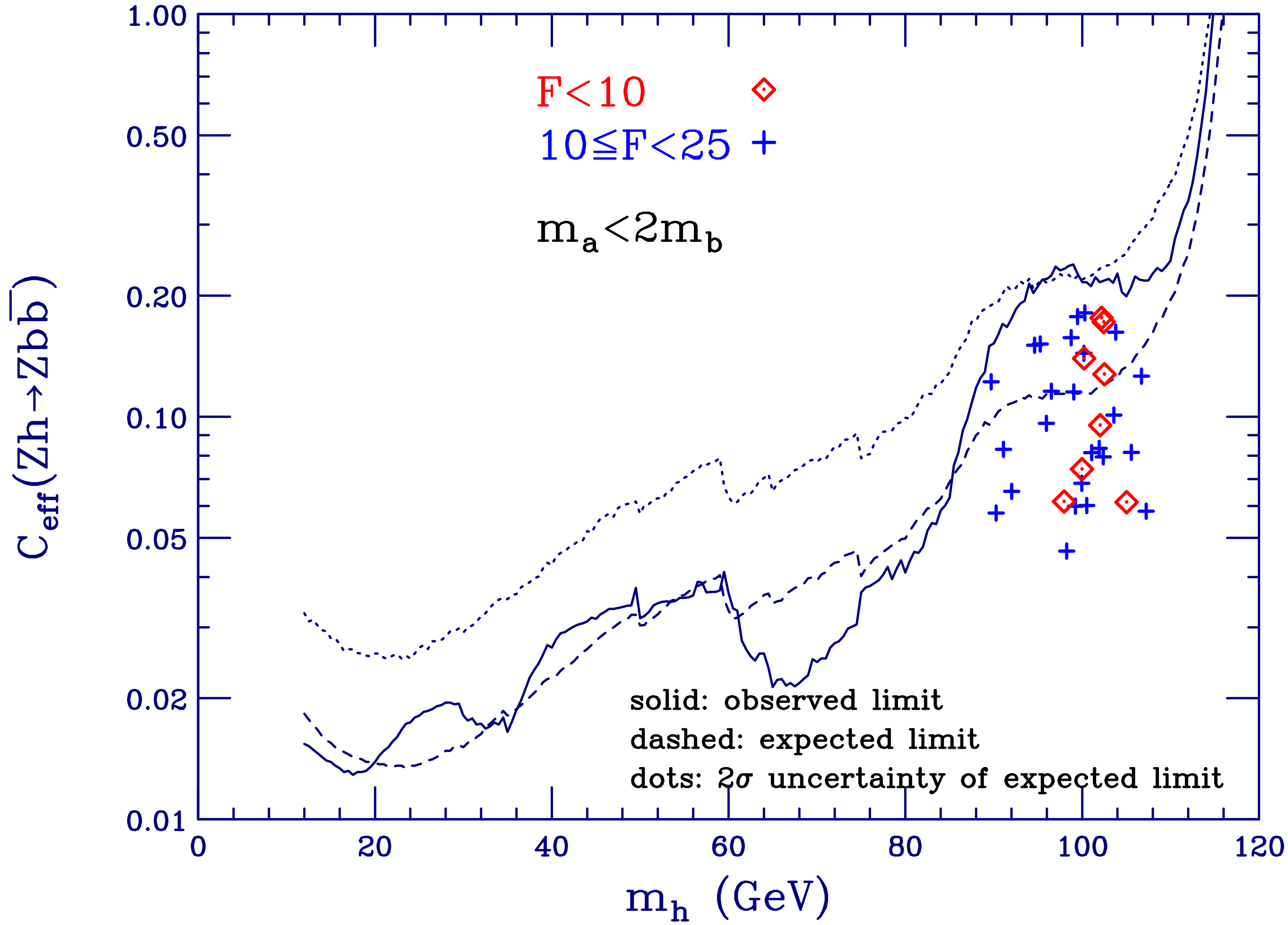


Figure 10: The excess at $M_{b\bar{b}} \sim 100$ GeV is easily explained, and almost automatically so when small fine-tuning F is required.

Such a situation has three very attractive features:

- Precision electroweak constraints are ideally satisfied.
- Fine-tuning for getting m_Z (i.e. v) correct is small = reduced little hierarchy.
- An a_1 with large $B(h_1 \to a_1 a_1)$ and $m_{a_1} < 2m_b$ corresponds to a natural symmetry limit of the NMSSM in which the A_λ and A_κ soft-SUSY breaking parameters ($V \ni A_\lambda S H_u H_d + \frac{1}{3} A_\kappa S^3$) are small.

This scenario is very hard to constrain/detect.

- ALEPH (Cranmer *et al.*, arXiv:1003.0705) have looked at $Zh_1 \to Z4\tau$ and eliminated about 1/2 of the preferred points at large $\tan\beta$, but there are still plenty left.
- ALEPH is also looking at the more complicated $Zh_1 \to Z4j$ scenarios appropriate to low $\tan\beta$, but no results yet.
- At the Tevatron and LHC, one approach (Lisanti, Wacker, arXiv:0903.1377) is to look for $W, Z + h_1$ with $h_1 \to a_1 a_1 \to 2\mu + 2\mu, 2\mu + 2\tau$, relying on the 0.3% branching ratio for $a_1 \to \mu^+\mu^-$. Some not very constraining results were obtained (Has *et al.*, arXiv:0905.3381).

  LHC estimates by (Lisanti, Wacker, arXiv:0903.1377) in this same mode suggested it was quite promising, but the study of (Balyaev *et al.*, arXiv:1002.1956) suggests the backgrounds are much larger than anticipated.

- Forshaw, Gunion *et al.*, arXiv:0712.3510 looked at $pp \to pp + h_1 \to pp + 4\tau$. Detection is possible, but requires very high $L > 100~\mathrm{fb}^{-1}$.
- Many of the "ideal" scenarios have large enough $C_{a_1 b\bar b} = \tan\beta\cos\theta_A$ coupling that $gg \to a_1 \to \mu^+\mu^-$ would have a significant event rate (Gunion, Dermisek, arXiv:0911.2460).

  Detectability in this mode is being studied by both CMS and ATLAS, with some low L results from ATLAS publicly available (Hal Evans *et al.*), but not very constraining yet.

  Unfortunately, in the light of BaBar/Belle constraints from $\Upsilon(3S) \to \gamma a_1 \to \gamma\mu^+\mu^-, \gamma\tau^+\tau^-$ the preferred m_{a_1} range lies within the Υ peaks, preferably fairly close to $2m_b$. This region will be hard.

Of course, we can easily imagine that LEP limits are avoided by simply choosing parameters so that $m_{h_1} > 114~\mathrm{GeV}$.

This would still be quite good for PEW, but then

- $m_{a_1} > 2m_b$ would be entirely acceptable and one must also consider

scenarios with $h_1 \to a_1 a_1 \to 2b + 2b$ as the main decay channel.
This was a channel pointed out early in the NMSSM game (Haber, Gunion, Moroi, hep-ph/9610337; Ellwanger, Gunion, Hugonie; Moretti, hep-ph/0305109, hep-ph/0401228).

- As discussed already, while such a channel will eventually be probed in $W, Z + h_1$, $t\bar{t} + h_1$ and (at large $\tan\beta$) $b\bar{b} + h_2$ production (assuming h_1 is SM-like), it is likely to take more L than will be available by the end of the current LHC run (see, in particular, studies by Almarashi, Moretti, arXiv:1105.4191).

8. The NNNN....MSSM: = MSSM + extra singlet superfields

- Multi-singlet extensions of the NMSSM will expand the possibilities. Indeed, typical string models predict a plethora of light a's, light h's and light $\widetilde{\chi}$'s .
- This supersymmetry scenario is closely related to the "worst case" Higgs scenario (Espinosa, Gunion, hep-ph/9807275) in which there are many Higgs bosons reasonably closely spaced (or continuously spaced) with net $g^2_{ZZh_i}$

weight centered in the vicinity of the ideal PEW value of 100 GeV. See also, the van der Bij scenarios, arXiv:0804.3534 and references therein)

In general, the different h_i will have $h_i \to h_k h_l$ decays so that final states will be complicated and overlapping.

- Estimates are that the LHC would not be able to detect the Higgs signal(s) directly.

  Only an ILC, preferably at modest $\sqrt{s} \sim 250 - 350$ GeV, could reveal the more or less continuum enhancement in the recoil M_X spectrum predicted in the $e^+e^- \to Z + X$ channel.

  High L would certainly be needed.

9. Other NMSSM-related scenarios

One can construct SUSY models using a singlet superfield in which the $a \to b\bar{b}$ decay partial width is suppressed and $a \to gg$ is dominant with $B(a \to \gamma\gamma) \sim 1\%$. (Bellazini *et al.*, arXiv:0910.3210, Luty *et al.*, arXiv 1012.21347)

In particular, the Luty *et al.* model extends the MSSM with two singlet Higgs fields, S and N, as well as vector-like colored particles, X. As in the NMSSM, $h \to aa$ is easily dominant. However, since the a is a pseudo-Nambu Goldstone boson of a new global $U(1)$ symmetry, $a \to b\bar{b}$ decays are suppressed and even if $m_A > 2m_b$ the dominant a decay will be $a \to gg$ (via X loops, leading to $\Delta\mathcal{L} = \frac{1}{\Lambda} a\widetilde{G}_{\mu\nu}G^{\mu\nu}$, where $\Lambda \sim m_X$). All interactions can be perturbative up to the GUT scale, and gauge coupling unification is preserved if the colored mediators come in complete GUT representations.

The potential, but very difficult, h discovery modes would employ $h \to aa \to (gg)(gg)$ or $(gg)(\gamma\gamma)$. The h could easily remain undiscovered at the LHC. (See, however, the claim by Falkowski *et al.*, arXiv:1006.1650, that the $4g$ final state could yield 5σ for $L = 100~\mathrm{fb}^{-1}$ and $\sqrt{s} = 14~\mathrm{TeV}$ using jet substructure techniques in Zh and $t\bar{t}h$ production with $h \to 4g$.)

Also, Luty *et al.* argue that the colored particles X must be below the TeV scale, and can therefore be produced at the LHC, so there would be some LHC signature for the model. $m_X \sim~\mathrm{TeV}$ is also mandated so that $\Delta\mathcal{L}$ is not too small.

10. Other scenarios based on supersymmetry

There are many and there is no time to consider them here.

11. Explaining the excesses in the current data: RS higgs-radion

The other possibility is that we should take seriously the excesses seen at the moment and try to explain them. This is quite hard in SUSY-like models. There are too many excesses. We ideally want:

(a) At 119 GeV

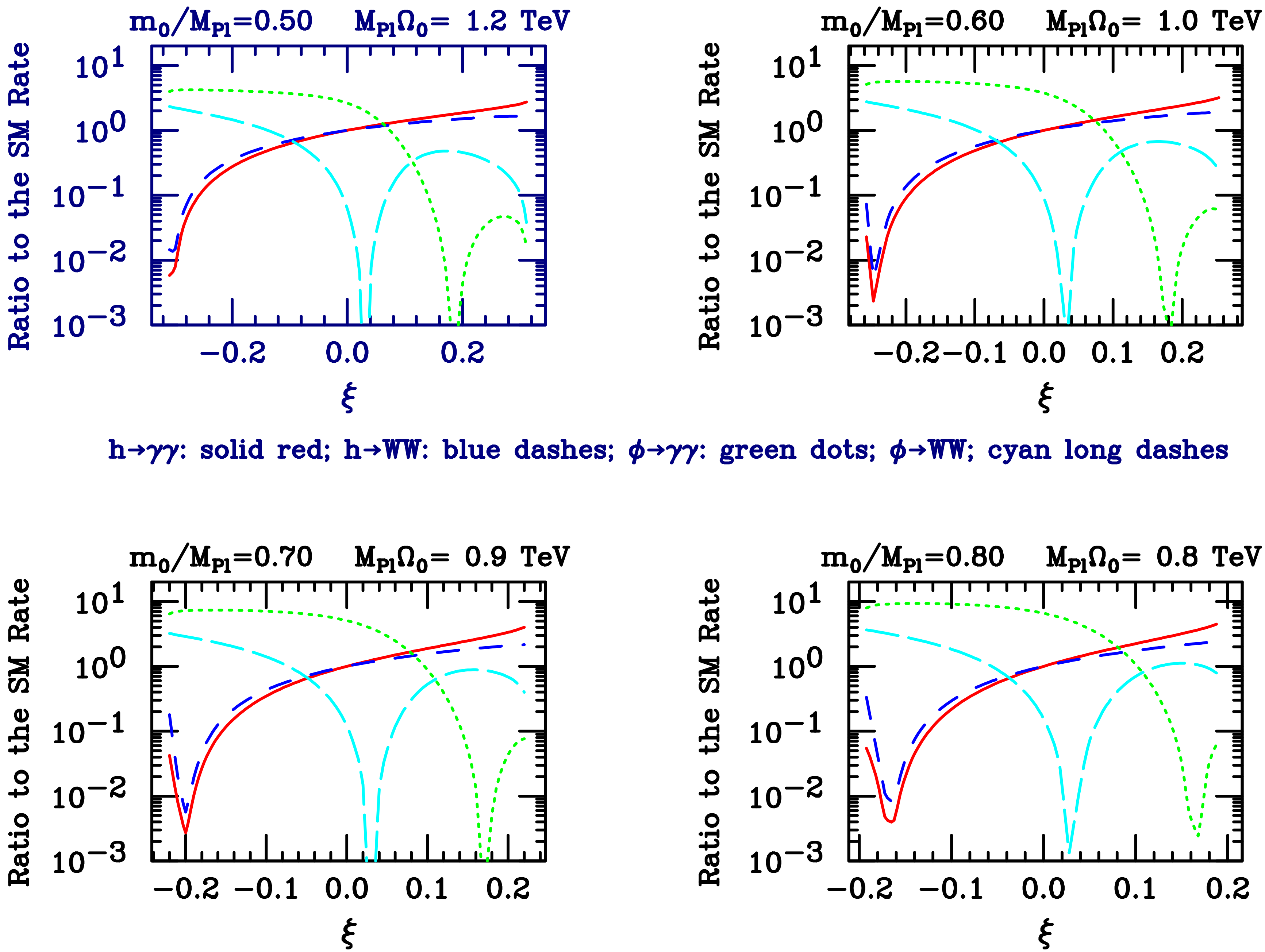
$$\delta\mu(\gamma\gamma) \sim \delta\mu(ZZ) \sim 1.5 - 2\,, \quad (\delta\mu(WW)\ irrelevant) \tag{2}$$

(b) At 140 GeV

$$\delta\mu(\gamma\gamma) \sim 1 - 1.5\,, \quad \delta\mu(ZZ) \sim \delta\mu(WW) \sim 0.5 - 0.6 \tag{3}$$

A solution (Grzadkowski, Gunion, in preparation) is provided in the RS scenario with brane Higgs and all else in the bulk, provided one allows for higgs-radion mixing, parameterized by the parameter ξ. No time for details.

$m_h = 120$ GeV $\quad m_\phi = 140$ GeV



Look at $m_0/M_{\rm Pl} = .7$ **at** $\xi = 0.08$. **Note:** $h \to ZZ \simeq h \to WW$.

Conclusion

Thus, while the Higgs boson(s) may end up being temporarily buried as we increase the data sample, they could be alive and well just below the surface and will eventually be dug out using specialized channels/tools.

If anything, the failure to see a SM-like Higgs in the SM-like channels would be no surprise to many of us.

Or perhaps the excesses we now see will survive and we must explain them.

Certainly, I will continue watching and waiting