Are there Hidden Higgs Bosons?

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Higgs Basics and Current Limits

- **In the SM the W, Z acquire mass by virtue of spontaneous symmetry breaking due to a Mexican-hat Higgs (spin-0 scalar) potential:**

$$\phi \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} . \tag{1}$$

Above, $h(x)$ is a fluctuating degree of freedom relative to the vacuum expectation value, v, of the Higgs field and corresponds to what we call the Higgs boson. The other ϕ dof $\Rightarrow$ longitudinal components of the $W^{\pm}$ and Z.

- **Using the Lagrangian forms (very rough)**

$$\mathcal{L} \ni \frac{1}{2} g^2 \phi^* \phi (W^+)^\mu (W^-)_\mu - y_f \overline{f} \phi f \tag{2}$$

with $\phi \to v/\sqrt{2}$ yields

$$m_W = \frac{gv}{2}, \quad m_f = \frac{y_f v}{\sqrt{2}}, \tag{3}$$

where the former determines $v = 246~\mathrm{GeV}$.

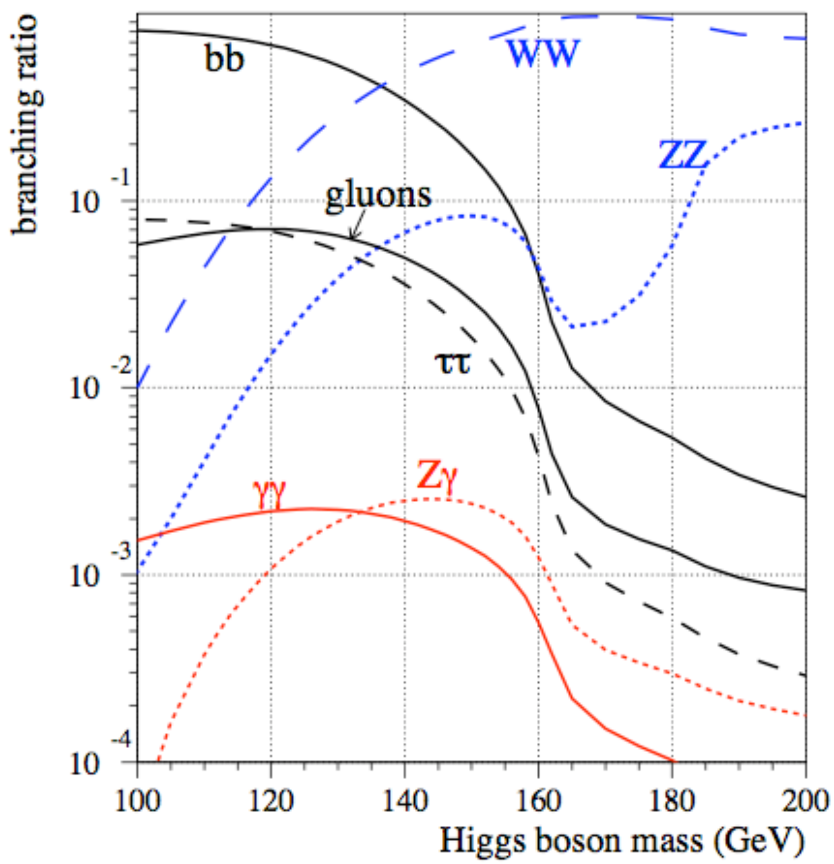
- Substituting (one) $\phi \to h/\sqrt{2} \Rightarrow$ the couplings of the h to matter fields:

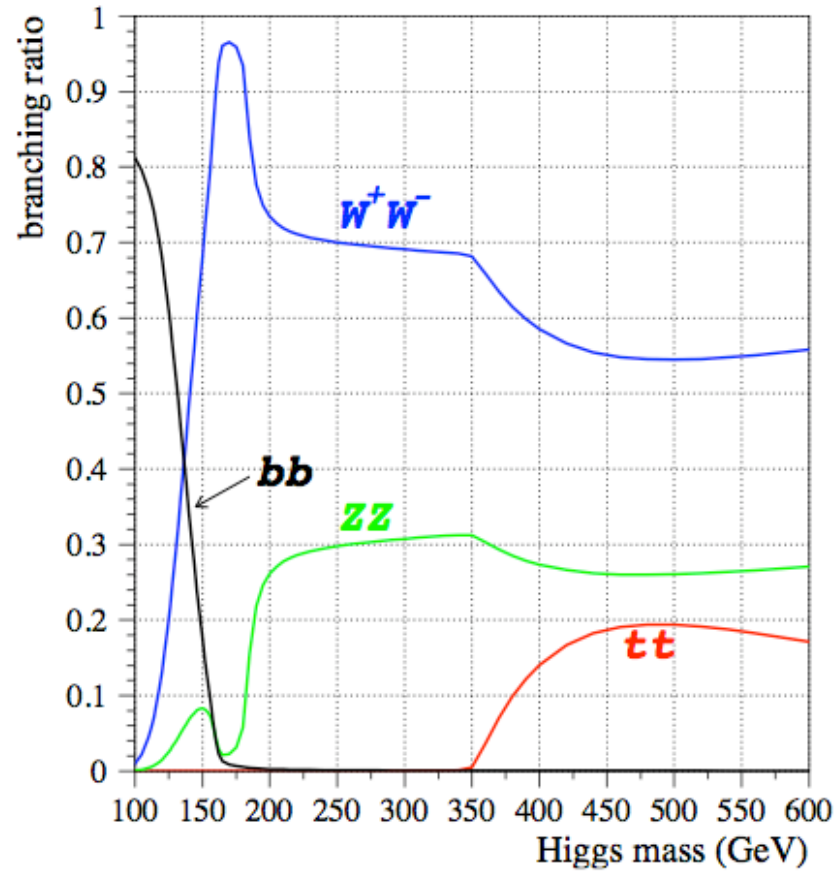
$$hW^+W^- : \quad igm_W g^{\mu\nu}, \qquad h\overline{f}f : \quad -i\frac{y_f}{\sqrt{2}} = -i\frac{gm_f}{2m_W} \tag{4}$$

  i.e. the largest couplings are to $t\bar{t}$, WW and ZZ.

  However, $h \to b\overline{b}$ and $h \to \tau^+\tau^-$ couplings can also play a crucial role. That these are quite small Yukawa couplings will be important later.

- In particular, for $m_h < 2m_W$, the main decay mode of the Higgs is to $b\overline{b}$ and $\Gamma_h^{\rm tot}$ is very tiny.

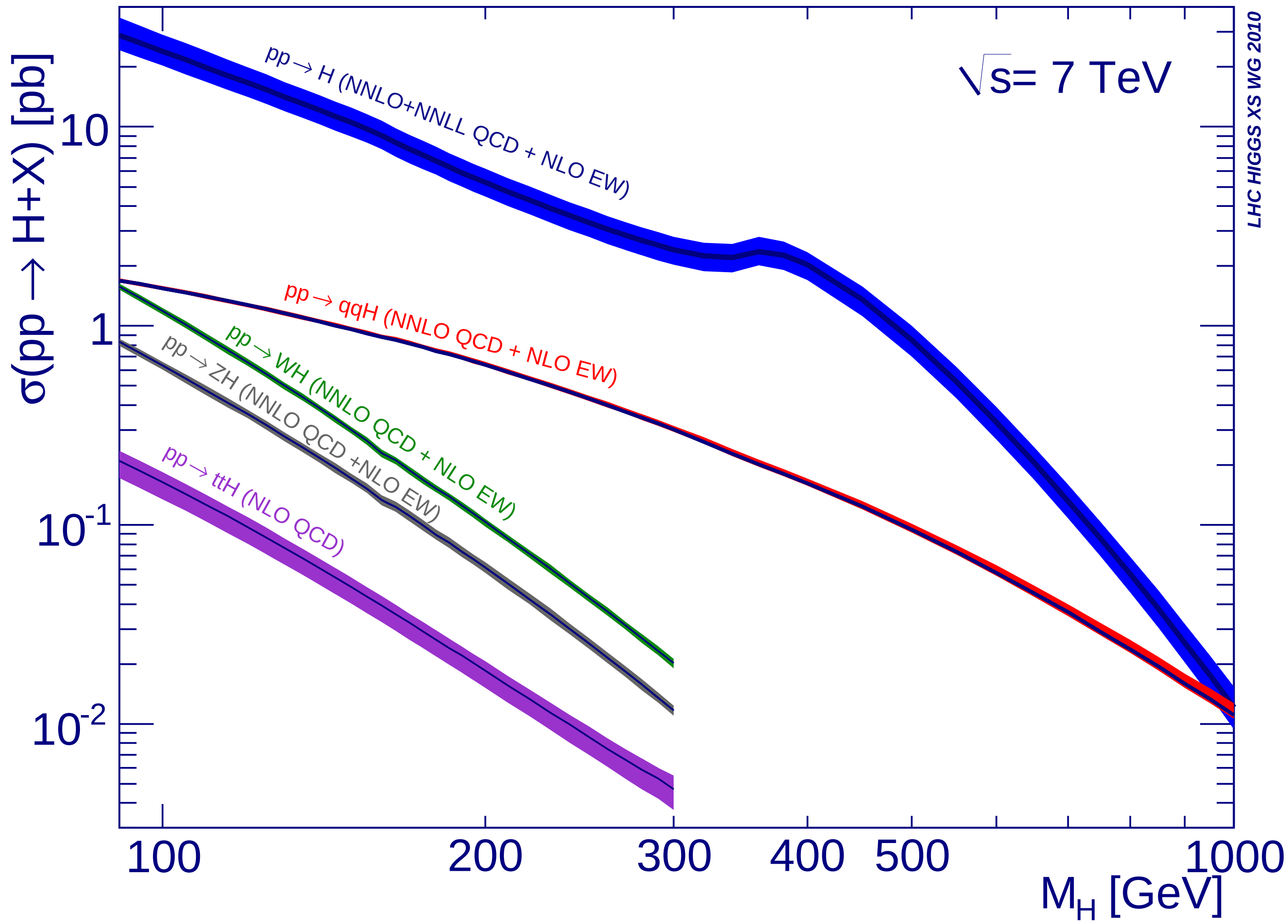




- **One-loop couplings of the Higgs can also play an important role:**
  - $h \to \gamma\gamma$ **(dominated by the** W **loop, but with** t **loop subtracting off some) leads to the small but very useful** $B(h \to \gamma\gamma) \sim 2 \times 10^{-3}$ **at low**

mass.

– $h \to gg$ **(dominated by the** t **loop — only colored particles matter) leads to the production mechanism** $gg \to h$ **which is all-important at the LHC.**



A reminder: the number of events in a given channel X is given by

$$N_X = L(\text{ fb}^{-1}) \times \sigma(\text{ fb}) \times B(X)\,, \tag{5}$$

where the integrated luminosity analyzed for ATLAS and CMS (each) is of order $1-2 \text{ fb}^{-1}$ depending upon the channel. Note: $1 \text{ pb} = 1000 \text{ fb}$, so for the σ values from gg fusion, we get lots of Higgs produced.

So, what do they see?

- First of all, there are lots of backgrounds.

  In some cases, the backgrounds can be measured in regions away from a potential Higgs signal region and then extrapolated into the signal region.

  This is easy for the $h \to \gamma\gamma$ final state, but hard for example for the $h \to WW \to \ell\nu\ell\nu$ final state.

  In the latter case, they have to rely fairly heavily on a Monte Carlo simulation of the SM background since the signal is spread out in any observable, in particular $M_{\ell\ell}$, because of the missing energy associated with the neutrinos.

- **They must determine if there is any excess above the backgrounds.**

  In the $\gamma\gamma$ case, they look for a tiny peak (with width of order the experimental resolution, $\sim 2~\mathrm{GeV}$) above the background.

  In the $\ell\nu\ell\nu$ case, they are looking for a broad excess in $M_{\ell\ell}$, or the better variable

$$m_T = \sqrt{(E_T^{\ell\ell} + \not{E}_T)^2 - (\vec{p}_T^{\,\ell\ell} + \vec{\not{p}}_T)^2} \tag{6}$$

  where

$$E_T^{\ell\ell} = \sqrt{(\vec{p}_T^{\,\ell\ell})^2 + m_{\ell\ell}^2}, \quad \not{E}_T = |\vec{\not{p}}_T| \tag{7}$$

  - **Should they see such an excess they have to compare to what they would expect for a Higgs of a given mass and then test what Higgs mass gives the best fit.**
  - **In general, there will be a range of Higgs masses for which a reasonable fit is obtained.**

- **If an excess is seen, one must then typically compute two probabilities:**
  - **The probability that this excess is consistent with a statistical fluctuation of the SM background(s), often labelled p_0.**

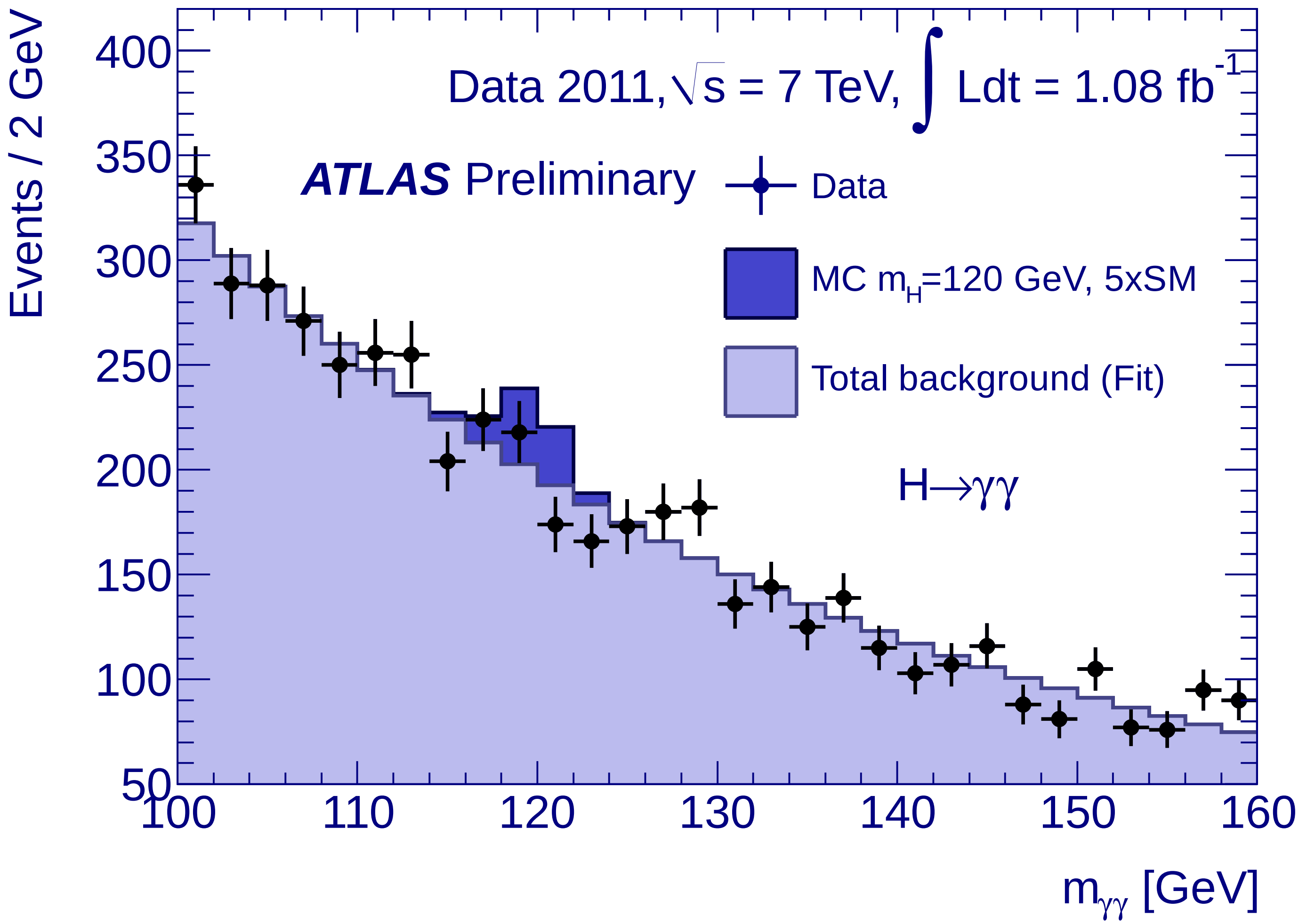
– **The probability that the excess is consistent with the presence of a SM Higgs of a given mass.**

- **In assessing the importance of any excess they must also consider the "look elsewhere effect" (LEE) which refers to the fact that statistically speaking a deviation from the SM background has equal probability to occur "anywhere".**

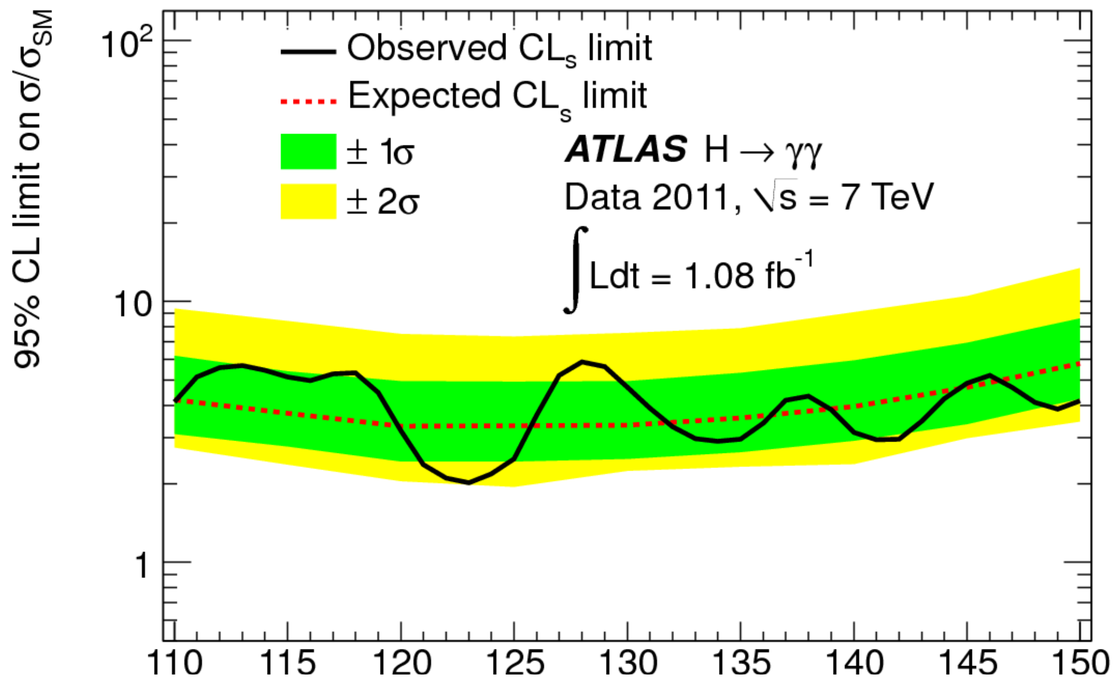
  It is easiest to think of this in the $\gamma\gamma$ case, where a tiny peak that one might be tempted to associate with a Higgs signal could pop up at any $M_{\gamma\gamma}$ as a statistical fluctuation.

  Some sample plots from the CMS and ATLAS experiments will illustrate.

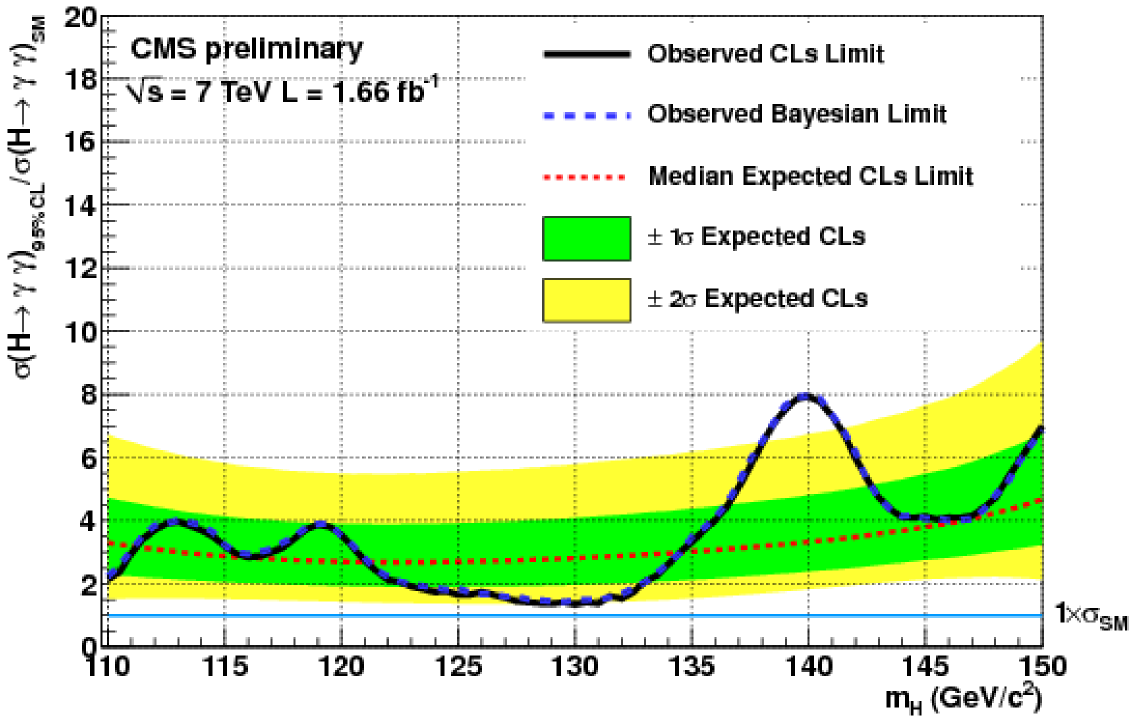
  The first plots are for the $\gamma\gamma$ final state. The 3rd plot is the m_T distribution for the $WW \to \ell\nu\ell\nu$ final state.



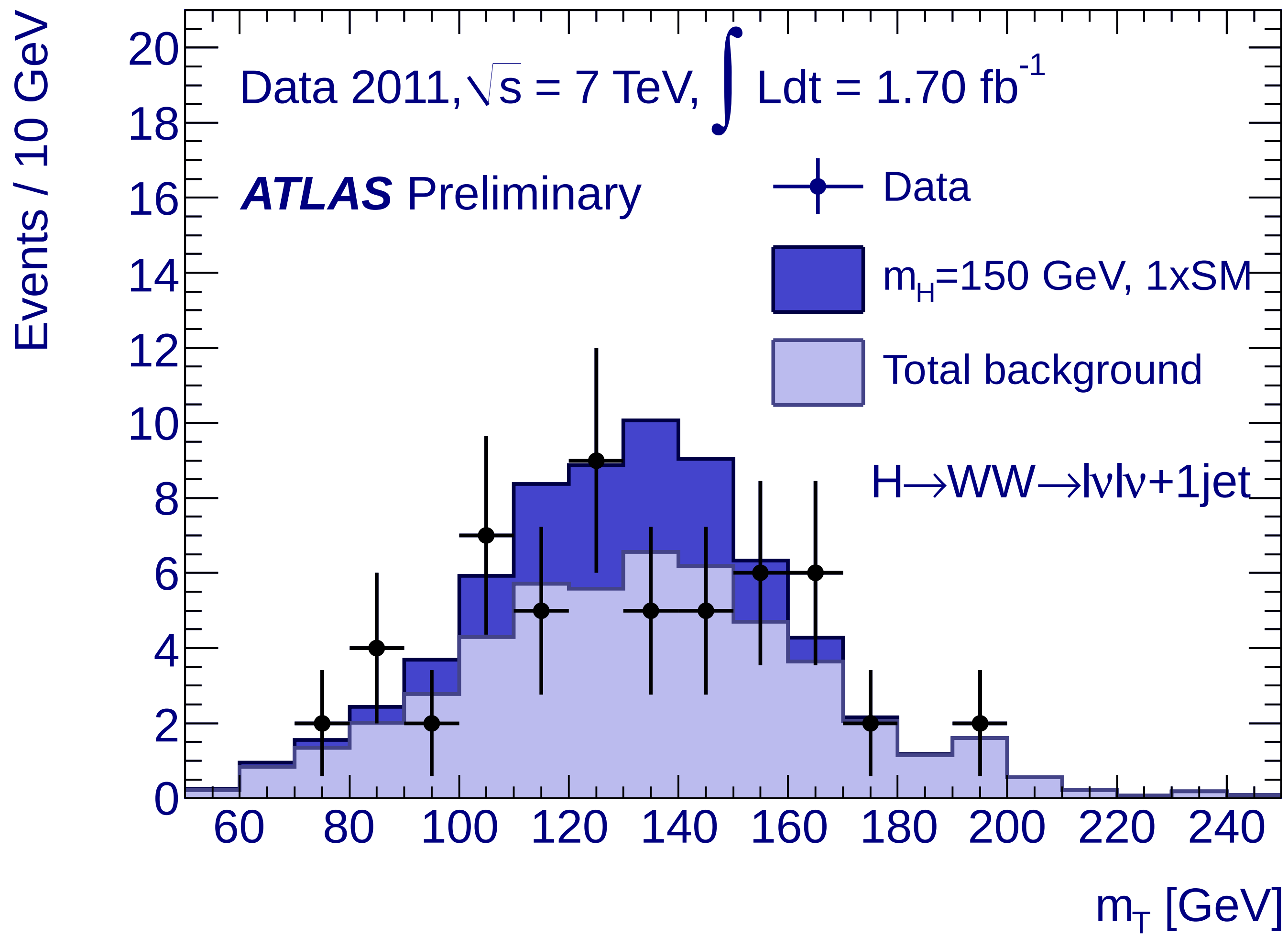
Note scale factor of $5 \times SM$.



Observed CLs limit
Expected CLs limit
± 1σ
± 2σ
ATLAS H → γγ
Data 2011, √s = 7 TeV
∫Ldt = 1.08 fb-1
95% CL limit on σ/σSM

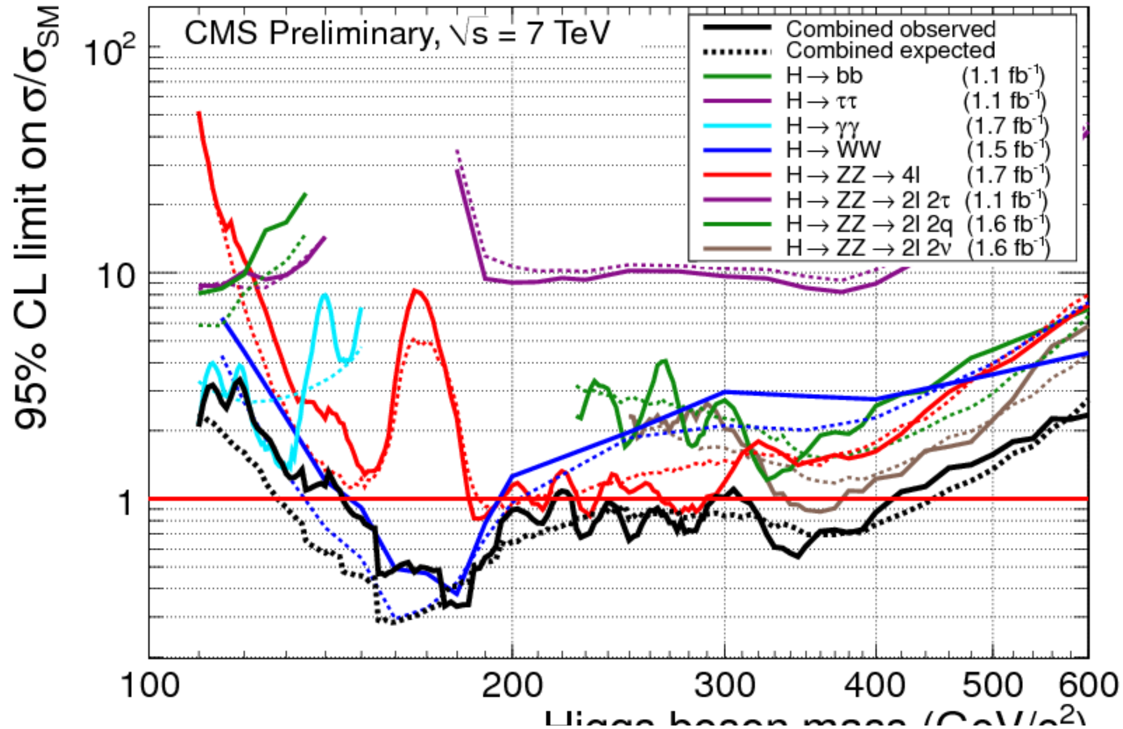


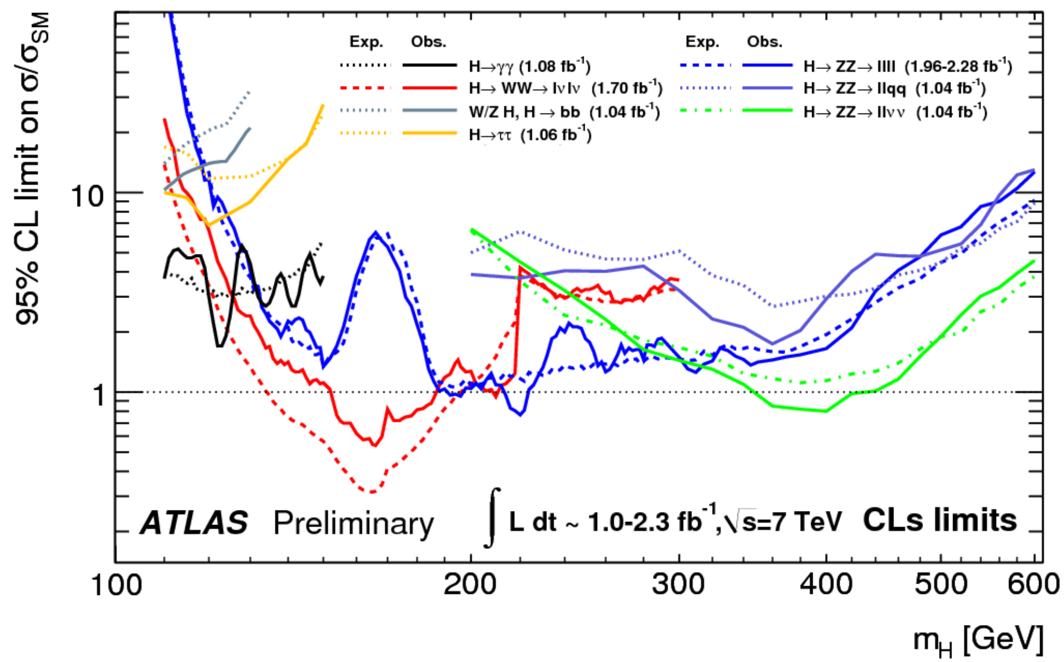
CMS preliminary
√s = 7 TeV L = 1.66 fb-1
Observed CLs Limit
Observed Bayesian Limit
Median Expected CLs Limit
± 1σ Expected CLs
± 2σ Expected CLs
1×σSM
σ(H→γγ)95%CL/σ(H→γγ)SM
mH (GeV/c2)



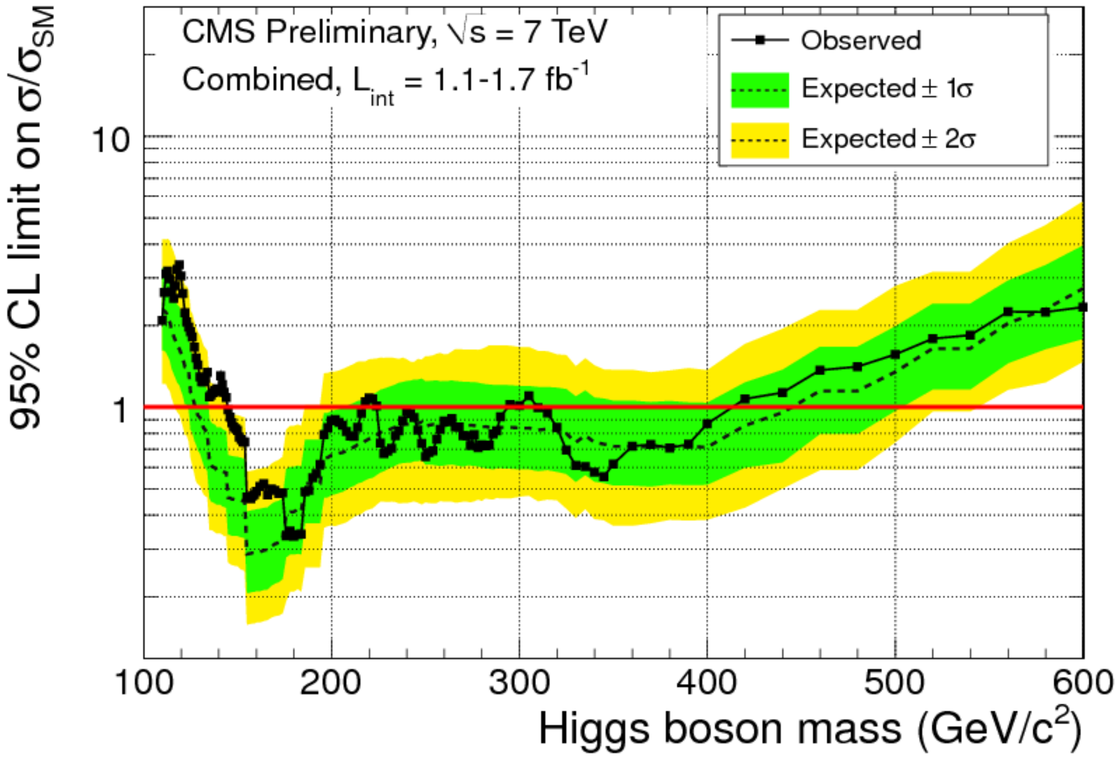
Note scale factor of $1 \times SM$.

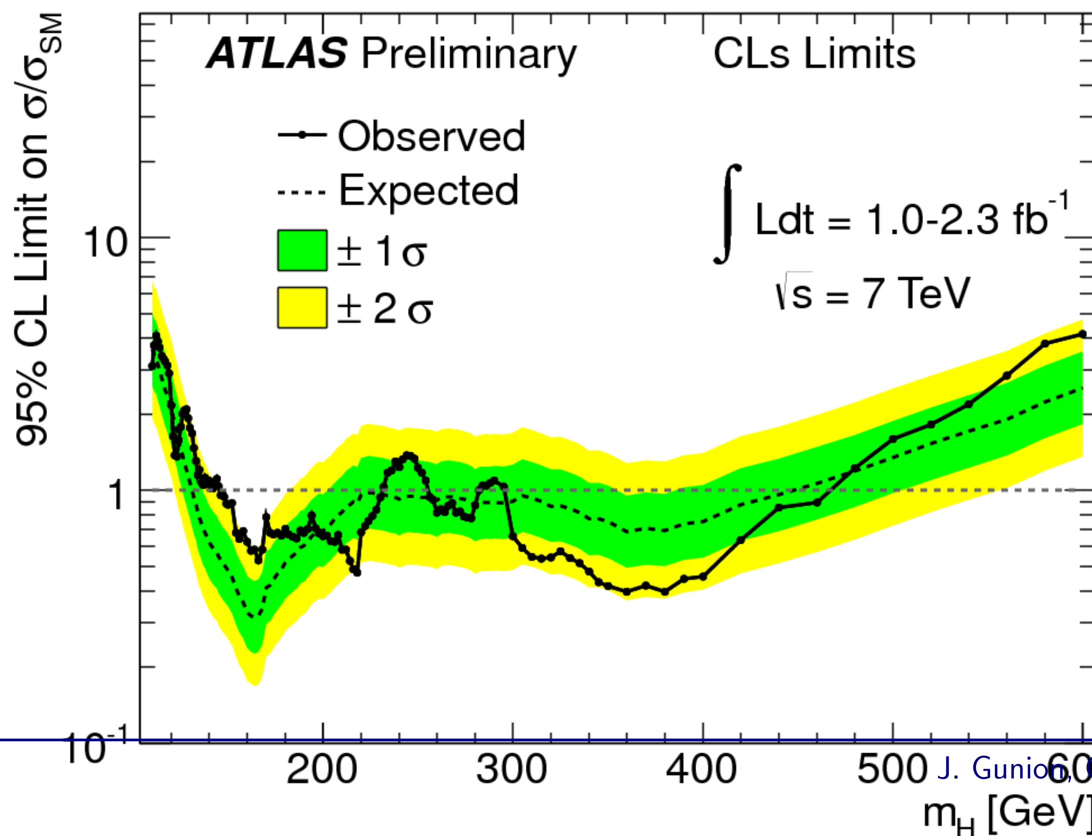
While the $\gamma\gamma$ and $\ell\nu\ell\nu$ are the channels with greatest sensitivity to the h, others also contribute. We now show all the different channels.

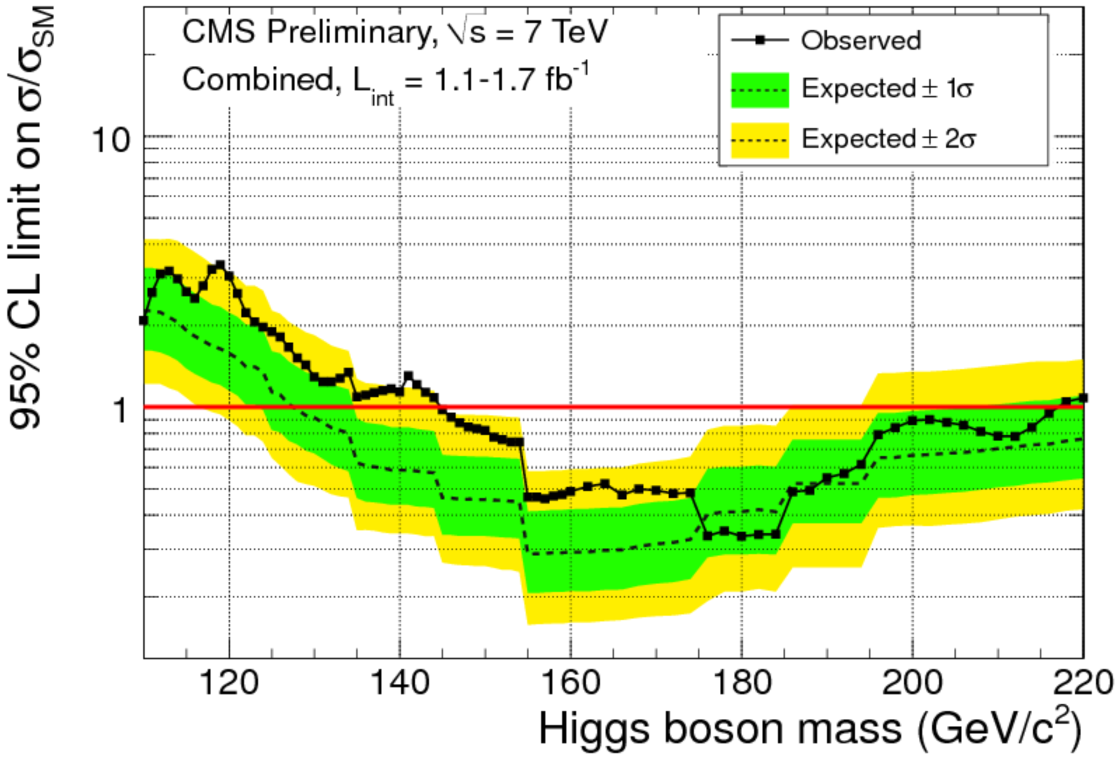




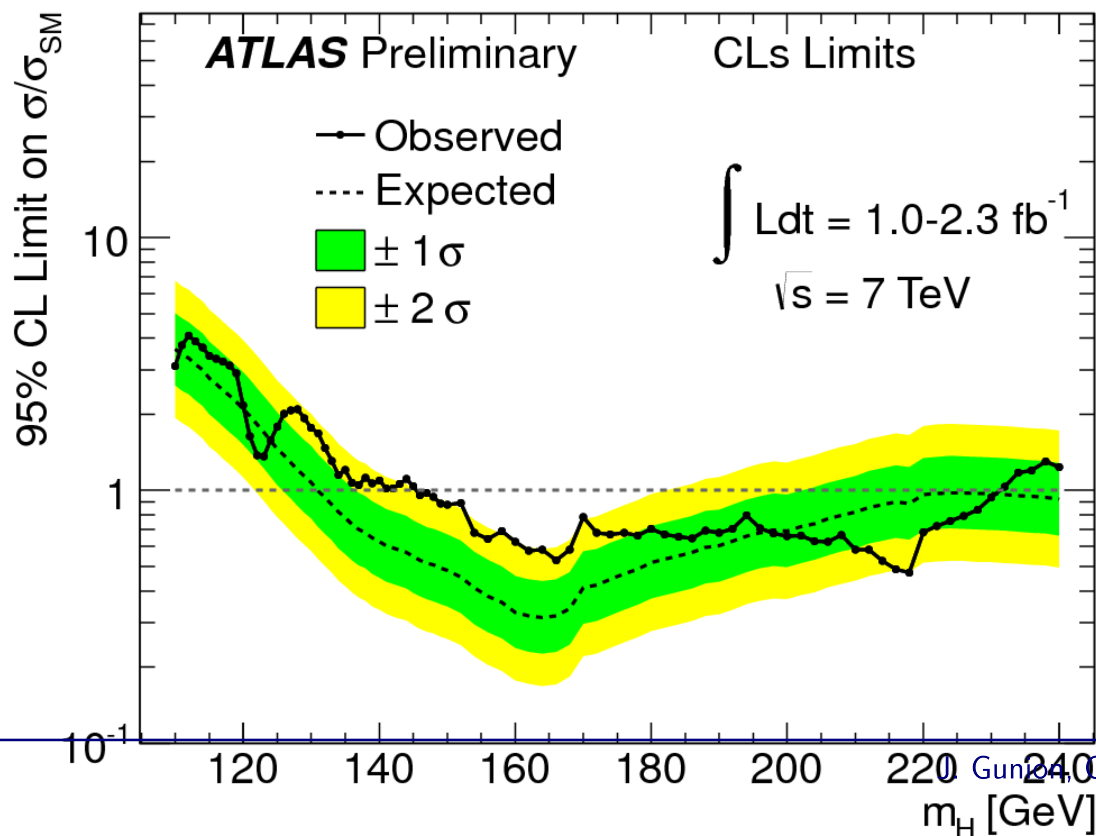
Note how the ATLAS $M_{\gamma\gamma} \sim 128~\mathrm{GeV}$ excess is "undercut" by the smaller upper limit from the $WW \to \ell\nu\ell\nu$ channel. The combined result for all channels follows.


CMS Preliminary, $\sqrt{s}$ = 7 TeV
Combined, L_{int} = 1.1-1.7 fb^{-1}
Observed
Expected ± 1σ
Expected ± 2σ
95% CL limit on σ/σ_{SM}
Higgs boson mass (GeV/c^2)
100
200
300
400
500
600
1
10

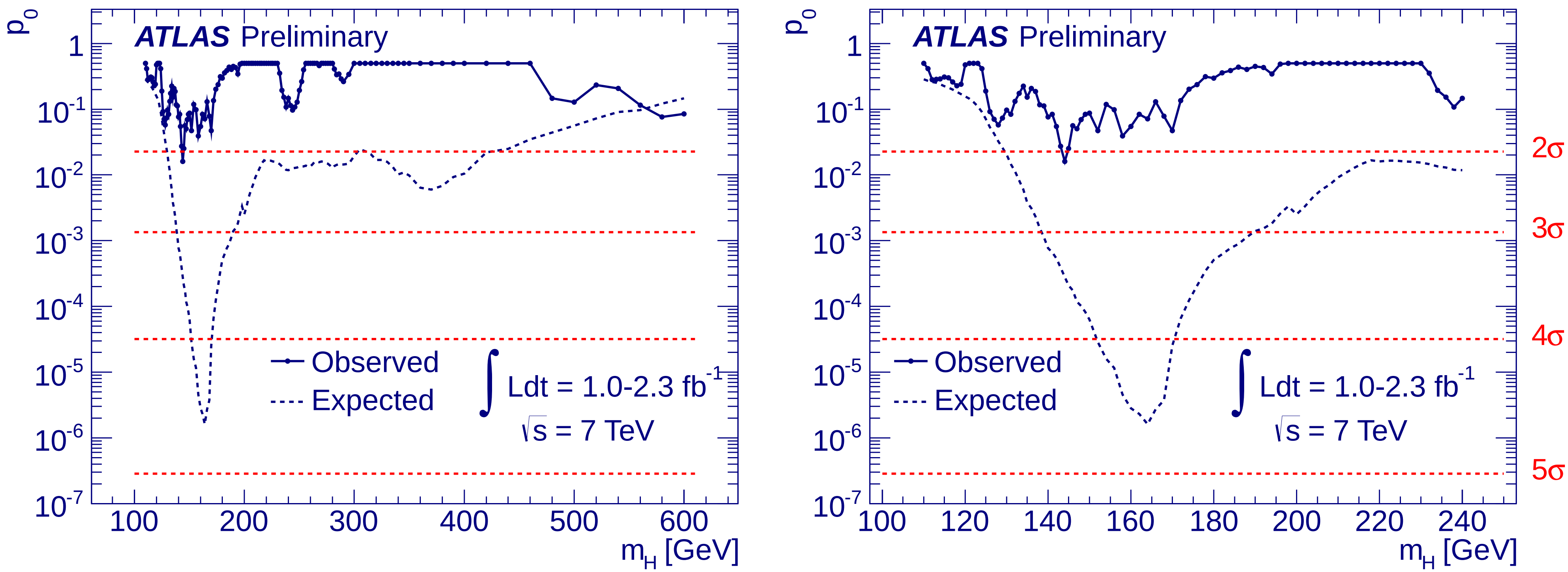

ATLAS Preliminary
CLs Limits
Observed
Expected
± 1 σ
± 2 σ
$\int$ Ldt = 1.0-2.3 fb^{-1}
$\sqrt{s}$ = 7 TeV
95% CL Limit on σ/σ_{SM}
m_H [GeV]
10^{-1}
1
10
200
300
400
500
600



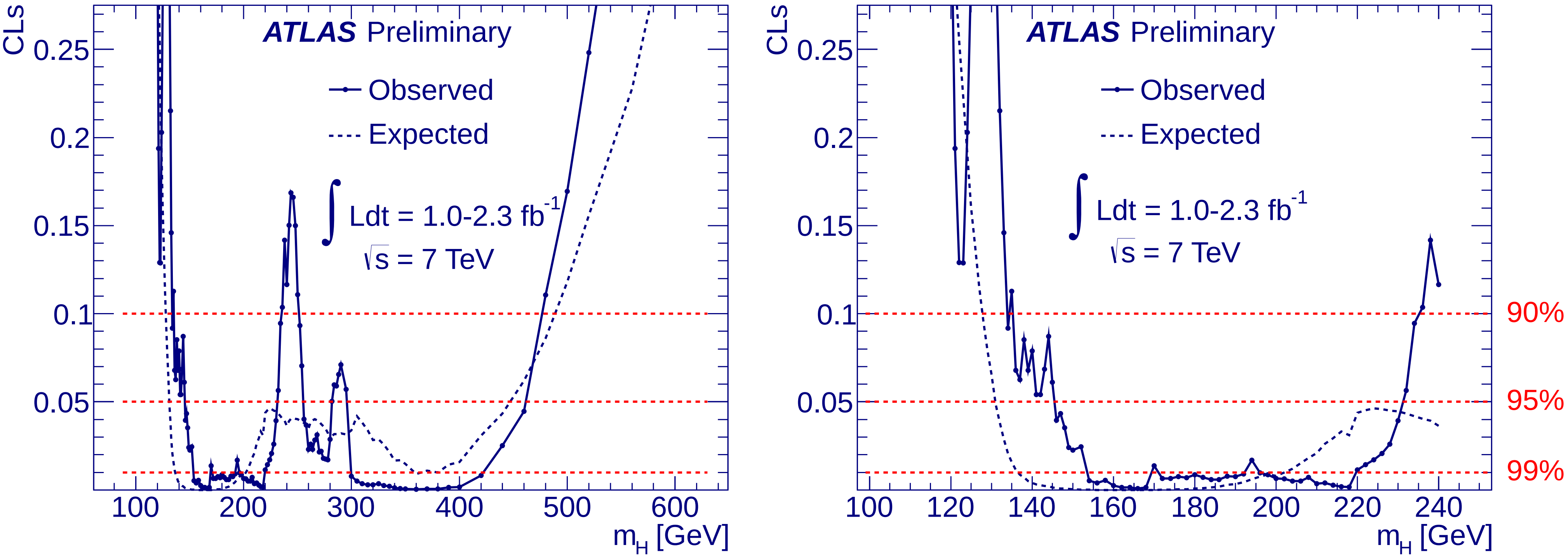
CMS Preliminary, $\sqrt{s}$ = 7 TeV
Combined, L_{int} = 1.1-1.7 fb^{-1}
Observed
Expected ± 1σ
Expected ± 2σ
95% CL limit on σ/σ_{SM}
Higgs boson mass (GeV/c^2)



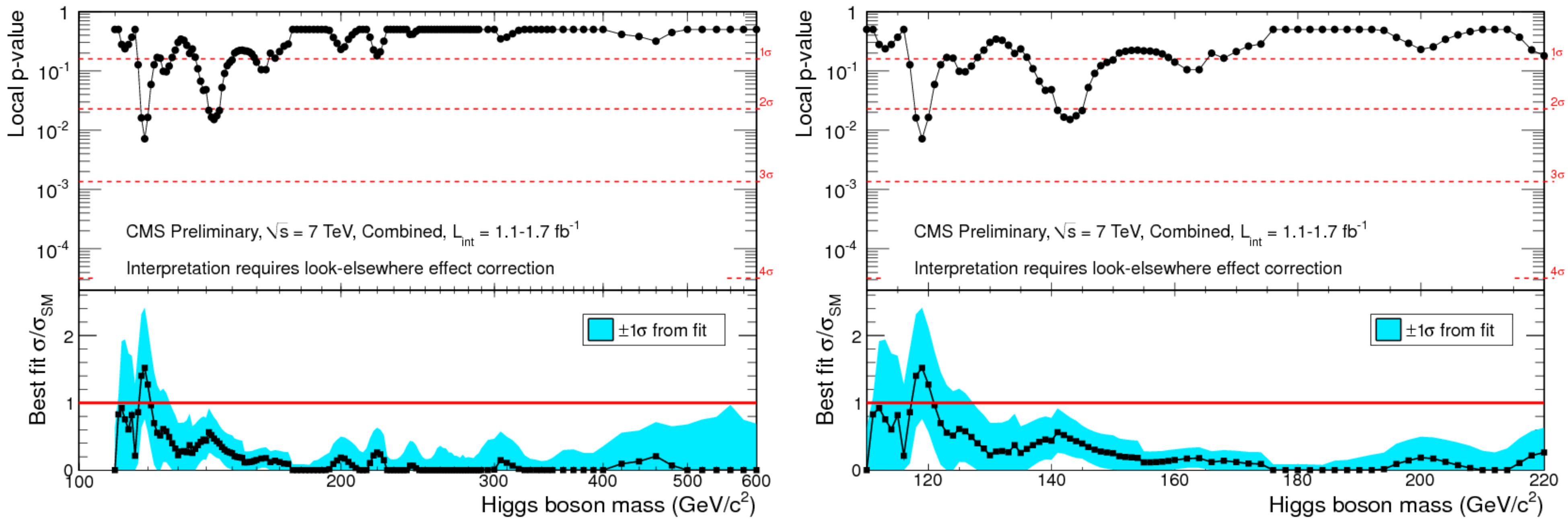
ATLAS Preliminary
CLs Limits
Observed
Expected
± 1 σ
± 2 σ
$\int$ Ldt = 1.0-2.3 fb^{-1}
$\sqrt{s}$ = 7 TeV
95% CL Limit on σ/σ_{SM}
m_H [GeV]



Plots show the consistency of the observed results with the background-only hypothesis, p_0. The dashed line shows the median expected significance in the hypothesis of a Standard Model Higgs boson production signal. The four horizontal dashed lines indicate the p-values corresponding to significances of 2σ, 3σ and 5σ. All the channels are combined (assuming SM weight for each).



The value of the combined CL_s for $\mu = 1$ (testing the Standard Model Higgs boson hypothesis) as a function of $m_{h_{\rm SM}}$ in the full mass range of the analysis. By definition, the regions with $CL_S < \alpha$ are considered excluded at the $(1-\alpha)CL$ or stronger.



CMS results for most probably μ.

Main Conclusions

- $m_h = 120~\mathrm{GeV}$ **might be ok — but ATLAS and CMS do not agree on location of $\gamma\gamma$ peak, showing that statistical fluctuations may still be dominating.**

  If you take CMS at $m_h = 128~\mathrm{GeV}$ and ATLAS at $m_h = 120~\mathrm{GeV}$, then no very strong indication of a SM-like Higgs in the $\gamma\gamma$ channel.

- Any Higgs responsible for the difference between observed and expected limits in the $m_h > 125$ GeV region must have reduced cross section in the $gg \to h \to WW \to \ell\nu\ell\nu$ channel.

- Taken together, this implies that we should certainly be taking 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.

In fact, an entirely reasonable expectation is a chameleon-like emergence from camouflage:

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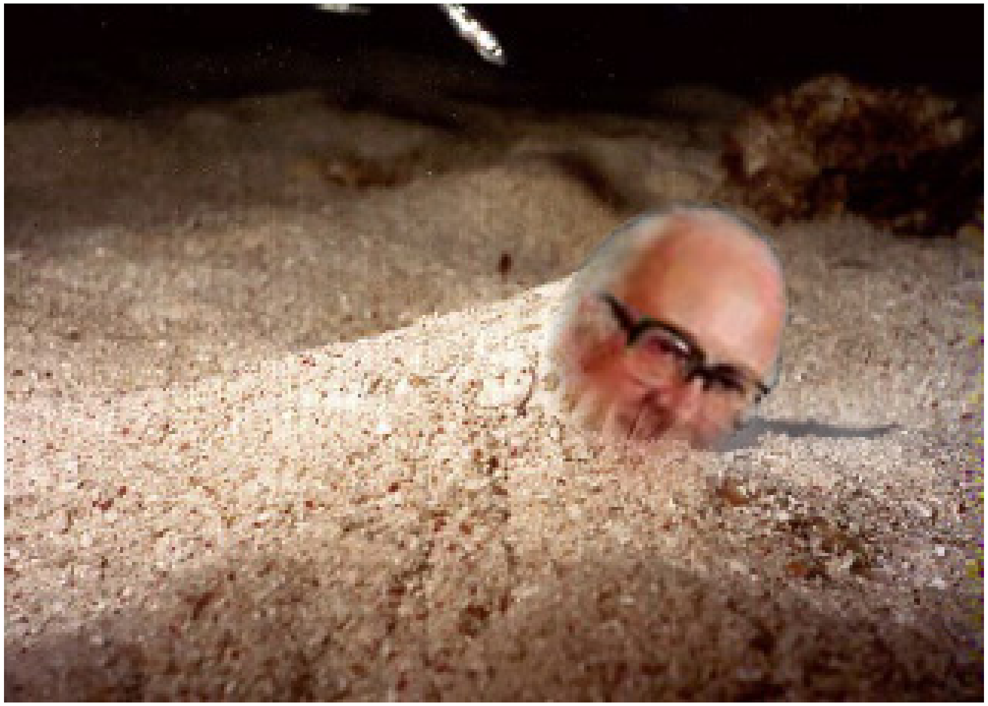


Indeed, there are at least 50 ways to hide the Higgs(es)[1] for now (possibly forever at the LHC) in very reasonable and well-motivated (extreme) models.

Of course, in doing so we should not forget

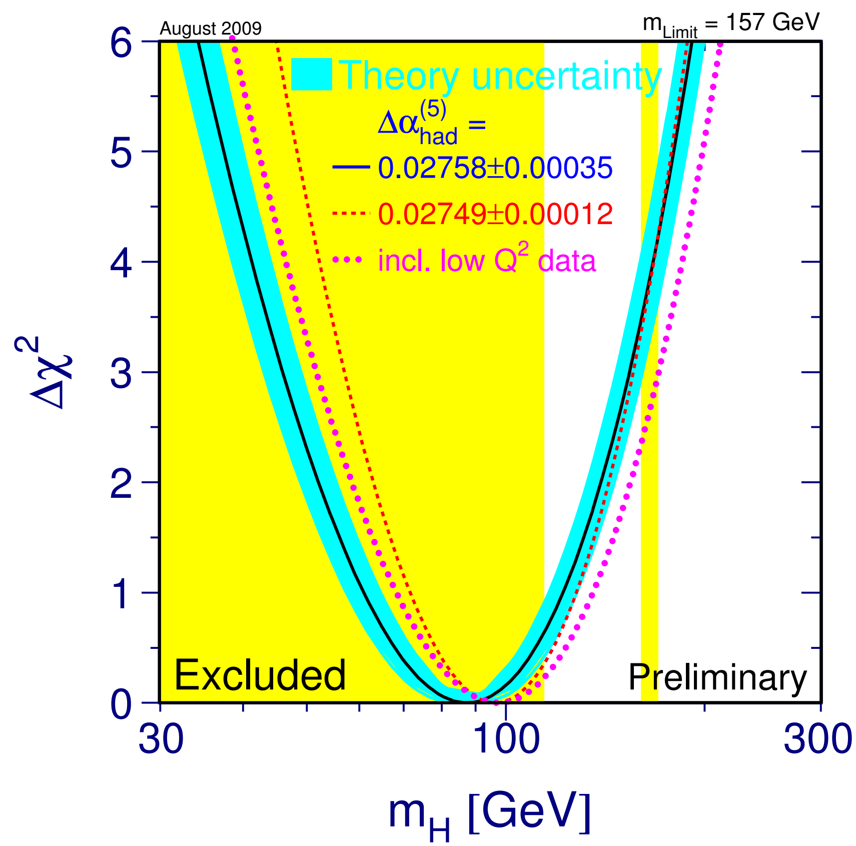


Figure 1: LEP precision electroweak suggests a light Higgs with SM-like WW, ZZ couplings-squared. Or, many light Higgs which cumulatively have SM-like $\sum_k g^2_{VVh_k} = 1$.

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

- If the $\gamma\gamma$ LHC signal "evaporates" a very attractive option is to have a light Higgs, $m_h \lesssim 100$ 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 $95 - 100$ GeV:

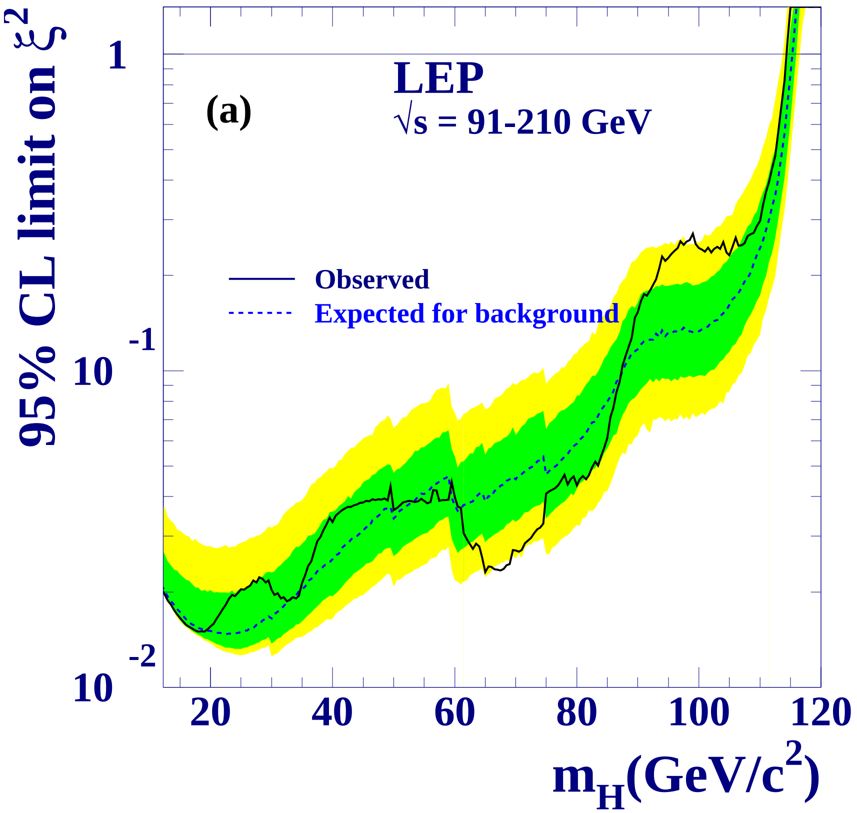


Figure 2: Preference is to retain a $e^+e^- \to Zb\bar{b}$ signal at about $20 - 30\%$ of SM strength.

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

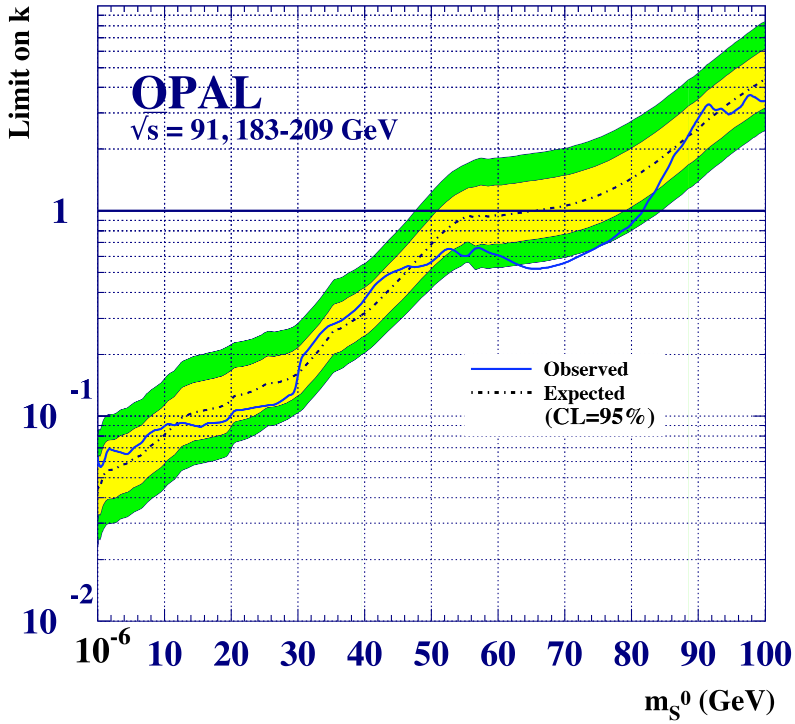


Figure 3: Limits on $\xi^2 = \sigma(e^+e^- \to Zh)/(e^+e^- \to Zh_{\rm SM})$ from OPAL with no assumption about $h \to X$ decays. m_h as small as $82~\mathrm{GeV}$ is allowed.

General Considerations

Experimental

- Experiment measures
$$\sigma(pp \to h) B(h \to X) \tag{8}$$
- $\sigma(pp \to h)$ depends on initial state, e.g. gg or $q\overline{q}$, with $\mathcal{L}(gg)_{eff}$ increasing much more rapidly with increasing energy than $\mathcal{L}(q\overline{q})_{eff}$.
- $gg \to h$ is quite sensitive to what goes inside the loop.
- Branching ratios probe the partial width to total width ratio:
$$B(h \to X) = \frac{\Gamma(h \to X)}{\Gamma_h^{\rm tot}} \tag{9}$$

When $\Gamma_h^{\rm tot}$ is small, as for Higgs masses below $2m_W, 2m_Z$, it is very easy to modify branching ratios when a new channel is added — one is typically only competing with the $b\overline{b}$ final state.

- If there is more than one Higgs and they mix or have special properties, their experimental signals can exhibit a great deal of variation.

- It will often be convenient to define

$$\xi^2(X) = \frac{\sigma(pp \to h) B(h \to X)}{\sigma(pp \to h_{\rm SM}) B(h_{\rm SM} \to X)} \tag{10}$$

where X is some final state. Usually, one production mechanism will be dominant for both $\sigma(pp \to h)$ and $\sigma(pp \to h_{\rm SM})$ for a given final state X.

Theoretical

- In this talk, I will only discuss supersymmetric and extra-dimension models.

These are the only ones that provide a solution to the hierarchy problem and are a complete theory in the ultraviolet regime.

They already provide a plethora of examples of how the Higgs can hide.

- My apologies to all the other interesting ideas I cannot cover.

Supersymmetric Models

- **Supersymmetry is well-motivated as a solution to the hierarchy problem.**

- **Gauge unification is successful.**

- **There is no little hierarchy problem if $m_{\widetilde{t}_1} \lesssim 700~\mathrm{GeV}$, and it is still reasonably acceptable to have $m_{\widetilde{t}_1} \sim 1~\mathrm{TeV}$.**

- **Very heavy first and second generation squarks are entirely acceptable and good for FCNC, ... and do not affect the little hierarchy issue.**

- **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

In even the simplest version of the MSSM, with all sparticles at ~ 1 TeV, 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 other states such as $\gamma\gamma, WW^*$.

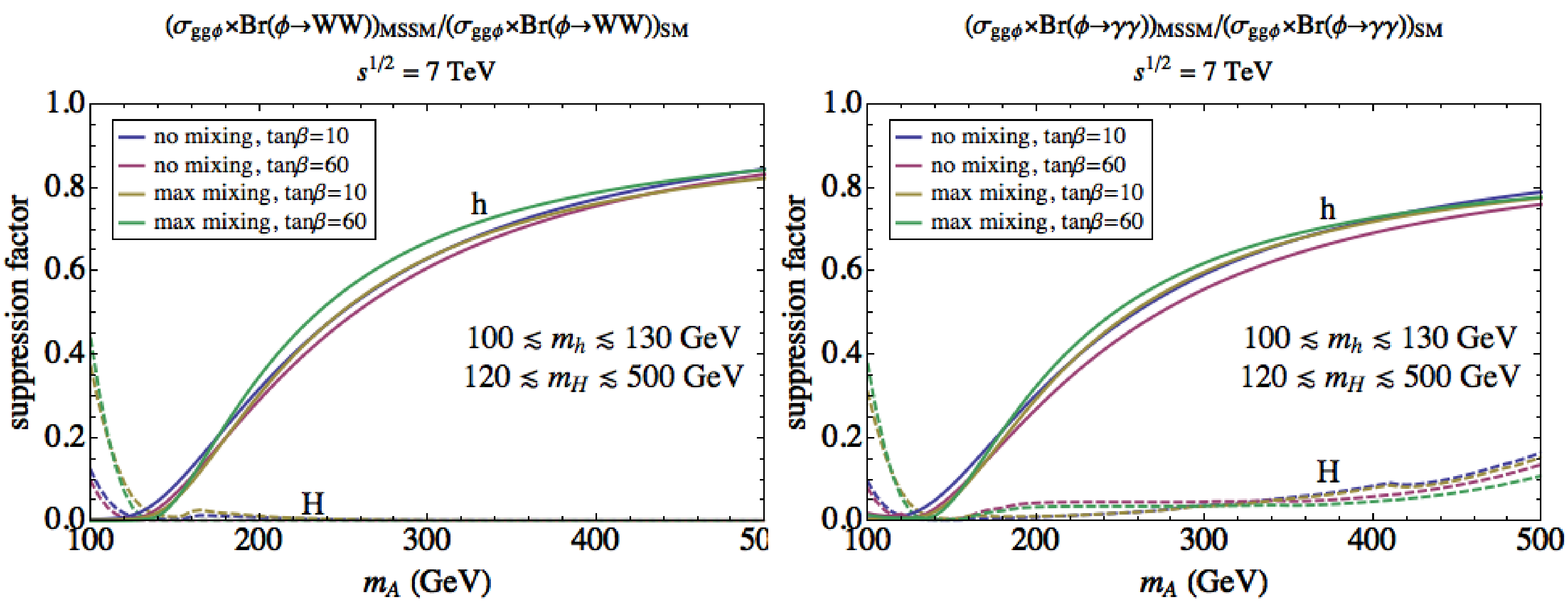


Figure 4: Suppression for the WW and $\gamma\gamma$ final states (Carena, Wagner, *et al.*)

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.**

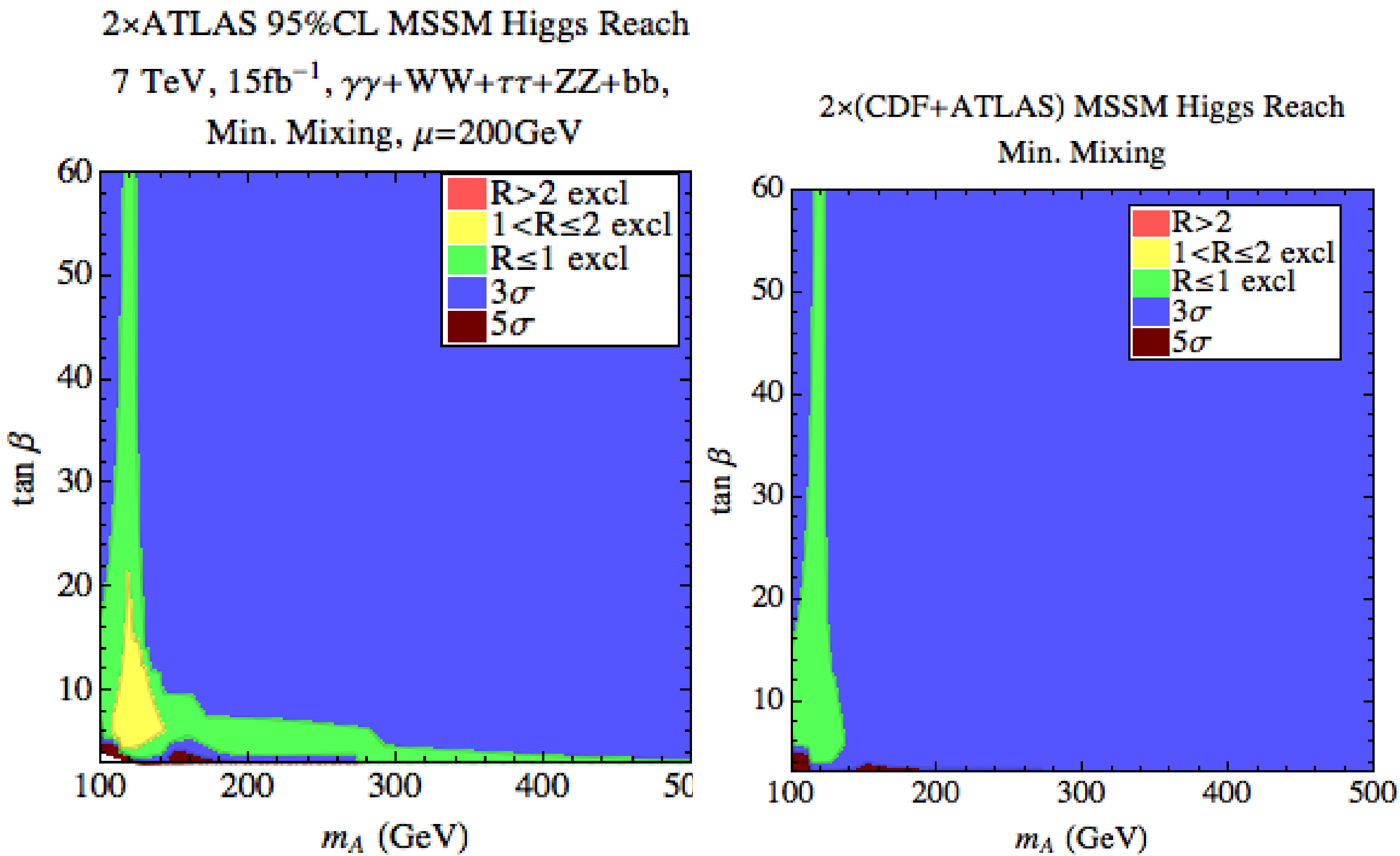


Figure 5: **For $L = 15\ \mathrm{fb}^{-1}$ and minimal mixing (the hardest case), most of parameter space is covered at 3σ (left figure). Or (right figure) combine $L = 5\ \mathrm{fb}^{-1}$ LHC and $L = 10\ \mathrm{fb}^{-1}$ Tevatron and do even better. The Tevatron helps at low Higgs mass where the LHC is weak.**

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 $h \to b\bar{b}$ and $h \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$ decays.

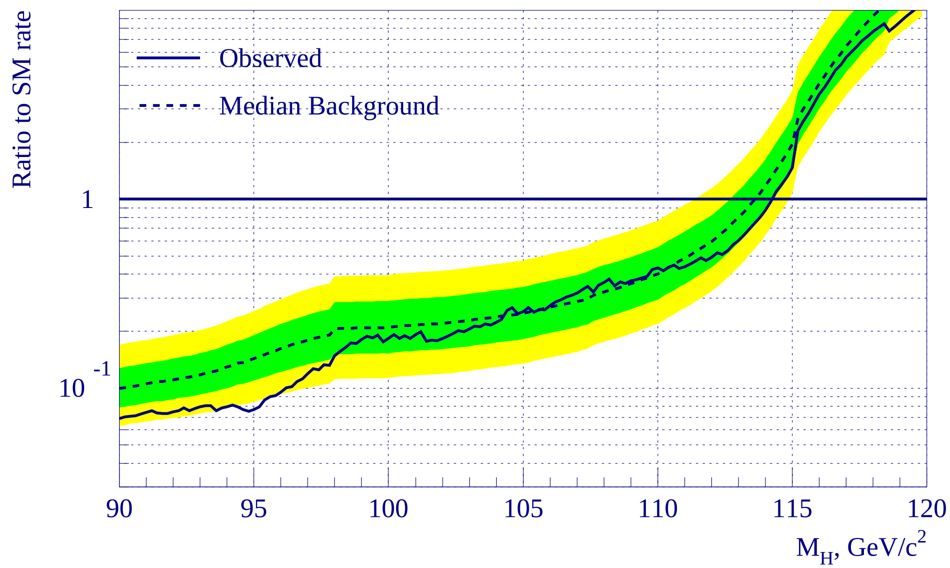


Figure 6: LEP limits on $\xi^2(inv) \equiv [\sigma(Zh)/\sigma(Zh)_{SM}] B(h \to invisible)$ — at $m_h = 112~\mathrm{GeV}$, $\xi^2(inv) = 0.5$ would be ok. Meanwhile, $\xi^2(b\bar{b}) = 0.5$ would also fall under LEP and Tevatron limits. LHC $\gamma\gamma$ rate would be decreased by more than 50%.

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.

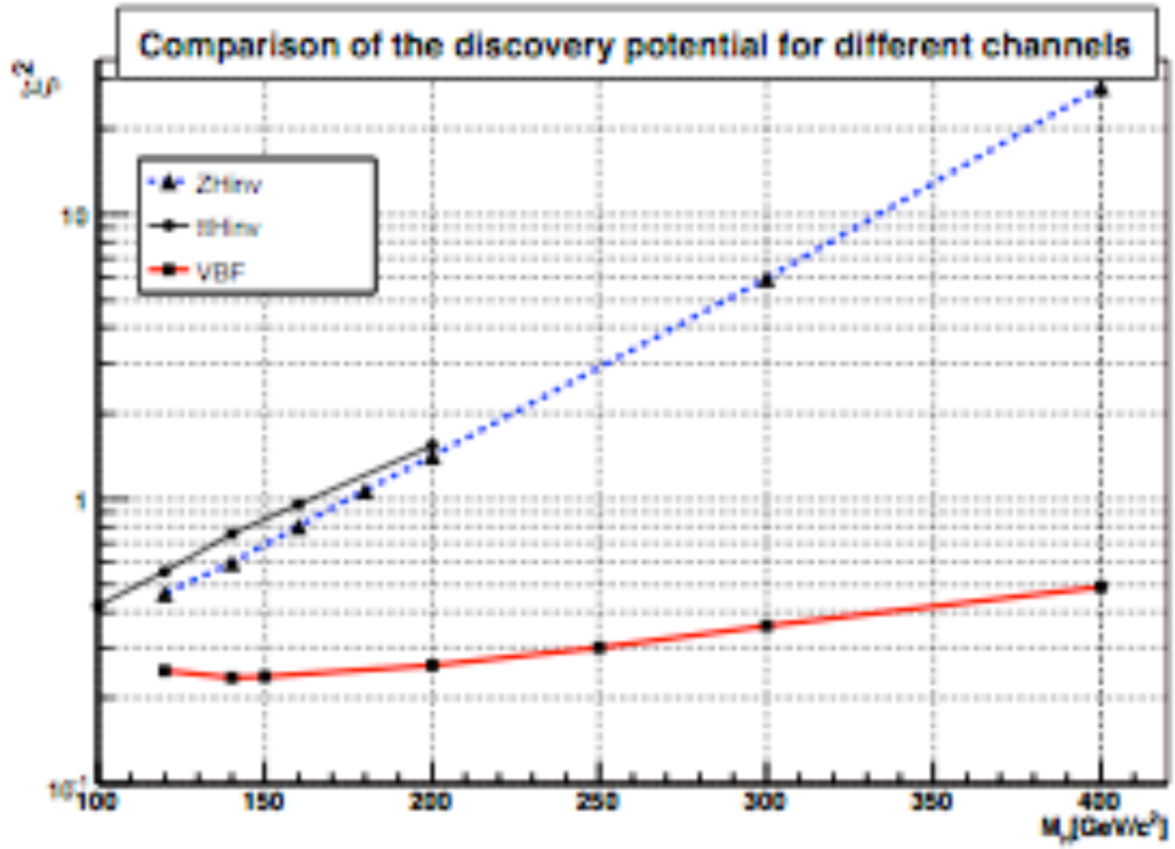


Figure 7: ATLAS-PHYS-PUB-2006-009 95% CL limits on $\xi^2(inv) \equiv [g^2_{hWW}/g^2_{h_{SM}WW}]B(h \to invisible)$ for $L = 30~\mathrm{fb}^{-1}$. Can probe $\xi^2(inv) \sim 0.25$ at low m_h.

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 $\widetilde{\chi}_1^0 \to 3j$ via baryonic R parity violating term in superpotential, $\Rightarrow$ very difficult Higgs detection scenario. (Carpenter, Kaplan, Rhee)

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.*) is that there could be a "dark sector" that communicates with our visible sector via kinematic mixing in the Lagrangian.

- In the simplest visualization, the dark sector contains a dark photon, γ_d associated with a $U(1)_d$ gauge field b_μ. The Lagrangian is:

$$\mathcal{L} = -\tfrac{1}{4} b_{\mu\nu} b^{\mu\nu} - \tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\epsilon}{2} \cos\theta_W b_{\mu\nu} F^{\mu\nu} \tag{11}$$

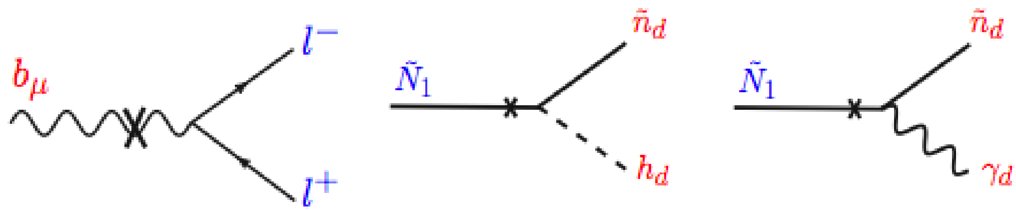
and there are interactions that include

$$V \ni \frac{1}{2} m_b b^2 + b_\mu J^\mu_{dark} + A_\mu J^\mu_{EM} \tag{12}$$

One shifts to remove the kinetic mixing

$$A_\mu \to A_\mu + \epsilon \cos\theta_W b_\mu \tag{13}$$

leading to an interaction of the form $\epsilon b_\mu J^\mu_{EM}$. Supersymmetric kinetic mixing includes gaugino mixing leading to an interaction of form $\epsilon \lambda_{\widetilde{B}} \widetilde{J}_b$. Thus we have the vertices



Various constraints from consistency with satellite and other experiments suggest $m_{\gamma_d} > 100\ \mathrm{MeV}$ and $\epsilon < 10^{-3}$.
The resulting Higgs decay picture would be:

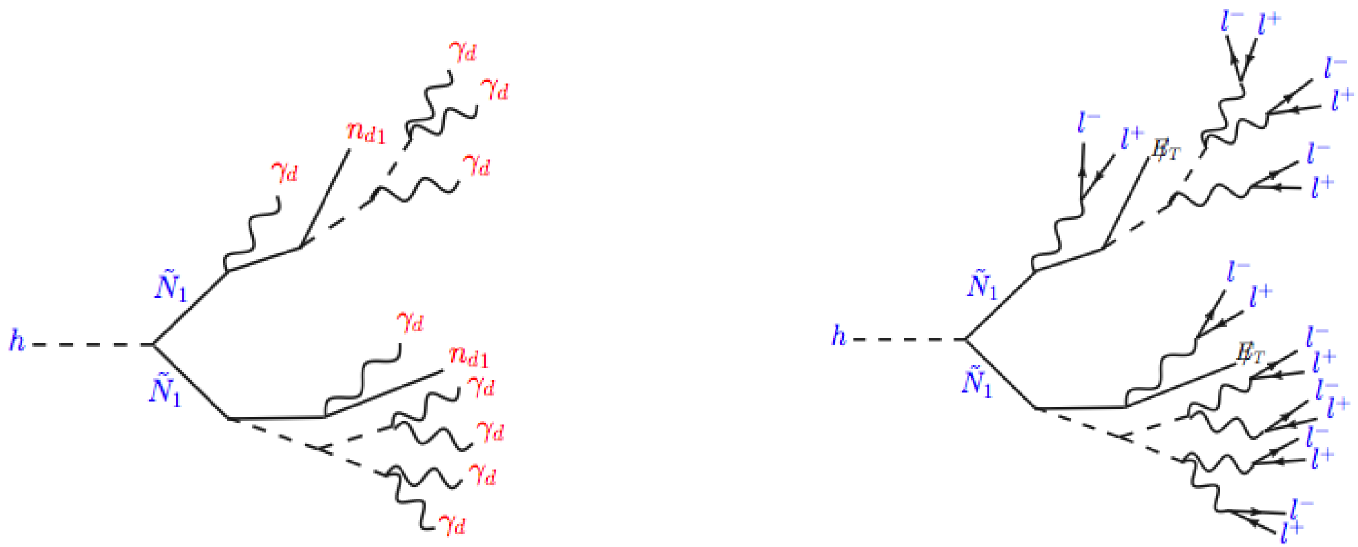
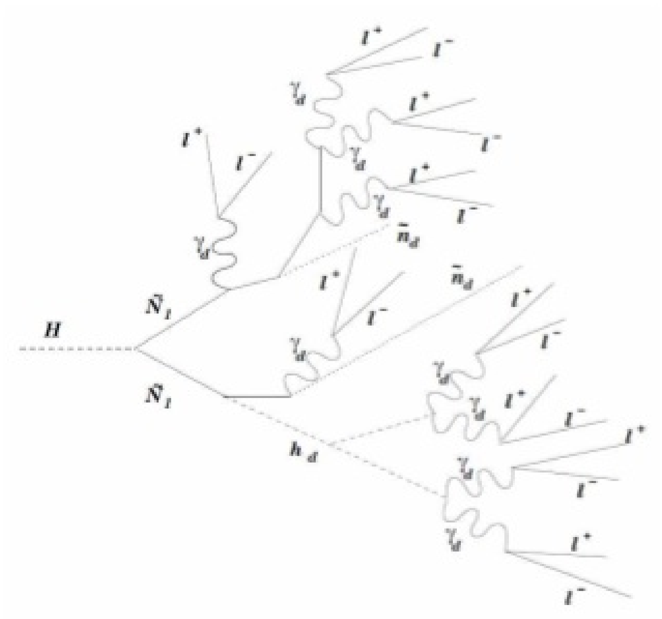


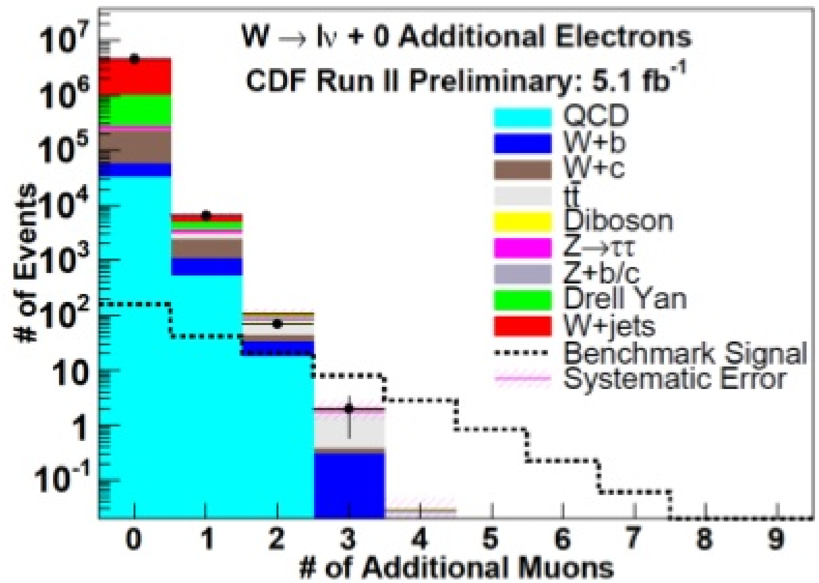
Figure 8: Picture of h decay to dark sector photons and neutralinos and ultimate final state of two lepton jets. Most likely $m_{\gamma_d} > 2m_\mu$ and the leptons would be μ's.

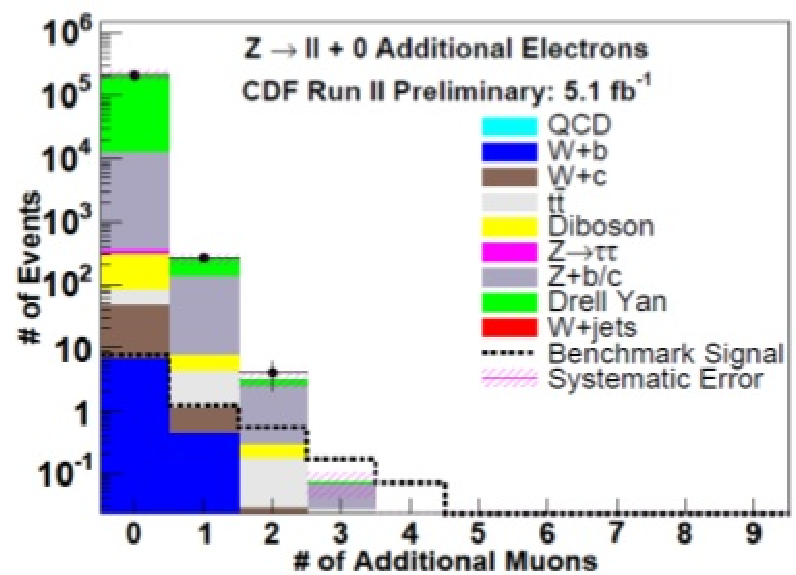
- **At SUSY, Wright showed this transparency which appears to eliminate possibility of muonic lepton jets – assumed $m_h \lesssim 150\ \mathrm{GeV}$, $m_{\gamma_d} \sim 300\ \mathrm{GeV}$ and prompt decays (delayed decays a possibility in the model).**

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







T. Wright SUSY 8/29/2011 26

5. Higgs decay via a Hidden Valley

- Hidden valley again mixes SM sector with a hidden sector (Strassler, Zurek, Han, ...).
- 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.*).

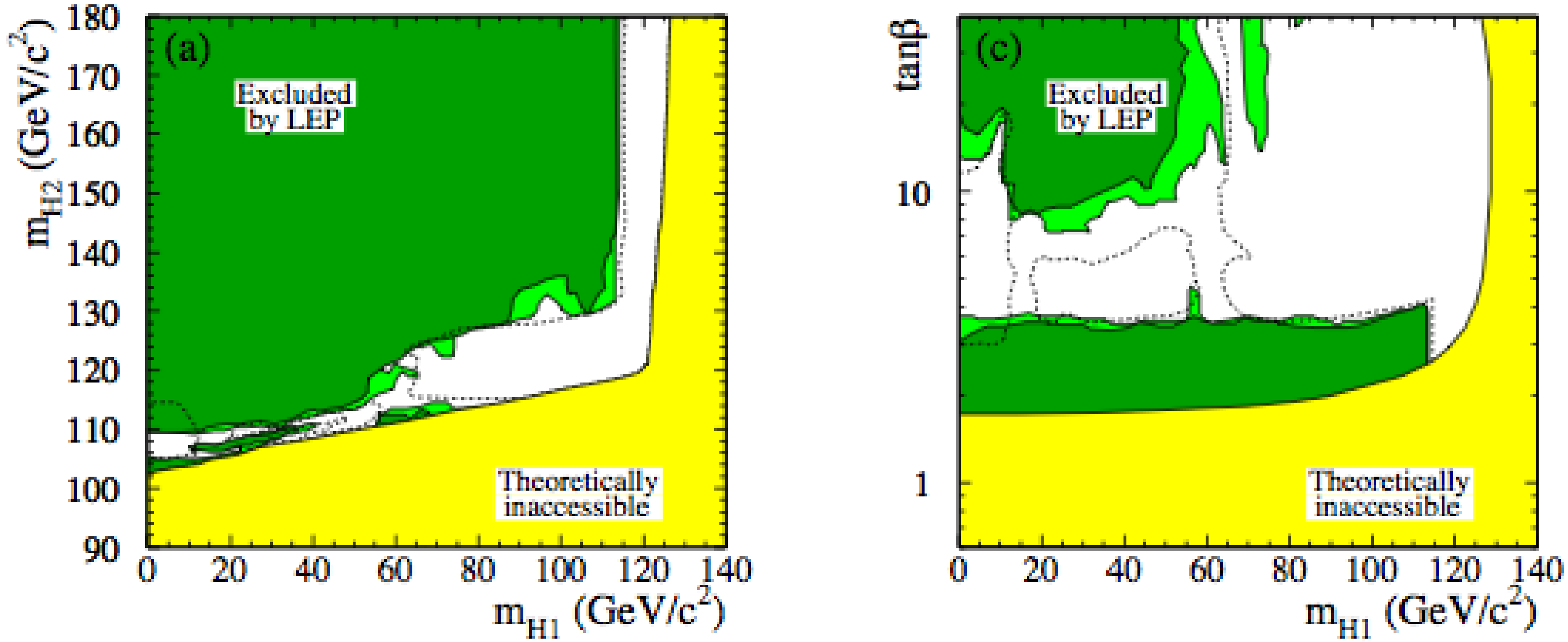


Figure 9: Exclusions from LEP at 95% CL (light-green) and 99.7% CL (dark-green) for the CPX scenario with $m_t = 179.3~\mathrm{GeV}$. For lower m_t excluded regions expand. Note that unexcluded $m_{h_2} < 2m_b$ cases appear for $m_{h_1} \sim 105~\mathrm{GeV}$.

The main reason holes develop is that the channel $e^+e^- \to Zh_2 \to Zh_1h_1$ with $h_1 \to b\overline{b}$ (or possibly $\tau^+\tau^-$) becomes important 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.*), 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

$$a_1 = \cos\theta_A A_s + \sin\theta_A A_{MSSM} \,. \tag{14}$$

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).

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:

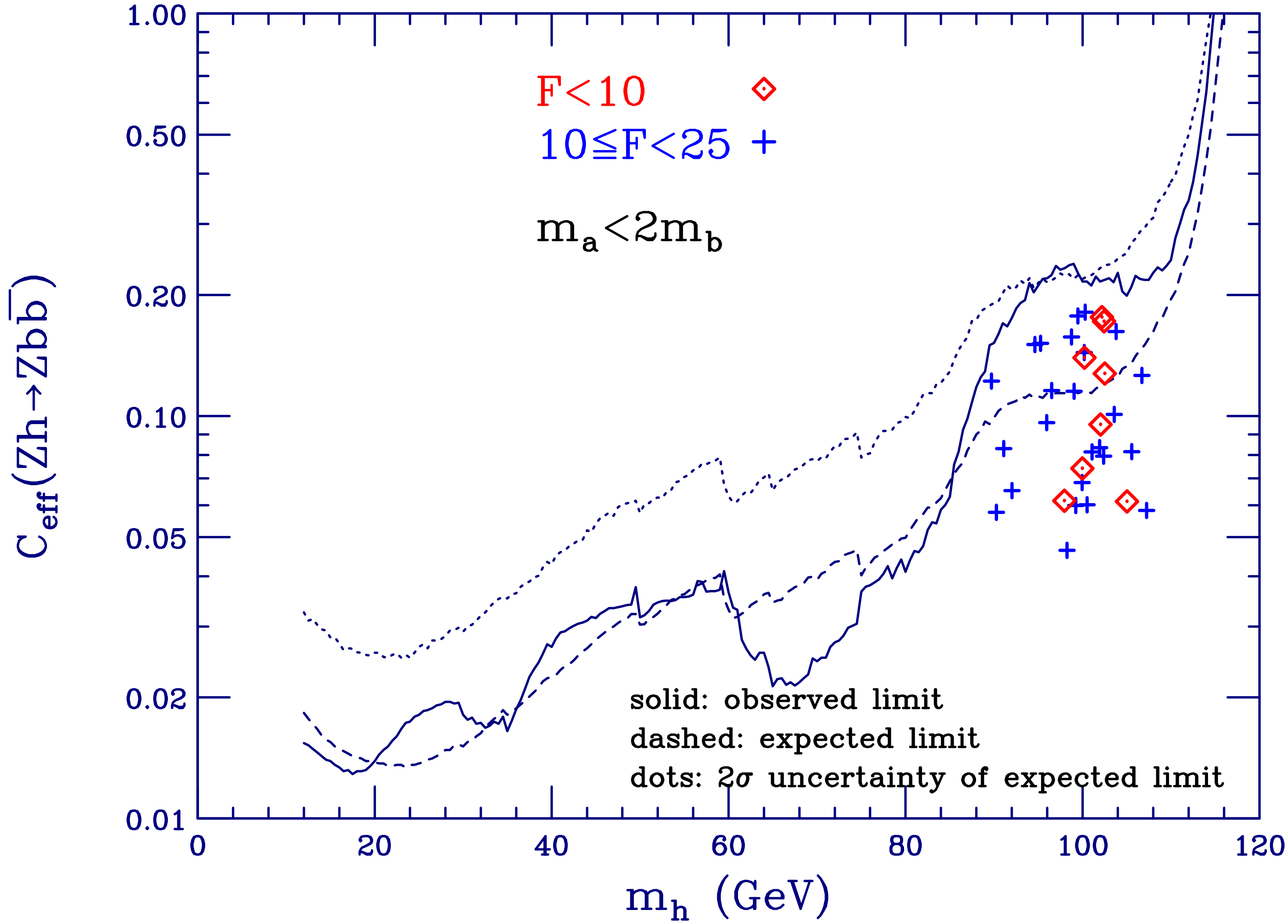


Figure 10: **The excess at $M_{b\bar{b}} \sim 100$ GeV is easily explained, and almost automatically so when small fine-tuning $\boldsymbol{F}$ is required.**

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.*) 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 (Wacker *et al.*) 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 by Has *et al.* (D0).

LHC estimates by Wacker *et al.* in this same mode suggested it was quite promising, but the study by Balyaev *et al.* suggests the backgrounds are much larger than anticipated.

- Forshaw *et al.* looked at $pp \to pp + h_1 \to pp + 4\tau$. Detection is possible, but requires very high $L > 100 \text{ fb}^{-1}$.
- 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).

  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 $m_{h_1} > 114 \text{ GeV}$.

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 (Gunion, Haber; Ellwanger, Gunion, Hugonie; Moretti)
- 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 Moretti *et al.*).

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) and the van der Bij scenarios 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 $100~\mathrm{GeV}$.

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 $\sqrt{s} \sim 250 - 350~\mathrm{GeV}$, 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 only potentially viable, but very difficult, h discovery mode would employ $h \to aa \to gg\gamma\gamma$. The h could easily remain undiscovered at the LHC.

However, 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.

Extra Dimensional Models

- There are many, but one of the simplest and more compelling is the Randall Sundrum (RS) model in which all of the SM fields, including the Higgs, resides on the TeV brane and only gravity propagates in the bulk.

- There are two branes, separated in the 5th dimension (y) and $y \to -y$ symmetry is imposed. With appropriate boundary conditions, the 5D Einstein equations $\Rightarrow$
$$ds^2 = e^{-2\sigma(y)}\eta_{\mu\nu}dx^\mu dx^\nu - b_0^2 dy^2, \tag{15}$$
where $\sigma(y) \sim m_0 b_0 |y|$.

- $e^{-2\sigma(y)}$ is the warp factor; scales at $y = 0$ of order M_{Pl} on the hidden brane are reduced to scales at $y = 1/2$ of order TeV on the visible brane, thereby solving the hierarchy problem.

- Fluctuations of $g_{\mu\nu}$ relative to $\eta_{\mu\nu}$ are the KK excitations $h^n_{\mu\nu}$.

- **Fluctuations of $b(x)$ relative to b_0 define the radion field, ϕ.**

- **In general, there is a term in the Lagrangian that mixes the radion and Higgs fields (Giudice, Ratazzi, Wells):**

$$S_\xi = \xi \int d^4x \sqrt{g_{\rm vis}} R(g_{\rm vis}) \widehat{H}^\dagger \widehat{H} \,, \tag{16}$$

  where $R(g_{\rm vis})$ is the Ricci scalar for the metric induced on the visible brane.

  There is no symmetry that requires $\xi = 0$. It can be anything consistent with basic positivity etc.

- **A crucial parameter is the ratio**

$$\gamma \equiv v_0/\Lambda_\phi \,. \tag{17}$$

  where Λ_ϕ is vacuum expectation value of the radion field and $v_0 = 246~\mathrm{GeV}$.

- **After diagonalizing, the mass eigenstates are h and ϕ.**

- **Higgs-radion mixing dramatically impacts LHC phenomenology.** (Gunion, Dominici, Grzadkowski, Toharia; Hewett, Rizzo)

- 4 independent parameters completely fix the mass diagonalization of the scalar sector when $\xi \neq 0$. These are: $\xi\,, \quad \gamma\,, \quad m_h\,, \quad m_\phi\,.$

  Two additional parameters completely fix the phenomenology of the scalar sector, including all possible decays: $\widehat{\Lambda}_W\,, \quad m_1\,,$ where $\widehat{\Lambda}_W$ will determine KK-graviton couplings to the h and ϕ and m_1 is the mass of the first KK graviton excitation given by $m_1 = x_1 \frac{m_0}{M_{Pl}} \frac{\Lambda_\phi}{\sqrt{6}}$. Here, $x_1 = 3.8$ is the 1st zero of a Bessel function and m_0/M_{Pl} is related to the curvature of the brane and should not be a large number for consistency of the RS scenario.

- Sample parameters that are safe from precision EW data and RunI Tevatron constraints are $\Lambda_\phi = 5~\mathrm{TeV}$ and $m_0/M_{Pl} = 0.1$.

  The latter $\Rightarrow m_1 \sim 780~\mathrm{GeV}$, a value no longer consistent with LHC limits, but I have not had time to update. Results should not be that sensitive.

- **Results shown take $m_0/M_{Pl} = 0.1$.**

- **Let us focus on a scenario that might have something to do with the LHC data.**

  Namely, some WW^* signal in the vicinity of $140~\mathrm{GeV}$ and a possibly SM-like $\gamma\gamma$ signal in the vicinity of $120~\mathrm{GeV}$.

  This can be accommodated for $m_\phi = 140~\mathrm{GeV}$ and $m_h = 120~\mathrm{GeV}$.

- **Indeed, the phenomenology of the ϕ eigenstate varies rapidly as a function of ξ and m_ϕ and we can get almost anything.**

  The LHC excess near $140~\mathrm{GeV}$ is "matched" for small negative ξ.

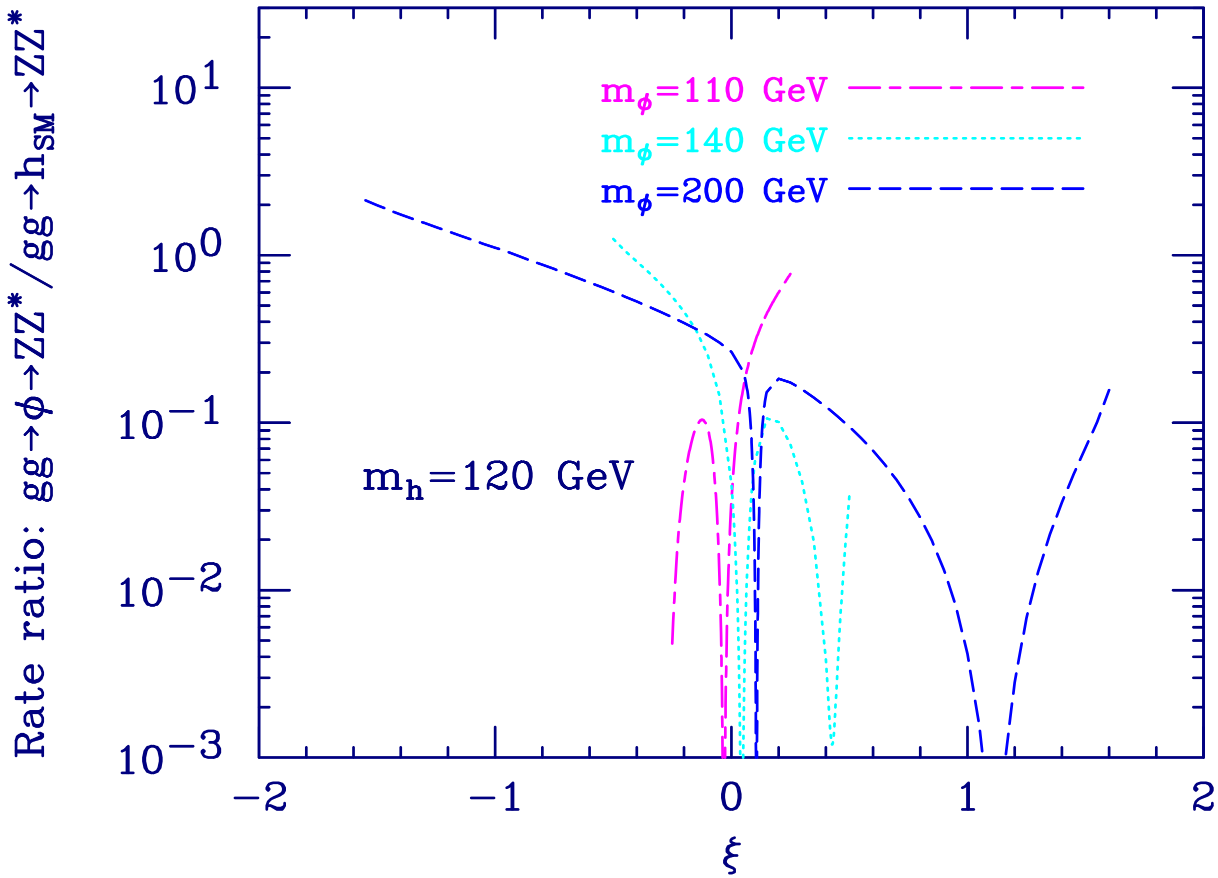


Figure 11: The ratio of the rate for $gg \to \phi \to ZZ$ to the corresponding rate for a SM Higgs boson with mass m_ϕ assuming $m_h = 120~\mathrm{GeV}$ and $\Lambda_\phi = 5~\mathrm{TeV}$ as a function of ξ for $m_\phi = 110$, 140 and $200~\mathrm{GeV}$. (Note: the allowed ξ range is increasingly restricted as m_ϕ becomes more degenerate with m_h.) For $m_\phi = 140~\mathrm{GeV}$ and ξ small and < 0, one gets between 0.1 and 1 times the SM rate in the WW^*, ZZ^* channels.

- **Meanwhile we can get a SM-like $\gamma\gamma$ signal from the h for $m_\phi = 140~\mathrm{GeV}$:**

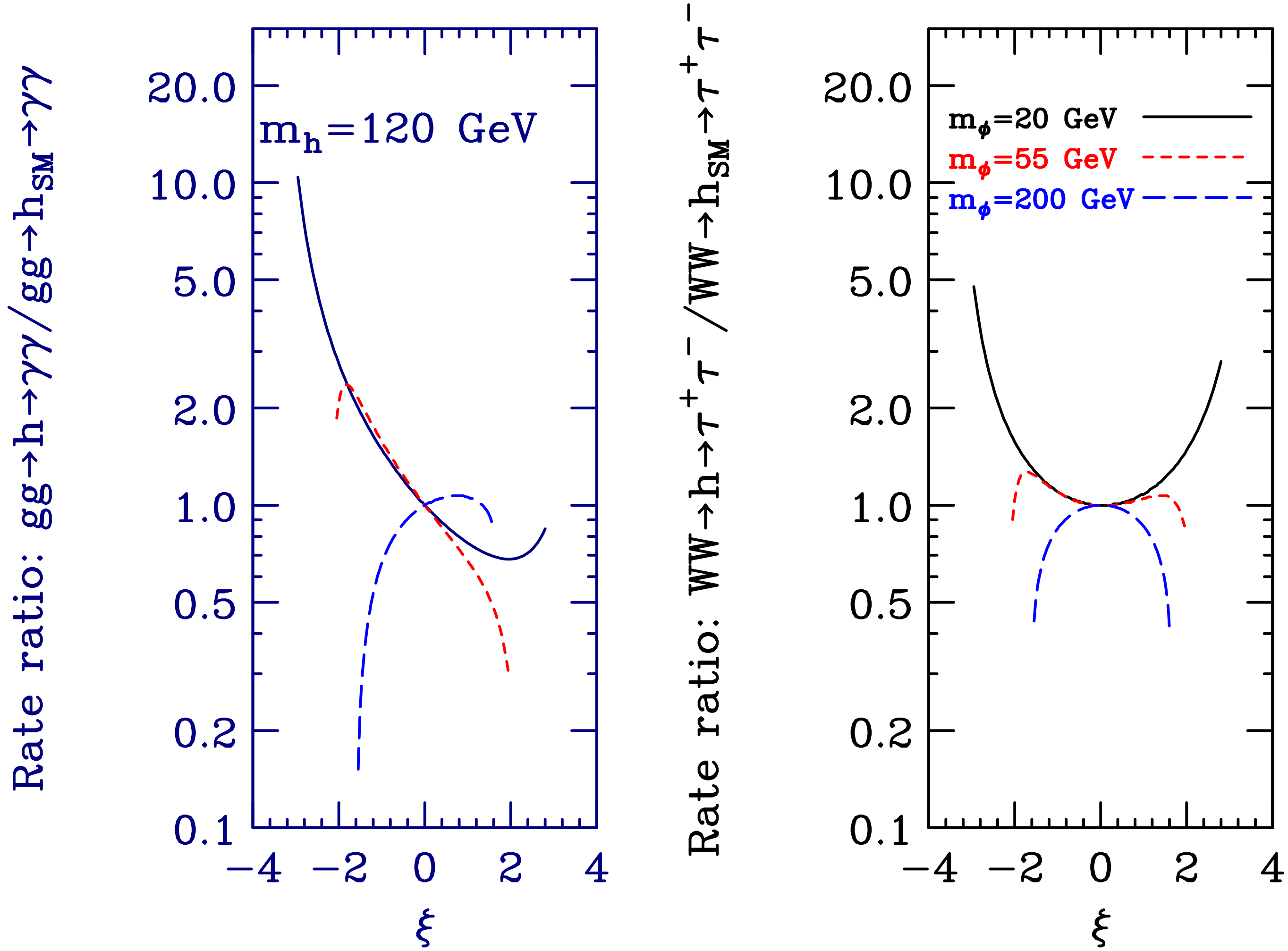


Figure 12: $gg \to h \to \gamma\gamma / gg \to h_{\rm SM} \to \gamma\gamma$ and $WW \to h \to \tau^+\tau^- / WW \to h_{\rm SM} \to \tau^+\tau^-$ (same as for $gg \to t\bar{t}h \to t\bar{t}b\bar{b}$) for $m_{h_{\rm SM}} = m_h$. Interpolating between the $m_\phi = 55~\mathrm{GeV}$ and $m_\phi = 200~\mathrm{GeV}$ curves we see that the $h \to \gamma\gamma$ rate will be close to SM for small negative ξ.

Conclusion

Thus, while the Higgs boson(s) may be buried, they could be alive and well just below the surface.

If anything, the failure to see a SM-like Higgs in the SM-like channels was "expected" by many of us.

Certainly, I am watching and waiting