# Exotic Higgs Scenarios

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# Outline

- SM, no SUSY + Additional Singlets, Doublets, Triplets
- MSSM + CP violation and/or singlets
- Left-Right Symmetric SUSY Model
- SM + radion

In many cases, must deal with strongly mixed, overlapping Higgs resonances

- No Higgs

There are so many "exotic" Higgs models now, that it is impossible to review more than a few.

# SM + ...

- **Add singlets**

  No particular theoretical problems (or benefits) but discovery becomes more challenging.

- **Add doublets**

  No $\rho = 1$ problems, but $m_{H^\pm}^2 > 0$ must be input.

- **Add triplets**

  Could be good for coupling unification.

  If vev=$0$, no $\rho = 1$ issues.

  If vev$\neq 0$, $\Rightarrow$ new game for tree-level precision EW (PEW), but $\rho$ is no longer computable at one loop. In fact, $\rho$ becomes another input parameter to the theory.

$Y \neq 0$ triplets are motivated by L-R models and seesaw neutrino mass generation. Aside from the triplet, an L-R model must contain at least one doublet and more are certainly a possibility.

- Coupling unification can be achieved without SUSY by introducing additional Higgs representations in the standard model.

Some simple choices are ($N_{T,Y} =$ number of reps. of given type):

| $N_{1/2,1}$ | $N_{1/2,3}$ | $N_{0,2}$ | $N_{0,4}$ | $N_{1,0}$ | $N_{1,2}$ | $\alpha_s$ | $M_U$ (GeV) |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 2 | 0 | 0 | 0.106 | $4 \times 10^{12}$ |
| 1 | 0 | 4 | 0 | 0 | 1 | 0.112 | $7.7 \times 10^{12}$ |
| 1 | 0 | 0 | 0 | 0 | 2 | 0.120 | $1.6 \times 10^{13}$ |
| 2 | 0 | 0 | 0 | 1 | 0 | 0.116 | $1.7 \times 10^{14}$ |
| 2 | 0 | 2 | 0 | 0 | 2 | 0.116 | $4.9 \times 10^{12}$ |
| 2 | 1 | 0 | 0 | 0 | 2 | 0.112 | $1.7 \times 10^{12}$ |
| 3 | 0 | 0 | 0 | 0 | 1 | 0.105 | $1.2 \times 10^{13}$ |

Find lower $M_U$ than comfortable for proton decay.

Can fix by not having true group unification, as in some string models

My personal favorite: $N_{\frac{1}{2},1} = 2, N_{1,0} = 1 \Rightarrow \alpha_s(m_Z) = 0.115$, $M_U = 1.7 \times 10^{14}$ GeV

Triplet members are denoted $\xi^{+,0,-}$ and $v_T = \langle \xi^0 \rangle$.

Notation for doublet members is the usual, with $v_u = \langle H_u \rangle$ and $v_d = \langle H_d \rangle$ and $v_D = \sqrt{v_u^2 + v_d^2}$.

Define $\tan\beta = v_u/v_d$ and $\tan\gamma = v_T/v_D$.

- For this (and other models) there is no guarantee that we will find a light Higgs.

  Examples:

  – $\boxed{\text{Case 1: } v_T = 0}$ JFG, Farris, Chankowski, Grzadkowski, Kalinowski, Krawczyk
  If triplet Higgs heavy, only role of triplet is for gauge coupling unification – i.e. at lower $\sqrt{s}$ just a special (non-decoupling) 2HDM case.
  Choose $m_{A^0}$ not too heavy, $m_{A^0} \lesssim 500$ GeV (possibly quite light).
  Choose $\tan\beta$ moderate so that $A^0$ is in LHC/LC wedge region of no discovery.

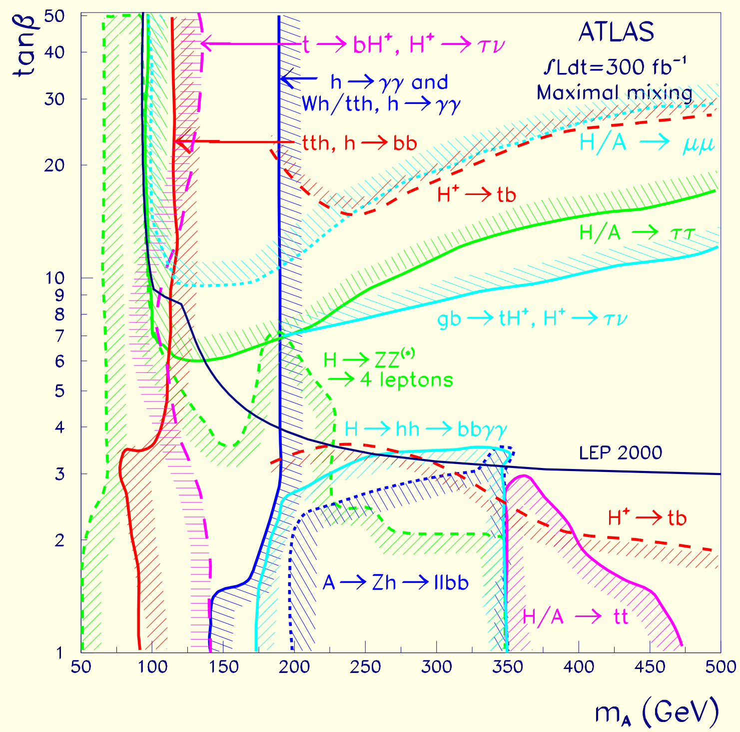



**Figure 1:** $5\sigma$ discovery contours for MSSM Higgs boson detection in various channels are shown in the $[m_{A^0}, \tan\beta]$ parameter plane, assuming maximal mixing and an integrated luminosity of $L = 300\mathrm{fb}^{-1}$ for the ATLAS detector. "Wedge" region for $A^0$ (without degenerate $H^0$) would be somewhat larger.

**Choose $m_{h^0}$ heavy (e.g. $\sim 800~\mathrm{GeV} - 1~\mathrm{TeV}$) and SM-like.**
**Choose $m_{H^0}$ and $m_{H^\pm}$ still heavier (but $\lesssim 1~\mathrm{TeV}$ for perturbative $\lambda_i$ in $V_{Higgs}$) with $m_{H^\pm} - m_{H^0} > 0$ but quite small (e.g. $\sim$ few $\mathrm{GeV}$).**
**A heavy SM-like $h^0 \Rightarrow$ large $\Delta S > 0$ and $\Delta T < 0$ contributions.**

## This is compensated by large $\Delta T > 0$ from $m_{H^\pm} - m_{H^0} > 0$.

$$\Delta\rho = \frac{\alpha}{16\pi m_W^2 c_W^2}\left\{\frac{c_W^2}{s_W^2}\frac{m_{H^\pm}^2 - m_{H^0}^2}{2} - 3m_W^2\left[\log\frac{m_{h^0}^2}{m_W^2} + \frac{1}{6} + \frac{1}{s_W^2}\log\frac{m_W^2}{m_Z^2}\right]\right\} \quad (1)$$

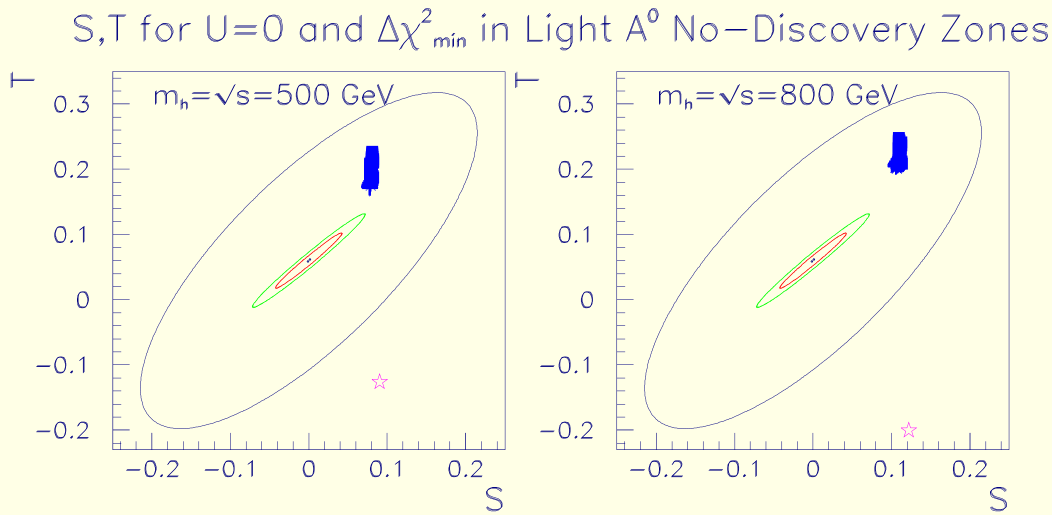



**Figure 2:** Outer ellipses = current 90% CL region for $U = 0$ and $m_{h_{\rm SM}} = 115$ GeV. Blobs = $S, T$ predictions for Yukawa-wedge 2HDM models with $m_{H^\pm} - m_{H^0}$ chosen to minimize PEW $\Delta\chi^2$. Innermost (middle) ellipse = 90% (99.9%) CL region for $m_{h_{\rm SM}} = 115$ GeV after Giga-$Z$ *and* a $\Delta m_W \lesssim 6$ MeV threshold scan measurement. Stars = SM $S, T$ prediction if $m_{h_{\rm SM}} = 500$ or $800$ GeV.

### Future phenomenology

Giga-$Z$ (with $\Delta m_W = 6 MeV$ from $WW$ threshold scan) would pinpoint situation.

The LHC woud discover a $\sim 1$ TeV SM-like $h^0$.

There would be no light CP-even Higgs boson (with $WW, ZZ$ couplings) as apparently needed to satisfy precision electroweak constraints.

The LC would see nothing in $e^+e^-$ collisions (for $\sqrt{s} \lesssim 1$ TeV), but $\gamma\gamma$ collisions could allow $A^0$ discovery in the wedge (JFG+Asner+Gronberg)

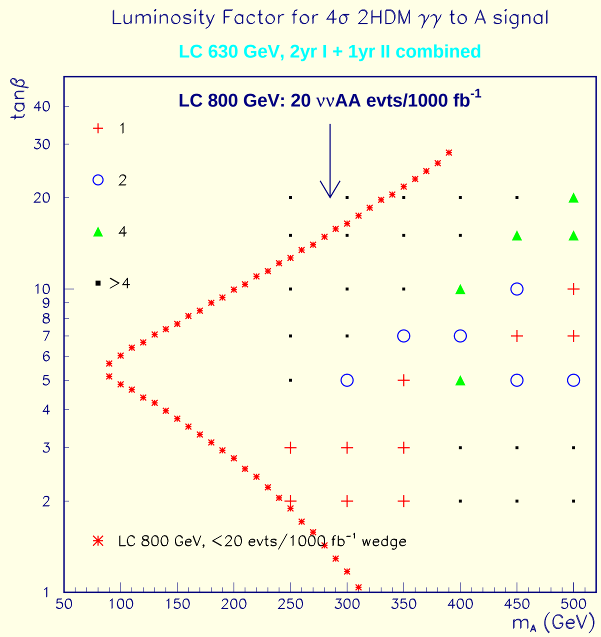



**Figure 3:** $+$'s show points with $> 4\sigma$ signal after combining $N_{SD}$'s for 2 yr type-I and 1 yr type-II NLC operation at $\sqrt{s} = 630$ GeV. o's show TESLA additions. (from JFG+Asner+Gronberg)

Note that $A^0 A^0 \nu\overline{\nu}$ production covers up to $m_{A^0} \sim 285$ GeV for $\sqrt{s} = 800$ GeV operation.

A muon collider could also be very competitive using $\mu^+\mu^- \to A^0$ and a carefully designed scan procedure. (JFG)

*Note* For $v_T = 0$, the lightest of the triplet Higgs members would be stable; set it up so that $\xi^0$ is the lightest, $\Rightarrow$ dark matter.

– $\boxed{\text{Case 2: } v_T \neq 0}$ (J. Forshaw + ...)

One finds $\rho = 1/\cos^2\gamma$, which for small $\gamma$ means $\alpha\Delta T \sim +\gamma^2$.

$\Delta S = 0$ since this is a $Y = 0$ triplet being considered.

In other words, this is another source of isospin breaking (at tree-level) that can allow a heavier $m_{h^0}$.

If $m_{h^0} \sim 1~\mathrm{TeV}$ and $m_{H^\pm} = m_{H^0}$, then $\gamma \sim 0.06$ gives acceptable PEW.

As stated, the problem is that the tree-level result is infinitely renormalized at one-loop and there is no actual prediction for $\rho$; it becomes another theory input that must be specified.

**The Problem** There is no stabilization of quadratic divergences from various sources.

One could use Veltman-like conditions on Higgs masses (in terms of top, $W$, $Z$, $\ldots$ masses) to delay this until scales of order 10 TeV, but beyond that?

We should consider SUSY and/or extra dimensions.

# Beyond the CPC MSSM.

- **MSSM with mSUGRA-like SUSY breaking is being pushed.**

  **In particular, Higgs lower mass bound $\Rightarrow$:**

  - **significant fine tuning;**
  - **too little baryogenesis;**
  - **fine-tuned windows for adequate dark matter after other constraints incorporated.**

  **And, the source of $\mu$ is still problematical.**

- **Enter:**

  - **CP-violation in MSSM Higgs sector (from CP-violating soft-SUSY)**
  - **The NMSSM**
  - **More singlets (doublets disfavored by coupling unification).**

  **All of these $\Rightarrow$ possible difficulties for detecting even one of the Higgs bosons at the LHC.**

  **Can choose parameters so that the following problems arise:**

- The easily produced Higgs boson(s), e.g. those with large $WW/ZZ$ coupling, decay dominantly to two lighter Higgs bosons. (a point made in (JFG, Haber, Moroi, Snowmass 96) and later examined by (Matchev, . . . ).
  For example, for CPC sector $h \to aa$ or $h' \to hh$.
  For CPV Higgs sector, $h \to h'h''$.
  Also $h \to h'V$ channels.
  In both the CPC and CPV cases, it can be arranged that these lighter Higgs bosons have $WW/ZZ$ couplings that are very weak or zero (when pseudoscalars in the CPC case) and unenhanced Yukawa couplings to $t\bar{t}$ and $b\bar{b}$.
  In this case, it will typically be very difficult to detect them directly.
- When there are multiple mixed CP-even Higgs bosons in a CPC Higgs sector or mixed CP-even and CP-odd Higgs bosons in a CPV Higgs sector, the Higgs bosons will generically tend to share the $WW/ZZ$ coupling strength.
  At the LHC, $\Rightarrow$ dramatic reduction of $W$-loop contribution to the $h\gamma\gamma$ couplings $\Rightarrow$ very small rate in the excellent resolution $gg \to h \to \gamma\gamma$ channels.
  $gg \to h \to ZZ \to 4\ell$ also suppressed relative to the poorer resolution $b\bar{b}$ and $t\bar{t}$ channel branching ratios (not to mention any possible $h \to Vh'$ or $h \to h'h''$ decays).

– Higgs bosons can differ in mass so that signals in, e.g., $gg \to t\bar{t}h$ with $h \to b\bar{b}$ or $h \to \tau^+\tau^-$ are overlapping as well as reduced in magnitude. $\Rightarrow$ obviates many discovery modes.
  Even in the absence of $h$ decays to other Higgs bosons, the $WW \to h \to \tau^+\tau^-$ detection channel will take a "double-hit".
  1. The production rate for each $h$ is suppressed due to reduced $WWh$ coupling.
  2. The poor mass resolution $\Rightarrow$ signals for different $h$'s (separated in mass by, say, $10~\mathrm{GeV}$) will overlap and make peak detection impossible.
     Instead, one must try to determine the presence of a broad excess in the $M_{\tau\tau}$ distribution.

When the LHC fails, the LC can succeed using $e^+e^- \to Zh$ in the inclusive $e^+e^- \to ZX$ missing-mass $X$ channel by looking for a bump or, at least, a broad enhancement in the reconstructed $M_X$.

Even if the signals from different Higgs bosons overlap somewhat and their strength is maximally shared, the excess in the $M_X$ distribution will be apparent at the LC.

And, of course, the inclusive $M_X$ peak or broad excess is independent of how the Higgs bosons decay.

**Important LHC ability** If light Higgs are present, but not seen, perturbativity for $WW \to WW$ implies that they (or some alternative source of electroweak symmetry breaking) are present below the TeV scale.

## CPV MSSM

(Carena, Pilaftsis, . . . )

- CPX scenario leaves parameter points in $m_{H^\pm}, \tan\beta$ plane such that Higgs bosons are light but cannot be discovered at LEP, Tevatron or LHC. A LC is required.

## CPC NMSSM

(JFG, Ellwanger, Hugonie, Moretti)

- The term $\mu \widehat{H}_1 \widehat{H}_2$ in the MSSM is replaced by

$$\lambda \widehat{H}_1 \widehat{H}_2 \widehat{S} \ + \ \frac{\kappa}{3} \widehat{S}^3 \ , \qquad (2)$$

so that the superpotential is scale invariant and $\mu_{\rm eff}$ is generated when $\langle S \rangle \neq 0$.

- **We make no assumption on "universal" soft terms. Hence, the five soft supersymmetry breaking terms**

$$m_{H_1}^2 H_1^2 \; + \; m_{H_2}^2 H_2^2 \; + \; m_S^2 S^2 \; + \; \lambda A_\lambda H_1 H_2 S \; + \; \frac{\kappa}{3} A_\kappa S^3 \qquad (3)$$

**are considered as independent.**

- **Assume the masses of sparticles are large enough to not give significant contributions to $gg \to h$ and $\gamma\gamma \to h$ couplings.**

- **In the stop sector, we chose the soft masses $m_Q = m_T \equiv M_{susy} = 1$ TeV and scan over $X_t \equiv 2 \, \frac{A_t^2}{M_{susy}^2 + m_t^2} \left(1 - \frac{A_t^2}{12(M_{susy}^2 + m_t^2)}\right)$ . As in the MSSM, the value $X_t = \sqrt{6}$ – so called maximal mixing – maximizes the radiative corrections to the Higgs boson masses.**

  **It leads to the most challenging points in NMSSM parameter space.**

- **We require $|\mu_{\rm eff}| = \lambda \langle S \rangle \; > \; 100$ GeV; otherwise a light chargino would have been detected at LEP.**

- We have performed a numerical scan over the free parameters.

  We eliminated parameter choices excluded by LEP constraints on $e^+e^- \to Zh_i$ and $e^+e^- \to h_i a_j$.

  We required $m_{h^\pm} > 155$ GeV, so that $t \to h^\pm b$ would not be seen.

**No SUSY or Higgs to Higgs**

- We examined the "usual" LHC discovery modes:

  1) $gg \to h/a \to \gamma\gamma$;

  2) associated $Wh/a$ or $t\bar{t}h/a$ production with $\gamma\gamma\ell^\pm$ in the final state;

  3) associated $t\bar{t}h/a$ production with $h/a \to b\bar{b}$;

  4) associated $b\bar{b}h/a$ production with $h/a \to \tau^+\tau^-$;

  5) $gg \to h \to ZZ^{(*)} \to$ 4 leptons;

  6) $gg \to h \to WW^{(*)} \to \ell^+\ell^-\nu\bar{\nu}$;

  7) $WW \to h \to \tau^+\tau^-$;

  8) $WW \to h \to WW^{(*)}$.

- We estimated the expected statistical significances at the LHC in all Higgs boson detection modes 1) – 8) by rescaling results for the SM Higgs boson and/or the the MSSM $h, H$ and/or $A$.

  Latest results for these modes were employed.

  Note that the $t\bar{t}h \to t\bar{t}b\bar{b}$ mode will be quite important. We have had the experimentalists extrapolate this beyond the usual SM mass range of interest.

- Some things that have changed recently:

  1. The $gg \to h_{\rm SM} \to \gamma\gamma$ $N_{SD}$ values from CMS have gotten smaller (detector cracks ...).
  2. The CMS $t\bar{t}h_{\rm SM} \to t\bar{t}b\bar{b}$ $N_{SD}$ vales are larger than the ATLAS values.
  3. The experimental evaluations of the $WW$ fusion channels yield lower $N_{SD}$ values than the original theoretical estimates.

- For each mode, our procedure has been to use the results for the "best detector" (e.g. CMS for the $t\bar{t}h$ channel), assuming $L = 300 {\rm fb}^{-1}$ for that *one* detector.

**The Result** We can always detect at least one of the NMSSM Higgs bosons.

## Higgs to Higgs Decays Allowed, but SUSY decays suppressed or absent

- We found cases for which all the modes 1) – 8) give very weak signals due to the fact that the only Higgs boson with significant $WW/ZZ$ coupling is light and decays via $h \to aa$.

  Properties of these points:

1. We get a SM-like CP-even Higgs boson with a mass between 115 and 135 GeV (*i.e.* above the LEP limit), which can be either $h_1$ or $h_2$, with near maximal SM-like $VV$ coupling.
2. This state decays dominantly to a pair of (very) light CP-odd states, $a_1 a_1$, with $m_{a_1}$ between 5 and 65 GeV.
3. Properties of 6 difficult benchmark points are displayed in Table 1.
   For points 1 – 3, $h_1$ is the SM-like CP-even state, while for points 4 – 6 it is $h_2$.
   Note the large $B(h \to a_1 a_1)$ of the SM-like $h$ ($h = h_1$ for points 1 – 3 and $h = h_2$ for points 4 –6).
   For points 4 – 6, with $m_{h_1} < 100~\mathrm{GeV}$, the $h_1$ is mainly singlet implying no LEP constraints on the $h_1$ and $a_1$ from $e^+e^- \to h_1 a_1$ production.
   We note that in the case of the points 1 – 3, the $h_2$ would not be detectable either at the LHC or the LC. For points 4 – 6, the $h_1$, though

light, is singlet in nature and would not be detectable.
Further, the $h_3$ or $a_2$ will only be detectable for points 1 – 6 if a super high energy LC is eventually built so that $e^+e^- \to Z \to h_3 a_2$ is possible.

4. Thus, we will focus on searching for the SM-like $h_1$ ($h_2$) for points 1 – 3 (4 – 6) using the dominant $h_1(h_2) \to a_1 a_1$ decay mode.
5. In the case of points 2 and 6, it should be noted that the $a_1 \to \tau^+\tau^-$ decays are dominant, with $a_1 \to jj$ decays making up most of the rest.
   For points 1 and 3 – 5, for which $B(a_1 \to b\bar{b})$ is substantial, the $b$ jets can be tagged. This brings us to:

   **The LHC $WW \to h \to aa \to b\bar{b}\tau^+\tau^-$ mode**

   After many cuts, including forward jet tagging and various vetoes, but before $b$-tagging we get the signals shown relative to the backgrounds.
   Note: $M_{jj\tau^+\tau^-}$ is really an effective mass computed by looking at the $\tau \to \ell\nu\bar{\nu}$ decays and projecting $\not{p}_T$ onto $\ell$ directions.

| Point Number | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Bare Parameters | | | | | | |
| $\lambda$ | 0.2872 | 0.2124 | 0.3373 | 0.3340 | 0.4744 | 0.5212 |
| $\kappa$ | 0.5332 | 0.5647 | 0.5204 | 0.0574 | 0.0844 | 0.0010 |
| $\tan\beta$ | 2.5 | 3.5 | 5.5 | 2.5 | 2.5 | 2.5 |
| $\mu_{\rm eff}$ (GeV) | 200 | 200 | 200 | 200 | 200 | 200 |
| $A_\lambda$ (GeV) | 100 | 0 | 50 | 500 | 500 | 500 |
| $A_\kappa$ (GeV) | 0 | 0 | 0 | 0 | 0 | 0 |
| CP-even Higgs Boson Masses and Couplings | | | | | | |
| $m_{h_1}$ (GeV) | 115 | 119 | 123 | 76 | 85 | 51 |
| $R_1$ | 1.00 | 1.00 | -1.00 | 0.08 | 0.10 | -0.25 |
| $t_1$ | 0.99 | 1.00 | -1.00 | 0.05 | 0.06 | -0.29 |
| $b_1$ | 1.06 | 1.05 | -1.03 | 0.27 | 0.37 | 0.01 |
| Relative gg Production Rate | 0.97 | 0.99 | 0.99 | 0.00 | 0.01 | 0.08 |
| $B(h_1 \to b\overline{b})$ | 0.02 | 0.01 | 0.01 | 0.91 | 0.91 | 0.00 |
| $B(h_1 \to \tau^+\tau^-)$ | 0.00 | 0.00 | 0.00 | 0.08 | 0.08 | 0.00 |
| $B(h_1 \to a_1a_1)$ | 0.98 | 0.99 | 0.98 | 0.00 | 0.00 | 1.00 |
| $m_{h_2}$ (GeV) | 516 | 626 | 594 | 118 | 124 | 130 |
| $R_2$ | -0.03 | -0.01 | 0.01 | -1.00 | -0.99 | -0.97 |
| $t_2$ | -0.43 | -0.30 | -0.10 | -0.99 | -0.99 | -0.95 |
| $b_2$ | 2.46 | -3.48 | 3.44 | -1.03 | -1.00 | -1.07 |
| Relative gg Production Rate | 0.18 | 0.09 | 0.01 | 0.98 | 0.99 | 0.90 |
| $B(h_2 \to b\overline{b})$ | 0.01 | 0.04 | 0.04 | 0.02 | 0.01 | 0.00 |
| $B(h_2 \to \tau^+\tau^-)$ | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| $B(h_2 \to a_1a_1)$ | 0.04 | 0.02 | 0.83 | 0.97 | 0.98 | 0.96 |
| $m_{h_3}$ (GeV) | 745 | 1064 | 653 | 553 | 554 | 535 |

| Point Number | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **CP-odd Higgs Boson Masses and Couplings** | | | | | | |
| $m_{a_1}$ (GeV) | 56 | 7 | 35 | 41 | 59 | 7 |
| $t_1'$ | 0.05 | 0.03 | 0.01 | -0.03 | -0.05 | -0.06 |
| $b_1'$ | 0.29 | 0.34 | 0.44 | -0.20 | -0.29 | -0.39 |
| Relative gg Production Rate | 0.01 | 0.03 | 0.05 | 0.01 | 0.01 | 0.05 |
| $B(a_1 \to b\overline{b})$ | 0.92 | 0.00 | 0.93 | 0.92 | 0.92 | 0.00 |
| $B(a_1 \to \tau^+\tau^-)$ | 0.08 | 0.94 | 0.07 | 0.07 | 0.08 | 0.90 |
| $m_{a_2}$ (GeV) | 528 | 639 | 643 | 560 | 563 | 547 |
| Charged Higgs Mass (GeV) | 528 | 640 | 643 | 561 | 559 | 539 |
| Most Visible Process No. | 2 ($h_1$) | 2 ($h_1$) | 8 ($h_1$) | 2 ($h_2$) | 8 ($h_2$) | 8 ($h_2$) |
| Significance at 300 $\mathrm{fb}^{-1}$ | 0.48 | 0.26 | 0.55 | 0.62 | 0.53 | 0.16 |

**Table 1:** *In the table, we give properties of selected scenarios that could escape detection at the LHC. In the table, $R_i$, $t_i$ and $b_i$ are the ratios of the $h_i$ couplings to $VV$, $t\overline{t}$ and $b\overline{b}$, respectively, as compared to those of a SM Higgs boson with the same mass; $t_1'$ and $b_1'$ denote the magnitude of the $i\gamma_5$ couplings of $a_1$ to $t\overline{t}$ and $b\overline{b}$ normalized relative to the magnitude of the $t\overline{t}$ and $b\overline{b}$ SM Higgs couplings. We also give the production for $gg \to h_i$ fusion relative to the $gg$ fusion rate for a SM Higgs boson with the same mass. Important absolute branching ratios are displayed. For points 2 and 6, $B(a_1 \to jj) \simeq 1 - B(a_1 \to \tau^+\tau^-)$. For the heavy $h_3$ and $a_2$, we give only their masses. In the case of the points 2 and 6, decays of $a_1$ into light quarks start to contribute. For all points 1 – 6, the statistical significances for the detection of any Higgs boson in any of the channels 1) – 8) (as listed in the introduction) are tiny; their maximum is indicated in the last row, together with the process number and the corresponding Higgs state.*

# LHC, $\sqrt{s_{pp}} = 14$ TeV

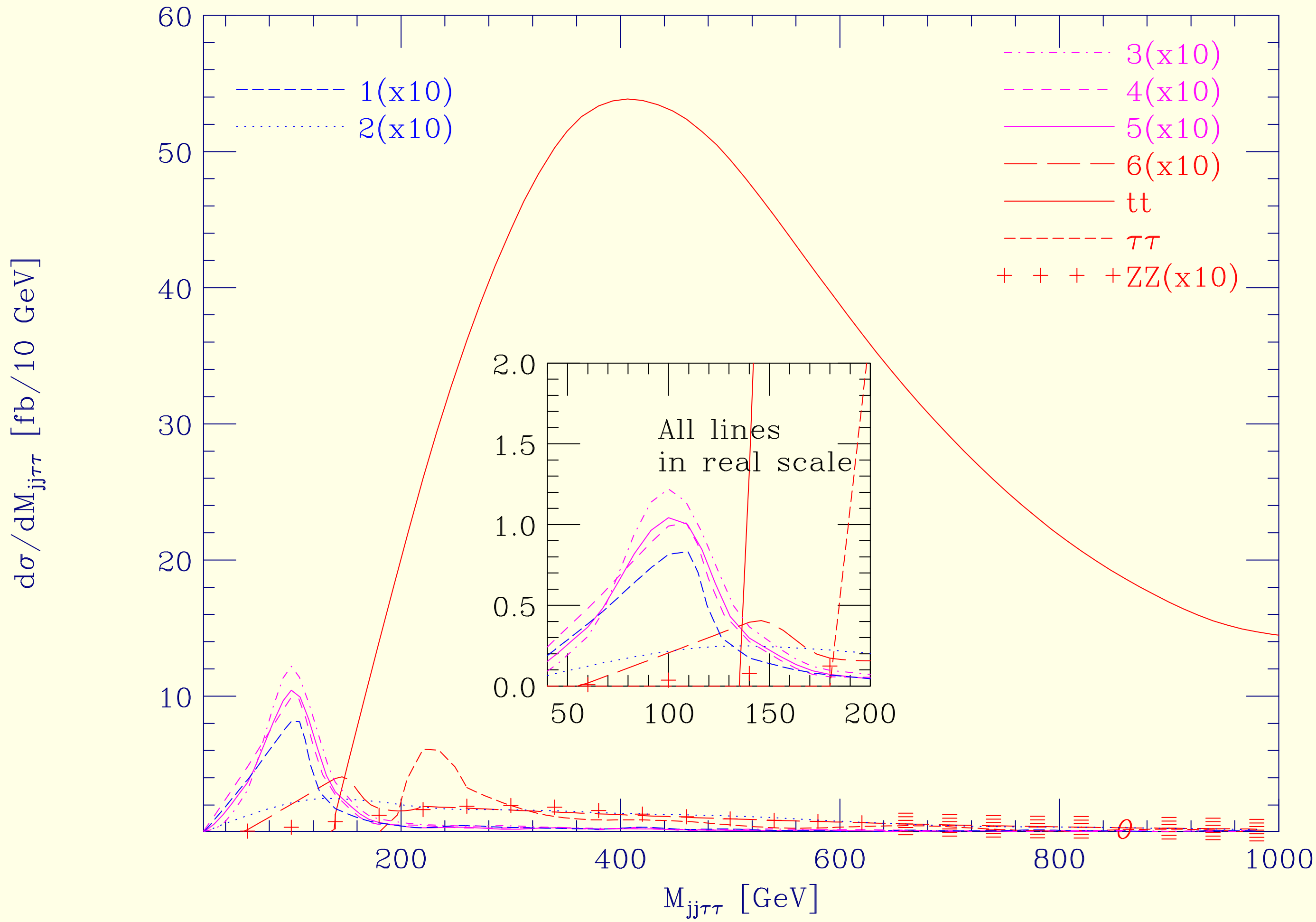



**Figure 4:** *Reconstructed mass of the $jj\tau^+\tau^-$ system for signals and backgrounds before $b$-tagging, at the LHC. We plot $d\sigma/dM_{jj\tau^+\tau^-}$ [fb/10 GeV] vs $M_{jj\tau^+\tau^-}$ [GeV]. The lines corresponding to points 4 and 5 are visually indistinguishable. No $K$ factors are included.*

- **Remarks:**

1. For all six NMSSM setups, the Higgs resonance produces a bump at low $M_{jj\tau^+\tau^-}$.
2. The potentially large DY background has been suppressed by strong cuts requiring 2 fast forward / backward jets + 2 softer jets.
   For $S/\sqrt{B}$ estimates, we assume $L = 300~\mathrm{fb}^{-1}$, a $K$ factor of 1.1 for $WW$ fusion and a $K$ factor of 1.6 for the $t\bar{t}$ background.
   (These $K$ factors are not included in the plots of Fig. 4.)
3. We sum events over the region $40 \leq M_{jj\tau^+\tau^-} \leq 150$ GeV. (We include a few bins with non-zero $t\bar{t}$ background as a conservative way of being sure that we have overestimated the tails of this background at low $M_{jj\tau^+\tau^-}$.)
   For points 1, 2, 3, 4, 5 and 6, we obtain signal rates of about $S = 1636$, $702$, $2235$, $2041$, $2013$, and $683$, respectively.
   The $t\bar{t}$+jets background rate is $B_{tt} \sim 795$.
   The $ZZ$ background rate is $B_{ZZ} \sim 6$.
   The DY $\tau^+\tau^-$ background rate is negligible. (We are continuing to increase our statistics to get a fully reliable estimate.)
   The resulting $N_{SD} = S/\sqrt{B}$ values for points 1-6 are 50, 22, 69, 63, 62, and 21, respectively. The smaller values for points 2 and 6 are simply a reflection of the difficulty of isolating and reconstructing the two jets coming from the decay of a very light $a_1$.

Overall, these preliminary results are very encouraging and suggest that a no-lose theorem for NMSSM Higgs detection at the LHC is close at hand.

4. For the above points, $a \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$ is not allowed.
   Scanning reveals points for which $h \to aa$ is dominant and $a \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$ is dominant.
   These are a small percentage of the total $h \to aa$ dominant points, but will require special attention. The CMS estimates for the $WW \to h \to invisible$ will come into play and may allow us to close this final loop-hole for the no-lose theorem.

- The LC scenario

- Although we may have a good LHC signal if nature chooses a difficult point, ultimately, a means of confirmation and further study will be critical.

  Thus, it is important to summarize the prospects at the LC, with energy up to 800 GeV, in the context of the difficult scenarios 1 — 6 of Table 1 discussed here.

  In the following, $h = h_1$ for points 1–3 and $h = h_2$ for points 4–6 in Table 1.

- Because the $ZZh$ coupling is nearly full strength in all cases, and because the $h$ mass is of order 100 GeV, discovery of the $h$ will be very straightforward via $e^+e^- \to Zh$ using the $e^+e^- \to ZX$ reconstructed $M_X$ technique which is independent of the "unexpected" complexity of the $h$ decay to $a_1a_1$.

  This will immediately provide a direct measurement of the $ZZh$ coupling with very small error.

  The next stage will be to look at rates for the various $h$ decay final states, $F$, and extract $BR(h \to F) = \sigma(e^+e^- \to Zh \to ZF)/\sigma(e^+e^- \to Zh)$.

  For the NMSSM points considered here, the main channels would be $F = b\bar{b}b\bar{b}$, $F = b\bar{b}\tau^+\tau^-$ and $F = \tau^+\tau^-\tau^+\tau^-$.

  At the LC, a fairly accurate determination of $BR(h \to F)$ should be possible in all three cases. This would allow us to determine $BR(h \to a_1a_1)$ independently.

- We have also shown that the $WW \to h \to aa \to jj\tau^+\tau^-$ mode always gives a good signal.

**NMSSM Conclusions**

- **We are getting closer to a no-lose theorem for NMSSM Higgs detection at the LHC, but some work remains.**

- **At the LC, discovery of a light SM-like $h$ is guaranteed to be possible in the $Zh$ final state using the recoil mass technique.**

- **Clearly, if SUSY is discovered at the LHC and no Higgs bosons are detected in the standard MSSM modes, a careful search for the signal we have considered should have a high priority.**

- **Eventually we will need to consider the CP-violating NMSSM Higgs sector with five mixed Higgs!**

## The Worst Case Scenario (JFG, Espinosa)

- **There are many singlet matter superfields in fermionic constructions with 3 families** (Cvetic, Langacker, . . . ), for example.

- **There is nothing to forbid a series of mixed Higgs bosons separated by intervals of $\sim 10$ GeV, i.e. of order the experimental mass resolution in $b\bar{b}$, $\tau^+\tau^-$, $WW$ and $X$ (in $ZX$).**

  **In the worst case, they should share roughly equally the $VV$ coupling strength.**

- **Constraints? Use continuum notation. Important issue is value of $m_C$ in**

$$\int_0^\infty dm K(m) m^2 = m_C^2 \,, \quad \text{where} \quad \int_0^\infty K(m) = 1 \qquad (4)$$

  **where $K(m)(gm_W)^2$ is the (density in Higgs mass of the) strength of the $hWW$ coupling-squared.**

  – **Precision electroweak suggests $m_C^2 \lesssim (200 - 250 \text{ GeV})^2$.**
  – **For multiple Higgs reps. of any kind in the most general SUSY context, RGE + perturbativity up to $M_U \sim 2 \times 10^{16}$ GeV gives same result.**

– Caution: Many types of new physics at low scale allow evasion of $m_C^2$ sizes above; e.g. large extra dimensions or appropriate extra Higgs structure.

Ignoring this caveat, assume sum rule and take $K(m)$=constant from $m_A = m_h^{\rm min}$ to $m_B = m_h^{\rm max}$: $K(m) = 1/(m_B - m_A)$.

LEP constraints do not allow much weight below $70~\mathrm{GeV}$.

For $K(m)$ =constant, $m_C = 200~\mathrm{GeV}$ and $m_A = 70~\mathrm{GeV} \Rightarrow m_B = 300~\mathrm{GeV}$ and $m_B - m_A = 230~\mathrm{GeV}$.

**At an LC**

A fraction $f = 100~\mathrm{GeV}/230~\mathrm{GeV} \sim 0.43$ of the continuum Higgs signal lies in the $100 - 200~\mathrm{GeV}$ region (which region avoids $Z$ peak region with largest background) while allowing little phase space suppression at $\sqrt{s} = 500~\mathrm{GeV}$.

- Summing $Z \to e^+e^- + \mu^+\mu^-$, $\Rightarrow S \sim 540f$ with a background of $B = 1080$, for $100 - 200~\mathrm{GeV}$ window, assuming $L = 200\mathrm{fb}^{-1}$.

$$\frac{S}{\sqrt{B}} \sim 16f\left(\frac{L}{200\mathrm{fb}^{-1}}\right) \text{ for } m \in [100 - 200]~\mathrm{GeV}\,. \quad (5)$$

$\Rightarrow$ **no problem!**

- With $L = 500\mathrm{fb}^{-1}$, after a few years will be able to determine signal magnitude with reasonable error ($\sim 15\%$) in each $10~\mathrm{GeV}$ interval.

- $\boxed{\text{At the LHC}}$

  **Hadron collider detection of continuum signal appears to be very challenging.**

  If the Higgs bosons all share the $VV$ coupling, the $\gamma\gamma$ (and $ZZ \to 4\ell$) excellent resolution modes are likely to fail.

  If the Higgs with some $WW/ZZ$ coupling decay to $aa$ or $hh$ type modes, all LHC signals, including the $aa$ signal studied above, turn to mush.

  There are no bumps anywhere – only broad excesses.

  **Note:** It is the $aa, \ldots$ type decays that obviate the argument (Rainwater, et al.) that one can use $WW \to h \to WW$ to get a significant signal in the $2$ forward/backward jets $+\ 2\ell\ + \not{E}_T$ channel.

  Higgs self couplings in a model with strong Higgs mixing can be chosen so that the $aa$ decays dominate most Higgs decays.

## Left-Right Symmetric supersymmetric model

( see, in particular, Mohapatra and Rasin, hep-ph/9604445)

### Motivations

- Using Higgs fields to break parity at some high scale $m_R$ is an attractive idea.
- SO(10), which automatically includes $\nu_R$ fields for neutrino masses as well as usual SU(5) representation structures, contains the subgroup SU(2)$_L\times$SU(2)$_R\times$U(1)$_{B-L}\times$SU(3)$_C$.
- SUSYLR context guarantees that R-parity is conserved.
- SUSYLR model guarantees no strong CP problem and no SUSY-CP problem ($i.e.$ the generic problem of SUSY phases giving large EDM unless cancellations are carefully arranged) at $m_R$.

  It is then a matter of making sure that evolution from $m_R$ down does not destroy these two properties.

### Details

## The fields:

| Fields | $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ representation |
|---|---|
| $Q$ | $(2, 1, 1/3)$ |
| $Q^c$ | $(1, 2, -1/3)$ |
| $L$ | $(2, 1, -1)$ |
| $L^c$ | $(1, 2, +1)$ |
| $\Phi_{1,2}$ | $(2, 2, 0)$ |
| $\Delta$ | $(3, 1, +2)$ |
| $\overline{\Delta}$ | $(3, 1, -2)$ |
| $\Delta^c$ | $(1, 3, +2)$ |
| $\overline{\Delta}^c$ | $(1, 3, -2)$ |

- Two bi-doublets $\Phi$ required in order to avoid CKM matrix = unity.
- $SU(2)_R$ triplets $\Delta^c$ required to break $SU(2)_R$ symmetry.
- $SU(2)_L$ triplets $\Delta$ required by L-R symmetry.

## Details of no strong CP or SUSY CP problem

### Strong CP arguments

$$\overline{\Theta} = \Theta + Arg\det(M_u M_d) - 3Arg(m_{\tilde{g}}) \tag{6}$$

where $\Theta$ is coefficient of $F_{\mu\nu}\widetilde{F}^{\mu\nu}$ term (which is P violating) and $\overline{\Theta}$ =very small is needed to solve strong CP problem.

- P invariance for scales above $m_R$ guarantees $\Theta = 0$ above $m_R$.
- L-R transformations require $m_{\widetilde{g}}$ =real above $m_R$.
- Yukawa coupling matrices are required to be hermitian by L-R transformations and if bi-doublet Higgs vevs. are real then quark mass matrices are hermitian (not real — reality of determinant is all that is required) and 2nd term above is 0.
  - This includes showing no spontaneous CP violation from Higgs potential, as can be shown in general for two pairs of Higgs doublets.
- Weak point: must introduce a single non-renormalizable operator $\frac{\lambda}{M}[\mathrm{Tr}(\Delta^c \tau_m \overline{\Delta}$ ($\Delta^c$'s are triple Higgs fields and $M = M_{\mathrm{P}}$ or $m_R$) to get vacuum with $\langle \widetilde{\nu}_R \rangle = 0$.
- Less weak point: to avoid evolution introducing $\overline{\Theta} \neq 0$ when evolving below $m_R$ (where SU(2)$_R$ gaugino loop no longer cancels SU(2)$_L$ gaugino loop) must construct theory so that SU(2)$_L$ gaugino masses are real in order to preserve these good properties when evolving to scales below $m_R$.

This can be motivated in SO(10) with suitably generalized L-R symmetry.

This allows large $m_R$ as appropriate for see-saw mechanism.

## SUSY CP arguments

- Generically speaking, need small phases for $Am_{\tilde{g}}$ and $\mu v_u m_{\tilde{g}}/v_d$.
- Above $m_R$, hermiticity of $A_u$ and $A_d$ (soft-SUSY-breaking) terms and of the Yukawa coupling matrices, along with reality of $m_{\tilde{g}}$ does the job.
- A detailed argument regarding evolution to scales below $m_R$ maintains this to adequate accuracy.

The result is a model with lots of Higgs fields, both triplets and doublets.

- If $m_R$ is large ($\Rightarrow$ nice see-saw phenomenology) then only MSSM two-doublet Higgs sector must necessarily survive at low scales.

  Still, the only non-MSSM particles of the model are all the Higgs bosons and their SUSY partners, and there is a possibility that some of them could be light.

  In particular the $\Delta_R$ doubly-charged Higgs and their higgsino partners could be the lightest of the non-MSSM particles.

- **If $m_R$ is $\sim$ TeV, then neutrino masses require careful adjustment (small values) of the associated lepton-number violating couplings, but there is very little evolution to possibly mess up strong CP and SUSY CP solutions and many Higgs will be observable.**

# If not SUSY, then what?

Require a solution to the hierarchy problem. $\Rightarrow$

$\boxed{\text{Extra Dimensions}}$ Many! ideas for this.

- Higgs + $n \geq 2$ flat curled-up dimensions.
- Higgs + Randall Sundrum warped single extra dimension.
- Scherk-Schwartz, ...
- No Higgs – KK excitations conspire to make $WW \to WW$ perturbative (Terning, . . . ), but warping is required to get PEW consistency!

$\boxed{\text{Little Higgs}}$

$\boxed{\ldots}$

The list goes on and on. $\boxed{\text{We need data!}}$

## One Higgs doublet in RS model

**Previous work:**

- $\xi = 0$:
  1. S. B. Bae, P. Ko, H. S. Lee and J. Lee, Phys. Lett. B 487, 299 (2000) [arXiv:hep-ph/0002224].
  2. H. Davoudiasl, J. L. Hewett and T. G. Rizzo, Phys. Rev. Lett. 84, 2080 (2000) [arXiv:hep-ph/9909255].
  3. K. Cheung, Phys. Rev. D 63, 056007 (2001) [arXiv:hep-ph/0009232].
  4. H. Davoudiasl, J. L. Hewett and T. G. Rizzo, Phys. Rev. D 63, 075004 (2001) [arXiv:hep-ph/0006041].
  5. S. C. Park, H. S. Song and J. Song, Phys. Rev. D 63, 077701 (2001) [arXiv:hep-ph/0009245].
- $\xi \neq 0$:
  1. G. Giudice, R. Rattazzi, J. Wells, Nucl. Phys. B595 (2001), 250, hep-ph/0002178.
  2. C. Csaki, M.L. Graesser, G.D. Kribs, Phys. Rev. D63 (2001), 065002-1, hep-th/0008151.
  3. T. Han, G. D. Kribs and B. McElrath, Phys. Rev. D 64, 076003 (2001) [arXiv:hep-ph/0104074].
  4. M. Chaichian, A. Datta, K. Huitu and Z. h. Yu, Phys. Lett. B 524, 161 (2002) [arXiv:hep-ph/0110035]. These authors (see their Appendix A) employ the same full mixing procedure as that employed in our paper (hep-ph/020619). Some of their results can be usefully compared to the LHC discussion of hep-ph/020619.
  5. J. L. Hewett and T. G. Rizzo, hep-ph/0202155. As pointed out in their recent revision of this work dated July 2, 2003, our paper (hep-ph/0206192) appeared 4 months after their original hep-ph submission. However, their results at that time, in their previous presentations, and in all but the most recent presentations, were incorrect except at rather small $\xi$ values due to the fact that they employed the small $\xi$ approximations to the mixing/diagonalization procedures that were given in Giudice etal., hep-ph/0002178. The revision of July 2, 2003 comes some 12 months after our hep-ph/0206192 preprint. Their results now appear to be in accord with ours. Our work was, of course, performed completely independently of their work and was fully in progress at the time of their earliest presentation.
  6. C. Csaki, M. Graesser, L. Randall and J. Terning, Phys. Rev. D 62, 045015 (2000) [arXiv:hep-ph/9911406].

**This work**

- D. Dominici, B. Grzadkowski, J. F. Gunion and M. Toharia, arXiv:hep-ph/0206192.
- M. Battaglia, S. De Curtis, A. De Roeck, D. Dominici and J. F. Gunion, Phys. Lett. B 568, 92 (2003) [arXiv:hep-ph/0304245].
- D. Asner *et al.*, arXiv:hep-ph/0308103.

- **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 $\Rightarrow$

$$ds^2 = e^{-2\sigma(y)}\eta_{\mu\nu}dx^\mu dx^\nu - b_0^2 dy^2, \tag{7}$$

where $\sigma(y) \sim m_0 b_0 |y|$.

- $e^{-2\sigma(y)}$ is the warp factor; scales at $y = 0$ of order $M_{\rm P}$ on the hidden brane are reduced to scales at $y = 1/2$ of order TeV on the visible brane.
- 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.
- In addition, we place a Higgs doublet $\widehat{H}$ on the visible brane. After various rescalings, the properly normalized quantum fluctuation field is called $h_0$.
- The radion is stabilized by introducing a radion mass by hand.

  A possible mechanism is to have scalar fields in the bulk (Goldberger and Wise). More later.

- **Higgs-radion mixing is allowed for.**

$$S_{\xi} = \xi \int d^4x \sqrt{g_{\rm vis}} R(g_{\rm vis}) \widehat{H}^{\dagger} \widehat{H} \,, \tag{8}$$

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

- **A crucial parameter is the ratio**

$$\gamma \equiv v_0 / \Lambda_{\phi} \,. \tag{9}$$

**where $\Lambda_{\phi}$ is vacuum expectation value of the radion field and $v_0 = 246~{\rm GeV}$.**

  – **Net result**
  **4 independent parameters to completely fix the mass diagonalization of the scalar sector when $\xi \neq 0$. These are:**

$$\xi \,, \quad \gamma \,, \quad m_h \,, \quad m_{\phi} \,, \tag{10}$$

  **where we recall that $\gamma \equiv v_0/\Lambda_{\phi}$ with $v_0 = 246~{\rm GeV}$.**
  **Observation of the 1st KK excitation spectrum at the LHC (as very likely possible) will fix $\Lambda_{\phi}$.**

– After writing out the full quadratic structure of the Lagrangian, including $\xi \neq 0$ mixing, we obtain a form in which the $h_0$ and $\phi_0$ fields for $\xi = 0$ are mixed ($h_0 = dh + c\phi$, $\phi_0 = a\phi + bh$) and have complicated kinetic energy normalization.
We must diagonalize the kinetic energy and rescale to get canonical normalization.
Given $m_h$ and $m_\phi$ we must invert the mixing equations. The process of inversion is very critical to the phenomenology and somewhat delicate.
The result found is that the physical mass eigenstates $h$ and $\phi$ cannot be too close to being degenerate in mass, depending on the precise values of $\xi$ and $\gamma$; extreme degeneracy is allowed only for small $\xi$ and/or $\gamma$.

**The $f\overline{f}$ and $VV$ couplings**

$$g_{ZZh} = \frac{g\, m_Z}{c_W}(d + \gamma b)\ , \quad g_{ZZ\phi} = \frac{g\, m_Z}{c_W}(c + \gamma a)\ . \qquad (11)$$

The $WW$ couplings are obtained by replacing $gm_Z/c_W$ by $gm_W$.

$$g_{f\bar{f}h} = -\frac{g\, m_f}{2\, m_W}(d + \gamma b)\, , \quad g_{f\bar{f}\phi} = -\frac{g\, m_f}{2\, m_W}(c + \gamma a)\, . \qquad (12)$$

Note same factors for $WW$ and $f\bar{f}$ couplings.

## The $gg$ and $\gamma\gamma$ couplings

- **There are the standard loop contributions, except rescaled by $f\overline{f}/VV$ strength factors $g_{fVh}$ or $g_{fV\phi}$.**
- **In addition, there are anomalous contributions, which are expressed in terms of the SU(3)×SU(2)×U(1) $\beta$ function coefficients $b_3 = 7$, $b_2 = 19/6$ and $b_Y = -41/6$.**
- **The anomalous couplings of $h$ and $\phi$ enter only through their radion admixtures**
- **Take $m_h = 120$ GeV and $\Lambda_\phi = 5$ TeV.**
- **In the figure, note the hourglass shape that defines the theoretically allowed region.**

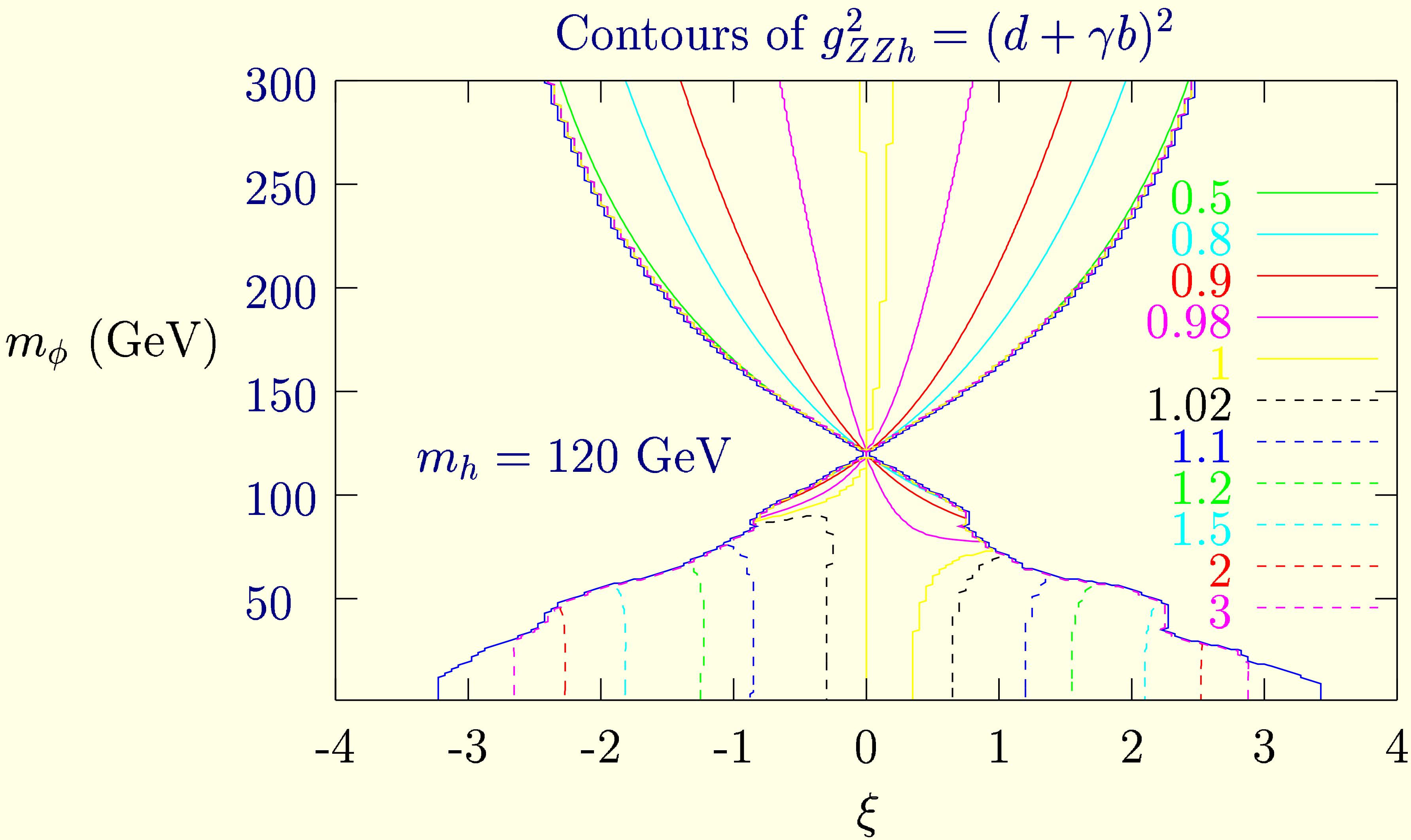



**Figure 5:** *Contours of* $g^2_{fVh}$ *(relative to SM) for* $\Lambda_\phi = 5$ TeV, $m_h = 120$ GeV.

- **Observe suppression if $m_\phi > m_h$ and vice versa.**

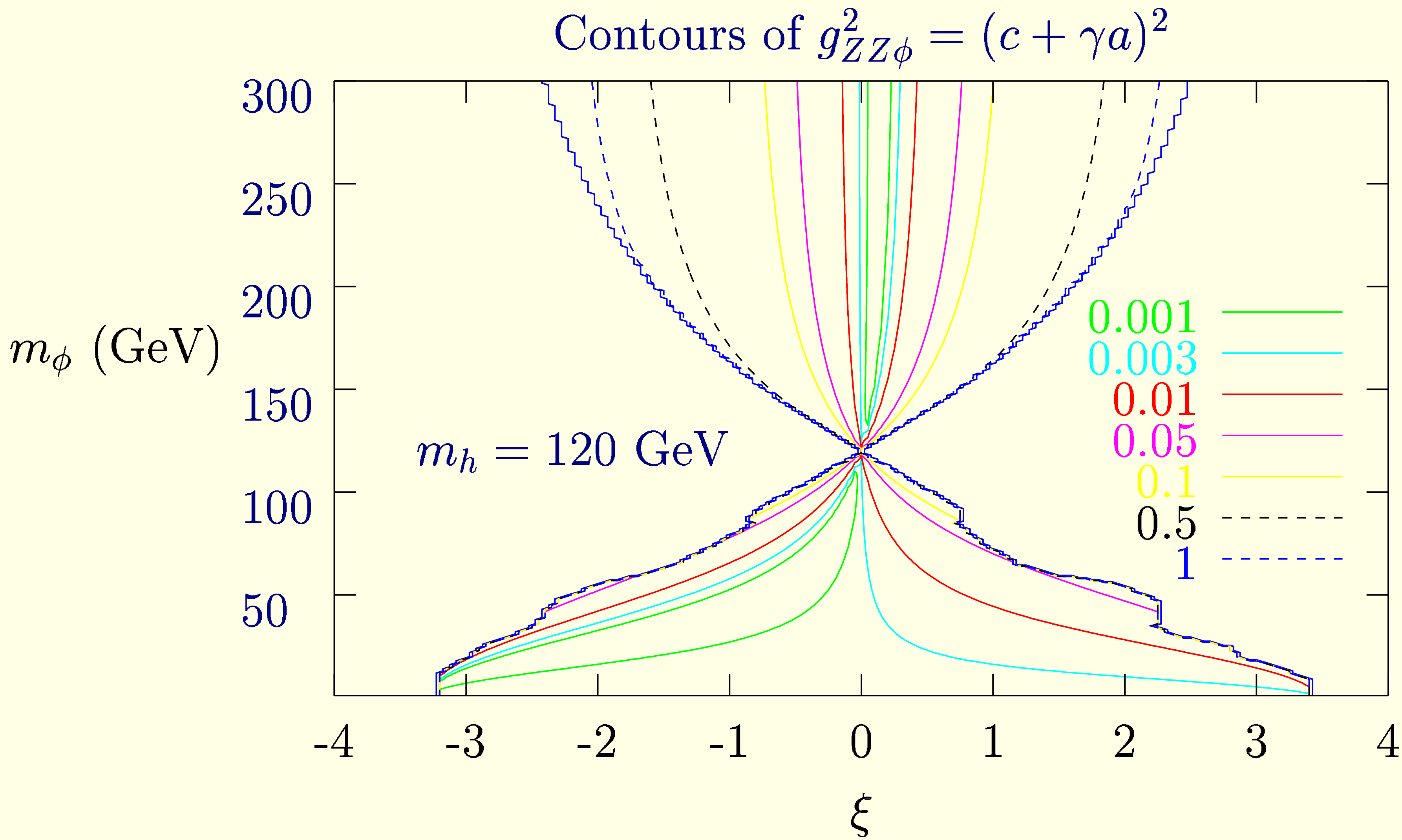



**Figure 6:** *Contours of* $g^2_{fV\phi}$ *for* $\Lambda_\phi = 5$ TeV, $m_h = 120$ GeV

- **Substantial $g^2_{fV\phi}$ is possible if $m_\phi > m_h$ and $\xi$ is not too small.**
- **However, $g^2_{fV\phi}$ is generically quite small and even exhibits a line of zeroes.**

## LHC Capabilities

At the LHC, we (Battaglia, Dominici, de Curtis, de Roeck, JFG) focused on the case of a relatively light Higgs boson, $m_h = 120~\mathrm{GeV}$ for example.

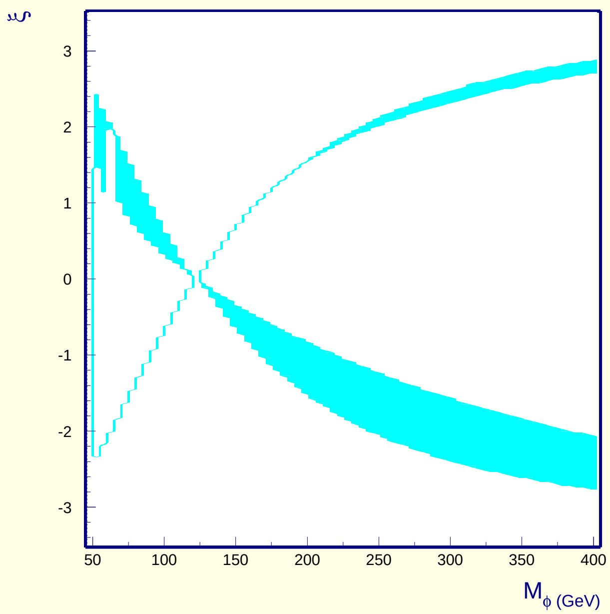
- The precision EW studies suggest that some of the larger $|\xi|$ range is excluded, but we studied the whole range just in case.

- We rescaled the statistical significances predicted for the SM Higgs boson at the LHC using the $h$ and $\phi$ couplings predicted relative to the $h_{\rm SM}$.

- The most important modes are $gg \to h \to \gamma\gamma$ and $gg \to \phi \to ZZ^{(*)} \to 4\ell$.

  Also useful are $t\bar t h$ with $h \to b\bar b$ and $h \to ZZ^* \to 4\ell$.

- An example of the type of effect that will be observed is that the $h \to \gamma\gamma$ mode becomes unobservable if $|\xi|$ is large and $m_\phi > m_h$ (which together imply suppressed $hWW$ coupling and hence suppressed $W$-loop contribution to the $\gamma\gamma h$ couplings).



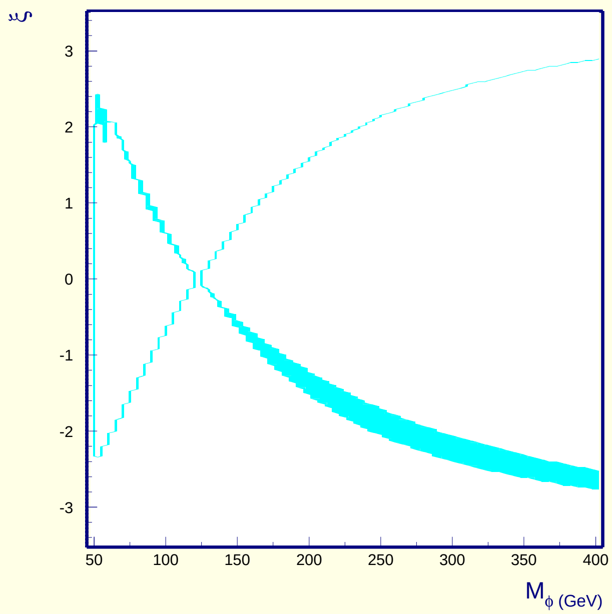




**Figure 7:** *The cyan regions are those where* $\boldsymbol{h}$ *discovery is not possible for* $\boldsymbol{\Lambda_\phi = 5}$ $\mathrm{TeV}$ *and* $\boldsymbol{m_h = 120}$ $\mathrm{GeV}$ *case assuming LHC* $\boldsymbol{L = 30}\mathrm{fb}^{-1}$ *(left) or* $\boldsymbol{L = 100}\mathrm{fb}^{-1}$ *(right).*

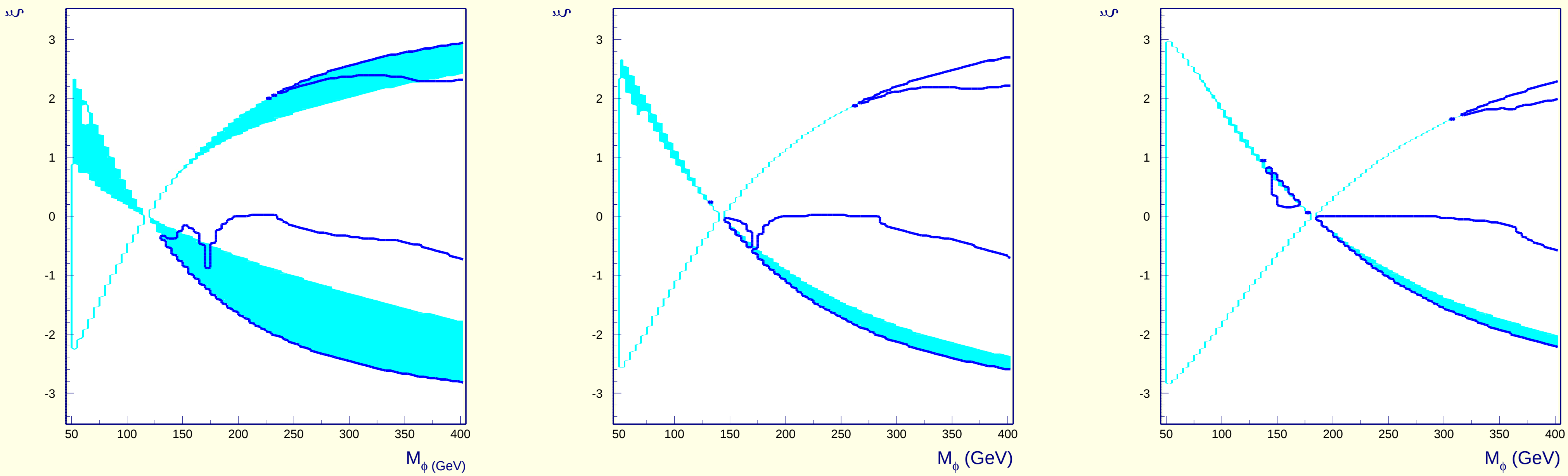



**Figure 8:** *$L = 30\text{fb}^{-1}$ illustration of mode complementarity at the LHC for $m_h = 120$ GeV. The cyan regions show the regions where neither the $gg \to h \to \gamma\gamma$ mode nor the (not very important at this $m_h$ value) $gg \to h \to 4\ell$ mode yields a $> 5\sigma$ signal. The regions between dark blue curves define the regions where $gg \to \phi \to 4\ell$ is $> 5\sigma$. The graphs are for $\Lambda_\phi = 5$ TeV and $m_h = 115$ GeV (left) $m_h = 140$ GeV (center) and $m_h = 180$ GeV (right).*

- **Above, we see that the region where neither the $h$ nor the $\phi$ can be detected grows (decreases) as $m_h$ decreases (increases). It diminishes as $m_h$ increases since the $gg \to h \to 4\ell$ increases in strength at higher $m_h$.**

**Figure 8 exhibits regions of $(m_h, \xi)$ parameter space in which** *both* **the $h$ and $\phi$ mass eigenstates will be detectable.**

**In these regions, the LHC will observe two scalar bosons somewhat separated in mass, with the lighter (heavier) having a non-SM-like rate for the $gg$-induced $\gamma\gamma$ ($Z^0 Z^0$) final state.**

**Additional information will be required to ascertain whether these two Higgs bosons derive from a multi-doublet or other type of extended Higgs sector or from the present type of model with Higgs-radion mixing.**

- **What about an LC?**

**An $e^+e^-$ LC should guarantee observation of both the $h$ and the $\phi$ in the region of low $m_\phi$, large $\xi > 0$ within which detection of either at the LHC might be difficult. This is because, relative to the SM, the $ZZh$ coupling-squared is always fairly substantial and even $ZZ\phi$ coupling-squared**

is $\gtrsim 0.01$ relative to the SM for most of this region.

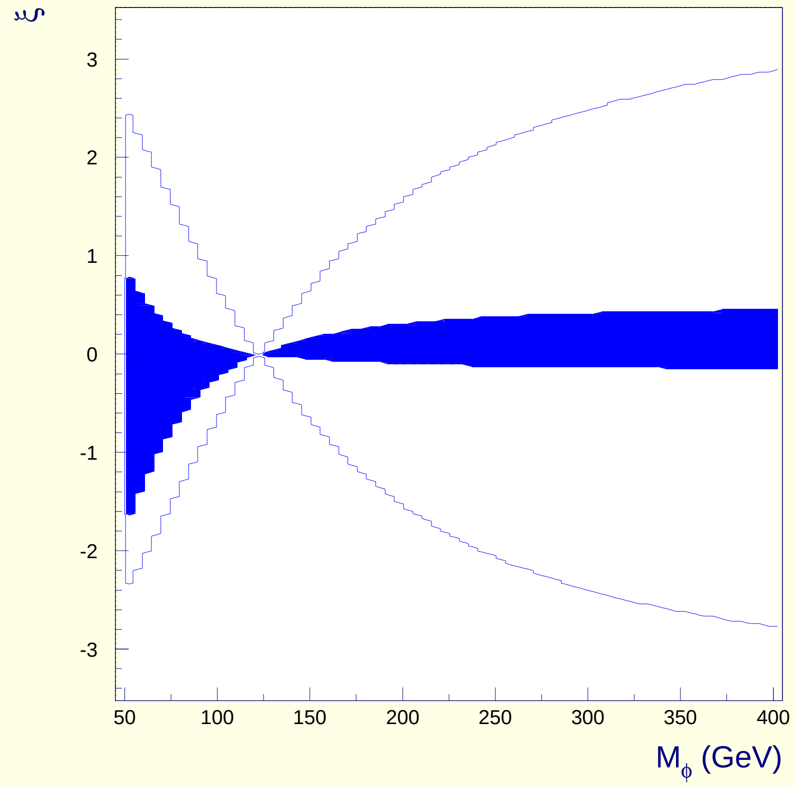



**Figure 9:** *Contour in $(m_\phi, \xi)$ parameter space with $g^2_{\phi ZZ}/g^2_{HZZ} < 0.01$ indicated by the dark region, for $M_h$ = 120 GeV and $\Lambda_\phi = 5$ TeV. The $h$ can be detected at the LC for all $(m_\phi, \xi)$ parameter choices.*

**But, what if there is no LC?**

## CLIC $\gamma\gamma$ Collider Capabilities

- **The $\gamma\gamma$ collider will allow $h$ discovery (for $m_h = 120$) throughout the entire hourglass, which is something the LHC cannot do.**

- **The $\phi$ with $m_\phi < 120\ \mathrm{GeV}$ is very likely to elude discovery at the $\gamma\gamma$ collider. (Recall that it also eludes discovery at the LHC for this region.)**

  **The only exceptions to this statement occur at the very largest $|\xi|$ values for $m_\phi \geq 55\ \mathrm{GeV}$.**

- **There is a big part of the hourglass where the $h$ will be seen in $\gamma\gamma \to h \to b\bar{b}$ at the $\gamma\mathrm{C}$ *and* in $gg \to h \to \gamma\gamma$ at the LHC.**

  **This is most of the hourglass when $L$ at the LHC is $> 100\mathrm{fb}^{-1}$.**

  **The ratio of the rates gives us $\frac{\Gamma(h\to gg)}{\Gamma(h\to b\bar{b})}$, in terms of which we may compute**

$$R_{hgg} \equiv \left[\frac{\Gamma(h \to gg)}{\Gamma(h \to b\bar{b})}\right] \left[\frac{\Gamma(h \to gg)}{\Gamma(h \to b\bar{b})}\right]_{SM}^{-1} . \tag{13}$$

  **This is a very!!!! interesting number since it directly probes for the presence of the anomalous $ggh$ coupling.**

**In particular, $R_{hgg} = 1$ if the only contributions to $\Gamma(h \to gg)$ come from quark loops and all quark couplings scale in the same way.**

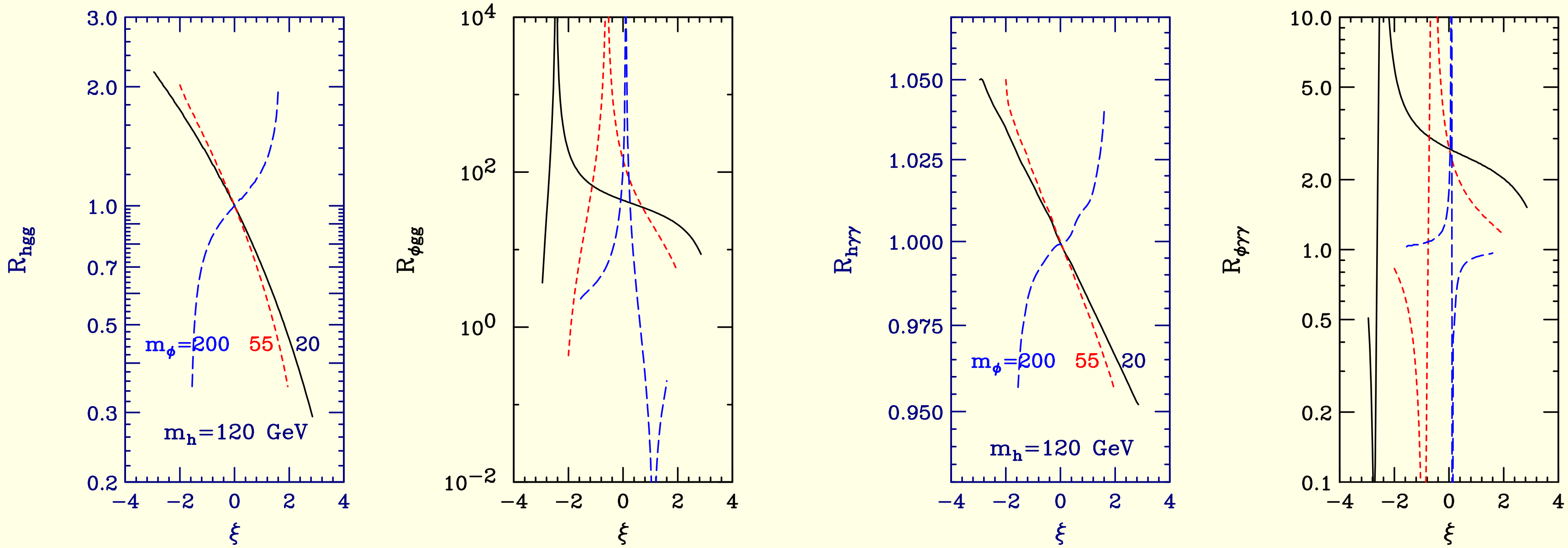



**Figure 10:** *In the left two plots, we give the ratios $R_{hgg}$ and $R_{\phi gg}$ of the $hgg$ and $\phi gg$ couplings-squared including the anomalous contribution to the corresponding values expected in its absence. Results for the the analogous ratios $R_{h\gamma\gamma}$ and $R_{\phi\gamma\gamma}$ are presented in the two plots on the right. Results are shown for $m_h = 120~\mathrm{GeV}$ and $\Lambda_\phi = 5~\mathrm{TeV}$ as functions of $\xi$ for $m_\phi = 20$, $55$ and $200~\mathrm{GeV}$. (The same type of line is used for a given $m_\phi$ in the right-hand figure as is used in the left-hand figure.)*

$\Gamma(h \to \gamma\gamma)\Gamma(h \to b\bar{b})/\Gamma^h_{tot}$ can be measured with an accuracy of about $0.035$

The dominant error will then be from the LHC which will typically measure $\Gamma(h \to gg)\Gamma(h \to \gamma\gamma)/\Gamma^h_{tot}$ with an accuracy of between $0.1$ and $0.2$ (depending on parameter choices and available $L$). From Fig. 10, we see that $0.2$ fractional accuracy will reveal deviations of $R_{hgg}$ from $1$ for all but the smallest $\xi$ values.

- The ability to measure $R_{hgg}$ may be the strongest reason in the Higgs context for having the $\gamma C$ as well as the LHC.

  Almost all non-SM Higgs theories predict $R_{hgg} \neq 1$ for one reason another, unless one is in the decoupling limit.

- Depending on $L$ at the LHC, there is a somewhat smaller part of the hourglass (large $|\xi|$ with $m_\phi > m_h$) where *only* the $\phi$ will be seen at the LHC and the $h$ will only be seen at the $\gamma C$.

  (We don't know for sure about the $\phi$ at the $\gamma C$ until $WW, ZZ$ final states are studied, but I am not all that optimistic.)

This is a nice example of complementarity between the two machines. By having both machines we maximize the chance of seeing both the $h$ and $\phi$.

- Thus, there is a strong case for the $\gamma C$ in the RS model context!, especially if a Higgs boson is seen at the LHC that has non-SM-like rates, ...

## RS Complications

- Introduction of a mass for the radion either by hand or via Goldberger-Wise approach leads to perturbations of the exact RS metric and/or curvature of the branes.

- However, if one introduces a bulk scalar with carefully tuned brane and bulk potential, it is possible to obtain a mass for the radion while retaining the RS metric as an exact solution. (JFG+Grzadkowski)

- The KK excitations of the bulk scalar then mix with the radion and the Higgs and the phenomenology could potentially become more difficult.

  In some limits, one can imagine getting a "warped" version of the multi-Higgs type of scenarios.

$pp \to pph$ (or $\phi$)

- It is claimed that doubly-elastic scalar production at the LHC will give a high-resolution ($\Delta m \sim 1~\mathrm{GeV}$) mass peak that may not have too large a background (Khoze, Martin, Ryskin) (Cox, Forshaw, Lee, Monk, Pilaftsis).

- The production rates are substantial for lighter Higgs bosons in the CPX scenario.

  Rates for the more general Higgs bosons we have considered and for the radion have not been computed yet.

- If doubly-elastic signal can be established, it would obviously play an important role in sorting out the type of models we have been discussing.

There is no time for "No Higgs" models.