Higgs Bosons in Supersymmetry and Extra Dimensions

Jack Gunion
Davis Institute for High Energy Physics, U.C. Davis

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Outline

- Introduction
- The MSSM and NMSSM
- The Randall-Sundrum Model
- Conclusions and LHC/LC Complementarity

The focus of this talk will be on phenomenological issues concerning our ability to discover the Higgs bosons of such models and eventually to study them.

Introduction

- **The number one issue in Higgs physics is the solution of the hierarchy / fine-tuning problems that arise in the Standard Model and Higgs sector extensions thereof.**

  Were it not for this problem, there is nothing to forbid the SM from being valid all the way up the to Planck scale. The two basic theoretical constraints are:

  - **the Higgs self coupling should not blow up below scale Λ; $\Rightarrow$ upper bound on $m_{h_{\rm SM}}$ as function of Λ.**
  - **the Higgs potential should not develop a new minimum at large values of the scalar field of order Λ; $\Rightarrow$ lower bound on $m_{h_{\rm SM}}$ as function of Λ.**

  These two constraints imply that the SM can be valid all the way up to M_{Pl} if $130 \lesssim m_{h_{\rm SM}} \lesssim 180~{\rm GeV}$.

  However, the survival of the SM as an effective theory all the way up to M_{Pl} is unlikely due to the problem of "naturalness" and the associated "fine-tuning" issue. We should impose the additional condition that:

– $m_{h_{\rm SM}} \sim m_Z$ is not a consequence of extreme fine-tuning.

Recall that after including the one loop corrections we have

$$m^2_{h_{\rm SM}} = \mu^2 + \frac{3\Lambda^2}{32\pi^2 v^2}(2m_W^2 + m_Z^2 + m^2_{h_{\rm SM}} - 4m_t^2) \quad (1)$$

where $\mu^2 = -2\lambda v^2 \sim \mathcal{O}(m_Z^2)$ is a fundamental parameter of the theory.

These two terms have entirely different sources, and so a value of $m_{h_{\rm SM}} \sim m_Z$ should not arise by fine-tuned cancellation between the two terms.

The simplest way to avoid too-much fine-tuning is to choose $\Lambda < 1~\mathrm{TeV}$. Choosing $m^2_{h_{\rm SM}}$ to satisfy the "Veltman" condition

$$m^2_{h_{\rm SM}} = 4m_t^2 - 2m_W^2 - m_Z^2 \sim (317~\mathrm{GeV})^2\,, \quad (2)$$

only delays the fine tuning problem to $\Lambda \sim 10 - 100~\mathrm{TeV}$, at which point the choice of $m_{h_{\rm SM}}$ itself becomes fine-tuned.

- There are really only two theories which can purport to be valid perturbative theories from $\Lambda \sim \mathcal{O}(1 - 10~\mathrm{TeV})$ all the way up to the appropriate scale of gravity.

1. Supersymmetry, which can be valid up to the 4-d M_{Pl} scale.
2. Large Scale Extra Dimensions which lower the scale of gravity to values much below the 4-d M_{Pl} scale.

All other approaches (technicolor, little Higgses, etc.) appear to require that the theory become strongly interacting at a scale of order 10 to 100 TeV.

- In Supersymmetry, Λ would be identified with the scale of SUSY breaking, suggesting low energy SUSY with new particles at a mass scale of order $1~\mathrm{TeV}$.

  Supersymmetry as implemented in the Minimal Supersymmetric Model and its close allies also leads to some very beautiful other benefits:

  1. coupling constant unification in the MSSM (and NMSSM-like extensions) context.
  2. RGE generated electroweak symmetry breaking

  These successes motivate us to take the minimal versions of SUSY very seriously as theories that could truly be valid all the way up to M_{Pl}.

- In Large Scale Extra Dimensions, the Planck scale is brought down to the level of $1 - 10$ TeV by one of several means.

Potentially, LSED theories provide alternative mechanisms for EWSB.

However, although LSED theories can allow for *apparent* coupling constant unification at M_{Pl} or actual coupling constant unification at a lower scale, this occurs more by construction than in a natural way.

One of the most intriguing LSED approaches is that of the Randall-Sundrum model in which scales of order M_{Pl} reside on one 4-dimensional "brane" in 5-dimensional space, while the Standard Model particles and fields are confined to a 2nd brane. The scales of order M_{Pl} on the 1st brane are reduced to $\mathcal{O}(1 - 10\ \mathrm{TeV})$ on the 2nd brane because of warping in the 5th dimensions.

- This talk will focus on aspects of Higgs phenomenology in my favorite cases that exemplify the possibilities in these two approaches:

1. The CP-violating Higgs sector version of the MSSM.
2. The NMSSM extension of the MSSM.
3. The RS model with Higgs-radion mixing.

In all these cases, LHC Higgs detection might prove to be very challenging.

SM and CP-conserving MSSM Higgs detection

- **You will be familiar with the detection modes for the SM Higgs boson ($h_{\rm SM}$) and the MSSM Higgs bosons ($h^0, H^0, A^0, H^\pm$). They are the following (with $\ell = e, \mu$):**

  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;**

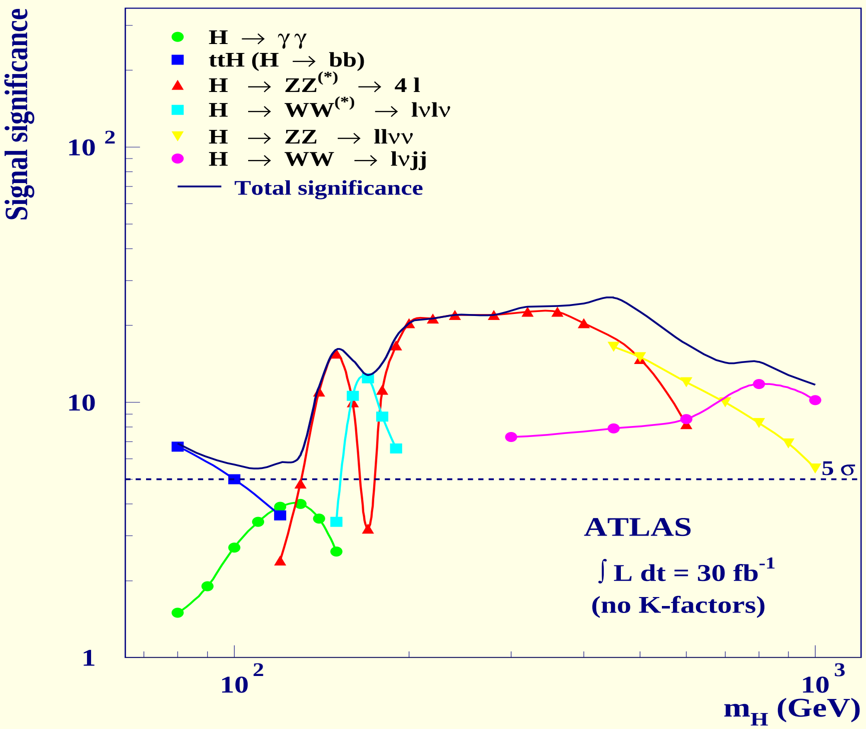
  6) $gg \to h \to WW^{(*)} \to \ell^+\ell^-\nu\bar{\nu}$;

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

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

  In order to assess Higgs discovery in the MSSM, one appropriately rescales the statistical significances estimated for the SM Higgs discovery modes

and adds $b\bar{b}H^0, A^0$ (with $H^0, A^0 \rightarrow \tau^+\tau^-, \mu^+\mu^-$) which can have high rate when $\tan\beta = v_u/v_d$ is large.



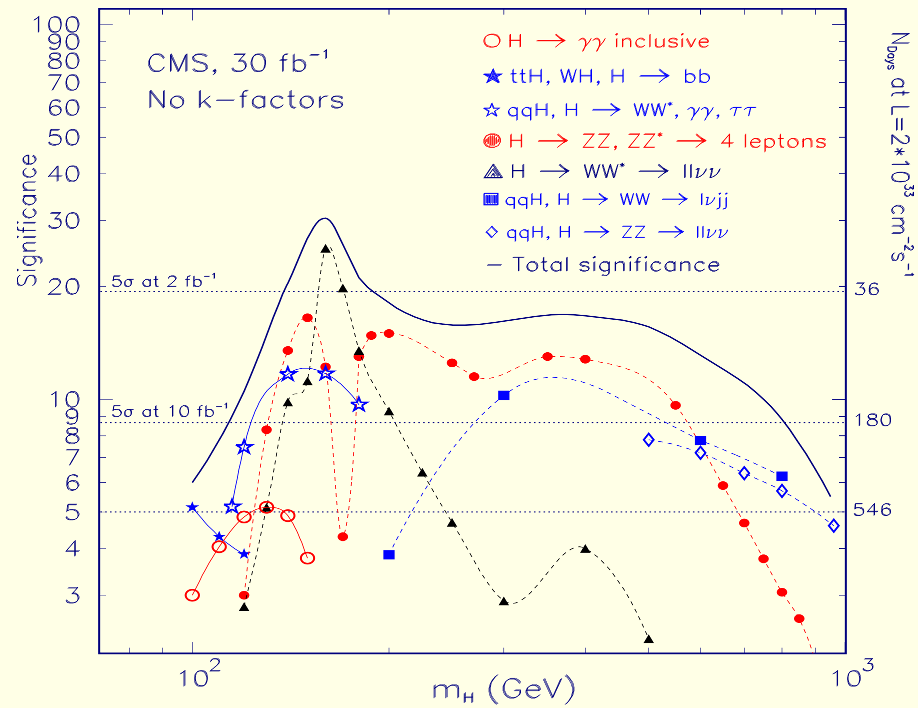


Figure 1: *SM Higgs signal significance as function of the Higgs boson mass. The curves show the signal significance for an integrated luminosity of 30 fb^{-1} for* Atlas *(left) and* Cms *(right). In the right plot the contributions from the* qqH *channel are also shown. No K-factors have been included.*

- **Translating to the CP-conserving MSSM one finds:**
  1. **If the Tevatron reaches full L, then it will be able to discover the h^0 in most cases. At very high $\tan\beta$ can see $b\bar{b}H^0/A^0$.**
  2. **The LHC is guaranteed to find at least one MSSM Higgs boson.**

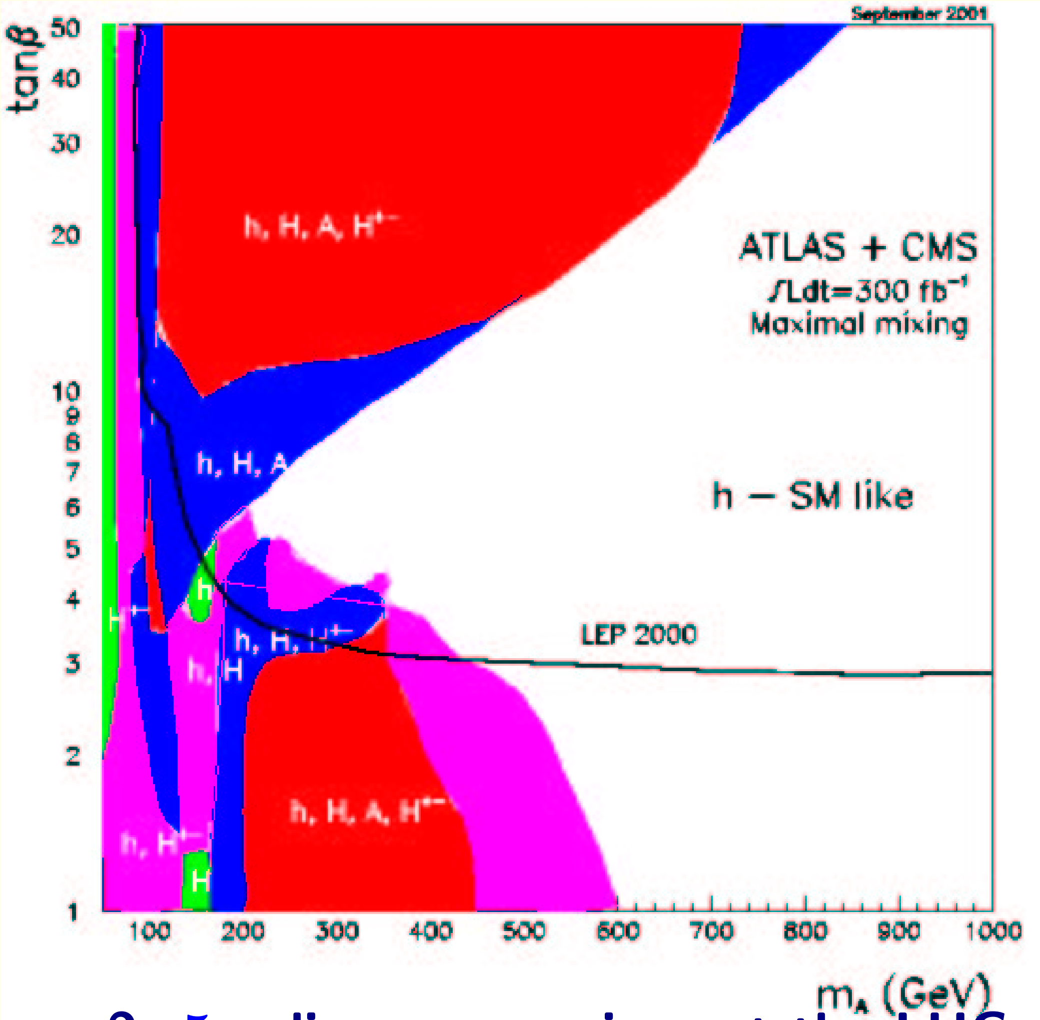


Figure 2: 5σ discovery regions at the LHC.

But, as one pushes further into the decoupling region, there is an increasingly large "wedge" of parameter space in which only the h^0 will be detectable.

3. A LC will certainly detect the h^0, and $e^+e^- \rightarrow H^0 A^0$ will be observable if $m_{A^0} \lesssim \sqrt{s}/2$ (e.g. $\lesssim 300~\mathrm{GeV}$ for $\sqrt{s} = 600~\mathrm{GeV}$).
   But, above this the LC wedge is even bigger than the LHC wedge.

If SUSY is observed at the LHC and/or LC and if the h^0 is seen, then one will know that there are (at least) the $H^0, A^0, H^\pm$ to be discovered.

If the MSSM parameters are in the "wedge" $\Rightarrow$ two options for direct discovery:

a) increase $\sqrt{s}$ past $2m_{A^0}$ if you know what m_{A^0} is (see below)?

b) operate the LC in the $\gamma\gamma$ collider mode;

$\Rightarrow$ H^0, A^0 discovery *precisely* in the "wedge" region up to $\sim 0.8\sqrt{s}$.

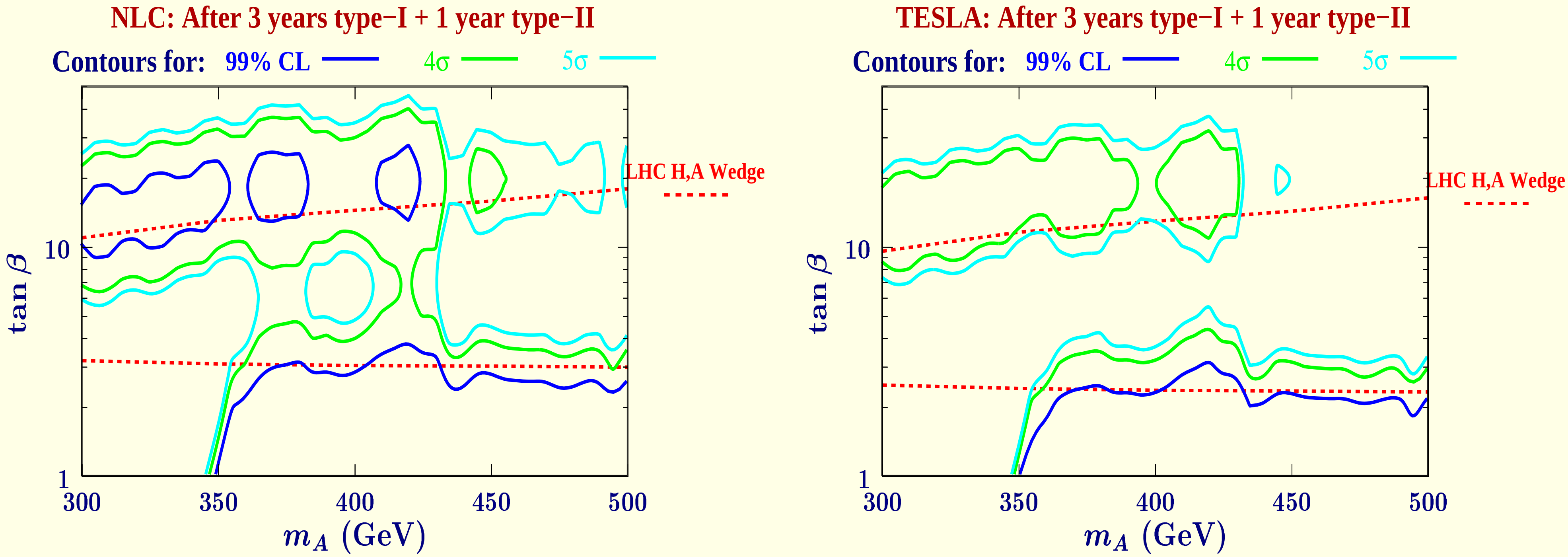


Figure 3: Contours for discovery and 99% CL exclusion after 4 years of NLC or TESLA $\gamma\gamma$ running, from Asner, Gronberg, G.

Obviously, the $\gamma\gamma$ option would be a priority at a certain point, and one could simultaneously have a very interesting overall $\gamma\gamma$ physics program.

CP Violation in the MSSM Higgs Sector induced at one-loop

– If the soft-SUSY-breaking parameters are complex, then the Higgs potential at 1-loop will be CP-violating. (see e.g. Carena etal)
– It is possible to find parameter choices consistent with EDM limits, and so forth, that give large CP-violation in the Higgs sector.
– Five crucial consequences

1. The h^0, H^0 and A^0 all mix together and one has simply three neutral eigenstates $h_{1,2,3}$.
2. The fermionic couplings of the $h_{1,2,3}$ will all have a mixture of $a + i\gamma_5 b$ couplings, where a is the CP-even part and b is the CP-odd part.
3. The $h_{1,2,3}$ will share the VV coupling strength squared, generalizing the usual sum rule to $\sum_{i=1,2,3} g^2_{h_iVV} = g^2_{h_{\rm SM}VV}$.
4. The $h_{1,2,3}$ could *at the same time* have somewhat similar masses, perhaps overlapping within the experimental resolution in certain channels.
5. Or, in some regions of parameter space, one h_i has substantial VV coupling (which is the usual requirement for easy discovery), but instead

of decaying in the usual way, decays to a pair of lighter $h_j h_j$ or $h_j h_k$ or to $Z h_k$.

– There is even a region of parameter space such that there is a fairly light Higgs boson ($\lesssim 50$ GeV) that would not have been seen at LEP.

– Potential consequences:

1. All Tevatron and LHC h_i signals might be too weak to be seen. For example:
   If the VVh_i coupling is not full strength, both the WW fusion and the $\gamma\gamma$ decay modes are quickly suppressed.
   Even if the VVh_i coupling is near maximal, and production is strong, $h_i \to h_j h_j$ (with each $h_j \to b\bar{b}$) or similar would be hard to isolate above backgrounds.
2. We would need to await the LC which can see an h_i with very weak $g^2_{ZZh_i}$ (down to ~ 0.01 of SM strength).

Perhaps the NMSSM study which we now discuss can be adapted to the CPV MSSM to show that at least one Higgs will be found at the LHC.

The NMSSM

Collaborators: U. Ellwanger, C. Hugonie, S. Moretti

– Our basic goal is to examine the extent to which Higgs bosons become more challenging to discover as compared to the MSSM case.
– We consider the simplest version of the NMSSM, where the term $\mu\widehat{H}_1\widehat{H}_2$ in the superpotential of the MSSM is replaced by (we use the notation $\widehat{A}$ for the superfield and A for its scalar component field)

$$\lambda\widehat{H}_1\widehat{H}_2\widehat{S} + \frac{\kappa}{3}\widehat{S}^3 \ , \tag{3}$$

so that the superpotential is scale invariant.
The great attractiveness of the NMSSM is that the λ superpotential term provides a very natural source for the μ term of the MSSM when the scalar component of $\widehat{S}$ acquires a vev.

$$\mu_{eff} = \lambda\langle S\rangle \, . \tag{4}$$

– Of course, there are additional soft-supersymmetry breaking terms, beyond those of the MSSM, that arise. The crucial soft-SUSY-breaking terms for this discussion are

$$m_{H_1}^2 H_1^2 + m_{H_2}^2 H_2^2 + m_S^2 S^2 + \lambda A_\lambda H_1 H_2 S + \frac{\kappa}{3} A_\kappa S^3 . \quad (5)$$

These will all be treated as independent parameters.

– The new feature of the NMSSM Higgs sector relative to the MSSM Higgs sector is the addition of two more Higgs bosons.
Assuming CP conservation in the Higgs sector, we have 3 neutral CP-even Higgs bosons, h_i ($i = 1, 2, 3$), 2 neutral CP-odd Higgses, a_i ($i = 1, 2$) and a charged Higgs pair, $h^\pm$.
Obviously, this will open up the possible scenarios very considerably.

– No time for details of scanning. We imposed known bounds (e.g. from LEP) and looked for worst cases.

Higgs Detection at the LHC

- In earlier work, a partial no-lose theorem for NMSSM Higgs boson discovery at the LHC was established.

In particular, it was shown that the LHC would be able to detect at least one of the NMSSM Higgs bosons (typically, one of the lighter CP-even Higgs states) throughout the full parameter space of the model, excluding only those parameter choices for which there is sensitivity to the model-dependent decays of Higgs bosons to other Higgs bosons and/or superparticles.

- Here, we will retain the assumption of a heavy superparticle spectrum and address the question of whether or not this no-lose theorem can be extended to those regions of NMSSM parameter space for which Higgs bosons can decay to other Higgs bosons.

- 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.

  Some very recent ATLAS and CMS updates, not reflected in the earlier figure are included.

No Higgs-to-Higgs Parameter Space

- In the original study at Snowmass96, we found many points for which the LHC saw no Higgs signal, even for parameter space regions where none of the decays

$$i)\ h \rightarrow h'h'\ , \quad ii)\ h \rightarrow aa\ , \quad iii)\ h \rightarrow h^\pm h^\mp\ , \quad iv)\ h \rightarrow aZ\ ,$$
$$v)\ h \rightarrow h^\pm W^\mp\ , \quad vi)\ a' \rightarrow ha\ , \quad vii)\ a \rightarrow hZ\ , \quad viii)\ a \rightarrow h^\pm W^\mp\ .$$

was kinematically allowed.

- For the most difficult points, there are substantial suppressions of many of the key production modes and branching fractions.

  In particular, the $gg \rightarrow h_i \rightarrow \gamma\gamma$ rates are all greatly suppressed.

  All the $h_i \rightarrow WW$ branching fractions and couplings are suppressed.

- The result is greatly decreased N_{SD} values for all the channels 1) – 6), and a not very wonderful combined statistical significance (denoted S_i) after summing over various sets of channels.

- **Summary of the most difficult point.**

$Ch.\#$	N_{SD} for $h1:$	$Ch.\#$	N_{SD} for $h2:$	$Ch.\#$	N_{SD} for $h3:$
1	0.41	1	0.27	1	0.77
2	1.07	2	0.80	2	0.44
3	3.72	3	5.27	3	0.00
4	0.70	4	0.70	4	2.42
5	0.00	5	0.14	5	4.05
6	0.00	6	0.00	6	4.85
7	0.00	7	6.13	7	0.00
8	0.00	8	0.18	8	1.11
$S_i = 1$ to 6	3.96	$S_i = 1$ to 6	5.39	$S_i = 1$ to 6	6.82
$S_i = 1$ to 8	3.96	$S_i = 1$ to 8	8.16	$S_i = 1$ to 8	6.91

(6)

$Ch.\#$	N_{SD} for $a1:$	$Ch.\#$	N_{SD} for $a2:$
1	0.00	1	0.00
2	0.00	2	0.00
3	0.60	3	0.00
4	2.31	4	2.42
$S_i = 1$ to 4	2.38	$S_i = 1$ to 4	2.42

(7)

We see that that only the h_2 has a full 5σ signal in any of the modes 1)–6), namely in $t\bar{t}h_2 \to t\bar{t}b\bar{b}$ mode 3). There is also a slightly $> 5\sigma$ signal in the $WW \to h_2 \to \tau^+\tau^-$ mode 7).

Of course, the h_3 signals in the $gg \to h_3 \to ZZ \to 4\ell$ and $gg \to h_3 \to WW \to 2\ell 2\nu$ are ok if one accepts the fact that they could be combined.

- The moral is that one should not give up on Higgs discovery in the "standard" channels after just $L = 30\mathrm{fb}^{-1}$.

- Or it could be even harder because none of the "standard" channels are applicable.

Allowing for Higgs-to-Higgs Decays

- In order to probe the complementary part of the parameter space, we required that at least one of the decay modes $i) - viii)$ is allowed.

- We obtained a lot of points, all with similar characteristics. Namely, in the Higgs spectrum, we always have a very 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 full SM strength WW, ZZ coupling.

- 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.

  In all cases of this type, the only hope for Higgs discovery at the LHC is to see the SM-like h using the dominant $h \to a_1 a_1$ decay mode.

- **We have studied 6 difficult benchmark points, for which all normal detection channels have $N_{SD} \lesssim 0.5$.**

- **We have focused on the $2b2\tau$ (or $2j2\tau$) signature, since the background is not pure QCD and since it still allows m_h reconstruction via $M_{jj\tau\tau}$.**

- **Results for the LHC**

- **We expect that $WW \to h \to aa$ allows the best hope for Higgs detection in these difficult NMSSM cases. (Recall that the h is question has nearly full SM strength WW coupling.)**

- **In order to extract the $2b2\tau$ NMSSM Higgs boson signature from the central detector region, we have exploited forward and backward jet tagging on the light quarks emerging after the double W-strahlung preceding WW-fusion.**

  The main background is due to $t\bar{t}$ production and decay via the purely SM process, $gg \to t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}\tau^+\tau^- + p^T_{\rm miss}$, in association with forward and backward jet radiation.

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

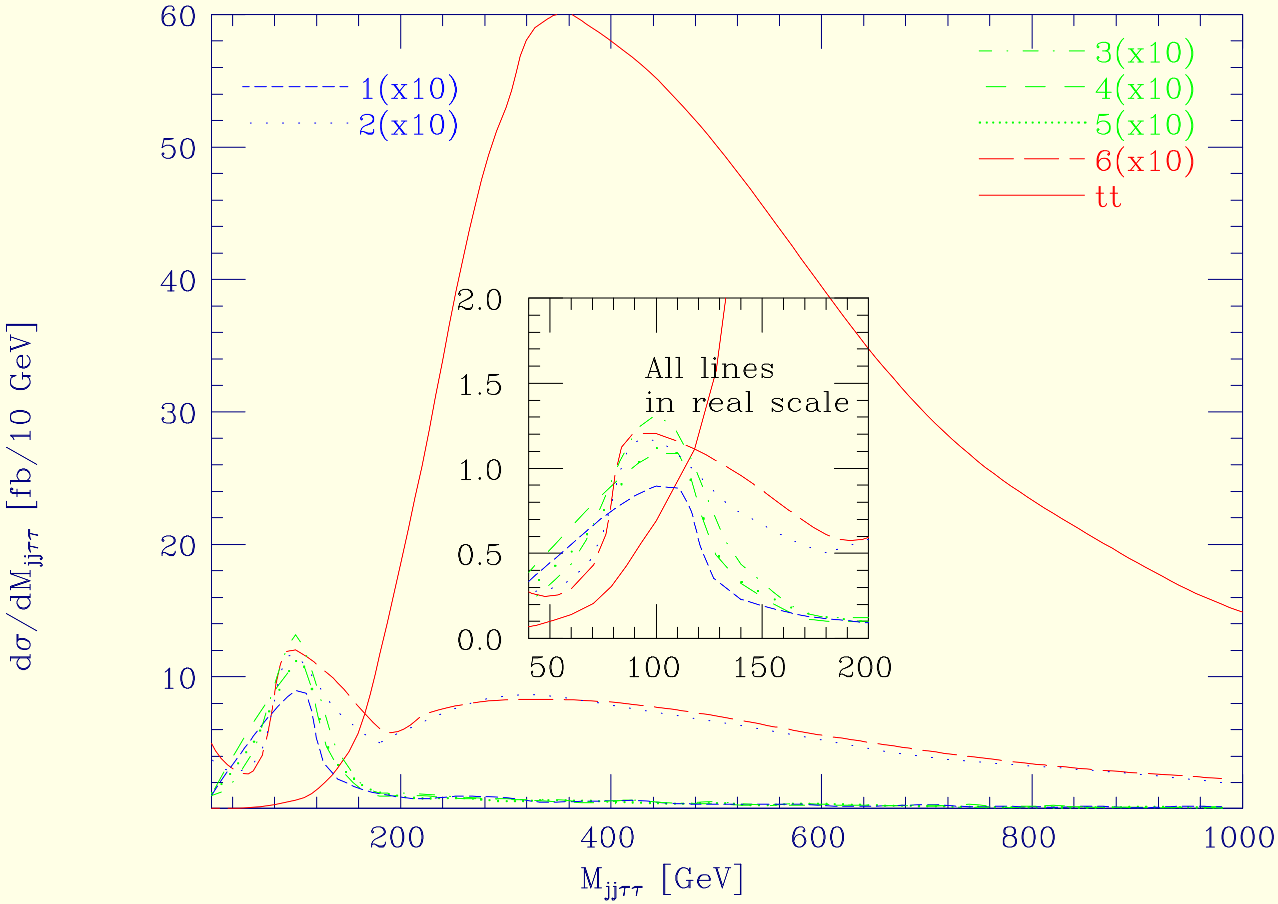


Figure 4: *Reconstructed mass of the $jj\tau^+\tau^-$ system for signals and backgrounds after the selections described, at the LHC. We plot $d\sigma/dM_{jj\tau^+\tau^-}$ [fb/10 GeV] vs $M_{jj\tau^+\tau^-}$ [GeV]. The lines corresponding to points 4 and 5 are visually indistinguishable. No K factors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

- **Remarks:**

1. **For all six NMSSM setups, the Higgs resonance produces a bump in the very end of the low mass tail of the $t\bar{t}$ background (see the insert in the top frame of Fig. 4).**
2. **Statistics are significant.**
   For $L = 300\ \mathrm{fb}^{-1}$, and summing events over the region $60 \leq M_{jj\tau^+\tau^-} \leq 90$ GeV, for points 1 – 6 we obtain $S = 890$, 600, 750, 1030, 915, 500, respectively.
   The $t\bar{t}$ background rate is $B \sim 320$.
   This gives $N_{SD} = S/\sqrt{B}$ of $50, 34, 42, 58, 51, 28$ for points 1 – 6, respectively.
   However, given the broad distribution of the signal, it is clear that the crucial question will be the accuracy with which the background shape can be predicted from theory.

- **The LC scenario**

- **An enhancement at low $M_{jj\tau^+\tau^-}$ of the type shown (for some choice of m_{a_1}) will be the only evidence on which a claim of LHC observation of Higgs bosons can be based.**

  Ultimately, a means of confirmation and further study will be critical.

What about the LC?

- $g^2_{ZZh} \sim 1$ and $m_h \sim \mathcal{O}(100~\mathrm{GeV})$ imply that detection of $e^+e^- \to Zh$ using the $e^+e^- \to ZX$ reconstructed M_X technique (which is independent of the "unexpected" complexity of the h decay to $a_1 a_1$) will be easy.

  Study of the h will also be possible.

- One can also consider the equally (or perhaps more) useful vector-vector fusion mode that will be active at a LC.

  At 800 GeV or above, it is the dominant Higgs boson production channel for CP-even Higgs bosons in the intermediate mass range and a cleaner signal of the LHC type can be easily detected.

- We are really quite close to a no-lose theorem for NMSSM Higgs detection at the LHC.

  However, there will undoubtedly be other possible interpretations for the bump observed if the $h \to aa$ scenario dominates.

  Possible steps to help confirm the nature of the LHC signal include:

1. A study (in progress) of the mass resolution in m_{a_1}.
2. A study of the resolution in m_h.
3. A very important thing would be to establish the signal in the $4b$ final state in addition to the $2b2\tau$ final state studied so far.
   If these two channels are in the ratio expected for an a-type Higgs boson that couples to mass, that would be a very strong argument in favor of the Higgs interpretation.

- For the future:

  Study whether an MSSM Higgs sector with one-loop induced CP violation has a no-lose theorem after including the $h \to aa$ type signal.

  Address whether a NMSSM LHC “no-lose” theorem holds in the case of a CP-violating NMSSM Higgs sector with five mixed Higgs.

The RS scenario with Higgs-radion mixing

Collaborators: M. Battaglia, S. de Curtis, A. De Roeck, D. Dominici, B. Grzadkowski, M. Toharia, J. Wells

Presuming the new physics scale to be close to the TeV scale, there can be a rich new phenomenology in which Higgs and radion physics intermingle if the $\xi R \widehat{H}^\dagger \widehat{H}$ mixing term is present in $\mathcal{L}$.

Randal-Sundrum Review

- 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 $\Rightarrow$

$$ds^2 = e^{-2\sigma(y)} \eta_{\mu\nu} dx^\mu dx^\nu - b_0^2 dy^2, \tag{8}$$

  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.

- **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.**

Including the ξ mixing term

- **We begin with**

$$S_\xi = \xi \int d^4x \sqrt{g_{\rm vis}} R(g_{\rm vis}) \widehat{H}^\dagger \widehat{H}\,, \quad (9)$$

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

- **A crucial parameter is the ratio**

$$\gamma \equiv v_0/\Lambda_\phi\,. \quad (10)$$

where Λ_ϕ is the vacuum expectation value of the radion field.

- 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 ϕ_0 fields for $\xi = 0$ are mixed and have complicated kinetic energy normalization.

  We must diagonalize the kinetic energy and rescale to get canonical normalization.

  An important quantity in the inversion process is

$$Z^2 \equiv 1 + 6\xi\gamma^2(1 - 6\xi)\,. \tag{11}$$

  $Z^2 > 0$ is required to avoid tachyonic situation.

  This $\Rightarrow$ constraint on maximum neg. and pos. ξ values.

- One also finds that the mass eigenstates h and ϕ cannot be too close to being degenerate in mass, depending on the precise values of ξ and γ; extreme degeneracy is allowed only for small ξ and/or γ.

  This leads to a 2nd constraint on the maximum and minimum possible values of ξ.

- Net result

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

$$\xi\,, \quad \gamma\,, \quad m_h\,, \quad m_\phi\,, \tag{12}$$

where we recall that $\gamma \equiv v_0/\Lambda_\phi$ with $v_0 = 246~\mathrm{GeV}$.

Two additional parameters will be required to completely fix the phenomenology of the scalar sector, including all possible decays. These are

$$\widehat{\Lambda}_W\,, \quad m_1\,, \tag{13}$$

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.

There are relations among parameters:

$$\widehat{\Lambda}_W \simeq \sqrt{2} M_{Pl}\Omega_0\,, \quad m_n = m_0 x_n \Omega_0\,, \quad \Lambda_\phi = \sqrt{6} M_{Pl}\Omega_0 = \sqrt{3}\widehat{\Lambda}_W\,, \tag{14}$$

where $\Omega_0 M_{Pl} = e^{-m_0 b_0/2} M_{Pl}$ should be of order a TeV to solve the hierarchy problem. In Eq. (14), the x_n are the zeroes of the Bessel function

J_1 ($x_1 \sim 3.8$, $x_2 \sim 7.0$). A useful relation following from the above equations is:

$$m_1 = x_1 \frac{m_0}{M_{Pl}} \frac{\Lambda_\phi}{\sqrt{6}} \,. \tag{15}$$

m_0/M_{Pl} is related to the curvature of the brane and should be a relatively small number for consistency of the RS scenario.

- Sample parameters that are safe from precision EW data and RunI Tevatron constraints are $\Lambda_\phi = 5~\mathrm{TeV}$ ($\Rightarrow \widehat{\Lambda}_W \sim 3~\mathrm{TeV}$) and $m_0/M_{Pl} = 0.1$.

  The latter $\Rightarrow m_1 \sim 780~\mathrm{GeV}$; i.e. m_1 is typically too large for KK graviton excitations to be present, or if present, important, in h, ϕ decays.

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

- KK excitation probably observable at LHC

  Will provide important information.

1. Mass gives m_1 in above notation.
2. Excitation spectrum as a function of m_{jj} determines m_0/M_{Pl}.
3. Combine ala Eq. (15) to get Λ_ϕ.
   This will really help in LHC-only study of Higgs sector.

However, if Λ_ϕ is very large the KK excitations will be out of reach. Studies of this show that the 95% CL limit for detecting the 1st KK excitation is given in terms of m_0/M_{Pl} by

$$m_1(\mathrm{TeV}) = 6.6 + 2\ln_{10}\left(\frac{m_0}{M_{Pl}}\right) . \quad (16)$$

Using Eq. (15), we find that the signal for the 1st KK excitation will be below the 95% CL for

$$\Lambda_\phi > \frac{\sqrt{6}}{x_1}\left(\frac{M_{Pl}}{m_0}\right)\left[6.6 + 2\ln_{10}\left(\frac{m_0}{M_{Pl}}\right)\right] \mathrm{TeV} . \quad (17)$$

For example, for $m_0/M_{Pl} = 0.1$ this corresponds to $\Lambda_\phi \gtrsim 30$ TeV.
In this case, the Higgs-radion sector becomes absolutely crucial for revealing the RS scenario.

Constraints?

- Quite weak once $m_h > 115$ GeV.

Small m_ϕ relative to m_h is entirely possible given current data so long as $m_h \gtrsim 115$ GeV.

$m_\phi > m_h$ is also possible, but perhaps less preferred in existing models for giving the radion mass.

Precision Electroweak Constraints

- There was considerable work on this in the past, but we (JFG, Toharia, Wells) claim there were some inaccuracies ... and we have done a very careful analysis. Details were presented by M. Toharia in a parallel session.
- One of our important new ingredients is a metric that solves the Einstein equations to 2nd order in the radion field expansion. This fixes some important components related to quartic couplings that contribute to the W and Z propagator corrections.
- The precision constraints are most interesting when $|\xi|$ is near its upper limits. In this case, and for $\Lambda_\phi > 5$ TeV or so, anomalous and KK-exchange contributions are quite small compared to the mixing effects.

- **One important result is that portions of the theoretically allowed parameter space for our canonical choice of $m_h = 120$ GeV are disfavored by the precision electroweak analysis.**

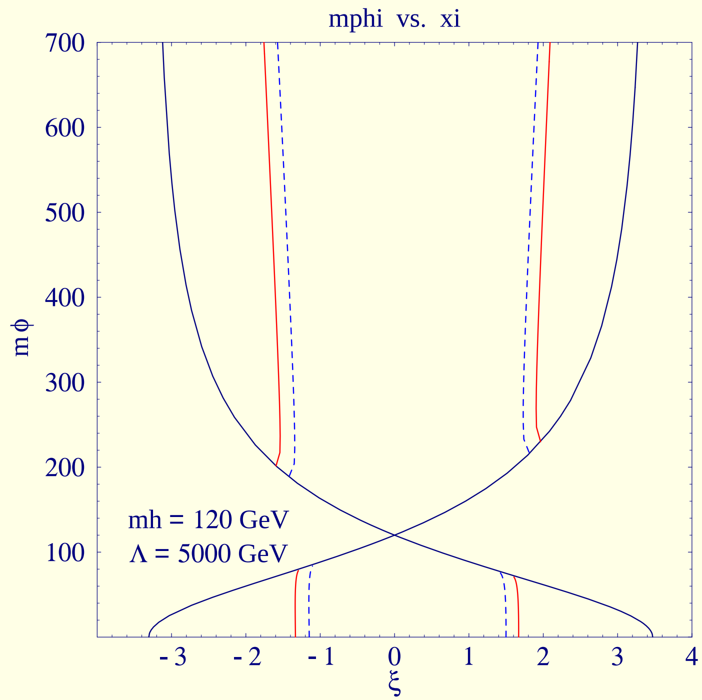


Figure 5: *Typical constraint on m_ϕ, ξ "hourglass" parameter space for $m_h = 120$ GeV. 68% and 90% CL contours are shown.*

- **Another important result, is that m_h and m_ϕ can both be quite large without violating precision electroweak constraints, so long as $|\xi|$ is large**

enough.

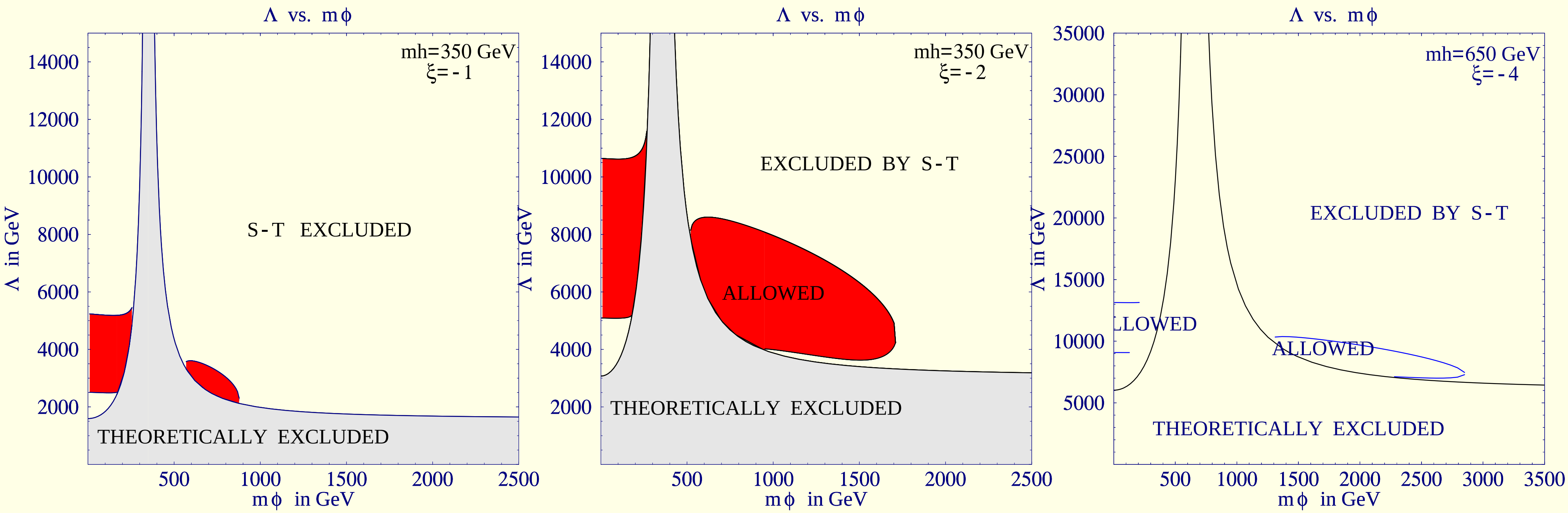


Figure 6: *Illustration of how modest ξ values allow region for which m_h and m_ϕ are both relatively large. Contours shown are 90% CL.*

This is possible without violating precision electroweak constraints because the radion contributions compensate the Higgs contributions in the S, T plane. But, note that this is only possible if Λ is not too large (so that the radion does not decouple as it does as $\Lambda \to \infty$).

In this domain of parameter space, one will have to move the LC to higher $\sqrt{s}$ or look carefully at the LHC sensitivity to the higher mass h and ϕ. This has not been done yet.

An example of LHC/LC Complementarity

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 ϕ couplings predicted relative to the h_{SM}.

- The most important discovery 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).

One interesting graph is below. Note how we lose the $h \to \gamma\gamma$ mode if $m_\phi > m_h$, especially if $\xi < 0$. If $m_\phi < m_h$, $h \to \gamma\gamma$ will be strong if $\xi < 0$, but can be considerably weakened if $\xi > 0$.

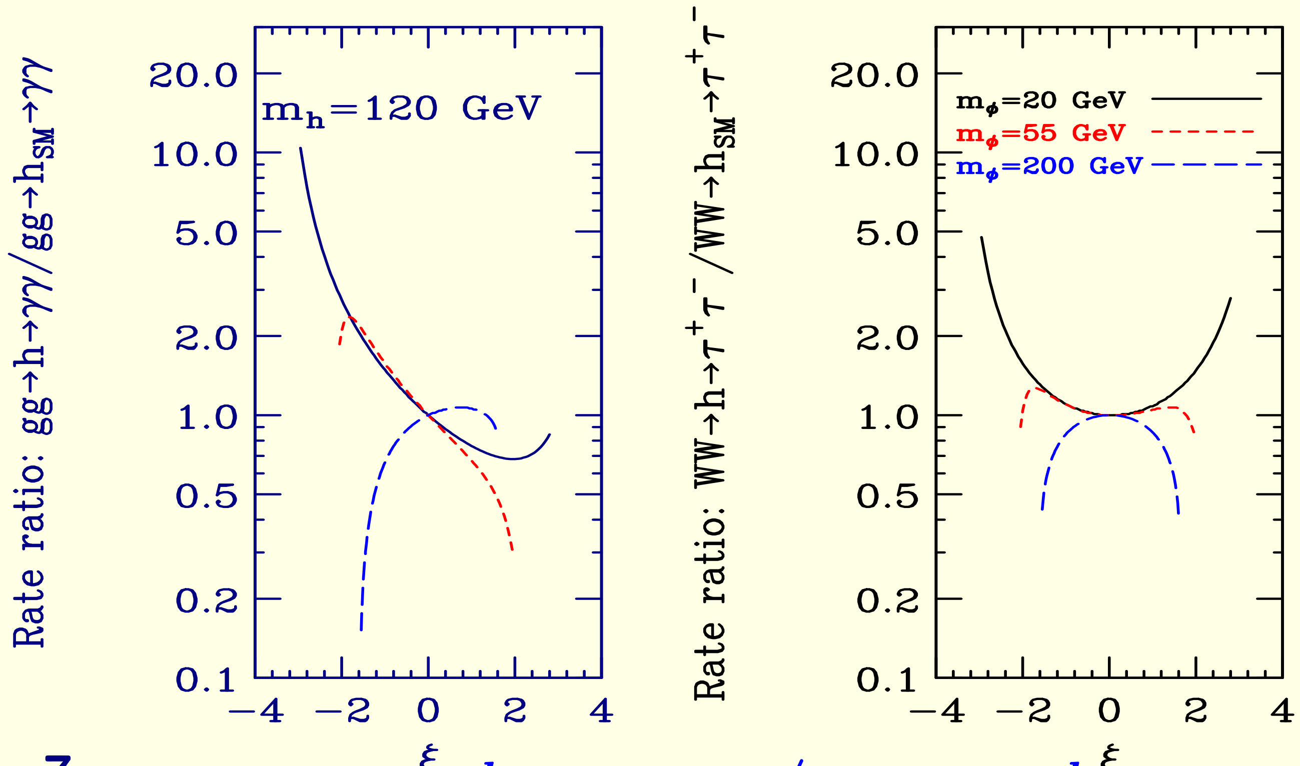


Figure 7: *$gg \to h \to \gamma\gamma/gg \to h_{\rm SM} \to \gamma\gamma$ and $WW \to h \to \tau^+\tau^-/WW \to h_{\rm SM} \to \tau^+\tau^-$ (same as for $gg \to t\bar{t}h \to t\bar{t}b\bar{b}$) for $m_{h_{\rm SM}} = m_h$; $\Lambda_\phi = 5$ TeV.*

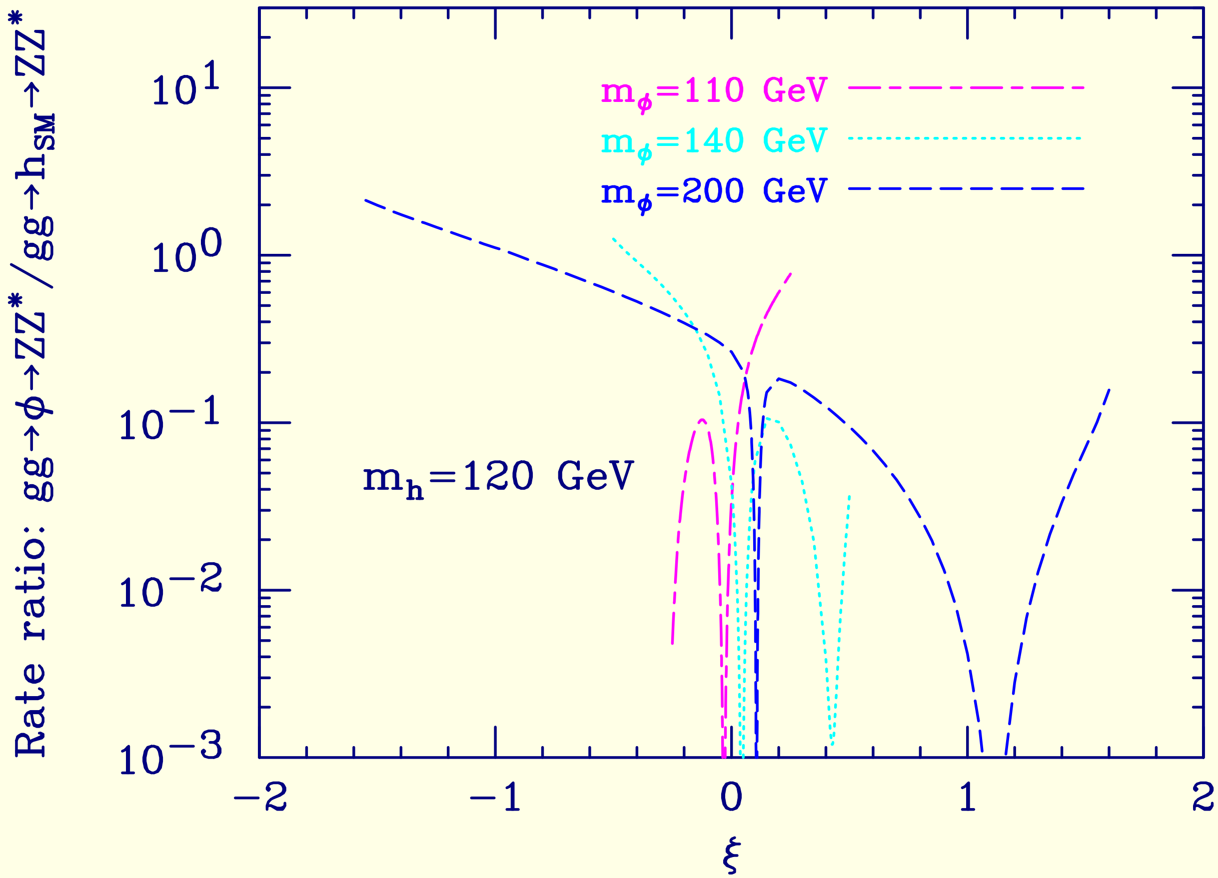


Figure 8: *The ratio of the rate for* $gg \to \phi \to ZZ$ *to the corresponding rate for a SM Higgs boson with mass* m_ϕ *assuming* $m_h = 120~\mathrm{GeV}$ *and* $\Lambda_\phi = 5~\mathrm{TeV}$ *as a function of* ξ *for* $m_\phi = 110$, 140 *and* $200~\mathrm{GeV}$. *Recall that the* ξ *range is increasingly restricted as* m_ϕ *becomes more degenerate with* m_h. *Note: for* $m_\phi > m_h$ *the mode approaches SM strength if* $\xi < 0$ *and is nearing SM strength if* $\xi > 0$ *and near maximal.*

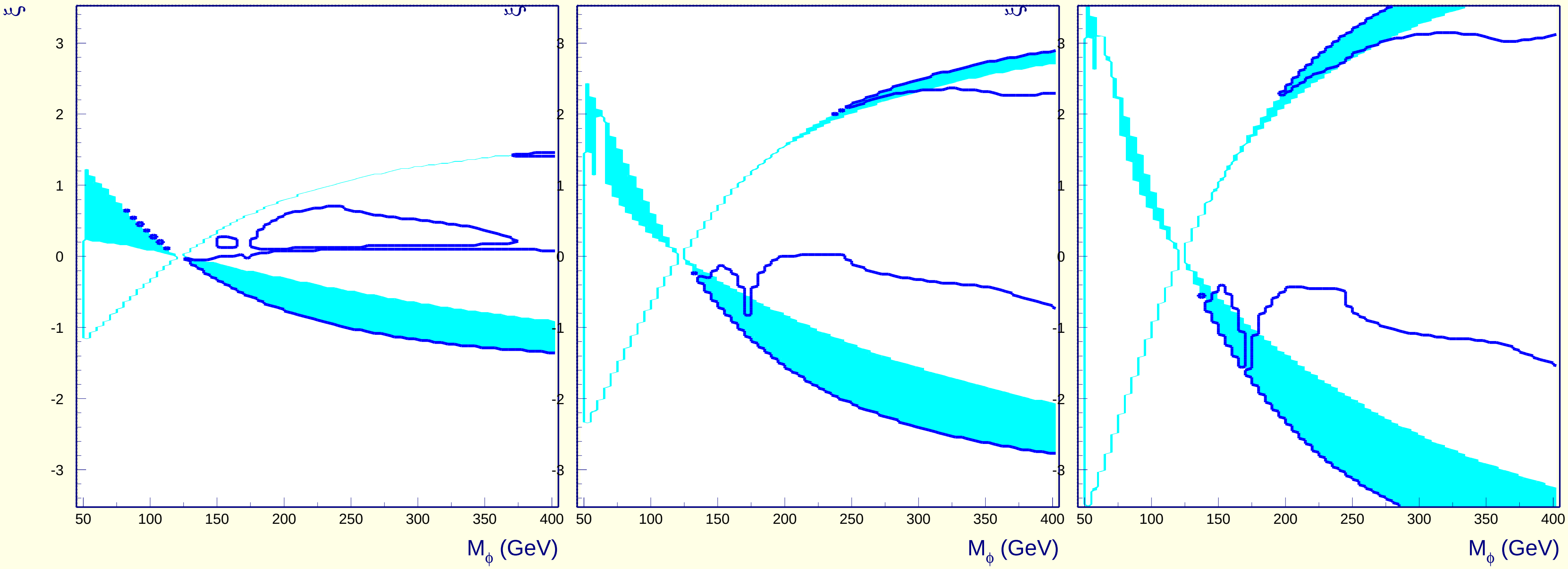


Figure 9: *$L = 30\mathrm{fb}^{-1}$ illustration of mode complementarity at the LHC for $m_h = 120$ GeV. The white regions show where the $gg \to h \to \gamma\gamma$ (and not very important at this m_h value, $gg \to h \to 4\ell$, $gg \to h \to WW^*$ and $t\bar{t}h$ modes) yield a $> 5\sigma$ combined signal. The cyan regions show where the h will not be seen at the LHC. The regions between dark blue curves define the regions where $gg \to \phi \to 4\ell$ is $> 5\sigma$. The graphs are for $\Lambda_\phi = 2.5$ TeV (left) $\Lambda_\phi = 5$ TeV (center) and $\Lambda_\phi = 7.5$ TeV (right). Increased L will eliminate the h non-detectability regions at large m_ϕ and large $\xi > 0$.*

The LHC is doing pretty well except for the $m_\phi < m_h$, $\xi > 0$ and large, region.

But, some portion of this difficult region is disfavored by the precision electroweak data — e.g. $|\xi| \lesssim 1.5$ in the $\Lambda_\phi = 5$ TeV case.

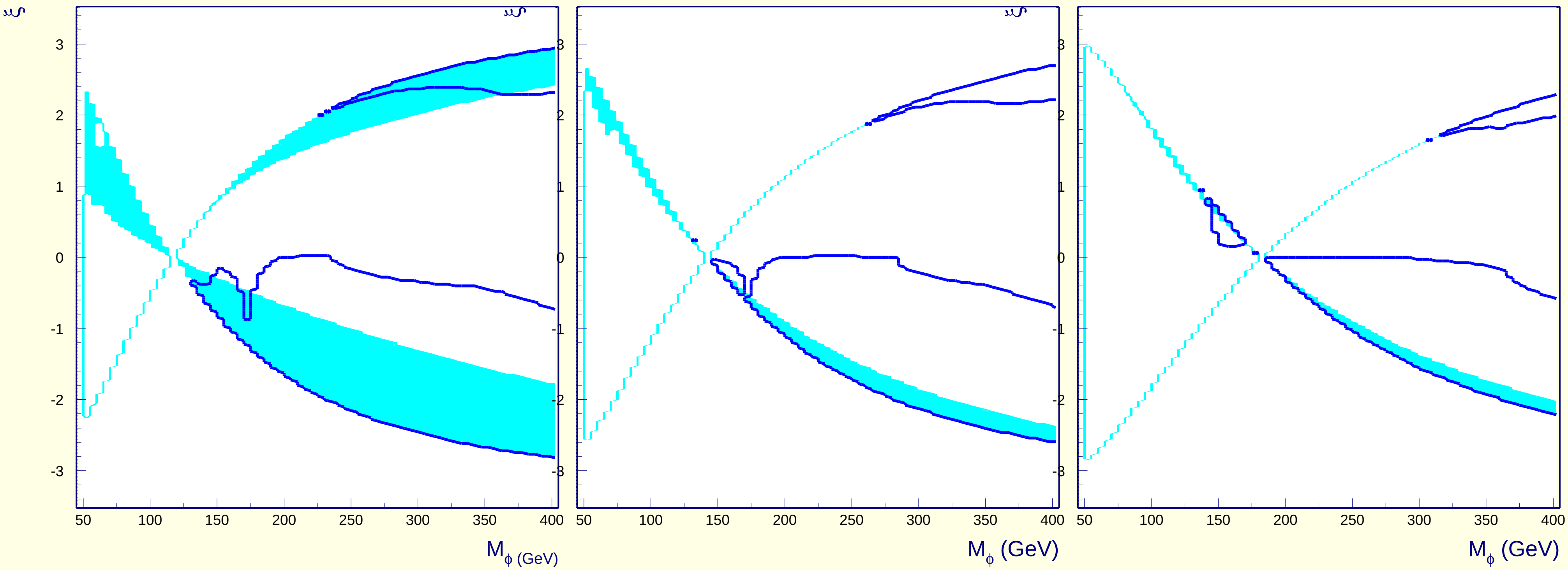


Figure 10: *As in previous figure. The graphs are for* $\Lambda_\phi = 5$ TeV *and* $m_h = 115$ GeV *(left)* $m_h = 140$ GeV *(center) and* $m_h = 180$ GeV *(right).*

Above, we see that the region where neither the h nor the ϕ 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.

The regions where the h is not observable are reduced by considering either a larger data set or qqh Higgs production, in association with forward jets. An integrated luminosity of 100 fb^{-1} would remove the regions at large positive ξ in the $\Lambda_\phi = 5$ and 7.5 TeV plots of Fig. 9.

- Figures 9 and 10 also exhibit regions of (m_h, ξ) parameter space in which *both* the h and ϕ 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 $\gamma\gamma$ (ZZ) final state.

- An e^+e^- LC should guarantee observation of both the h and the ϕ in the region of low m_ϕ, large $\xi > 0$ within which detection of either at the LHC might be difficult. This is because the $ZZ\phi$ coupling-squared is $\gtrsim 0.01$

relative to the SM for most of this region.

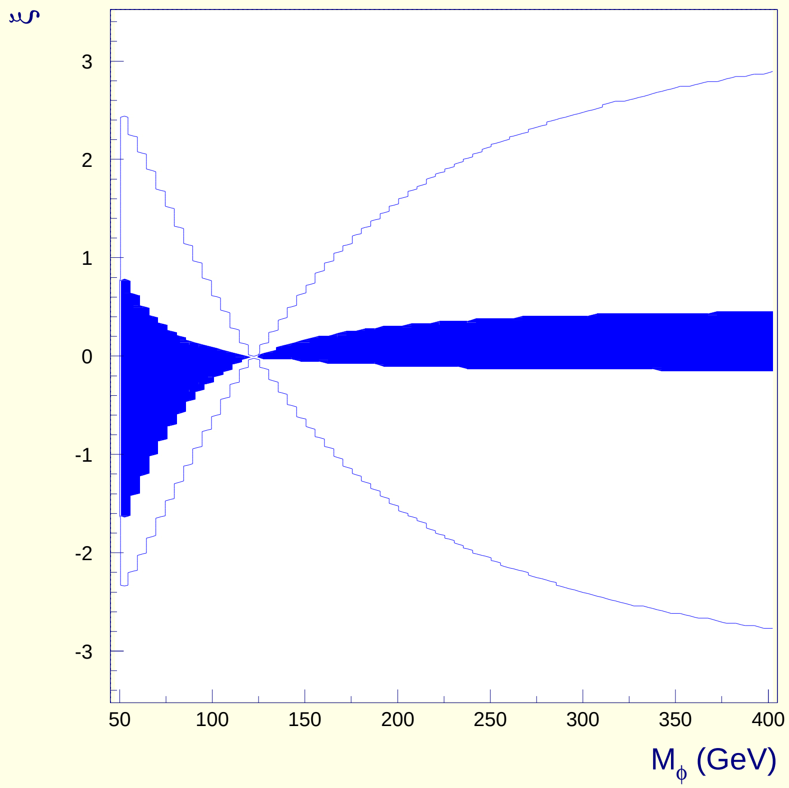


Figure 11: *Contour in (m_ϕ, ξ) parameter space with $g^2_{\phi ZZ}/g^2_{HZZ} < 0.01$ indicated by the dark region, for $M_h =$ 120 GeV and $\Lambda_\phi = 5$ TeV. The h can be detected at the LC for all (m_ϕ, ξ) parameter choices.*

Thus, this scenario provides another illustration of the complementarity between the two machines in the study of the Higgs sector.

- **Where both the h and ϕ can be seen, i.e. the white region inside the hourglass, the measurements of the ZZ boson couplings of both the Higgs and the radion particles as well as of m_h and m_ϕ would typically determine the values of ξ and Λ_ϕ up to a two-fold ambiguity.**

  Ultimately, having the two ZZ coupling measurements is absolutely crucial to really pinning down the model.

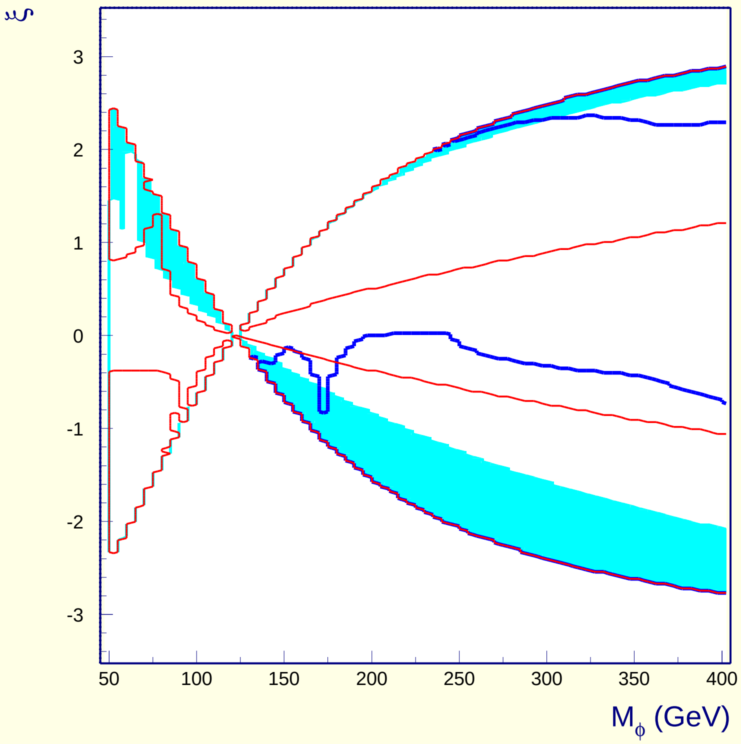
Determining the Nature of the Observed Scalar

- **Suppose we find a resonance with mass of $120\ \mathrm{GeV}$.**

  Higgs-radion mixing predicts that the ratios of VV and $f\overline{f}$ couplings remain unchanged relative to the SM. Thus, to the extent that the LHC measures only ratios of couplings, the presence of Higgs-radion mixing could easily be missed.

  However, large deviations are expected for the absolute rates, especially for the $gg \to h \to \gamma\gamma$ channel which can be dramatically enhanced or suppressed relative to the $gg \to h_{\rm SM} \to \gamma\gamma$ prediction for larger ξ values due to the large changes in the $gg \to h$ and $h \to \gamma\gamma$ couplings relative to the $h_{\rm SM}$ couplings. See Fig. 7.

However, to fully interpret, the ability of a LC to measure absolute couplings (not just ratios) will be required. A $> 2.5\sigma$ deviation is present for higher $|\xi|$ values.



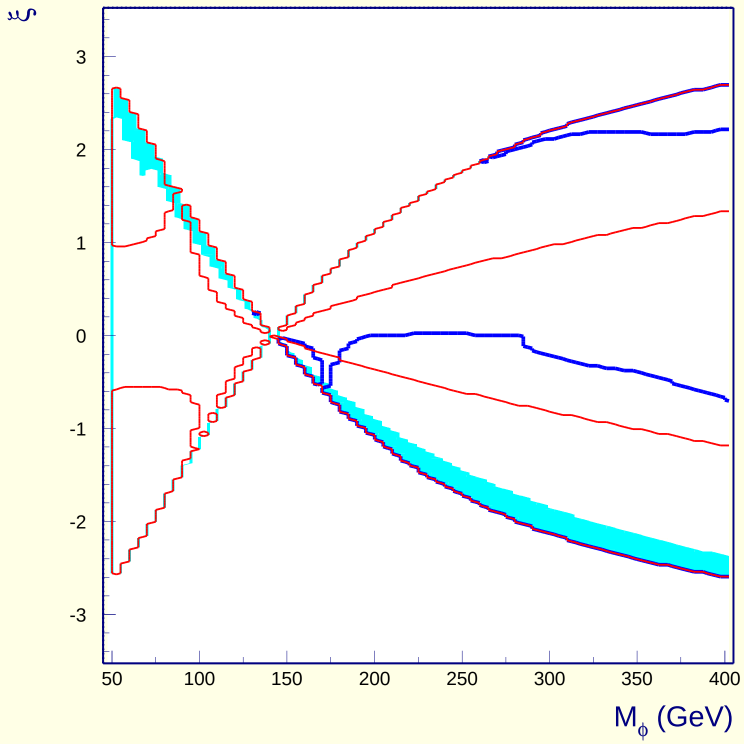


Figure 12: *Same as Figures 9 and 10 for m_h = 120 GeV (left), 140 GeV (right) and Λ_ϕ = 5 TeV with added contours, indicated by the medium gray (red) curves, showing the regions where the LC measurements of the h couplings to $b\bar{b}$ and W^+W^- would provide a $> 2.5\ \sigma$ evidence for the radion mixing effect.*

Determining that there is an anomalous ggh coupling at the LHC

- Return to scenario where we see a light h, but do not necessarily see the ϕ. How can you test for a radion-Higgs scenario using just h information from the LHC?

- An interesting case is if we see the $gg \to h \to \gamma\gamma$ mode and can compare this rate to that for $t\bar{t}h \to t\bar{t}b\bar{b}$ (probably observable since m_h is known).

- The small size of the anomalous contribution to the $h\gamma\gamma$ coupling implies that $B(h \to \gamma\gamma)$ and $B(h \to b\bar{b})$ are very nearly SM-like. All partial widths are rescaled but the ratios that define the B's remain unchanged

- Further, if there were no anomalous $gg \to h$ coupling, then the $t\bar{t}h/ggh$ ratio would be the same as in the SM.

  Both production rates would would scale in the same way.

- So, look at

$$R_{ttgg} \equiv \left[\frac{\sigma(t\bar{t}h \to t\bar{t}b\bar{b})}{\sigma(gg \to h \to \gamma\gamma)}\right] \left[\frac{\sigma(t\bar{t}h_{\rm SM} \to t\bar{t}b\bar{b})}{\sigma(gg \to h_{\rm SM} \to \gamma\gamma)}\right]^{-1} . \qquad (18)$$

If $R_{ttgg} = 1$ then there is no reason to believe that Higgs-radion mixing is present.

If $R_{ttgg} \neq 1$, one could imagine a $\xi \neq 0$ RS interpretation.

- In fact, R_{ttgg} deviates very substantially from 1 in general, to an extent that would probably be measurable.

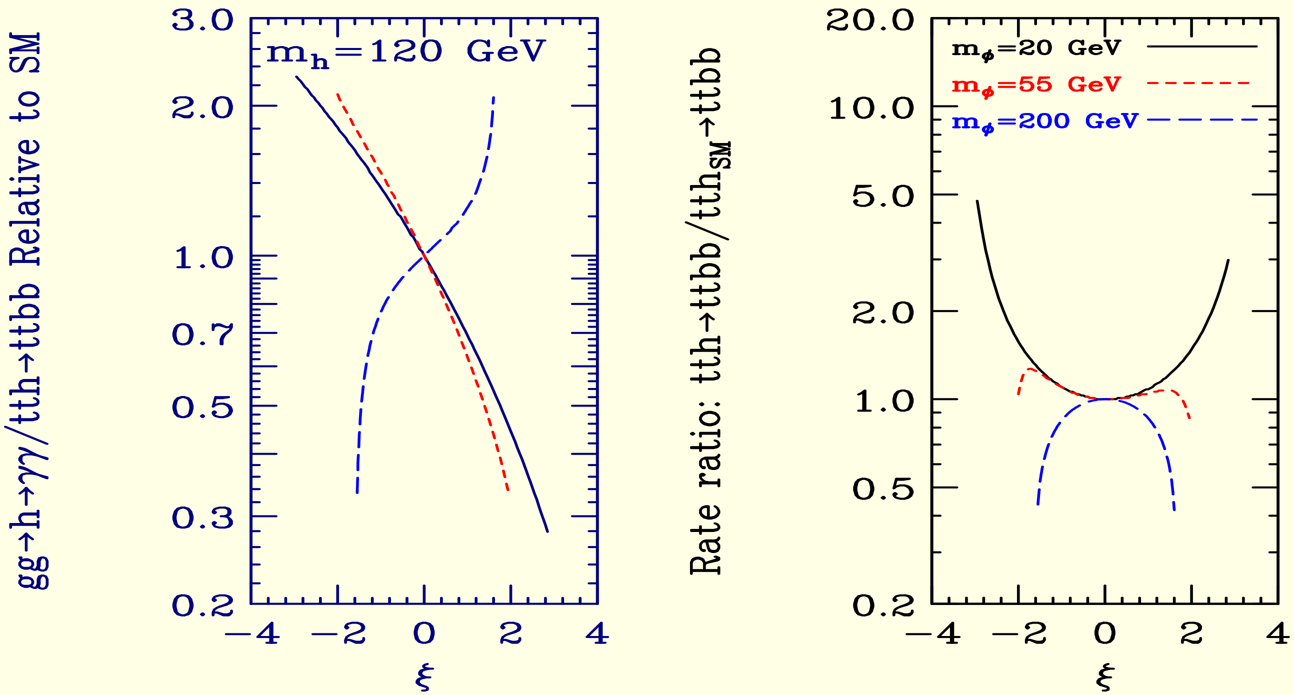


Figure 13: *The ratio* R_{ttgg} *as a function of* ξ *for our standard* m_ϕ *values and* $\Lambda_\phi = 5$ TeV. *Also plotted (again) is the* $t\bar{t}h \to t\bar{t}b\bar{b}$ *rate relative to that for the* $h_{\rm SM}$*, showing a good signal rate.*

- **Combining the measured value of $R_{ttgg} \neq 1$ with one of the independent rates, say $gg \to h \to \gamma\gamma$, we have two constraints on ξ and m_ϕ and could possibly solve for them.**

- **If we were in that part of parameter space where $gg \to \phi \to 4\ell$ was also observable, we would have very solid evidence for the RS Higgs-radion scenario with $\xi \neq 0$.**

General Conclusions and LHC/LC Complementarity

- One should be prepared for the possibility of a Higgs sector that is both far more interesting than that of the SM and at the same time harder to discover and study.

- Continued attention to improving every LHC discovery channel is particularly important.

- Certain new discovery channels may prove critical at the LHC.

  Here we have seen the importance of the $h \to aa$ channel, which could prove essential for LHC discovery of even one Higgs boson of the NMSSM, MSSM with CP violation (and general 2HDM models).

  So far, we have only shown the potential of the WW fusion mode when h has nearly SM-like WWh coupling.

  – How far down in WWh coupling can one go?

– Can a $gg \to h \to aa$ signal be extracted?

- Though not discussed, the $h \to \phi\phi$ or $\phi \to hh$ signals of the RS scenario are similar and would provide unique windows on the structure of the Higgs-radion sector.

  Here, the $WW\phi$ coupling is typically not very large while the $gg\phi$ coupling can be. Developing the potential of the $gg \to \phi \to hh$ channel appears to be quite important.

- When the LHC signals are subtle or weak, the power of the LC to detect all the light Higgs bosons and/or radions with $g^2_{ZZh} \gtrsim 0.01$ could prove essential for clarifying a signal seen at the LHC or possibly allowing first discovery of the scalars of the theory.

  In this regard, don't forget the worst case scenario (JFG + Espinosa) where we add a bunch of singlets (often found in string models) to the Higgs sector which mix with one another and with the doublet(s) in such a way that:

  a) their WW couplings are reduced, implying small branching ratios to the high-resolution $\gamma\gamma$ channel;

b) the resonance peaks are overlapping within the resolution of other discovery modes.

The LHC will not be able to detect a Higgs signal in this case, but *will* find that the WW scattering sector is perturbative, implying that there must be low-mass Higgses coupled to WW.

In contrast, the LC *can* detect the Higgs continuum as a broad excess in the M_X distribution obtained in the $e^+e^- \to ZX$ channel. It can even evaluate the amount of ZZh coupling as a function of m_h for bins of order $10~\mathrm{GeV}$.

This overlapping scenario can also arise in the CP-violating MSSM Higgs sector and in a general 2HDM model. There, the smaller number of Higgs bosons implies that some LHC signal might be seen, but that real analysis of the Higgs sector would require the LC.