Beyond the SM Higgs Boson

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Outline

- Finding a CP-odd A^0
- Covering the SUSY wedge with $\gamma\gamma$ collisions
- Using the Higgs Sector to Determine $\tan\beta$
- What is needed to guarantee NMSSM Higgs Discovery at the LHC
- Determining the CP of a Higgs boson
- Decays of Higgs bosons to Radions

Finding a CP-Odd A^0

Maybe it can't be seen in association with other Higgs because of kinematics, event rate etc. It could be *very* important to find the A^0 as we will see. Need to consider:

- $e^+e^- \to t\bar{t}A^0$ **and** $e^+e^- \to b\bar{b}A^0$.
- $e^+e^- \to Z^* \to ZA^0A^0$

  $e^+e^- \to e^+e^-W^*W^* \to e^+e^-A^0A^0$.
- $\gamma\gamma \to A^0$ **and** $\mu^+\mu^- \to A^0$.

Corresponding 'guarantees':

- **Fermionic couplings:** $g^2_{t\bar{t}A^0} = \left(\frac{\cos\beta}{\sin\beta}\right)^2, \quad g^2_{b\bar{b}A^0} = \left(\frac{\sin\beta}{\cos\beta}\right)^2$

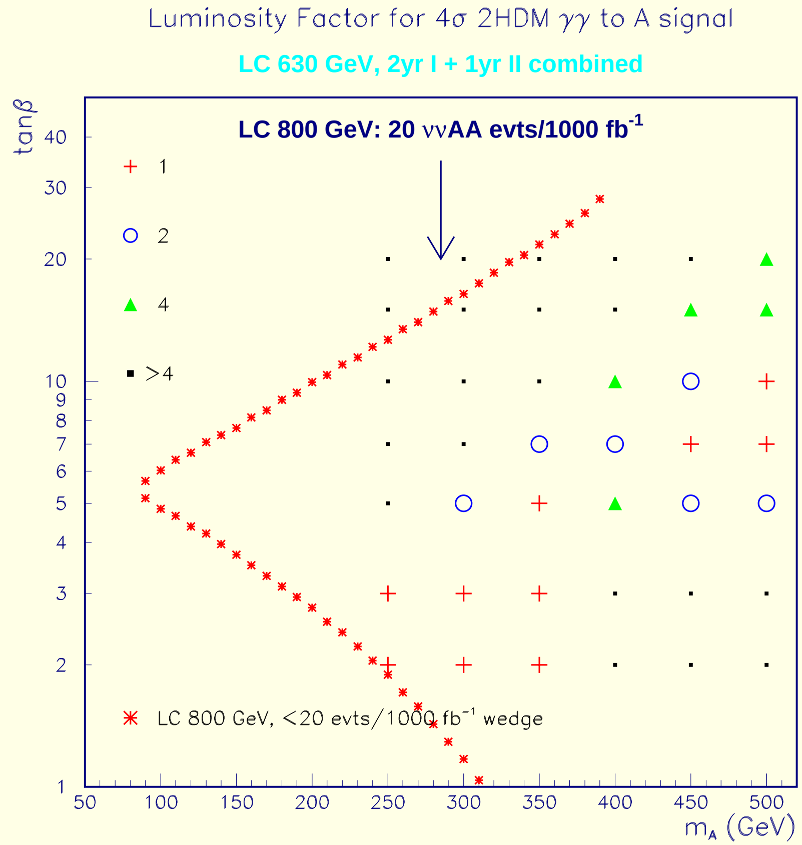
  $\Rightarrow$ **either** $t\bar{t}$ **or** $b\bar{b}$ **coupling of** A^0 **must be big.**
- **The quartic couplings** ZZA^0A^0 **and** $W^+W^-A^0A^0$**, from gauge covariant structure** $(D_\mu\Phi)^\dagger(D^\mu\Phi)$**, are of guaranteed magnitude.**
- $\gamma\gamma \to A^0$ **coupling from fermion loops,** $\mu^+\mu^- \to A^0$ **direct coupling to fermions.**

$e^+e^- \to t\bar t A^0$ always works if $\tan\beta$ is small enough (and process is kinematically allowed).

$e^+e^- \to b\bar b A^0$ always works if $\tan\beta$ is large enough, but increasingly large $\tan\beta$ is required as m_{A^0} increases.

$\nu\bar\nu A^0 A^0$ ok for $m_{A^0} \lesssim 300~\mathrm{GeV}$.

Only $\gamma\gamma \to A^0$ covers upper part of the wedge.



For $\sqrt{s} = 800~\mathrm{GeV}$, the maximum and minimum $\tan\beta$ values between which $t\bar t A^0$ and $b\bar b A^0$ final states both have fewer than 20 events for $L = 1000\mathrm{fb}^{-1}$. Arrow shows maximum reach of $e^+e^- \to \nu\bar\nu A^0$ via WW fusion — $Z^* \to A^0 A^0 Z$ has less reach. $+$'s show $\gamma\gamma \to A^0$ 4σ (3 year) signal region for NLC — circles show extra at TESLA (from Asner+JFG+Gronberg, hep-ph/0110320). Summary and references in Farris+JFG+Logan, hep-ph/0202087

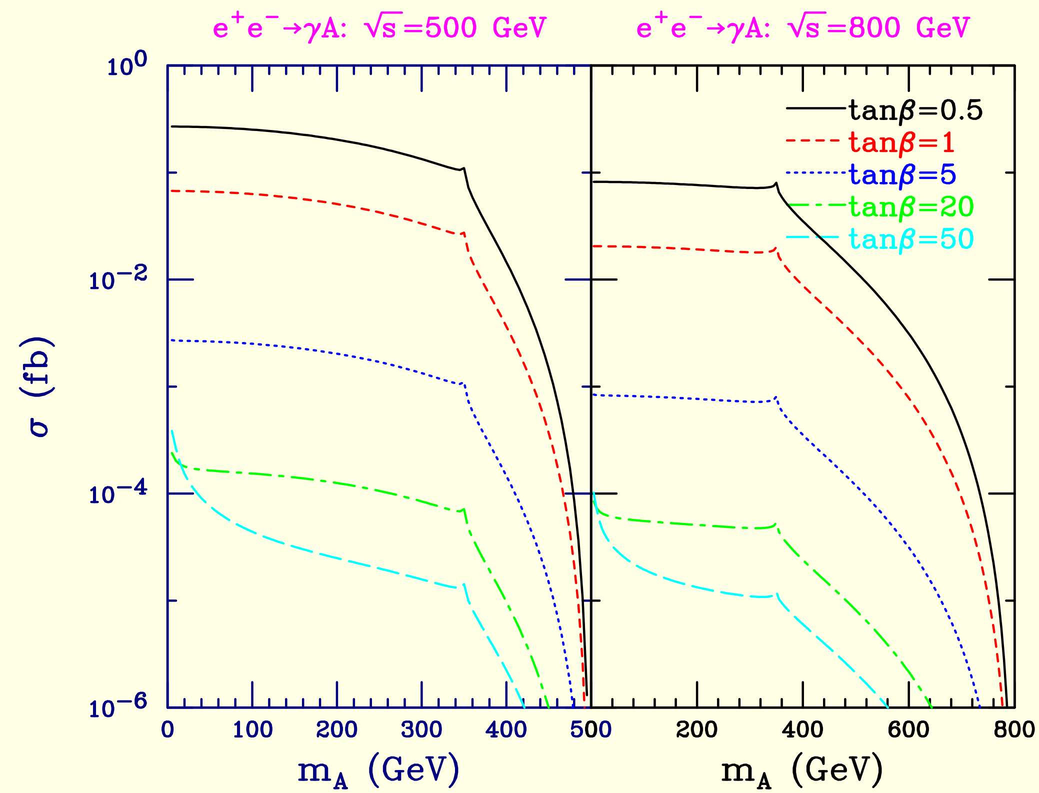
$L = 1000\mathrm{fb}^{-1}$ wedge begins at $m_{A^0} \sim 80~\mathrm{GeV}$.
Wedge extends to higher m_{A^0} than plotted. LHC wedge smaller.

Of single A^0 (one-loop) production processes, $e^+e^- \to \gamma A^0$ production has largest rate.

- Event rate $\neq 0$ only for $\tan\beta < 5$.

- $\frac{d\sigma}{dm_{b\bar b}}(e^+e^- \to \gamma b\bar b) = 0.5\ \mathrm{fb}/10\ \mathrm{GeV}$ at $m_{A^0} = 200\ \mathrm{GeV}$, $= 0.2\ \mathrm{fb}/10\ \mathrm{GeV}$ at $m_{A^0} = 400\ \mathrm{GeV}$ ($\sqrt{s} = 500\ \mathrm{GeV}$). (Casalbuoni, JFG, .., Nucl.Phys.B555:3-52,1999, hep-ph/9809523)

  $\Rightarrow$ very hard!



For $\sqrt{s} = 500\ \mathrm{GeV}$, we plot $\sigma(e^+e^- \to \gamma A^0)$ as a function of m_{A^0}. All other Higgs assumed heavy. No SUSY loops. etc. (also computed by Akeroyd, etal. Mod.Phys.Lett.A14:2093-2108,1999, Erratum-ibid.A17:373,2002, hep-ph/9907542.)

A muon collider could be very competitive using $\mu^+\mu^- \to A^0$ and a carefully designed scan procedure. (JFG as summarized in Barger etal., hep-ph/0110340)

Why might detecting a single A^0 be important?

(More generally, "a Higgs with no VV coupling".)

- **Can construct a 2HDM in which precision electroweak constraints are satisfied, but the only non-heavy Higgs is an A^0 (Chankowski+JFG+etal).**

  In 2HDM, you would see a heavy CP-even state, no SUSY particles, and wonder how precision EW is fixed up.

- **At the LHC, Higgs could be missed because they decay into an A^0A^0 pair.**

- **Technicolor might be relevant and the light scalars would be the CP-odd pseudo-Nambu-Goldstone bosons (P^0).**

SUSY HIGGS BOSONS

Although hierarchy need not be a problem for SM + Higgs sector as an effective low-E theory, the most motivated solution is TeV scale SUSY.

- MSSM contains exactly two doublets ($Y = +1$ and $Y = -1$), as required to give masses to both up and down quarks, give anomaly cancellation, coupling unification if $m_{\rm SUSY} \geq 1~{\rm TeV}$.

  Can add extra singlet Higgs fields without disturbing any of the above.

  More doublets, triplets, etc. $\Rightarrow$ generally need intermediate scale matter between ${\rm TeV}$ and M_U scales.

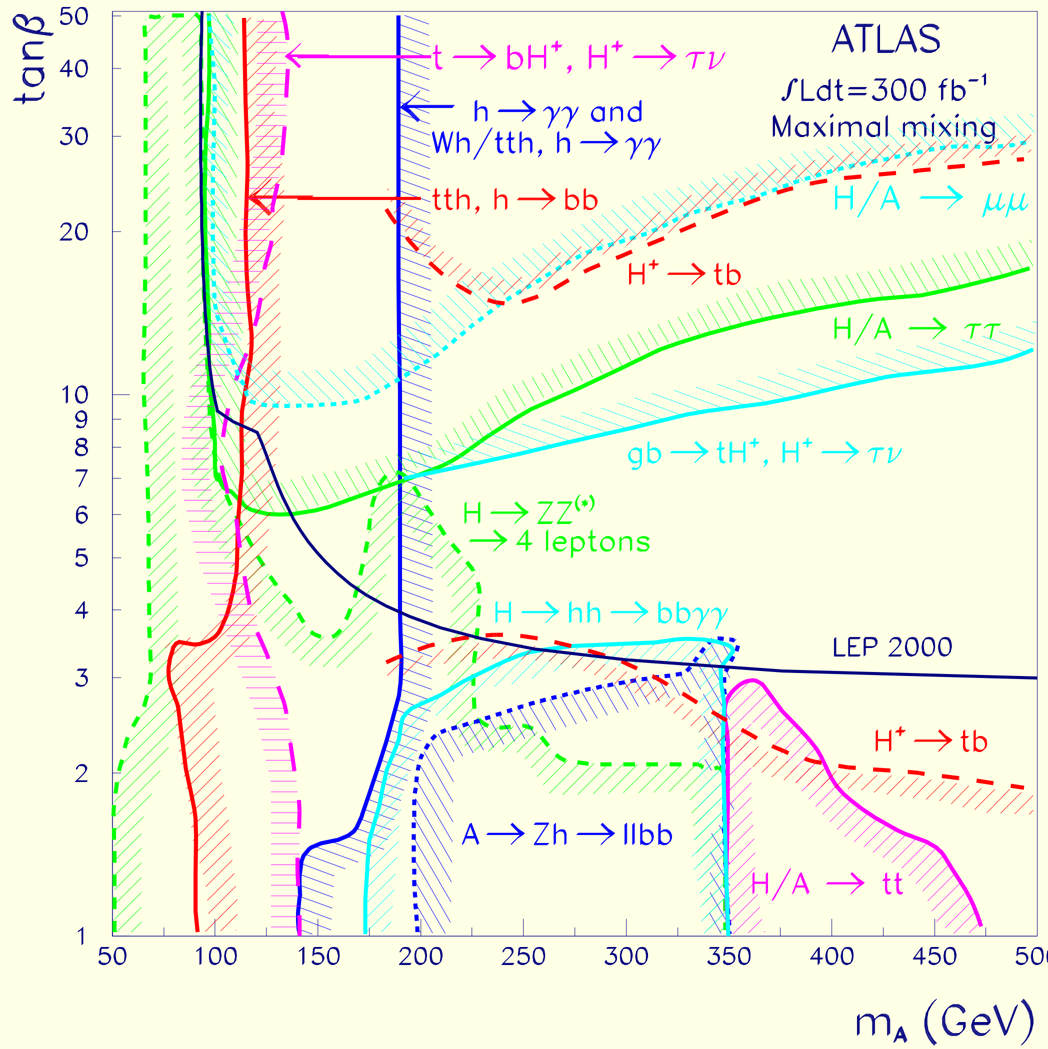
  BUT, if there are extra dimensions, or gauge-mediated SUSY breaking, or . . ., unification at M_U may be irrelevant!

⇒ **Guaranteed to find one of the MSSM Higgs bosons with $L = 300\mathrm{fb}^{-1}$ (3 years).**

⇒ **significant wedge of moderate $\tan\beta$ where see only the h^0.**

Can we detect the H^0, A^0 and $H^\pm$?

SUSY decay final states?
Appearance in decay chains of $\widetilde{g}, \ldots$?
Go to LC?



5σ 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. This figure is preliminary.

Discovery at Linear e^+e^- collider

- For h^0 use same production/decay modes as for light $h_{\rm SM}$.

  $\Rightarrow$ precision measurements of $\sim$SM properties ($m_{A^0} > 2m_Z$).

- For $A^0, H^0, H^\pm$:

  If $m_{A^0} > 2m_Z$ (as probable given RGE EWSB), most substantial e^+e^- production mechanisms are $e^+e^- \to H^0 + A^0$ and $e^+e^- \to H^+ + H^-$.

  But, given that $m_{H^0} \sim m_{A^0} \sim m_{H^\pm}$ for large m_{A^0}, these all require $\sqrt{s} \gtrsim 2m_{A^0}$.

- For very high $\tan\beta$, can look to $e^+e^- \to b\bar{b}A^0, b\bar{b}H^0, btH^\pm$.

- The challenge: find the H^0 and A^0 in the moderate $\tan\beta$ LHC wedge where only h^0 is seen.

- It could be that a e^+e^- linear collider will be needed.

- But, the LC will have a wedge region in which $t\bar{t}H^0+t\bar{t}A^0$ and $b\bar{b}H^0+b\bar{b}A^0$ both fail and $e^+e^- \to \nu\bar{\nu}H^0 + \nu\bar{\nu}A^0$ will fail for $m_{A^0} \gtrsim 300$ GeV (at $\sqrt{s} = 800$ GeV).

Strategies at the LC

- Raise $\sqrt{s}$! (longer machine, improved gradient, CLIC, muon collider, . . .)

- Go to single production via $\gamma\gamma$ collisions (Asner+JFG+Gronberg, hep-ph/0110320; see also Muhlleitner, etal, Phys.Lett.B508:311-316,2001, hep-ph/0101083). Two distinct possibilities.
  - Use precision h^0 measurements to get first indication of presence of A^0, H^0 and rough determination of $m_{A^0} \sim m_{H^0}$.

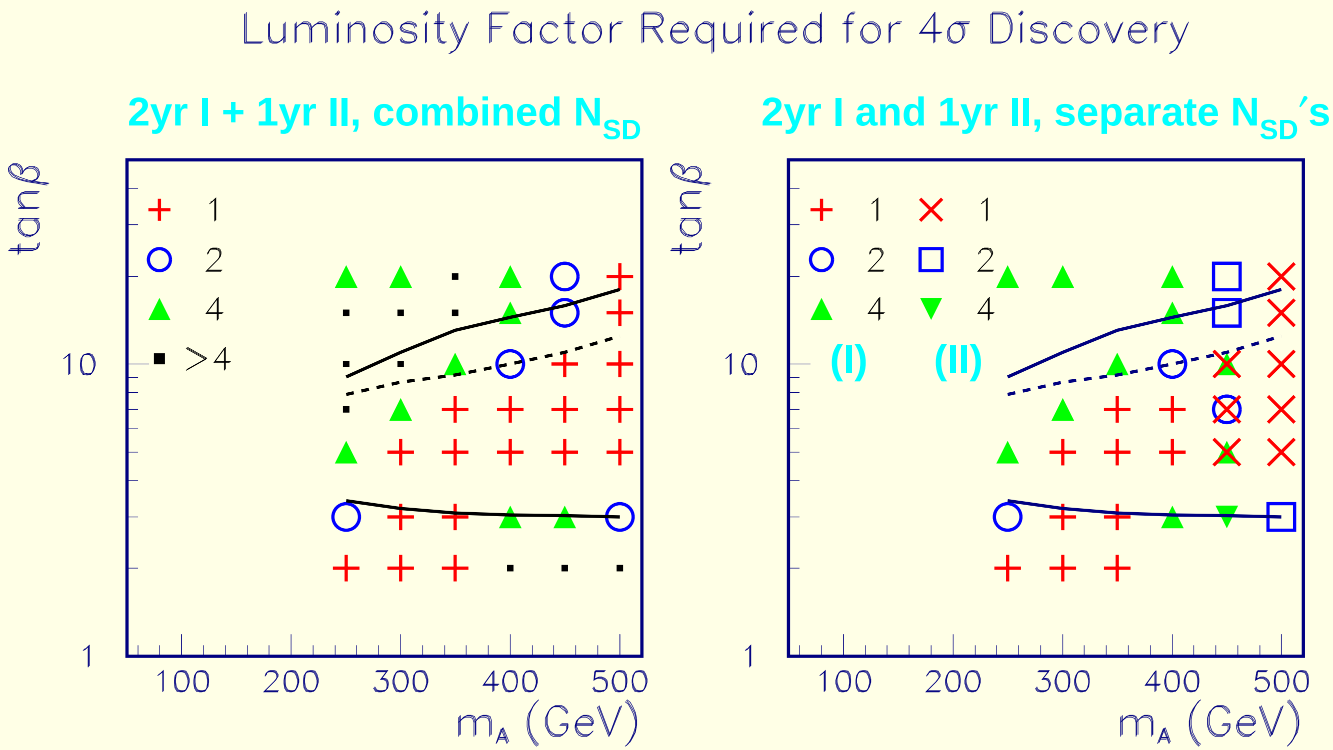
    (Requires determining extent to which one is in 'normal' vs. 'unusual' early/exact decoupling scenario.)

    Then use peaked $\gamma\gamma$ spectrum to look for H^0, A^0 (usually overlapping) combined signal over narrow interval.

    < 1 year's luminosity needed if you know m_{A^0} within $\sim 50~\mathrm{GeV}$. Use 2 or 3 steps in $\sqrt{s}$ to explore interval.
  - You don't trust indirect m_{A^0} determination (is there a way to know if you should trust it?).
    Then use highest $\sqrt{s}$ and two different electron helicity / laser-photon polarization configurations to get peaked $E_{\gamma\gamma}$ spectrum for highest masses and broad spectrum for lower masses.

The Wedge Results: peaked + broad spectrum running.

(from JFG+Asner+Gronberg)



RH window: separate N_{SD}'s for 2 yr type-I and 1 yr type-II operation.
LH window: combined N_{SD}'s.
Solid lines = LHC H^0, A^0 wedge.
Above dashed line = LHC $H^\pm$ discovery (then know $\sqrt{s}$ for $m_{A^0} \sim m_{H^\pm}$).
Pair production covers up to $m_{A^0} \sim 300$ GeV. Most of remainder is covered by $\gamma\gamma$!

Determining $\tan\beta$

If observable, the non-SM-like Higgs bosons will provide the best determination at large $\tan\beta$. Also can $\Rightarrow$ good determination at low $\tan\beta$. (LHC study: JFG+Kao+Poggioli, Snowmass96, hep-ph/9703330; LC study: JFG+Han+Jiang+Mrenna+Sopczak, hep-ph/0112334 — see also: JFG+Kelly, Phys. Rev. D 56, 1730 (1997) [arXiv:hep-ph/9610495] and Snowmass96, arXiv:hep-ph/9610421; Barger, Han, Jiang, Phys. Rev. D 63, 075002 (2001) [arXiv:hep-ph/0006223]; Feng+Moroi, Phys. Rev. D 56, 5962 (1997) [arXiv:hep-ph/9612333].)

- In particular, at large $\tan\beta$ one finds couplings $t\bar tH^0, t\bar tA^0 \propto \cot\beta$ and $b\bar bH^0, b\bar bA^0 \propto \tan\beta$.
- Simple observables sensitive to these couplings at a Linear Collider are:

1. The rate for $e^+e^- \to b\bar bA^0 + b\bar bH^0 \to b\bar bb\bar b$.
   Not background free and must use cuts to remove $e^+e^- \to H^0A^0 \to b\bar bb\bar b$. $\Rightarrow$ need large $\tan\beta$ for sufficient rate.
2. The average width of the H^0 and A^0 as measured in the $b\bar bb\bar b$ final state of $e^+e^- \to H^0A^0 \to b\bar bb\bar b$.
   Simple cuts can make quite background free, but finite experimental resolution ($\Gamma_{\rm res} \sim 5~{\rm GeV}$) and $\sim 10\%$ systematic uncertainty in $\Gamma_{\rm res}$ limit reach lower $\tan\beta$ where H^0, A^0 widths are $\leq 5~{\rm GeV}$.

3. The average width of the H^0 and A^0 as measured in $e^+e^- \to b\bar{b}H^0 + b\bar{b}A^0$.

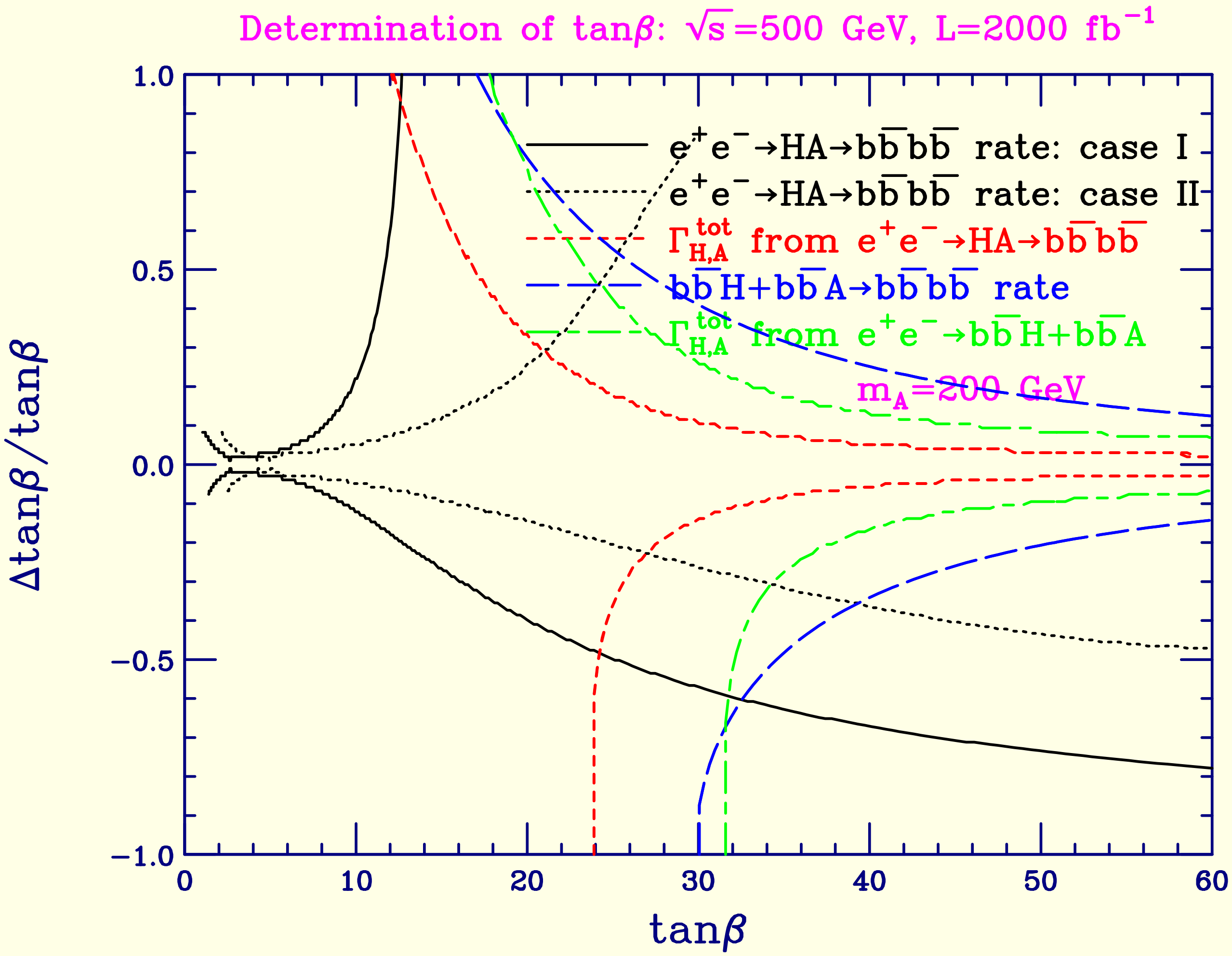
   Need high $\tan\beta$ to overcome both background and $\Gamma_{\rm res}$.

4. The rate for $e^+e^- \to H^0A^0 \to b\bar{b}b\bar{b}$.

   This gives good results over region where $H^0, A^0 \to b\bar{b}$ branching ratios vary. If there are $H^0, A^0 \to$SUSY decays present (case I), variation continues out to substantial $\tan\beta$. If not (case II), the event rate asymptotes quickly and one loses sensitivity at high $\tan\beta$.

- Need knowledge of SUSY parameters (e.g. $\mu, m_{\widetilde{g}}$) to determine one-loop $\Delta\lambda_b$ radiative corrections for definite interpretation in terms of $\tan\beta$.
- Analogous charged Higgs observables are also useful, but determination of width in $H^\pm \to tb$ decay mode will not be as precise. $\Rightarrow$ should study this.
- Other decay channels will provide additional $\tan\beta$ information at low to moderate $\tan\beta$.

  In particular, $e^+e^- \to H^0A^0 \to X$ ratios for different X and $e^+e^- \to H^+H^- \to X'$ ratios for different X', especially when SUSY decays of $H^0, A^0, H^\pm$ are allowed.
- $\gamma\gamma \to H^0, A^0$ rates also provide reasonably good $\tan\beta$ determination (JFG+Asner+Gronberg).



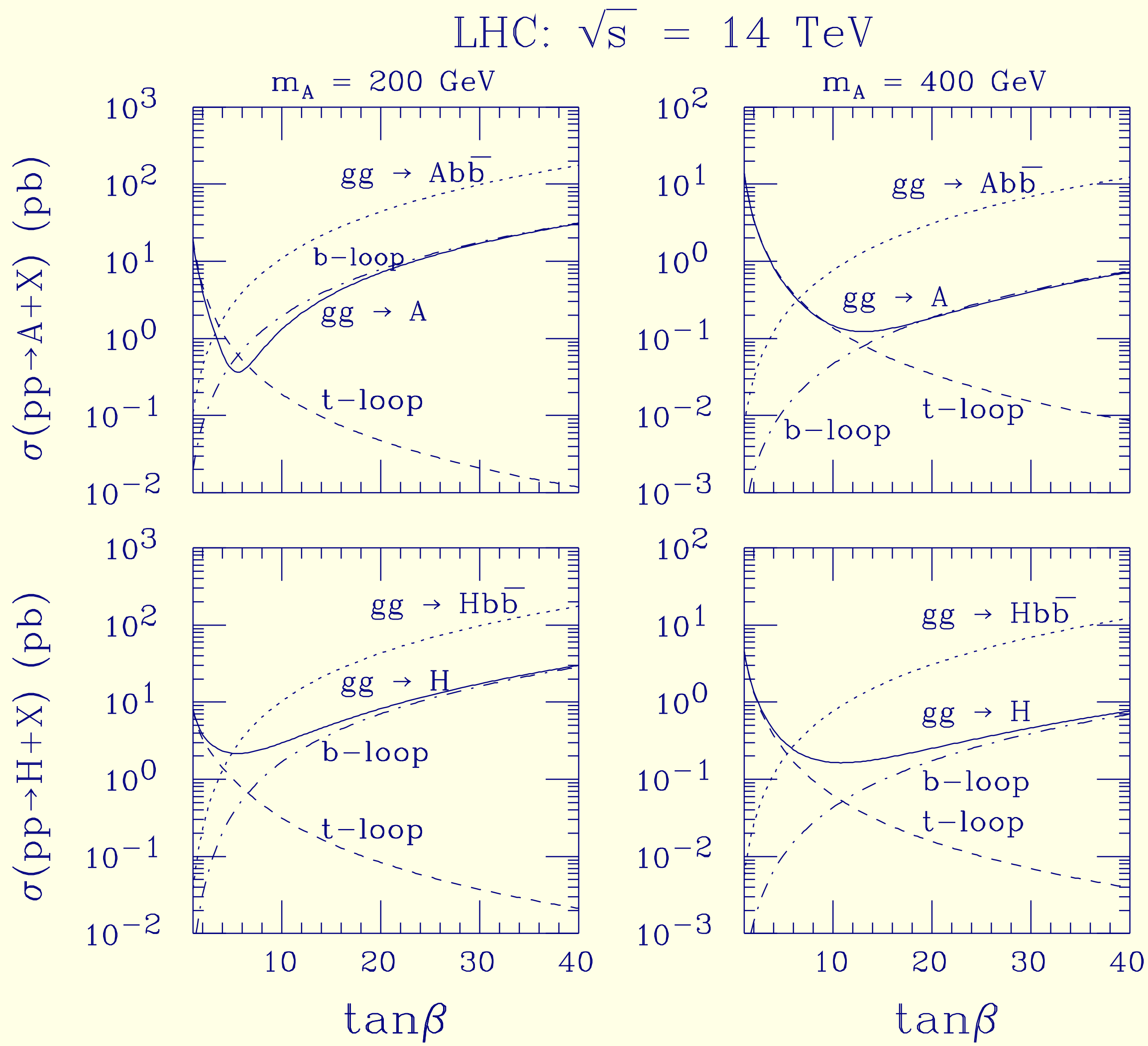
We see significant sensitivity of the $\tan\beta$ errors from $H^0A^0 \to b\bar{b}b\bar{b}$ rates to the scenario choice, with the errors worse for scenario (I).

Errors for $\tan\beta$ from the $b\bar{b}H^0+b\bar{b}A^0 \to b\bar{b}b\bar{b}$ rate are essentially independent of the scenario choice. Running m_b has big impact on these errors.

All results (from JFG+Han+Jiang+Mrenna+Sopczak) **employ couplings and widths ala HDECAY.**

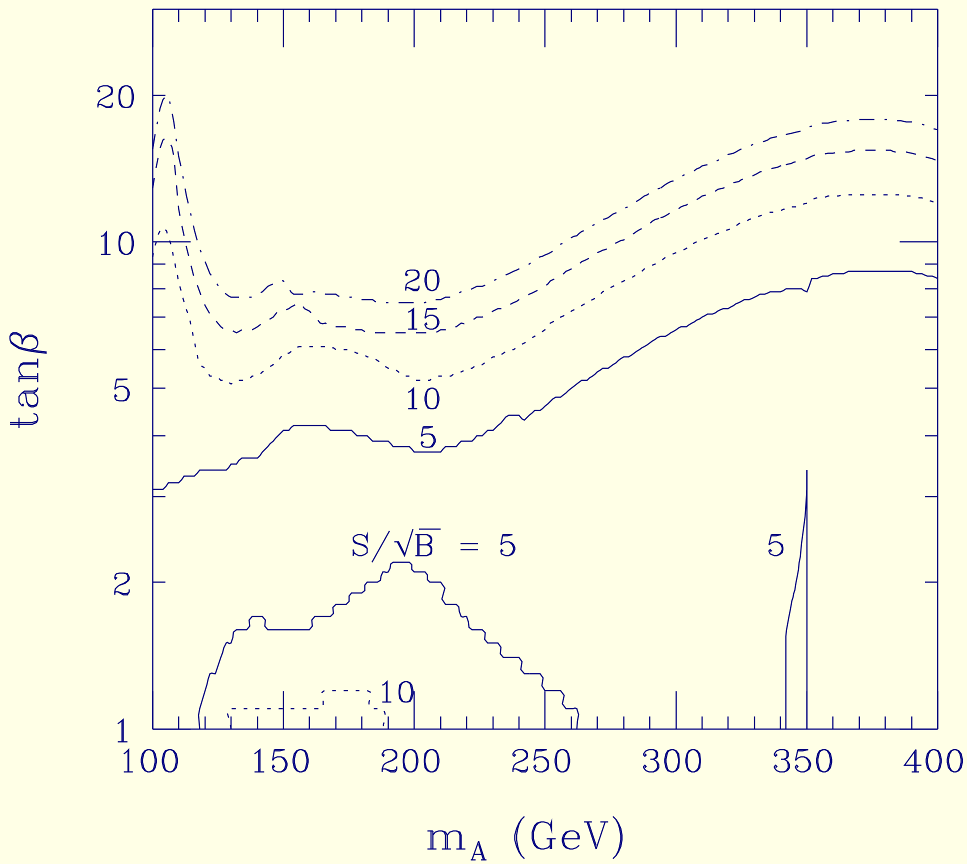
- **What about at the LHC? Summarize Snowmass 96 results.** (JFG+Kao+Poggioli)
  - $gg \to H^0$ and $gg \to A^0$ (mainly the latter) inclusive production can be isolated in the $H^0, A^0 \to \tau^+\tau^-$ decay mode if $\tan\beta$ is modest in size ($\lesssim 3$) and m_{A^0}, m_{H^0} are below $2m_t$.
  - At high $\tan\beta$, the $gg \to H^0 b\overline{b}$ and $gg \to A^0 b\overline{b}$ processes with $H^0, A^0 \to \tau^+\tau^-$, $\mu^+\mu^-$ and, perhaps, $b\overline{b}$ decay channels will be possible, with $\tau^+\tau^-$ reaching to lowest $\tan\beta$.
  - Since $m_{A^0} \sim m_{H^0}$, their signals would not be separable, except, possibly, in the $\mu^+\mu^-$ mode.
  - The figure displays the $gg \to H^0$, $gg \to A^0$, $gg \to b\overline{b}H^0$ and $gg \to b\overline{b}A^0$ cross sections (and separate t and b loop contributions to the first two).
  - At low $\tan\beta$, $gg \to H^0$ and, especially, $gg \to A^0$ falls rapidly as the t-loop contribution falls with increasing $\tan\beta$. At high $\tan\beta$, the rapid rise of the $gg \to H^0 b\overline{b}$ and $gg \to A^0 b\overline{b}$ cross sections is apparent.

  The strong $\tan\beta$ dependence $\Rightarrow$ $\tan\beta$ determination is possible.
  We used only the $\tau^+\tau^-$ mode based on results of ATLAS TDR Table 34, and corresponding background tabulation.



$gg \to H^0, A^0$ and $gg \to H^0 b\bar{b}, A^0 b\bar{b}$ vs. $\tan\beta$ for $m_{A^0} = 200$ and $400\ \mathrm{GeV}$ at the LHC. Also shown are the $gg \to H^0, A^0$ cross sections obtained by retaining only b- or t-loop contributions to the one-loop coupling.

– **The accuracy with which you can determine $\tan\beta$ is strongly correlated with the $S/\sqrt{B}$. For the $\tau^+\tau^-$ mode, contours of $S/\sqrt{B}$ in the $[m_{A^0}, \tan\beta]$ plane are given below.**



Contours of $S/\sqrt{B}$ for combined A^0 plus H^0 signal at the LHC. Signal combination done via $\frac{S}{\sqrt{B}} = \left[\left(\frac{S}{\sqrt{B}}\right)^2_H + \left(\frac{S}{\sqrt{B}}\right)^2_A - 2\epsilon_{HA}\left(\frac{S}{\sqrt{B}}\right)_H\left(\frac{S}{\sqrt{B}}\right)_A\right]^{1/2}$**. Here,** $\epsilon_{HA} = f(|m_{H^0} - m_{A^0}|/\sigma_M)$, $\sigma_M = \tau^+\tau^-$ **mass resolution.**

– We computed the error in the cross section determination as

$$\frac{\Delta\sigma}{\sigma} = \left[\frac{S+B}{S^2} + (0.1)^2\right]^{1/2}, \quad (1)$$

(0.1 for systematics) of parameter choices for the $\tan\beta$ values such that $S/\sqrt{B} = 5, 10, 15, 20$ at $m_{A^0} = 200$ GeV and 400 GeV.

– $\Delta\tan\beta$ is found by searching for the $\tan\beta$ values such that σ changes by $\Delta\sigma$. The results are:

We tabulate the percentage errors at $m_{A^0} = 200$ GeV and 400 GeV for the $H^0, A^0 \to \tau^+\tau^-$ signal and the corresponding errors in the determination of $\tan\beta$ for the high-$\tan\beta$ contours such that $S/\sqrt{B} = 5, 10, 15, 20$, assuming $L = 600\mathrm{fb}^{-1}$ accumulated at the LHC.

Quantity	Errors			
m_{A^0}	200 GeV		400 GeV	
	$\Delta\sigma/\sigma$	$\Delta\tan\beta/\tan\beta$	$\Delta\sigma/\sigma$	$\Delta\tan\beta/\tan\beta$
$S/\sqrt{B} = 5$	$\pm 20\%$	$\pm 22\%$	$\pm 22\%$	$\pm 12\%$
$S/\sqrt{B} = 10$	$\pm 14\%$	$\pm 7.8\%$	$\pm 14\%$	$\pm 7.4\%$
$S/\sqrt{B} = 15$	$\pm 12\%$	$\pm 6.2\%$	$\pm 12\%$	$\pm 6.2\%$
$S/\sqrt{B} = 20$	$\pm 11\%$	$\pm 5.6\%$	$\pm 11\%$	$\pm 5.7\%$

– The errors are quite respectable once $\tan\beta > 10$.

– We have implicitly assumed that $B(H^0, A^0 \to \tau^+\tau^-)$ will be either measured or calculable.

Determining $B(H^0, A^0 \rightarrow \tau^+\tau^-)$ might require the LC!
If the H^0, A^0 rates could be measured well in the $H^0, A^0 \rightarrow b\bar{b}$ final states, we would have some cross check.

- As before, reinterpretation after correcting for $\Delta\lambda_b$ radiative corrections might be significant.

- The viability of the $tbH^{\pm}$ with $H^{\pm} \rightarrow \tau^{\pm}\nu$ has been established by the LHC collaborations.
  This will allow an independent determination of $\tan\beta$. Study is required to assess this quantitatively.

- The $H^0, A^0 \rightarrow \tau^+\tau^-$ channel cannot be used for direct width reconstruction because of the poor experimental width resolution, $\sim 15\%$.
  The $\mu^+\mu^-$ decay channel would be great where viable. The $b\bar{b}$ channel must be studied, but the $4b$ final state is a challenge (triggering, ...).

- A group (JFG+Weiglein+Heinemeyer+?) is working on updating all of this. Would experimentalist(s) like to work with us on all this?

The NMSSM Higgs Sector

$W \ni \lambda \hat{H}_1 \hat{H}_2 \hat{N}$. Assuming no CP violation, $\Rightarrow$ 3 CP-even Higgs bosons: $h_{1,2,3}$ and 2 CP-odd Higgs bosons: $a_{1,2}$.

Linear Collider

Many groups have shown that one can add a singlet (e.g. Ellwanger, Hugonie and collaborators), and indeed a continuum of singlets (JFG+Espinosa), and still find signal.

LHC?

Old Snowmass96 Result (JFG+Haber+Moroi, hep-ph/9610337) $\Longrightarrow$

Could find parameter choices for Higgs masses and mixings such that LHC would find no Higgs.

New Results (JFG+Ellwanger+Hugonie, hep-ph/0111179) $\Longrightarrow$

An important new mode that allows discovery of many of the 'bad' points of SM96 is $t\bar{t}h \to t\bar{t}b\bar{b}$ (ref: ATLAS (Sapinski) + CMS (Drollinger) analysis for $h_{\rm SM}$).

But, we find new 'bad' points with just this one addition. $\Rightarrow$ include WW fusion modes to remove all bad points (subject to no Higgs pair ... decays).

Our procedure:

The modes employed in 1996 were:

1) $gg \to h \to \gamma\gamma$ at LHC;

2) $Wh, t\bar{t}h \to \ell + \gamma\gamma$ at LHC;

4) $gg \to h, a \to \tau^+\tau^-$ plus $b\bar{b}h, b\bar{b}a \to b\bar{b}\tau^+\tau^-$ at LHC;

5) $gg \to h \to ZZ^*$ or $ZZ \to 4\ell$ at LHC;

6) $gg \to h \to WW^*$ or $WW \to 2\ell 2\nu$ at LHC;

7) $Z^\star \to Zh$ and $Z^\star \to ha$ at LEP2;

To these we add:

3) $gg \to t\bar{t}h \to t\bar{t}b\bar{b}$; (JFG+ ..., Sapinski, ...)

8) $WW \to h \to \tau^+\tau^-$; (Zeppenfeld+...)

9) $WW \to h \to WW^{(*)}$. (Zeppenfeld+...)

We avoided regions of parameter space:

Where the highly model-dependent decays a) $h \to aa$; b) $h \to h'h'$; c) $h \to H^+H^-$; d) $h \to aZ$; e) $h \to H^+W^-$; f) $a \to ha'$; g) $a \to Zh$; h) $a \to H^+W^-$; are present, and where i) $a, h \to t\bar{t}$ j) $t \to H^{\pm}b$ decays are possible.

Parameter space:

λ, κ, μ, $\tan\beta$, A_λ, A_κ with RGE and perturbativity constraints.

Comments:

- The most difficult points for LHC found are typified by 'point 6' (in later tables): WW fusion modes are essential to claim it can be discovered.

  It has parameters: $\lambda = 0.0230$, $\kappa = 0.0114$, $\tan\beta = -6$, $\mu_{\rm eff}(GeV) = 150$, $A_\lambda(GeV) = -100$, $A_\kappa(GeV) = -110$.

  Scalar masses and couplings/br's/rates relative to SM:

  – h_1
    $m_{h_1} = 112$ GeV, with $c_V = -0.71$, $c_t = -0.66$, $c_b = -2.4$, gg Production Rate = 0.36, $B\gamma\gamma = 0.11$, $Bb\bar{b} = B\tau\bar{\tau} = 1.15$, $BWW^{(*)} = 0.10$.

  – h_2
    $m_{h_2} = 122$ GeV, $c_V = +0.59$, $c_t = +0.54$, $c_b = +2.24$, gg Production Rate = 0.23, $B\gamma\gamma = 0.10$, $Bb\bar{b} = B\tau\bar{\tau} = 1.31$, $BWW^{(*)} = 0.09$.

- h_3
  $m_{h_3} = 155$ GeV, $c_V = -0.39$, $c_t = -0.55$, $c_b = 5.12$, gg Production Rate = 0.80, $B\gamma\gamma = 0.03$, $Bb\bar{b} = B\tau\bar{\tau} = 8.12$, $BWW^{(*)} = 0.05$.
- a_1
  $m_{a_1} = 145$ GeV, $c_t = -0.16$, $c_b = -5.77$, gg Production Rate = 0.08.
- a_2
  $m_{a_2} = 158$ GeV, $c_t = -0.05$, $c_b = -1.65$, gg Production Rate = 0.00.
- $H^\pm$
  $m_{H^\pm} = 167$ GeV.

Rates are made more marginal because:

- All WW, ZZ coupling shared among the $h_i \Rightarrow$ demotes decays and production using this coupling.
  In particular, it is easy to make $\gamma\gamma$ coupling and decays small — reduced W loop cancels strongly against t, b loops.
- $\tan\beta$ not very large $\Rightarrow$ well inside 'LHC wedge' for all Higgs bosons.
- Need full $L = 300\text{fb}^{-1}$ for ATLAS and CMS to achieve the following.

Table 3

Summary for all Higgs bosons. The entries are: maximum non-WW fusion LHC N_{SD}; maximum LHC WW fusion N_{SD}; best combined N_{SD} after summing over all non-WW-fusion LHC channels; and best combined N_{SD} after summing over all LHC channels. The Higgs boson for which these best values are achieved is indicated in the parenthesis.
One should refer to the following tables in order to find which channel(s) give the best '1-mode' N_{SD} values.

Point Number	1	2	3
Best 1-mode LHC non-WW fusion N_{SD}	4.37 (h_1)	3.95 (h_2)	3.62 (h_3)
Best 1-mode LHC WW fusion N_{SD}	15.39 (h_2)	15.17 (h_2)	13.46 (h_2)
Best combined N_{SD} w.o. WW-fusion modes	6.54 (h_1)	5.05 (h_2)	4.76 (h_2)
Best combined N_{SD} with WW-fusion modes	17.65 (h_2)	16.00 (h_2)	14.28 (h_2)
Point Number	4	5	6
Best 1-mode LHC non-WW fusion N_{SD}	4.46 (h_3)	4.83 (h_1)	4.86 (h_3)
Best 1-mode LHC WW fusion N_{SD}	15.05 (h_2)	16.78 (h_1)	10.08 (h_1)
Best combined N_{SD} w.o. WW-fusion modes	6.31 (h_2)	6.69 (h_1)	5.37 (h_3)
Best combined N_{SD} with WW-fusion modes	17.40 (h_2)	18.07 (h_1)	10.73 (h_1)

Point	1	2	3	4	5	6
Channel			h_1 Higgs boson			
$N_{SD}(1)$	3.74	0.35	0.13	3.18	0.62	0.83
$N_{SD}(2)$	4.37	0.59	0.22	3.92	0.85	1.22
$N_{SD}(3)$	2.79	0.85	0.85	3.03	4.83	3.30
$N_{SD}(4)$	0.08	0.07	0.76	0.09	4.52	0.40
$N_{SD}(5)$	0.83	0.00	0.00	0.64	0.12	0.16
$N_{SD}(6)$	1.10	0.09	0.03	0.90	0.16	0.22
$N_{SD}(7)$	0.00	3.37	3.40	3.29	0.00	4.79
$N_{SD}(8)$	9.29	1.22	1.59	8.93	16.78	10.08
$N_{SD}(9)$	2.39	0.00	0.00	1.74	0.41	0.49
$\sqrt{\sum_{i=1}^{6}[N_{SD}(i)]^2}$	6.54	1.09	1.17	5.99	6.69	3.65
$\sqrt{\sum_{i=1}^{7}[N_{SD}(i)]^2}$	6.54	3.55	3.59	6.84	6.69	6.02
$\sqrt{\sum_{i=1-6,8,9}[N_{SD}(i)]^2}$	11.61	1.64	1.97	10.89	18.07	10.73
$\sqrt{\sum_{i=1}^{9}[N_{SD}(i)]^2}$	11.61	3.75	3.93	11.38	18.07	11.75

Point	1	2	3	4	5	6
Channel	h_2 Higgs boson					
$N_{SD}(1)$	3.69	0.83	0.61	3.62	0.22	0.55
$N_{SD}(2)$	4.01	1.25	0.92	3.93	0.05	0.74
$N_{SD}(3)$	2.49	3.95	3.58	2.30	0.99	1.77
$N_{SD}(4)$	0.16	2.76	2.93	0.16	3.62	2.99
$N_{SD}(5)$	1.84	0.16	0.11	1.94	0.56	0.20
$N_{SD}(6)$	1.44	0.22	0.16	1.46	0.38	0.18
$N_{SD}(7)$	0.00	0.00	3.31	0.00	0.00	0.00
$N_{SD}(8)$	15.39	15.17	13.46	15.05	7.41	9.89
$N_{SD}(9)$	5.79	0.63	0.44	6.05	0.19	0.82
$\sqrt{\sum_{i=1}^{6}[N_{SD}(i)]^2}$	6.44	5.05	4.76	6.31	3.82	3.61
$\sqrt{\sum_{i=1}^{7}[N_{SD}(i)]^2}$	6.44	5.05	5.80	6.31	3.82	3.61
$\sqrt{\sum_{i=1-6,8,9}[N_{SD}(i)]^2}$	17.65	16.00	14.28	17.40	8.34	10.56
$\sqrt{\sum_{i=1}^{9}[N_{SD}(i)]^2}$	17.65	16.00	14.66	17.40	8.34	10.56

Point	1	2	3	4	5	6
Channel	h_3 Higgs boson					
$N_{SD}(1)$	0.00	0.59	0.66	0.01	0.00	0.32
$N_{SD}(2)$	0.00	0.21	0.25	0.00	0.00	0.08
$N_{SD}(3)$	0.00	0.00	1.13	0.00	0.00	0.00
$N_{SD}(4)$	3.79	3.43	3.62	3.56	1.55	4.86
$N_{SD}(5)$	3.65	2.51	2.07	4.46	1.54	1.66
$N_{SD}(6)$	0.80	2.13	1.52	1.17	0.38	1.55
$N_{SD}(7)$	0.00	0.00	0.00	0.00	0.00	0.00
$N_{SD}(8)$	0.00	0.00	9.06	0.00	0.00	0.00
$N_{SD}(9)$	0.00	0.77	0.79	0.00	0.00	0.43
$\sqrt{\sum_{i=1}^{6}[N_{SD}(i)]^2}$	5.32	4.80	4.64	5.83	4.76	5.37
$\sqrt{\sum_{i=1}^{7}[N_{SD}(i)]^2}$	5.32	4.80	4.64	5.83	4.76	5.37
$\sqrt{\sum_{i=1-6,8,9}[N_{SD}(i)]^2}$	5.32	4.86	10.21	5.83	4.76	5.39
$\sqrt{\sum_{i=1}^{9}[N_{SD}(i)]^2}$	5.32	4.86	10.21	5.83	4.76	5.39

Are the WW fusion with $\tau^+\tau^-$ decay modes really so strong?
(Did they include $t\bar{t}$ backgrounds?)

- **Unfortunately,** if we enter into parameter regions where the $h_i \rightarrow a_j a_j$, $a_j \rightarrow Z h_k$, ... decays are allowed, these decays can be very strong and all the previous modes 1)-9) will not be useful.

  $\Rightarrow$ much more work to do on how to detect Higgs bosons in Higgs pair or Z+Higgs decay modes at the LHC.

  - The LHC collaborations studied the MSSM modes
    - $gg \rightarrow H^0 \rightarrow h^0 h^0$;
    - $gg \rightarrow A^0 \rightarrow Z h^0$.

    But final states employed (e.g. requiring $h^0 \rightarrow \gamma\gamma$) are not relevant here.
  - Dai+Vega+JFG (Phys.Lett.B371:71-77,1996 e-Print Archive: hep-ph/9511319) studied the $H^0 \rightarrow A^0 A^0 \rightarrow 4b$ final state at the partonic level in the MSSM.

    With 3 or 4 b tagging, reconstructing the double A^0 mass peak, and reconstructing the H^0 mass peak, there was some real hope.

This has not yet been repeated by LHC experimentalists.

K factors were not included.

The results also need to be translated into the NMSSM context.

– The $WW \to h_i \to a_j a_j, h_k h_k$ modes could also prove extremely valuable, but have not yet been simulated.

– Clearly, detection of a single isolated a_i or weakly-VV-coupled h_j would help put us on the right track.

CP DETERMINATIONS

Vital for sorting out a complex Higgs sector.

- At LC there are many techniques based on WW and/or ZZ couplings for verifying a substantial CP=+ component.

  But such couplings only sensitive to CP=$-$ component at loop level in Higgs models. $\Rightarrow$ very hard to see CP=$-$ coupling even if there.

- Since CP=+ and CP=$-$ couplings to $t\bar{t}$ of any h are both tree-level ($\bar{t}(a+ib\gamma_5)t$), $t\bar{t}h$ angular distributions allow CP determination for lighter h's. Use optimal observables.

  – At the LC, as long as there is reasonable event rate ($\sqrt{s} > 800~\mathrm{GeV}$), this is straightforward. (JFG, Grzadkowski, He), (carried on by TESLA TDR, Reina,Dawson, ...).

– **At the LHC, there will be a high event rate, but reconstruction of t and $\bar{t}$ (identification required) is trickier and backgrounds will be larger. Still, there is considerable promise.** (JFG, He; JFG, Pliszka, Sapinski).

LHC experimentalists must convince themselves they can do this.

- **CP=+ and CP=$-$ components also couple with similar** $magnitude$ **but different structure to $\gamma\gamma$ (via 1-loop diagrams),**

At the LC, $\Rightarrow$ use $\gamma\gamma$ collisions. (JFG, Grzadkowski; JFG, Kelly; Djouadi etal, ..)

$$\mathcal{A}_{CP=+} \propto \vec{\epsilon}_1 \cdot \vec{\epsilon}_2\,, \quad \mathcal{A}_{CP=-} \propto (\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot \hat{p}_{\rm beam}\,. \tag{2}$$

– **For pure CP states, maximize linear polarization and adjust orientation ($\perp$ for CP odd dominance, $\parallel$ for CP even**

dominance) to determine CP nature of any Higgs by using appropriate linearly polarized laser photons..
In particular, can separate A^0 from H^0 when these are closely degenerate (as typical for $\tan\beta \gtrsim 4$ and $m_{A^0} > 2m_Z$).

– For mixed CP states, can use circularly polarized photons (better luminosity, reduced background) and employ helicity asymmetries to determine CP mixture.

- At a muon collider Higgs factory could probe CP of s-channel produced h by rotating transverse polarizations of colliding muons relative to one another.
  Must take into account precession, but theoretical study suggests great promise (JFG, Pliszka).

  Excellent determination of b and a is possible if luminosity can be upgraded from SM96.

- $h \to \tau^+\tau^-$ decays are self-analyzing through correlations among decay products of τ's (which differ according to the CP-nature of the h.

  For high rate production (e.g. $e^+e^- \to Zh$ with h ∼CP-even, or $\mu^+\mu^- \to H^0, A^0$ at high $\tan\beta$, ...) theorists (Kramer etal, hep-ph/9404280; JFG+Grzadkowski, hep-ph/9501339) found that a decent CP-determination was possible.

  This should be redone at the experimental level. Would some experimentalist(s) like to work with me/us on this?

Randal-Sundrum Radion and the SM Higgs

Some possibly very dramatic changes in phenomenology.

- **We** (JFG+Dominici+Grzadkowski, in preparation) **consider the usual two-brane (one visible, one hidden) RS 5D warped space scenario.**

- **We include the effects of the possible mixing term:**

$$S_\xi = \xi \int d^4x \sqrt{g_{\rm vis}} R(g_{\rm vis}) H_0^\dagger H_0 \,, \tag{3}$$

where $R(g_{\rm vis})$ is the Ricci scalar for the metric induced on the visible brane. One writes $g_{\rm vis}^{\mu\nu} = \Omega_b(x)(\eta^{\mu\nu} + \epsilon h^{\mu\nu})$ and has

$$\Omega_b(x) = \Omega_0 \Omega(x) \equiv \Omega_0 (1 + \phi/\Lambda_\phi) \tag{4}$$

where ϕ is the radion field and Ω_0 is the usual warp factor that reduces $M_{\rm P}$ to order $1~{\rm TeV}$ on the visible brane.

- One defines $H = \Omega_0 H_0$ and isolates the kinetic energy terms by using the expansion

$$H = \frac{1}{\sqrt{2}}(v + h)\,, \quad \Omega(x) = 1 + \frac{\phi}{\Lambda_\phi}\,. \tag{5}$$

where $\Lambda_\phi \gtrsim \mathcal{O}(1\ \mathrm{TeV})$.

- We then find the following kinetic energy terms:

$$\mathcal{L} = -\tfrac{1}{2}\left\{1 + 6\gamma^2\xi\right\}\phi\Box\phi - \tfrac{1}{2}\phi m_\phi^2\phi - \tfrac{1}{2}h(\Box + m_h^2)h - 6\gamma\xi\phi\Box h\,, \tag{6}$$

where $\gamma \equiv v/\Lambda_\phi \ll 1$ is expected.

- The extra $\phi\Box\phi$ piece proportional to ξ is missed in some papers.

- We define the mixing angle θ by

$$\tan 2\theta \equiv 12\gamma\xi Z \frac{m_h^2}{m_\phi^2 - m_h^2(Z^2 - 36\xi^2\gamma^2)}\,, \tag{7}$$

where

$$Z^2 \equiv 1 + 6\xi\gamma^2(1-6\xi)\,. \tag{8}$$

- In terms of these quantities, we obtain the h_m, ϕ_m states that diagonalize the kinetic energy:

$$\begin{aligned} h &= \left(\cos\theta - \frac{6\xi\gamma}{Z}\sin\theta\right) h_m + \left(\sin\theta + \frac{6\xi\gamma}{Z}\cos\theta\right)\phi_m \\ &\equiv d h_m + c\phi_m \qquad (9) \\ \phi &= -\cos\theta\frac{\phi_m}{Z} + \sin\theta\frac{h_m}{Z} \equiv a\phi_m + b h_m\,. \qquad (10) \end{aligned}$$

- The corresponding mass-squared eigenvalues are

$$m^2_{h_m,\phi_m} = \frac{1}{2Z^2}\Big(m^2_\phi + (1+6\xi\gamma^2)m^2_h \pm \Big\{[m^2_\phi - m^2_h(1+6\xi\gamma^2)]^2 + 144\gamma^2\xi^2 m^2_\phi m^2_h\Big\}^{1/2}\Big) \quad (11)$$

For small γ, $m^2_{h_m} \sim m^2_h$ and $m^2_{\phi_m} \sim m^2_\phi$ unless $m_h \sim m_\phi$.

- We will want the triple boson (e.g. hhh) interactions, that come from:

a) the ξ independent part of $\mathcal{L}$ for the radion

$$-\frac{\phi}{\Lambda_\phi} T^\mu_\mu(h)\,, \quad (12)$$

b) and that for the KK-gravitons

$$\epsilon h_{\mu\nu}T^{\mu\nu} = \frac{2}{\widehat{\Lambda}_W}\sum_n h^n_{\mu\nu}\partial^\mu h \partial^\nu h\,, \tag{13}$$

c) tri-linear stuff from ξ mixing term.

- $\widehat{\Lambda}_W$ and Λ_ϕ are both expected to be of order > 1 TeV.

Couplings

- Relative to $g m_Z/c_W$, the ZZh_m and $ZZ\phi_m$ vertices are

$$g_{ZZh_m} = d + \gamma b \sim 1 + \mathcal{O}(\gamma^2) \tag{14}$$

$$g_{ZZ\phi_m} = c + \gamma a \sim -\gamma\left(1 + \frac{6\xi m_\phi^2}{m_h^2 - m_\phi^2}\right) + \mathcal{O}(\gamma^3) \tag{15}$$

There is no $Zh_m\phi_m$ tree level coupling.

$m_h \neq m_\phi \Rightarrow$ small $\gamma \Rightarrow$ small $g_{ZZ\phi_m}$.

- One finds

$$g^2_{ZZh_m} + g^2_{ZZ\phi_m} = 1 + \frac{\gamma^2(1-6\xi)^2}{Z^2} \equiv R^2 \,. \qquad (16)$$

- $Z \to 0$ yields nonsense and so we have the restriction

$$\frac{1}{12}\left(1 - \sqrt{1+\frac{4}{\gamma^2}}\right) \leq \xi \leq \frac{1}{12}\left(1 + \sqrt{1+\frac{4}{\gamma^2}}\right) \qquad (17)$$

- For Yukawa couplings (relative to $-gm_f/(2m_W)$,

$$g^2_{f\bar{f}h_m} + g^2_{f\bar{f}\phi_m} = 1 + \frac{\gamma^2(2-3\xi)^2}{Z^2} \qquad (18)$$

where the Yukawa couplings for the mass eigenstates are:

$$g_{f\bar{f}h_m} = d + \gamma b\,, \quad g_{f\bar{f}\phi_m} = -c + \gamma a\,. \tag{19}$$

Note: $d + \gamma b$ is same factor for WW and $f\bar{f}$ coupling of h_m, relative to SM.

From here on, we drop the subscript m notation; the h and ϕ will denote the mass eigenstates.

LEP Constraints from the sum rule

- Choose $\Lambda_\phi = 1000~\mathrm{GeV}$. The constraint $\Rightarrow -0.60 \leq \xi \leq 0.77$. Perturbativity requires $|\xi| \leq 0.4$

  $R^2 = 1.15(2.38)$ for $\xi = 0.4$ (-0.4).

- LEP provides an upper limit on ZZs ($s = h$ or ϕ) from which we can exclude regions in the (m_h, m_ϕ) plane for a given choice of R^2.

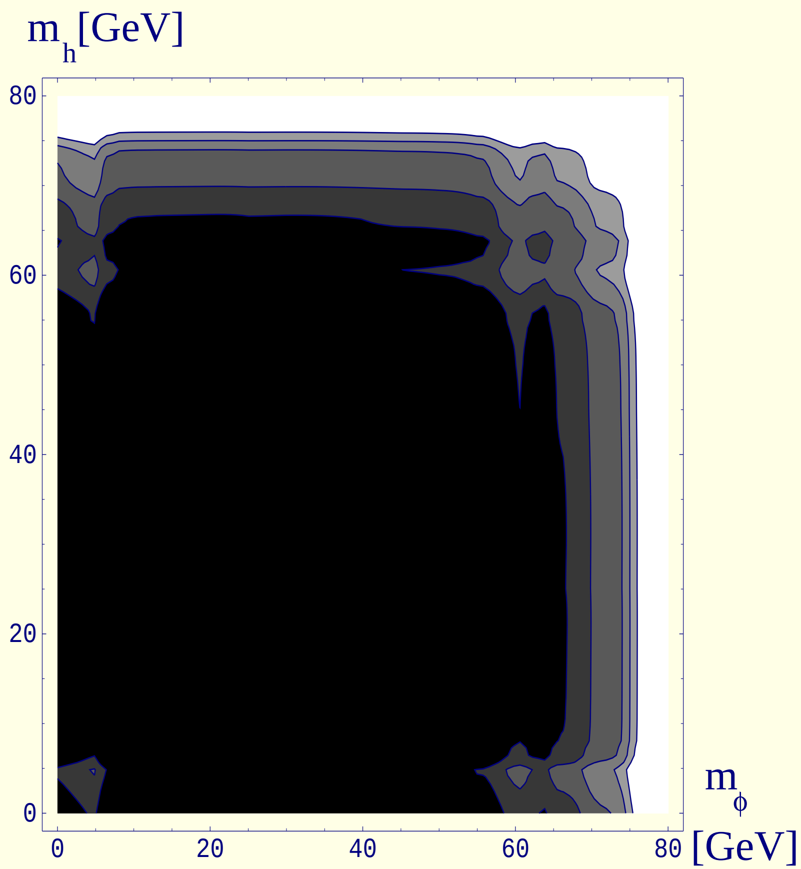
$R^2 > 1 \Rightarrow$ stronger constraints than for analogous 2HDM case.

Use upper limits on the ZZs coupling in absence of b tagging. (Decays can be altered, so b tagging might not be appropriate.)

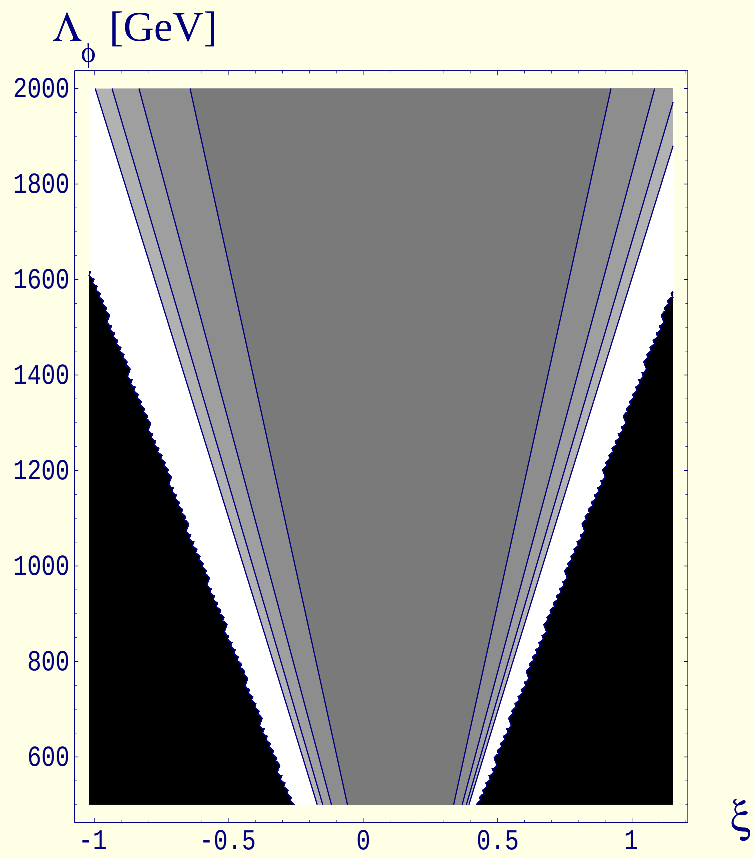
- **Conclusion:**

  Small m_ϕ relative to m_h is entirely possible given current data so long as $m_h \gtrsim 80~\mathrm{GeV}$. (The $ZZ\phi$ coupling does not blow up.)

  There is also ample theoretical argument to suggest that m_ϕ could be substantially smaller than m_h



The region in (m_h, m_ϕ) excluded by the LEP data for $R^2 = 1.0, 1.5, 2.0, 2.5, 3.0$; the lighter shadowing corresponds to increasing values of R^2.



Contour plots for constant $R^2 = 1.0, 1.5, 2.0, 2.5, 3.0$ as used in LH window, in (ξ, Λ_ϕ) space. The regions with higher R^2 are lighter.

Decays of the Higgs to one or two radions

- This requires the full development of the $\phi\phi h$ and $h^n_{\mu\nu}\phi h$ interaction terms.

- For small ξ one finds these couplings are of order v^2/Λ_ϕ^2 or $v^2/(\Lambda_\phi\widehat{\Lambda}_W)$.

- To exemplify, we can expand in powers of $\gamma = v/\Lambda_\phi$ to find:

$$g_{n\phi h} = -12\gamma\xi\left(3 - \frac{2}{1-r_\phi}\right) + \mathcal{O}(\gamma^3)\,. \qquad (20)$$

and

$$g_{\phi\phi h} = \frac{12\gamma\xi r_\phi}{1-r_\phi}(-2 - r_\phi + 6r_\phi\xi) + \mathcal{O}(\gamma^3)\,. \qquad (21)$$

- **Partial widths.**

$$\Gamma(h \to h^n \phi) = \frac{g^2_{n\phi h}}{384\pi} \frac{m_h^3}{\widehat{\Lambda}_W^2} \frac{\lambda^{5/2}(1, r_\phi, r_n)}{r_n^2}\,, \qquad (22)$$

and

$$\Gamma(h \to \phi\phi) = \frac{g^2_{\phi\phi h}}{32\pi} \frac{m_h^3}{\Lambda_\phi^2} (1 - 4r_\phi)^{1/2}\,, \qquad (23)$$

where $\lambda(1, r_1, r_2) \equiv 1 + r_1^2 + r_2^2 - 2r_1 - 2r_2 - 2r_1 r_2$**,** $r_\phi = m_\phi^2/m_h^2$ **and** $r_n = m_n^2/m_h^2$**.**

- **Notice that** $\Gamma(h \to h^n \phi) \sim m_h^3/r_n^2 \sim m_h^7/m_n^4$**. Thus, one could expect relevant modifications of the SM Higgs-boson branching ratio for large** m_h**.**

- **For** h **branching ratios we use the total width**

$$\Gamma(h \to all) \;=\; (d + \gamma b)^2 \Gamma_{SM}(h \to all)$$

$$+\Gamma(h \to h^n \phi) + \Gamma(h \to \phi\phi)\,, \quad (24)$$

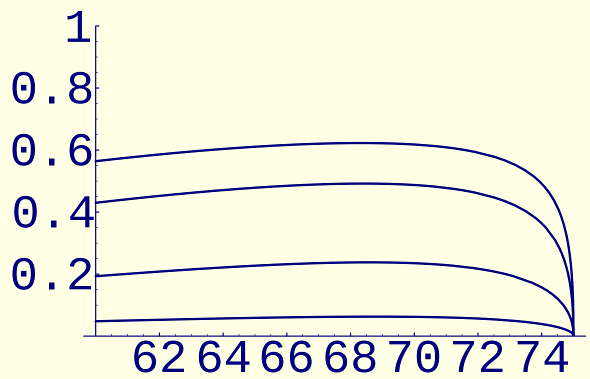
where $\Gamma_{SM}(h \to all)$ is the SM total width.

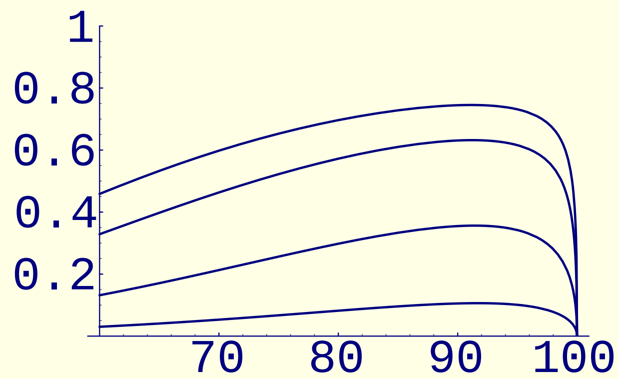
Results

- Let us take $\Lambda_\phi = \widehat{\Lambda}_W = 1~\mathrm{TeV}$ (which gives $\gamma \sim 0.27$) and adopt parameters such that the h^n excitations are too heavy to contribute.

  For this γ, LEP limits for $Z\phi$ production are strong until $m_\phi \geq 60~\mathrm{GeV}$ or so. $\Rightarrow$ restrict to $m_h \geq 120~\mathrm{GeV}$; we consider $m_h = 150$ and $200~\mathrm{GeV}$.

  Higher $\Lambda_\phi \Rightarrow$ smaller γ and eventually no LEP limit is present.





The branching ratio for $h \rightarrow \phi\phi$ for $m_h = 150$ GeV and $m_h = 200$ GeV as a function of m_ϕ

for $\xi = .35, .30, .20$ and .10, with highest ξ giving highest BR.

CONCLUSIONS

- **The Higgs sector may prove challenging to fully explore.**
- **The variety of models, complications due to invisible decays (e.g. SUSY), CP violation, etc. make attention to multi-channel analysis vital.**
- **Higgs physics will almost surely be impacted by extra dimensions and might be very revealing in this regard.**
- **There is enough freedom in the Higgs sector that we should not take Higgs discovery at the Tevatron or LHC for granted.**

  $\Rightarrow$ **keep improving and working on every possible signature.**

  $\Rightarrow$ **LHC ability to show that WW sector is perturbative could be important.**

- The precision electroweak data does not guarantee that a $\sqrt{s} = 600~\mathrm{GeV}$ machine will find some Higgs signal in most general model.

  But, the scenarios of this type constructed so far always have a SM-like Higgs that will be found by the LHC.

- Exotic Higgs representations, e.g. triplet as motivated by seesaw approach to neutrino masses, will lead to exotic collider signals and possibilities.

- Direct CP determination will probably prove to be vital to disentangling any but the simplest SM Higgs sector.

- **We are still not able to show that at least one of the Higgs bosons of the very attractive NMSSM model must be discovered at the LHC. But, progress is being made and it is quite clear as to the additional modes that must be examined/developed in order to reach a no-lose theorem.**

- **The ability to directly detect and study a CP-odd Higgs boson with light to moderate mass would be of substantial importance in a variety of different model contexts.**