Extended Higgs Sectors

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Thanks to all my collaborators.

Outline

- Do we need SUSY?
  - Coupling unification without SUSY.
  - ‘Solving’ the hierarchy problem without SUSY: the RS model.
- How well can we explore the MSSM Higgs sector?
  - Covering the SUSY wedge with $\gamma\gamma$ collisions.
  - Using the Higgs Sector to determine $\tan\beta$.
- The NMSSM
- Still more singlets?
- Left-right supersymmetric models

Do we need SUSY?

- Coupling unification can be achieved without SUSY by introducing additional Higgs representations in the standard model.
  - $\rho = 1$ suggests that representations other than $T = 1/2, |Y| = 1$ should have zero vev for the neutral field member (if there is one).
  - Some simple choices are ($N_{T,Y}$ = number of reps. of given type):

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

Find lower M_U than comfortable for proton decay: must fix by not having true group unification, as in some string models, or ...

Very low M_U (to get coupling unification in large-scale extra-dimension models) requires very complicated Higgs sectors, but is possible.

Phenomenological consequences of expanded SM Higgs sector

– **Multi-doublet models are a strong possibility for coupling unification and as effective low-energy theory in many models.**

This can lead to greater freedom in how precision electroweak constraints are satisfied (Chankowski+JFG etal, hep-ph/0009271). For example, consider:

* **Heavy $h_{\rm SM}$-like Higgs $\Rightarrow$ large $\Delta S > 0$ and large $\Delta T < 0$.**
* **Compensate by large $\Delta T > 0$ from small mass non-degeneracy (weak isospin breaking) of heavier Higgs. Light A^0 + heavy SM-like $h^0 \Rightarrow$**

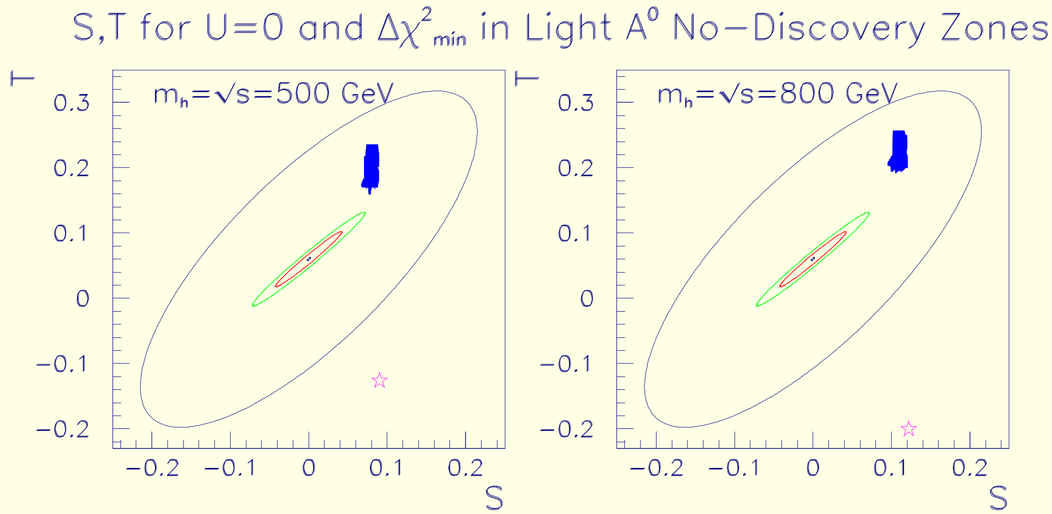
$$\Delta\rho = \frac{\alpha}{16\pi m_W^2 c_W^2}\left\{\frac{c_W^2}{s_W^2}\frac{m_{H^\pm}^2 - m_{H^0}^2}{2} - 3m_W^2\left[\log\frac{m_{h^0}^2}{m_W^2} + \frac{1}{6} + \frac{1}{s_W^2}\log\frac{m_W^2}{m_Z^2}\right]\right\} \tag{1}$$

Can adjust $m_{H^\pm} - m_{H^0} \sim \mathrm{few~GeV}$ (both heavy) so that the S,T prediction is OK.

* **Heavy h^0 ($m_{h^0} \lesssim 1~\mathrm{TeV}$) would be seen at LHC, and Z-pole and/or $\sqrt{s} > 1~\mathrm{TeV}$ data at LC would clarify role of other Higgs bosons.**

E.G. choose $\tan\beta$ and m_{A^0} so that A^0 is in Yukawa no-discovery wedge and choose $m_{h^0} > \sqrt{s} =$ 500 GeV or 800 GeV and $m_{H^0}, m_{H^\pm}$ still heavier but adjusted to minimize $\Delta\chi^2$ for precision electroweak data.

$\Rightarrow$ the blue Blobs (for $\tan\beta > 1$).



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 minimum relative $\Delta\chi^2$. 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.

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

– Triplets are a very interesting possibility.

Generic 2×2 notation: $\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$.

* Very attractive are the L-R symmetric and related models (Mohapatra ...):
  - Neutrino masses arise via seesaw from lepton-no.-violating (Majorana-like) coupling of two leptons to a Δ.
  - The L-R arrangement: Δ_R and Δ_L with $\langle \Delta_L^0 \rangle = 0$ (keeps $\rho = 1$ natural) and $\langle \Delta_R^0 \rangle =$large (for large Majorana ν_R mass and large m_{W_R}).
  - L-R symmetry $\Rightarrow$ Majorana lepton-number-violating coupling must be present for both Δ_R and Δ_L.
* More generally, we should simply consider the possibility of a Δ_L. For a $|Y| = 2$ triplet representation (to which we now specialize) the lepton-number-violating coupling Lagrangian is:

$$\mathcal{L}_Y = i h_{ij} \psi_i^T C \tau_2 \Delta \psi_j + \mathrm{h.c.}\,, \quad i,j = e,\mu,\tau\,. \tag{2}$$

$\Rightarrow$ lepton-number-violating $e^- e^- \to \Delta^{--}$ (or $\mu^- \mu^- \to \Delta^{--}$) coupling.

* Write $|h_{\ell\ell}^{\Delta^{--}}|^2 \equiv c_{\ell\ell} m_{\Delta^{--}}^2 (\,\mathrm{GeV})$, strongest limits are $c_{ee} < 10^{-5}$ (Bhabha) and $c_{\mu\mu} < 10^{-6}$ ($(g-2)_\mu$ – triplet gives wrong sign for current deviation).

If $\langle\Delta^0\rangle = 0$ (for $\rho = 1 =$ natural), $\Gamma^T_{\Delta^{--}}$ would be small. $\Rightarrow$ possibly very large s-channel e^-e^- and $\mu^-\mu^-$ production rates.

* **Strategy:**
  - Discover Δ^{--} in $p\overline{p} \to \Delta^{--}\Delta^{++}$ with $\Delta^{--} \to \ell^-\ell^-, \Delta^{++} \to \ell^+\ell^+$ ($\ell = e, \mu, \tau$) at TeV33 (for $m_{\Delta^{--}} \lesssim 350~\mathrm{GeV}$) or LHC (for $m_{\Delta^{--}} \lesssim 900~\mathrm{GeV}$) (JFG, Loomis, Pitts: hep-ph/9610237).
    $\Rightarrow$ TeV33 + LHC will tell us if such a Δ^{--} exists in the mass range accessible to NLC and FMC *and how it decays*.
  - Study in e^-e^- and $\mu^-\mu^-$ s-channel collisions via the allowed Majorana-like bi-lepton coupling.
    Event rates can be enormous (see JFG, hep-ph/9803222 and hep-ph/9510350): equivalently can probe to very small $c_{\ell\ell}$ — *e.g.* $c_{ee} \sim 10^{-16}$ at e^-e^- collider with $L = 300\mathrm{fb}^{-1}$.
    This would cover essentially the entire range of coupling relevant for see-saw mechanism.

- **Can 'solve' hierarchy problem: example – RS two-brane + bulk model**
  - The picture is two branes: one on which we live with TeV scale physics, another with GUT scale physics communicated to us via gravity through "warped" space time.
  - Many fascinating possibilities — in all cases $\Rightarrow$ strong affect on the Higgs sector.

    If all matter (esp. the one Higgs doublet) is on the TeV brane, the most interesting deviations from SM Higgs physics arise if there is mixing of the Higgs doublet with the radion: (JFG+Dominici+Grzadkowski+Toharia: hep-ph/0206141; see also: Giudice etal, hep-ph/0002178; Csaki etal, hep-th/0008151; Chaichian etal, hep-ph/0110035; Han etal, hep-ph/0104074; Hewett and Rizzo, hep-ph/0202155.)

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

    where $R(g_{\rm vis})$=Ricci scalar for the metric induced on the visible brane, $g_{\rm vis}^{\mu\nu} = \Omega_b^2(x)(\eta^{\mu\nu} + \epsilon h^{\mu\nu})$, $\widehat{H}$ is the Higgs field (before rescaling to canonical normalization on the brane) and $\Omega_b(x)$ is basically the radion field (before rescaling).
  - For $\xi \neq 0$, the Higgs and radion mix and one must rediagonalize and rescale to canonically-normalized mass eigenstates h and ϕ.
  - Basic parameters are m_h, m_ϕ, Λ_ϕ (the new physics scale characterizing

the radion interactions) and ξ. Complicated inversion process relates these to bare parameters of Lagrangian that specify couplings.

* Gives possibility of slightly lighter Higgs boson satisfying LEP constraints on g^2_{ZZh}.

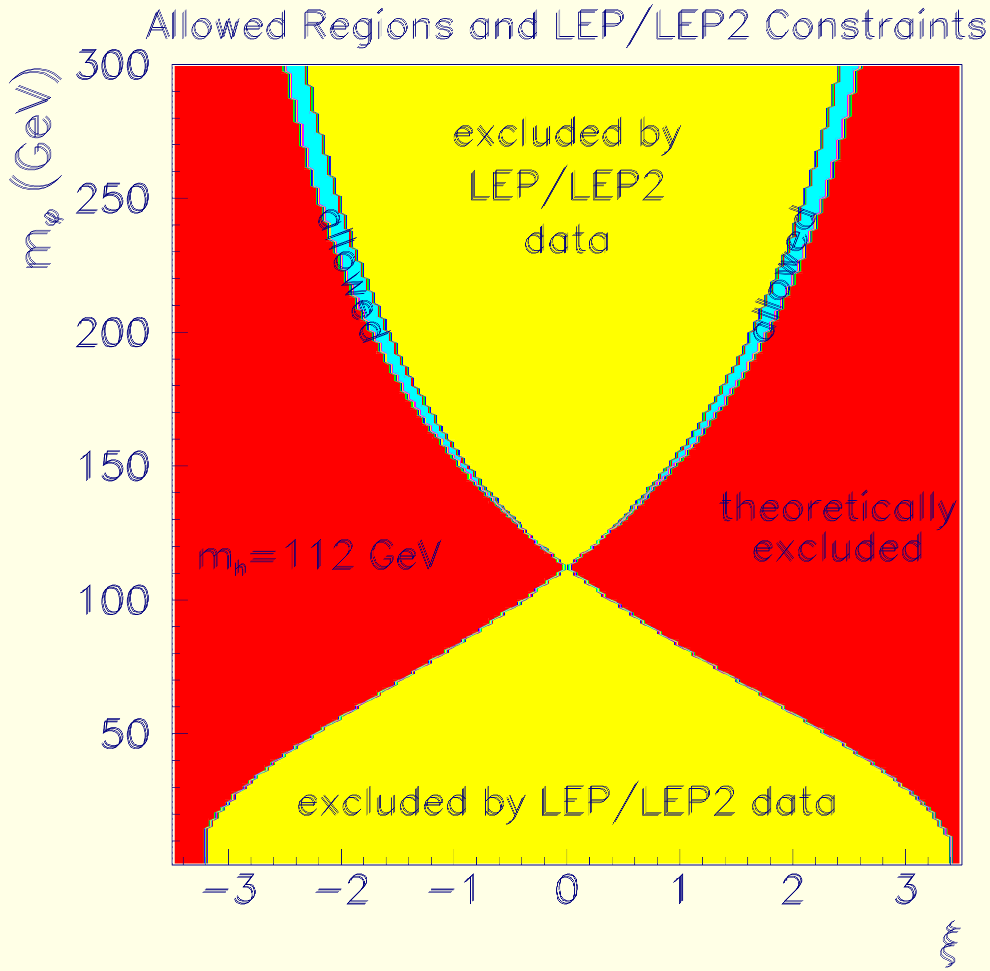
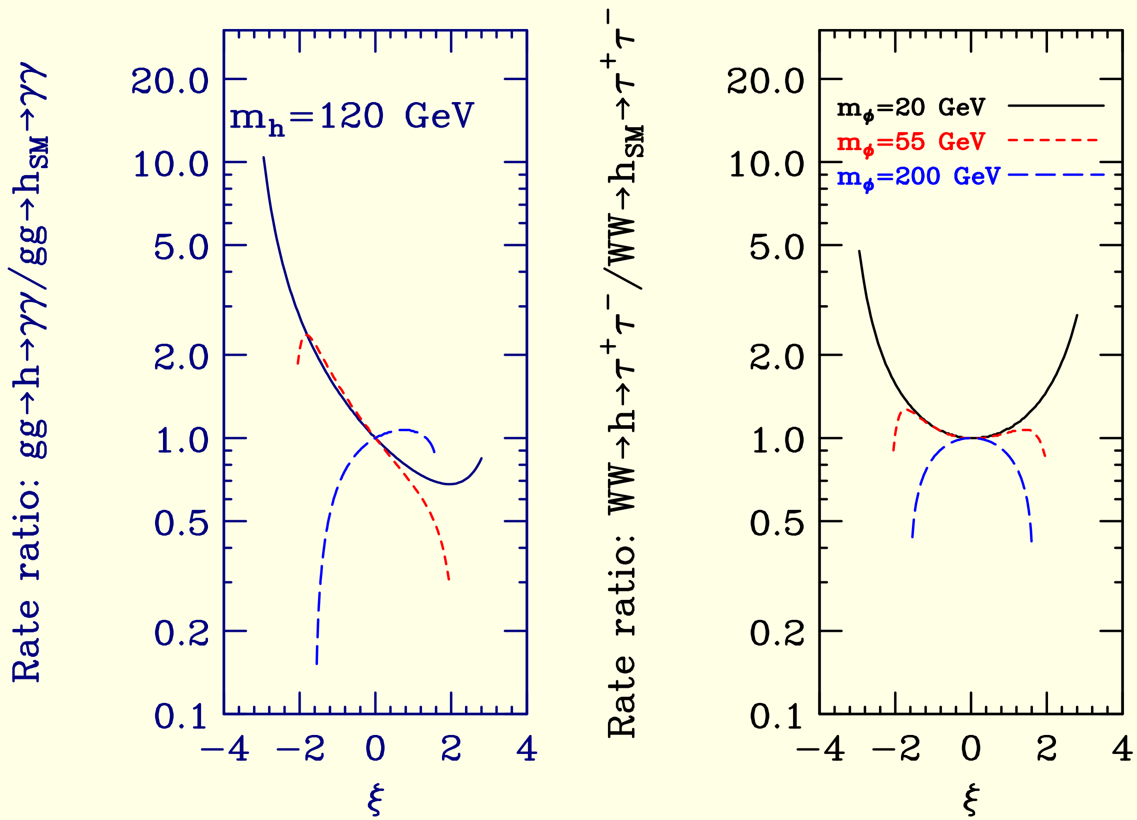


Figure 1: Allowed regions in (ξ, m_ϕ) parameter space for $\Lambda_\phi = 5~\mathrm{TeV}$ and $m_h = 112~\mathrm{GeV}$. Uses LEP/LEP2 constraints on ϕ and h.

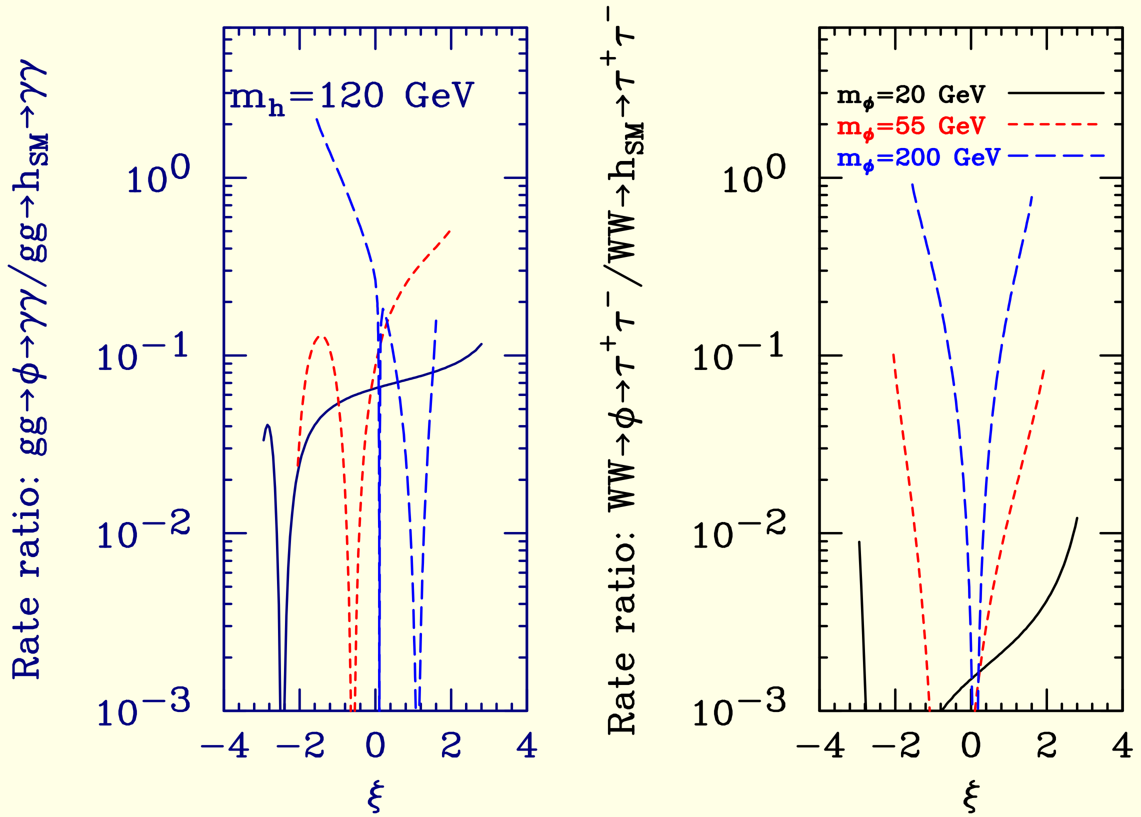
Where $g_{ZZ\phi}$ is big, some portions of $m_h = 120$ GeV parameter space are also excluded by LEP/LEP2.

* There are significant (order factor $2 \div 5$) affects on h discovery modes, both at the LHC and at the LC.



Precision h measurements will pin down parameters of model.

* Search for the physical radion is very challenging at the LHC, unless $h \to \phi\phi$ is big (which is quite possible) and $4b$ and $2b2g$ final states from $\phi\phi$ could be accessed.



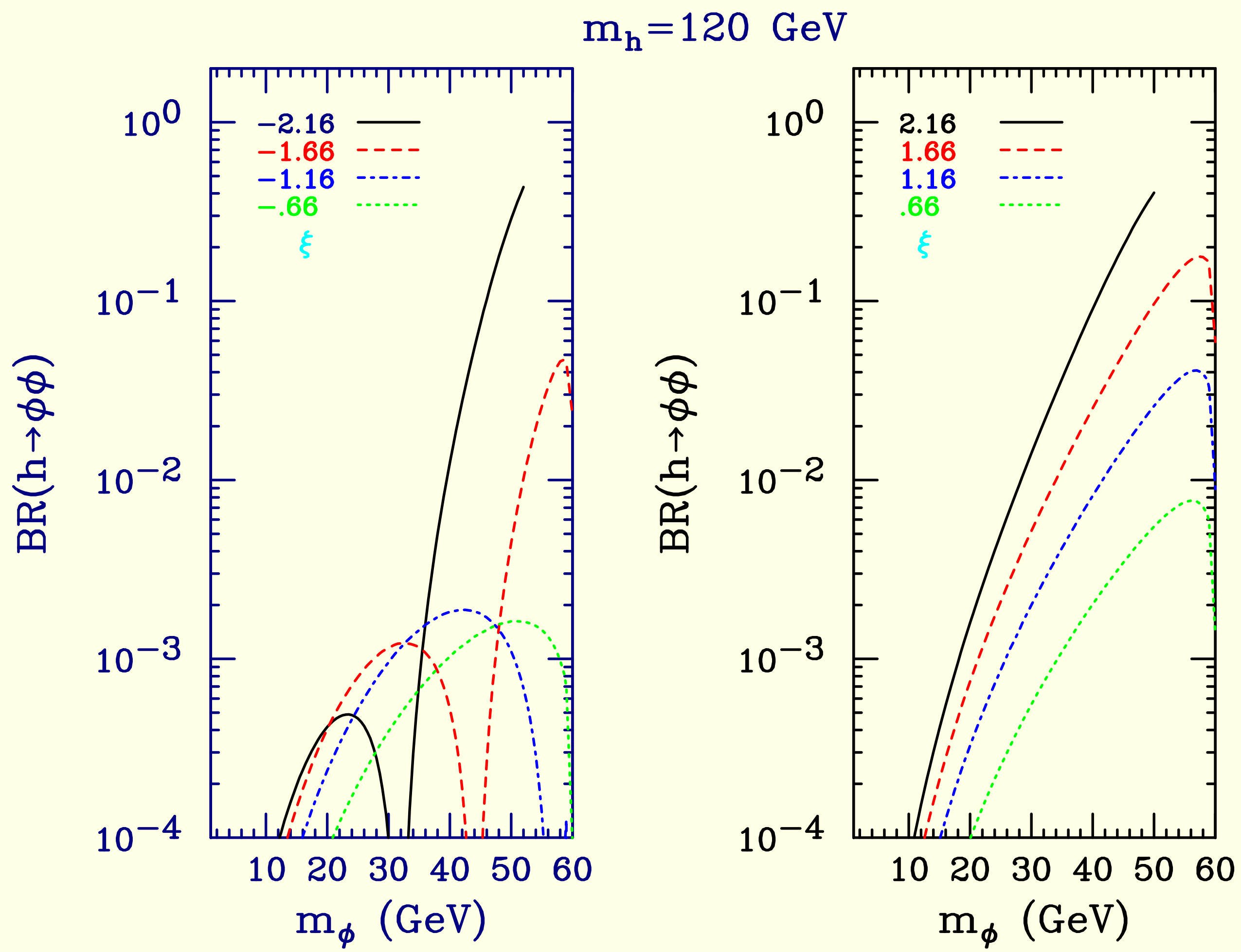


Figure 2: The branching ratio for $h \rightarrow \phi\phi$ for $m_h = 120$ GeV and $\Lambda_\phi = 5$ TeV as a function of m_ϕ for $\xi = -2.16$, -1.66, -1.16 and -0.66 (left-hand graphs) and for $\xi = 0.66$, 1.16, 1.66, and 2.16 (right-hand graphs).

$h \rightarrow \phi\phi$ can be 50% if $\Lambda_\phi = 1$ TeV, but $\Lambda_\phi = 1$ TeV is possibly excluded by Run I Tevatron data when curvature of brane is required to be small.

* Even though $g^2_{ZZ\phi} \sim 0.001$ is possible, LC with $L = 500\mathrm{fb}^{-1}$ will have

no problem seeing $e^+e^- \to Z\phi \Rightarrow$ complementarity.

– Downsides of RS model:

  * New hierarchy/fine-tuning problem of adjusting cosmological constants on the branes and in the bulk to have exactly the right relationships. Is there a more fundamental source for these relationships.
  * Coupling unification at low scale requires a complicated Higgs sector, or ... Much more work here is needed.

    Coupling unification *as if* run down from the 4-d Planck scale requires matter off the brane (Randall and Schwartz, hep-th/0108115, Agashe etal, hep-ph/0206099).

Summary

It requires a rather complicated and ad hoc extension of the SM Higgs sector in combination with some TeV-scale extra dimension ingredients (or warping equivalent) to simultaneously get coupling unification and a solution to the hierarchy problem.

$\Rightarrow$ "Surely" the SUSY approach is the better way to go.

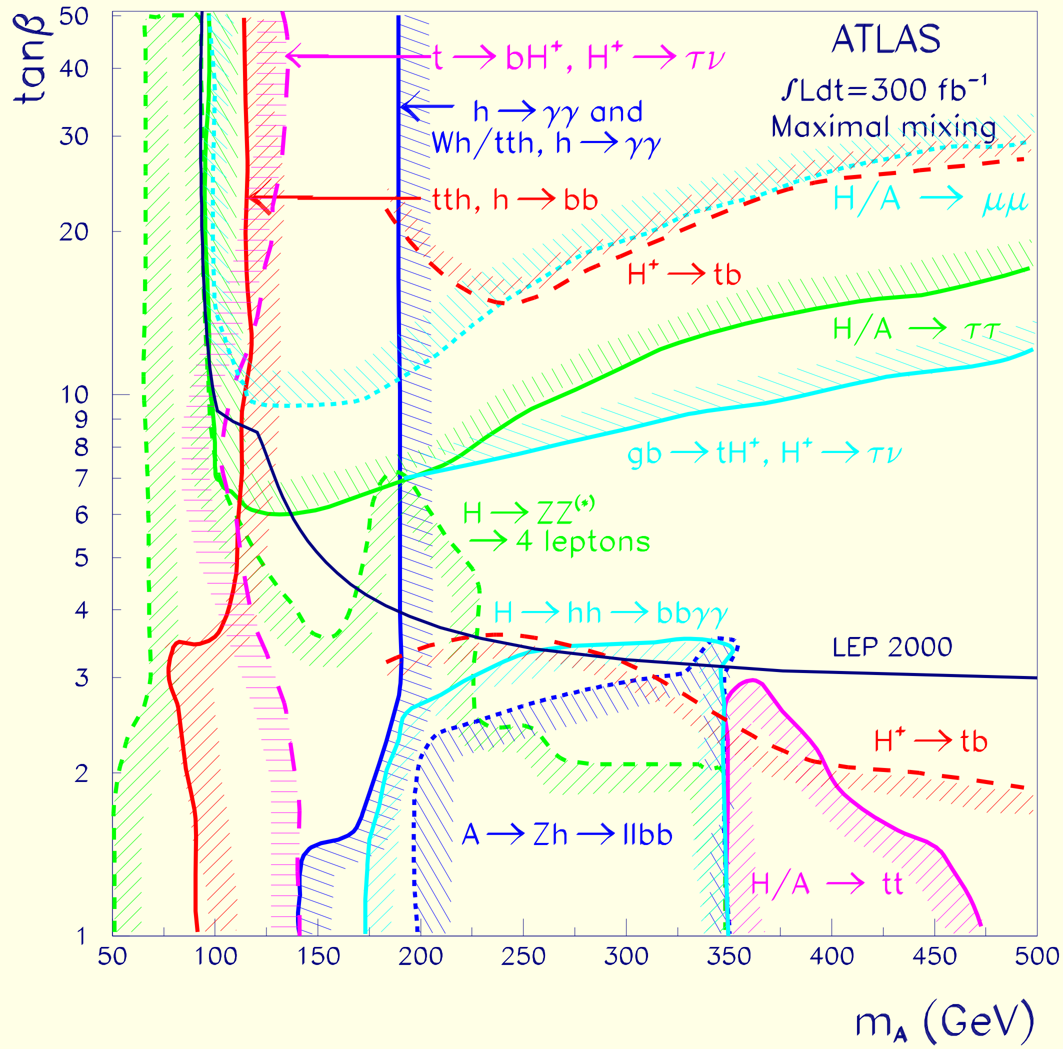
How well can we explore the MSSM Higgs sector

⇒ 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 $e^+e^- \to b\bar{b}A^0, b\bar{b}H^0, btH^\pm$.**

- **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.**

- **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 $\gamma\gamma$ collider will be needed for $\gamma\gamma \to H^0 + \gamma\gamma \to A^0$.**

  (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 ~ 50 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 $\sqrt{s}$, *e.g.* $\sqrt{s} = 630$ GeV and two different electron helicity / laser-photon polarization configurations.

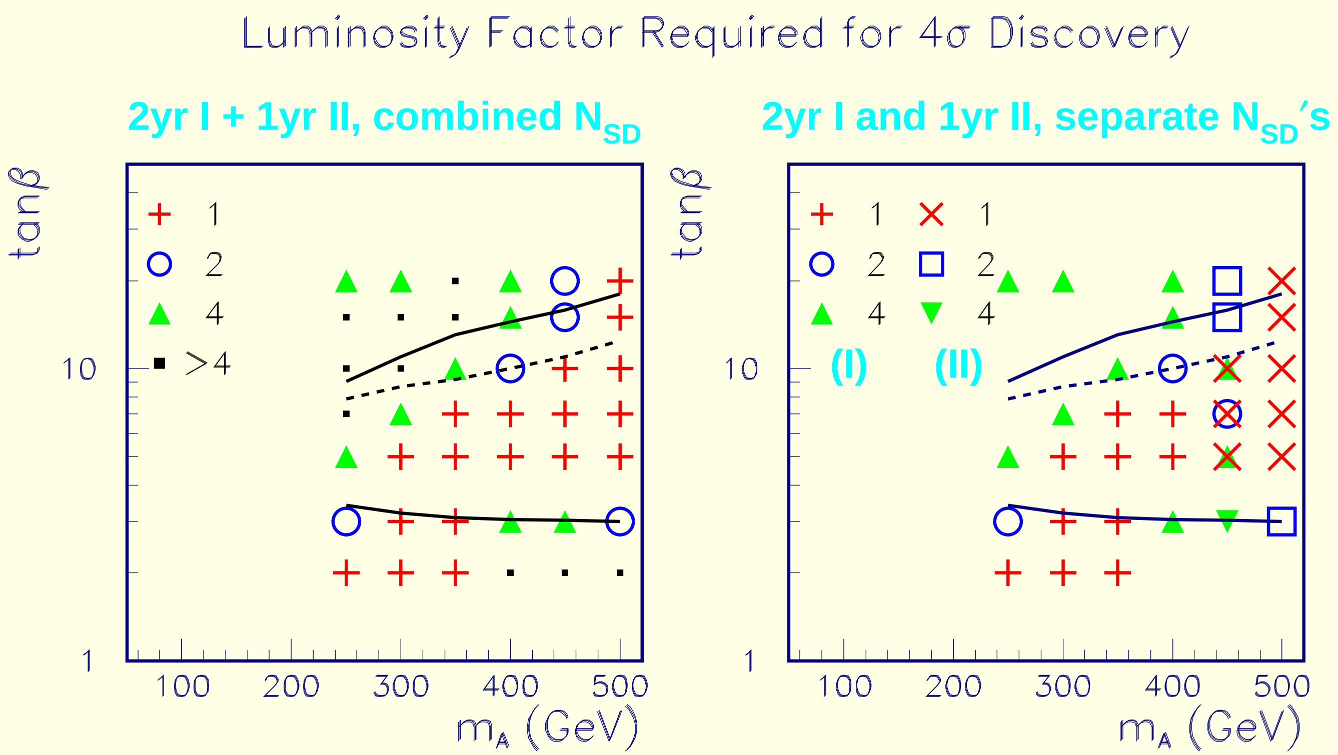
  Type-II $\Rightarrow$ peaked $E_{\gamma\gamma}$ spectrum for highest masses — good for $m_{A^0} \sim m_{H^0} \in [450, 500]$ GeV.

  Type-I $\Rightarrow$ broader $E_{\gamma\gamma}$ spectrum with ability to probe a range of lower masses, $m_{A^0} \sim m_{H^0} \in [300, 450]$ GeV.

  Where good, both spectra types have substantial $\langle\lambda\lambda'\rangle$ of back-scattered photons, as needed to suppress $\gamma\gamma \to b\bar{b}$ background.

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 $m_{A^0} \sim 300~\mathrm{GeV}$. Most of remainder is covered by $\gamma\gamma$! Extra TESLA luminosity would be helpful to ensure coverage.

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 $t\bar{t}H^0, t\bar{t}A^0 \propto \cot\beta$ and $b\bar{b}H^0, b\bar{b}A^0 \propto \tan\beta$.

- Simple observables sensitive to these couplings at a Linear Collider are:

1. The rate for $e^+e^- \to b\bar{b}A^0 + b\bar{b}H^0 \to b\bar{b}b\bar{b}$.
   Not background free and must use cuts to remove $e^+e^- \to H^0A^0 \to b\bar{b}b\bar{b}$. $\Rightarrow$ need large $\tan\beta$ for sufficient rate.
2. The average width of the H^0 and A^0 as measured in the $b\bar{b}b\bar{b}$ final state of $e^+e^- \to H^0A^0 \to b\bar{b}b\bar{b}$.
   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 lower $\tan\beta$ reach 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 $e^+e^- \to H^0A^0 \to b\overline{b}b\overline{b}$.**

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

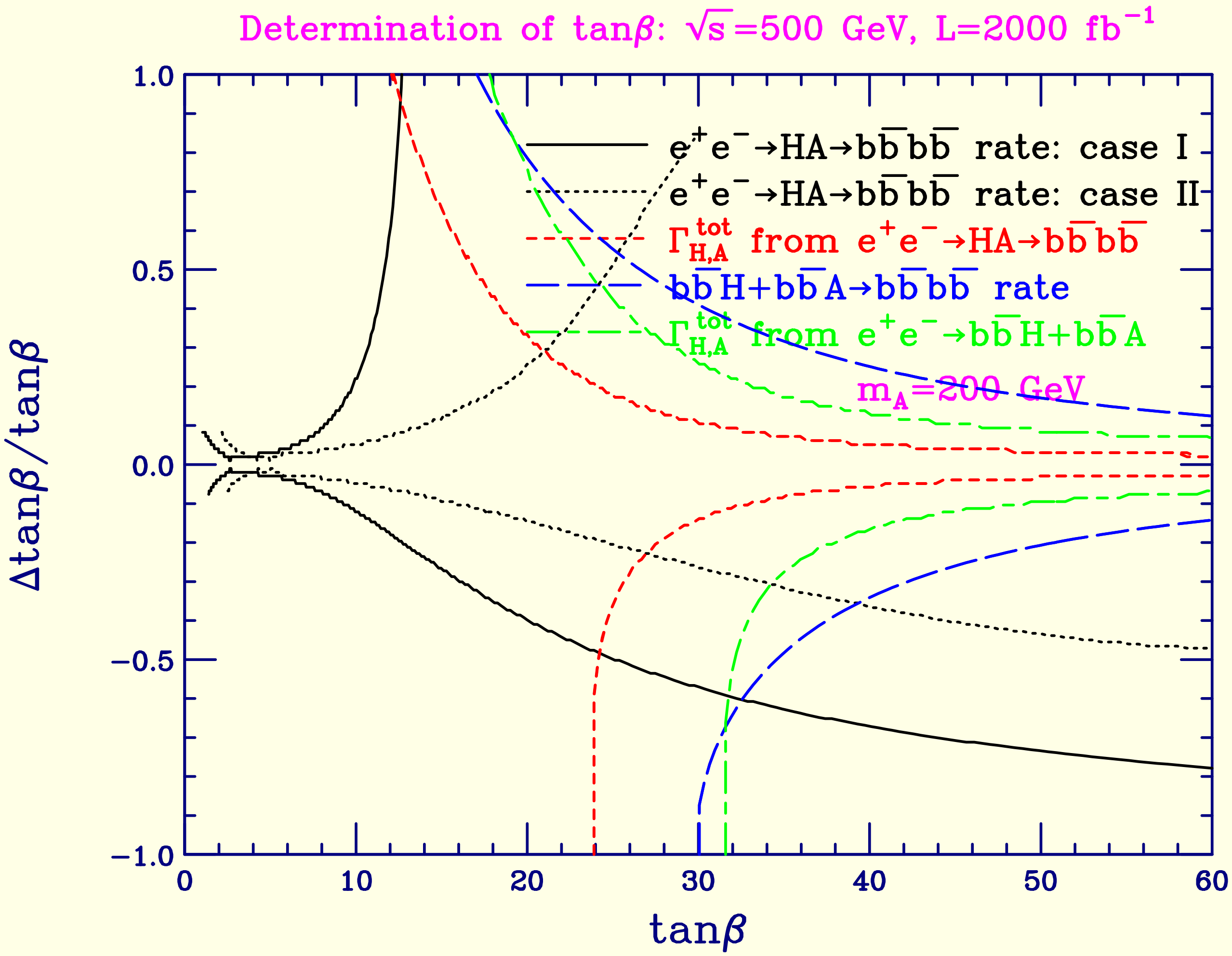
- Need knowledge of SUSY parameters (e.g. $\mu, m_{\widetilde{g}}$) to determine one-loop $\Delta\lambda_b$ radiative corrections for definite interpretation in terms of $\tan\beta$.

- Analogous charged Higgs observables are also useful, but determination of width in $H^\pm \to tb$ decay mode will not be as precise. $\Rightarrow$ under study (Sopczak may present preliminary results).

- 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). $\Rightarrow$ **only way if in wedge region.**



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 $gg \to H^0 b\bar{b}$ and $gg \to A^0 b\bar{b}$ processes with $H^0, A^0 \to \tau^+\tau^-$, $\mu^+\mu^-$ and, perhaps, $b\bar{b}$ 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 strong $\tan\beta$ dependence of $gg \to H^0$ and $gg \to A^0$ at low/moderate $\tan\beta$ and of $gg \to H^0 b\bar{b}$ and $gg \to A^0 b\bar{b}$ at high $\tan\beta \Rightarrow \tan\beta$ determination is possible.

    We used only the $\tau^+\tau^-$ mode based on results of ATLAS TDR Table 34, and corresponding background tabulation.
  - We computed the error in the cross section determination as

$$\frac{\Delta\sigma}{\sigma} = \left[\frac{S+B}{S^2} + (0.1)^2\right]^{1/2}, \tag{4}$$

  - $\Delta\tan\beta$ 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 $L = 600\text{fb}^{-1}$ 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 $B(H^0, A^0 \to \tau^+\tau^-)$ might require the LC!

– If the H^0, A^0 rates could be measured well in the $H^0, A^0 \to b\bar{b}$ 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 $H^\pm \to \tau^\pm\nu$ has been established by the LHC collaborations.

This will allow an independent determination of $\tan\beta$. Study is required to assess this quantitatively.

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

– A group is working on updating all of this.

The NMSSM Higgs Sector

Motivation: Introducing an extra singlet superfield and the interaction $W \ni \lambda \hat{H}_1 \hat{H}_2 \hat{N}$ leads to natural explanation of μ term (as simply inserted in MSSM) when $\langle (\widehat{N})_{\text{scalar component}} \rangle = n$ with n at electroweak scale (as is natural in many cases).

Clearly, n can be traded for $\mu_{\rm eff}$ in describing parameter space.

We also include $\kappa \widehat{N}^3$ in W.

Assuming no CP violation, the NMSSM $\Rightarrow$ 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 a signal.

LHC?

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

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 low-scale 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**, $B\gamma\gamma = 0.11$, $Bb\overline{b} = B\tau\overline{\tau} = 1.15$, $BWW^{(*)} = 0.10$.
- h_2
  $m_{h_2} = 122$ GeV, $c_V = +0.59$, $c_t = +0.54$, $c_b = +2.24$, **gg Production Rate = 0.23**, $B\gamma\gamma = 0.10$, $Bb\overline{b} = B\tau\overline{\tau} = 1.31$, $BWW^{(*)} = 0.09$.
- h_3
  $m_{h_3} = 155$ GeV, $c_V = -0.39$, $c_t = -0.55$, $c_b = 5.12$, **gg Production Rate = 0.80**, $B\gamma\gamma = 0.03$, $Bb\overline{b} = B\tau\overline{\tau} = 8.12$, $BWW^{(*)} = 0.05$.
- 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 $L = 300\mathrm{fb}^{-1}$ 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)

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 $h_i \to a_j a_j$, $a_j \to Z h_k$, $\ldots$ 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
    * $gg \to H^0 \to h^0 h^0$;
    * $gg \to A^0 \to Z h^0$.

    But final states employed (e.g. requiring $h^0 \to \gamma\gamma$) are not relevant here.

  – Dai+Vega+JFG (Phys.Lett.B371:71-77,1996 e-Print Archive: hep-ph/9511319) studied the $H^0 \to A^0 A^0 \to 4b$ 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 $WW \rightarrow h_i \rightarrow a_j a_j, h_k h_k$ 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.

The Continuum Higgs Model

- The most difficult case (JFG+Espinosa) for Higgs discovery is when there is a series of Higgs bosons separated by the mass resolution in the discovery channel(s), *e.g.* one every ~ 10 GeV (the detector resolution in the recoil mass spectrum for $Z+$Higgs.

  For example, extra singlets are abundant in string models.

- In general, all these Higgs could mix with the normal SM Higgs (or the MSSM scalar Higgs bosons) in such a way that the physical Higgs bosons share the WW/ZZ coupling and decay to a variety of channels

  May be forced to use $Z+X$ and look for broad excess in M_X.

- Constraints? Use continuum notation. Important issue is value

of m_C in

$$\int_0^\infty dm K(m) m^2 = m_C^2 \,, \quad \text{where} \quad \int_0^\infty K(m) = 1 \qquad (5)$$

where $K(m)(g m_W)^2$ 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 $m_B = m_h^{\rm max}$: $K(m) = 1/(m_B - m_A)$.

$\Rightarrow m_B^2 + m_B m_A + m_A^2 = 3 m_C^2$. For example, for $m_A = 0$, $m_B = \sqrt{3} m_C$.

LEP constraints (OPAL: hep-ex/0206022)

They have performed the necessary analysis of $e^+e^- \to SZ$ with $Z \to e^+e^-$ or $\mu^+\mu^-$ (recoil missing mass analysis).

$\Rightarrow$ upper limit (95% CL) on $\int_{m_A}^{m_B} dm K(m)$ for any choice of m_A and m_B.

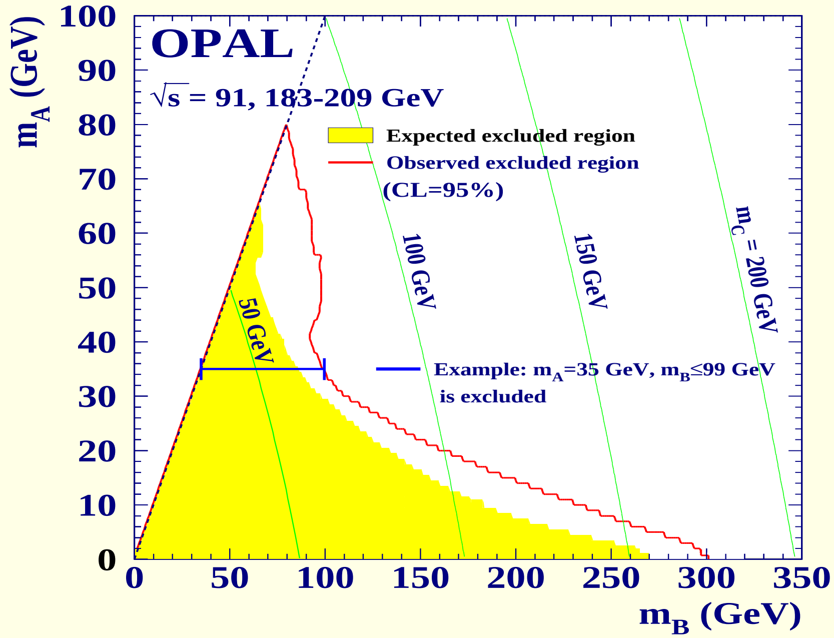


Figure 3: All mass intervals (m_A, m_B) within the area bordered by the dark red line are excluded at 95% CL. The light green lines indicate isolines for various values of m_C. All intervals (m_A, m_B) to the right of each isoline (down to $m_A = m_B$ dashed line) are theoretically disallowed.

- Thus, for $m_A = 0$, they have eliminated almost the full interval up to $m_B \sim 350$ GeV assuming $m_C = 200$ GeV.
- But, for $m_A \geq 80$ GeV, they have not eliminated any interval.

  To go further, requires higher energy. $\sqrt{s} = 500$ GeV is more or less ideal.
- Use JFG, Han Sobey analysis (*Phys. Lett.* B429 (1998) 79) available for $Z \to e^+e^-, \mu^+\mu^-$, $\sqrt{s} = 500$ GeV and $m = 70 - 200$ GeV region.
- For $K(m)$ =constant, $m_C = 200$ GeV and $m_A = 70$ GeV $\Rightarrow m_B = 300$ GeV and $m_B - m_A = 230$ GeV.

  A fraction $f = 100 \text{ GeV}/230 \text{ GeV} \sim 0.43$ of the continuum Higgs signal lies in the $100 - 200$ GeV region (which region avoids Z peak region with largest background).

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

$$\frac{S}{\sqrt{B}} \sim 16f\left(\frac{L}{200\mathrm{fb}^{-1}}\right) \text{ for } m \in [100 - 200] \text{ GeV} . \quad (6)$$

$\Rightarrow$ **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 GeV interval.**
- **Hadron collider detection of continuum signal appears to be very challenging.**

Left-Right Symmetric supersymmetric model

(see, in particular, Mohapatra and Rasin, hep-ph/9604445, revised January 2, 2002)

Motivations

- Using Higgs fields to break parity at some high scale m_R is an attractive idea.
- SO(10), which automatically includes ν_R fields for neutrino masses as well as usual SU(5) representation structures, contains SU(2)$_L\times$SU(2)$_R\times$U(1)$_{B-L}\times$SU(3)$_C$ as a subgroup.
- 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	$(1, 2, +1)$
$\Phi_{1,2}$	$(2, 2, 0)$
Δ	$(3, 1, +2)$
$\overline{\Delta}$	$(3, 1, -2)$
Δ^c	$(1, 3, +2)$
$\overline{\Delta}^c$	$(1, 3, -2)$

- Two bi-doublets Φ required in order to avoid CKM matrix = unity.

- SU(2)$_R$ triplets Δ^c required to break SU(2)$_R$ symmetry.

- SU(2)$_L$ triplets Δ required by L-R symmetry.

Details of no strong CP or SUSY CP problem

Strong CP arguments

$$\overline{\Theta} = \Theta + Arg det(M_u M_d) - 3Arg(m_{\widetilde{g}}) \quad (7)$$

where Θ 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 $\frac{\lambda}{M}[\mathrm{Tr}(\Delta^c \tau_m \overline{\Delta}^c)]^2$ (Δ^c's are triple Higgs fields and $M = M_{Pl}$ 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 Δ_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.**

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 heavy SM-like Higgs that will be found by the LHC.

- **The LC and the LHC will be vital to guarantee discovery of a Higgs boson in the most general case.**

  The LHC, in case there is a heavy Higgs as in general 2HDM.

  The LC, in case of NMSSM (probably) and certainly in the case of a continuum of strongly mixed Higgs bosons.

- **Observation of the heavy H^0, A^0 may require $\gamma\gamma$ collisions to cover the "wedge" region.**

  Once observed, the properties/rates for the H^0, A^0 will help

enormously in determining important SUSY parameters, esp. $\tan\beta$.

- 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.
- Altogether, our ability to fully explore the Higgs sector will be very important to a full understanding of the ultimate theory.