Extended Higgs Sectors

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Outline

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- Extended Standard Model Higgs Sectors
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- **The MSSM Higgs Sector**
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- **Beyond the MSSM**

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- Extended Standard Model Higgs Sectors
- The MSSM Higgs Sector
- Beyond the MSSM

Also interesting but not discussed here are:
Higgs-like particles and associated changes

- Radions
- Top-condensates etc., except to the extent that effective low-energy theory = SM + extended Higgs sector.
- Pseudo-Nambu Goldstone Bosons of Technicolor

EXTENDED STANDARD MODEL

Even within SM context, should consider extended Higgs sector possibilities.

- **Add singlets**

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

- **Add doublets**

  $-$**: Veltman: charged Higgs** m^2 **not automatically positive (EM?).**

  $+$**: Weinberg: can get CP violation from Higgs sector.**

- **Add triplets.**

  If neutral vev $\neq 0$**,** $\Rightarrow \rho$ **is no longer computable (even if representations and vevs are chosen so that** $\rho = 1$ **at tree level);** ρ **becomes another input parameter to the theory; is this so bad?**

  If neutral vev $= 0$**, then no EWSB impact and** $\rho = 1$ **is natural.**

- Add higher reps. e.g. $T = 3, |Y| = 4$ representations $\Rightarrow \rho = 1$+finite loop correction for vev$\neq 0$, but not easy to avoid massless states from unbroken symmetries.

- Triplets very desirable for neutrino mass game in L/R symmetric models. Usual notation is

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix} . \tag{1}$$

  Introduce Δ_R triplet for see-saw with $\langle \Delta_R^0 \rangle =$large.

  L/R symmetry requires Δ_L and $\langle \Delta_L^0 \rangle \equiv v_\Delta = 0$ is natural.

- Triplets are good for unification without SUSY, but at lower scale than usual (maybe desirable for large-scale extra dimensions, . . .).

  Use notation $N_{T,Y}$ for number of Higgs reps. of given T, Y. $T, Y = 1, 2$ and $T, Y = 1/2, 3$ both imply Δ^{--} state.

  $N_{\frac{1}{2},1} = 2, N_{1,0} = 1 \Rightarrow \alpha_s(m_Z) = 0.115$, $M_U = 1.6 \times 10^{14}$ GeV

$N_{\frac{1}{2},1} = 1$, $N_{1,2} = 2 \Rightarrow M_U \sim 1.5 \times 10^{13}$ GeV.

$N_{\frac{1}{2},1} \geq 1$ and $N_{\frac{1}{2},3} \neq 0$ solutions $\Rightarrow M_U \lesssim 10^{13}$ GeV.

- Can get really low unification scales for TeV gravity scenarios, but need complicated Higgs sector. Example:

  $N_{\frac{1}{2},1} = N_{\frac{1}{2},3} = N_{1,2} = N_{1,0} = 4, N_{3,4} = 3 \Rightarrow \alpha_s(m_Z) = 0.112$, $M_U = 1000$ TeV, $\alpha_U = 0.04$

- Mass limits on triplets from LEP/LEP2 are model dependent, but certainly pair production pretty much excludes masses below 100 GeV.

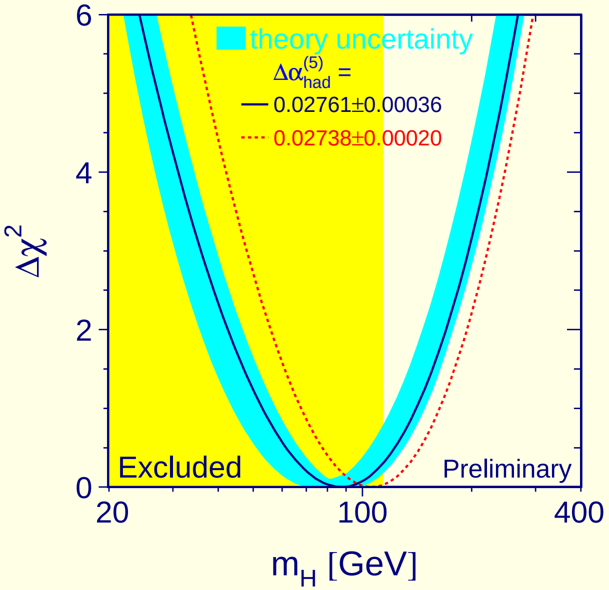
In all cases, detection, simulation considerations change dramatically.

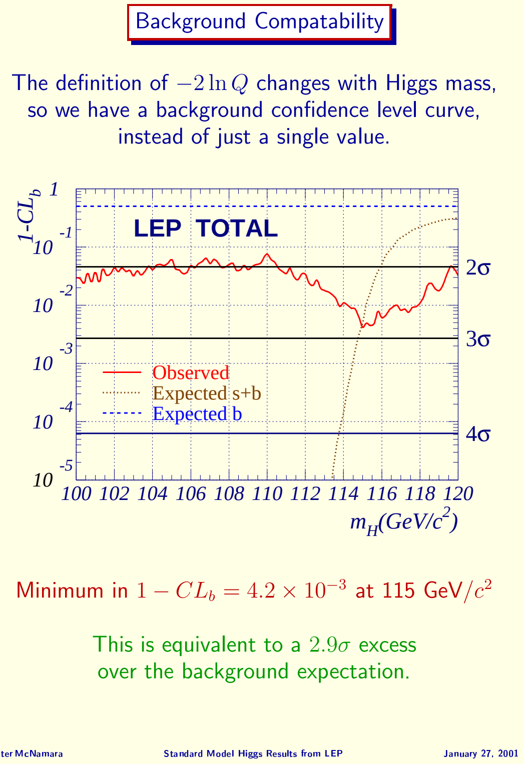
Discovery prospects can vary widely: e^+e^- collider is often best.

Some examples will follow.

Hints from Current Data?

Global fit (all observables) ⇒ Higgs mass below current LEP limit for single SM Higgs: $m_h = 88$ GeV preferred.




Background Compatability

The definition of $-2\ln Q$ changes with Higgs mass,
so we have a background confidence level curve,
instead of just a single value.

Minimum in $1 - CL_b = 4.2 \times 10^{-3}$ at 115 GeV/c^2

This is equivalent to a 2.9σ excess
over the background expectation.

Peter McNamara Standard Model Higgs Results from LEP January 27, 2001

There is possibility for spread-out Higgs weight (at $<$ SM strength) throughout the interval plotted.

There are also the “weak” signals: $m_h \sim 115$ GeV and $m_h = 97$ GeV in hZ production and $m_h + m_{A^0} = 187$ GeV in hA^0 production.

All are consistent with a more complicated Higgs sector with multiple Higgs sharing the ZZ coupling.

Many Singlets

Suppose you have lots, and they mix with the normal SM Higgs in such a way that the physical Higgs bosons share the WW/ZZ coupling and decay to a variety of channels and have masses spread out every $10-20~\mathrm{GeV}$ (i.e. smaller than detector resolution in recoil mass spectrum) over some substantial range $\Rightarrow$ diffuse signal$\equiv$worst case (Espinosa +JG). May be forced to use $Z+X$ and look for broad excess in M_X.

Constraints? Important issue is value of M^2 in

$$\sum_i C_i^2 m_{h_i}^2 = \langle M^2 \rangle \,. \tag{2}$$

where $C_i g m_W$ is the strength of $h_i WW$ coupling.

- Precision electroweak suggests $\langle M^2 \rangle \lesssim (200-250~\mathrm{GeV})^2$.
- For multiple Higgs reps. of any kind in the most general SUSY context, RGE + perturbativity up to $M_U \sim 2\times 10^{16}~\mathrm{GeV}$ gives same result.
- Caution: Many types of new physics at low scale allow evasion; e.g. large extra dimensions or appropriate extra Higgs structure.

Ignoring this caveat, assume sum rule and take C_i^2=constant from $m_h^{\min}$ to $m_h^{\max}$ (use continuum limit, $C^2(m_h)$).

- Suppose LEP2 data eventually $\Rightarrow C^2(m_h)$ is small for $m_h \leq 70$ GeV in continuum spread-out sense, then $\langle M^2 \rangle = [200 \text{ GeV}]^2 \Rightarrow m_h^{\max} = 300$ GeV. $\Rightarrow$ need $\sqrt{s} \gtrsim 500$ GeV for big $\sigma(ZH)$ over most of the region.
- Use JFG, Han Sobey analysis (*Phys. Lett.* B429 (1998) 79) available for $Z \rightarrow e^+e^-, \mu^+\mu^-$, $\sqrt{s} = 500$ GeV and $M_X = 70 - 200$ GeV region.
- For $C^2(m_h)$ =constant for $70 \text{ GeV} < m_h < 300$ GeV find a fraction $f \sim 0.43$ of the continuum Higgs signal in $100 - 200$ GeV (which region avoids Z region with largest background).
- Summing $Z \rightarrow e^+e^- + \mu^+\mu^-$, $S \sim 540f$ with a background of $B = 1080$, for $100 - 200$ GeV window, assuming $L = 200\text{fb}^{-1}$.
- $$\frac{S}{\sqrt{B}} \sim 16f \left(\frac{L}{200\text{fb}^{-1}} \right) \text{ for } M_X \in [100 - 200] \text{ GeV} . \quad (3)$$

Hadron collider situation probably very challenging.

- $\gamma\gamma$ decay width reduced (less W loop) for each Higgs.
- WH and ZH channels weak and probably $\Rightarrow$ spread-out signal.
- $t\bar{t}h$ probably ok in strength, but signal spread out and many possible h decay modes.

Is there a way at the LHC?

General Two Higgs Doublet Model ($h^0_{1,2,3}, H^\pm$ – CPV – or $h^0, H^0, A^0, H^\pm$ – CPC)

Q: Are we guaranteed to find a light Higgs boson if one exists?

A: It depends.

Consider CPC 2HDM with light A^0, all others heavy. (Cure precision EW problem using isospin-split heavy pair.)

Need to consider:

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

- $e^+e^- \rightarrow Z^* \rightarrow ZA^0A^0$

  $e^+e^- \rightarrow e^+e^-W^*W^* \rightarrow e^+e^-A^0A^0$.

- $\gamma\gamma \rightarrow A^0$ **and** $\mu^+\mu^- \rightarrow A^0$.

Corresponding 'guarantees':

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

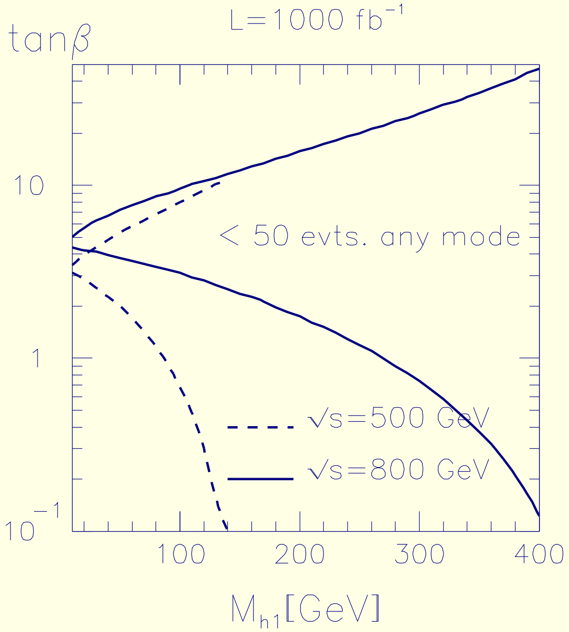
  $\Rightarrow$ **either $t\bar{t}$ or $b\bar{b}$ coupling of A^0 must be big.**

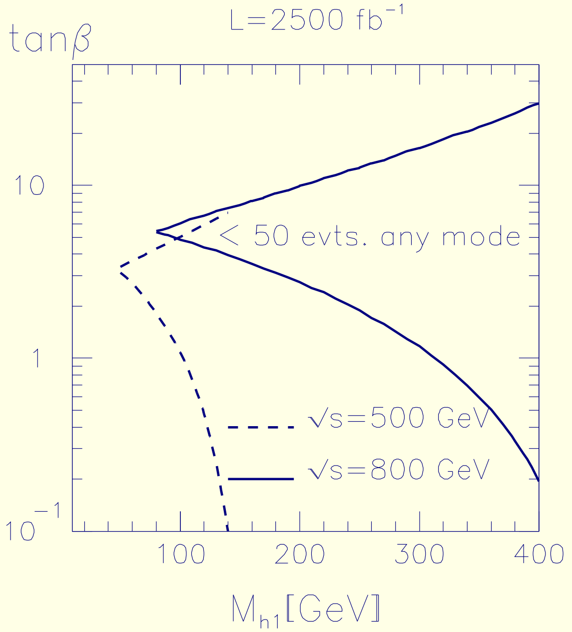
- **The quartic couplings ZZA^0A^0 and $W^+W^-A^0A^0$, from gauge covariant structure $(D_\mu\Phi)^\dagger(D^\mu\Phi)$, are of guaranteed magnitude.**
- **$\gamma\gamma \to A^0$ coupling from fermion loops, $\mu^+\mu^- \to A^0$ direct coupling to fermions.**

Q: Are these processes enough?

A: No, but they certainly help.

$e^+e^- \to t\bar{t}A^0$ 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.





For $\sqrt{s} = 500$ GeV (dashes) and $= 800$ GeV (solid) 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 50 events for decoupled A^0 (a) $L = 1000\mathrm{fb}^{-1}$ or (b) $L = 2500\mathrm{fb}^{-1}$. (from JFG+Grzadkowski+Kalinowski)

$L = 2500\mathrm{fb}^{-1}$ wedge begins at $m_{A^0} \sim 80$ GeV ($\sqrt{s} = 800$ GeV).

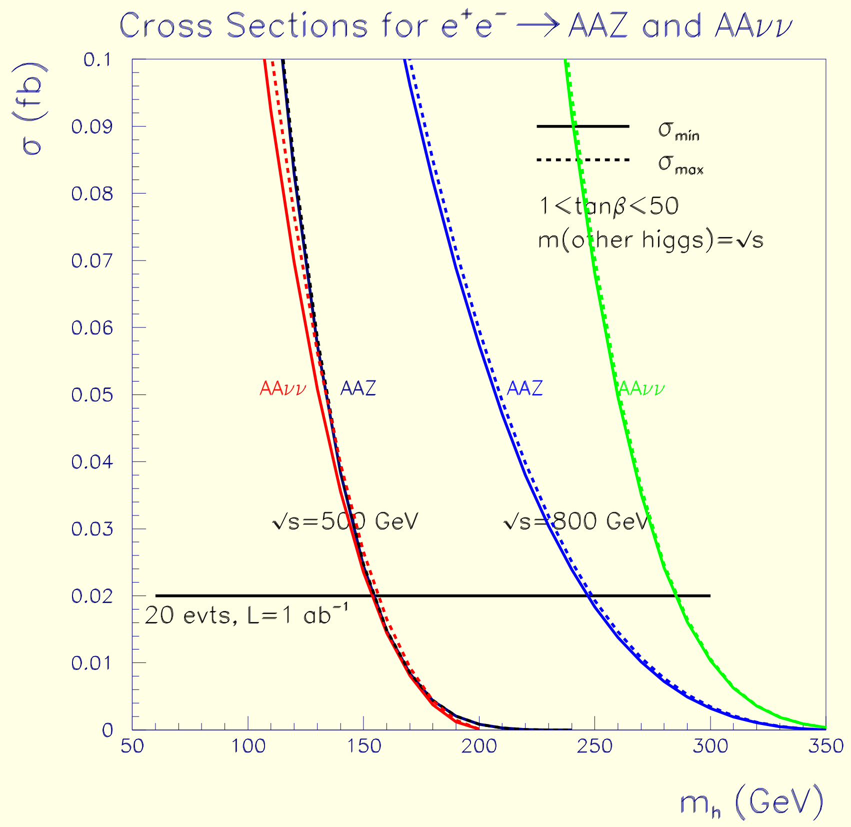
LHC ⇒ smaller bad region (due to high rates)? – MSSM studies suggest so.

Challenge: close these wedges!

Wedges extend to higher m_{A^0} than plotted.

A^0A^0Z **and** $A^0A^0\nu\overline{\nu}$ **production allows discovery of light (decoupled)** A^0.

- $\sqrt{s} = 500$ GeV **probes** $m_{A^0} \lesssim 150$ GeV.
- $\sqrt{s} = 800$ GeV **probes** $m_{A^0} \lesssim 250 - 300$ GeV.

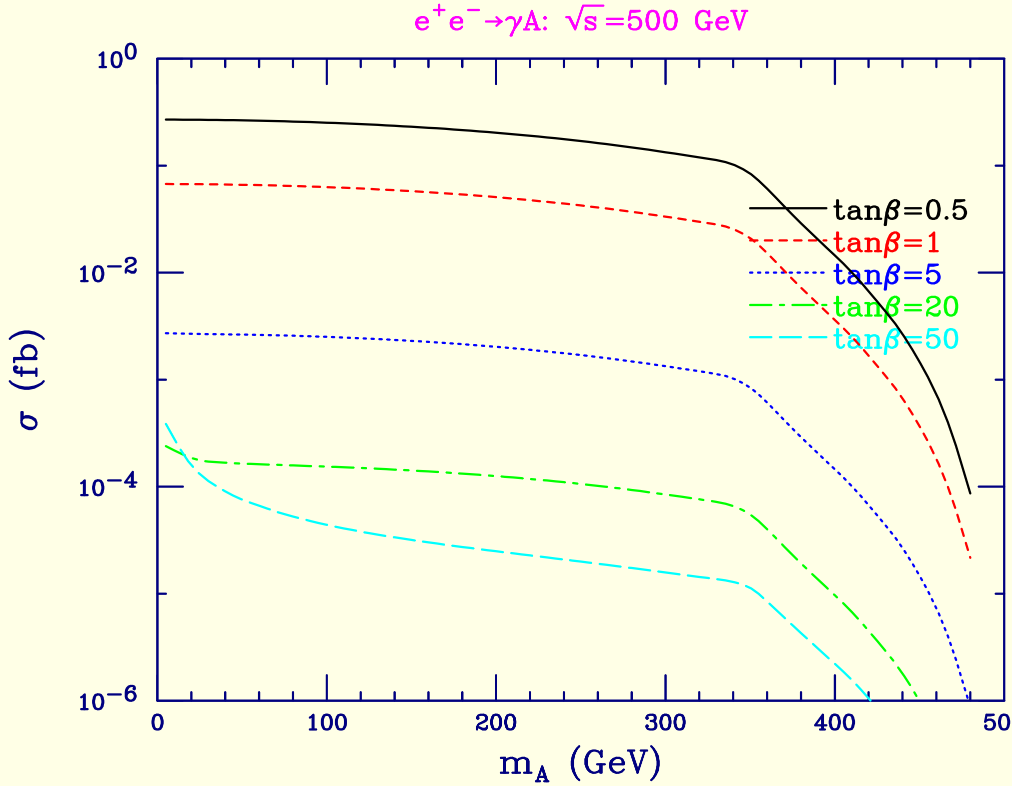


For $\sqrt{s} = 500$ GeV and 800 GeV we plot the maximum and minimum values of $\sigma(e^+e^- \to A^0A^0Z)$ and $\sigma(e^+e^- \to A^0A^0\nu\overline{\nu}$ found for $1 < \tan\beta < 50$ for $m_{\rm other\ Higgs} = \sqrt{s}$. The 20 event level for $L = 1~{\rm ab}^{-1}$ is indicated. (from JFG+Farris)

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 $m_{A^0} = 400\ \mathrm{GeV}$ ($\sqrt{s} = 500\ \mathrm{GeV}$).

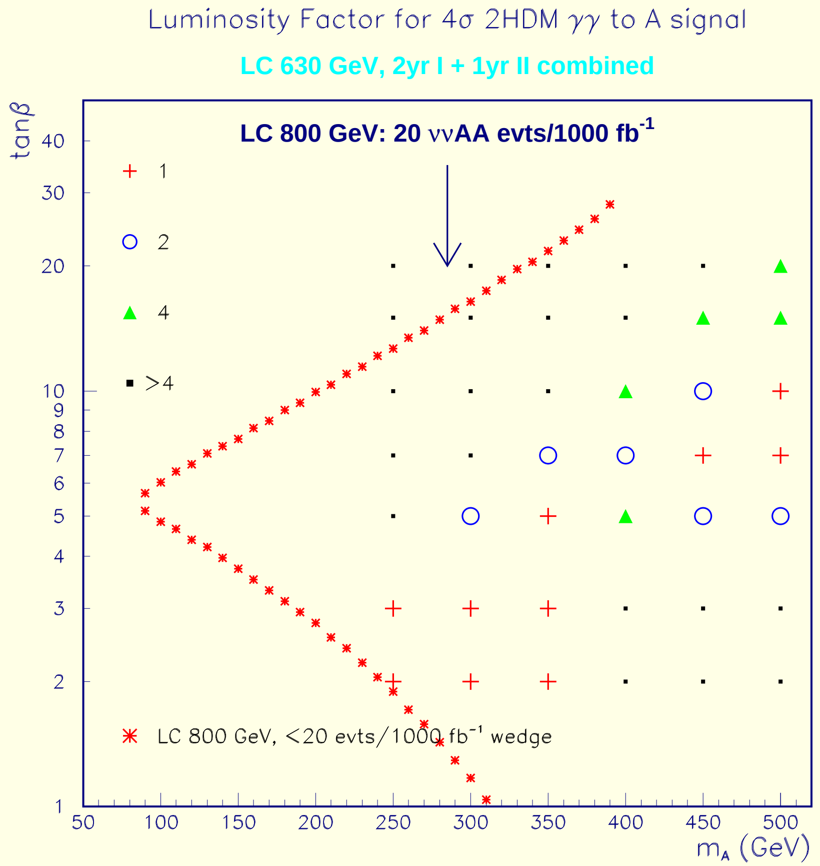
$\Rightarrow$ very hard!



For $\sqrt{s} = 500\ \mathrm{GeV}$, we plot $\sigma(e^+e^- \to \gamma A^0)$ as a function of m_{A^0}. (from JFG+Farris)

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

$\gamma\gamma \to A^0$ collider results: peaked + broad spectrum running.



Points with $> 4\sigma$ signal after combining N_{SD}'s for 2 yr type-I and 1 yr type-II operation at $\sqrt{s} = 630$ GeV. (from JFG+Asner+Gronberg)

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

For $\tan\beta \gtrsim 30 - 40$, $\gamma\gamma \to A^0$ becomes detectable for m_{A^0} range shown.

Precision Electroweak Constraints for a light A^0 and no other observable Higgs at e^+e^- collider ($\sqrt{s} \lesssim 800\ \mathrm{GeV}$)?

Can arrange so it is ok: (JFG, Farris, Chankowski, Grzadkowski, Kalinowski, Krawczyk)

Precision EW is best if h^0 is SM-like. Perturbativity of 2HDM couplings requires $m_{h^0} \lesssim 1\ \mathrm{TeV}$. $\Rightarrow$ LHC!!

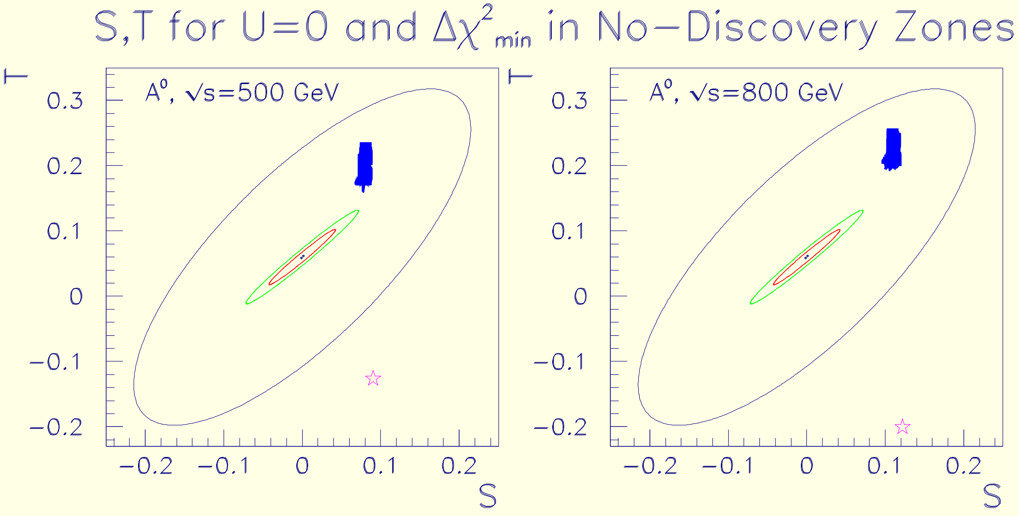
- Heavy h_{SM}-like Higgs $\Rightarrow$ large $\Delta S > 0$ and large $\Delta T < 0$.
- Compensate by large $\Delta T > 0$ from small mass non-degeneracy (weak isospin breaking) of heavier Higgs. Light A^0 + heavy SM-like h^0 $\Rightarrow$

$$\Delta\rho = \frac{\alpha}{16\pi m_W^2 c_W^2}\left\{\frac{c_W^2}{s_W^2}\frac{m_{H^\pm}^2 - m_{H^0}^2}{2} - 3m_W^2\left[\log\frac{m_{h^0}^2}{m_W^2} + \frac{1}{6} + \frac{1}{s_W^2}\log\frac{m_W^2}{m_Z^2}\right]\right\} \tag{4}$$

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

E.G. choose $\tan\beta$ and m_{A^0} so that A^0 is in Yukawa no-discovery wedge and choose $m_{h^0} > \sqrt{s} = 500~\mathrm{GeV}$ or $800~\mathrm{GeV}$ 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 $\tan\beta > 1$).



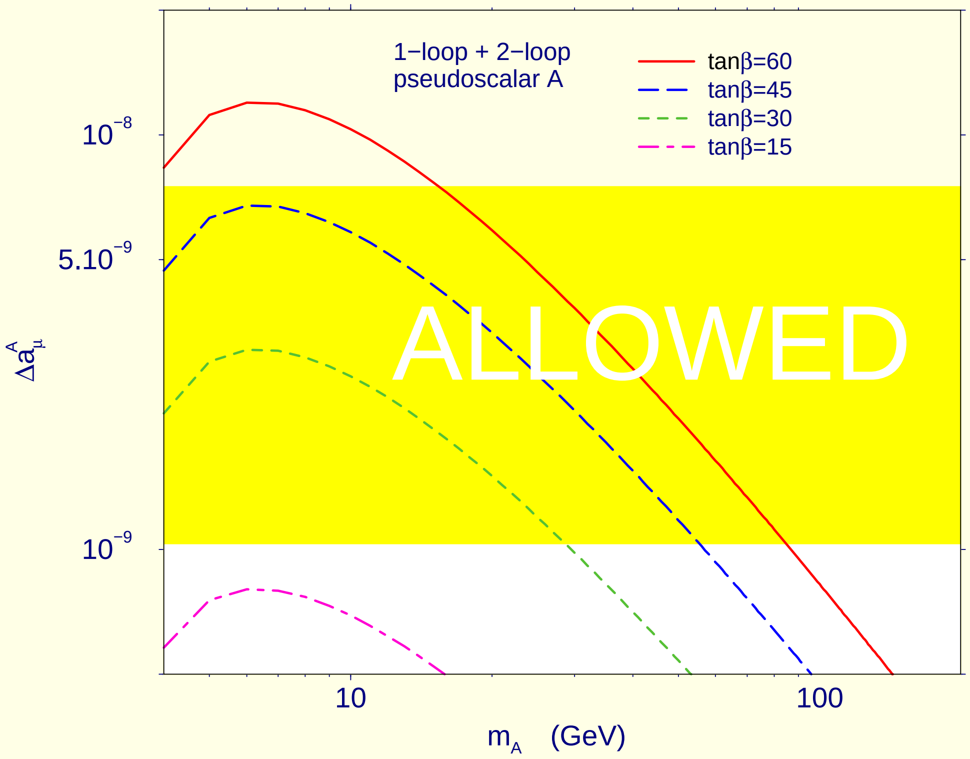
Giga-Z (with $\Delta m_W = 6MeV$ from WW threshold scan) would pinpoint situation.

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.

a_μ = evidence for light 2HDM A^0?

A light A^0 (h^0) gives a positive (negative) contribution dominated by two-loop Bar-Zee graph.

Light A^0 can $\Rightarrow$ appropriate Δa_μ. For latest lower Δa_μ range (lower the yellow band), moderate m_{A^0} and $\tan\beta$ do the job. If Δa_μ decreases further with final data set and other inputs, $\Rightarrow$ could enter LC/LHC wedges.



Explanation of old BNL a_μ value via light 2HDM A^0. (Cheung, Chou, Kong)

Models with Higgs triplet representations

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:

- Neutrino masses arise via seesaw from lepton-number-violating (Majorana-like) coupling of two leptons to a triplet Higgs boson.
- The L-R arrangement is to have two Higgs triplet representations: 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 neutrino 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.
- In SUSY L-R context, the triplet Higgs field(s) destroy unification if intermediate scale matter not included, but such matter is natural in LR models.

More generally, we should simply consider the possibility of a (left-handed) triplet field.

For a $|Y| = 2$ triplet representation (to which we now specialize) the lepton-number-violating coupling Lagrangian is:

$$\mathcal{L}_Y = i h_{ij} \psi_i^T C \tau_2 \Delta \psi_j + \mathrm{h.c.}\,, \quad i,j = e,\mu,\tau\,. \tag{5}$$

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

Limits on the h_{ij} by virtue of the $\Delta^{--} \to \ell^- \ell^-$ couplings: writing $|h_{\ell\ell}^{\Delta^{--}}|^2 \equiv c_{\ell\ell} m_{\Delta^{--}}^2 (\ \mathrm{GeV})$, strongest limits (no limits on $c_{\tau\tau}$) are:

- $c_{ee} < 10^{-5}$ (Bhabbha),
- $c_{\mu\mu} < 5 \times 10^{-7}$ ($(g-2)_\mu$ – predicted contribution has wrong sign) and
- $\sqrt{c_{ee} c_{\mu\mu}} < 10^{-7}$ (muonium-antimuonium).

If $\langle \Delta^0 \rangle = 0$ (for $\rho = 1$ = natural), $\Gamma_{\Delta^{--}}^T$ 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 or LHC (J.G., 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 $c_{\ell\ell}$.

– For small beam energy spread (R) (equivalently, small $\sigma_{\sqrt{s}}$)

$$N(\Delta^{--})_{L=50\mathrm{fb}^{-1}} \sim 3 \times 10^{10} \left(\frac{c_{ee}}{10^{-5}}\right) \left(\frac{0.2\%}{R}\right) ; \tag{6}$$

$\Rightarrow$ an enormous event rate if c_{ee} near its upper bound.

– For 100 events, Eq. (6) $\Rightarrow$ we probe

$$c_{ee}|_{100 \text{ events}} \sim 3.3 \times 10^{-14} \left(\frac{R}{0.2\%}\right) \left(\frac{50\mathrm{fb}^{-1}}{L}\right) , \quad \Gamma^{T}_{\Delta^{--}} \ll \sigma_{\sqrt{s}} , \tag{7}$$

independent of $m_{\Delta^{--}}$.
$\Rightarrow$ dramatic sensitivity — at least factor of $10^8 - 10^9$ improvement over current limits. Observation $\Rightarrow$ actual measurement of c_{ee} at level relevant to neutrino mass generation.

If $\Delta^{--} \to \mu^-\mu^-$ primarily, 10 events might → a viable signal.

The Challenge: if you see a Δ^{--}, how do you look for all its partners.

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.**

  Two doublets, and their higgsino partners, $\Rightarrow$ anomaly cancellation.

- **Two doublets yield perfect coupling constant unification if the SUSY scale is $m_{\rm SUSY}\sim 1~{\rm TeV}$ (actually, significant SUSY stuff at $10~{\rm TeV}$ works better for α_s).**

  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!

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

- **What are the bounds on m_{h^0} (take $m_{\widetilde t}\leq 1~{\rm TeV}$ for naturalness)?**

- In two-doublet MSSM, $m_{h^0} \lesssim 130-135~\mathrm{GeV}$, although extra dimension effects might modify.
- Adding singlets, e.g. NMSSM one complex singlet added, pushes this up to roughly $150~\mathrm{GeV}$ assuming perturbativity for new coupling(s) up to M_U
- Adding more doublets, lowers mass bound.
- Adding most general structure ($Y = 2$ triplets being the 'worst' for moving up the mass bound), and allowing most general mixings etc., one finds (assuming perturbativity up to M_U again) upper bound of $\sim 200~\mathrm{GeV}$.

Experimental limits from LEP2 on MSSM Higgs bosons are significant.

For maximal-mixing (a certain choice of $X_t \equiv A_t - \mu \cot\beta$): $m_{h^0}, m_{A^0} \gtrsim 91~\mathrm{GeV}$ are required and $0.5 \lesssim \tan\beta \lesssim 2.4$ is excluded. No-mixing scenario: $0.7 \lesssim \tan\beta \lesssim 10.5$ is excluded.

But: $m_{\widetilde{t}} < 1~\mathrm{TeV}$ is assumed; CP violation in Higgs sector is neglected; invisible decays are not allowed for.

Higher $m_{\widetilde{t}}$: (Might be preferred for exact coupling unification.)

Higgs masses at given $\tan\beta$ increase ⇒ less parameter space in $m_{A^0}-\tan\beta$ plane excluded

CP Violation:

CP violation arises in the MSSM through phases of the μ parameter and the A parameters, especially A_t.

This CP violation leads to CP violation in the MSSM two-doublet Higgs sector brought in via the one-loop corrections sensitive to these phases.

$\Rightarrow$ effectively 2 new parameters: $\phi_\mu + \phi_A$ and θ, the latter being the phase of one of the Higgs doublet fields relative to the other.

MSSM Higgs mass limits will be weakened significantly, implying that the disallowed $\tan\beta$ region is probably still allowed when CP violation is allowed.

Invisible Decays:

Allowing for h^0 and A^0 to have some, perhaps substantial, invisible decays would probably considerably weaken the constraints on the $h^0 A^0$ cross section.

$Z + X$ would have to be relied upon more heavily.

How much do the limits deteriorate?

This deserves study by the experimental groups.

Discovery prospects in the MSSM at Tevatron and LHC

The Tevatron

Use $q\bar{q} \to Vh^0 + VH^0$ $(h^0, H^0 \to b\bar{b})$ for Higgs with significant VV coupling.

Use $gg, q\bar{q} \to b\bar{b}h^0, b\bar{b}H^0, b\bar{b}A^0$ for high $\tan\beta$ non SM-like Higgs.

$\Rightarrow L > 15\mathrm{fb}^{-1}$ needed for 5σ discovery of h^0.

Higher m_{A^0} (predicted by RGE EWSB) $\to$ larger m_{h^0} $\Rightarrow$ hard.

The LHC

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

At high $\tan\beta$, use $gg, q\bar{q} \to b\bar{b}H^0, b\bar{b}A^0$, with $H^0, A^0 \to \tau^+\tau^-$ or $\mu^+\mu^-$ and $gb \to H^\pm t$ with $H^\pm \to \tau^\pm\nu$.

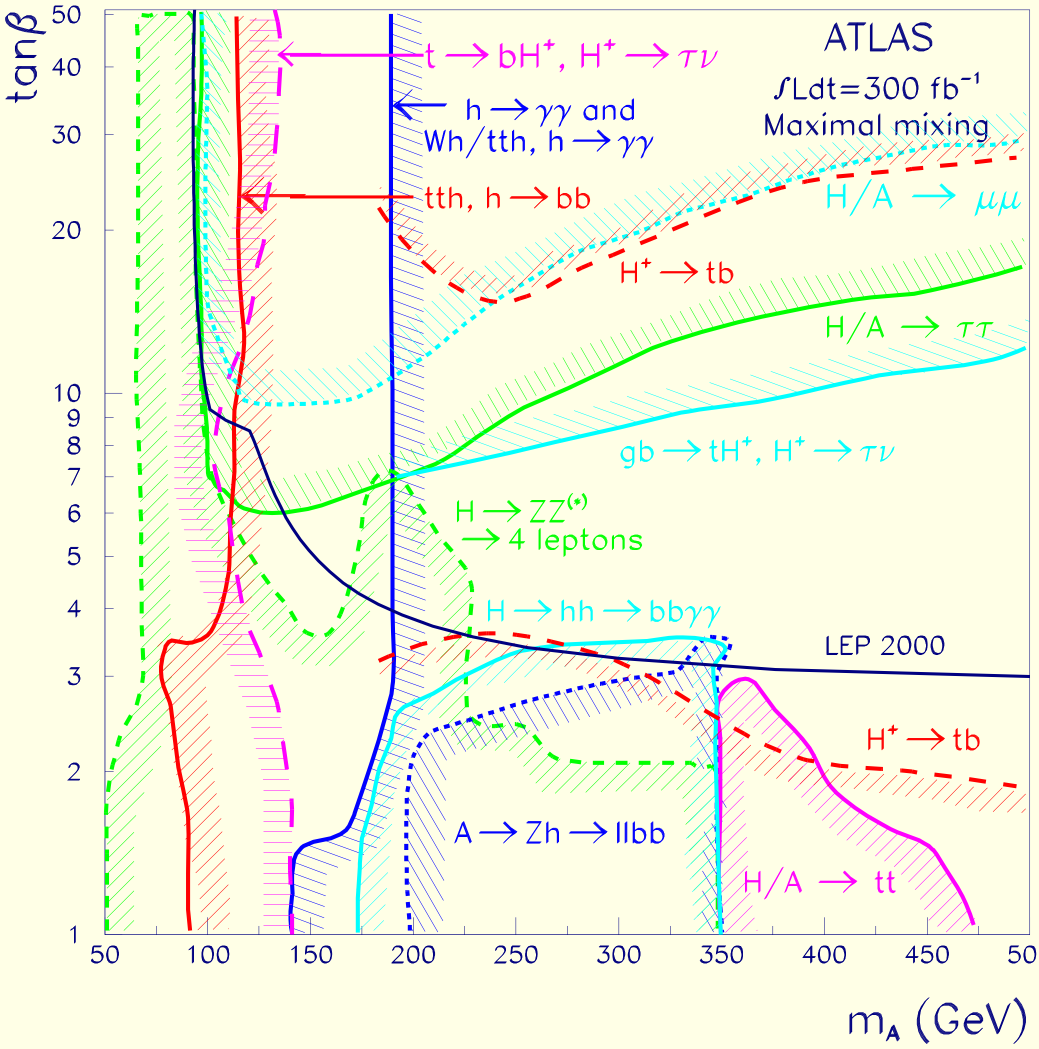
LEP2 limits pretty much exclude $\tan\beta < 3$ where other modes could be important

⇒ Guaranteed to find one of the MSSM Higgs bosons with $L = 300\text{fb}^{-1}$ (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 $L = 300\text{fb}^{-1}$ 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 $e^+e^- \to b\overline{b}A^0, b\overline{b}H^0, btH^\pm$.

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

Strategies

- Raise $\sqrt{s}$! (longer machine, new/improved technology, CLIC, muon collider, . . .)
- 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 — more later.)

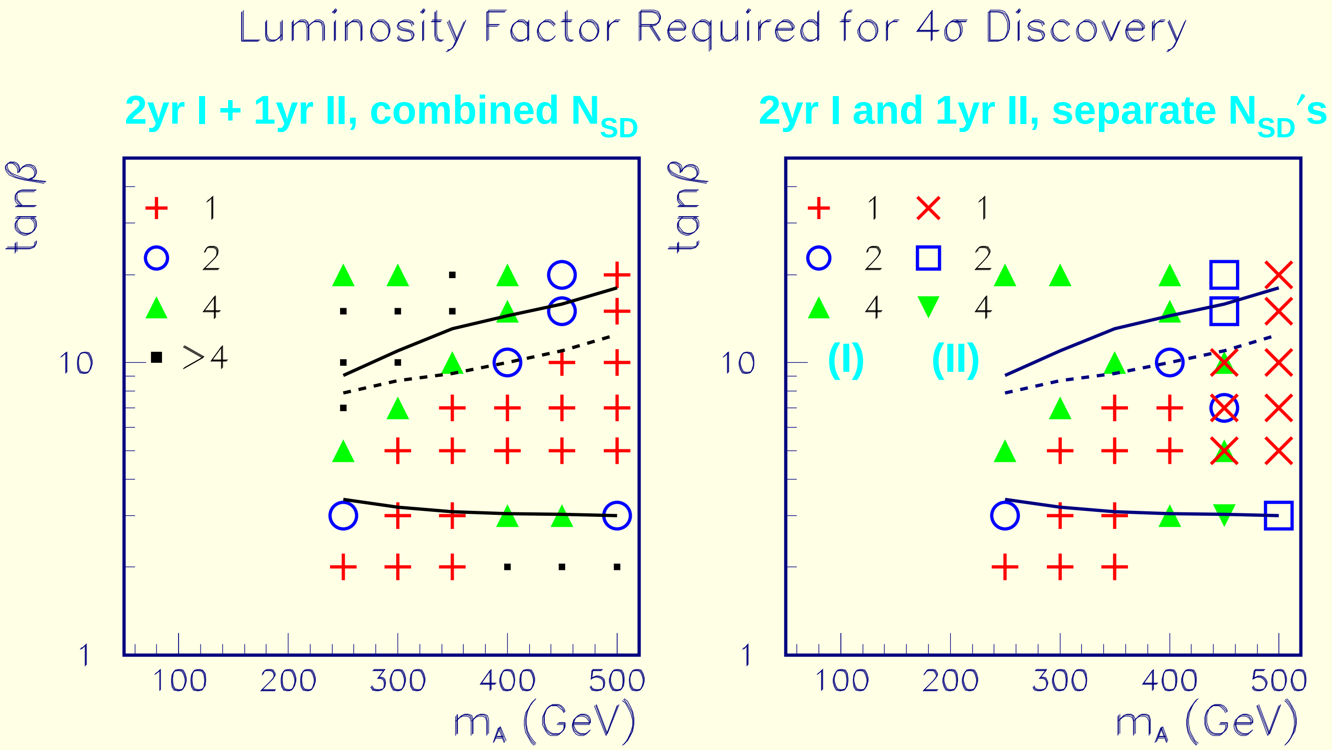
  Then use peaked $\gamma\gamma$ spectrum to look for H^0, A^0 (usually overlapping) combined signal over narrow interval.

  < 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.

If you don't trust indirect m_{A^0} determination (is there a way to know if you should trust it?) then what?

The Wedge Results: peaked + broad spectrum running.

(from JFG+Asner+Gronberg)



Luminosity Factor Required for 4σ Discovery

2yr I + 1yr II, combined N_{SD}

2yr I and 1yr II, separate N_{SD}′s

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 $\gamma\gamma$!

Variants of ‘standard’ results $\Rightarrow$ be cautious.

Invisible decays.

Will probably allow non-detection scenarios at hadron colliders.

$h^0 \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1$ still possible given LEP2 data.

To maximize $B(h^0 \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1)$:

- Choose M_1/M_2 small $\Rightarrow m_{\widetilde{\chi}^0_1}$ can be small (*i.e.* good phase space for decay despite limits on m_{h^0}) while $m_{\widetilde{\chi}^\pm_1}$ can satisfy $m_{\widetilde{\chi}^\pm_1} > 103~\mathrm{GeV}$ (LEP2).
  ‘Standard’ $M_1/M_2 = 1/2$, $\Rightarrow$ maximum $B(h^0 \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1) \sim 20\%$.
  $M_1/M_2 = 1/10 - 1/5$ allows $B(h^0 \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1) > 50\%$.
- need $(O_{12} - \tan\theta_W O_{11})(\sin\beta O_{14} - \cos\beta O_{13})$ large — *i.e.* $\widetilde{\chi}^0_1$ must have substantial higgsino content.
  $\Rightarrow \mu$ (and M_2) not too big.
- small M_1, M_2 and μ also good for a_μ.

Stop loop corrections to one-loop couplings

Stop and top loops negatively interfere: $\Rightarrow$

- **Reduction of gg fusion production.**
- **Some increase in $B(H \to \gamma\gamma)$.**

Radiative corrections to a) mass matrix and b) couplings.

a) can cause early/exact decoupling, $i.e.$ $\cos^2(\beta - \alpha) = 0$ **independent of** m_{A^0}.

- **Can get $\cos(\beta - \alpha) = 0$ or $\sin(\beta - \alpha) = 0$ if**

$$\frac{2\mathcal{M}^2_{12}}{\mathcal{M}^2_{11} - \mathcal{M}^2_{22}} = \tan 2\beta\,. \tag{8}$$

- **If $2\mathcal{M}^2_{12} = -m^2_{A^0} s_\beta c_\beta + \mathcal{B}^2_{12} < 0 \quad (> 0) \Rightarrow c_{\beta-\alpha} = 0$ ($s_{\beta-\alpha} = 0$), where the $\mathcal{B}^2$ is the mass matrix stuff not directly proportional to $m^2_{A^0}$.**
- **Exact decoupling of this type is possible not only for appropriate choices of the λ_i in the general 2HDM Higgs potential and/or $\tan\beta$ in the general 2HDM, but also can arise in the MSSM when SUSY parameters are appropriately chosen.**

b) can modify $b\bar{b}$ decays of h^0 (when h^0 SM-like).

- Notation: at tree-level H_u^0 (H_d^0) couples to $t\bar{t}$ ($b\bar{b}$).

  $h^0 = -\sin\alpha \mathrm{Re} H_d^0 + \cos\alpha \mathrm{Re} H_u^0\,, \quad H^0 = \cos\alpha \mathrm{Re} H_d^0 + \sin\alpha \mathrm{Re} H_u^0\,.$

  $\mathcal{L} \simeq \lambda_b H_d^0 b\bar{b} + \Delta\lambda_b H_u^0 b\bar{b}$, where $\Delta\lambda_b$ is one-loop: $\widetilde{b} - \widetilde{g} + \widetilde{t} - \widetilde{H}_{u,d}$.

  $\Delta\lambda_b/\lambda_b \sim 0.01$, either sign (does not vanish for heavy sparticle masses).
- Result: h^0 can decouple from b's (i.e. $h^0 \simeq H_u$).

$$\lambda_b^{h^0} \simeq -\frac{m_b \sin\alpha}{v\cos\beta} \frac{1}{1+\frac{\Delta\lambda_b}{\lambda_b}\tan\beta} \left[1 - \frac{\frac{\Delta\lambda_b}{\lambda_b}}{\tan\alpha}\right].$$

  If $\tan\alpha \simeq \frac{\Delta\lambda_b}{\lambda_b}$ then $\lambda_b^{h^0} \simeq 0$. E.g. if $m_{A^0} \to \infty$ and $\Delta\lambda_b/\lambda_b < 0$, $\alpha \to \pi/2 - \beta$ so that $\tan\alpha \to -1/\tan\beta$ is small.

  Conversely, for $\Delta\lambda_b/\lambda_b > 0$, substantial enhancement of $\lambda_b^{h^0}$ is possible.
- Many effects on discovery modes of light Higgs:

Extra Decays

- The usual LHC contours for $H^0, A^0, H^\pm$ discovery in various modes

will be modified (at low to moderate $\tan\beta$ when $m_{A^0} > m_Z$) if $\widetilde\chi_1^0\widetilde\chi_1^0, \widetilde\chi_1^+\widetilde\chi_1^-, \widetilde\tau^+\widetilde\tau^-, \widetilde\nu\overline{\widetilde\nu}, \ldots$ decays are kinematically allowed.
However, at high $\tan\beta$ the usual dominance of decays to $b\overline{b}$ and $\tau^+\tau^-$ will be preserved.
$\Rightarrow$ only some widening of h^0-only LHC wedge.

- e^+e^- collider H^0A^0 and H^+H^- detection quite robust against complicated decays if pair production not too near kinematic limit. (JFG, Kelly) (Feng, Moroi) (...)
  In fact, precise decay mixtures $\Rightarrow$ immensely powerful probe of soft SUSY breaking.
  But, must separate different final state channels ($[3\ell, 2b]$, $[1\ell, 0b]$, ... — maybe 15 or 20 different channels) and know efficiencies for different channels with good precision.
- $\gamma\gamma \to H^0, A^0$ discovery could become much more difficult.
- $\mu^+\mu^- \to H^0, A^0$ discovery could become more difficult.

Last two items need serious study in a few reasonable models.

Determining $\tan\beta$

The non-SM-like Higgs bosons will provide the best determination at large $\tan\beta$. Also $\Rightarrow$ good determination at low $\tan\beta$.

- 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.
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, variation continues out to substantial $\tan\beta$. If not, the event rate asymptotes quickly and one loses sensitivity at high $\tan\beta$.

- Need to have sufficient knowledge of SUSY parameters (e.g. μ) to determine magnitude of $\Delta\lambda_b$ corrections.

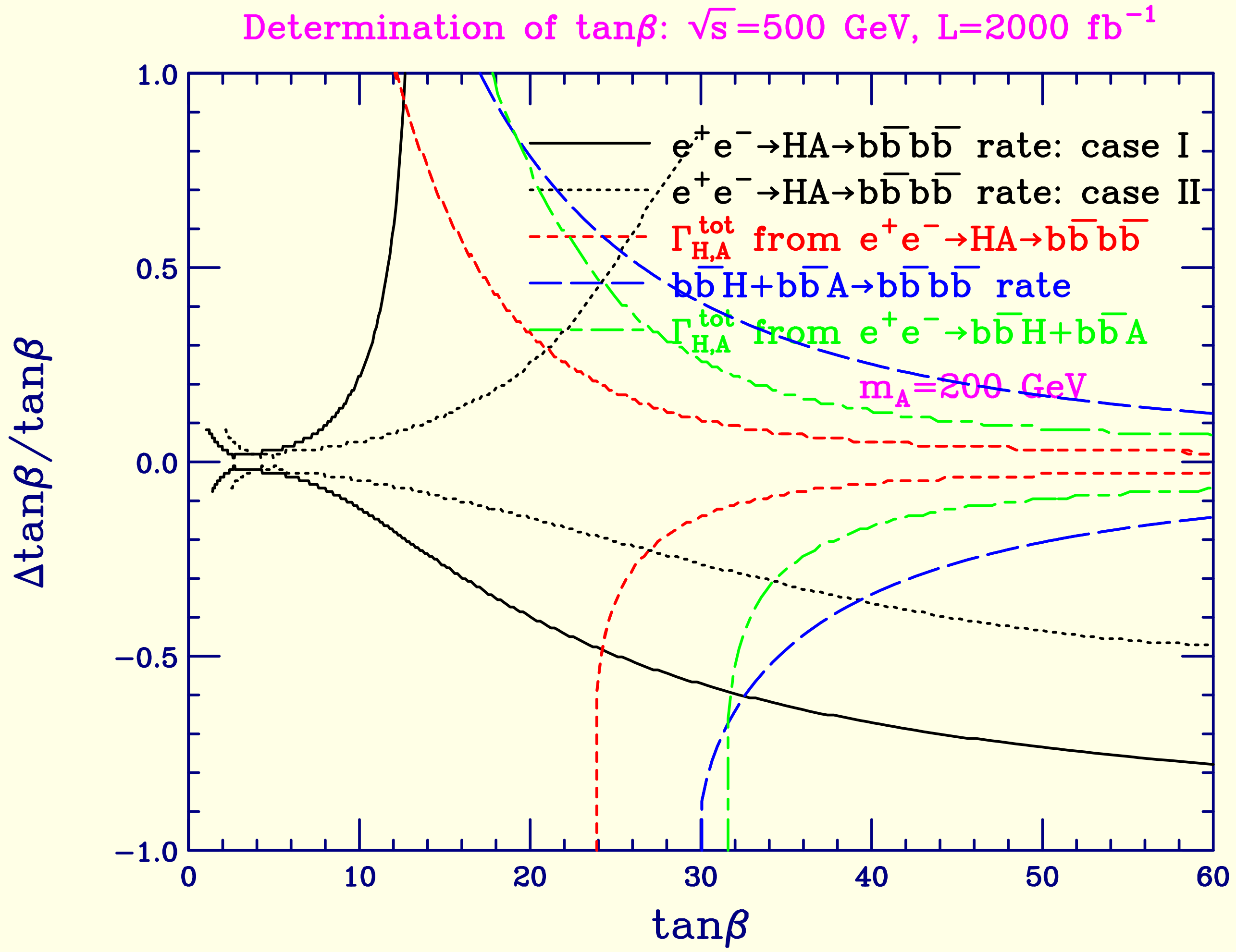
  This will allow interpretation of the above measurements after including one-loop radiative corrections.

- 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.

The NMSSM Higgs Sector

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

Linear Collider

Have already discussed how we can add any number of singlets, and still find signal. One singlet is very easy.

LHC?

Old Snowmass96 Result (JFG+Haber+Moroi) $\Longrightarrow$

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

New Results (JFG+Ellwanger+Hugonie) $\Longrightarrow$

An important new mode that allows discovery of many of the 'bad' points of SM96 is $t\bar{t}h \rightarrow t\bar{t}b\bar{b}$ (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: $\lambda = 0.0121$, $\kappa = 0.0070$, $\tan\beta = 5.2$, $\mu_{\rm eff}(GeV) = -105$, $A_\lambda(GeV) = 25$, $A_\kappa(GeV) = 36$.

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

  - h_1
    m_{h_1} (GeV)=111, with c_V=0.63, c_t=0.57, c_b=2.34, gg Production Rate = 0.26, $B\gamma\gamma$ =0.09, $Bb\bar{b} = B\tau\bar{\tau}$ = 1.15, $BWW^{(*)}$= 0.08.
  - h_2
    m_{h_2} (GeV)=113, c_V=$-$0.60, c_t=$-$0.53, c_b=$-$2.52, gg Production Rate = 0.24, $B\gamma\gamma$ = 0.08, $Bb\bar{b} = B\tau\bar{\tau}$ = 1.17, $BWW^{(*)}$ = 0.07.

- h_3
  m_{h_3} (GeV)=150, c_V=$-$0.49, c_t=$-$0.66, c_b=4.06, gg Production Rate = 0.89, $B\gamma\gamma$ = 0.05, $Bb\overline{b} = B\tau\overline{\tau}$ = 4.63, $BWW^{(*)}$ = 0.07.
- a_1
  m_{a_1} (GeV)=81, c_t= 0.00, c_b=$-$0.13, gg Production Rate = 0.00.
- a_2
  m_{a_2}(GeV)=137, c_t=0.19, c_b=5.22, gg Production Rate = 0.08.
- $H^\pm$
  $m_{H^\pm}$(GeV)=159.

Why so hard?

All WW, ZZ coupling shared among the h_i ⇒ kills decays and production using this coupling and also kills $\gamma\gamma$ coupling and decays.

$\tan\beta$ not very large ⇒ well inside 'LHC wedge' for all Higgs bosons.

Note: our entries for point 6 in the table are a bit pessimistic in that h_1 and h_2 are sufficiently degenerate that we should probably combine their signals. (Probably we can find a closely related point with significant mass separations so that discovery is challenging in the manner tabulated.)

Point	1	2	3	4	5	6
Channel	h_1 **Higgs boson**					
$N_{SD}(1)$	3.67	0.42	0.55	3.23	0.62	0.51
$N_{SD}(2)$	4.34	0.64	0.83	3.88	0.85	0.80
$N_{SD}(3)$	3.42	1.24	1.89	3.19	4.83	2.49
$N_{SD}(4)$	0.13	0.09	0.20	0.12	4.52	2.48
$N_{SD}(5)$	0.85	0.00	0.10	0.73	0.12	0.09
$N_{SD}(6)$	1.09	0.11	0.14	0.95	0.16	0.13
$N_{SD}(7)$	0.00	3.02	3.16	0.00	0.00	4.82
$N_{SD}(8)$	12.04	3.16	5.85	11.10	16.78	7.63
$N_{SD}(9)$	2.62	0.15	0.32	2.24	0.41	0.28
$\sqrt{\sum_{i=1}^{6}[N_{SD}(i)]^2}$	6.78	1.46	2.16	6.10	6.69	3.64
$\sqrt{\sum_{i=1}^{7}[N_{SD}(i)]^2}$	6.78	3.35	3.83	6.10	6.69	6.04
$\sqrt{\sum_{i=1-6,8,9}[N_{SD}(i)]^2}$	14.06	3.48	6.24	12.86	18.07	8.46
$\sqrt{\sum_{i=1}^{9}[N_{SD}(i)]^2}$	14.06	4.61	6.24	12.86	18.07	9.74

Point	1	2	3	4	5	6
Channel	h_2 Higgs boson					
$N_{SD}(1)$	3.59	0.97	0.79	3.61	0.22	0.39
$N_{SD}(2)$	3.79	1.46	1.19	3.88	0.05	0.60
$N_{SD}(3)$	1.88	3.76	2.09	2.17	0.99	2.13
$N_{SD}(4)$	0.11	1.29	0.45	0.12	3.62	2.54
$N_{SD}(5)$	2.00	0.19	0.15	1.78	0.56	0.07
$N_{SD}(6)$	1.49	0.26	0.21	1.40	0.38	0.10
$N_{SD}(7)$	0.00	0.00	3.13	0.00	0.00	2.76
$N_{SD}(8)$	12.50	13.89	11.11	13.23	7.41	7.63
$N_{SD}(9)$	6.03	0.71	0.56	5.53	0.19	0.26
$\sqrt{\sum_{i=1}^{6}[N_{SD}(i)]^2}$	6.09	4.35	3.45	6.16	3.82	3.39
$\sqrt{\sum_{i=1}^{7}[N_{SD}(i)]^2}$	6.09	4.35	4.66	6.16	3.82	4.37
$\sqrt{\sum_{i=1-6,8,9}[N_{SD}(i)]^2}$	15.15	14.57	11.64	15.61	8.34	8.35
$\sqrt{\sum_{i=1}^{9}[N_{SD}(i)]^2}$	15.15	14.57	12.06	15.61	8.34	8.80

Point	**1**	**2**	**3**	**4**	**5**	**6**
Channel	h_3 **Higgs boson**					
$N_{SD}(1)$	**0.00**	**0.60**	**0.59**	**0.01**	**0.00**	**0.65**
$N_{SD}(2)$	**0.00**	**0.19**	**0.19**	**0.00**	**0.00**	**0.24**
$N_{SD}(3)$	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
$N_{SD}(4)$	**3.82**	**3.13**	**3.19**	**3.50**	**1.55**	**3.39**
$N_{SD}(5)$	**3.64**	**3.16**	**3.06**	**4.41**	**1.54**	**2.36**
$N_{SD}(6)$	**0.83**	**3.00**	**2.88**	**1.19**	**0.38**	**1.85**
$N_{SD}(7)$	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
$N_{SD}(8)$	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
$N_{SD}(9)$	**0.00**	**1.00**	**0.96**	**0.00**	**0.00**	**0.70**
$\sqrt{\sum_{i=1}^{6}[N_{SD}(i)]^2}$	**5.52**	**5.40**	**5.32**	**5.92**	**4.76**	**4.58**
$\sqrt{\sum_{i=1}^{7}[N_{SD}(i)]^2}$	**5.52**	**5.40**	**5.32**	**5.92**	**4.76**	**4.58**
$\sqrt{\sum_{i=1-6,8,9}[N_{SD}(i)]^2}$	**5.52**	**5.49**	**5.40**	**5.92**	**4.76**	**4.64**
$\sqrt{\sum_{i=1}^{9}[N_{SD}(i)]^2}$	**5.52**	**5.49**	**5.40**	**5.92**	**4.76**	**4.64**

- **Unfortunately,** if we enter into parameter regions where the $h_i \rightarrow a_j a_j$, $a_j \rightarrow Z h_k$, $\ldots$ 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

  – $gg \rightarrow H^0 \rightarrow h^0 h^0$;
  – $gg \rightarrow A^0 \rightarrow Z h^0$.

  They provided some coverage at low $\tan\beta$ (where the above decays are strong), and should should provide coverage for NMSSM parameter choices for which these types of decays are dominant.

  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.

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, ..)

$$\mathcal{A}_{CP=+} \propto \vec{\epsilon}_1 \cdot \vec{\epsilon}_2\,, \quad \mathcal{A}_{CP=-} \propto (\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot \hat{p}_{\rm beam}\,. \tag{9}$$

  - 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.

CONCLUSIONS

- **In the simplest models (SM, MSSM), discovery and precision studies of a SM-like Higgs boson will be possible at the LHC and LC, and possibly the Tevatron.**

- **But, even in these models, complications due to invisible decays, 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.