Higgs sectors in which the only light Higgs is a A^0

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Outline

- **Motivations for Higgs doublets and beyond**
- **Escaping precision Electroweak constraints**
- **What will it take to find such an A^0?**

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 higher representations, e.g. triplets.**

  If neutral vev $\neq 0$, $\Rightarrow$ ρ **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.**

  Triplets are motivated by L-R models and seesaw neutrino mass generation. Aside from the triplet, an L-R must contain at least one doublet and more are certainly a possibility.

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

  To repeat, $\rho = 1$ 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 ...

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

- **We will find that there is no guarantee that in such generalized models we will find a light Higgs.**
  - **In particular, it is possible to construct a model in which the only (moderately light, i.e. $\lesssim \mathbf{0.5}~\mathrm{TeV}$) Higgs boson is a pseudoscalar member of a two (or more) doublet Higgs sector.**
  - **Such a model can be consistent with precision electroweak constraints.**
  - **Parameters are easily chosen so that discovery of the $\boldsymbol{A^0}$ is very difficult.**

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

For simplicity we will focus on the CPC case. It contains:

- CP-even h^0 and H^0.
- CP-odd A^0.
- Charged Higgs bosons $H^\pm$.

Some general points:

- A priori, there are no constraints on the masses other than ones required by perturbativity of the $\lambda_{i=1,7}$ quartic couplings of the most general potential for the model.
- An often discussed natural limit for the model is one in which m_{A^0} (along with m_{H^0} and $m_{H^\pm}$) become large (possibly well in excess of $1~\mathrm{TeV}$) while the h^0 remains relatively light.

  This is possible while keeping all the λ_i perturbative.

- **The scenarios we discuss are completely different from the above 'decoupling' limit.**

  In particular, the heavier Higgs bosons (h^0, H^0, $H^\pm$) must have masses not much above the $1~\mathrm{TeV}$ scale in order for the λ_i to remain in the perturbative domain.

  $\Rightarrow$ **They will be discovered at machines with large enough mass reach.**

- **A possible scenario if only the A^0 is light.**

  The LHC discovers a $1~\mathrm{TeV}$ SM-like h^0.

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

  What should one do next?

Satisfying precision electroweak constraints with only a light A^0.

(JFG, Farris, Chankowski, Grzadkowski, Kalinowski, Krawczyk)

- Assume that the $h_{\rm SM}$-like Higgs boson is heavy.

  $\Rightarrow$ 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 $\Rightarrow$

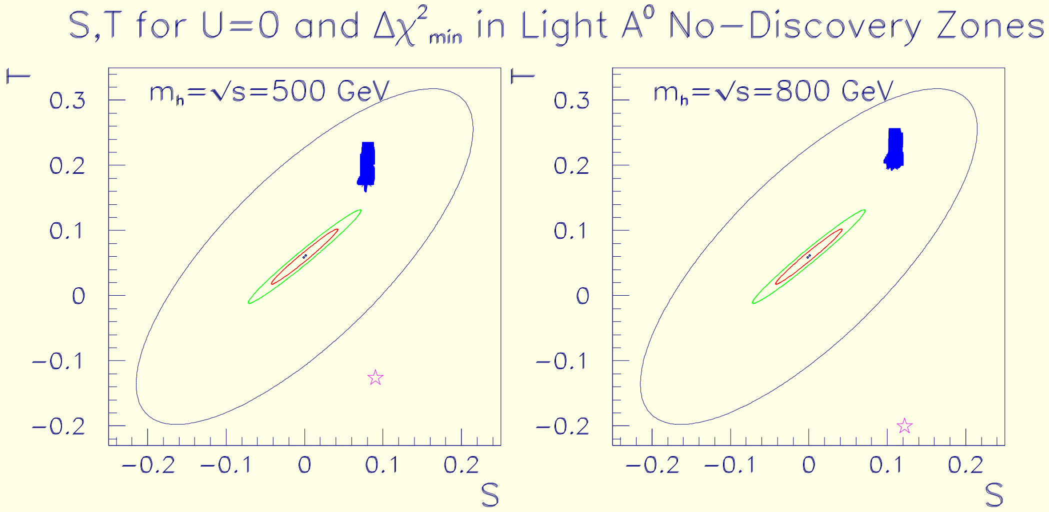
$$\Delta\rho = \frac{\alpha}{16\pi m_W^2 c_W^2}\left\{\frac{c_W^2}{s_W^2}\frac{m_{H^\pm}^2 - m_{H^0}^2}{2} - 3m_W^2\left[\log\frac{m_{h^0}^2}{m_W^2} + \frac{1}{6} + \frac{1}{s_W^2}\log\frac{m_W^2}{m_Z^2}\right]\right\} \tag{1}$$

Can adjust $m_{H^\pm} - m_{H^0} \sim \text{few GeV}$ (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 $\Delta m_W = 6 MeV$ from WW threshold scan) would pinpoint situation.



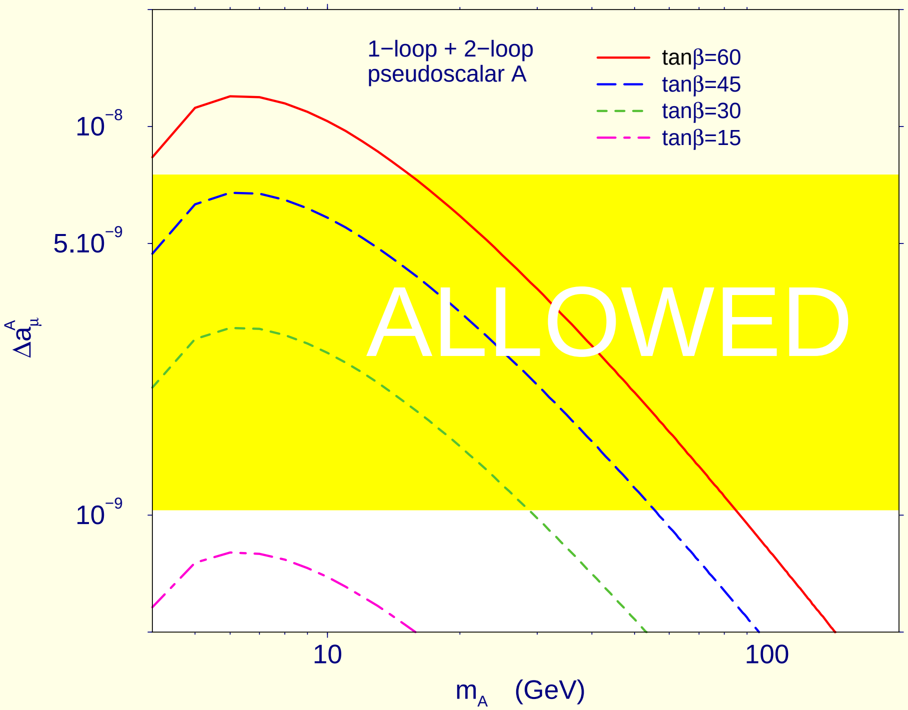
Outer ellipses = current 90% CL region for $U = 0$ and $m_{h_{\rm SM}} = 115$ GeV. Blobs = S,T predictions for Yukawa-wedge 2HDM models with minimum relative $\Delta\chi^2$. Innermost (middle) ellipse = 90% (99.9%) CL region for $m_{h_{\rm SM}} = 115$ GeV after Giga-Z *and* a $\Delta m_W \lesssim 6$ 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. (Cheung *et al.*, Krawczyk)

Light A^0 can $\Rightarrow$ appropriate Δa_μ.

For latest Δa_μ range ($\sim 3 \pm 1 \times 10^{-9}$), at moderate $m_{A^0} \gtrsim 50$ GeV, high $\tan\beta > 30 - 70$ is needed to explain Δa_μ. $\Rightarrow$ A^0 in LC/LHC 'no-discovery' wedges (roughly defined by $m_{A^0} > 50 - 100$ GeV and $\tan\beta \sim 6 \pm \Delta(m_{A^0})$) could only supply part of Δa_μ.



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

Detecting a light A^0.

At the LHC

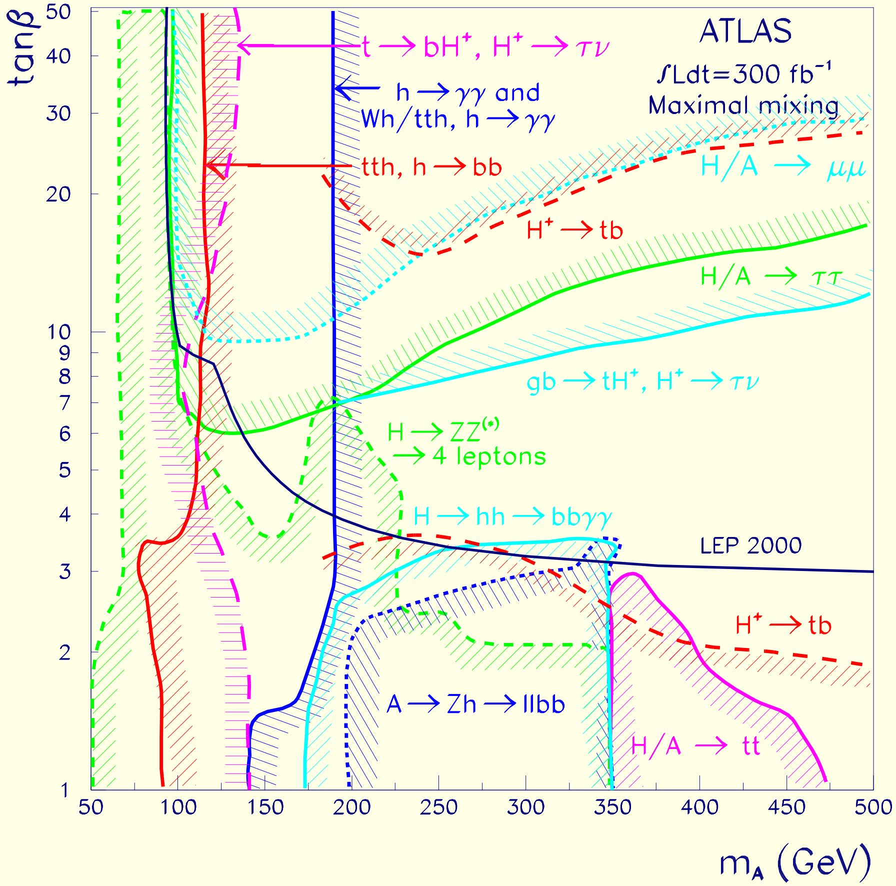


Figure 1: 5σ discovery contours for MSSM Higgs boson detection in various channels are shown in the $[m_{A^0}, \tan\beta]$ parameter plane, assuming maximal mixing and an integrated luminosity of $L = 300\mathrm{fb}^{-1}$ for the ATLAS detector.

The LHC MSSM wedge for $b\overline{b}H^0$ + $b\overline{b}A^0$ production ⇒ a presumably larger wedge for A^0 alone. Also note that there are no A^0 only modes below $m_{A^0} \sim 150$ GeV.

At e^+e^- , $\gamma\gamma$ and $\mu^+\mu^-$ colliders

Need to consider:

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

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

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

- $e^+e^- \to \gamma A^0$, ZA^0, $\nu_e\overline{\nu}_eA^0$ (all one-loop induced)

- $\gamma\gamma \to A^0$ (loop) and $\mu^+\mu^- \to A^0$ (tree).

Corresponding 'guarantees':

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

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

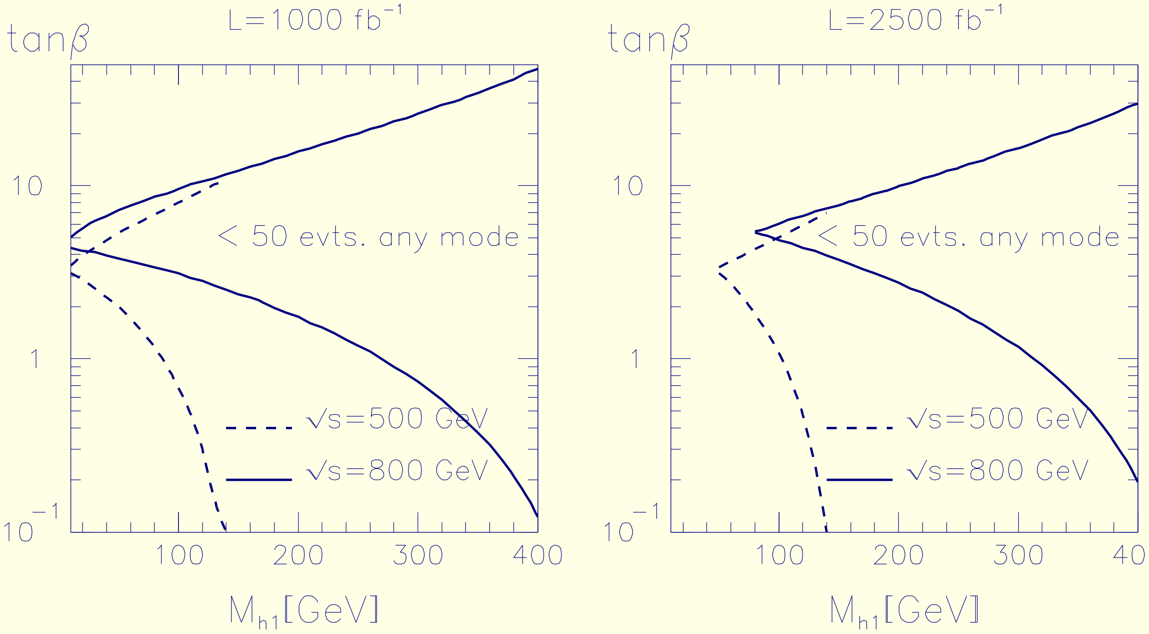
- The quartic couplings ZZA^0A^0 and $W^+W^-A^0A^0$, from gauge covariant structure $(D_\mu\Phi)^\dagger(D^\mu\Phi)$, are of guaranteed magnitude.

- $\gamma\gamma \to A^0$ 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 $\sqrt{s} = 500~\mathrm{GeV}$ (dashes) and $= 800~\mathrm{GeV}$ (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 $m_{A^0} \sim 80~\mathrm{GeV}$ ($\sqrt{s} = 800~\mathrm{GeV}$).

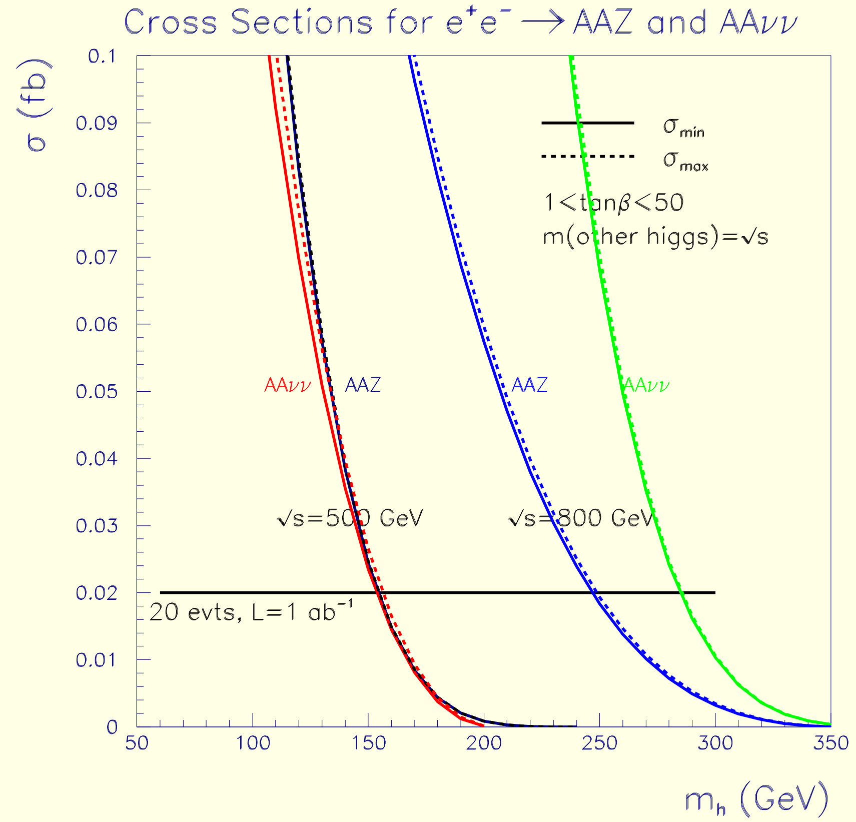
LHC ⇒ smaller bad region (due to high rates)? – MSSM studies suggest so.

Challenge: close these wedges!

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

A^0A^0Z and $A^0A^0\nu\bar{\nu}$ production allows discovery of light (decoupled) A^0. If 20 events sufficient:

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



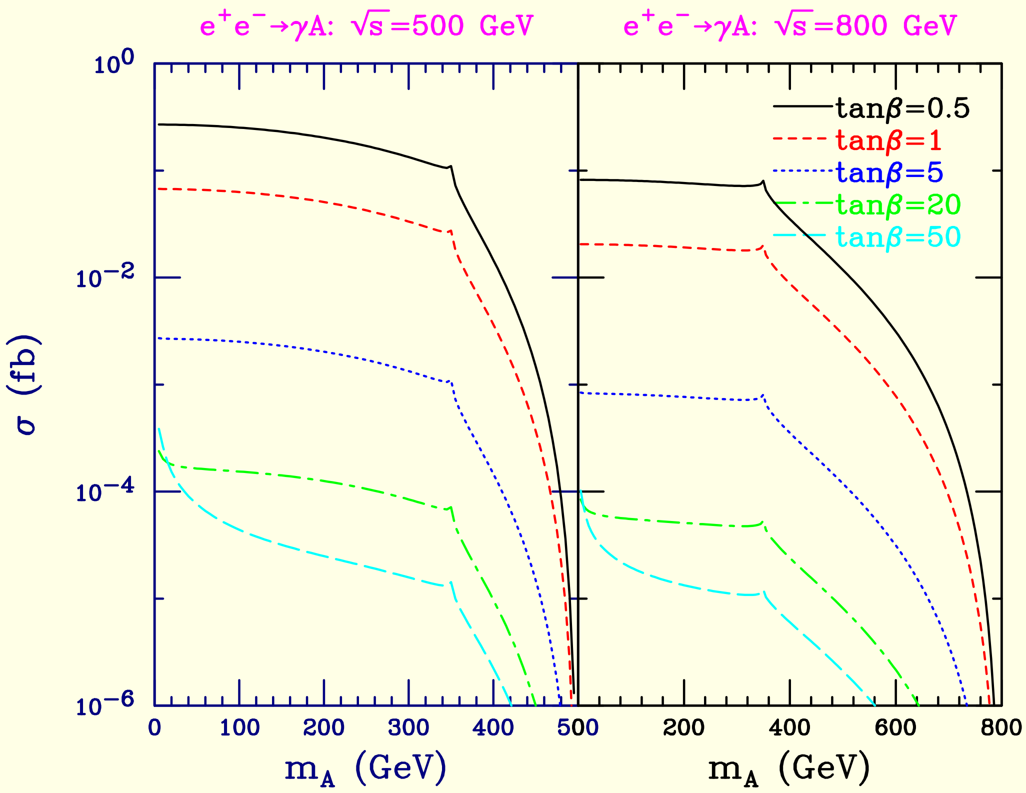
For $\sqrt{s} = 500~\mathrm{GeV}$ and $800~\mathrm{GeV}$ we plot the maximum and minimum values of $\sigma(e^+e^- \to A^0A^0Z)$ and $\sigma(e^+e^- \to A^0A^0\nu\bar{\nu}$ found for $1 < \tan\beta < 50$ for $m_{\text{other Higgs}} = \sqrt{s}$. The 20 event level for $L = 1~\mathrm{ab}^{-1}$ is indicated.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

But, 20 events probably not enough given that there are backgrounds.

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

- 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!

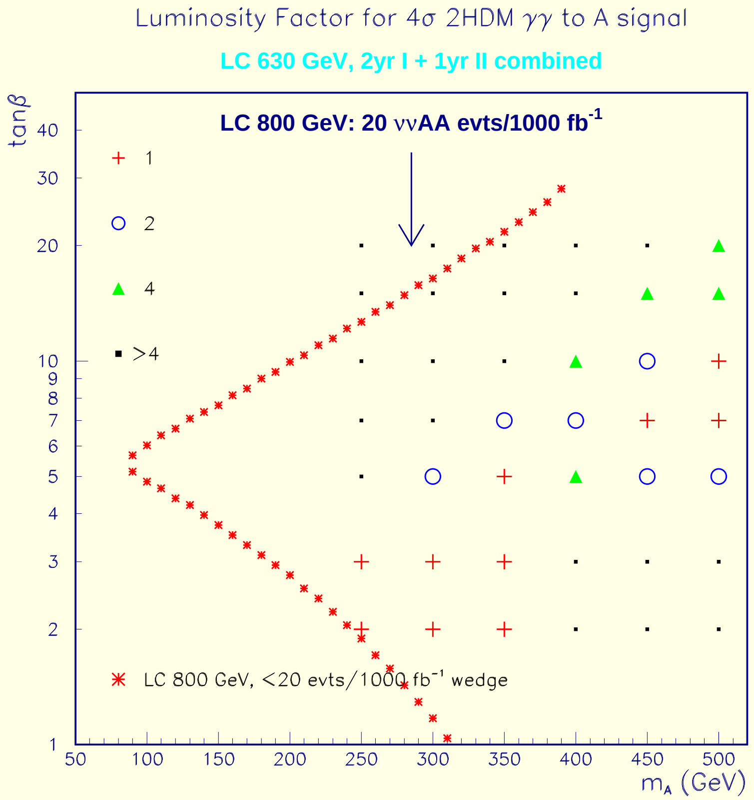


For $\sqrt{s} = 500~\mathrm{GeV}$, we plot $\sigma(e^+e^- \to \gamma A^0)$ as a function of m_{A^0}. (from JFG+Farris; see also Arhrib)

On the next page we show that $\gamma\gamma$ collisions could allow A^0 discovery in the wedge.

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.



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

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

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

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.

Conclusions

- It could happen that the only light Higgs boson is a multi-doublet A^0.

- 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.

- The precision electroweak data does not guarantee that a $\sqrt{s} = 600~\mathrm{GeV}$ e^+e^- LC 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.

  Further, Giga-Z studies and $\gamma\gamma$ collisions at the LC would then be very crucial to exposing the A^0.

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