Phenomenology of Generalized Higgs Boson Scenarios

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Outline

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• Extended Standard Model Higgs Sector

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• Perturbations of ‘Standard’ MSSM Phenomenology
Outline

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- Perturbations of ‘Standard’ MSSM Phenomenology
- Beyond the MSSM
• Extended Standard Model Higgs Sector

• Perturbations of ‘Standard’ MSSM Phenomenology

• Beyond the MSSM

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

• Radions

• Top-condensates etc.

• Pseudo-Nambu Goldstone Bosons of Technicolor
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 or higher reps.
  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); $\rho$ becomes another input parameter to the theory; is this so bad?

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

  $T = 3, |Y| = 4$ representations $\Rightarrow \rho = 1 + \text{finite loop correction for vev} \neq 0$
Coupling Unification Motivations for Multiple Exotic Representations

Recall 1-loop results (notation used is $N_{T,|Y|}$):

$$\alpha_s(m_Z) = \alpha_{QED}(m_Z) \frac{5(b_1 - b_2)}{\sin^2 \theta_W (5b_1 + 3b_2 - 8b_3) - 3(b_2 - b_3)}$$

$$M_U = \exp(2\pi t_U) \quad \text{with} \quad t_U = \frac{3 - 8 \sin^2 \theta_W}{5(b_1 - b_2) \alpha_{QED}(m_Z)}$$

$$b_1 - b_2 \quad SM = \frac{1}{5}(N_{0,2} + 4N_{0,4}) - \frac{1}{15}(N_{1/2,1} + N_{1,2}) + \frac{11}{15}N_{1/2,3} - \frac{2}{3}N_{1,0} + \ldots + \frac{616}{135}N_{3,4}$$

High-scale coupling unification without SUSY (want small $b_1 - b_2$):

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

Low-scale (extra dimensions . . .) unification with or without SUSY but keeping all SM particles and Higgs on the brane (want big $b_1 - b_2$):

e.g. SM case: $N_{1/2,1} = N_{1/2,3} = N_{1,2} = N_{1,0} = 4$, $N_{3,4} = 3 \Rightarrow \alpha_s(m_Z) = 0.112$, $M_U = 1000$ TeV, $\alpha_U = 0.04$.

e.g. SUSY case: $N_{1/2,1} = N_{1,2} = N_{1,0} = 4$, $N_{3,4} = 4 \Rightarrow \alpha_s(m_Z) = 0.114$, $M_U = 4$ TeV, $\alpha_U = 0.07$. 
In all cases, detection, simulation considerations change dramatically. Discovery prospects can vary widely: $e^+e^-$ collider is often best. Some examples will follow.

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Hints from Current Data?

Global fit (all observables) $\Rightarrow$ Higgs mass below current LEP limit for single SM Higgs.

There is possibility for spread-out Higgs weight (at $< \text{SM strength}$) throughout the interval plotted.
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 $10 - 20$ GeV (i.e. smaller than detector resolution in recoil mass spectrum) over some substantial range ⇒ diffuse signal≡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

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

(1)

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

- Precision electroweak suggests $\langle M^2 \rangle \lesssim (200 - 250 \text{ GeV})^2$.

- For multiple Higgs reps. of any kind in the most general SUSY context, RGE + perturbativity gives same result.

Assume $C_i^2$ constant from $m_{h_i}^{\text{min}}$ to $m_{h_i}^{\text{max}}$ (use continuum limit, $C_i^2(m_{h_i})$):
If LEP2 data eventually ⇒ $C^2(m_h)$ is small for $m_h \leq 70$ GeV in continuum spread-out sense (LEP2 ⇒ weak spread out signal for higher $m_h$ possibly present), then $\langle M^2 \rangle = [200 \text{ GeV}]^2 \Rightarrow m_h^{\text{max}} = 300$ GeV. ⇒ 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 $Z \to e^+e^−, \mu^+\mu^−$, $\sqrt{s} = 500$ GeV and $M_X = 70 − 200$ GeV region.

For $C^2(m_h) = \text{constant}$ for $70$ GeV $< m_h < 300$ GeV, evaluate fraction $f$ of Higgs signal.

- ⇒ $f \sim 0.43$ in $100 − 200$ GeV mass interval (avoids $Z$ region with largest background)

- $S \sim 1350f$ with a background of $B = 2700$, for $100 − 200$ GeV window, assuming $L = 500 \text{fb}^{-1}$.

- ⇒ we have to detect the presence of a broad ($\sim 50%f$) excess over background. For $f \sim 0.43$ ⇒ OK.

- Nominally, $S/\sqrt{B} \sim \frac{L}{500\text{fb}^{-1}} \times 26f$ for the $100 − 200$ GeV window in $M_X$.

Need $L \gtrsim 200 \text{fb}^{-1}$ to have a $S/\sqrt{B} > 5$ broad enhancement signal for $f \sim 0.5$. ⇒ NLC is ok.
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?
Q: Are we guaranteed to find a light Higgs boson if one exists?
A: It depends.

Suppose the only light Higgs boson has no $WW/ZZ$ couplings. (Cure precision EW problem using extra dimensions or ..., more later.)

Need to consider:

- $e^+e^- \rightarrow t\bar{t}h$ and $e^+e^- \rightarrow b\bar{b}h$. (JFG, Grzadkowski, Kalinowski)

- $e^+e^- \rightarrow Z^* \rightarrow Zhh$ (JFG, Farris)
  
  $e^+e^- \rightarrow e^+e^-W^*W^* \rightarrow e^+e^-hh$. (JFG, Farris, Zerwas etal)

- $\gamma\gamma \rightarrow h$ (JFG, Asner) and $\mu^+\mu^- \rightarrow h$ (JFG).

Corresponding ‘guarantees’:

- Fermionic coupling sum rules (Grzadkowski, Kalinowski, JG): for any $h$,
  
  $$(\hat{S}_h^t)^2 + (\hat{P}_h^t)^2 = \left(\frac{\cos\beta}{\sin\beta}\right)^2, \quad (\hat{S}_h^b)^2 + (\hat{P}_h^b)^2 = \left(\frac{\sin\beta}{\cos\beta}\right)^2$$

  where $\hat{S}$ and $\hat{P}$ are 1 and $\gamma_5$ couplings defined relative to usual SM type weight.

  $\Rightarrow$ either $t\bar{t}$ or $b\bar{b}$ coupling of $h$ must be big.
• The quartic couplings $ZZhh$ and $W^+W^-hh$, from gauge covariant structure $(D_\mu \Phi)^(D^\mu \Phi)$, are of guaranteed magnitude.

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A: No, but they certainly help.

e^+e^- \rightarrow t\bar{t}h$ always works if $\tan \beta$ is small enough (and process is kinematically allowed).
e^+e^- \rightarrow b\bar{b}h$ always works if $\tan \beta$ is large enough, but increasingly large $\tan \beta$ is required as $m_h$ increases.

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

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

Challenge: close these wedges!
Wedges extend to higher $m_h$ than plotted.

Conclusion: the fermionic coupling sum rules do not yield any guarantees. They only restrict the problematical region.
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Double Higgs production allows discovery of light decoupled $h$'s.

- $\sqrt{s} = 500$ GeV probes $m_h \lesssim 150$ GeV.
- $\sqrt{s} = 800$ GeV probes $m_h \lesssim 250$ GeV.

$WW \to hh$ fusion production $\Rightarrow$ similar.

For $\sqrt{s} = 500$ GeV and 800 GeV and for $h = h^0$ and $h = A^0$, we plot as a function of $m_h$ the maximum and minimum values of $\sigma(e^+e^- \to hhZ)$ found after scanning $1 < \tan \beta < 50$ taking all other Higgs masses equal to $\sqrt{s}$. For $h = h^0$, we require $\sin(\beta - \alpha) = 0$ during the scan. The 20 event level for $L = 1 \text{ ab}^{-1}$ is indicated.
Ability of $\gamma\gamma$ collisions to find a decoupled $h$ is marginal. Efficiency losses due to boosted $h$ rest frame ⇒ poor sensitivity if $m_h$ substantially below $\sqrt{s}$.
⇒ best approach is to run at various $\sqrt{s}$ values using spectrum peaked at high $E_{\gamma\gamma}$.
⇒ must use many $\sqrt{s}$ settings to cover a substantial $m_h$ range.

Result for 1 year of NLC operation assuming 80% polarization for both beams (need $e^-e^-$? — i.e. not parasitic to $e^+e^-$) is that for $\tan\beta \geq 7$, even the parton level results with unrealistically small 6 GeV mass bin ⇒ poor coverage. Would have to run at many energies, requiring many years! Is TESLA enough better? Hot off the press: New flat beam design ⇒ $L \to \sim 4L$. 

Assuming CAIN 1 year spectra, we plot the statistical significance of the $A^0$ signals for a 6 GeV $b\bar{b}$ mass bin centered on $m_{A^0}$. We employ a peaked spectrum at $\sqrt{s} = 630$ GeV. Various cuts are performed to reduce the background. Efficiency factors are not included and resolved photon backgrounds are neglected. JFG+Asner+...
Could a muon collider do better?
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Using the bremsstrahlung return tail in $E_{\mu^+\mu^-}$:

If $\tan \beta > 5$, operation at $R = 0.1\% \Rightarrow 4\sigma$ or higher bump in $m_{b\bar{b}}$ dist. after 3 to 4 years.
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**Scanning**

Adjust \( R \) so that \( \sigma \sqrt{s} \lesssim \Gamma_{h}^{\text{tot}} \) and employ appropriate \( L(R) \).

Steps of size \( \Gamma_{h}^{\text{tot}} \sim \sigma \sqrt{s} \).

\( 2m_t > m_h > 150 \text{ GeV} \Rightarrow h \rightarrow b\bar{b} \) and \( \Gamma_{h}^{\text{tot}} \sim 0.05 - 0.1 \text{ GeV} \) for \( \tan \beta > 1 \): employ \( R = 0.05 - 0.1\% \).

\( m_h > 2m_t \Rightarrow \Gamma_{h}^{\text{tot}} \gtrsim 1 \text{ GeV} \) : employ \( R = 0.5 - 1\% \).

3 – 4 year program, \( \Rightarrow \) devote:

- \( L = 0.003 \text{fb}^{-1} \) to 2000 points separated by 0.1 GeV in \( \sqrt{s} = 150 - 350 \text{ GeV} \) range — \( L_{\text{tot}} = 4 \text{fb}^{-1} = 3 \) years \( \Rightarrow \) \( 4\sigma \) level \( h \) signal in \( b\bar{b} \) if \( \tan \beta \gtrsim 4 - 5 \).

- \( L = 0.03 \text{fb}^{-1} \) to 100 points separated by 0.5 GeV in the \( \sqrt{s} = 350 - 400 \text{ GeV} \) range — \( L_{\text{tot}} = 3 \text{fb}^{-1} = 1/2 \) year \( \Rightarrow \) \( 4\sigma \) signal in \( b\bar{b} (t\bar{t}) \) for \( \tan \beta > 6 \) (\( \tan \beta < 6 \)).

- \( L = 0.01 \text{fb}^{-1} \) to 100 points separated by 1 GeV in the \( \sqrt{s} = 400 - 500 \text{ GeV} \) range — \( L_{\text{tot}} = 1 \text{fb}^{-1} = 1/10 \) year \( \Rightarrow \) \( 4\sigma \) signal in \( b\bar{b} (t\bar{t}) \) for \( \tan \beta > 7 \) (< 8).

**MUC** \( \Rightarrow \) \( 4\sigma \) if \( m_h < 2m_t \), \( \tan \beta \gtrsim 5 \) or if \( m_h > 2m_t \), any \( \tan \beta \).
Precision Electroweak Constraints for a light decoupled 
h = A^0 or h = h^0 and no other observable Higgs at e^+e^- 
collider (\sqrt{s} \lesssim 800 \text{ GeV})?

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

If h = A^0 (decoupled h^0) then want h^0 (H^0) to be SM-like with mass \lesssim 1 \text{ TeV}. 
\Rightarrow \text{ 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. E.g. for light A^0, take h^0 heavy and SM-like \Rightarrow

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

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 $m_{h^0} > \sqrt{s} = 500$ 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 $\tan \beta > 1$).

Giga-Z (with $\Delta m_W = 6$ MeV from $WW$ threshold scan) would pinpoint situation.
$a_\mu = \text{evidence for light 2HDM } A^0$?

A light $A^0 (h^0)$ gives a positive (negative) contribution dominated by two-loop Bar-Zee graph. $10.3 \times 10^{-10} < \Delta a_\mu < 74.9 \times 10^{-10}$ at 95% C.L. ($\pm 1.96\sigma$) for ‘standard’ $\sigma(e^+e^- \rightarrow \text{hadrons})$ at low $\sqrt{s}$.

If we use light $A^0$ as entire explanation, $\Rightarrow$ appropriate $\Delta a_\mu$.
In the indicated range of $\tan \beta > 17$, it will be found at $LC$ for sure.

Is light $A^0$ discovery at the LHC hard?? Possibly not.
Alternative low-$E$ $\sigma(e^+e^- \rightarrow \text{hadrons})$ $\rightarrow$ less $\Delta a_\mu$ needed $\rightarrow$ smaller $\tan \beta$ and/or higher $m_{A^0}$ wanted $\Rightarrow$ enter LC/LHC wedges.

Explanation of new BNL $a_\mu$ value via light 2HDM $A^0$. (Cheung, Chou, Kong)
Extra Dimensions and the ‘SM’ Higgs
Extra Dimensions and the ‘SM’ Higgs

A single SM Higgs and its small couplings could be natural after all. (Dimopoulos, Arkani-Hamed, Schmaltz, . . .).

- In simplest model, SM particles live on a ‘brane’ (3+1 dimensions), and gravity resides in the bulk. (Can allow SM particles in bulk.)

- In extra dimension theories, $\Lambda$ (new physics scale) $= M_S$, the string scale, which is possibly as small as 1 TeV.

- Quadratic divergence at 1-loop for $m_H^2$ is cutoff by string at $M_S$.

- Small fermionic couplings could arise if the brane is ‘fat’ and the fermion fields are localized within brane so as to have little overlap with the Higgs field(s) (except top).
The precision electroweak constraints need not be so constraining as before (Kolda, Rizzo, Wells, . . .). Example:

- Suppose fermions live on the brane, but gauge bosons propagate in the bulk.

- Consider precision observable $O_i$. Roughly we can write

$$O_i = O_i^{SM} + a_i \ln \frac{m_H}{m_Z} + b_i V$$

where $V \equiv 2 \sum \bar{n} \frac{g^2}{g^2} \frac{m_W}{M_c^2}$ ($M_c = 1/R$, $R =$compactification radius, and $\bar{n} = (n_1, \ldots, n_\delta)$ labels the KK excitations of the gauge bosons).

- A good fit is $m_H \sim m_Z$ and $b_i V = 0$.

  But, if $b_i V$ cancels $a_i$ term to appropriate level, then $m_H > m_Z$ gives equally good fit.

- Full analysis shows that $m_H \leq 1$ TeV is required at the 95% CL after computing full $\Delta \chi^2$ coming from all observables and allowing $V$ to choose best overall value.

  In above scenario, there is new physics at the 1 to 10 TeV scale!
The KK graviscalar excitations could provide the mechanism for electroweak symmetry breaking (Grzadkowski+JG).

- All SM particles on the brane = the simplest case.

- Must minimize effective potential consisting of \( V(\phi) - L_{\text{mass}}(\phi_{KK}) - L_{\text{mix}}(\phi_{KK}, \phi) \), where \( \phi \) is the usual Higgs field, \( L_{\text{mass}} \) contains the quadratic mass terms for the KK graviscalar fields \( \phi_{KK} \), and \( L_{\text{mix}} \propto \kappa \sum \bar{n} \phi_{KK} T^\mu, \) Higgs \( \propto \kappa \sum \bar{n} \phi_{KK} V(\phi) \) arises because gravity sees the energy-momentum tensor.

\[ \kappa \propto 1/M_P \] is small, but there are many \( KK \) modes.

- After integrating out \( KK \) modes, get \( \bar{V}_{\text{tot}} = V(\phi) - \bar{D} V^2(\phi) \), where
\[ \bar{D} \equiv \kappa^2 \frac{\delta - 2}{\delta + 2} \sum_{\text{all} \bar{n}} \bar{n} \frac{1}{m_n^2} \] (\( \delta =\) number of extra dimensions).

For \( \delta = 1 \), \( \bar{D} < 0 \).

For \( \delta > 2 \), the sum is divergent – after regulation by the string, \( \bar{D} \sim M_S^{-4} \) with sign that depends upon the string regulation. It is possible that \( \bar{D} < 0 \).

**Note that even if** \( V(\phi) = \frac{1}{2} m^2 \phi^2 + \Xi \) (no quartic self interactions), \( L_{\text{mix}} \) generates \( \phi^4 \) interactions (of correct sign if \( \bar{D} < 0 \)).
• If $\overline{D} < 0$, then $\overline{V}_{\text{tot}}$ has a minimum at $V(\phi) = \frac{1}{2\overline{D}}$, which determines values for $\phi$ and the $\phi_{KK}$ fields at the minimum.

• Expanding about the vev’s, rescaling $\phi \rightarrow \hat{\phi}$ for canonical normalization, and diagonalizing the mass matrix, one finds:
  
  – a Higgs boson $s_{\text{phys}}$ with $m_{s_{\text{phys}}}^2 > 0$.
  – Standard $WW/ZZ$ couplings for $s_{\text{phys}}$ (with tiny corrections) requiring $\hat{v} = 246$ GeV;
  – Absence of fermionic couplings of $s_{\text{phys}}$ at tree level;
  – Large decays of $s_{\text{phys}}$ to states containing two graviscalar $KK$ excited states (which are invisible decays).

• Any non-zero value of $\langle V(\phi) \rangle$ ($\overline{D} < 0 \text{ or } \overline{D} > 0$), modifies all KK mode couplings to fermions and scalars.

• Actual size of $M_S$ not important; mechanism operates even if $M_S$ is very large.
For normal EWSB minimum, mixing between graviscalar-KK excitations and Higgs could lead to effectively invisible Higgs decays (Giudice, Ratazzi, Well).

- Introduce extra $-\frac{\zeta}{2} R(g) \phi \phi^\dagger$ interaction, where $R$ is the usual Ricci scalar.
  
  No particular motivation, but certainly allowed, and if allowed . .

- This leads to an addition to $T_\mu^\mu$ for the $\phi$; in unitary gauge $\Delta T_\mu^\mu = -6 \zeta v m_H^2 H$ and the graviscalar KK modes $\phi^{\vec{n}}_{KK}$ couple to this: $\mathcal{L} \ni \frac{f(\delta)}{M_p} \sum \vec{n} \phi^{\vec{n}}_{KK} T_\mu^\mu$.

- The resulting $H-\phi^{\vec{n}}_{KK}$ mixing must be removed by rediagonalization, and the physical Higgs ends up having some KK-graviscalar excitation components.
  
  $\Rightarrow H_{\text{phys}}$ is invisible, due not only to mixing with but also decays to KK-graviscalars.
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Combining Higgs-graviscalar mixing, possibly with unconventional EWSB minimum, $\Rightarrow$ many phenomenological variants. Sorting it all out may be a challenge.
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At LEP2, NLC

For any Higgs with $ZZ$ coupling, simply use $Z + X$, recoil $M_X$ distribution and look for peak.

LEP2 limits on a single H with SM-like coupling to $ZZ$ from $Z + X$, even after allowing most general mixture between normal and invisible, are near kinematic limit.

NLC presumably would achieve kinematic limit also.

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Life at hadron colliders is tougher.

For any Higgs with $WW, ZZ$ couplings, use $WH$, $ZH$ (Frederikson etal, Roy+Choudhury) or $WW$ fusion (Zeppenfeld) (with jet tags). Assume pure invisible decays.
• Tevatron result: Need (Martin+Wells) $L > 5\text{fb}^{-1}$ to surpass LEP2 limit.

• At the LHC, $L = 100\text{fb}^{-1}$ in $WH, ZH$ will probe up to $\sim 200\text{ GeV}$; in $WW$ fusion, estimated reach (Zeppenfeld) is $300 - 500\text{ GeV}$.

For any Higgs with $t\bar{t}$ coupling, use (JFG) $t\bar{t}H$ production (LHC only); estimated reach is $250 - 300\text{ GeV}$ at $L = 100\text{fb}^{-1}$.

Note complementarity of the modes depending on $VV$ couplings and the $t\bar{t}H$ mode. $\Rightarrow$ should work on both.

If invisible+normal decays, would the Higgs be missed?

LEP2 analyses show little loss. Probably also applies to LC. Probably makes LHC discovery difficult.

Challenge: improve sensitivity to Higgs which decays invisibly or 50% so at Tevatron and, especially, LHC.
Models with Higgs triplet representations

Generic $2 \times 2$ 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: \( \Delta_R \) and \( \Delta_L \) with \( \langle \Delta^0_L \rangle = 0 \) (keeps \( \rho = 1 \) natural) and \( \langle \Delta^0_R \rangle \) = 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 \( \Delta_R \) and \( \Delta_L \).

- 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:

\[
\mathcal{L}_Y = i h_{ij} \psi_i^T C \tau_2 \Delta \psi_j + \text{h.c.}, \quad i, j = e, \mu, \tau .
\] (3)
⇒ lepton-number-violating $e^-e^- \rightarrow \Delta^{--}$ (or $\mu^-\mu^- \rightarrow \Delta^{--}$) coupling.

Limits on the $h_{ij}$ by virtue of the $\Delta^{--} \rightarrow \ell^-\ell^-$ couplings: writing $|h_{\ell\ell}^{\Delta^{--}}|^2 \equiv c_{\ell\ell}m_{\Delta^{--}}^2$ (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 $\rho = 1 = \text{natural}$), $\Gamma_T^{\Delta^{--}}$ would be small. ⇒ possibly very large $s$-channel $e^-e^-$ and $\mu^-\mu^-$ production rates.

**Strategy:**

- Discover $\Delta^{--}$ in $p\bar{p} \rightarrow \Delta^{--}\Delta^{++}$ with $\Delta^{--} \rightarrow \ell^-\ell^-$, $\Delta^{++} \rightarrow \ell^+\ell^+$ ($\ell = e, \mu, \tau$) at TeV33 or LHC (J.G., Loomis, Pitts: hep-ph/9610237).

  ⇒ TeV33 + LHC will tell us if such a $\Delta^{--}$ 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 \(\sigma\sqrt{s}\))

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

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

– For 100 events, Eq. (4) \(\Rightarrow\) we probe

\[c_{ee}\big|_{100 \text{ events}} \sim 3.3 \times 10^{-14} \left(\frac{R}{0.2\%}\right) \left(\frac{50fb^{-1}}{L}\right), \quad \Gamma_{\Delta^{--}}^{T} \ll \sigma\sqrt{s},\]

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 \(\Delta^{--} \rightarrow \mu^{-}\mu^{-}\) primarily, 10 events might \(\rightarrow\) a viable signal.

The Challenge: if you see a \(\Delta^{--}\), how do you look for all its partners.
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  More doublets, triplets, etc. $\Rightarrow$ generally need intermediate scale matter between TeV and $M_U$ scales.

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  **BUT**, if there are extra dimensions, 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 $m_{\tilde{t}} \leq 1$ TeV for naturalness)?
– In two-doublet MSSM, $m_{h^0} \lesssim 130 - 135$ GeV, although extra dimension effects might modify.
– Adding singlets, e.g. NMSSM one complex singlet added, pushes this up to roughly 150 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 $\sim 200$ GeV.
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**Experimental limits from LEP2 on MSSM Higgs bosons are significant.**

For maximal mixing (a certain choice of $X_t \equiv A_t - \mu \cot \beta$): $m_{h^0}, m_{A^0} \gtrsim 91$ GeV are required and $\tan \beta \lesssim 2.7$ is excluded.

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**But:** $\tilde{m}_t < 1$ TeV is assumed; CP violation in Higgs sector is neglected; invisible decays are not allowed for.

**Higher $\tilde{m}_t$:**

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

CP violation arises in the MSSM through phases of the $\mu$ 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 $\theta$, the latter being the phase of one of the Higgs doublet fields relative to the other.

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**Invisible Decays:**

Allowing for $h^0$ and $A^0$ to have some, perhaps substantial, invisible decays would considerably weaken the constraints on the $h^0 A^0$ cross section, $Z + X$ would have to be relied upon more heavily.

I would guess that the limits deteriorate substantially.

This deserves study by the experimental groups.
Discovery prospects in the MSSM at Tevatron and LHC
The Tevatron

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

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

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

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

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

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

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 $\tilde{g}, \ldots$?

Go to LC?

5σ discovery contours for MSSM Higgs boson detection in various channels are shown in the $[m_{A0}, \tan\beta]$ 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 $h_{SM}$.

⇒ precision measurements of $\sim$SM properties ($m_{A^0} > 2m_Z$).
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  \[ \Rightarrow \text{precision measurements of } \sim \text{SM properties} \left( m_{A^0} > 2m_Z \right). \]

• 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 $e^+e^- \rightarrow H^0 + A^0$ and $e^+e^- \rightarrow H^+ + H^-$. 
  
  But, given that $m_{H^0} \sim m_{A^0} \sim m_{H^\pm}$ for large $m_{A^0}$, these all require $\sqrt{s} \gtrsim 2m_{A^0}$. 
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• **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, . . .)
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- 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 $m_{A^0} \sim m_{H^0}$.
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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 $\sim 50$ GeV and use 5 steps in $\sqrt{s}$ to explore each of 5 intervals of width 10 GeV — $m_{A^0} \in [E_{\gamma\gamma}^{\text{peak}}, E_{\gamma\gamma}^{\text{peak}} + 10 \text{ GeV}]$.

If you don’t trust indirect $m_{A^0}$ determination (is there a way to know if you should trust it?) then what?
6 GeV $m_{b\bar{b}}$ resolution is too optimistic – perhaps 7% or so ⇒ much larger background at high mass Beamstrahlung, etc. means $\langle \lambda \lambda' \rangle$ is not large enough to really kill the background except near the $\sim 500$ GeV peak.

Larger $N_{SD} \equiv S/\sqrt{B}$ than for $A^0$ only because of overlapping $H^0 + A^0$ signals.

1-2 years of operation will not allow discovery throughout the LHC wedge.

Results after 1 year or running assuming $\sqrt{s} = 630$ GeV, NLC peaked CAIN spectrum and 6 GeV resolution in $b\bar{b}$ mass.
If $m_{A_0}$ is unconstrained by precision $h^0$ measurements and/or we distrust ‘standard scenario’ interpretations of these measurements, $\Rightarrow$ same two options discussed earlier for decoupled light $h$: 
Discovery at a Muon Collider

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- **Bremsstrahlung tail:**
  
  3 years of operation at maximum energy ⇒ $4\sigma$ $m_{b\bar{b}}$ bump for $m_{A^0} < 2m_t$ if $\tan\beta > 6 - 7$ and for all $\tan\beta$ if $m_{A^0} > 2m_t$

  Mass resolution critical: we have assumed optimistic value for above statement. Study needed.
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- **Scanning:**
  Use strategy of adjusting $R$ as expected size of $\Gamma_{A_0}^{\text{tot}}, \Gamma_{H^0}^{\text{tot}}$ increases with mass, $\Rightarrow 4\sigma$ signal after 3 years for $\tan \beta > 5$ if $m_{A_0} < 2m_t$) and for all $\tan \beta > 1$ if $m_{A_0} > 2m_t$.
  Mass resolution in $b\bar{b}$ final state again important.
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Once found, a fine scan can separate out even very degenerate $A^0$ and $H^0$. Note: $m_{A^0} - m_{H^0}$ will provide a very important constraint on SUSY parameters.
Variants of ‘standard’ results ⇒ be cautious.
**Invisible decays.**

Will probably allow non-detection scenarios at hadron colliders.

\( h^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \) still possible given LEP2 data.

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

- Choose \( M_1/M_2 \) small \( \Rightarrow \) \( m_{\tilde{\chi}_1^0} \) can be small \( (i.e. \) good phase space for decay despite limits on \( m_{h^0} \)) while \( m_{\tilde{\chi}_1^\pm} \) can satisfy \( m_{\tilde{\chi}_1^\pm} > 103 \text{ GeV} \) (LEP2).

  ‘Standard’ \( M_1/M_2 = 1/2, \Rightarrow \) maximum \( B(h^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) \sim 20\% \).

  \( M_1/M_2 = 1/10 - 1/5 \) allows \( B(h^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) > 50\% \).

- need \( (O_{12} - \tan \theta_W O_{11})(\sin \beta O_{14} - \cos \beta O_{13}) \) large \( -- i.e. \) \( \tilde{\chi}_1^0 \) must have substantial higgsino content.

\( \Rightarrow \mu \) (and \( M_2 \)) not too big.

- small \( M_1, M_2 \) and \( \mu \) also good for \( a_\mu \).
Sample case (Belanger et al.): \( M_1/M_2 = 1/5 \)

- Semi-vertical lines are \( B(h^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0) \) contours.

- Dotted lines show \( a_\mu \).

- \( 0.1 < \Omega h^2 < 0.3 \) in white areas.

- Black region is where \( m_{\tilde{\chi}_1^\pm} < 103 \text{ GeV} \) and is excluded.

\[ \Rightarrow \text{large } B(h^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0) \text{ possible if } \tilde{\chi}_1^\pm \text{ and } \ell_R \text{ are nearby} \]
Stop loop corrections to one-loop couplings

Stop and top loops negatively interfere: ⇒

- Reduction of $gg$ fusion production.
- Some increase in $B(H \rightarrow \gamma\gamma)$. 
Stop loop corrections to one-loop couplings

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Radiative corrections to couplings.

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

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

Consider latter in more detail.

• Notation: at tree-level $H^0_u$ ($H^0_d$) couples to $t\bar{t}$ ($b\bar{b}$).

\[ h^0 = -\sin \alpha \text{Re} H^0_d + \cos \alpha \text{Re} H^0_u, \quad H^0 = \cos \alpha \text{Re} H^0_d + \sin \alpha \text{Re} H^0_u. \]

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

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

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

If $\tan \alpha \simeq \frac{\Delta \lambda_b}{\lambda_b}$ then $\lambda^h_{b} \simeq 0$. 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 $\lambda^h_{b}$ is possible.

Many effects on discovery modes of light Higgs:

Suppressed $\Gamma(h^0 \to b\bar{b})$ implies enhanced $B(h^0 \to \gamma\gamma)$, $B(h^0 \to WW^*)$.

In fact, the $\gamma\gamma$ mode can be viable for some range of $m_{h^0}$ at the Tevatron if $h^0 \sim H_u$ (Mrenna+Wells).

Allowing for either suppressed or enhanced $\lambda^h_{b}$, $\Rightarrow$ (Carena etal) LHC $gg \to h^0 \to \gamma\gamma$ and Tevatron $Wh^0[\to WW^*]$ modes improve when LHC, Tevatron $W, Zh^0[\to b\bar{b}]$ modes deteriorate.

Tevatron and LHC are complementary as $\lambda^h_{b}$ and $m_{h^0}$ vary in that $h^0$ discovery will occur at one or the other machine, even if not both.

$e^+e^- \to ZX$ (inclusive recoil) $= \text{robust vs. decay uncertainties.}$
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 $\tilde{\chi}_1^0 \tilde{\chi}_1^0, \tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\tau}^+ \tilde{\tau}^-, \tilde{\nu} \tilde{\nu}, \ldots$ decays are kinematically allowed.
However, at high $\tan \beta$ the usual dominance of decays to $b\bar{b}$ and $\tau^+ \tau^-$ will be preserved.
$\Rightarrow$ only some widening of $h^0$-only LHC wedge.
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- $e^+e^- \text{ collider } H^0A^0$ 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 ⇒ immensely powerful probe of soft SUSY breaking. But, must separate different final state channels ($[3\ell, 2b], [1\ell, 0b], \ldots \ldots$ — maybe 15 or 20 different channels) and know efficiencies for different channels with good precision.
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- $\gamma\gamma \rightarrow H^0, A^0$ discovery could become much more difficult.

- $\mu^+ \mu^- \rightarrow H^0, A^0$ discovery could become more difficult.

Last two items need serious study in a few reasonable models.
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) \( \Rightarrow \)

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

New Results (JFG+Ellwanger+Hugonie) \( \Rightarrow \)

One important missing item in 96 was a mode in which a light Higgs could be found in \( b\bar{b} \) decay channel.

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) analysis for \( h_{SM} \)).
Our procedure:
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The modes employed in 1996 were:

1) $Z^* \rightarrow Zh$ at LEP2; 2) $Z^* \rightarrow ha$ at LEP2; 3) $gg \rightarrow h \rightarrow \gamma\gamma$ at LHC; 4) $gg \rightarrow h \rightarrow ZZ^*$ or $ZZ \rightarrow 4\ell$ at LHC; 5) $t \rightarrow H^+b$ at LHC; 6) $gg \rightarrow b\bar{b}h, b\bar{b}a \rightarrow b\bar{b}\tau^+\tau^-$ at LHC; 7) $gg \rightarrow h, a \rightarrow \tau^+\tau^-$ at LHC.

The new mode of 2001 is: 8) $gg \rightarrow t\bar{t}h \rightarrow t\bar{t}b\bar{b}$
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We avoided regions of parameter space:

Where the highly model-dependent decays a) $a \rightarrow Zh$; b) $h \rightarrow aa$; c) $h_j \rightarrow h_i h_i$; d) $a, h \rightarrow t\bar{t}$ would be relevant.
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- A scan of all ‘1996 no-discovery’ cases encountered no points and parameter choices for which no Higgs would be discovered at the LHC with $L = 300 \text{fb}^{-1}$ per detector.

But, a more complete scan shows some points with at most $3\sigma$ discovery.
CP DETERMINATIONS

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• 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. ⇒ 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 ($\sqrt{s} > 800$ 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 γγ (via 1-loop diagrams),

At the LC, ⇒ use γγ collisions. (JFG, Grzadkowski; JFG, Kelly; Djouadi etal, ..)

\[ A_{CP=+} \propto \vec{\epsilon}_1 \cdot \vec{\epsilon}_2, \quad A_{CP=-} \propto (\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot \hat{p}_{\text{beam}}. \] (6)

– 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 the LHC, can used polarized protons which transmit polarization to the gluons (substantially, according to many estimates) and can then proceed as in γγ collisions. (JFG, Yuan) **Backgrounds/sensitivity need experimental study.**

• At a muon collider Higgs factory there is a particularly appealing approach. For
resonance, $R$, production at a $\mu C$ with $\bar{\mu}(a + ib\gamma_5)\mu$ coupling to the muon,

$$
\bar{\sigma}_S(\zeta) = \bar{\sigma}_S^0 \left(1 + P_L^+ P_L^- + P_T^+ P_T^- \left[\frac{a^2 - b^2}{a^2 + b^2} \cos \zeta - \frac{2ab}{a^2 + b^2} \sin \zeta\right]\right)
\begin{equation}
= \bar{\sigma}_S^0 \left[1 + P_L^+ P_L^- + P_T^+ P_T^- \cos(2\delta + \zeta)\right],
\end{equation}
$$

\begin{align*}
\delta &\equiv \tan^{-1} \frac{b}{a}, \\
P_T \ (P_L) &\text{ is the degree of transverse (longitudinal) polarization: no } P_T \Rightarrow \text{ sensitivity to } \bar{\sigma}_S^0 \propto a^2 + b^2 \text{ only.} \\
\zeta &\text{ = angle of the } \mu^+ \text{ transverse polarization relative to that of the } \mu^- \text{ as measured using the the direction of the } \mu^- \text{'s momentum as the } \hat{z} \text{ axis.} \\
\text{Only the } \sin \zeta \text{ term is truly CP-violating, but } \cos \zeta \text{ also } \Rightarrow \text{ significant sensitivity to } a/b.
\end{align*}

Ideal = isolate $\frac{a^2 - b^2}{a^2 + b^2}$ and $\frac{-2ab}{a^2 + b^2}$ via the asymmetries (take $P_T^+ = P_T^- \equiv P_T$ and $P_L^\pm = 0$)

$$
\mathcal{A}_I \equiv \frac{\bar{\sigma}_S(\zeta = 0) - \bar{\sigma}_S(\zeta = \pi)}{\bar{\sigma}_S(\zeta = 0) + \bar{\sigma}_S(\zeta = \pi)} = P_T^2 \frac{a^2 - b^2}{a^2 + b^2} = P_T^2 \cos 2\delta,
$$

$$
\mathcal{A}_{II} \equiv \frac{\bar{\sigma}_S(\zeta = \pi/2) - \bar{\sigma}_S(\zeta = -\pi/2)}{\bar{\sigma}_S(\zeta = \pi/2) + \bar{\sigma}_S(\zeta = -\pi/2)} = -P_T^2 \frac{2ab}{a^2 + b^2} = -P_T^2 \sin 2\delta.
$$
But, must account for polarization precession: $\Rightarrow$ can’t fix polarization directions. But, precession can be easily incorporated (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 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.

  ⇒ keep improving and working on every possible signature.

  ⇒ LHC ability to show that $W W$ sector is perturbative could be important

• The precision electroweak data does not guarantee that a $\sqrt{s} = 600$ 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.

- **LHC must:**
  (a) prove ability to separate $gg$ fusion from $WW$ fusion (for SM Higgs at least) to allow real access to model independent coupling determinations (Zeppenfeld, etal);
  (b) make one of the proposed CP determination techniques work;
  (c) work hard to close the $h^0$-only wedge as much as possible;
  (d) work hard on Higgs $\rightarrow b\bar{b}$ and $\rightarrow$ invisible detection channels.

- **LC must:**
  (a) provide clear path to $\sqrt{s} > 1$ TeV;
  (b) improve $\gamma\gamma$ collision option to point where:
    (i) Detection of Higgs with no $WW, ZZ$ (including $H^0, A^0$) is possible in ‘wedge’ region.
(ii) Transverse polarization asymmetry determinations of Higgs CP properties are possible at a precision level.

New design with increased luminosity a big step forward. But, must also decrease mass resolution in $b\bar{b}$ final state as much as possible.

- **Muon Collider must:**

  (a) get more R&D funding;
  (b) design for higher luminosity for all $R$ values and for higher degrees of beam polarization.

  A factor of 5 increase in the luminosities would:
  - allow precision studies of SM-like Higgs that would exceed in some respects the LC sensitivity to higher scale phenomena.
  - allow the best CP determination of a light narrow Higgs boson using transverse polarization asymmetries.
  - allow scan discovery of Higgs bosons with no $WW, ZZ$ coupling for all $\tan\beta \gtrsim 1$; followup measurements of properties including CP determination would also be possible with high precision.