Phenomenology of Generalized Higgs Boson Scenarios

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Outline

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

- Radions
- Top-condensates etc.
- 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 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); 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.

  $T = 3, |Y| = 4$ representations $\Rightarrow \rho = 1+$finite loop correction for vev$\neq 0$

Coupling Unification Motivations for Multiple Exotic Representations

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

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

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

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

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

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

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

e.g. SUSY case: $N_{\frac{1}{2},1}=N_{1,2}=N_{1,0}=4, N_{3,4}=4 \Rightarrow \alpha_s(m_Z)=0.114$, $M_U=4\text{ TeV}$, $\alpha_U=0.07$.

In all cases, detection, simulation considerations change dramatically.

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

Some examples will follow.

Hints from Current Data?

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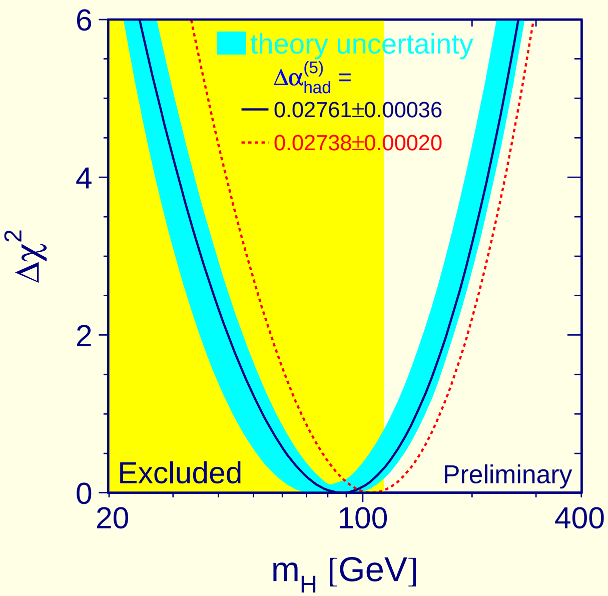
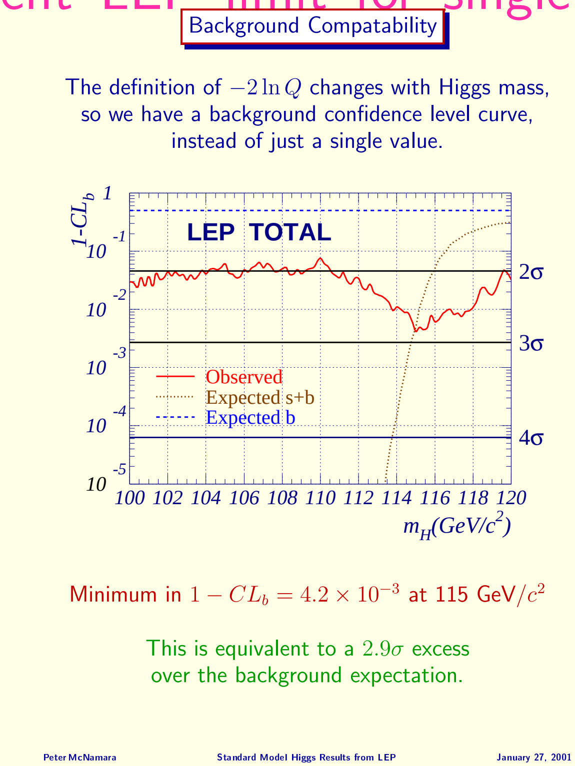
Hints from Current Data?

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





There is possibility for spread-out Higgs weight (at $<$ 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 $10-20~\mathrm{GeV}$ (i.e. smaller than detector resolution in recoil mass spectrum) over some substantial range $\Rightarrow$ **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

$$\sum_i C_i^2 m_{h_i}^2 = \langle M^2 \rangle \,. \tag{1}$$

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

- Precision electroweak suggests $\langle M^2 \rangle \lesssim (200-250~\mathrm{GeV})^2$.
- For multiple Higgs reps. of any kind in the most general SUSY context, RGE + perturbativity gives same result.

Assume C_i^2 constant from $m_h^{\min}$ to $m_h^{\max}$ (use continuum limit, $C^2(m_h)$):

If LEP2 data eventually $\Rightarrow C^2(m_h)$ is small for $m_h \leq 70~\mathrm{GeV}$ **in continuum spread-out sense** (LEP2 $\Rightarrow$ weak spread out signal for higher m_h possibly present), then $\langle M^2 \rangle = [200~\mathrm{GeV}]^2 \Rightarrow m_h^{\max} = 300~\mathrm{GeV}$. $\Rightarrow$ need $\sqrt{s} \gtrsim 500~\mathrm{GeV}$ for big $\sigma(ZH)$ over most of the region.

Use JFG, Han Sobey analysis (*Phys. Lett.* **B429** (1998) 79) available for $Z \to e^+e^-, \mu^+\mu^-$, $\sqrt{s} = 500~\mathrm{GeV}$ and $M_X = 70 - 200~\mathrm{GeV}$ region.

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

- $\Rightarrow \boldsymbol{f \sim 0.43}$ in $\mathbf{100-200}~\mathrm{GeV}$ mass interval (avoids Z region with largest background)

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

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

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

Need $\boldsymbol{L \gtrsim 200}\mathrm{fb}^{-1}$ to have a $\boldsymbol{S/\sqrt{B} > 5}$ broad enhancement signal for $\boldsymbol{f \sim 0.5}$. $\Rightarrow$ 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?

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

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:

- $e^+e^- \to t\bar{t}h$ **and** $e^+e^- \to b\bar{b}h$. (JFG, Grzadkowski, Kalinowski)
- $e^+e^- \to Z^* \to Zhh$ (JFG, Farris)

  $e^+e^- \to e^+e^-W^*W^* \to e^+e^-hh$. (JFG, Farris, Zerwas etal)
- $\gamma\gamma \to h$ (JFG, Asner) and $\mu^+\mu^- \to h$ (JFG).

Corresponding 'guarantees':

- Fermionic coupling sum rules (Grzadkowski, Kalinowski, JG): for any h, $(\hat{S}^t_h)^2 + (\hat{P}^t_h)^2 = \left(\frac{\cos\beta}{\sin\beta}\right)^2$, $(\hat{S}^b_h)^2 + (\hat{P}^b_h)^2 = \left(\frac{\sin\beta}{\cos\beta}\right)^2$ where $\hat{S}$ and $\hat{P}$ are 1 and γ_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 $(D_\mu\Phi)^\dagger(D^\mu\Phi)$, are of guaranteed magnitude.

- $\gamma\gamma \to h$ coupling from fermion loops, $\mu^+\mu^- \to h$ direct coupling to fermions.

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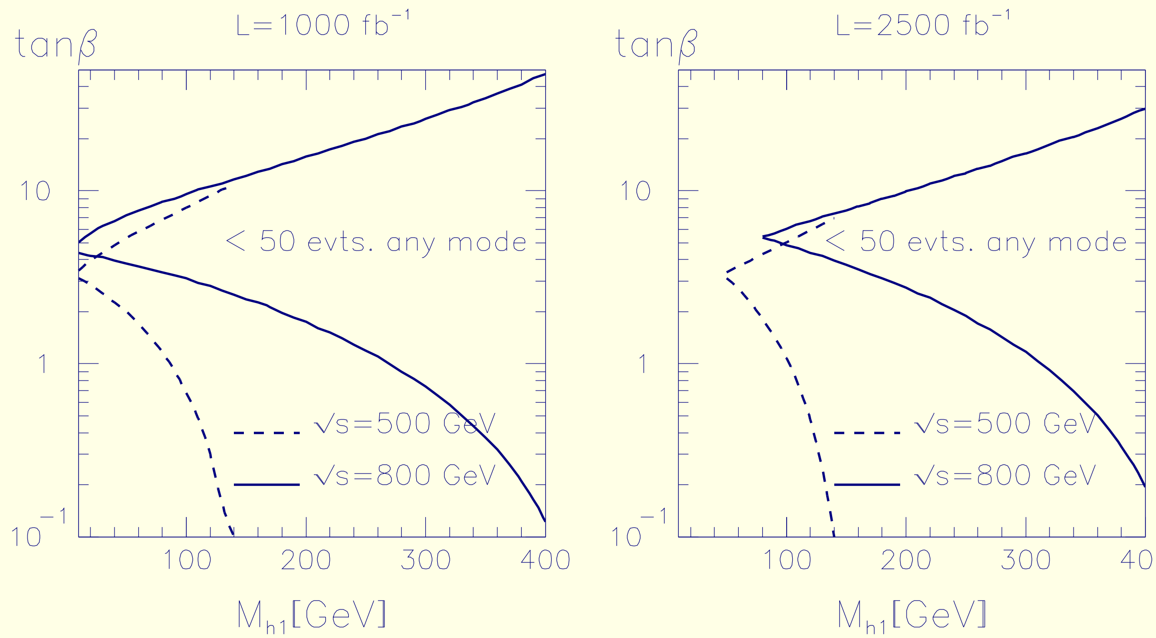
$e^+e^- \to t\bar{t}h$ always works if $\tan\beta$ is small enough (and process is kinematically allowed).
$e^+e^- \to b\bar{b}h$ always works if $\tan\beta$ is large enough, but increasingly large $\tan\beta$ is required as m_h increases.



For $\sqrt{s} = 500~\mathrm{GeV}$ (dashes) and $\sqrt{s} = 800~\mathrm{GeV}$ (solid) the maximum and minimum $\tan\beta$ values between which $t\bar{t}h$ and $b\bar{b}h$ final states both have fewer than 50 events for decoupled h (a) $L = 1000\mathrm{fb}^{-1}$ or (b) $L = 2500\mathrm{fb}^{-1}$.

$L = 2500\mathrm{fb}^{-1}$ wedge begins at $m_h \sim 80~\mathrm{GeV}$ ($\sqrt{s} = 800~\mathrm{GeV}$).
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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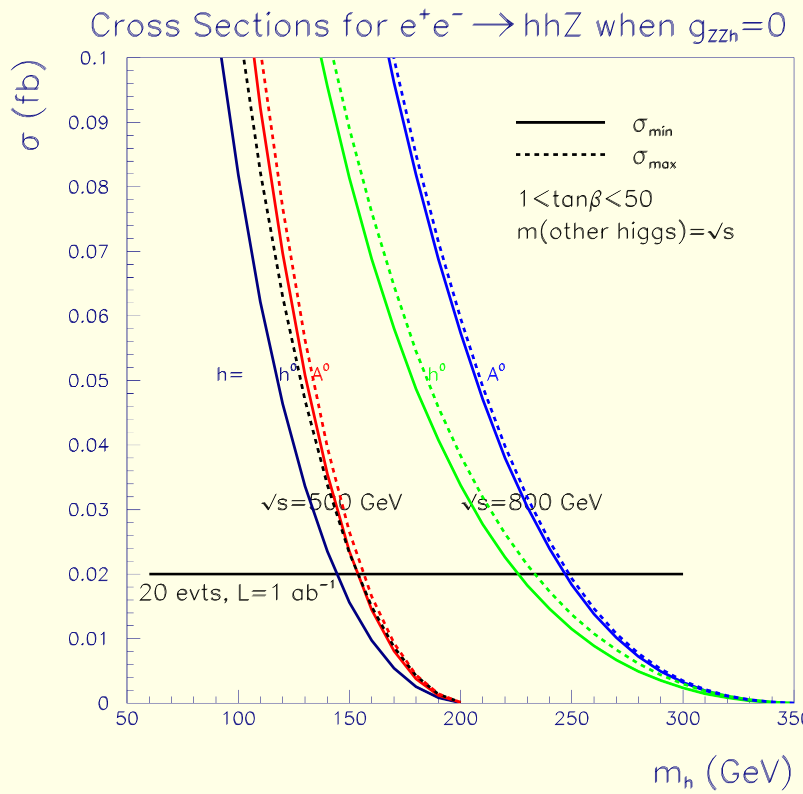
Double Higgs production allows discovery of light decoupled h's.

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

$WW \to hh$ fusion production ⇒ similar.

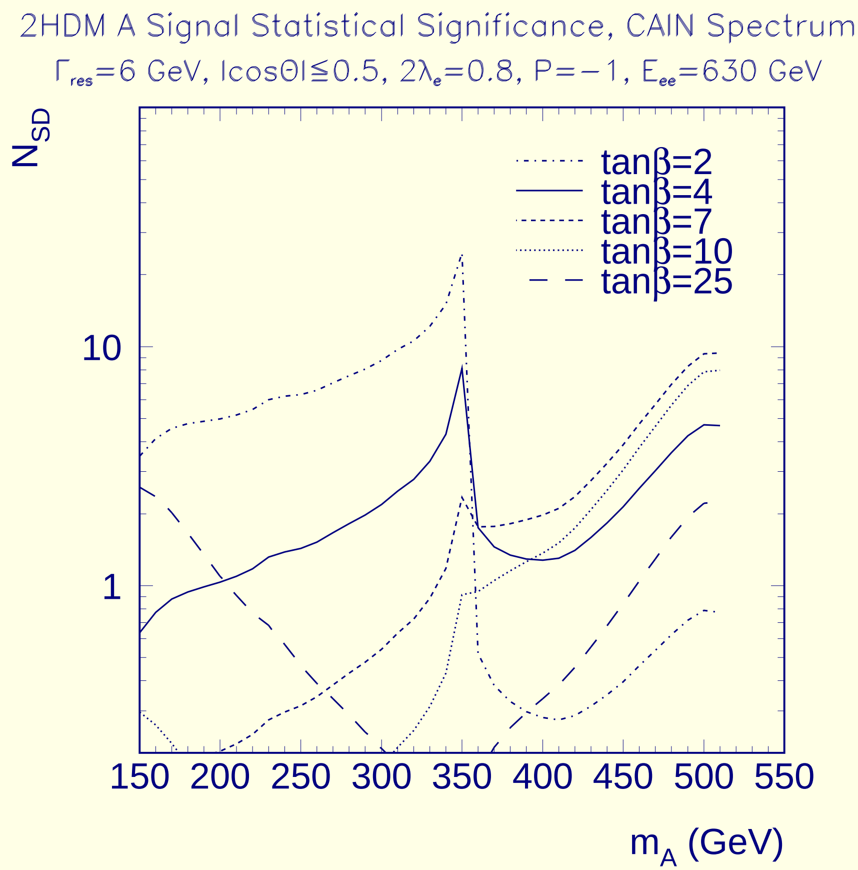


For $\sqrt{s} = 500~\mathrm{GeV}$ and $800~\mathrm{GeV}$ and for $h = h^0$ and $h = A^0$, we plot as a function of m_h the maximum and minimum values of $\sigma(e^+e^- \to hhZ)$ found after scanning $1 < \tan\beta < 50$ taking all other Higgs masses equal to $\sqrt{s}$. For $h = h^0$, we require $\sin(\beta - \alpha) = 0$ during the scan. The 20 event level for $L = 1~\mathrm{ab}^{-1}$ is indicated.

Ability of $\gamma\gamma$ collisions to find a decoupled h is marginal. Efficiency losses due to boosted h rest frame $\Rightarrow$ poor sensitivity if m_h substantially below $\sqrt{s}$.

$\Rightarrow$ best approach is to run at various $\sqrt{s}$ values using spectrum peaked at high $E_{\gamma\gamma}$.

$\Rightarrow$ must use many $\sqrt{s}$ settings to cover a substantial m_h range.



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+...

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 $\Rightarrow$ poor coverage. Would have to run at many energies, requiring many years! **Is TESLA enough better?** Hot off the press: New flat beam design $\Rightarrow L \rightarrow\sim 4L$.

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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 $\sigma_{\sqrt{s}} \lesssim \Gamma_h^{\rm tot}$ and employ appropriate $L(R)$.

Steps of size $\Gamma_{\widehat{h}}^{\rm tot} \sim \sigma_{\sqrt{s}}$.

$2m_t > m_h > 150~{\rm GeV} \Rightarrow h \to b\bar{b}$ and $\Gamma_h^{\rm tot} \sim 0.05 - 0.1~{\rm GeV}$ for $\tan\beta > 1$: employ $R = 0.05 - 0.1\%$.

$m_h > 2m_t \Rightarrow \Gamma_h^{\rm tot} \gtrsim 1~{\rm GeV}$: employ $R = 0.5 - 1\%$.

$3 - 4$ year program, $\Rightarrow$ devote:

- $L = 0.003{\rm fb}^{-1}$ to 2000 points separated by $0.1~{\rm GeV}$ in $\sqrt{s} = 150 - 350~{\rm GeV}$ range — $L_{\rm tot} = 4{\rm fb}^{-1} =$ 3 years $\Rightarrow 4\sigma$ level h signal in $b\bar{b}$ if $\tan\beta \gtrsim 4 - 5$.
- $L = 0.03{\rm fb}^{-1}$ to 100 points separated by $0.5~{\rm GeV}$ in the $\sqrt{s} = 350 - 400~{\rm GeV}$ range — $L_{\rm tot} = 3{\rm fb}^{-1} = 1/2$ year $\Rightarrow 4\sigma$ signal in $b\bar{b}$ ($t\bar{t}$) for $\tan\beta > 6$ ($\tan\beta < 6$).
- $L = 0.01{\rm fb}^{-1}$ to 100 points separated by $1~{\rm GeV}$ in the $\sqrt{s} = 400 - 500~{\rm GeV}$ range — $L_{\rm tot} = 1{\rm fb}^{-1} = 1/10$ 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 ($\sqrt{s} \lesssim 800$ 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 $\lesssim 1$ TeV.** $\Rightarrow$ **LHC!!**

- Heavy $h_{\rm SM}$-like Higgs $\Rightarrow$ large $\Delta S > 0$ and large $\Delta T < 0$.

- Compensate by large $\Delta T > 0$ from small mass non-degeneracy (weak isospin breaking) of heavier Higgs. E.g. for light A^0, take h^0 heavy and SM-like $\Rightarrow$

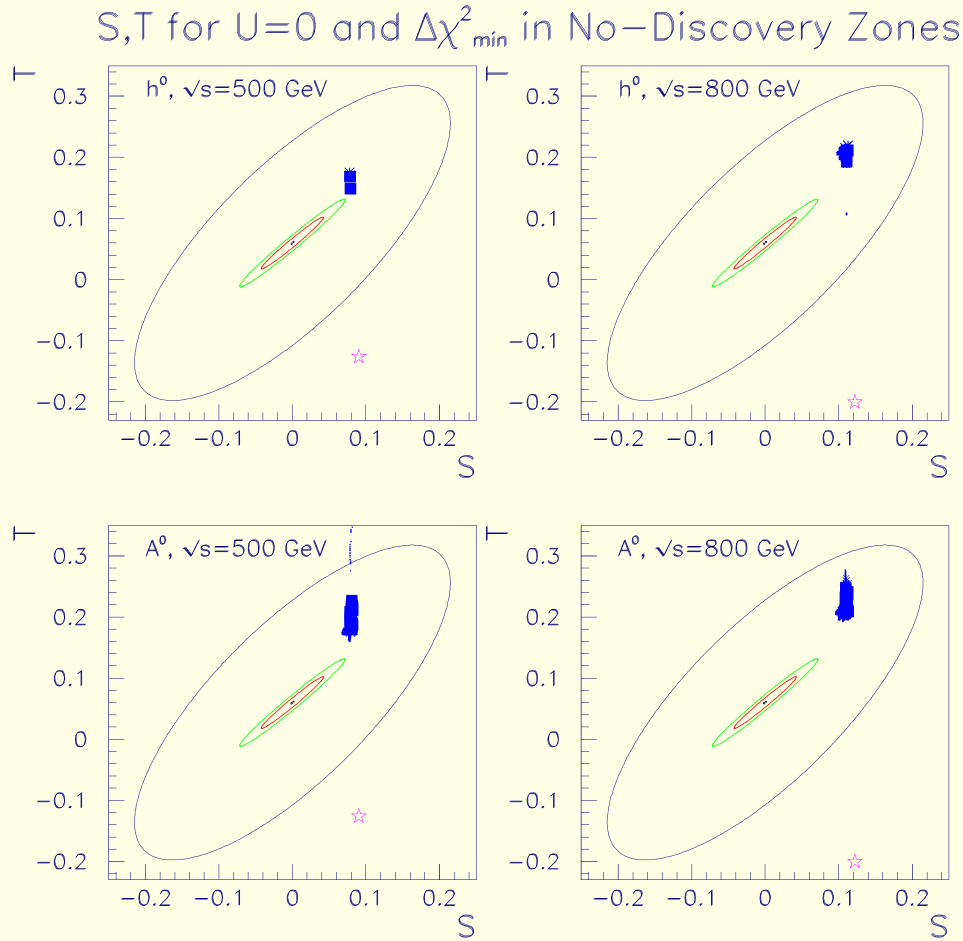
$$\Delta\rho = \frac{\alpha}{16\pi m_W^2 c_W^2}\left\{\frac{c_W^2}{s_W^2}\frac{m_{H^\pm}^2 - m_{H^0}^2}{2} - 3m_W^2\left[\log\frac{m_{h^0}^2}{m_W^2} + \frac{1}{6} + \frac{1}{s_W^2}\log\frac{m_W^2}{m_Z^2}\right]\right\} \quad (2)$$

Can adjust $m_{H^\pm} - m_{H^0} \sim$ 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.

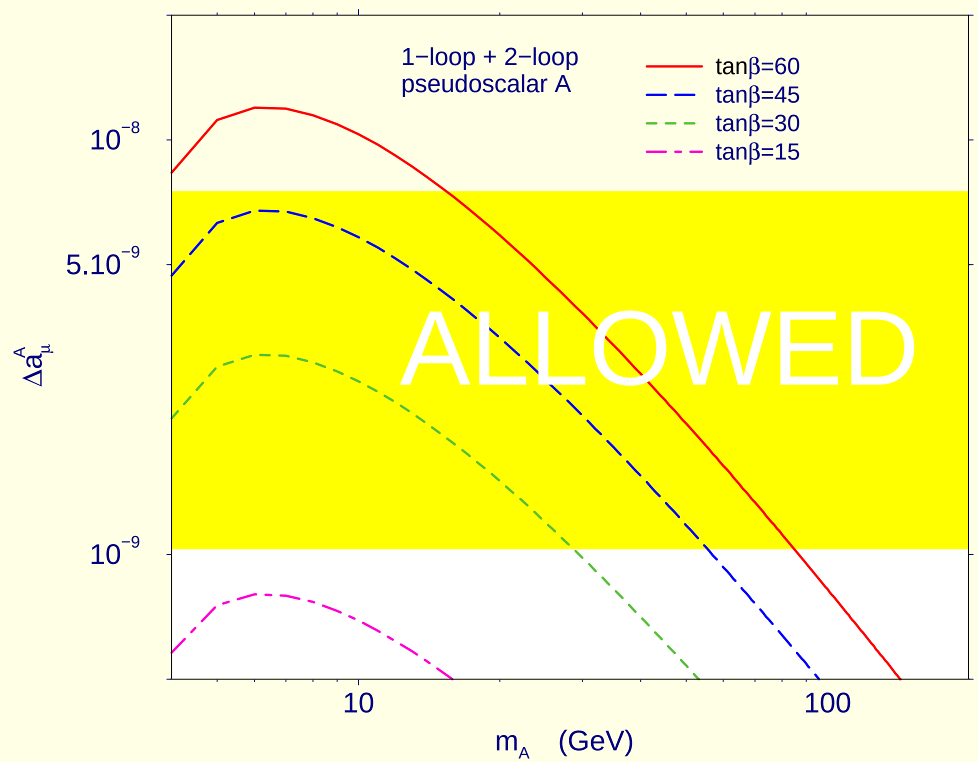


Outer ellipses = current 90% CL region for $U = 0$ and $m_{h_{\rm SM}} = 115$ GeV. Blobs = S, T predictions for Yukawa-wedge 2HDM models with minimum relative $\Delta\chi^2$. Innermost (middle) ellipse = 90% (99.9%) CL region for $m_{h_{\rm SM}} = 115$ GeV after Giga-Z *and* a $\Delta m_W \lesssim 6$ 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. $10.3 \times 10^{-10} < \Delta a_\mu < 74.9 \times 10^{-10}$ at 95% C.L. ($\pm 1.96\sigma$) for 'standard' $\sigma(e^+e^- \to hadrons)$ at low $\sqrt{s}$.

If we use light A^0 as entire explanation, $\Rightarrow$ appropriate Δa_μ.
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 $\sigma(e^+e^- \to \text{hadrons})$ $\to$ less Δa_μ needed $\to$ smaller $\tan\beta$ and/or higher m_{A^0} wanted $\Rightarrow$ **enter LC/LHC wedges.**



Explanation of new BNL a_μ 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, Λ (new physics scale) $= M_S$, the string scale, which is possibly as small as $1~\mathrm{TeV}$.

- 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 $\mathcal{O}_i$. Roughly we can write

$$\mathcal{O}_i = \mathcal{O}_i^{\rm SM} + a_i \ln \frac{m_H}{m_Z} + b_i V$$

  where $V \equiv 2\sum_{\vec{n}} \frac{g_{\vec{n}}^2}{g^2}\frac{m_W^2}{M_c^2}$ ($M_c = 1/R$, R =compactification radius, and $\vec{n} = (n_1, \ldots, n_\delta)$ 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 $m_H \leq 1~\mathrm{TeV}$ 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 $V(\phi)-\mathcal{L}_{\rm mass}(\phi^{\vec n}_{KK})-\mathcal{L}_{\rm mix}(\phi^{\vec n}_{KK},\phi)$, where ϕ is the usual Higgs field, $\mathcal{L}_{\rm mass}$ contains the quadratic mass terms for the KK graviscalar fields $\phi^{\vec n}_{KK}$, and $\mathcal{L}_{\rm mix}\propto\kappa\sum_{\vec n}\phi^{\vec n}_{KK}T^{\mu,\ {\rm Higgs}}_{\mu}\propto\kappa\sum_{\vec n}\phi^{\vec n}_{KK}V(\phi)$ arises because gravity sees the energy-momentum tensor.

  $\kappa\propto 1/M_{\rm P}$ is small, but there are many KK modes.

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

  For $\delta=1$, $\overline{D}<0$.

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

  Note that even if $V(\phi)=\frac{1}{2}m^2\phi^2+\Xi$ (no quartic self interactions), $\mathcal{L}_{\rm mix}$ generates ϕ^4 interactions (of correct sign if $\overline{D}<0$).

- If $\overline{D} < 0$, then $\overline{V}_{\rm tot}$ has a minimum at $V(\phi) = \frac{1}{2\overline{D}}$, which determines values for ϕ and the ϕ_{KK} fields at the minimum.

- Expanding about the vev's, rescaling $\phi \to \widehat{\phi}$ for canonical normalization, and diagonalizing the mass matrix, one finds:

  - a Higgs boson $s_{\rm phys}$ with $m^2_{s_{\rm phys}} > 0$.
  - Standard WW/ZZ couplings for $s_{\rm phys}$ (with tiny corrections) requiring $\widehat{v} = 246~{\rm GeV}$;
  - Absence of fermionic couplings of $s_{\rm phys}$ at tree level;
  - Large decays of $s_{\rm phys}$ to states containing two graviscalar KK excited states (which are invisible decays).

- Any non-zero value of $\langle V(\phi) \rangle$ ($\overline{D} < 0$ **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.

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- This leads to an addition to T^μ_μ for the ϕ: 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: $\mathcal{L} \ni \frac{f(\delta)}{M_\mathrm{P}} \sum_{\vec{n}} \phi^{\vec{n}}_{KK} T^\mu_\mu$.

- 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.

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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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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.

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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) $L > 5\mathrm{fb}^{-1}$ to surpass LEP2 limit.
- **At the LHC,** $L = 100\mathrm{fb}^{-1}$ in WH, ZH will probe up to $\sim 200\ \mathrm{GeV}$; in WW fusion, esimated reach (Zeppenfeld) is 300 – 500 GeV.

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

Note complementarity of the modes depending on $\boldsymbol{VV}$ couplings and the $\boldsymbol{t\bar{t}H}$ 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 2×2 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 arrangment 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:

$$\mathcal{L}_Y = i h_{ij} \psi_i^T C \tau_2 \Delta \psi_j + \mathrm{h.c.}\,, \quad i,j = e, \mu, \tau\,. \tag{3}$$

$\Rightarrow$ 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 $|h_{\ell\ell}^{\Delta^{--}}|^2 \equiv c_{\ell\ell} m^2_{\Delta^{--}}(\text{ GeV})$, 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 $\langle\boldsymbol{\Delta}^{\mathbf{0}}\rangle = \mathbf{0}$ (for $\boldsymbol{\rho} = \mathbf{1}$ = natural), $\boldsymbol{\Gamma}^{\boldsymbol{T}}_{\boldsymbol{\Delta}^{--}}$ would be small. $\Rightarrow$ possibly very large $\boldsymbol{s}$-channel $\boldsymbol{e^-e^-}$ and $\boldsymbol{\mu^-\mu^-}$ 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 $\sigma_{\sqrt{s}}$)

$$\boldsymbol{N(\Delta^{--})_{L=50\mathrm{fb}^{-1}} \sim 3 \times 10^{10} \left(\frac{c_{ee}}{10^{-5}}\right)\left(\frac{0.2\%}{R}\right)\,;} \tag{4}$$

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

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

$$c_{ee}|_{100\ \mathrm{events}} \sim 3.3 \times 10^{-14}\left(\frac{R}{0.2\%}\right)\left(\frac{50\mathrm{fb}^{-1}}{L}\right), \quad \Gamma^T_{\Delta^{--}} \ll \sigma_{\sqrt{s}}\,, \tag{5}$$

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 $\to$ a viable signal.

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

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- 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 $\sim 200~\mathrm{GeV}$.

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Experimental limits from LEP2 on MSSM Higgs bosons are significant.

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

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Higher $m_{\widetilde{t}}$:

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 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.

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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

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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.

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The LHC

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

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

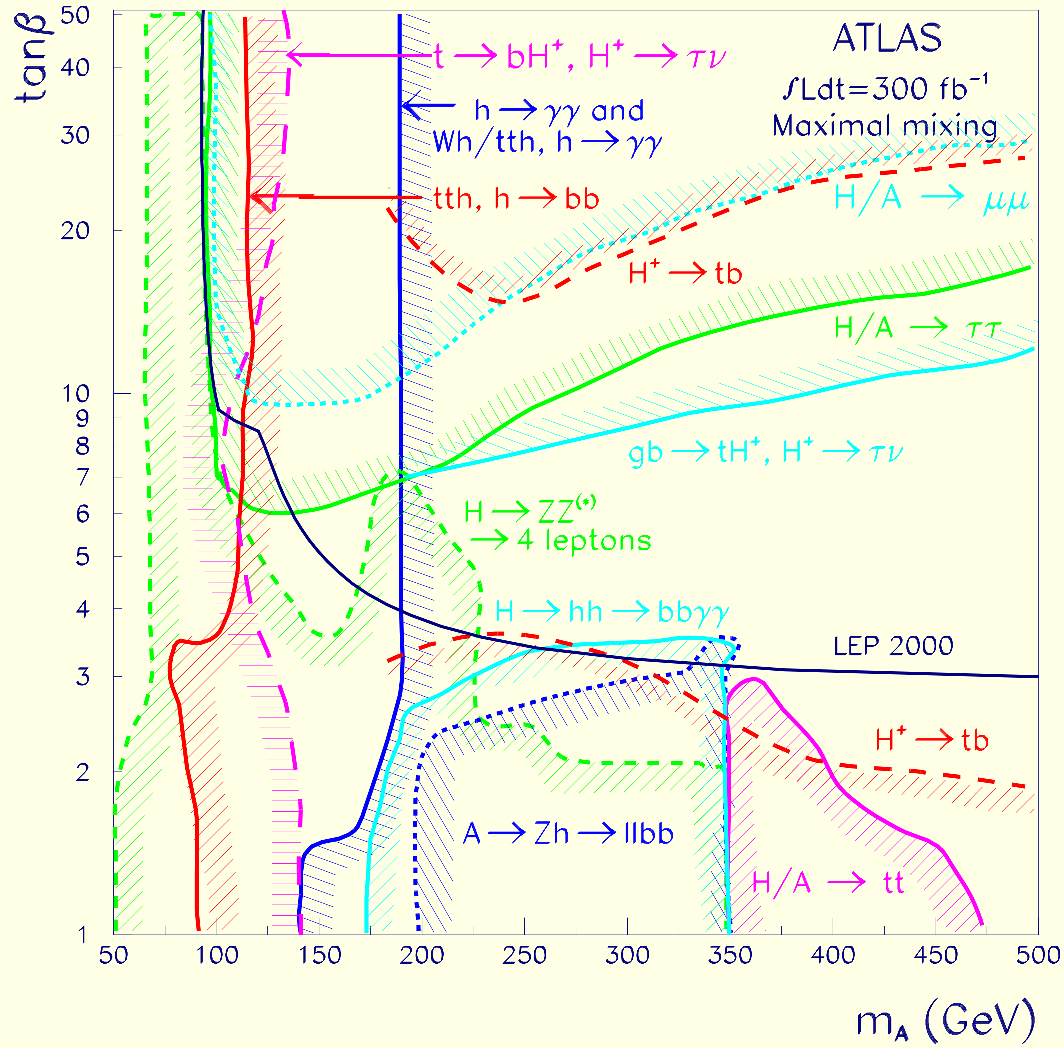
LEP2 limits pretty much exclude $\tan\beta < 3$ where other modes could be important

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

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

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

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



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

Discovery at Linear e^+e^- collider

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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 ~ 50 GeV and use 5 steps in $\sqrt{s}$ to explore each of 5 intervals of width 10 GeV — $m_{A^0} \in [E_{\gamma\gamma}^{\rm peak}, E_{\gamma\gamma}^{\rm peak} + 10~{\rm GeV}]$.

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

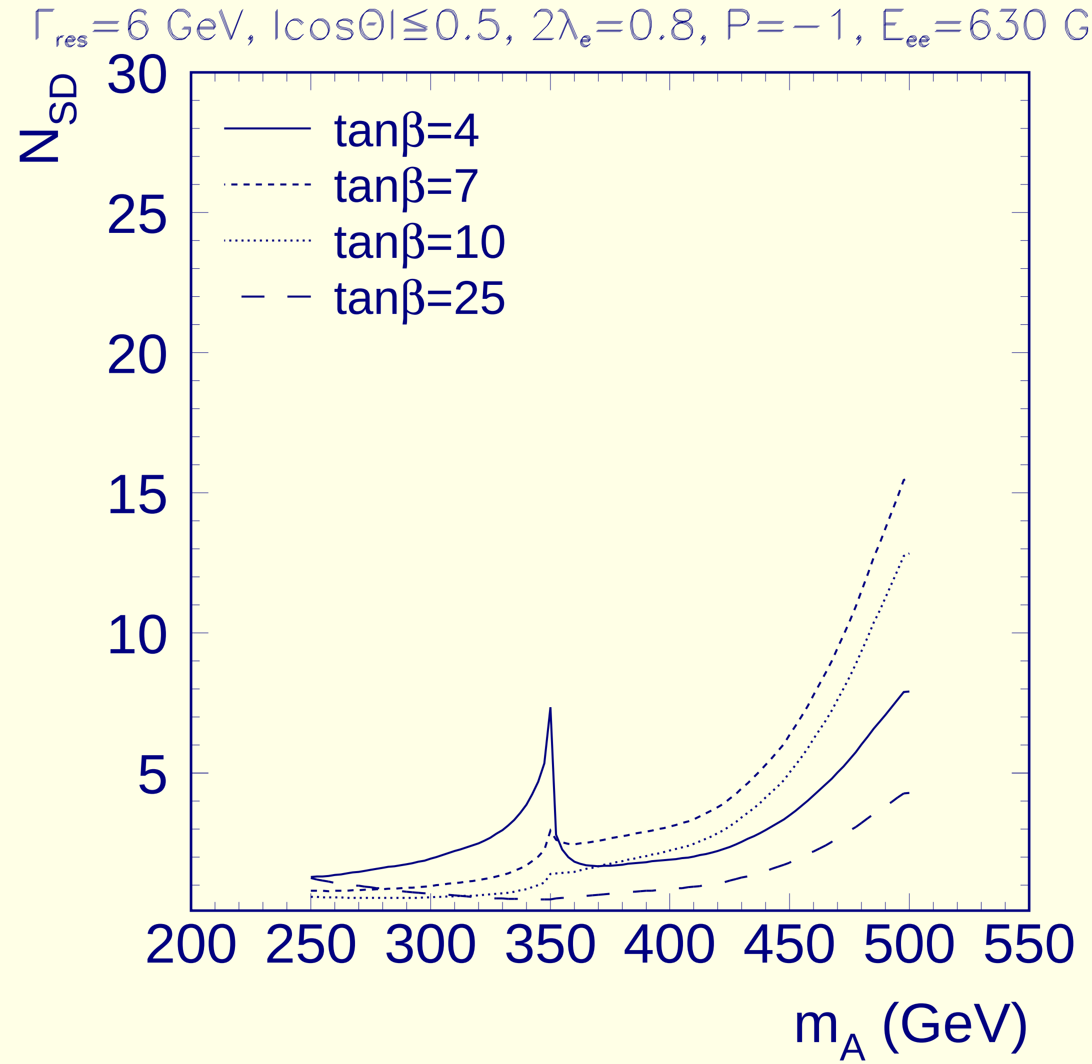
6 GeV $m_{b\bar{b}}$ resolution is too optimistic – perhaps 7% or so $\Rightarrow$ much larger background at high mass

Beamstrahlung, etc. means $\langle\lambda\lambda'\rangle$ is not large enough to really kill the background except near the ~ 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.

Signal Statistical Significance: CAIN Spectrum



Results after 1 year or running assuming $\sqrt{s} = 630$ GeV, NLC peaked CAIN spectrum and 6 GeV resolution in $b\bar{b}$ mass.

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- **Bremsstrahlung tail:**

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

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- **Scanning:**

  Use strategy of adjusting R as expected size of $\Gamma^{\rm tot}_{A^0}, \Gamma^{\rm tot}_{H^0}$ 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 $m_{A^0} > 2m_t$.

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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.

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Invisible decays.

Will probably allow non-detection scenarios at hadron colliders.

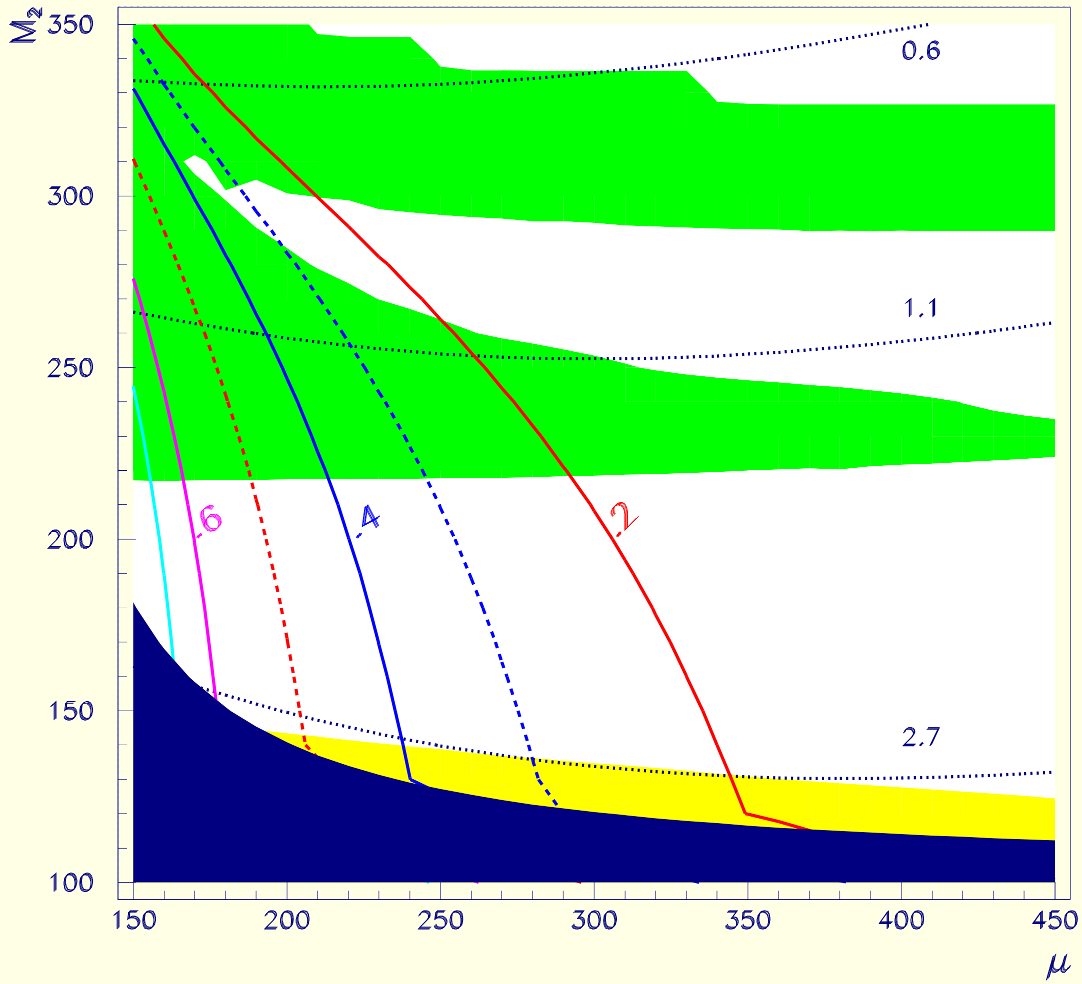
$h^0 \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0$ still possible given LEP2 data.

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

- Choose M_1/M_2 small $\Rightarrow m_{\widetilde{\chi}_1^0}$ can be small ($i.e.$ good phase space for decay despite limits on m_{h^0}) while $m_{\widetilde{\chi}_1^\pm}$ can satisfy $m_{\widetilde{\chi}_1^\pm} > 103~\mathrm{GeV}$ (LEP2).
  ‘Standard’ $M_1/M_2 = 1/2$, $\Rightarrow$ maximum $B(h^0 \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0) \sim 20\%$.
  $M_1/M_2 = 1/10 - 1/5$ allows $B(h^0 \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0) > 50\%$.
- need $(O_{12} - \tan\theta_W O_{11})(\sin\beta O_{14} - \cos\beta O_{13})$ large — $i.e.$ $\boldsymbol{\widetilde{\chi}_1^0}$ **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.

Sample case (Belanger et.al.): $M_1/M_2 = 1/5$

- Semi-vertical lines are $B(h^0 \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0)$ contours.
- Dotted lines show a_μ.
- $0.1 < \Omega h^2 < 0.3$ in white areas.
- Black region is where $m_{\widetilde{\chi}_1^\pm} < 103$ GeV and is excluded.
- **$\Rightarrow$ large $B(h^0 \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0)$ possible if $\widetilde{\chi}_1^\pm$ and $\widetilde{\ell}_R$ are nearby**



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Stop and top loops negatively interfere: $\Rightarrow$

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- Some increase in $B(H \to \gamma\gamma)$.

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Radiative corrections to couplings.

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

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

Consider latter in more detail.

- 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:**

  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 $\lambda_b^{h^0}$, $\Rightarrow$ (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 $\lambda_b^{h^0}$ 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) = 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 $\widetilde\chi_1^0\widetilde\chi_1^0, \widetilde\chi_1^+\widetilde\chi_1^-, \widetilde\tau^+\widetilde\tau^-, \widetilde\nu\overline{\widetilde\nu}, \ldots$ decays are kinematically allowed.
  However, at high $\tan\beta$ the usual dominance of decays to $b\overline{b}$ and $\tau^+\tau^-$ will be preserved.
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- $\mu^+\mu^- \to H^0, A^0$ 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 $t\bar{t}h \to t\bar{t}b\bar{b}$ (ref: ATLAS (Sapinski) analysis for $h_{\rm SM}$).

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The modes employed in 1996 were:

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

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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 $L = 300 \mathrm{fb}^{-1}$ per detector.**

  But, a more complete scan shows some points with at most 3σ 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. $\Rightarrow$ 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, ..)

$$\mathcal{A}_{CP=+} \propto \vec{\epsilon}_1 \cdot \vec{\epsilon}_2 \,, \quad \mathcal{A}_{CP=-} \propto (\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot \hat{p}_{\rm beam} \,. \tag{6}$$

  – 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 $\gamma\gamma$ 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 μC with $\overline{\mu}(a+ib\gamma_5)\mu$ coupling to the muon,

$$\overline{\sigma}_S(\zeta) = \overline{\sigma}_S^0\left(1+P_L^+P_L^- + P_T^+P_T^-\left[\frac{a^2-b^2}{a^2+b^2}\cos\zeta - \frac{2ab}{a^2+b^2}\sin\zeta\right]\right)$$
$$= \overline{\sigma}_S^0\left[1+P_L^+P_L^- + P_T^+P_T^-\cos(2\delta+\zeta)\right], \quad (7)$$

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

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 $P_L^\pm = 0$)

$$\mathcal{A}_I \equiv \frac{\overline{\sigma}_S(\zeta=0)-\overline{\sigma}_S(\zeta=\pi)}{\overline{\sigma}_S(\zeta=0)+\overline{\sigma}_S(\zeta=\pi)} = P_T^2\frac{a^2-b^2}{a^2+b^2} = P_T^2\cos 2\delta\,,$$
$$\mathcal{A}_{II} \equiv \frac{\overline{\sigma}_S(\zeta=\pi/2)-\overline{\sigma}_S(\zeta=-\pi/2)}{\overline{\sigma}_S(\zeta=\pi/2)+\overline{\sigma}_S(\zeta=-\pi/2)} = -P_T^2\frac{2ab}{a^2+b^2} = -P_T^2\sin 2\delta\,.$$

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 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.

- 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 $\sqrt{s} > 1~\mathrm{TeV}$;
  (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.