CHALLENGES FOR HIGGS SEARCHES

J. F Gunion, Workshop on the Future of Higgs Physics, May 5, 2001

OUTLINE

- Extended Standard Model Higgs Sector
- MSSM
- 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

1 EXTENDED STANDARD MODEL

- Even within SM context, should consider extended Higgs sector possibilities. To keep $\rho \sim 1$ most natural to
  - 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. (with neutral member vev $\neq 0$).

    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; is this so bad?

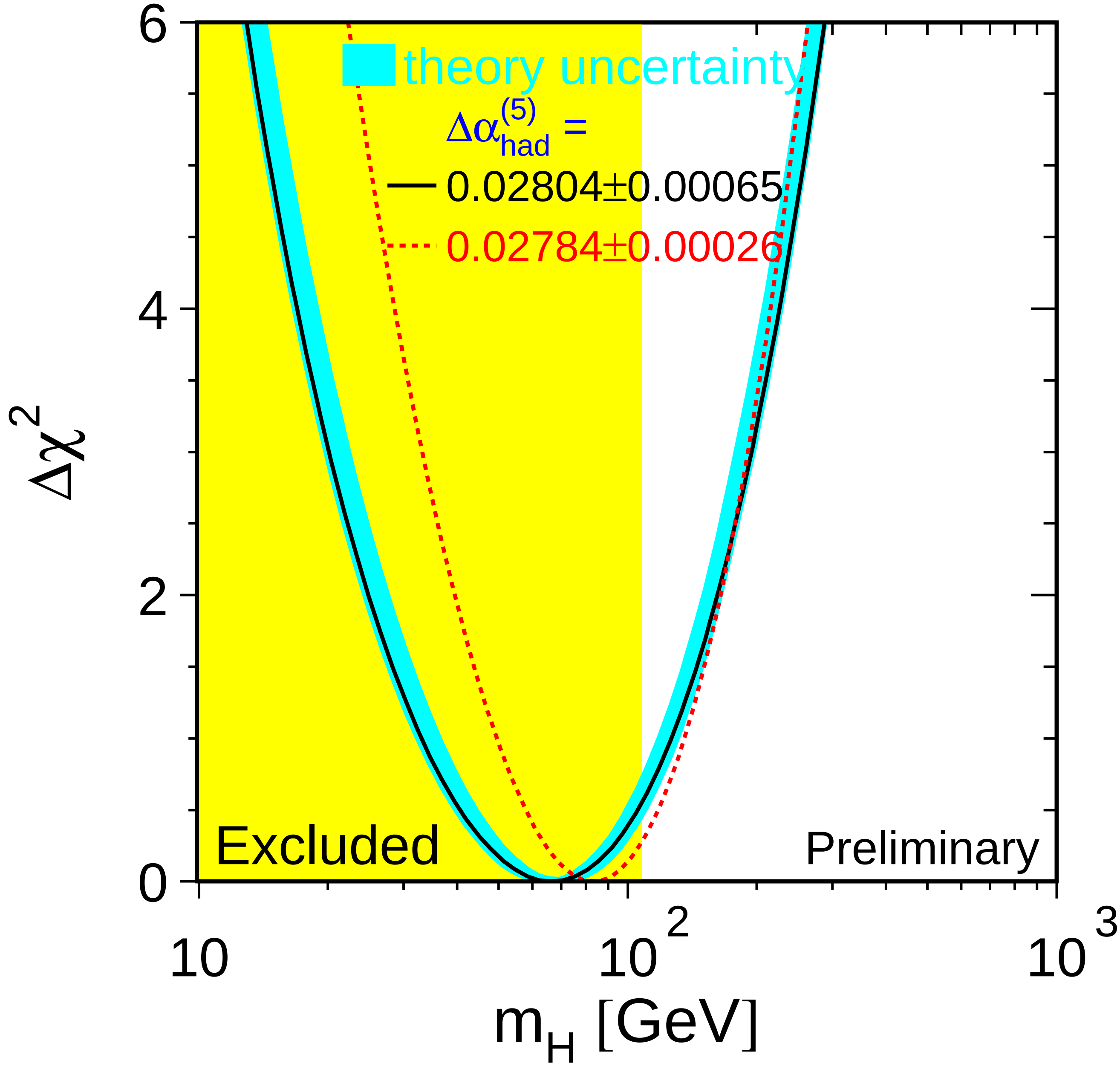
  In all cases, detection, simulation considerations change dramatically.

Some examples

For assessing discovery prospects, we will focus on e^+e^- collider; other colliders $\Rightarrow$ increased difficulty of discovery (usually).

An important question: is there some indication of Higgs 'weight' below 100 GeV from the precision electroweak χ^2 minimum?

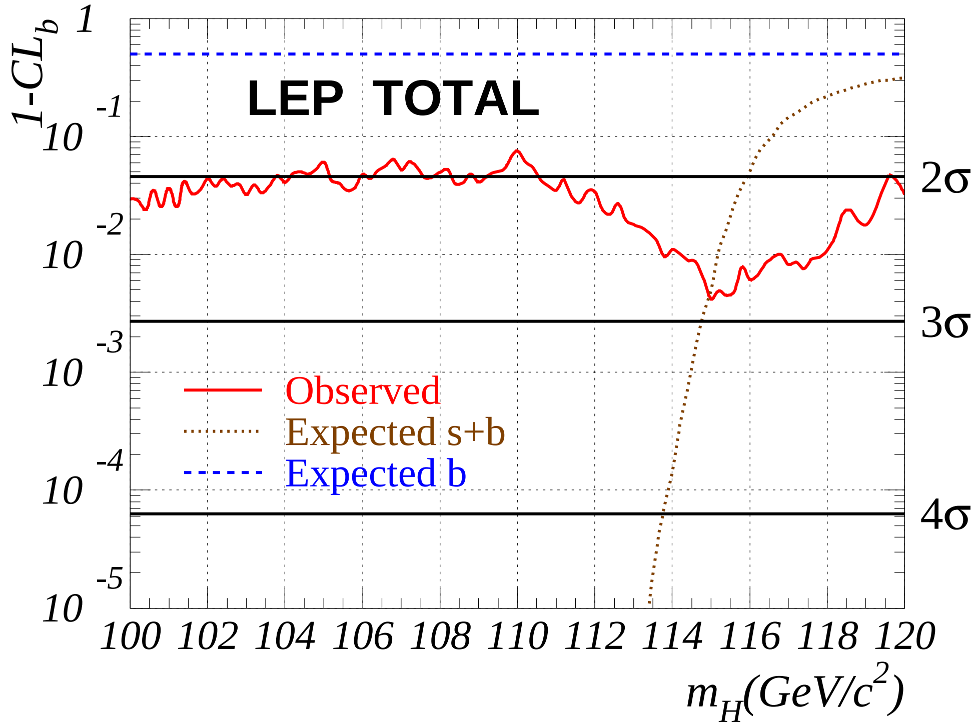
Answer: Maybe!



Global fit (including all observables) prefers Higgs mass below current LEP limit for single SM Higgs.

Background Compatability

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



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

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

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

There is preference for some Higgs weight throughout the interval plotted. Chanowitz: discarding hadronic asymmetries and keeping leptonic increases evidence.

- **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 $\Rightarrow$ **diffuse signal$\equiv$worst case** (Espinosa +JG). May be forced to use $Z+X$ and look for broad excess in M_X.

Constraints? Important issue is value of M^2 in

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

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 $m_h^{\rm min}$ to $m_h^{\rm max}$ (use continuum limit, $C^2(m_h)$):

- maximal spread: $m_h^{\rm min}=0$, with $\langle M^2\rangle \leq [200\text{ GeV}]^2 \Rightarrow m_h^{\rm max} = \sqrt{3\langle M^2\rangle} = 340$ GeV.
- If LEP2 data eventually $\Rightarrow C^2(m_h)$ is small for $m_h \leq 70$ GeV (say) **in continuum spread-out sense**, then $\langle M^2\rangle = [200\text{ GeV}]^2$ $\Rightarrow m_h^{\rm max} = 300$ GeV.
- LEP2 provides weak evidence for spread out signal for higher m_h.

$\Rightarrow$ need $\sqrt{s} \gtrsim 500$ GeV for big $\sigma(ZH)$ over most of the region.

Use JFG, Han Sobey analysis (*Phys. Lett.* **B429** (1998) 79; hep-ph/9801317) available for $Z \to e^+e^-, \mu^+\mu^-$, $\sqrt{s} = 500$ GeV and $M_X = 70 - 200$ GeV region.

For $C^2(m_h)$ =constant, evaluate fraction $\boldsymbol{f}$ of Higgs signal in a given region taking $\langle M^2 \rangle = (200 \text{ GeV})^2$. Assume LEP2 limits $\Rightarrow m_h^{\min} = 70$ GeV, $m_h^{\max} = 300$ GeV.

- $\Rightarrow \boldsymbol{f \sim 0.43}$ in **$\mathbf{100 - 200}$ GeV** mass interval (avoids Z region with largest background)
- $\boldsymbol{S \sim 1350 f}$ with a background of $\boldsymbol{B = 2700}$, for **$\mathbf{100 - 200}$ GeV** window, **assuming $\boldsymbol{L} = \mathbf{500}$ fb$^{\mathbf{-1}}$**.
- $\Rightarrow$ 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, $S/\sqrt{B} \sim \frac{L}{500 \text{ fb}^{-1}} \times \boldsymbol{26 f}$ for the **$\mathbf{100 - 200}$ GeV** window in M_X.

Need $\boldsymbol{L \gtrsim 200}$ fb$^{\mathbf{-1}}$ 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 $\Rightarrow$ spreadout 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:

- $e^+e^- \to t\overline{t}h$ **and** $e^+e^- \to b\overline{b}h$. (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)
- Fermionic coupling sum rules (Grzadkowski, Kalinowski, JG):

$$(\hat{S}_i^t)^2 + (\hat{P}_i^t)^2 = \left(\frac{\cos\beta}{\sin\beta}\right)^2 , \quad (\hat{S}_i^b)^2 + (\hat{P}_i^b)^2 = \left(\frac{\sin\beta}{\cos\beta}\right)^2 \tag{2}$$

  where ($f = t, b$) and $\hat{S}$ and $\hat{P}$ are normalized (relative to usual SM type weight) scalar and pseudoscalar fermionic couplings.
  $\Rightarrow$ either $t\overline{t}$ or $b\overline{b}$ coupling of h_i 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 will be present.

Q: Are these processes enough?

A: No, but they certainly help.

For simplicity, discussion below assumes CP-conserving Higgs sector.

Yukawa processes

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

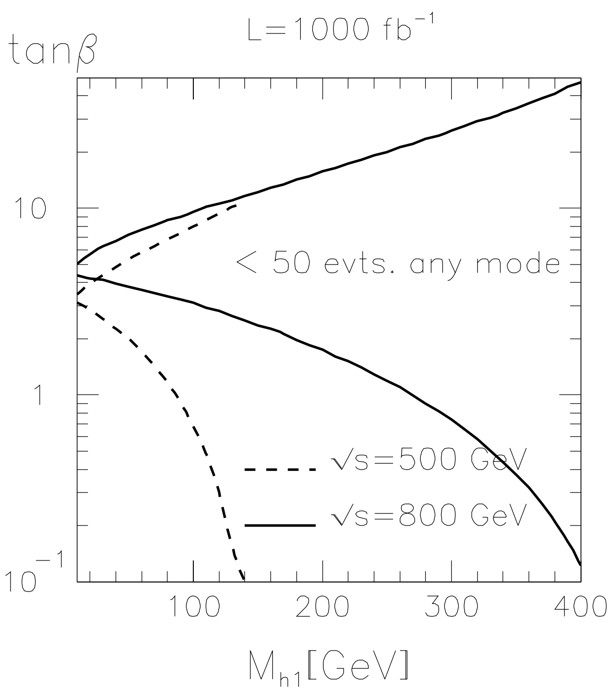


Figure 1: For $\sqrt{s} = 500$ GeV (dashes) and $\sqrt{s} = 800$ GeV (solid) the maximum and minimum $\tan\beta$ values between which $t\bar{t}h$ and $b\bar{b}h$ final states both have fewer than 50 events for decoupled h (a) $L = 1000$ fb^{-1} or (b) $L = 2500$ fb^{-1}.

$L = 2500$ fb^{-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.

Double Higgs production processes

Allows discovery of lighter h's regardless of their nature.

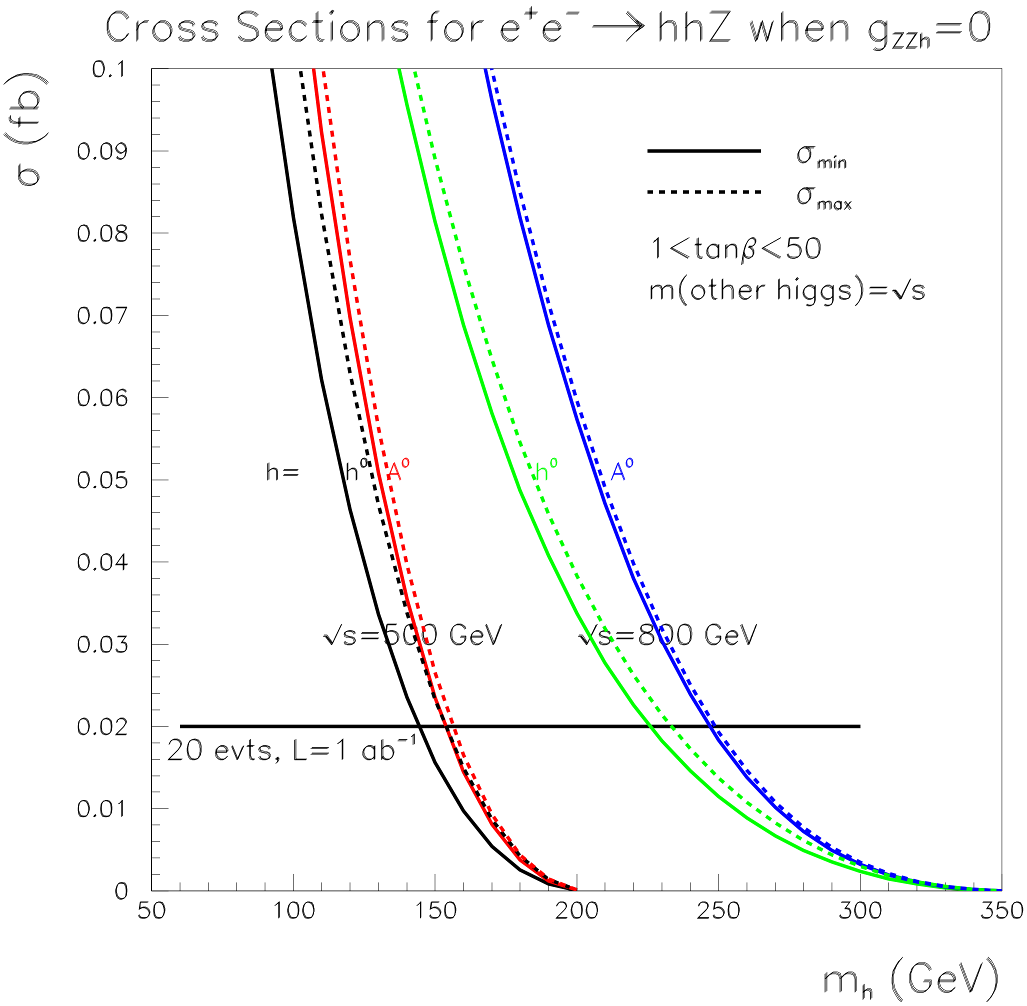


Figure 2: For $\sqrt{s} = 500$ GeV and 800 GeV and for $\hat{h} = h^0$ and $\hat{h} = A^0$, we plot as a function of $m_{\hat{h}}$ the maximum and minimum values of $\sigma(e^+e^- \to \hat{h}\hat{h}Z)$ found after scanning $1 < \tan\beta < 50$ taking all other Higgs masses equal to $\sqrt{s}$. For $\hat{h} = h^0$, we require $\sin(\beta - \alpha) = 0$ during the scan. The 20 event level for $L = 1$ ab^{-1} is indicated.

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

Similar results are obtained for $WW \to hh$ fusion production.

$\gamma\gamma$ Collisions: e.g. $\gamma\gamma \to A^0$.

What does $\gamma\gamma$ luminosity profile look like? CAIN (NLC) $\Rightarrow$

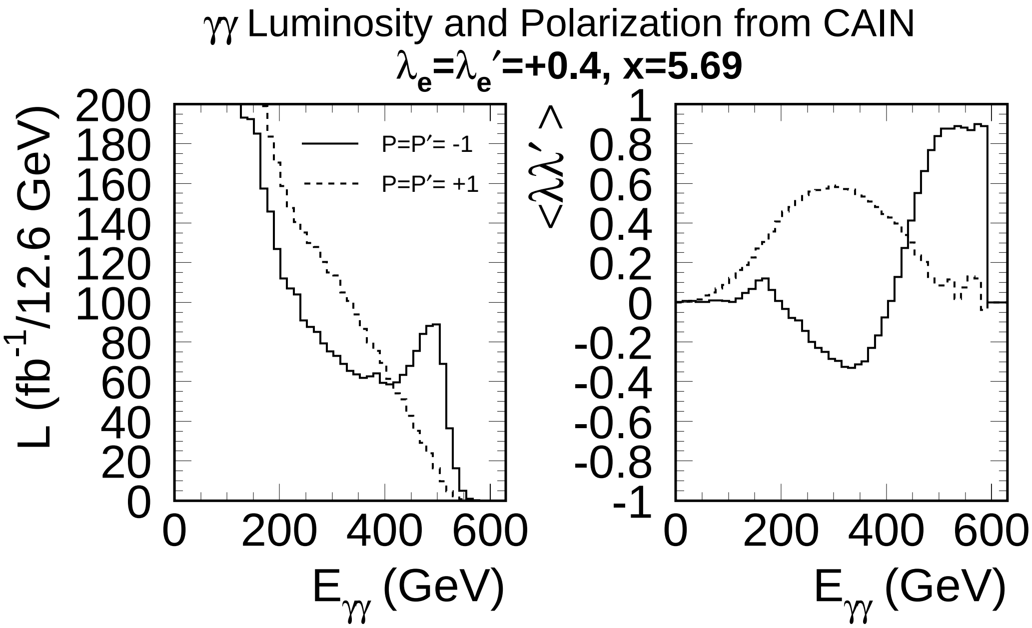


Figure 3: Yearly luminosity in units $\mathrm{fb}^{-1}/12.6$ GeV and associated $\langle\lambda\lambda'\rangle$ are plotted for $\sqrt{s} =$ 630 GeV ($x = 5.69$ for 1.054 μm laser wavelength), assuming 80% electron beam polarizations, for polarization orientation cases (I) and (II).

Using peaked spectrum and resetting $\sqrt{s}$ at appropriate intervals to scan for A^0 over $150 \lesssim m_{A^0} \lesssim 500$ GeV requires many years.

$\Rightarrow$ Best to sit at highest $\sqrt{s}$, run 1/2 time with broad low-$E_{\gamma\gamma}$ spectrum and 1/2 time with spectrum peaked at high $E_{\gamma\gamma}$.

Result for 1 year of operation (in each configuration) *assuming 80% polarization for both beams* **(need e^-e^-? — i.e. not parasitic to e^+e^-)** is marginal sensitivity to interesting region.

For $\tan\beta \geq 7$, even the parton level results with no resolved photon background $\Rightarrow$ poor coverage of the Yukawa process no-discovery wedge.

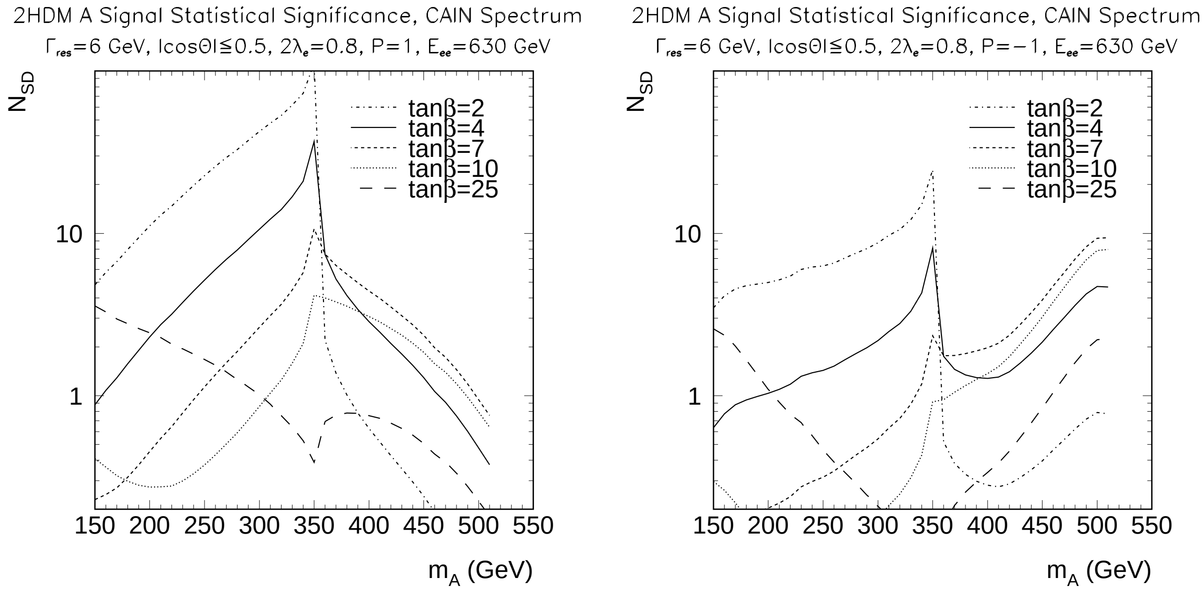


Figure 4: Assuming CAIN 1 year spectra (Fig. 3), we plot the statistical significance of the A^0 signals for a 6 GeV $b\bar{b}$ mass bin centered on m_{A^0}. In (a) [(b)] we employ the case (I) [(II)] spectrum. Various cuts are performed to reduce the background. Efficiency factors other than those coming from kinematic cuts are not included. **Resolved photon backgrounds are neglected.**

– Can TESLA do better? No realistic spectrum presented yet, but rep rate and charge bunch density suggest factor of 2 better yearly luminosity, which helps.

– Can we get better than 80% e polarization? without sacrificing luminosity? That would help at higher $m_{A^0} \sim E_{\gamma\gamma}$, but does not help much at lower $E_{\gamma\gamma}$ since big tail is from beamstrahlung, secondary pair creation, . . .

- **A natural question: Can a scenario with a light decoupled $h = A^0$ or $h = h^0$ and no other observable Higgs at e^+e^- collider ($\sqrt{s} \lesssim$ 800 GeV) be consistent with precision electroweak?** (JFG, Farris, Chankowski, Grzadkowski, Kalinowski, Krawczyk)

  Answer: Yes! In minimum $\Delta\chi^2$ scenarios, if $h = A^0$ (decoupled h^0) then h^0 (H^0) is SM-like **with mass $\lesssim$ 1 TeV. $\Rightarrow$ LHC!!**

– Heavy $h_{\rm SM} \Rightarrow$ 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 $\Rightarrow$

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

Can adjust $m_{H^\pm} - m_{H^0} \sim$ few GeV (both heavy) so that the S, T prediction = 'blob' for points within the Yukawa non-discovery wedges.

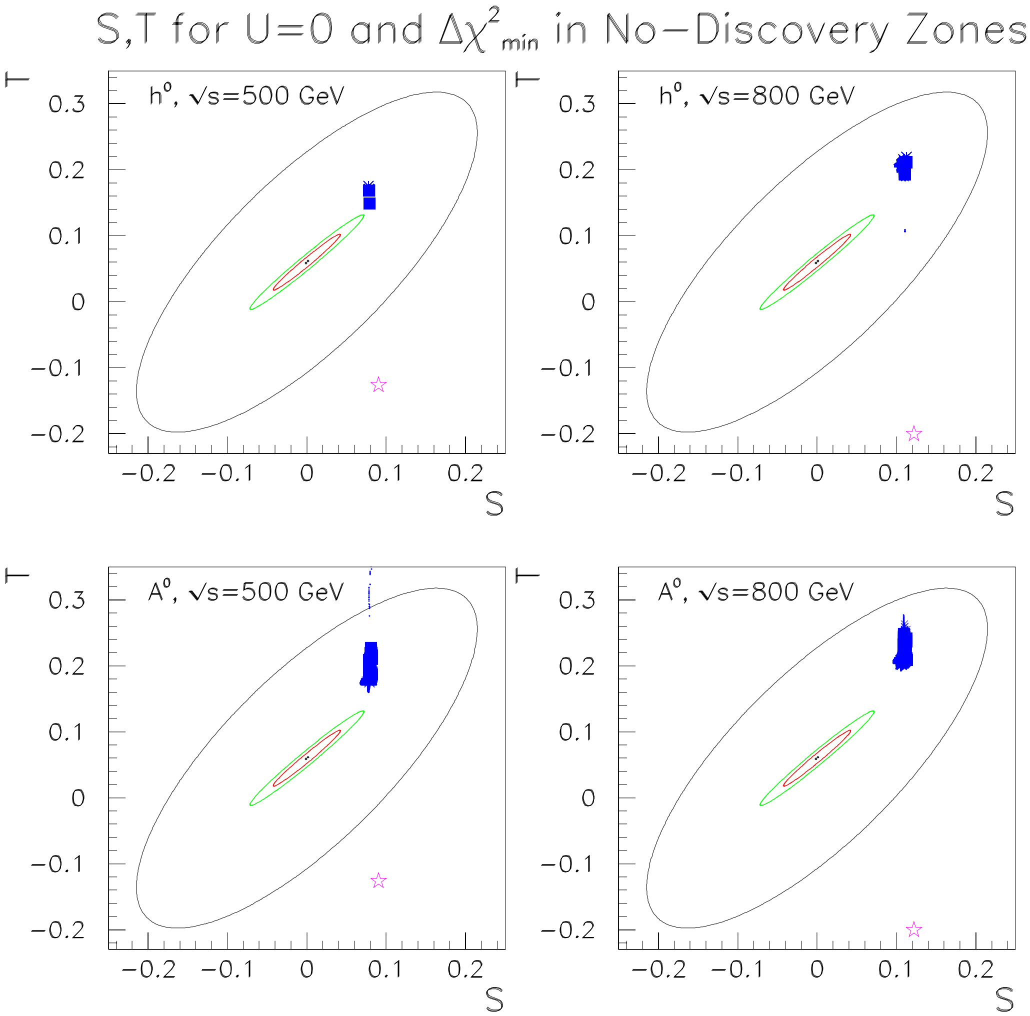


Figure 5: Outer ellipses = current 90% CL region for $U = 0$ and $m_{h_{\rm SM}} = 115$ GeV. Blobs = S, T predictions for Yukawa-wedge 2HDM models with minimum relative $\Delta\chi^2$. Innermost (middle) ellipse = 90% (99.9%) CL region for $m_{h_{\rm SM}} = 115$ GeV after Giga-Z *and* a $\Delta m_W \lesssim 6$ 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?

Latest BNL result for a_μ differs by 2.6σ from SM prediction (with one set of inputs for low energy $\sigma(e^+e^- \to \text{hadrons})$).

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 426(165) \ \times \ 10^{-11} \ , \tag{4}$$

Taking the above numbers at face value, the range of Δa_μ at 95% C.L. ($\pm 1.96\sigma$) is given by $10.3 \times 10^{-10} < \Delta a_\mu < 74.9 \times 10^{-10}$.

A light A^0 (h^0) gives a positive (negative) contribution dominated by two-loop Bar-Zee graph. If we use light A^0 as entire explanation, $\Rightarrow$

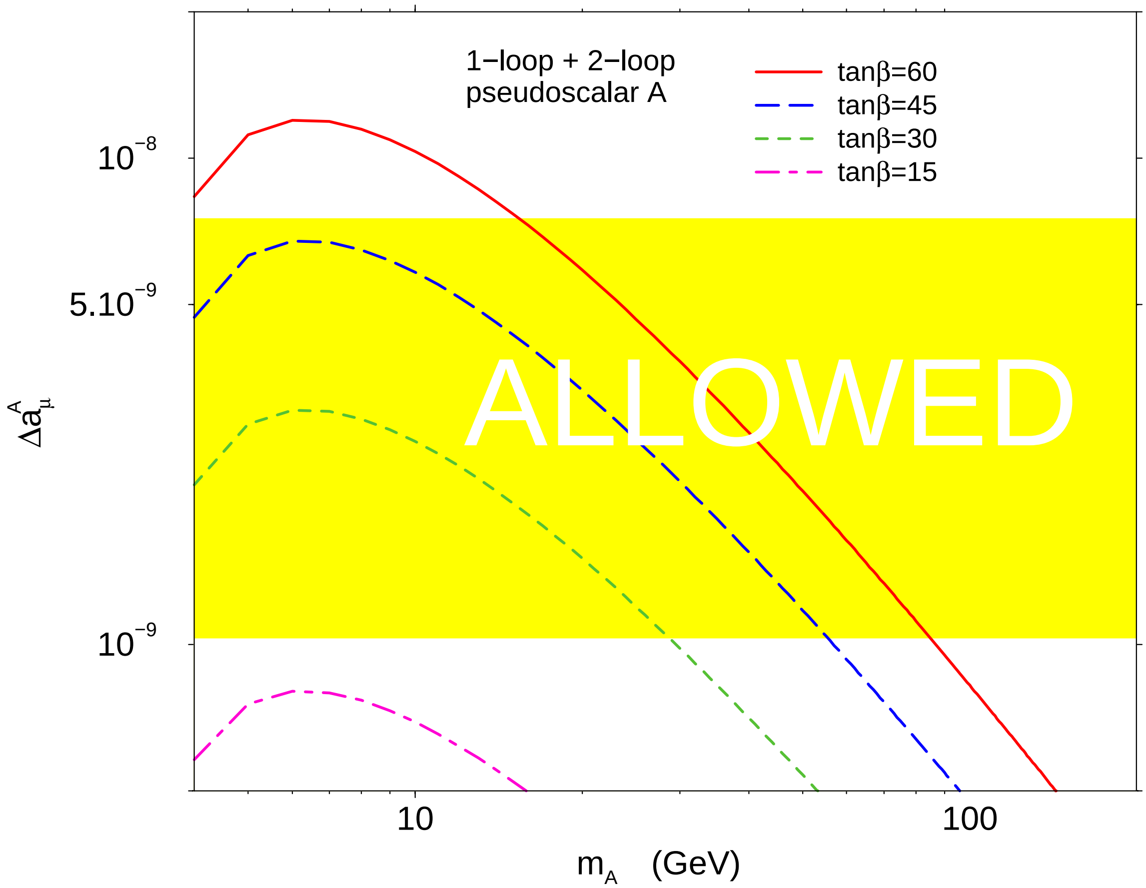


Figure 6: Explanation of new BNL a_μ value via light 2HDM A^0. (Cheung, Chou, Kong)

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.**

2 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 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 $b_i V < 0$, then $m_H > m_Z$ gives equally good fit.

– Must consider all available precisely measured $\mathcal{O}_i$ at same time. i.e. $\sin^2\theta_W^{\rm eff}$, Γ_Z, *etc.*

– Full analysis shows that $m_H \leq 500$ GeV 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

$$\mathcal{L}_{\rm mix} \propto \kappa \sum_{\vec n} \phi^{\vec n}_{KK} T_\mu^{\mu,\ \rm Higgs} \propto \kappa \sum_{\vec n} \phi^{\vec n}_{KK} V(\phi)$$

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

$$\sum_{{\rm all}\,\vec n} \frac{1}{m_n^2} \equiv \frac{\overline{D}}{\kappa^2} \frac{\delta + 2}{\delta - 2}\,, \tag{5}$$

where δ =number of extra dimensions.

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

For $\delta > 2$, the sum is divergent – after regulation by the string, $\overline{D} \sim M_S^{-4}$ but the sign of $\overline{D}$ 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 with $m^2_{s_{\rm phys}} > 0$.

  ∗ Standard WW/ZZ couplings for $s_{\rm phys}$ (with tiny corrections) requiring $\hat{v} = 246$ 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.

  No particular motivation, but certainly allowed, and if allowed . .

– 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 $\phi_{KK}^{\vec{n}}$ couple to this: $\mathcal{L} \ni \frac{f(\delta)}{M_\mathrm{P}} \Sigma_{\vec{n}}\, \phi_{KK}^{\vec{n}} T_\mu^\mu$.

– The resulting H–$\phi_{KK}^{\vec{n}}$ mixing must be removed by rediagonalization, and the physical Higgs ends up having some KK-graviscalar excitation components.

  $\Rightarrow$ decays of H_phys to KK-graviscalars, again invisible.

Combining Higgs-graviscalar mixing, possibly with unconventional EWSB minimum, $\Rightarrow$ many phenomenological variants. Sorting it all out may be a challenge.

3 An invisibly decaying SM-like Higgs boson

This has been studied for various colliders by many people (Frederikson etal, JFG, Choudhury and Roy, Martin and Wells, ...), but takes on particular importance in the extra dimension schemes (but also other models as well: Majorons, spin-0 scalars, ...).

– **At LEP2, NLC 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.

– **Life at hadron colliders is tougher.**

  Use WH, ZH or $t\bar{t}H$ production (LHC only for latter).

  Assume pure invisible decays.

  * **Tevatron result is:**

    $\Rightarrow$ Need $L > 5$ fb^{-1} to surpass LEP2 limit.

  * **At the LHC,** $L = 100$ fb^{-1} will probe up to ~ 200 GeV.

  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.

4 Models with Higgs triplet representations

Most strongly motivated are the L-R symmetric and related models in which neutrino masses arise via seesaw from lepton-number-violating (Majorana-like) coupling of two leptons to a triplet Higgs boson.

- Triplet Higgs field(s) destroy unification (SUSY) if intermediate scale matter not included, but such matter is natural in LR models.

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

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

$$\boldsymbol{\mathcal{L}_Y = i h_{ij} \psi_i^T C \tau_2 \Delta \psi_j + \mathrm{h.c.}\,,} \tag{6}$$

  where $i, j = e, \mu, \tau$ are generation indices, and Δ is the 2×2 matrix of Higgs fields:

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix} . \tag{7}$$

- Limits on the h_{ij} by virtue of the $\Delta^{--} \to \ell^-\ell^-$ couplings include: Bhabbha scattering, $(g-2)_\mu$, muonium-antimuonium conversion, and $\mu^- \to e^-e^-e^+$. Writing

$$|h_{\ell\ell}^{\Delta^{--}}|^2 \equiv c_{\ell\ell} m_{\Delta^{--}}^2(\text{ GeV})\,, \tag{8}$$

  $c_{ee} < 10^{-5}$ (Bhabbha) and $\sqrt{c_{ee}c_{\mu\mu}} < 10^{-7}$ (muonium-antimuonium) are the strongest of the limits. No limits on $c_{\tau\tau}$.

- $\Gamma_{\Delta^{--}}^T$ could be small (triplet vev=0 limit which $\to \rho = 1$ is natural).

  $\Rightarrow$ possibly very large s-channel e^-e^- and $\mu^-\mu^-$ production rates.

- Strategy:

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

    $\Rightarrow$ TeV33 + LHC will tell us if such a Δ^{--} exists in the mass range accessible to NLC and FMC *and how it decays*.

  – Study in e^-e^- and $\mu^-\mu^-$ s-channel collisions via the allowed Majorana-like bi-lepton coupling.

    Event rates can be enormous (see JFG, hep-ph/9803222 and hep-ph/9510350): equivalently can probe to very small $c_{\ell\ell}$.

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

$$\boldsymbol{N(\Delta^{--})_{L=50\ \mathrm{fb}^{-1}} \sim 3 \times 10^{10} \left(\frac{c_{ee}}{10^{-5}}\right)\left(\frac{0.2\%}{R}\right)\ ;} \quad (9)$$

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

    * For 100 events, Eq. (9) $\Rightarrow$ we probe

$$c_{ee}|_{100\ \mathrm{events}} \sim 3.3 \times 10^{-14}(R/0.2\%)\,, \quad \Gamma^T_{\Delta^{--}} \ll \sigma_{\sqrt{s}}\,, \quad (10)$$

      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.

5 SUSY Higgs

- Despite all the fun with extra dimension in SM case, naturalness problem can also easily be cured by TeV scale SUSY.
- MSSM contains exactly two doublets ($Y = +1$ and $Y = -1$), as required to give masses to both up and down quarks.

  Two doublets, and their higgsino partners, $\Rightarrow$ anomaly cancellation.
- Two doublets yield perfect coupling constant unification if the SUSY scale is $m_{\rm SUSY} \sim 1$ TeV (actually, significant SUSY stuff at 10 TeV works better for α_s).

  More doublets, triplets, etc. $\Rightarrow$ generally need intermediate scale matter between TeV and M_U scales.

  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.
- SUSY Higgs mass bounds: Assume $m_{\widetilde t} \leq 1$ TeV (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):

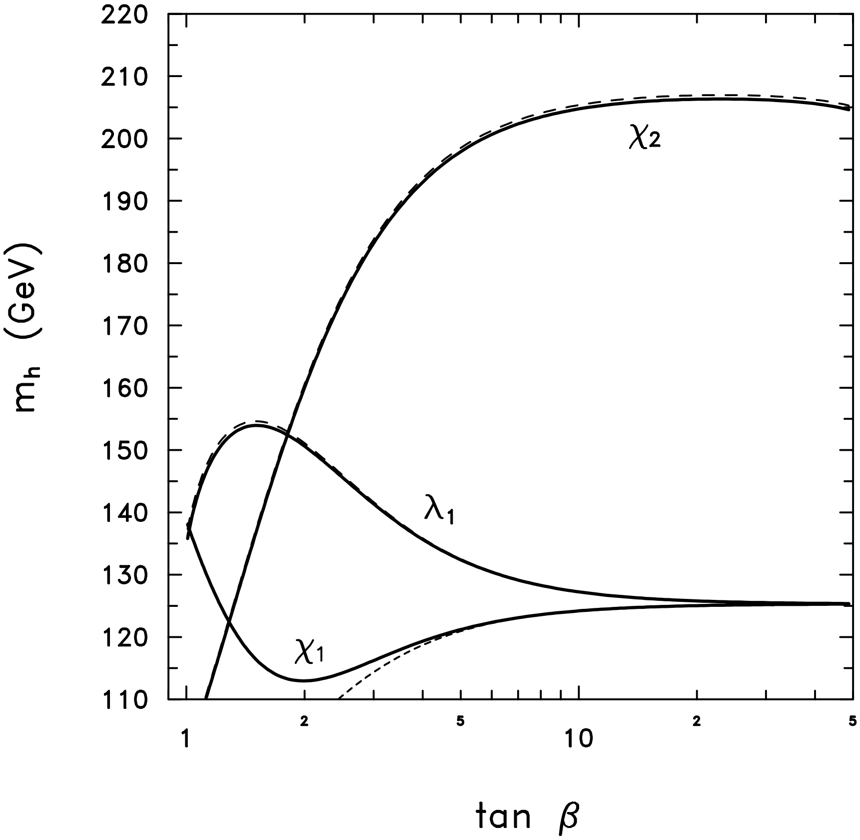


Figure 7: Bounds on SUSY m_h in presence of different types of multiplets. From Espinosa and Quiros, hep-ph/9804235

NOTE: $\Rightarrow \langle M^2 \rangle \leq (200\ \mathrm{GeV})^2$ in sum rule used for no-lose theorem for finding neutral Higgs effect at LC.

- **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.

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

Higher $m_{\tilde t}$:

– 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.

– One study (Kane + Wang) suggests that MSSM Higgs mass limits will be weakened by about 10%, implying that the disallowed $\tan\beta$ region is probably still allowed when CP violation is allowed.

Invisible Decays:

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

- **'Standard' discovery prospects in the MSSM at Tevatron, LHC, NLC**

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. $\Rightarrow$

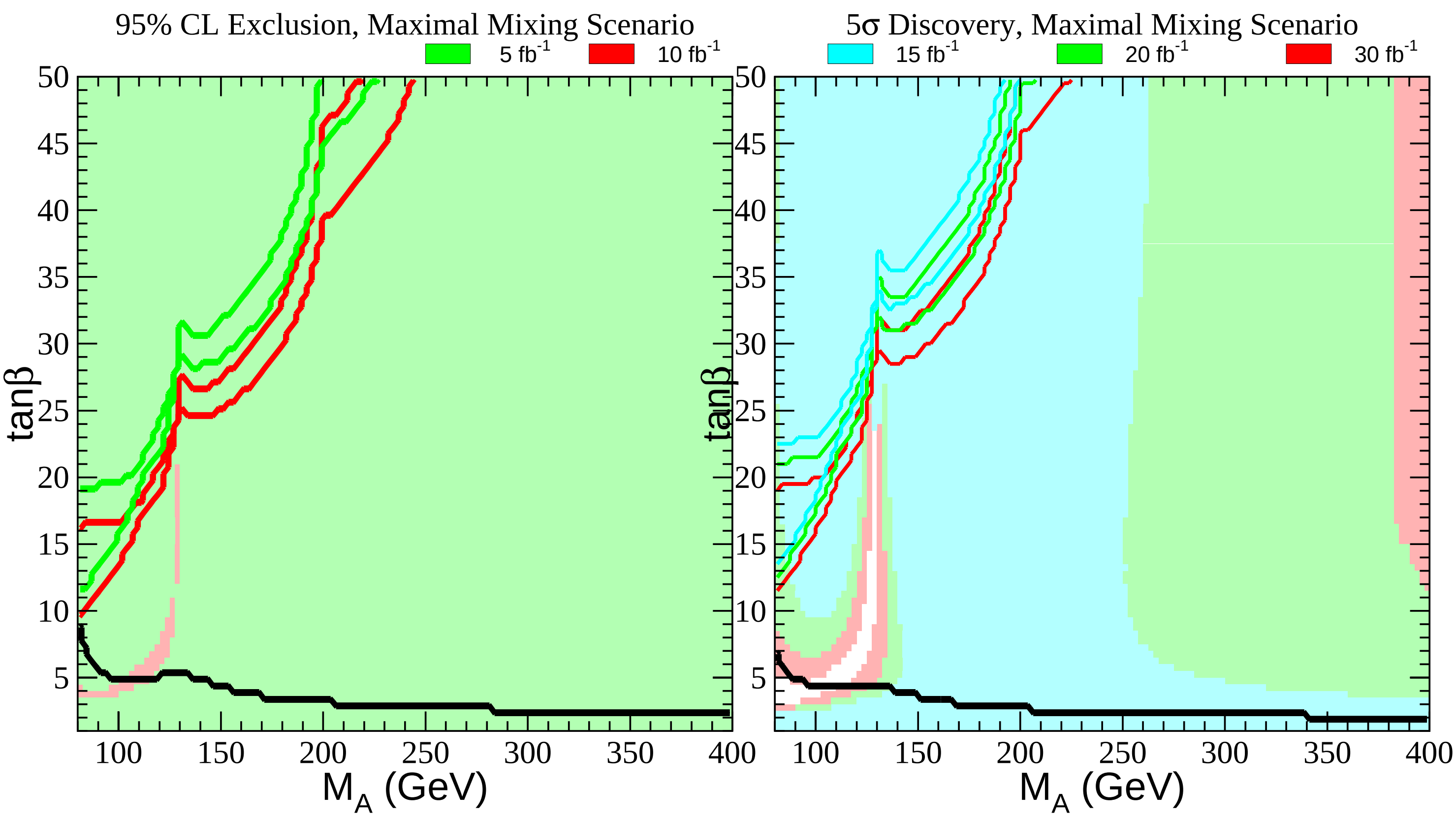


Figure 8: (a) 95% CL exclusion region and (b) 5σ discovery region on the m_{A^0}–$\tan\beta$ plane, for the maximal mixing scenario and two different search channels: $q\bar{q} \to V\phi$ [$\phi = h^0$, H^0], $\phi \to b\bar{b}$ (shaded regions) and gg, $q\bar{q} \to b\bar{b}\phi$ [$\phi = h^0$, H^0, A^0], $\phi \to b\bar{b}$ (region in the upper left-hand corner bounded by the solid lines). Region below the solid black line is excluded by no $e^+e^- \to Z\phi$ events at LEP2.

$L > 15$ fb^{-1} needed for 5σ discovery (see h^0).

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

The LHC

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

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

LEP2 limits pretty much exclude $\tan\beta < 4$ where other modes could be important

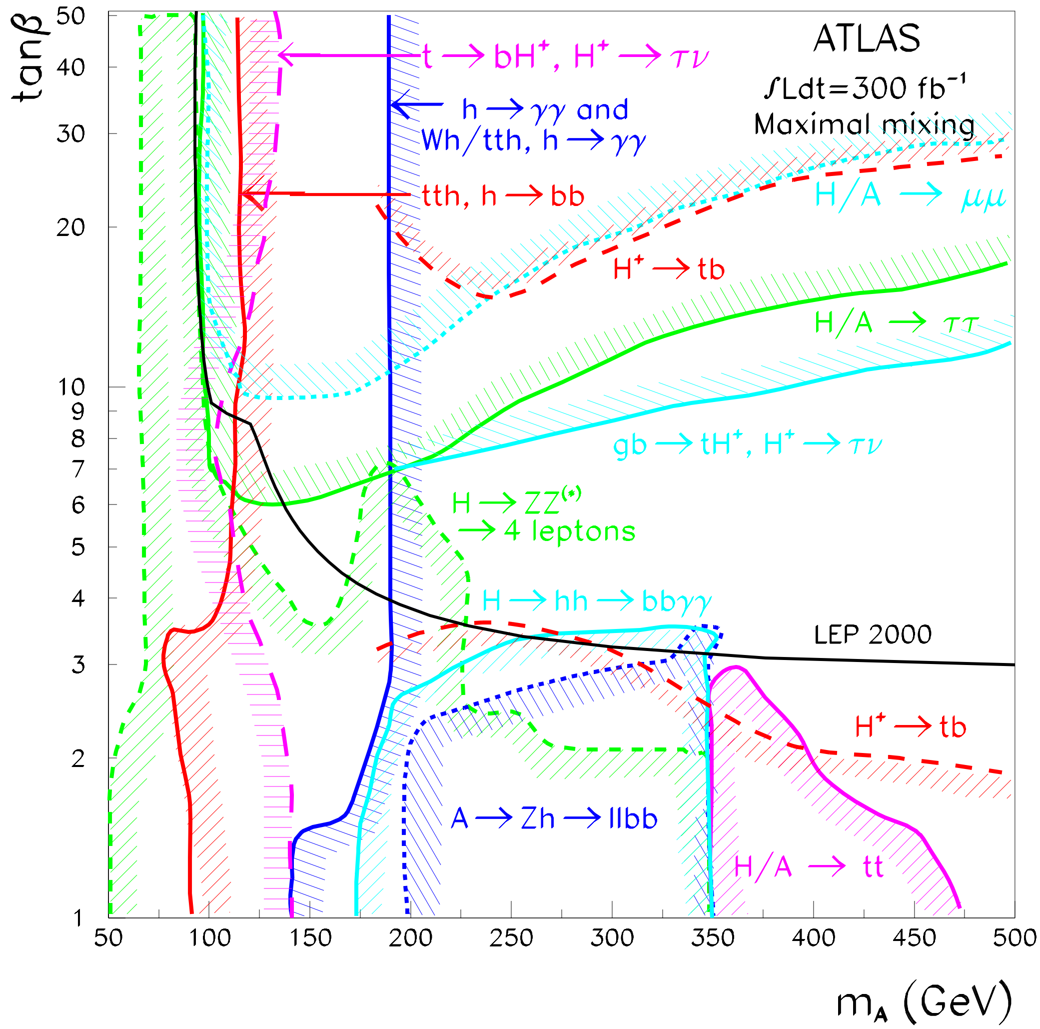


Figure 9: 5σ discovery contours for MSSM Higgs boson detection in various channels are shown in the $[m_{A^0}, \tan\beta]$ parameter plane, assuming maximal mixing and an integrated luminosity of $L = 300$ fb^{-1} for the ATLAS detector. This figure is preliminary.

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

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

Linear e^+e^- collider

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

$\Rightarrow$ precision measurements of $\sim$SM properties ($m_{A^0} > 2m_Z$).

– For $A^0, H^0, H^\pm$:

If $m_{A^0} > 2m_Z$ (as probable given RGE EWSB), most substantial e^+e^- production mechanisms are $e^+e^- \to H^0 + A^0$ and $e^+e^- \to H^+ + H^-$.

But, given that $m_{H^0} \sim m_{A^0} \sim m_{H^\pm}$ for large m_{A^0}, these all require $\sqrt{s} \gtrsim 2m_{A^0}$.

– For very high $\tan\beta$, can look to $e^+e^- \to b\overline{b}A^0, b\overline{b}H^0, btH^\pm$.

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

Strategies

* Raise $\sqrt{s}$! (longer machine, new/improved technology, CLIC, muon collider, . . .)
* Use precision h^0 measurements to get first indication of presence of A^0, H^0 and rough determination of $m_{A^0} \sim m_{H^0}$.
  (Requires determining extent to which one is in 'normal' vs. 'unusual' bb coupling scenario.)
  Then use peaked $\gamma\gamma$ spectrum to look for H^0, A^0 (usually overlapping) combined signal over narrow interval.
  <1 year's luminosity needed if you know m_{A^0} within ~ 50 GeV and use 5 steps in $\sqrt{s}$ to explore each test interval $m_{A^0} \in [E_{\gamma\gamma}^{\rm peak}, E_{\gamma\gamma}^{\rm peak} + 10 \text{ GeV}]$.

$$N(\gamma\gamma \to \hat{h} \to X) = \frac{4\pi^2 \Gamma(\hat{h} \to \gamma\gamma) B(\hat{h} \to X)(1 + \langle\lambda\lambda'\rangle)}{\sqrt{s} m_{\hat{h}}^2} \frac{d\mathcal{L}_{\gamma\gamma}}{dy}$$
$$\equiv \langle\sigma(\gamma\gamma \to \hat{h} \to X)\rangle m_{\hat{h}} \frac{d\mathcal{L}_{\gamma\gamma}}{dE_{\gamma\gamma}} \quad (11)$$

where $y = m_{\hat{h}}/\sqrt{s}$, $d\mathcal{L}_{\gamma\gamma}/dy$ is the differential luminosity, $\Gamma_{\rm res}$ ($b\overline{b}$ mass resolution) assumed $\gg \Gamma^{\rm tot}_{\hat{h}}$.

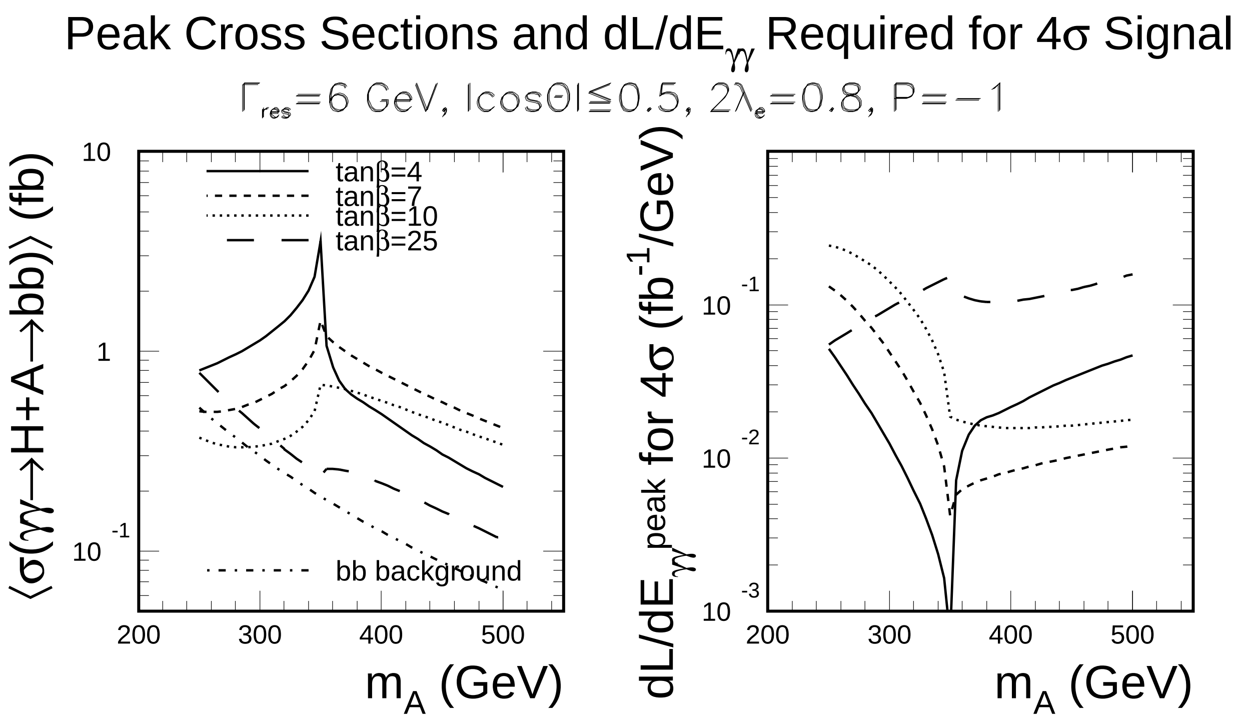


Figure 10: (a) The effective cross section $\langle\sigma(\gamma\gamma \to H^0, A^0 \to b\overline{b})\rangle$ and corresponding background vs. m_{A^0} for $\langle\lambda\lambda'\rangle = 0.8$. $\Gamma_{\rm res}(b\overline{b}) = 6$ GeV is assumed and various cuts are performed. Supersymmetric particle loops are neglected. These results can only roughly be compared to those for $\tan\beta = 7$ in Muhlleitner:etal (w/o SUSY curve), computed using more optimistic assumptions regarding $\langle\lambda\lambda'\rangle$ and a somewhat different definition of $\langle\sigma(\gamma\gamma \to H^0, A^0 \to b\overline{b})\rangle$. (b) $\frac{dL_{\gamma\gamma}}{dE_{\gamma\gamma}}$ at the peak required to detect a Higgs signal at the 4σ level.

$*$ If you don't trust indirect m_{A^0} determination, $\Rightarrow$ go to earlier maximal $\sqrt{s}$ procedure using 1 year broad spectrum + 1 year peaked spectrum.

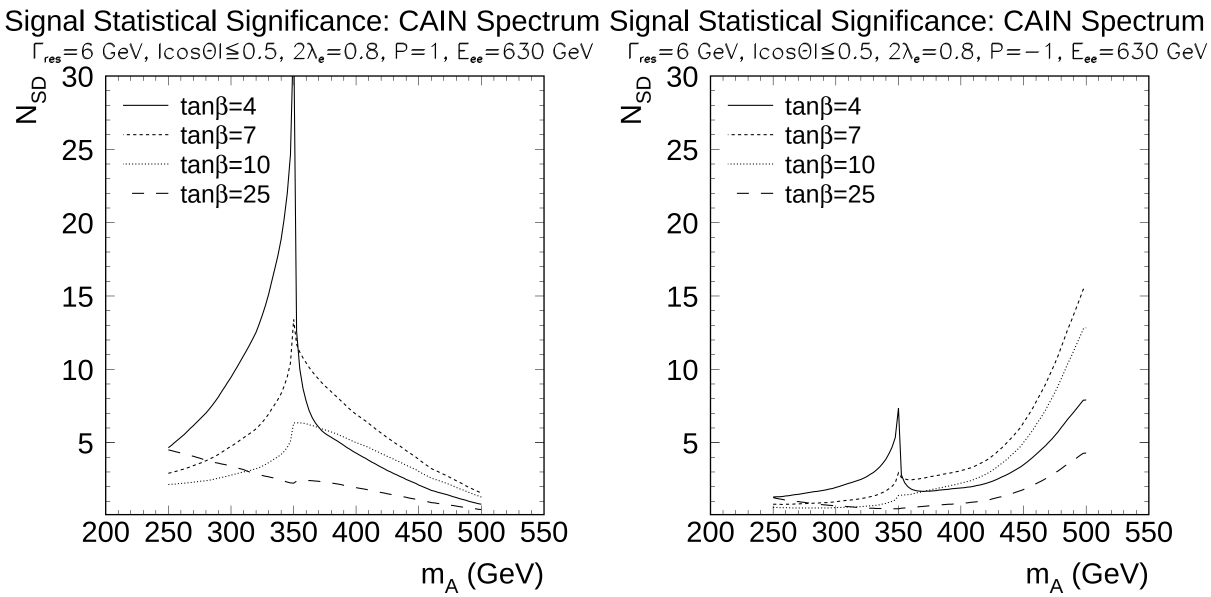


Figure 11: As for A^0 only, but combining H^0 and A^0 signals for maximal mixing case.

$\Rightarrow$ somewhat better than A^0-only due to nearby H^0, but still does not cover whole LHC wedge without higher luminosity. TESLA?

NB. Beamstrahlung, etc. means $\langle\lambda\lambda'\rangle$ is not large enough to really kill the background except near the $\sim$ 500 GeV maximum.

– Once a Higgs is detected, use peaked spectrum and study it.

Variants of 'standard' results $\Rightarrow$ be cautious.

– Invisible decays.

As stated earlier, this will probably allow non-detection scenarios at hadron colliders. New mode: $h^0 \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$ still possible given LEP2 data.

– Stop loop corrections to one-loop couplings

Stop and top loops negatively interfere: $\Rightarrow$

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

– Radiative corrections to couplings.

Especially important for $b\overline{b}$ decays of h^0 (when h^0 SM-like).

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

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

* After including radiative corrections, for $b\overline{b}$ we have

$$\mathcal{L} \simeq \lambda_b H_d^0 b\overline{b} + \Delta\lambda_b H_u^0 b\overline{b}.$$

The coupling $\Delta\lambda_b$ is one-loop: $\tilde{b} - \tilde{g}$ loops + $\tilde{t} - \widetilde{H}_{u,d}$ loops.

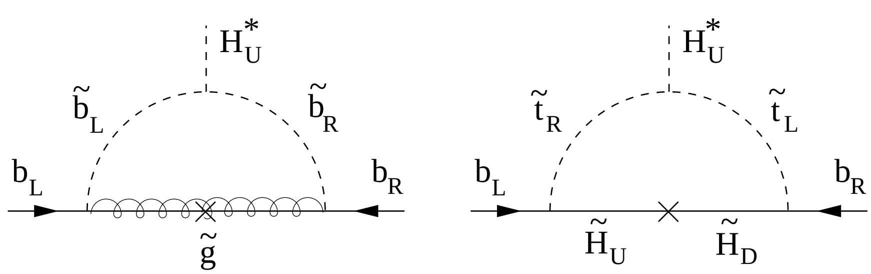


Figure 12: Loop contributions to $\Delta\lambda_b$.

$\frac{\Delta\lambda_b}{\lambda_b}$ does not vanish in limit of large SUSY masses (no decoupling).

* **Result: h^0 can decouple from b's (i.e. $h^0 \simeq H_u$).**
* **Many effects on discovery modes of light Higgs:** Typically, LHC $gg \to h^0 \to \gamma\gamma$ and Tevatron $Wh^0[\to WW^*]$ modes win when LHC, Tevatron $W, Zh^0[\to b\overline{b}]$ modes lose.

  $\Rightarrow$ Complementarity of Tevatron and LHC.
* **e^+e^- collider Zh^0 mode (using inclusive recoil) $\to$ completely robust against 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 $\widetilde{\chi}_1^0\widetilde{\chi}_1^0, \widetilde{\chi}_1^+\widetilde{\chi}_1^-, \tilde{\tau}^+\tilde{\tau}^-, \tilde{\nu}\overline{\tilde{\nu}}, \ldots$ decays are kinematically allowed. However, at high $\tan\beta$ the usual dominance of decays to $b\overline{b}$ and $\tau^+\tau^-$ will be preserved.

  $\Rightarrow$ only some widening of h^0-only LHC wedge.

  – **e^+e^- collider H^0A^0 and H^+H^- detection quite robust against complicated decays if pair production not too near kinematic limit.** (JFG, Kelly) (Feng, Moroi) (...)

  In fact, precise decay mixtures $\Rightarrow$ immensely powerful probe of soft SUSY breaking.

  But, must separate different final state channels ($[3\ell, 2b]$, $[1\ell, 0b]$, ... — maybe 15 or 20 different channels) and know efficiencies for different channels with good precision.

  – $\gamma\gamma \to H^0, A^0$ discovery could become much more difficult.

- **Beyond the MSSM:**

  – The NMSSM brings in an extra scalar and an extra pseudoscalar.

  $\Rightarrow$ dilution of signals due to mixing of the two doublets with the singlet Higgs fields.

  $\Rightarrow$ no absolute guarantee of discovery at the LHC. (JFG, Haber Moroi)

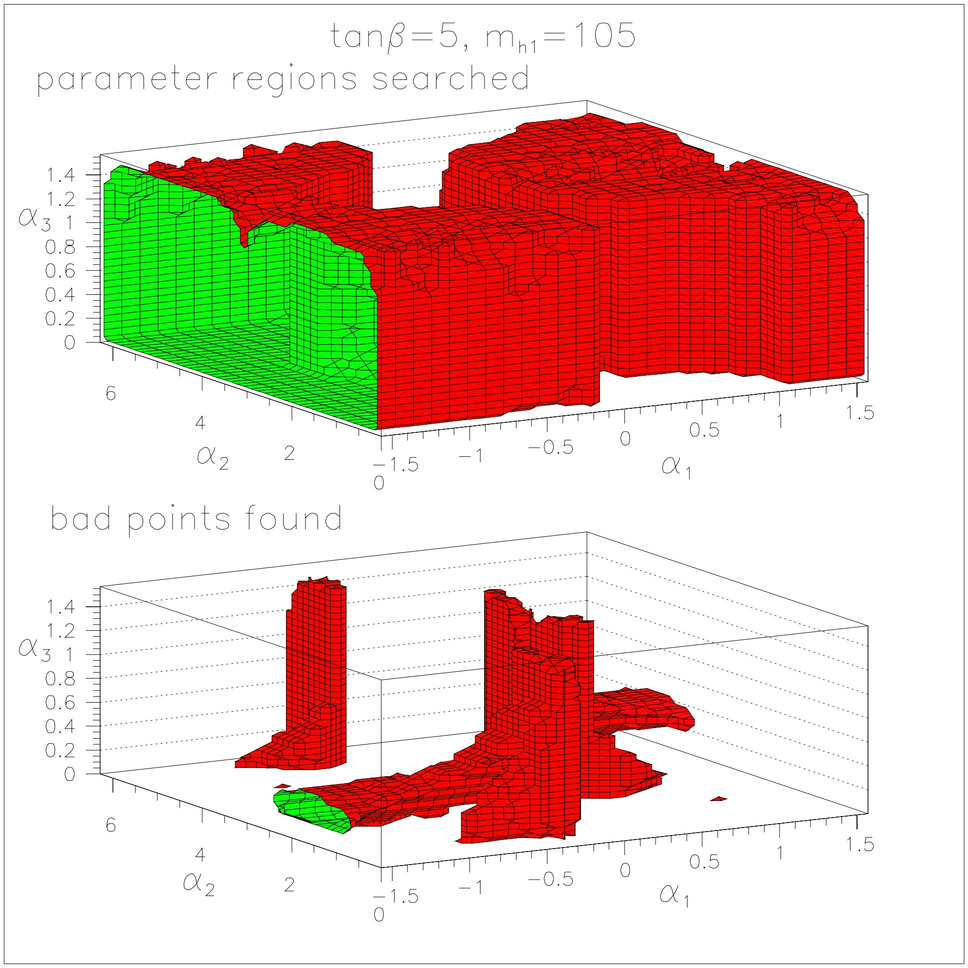


Figure 13: For $\tan\beta = 5$ and $m_{h_1^0} = 105$ GeV, we display in three dimensional $(\alpha_1, \alpha_2, \alpha_3)$ parameter space the parameter regions searched (which lie within the surfaces shown), and the regions therein for which the remaining model parameters can be chosen so that no Higgs boson is observable (interior to the surfaces shown).

Challenge: improve all modes to cut down non-discovery parameter regions.

– String models suggest that there could be many extra U(1)'s.

$\Rightarrow$ a real possibility for the diffuse type of signal discussed earlier.

– If R-parity is violated, Higgs production could produce very different types of signals than so far considered.

One example: if $h^0 \to \widetilde\chi_1^0\widetilde\chi_1^0$ and $\widetilde\chi_1^0 \to csd$ via baryonic R-parity violation, $\Rightarrow$ $Zh^0 \to Z + 6$ soft jets.

* We know that we don't see $e^+e^- \to \widetilde\chi_1^0\widetilde\chi_1^0 \to 6$ jets at LEP, $\Rightarrow$ not relevant there.
* Probably ok at NLC, especially since $e^+e^- \to \widetilde\chi_1^0\widetilde\chi_1^0 \to 6$ jets will display a big excess and warn us as to what to look for.
* Probably a big problem at hadron colliders. **Challenge: prove that I am wrong.**

6 Muon Colliders

- Potential for doing e^+e^- type physics.

  Challenge: match new LC luminosity levels.

- Higgs factory:

  $\sigma_{\sqrt{s}}$, the Gaussian resolution in $\sqrt{s}$, can be tiny (few MeV) $\Rightarrow$

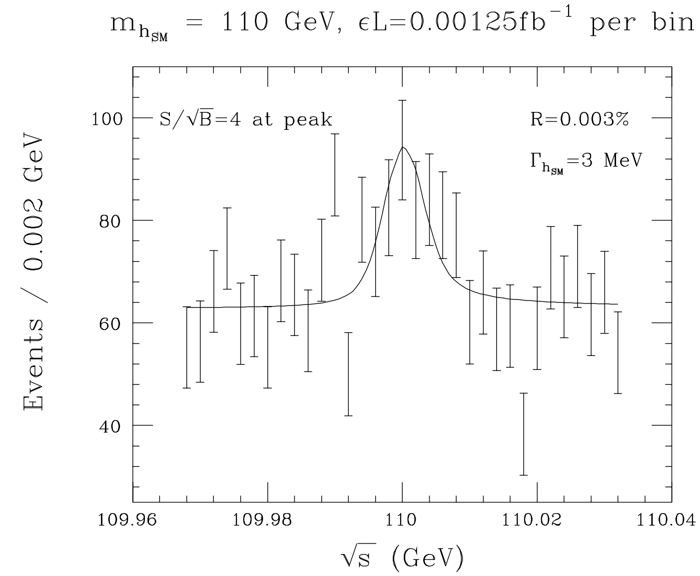


Figure 14: Initial scan for centering on $m_{h_{SM}} = 110$ GeV Higgs boson.

  $\Rightarrow$ direct scan determination of SM Higgs (and other widths).

  $\Rightarrow$ separate H^0 from A^0 very cleanly.

  $\Rightarrow$ scan for decoupled light h.

  Challenges: prove cooling; upgrade SM96 luminosity.

- Could reach very high energy:

  $\Rightarrow$ pair produce anything, but in particular pairs of Higgs.

  $\Rightarrow$ study strong WW sector, resonances, technicolor resonances, . . .

Overall Challenge: convince community to pursue on shorter time scale $\rightarrow$ sacrifice something else?

7 A Grand Challenge: Determine the CP of a Higgs.

Techniques not employing $t\bar{t}$ or $\tau^+\tau^-$ decays..

- 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. ⇒ will not 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). **Challenge: 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, ⇒ use $\gamma\gamma$ collisions. (JFG, Grzadkowski; JFG, Kelly; Djouadi etal, . . .)

$$\mathcal{A}_{CP=+} \propto \vec{\epsilon}_1 \cdot \vec{\epsilon}_2\,, \quad \mathcal{A}_{CP=-} \propto (\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot \hat{p}_{\rm beam}\,. \tag{12}$$

– For pure CP states, maximize linear polarization and adjust orientation ($\perp$ for CP odd dominance, $\|$ 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 and sensitivity need experimental level 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 the cross section takes the form

$$\begin{aligned}\overline{\sigma}_S(\zeta) &= \overline{\sigma}_S^0 \left(1 + P_L^+ P_L^- + P_T^+ P_T^- \left[\frac{a^2 - b^2}{a^2 + b^2}\cos\zeta - \frac{2ab}{a^2 + b^2}\sin\zeta\right]\right) \\ &= \overline{\sigma}_S^0 \left[1 + P_L^+ P_L^- + P_T^+ P_T^- \cos(2\delta + \zeta)\right] , \qquad (13)\end{aligned}$$

– $\delta \equiv \tan^{-1}\frac{b}{a}$,

– 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.**

8 Conclusions

- The simplest models (SM, MSSM) will allow discovery of a Higgs boson.
- But, even in these models, care is necessary.
- 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 $\sqrt{s} = 600$ 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

- **Let's not forget about muon colliders. They could play a uniquely valuable role in a number of cases.**
- **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) **(rapidity gap backgrounds?)** (Albrow, . . .)**;**

  (b) make one of the proposed CP determination techniques work;

  (c) work hard to close the h^0-only wedge as much as possible.
- **LC must provide clear path to $\sqrt{s} > 1$ TeV.**