HUNTING THE HIGGS BOSON(S)

J. F Gunion, Pascos 2001, April 10, 2001

OUTLINE

- Standard Model
- 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 STANDARD MODEL

- **Bounds:** use λ, the quartic Higgs coupling: $V \ni \lambda\phi^4$.

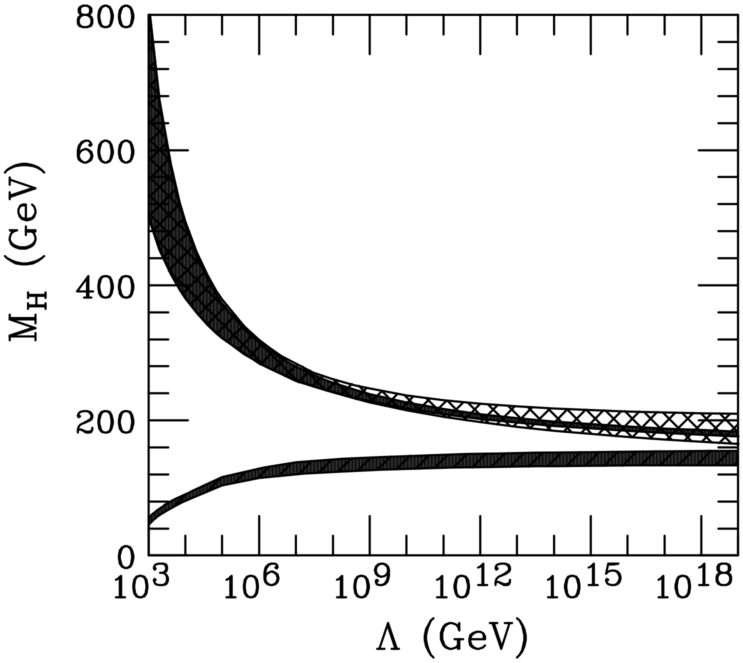


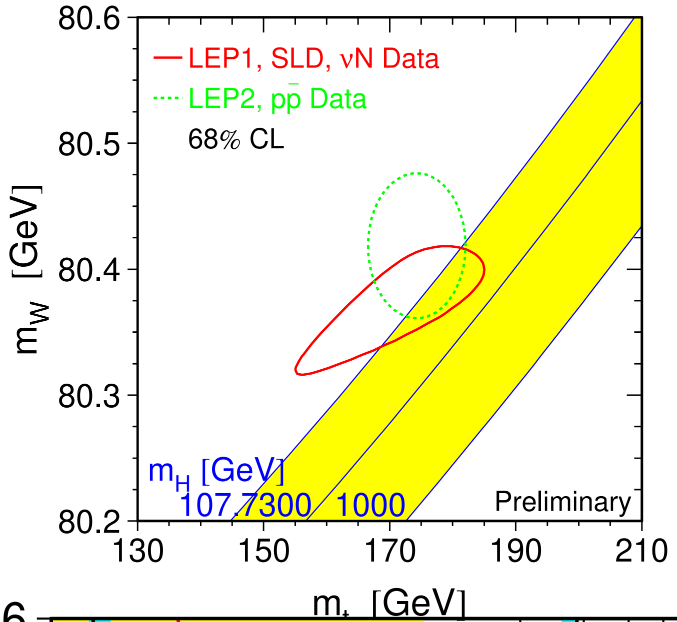
Figure 1: Triviality and (Meta)stability bounds for the SM Higgs boson as a function of the new physics scale Λ. From Hambye and Riesselmann, hep-ph/9610272

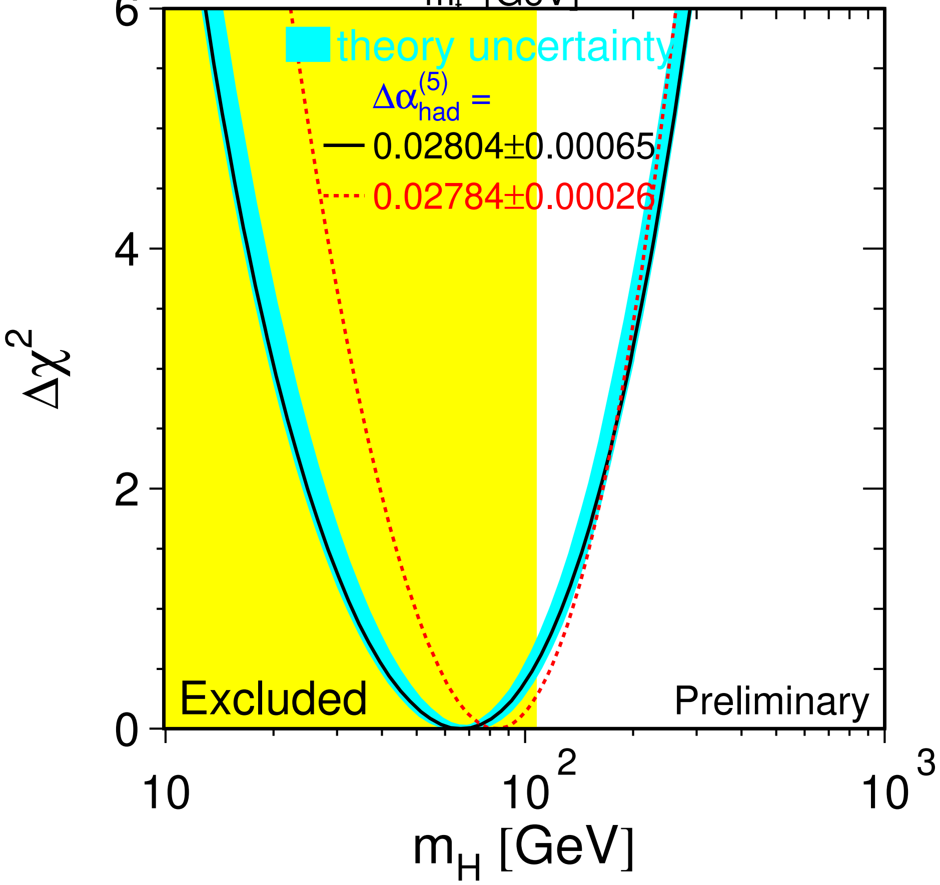
Bound $\lambda(m_h)$ which bounds m_h [$m_h \sim 2v^2\lambda(m_h)$, v =vev] by bounding $\lambda(\Lambda)$ (recall λ grows with energy scale).

Bound from (meta)stability of the potential. We use $\lambda(\Lambda) > 0$ stability requirement. Meta-stability not very different.

SM Higgs clearly within LHC, $\sqrt{s} = 500$ GeV NLC reach. Tevatron?

  – If no new physics until $\Lambda \sim M_{\rm P}, M_U$, then $m_H \in [160, 200]$ GeV, as consistent with, but not preferred by, current precision electroweak data (center of fit is lower).





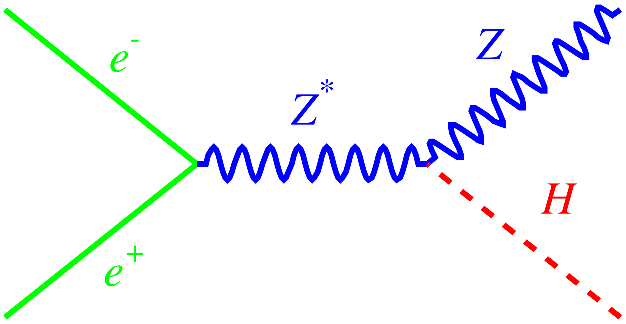
Is the indication for $m_{h_{SM}} <$ current LEP lower limit a sign of new physics contributions to the observables that force this? Could there be some Higgs weight below 100 GeV?

– But, these results are from RGE log variation. Does not answer ab initio quadratic divergence problem; control $\Rightarrow$ **SUSY**.

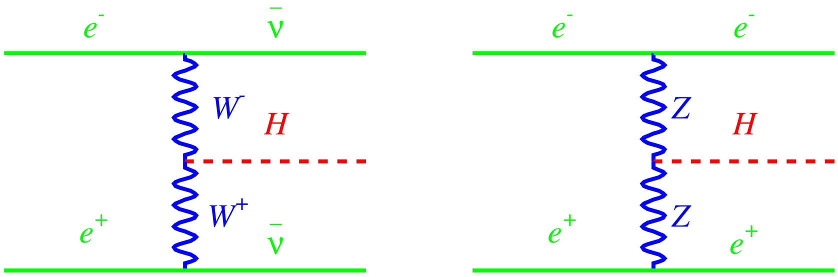
- **Have we seen the SM Higgs at LEP?**

Higgs Production at LEP2

At LEP, Higgs is predominantly produced via the Higgs-strahlung process



with additional small contributions from WW- and ZZ-fusion.



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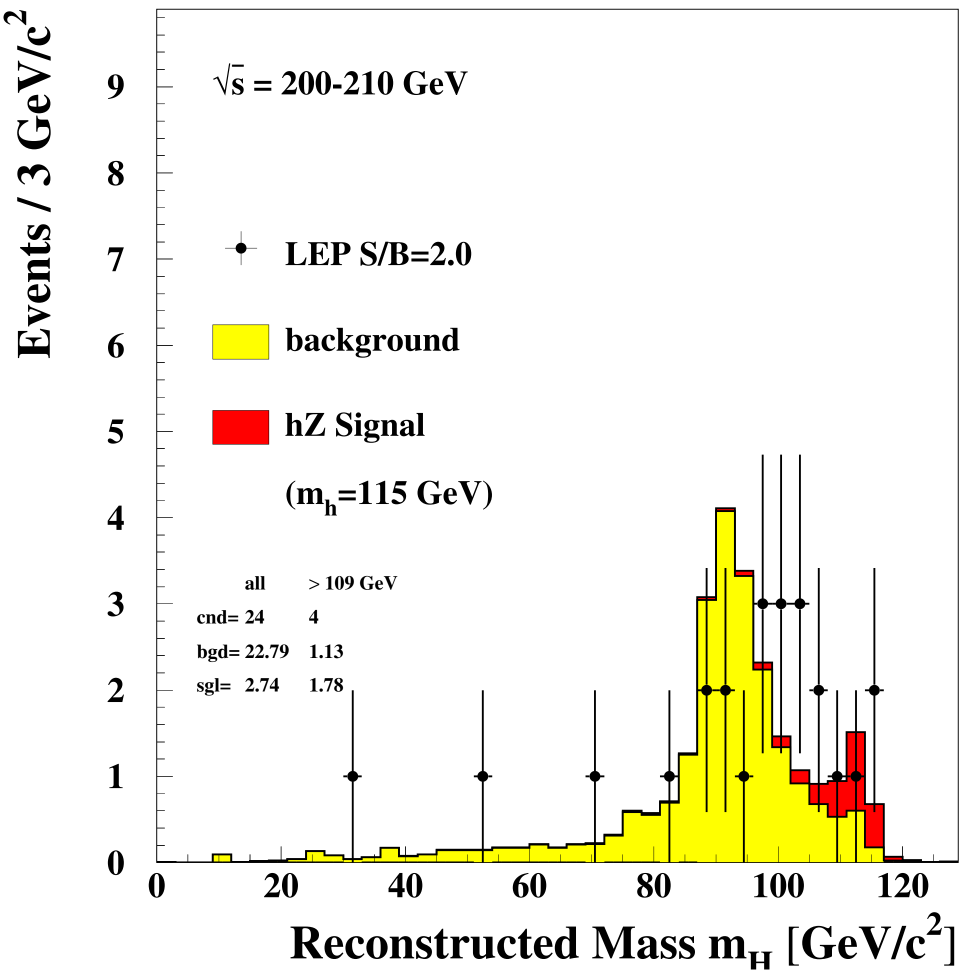
Tight Mass Plot

In the tightest selection, above 109 GeV/c^2, 4 events are observed with 1.13 expected from background and 1.78 expected from signal.



This is for display only– doing the analysis this way discards a lot of valuable signal

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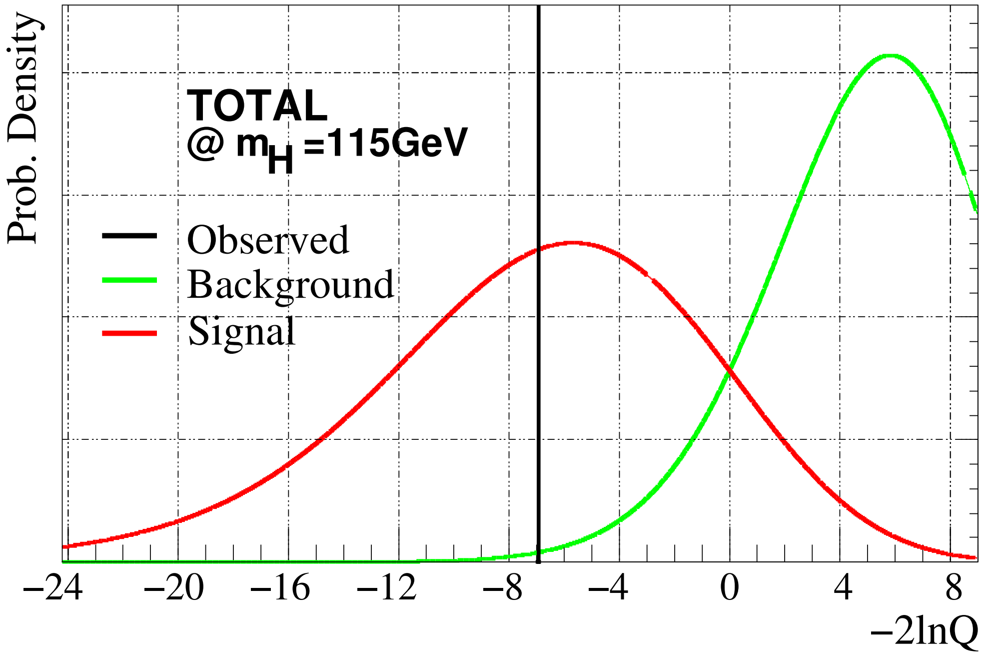
Comparison to Signal and Background

For the 115 GeV/c^2 Signal Hypothesis:



When all channels/all experiments are combined result significantly favors signal hypothesis.

With $-2\ln Q = -7$, result is very close to mode of signal distribution

Would require a large fluctuation to be considered compatible with background

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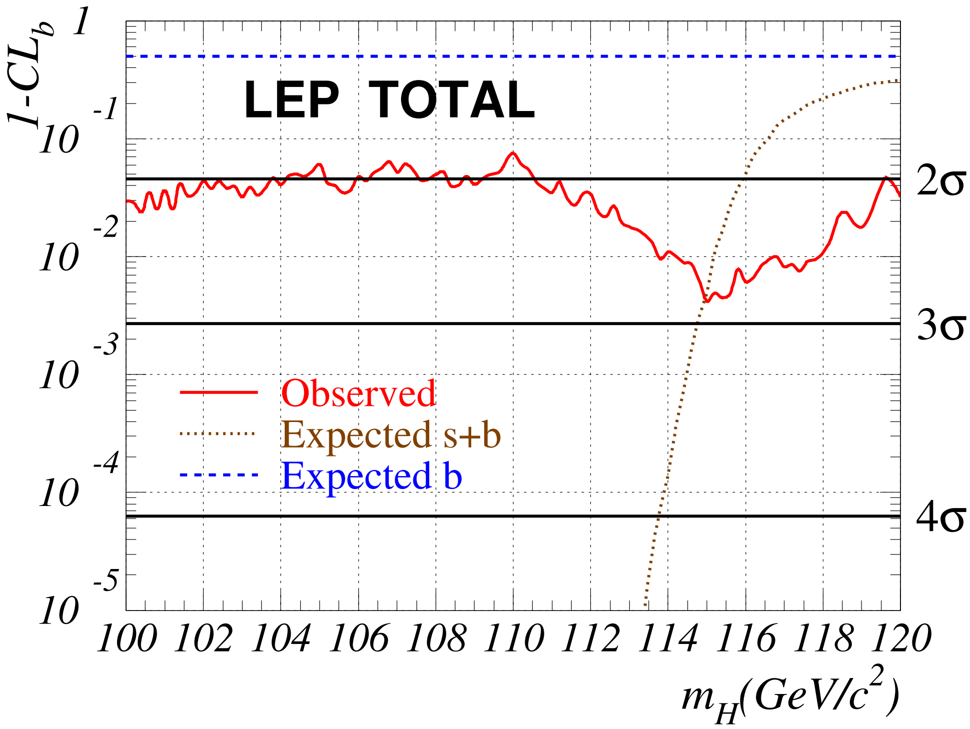
$$Q = \text{Likelihood Ratio} = \frac{\mathcal{L}(s(m_{h_{\rm SM}}) + b)}{\mathcal{L}(b)} \tag{1}$$

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.

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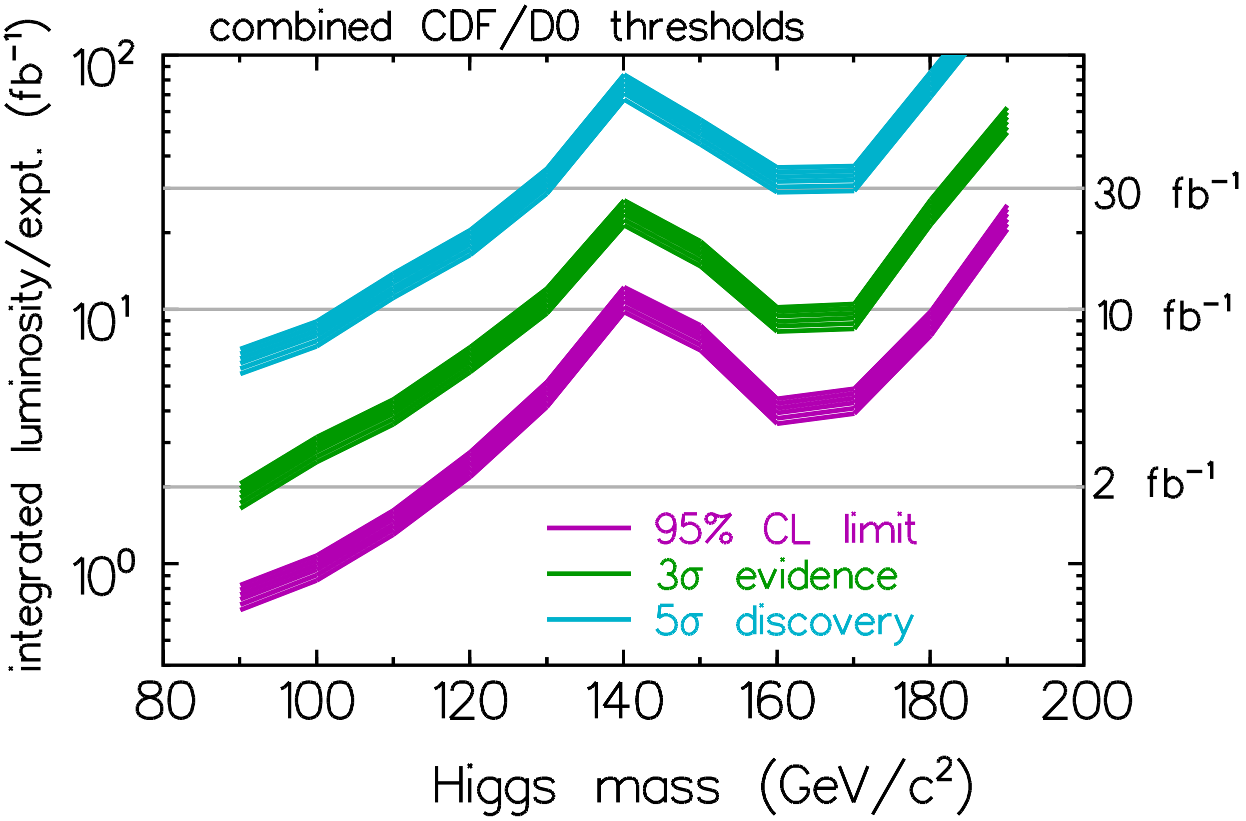
Note: could have some spread-out Higgs-like effect at lower masses of plot and improve $1 - CL_b$ consistency with pure background.

• Will we see the SM Higgs at the Tevatron?

– 90 GeV $\lesssim m_{h_{SM}} \lesssim$ 130 GeV: use $q'\overline{q} \to W^* \to Wh_{SM} \to \ell\nu b\bar{b}$ and $q\overline{q} \to Z^* \to Zh_{SM} \to \nu\bar{\nu}b\bar{b}$ and $\ell^+\ell^- b\bar{b}$

– 130 GeV $\lesssim m_{h_{SM}} \lesssim$ 190 GeV: use $gg, W^*W^* \to h_{SM}$ as well as $q'\overline{q} \to W^* \to Wh_{SM}$ and $q\overline{q} \to Z^* \to Zh_{SM}$, all with $h_{SM} \to WW^*, ZZ^*$. Relevant final states = $\ell^\pm\ell^\pm jjX$ and $\ell^+\ell^-\nu\bar{\nu}$



If $m_{h_{SM}} \sim$ 115 GeV, we have an excellent chance of seeing the SM Higgs! Accumulation of $L = 15$ fb^{-1} by 2006-2007 likely.

Will the Tevatron accumulate enough L before LHC running to find a heavier h_{SM} first?

- **Guaranteed discovery at the LHC**
  - $m_{h_{SM}} \lesssim 130$ GeV: $gg, W^*W^* \to h_{SM} \to \gamma\gamma$, $q_i\overline{q}_j \to W^\pm h_{SM}$ and $gg \to t\overline{t}h_{SM}$ with $h_{SM} \to \gamma\gamma$ and $h_{SM} \to b\overline{b}$
  - $m_{h_{SM}} > 130$ GeV: $gg, W^*W^* \to h_{SM} \to ZZ^{(*)} \to 4\ell$ ($gg, W^*W^* \to h_{SM} \to WW^* \to \ell\nu\ell\nu$ for $m_{h_{SM}} \sim 2m_W$)
  - $m_{h_{SM}} > 300$ GeV (400 GeV): $h_{SM} \to WW \to \ell\nu jj$ ($h_{SM} \to ZZ \to \ell\ell\nu\nu$), from $gg, W^*W^* \to h_{SM}$

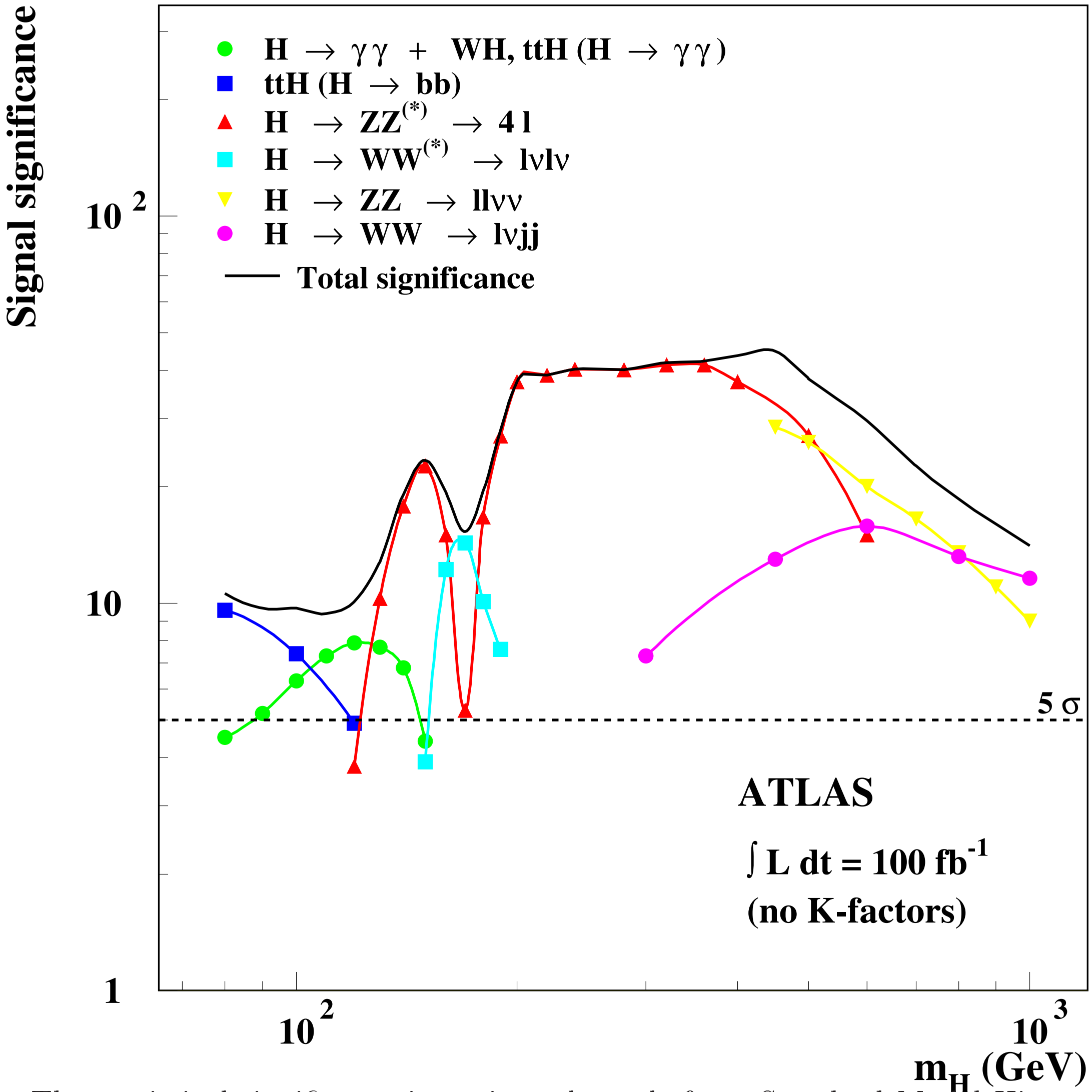


Figure 2: The statistical significance in various channels for a Standard Model Higgs signal with $L = 100$ fb^{-1} of accumulated luminosity for the ATLAS detector at the LHC. Also shown is the net statistical significance after combining channels.

- **Linear e^+e^- Collider:**

  - $\boldsymbol{e^+e^- \to Z^* \to Zh_{\rm SM}}$ remains the optimal channel.

    Allows a very detailed study of Higgs branching ratios

    * Measure $e^+e^- \to Zh_{\rm SM}$ using only Z and looking at the $h_{\rm SM}$ only as a peak in the mass spectrum recoiling against the Z

      $\Rightarrow$ insensitive to how $h_{\rm SM}$ decays.

      $\Rightarrow$ direct measure of $ZZh_{\rm SM}$ coupling-squared

    * Measure $e^+e^- \to Zh_{\rm SM} \to ZX$ from $h_{\rm SM} \to X$ and compute

    $$B(h_{\rm SM} \to X) = \frac{\sigma(e^+e^- \to Zh_{\rm SM} \to ZX)}{\sigma(e^+e^- \to Zh_{\rm SM})}$$

    Can even get $B(h_{\rm SM} \to WW^*)$ if $m_{h_{\rm SM}} \gtrsim 125$ GeV and $B(h_{\rm SM} \to \gamma\gamma)$ if $m_{h_{\rm SM}} \lesssim 130$ GeV.

  - $\boldsymbol{e^+e^- \to e^+e^-W^*W^* \to e^+e^-h_{\rm SM}}$

    Extract total width via

    $$\Gamma^{\rm tot}_{h_{\rm SM}} = \frac{\sigma(W^*W^* \to h_{\rm SM} \to WW^*)}{[B(h_{\rm SM} \to WW^*)]^2}$$

  - **$\boldsymbol{\gamma\gamma}$ Collider: $\boldsymbol{\gamma\gamma \to h_{\rm SM}}$** reveals heavy particle loops.

    $\gamma\gamma \to h_{\rm SM}$ allows extraction of $\Gamma^{\rm tot}_{h_{\rm SM}}$ as

    $$\Gamma^{\rm tot}_{h_{\rm SM}} = \frac{\sigma(\gamma\gamma \to h_{\rm SM} \to b\overline{b})}{B(h_{\rm SM} \to \gamma\gamma)B(h_{\rm SM} \to b\overline{b})}$$

    $\gamma\gamma \to h_{\rm SM}$ also allows determination of CP via studying cross section dependence upon relative orientation of (transverse) polarizations of colliding γ's. (CP=+ $\Rightarrow \vec{\epsilon}_1 \cdot \vec{\epsilon}_2$, CP=$-$ $\Rightarrow \vec{\epsilon}_1 \times \vec{\epsilon}_2$)

  - $\boldsymbol{e^+e^- \to t\overline{t}h_{\rm SM}}$ also quite interesting ($b\overline{b}h_{\rm SM}$ too small to see) and allows check of CP nature of observed Higgs boson by studying angular distributions of final state objects.

2 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).

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

  Constraints? Important issue is value of M^2 in

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

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

  - Precision electroweak suggests $\langle M^2 \rangle \lesssim (200-250 \text{ GeV})^2$.
  - 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 allows us to say that $C^2(m_h)$ 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.

    But, could it be that precision data is suggesting some C_i^2 weight at $m_{h_i} < 100$ GeV, spread out so as to not be observable as a peak in LEP2 data?

    LEP2 data allows (maybe prefers) this latter.

$\Rightarrow$ 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 strong LEP2 limits $\Rightarrow$ $m_h^{\rm min} = 70$ GeV, $m_h^{\rm max} = 300$ GeV.

- $\Rightarrow$ $\boldsymbol{f = 0.55}$ in **70 − 200 GeV** mass region.
- $\Rightarrow$ $\boldsymbol{f \sim 0.43}$ in **100 − 200 GeV** mass interval (avoids Z region with largest background)
- $S \sim 1350 f$ with a background of either $\boldsymbol{B = 6350}$ or $\boldsymbol{B = 2700}$, for **70 − 200 GeV** and **100 − 200 GeV** windows, respectively.
- $\Rightarrow$ we have to detect the presence of a broad $\boldsymbol{\sim 21\% f}$ $\boldsymbol{(\sim 50\% f)}$ excess over background, respectively.

  For $\boldsymbol{f \sim 0.55}$ in 1st case and $\boldsymbol{f \sim 0.43}$ in 2nd case, $\Rightarrow$ OK.
- Nominally, $S/\sqrt{B} \sim$ **17f** and $\boldsymbol{\sim 26 f}$ for the **70 − 200 GeV** and **100 − 200 GeV** windows in M_X, respectively.

Need $\boldsymbol{L \gtrsim 200}$ 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 much harder.$\Rightarrow$ bring in WH and ZH channels with all viable W and Z decay modes.

- **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 $e^+e^- \to b\bar b h$. Also $e^+e^- \to Z^* \to Zhh$.

  – Fermionic coupling sum rules (Grzadkowski, Kalinowski, JG):

  $$(\hat S^t_i)^2 + (\hat P^t_i)^2 = \left(\frac{\cos\beta}{\sin\beta}\right)^2, \quad (\hat S^b_i)^2 + (\hat P^b_i)^2 = \left(\frac{\sin\beta}{\cos\beta}\right)^2 \tag{3}$$

  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 $t\bar t$ or $b\bar b$ coupling of h_i must be big.

  – The quartic couplings $ZZhh$ and W^+W^-hh, deriving from gauge covariant structure of $(D_\mu\Phi)^\dagger(D^\mu\Phi)$, are also of guaranteed magnitude.

  Q: Are these processes enough?

  A: No, but they certainly help.

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.

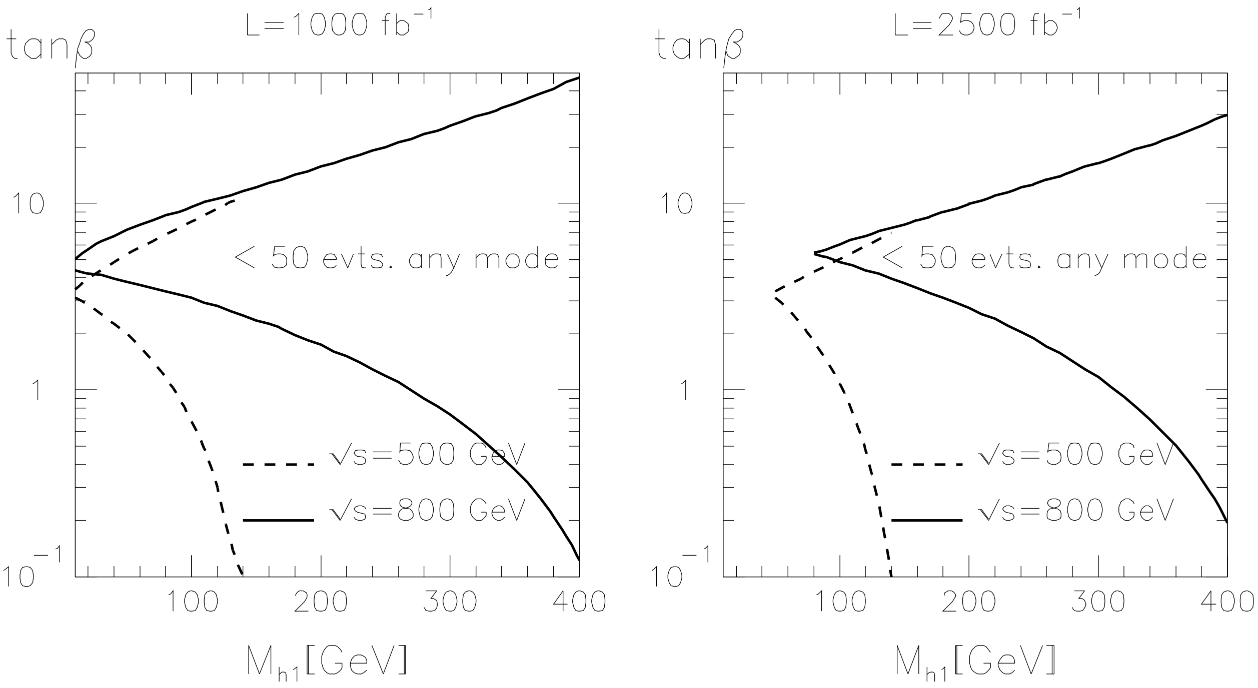


Figure 3: For $\sqrt{s} = 500$ GeV (dashes) and $\sqrt{s} = 800$ GeV (solid) the maximum and minimum $\tan\beta$ values between which $t\bar{t}h_1$, $b\bar{b}h_1$ and Zh_1 final states can (for some choice of (α_1, α_2) consistent with constraint (II)) all have fewer than 50 events assuming (a) $L = 1000\ \mathrm{fb}^{-1}$ or (b) $L = 2500\ \mathrm{fb}^{-1}$.

Even the $L = 2500\ \mathrm{fb}^{-1}$ wedge begins at $m_{h_1} \sim 80$ GeV for $\sqrt{s} = 800$ GeV. Hadron colliders $\Rightarrow$ bigger bad region.

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.

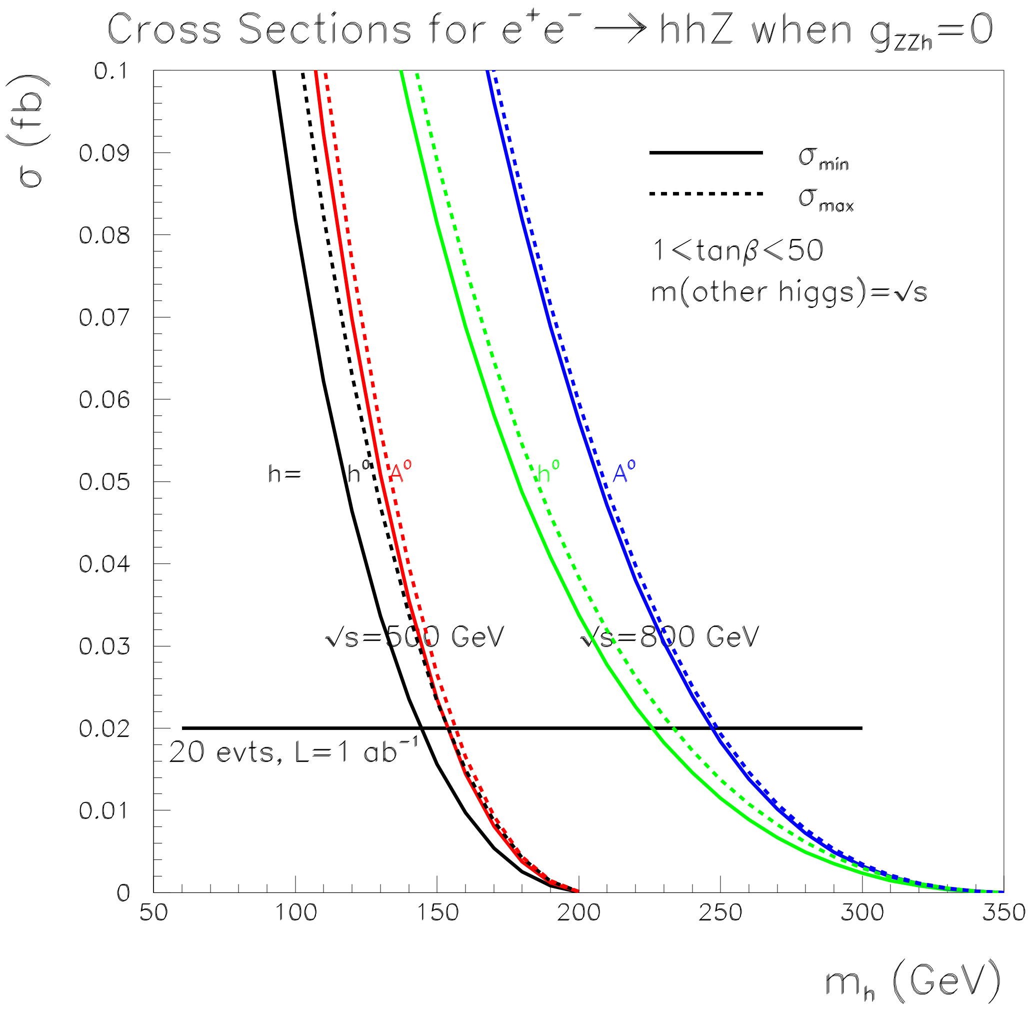


Figure 4: For $\sqrt{s} = 500$ GeV and 800 GeV and for $\hat{h} = h^0$ and $\hat{h} = A^0$, we plot as a function of $m_{\hat{h}}$ the maximum and minimum values of $\sigma(e^+e^- \to \hat{h}\hat{h}Z)$ found after scanning $1 < \tan\beta < 50$ taking all other Higgs masses equal to $\sqrt{s}$. For $\hat{h} = h^0$, we require $\sin(\beta - \alpha) = 0$ during the scan. The 20 event level for $L = 1$ ab^{-1} is indicated.

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

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

Answer: yes.

– 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 $\Rightarrow$

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

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

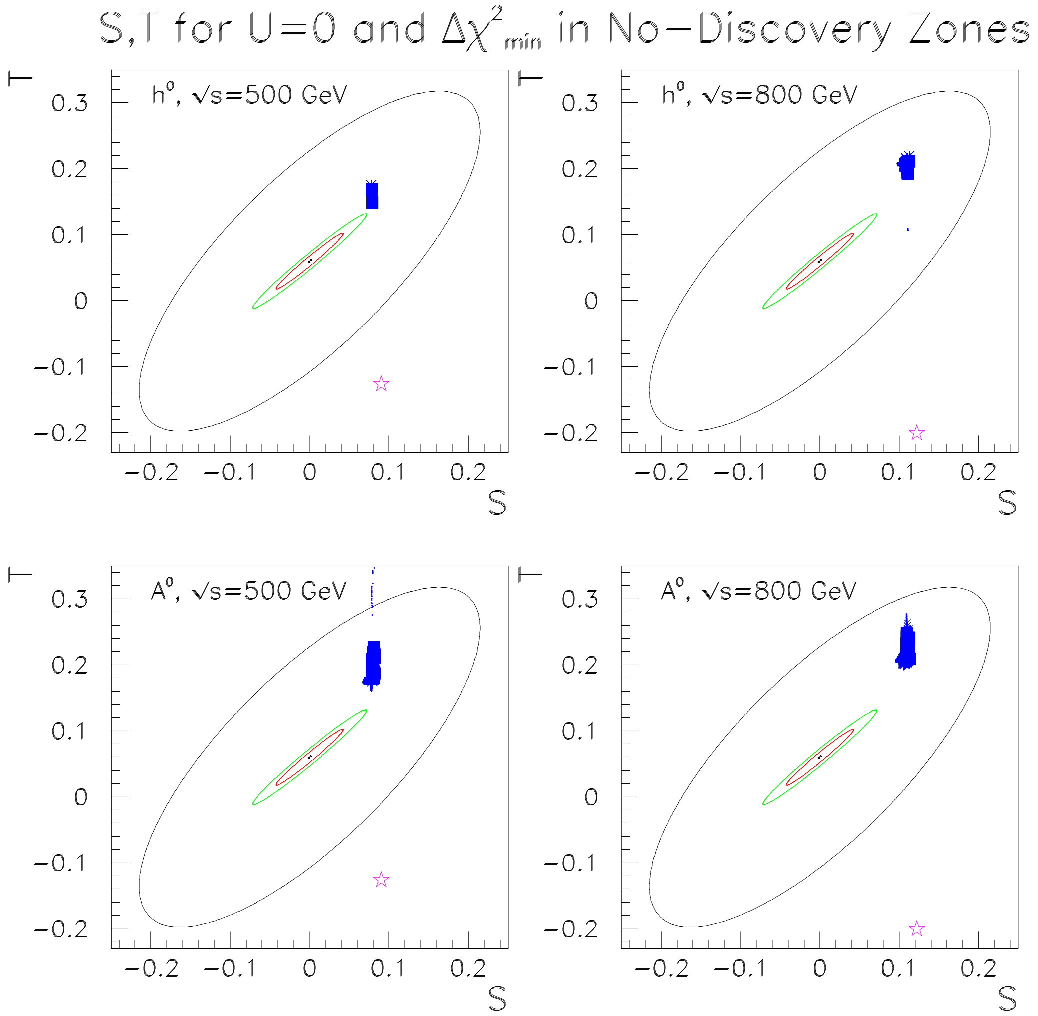


Figure 5: Outer ellipses = current 90% CL region for $U = 0$ and $m_{h_{\rm SM}} = 115$ GeV. Blobs = S, T predictions for Yukawa-wedge 2HDM models with minimum relative $\Delta\chi^2$. Innermost (middle) ellipse = 90% (99.9%) CL region for $m_{h_{\rm SM}} = 115$ GeV after Giga-Z *and* a $\Delta m_W \lesssim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

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 426(165) \times 10^{-11} , \qquad (5)$$

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, $\Rightarrow$

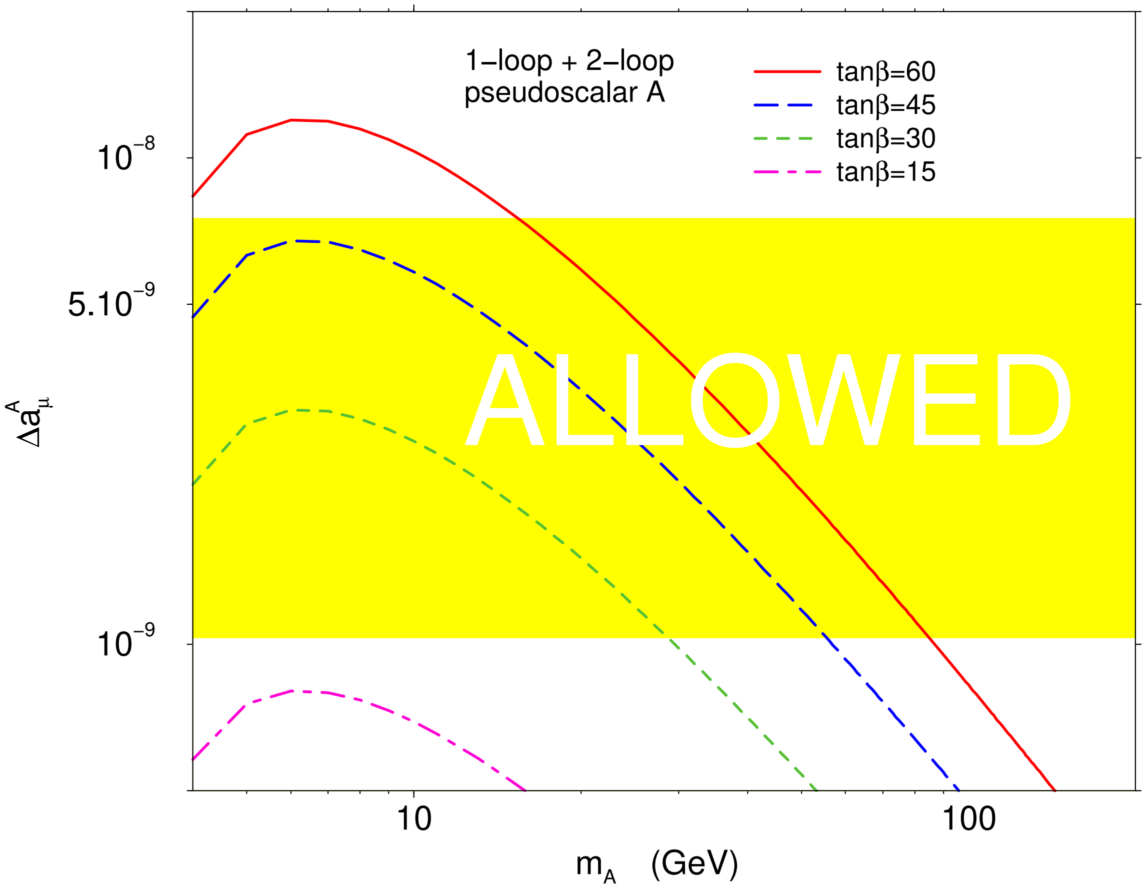


Figure 6: Explanation of new BNL a_μ value via light 2HDM A^0. (Cheung, Chou, Kong)

In the indicated range of $\tan\beta > 17$, it will be found at LC for sure, but hard at LHC. With alternative low-energy $\sigma(e^+e^- \to \text{hadrons})$, needed contribution declines and smaller $\tan\beta$ and/or higher m_{A^0} is called for $\Rightarrow$ harder to see. Many other new physics explanations.

3 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.

Example:

$$\begin{aligned}\sin^2\theta_W^{\rm eff} &= \sin^2\theta_W^{\rm eff,\ SM} + 0.00053\ln\frac{m_H}{m_Z} - 0.44V\\ \Gamma_Z^{\rm tot} &= \Gamma_Z^{\rm tot,\ SM} - (0.0032\ {\rm GeV})\ln\frac{m_H}{m_Z} + (4.47\ {\rm GeV})V\end{aligned}$$

Cancellation in $\sin^2\theta_W^{\rm eff}$ is exact for $m_H = 500$ GeV if $V = 2\times 10^{-3}$ ($\Rightarrow M_c = 3.3$ TeV for $\delta = 1$, which is ok), but then $\Gamma_Z^{\rm tot} = \Gamma_Z^{\rm tot,\ SM} + 3.4$ MeV, which is marginal.

– 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.

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 $V(\phi) - \mathcal{L}_{\rm mass}(\phi_{KK}^{\vec n}) - \mathcal{L}_{\rm mix}(\phi_{KK}^{\vec n}, \phi)$, where ϕ is the usual Higgs field, $\mathcal{L}_{\rm mass}$ contains the quadratic mass terms for the KK graviscalar fields $\phi_{KK}^{\vec n}$, and

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

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

$$\sum_{{\rm all}\,\vec n} \frac{1}{m_n^2} \equiv \frac{\overline{D}}{\kappa^2}\frac{\delta+2}{\delta-2}\,, \tag{6}$$

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.

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 $\phi^{\vec{n}}_{KK}$ couple to this: $\mathcal{L} \ni \frac{f(\delta)}{M_{\rm P}}\Sigma_{\vec{n}}\,\phi^{\vec{n}}_{KK}T^\mu_\mu$.
* 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.

  $\Rightarrow$ decays of $H_{\rm phys}$ to KK-graviscalars, again invisible.

Combining Higgs-graviscalar mixing with unconventional EWSB minimum $\Rightarrow$ many phenomenological variants.

4 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 $L > 5~\mathrm{fb}^{-1}$ to surpass LEP2 limit.

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

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

5 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:

$$\boldsymbol{\mathcal{L}_Y = i h_{ij} \psi_i^T C \tau_2 \Delta \psi_j + \mathrm{h.c.}}\,, \tag{7}$$

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

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix} . \tag{8}$$

- 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

$$|h_{\ell\ell}^{\Delta^{--}}|^2 \equiv c_{\ell\ell} m_{\Delta^{--}}^2(\,\mathrm{GeV})\,, \tag{9}$$

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

- General possibility is that Δ^{--} width could be quite small.

  $\Rightarrow$ possibly very large 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 $\sigma_{\sqrt{s}}$)

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

      $\Rightarrow$ an enormous event rate if c_{ee} near its upper bound.
    * For 100 events, Eq. (10) $\Rightarrow$ we probe

    $$c_{ee}|_{100 \text{ events}} \sim 3.3 \times 10^{-14}(R/0.2\%)\,, \quad \Gamma_{\Delta^{--}} \ll \sigma_{\sqrt{s}}\,, \quad (11)$$

      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}.**

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

6 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 $m_{\tilde t} \leq 1$ 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):

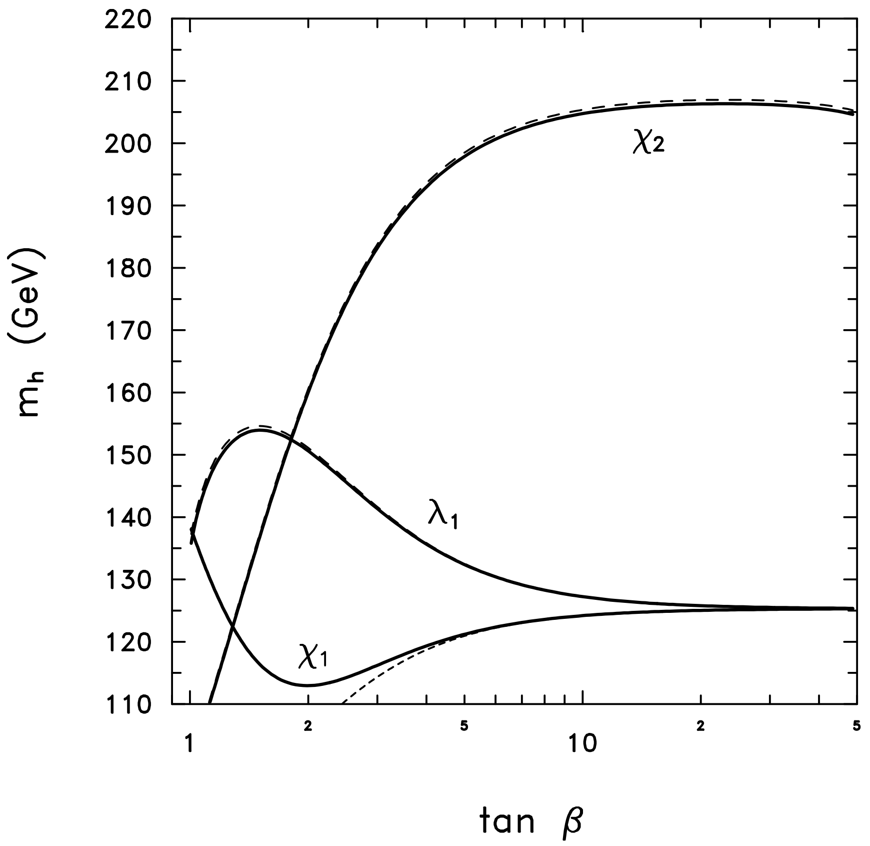


Figure 7: Bounds on SUSY m_h in presence of different types of multiplets. From Espinosa and Quiros, hep-ph/9804235

NOTE: $\Rightarrow \langle M^2 \rangle \leq (200 \text{ GeV})^2$ 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 $X_t \equiv A_t - \mu \cot\beta$): $m_{h^0}, m_{A^0} \gtrsim 80$ GeV are required and $\tan\beta \lesssim 2.3$ 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. $\Rightarrow$

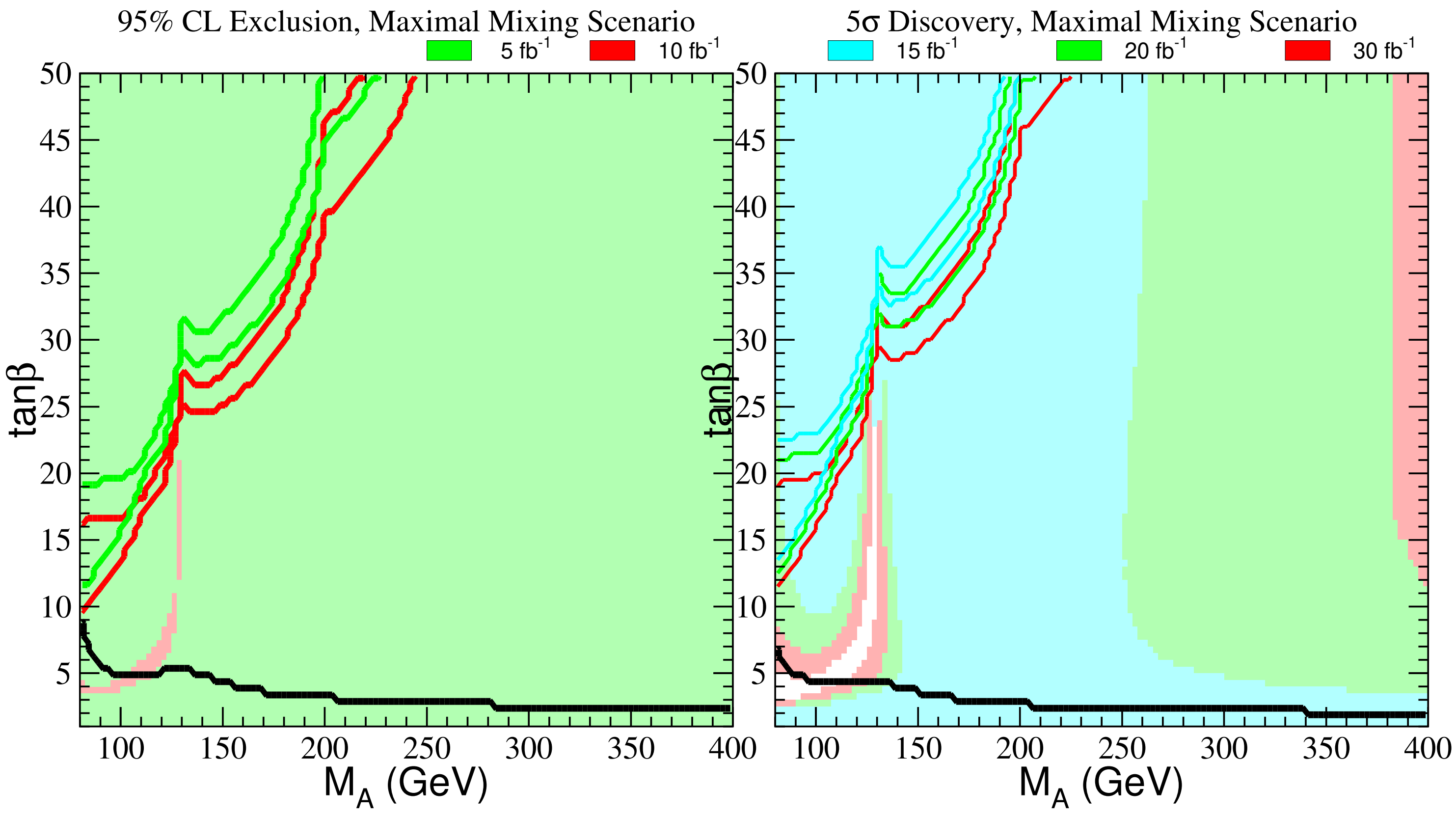


Figure 8: (a) 95% CL exclusion region and (b) 5σ discovery region on the m_{A^0}–$\tan\beta$ plane, for the maximal mixing scenario and two different search channels: $q\bar{q} \to V\phi$ [$\phi = h^0$, H^0], $\phi \to b\bar{b}$ (shaded regions) and gg, $q\bar{q} \to b\bar{b}\phi$ [$\phi = h^0$, H^0, 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 $h_{\rm SM}$.

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

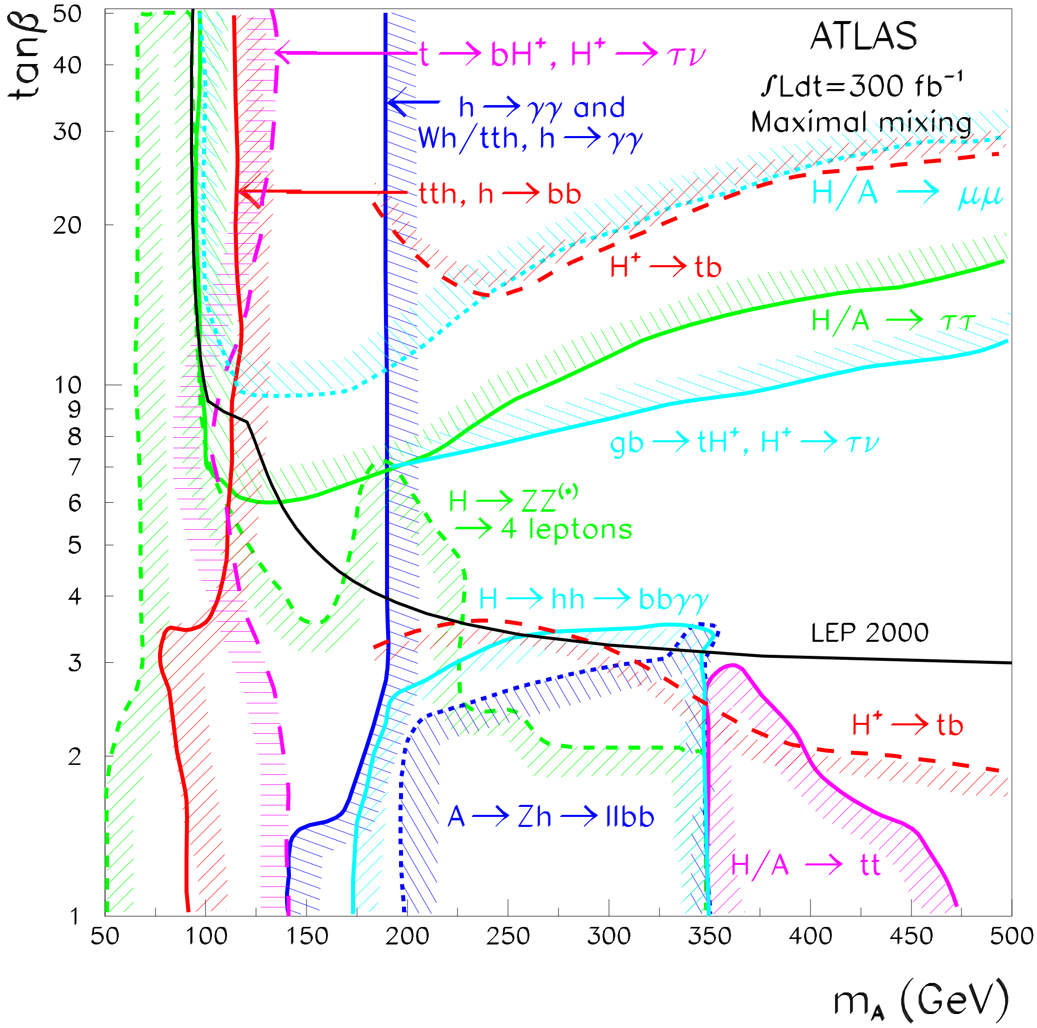


Figure 9: 5σ discovery contours for MSSM Higgs boson detection in various channels are shown in the $[m_{A^0}, \tan\beta]$ parameter plane, assuming maximal mixing and an integrated luminosity of $L = 300\ \mathrm{fb}^{-1}$ for the ATLAS detector. This figure is preliminary.

$\Rightarrow$ Guaranteed to find one of the MSSM Higgs bosons with $L = 300\ \mathrm{fb}^{-1}$ (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 $h_{\rm SM}$.

$\Rightarrow$ guaranteed to find it given $m_{h^0} \lesssim 135$ GeV (MSSM) limit and increasingly SM-like nature once $m_{A^0} > 2m_Z$.

– 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 $e^+e^- \to b\overline{b}A^0, b\overline{b}H^0, btH^\pm$.

– For moderate $\tan\beta$ in LHC wedge where none are seen, $\gamma\gamma \to H^0, A^0$ provides a decent signal.

Luminosity achievable at TESLA allows for scan detection (using peaked $\gamma\gamma$ spectrum and varying $\sqrt{s}$ of machine to shift peak over a range of $E_{\gamma\gamma} \sim m_{A^0}$). NLC luminosity for $\gamma\gamma$ collisions a bit uncertain at the moment.

– $\gamma\gamma \to h^0$ also good for studying the h^0.

– $\gamma\gamma \to h^0, H^0, A^0$ will allow determination of CP nature of the various Higgs bosons.

In particular, by adjusting linear polarization orientation, can separate A^0 from H^0 when these are closely degenerate (as typical for $\tan\beta \gtrsim 4$ and $m_{A^0} > 2m_Z$).

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

– **Invisible decays.**

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

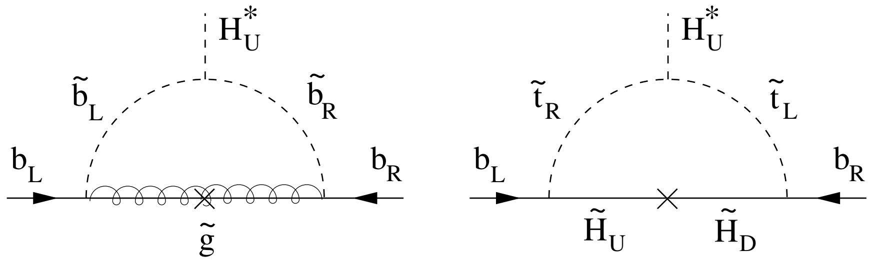


Figure 10: Loop contributions to $\Delta\lambda_b$.

Typically, $\frac{\Delta\lambda_b}{\lambda_b} \sim 0.01$ (either sign).
$\frac{\Delta\lambda_b}{\lambda_b}$ does not vanish in limit of large SUSY masses (no decoupling).

∗ **Result: h^0 can decouple from b's (i.e. $h^0 \simeq H_u$).**

Full $\lambda_b^{h^0}$ coupling takes the form:

$$\lambda_b^{h^0} \simeq -\frac{m_b \sin\alpha}{v\cos\beta} \frac{1}{1+\frac{\Delta\lambda_b}{\lambda_b}\tan\beta}\left[1-\frac{\frac{\Delta\lambda_b}{\lambda_b}}{\tan\alpha}\right], \tag{12}$$

$$\tan\alpha \simeq \frac{\Delta\lambda_b}{\lambda_b} \quad \Rightarrow \quad \lambda_b^{h^0} \simeq 0\,. \tag{13}$$

As $m_{A^0} \to \infty$, $\alpha \to \pi/2-\beta$ and $\tan\alpha \to -1/\tan\beta$.
$\Rightarrow$ cancellation typically occurs if $\Delta\lambda_b/\lambda_b < 0$ as m_{A^0} passes through some $\tan\beta$ dependent value.

∗ **Effects on discovery modes of light Higgs:**

Since $\Gamma(h^0 \to \gamma\gamma)$ is dominated by W and t loops, changing $\lambda_b^{h^0}$ will affect the $\gamma\gamma$ partial width very little. Also little impact on gg partial width.

· Thus, suppressed (enhanced) $\Gamma(h^0 \to b\overline{b}) \Rightarrow$ enhanced (suppressed) $B(h^0 \to \gamma\gamma)$, $B(h^0 \to WW^*)$.

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

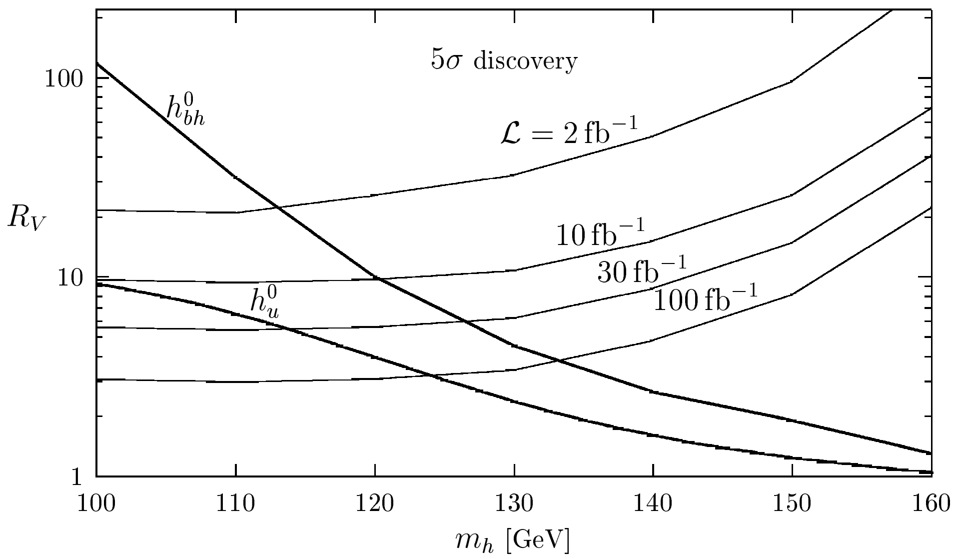


Figure 11: L required for Tevatron 5σ discovery in $\gamma\gamma$ mode.

· More 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.

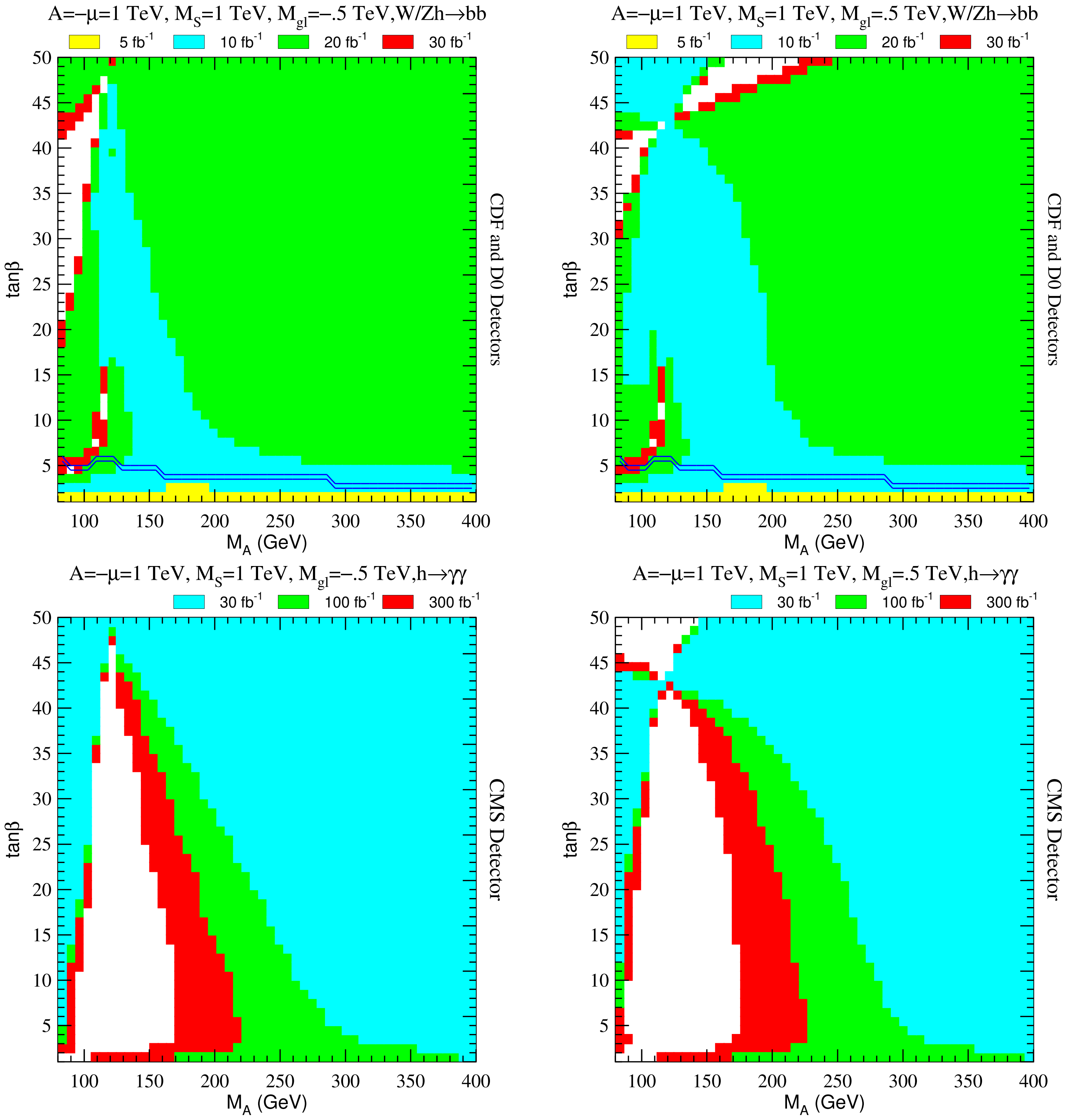
$\Rightarrow$ Complementarity of Tevatron and LHC.

Illustrate for *LHC* $\gamma\gamma$ mode vs. Tevatron $Wh^0[\to b\overline{b}]$ modes.

– Extra Decays

Of course, 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 $\widetilde{\chi}^0_1\widetilde{\chi}^0_1, \widetilde{\chi}^+_1\widetilde{\chi}^-_1, \tilde{\tau}^+\tilde{\tau}^-, \tilde{\nu}\overline{\tilde{\nu}}, \ldots$ decays are kinmatically allowed.

However, at high $\tan\beta$ the usual dominance of decays to $b\overline{b}$ and $\tau^+\tau^-$ will be preserved.



Stephen Mrenna (UC Davis)

Upper graphs are Tevatron, CDF+D0 $Vh^0 \to Vb\bar{b}$ final state. Lower graphs are $gg, W^*W^* \to h^0 \to \gamma\gamma$ at CMS detector of LHC

- **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.

    Even if no CP violation $\Rightarrow$ no absolute guarantee of discovery at the Tevatron, LHC.

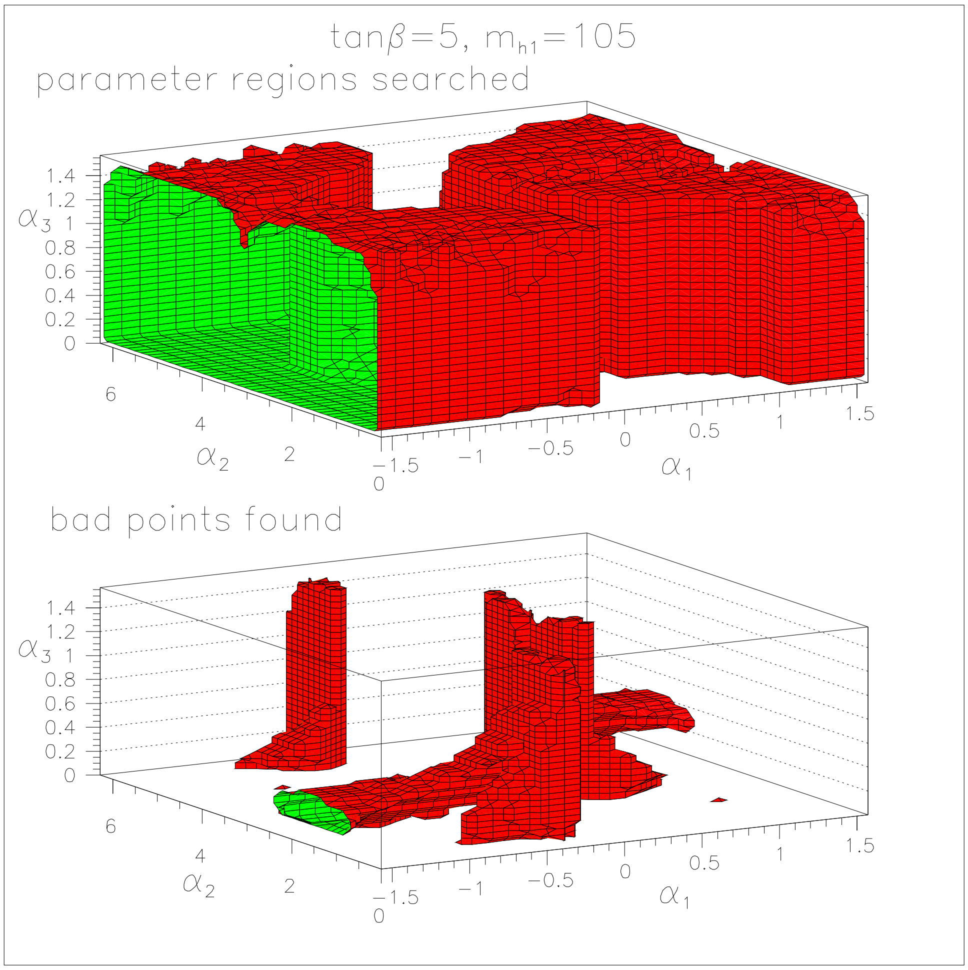


Figure 12: For $\tan\beta = 5$ and $m_{h_1^0} = 105$ GeV, we display in three dimensional $(\alpha_1, \alpha_2, \alpha_3)$ parameter space the parameter regions searched (which lie within the surfaces shown), and the regions therein for which the remaining model parameters can be chosen so that no Higgs boson is observable (interior to the surfaces shown).

– 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 $h^0 \to \widetilde\chi^0_1\widetilde\chi^0_1$ and $\widetilde\chi^0_1 \to csd$ via baryonic R-parity violation, $\Rightarrow$ $Zh^0 \to Z + 6$ soft jets.

* We know that we don't see $e^+e^- \to \widetilde\chi^0_1\widetilde\chi^0_1 \to 6$ jets at LEP, $\Rightarrow$ not relevant there.
* Probably ok at NLC, especially since $e^+e^- \to \widetilde\chi^0_1\widetilde\chi^0_1 \to 6$ jets will display a big excess and warn us as to what to look for.
* Probably a big problem at hadron colliders.

7 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