HIGGS PHYSICS AT COLLIDERS
Old and New Ideas

J. F Gunion, SusyTools, April 26, 2000

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: $V \ni \lambda\phi^4$.

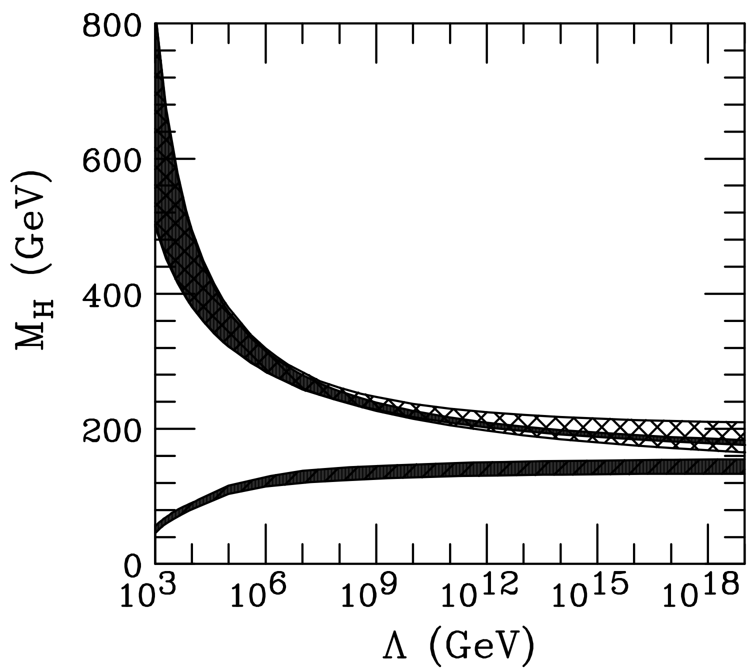


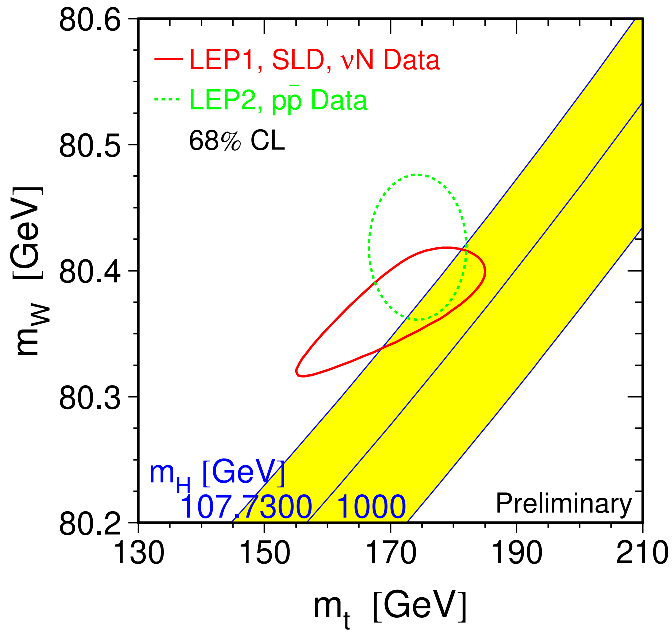
Figure 1: Triviality and (Meta)stability bounds for the SM Higgs boson as a function of the new physics scale Λ. From Hambye and Riesselmann, hep-ph/9610272

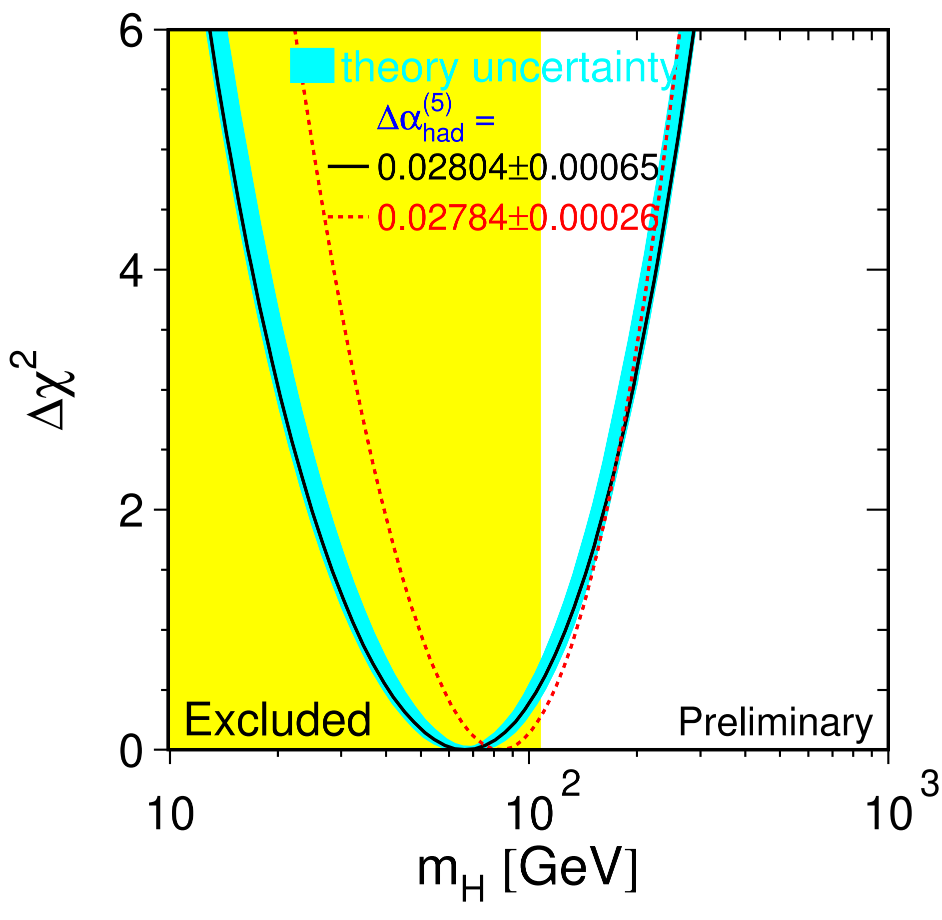
Bound $\lambda(m_h)$ which bounds m_h [$m_h \sim 2v^2\lambda(m_h)$, v =vev] by bounding $\lambda(\Lambda)$ (recall λ grows with energy scale).

Bound from (meta)stability of the potential. We use $\lambda(\Lambda) > 0$ stability requirement. Metastability 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 certainly consistent with current precision electroweak data.

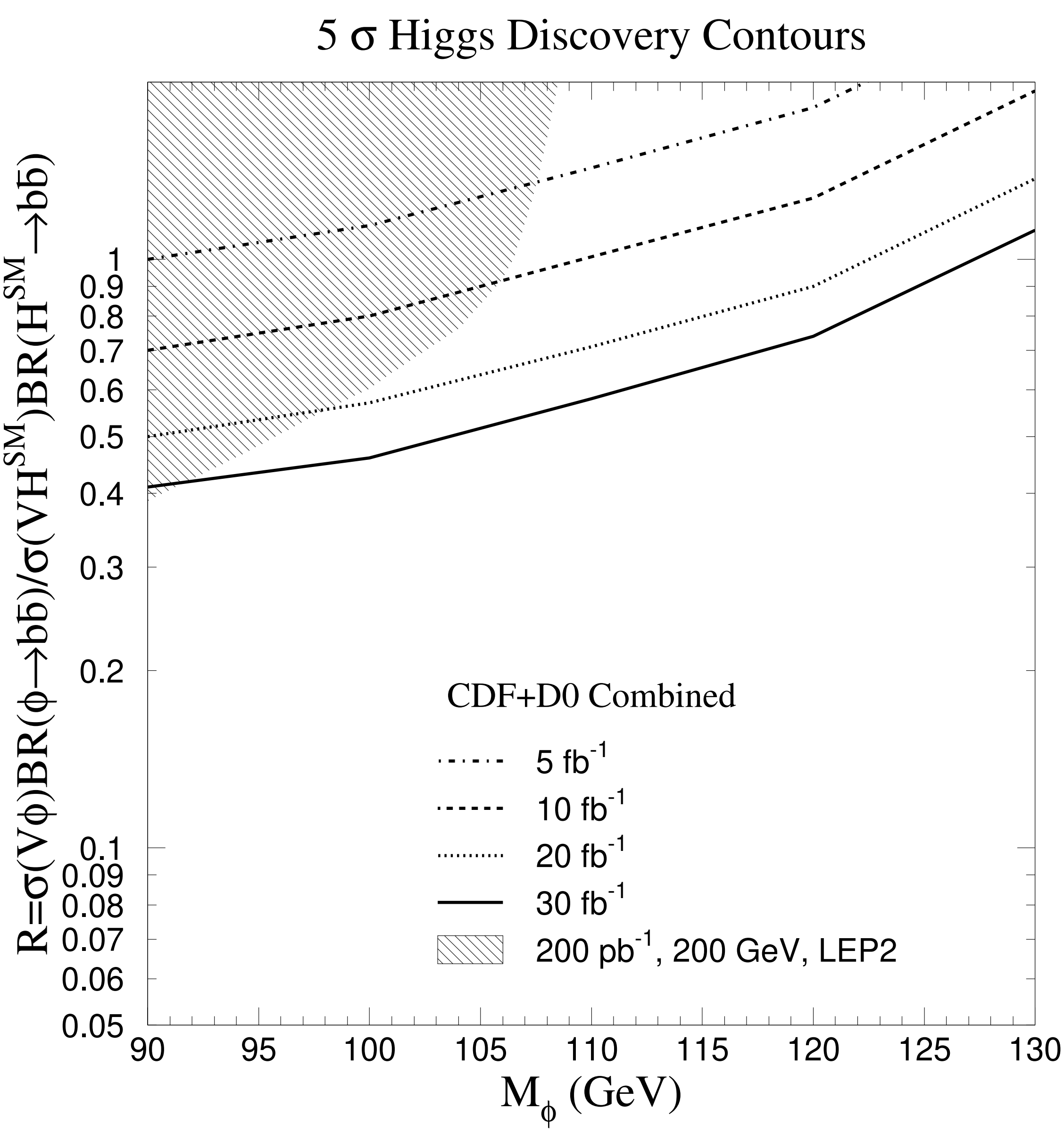

LEP1, SLD, νN Data
LEP2, pp̄ Data
68% CL
m_H [GeV]
107.7300 1000
Preliminary
m_W [GeV]
m_t [GeV]


theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02804±0.00065
0.02784±0.00026
Excluded
Preliminary
$\Delta\chi^2$
m_H [GeV]

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

- **Prospects for SM Higgs detection are good.**

LEP2 and Tevatron: Pascos 99



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LHC:

– $gg \to H \to \gamma\gamma$, low and high L.

– $t\bar{t}H + WH \to \ell\gamma\gamma + X$ at high L

- Even within SM context, should consider extended Higgs sector possibilities. To keep $\rho \sim 1$ most natural to

  – Add singlets

    No particular problem or benefits.

  – Add doublets

    $-$: Veltman: charged Higgs m^2 not automatically positive (EM?).

    $+$: Weinberg: can get CP violation from Higgs sector.

  For triplet fields (with neutral member vev $\neq 0$) and higher reps., 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

- **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 $t\bar{t}h$ and $b\bar{b}h$.

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

$$(\hat{S}_i^t)^2 + (\hat{P}_i^t)^2 = \left(\frac{\cos\beta}{\sin\beta}\right)^2, \quad (\hat{S}_i^b)^2 + (\hat{P}_i^b)^2 = \left(\frac{\sin\beta}{\cos\beta}\right)^2 \qquad (1.1)$$

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.

But, this is not enough, even at a high-L NLC.

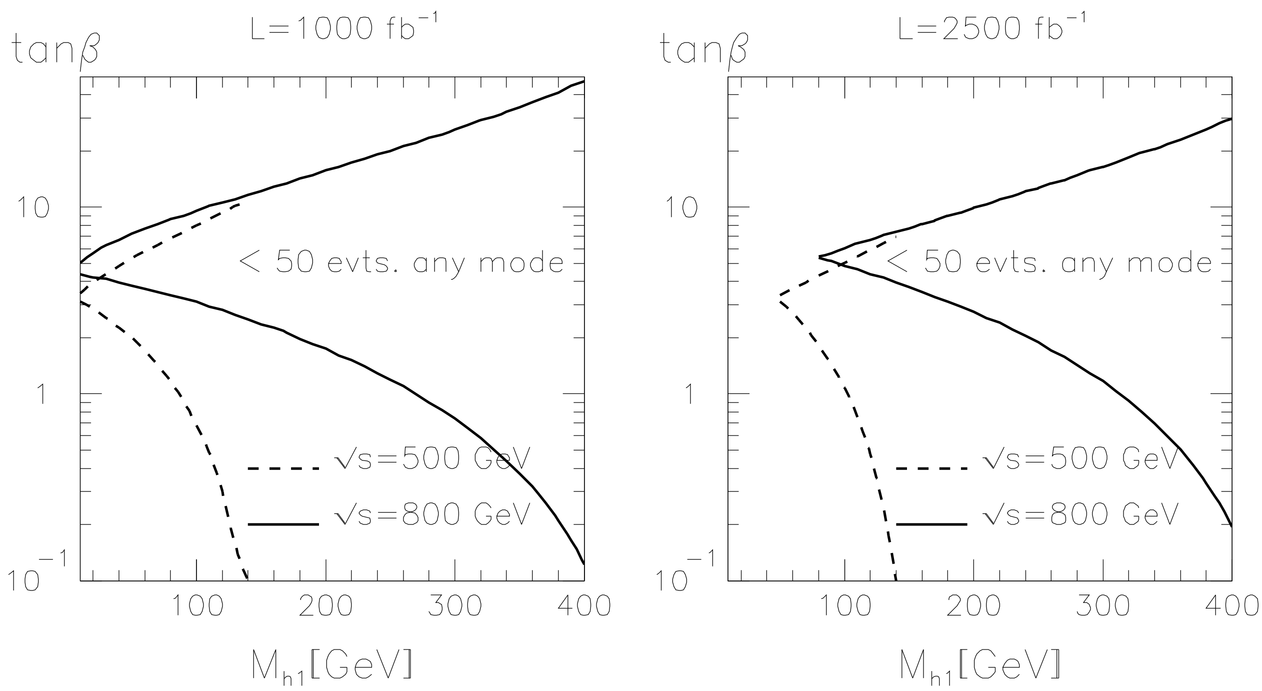


Figure 2: For $\sqrt{s} = 500$ GeV (dashes) and $\sqrt{s} = 800$ GeV (solid) the maximum and minimum $\tan\beta$ values between which $t\bar{t}h_1$, $b\bar{b}h_1$ and Zh_1 final states can (for some choice of (α_1, α_2) consistent with constraint (II)) all have fewer than 50 events assuming (a) $L = 1000$ fb^{-1} or (b) $L = 2500$ fb^{-1}.

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

Conclusion: the fermionic coupling sum rules do not yield any guarantees. They only restrict the problematical region.

- **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≡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

$$\sum_i C_i^2 m_{h_i}^2 = \langle M^2 \rangle \,. \tag{1.2}$$

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

- maximal spread: $m_h^{\min}=0$, with $\langle M^2\rangle \leq [200~\text{GeV}]^2 \Rightarrow m_h^{\max} = \sqrt{3\langle M^2\rangle} = 340$ 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 $\langle M^2\rangle = [200~\text{GeV}]^2 \Rightarrow m_h^{\max} = 300$ GeV.

$\Rightarrow$ 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)
- $S \sim 1350f$ 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 $\boldsymbol{\sim 26f}$ 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.

2 Extra Dimensions and the ‘SM’ Higgs

A single SM Higgs and its many 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 also allow gauge bosons 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.

- But must consider all available precisely measured $\mathcal{O}_i$ at same time.

  Example:

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

  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, especially if the number of extra dimensions $\delta > 2$.

- After integrating out KK modes, get $\overline{V}_{\rm tot} = V(\phi) - \overline{D}V^2(\phi)$, where

$$\sum_{{\rm all}\,\vec n} \frac{1}{m_n^2} \equiv \frac{\overline{D}}{\kappa^2}\frac{\delta+2}{\delta-2}\,, \tag{2.1}$$

where δ =number of extra dimensions and, 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

  $$m^2_{s_{\rm phys}} = -\epsilon^2 \sum_{\vec n > 0} \frac{1}{m_n^2} \sim -\frac{8}{3}\overline{D}\frac{\delta-1}{\delta-2}\left(\frac{\partial V}{\partial\widehat{\phi}}\right)^2_{\widehat{\phi}=\widehat{v}}\,, \tag{2.2}$$

  which is positive if $\overline{D} < 0$ when $\delta > 2$.

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

Even 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.

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:**

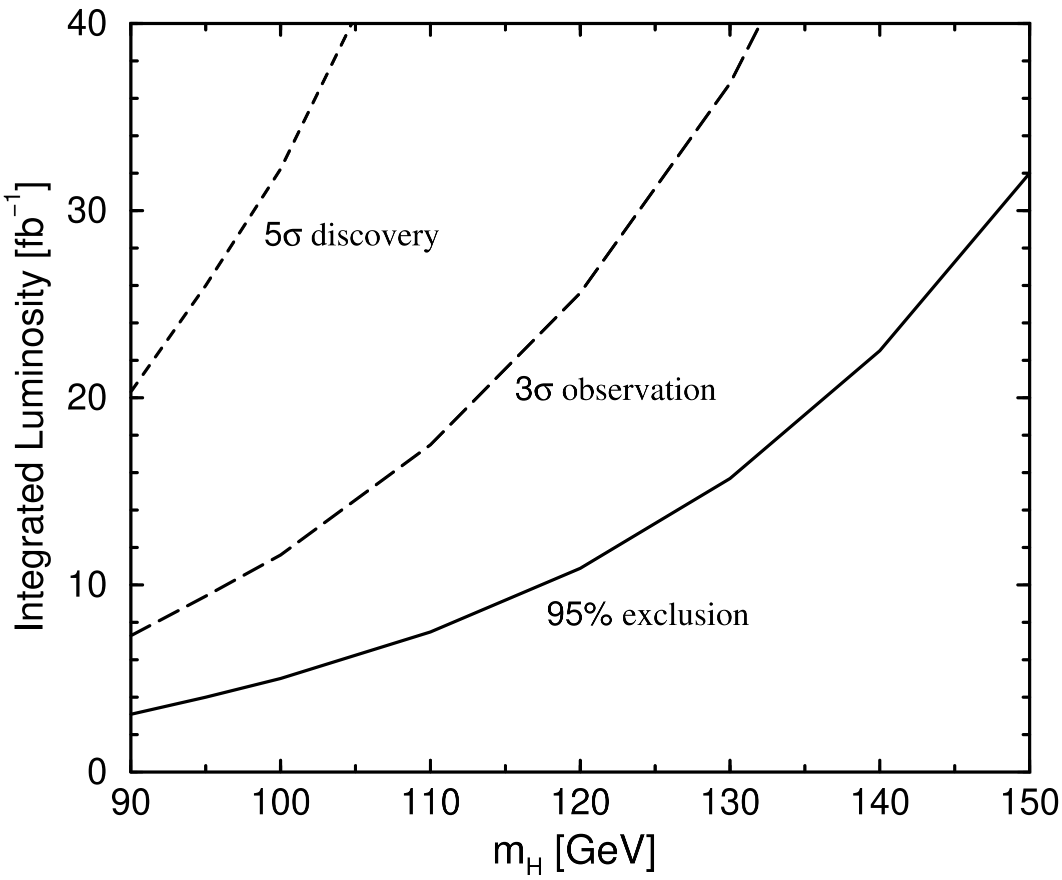


Figure 3: Tevatron luminosity required for sensitivity to an invisibly decaying SM-coupled Higgs boson (from Martin and Wells).

$\Rightarrow$ 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?

4 SUSY Higgs

- Despite all the fun with extra dimension in SM case, extra dimensions most naturally arise in string theories which usually are supersymmetric in nature.
- 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):

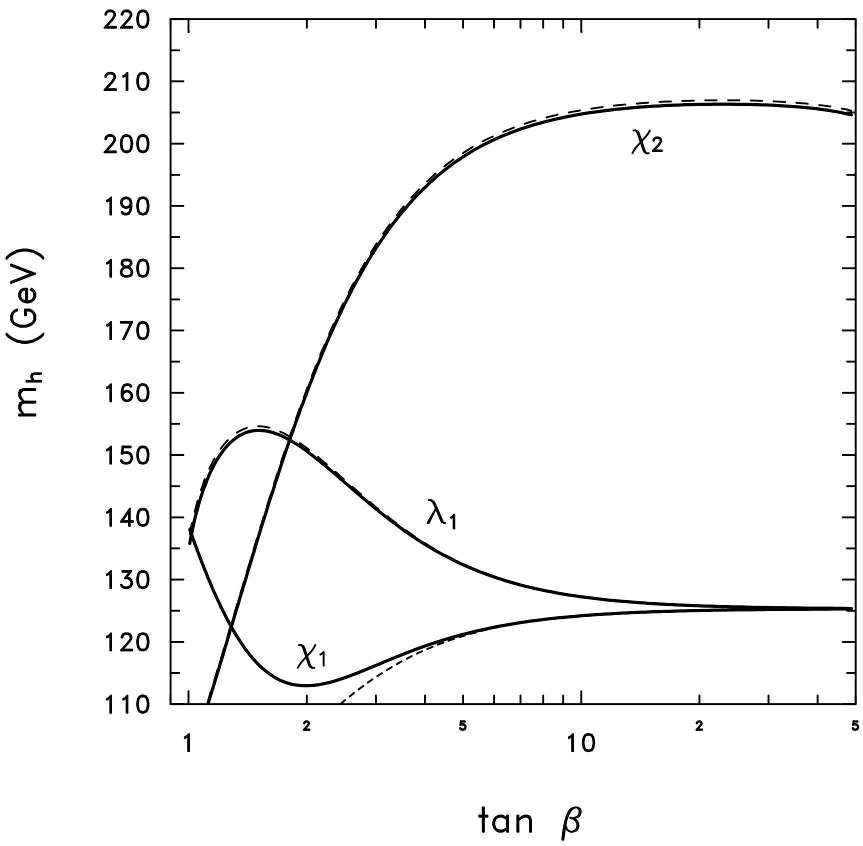


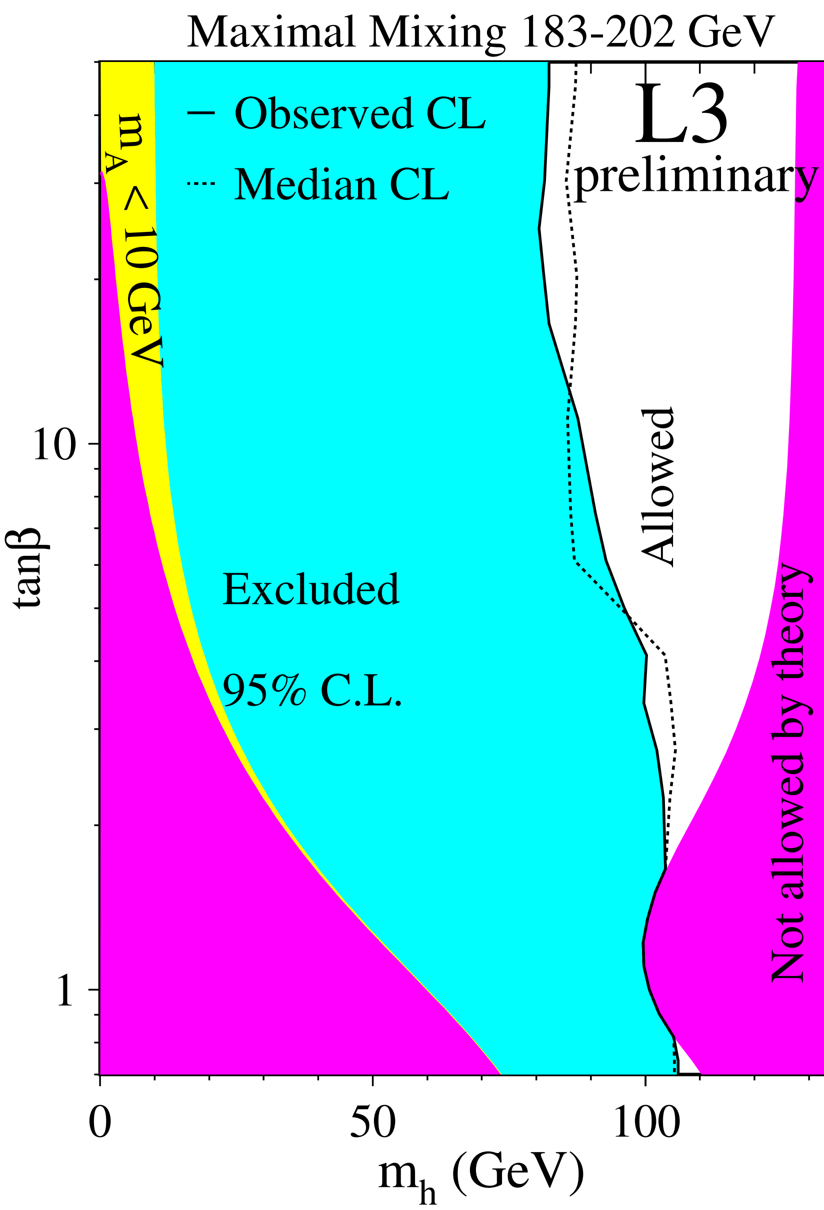
Figure 4: Bounds on SUSY m_h in presence of different types of chiral multiplets. From Espinosa and Quiros, hep-ph/9804235

NOTE: $\Rightarrow \langle M^2 \rangle \leq (200 \text{ GeV})^2$ in sum rule used for no-lose theorem.

- **Experimental limits for MSSM from LEP2 are significant.**

For maximal mixing: $m_{h^0} > 80.5$ GeV, $m_{A^0} > 81$ GeV, $0.8 < \tan\beta < 1.6$ excluded.

MSSM Neutral Higgs Bosons



$M_h > 80.5$ GeV (85.5 GeV expected)

$M_A > 81.0$ GeV (86.0 GeV expected)

$0.8 < \tan\beta < 1.6$ excluded

Figure 5: L3 limits on MSSM Higgs.

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

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.

– A first 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:

– This possibility would considerably weaken the constraints on the $h^0 A^0$ cross section, allowing for both to have some, perhaps substantial, invisible decays.

– $Z + X$ would have to be relied upon more heavily.

– I would guess that the limits detiorate substantially.

This deserves study by the experimental groups.

- **‘Standard’ discovery prospects in the MSSM at Tevatron, LHC, NLC will be reviewed in detail in the next talks. But, there are many points of caution.**
  - **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.

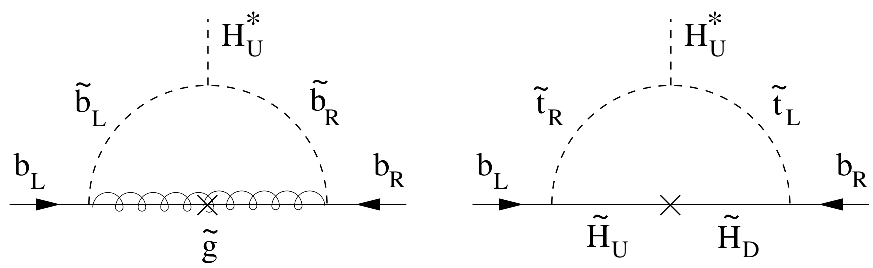


Figure 6: Loop contributions to $\Delta\lambda_b$.

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:

$$\lambda_b^{h^0} \simeq -\frac{m_b \sin\alpha}{v\cos\beta}\frac{1}{1+\frac{\Delta\lambda_b}{\lambda_b}\tan\beta}\left[1-\frac{\frac{\Delta\lambda_b}{\lambda_b}}{\tan\alpha}\right], \tag{4.1}$$

$$\tan\alpha \simeq \frac{\Delta\lambda_b}{\lambda_b} \quad \Rightarrow \quad \lambda_b^{h^0} \simeq 0\,. \tag{4.2}$$

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 $h^0 \sim H_u$.

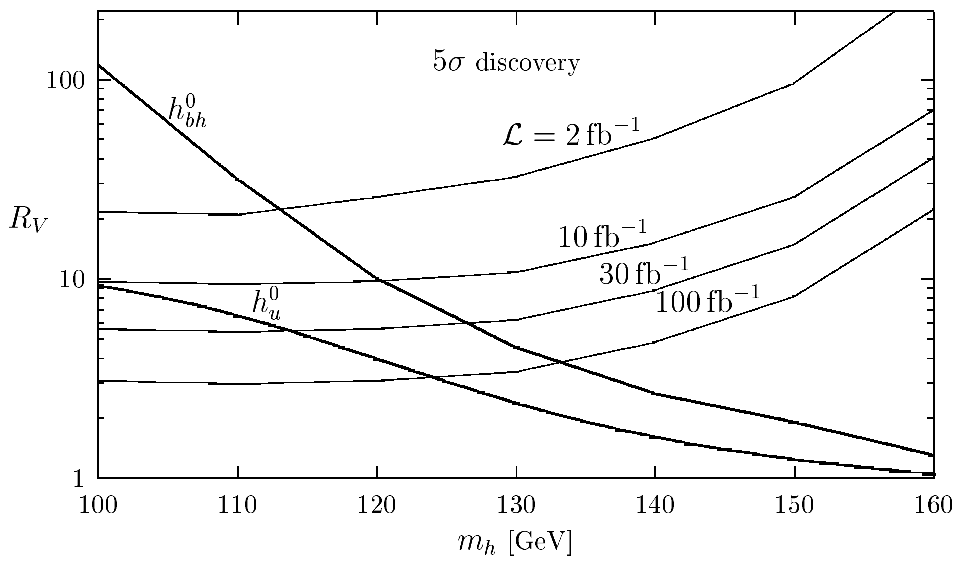


Figure 7: L required for Tevatron 5σ discovery in $\gamma\gamma$ mode.

· More typically,

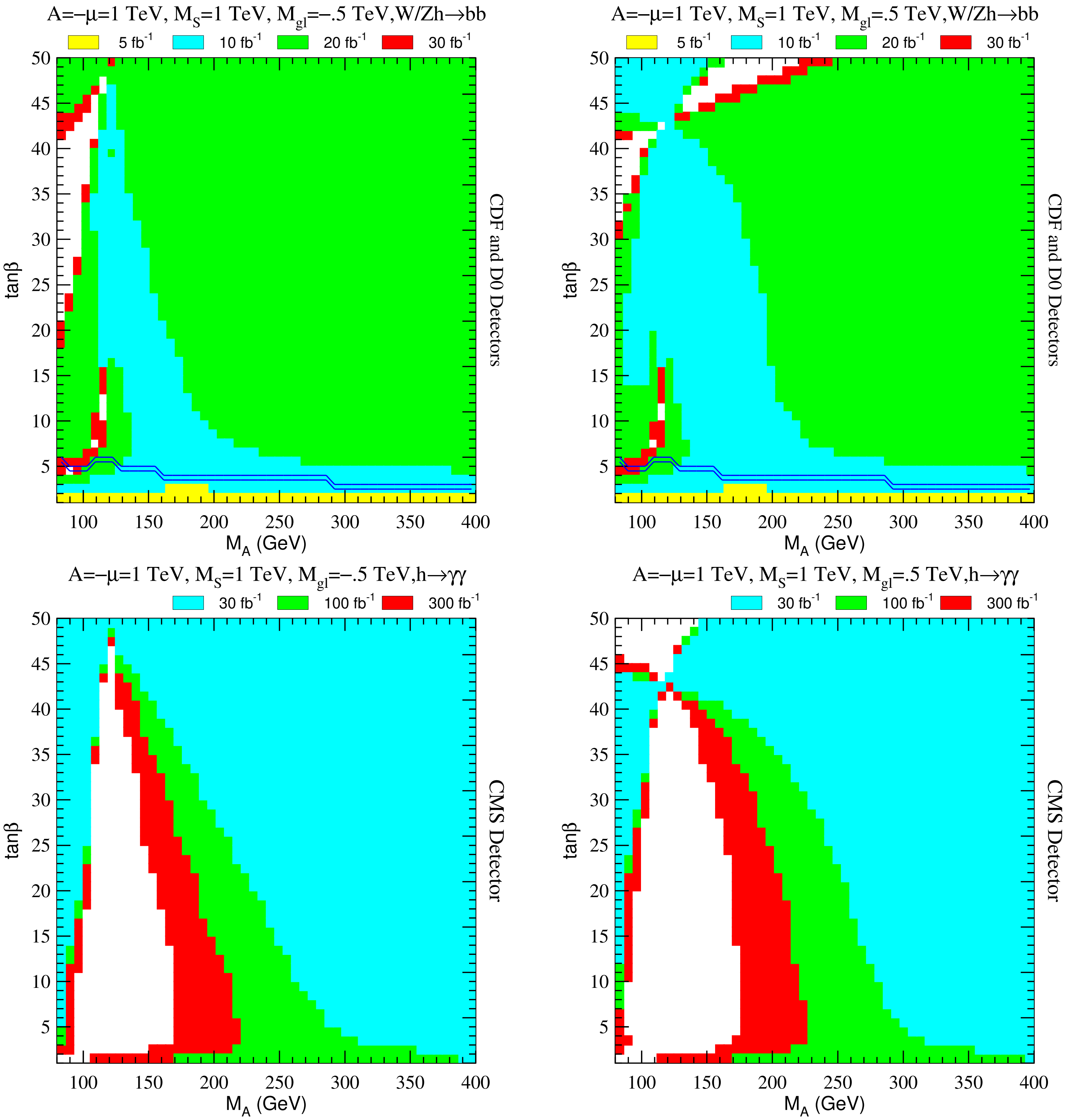
LHC $gg \to h^0 \to \gamma\gamma$ and Tevatron $Wh^0[\to WW^*]$ modes win when LHC, Tevatron $W, Zh^0[\to b\overline{b}]$ modes lose.

$\Rightarrow$ 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 $H^0, H^\pm$ 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)

- **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.

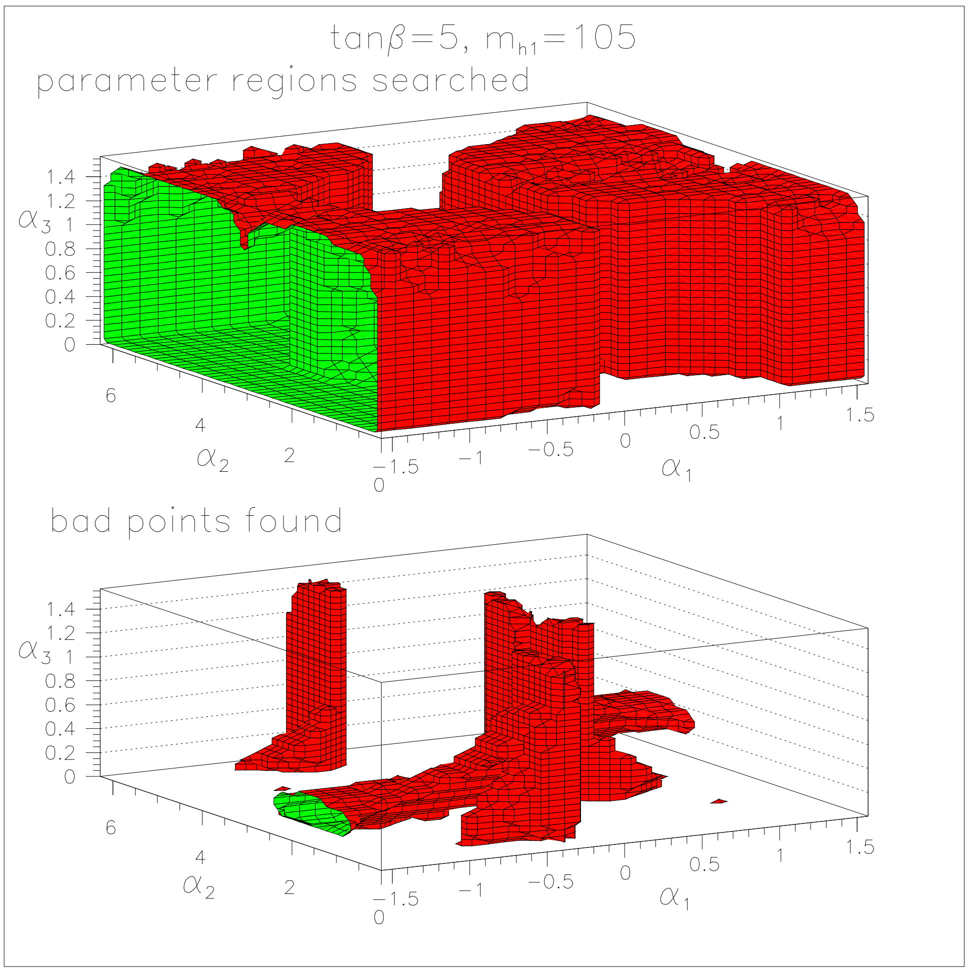


Figure 8: For $\tan\beta = 5$ and $m_{h_1^0} = 105$ GeV, we display in three dimensional $(\alpha_1, \alpha_2, \alpha_3)$ parameter space the parameter regions searched (which lie within the surfaces shown), and the regions therein for which the remaining model parameters can be chosen so that no Higgs 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 a diffuse type of signal.

- 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.

5 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.
- The precision electroweak data suggests that a $\sqrt{s} = 600$ GeV machine (so as to be sensitive to a 500 GeV SM-like Higgs or to Higgses with masses weighted below this) is very likely to find some Higgs signal, even if only using $Z + X$ recoil mass excesses.
- However, there is enough freedom in the Higgs sector that we should not take Higgs discovery at a 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