The 2HDM at low tan beta: Wjj and $\gamma\gamma$ signals as case studies

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- **Basic goal: Is there a purely Higgs sector explanation of a Wjj excess with $\sigma(Wjj) \sim 4 \text{ pb}$?**

- **Only simple thing that comes to mind is $gg \to H, A \to H^\pm W^\mp$ with $H^\pm \to cs$ (which avoids b's in the $jj = cs$ channel but requires small $\tan\beta$).**

- The MSSM and NMSSM appear to be too constrained because of mass constraints among the relevant $H^{\pm}$ and A, H, given that we want $m_{H^{\pm}} \sim 140~\mathrm{GeV}$ and $m_A > m_{H^{\pm}} + m_W$, especially if we also require that the light h be SM-like.

- If m_H and m_A are somewhat separated in mass, then a resonance peak in the Wjj mass spectrum might not be very apparent, as perhaps consistent with the CDF observation.

- Large cross section, in addition to $H^{\pm} \to cs$, requires $\tan\beta < 1$. Such small $\tan\beta$ is not consistent with 1-loop constraints without additional new physics contributing to loops.

Outline

- **2HDM reminders**
- **1-loop constraints**
- $\sigma(gg \to A)$, $B(A \to H^\pm W^\mp)$ **and** $B(H^\pm \to cs)$
- **Net** $\sigma(Wjj)$
- **Correlated signals**

2HDM Reminders

- **The potential**

$$
\begin{aligned}
V^{2HDM} \;=\; & +m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - m_3^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) \\
& +\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\
& +\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right]. \qquad (1)
\end{aligned}
$$

- **Define**

$$
M^2 \equiv \frac{m_3^2}{\cos\beta\sin\beta}, \quad \tan\beta = \frac{v_2}{v_1}, \quad v^2 = v_1^2 + v_2^2 = (246\ \mathrm{GeV})^2 \qquad (2)
$$

- **Then, for a given CP-even Higgs mixing angle α and a given choice of M^2,** all the λ_i are determined by choices for the masses of the h, H, A and $H^\pm$:

$$\lambda_1 = \frac{1}{v^2\cos^2\beta}\left(-M^2\sin^2\beta + m_H^2\cos^2\alpha + m_h^2\sin^2\alpha\right), \tag{3}$$

$$\lambda_2 = \frac{1}{v^2\sin^2\beta}\left(-M^2\cos^2\beta + m_H^2\sin^2\alpha + m_h^2\cos^2\alpha\right), \tag{4}$$

$$\lambda_3 = \frac{1}{v^2}\left[-M^2 + (m_H^2 - m_h^2)\frac{\sin 2\alpha}{\sin 2\beta} + 2m_{H^+}^2\right], \tag{5}$$

$$\lambda_4 = \frac{1}{v^2}(M^2 + m_A^2 - 2m_{H^+}^2), \tag{6}$$

$$\lambda_5 = \frac{1}{v^2}(M^2 - m_A^2). \tag{7}$$

If the λ_i of the Higgs potential are kept very perturbative, the decoupling limit, in which $m_H, m_{H^\pm} \rightarrow m_A$ and $\sin^2(\beta-\alpha) \rightarrow 1$, sets in fairly quickly as m_A increases

- In the 2HDM there are only two possible models for the fermion couplings that naturally avoid flavor-changing neutral currents (FCNC), Model I and Model II.

Table 1: Summary of 2HDM quark couplings in Model I and Model II.

	Model I			Model II		
	h	H	A	h	H	A
$t\bar{t}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$-i\gamma_5\cot\beta$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$-i\gamma_5\cot\beta$
$b\bar{b}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$i\gamma_5\cot\beta$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$-i\gamma_5\tan\beta$

(8)

Our Wjj model will employ Model II since this is only model for which one a cross section as large as $\gtrsim 1~\mathrm{pb}$.

- In both Model I and Model II the WW, ZZ couplings of the h and H are given by $\sin(\beta-\alpha)$ and $\cos(\beta-\alpha)$, respectively, relative to the SM values.

- And, very importantly, AWW and AZZ couplings are absent at tree level. Also, H^+ does not contribute to $A\to\gamma\gamma$ loop since no AH^+H^- vertex

1-loop constraints

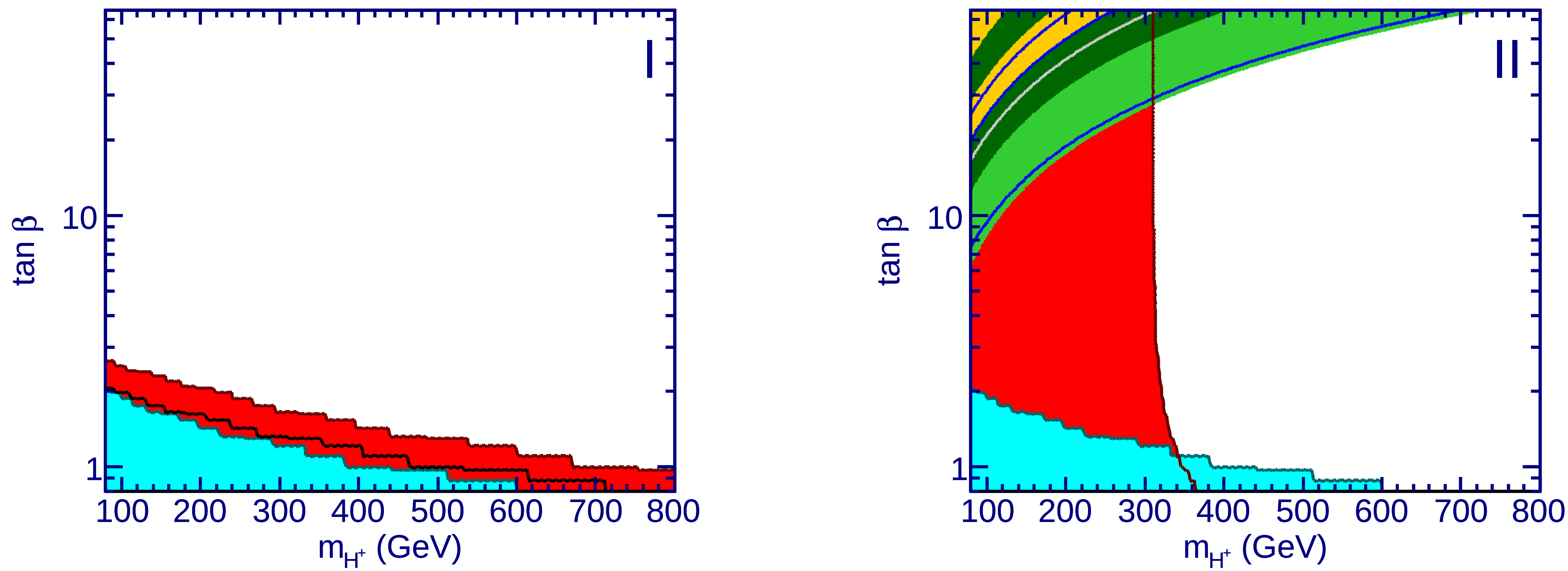

Figure 1: **Excluded regions of the $(m_{H^+}, \tan\beta)$ parameter space for Z_2-symmetric 2HDM types. The color coding is as follows: $\mathrm{BR}(B \to X_s\gamma)$ (red), Δ_{0-} (black contour), ΔM_{B_d} (cyan), $B_u \to \tau\nu_\tau$ (blue), $B \to D\tau\nu_\tau$ (yellow), $K \to \mu\nu_\mu$ (gray contour), $D_s \to \tau\nu_\tau$ (light green), and $D_s \to \mu\nu_\mu$ (dark green). Taken from arXiv:0907.1791.**

- **We see that $\mathrm{BR}(B \to X_s\gamma)$ (red), Δ_{0-} (black contour), ΔM_{B_d} (cyan)** constrain the small $\tan\beta$ and small m_{H^+} regions. Here

$$\Delta_{0-} \equiv \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) - \Gamma(\bar{B}^- \to \bar{K}^{*-}\gamma)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) + \Gamma(\bar{B}^- \to \bar{K}^{*-}\gamma)}. \tag{9}$$

We need some other new physics in the loops if the model is to be consistent.

- Alternatively, as sometimes argued by Luty and collaborators, an effective 2HDM-II at tree level often emerges from technicolor-like theories and there could be other contributions to the 1-loop observables.

- Of course, if these extra contributions or new physics were to influence $gg \to A$ and $A \to \gamma\gamma$ then our results would be inaccurate.

  A charged object that does not couple to the A and contributes with opposite sign in the loops for $B \to \gamma s$ and ΔM_{B_d} would be ideal.

  Any ideas?

What is needed

- To obtain a Wjj signal with Tevatron cross section of order $\gtrsim 1~\mathrm{pb}$, first note that the cross section for $gg \to A$ is highly enhanced at a given m_A relative to the cross section for a SM Higgs boson at $m_{h_{\mathrm{SM}}} = m_A$ when $\tan\beta < 1$.

- The Wjj signal derives from the (dominant) $A \to H^\pm W^\mp$ decay channel with $H^\pm \to cs$. Note that this particular mode does not contain b quarks, as consistent with the CDF observations.[1]

- Using the predicted value of $BR(H^+ \to cs) \sim 0.2$ for $m_{H^\pm} \sim 140~\mathrm{GeV}$ when $\tan\beta$ is small, one finds that a cross section for $gg \to A \to H^\pm W^\mp \to csW^\mp$ as large as the CDF value of $\sim 4~\mathrm{pb}$ can only be achieved for $m_A \in [250, 300]~\mathrm{GeV}$ if $\tan\beta \lesssim 1/10$.

[1]However, $H^\pm \to t^* b$ has a large branching fraction, as discussed later, but since $t^* \to Wb$, this channel will not lead to a jj resonance signal.

This is a domain for which the top-quark Yukawa coupling is non-perturbative, $\alpha_t \equiv \lambda_t^2/(4\pi) > 1$.

However, a smaller Wjj cross section of order $1 - 2$ pb is possible for $\alpha_t \sim 1$.

- **We will fix α relative to β by requiring that the h be SM-like, *i.e.* $\sin(\beta - \alpha) = 1$.**

- **We also choose $m_h = 115$ GeV for easy consistency with precision electroweak data, but results depend only weakly on precise m_h value.**

- **To describe a Wjj excess requires that $m_A > m_{H^\pm} + m_W$ (but $m_H \sim m_A$ is useful to enhance the signal), implying that the decoupling limit does not apply at the masses of interest.**

- **This requires that several of the λ_i are substantial but still below the $\lambda_i^2/(4\pi) \sim 1$ beginning of the non-perturbative domain.**

$gg \to A$

- Looking at Eq. (1), it is apparent that the cross section for $gg \to A$ can be large when $\cot\beta > 1$.

- The reason to focus on A is that the fermionic loop function for the A is substantially larger than that for the H (the CP-even Higgs that could contribute to the Wjj excess if the h is SM-like)

  Asymptotically

$$F^A_{1/2}(\tau) \to 2\,, \quad vs. \quad F^H_{1/2}(\tau) \to -4/3 \tag{10}$$

  when $\tau = 4m_f^2/m_A^2 \to \infty$, implying a cross section gain by a factor of $9/4$ for A vs. the H in the heavy fermion mass limit.

- We have computed the $gg \to A$ (and $gg \to H$) cross section using HIGLU (Spira) and a private program and obtained essentially the same results.

Results for $\sigma(gg \to A)$ are plotted in Fig. 2. These results include NLO and NNLO corrections as in HIGLU.

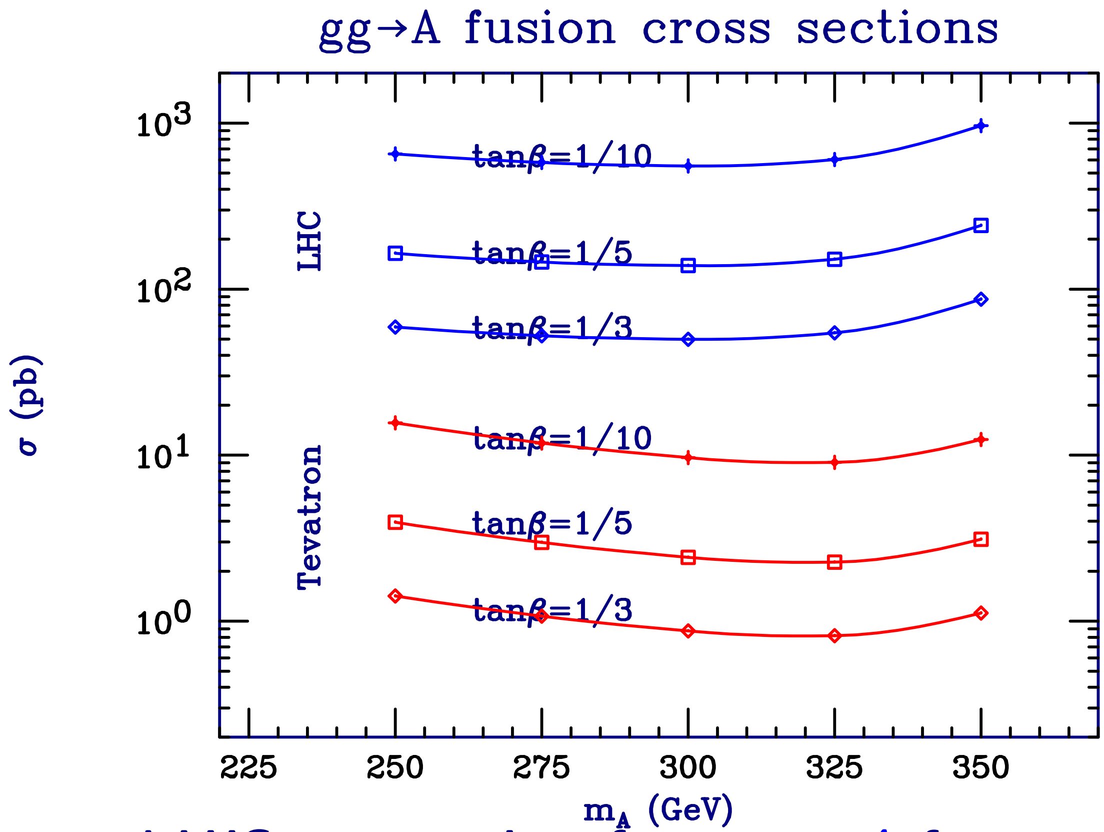

Figure 2: Tevatron and LHC cross sections for $gg \to A$ for representative $\tan\beta < 1$ values in 2HDM-II.

$m_A = 250$ GeV $\Rightarrow$ (11)

$\tan\beta$	$1/3$	$1/5$	$1/10$
$\sigma(gg \to A)_{Tevatron}$	1.4 pb	3.9 pb	15.7 pb
$\sigma(gg \to A)_{LHC}$	59.1 pb	164.3 pb	652.9 pb

- **What about $B(H^+ \to c\bar{s})$? Inclusion of the off-shell decay $H^+ \to t^*\bar{b}$ is essential to get $B(H^+ \to c\bar{s})$ right.**

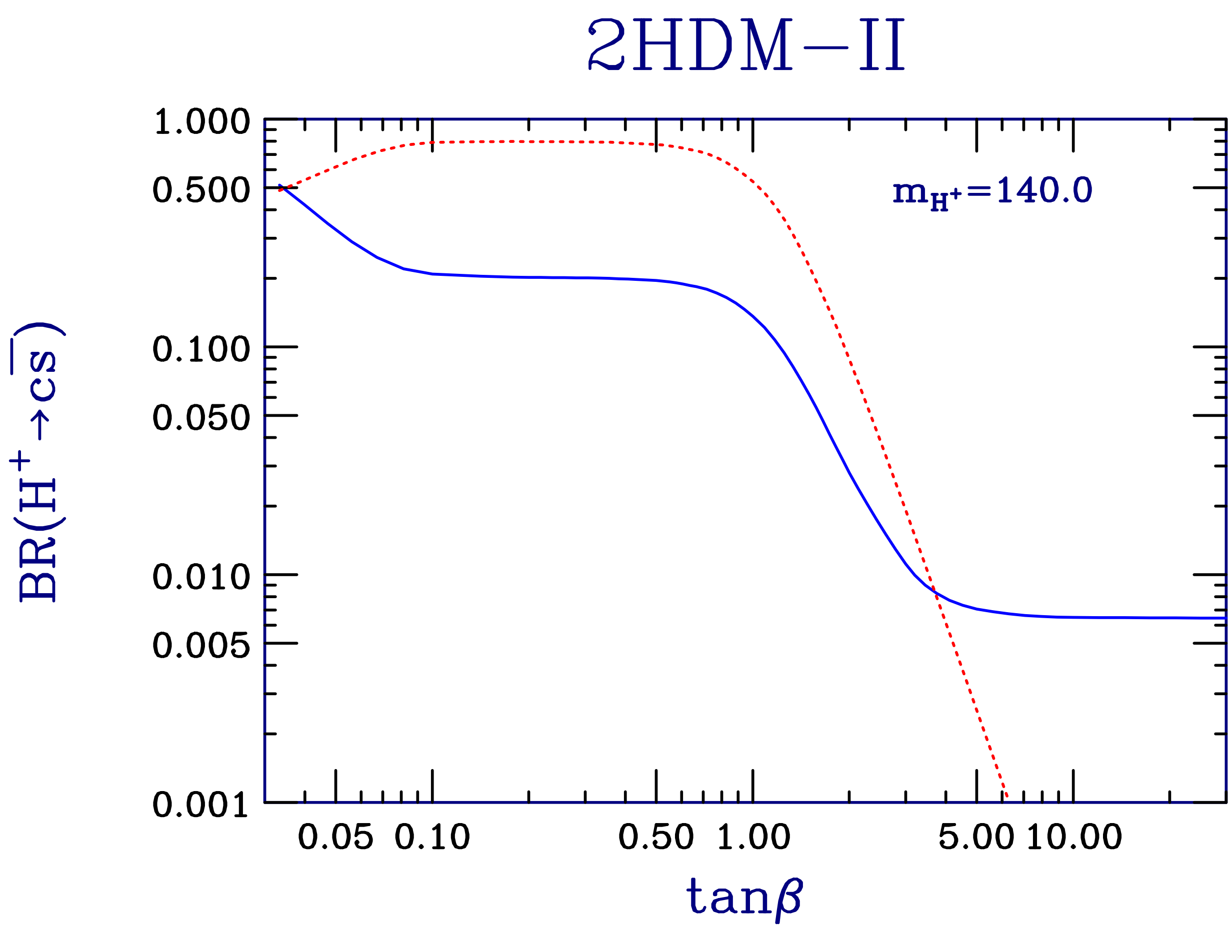

Figure 3: $B(H^+ \to c\bar{s})$ **(solid blue) and** $B(H^+ \to t^*\bar{b})$ **(red dots) as a function of** $\tan\beta$ **for** $m_{H^\pm} = 140~\mathrm{GeV}$ **and Model II couplings.**

- **And finally, $B(A \to H^\pm W^\mp)$ (note: $\tan\beta = 1/5$ is magenta line)**

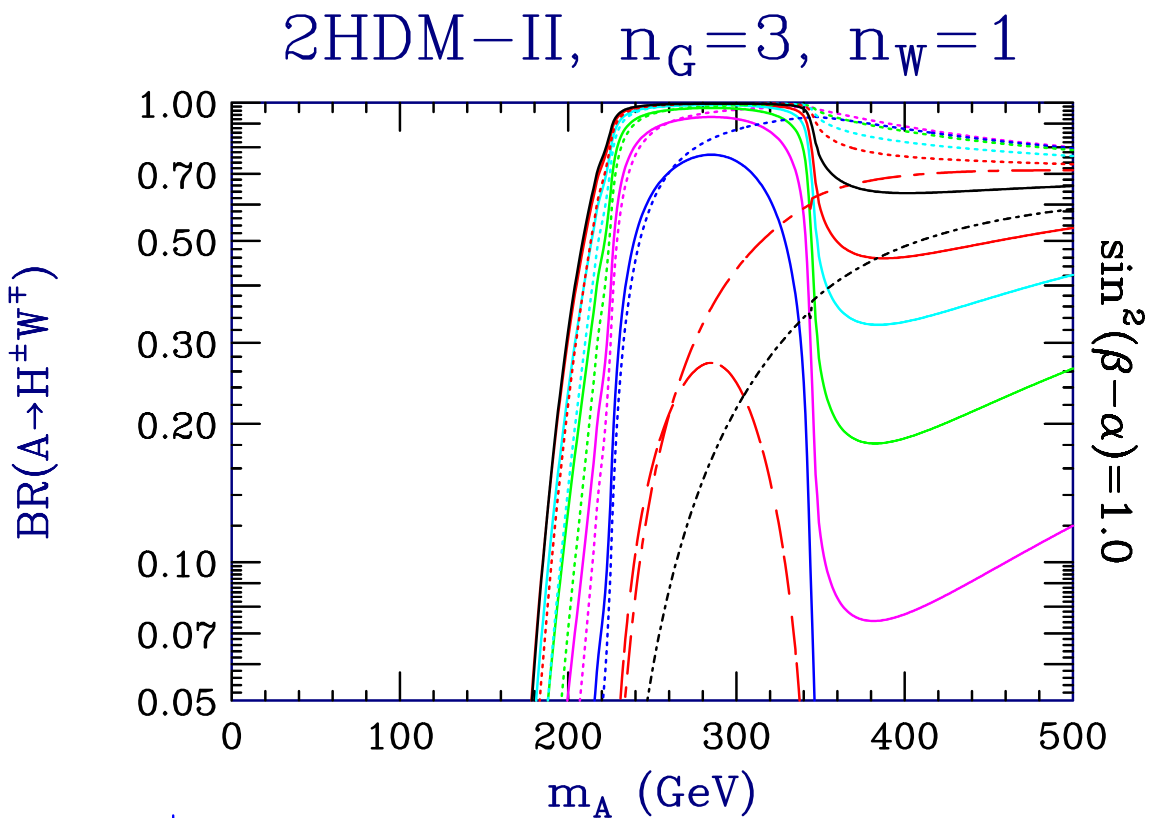

Figure 4: $B(A \to H^\pm W^\mp)$ **as a function of** m_A **for** $m_{H^\pm} = 140~\mathrm{GeV}$ **and Model II couplings. In this and subsequent plot for the** A**, we have taken** $m_H = 140~\mathrm{GeV}$**. The legend is as follows: solid black**$\longrightarrow$ $\tan\beta = 1$; **red dots**$\longrightarrow$ $\tan\beta = 1.5$; **solid red**$\longrightarrow$ $\tan\beta = 1/1.5$; **cyan dots**$\longrightarrow$ $\tan\beta = 2$; **solid cyan**$\longrightarrow$ $\tan\beta = 1/2$; **green dots**$\longrightarrow$ $\tan\beta = 3$; **solid green**$\longrightarrow$ $\tan\beta = 1/3$; **magenta dots**$\longrightarrow$ $\tan\beta = 5$; **solid magenta**$\longrightarrow$ $\tan\beta = 1/5$; **blue dots**$\longrightarrow$ $\tan\beta = 10$; **solid blue**$\longrightarrow$ $\tan\beta = 1/10$; **long red dashes plus dots**$\longrightarrow$ $\tan\beta = 30$; **pure long red dashes**$\longrightarrow$ $\tan\beta = 1/30$; **black dotdash**$\longrightarrow$ $\tan\beta = 50$**. Results plotted include off-shell decay configurations.** $n_G = 3$, $n_W = 1$ **means 3 generations, no sequential** W'**.**

Net Wjj signal

- We define the effective Wjj cross section for a Higgs boson X:

$$\sigma^X_{Wjj} \equiv B(X \to H^\pm W^\mp) B(H^+ \to c\overline{s}) \sigma(gg \to X), \tag{12}$$

where $X = A$ and $X = H$ are the relevant Higgs bosons.

- As a benchmark to keep in mind, we will suppose that $\sigma^A_{Wjj} \sim 1~\mathrm{pb}$ is the minimum appropriate for an observable Tevatron Wjj excess.

- $B(H^+ \to c\overline{s}) \sim 0.22$ applies for $\tan\beta \in [1/10, 1/3]$.

- For $m_A = 250~\mathrm{GeV}$, $B(A \to H^\pm W^\mp) \sim 0.95, 0.874, 0.64$ for $\tan\beta = 1/3, 1/5, 1/10$ (the solid green, magenta, blue lines), respectively.

- For $m_A = 250~\mathrm{GeV}$ we then obtain $B(A \to H^\pm W^\mp) B(H^+ \to c\overline{s}) \sim 0.21, 0.19, 0.14$ for $\tan\beta = 1/3, 1/5, 1/10$.

- Using $\sigma(gg \to A)$ from Eq. (11), for $m_A = 250$ GeV we find $\sigma^A_{Wjj}(Tev) \sim 0.3$ pb, 0.75 pb, 2.2 pb for $\tan\beta = 1/3,\ 1/5,\ 1/10$, respectively.

- The corresponding values of α_t are $0.63,\ 1.75,\ 7$. Only the latter is uncomfortably non-perturbative, implying a preference for $\sigma^A_{Wjj} \lesssim 1$ pb.

- σ^A_{Wjj} is not larger due to the small value of $B(H^+ \to c\overline{s})$ that results from the dominance of *off-shell* $H^+ \to t^*\overline{b}$ decays for $m_{H^\pm} = 140$ GeV.

  This dominance decreases rapidly if $m_{H^\pm}$ is decreased; for $m_{H^\pm}$ significantly lower that 140 GeV higher σ^A_{Wjj} would thus be achieved.

- For $m_A \gtrsim 300$ GeV, σ^A_{Wjj} is about 50% smaller than the $m_A = 250$ GeV values quoted above, see Fig. 2.

- As apparent from Eq. (11), $\sigma(gg \to A)$ is much larger at the LHC.

  Focusing on $m_A = 250$ GeV and including the earlier quoted $B(A \to H^\pm W^\mp)B(H^+ \to c\overline{s})$ values of $0.21,\ 0.19,\ 0.14$ we obtain $\sigma^A_{Wjj}(LHC) = 12.4$ pb, 31.2 pb, 91.4 pb for $\tan\beta = 1/3,\ 1/5,\ 1/10$, respectively.

We are close to getting meaningful constraints from the LHC. ATLAS has presented the following plots (ATLAS-CONF-2011-097)

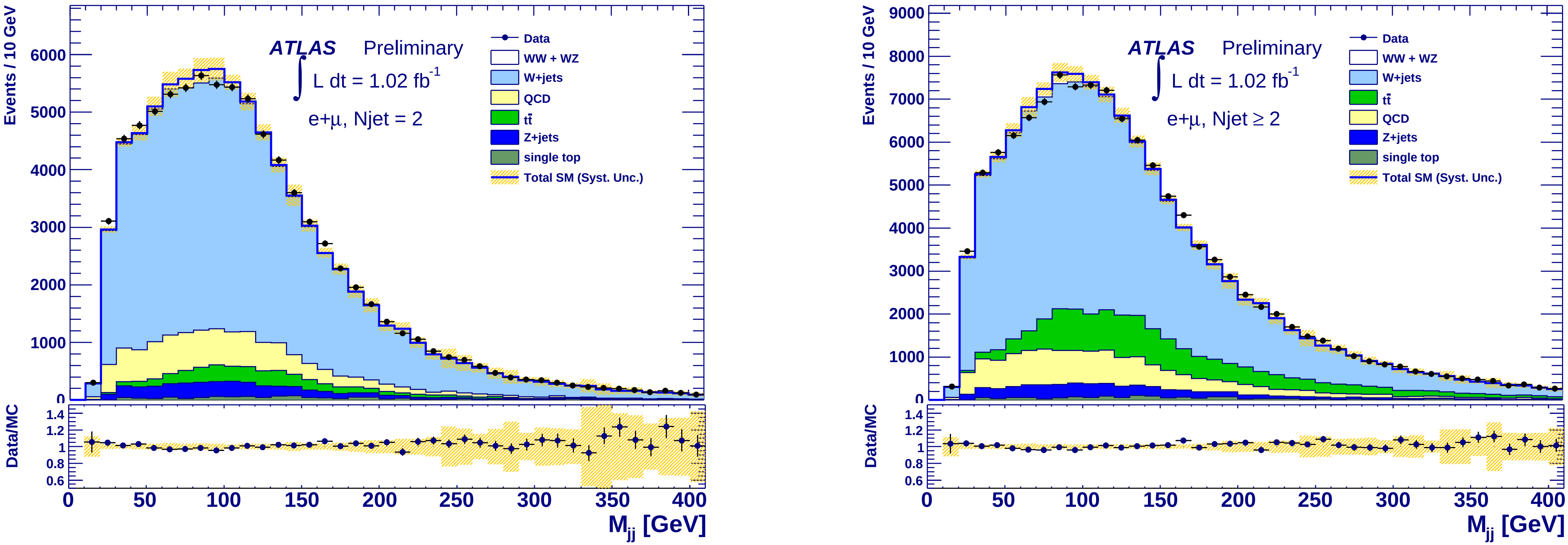

Figure 5: M_{jj} distributions for $n_{jet} = 2$ and $n_{jet} \geq 2$.

Since something like 80% of the cross section comes from higher order corrections, including radiated real gluons, and since a Monte Carlo would also have most events accompanied by radiated gluons, it seems certain that one should look at the $n_{jet} \geq 2$ plot.

For $\tan\beta = 1/5$ and $L = 1~\mathrm{fb}^{-1}$, $\sigma^A_{Wjj} = 31~\mathrm{pb}$ yields an expected number of events in the plot of $1000~\mathrm{pb}^{-1} \times 31~\mathrm{pb} \times 0.2 \times 0.1 = 600$, where $B(W \to \ell\nu) \sim 0.2$ and acceptance etc. efficiency of 10% was employed.

If we spread this over 5 bins, that would be 120 events per $10~\mathrm{GeV}$ bin. The SM background in the bin centered at $140~\mathrm{GeV}$ is about 5000 events, yielding $S/\sqrt{B} \sim 120/70 \sim 2$ in each of several bins.

Naively, one might conclude that this is excluded. However, one is relying on the accuracy of the SM simulation of the backgrounds, which are obviously very large. We must wait to see what kind of systematic error ATLAS will assign (i.e. we need the usually 1σ and 2σ bands on expected exclusion).

- How much will H contribute (as relevant when h is SM-like)?

  We have already noted that $\sigma^H_{Wjj} < \sigma^A_{Wjj}$ due to the smaller fermionic loop function.

Actual ratios at the Tevatron are: $\sigma^A_{Wjj}/\sigma^H_{Wjj} \sim 2.6,\ 3.0,\ 5.0$ **for** $m_A = m_H = 250,\ 300,\ 350~\mathrm{GeV}$.

Meanwhile, the $B(H \to H^\pm W^\mp)$ **(and hence** $B(H \to H^\pm W^\mp)B(H^+ \to c\bar{s})$**) values are slightly larger than those quoted for the** A**. (e.g. compare** $\tan\beta = 1/5$ **magenta lines)**

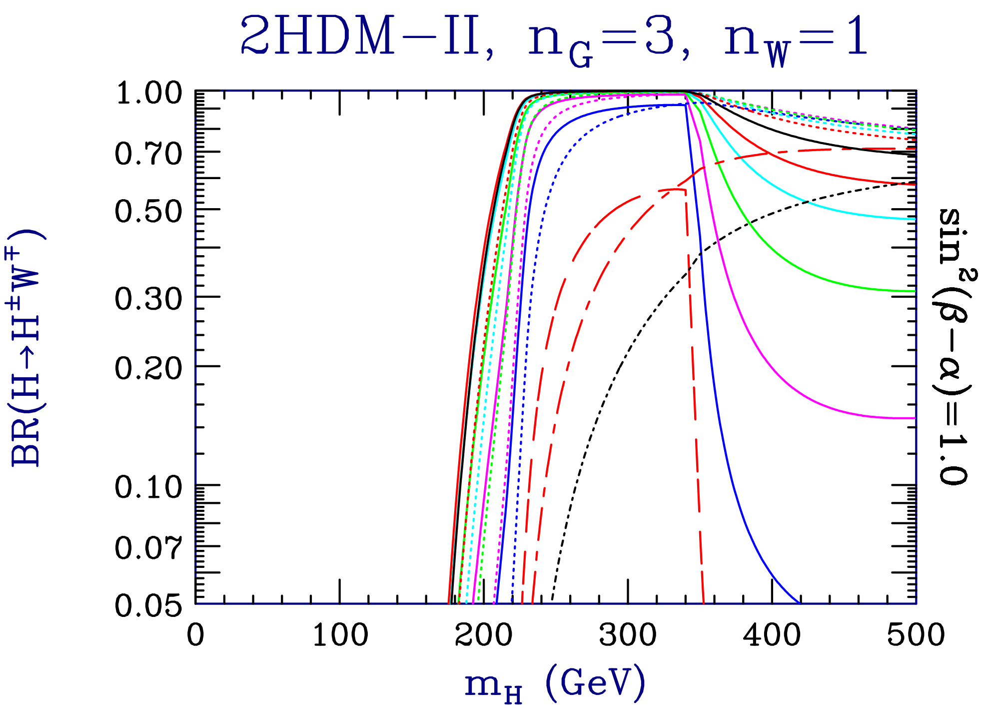

Figure 6: $B(H \to H^\pm W^\mp)$ **as a function of** m_A **for** $m_{H^\pm} = 140~\mathrm{GeV}$ **and Model II couplings. In this and subsequent plots for the** H**, we have taken** $m_A = 200~\mathrm{GeV}$**. The legend is as in Fig. 4.**

Thus, for the preferred $m_H \in [250 - 300]$ GeV mass range, the H would yield a Wjj signal of order $30\% - 40\%$ of the A result.

If the H and A are not fairly degenerate, this would yield a somewhat spread out net Wjj signal, despite the $\lesssim 1$ GeV total widths of the A and H (for the $\tan\beta$ values being discussed), given the experimental M_{jj} resolution of order 15 GeV.

This is perhaps suggested by the absence of any distinct peaking in the Wjj mass in the data.

Another interesting point is that in this model with m_H not very different from m_A, there would be no signal in the Zjj channel due to the absence of $H \to AZ$ and $A \to HZ$ decays.

Correlated Signals

- **$\gamma\gamma$ peak(s)** **There is a very large $A \to \gamma\gamma$ signal for small $\tan\beta$.**

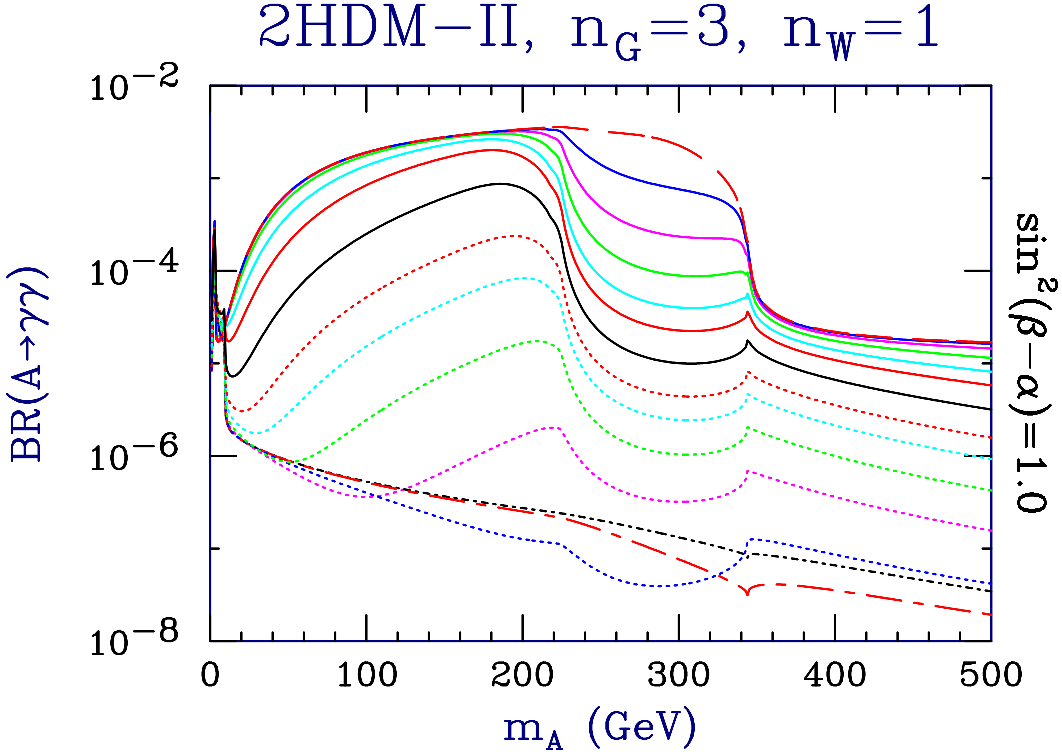

Figure 7: $B(A \to \gamma\gamma)$ **for the 2HDM-II** A **after including** $A \to H^{\pm}W^{\mp}$ **and** $A \to t\bar{t}$ **off-shell decays in the present scenario. The legend is as in Fig. 4.**

Since $B(A \to \gamma\gamma)$ is so large, the resulting signal will soon be observed at the LHC if present and might also be observable with current Tevatron data.

To assess actual event rates one can combine the actual branching ratio for $A \to \gamma\gamma$, plotted in Fig. 7 with the cross sections for $gg \to A$ plotted in Fig. 2.

For example, for $\tan\beta = 1/5$ and $m_A = 250~\mathrm{GeV}$, in the case of the Tevatron one finds $\sigma(gg \to A)B(A \to \gamma\gamma) \sim 3.9~\mathrm{pb} \times 4.8 \cdot 10^{-4} \simeq 1.9 \times 10^{-3}~\mathrm{pb}$, yielding ~ 10 events for $L = 5.4~\mathrm{fb}^{-1}$.

The net CDF efficiency times acceptance is ~ 0.12, $\Rightarrow 1.2$ $A \to \gamma\gamma$ events.

The actual number of observed events is consistent with the SM prediction. They set a 95% CL limit of $\sigma B(\gamma\gamma) \lesssim 0.05~\mathrm{pb}$ at $M_{\gamma\gamma} = 250~\mathrm{GeV}$, a factor of ~ 25 above our typical prediction.

At the LHC, the corresponding calculation is $\sigma(gg \to A)B(A \to \gamma\gamma) \sim 164~\mathrm{pb} \times 4.8 \cdot 10^{-4} = 0.08~\mathrm{pb}$. For $L = 36~\mathrm{pb}^{-1}, 1~\mathrm{fb}^{-1}$ this yields $\sim 3, 80$ events, respectively.

At CMS with $L = 36\ \mathrm{pb}^{-1}$ they find $\sigma \times B(\gamma\gamma) \lesssim 0.7\ \mathrm{pb}$ at $M_{\gamma\gamma} = 250\ \mathrm{GeV}$, a factor of about 8 above the prediction for the present scenario.

This shows that the present scenario for obtaining a Wjj excess will be strongly tested once the currently available LHC data sets with $L = 1\ \mathrm{fb}^{-1}$ are analyzed.

Of course, the H also yields a large $\gamma\gamma$ signal (again of order $30\% - 40\%$ that of the A) that most probably would be detected as a separate peak if m_H differs from m_A by more than $10\ \mathrm{GeV}$, given the excellent $\sim 2\ \mathrm{GeV}$ mass resolution in $M_{\gamma\gamma}$ for the LHC detectors and given that the total A and H widths are of order $1\ \mathrm{GeV}$.

- **$WWbb$ non-resonant signal**

$gg \to A \to H^\pm W^\mp \to t^*\overline{b}W^- + \overline{t}^* bW^+$ with $t^* \to W^+ b$ leads to a $W^+W^-b\overline{b}$ final state that will not peak in either Wb mass combination.

The cross section for this final state is significant:

At the Tevatron, for $m_A = 250$ GeV and $\tan\beta = 1/5$, one finds $\sigma(WWbb) \sim 2.8$ pb compared to $\sigma^A_{Wjj} \sim 0.75$ pb and $\sigma^H_{Wjj} \sim 0.28$ pb.

Although this $\sigma(WWbb)$ is somewhat smaller than that for direct $t\bar{t} \to W^+W^-b\bar{b}$ production, it is still sizable and might lead to some “anomalies” in the $W^+W^-b\bar{b}$ final state.

It would be very interesting to determine whether or not such anomalies in the $W^+W^-b\bar{b}$ final state would have been noticed in current data and, if not, how much LHC integrated luminosity would be needed to detect them.

One should note that for this model to achieve the CDF Wjj cross section of ~ 4 pb would imply an anomalous $W^+W^-b\bar{b}$ final state cross section that is larger than that coming directly from $t\bar{t} \to W^+W^-b\bar{b}$ production.

$\gamma\gamma$ signals in general for the 2HDM

- Even if you forget the Wjj model, it is interesting to see what level of $\gamma\gamma$ cross section derives from $gg \to A \to \gamma\gamma$.

- In particular, consider the case of $m_A \ll m_h, m_H, m_{H^\pm}$.

  For large $m_{H^\pm}$, in particular, this would avoid the 1-loop problems.

  Further, $m_{H^\pm} - m_H$ can be adjusted so that the large $\Delta T > 0$ coming from this mass splitting would make it possible to remain inside the S, T PEW ellipse when m_h is large.

  In this case, one would want to focus on $A \to \gamma\gamma$ signals

- Alternatively, one might be in the decoupling limit of $m_A \sim m_H \sim m_{H^\pm}$, a situation that would inconsistent with 1-loop constraints if the common mass were below $300~\mathrm{GeV}$ without additional new physics contributing to the loops.

In this case, both $A \to \gamma\gamma$ and $H \to \gamma\gamma$ signals would be of interest.

- In figures to follow, "recall" that the dotted curves are for $\tan\beta > 1$, solid black curve is for $\tan\beta = 1$, and, as a useful reference point, solid magenta is for $\tan\beta = 1/5$.

- Branching ratios for $H, A \to \gamma\gamma$ are large at low $\tan\beta$.

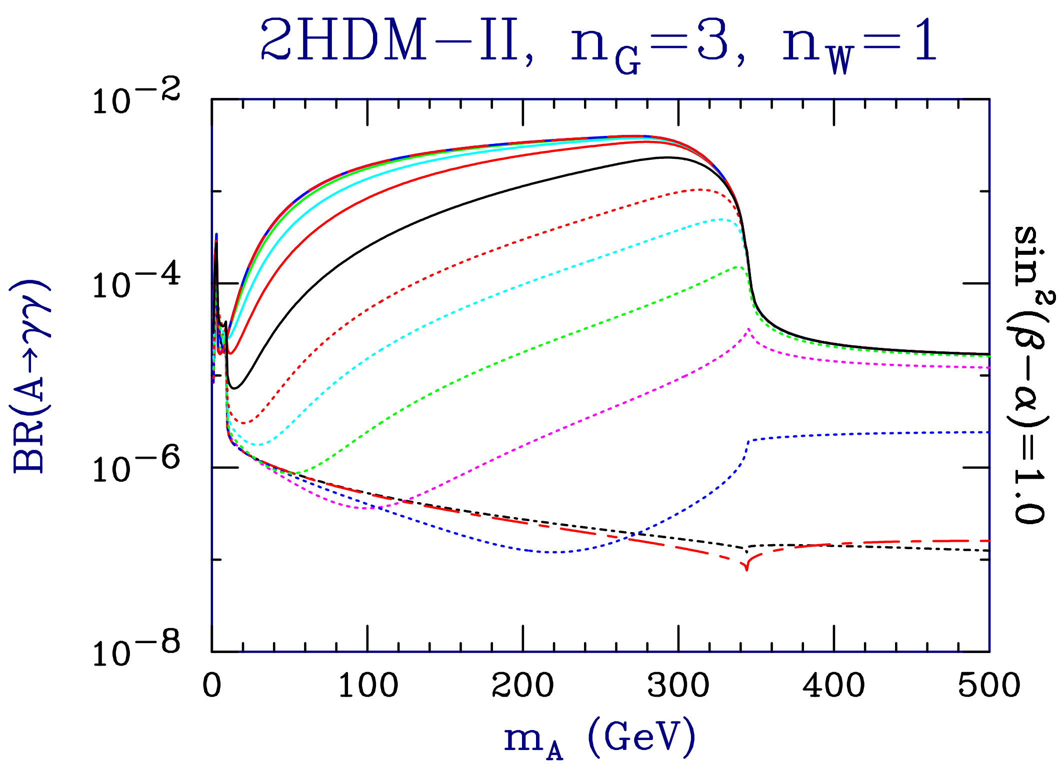

Figure 8: $B(A \to \gamma\gamma)$ for $m_H \sim m_A$. $B(H \to \gamma\gamma)$ similar.

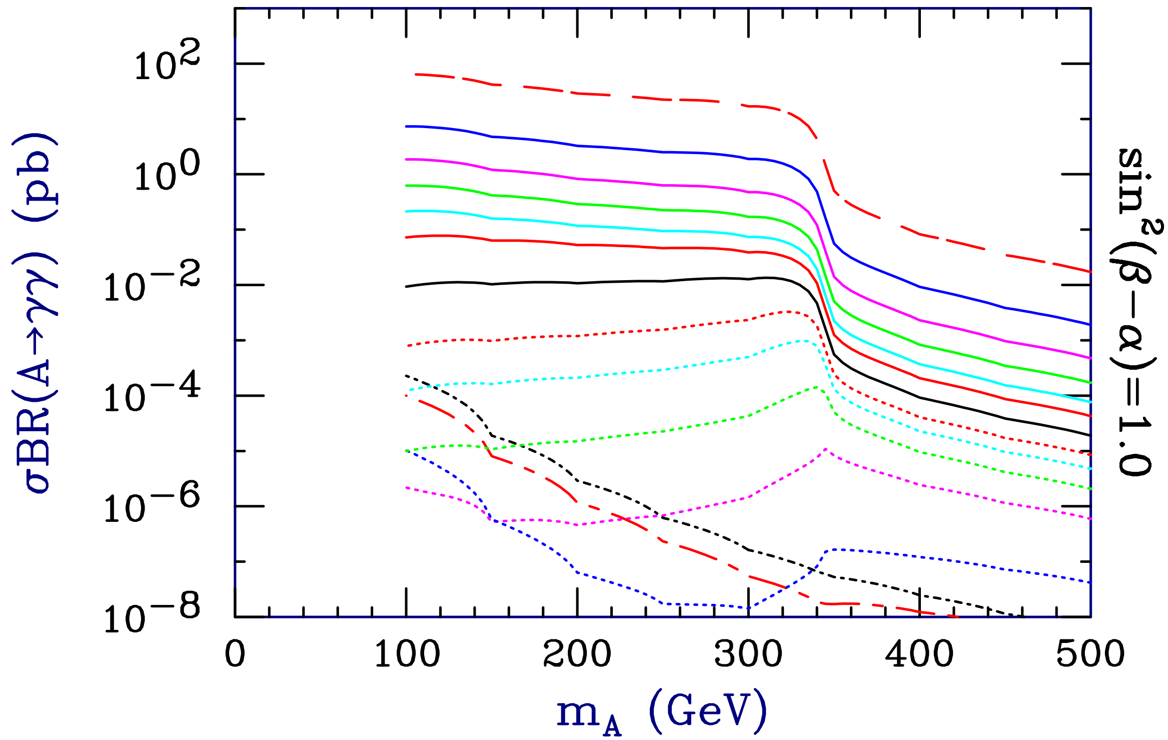

Figure 9: $\sigma(gg \to A \to \gamma\gamma)$ **for** $m_A \leq m_H, m_{H^\pm}$ **and 3 generations at** $\sqrt{s} = 7$ TeV.

For $\tan\beta < 1$**, the rate would be significant if** $m_A < 2m_t$.

For $m_H \sim m_A$**, the** $H \to \gamma\gamma$ **signal level would be about 50% of the** $A \to \gamma\gamma$ **signal (because** $\sigma(gg \to H) \sim 0.5\sigma(gg \to A)$**).**

Barring $m_A = m_H$**, two peaks would be evident.**

- **It is interesting to see the big increase for** $\tan\beta > 1$ **range were there 4** generations.

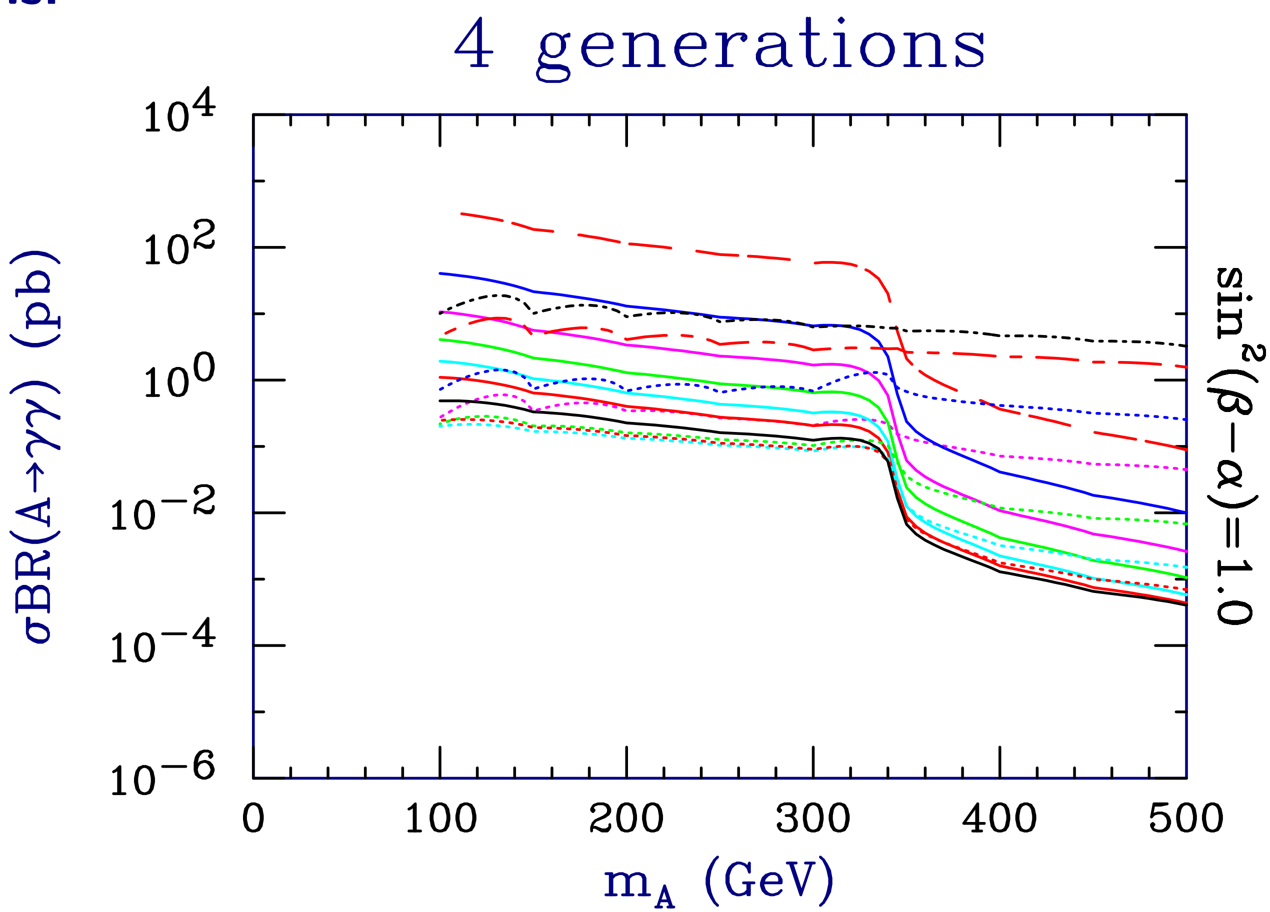

Figure 10: $\sigma(gg \to A \to \gamma\gamma)$ for $m_H = m_A = m_{H^\pm}$ and 4 generations at $\sqrt{s} = 7~\mathrm{TeV}$.

Of course, if we see a SM-like Higgs with normal rate then 4 generations are ruled out.

But, in the 2HDM the h (and therefore the H) can be heavy and out of range and the A can be the lightest state.

In fact, one can have $m_A \ll m_h \sim m_H \sim m_{H^\pm}$ by choosing $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_5 = -\lambda_4$. The 2HDM potential has a special symmetry attached to this scenario. See hep-ph/0009271 (Chankowski, Farris, Grzadkowski, Gunion, Kalinowski, Krawczyk).

$$V = \frac{1}{2}\lambda_1 \left[|\delta_{ij}\Phi_i^\dagger \Phi_j|^2 - |\epsilon_{ij}\Phi_i^\dagger \Phi_j|^2 \right] = \frac{1}{2}\lambda_1 \left[|K_0|^2 - |K_2|^2 \right] \qquad (13)$$

(the latter references Haber's talk) which is invariant under rotations of the Φ_i fields and antisymmetric under interchange of the symmetric and antisymmetric forms. One cannot yet rule out this very unusual 2HDM scenario!

In this kind of model, PEW is ok if you just perturb the potential slightly to give small $m_{H^\pm} - m_H > 0$ isospin splitting.

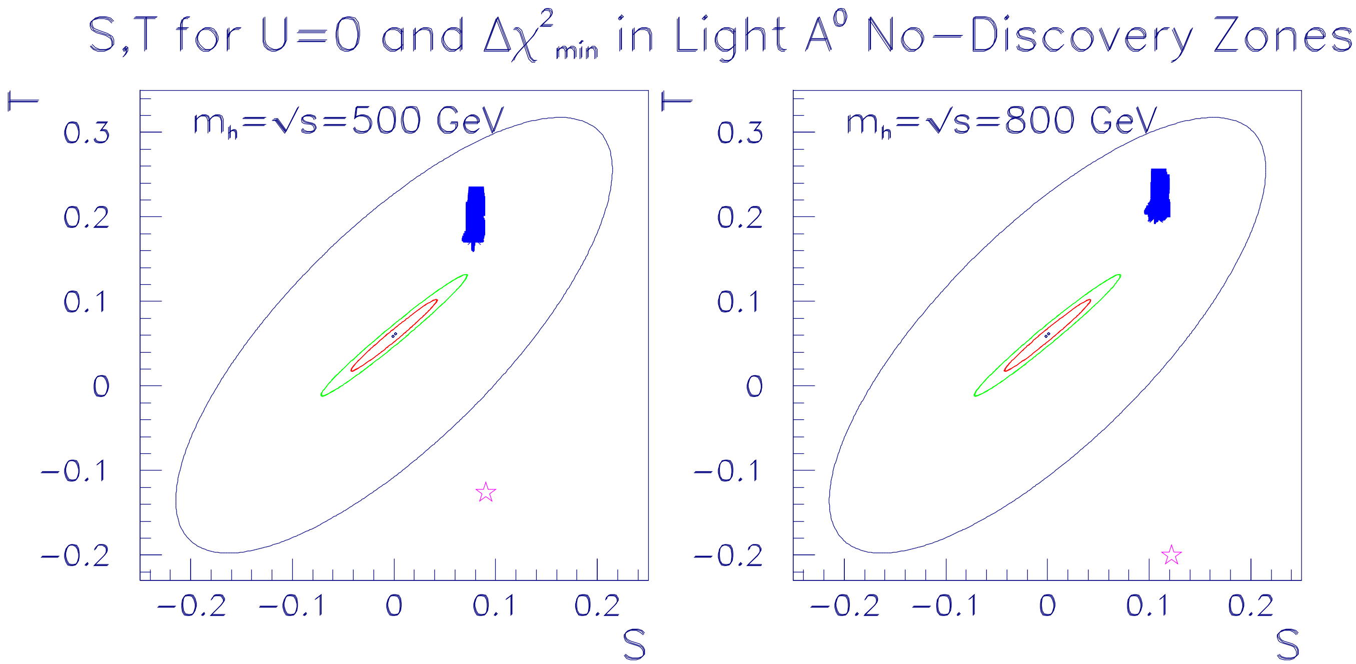

Figure 11: The S,T plane picture for special 2HDM potential.

The associated $\gamma\gamma$ signal could then be the only evidence of the Higgs sector and would provide indirect evidence about 4th generation absence or presence.

- **At the LHC, CMS and ATLAS Higgs searches currently impose the limit $\sigma B(\gamma\gamma) \lesssim 0.06~\mathrm{pb} - 0.26~\mathrm{pb}$, depending on $M_{\gamma\gamma}$ for any narrow state $\in [110~\mathrm{GeV}, 150~\mathrm{GeV}]$ using $L \sim 1~\mathrm{fb}^{-1}$ data.**

This is already excluding some of the $\tan\beta < 1$ values over this mass range for the 3-generation case, and is excluding nearly all $\tan\beta$ values in this mass range for the 4-generation case.

- **Graviton searches in the $\gamma\gamma$ final state give $\sigma B(\gamma\gamma) \lesssim 0.3~\mathrm{pb}$ for $M_{\gamma\gamma} \in [500~\mathrm{GeV}, 1200~\mathrm{GeV}]$, a range somewhat above the range of interest.**
- **An analysis in the range $M_{\gamma\gamma} \in [150~\mathrm{GeV}, 500~\mathrm{GeV}]$ is needed.**

Summary

- If $\tan\beta < 1$ then a Model II two-Higgs-doublet sector with m_A, and possibly m_H, of order $250~\mathrm{GeV} - 300~\mathrm{GeV}$ can lead to a very interesting signal in the Wjj final state.

- To get a cross section as large as that originally claimed by CDF would force one to $\tan\beta \lesssim 1/10$, values for which the top-quark Yukawa coupling is quite large and significantly non-perturbative.

- However, a Wjj signal with cross section of order $1~\mathrm{pb}$, as possibly consistent with a combination of CDF and D0 data, is quite possible without entering into the domain of non-perturbative top-quark Yukawas.

- Correlated signals in the $W^+W^-b\bar{b}$ and $\gamma\gamma$ final states are expected. These final states are interesting targets for exploration in their own right. The predicted correlations between the Wjj, $W^+W^-b\bar{b}$ and $\gamma\gamma$ signals makes the model proposed herein highly testable and points out the importance of taking into account the latter types of signals in order to fully assess the consistency of the model.

- At the LHC, the predicted Wjj cross sections and those for the correlated signals are of order 40 times as large as at the Tevatron.

  Now that the integrated LHC luminosity is exceeding $L = 1~\mathrm{fb}^{-1}$ the model will most probably be definitively eliminated or confirmed.

- Note: the masses for the $m_{H^\pm}$, m_A and m_H needed to explain the possible Wjj excess using the approach described here cannot be achieved within the minimal supersymmetric model context.

- Enhanced $gg \to A$ cross sections also arise in a Model I 2HDM if $\tan\beta < 1$.

  However, the enhancement is not quite as great as for Model II.

  In addition, $B(H^+ \to c\bar{s}) \sim 0.13$ for $\tan\beta \in [1/3, 1/10]$.

As a result, the Wjj cross section that can be achieved in Model I is smaller by about a factor of three as compared to that achieved for the Wjj final state in the case of Model II.

- Of course, one must still have additional physics contributing at one-loop to obtain acceptable $B(b \to \gamma s)$ and ΔM_{B_d}.

  Such physics might or might not affect the Wjj signal. A specific model is needed.

- In the case where the A is the lightest state and all other Higgs are substantially heavier, one escapes the above 1-loop issues and the $\sigma B(\gamma\gamma)$ limits from the LHC are starting to encroach on the predicted rates for some $\tan\beta$ and m_A values.