Physics 222 UCSD/225b UCSB

Lecture 15

- Extending the Higgs Sector => 2 Higgs Doublet Models (2HDM).
- I am using the following for today's lecture:
  - "Higgs Hunter's guide" (1990)
  - TASI 06 lectures by Rainwater

Logic of Today’s Lecture

- Reminder of single higgs doublet, i.e. Minimal Standard Model (SM or MSM).
- Overview of constraints for extending the higgs sector.
- Focus on 2 higgs doublet models
  - 4 types => discuss 2 of them
- Focus on 2HDM type 2, as implemented in Minimal Supersymmetric Standard Model (MSSM).

Higgs Field in SM

- Standard Model assumes the simplest choice for the higgs field:
  - a complex doublet with Y = 1.
    - Complex for U(1)
    - Doublet for SU(2)
    - Y=1 to make quatum numbers come out right.

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \frac{1}{\sqrt{2}}$$

The superscript indicate the charge according to:

$Q = T^3 + Y/2$

Higgs Ground State in SM

- This particular choice of multiplets is exactly what we need because it allows us to break both SU(2) and $U(1)_Y$, while at the same time allowing us to choose a ground state that leaves $U(1)_{em}$ unbroken.
- The latter is accomplished by choosing a ground state that leaves $\phi^+ = 0$.

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} 0 \\ v \end{pmatrix} \frac{1}{\sqrt{2}}$$

- Use the same higgs field to give mass to fermions and bosons.

Extended Higgs Fields

- There are in principle many choices one could make.
- The only constraint is that the higgs fields belongs to some multiplet of SU(2) x U(1).
- And unitarity should not be violated at large s.
- Apart from that, there are experimental constraints, the most stringent of which are:
  - $$\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} \approx 1$$
  - FCNC are heavily suppressed in nature.

Comments on ρ=1

- Halzen & Martin Exercise 15.4 explores this further.
- Additional discussion can be found in “Higgs Hunter’s Guide” chapter 4, and references therein.
- Bottom line:
  - There are many ways to satisfy this constraints.
  - In particular, any model with arbitrary number of higgs doublets and higgs singlets will satisfy the constraint.

Comments on FCNC

- Flavor changing neutral currents in quark sector are heavily suppressed in the SM, proceeding only via “penguin” loops, and other 2nd order weak transitions.
- Glashow & Weinberg showed that tree-level FCNC are forbidden IFF all fermions of a given electric charge couple one-to-one to higgs doublets. (see references for details)

=> Multi-higgs doublet models are thus ok as long as they obey this rule.

Two higgs Doublet Models

- Has been studied theoretically, as well as limited experimentally, in great detail because:
  - It's a minimal extension of the SM higgs sector.
  - It satisfies both experimental constraints we mentioned.
  - It adds new phenomenology by predicting a charged higgs particle.
  - It is required in the MSSM, as well as "low energy" SUSY models in general.

General 2HDM Potential

$$V(\phi_1,\phi_2) = \lambda_1\left(|\phi_1|^2 - v_1^2\right)^2 + \lambda_2\left(|\phi_2|^2 - v_2^2\right)^2$$

$$+\lambda_3\left[\left(|\phi_1|^2 - v_1^2\right) + \left(|\phi_2|^2 - v_2^2\right)\right]^2$$

$$+\lambda_4\left[|\phi_1|^2|\phi_2|^2 - \left(\phi_1^{*T}\phi_2\right)\left(\phi_2^{*T}\phi_1\right)\right]$$

All λ are real.

$$+\lambda_5\left[\mathrm{Re}\left(\phi_1^{*T}\phi_2\right) - v_1 v_2\cos\xi\right]^2$$

$$+\lambda_6\left[\mathrm{Im}\left(\phi_1^{*T}\phi_2\right) - v_1 v_2\sin\xi\right]^2$$

From “Higgs Hunter’s guide”.

$$\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix}_1 = \begin{pmatrix}0\\ v_1\end{pmatrix}\frac{1}{\sqrt{2}}\ ;\quad \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix}_2 = \begin{pmatrix}0\\ v_2 e^{i\xi}\end{pmatrix}\frac{1}{\sqrt{2}}\ ;\quad \tan\beta = \frac{v_2}{v_1}$$

A slightly less opaque notation:

$$
\begin{aligned}
V(\Phi) = \sum_{i=1}^{2} (-\mu_i^2 |\Phi_i|^2 + \lambda_i^2 |\Phi_i|^4) \\
+ \lambda_3 |\Phi_1|^2 |\Phi_2|^2 \\
+ \lambda_4 |\Phi_1^\dagger \Phi_2|^2 \\
+ \frac{1}{2} [\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_5^* (\Phi_2^\dagger \Phi_1)^2]
\end{aligned}
$$

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I will stick with Higgs Hunter's guide notation as that's my primary reference.

CP violation

- In principle, we have the freedom to choose the two vevs to have an arbitrary phase with regard to each other.

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \frac{1}{\sqrt{2}} \qquad \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}_2 = \begin{pmatrix} 0 \\ v_2 e^{i\xi} \end{pmatrix} \frac{1}{\sqrt{2}}$$

- If on top, $\lambda_5 \neq \lambda_6$ then we have CP violation in the higgs sector.
- In the interest of time, we’re going to ignore this. See Higgs Hunter’s guide for details.

Vevs, G_F, and m_W

- For Standard Model (H&M Exercise 15.2)

$$m_W = \frac{1}{2} g v$$

$$G_F = \frac{\sqrt{2}}{v^2}$$

- For 2HDM this stays the same, except for:

$$(v_1^2 + v_2^2) \equiv v^2 \approx 246 GeV$$

Higgs Boson Spectroscopy

- One Charged Higgs with mass:

$$m_{H^{\pm}} = \sqrt{\lambda_4 (v_1^2 + v_2^2)}$$

- One CP-odd neutral Higgs with mass:

$$m_{A^0} = \sqrt{\lambda_6 (v_1^2 + v_2^2)}$$

- And two CP-even higgs that mix.

$$M = \begin{pmatrix} 4v_1^2\left(\lambda_1 + \lambda_3\right) + v_2^2\lambda_5 & \left(4\lambda_3 + \lambda_5\right)v_1 v_2 \\ \left(4\lambda_3 + \lambda_5\right)v_1 v_2 & 4v_2^2\left(\lambda_2 + \lambda_3\right) + v_1^2\lambda_5 \end{pmatrix}$$

Free Parameters in 2HDM

- Four higgs masses
- The ratio of vevs: $\tan\beta = \frac{v_2}{v_1}$
- and a higgs mixing angle, α, for the neutral CP-even higgs states to mix.

Some guiding principles

- Charged higgs mass can be very large, to limit loop contributions to precision data. (Replace a W^+ with a H^+ wherever you want.)
- A_0, CP-odd higgs, doesn't couple to the Gauge bosons, i.e. no A_0WW nor A_0ZZ coupling. It's mass can also be very large.
- Of the remaining neutral CP-even h,H, one must be reasonably low mass to meet the m_h constraints from indirect measurements.

$$m_{H,h}^2 = \frac{1}{2}\left[M_{11} + M_{22} \pm \sqrt{(M_{11} - M_{22})^2 + 4M_{12}^2} \right]$$

$$m_{H,h}^{2}=\frac{1}{2}\left[M_{11}+M_{22}\pm\sqrt{(M_{11}-M_{22})^{2}+4M_{12}^{2}}\right]$$

If $M_{11} >> M_{22}$ and $M_{11} >> M_{12}$, then:

$m_H^2 = M_{11}$ >> $m_h^2 = M_{22} / 2$

This is easy to arrange via appropriate choice of λ_i and without restricting the choice of $\tan\beta = v_2 / v_1$

$$M=\begin{pmatrix} 4v_1^2\left(\lambda_1+\lambda_3\right)+v_2^2\lambda_5 & \left(4\lambda_3+\lambda_5\right)v_1v_2 \\ \left(4\lambda_3+\lambda_5\right)v_1v_2 & 4v_2^2\left(\lambda_2+\lambda_3\right)+v_1^2\lambda_5 \end{pmatrix}$$

Categorizing 2HDM

- I only Φ_2 couples to fermions
- II Φ_1 couples to down-type, Φ_2 to up-type fermions
- III Φ_1 couples to down quarks, Φ_2 to up quarks and down leptons
- IV Φ_1 couples to quarks, Φ_2 to leptons

Options III and IV lead to FCNC and are thus not studied any more in any significant way.

Option I leads to “fermiphobic” higgs,
i.e. higgs that only couples to gauge bosons.

MSSM is a special case of Option II.

Comparing Type I & II

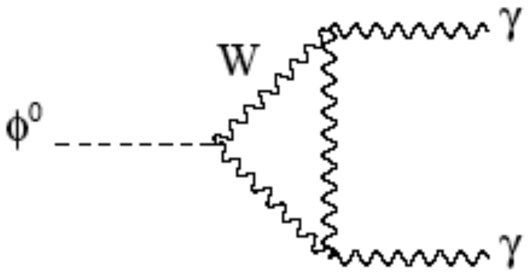
	Φ	$\frac{g_{\Phi u\bar{u}}}{g_f}$	$\frac{g_{\Phi d\bar{d}}}{g_f}$	$\frac{g_{\Phi VV}}{g_V}$	$\frac{g_{\Phi ZA}}{g_V}$
Type I	h	$-\frac{\cos\alpha}{\sin\beta}$	$-\frac{\cos\alpha}{\sin\beta}$	$\sin(\beta-\alpha)$	$-\frac{1}{2}i\cos(\beta-\alpha)$
	H	$-\frac{\sin\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\sin\beta}$	$\cos(\beta-\alpha)$	$\frac{1}{2}i\sin(\beta-\alpha)$
	A	$-i\gamma_5\cot\beta$	$i\gamma_5\cot\beta$	0	0
Type II	h	$-\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\cos\beta}$	$\sin(\beta-\alpha)$	$-\frac{1}{2}i\cos(\beta-\alpha)$
	H	$-\frac{\sin\alpha}{\sin\beta}$	$-\frac{\cos\alpha}{\cos\beta}$	$\cos(\beta-\alpha)$	$\frac{1}{2}i\sin(\beta-\alpha)$
	A	$-i\gamma_5\cot\beta$	$-i\gamma_5\tan\beta$	0	0

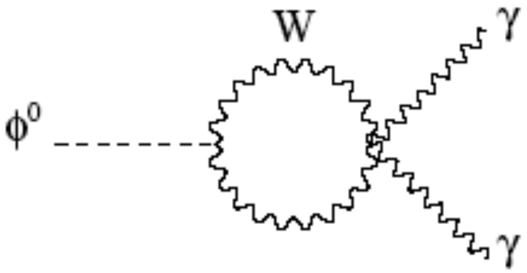
Up and down fermions couple the same way in type I models. We can thus eliminate fermion coupling to m_h entirely while at the same time keeping boson coupling maximal.

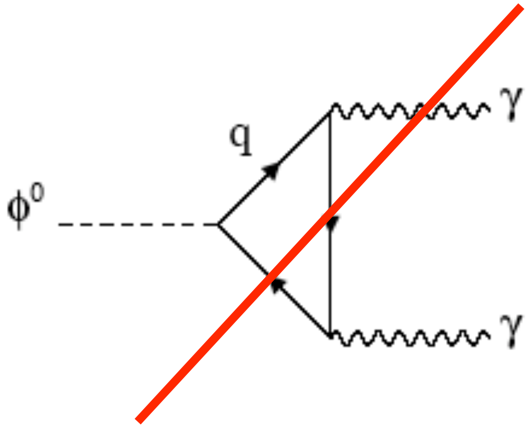
=> $\cos\alpha = 0$ while $\sin(\beta-\alpha)=1$.

Type-I: Fermiphobic Higgs

- Example higgs to di-photon decay:



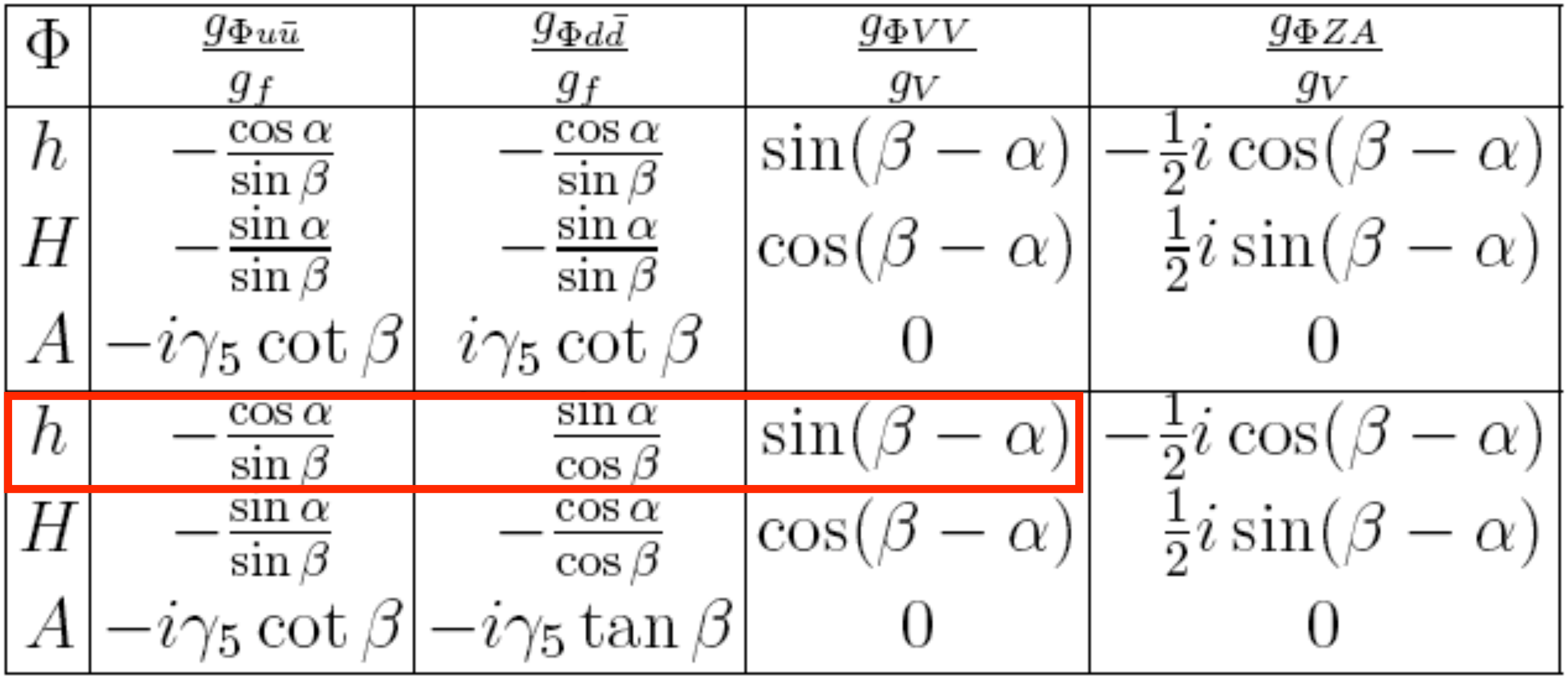




This is not allowed.

Leave it to you as an exercise to think through what happens to the rest of higgs phenomenology in fermiphobic models.

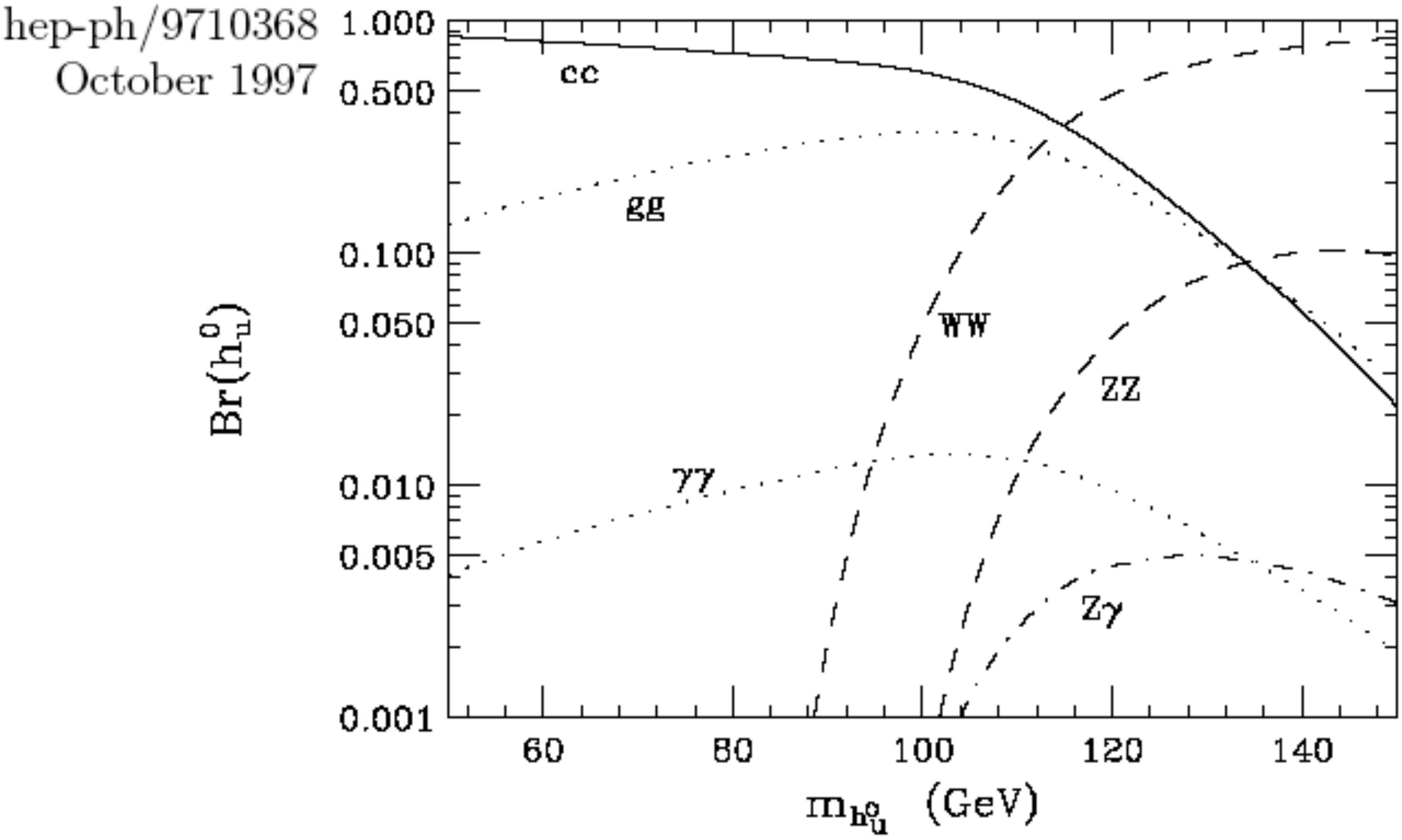
Comparing Type I & II



	Φ	$\frac{g_{\Phi u\bar{u}}}{g_f}$	$\frac{g_{\Phi d\bar{d}}}{g_f}$	$\frac{g_{\Phi VV}}{g_V}$	$\frac{g_{\Phi ZA}}{g_V}$
Type I	h	$-\frac{\cos\alpha}{\sin\beta}$	$-\frac{\cos\alpha}{\sin\beta}$	$\sin(\beta-\alpha)$	$-\frac{1}{2}i\cos(\beta-\alpha)$
	H	$-\frac{\sin\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\sin\beta}$	$\cos(\beta-\alpha)$	$\frac{1}{2}i\sin(\beta-\alpha)$
	A	$-i\gamma_5\cot\beta$	$i\gamma_5\cot\beta$	0	0
Type II	h	$-\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\cos\beta}$	$\sin(\beta-\alpha)$	$-\frac{1}{2}i\cos(\beta-\alpha)$
	H	$-\frac{\sin\alpha}{\sin\beta}$	$-\frac{\cos\alpha}{\cos\beta}$	$\cos(\beta-\alpha)$	$\frac{1}{2}i\sin(\beta-\alpha)$
	A	$-i\gamma_5\cot\beta$	$-i\gamma_5\tan\beta$	0	0

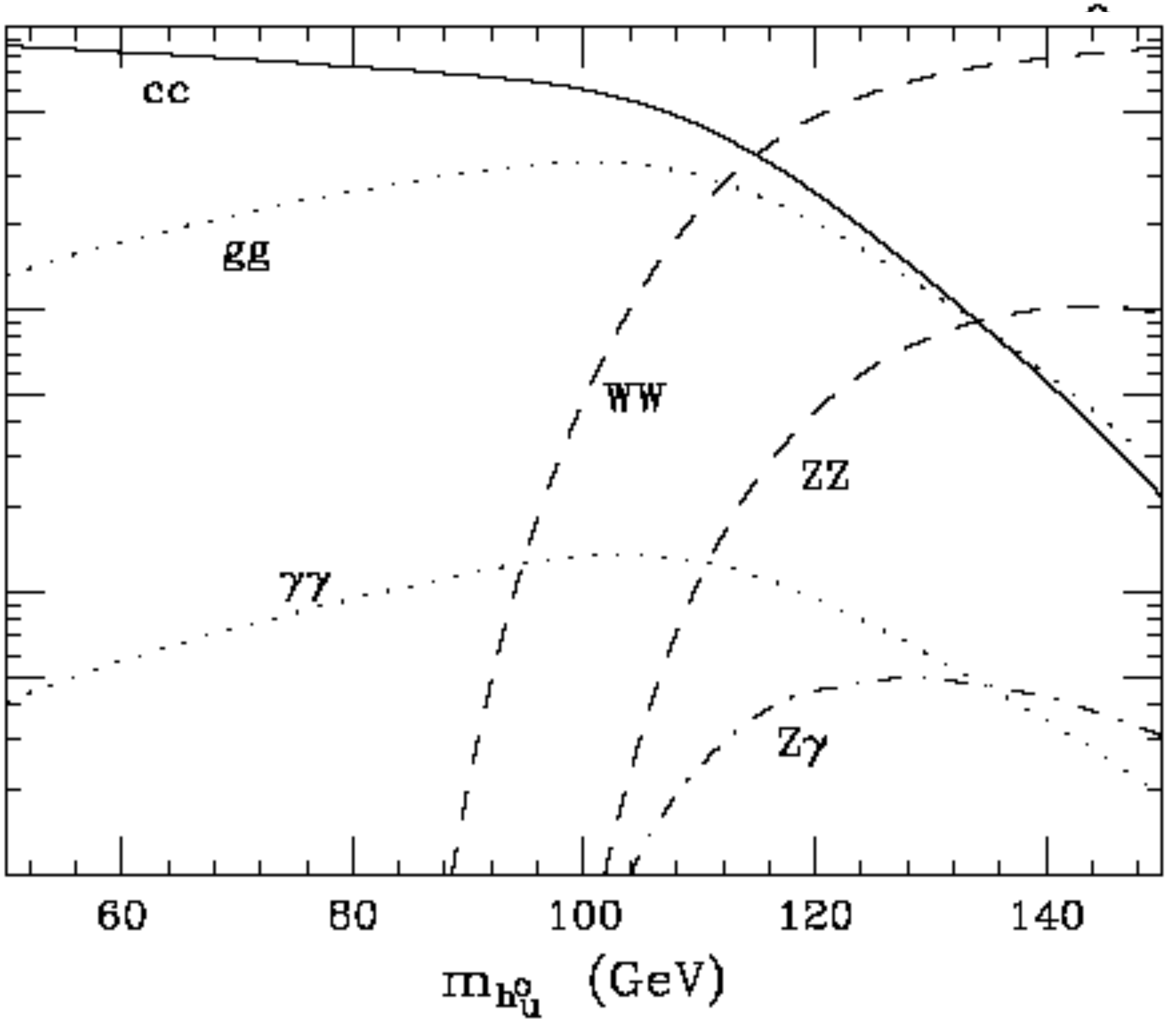
Up and down fermions couple differently in type II models.
We can thus eliminate down quark coupling to m_h entirely while at the same time keeping boson coupling maximal.

=> sin α = 0 while sin(β- α)=1.

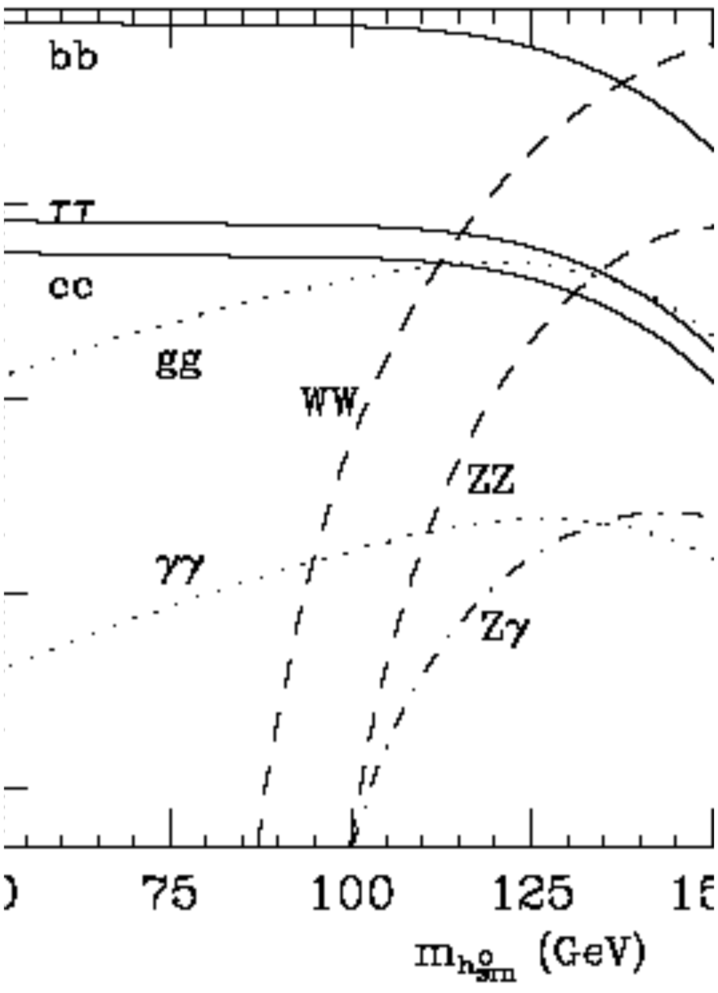


BR’s for low mass m_h , i.e. below WW threshold.
Partial width to bb and tautau are turned off as promised.

m_h~110GeV has 50% BR to WW



No down-quark couplings



SM

Higgs in MSSM

- MSSM is basically a type II 2HDM, but with a variety of constraints among the parameters defining the model.
- The details of these are well beyond the scope of this lecture.
- Instead, we will simply be descriptive, and focus on the few statements that can be made simply.
- As reference, we use the TASI06 lectures by Rainwater.

MSSM Higgs

- Assuming no CP violation, it is convenient to look at the masses of the other 3 higgs states as a function of m_A , the mass of the CP-odd higgs.
- At tree level:

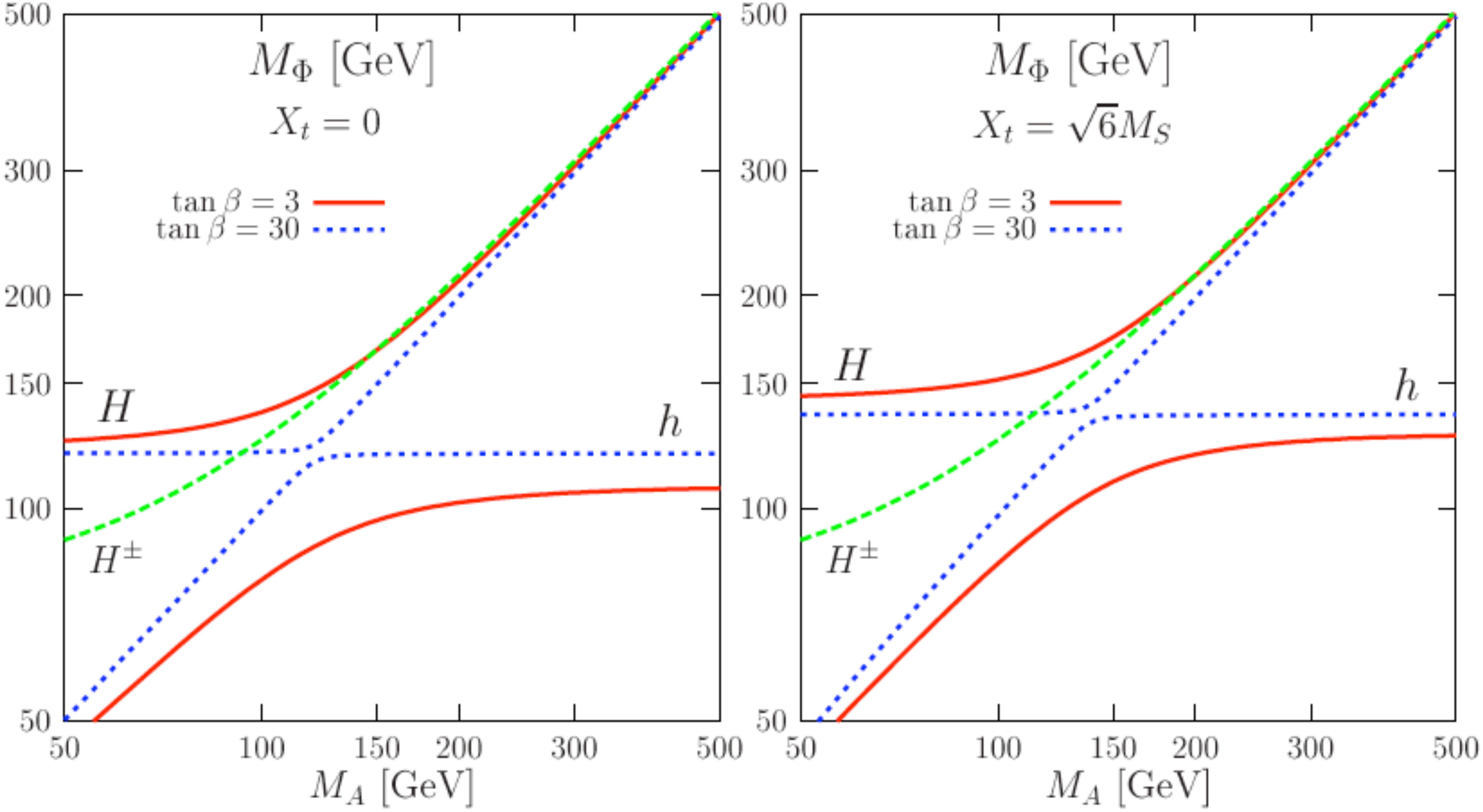
$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

$$M_{H,h}^2 = \frac{1}{2}\left(M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 + 4M_A^2 M_Z^2 \sin^2(2\beta)}\right)$$

This would imply that $m_h < m_Z$ for large m_A , which is of course already ruled out by experiment.

Loop corrections proportional to m_t^2 increase m_h somewhat.

The details depend on mixing in the stop sector, and v_2 / v_1



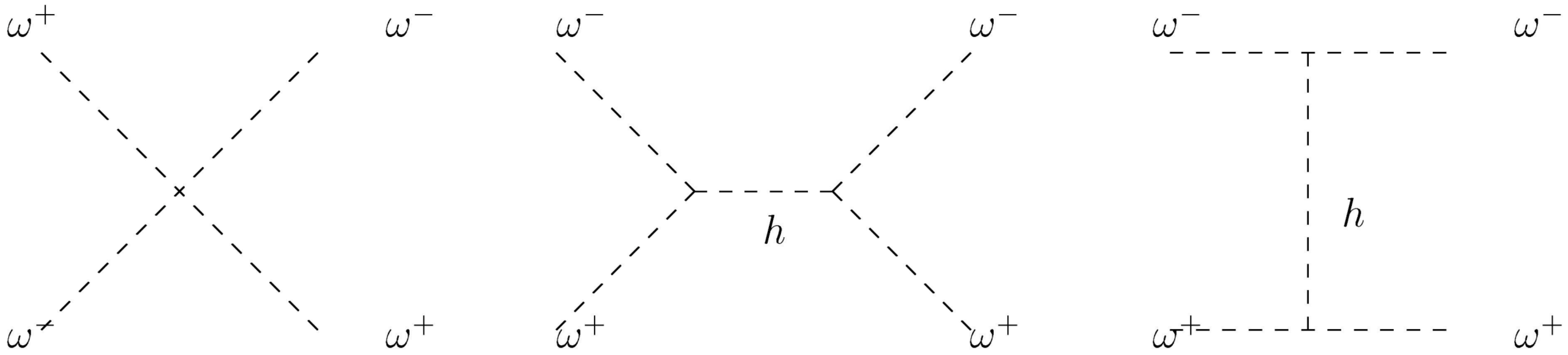
m_h < 140GeV in all cases, and getting close to the limit requires large v_2 / v_1 or large masses for all other higgs.

Conclusions from 2HDM

- All the existing standard model constraints can be met.
- There are 3 additional higgs bosons, that all three of them can be so high in mass that we won’t find them easily.
- At the same time, both the production and decay properties of the light higgs can be altered such as to affect the higgs hunting significantly.

Aside or backup

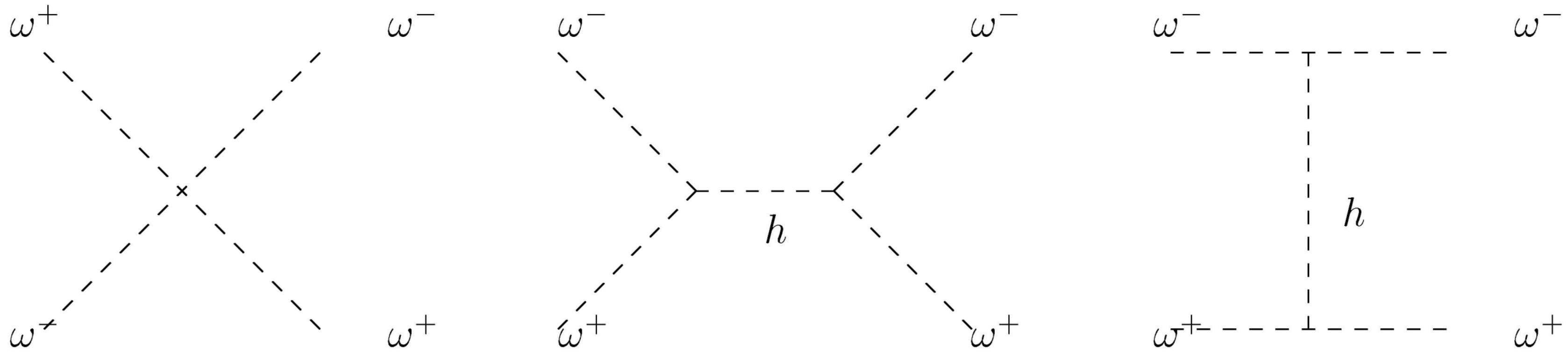
SM & WW scattering



Without the higgs, we get M $\propto$ s / m_W^2 for large s.
This violates unitarity, as previously discussed.
(see H&M 15.6 and homework)

In SM, higgs, and the hWW vertex of a igm_w resolve that.
(see H&M Exercise 15.5)

2HDM & WW scattering



The same cancellation is still satisfied if: $(v_1^2 + v_2^2) \equiv v^2$

G_F now relates to the sum of the squares of the vevs.
As a result, the total cross section for higgs associate production is easy to suppress, but difficult to enhance.