Identifying extended Higgs models at the LHC

with

V. Barger, H. E. Logan

arxiv:0902.0170

Gabe Shaughnessy

Argonne National Laboratory
Northwestern University

Collider Physics 2009

May 21, 2009

The Higgs and the LHC

- One of the first goals of the LHC is to discover the Higgs boson
- Higgs coupling measurements are key to identifying a true Higgs boson (i.e. W/Z couplings)
- Many models contain Higgs sector that includes more Higgs states than in SM
- If we only see one Higgs state, can we expect to differentiate various Higgs sectors based on small deviations from SM couplings?

What we assume

- Natural flavor conservation
  - Due to symmetry of model Glashow & Weinberg, PRD15, 1958 (1977); Paschos, PRD15, 1966 (1977)
  - FCNCs can be mitigated by coupling of each fermion sector $(u, d, \ell^{\pm})$ to just one Higgs doublet
- Flavor conservation motivates three general classes of models based on the number of Higgs doublets
  - One doublet, Φ_f, couples to the three fermion sectors
  - Two doublets, Φ_f, $\Phi_{f'}$, couples to the three fermion sectors in 3 combinations
  - Three distinct doublets, $\Phi_u, \Phi_d, \Phi_\ell$, couple to each fermion sector separately
- Neglect loop induced couplings: $ggh, \gamma\gamma h, Z\gamma h$
  - Many new physics states can propagate in loop. Interference can induce large shifts in effective couplings

Notation

- Define the Higgs state as a sum of neutral, CP-even components of the doublets (and singlets, when present)

$$h = \sum_i a_i \phi_i$$

where $a_i \equiv \langle h|\phi_i\rangle$ are properly normalized: $\sum_i |a_i|^2 \equiv 1$

- Define the Higgs VEV that gives masses to W/Z bosons in a similar way:

$$\phi_v = \sum_i b_i \phi_i$$

with $g_W = g_W^{SM} \langle h|\phi_v\rangle$ so that $\sum_i |b_i|^2 \equiv 1$

- Barred couplings indicate rescaling with SM coupling
  - Observables from rate measurements:

$$\bar{g}_W = g_W / g_W^{SM} = \langle h|\phi_v\rangle$$

Couplings

- The W/Z coupling can be easily written as overlap of Higgs state with VEV that gives W/Z their mass $\bar{g}_W = g_W / g_W^{SM} = \langle h | \phi_v \rangle$

$$\bar{g}_W = \langle h | \phi_i \rangle \langle \phi_i | \phi_v \rangle = \sum_i a_i b_i \qquad (\ b_i = 0 \text{ for singlets})$$

- Fermion couplings induced via Yukawa int. $\mathcal{L} = y_f \bar{f}_R \Phi_f^\dagger F_L + \text{h.c.}$ so that $m_f = y_f b_f v_{SM} / \sqrt{2}$

$$\rightarrow g_f = y_f / \sqrt{2} \langle h | \phi_f \rangle = \frac{m_f}{v_{SM}} a_f / b_f$$

$$\rightarrow \bar{g}_f = g_f / g_f^{SM} = a_f / b_f$$

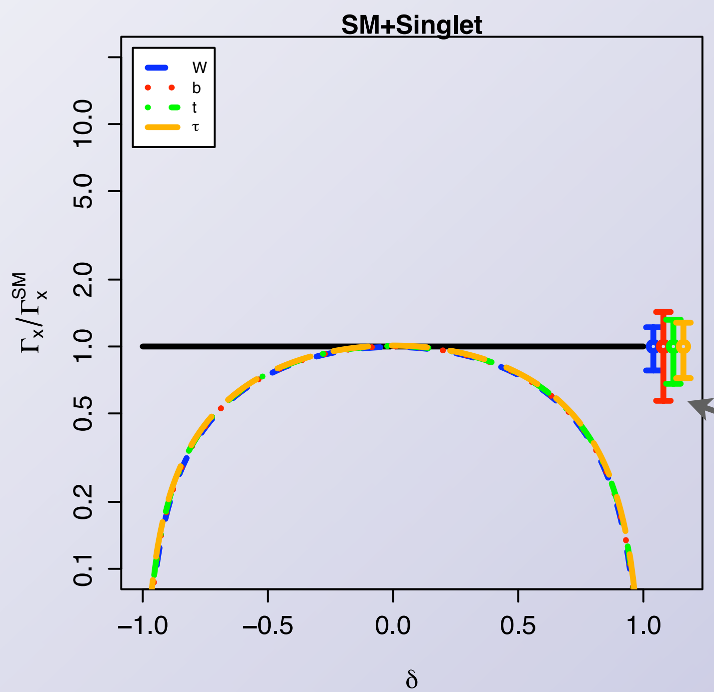
- Decoupling limit: $\bar{g}_W = \bar{g}_f = 1$

Class 1: Fermion masses from 1 Doublet

- Standard Model
- SM + 1 gauge singlet
- 2HDM-I (SM + 1 SU(2) doublet)
- 2HDM-I + 1 gauge singlet
- 2HDM-I + extra doublets

SM + 1 gauge singlet

- Simplest extension of SM - all couplings universally reduced
  - Higgs state $h = a_f \phi_f + a_s S$
  - Normalization requires $a_f = \sqrt{1-\delta^2}$ where $\delta \equiv a_s$ is a decoupling parameter



- Couplings set only by decoupling parameter:

$$\bar{g}_W = \bar{g}_f = \sqrt{1-\delta^2}$$

- No sensitivity to number of gauge singlets

Expected LHC sensitivities to W, b, t and τ for M_h=120 and 300 fb^{-1} x 2 detectors

Duhrssen, Heinemeyer, Logan, Rainwater, Weiglein, Zeppenfeld

2HDM-I (SM + 1 new Doublet)

- Only SM doublet, ϕ_f, gives masses to fermions. Both doublets, ϕ_f and ϕ_0 give masses to W/Z bosons
  - Higgs state: $h = a_f \phi_f + a_0 \phi_0$

- Two parameters: $\tan\beta \equiv b_f / b_0 \,, \quad \delta \equiv \cos(\beta - \alpha) = a_f b_0 - a_0 b_f$

- W/Z Couplings:

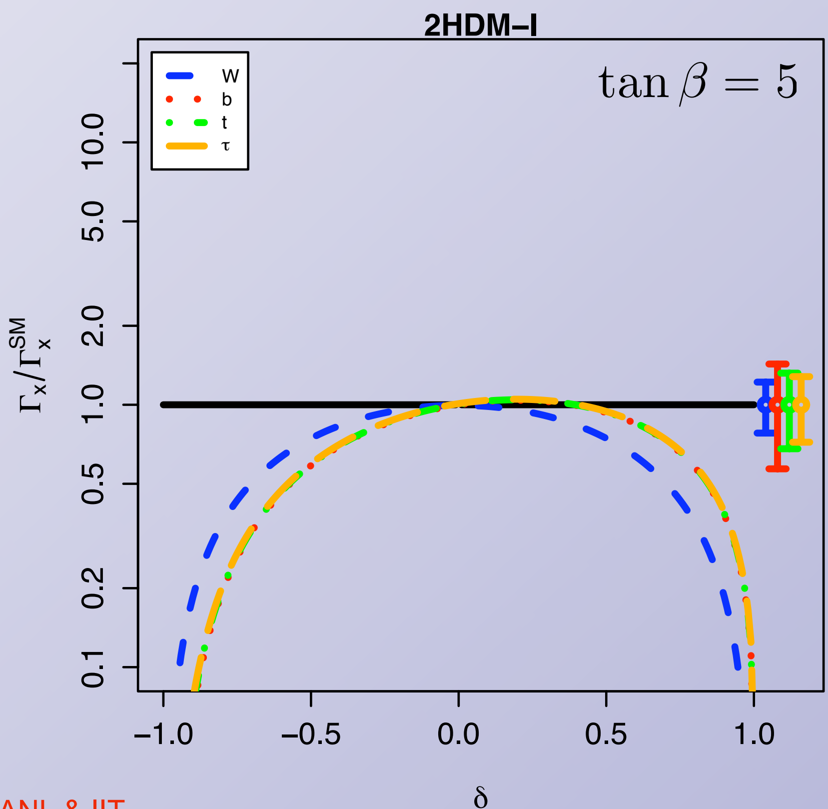
$$\bar{g}_W = a_f b_f + a_0 b_0 = \sqrt{1 - \delta^2}$$

- Fermion couplings:

$$\bar{g}_f = \sqrt{1 - \delta^2} + \delta \cot\beta$$

- Generic features:

$$\bar{g}_W \neq \bar{g}_f \equiv \bar{g}_u = \bar{g}_d = \bar{g}_\ell$$



Class 2: Fermion masses from 2 Doublets

- Classic 2HDM-II model (think SUSY Higgs sector)
- Flipped 2HDM
- Lepton-specific 2HDM
- Free to add SU(2) doublet and singlet scalars for more extensions

2HDM-II

- Masses for up fermions given by ϕ_u and down fermions by ϕ_d both contribute to W/Z masses
  - Higgs state: $h = a_u\phi_u + a_d\phi_d$

- Two parameters: $\tan\beta \equiv b_u/b_d\,, \quad \delta \equiv \cos(\beta-\alpha) = a_u b_d - a_d b_u$

- W/Z Couplings: $\bar{g}_W = a_u b_u + a_d b_d = \sqrt{1-\delta^2}$

- Fermion couplings:

$$\bar{g}_u = \sqrt{1-\delta^2} + \delta\cot\beta$$

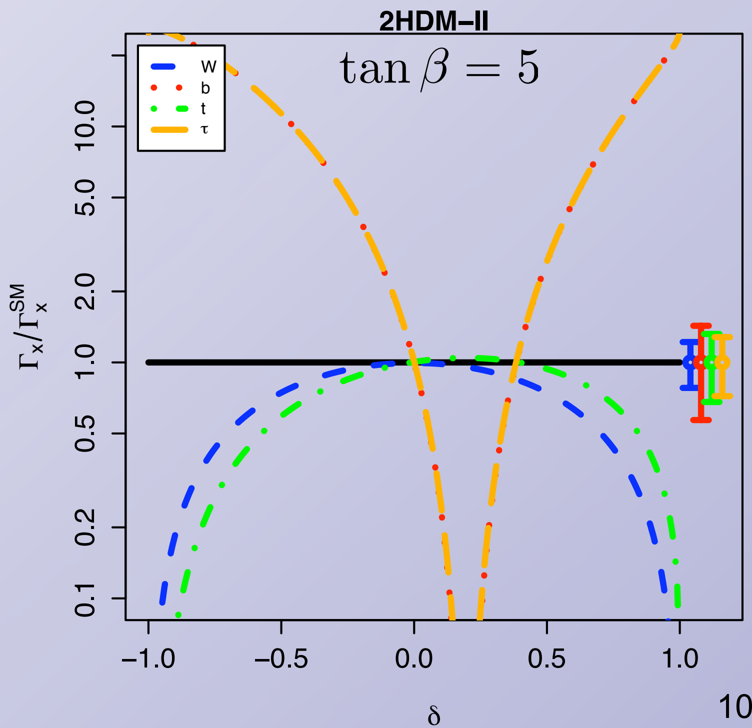
$$\bar{g}_d = \bar{g}_\ell = \sqrt{1-\delta^2} - \delta\tan\beta$$

- Generic features:

$$\bar{g}_W \neq \bar{g}_u \neq \bar{g}_d = \bar{g}_\ell$$

- Pattern relation:

$$P_{ud} = \bar{g}_W(\bar{g}_u + \bar{g}_d) - \bar{g}_u\bar{g}_d = 1$$



MSSM

- At tree-level, MSSM is 2HDM-II, but loop induced couplings allows fermions to couple to “wrong” Higgs - Extended to Type-III 2HDM
  - Effect is dominant on bottom coupling with large $\tan\beta$:

$$-\mathcal{L}_{\rm eff} = \epsilon_{ij} h_b \bar{b}_R H_d^i Q_L^j + \Delta h_b \bar{b}_R Q_L^k H_u^{k*} + \text{h.c.},$$

$$m_b = \frac{h_b v_d}{\sqrt{2}} + \frac{\Delta h_b v_u}{\sqrt{2}} = \frac{h_b v_{SM}\cos\beta}{\sqrt{2}}\left(1 + \frac{\Delta h_b \tan\beta}{h_b}\right) \equiv \frac{h_b v_{SM}\cos\beta}{\sqrt{2}}\left(1+\Delta_b\right).$$

- Essentially a shifted coupling only for bottom-quarks:

$$\bar{g}_b = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\frac{1-\cot^2\beta\,\Delta_b}{1+\Delta_b}.$$

- Extraction of Δ_b possible: $\Delta_b = \frac{\bar{g}_b - \bar{g}_\ell}{\bar{g}_u - \bar{g}_b}.$

- Patter relations shift from 2HDM-II

$$P_{u\ell} \equiv \bar{g}_W(\bar{g}_u + \bar{g}_\ell) - \bar{g}_u\bar{g}_\ell = 1.$$

$$P_{ud} \equiv \bar{g}_W(\bar{g}_u + \bar{g}_d) - \bar{g}_u\bar{g}_d = 1 - \cos^2(\beta-\alpha)\frac{\Delta_b(1+\cot^2\beta)}{1+\Delta_b}.$$

Lepton-specific 2HDM

- Masses for quarks given by ϕ_q and leptons by ϕ_ℓ both contribute to W/Z masses
  - Higgs state: $h = a_q\phi_q + a_\ell\phi_\ell$

See talks by B. Thomas and H.S. Goh

- Two parameters: $\tan\beta \equiv b_q/b_\ell$, $\delta \equiv \cos(\beta-\alpha) = a_q b_\ell - a_\ell b_q$

- W/Z Couplings: $\bar{g}_W = a_q b_q + a_\ell b_\ell = \sqrt{1-\delta^2}$

- Fermion couplings:

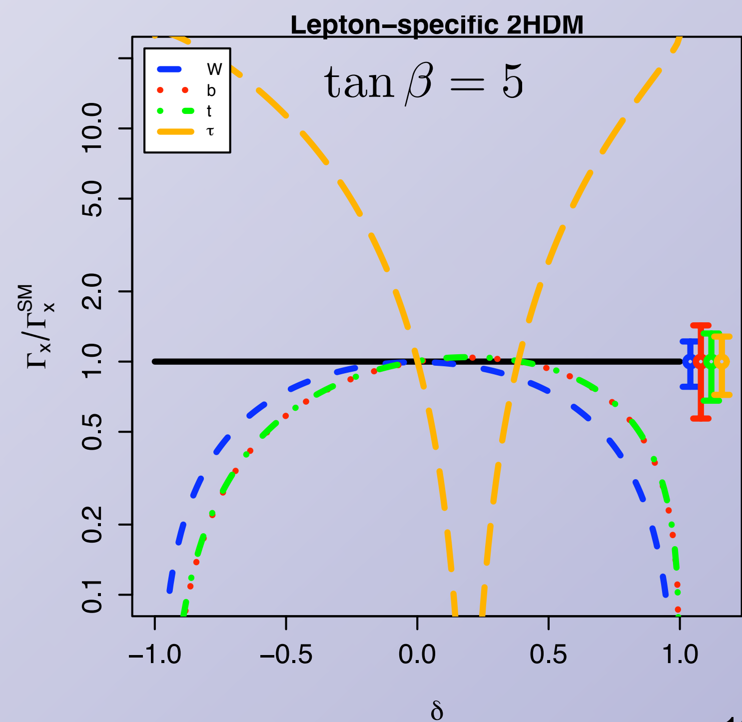
$$\bar{g}_q = \sqrt{1-\delta^2} + \delta\cot\beta$$
$$\bar{g}_\ell = \sqrt{1-\delta^2} - \delta\tan\beta$$

- Generic features:

$$\bar{g}_W \neq \bar{g}_u = \bar{g}_d \neq \bar{g}_\ell$$

- Pattern relation:

$$P_{u\ell} = \bar{g}_W(\bar{g}_q + \bar{g}_\ell) - \bar{g}_q\bar{g}_\ell = 1$$



What if we include more singlets/doublets?

- Take 2HDM-II as example and add singlet:
  - Higgs state: $h = a_u \phi_u + a_d \phi_d + a_s S$
- All coupling-squareds scaled down by a common factor

$$\xi = 1 - a_s^2 \leq 1$$

- Pattern relation:

$$P_{ud} = \bar{g}_W(\bar{g}_u + \bar{g}_d) - \bar{g}_u \bar{g}_d = \xi \leq 1$$

- Add fermion-sterile doublets
  - Higgs state: $h = a_u \phi_u + a_d \phi_d + a_0 \phi_0$
  - If $\langle \phi_0 \rangle = 0$, revert to singlet case
  - If $a_0 = 0$, no mixing into extra doublet: Yukawas are enhanced

$$P_{ud} \equiv \bar{g}_W(\bar{g}_u + \bar{g}_d) - \bar{g}_u \bar{g}_d = 1 + \frac{b_0^2}{b_u^2 + b_d^2} \frac{\sin\alpha\cos\alpha}{\sin\beta\cos\beta}.$$

$$\rightarrow P_{ud} > 1 \text{ if } \sin\alpha\cos\alpha > 0$$

How can we discriminate models?

- Pattern relation helps discriminate models
- Example: Lepton-specific 2HDM + additional singlets (with $\xi \leq 1$)

$$P_{u\ell} = \bar{g}_W(\bar{g}_q + \bar{g}_\ell) - \bar{g}_q\bar{g}_\ell = \xi$$

  - Fills 3-dim space of $\bar{g}_W, \bar{g}_q, \bar{g}_\ell$ with $0 \leq P_{u\ell} \leq 1$
  - Distinct relation from other models
  - Footprint of model inhabits different regions in $\bar{g}_W, \bar{g}_u, \bar{g}_d, \bar{g}_\ell$

- Invert relations to extract the Higgs components and VEV sharing of the model (step closer to understanding model):

$$\begin{aligned} b_q &= \left[\frac{\bar{g}_W - \bar{g}_\ell}{\bar{g}_q - \bar{g}_\ell}\right]^{1/2} = \left[\frac{\xi - \bar{g}_\ell^2}{\bar{g}_q^2 - \bar{g}_\ell^2}\right]^{1/2}, \\ b_\ell &= \left[\frac{\bar{g}_W - \bar{g}_q}{\bar{g}_\ell - \bar{g}_q}\right]^{1/2} = \left[\frac{\xi - \bar{g}_q^2}{\bar{g}_\ell^2 - \bar{g}_q^2}\right]^{1/2}, \\ a_q &= b_q\bar{g}_q, \qquad a_\ell = b_\ell\bar{g}_\ell, \qquad a_s = \sqrt{1-\xi}, \end{aligned}$$

Class 3: Fermion masses from 3 Doublets

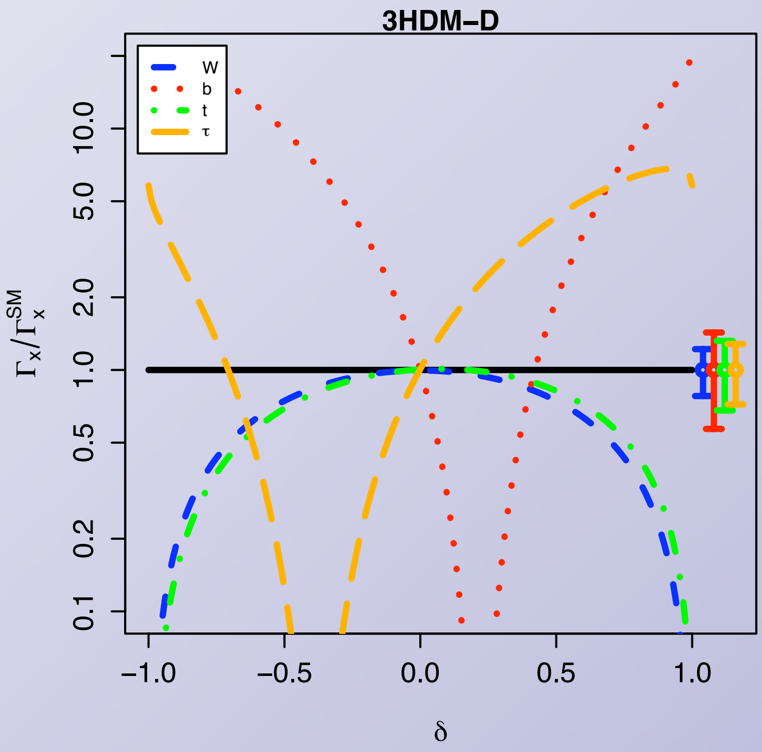
- Each doublet corresponds to each fermion sector (3HDM-D)
  - May add additional doublets and singlets that do not couple to fermions

$$b_u = \left[\frac{1-\bar{g}_W(\bar{g}_d+\bar{g}_\ell)+\bar{g}_d\bar{g}_\ell}{(\bar{g}_u-\bar{g}_d)(\bar{g}_u-\bar{g}_\ell)}\right]^{1/2},$$

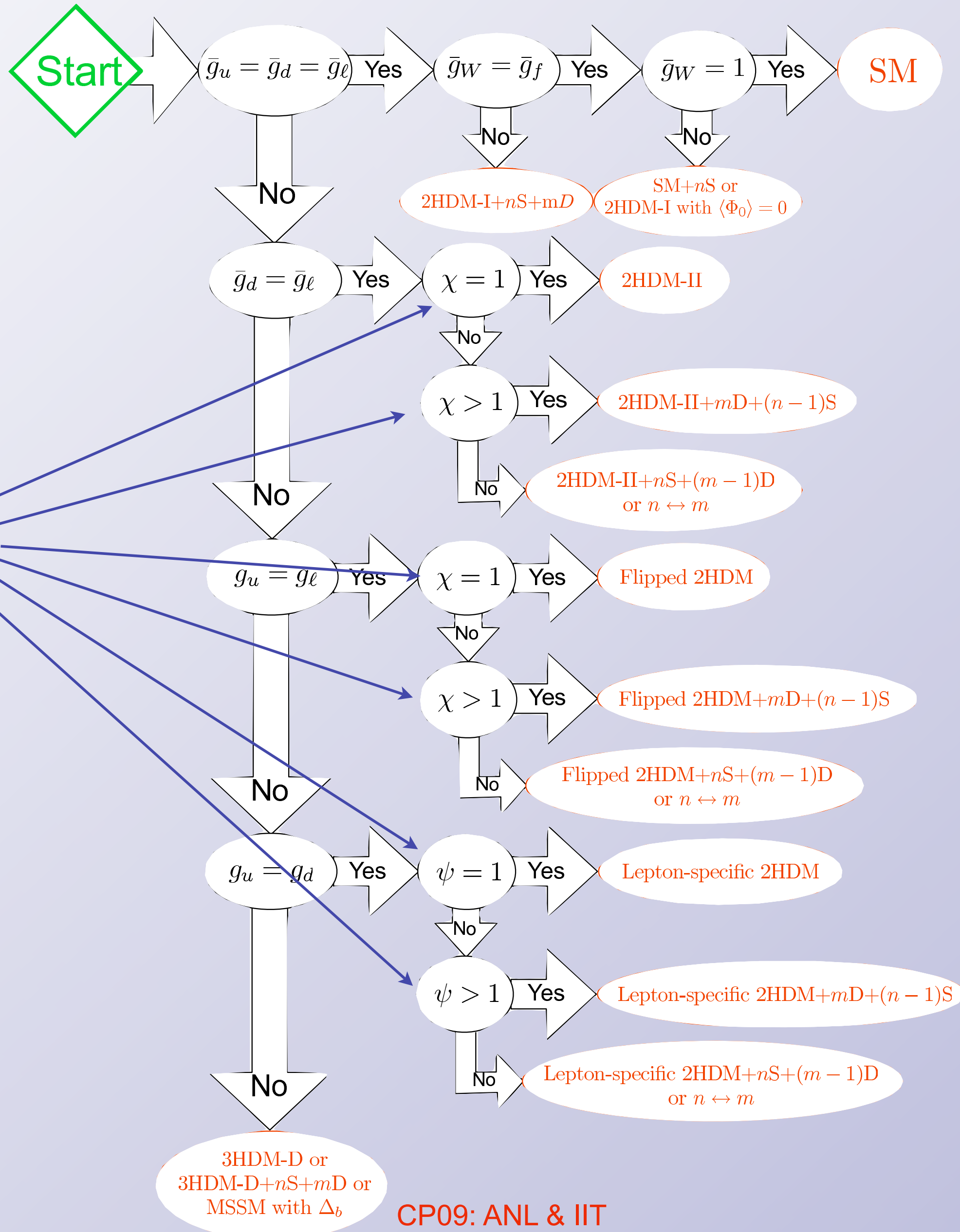
$$b_d = \left[\frac{1-\bar{g}_W(\bar{g}_u+\bar{g}_\ell)+\bar{g}_u\bar{g}_\ell}{(\bar{g}_d-\bar{g}_u)(\bar{g}_d-\bar{g}_\ell)}\right]^{1/2},$$

$$b_\ell = \left[\frac{1-\bar{g}_W(\bar{g}_u+\bar{g}_d)+\bar{g}_u\bar{g}_d}{(\bar{g}_\ell-\bar{g}_u)(\bar{g}_\ell-\bar{g}_d)}\right]^{1/2}.$$

$$a_u = b_u\bar{g}_u, \qquad a_d = b_d\bar{g}_d, \qquad a_\ell = b_\ell\bar{g}_\ell.$$



Decision tree



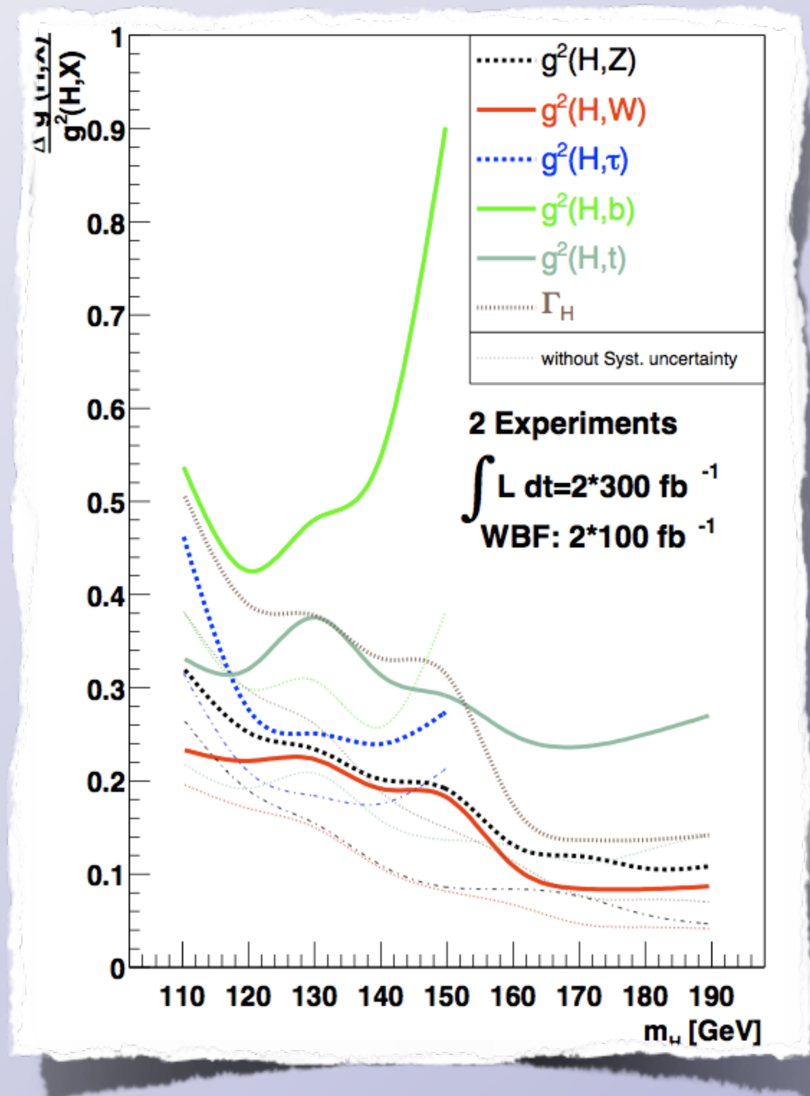
χ, ψ defined as pattern relation for specific model

How well can couplings be measured?

- Couplings can be extracted via relative production rates and branchings:

$$\overline{\sigma\ H} \times \quad H \to xx \qquad \underbrace{\sigma\ H^{SM} \frac{\Gamma_p}{\Gamma_p^{SM}}}_{\text{Production}} \underbrace{\frac{\Gamma_x}{\Gamma}}_{\text{Decay}}$$

- At LHC, couplings-squared measured to 10-20% at best



Duhrssen, Heinemeyer, Logan, Rainwater, Weiglein, Zeppenfeld

Decoupling limit - small variations

- Shifts in partial widths for expansions in small decoupling parameters

Model	Γ^h_W/Γ^{SM}_W	Γ^h_d/Γ^{SM}_d	Γ^h_u/Γ^{SM}_u	$\Gamma^h_\ell/\Gamma^{SM}_\ell$
SM	1	1	1	1
SM+S	$1-\delta^2$	$1-\delta^2$	$1-\delta^2$	$1-\delta^2$
2HDM-I	$1-\delta^2$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$
2HDM-II	$1-\delta^2$	$1-2t_\beta\delta$	$1+2\delta/t_\beta$	$1-2t_\beta\delta$
2HDM-II+S	$1-\delta^2-\epsilon^2$	$1-2t_\beta\delta-\epsilon^2$	$1+2\delta/t_\beta-\epsilon^2$	$1-2t_\beta\delta-\epsilon^2$
2HDM-II+D	$1-\delta^2$	$1-2\delta(s_\gamma t_\beta/c_\Omega+c_\gamma t_\Omega)$	$1+2\delta(s_\gamma/c_\Omega t_\beta-c_\gamma t_\Omega)$	$1-2\delta(s_\gamma t_\beta/c_\Omega+c$
Flipped 2HDM	$1-\delta^2$	$1-2t_\beta\delta$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$
Lepton-specific 2HDM	$1-\delta^2$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$	$1-2t_\beta\delta$
MSSM	$1-\delta^2$	$1-2t'_\beta\delta$	$1+2\delta/t_\beta$	$1-2t_\beta\delta$
3HDM-D	$1-\delta^2$	$1-2\delta(s_\gamma t_\beta/c_\Omega+c_\gamma t_\Omega)$	$1+2\delta(s_\gamma/c_\Omega t_\beta-c_\gamma t_\Omega)$	$1+2\delta c_\gamma/t_\Omega$

Behavior of the Higgs partial widths (equivalently couplings squared) near the decoupling limit, $|\delta| \ll 1$. For the 2HDM-II+S we also require $\epsilon^2 \ll 1$. The other parameters are defined as $t_\beta \equiv \tan\beta = v_f/v_0$ in the 2HDM-I, v_u/v_d in the 2HDM-II, flipped 2HDM, and 3HDM-D, and v_q/v_ℓ in the lepton-specific 2HDM. For the MSSM we define $t'_\beta \equiv \tan\beta' \equiv v_u(1-\cot^2\beta\,\Delta_b)/v_d(1+\Delta_b)$. For the 2HDM-II+D and 3HDM-D we also define $c_\Omega \equiv \cos\Omega = \sqrt{v_u^2+v_d^2}/v_{SM}$ and γ is the remaining mixing angle that parameterizes the state h.

Decoupling limit at the LHC

- Method, of course, fails up to uncertainties in coupling measurements

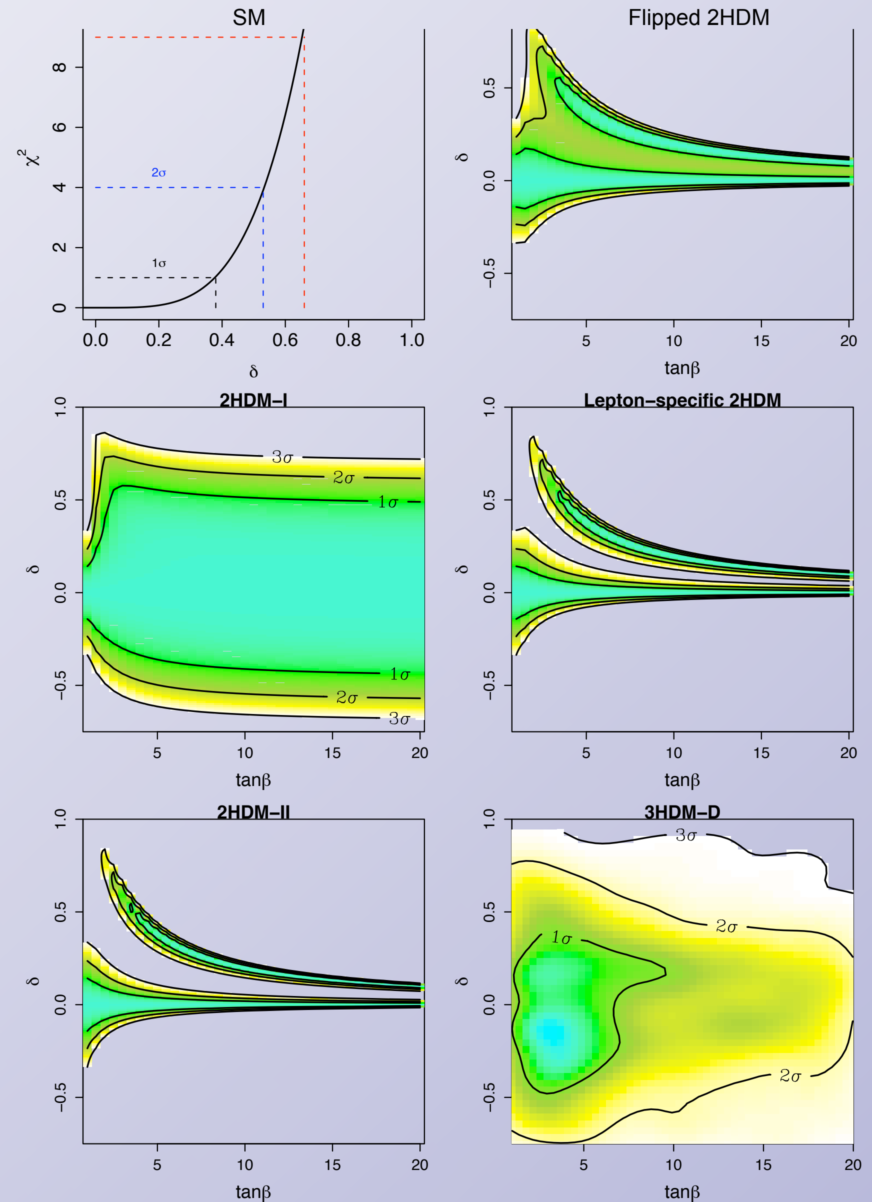
- Decoupling region defined by uncertainties at the LHC/ILC for 120 GeV Higgs mass:

	g_W^2	g_b^2	g_t^2	g_τ^2
LHC	22%	43%	32%	27%

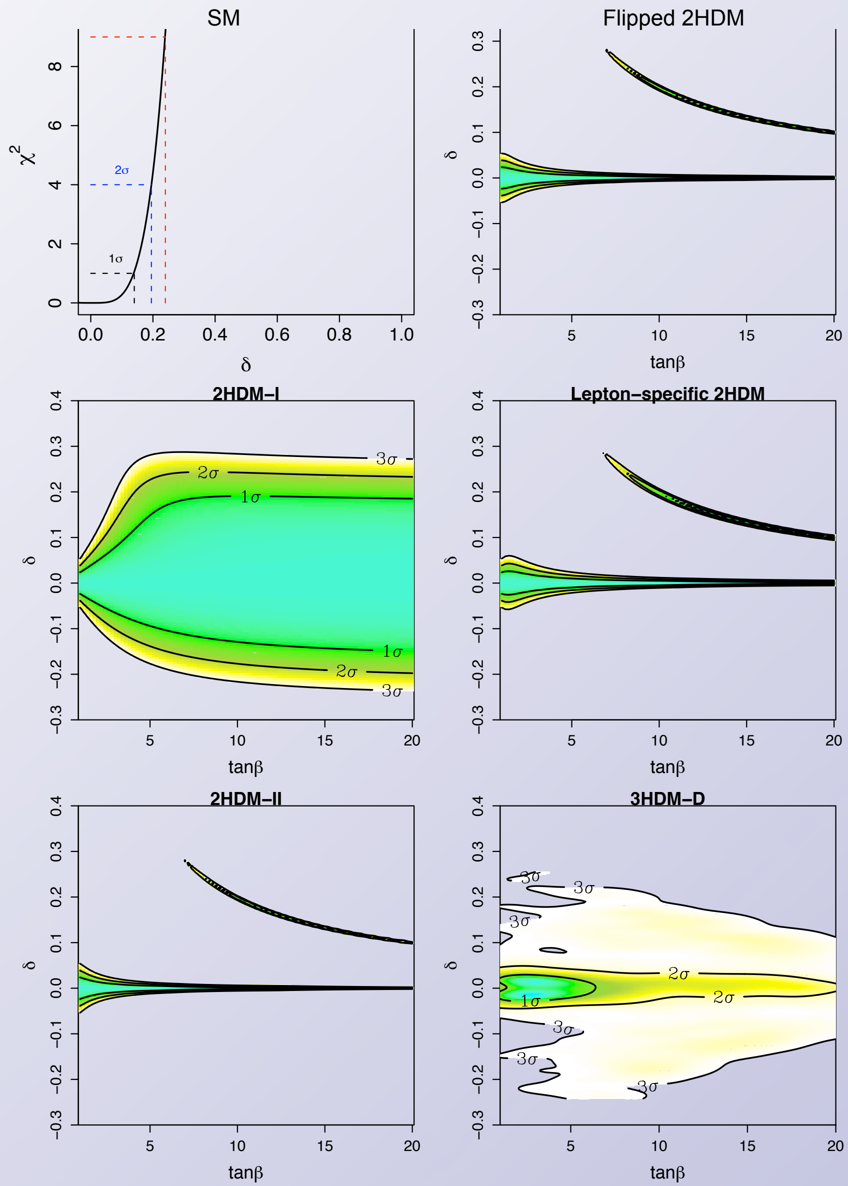
Duhrssen, Heinemeyer, Logan, Rainwater, Weiglein, Zeppenfeld.
Look at Lafaye, Plehn, Rauch, Zerwas and Duhrssen for an updated analysis

- Regions defined by χ^2:

$$\chi^2 = \sum_{i=W,b,t,\tau} \frac{(\Gamma_i - \Gamma_i^{SM})^2}{[\delta\Gamma_i^{SM}]^2}$$



Decoupling limit at the ILC



	g_W^2	g_b^2	g_t^2	g_τ^2
ILC	2.4%	4.4%	6.0%	6.6%

Djouadi

Phys. Rept. 457:1-216,2008

Summary

- Based on the coupling patterns of the Higgs with $u, d, \ell^{\pm}, W$ various Higgs doublet/singlet models can be differentiated

- Decision tree points to underlying Higgs model

- Decoupling limit defined for the LHC and ILC