Higgs ID at the LHC

with

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arxiv:0902.0170

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Pheno 2009

May 11, 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 (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 combination
  - 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. $\mathcal{L} = y_f \bar{f}_R \Phi_f^\dagger F_L + \mathrm{h.c.}$ so that $m_f = y_f b_f v_{SM} / \sqrt{2}$

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

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

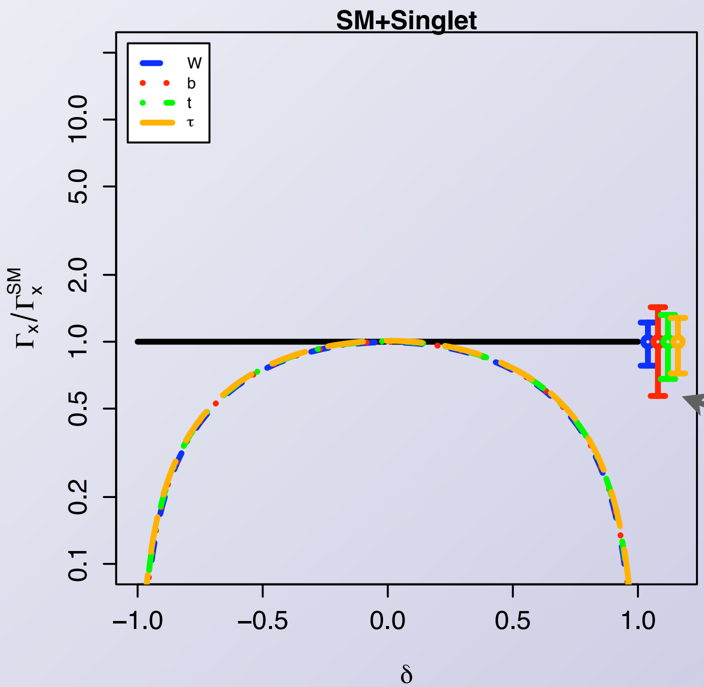
- Decoupling limit: $\bar{g}_W = \bar{g}_f = 1$

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

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:

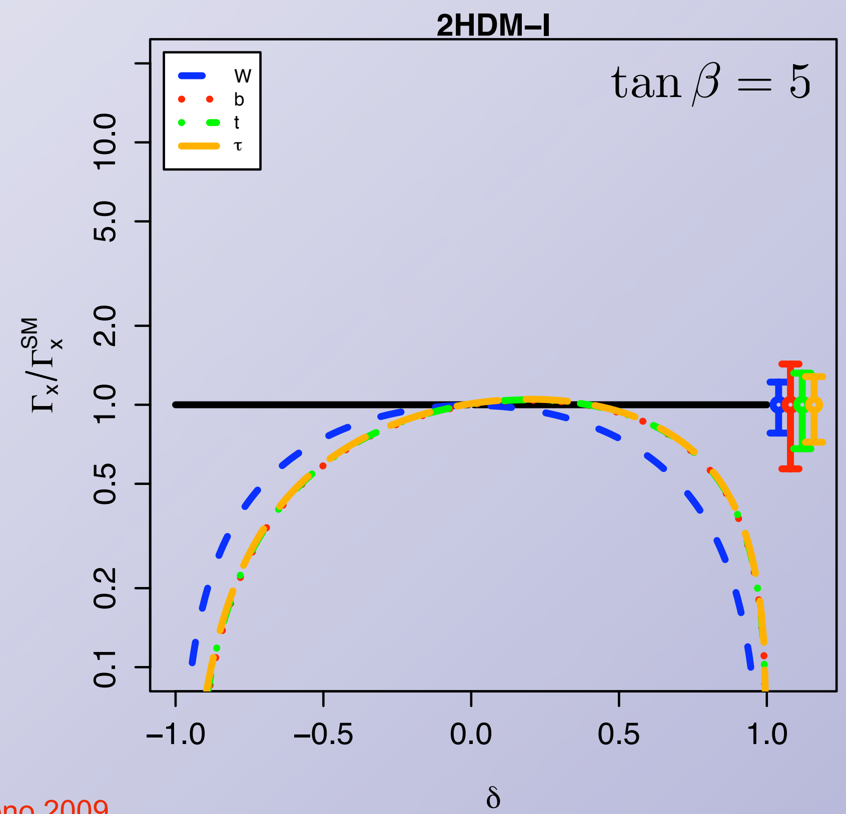
$$\bar{g}_W = a_f b_f + a_0 b_0 = \sqrt{1-\delta^2}$$

- 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:

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

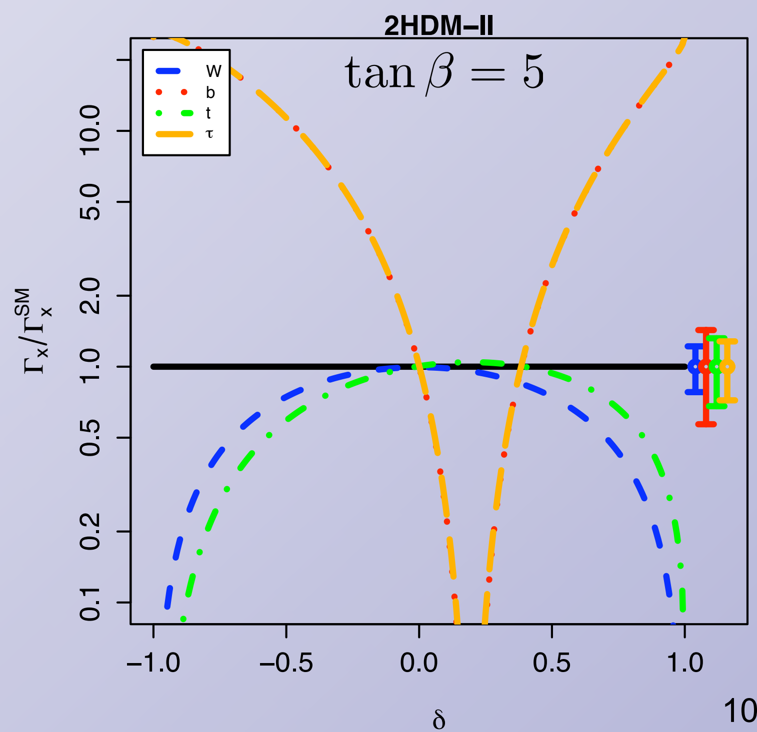
$$\bar{g}_d = \bar{g}_\ell = \sqrt{1-\delta^2} - \delta \tan\beta$$

- Generic features:

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

- Pattern relation:

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



Lepton-specific 2HDM

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

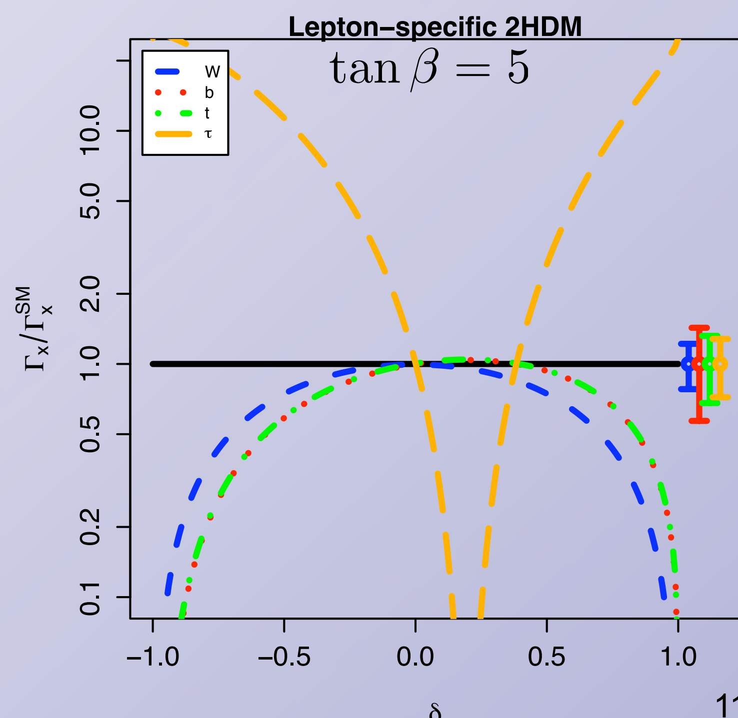
$$\bar{g}_q = \sqrt{1-\delta^2} + \delta\cot\beta$$
$$\bar{g}_\ell = \sqrt{1-\delta^2} - \delta\tan\beta$$

- Generic features:

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

- Pattern relation:

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



How can we discriminate models?

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

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

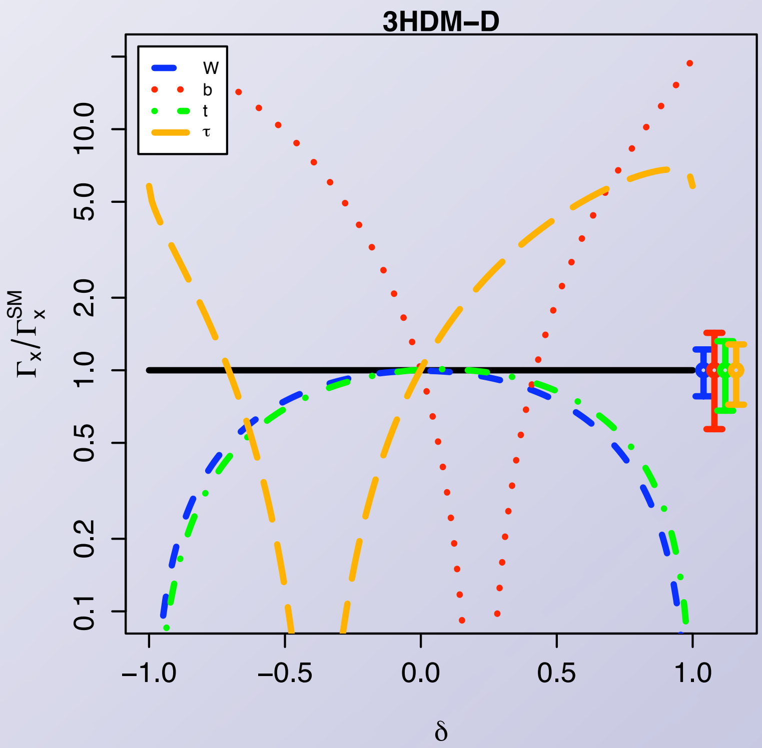
  - Fills 3-dim space of $\bar{g}_W, \bar{g}_q, \bar{g}_\ell$ with $0 \leq P_{u\ell} \leq 1$
  - Distinct relation from other models
  - Footprint of model inhabits different regions in $\bar{g}_W, \bar{g}_u, \bar{g}_d, \bar{g}_\ell$

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

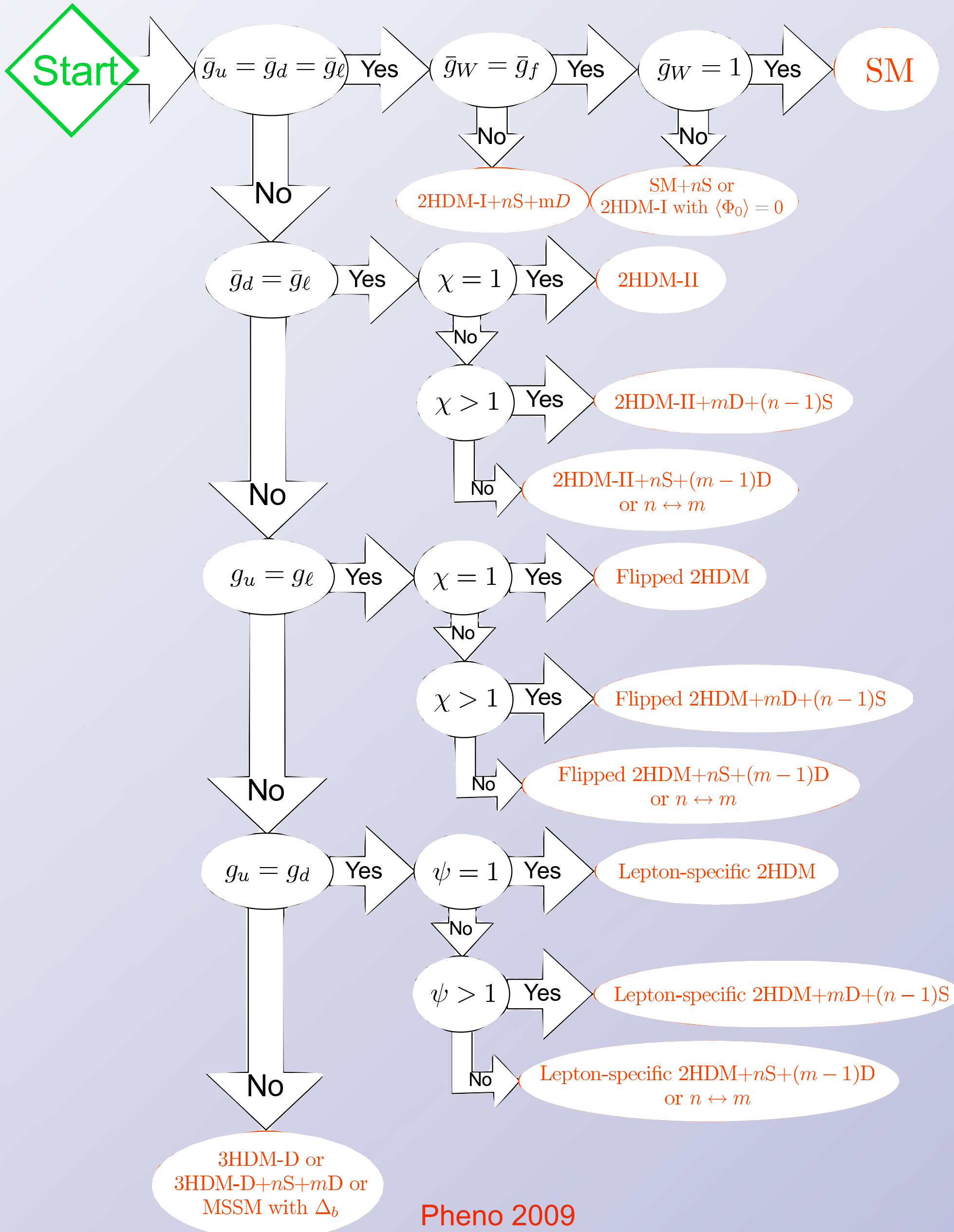
$$\begin{aligned}
b_q &= \left[\frac{\bar{g}_W - \bar{g}_\ell}{\bar{g}_q - \bar{g}_\ell}\right]^{1/2} = \left[\frac{\xi - \bar{g}_\ell^2}{\bar{g}_q^2 - \bar{g}_\ell^2}\right]^{1/2}, \\
b_\ell &= \left[\frac{\bar{g}_W - \bar{g}_q}{\bar{g}_\ell - \bar{g}_q}\right]^{1/2} = \left[\frac{\xi - \bar{g}_q^2}{\bar{g}_\ell^2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

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



Decision tree



χ, ψ defined as pattern relation for specific model

Decoupling limit at the LHC

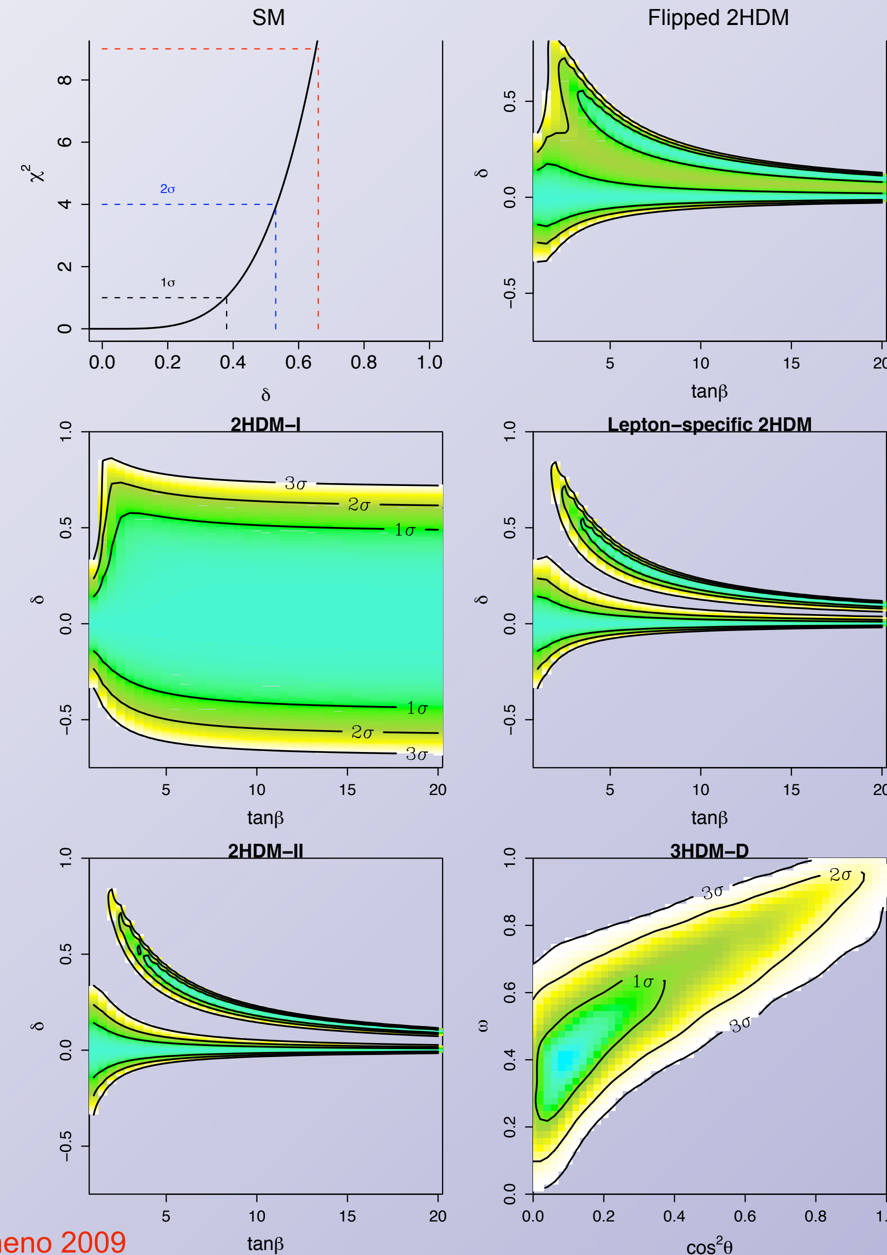
- Method, of course, fails up to uncertainties in coupling measurements

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

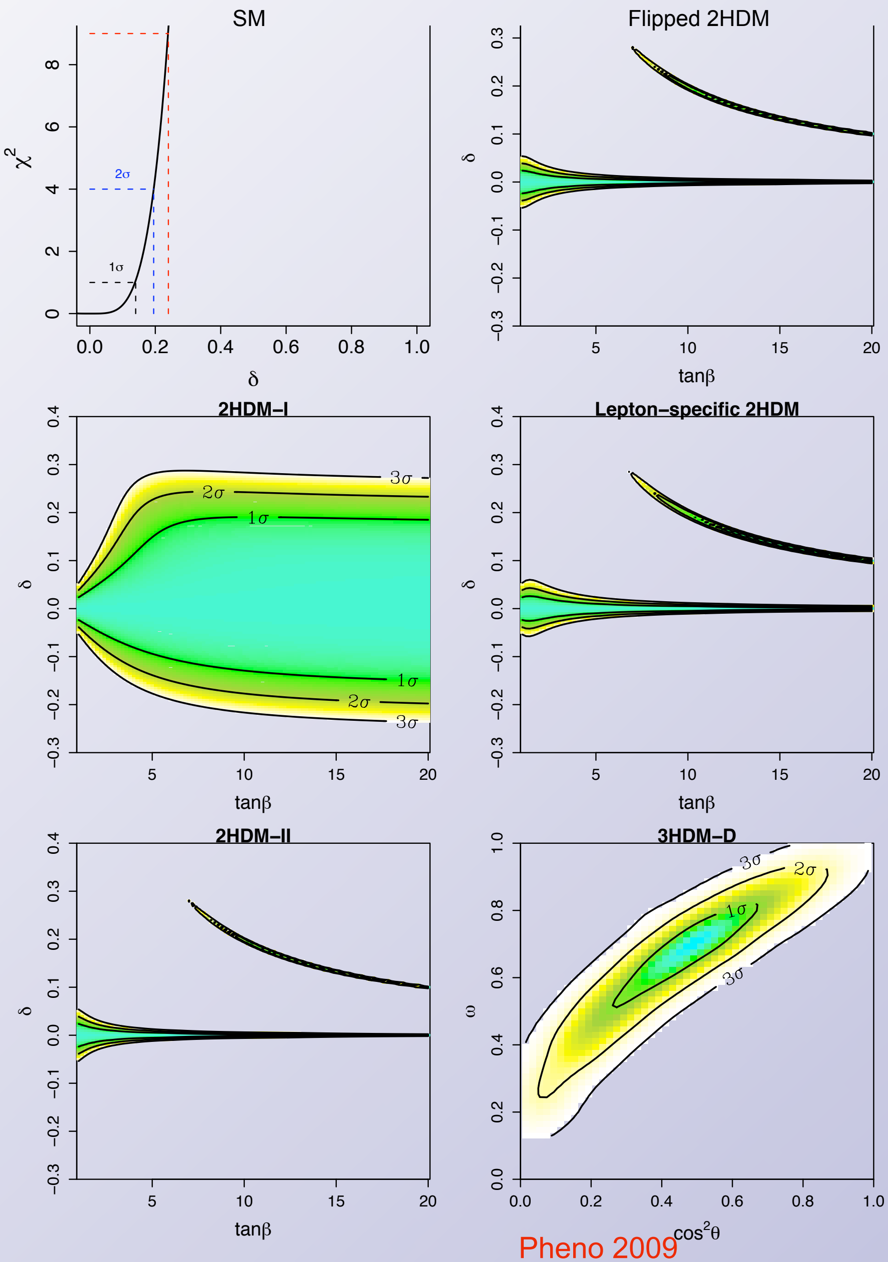
	g_W^2	g_b^2	g_t^2	g_τ^2
LHC	22%	43%	32%	27%
ILC	2.4%	4.4%	6.0%	6.6%

- Regions defined by χ^2:

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



Decoupling limit at the ILC



	g_W^2	g_b^2	g_t^2	g_τ^2
LHC	22%	43%	32%	27%
ILC	2.4%	4.4%	6.0%	6.6%

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