2HDM Update

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Snowmass NP 04/22/13

The 2hdm storyboard

- Higgs coupling measurements will continue to improve in next 2-3 years with potential to observe deviations
- Searches for high-mass Higgses in VV and di-tau will gain considerable sensitivity
- Searches for di-Higgs production should commence

Signals in any of these channels suggest extended EWSB. 2HDM are natural candidates. *The story is how to combine higgs coupling data and direct signals to hone in on 2HDM physics.*

A simplified parameter space

- General parameter space of 2HDM is vast, but there are well-motivated simplifying assumptions.
- Flavor limits suggest 2HDM should avoid new tree-level contributions to FCNC; satisfied by four discrete choices of couplings to fermions.
- Lack of large BSM CP violation suggests new sources of CP violation coupled to SM are small; motivates focusing on CP-conserving 2HDM potentials.
- Imposing these constraints leads to tractable parameter space for signals.

A simplified parameter space

If CP conservating, after EWSB there are 9 free parameters

$$
\begin{aligned}
V &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] \\
&+ \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2) + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
&+ \left[\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)\Phi_1^\dagger \Phi_2 + \text{h.c.} \right]
\end{aligned}
$$

Useful basis consists of 4 physical masses, 2 angles, 3 couplings:

$$
m_h, m_H, m_A, m_{H^\pm} \qquad \alpha \quad \tan\beta \equiv \langle \Phi_2 \rangle / \langle \Phi_1 \rangle \qquad \lambda_5, \lambda_6, \lambda_7
$$

Discrete symm. for flavor: $\lambda_{6,7} = 0$ MSSM: $\lambda_{5,6,7} = 0$

A simplified parameter space

	2HDM I	2HDM II	2HDM III	2HDM IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2

Four discrete 2HDM types.
All couplings to SM states fixed in terms of two angles!

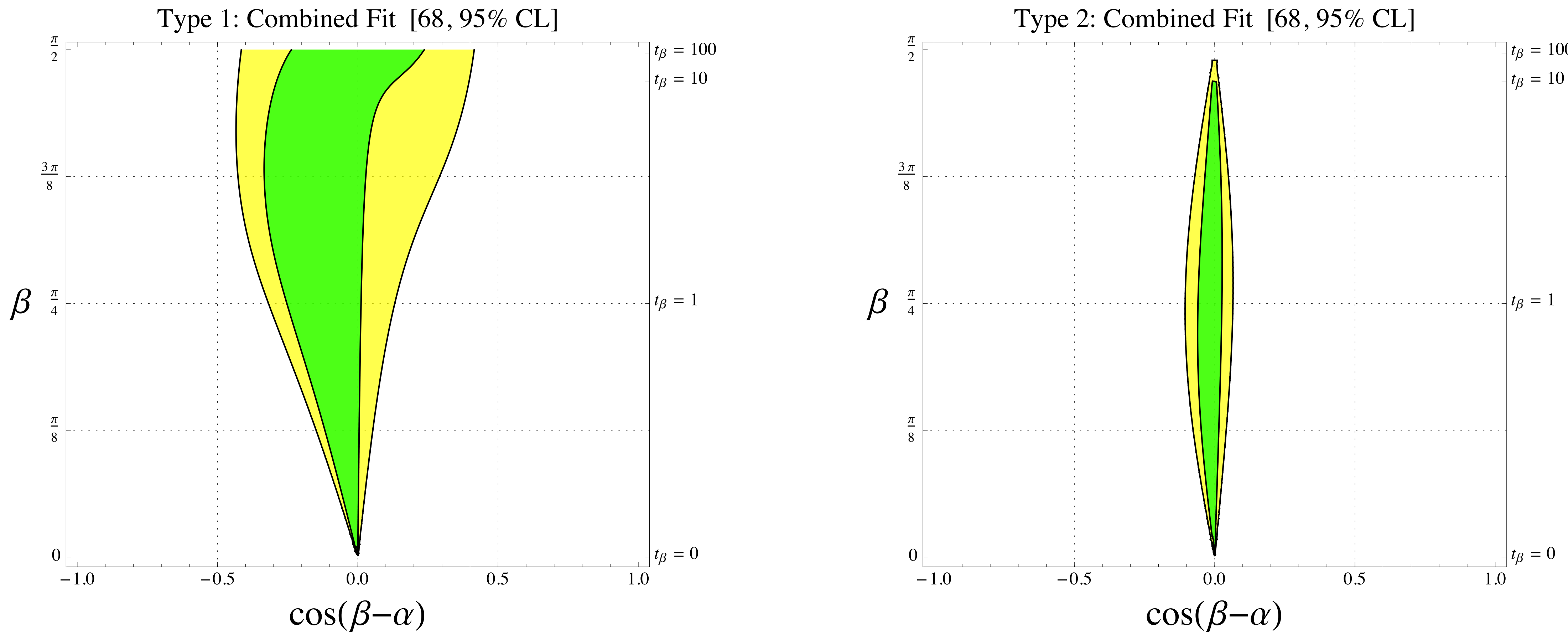
$y_{\rm 2HDM}/y_{\rm SM}$	2HDM I	2HDM II	2HDM III	2HDM IV
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
HVV	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
HQu	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
HQd	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
HLe	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
AVV	0	0	0	0
AQu	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
AQd	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ALe	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

- Scalar self-couplings have additional parametric freedom.
- Gives a map between current fits to the Higgs couplings and the possible size of NP signals!

[NC, J. Galloway, S. Thomas]

Interplay with h

Coupling measurements of the state at 126 GeV shape the space of likely signatures for heavier scalars

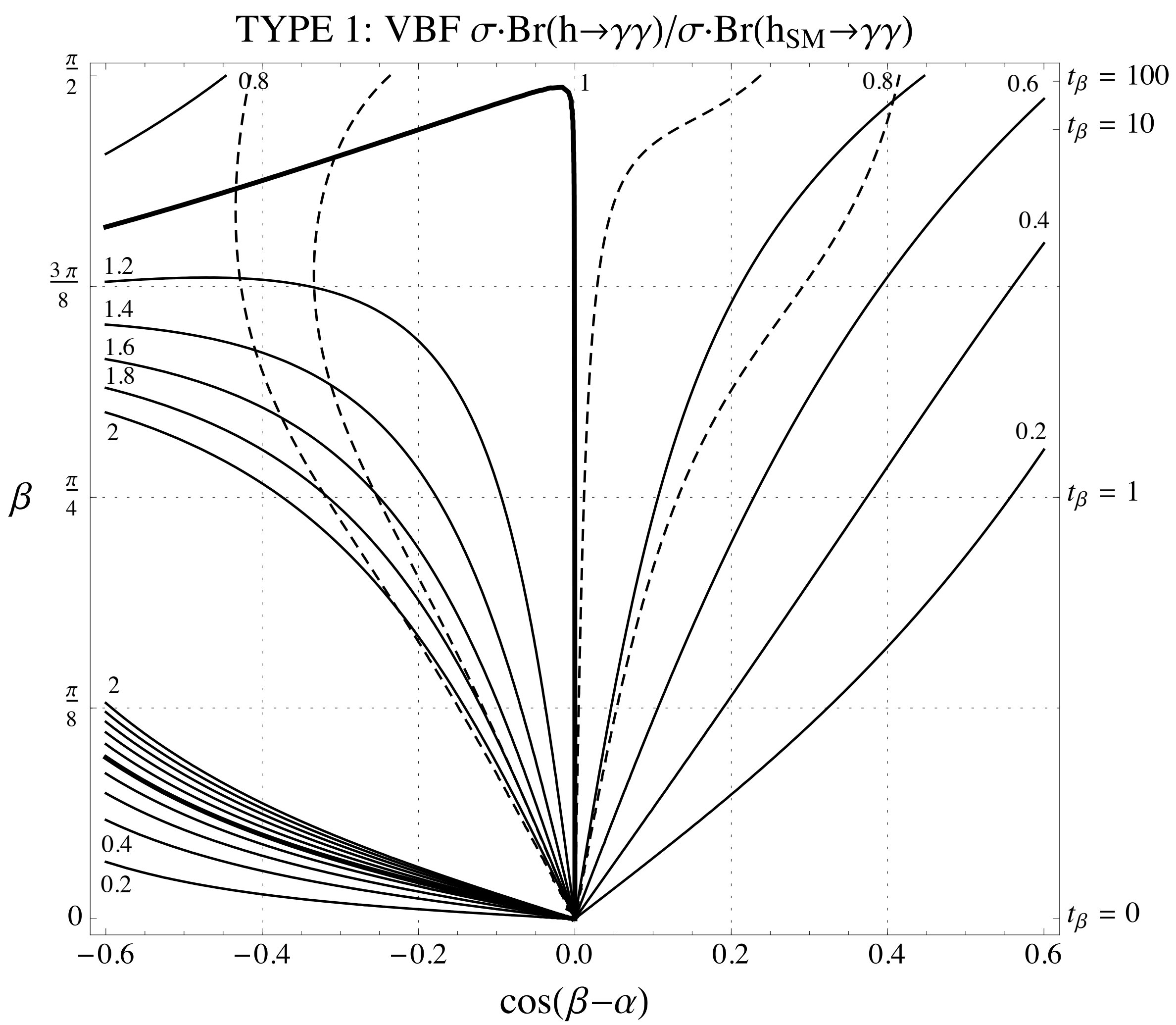


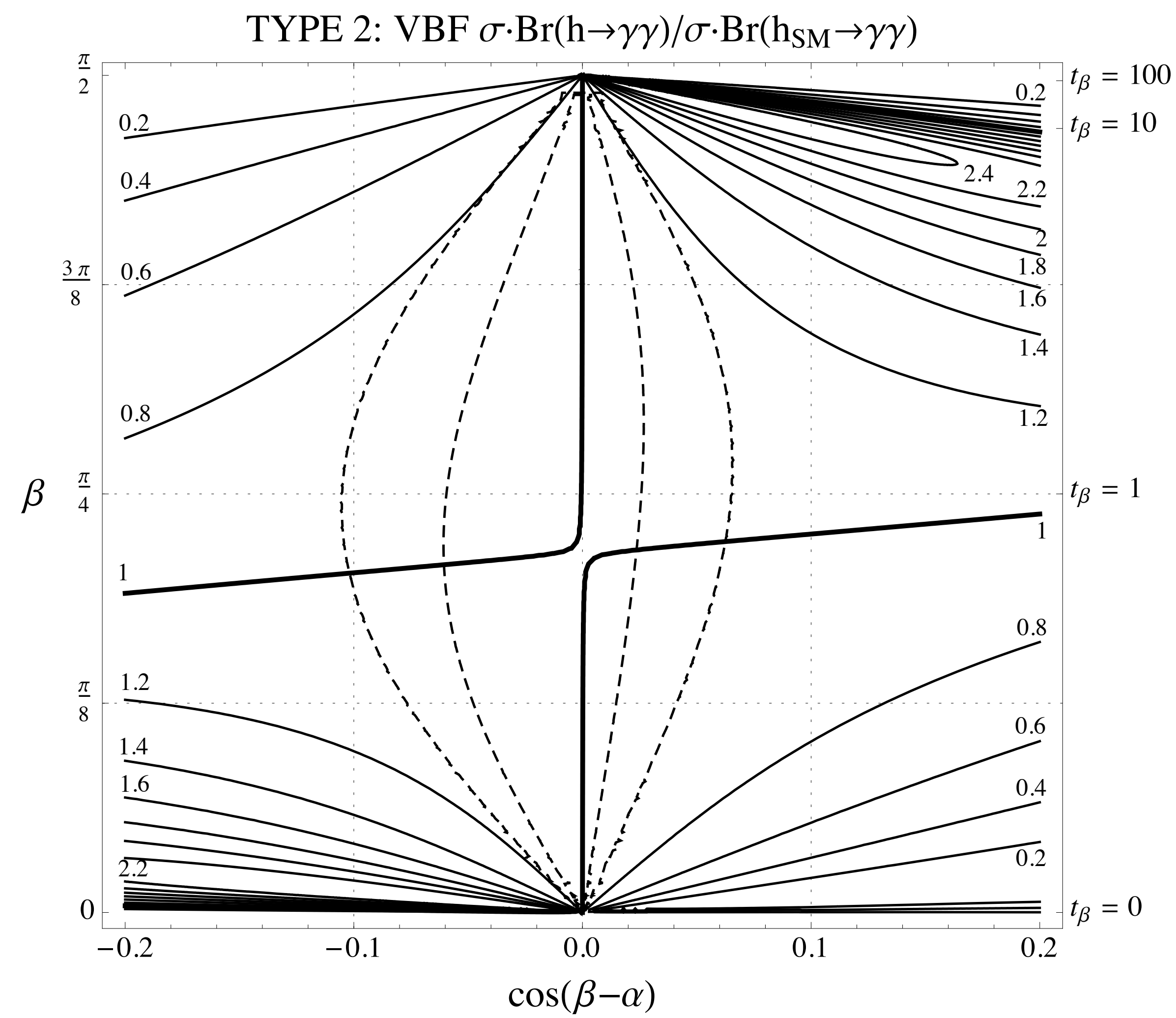
We are close to the decoupling limit.

Shapes the likely signals at LHC and e+ e- colliders

Indirect signals

The simplified coupling space allows us to map h couplings into 2d space. In the event of deviations, can use this to come up with correlated predictions and narrow space of models.





Direct signals

In decoupling limit, it's natural for

$$m_H \sim m_A \sim m_{H^\pm} > m_h$$

In this case the kinematically available decays are:

- H decays to SM fermions, vectors, and also $H \to hh$
- A decays to SM fermions, photons, and also $A \to Zh$
- H^+ decays to SM fermions and also $H^+ \to Wh$

Most promising modes are hh, Zh, VV, di-tau, diphoton

What to do?

First priority, look for these processes at LHC:

- $gg \to A \to Zh$
- $gg \to H \to hh$

← Qualitatively new channels (points to the two processes above)

- $gg \to A,H \to$ gamma gamma ← Extend to high mass
- $gg \to A,H \to$ tau tau
- $gg \to H \to VV$

← Study reach (points to the two processes above)

General interplay between signals. If diphoton signal exists, a di-tau signal is likely. If VV signal exists, an hh signal is likely. Deviations in h couplings point to param space.

Searches get harder at lepton machines because VA production is zero and VH production is suppressed. So focus on pp machines.

Simulation for Snowmass

Prohibitive to simulate each individual point in the 2HDM parameter space of masses and mixing angles

$$\sigma \cdot \mathrm{Br} \cdot \mathcal{A}(pp \to f) = \sum_t \sigma(pp \to t)\mathcal{A}(pp \to t \to f) \prod_a \mathrm{Br}_a(t \to f)$$

↑ Analytic ↑ Simulation ↑ Analytic

Instead factorize into topologies, compute acceptance for each topology through simulation, then re-weight analytically using functional dependence of cross section and branching ratios.

Simulation for Snowmass

- 2HDM model file in MG4.
- Choose model couplings simply to ensure all topologies are available and widths are sensible.
- Simulate 2-to-2 production of various motivated process in MG4/5.
- Decay h bosons in BRIDGE to exclusive SM final states.
- Use these exclusive topologies to determine acceptance.
- Reweight each topology analytically to determine signal.

14 TeV signal files are ready; 33/100 TeV samples easy.
Ideally work with experimentalists for detailed studies.

[John Stupak (CMS), ...??] *More HEX volunteers needed.*