Searching for signs of the second Higgs

Nathaniel Craig
IAS + Rutgers

NC, J. Galloway, S. Thomas [1305.2424]
+G. Kukartsev, M. Narain, J. Stupak [Snowmass]

Snowmass on the Pacific

Looking for extended EWSB

- We've discovered one SM-like Higgs, but there is considerable room for additional degrees of freedom associated with EWSB.
- A strongly motivated scenario! Naturalness often implies extended Higgs sector.

- Two Higgs doublet models provide an effective description for many such EWSB extensions:
  - Higgs sector of MSSM,
  - Various Twin Higgs models,
  - Composite Higgs models (e.g. SO(6)/SO(4)xSO(2))
  - ...

Looking for extended EWSB

Three (EF) avenues to pursue:

1. Study the couplings of the recently-discovered SM-like Higgs.

2. Search for additional scalars in standard Higgs channels.

3. Search for additional scalars in non-standard Higgs channels.

Useful to develop a concrete framework in which all three avenues are related.

Also have complementarity with intensity frontier!

A simplified parameter space

- Need to develop an efficient search strategy. The general parameter space of 2HDM is vast, but there are well-motivated simplifying assumptions:
- Flavor limits suggest 2HDM should avoid new tree-level FCNC; satisfied by four discrete choices of couplings to fermions.
- Lack of large 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 & relations between search avenues.

A simplified parameter space

Physical d.o.f. are $h, H, A, H^{\pm}$

After EWSB there are 9 free parameters in CP-conserving scalar potential.

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

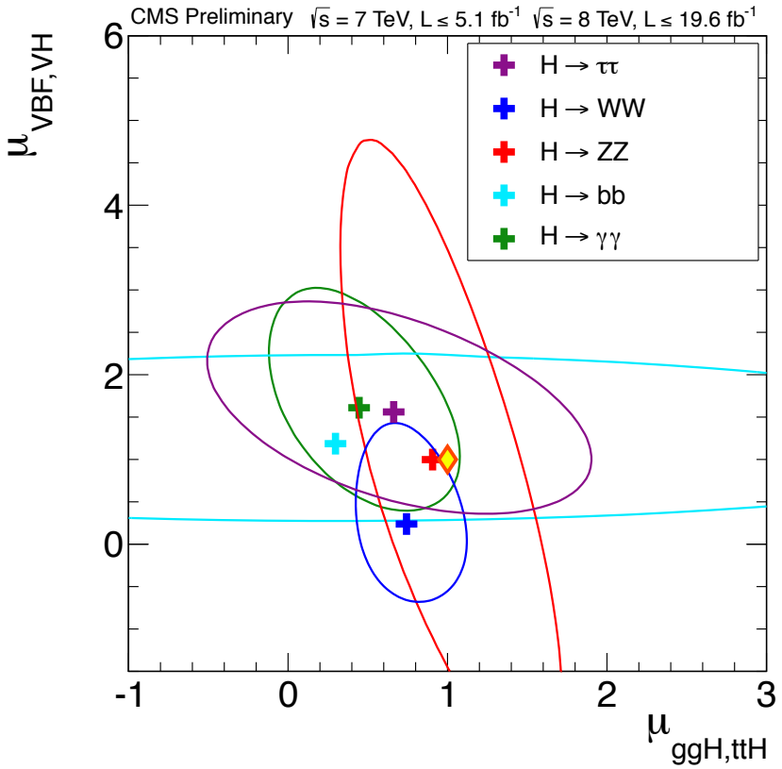
$m_h, m_H, m_A, m_{H^{\pm}}$ $\qquad$ $\tan\beta \equiv \langle\Phi_2\rangle / \langle\Phi_1\rangle$

$$\alpha: \begin{pmatrix} \sqrt{2}\,\mathrm{Re}(\Phi_2^0) - v_2 \\ \sqrt{2}\,\mathrm{Re}(\Phi_1^0) - v_1 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

$\lambda_5, \lambda_6, \lambda_7$ $\qquad$ (only appear in trilinear couplings)

Couplings of scalars to fermions, vectors only depend on angles.

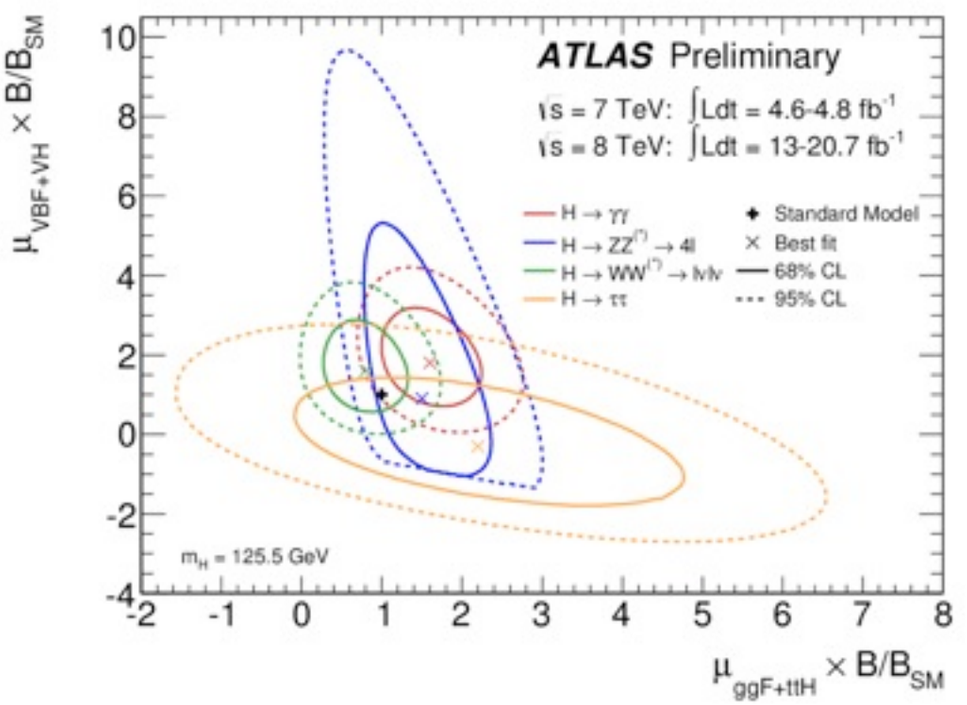
Discrete symm. for flavor: $\lambda_{6,7} = 0$ $\qquad$ MSSM: $\lambda_{5,6,7} = 0$



Alignment limit

- Couplings of the observed Higgs are approximately SM-like
- Strongly suggests proximity to the alignment limit

$$\alpha \approx \beta - \pi/2$$



- In this limit h is the fluctuation around the vev, while remaining scalars are spectators to EWSB
- (Limit obtainable via decoupling or accidentally)
- Useful to expand in

$$\delta = \beta - \alpha - \pi/2$$

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

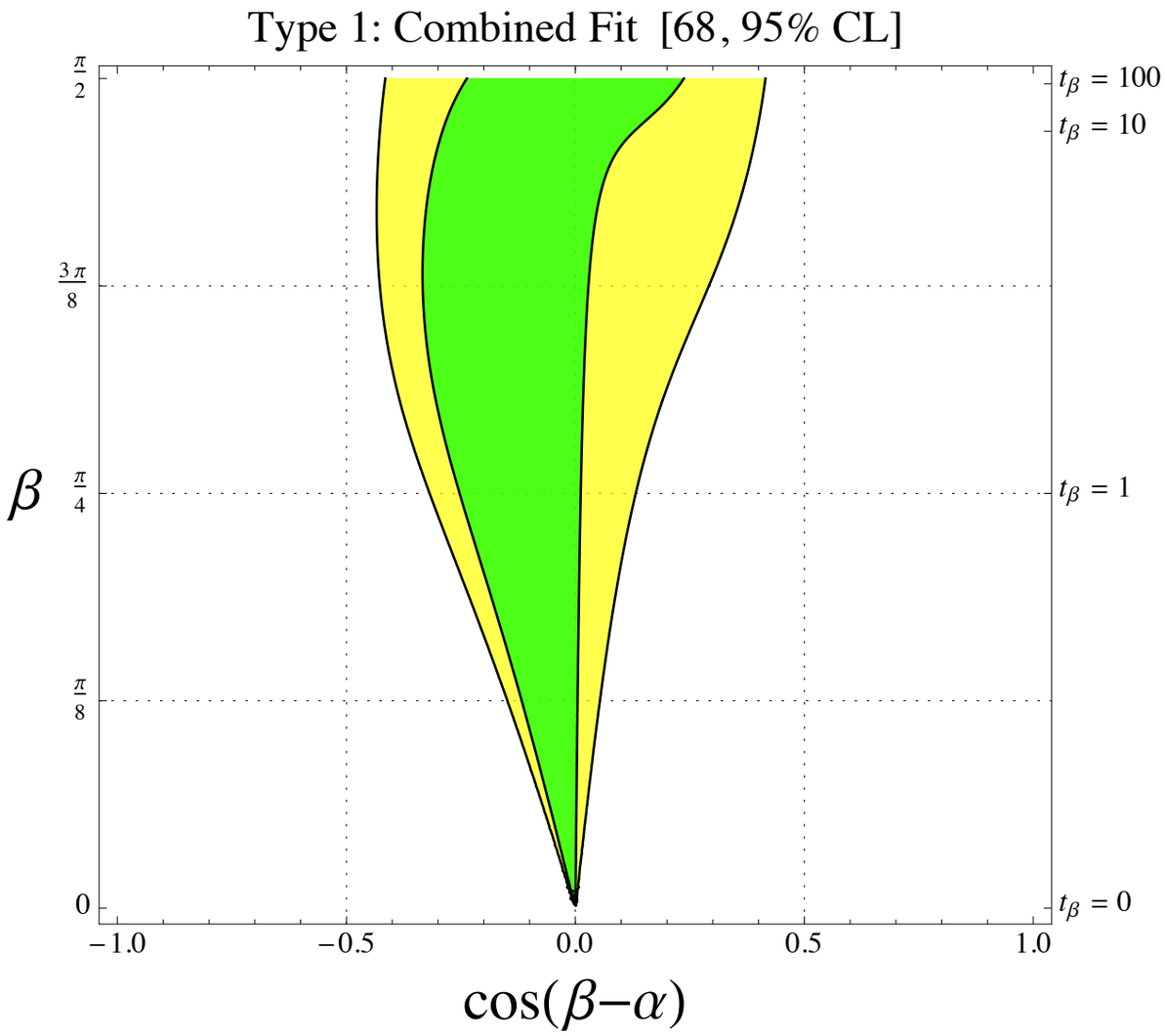
$y_{\rm 2HDM}/y_{\rm SM}$	2HDM 1	2HDM 2
hVV	$1-\delta^2/2$	$1-\delta^2/2$
hQu	$1-\delta/t_\beta$	$1-\delta/t_\beta$
hQd	$1-\delta/t_\beta$	$1+\delta t_\beta$
hLe	$1-\delta/t_\beta$	$1+\delta t_\beta$
HVV	$-\delta$	$-\delta$
HQu	$-\delta-1/t_\beta$	$-\delta-1/t_\beta$
HQd	$-\delta-1/t_\beta$	$-\delta+t_\beta$
HLe	$-\delta-1/t_\beta$	$-\delta+t_\beta$
AVV	0	0
AQu	$1/t_\beta$	$1/t_\beta$
AQd	$-1/t_\beta$	t_β
ALe	$-1/t_\beta$	t_β

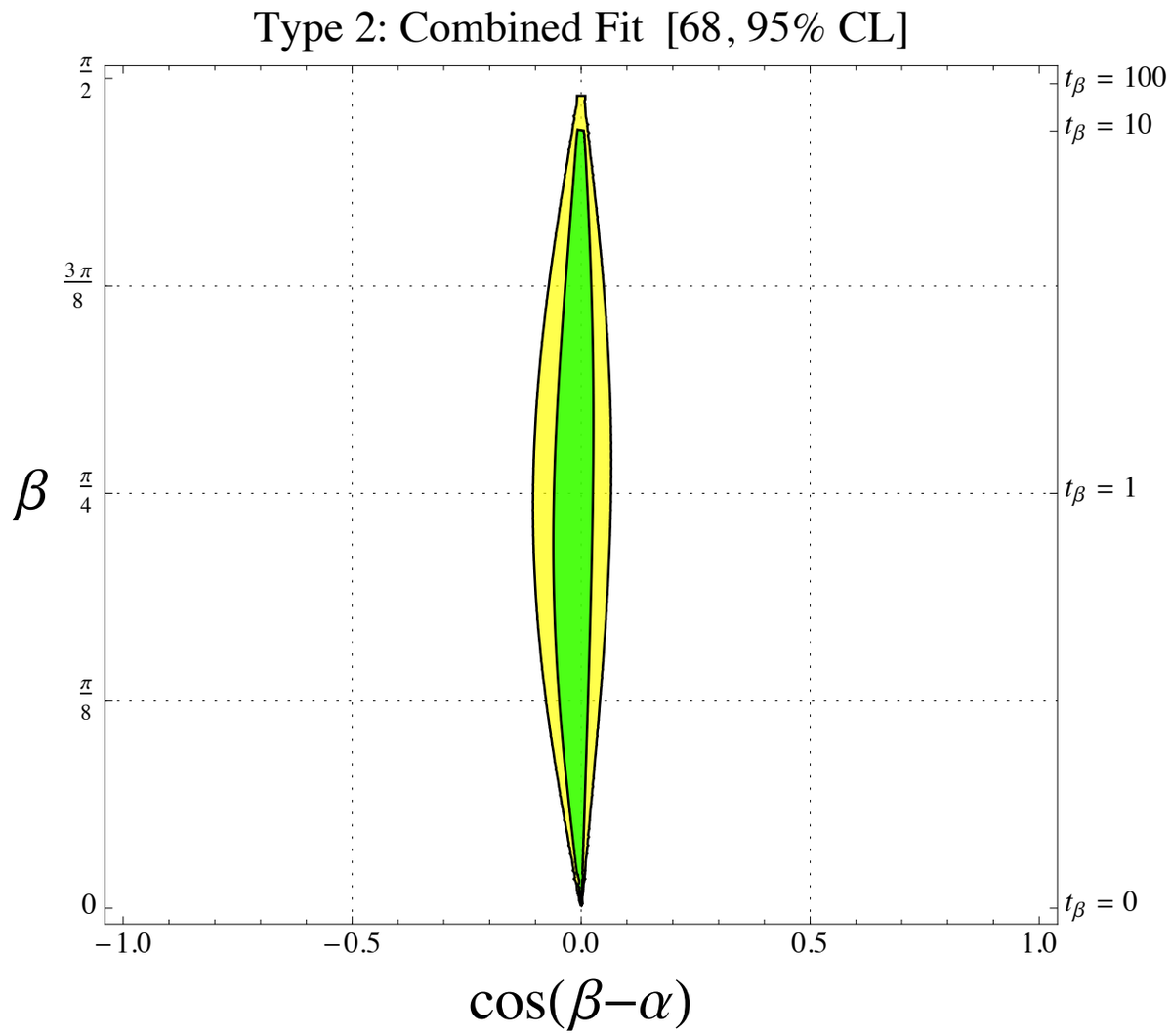
$$\delta = \beta - \alpha - \pi/2$$

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

- Scalar self-couplings have additional parametric freedom.
- Gives a map between current fits to the Higgs couplings and the possible size of NP signals.
- H, A are similar d.o.f. in alignment limit

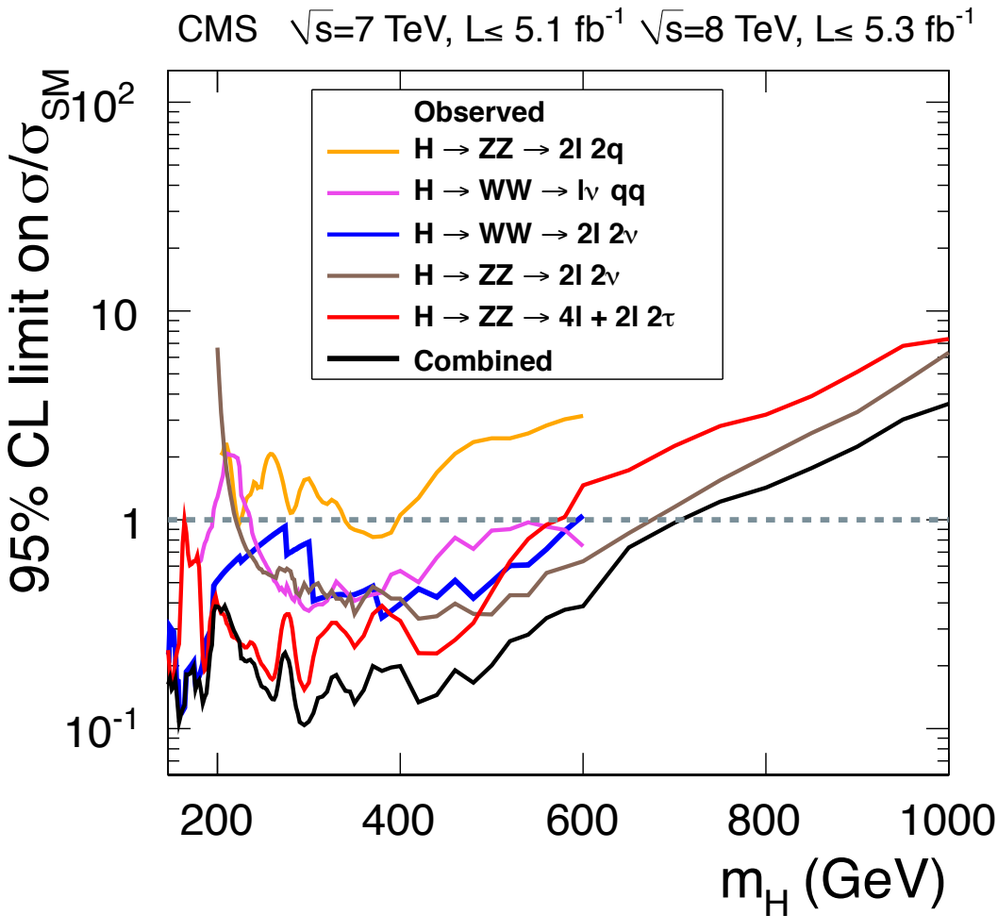
(1) Study the couplings





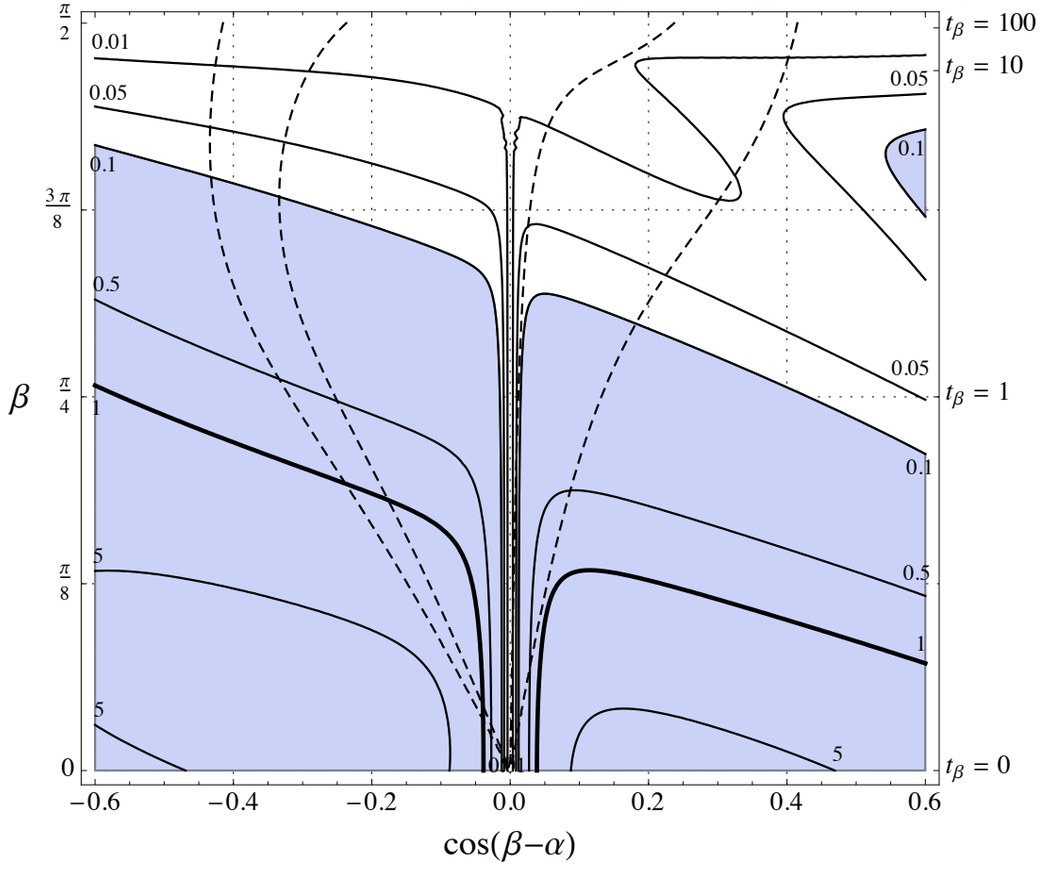
Construct a fit to couplings of SM-like Higgs in terms of tree-level 2HDM parameter space. Provides a useful benchmark for the signal expectations of extra scalars.

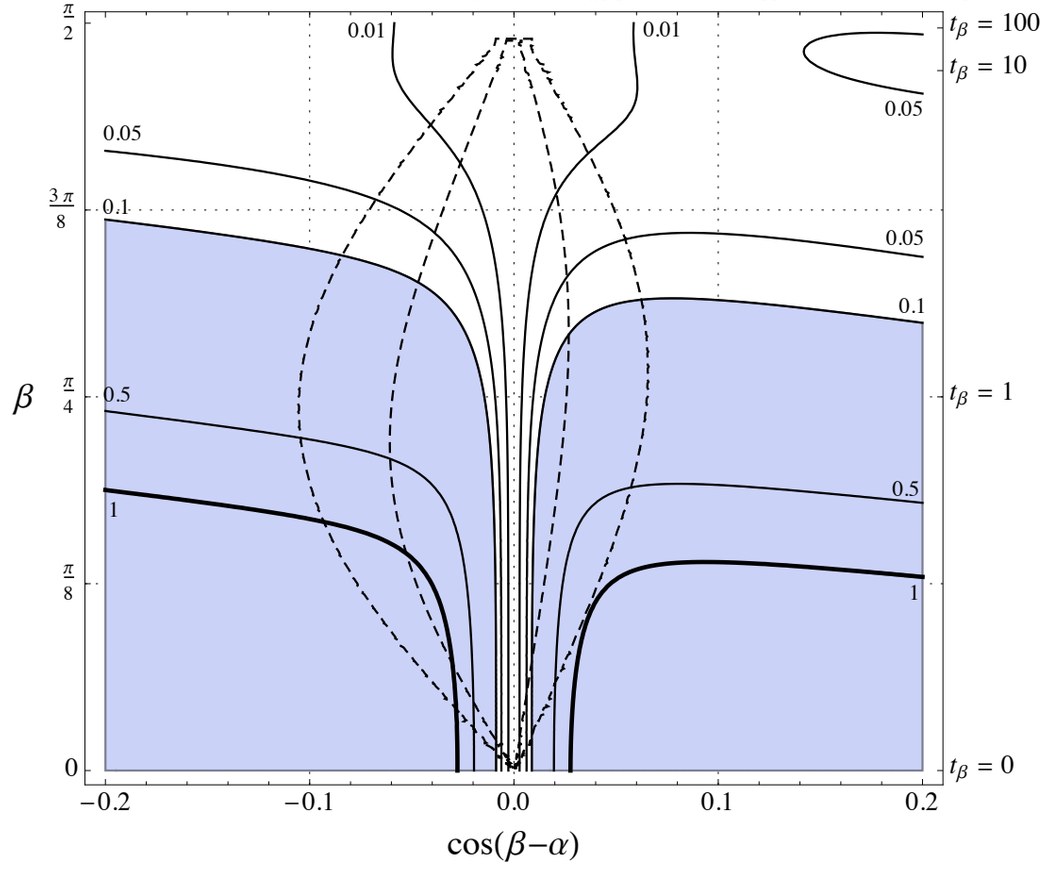
Second Higgs Doublet Decay Topology			Alignment Limit
H	$\to$	WW, ZZ	–
H, A	$\to$	$\gamma\gamma$	✓
H, A	$\to$	$\tau\tau, \mu\mu$	✓
H, A	$\to$	tt	✓
A	$\to$	Zh	–
H	$\to$	hh	–
t	$\to$	$H^{\pm}b$	✓



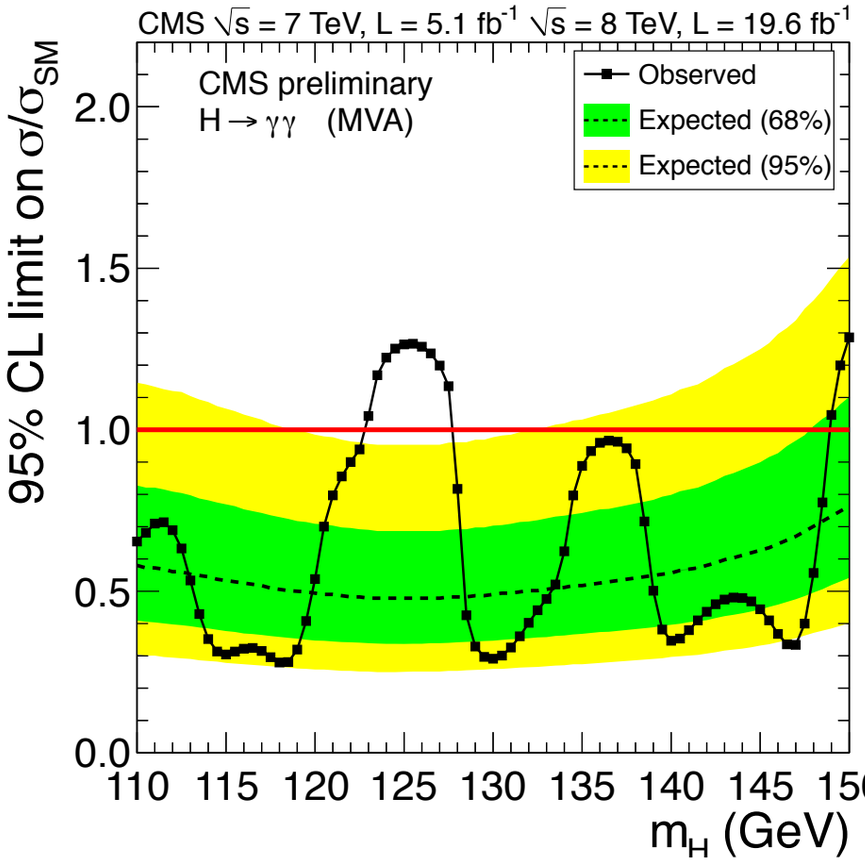
(2) Search for scalars in standard channels

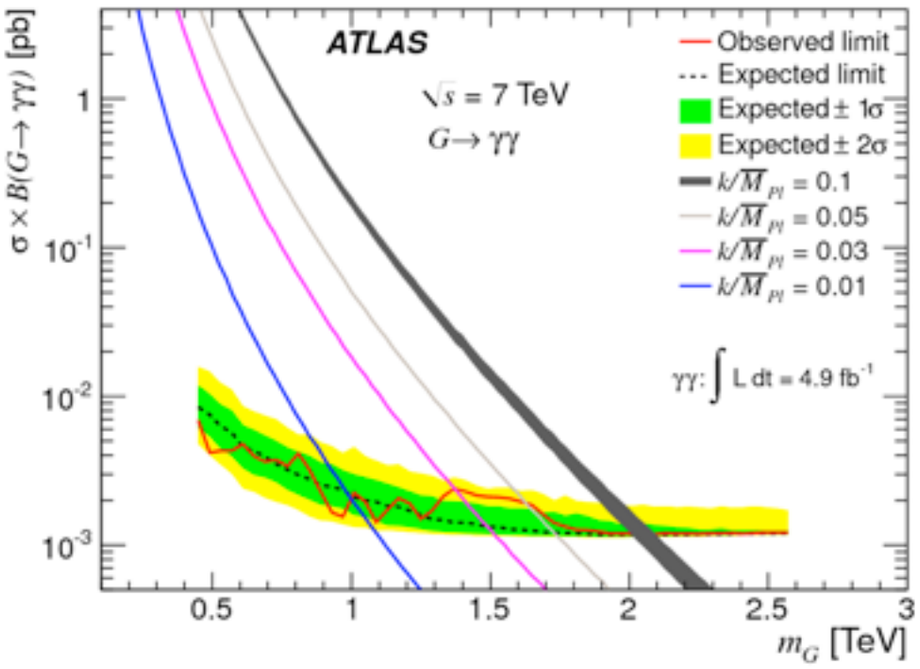
Good limits to high mass in VV.
Surprisingly constraining even close to alignment limit.
Could improve limits by exploiting narrowness.



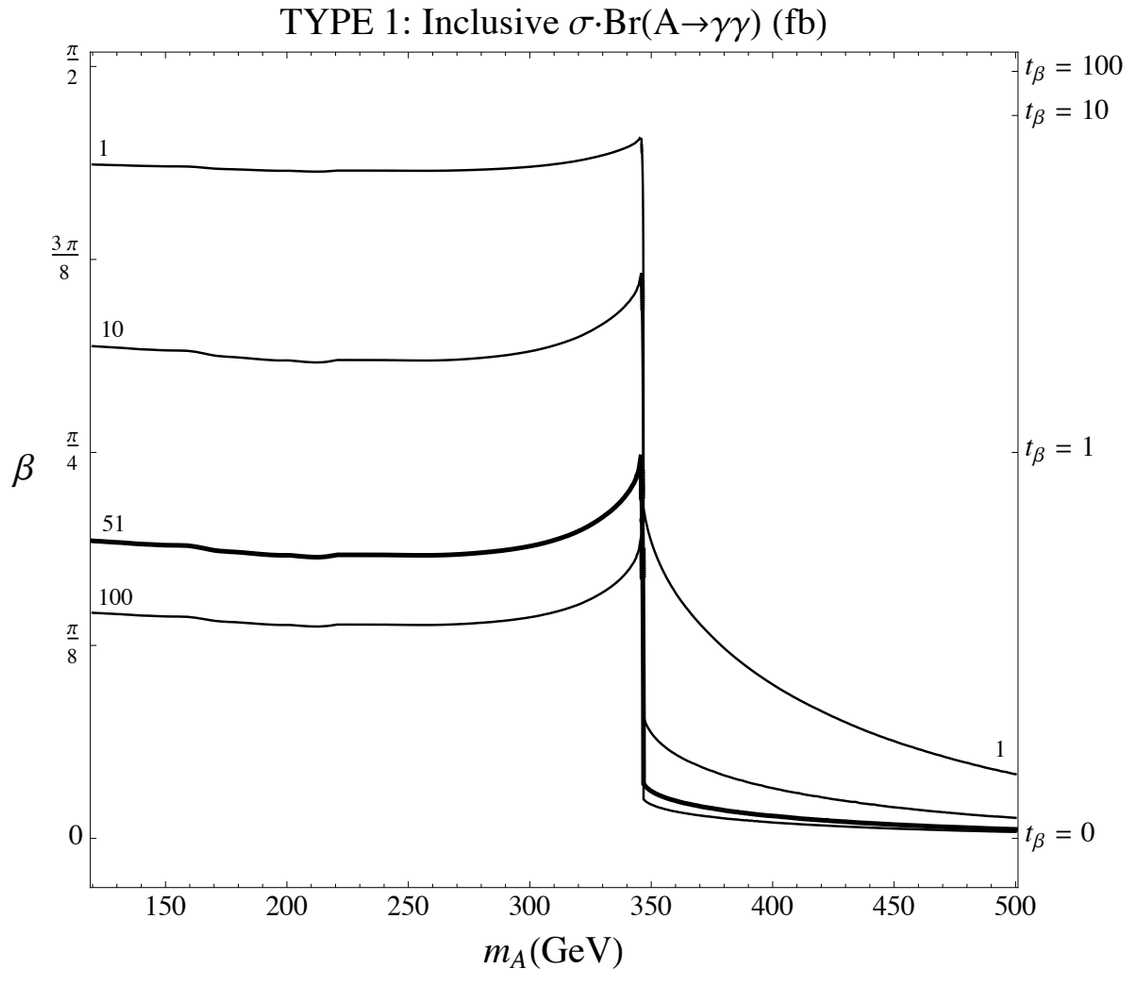


(2) Search more in standard channels

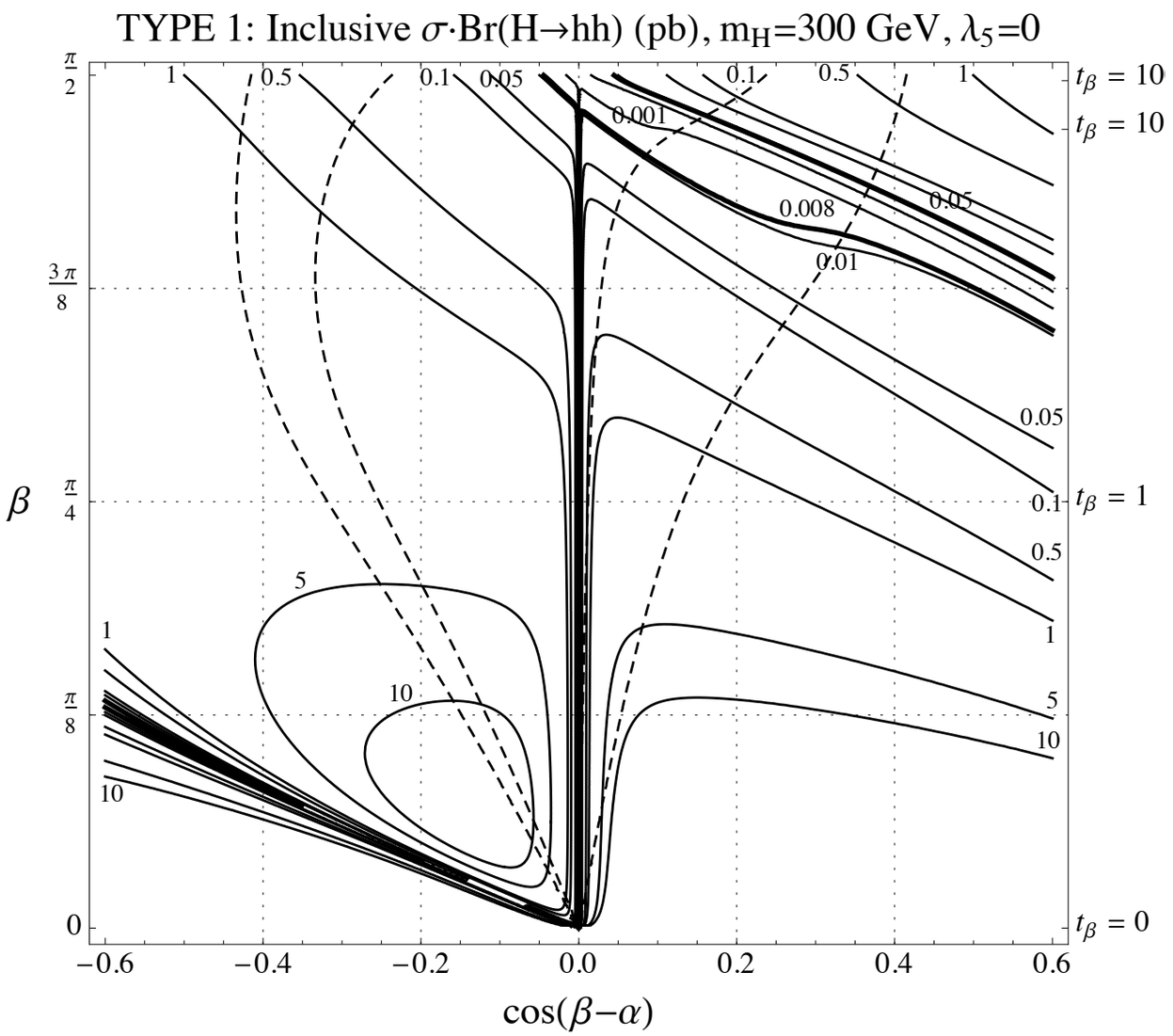


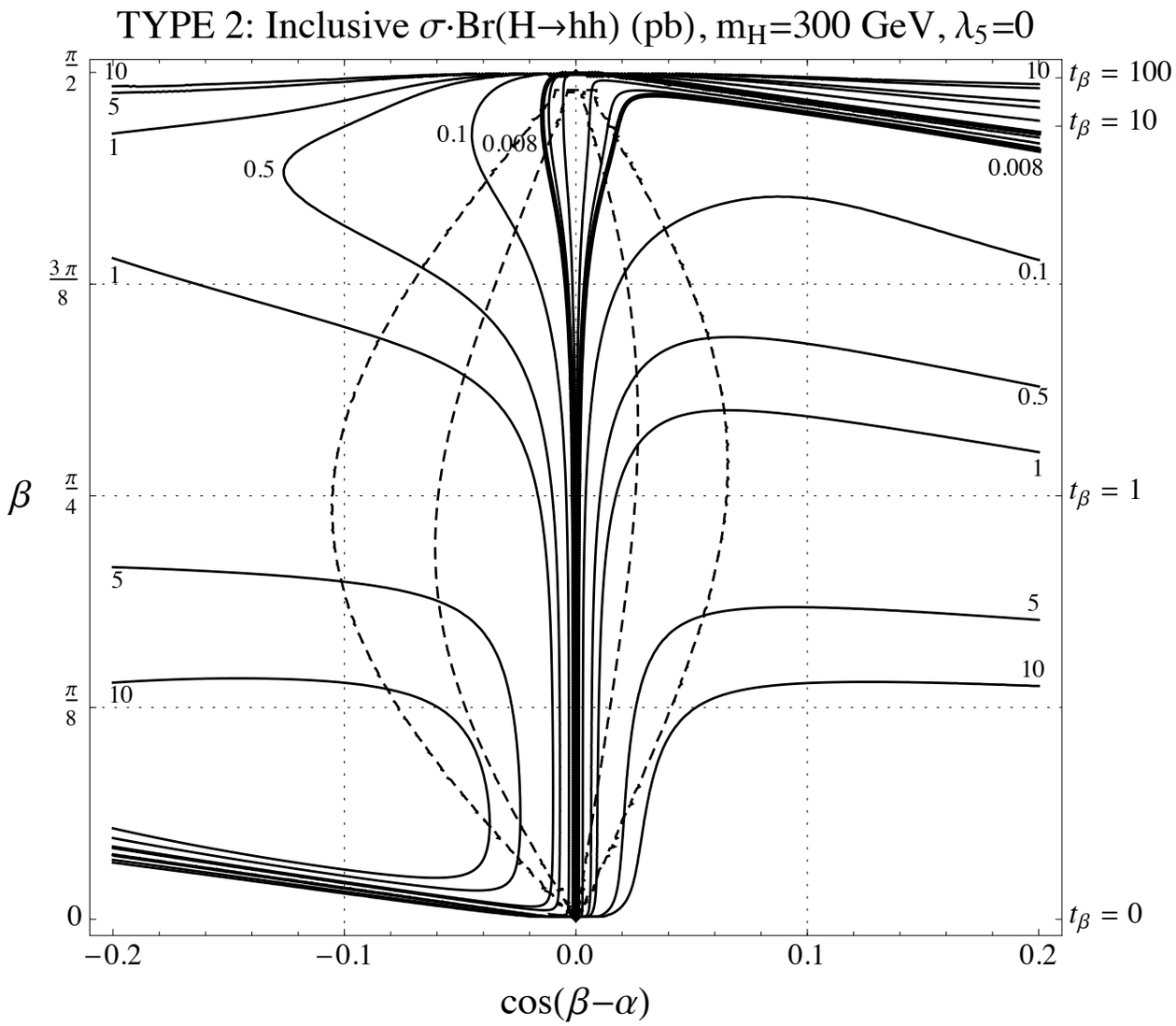


Decays to diphotons can be observable out to the top pair threshold; currently there is a large hole in coverage between SM Higgs and KK searches.



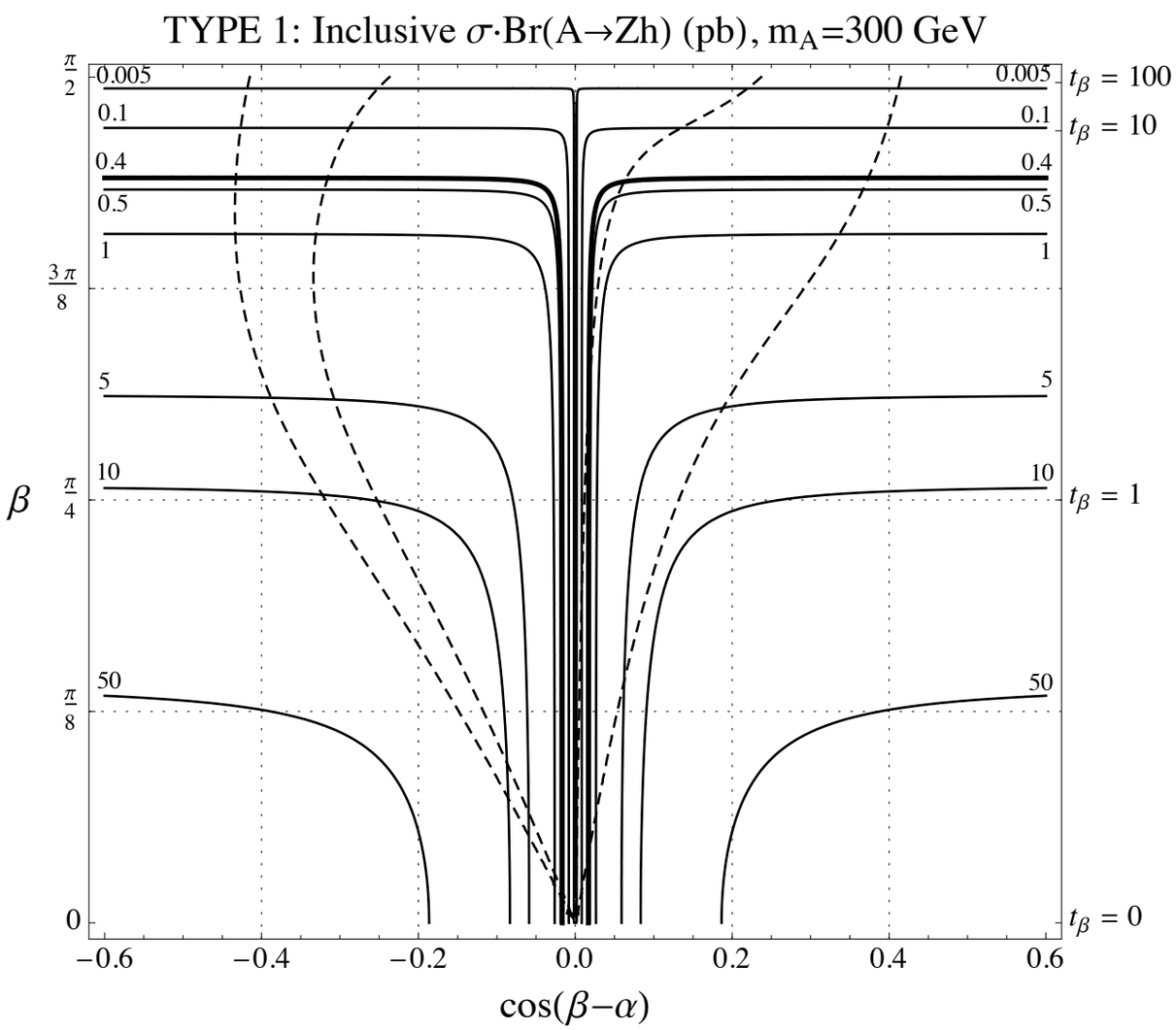
(3) Search in nonstandard channels: hh

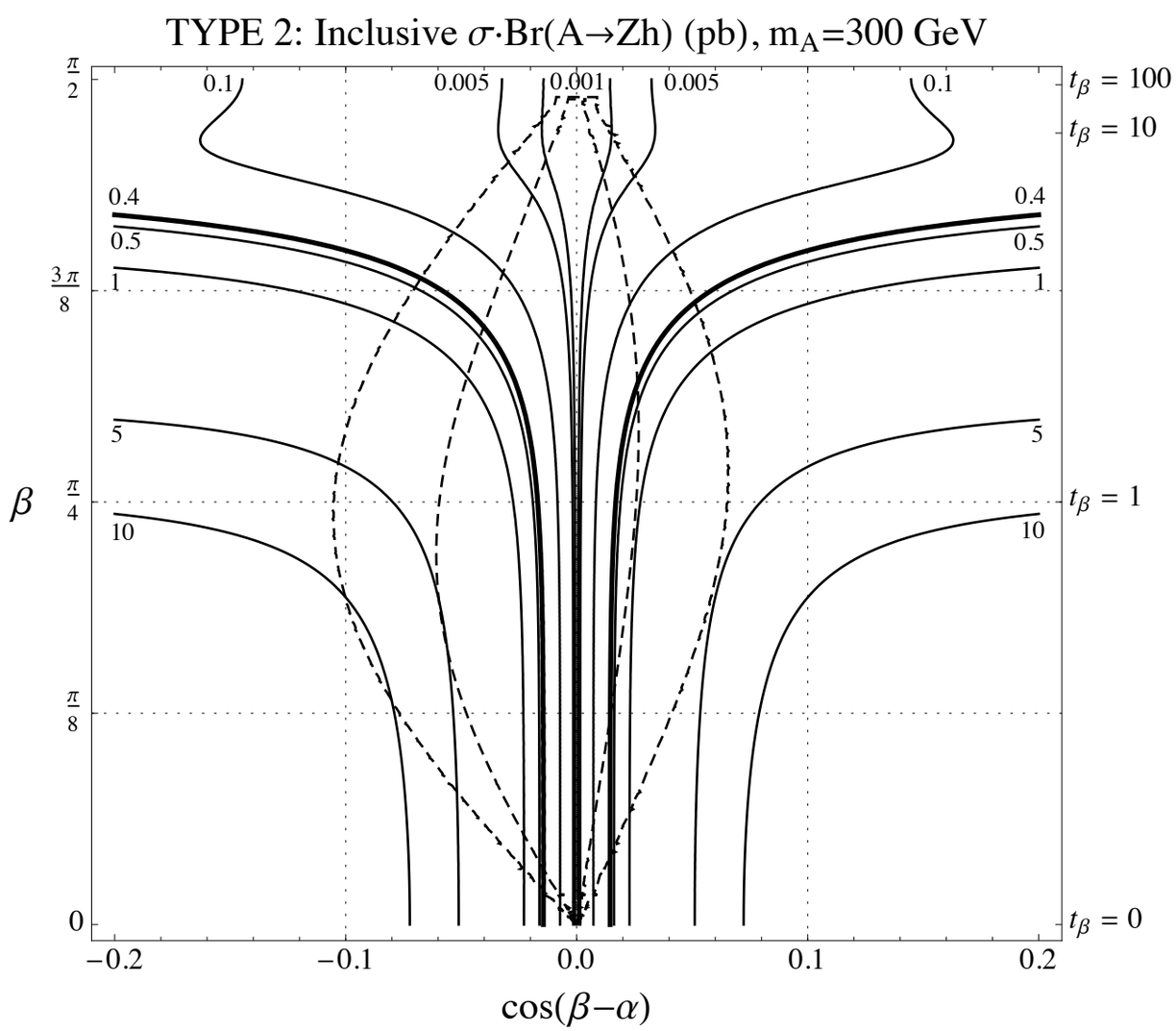




Appreciable rates (~1000 x SM)
consistent with fits and VV limits.

(3) Search in nonstandard channels: Zh





Appreciable rates (~few x SM) consistent with fits and Zh cross section limits (~3 x SM).

(2)+(3) @ Snowmass

- HEX-HET collaboration with Gena Kukartsev, Meenakshi Narain, John Stupak
- Studying 13, 30 TeV pp reach in H>VV, H>hh, A>Zh. Should be the most promising channels for direct limits on heavy scalars.
- Considering a wide range of various final states, but open to suggestions.
- *This is also an opportunity to shape current LHC search strategies.*

Finding the second Higgs

1. Coupling measurements of h proceeding apace, still room for surprises.
2. Can improve search for additional scalars in standard Higgs channels by e.g. extending diphoton, exploiting narrowness of H,A.
3. Substantial opportunity to search for additional scalars in non-standard Higgs channels such as hh, Zh

Exciting opportunities for present+future LHC, high utility for Snowmass.