Searching for signs of the second Higgs

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Based on work with J. Galloway, S. Thomas;
J. Evans, R. Gray, S. Somalwar, S. Thomas.

The state of EWSB

- We've discovered a (more or less) SM-like Higgs at ~126 GeV. Its couplings are SM-like to within ~25%.
- We've discovered no evidence thus far for degrees of freedom that could ensure the naturalness of the Higgs mass.
- What do we do now?

Abandon all hope

~~Abandon all hope~~

Look for the
second Higgs.

At the very least, finding a second scalar associated with EWSB could partly differentiate between:

1. Fine-tuning is not a meaningful guide, no problem with light scalars.

2. Fine-tuning is a meaningful guide, the weak scale is natural, but we haven't seen the relevant d.o.f. yet.

3. Fine-tuning is a meaningful guide, the weak scale is tuned, but it's anthropic.

Unlikely that (3.) can explain two light scalars.

Plus additional Higgs scalars often arise in natural theories of EWSB.

- Higgs sector of the MSSM/NMSSM...
- Twin Higgs models and their variants
- Superconformal technicolor
- Composite Higgs models [e.g., SO(6)/SO(4)xSO(2) or Sp(6)/Sp(4)xSU(2)]

We should look as hard as we can for evidence of additional Higgs scalars.

Perhaps as important as looking for top partners!

(even if we find one, it will be hard to verify its role)

Today's talk

A compact parameterization of additional Higgses

Implications of coupling measurements of the SM-like Higgs

Searching in standard channels

Searching in non-standard channels

Today's talk

A compact parameterization of additional Higgses

Implications of coupling measurements of the SM-like Higgs

Searching in standard channels

Searching in non-standard channels

There is enormous room for improvement here.

Looking for another Higgs

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.

2HDM

- For the purposes of this talk, I'll focus on extended EWSB sectors whose IR physics is described by two Higgs doublets.
- This covers a broad class of known models and allows for convenient parameterization.
- ...but many of the qualitative features are shared by other extended EWSB sectors.
- I'll keep the focus on bottom-up phenomena, generalizing beyond SUSY 2HDM.

A simplified parameter space

- Need to develop an efficient parameterization. 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 (8-3=5): $h, H, A, H^{\pm}$

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

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

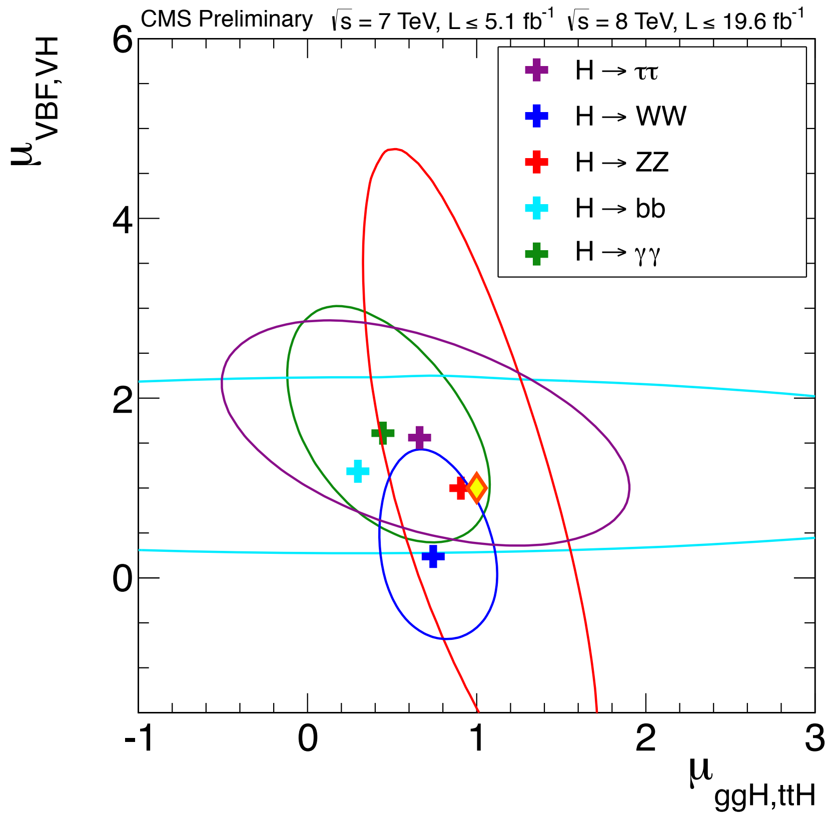
$m_h, m_H, m_A, m_{H^\pm}$ $\qquad$ $\tan\beta \equiv \langle\Phi_2\rangle/\langle\Phi_1\rangle$

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

$\lambda_5, \lambda_6, \lambda_7$ (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: $\lambda_{5,6,7} = 0$



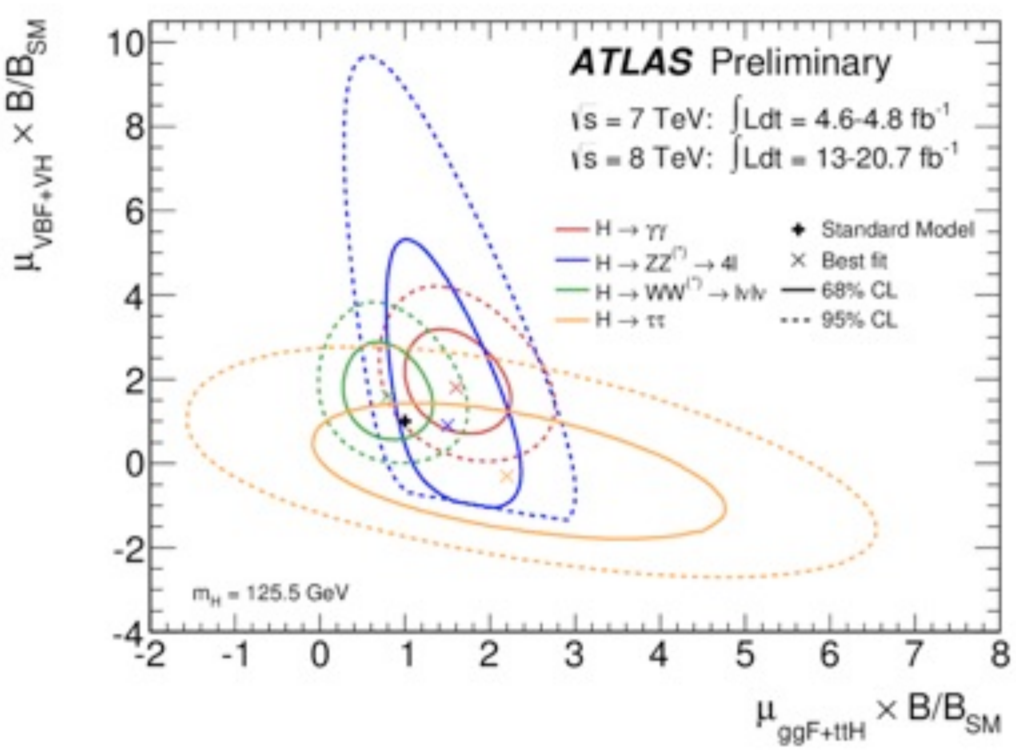
Alignment limit

- 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

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



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

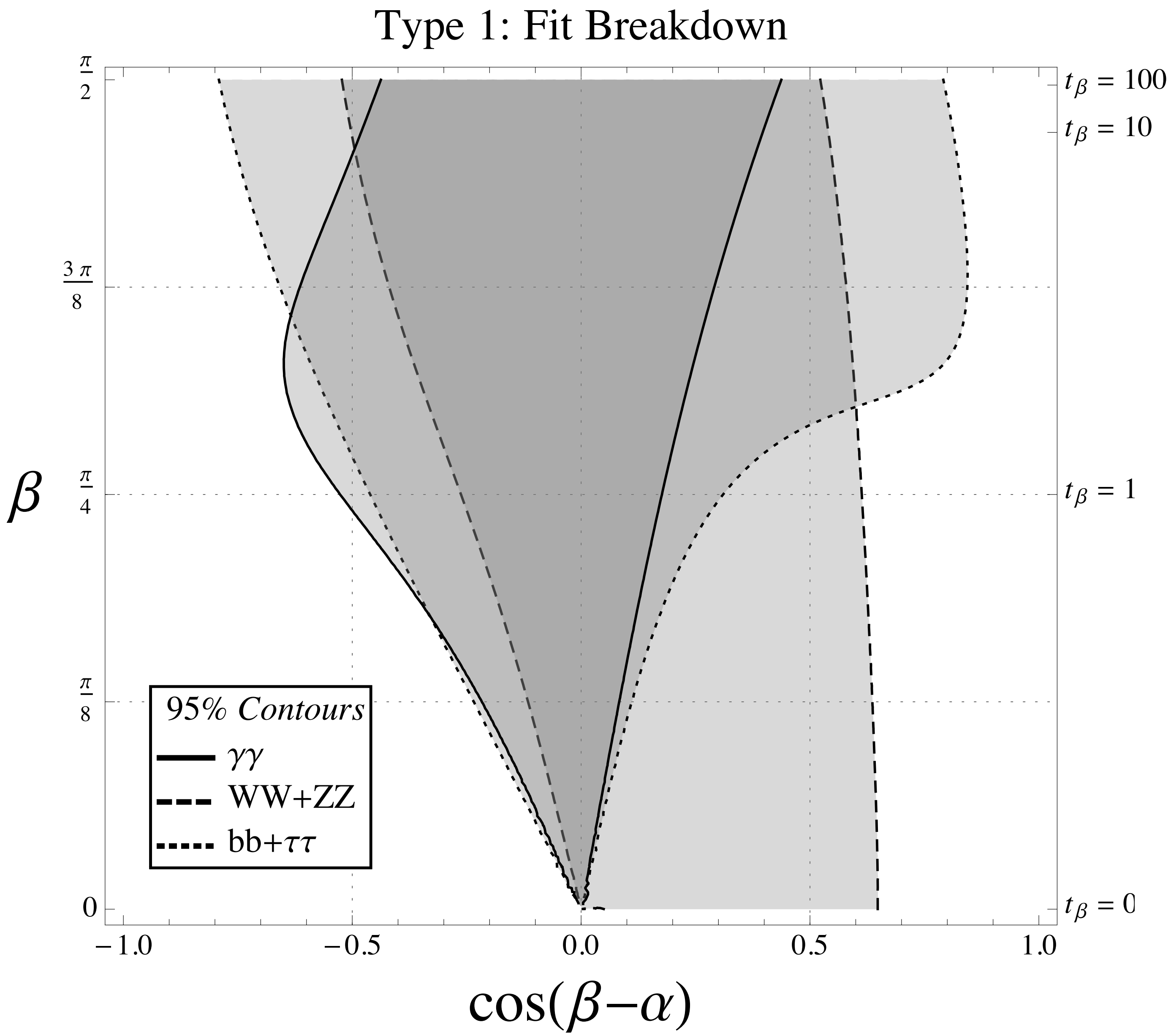
	2HDM I	2HDM II	2HDM III	2HDM IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2

$y_{\rm 2HDM}/y_{\rm SM}$	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

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

- 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



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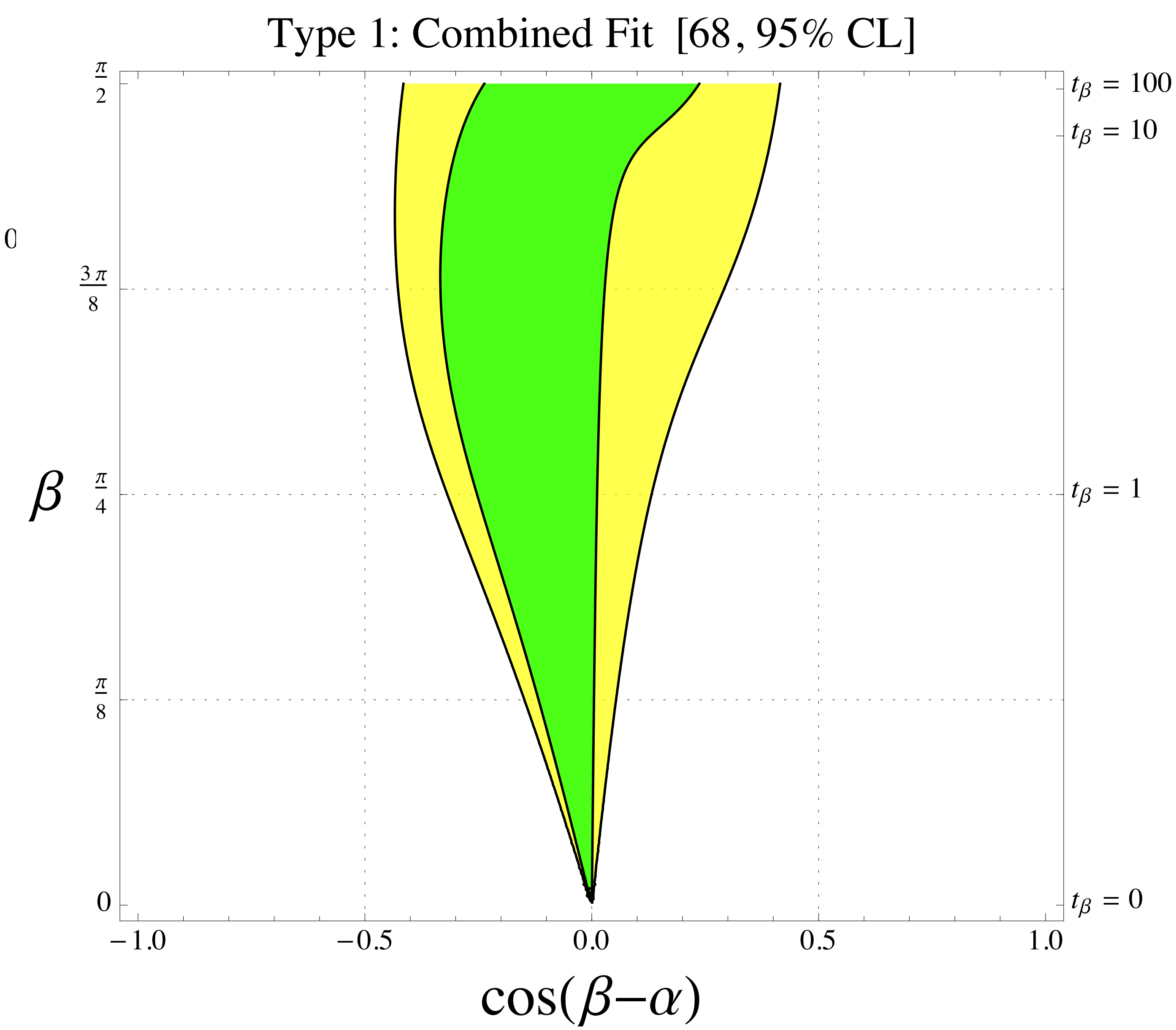

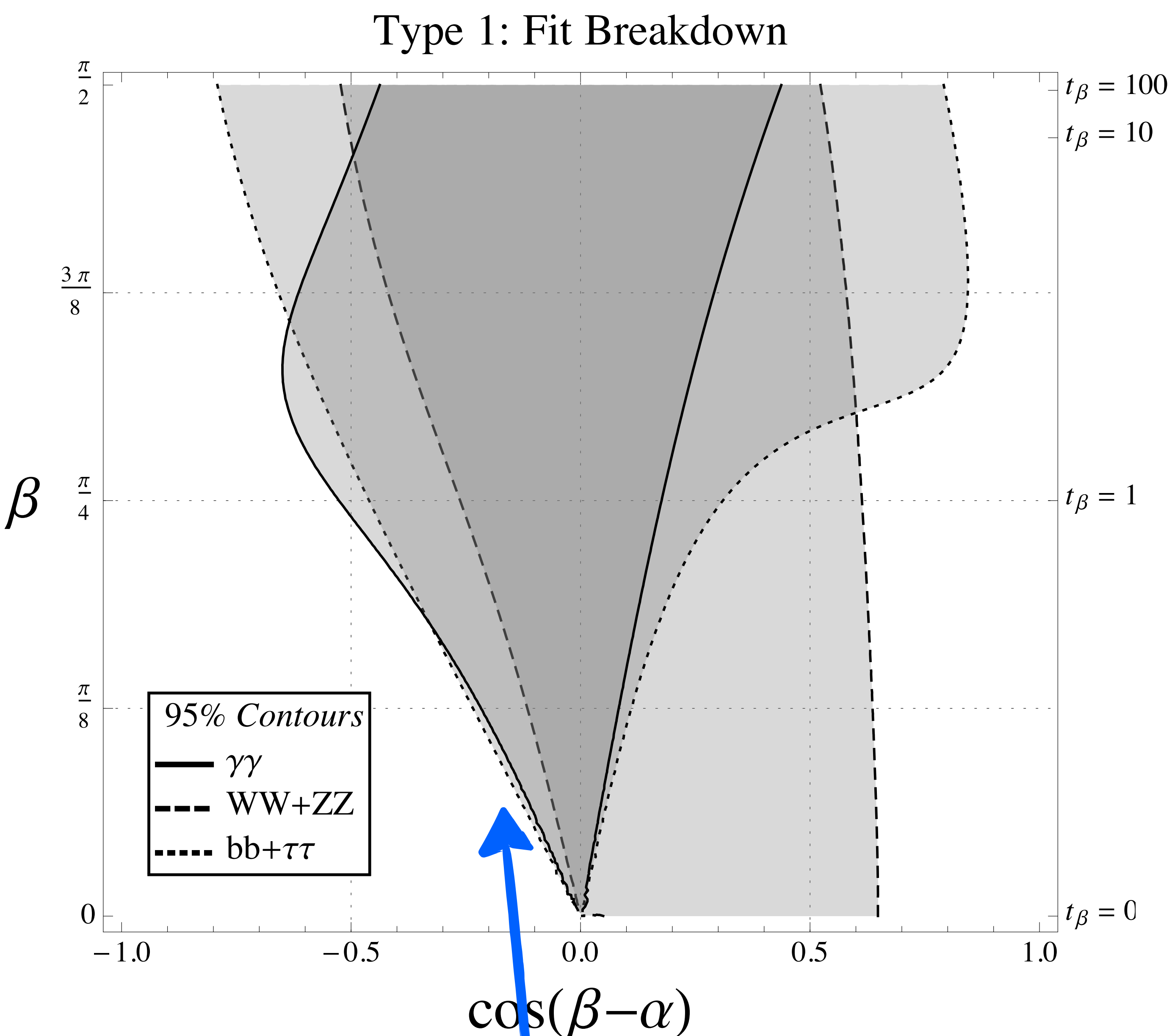

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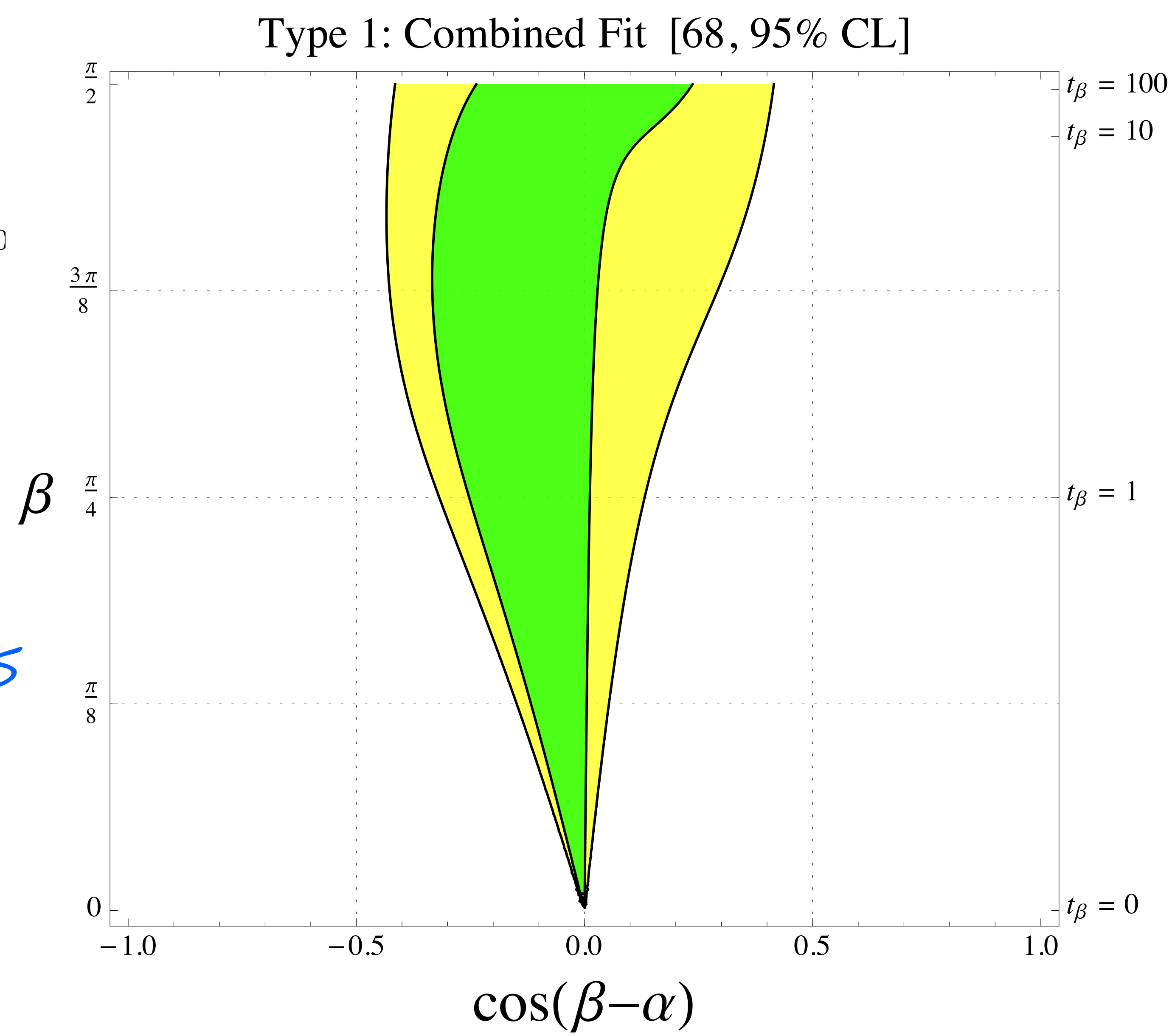
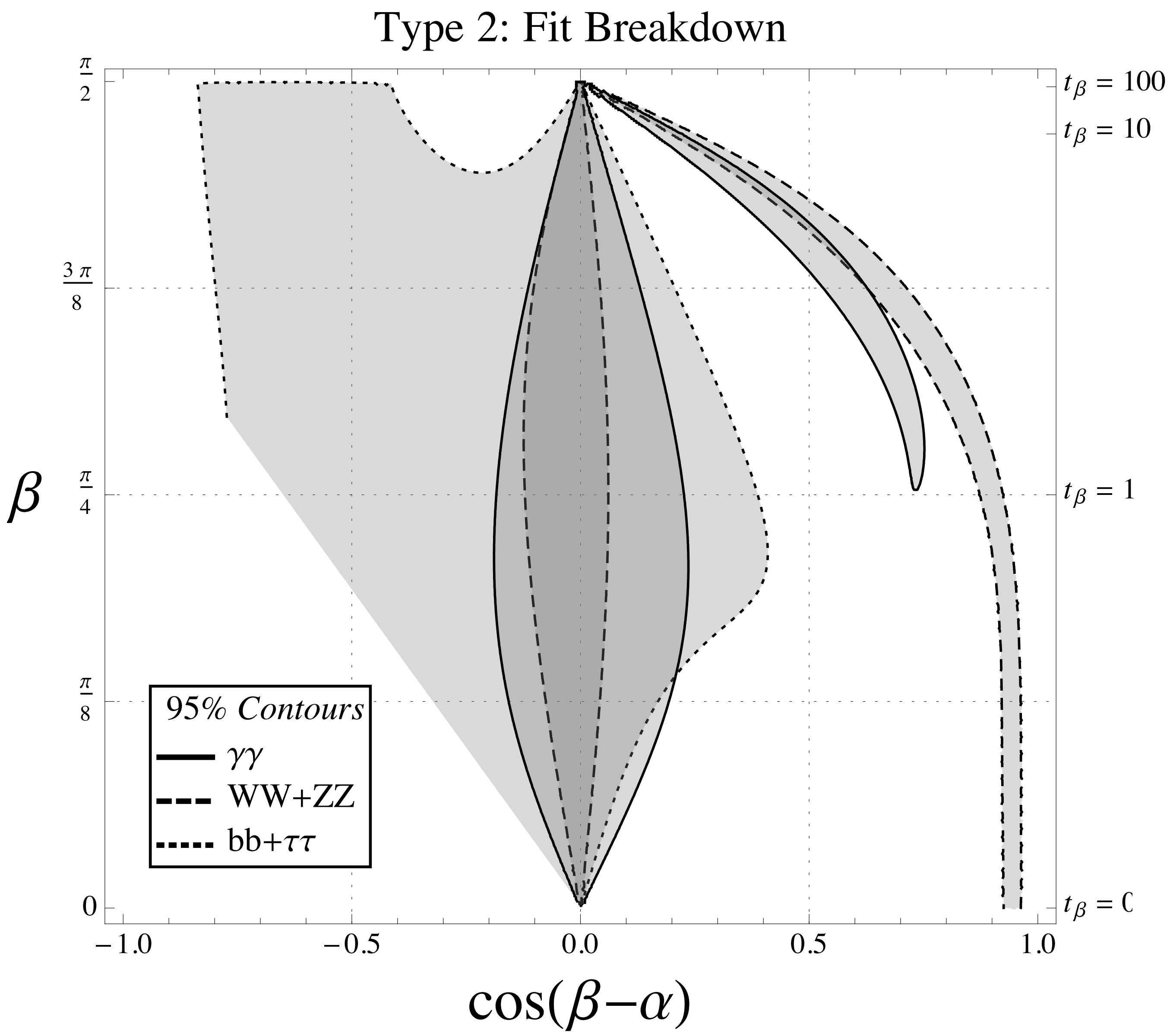


htt, hbb dropping, hVV takes over total width



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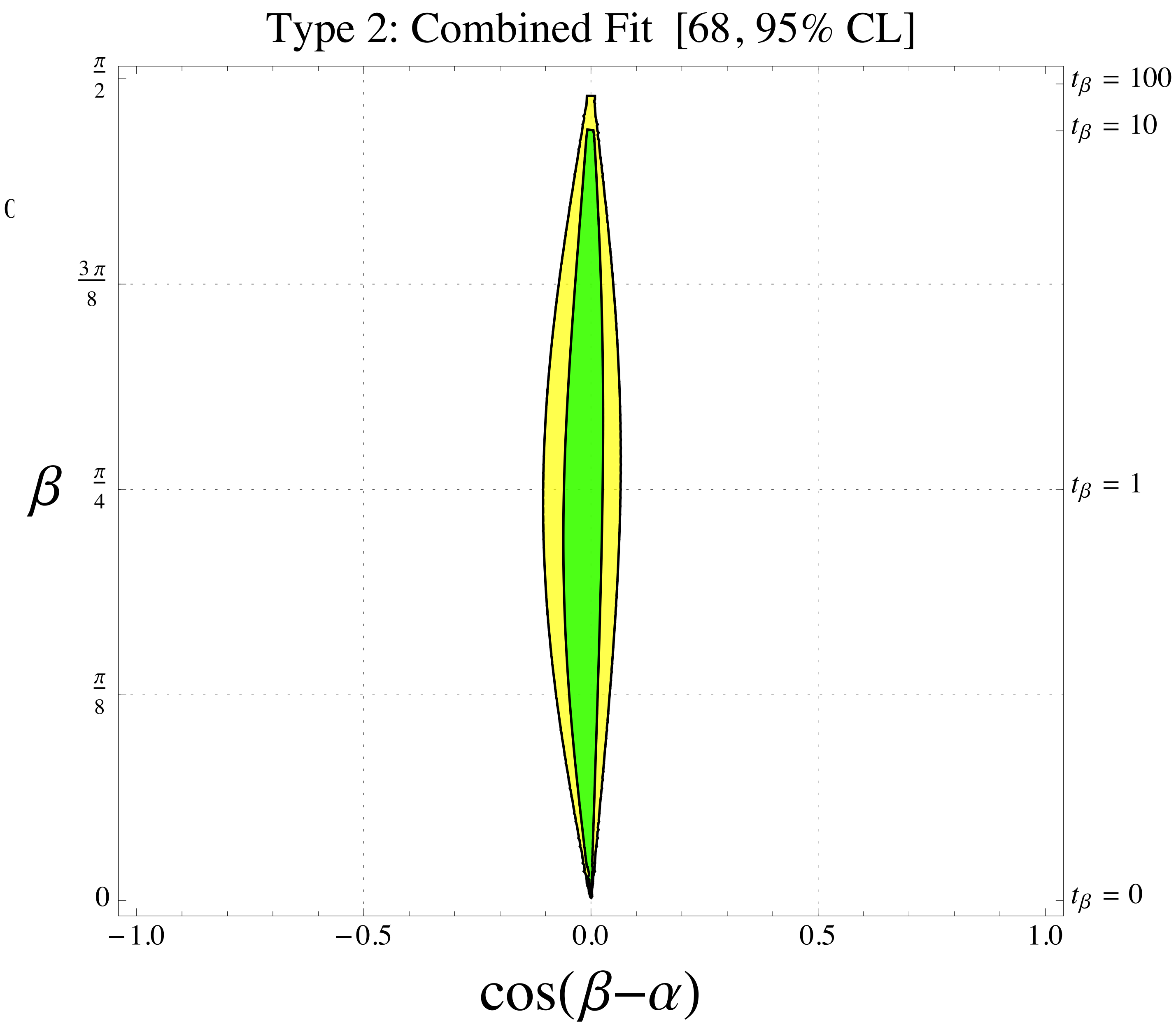
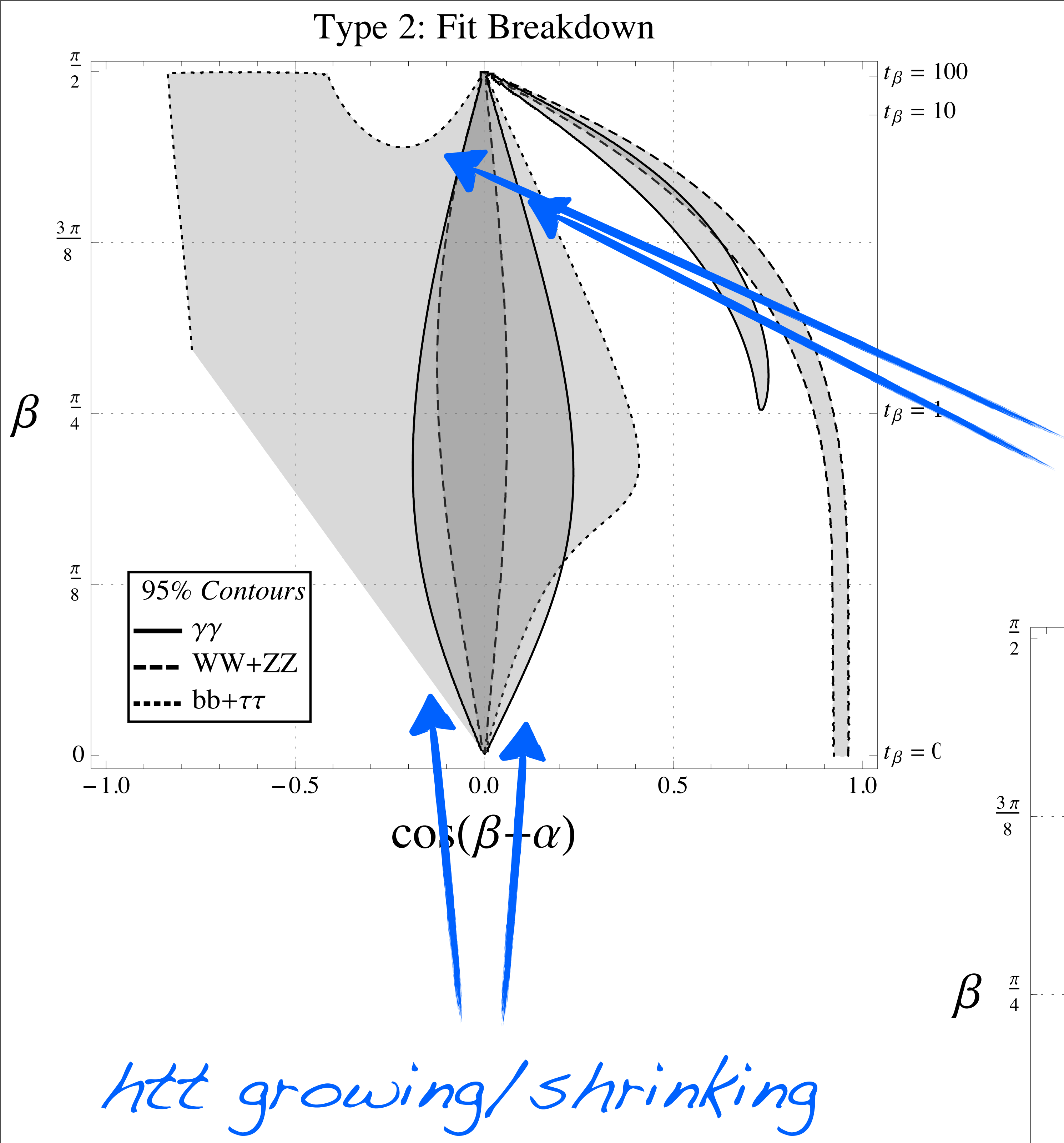
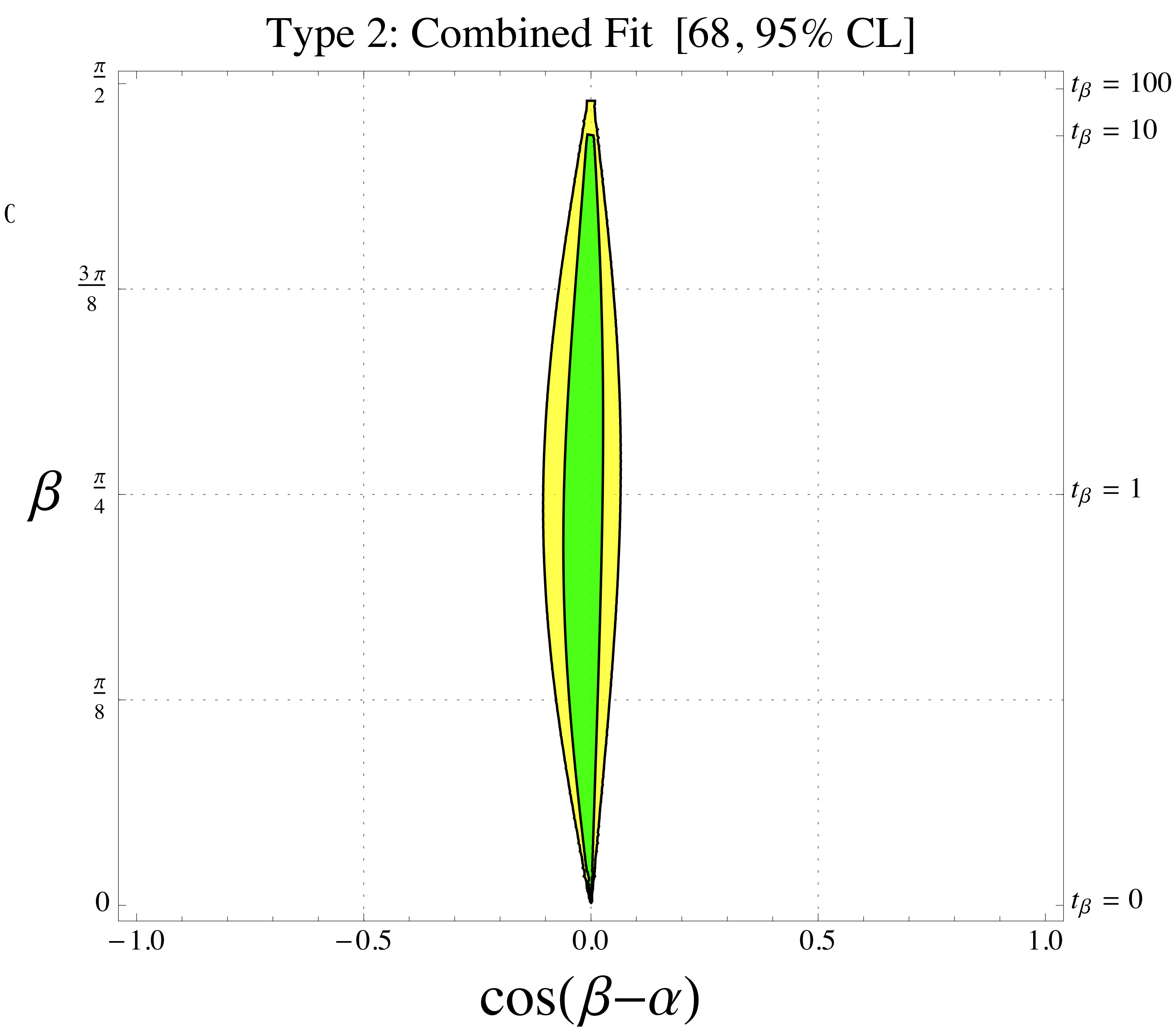
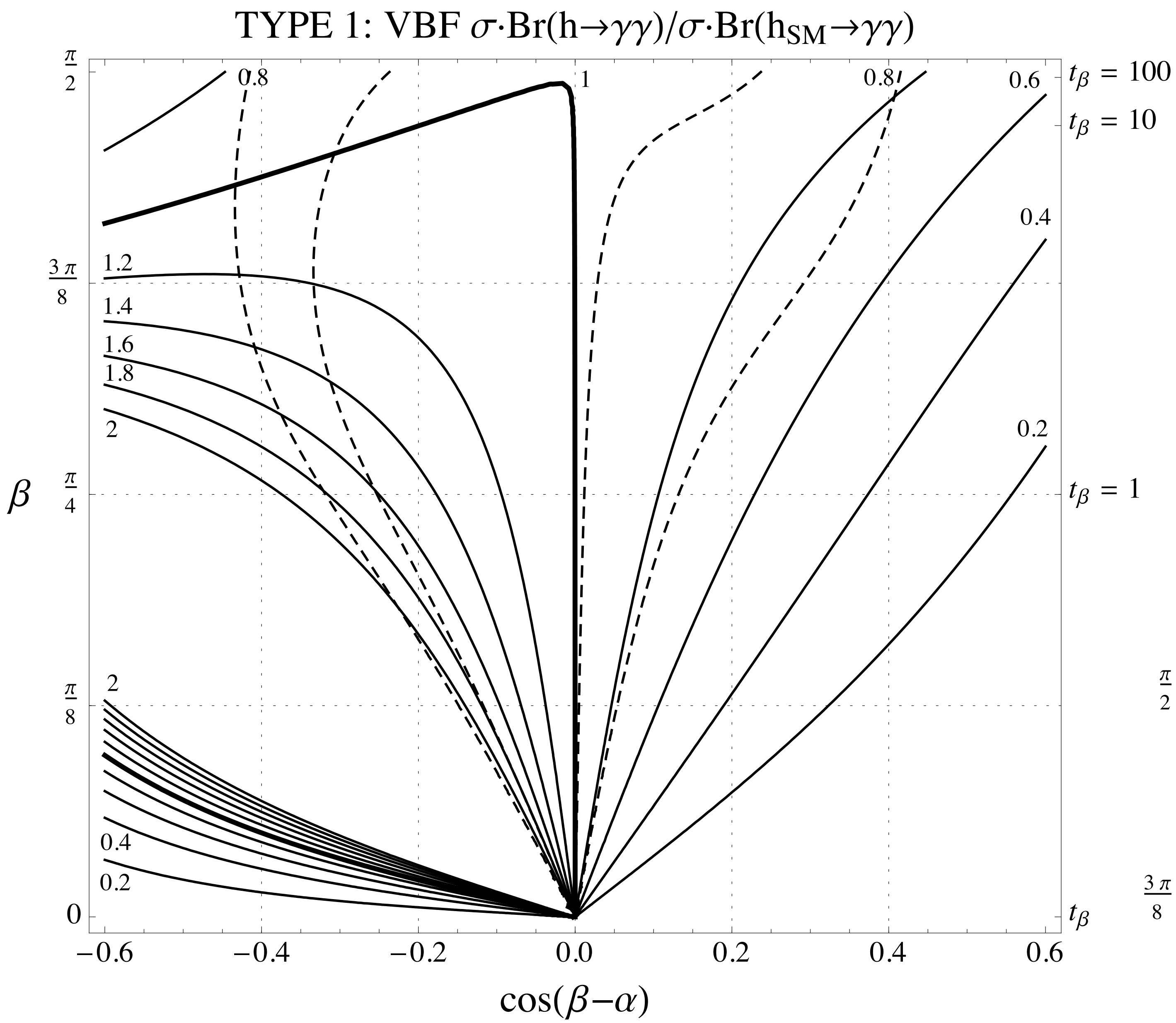
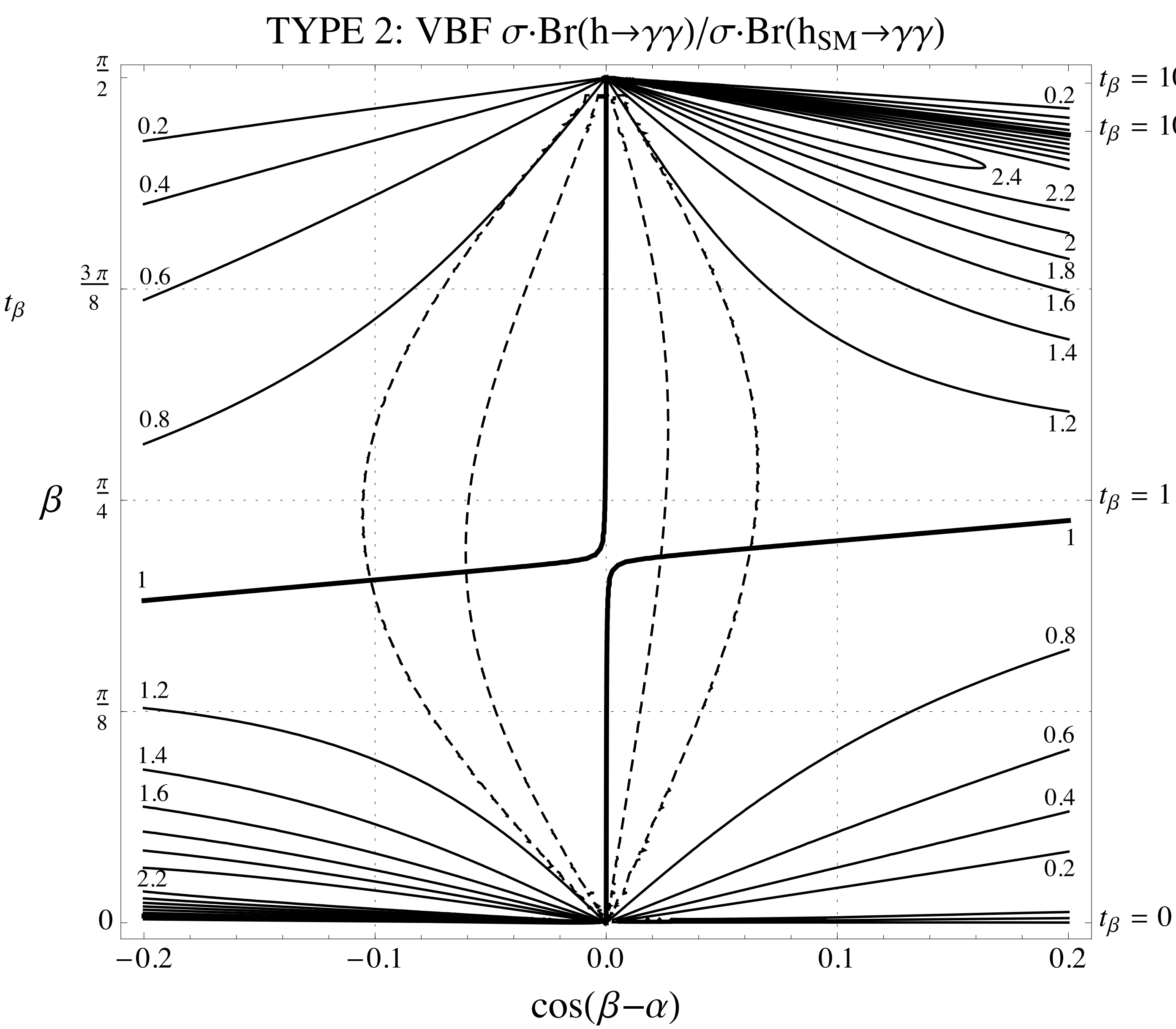


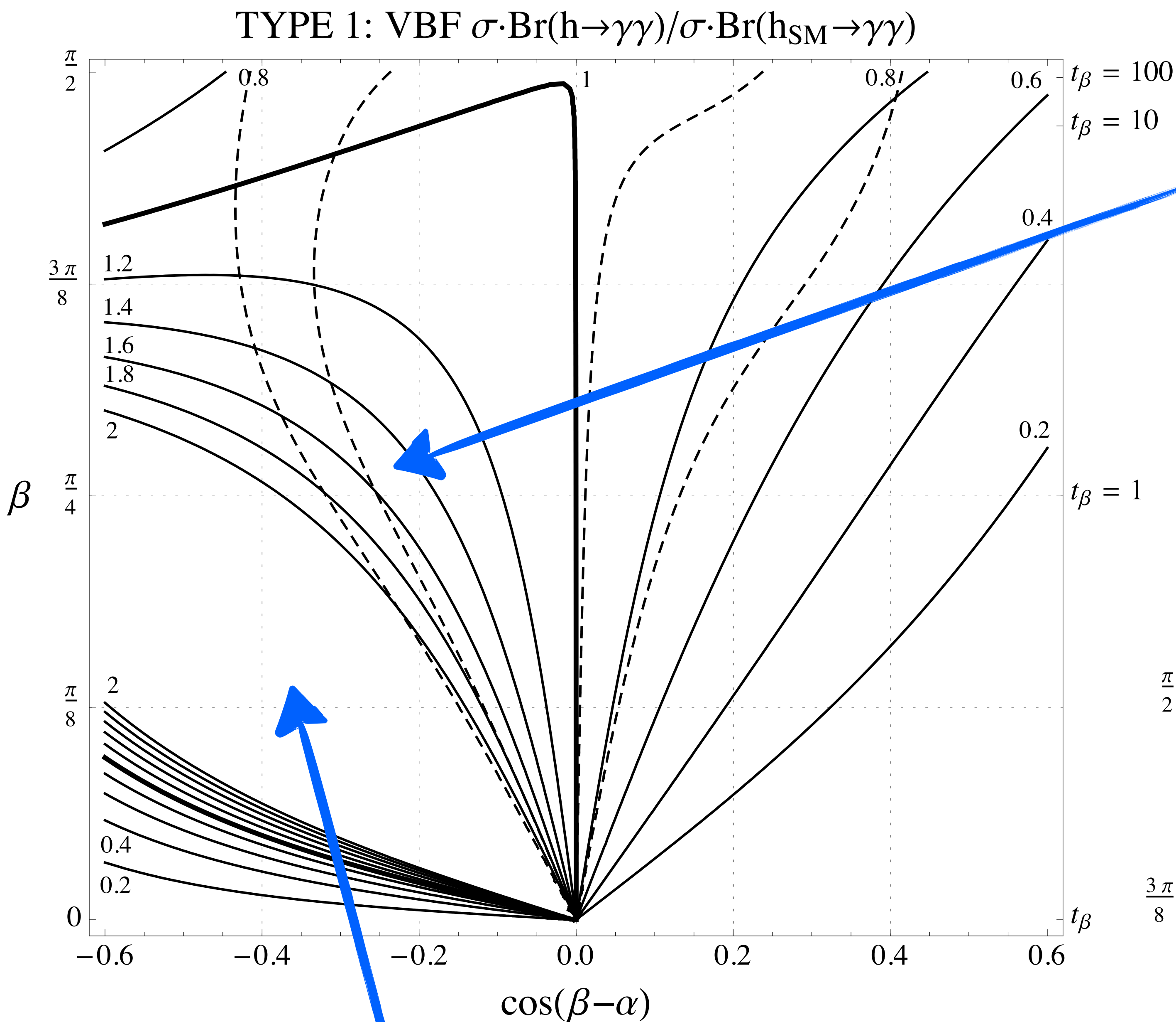


(1) Study the couplings



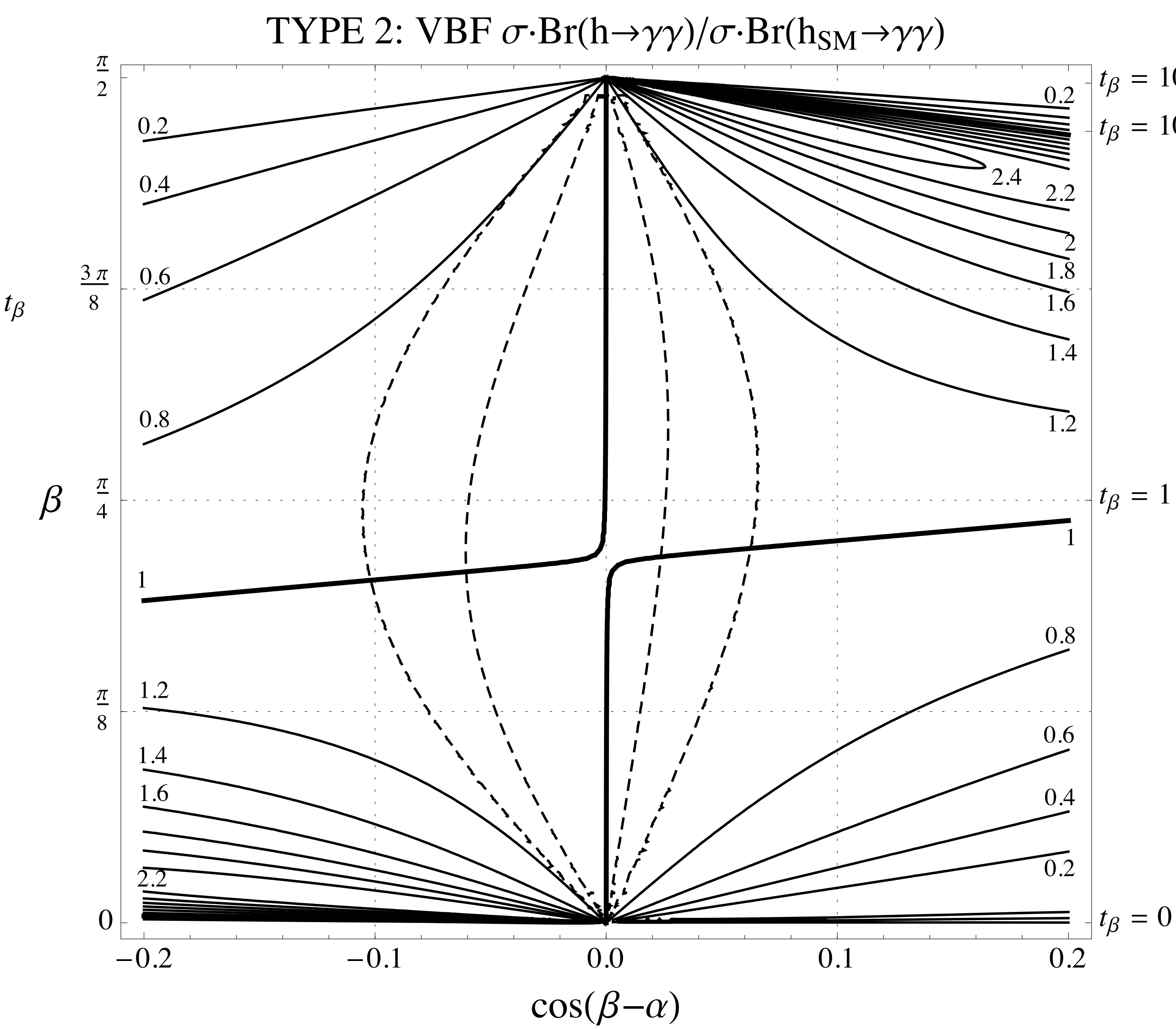

TYPE 1: VBF $\sigma\cdot$Br(h→$\gamma\gamma$)/$\sigma\cdot$Br(h_{SM}→$\gamma\gamma$)
t_β = 100
t_β = 10
t_β = 1
t_β
β
cos($\beta-\alpha$)


TYPE 2: VBF $\sigma\cdot$Br(h→$\gamma\gamma$)/$\sigma\cdot$Br(h_{SM}→$\gamma\gamma$)
t_β = 100
t_β = 10
t_β = 1
t_β = 0
β
cos($\beta-\alpha$)



Room for excitement
Total width & hgg drop but hVV large.

Zero in fermion couplings



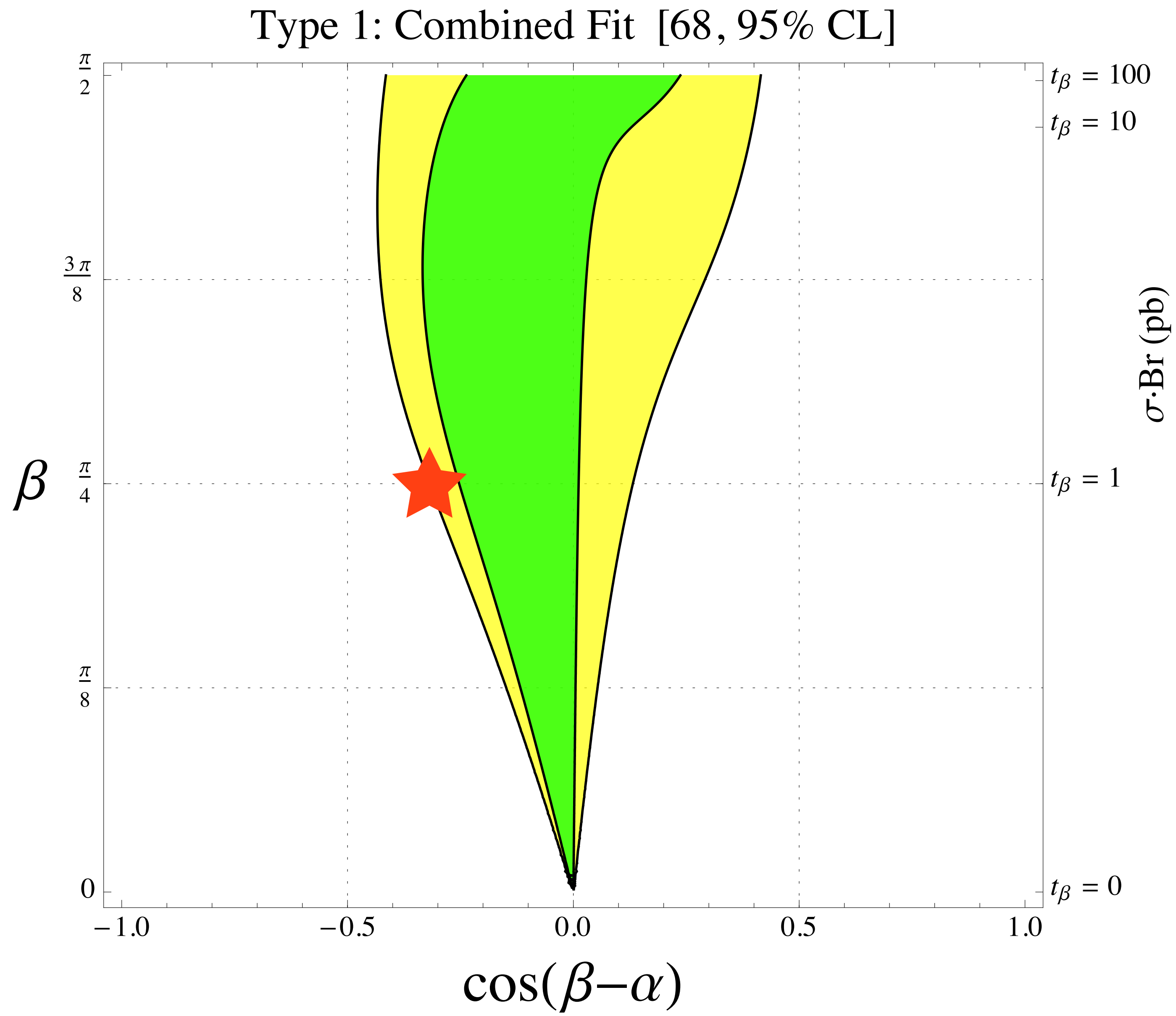
- We live near the alignment limit, but precisely how near depends sensitively on the 2HDM type.

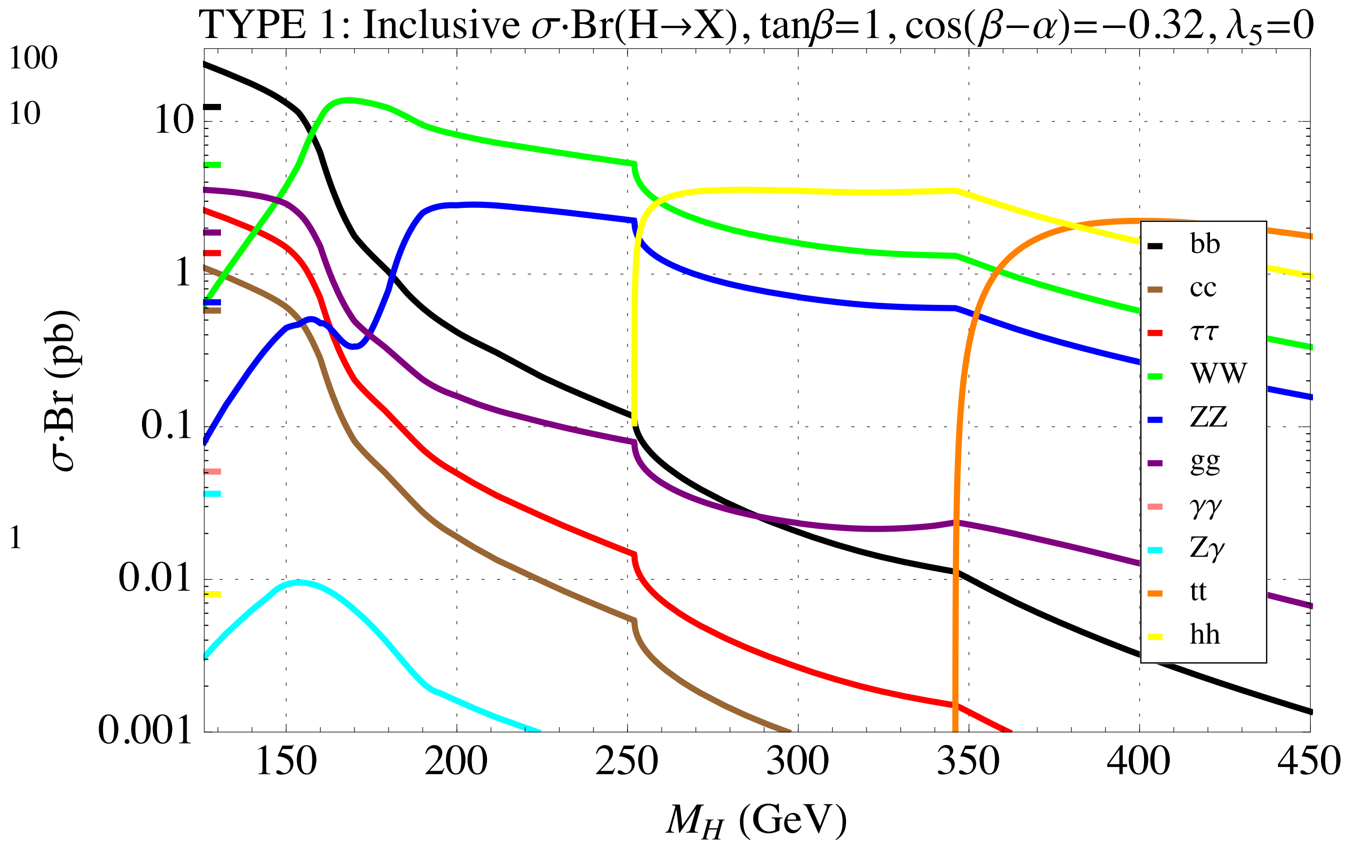
- This proximity has little to do with directly measuring the coupling to vectors, and a lot to do with the total width and gluon coupling.

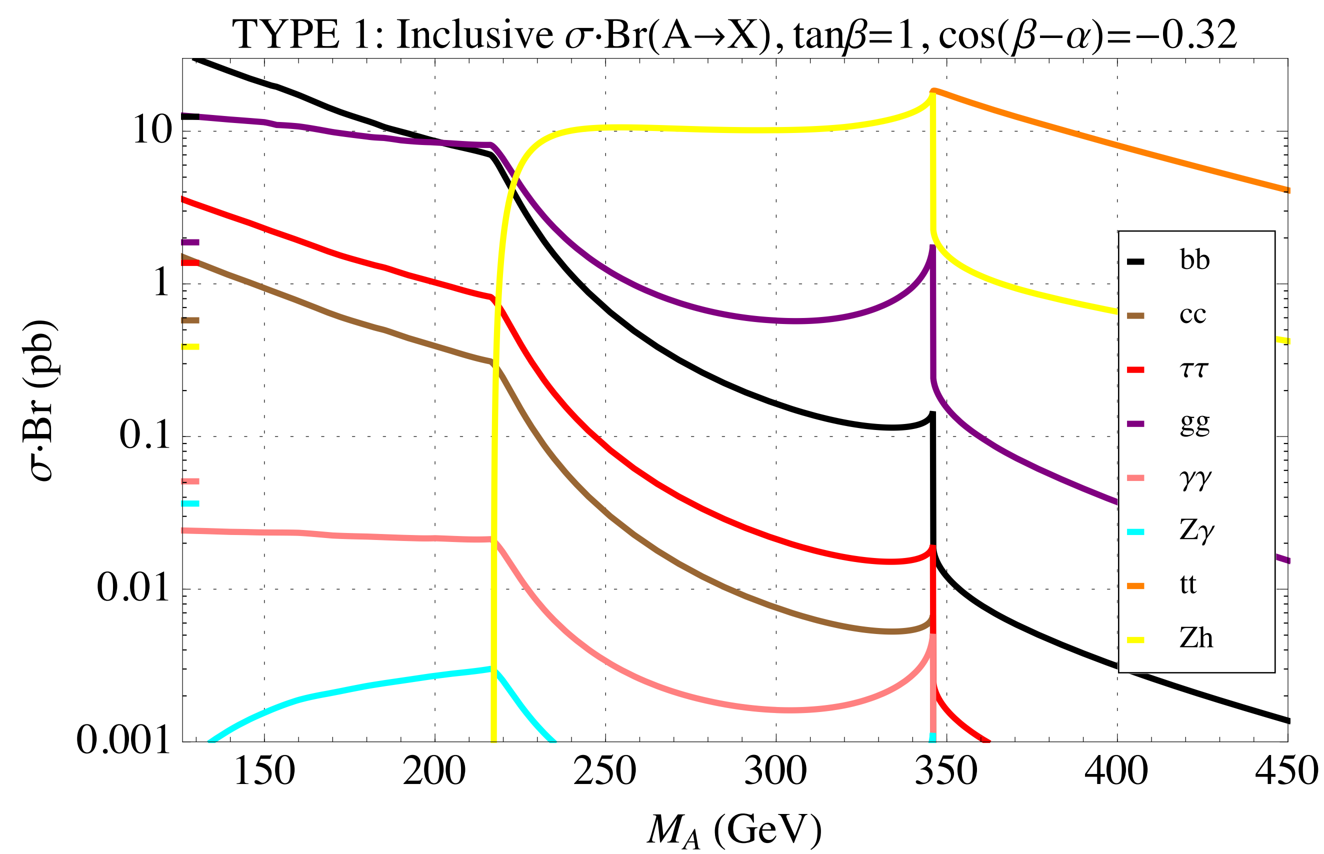
- There is room for surprises, especially in future measurement of VBF diphoton.

Look directly for the second Higgs

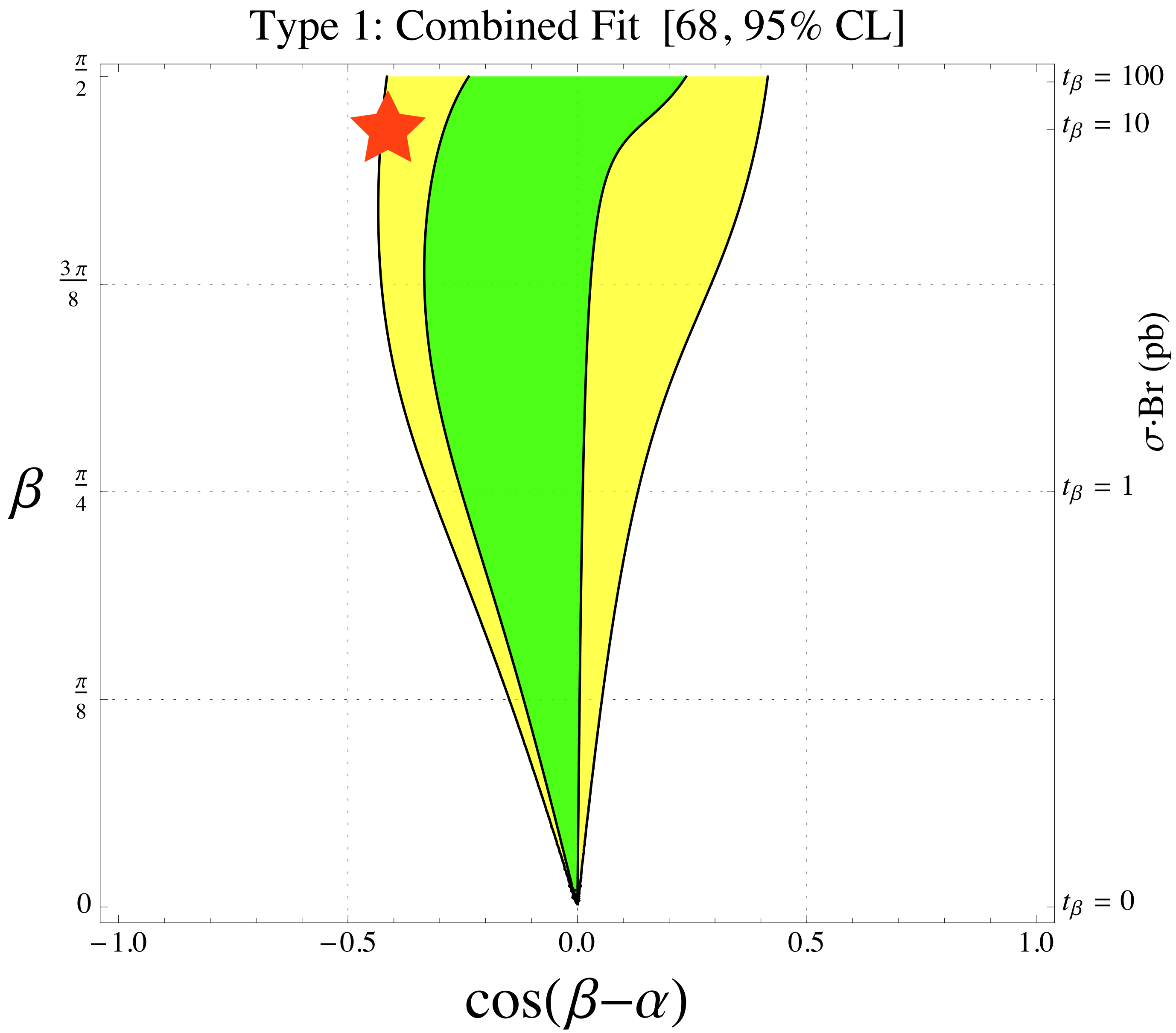
Second Higgs Doublet Decay Topology	Alignment Limit
$H \to WW, ZZ$	–
$H, A \to \gamma\gamma$	✓
$H, A \to \tau\tau, \mu\mu$	✓
$H, A \to tt$	✓
$A \to Zh$	–
$H \to hh$	–
$t \to H^{\pm}b$	✓

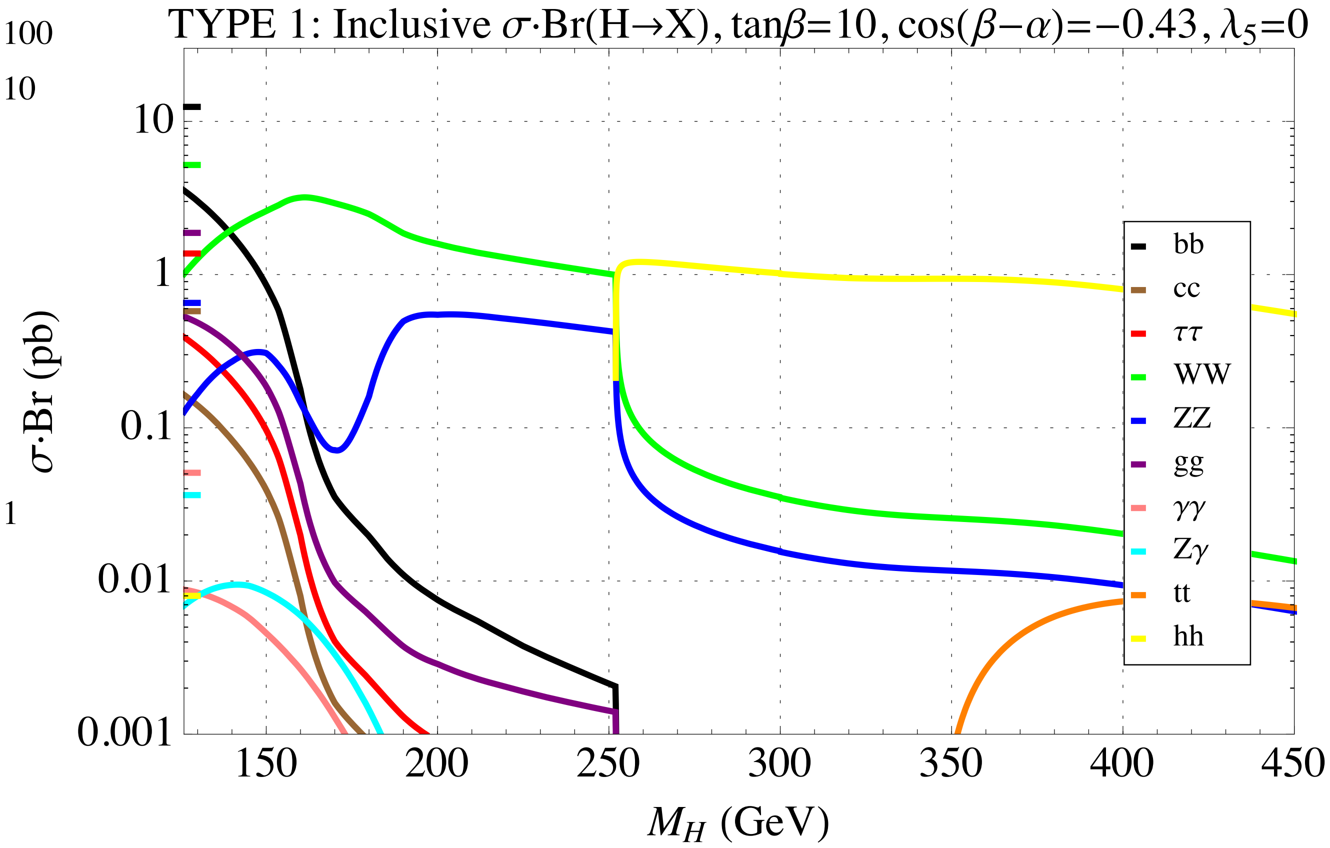


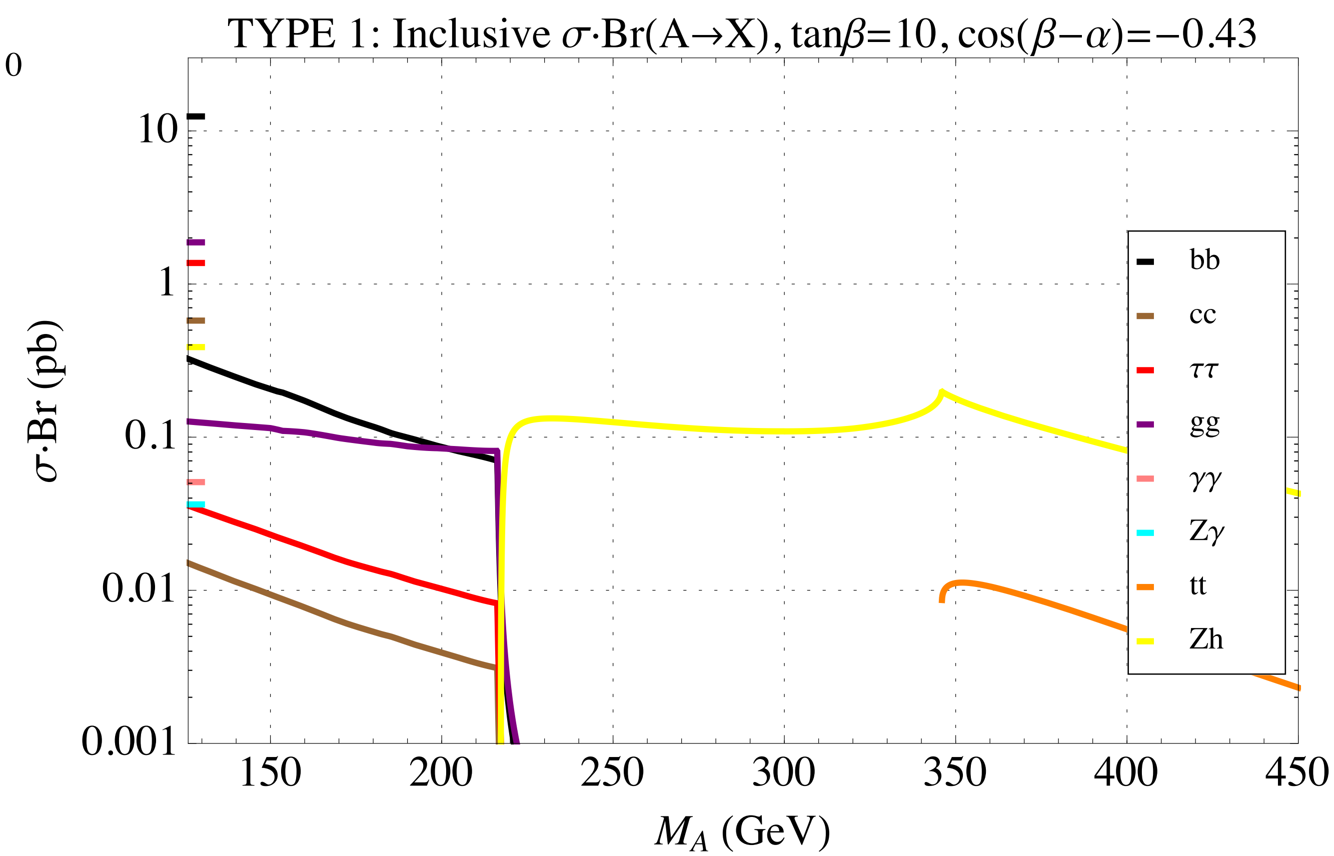




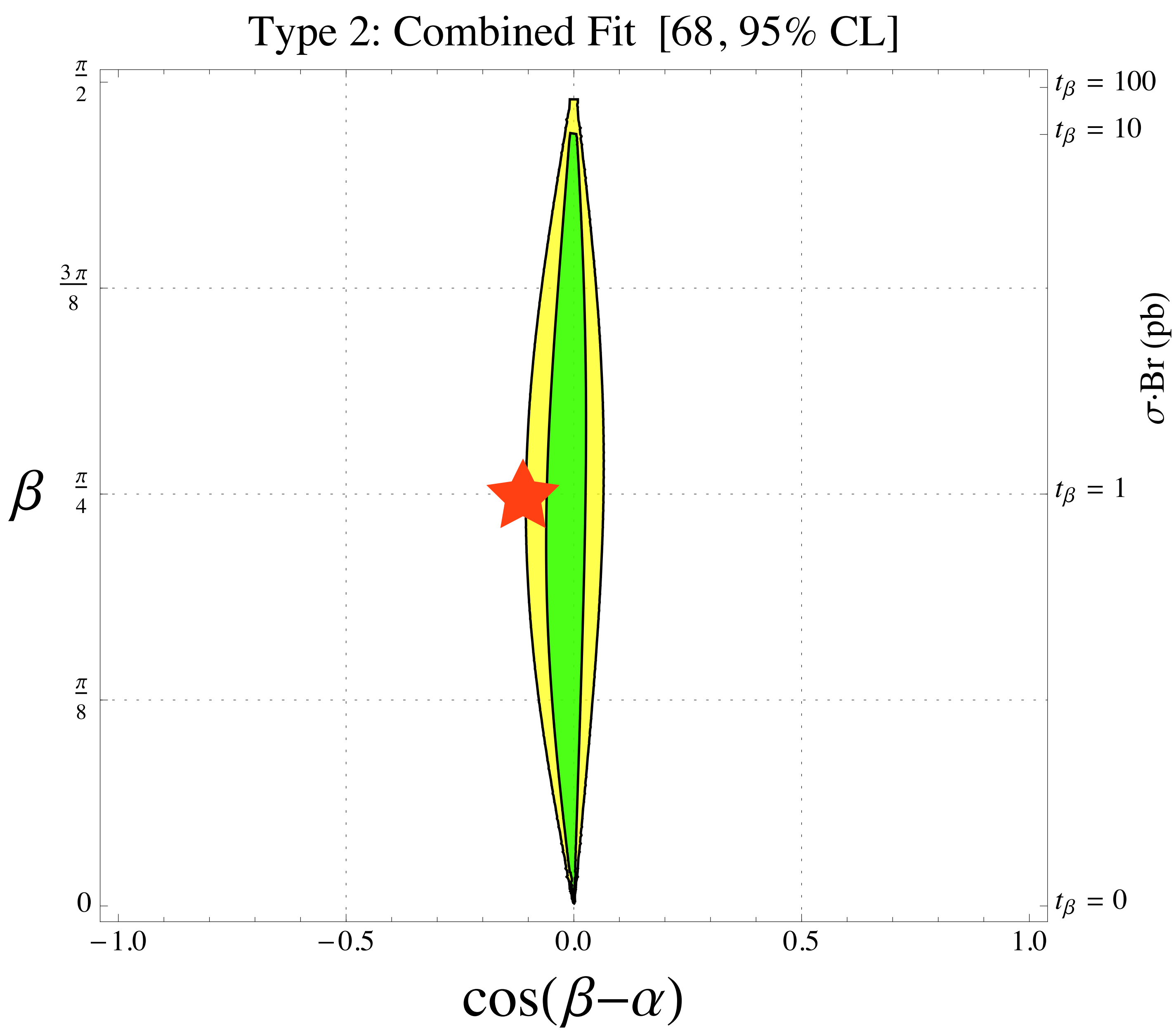
Type 1 2HDM,
low tan beta

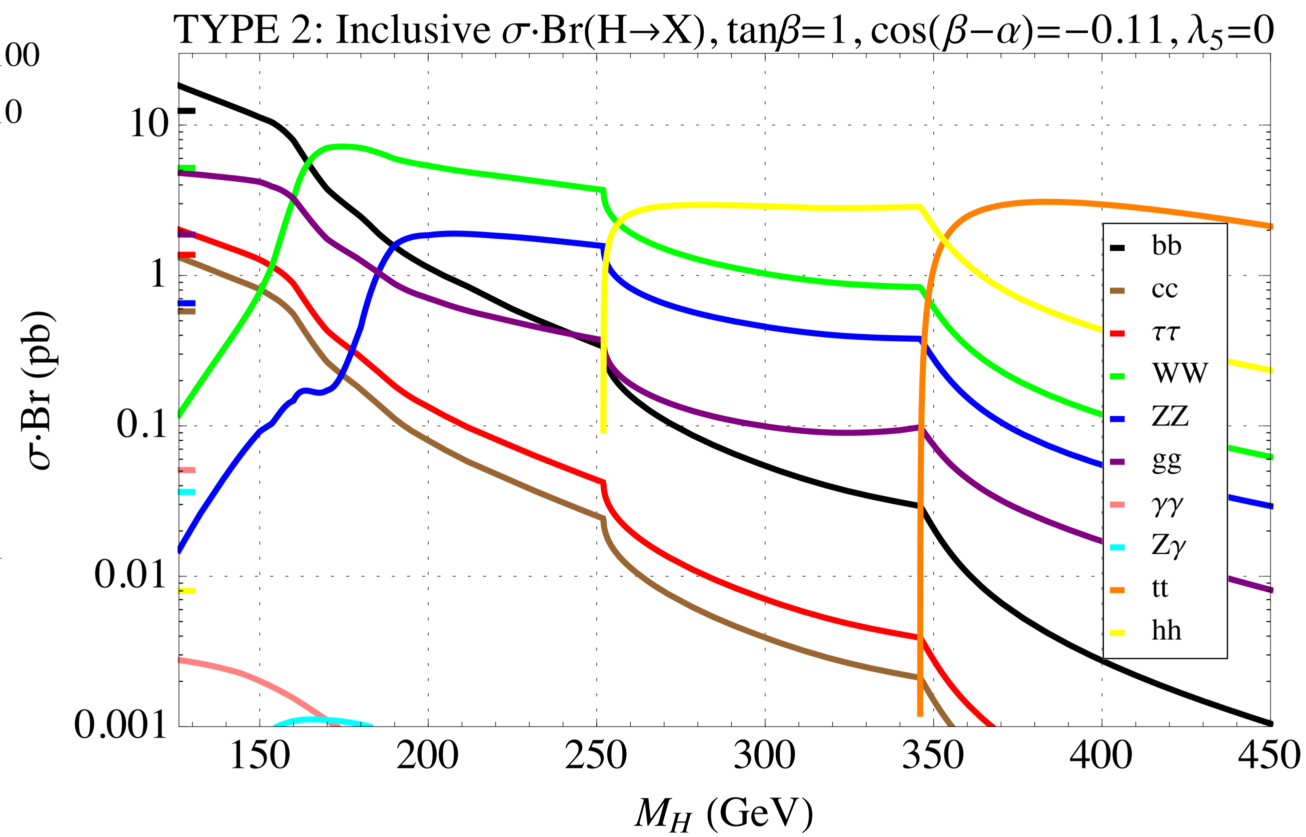




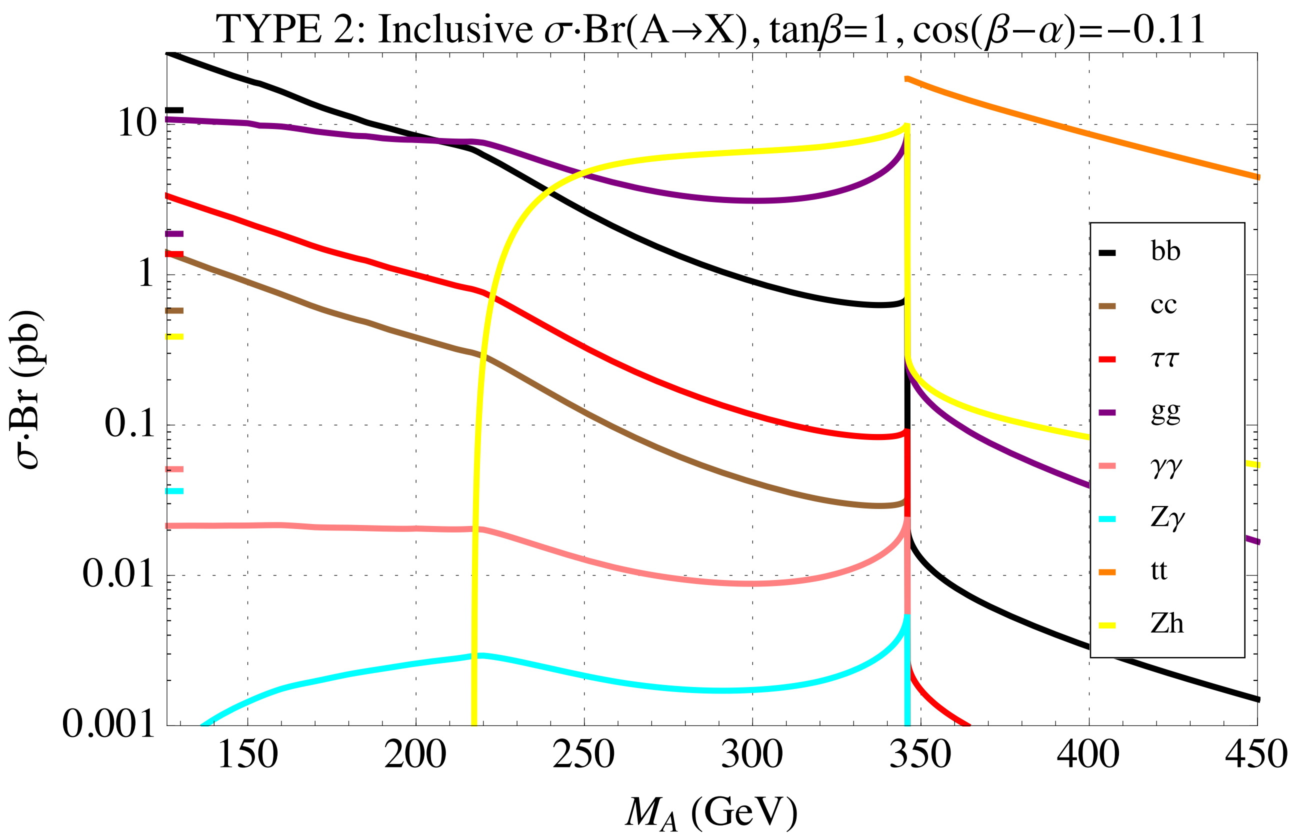


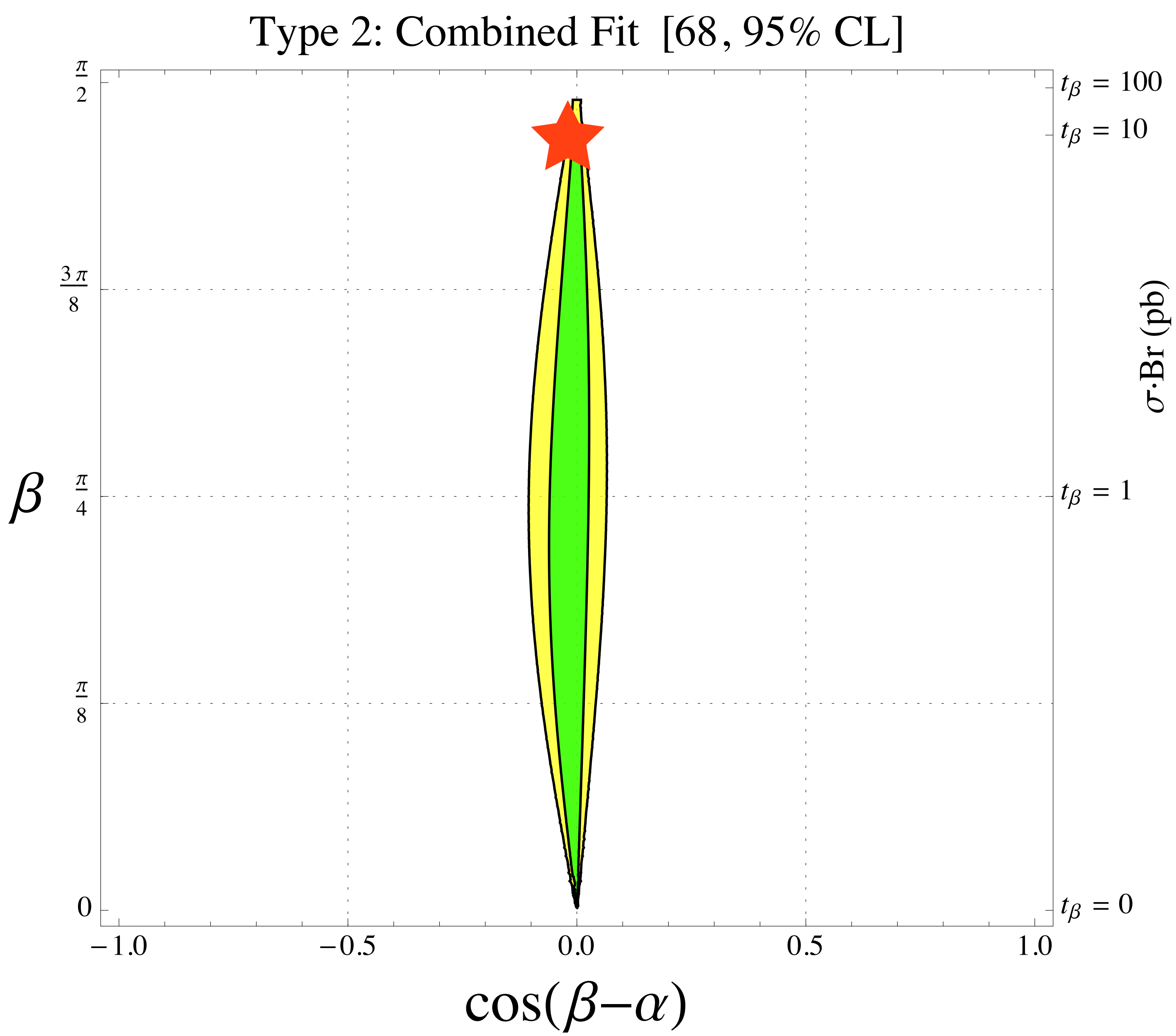
Type 1 2HDM,
high tan beta

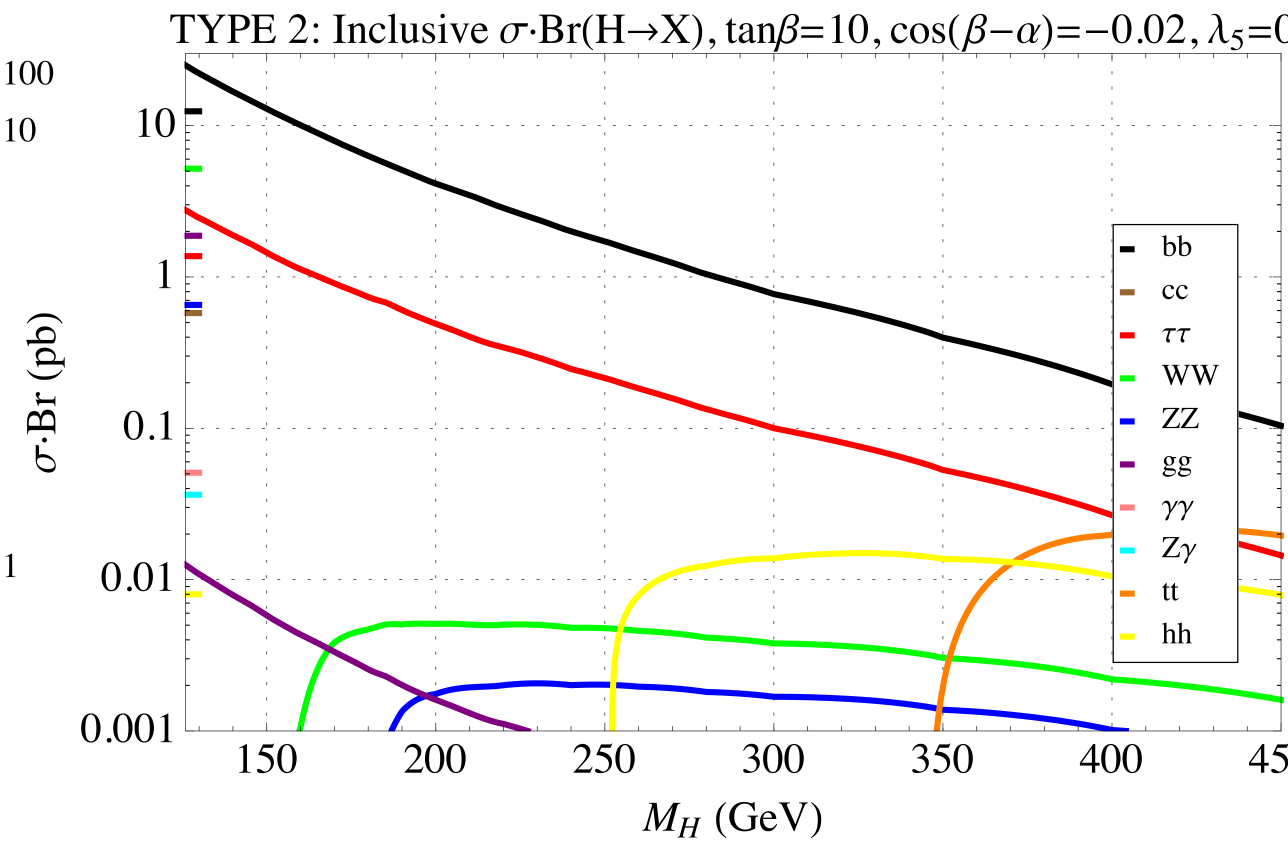


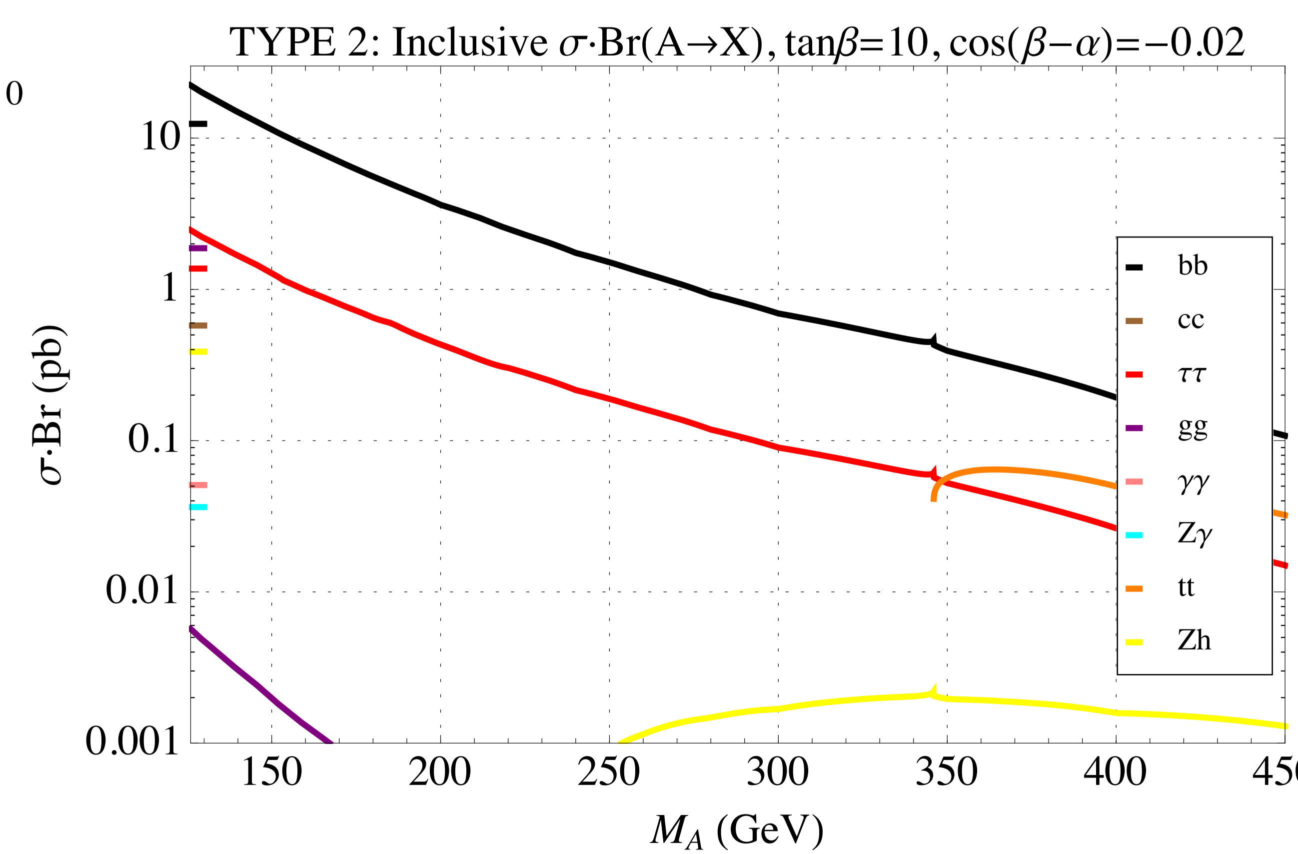


Type 2 2HDM,
low tan beta









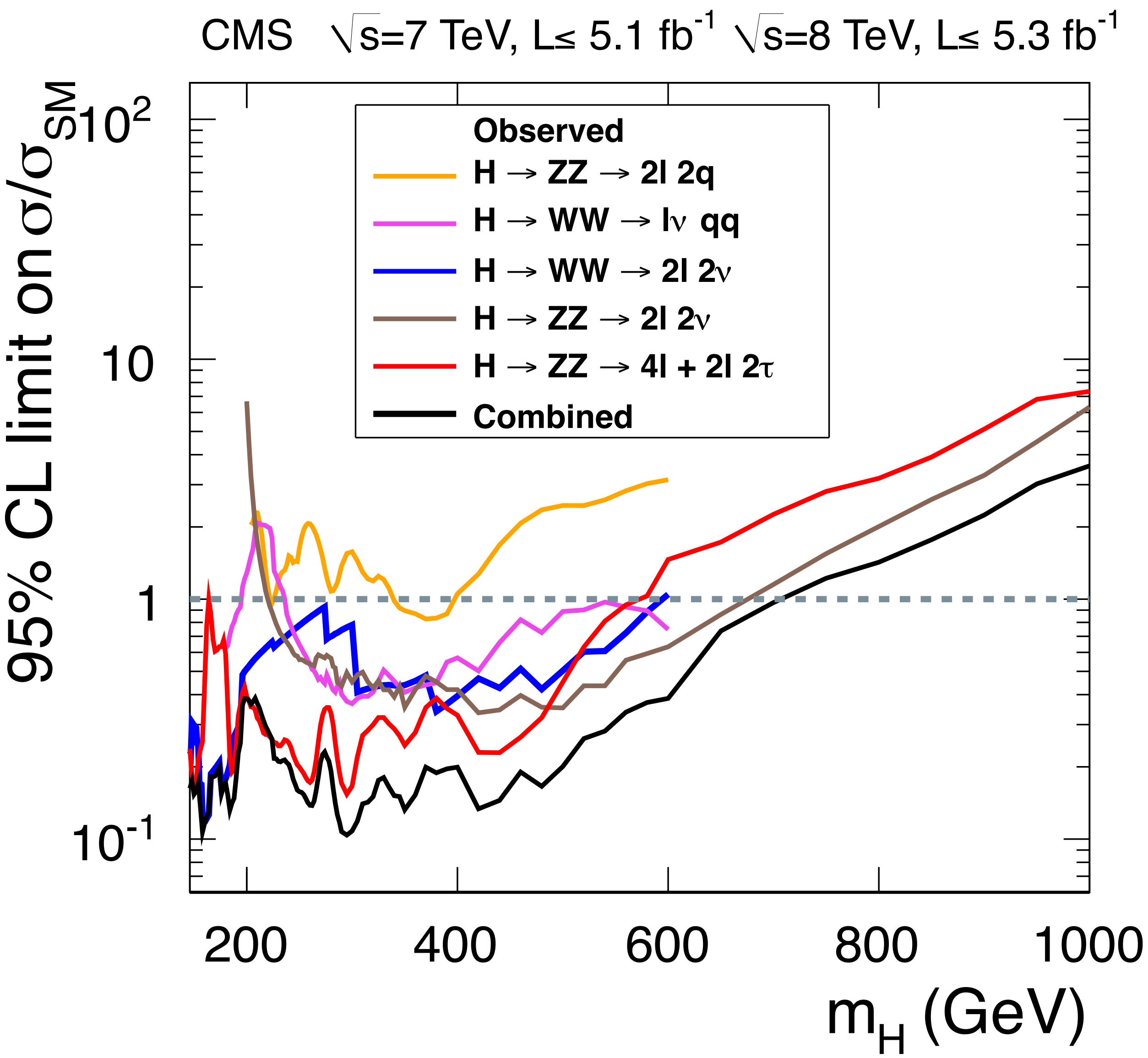
Type 2 2HDM,
high tan beta

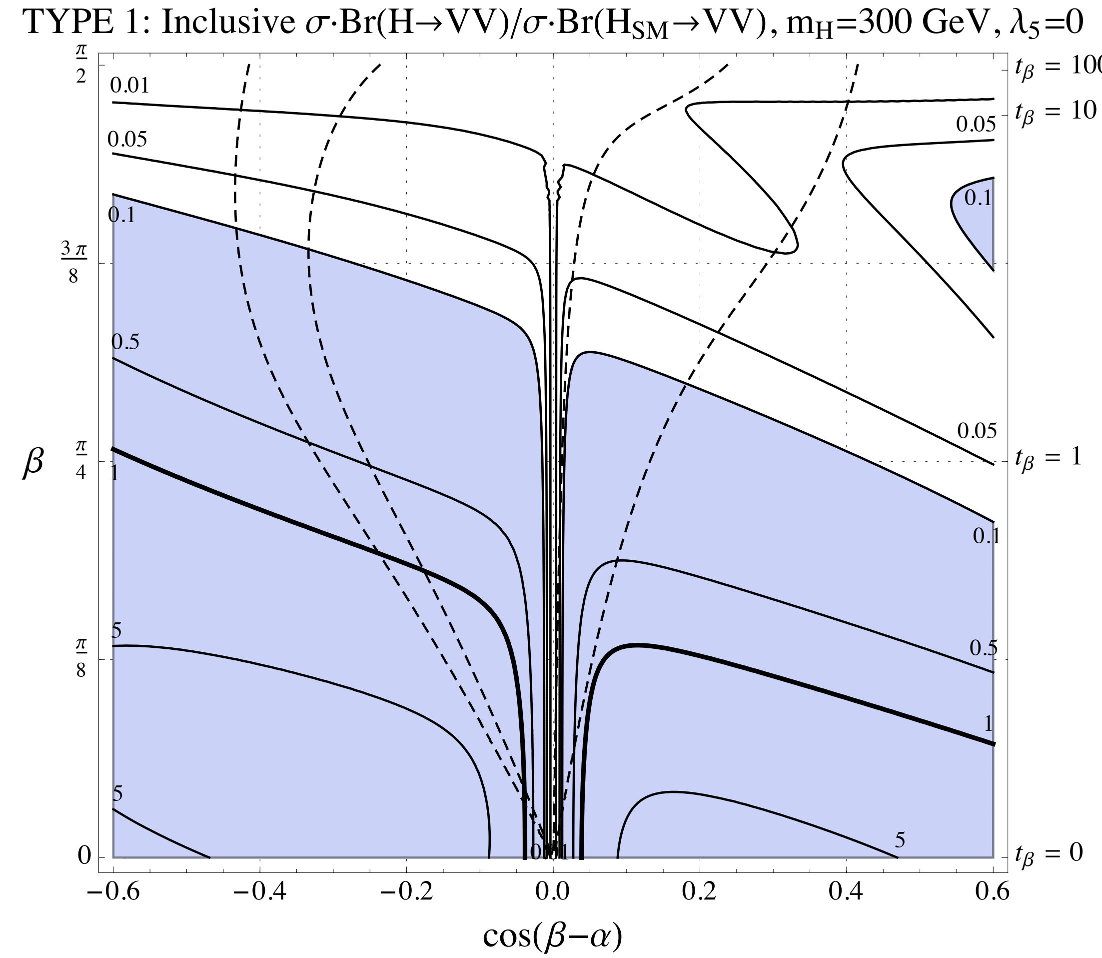
- Even in the exact alignment limit, the scalars H and A have large gluon fusion production cross sections, since their top couplings are nonzero.

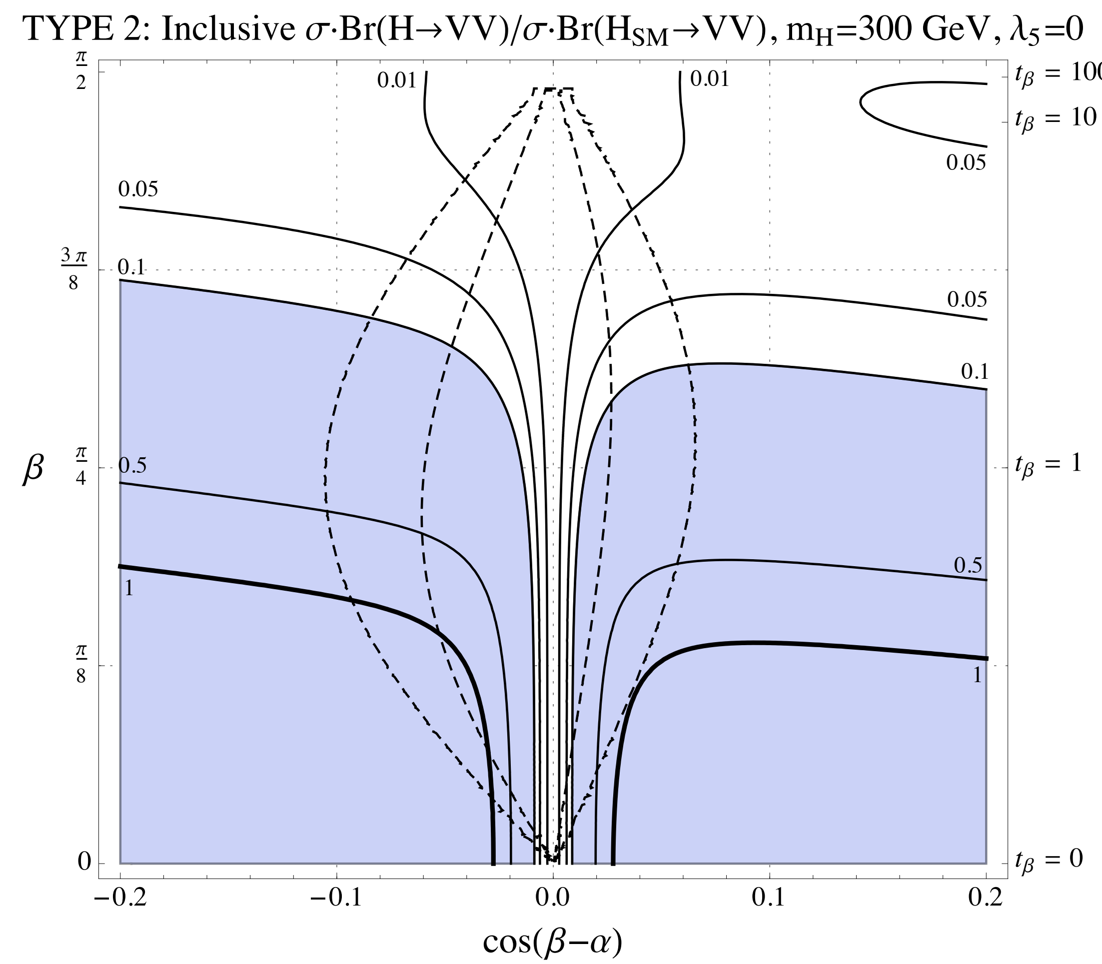
- Even close to the exact alignment limit, processes such as H>VV can be appreciable because the competition is only with H > bb below the top pair threshold.

(2) Look in standard Higgs channels

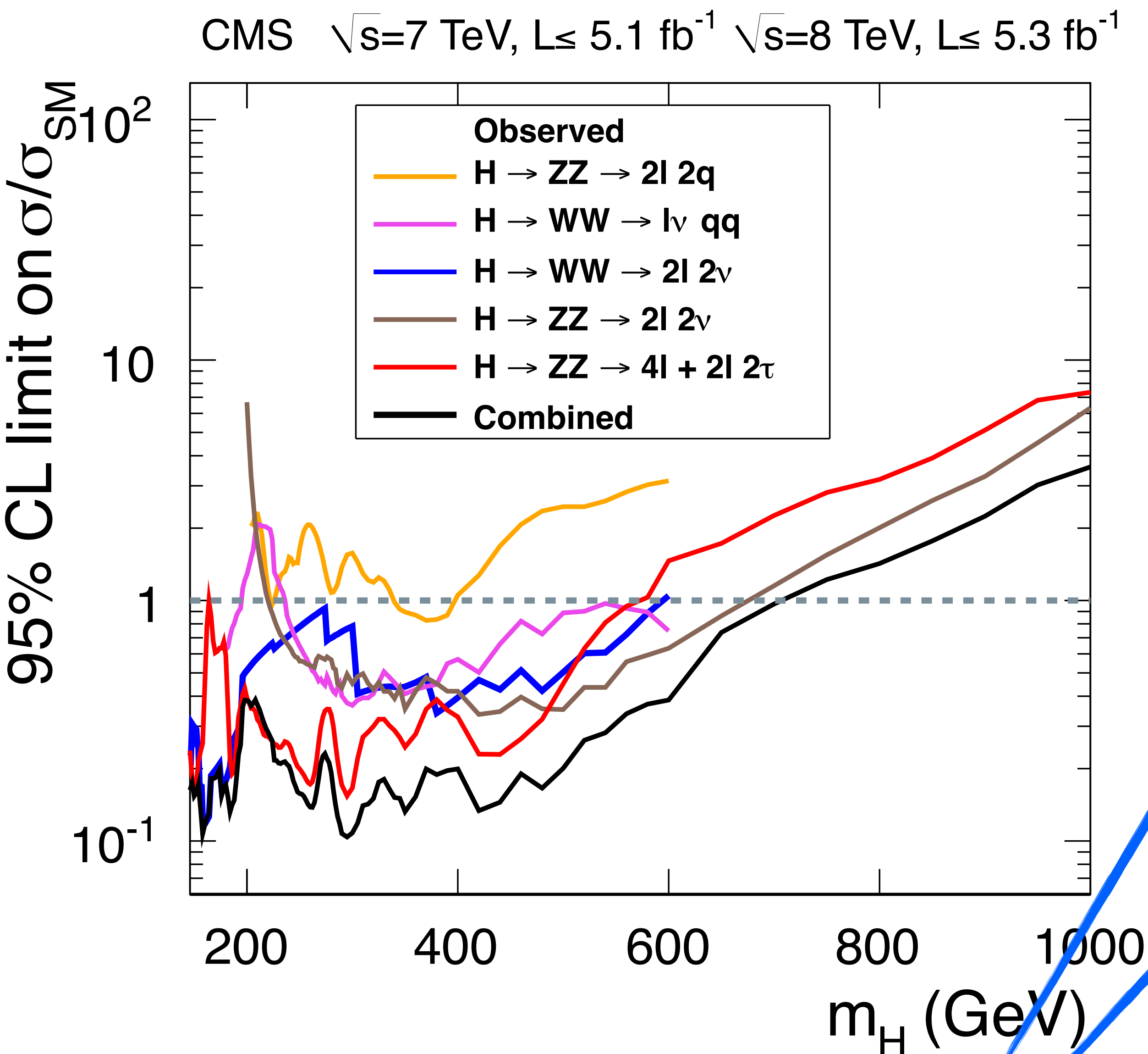
H → WW, ZZ

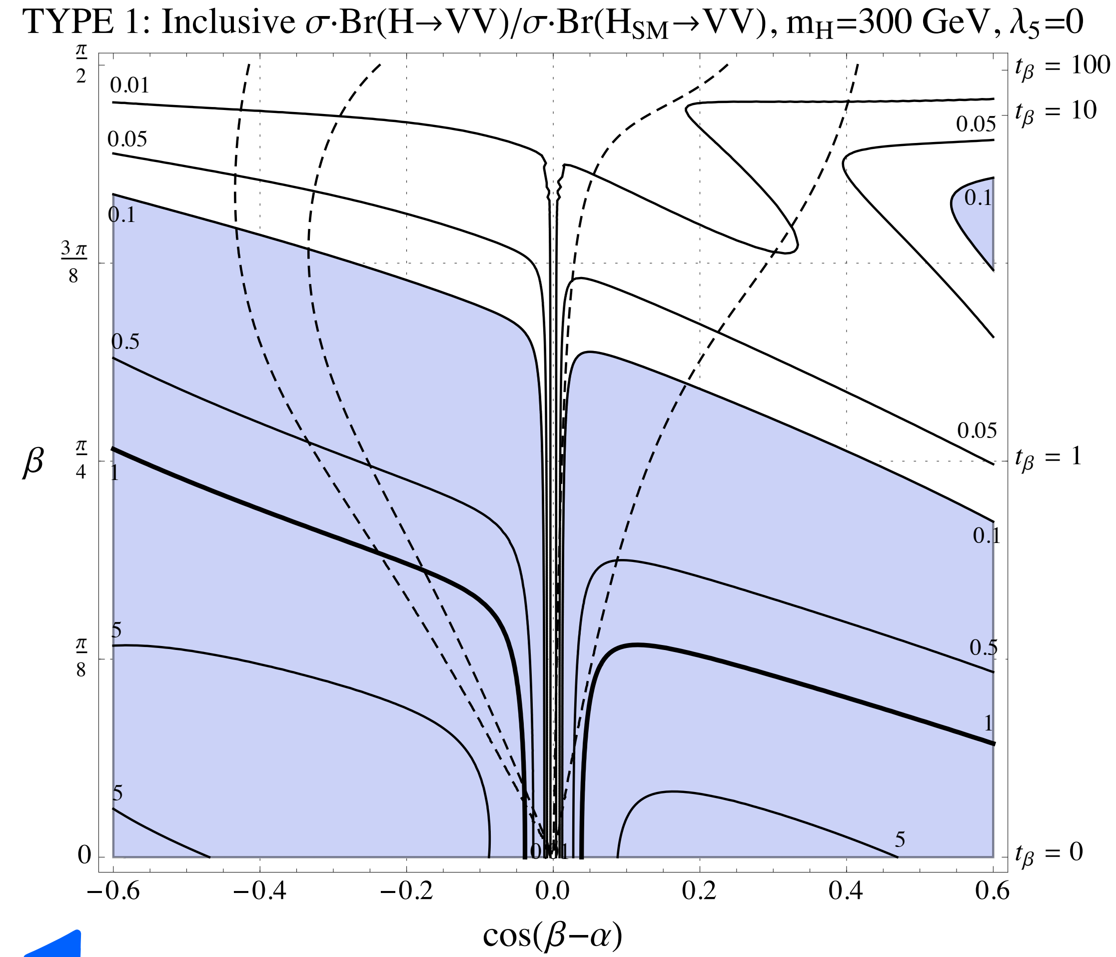

CMS √s=7 TeV, L≤ 5.1 fb^{-1} √s=8 TeV, L≤ 5.3 fb^{-1}
Observed
H → ZZ → 2l 2q
H → WW → lν qq
H → WW → 2l 2ν
H → ZZ → 2l 2ν
H → ZZ → 4l + 2l 2τ
Combined
95% CL limit on σ/σ$_{SM}$
10^2
10
1
10^{-1}
200
400
600
800
1000
m$_H$ (GeV)

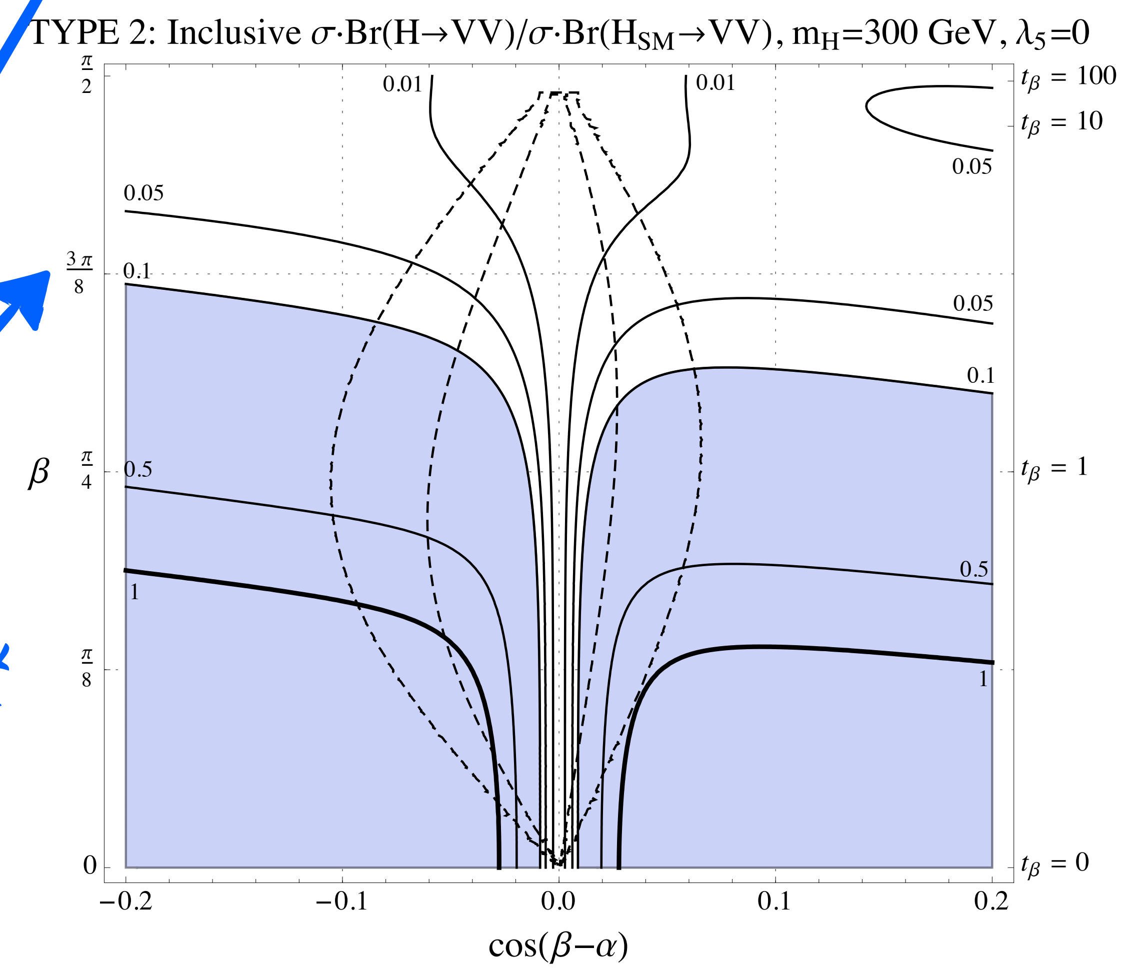

TYPE 1: Inclusive σ·Br(H→VV)/σ·Br(H$_{SM}$→VV), m$_H$=300 GeV, λ$_5$=0
β
t_β = 100
t_β = 10
t_β = 1
t_β = 0
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
cos(β−α)


TYPE 2: Inclusive σ·Br(H→VV)/σ·Br(H$_{SM}$→VV), m$_H$=300 GeV, λ$_5$=0
β
t_β = 100
t_β = 10
t_β = 1
t_β = 0
−0.2
−0.1
0.0
0.1
0.2
cos(β−α)

H > WW, ZZ



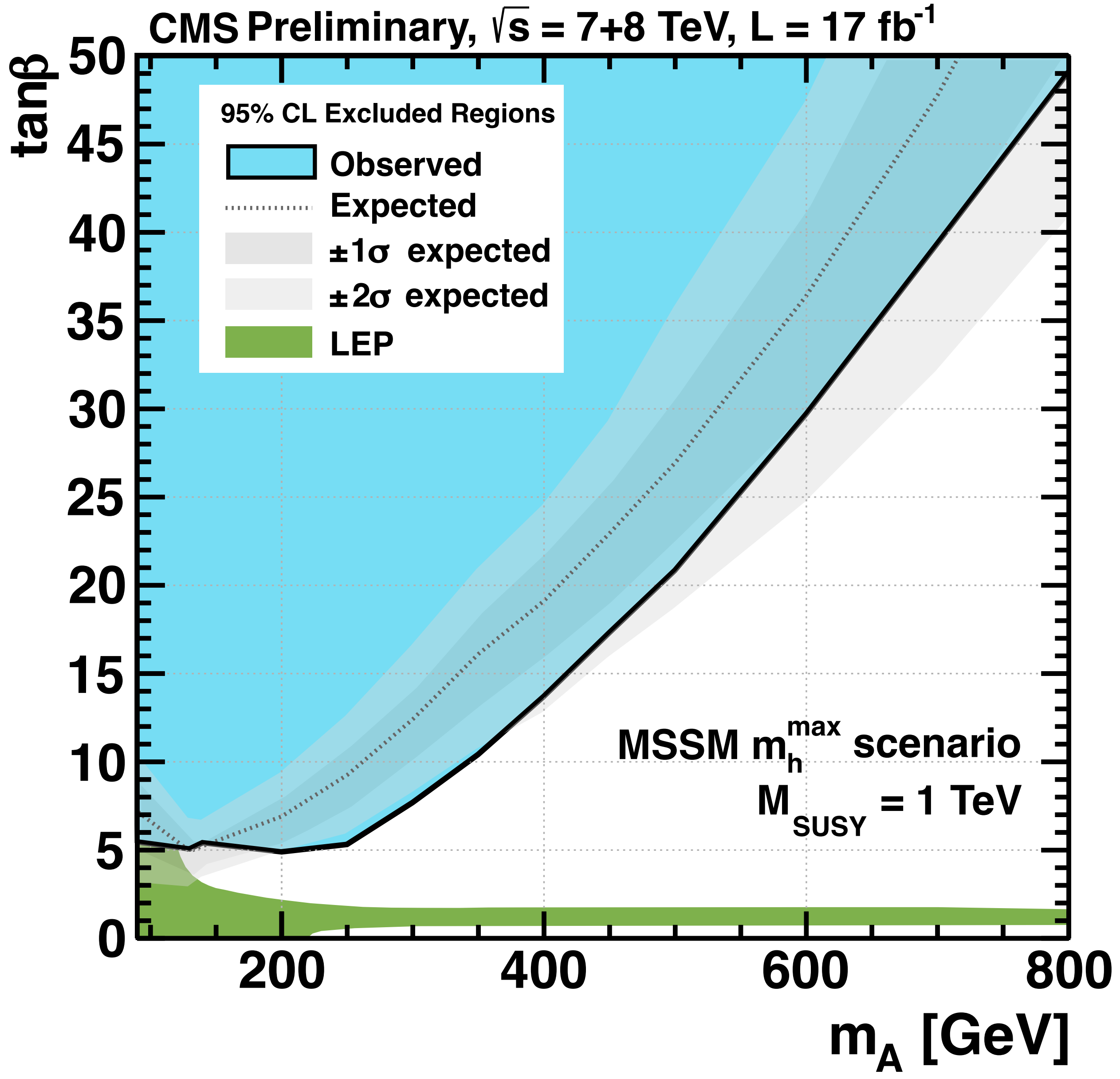


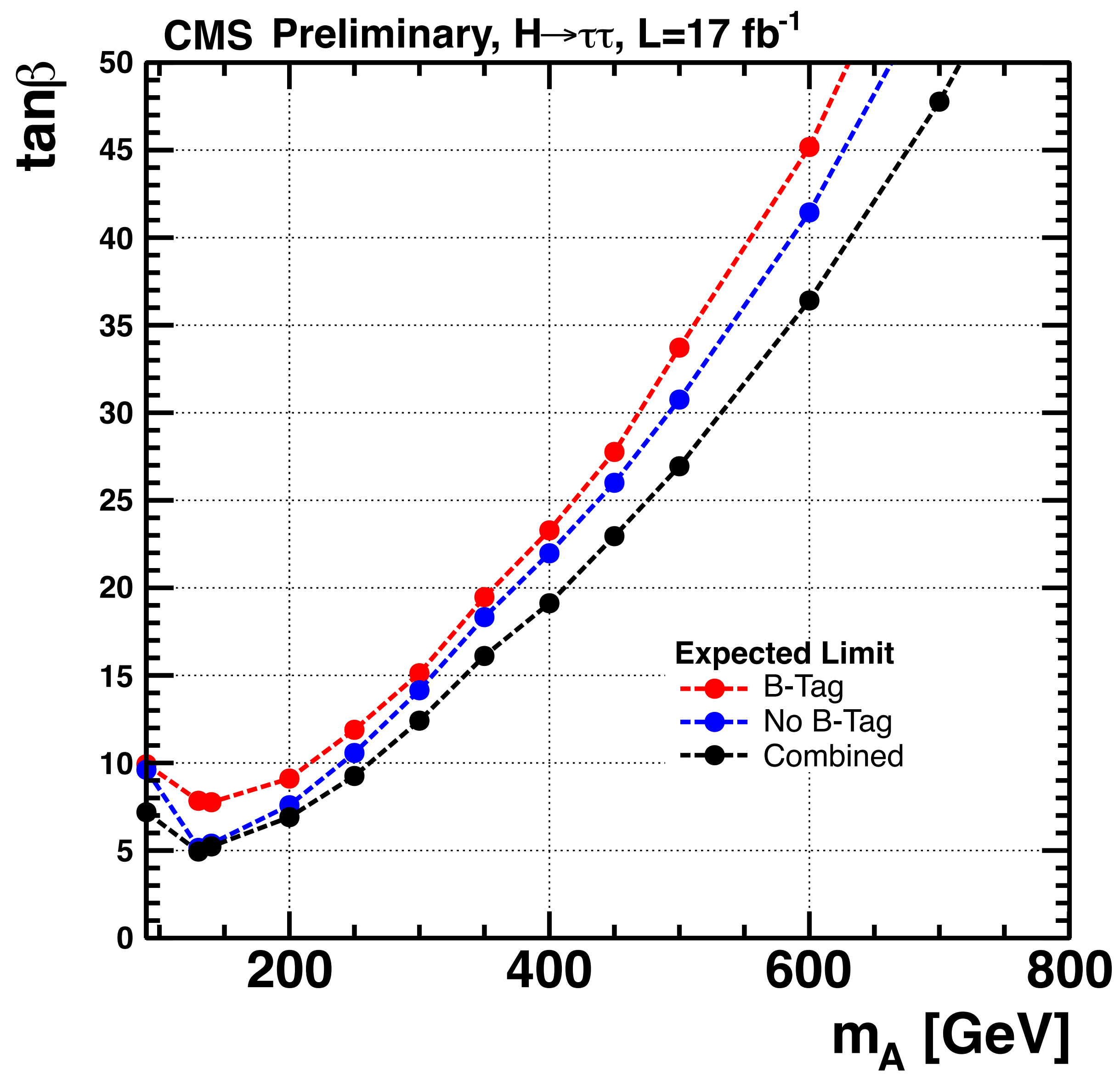


Contours are essentially just Htt, not HVV

H,A > tau tau

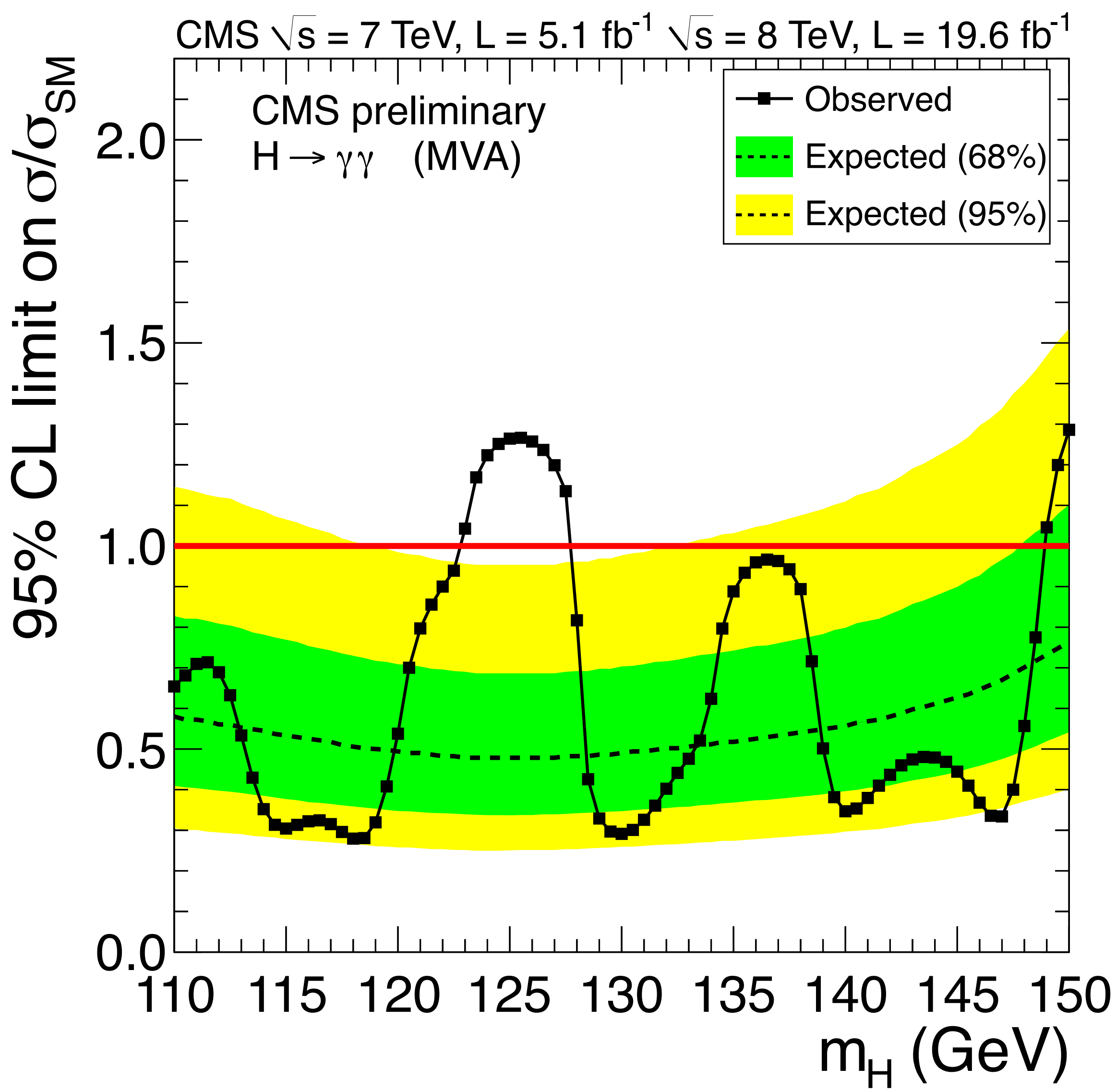
Sum of h, H, A signals
(no mass resolution)

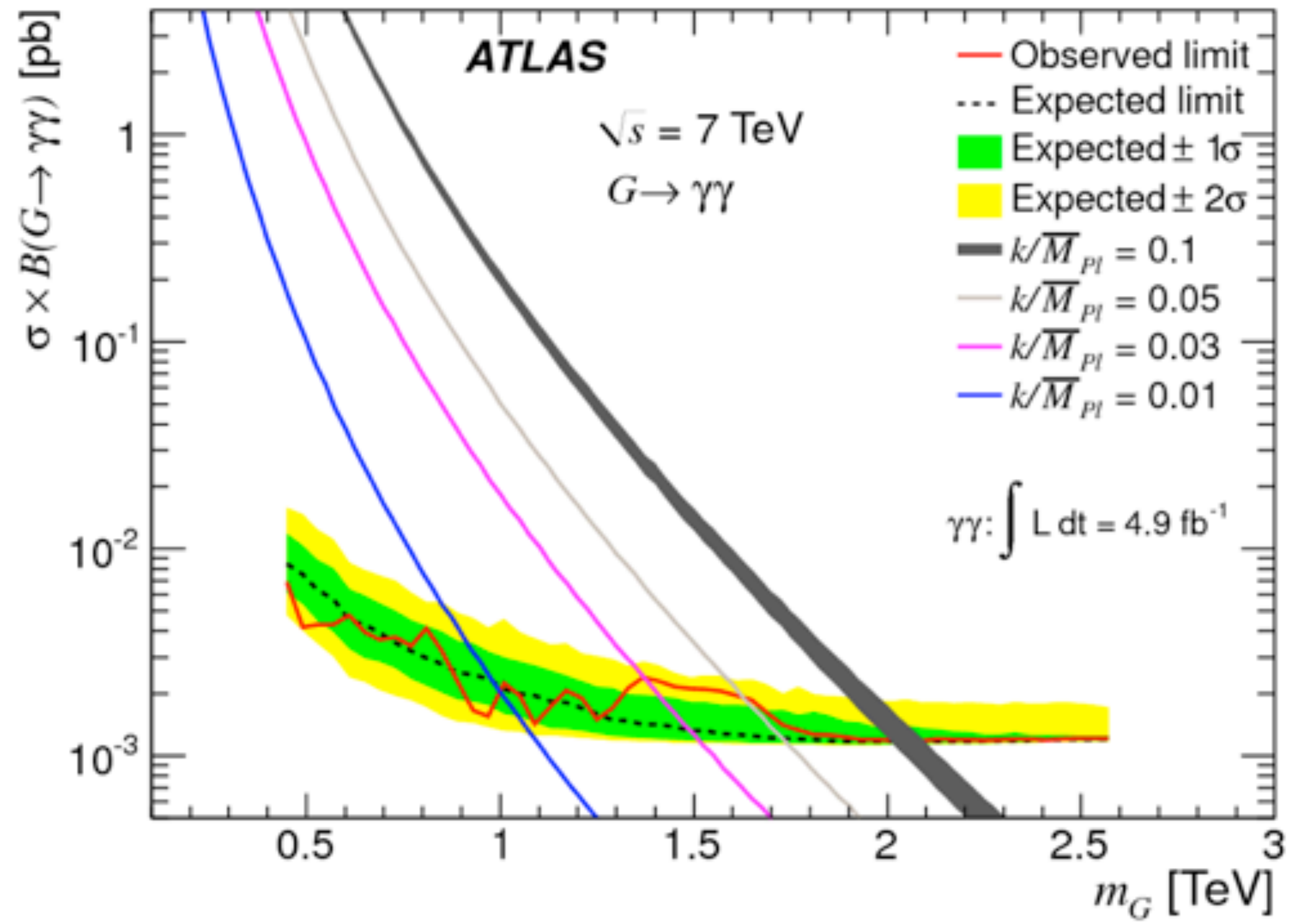


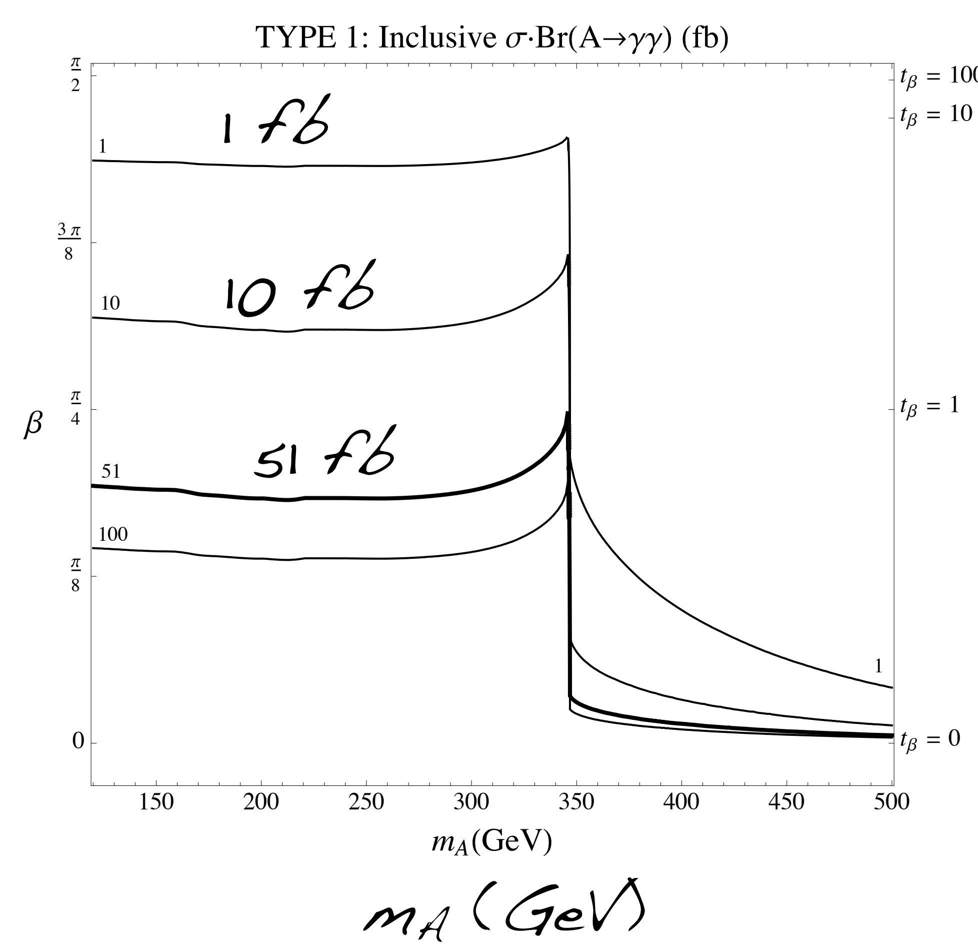


Sensitivity at large tan beta coming from enhanced production modes, rather than decay couplings.

H,A > diphoton



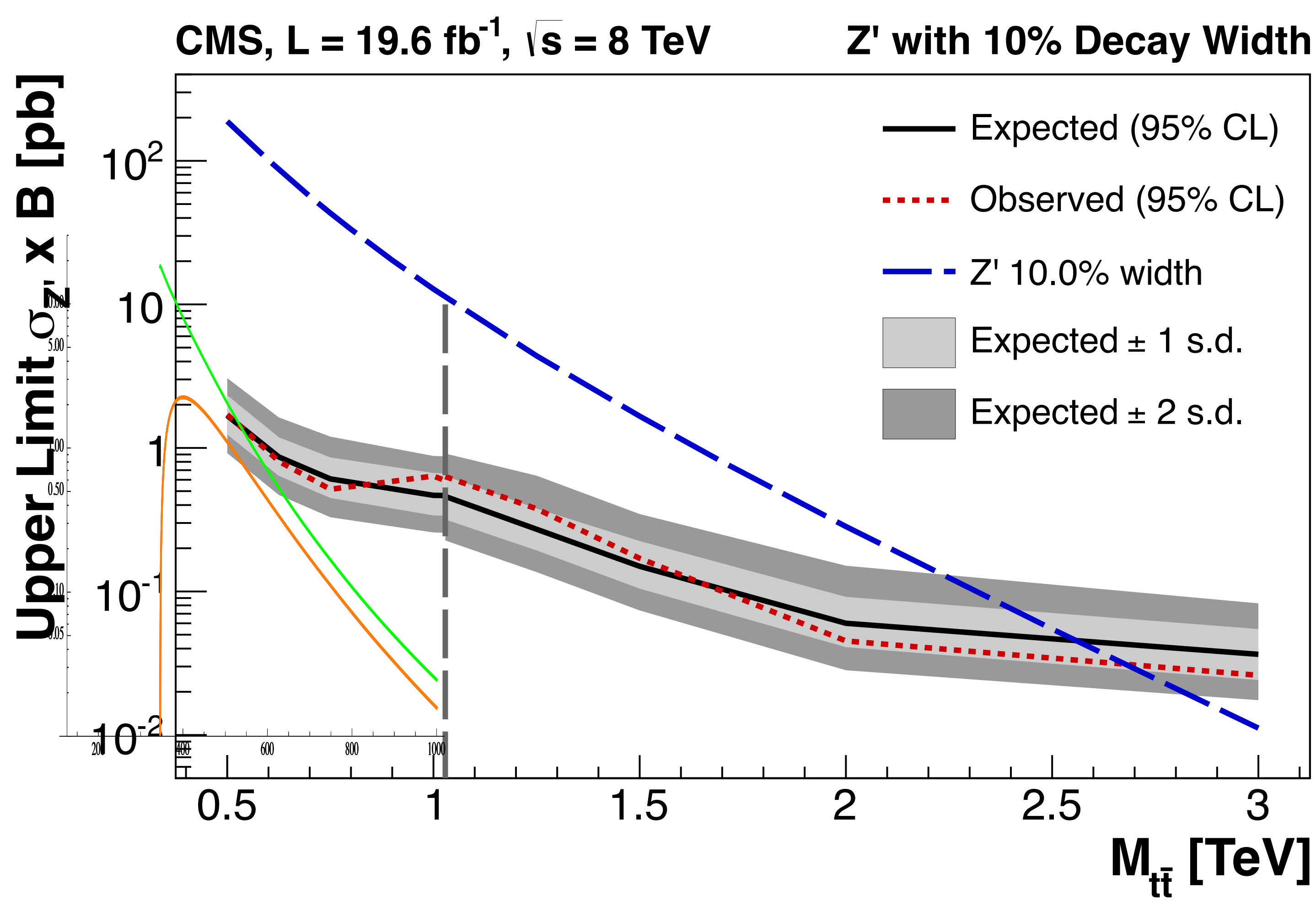




One of the most promising channels at low tan beta in alignment limit!

H,A > t tbar?

Another final state we don't typically pursue because subdominant to VV in SM-like heavy Higgs.



But at low tan beta the cross section for H, A > ttbar can be large! Needs further study.

- H>VV is useful even quite near the alignment limit, since the coupling must be radically suppressed before it's beaten by light fermions.

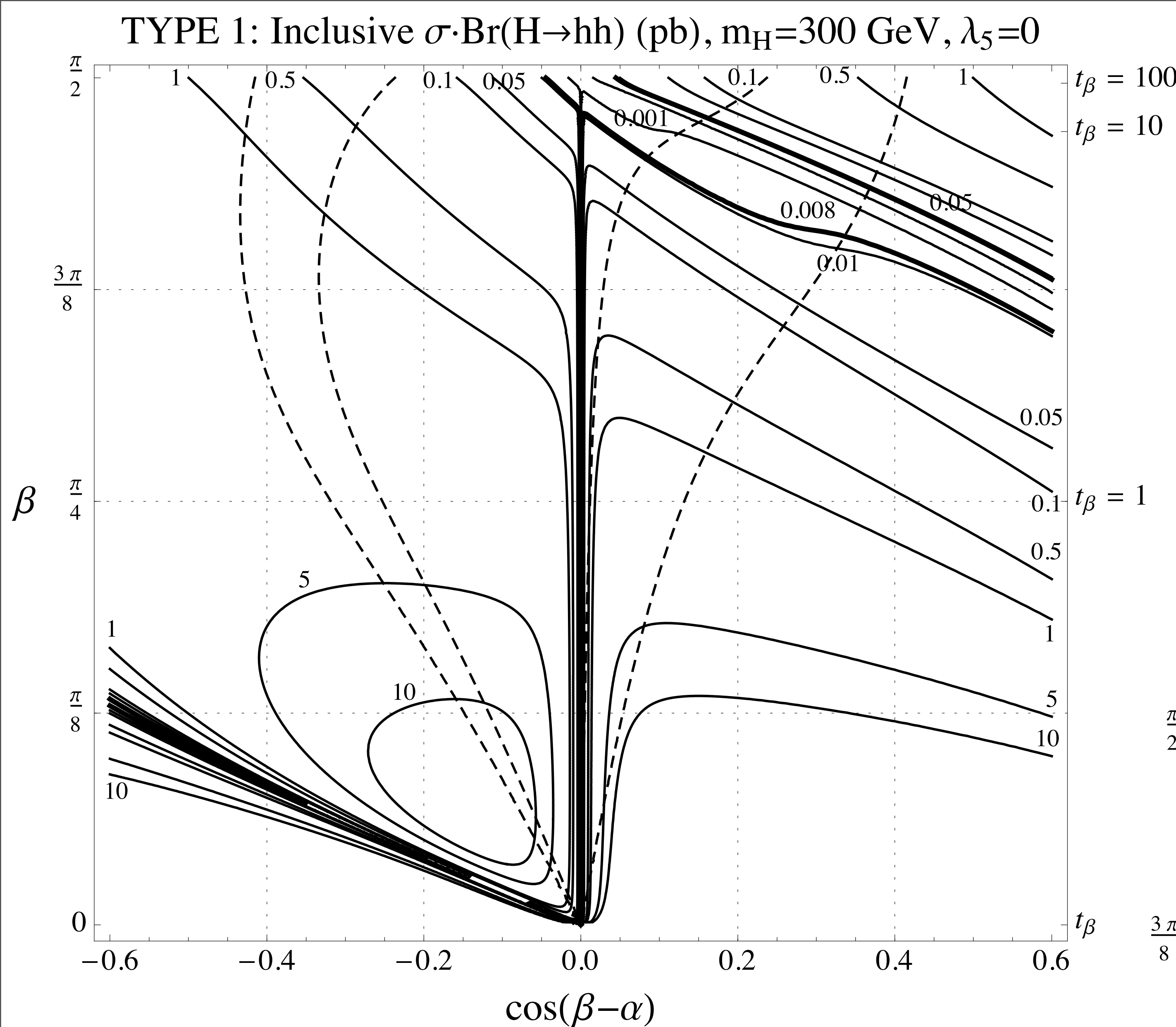
- Ditau and diphoton are the best states for the exact alignment limit. But H,A > tau tau only works at large tan beta in Type 2 2HDM.

- So we desperately need to extend our reach in diphoton past 150 GeV.

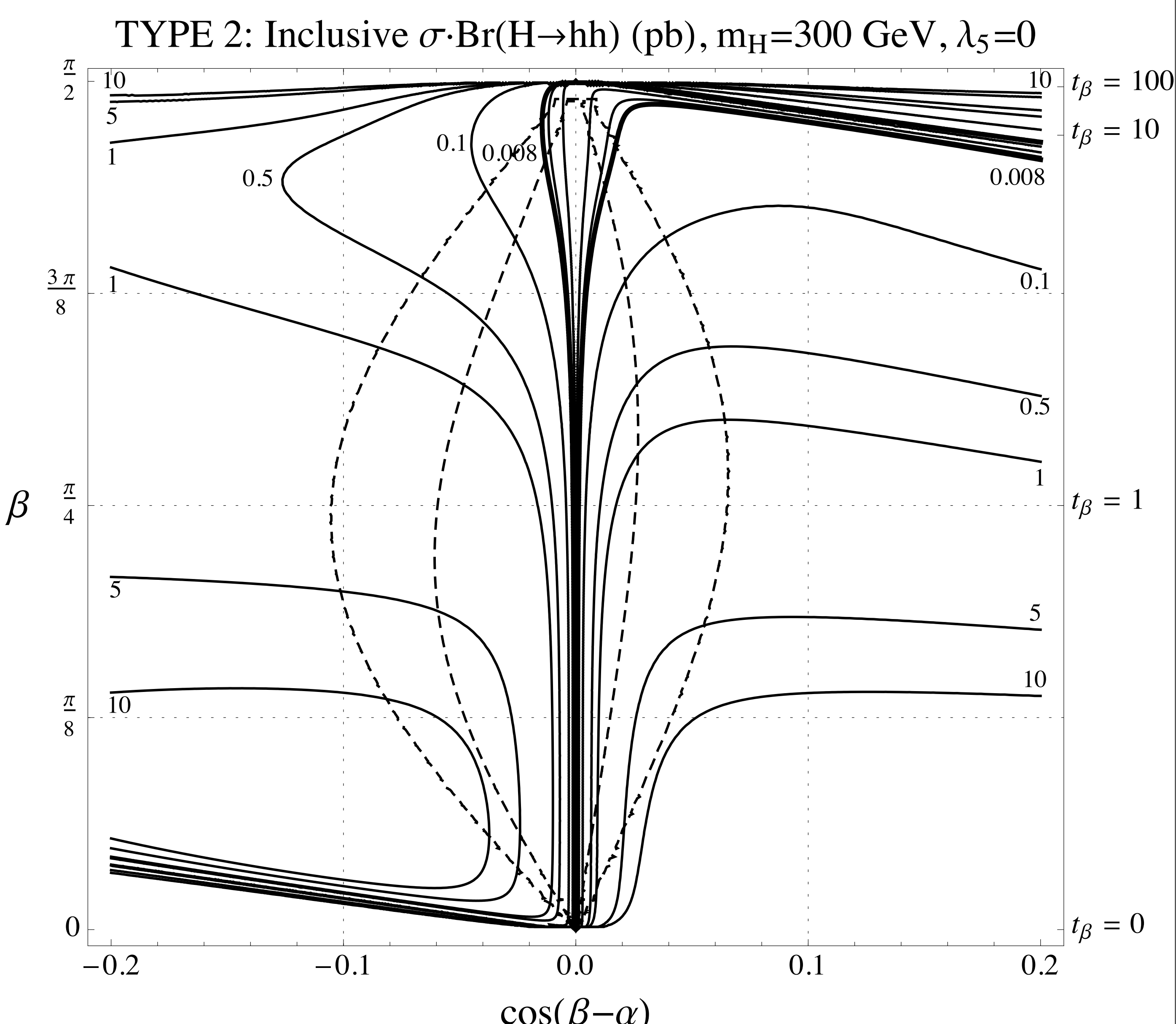
- Top pairs???

(3) Look in non-standard Higgs channels

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



H → hh

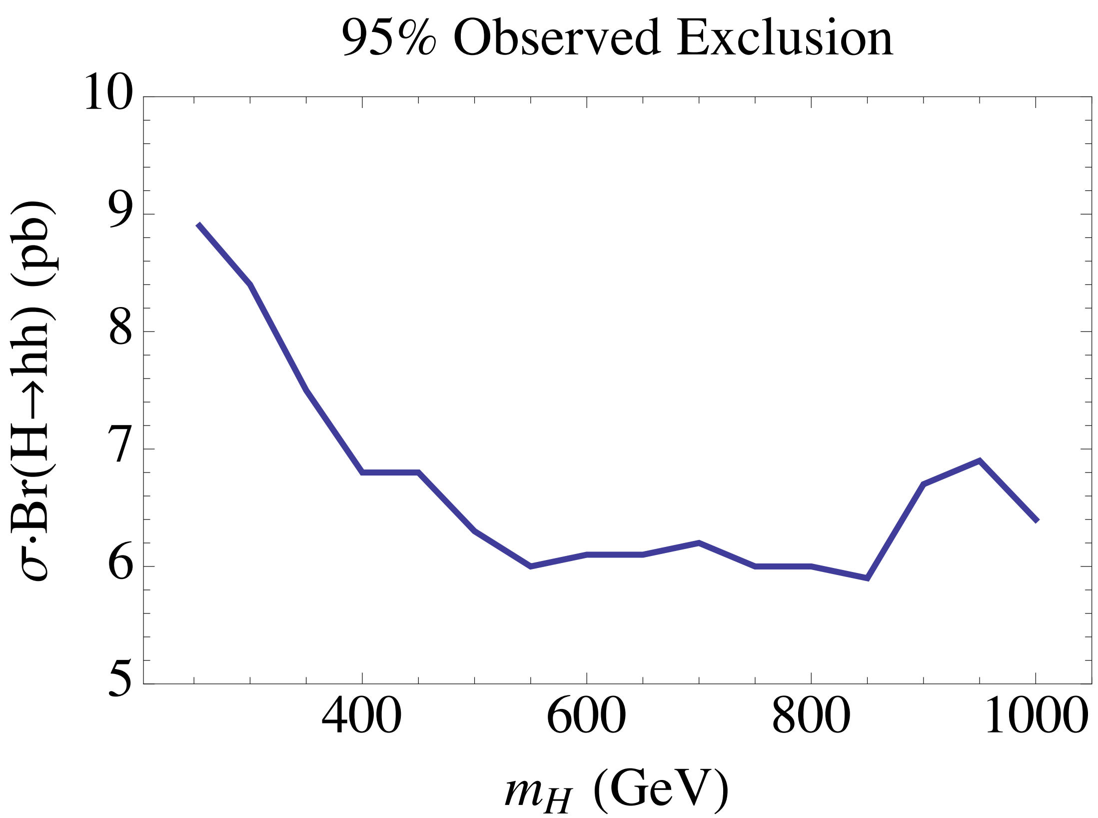


Appreciable rates (~1000 x SM) consistent with fits and VV limits.

H > hh while we wait

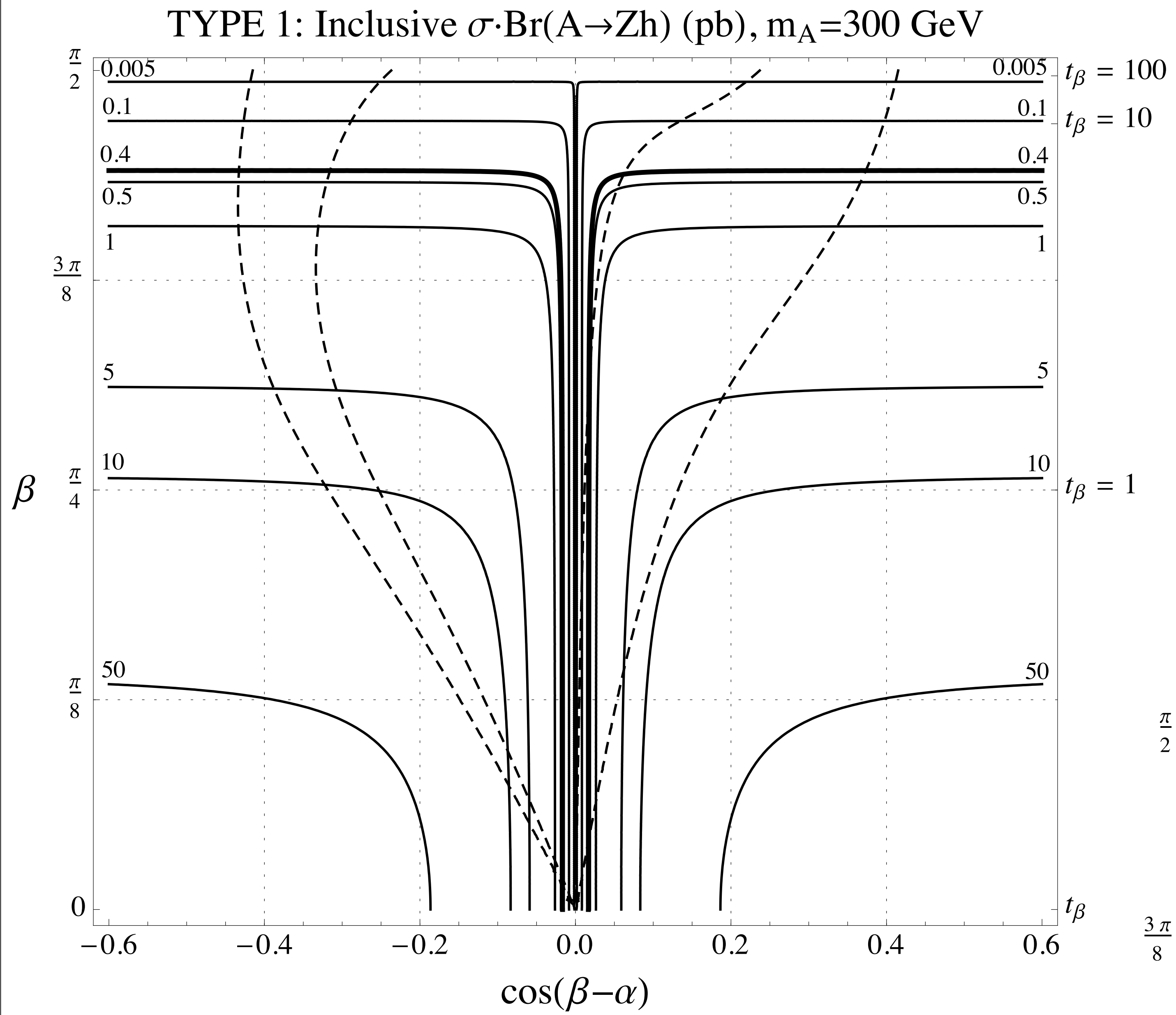
- Two promising ways to look for resonant H>hh: in diphoton+bb, and in multileptons.

- Resonant production from a heavier state pushes events out to lower-background channels.

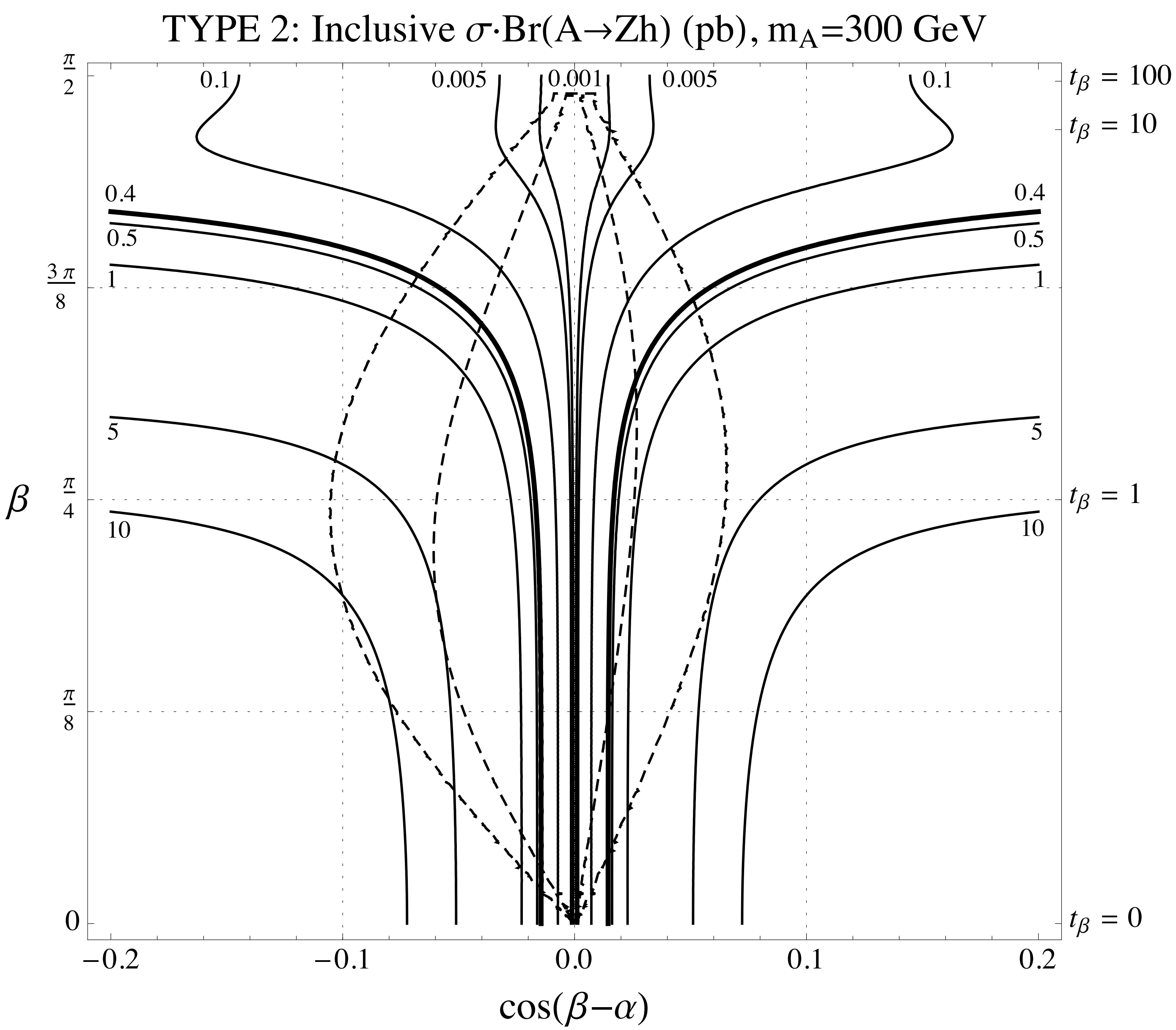


- Using 5/fb, 7 TeV CMS multilepton results (no b-tags, no had. taus), observed limit is ~6pb. Using full 8 TeV set + b-tags, expect closer to ~3pb.

- With this motivation, CMS is doing a dedicated hh search in above channels with 8 TeV data. Sensitivity should be at ~few pb level.



A > Zh

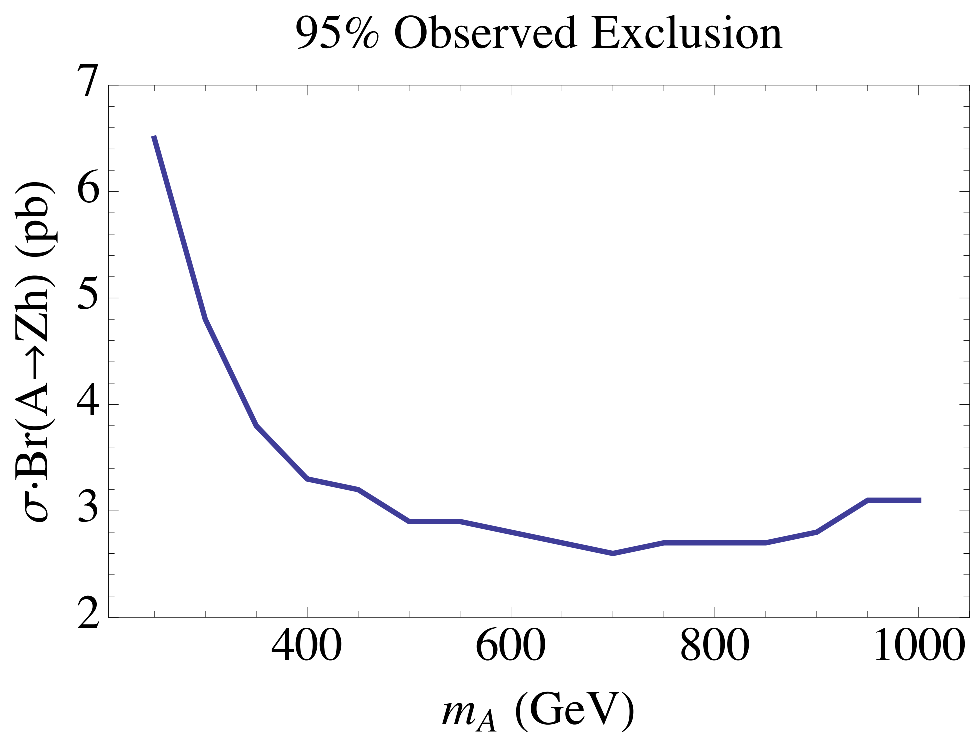


Appreciable rates (~few × SM) consistent with fits and Zh cross section limits (~3 × SM).

A > Zh while we wait

- Most promising way to look for A>Zh is in ll+WW, with approx. kinematic reconstruction. But pure multi-leptons also not bad.

- Resonant production from a heavier state pushes events out to lower-background channels.



- Using 5/fb, 7 TeV CMS multilepton results (no b-tags, no had. taus), observed limit is ~2.5pb. Slightly worse than 8 TeV Zh cross section limit.

- With this motivation, CMS is doing a dedicated Zh search with 8 TeV data. Sensitivity should be at ~pb level, better than Zh cross section limit.

- There can be appreciable rates for H>hh and A>Zh even quite close to the alignment limit, for the same reason as H>VV.

- We are not (yet, publicly) searching in these channels, but there can be observation-level rates consistent with the couplings of h.

- Sensitivity is currently in the range of ~pb using only crude search techniques, so there's considerable room for refinement.

Today's talk

A compact parameterization of additional Higgses

(We look in H>VV, H,A > tau tau, but given prox. to alignment, crucial to look in H,A > diphoton)

Searching in standard channels

Implications of coupling measurements of the SM-like Higgs

(Close to alignment limit but with room for surprises)

Searching in non-standard channels

(Look in H>hh, A>Zh!)