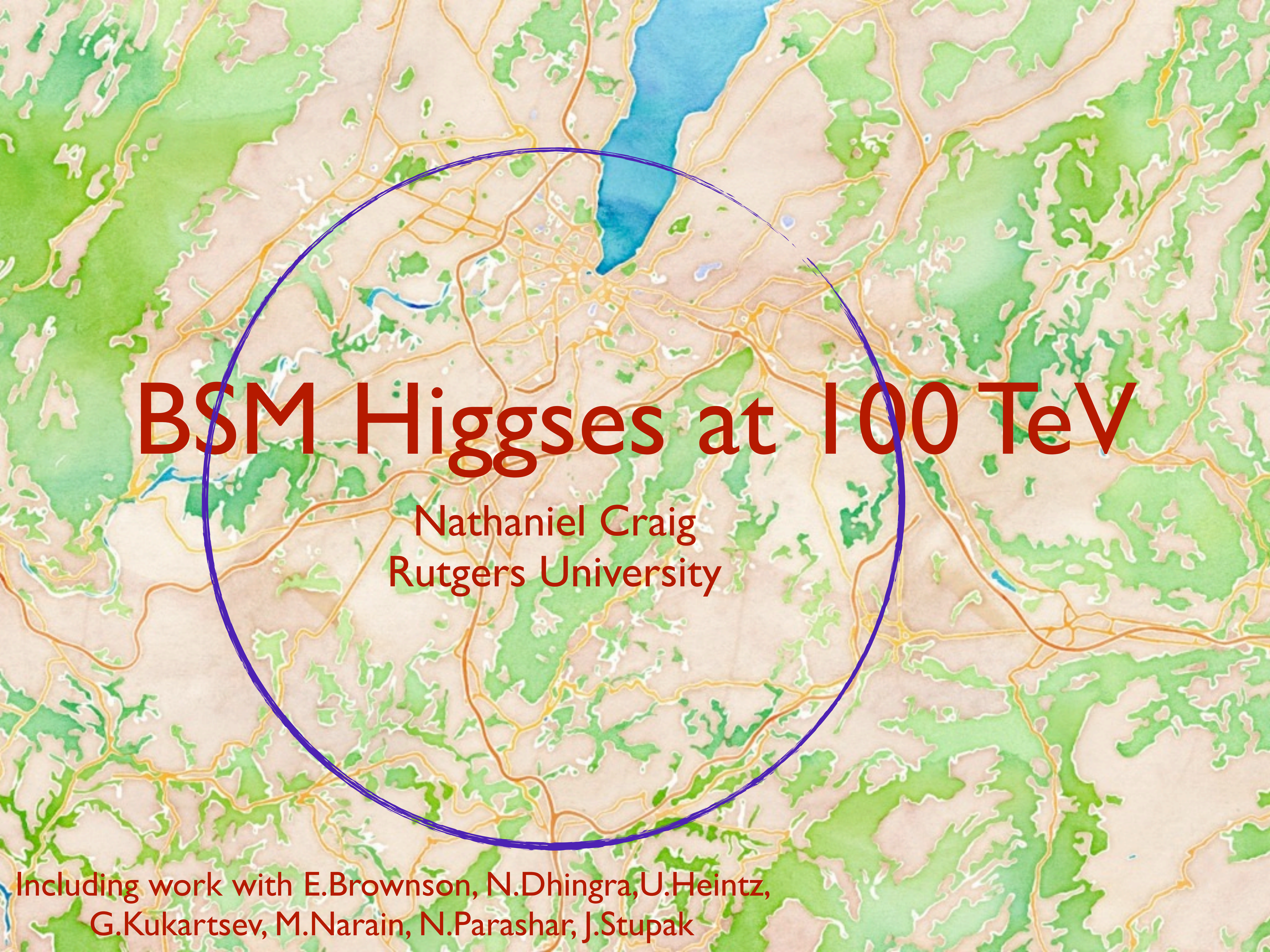


BSM Higgses at 100 TeV

Nathaniel Craig
Rutgers University

Including work with E.Brownson, N.Dhingra, U.Heintz, G.Kukartsev, M.Narain, N.Parashar, J.Stupak

Disclaimer: this whole talk comes with a large PRELIMINARY stamp attached; almost every plot was home-grown over the last few days or part of our still-in-progress extension of 2HDM Snowmass studies to 100 TeV.

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 the relevant d.o.f. were hiding at 14 TeV (or partly discovered).

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

Unlikely that (3.) can explain two light scalars.
(whereas (1.) and (2.) generically allow or predict new 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
- (Some) Composite Higgs models
  [e.g., SO(6)/SO(4)xSO(2) or Sp(6)/Sp(4)xSU(2)]
- ....

Plus overlap with heavy resonance final states.

2HDM

- For the purposes of this talk, I'll primarily 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.

*There are, of course, exceptions to these statements, but the above assumptions cover the broadest class of possibilities.

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:

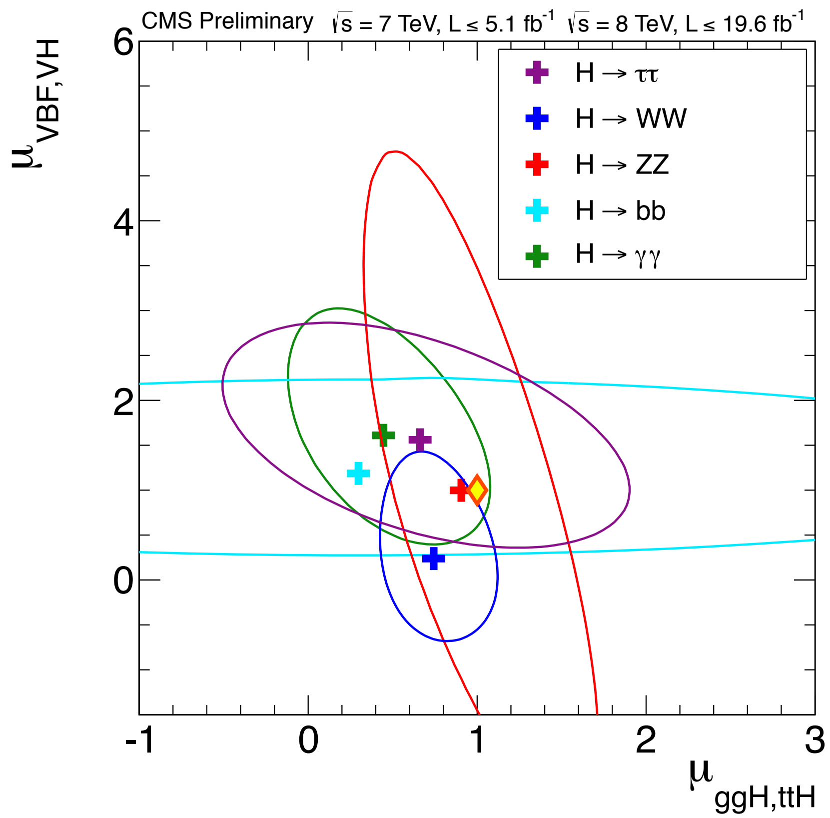
$m_h, m_H, m_A, m_{H^\pm}$ $\tan\beta \equiv \langle\Phi_2\rangle/\langle\Phi_1\rangle$

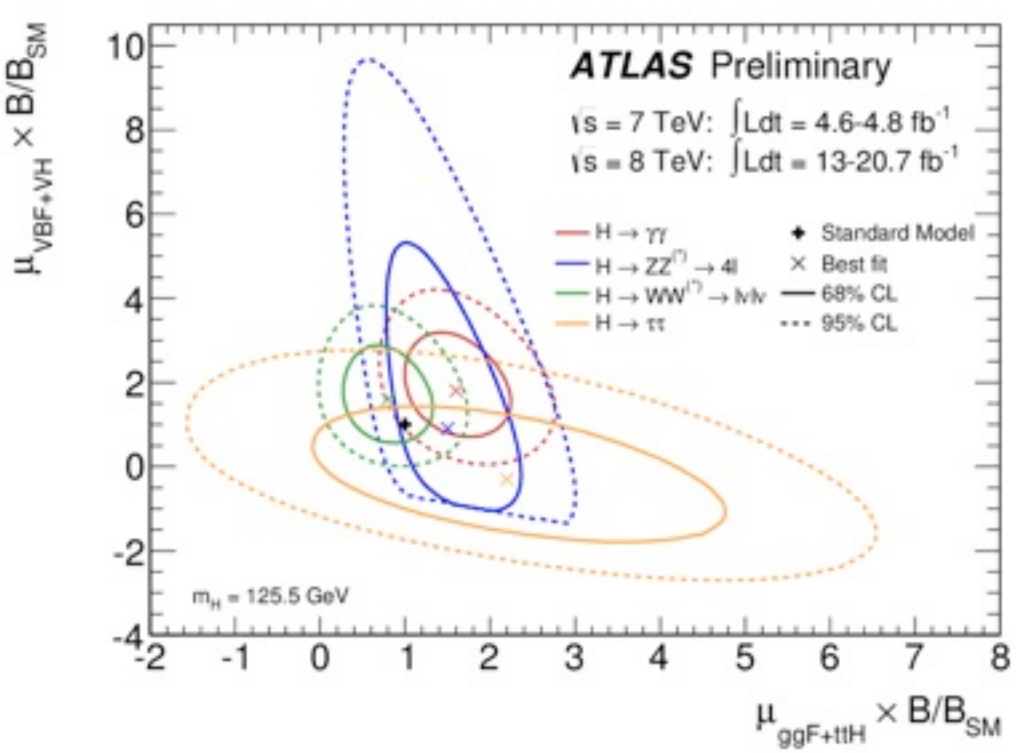
$$\alpha : \quad \begin{pmatrix} \sqrt{2}\ \mathrm{Re}(\Phi_2^0) - v_2 \\ \sqrt{2}\ \mathrm{Re}(\Phi_1^0) - v_1 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

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

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

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





Alignment limit

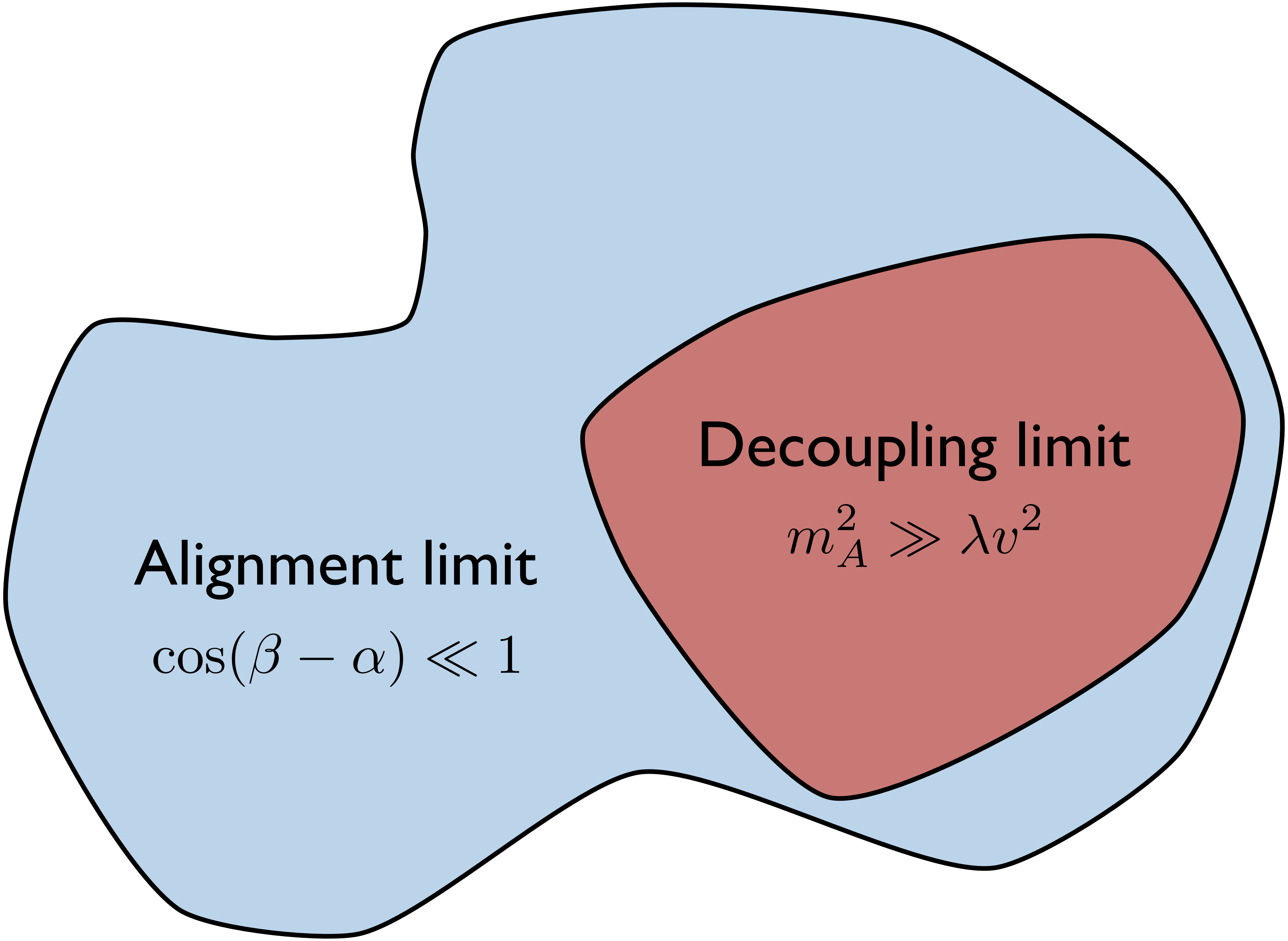
- Couplings of the observed Higgs are so far approximately SM-like
- Strongly suggests proximity to the alignment limit

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

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

$$\delta = \beta - \alpha - \pi/2$$
$$\approx -\cos(\beta - \alpha)$$

[Craig, Thomas 1207.4835; Craig, Galloway, Thomas 1305.2424;
Carena, Low, Shah, Wagner 1310.2248]



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; H^+ couplings analogous to A.
- Focus on the two most familiar, Types 1 and 2.

Why heavy(ish) Higgses?

Generically, the mass scale of heavy Higgses is only constrained by the distribution of the EWSB vev, which can naturally be (reasonably) asymmetric.

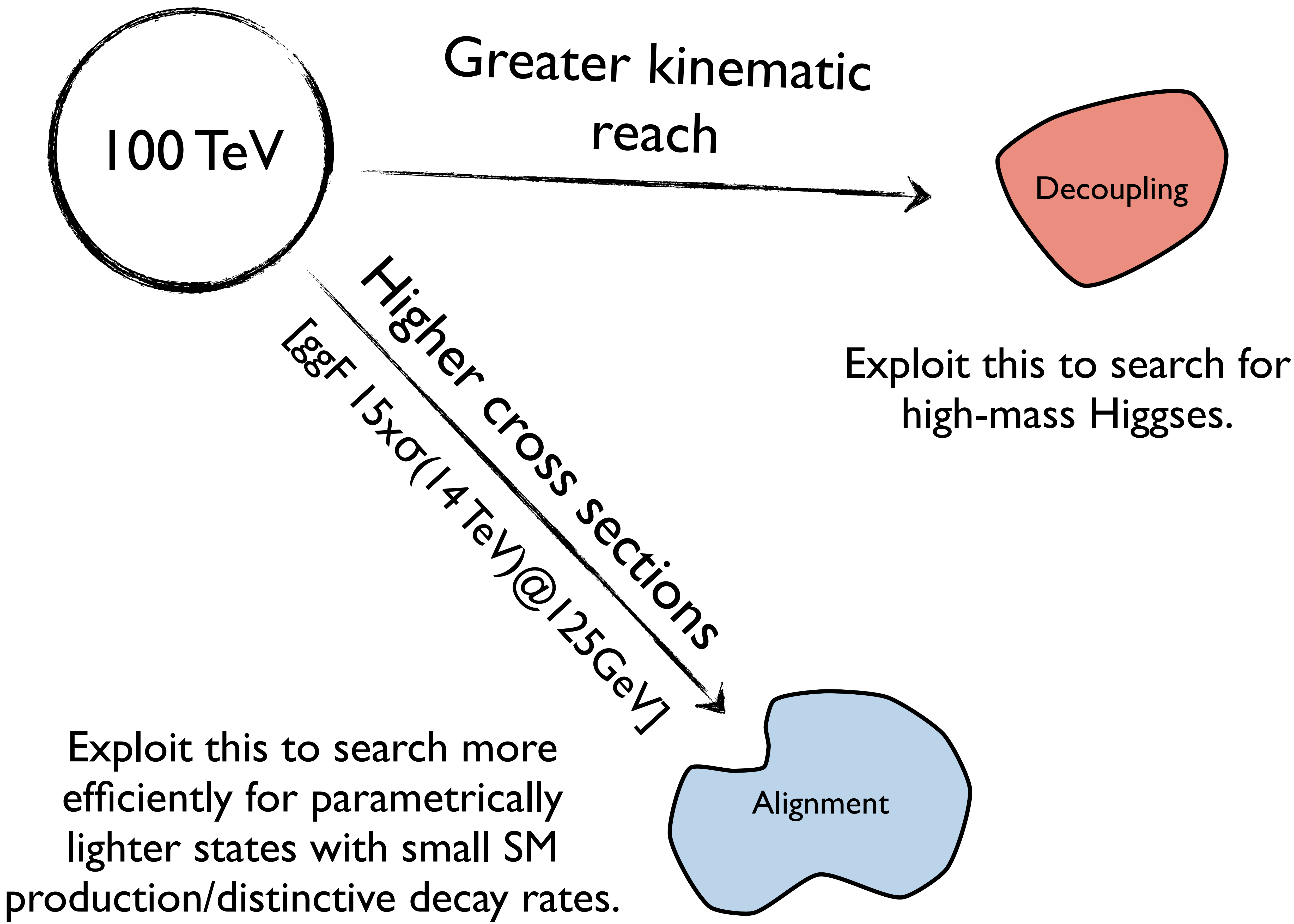
E.g. SUSY:

$$\Delta \approx \sin^2(2\beta)\frac{m_H^2}{m_h^2} + \mathcal{O}(m_H^0)$$

In the limit of large tanβ implies suppressed sensitivity;

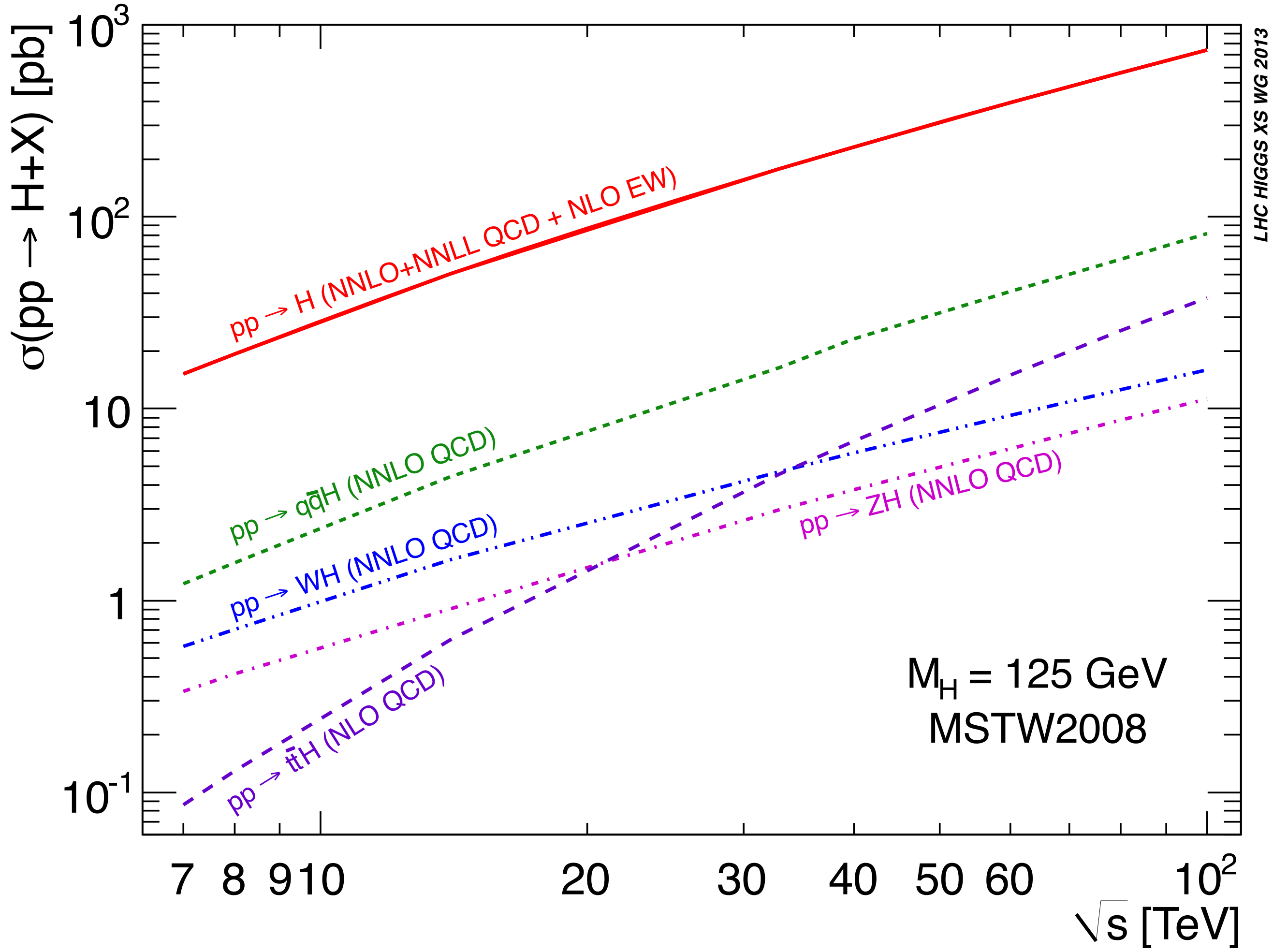
$$\Delta(\tan\beta = 50) \leq 1 \to m_H \lesssim 3.1 \text{ TeV}$$

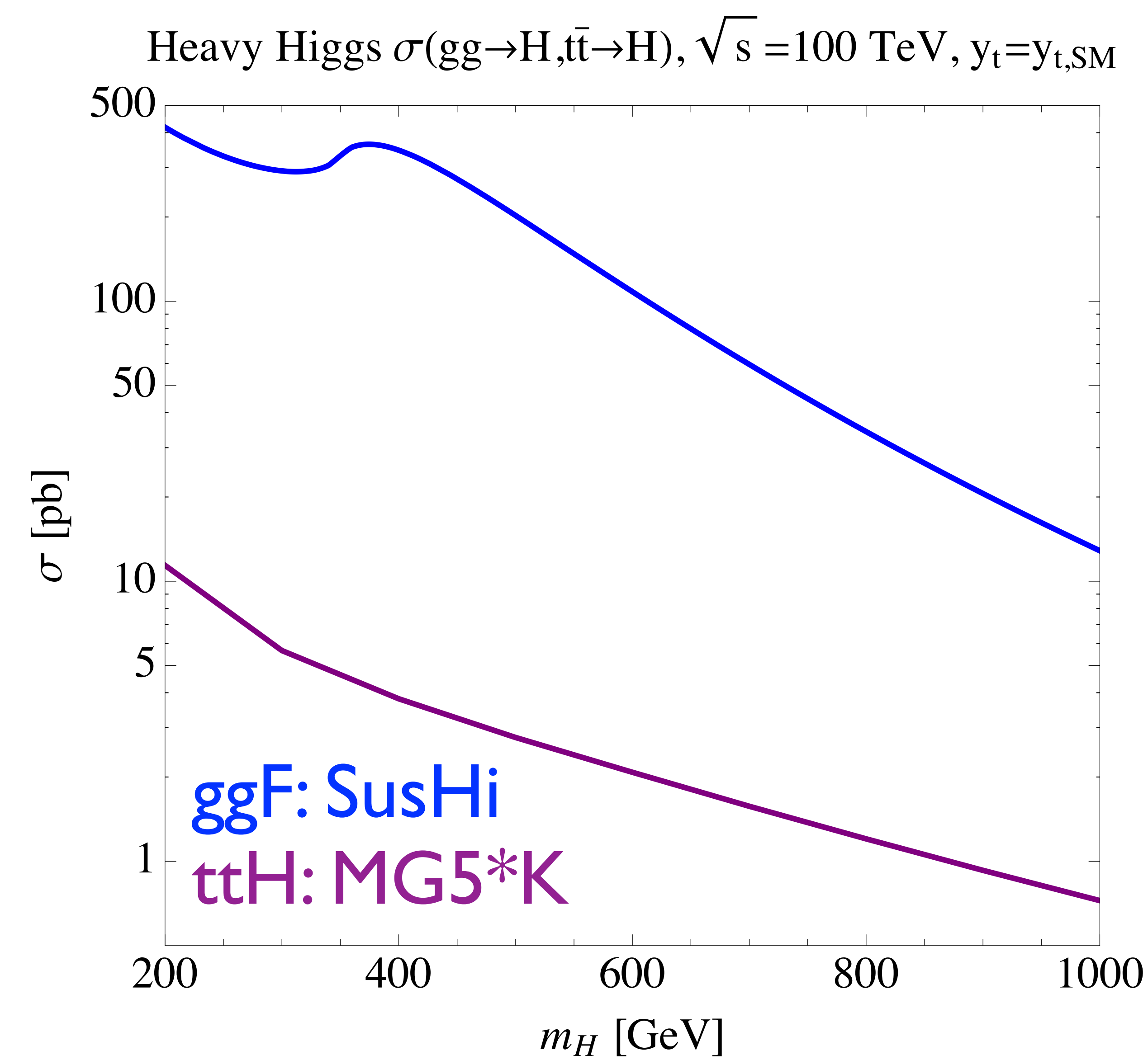
So multi-TeV additional Higgs states are very consistent with naturalness in this framework. Not a scale we're likely to reach at 14 TeV, but certainly could be within reach of 100 TeV.


100 TeV
Greater kinematic reach
Decoupling
Exploit this to search for high-mass Higgses.
Higher cross sections
[ggF 15xσ(14 TeV)@125GeV]
Alignment
Exploit this to search more efficiently for parametrically lighter states with small SM production/distinctive decay rates.

100 TeV Opportunities

(1) ttH grows due to gluon pdfs & improved kinematics

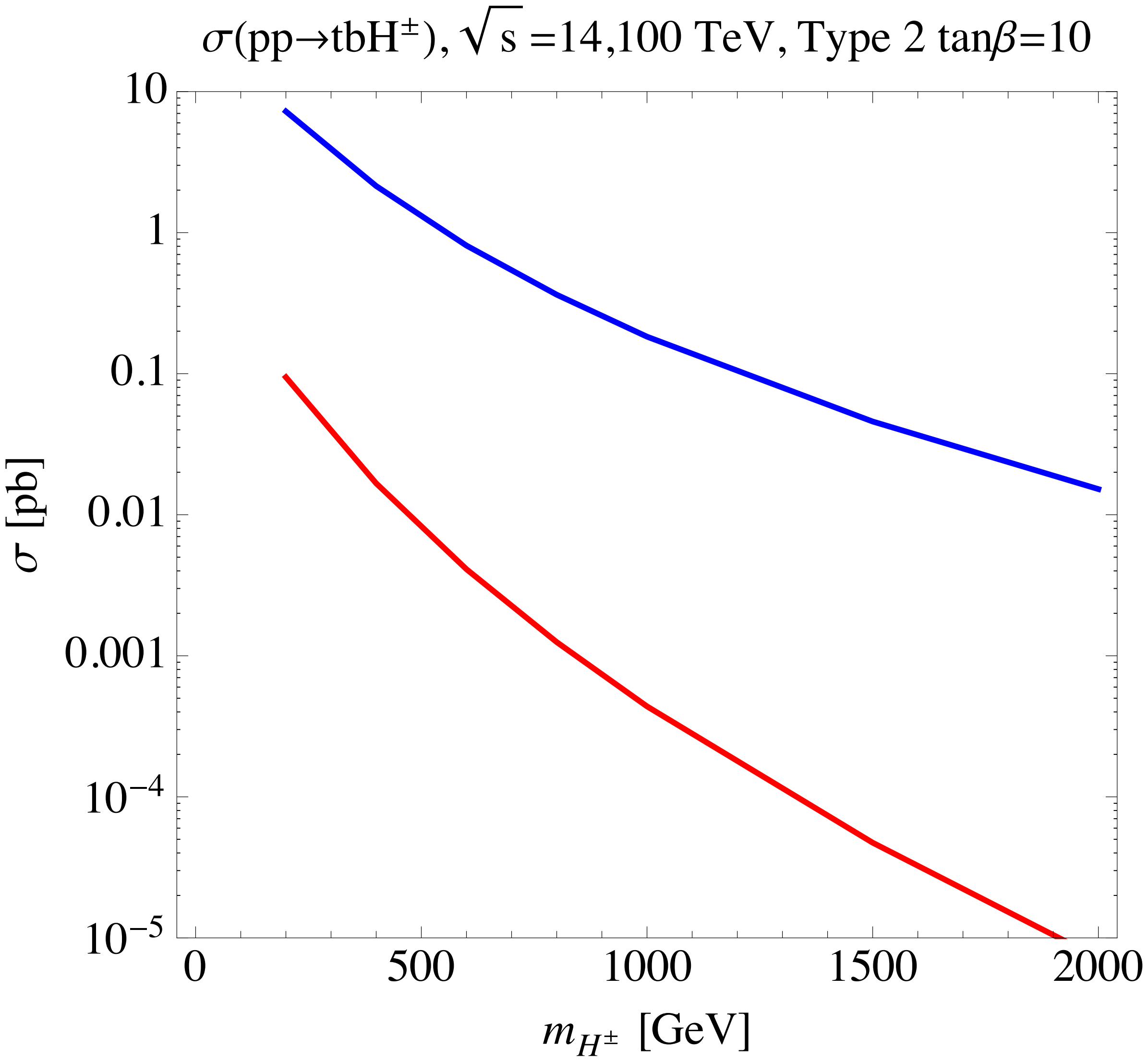




ttH: 61xσ(14 TeV); ggF: 15xσ(14 TeV)

100 TeV Opportunities

(2) Charged Higgs production becomes appreciable. Also improved by kinematics, pdfs at 100 TeV

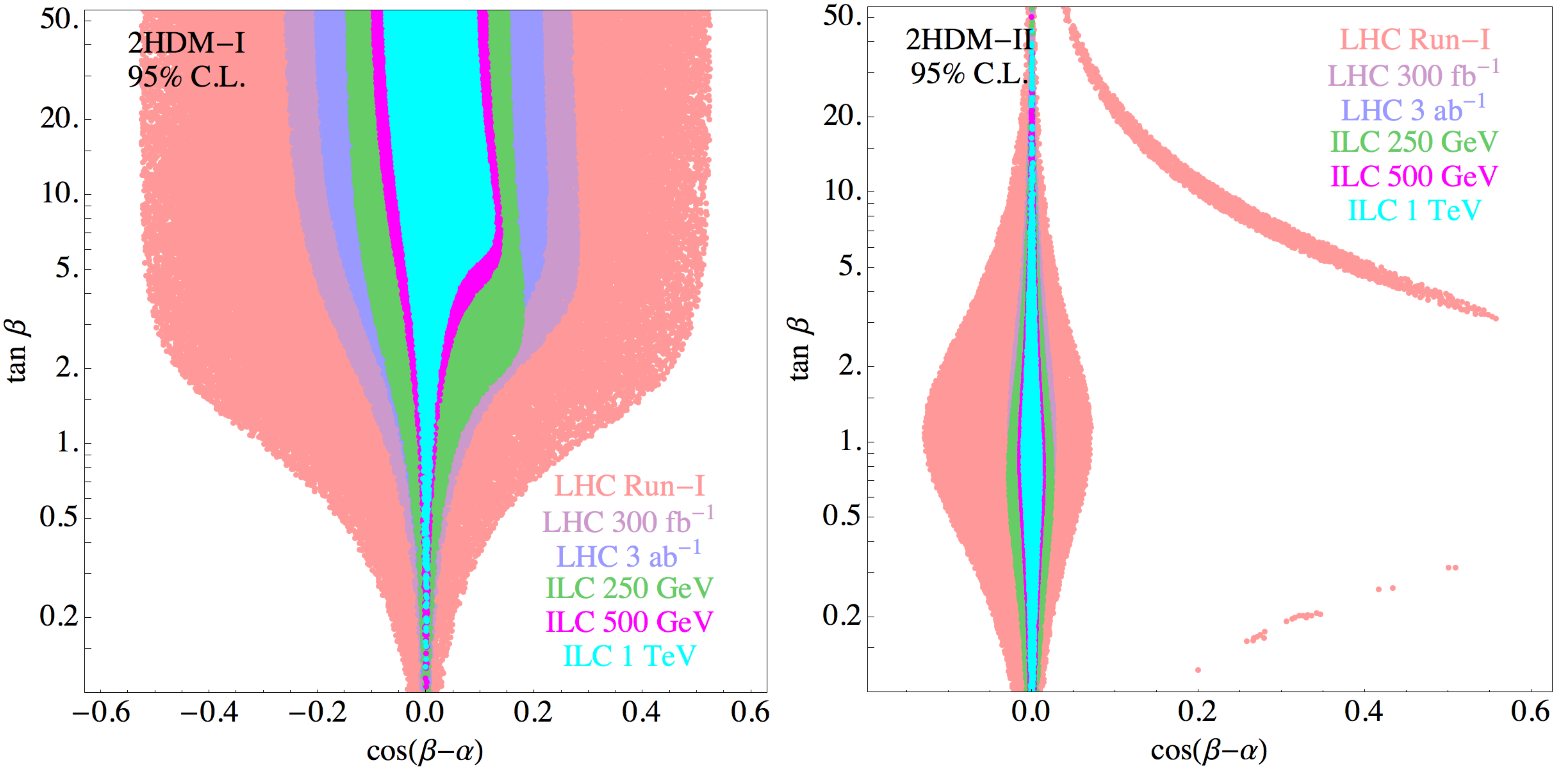


Preliminary estimate (LO MG4): tb$H^\pm$: 80xσ(14 TeV) @tanβ=10 $m_{H\pm}$=200 GeV. σ >100fb to $m_{H\pm}$~TeV

This is the "worst-case" value of tanβ; rate increases at higher and lower tanβ

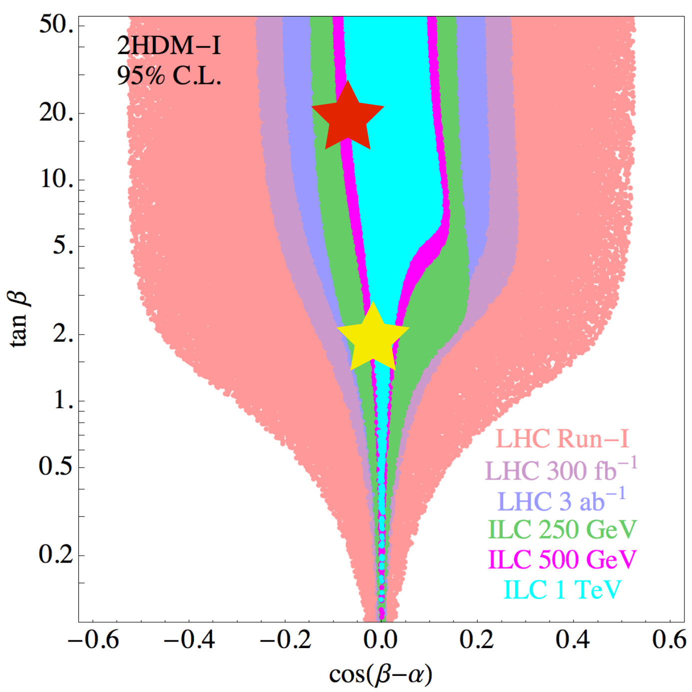
Complementarity

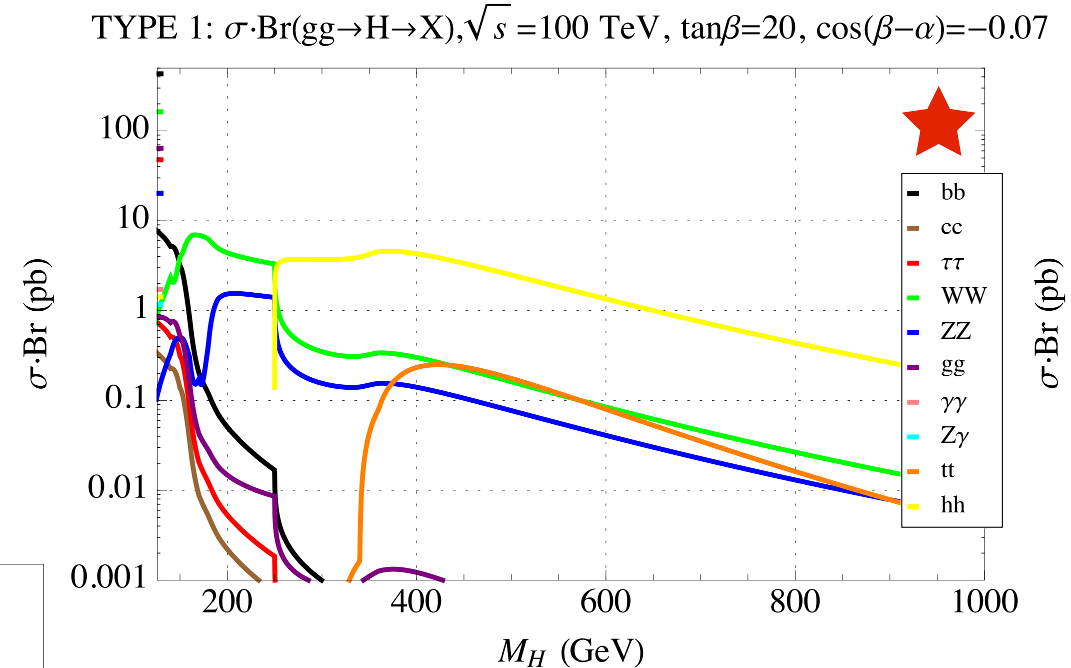
[Barger, Everett, Logan, Shaughnessy 1308.0052]

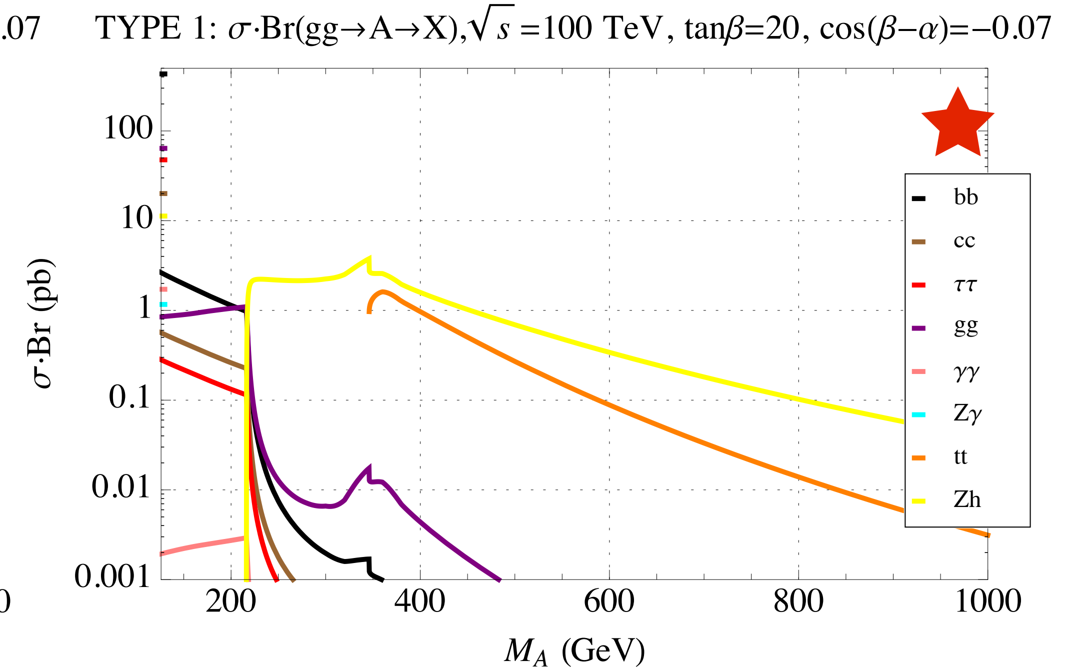


Where can we expect signs of heavy Higgses given the envelope of coupling measurements? E.g., starting the VLHC after ILC1000-level precision?

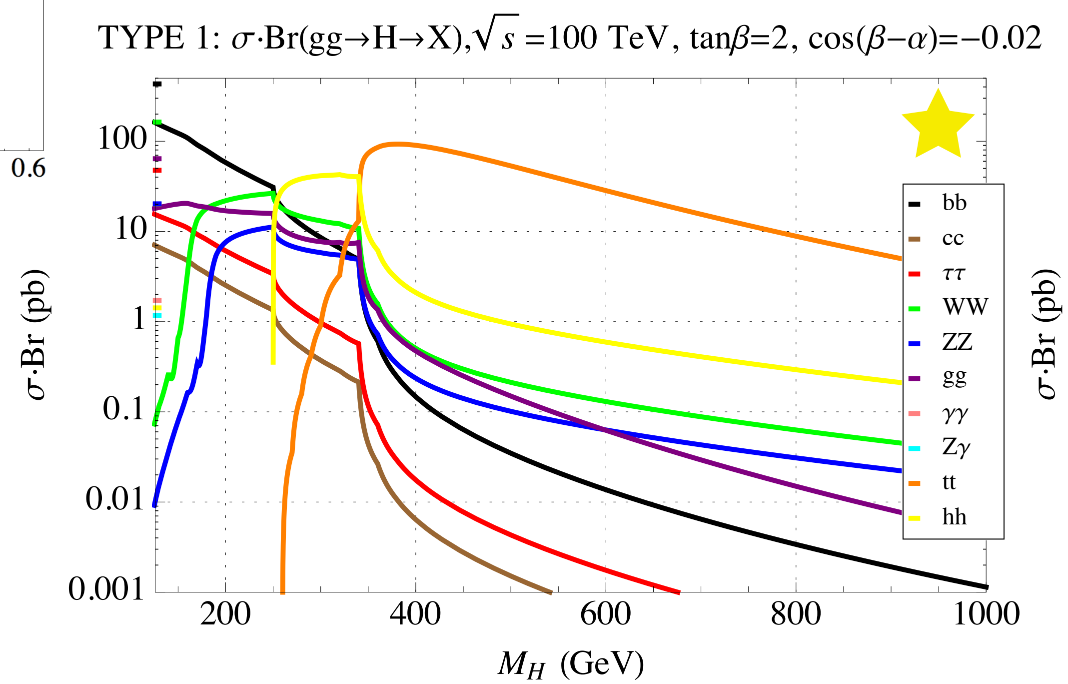
Type I

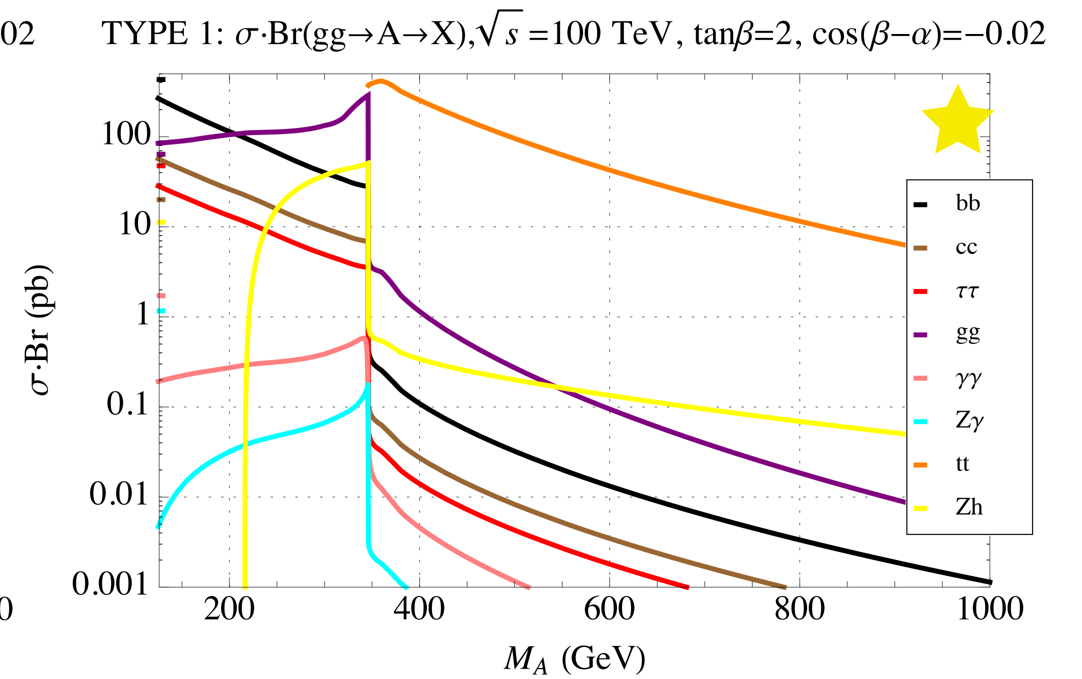






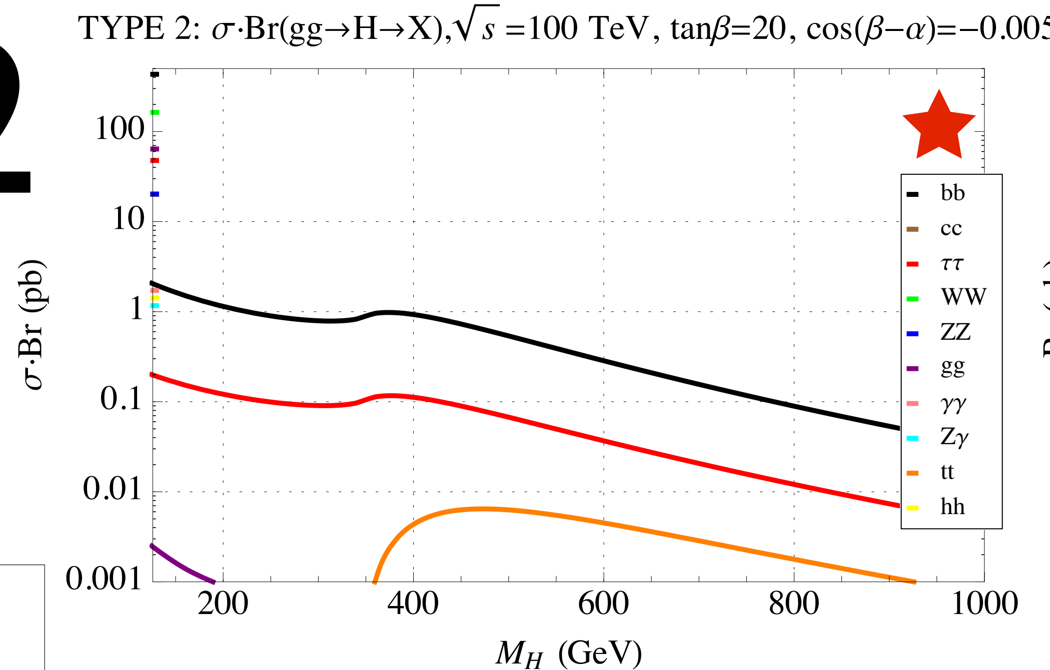
High tanβ dominated by hh, Zh, VV, tt

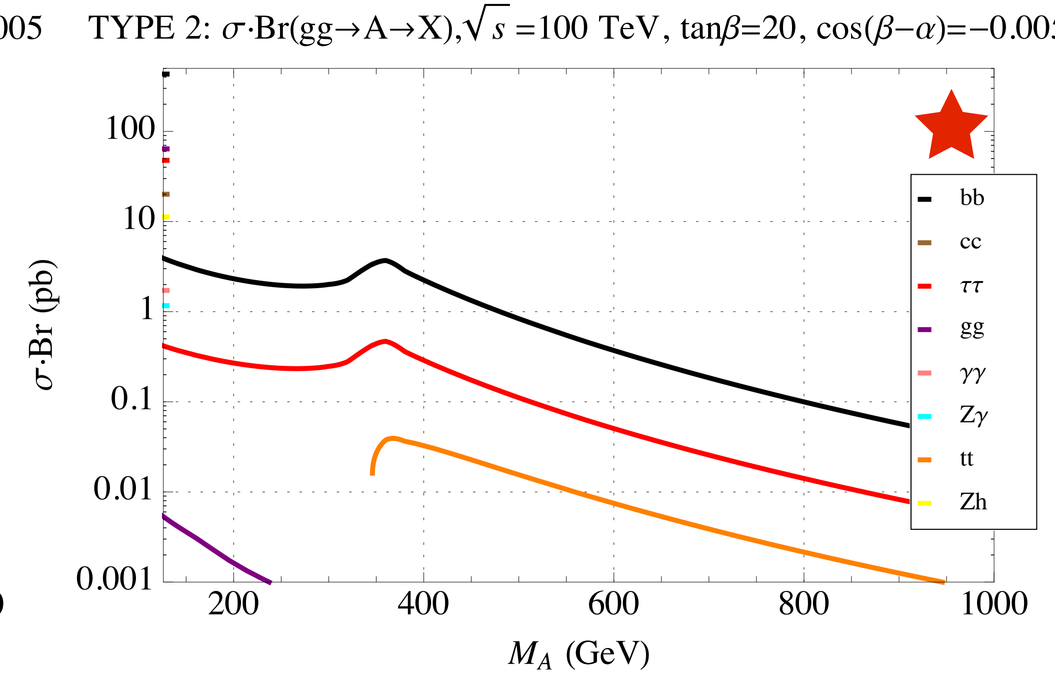


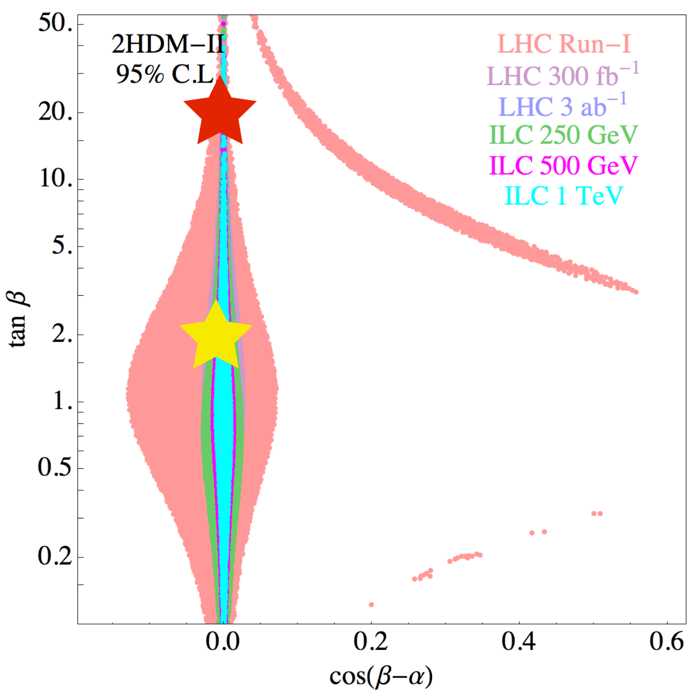


Low tanβ dominated by tt, hh, Zh, still some distance from alignment

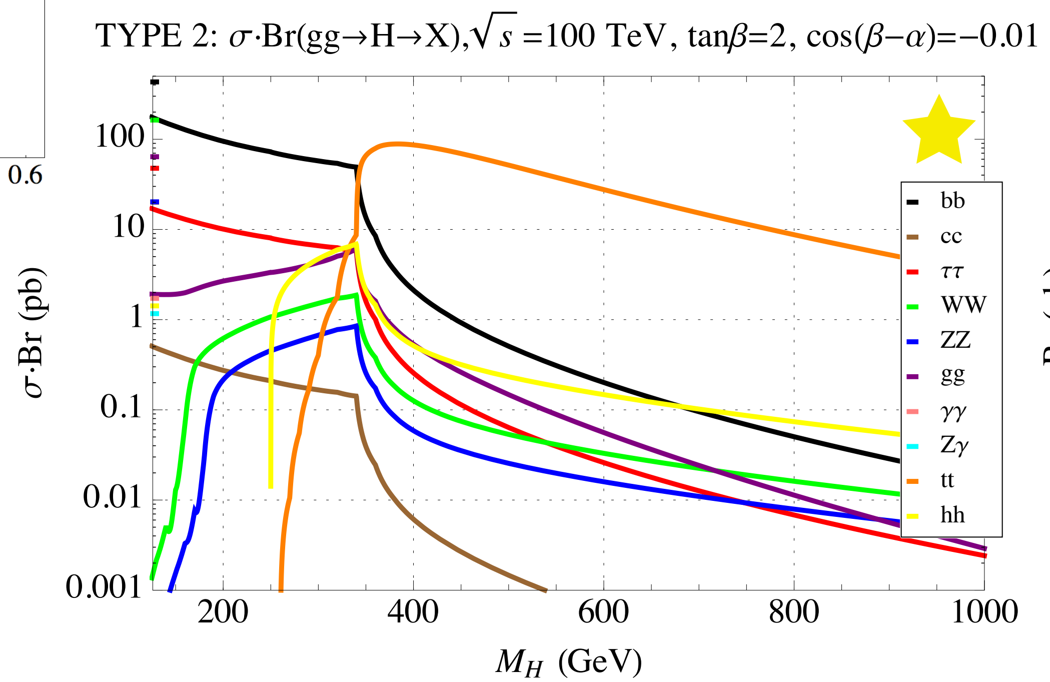
Type 2

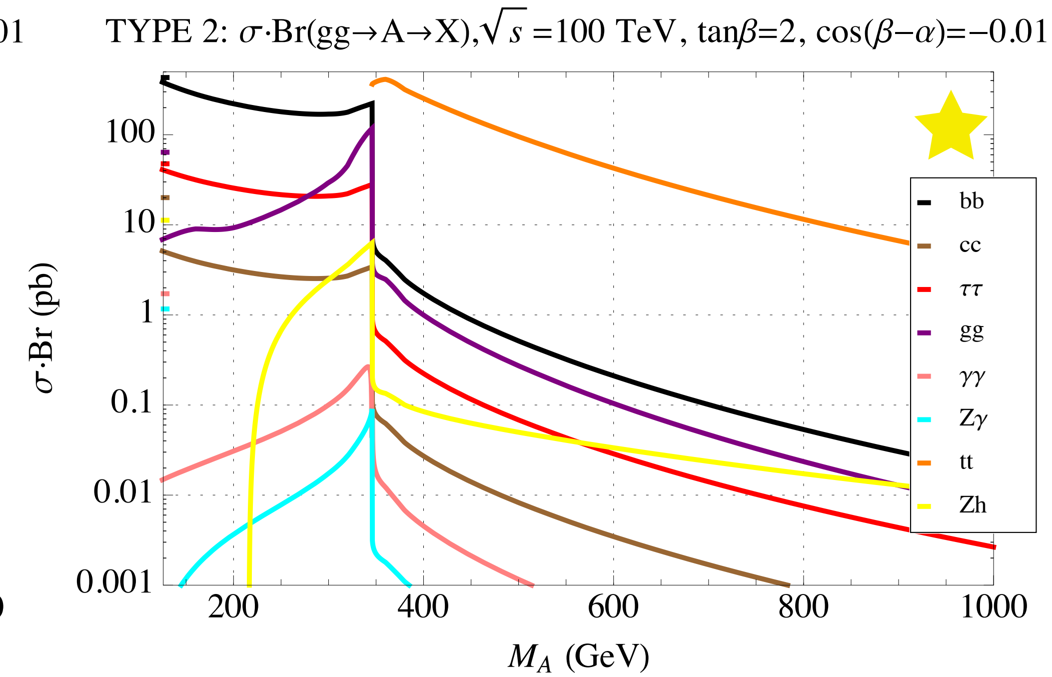






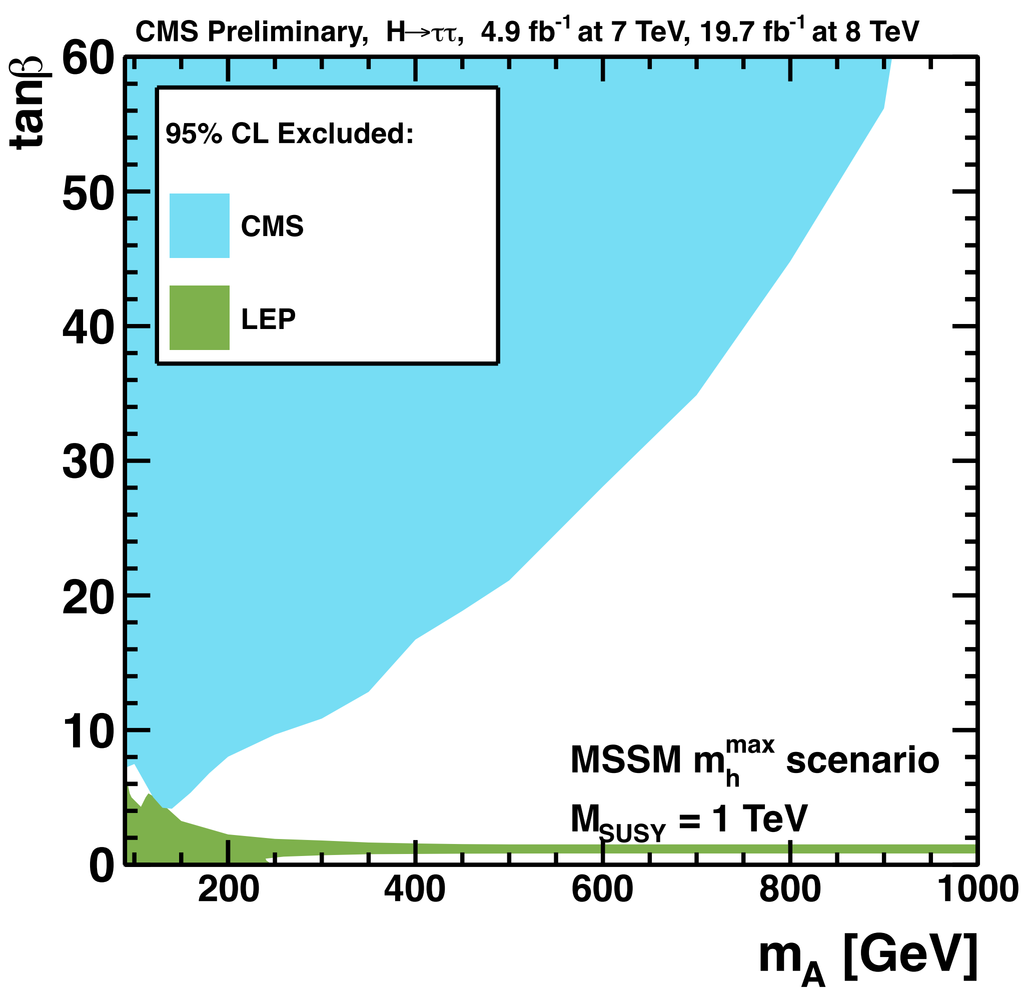
High tanβ dominated by bb, ττ, as expected from MSSM

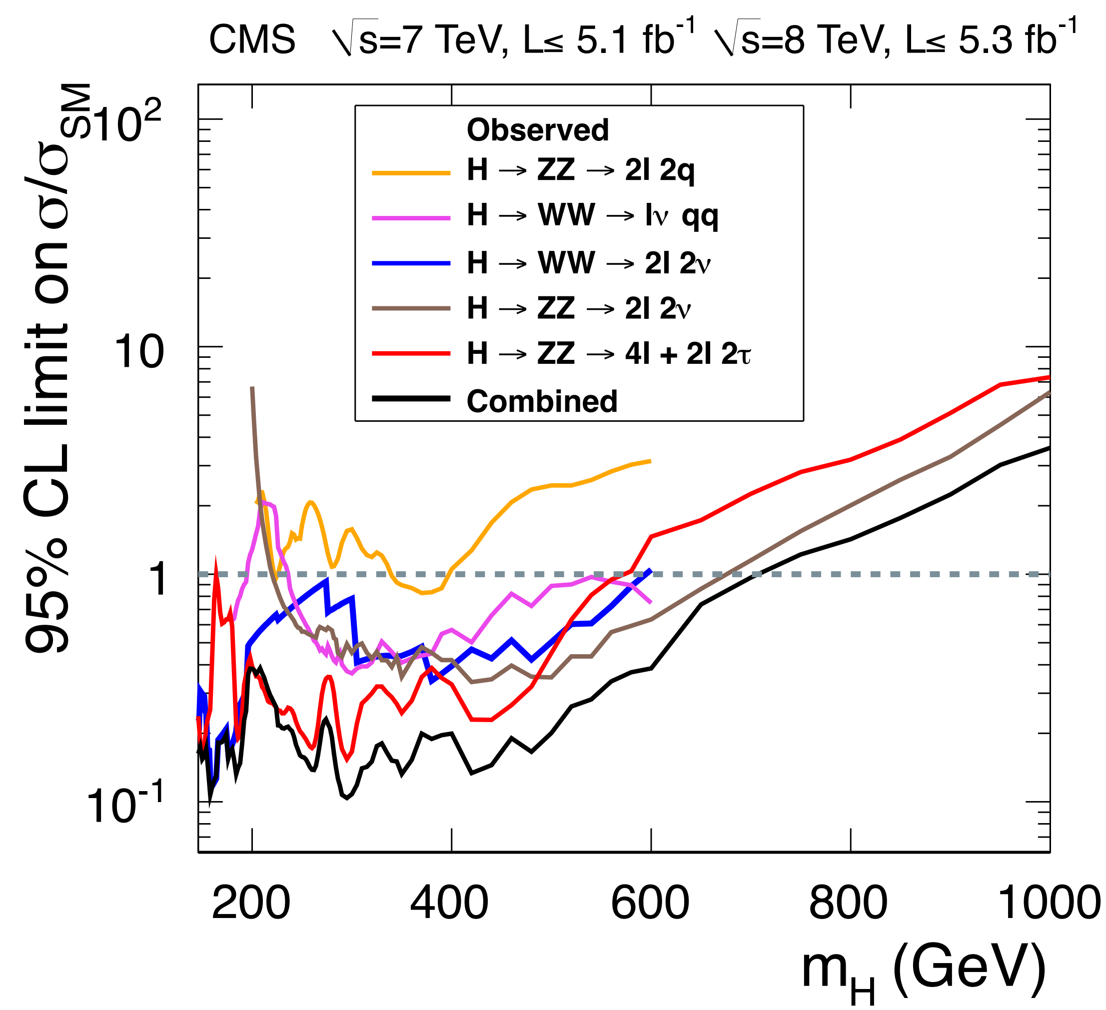




Low tanβ dominated by tt, bb; vectors suppressed by alignment

Standard searches

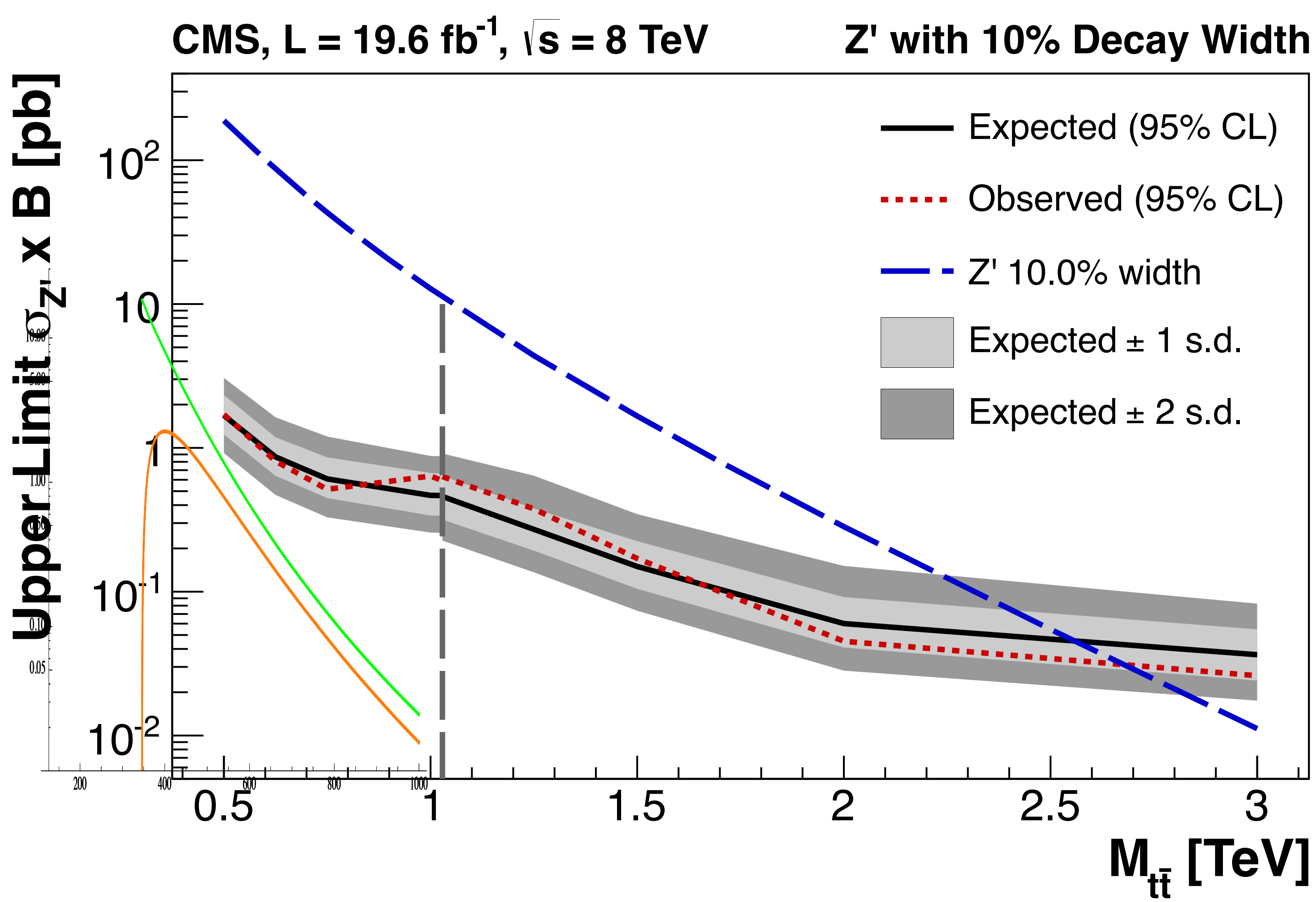




Clearly useful to extend existing high-mass ττ, VV searches; not much new to say here in terms of philosophy. Vectors are increasingly squeezed out by proximity to the alignment limit.

H,A → tt

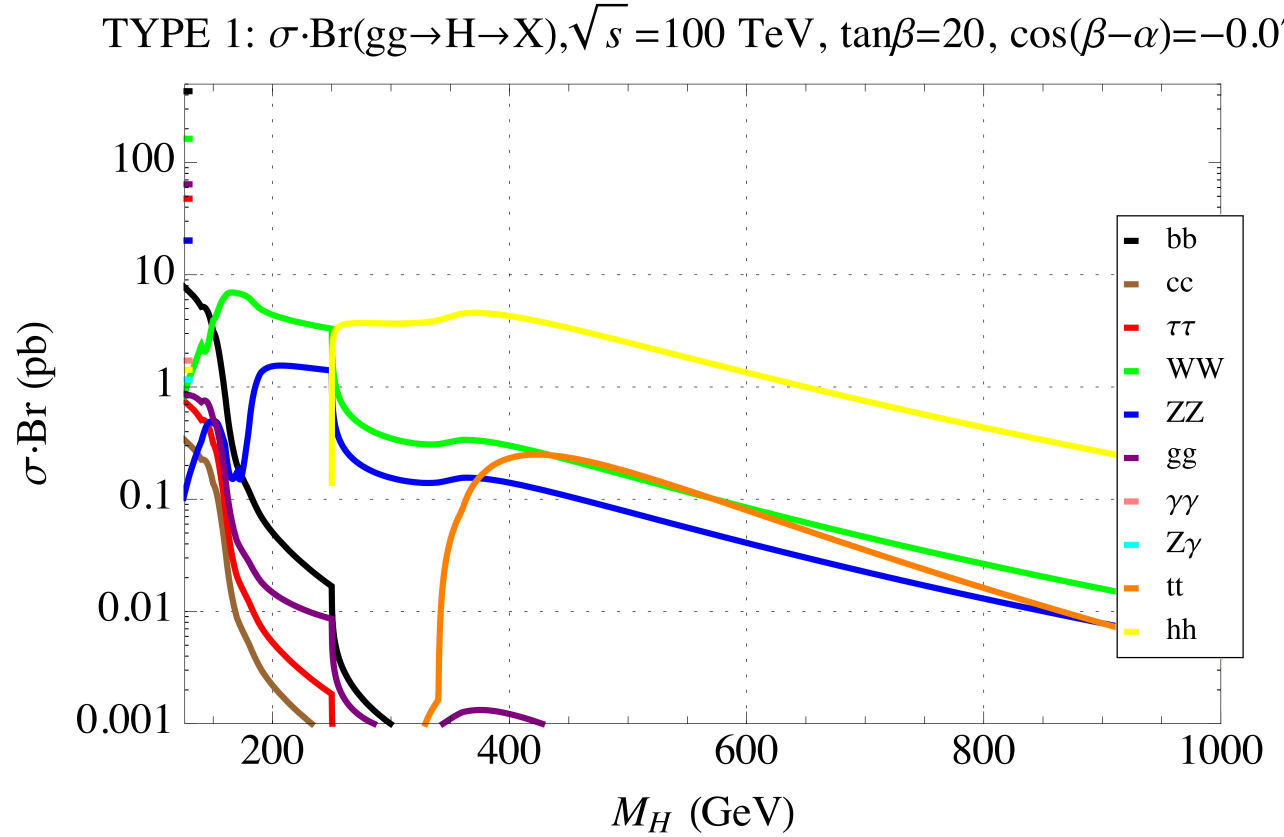
A final state we don't typically pursue because subdominant to VV in SM-like heavy Higgs, but substantial for 2HDM. Would certainly benefit from an 8 TeV search and becomes increasingly important as coupling limits improve.

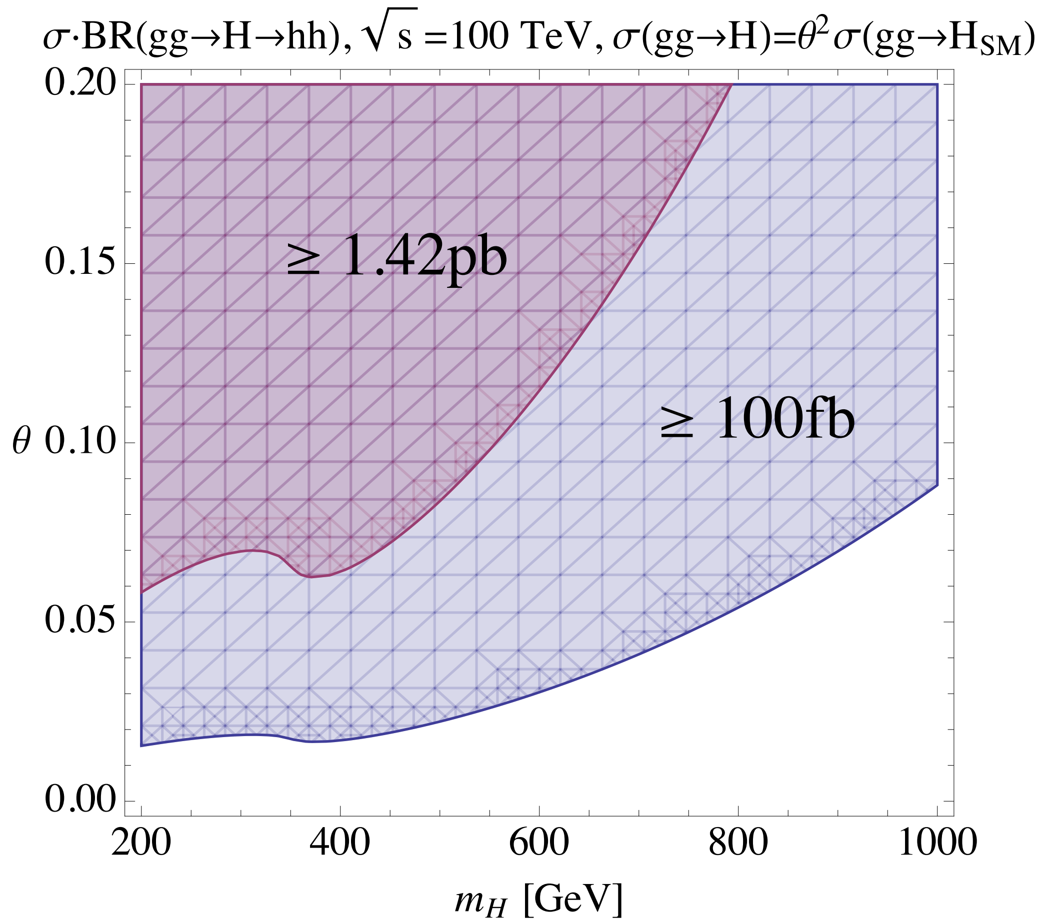


At low tan beta the cross section for H,A → ttbar can be large; needs further study. Plausible to distinguish ~pb on top of 250pb SM ttbar @ 8 TeV. Can we exploit ttH/ttA associated production?

H → hh

Can be a dominant mode for Type I 2HDM; also often the dominant decay mode of a heavy Higgs for singlet-doublet mixing or twin Higgs (see Roni's talk).



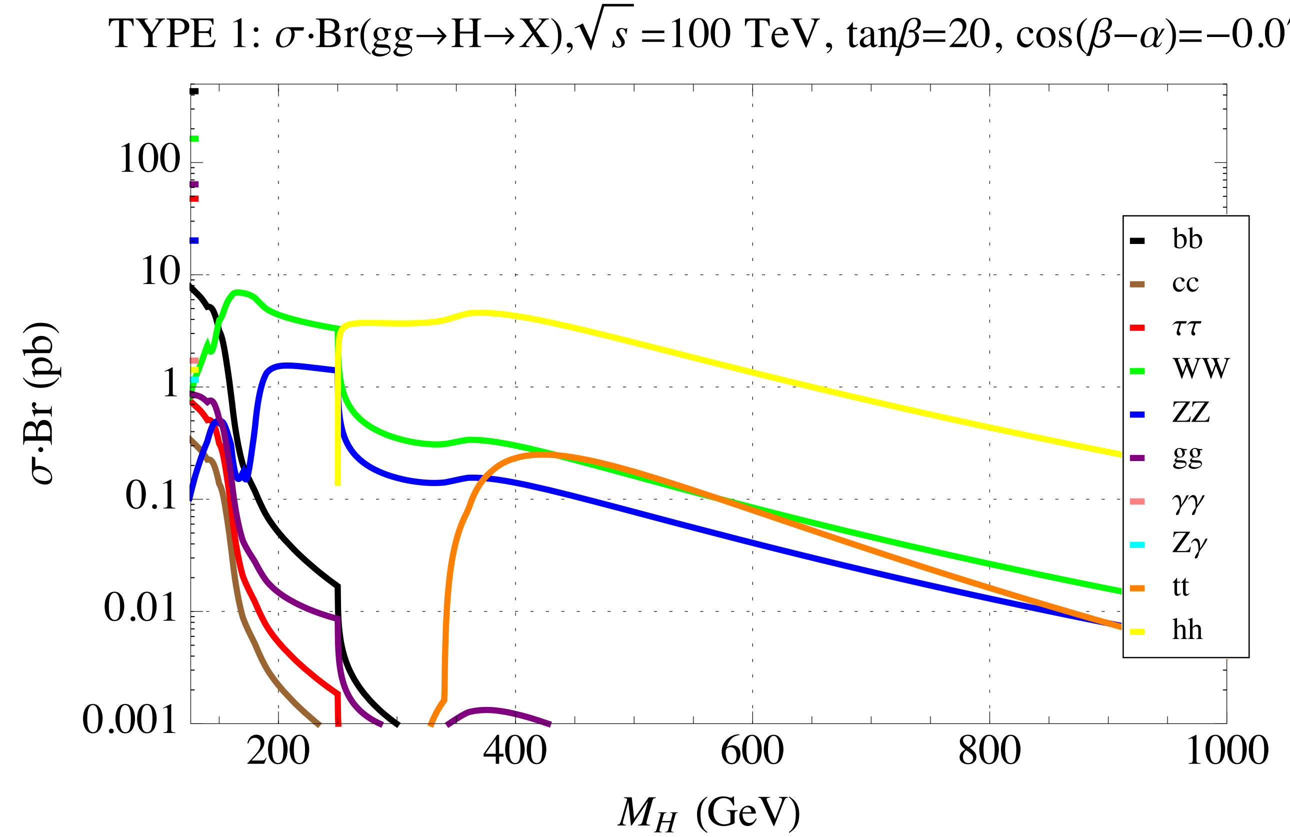


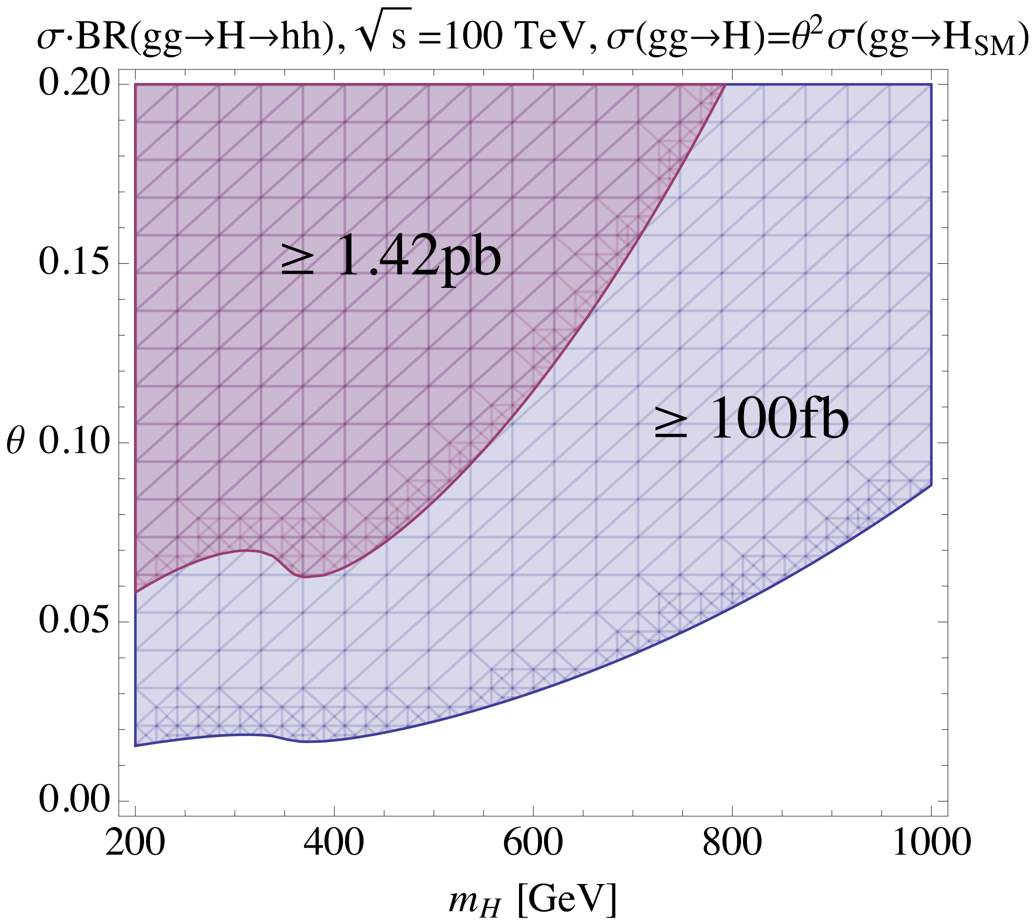
c.f. SM hh~1.42pb@100 TeV

c.f. SM hh~16fb@8 TeV

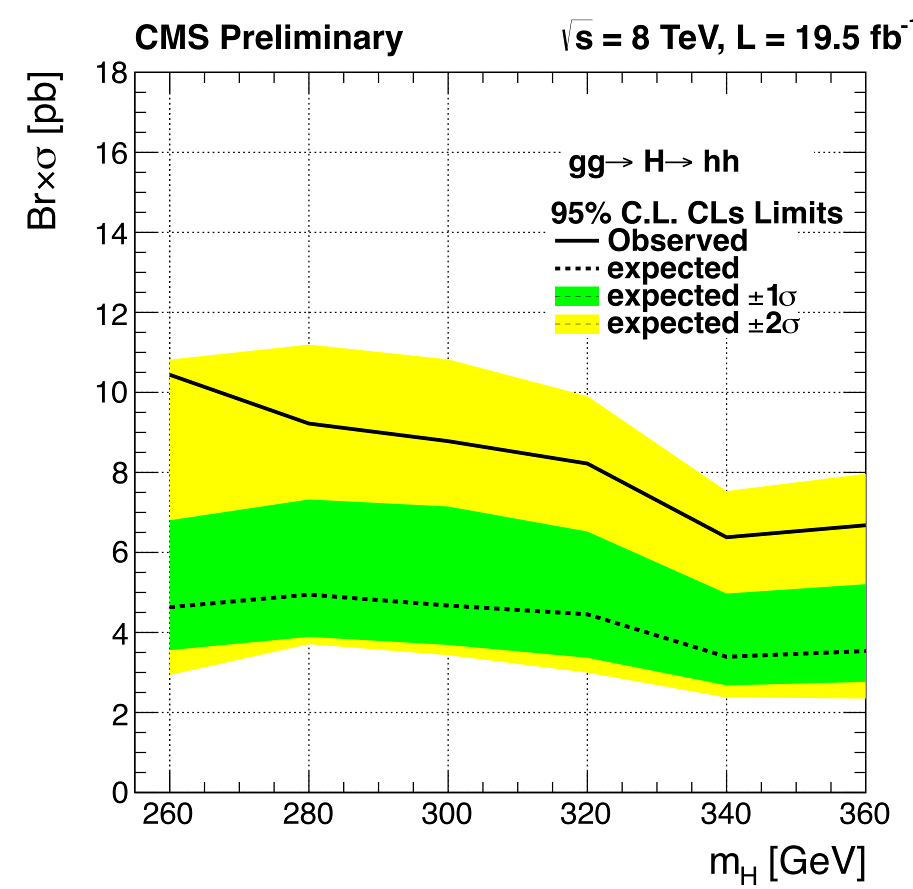
H → hh

Can be a dominant mode for Type I 2HDM; also often the dominant decay mode of a heavy Higgs for singlet-doublet mixing or twin Higgs (see Roni's talk).



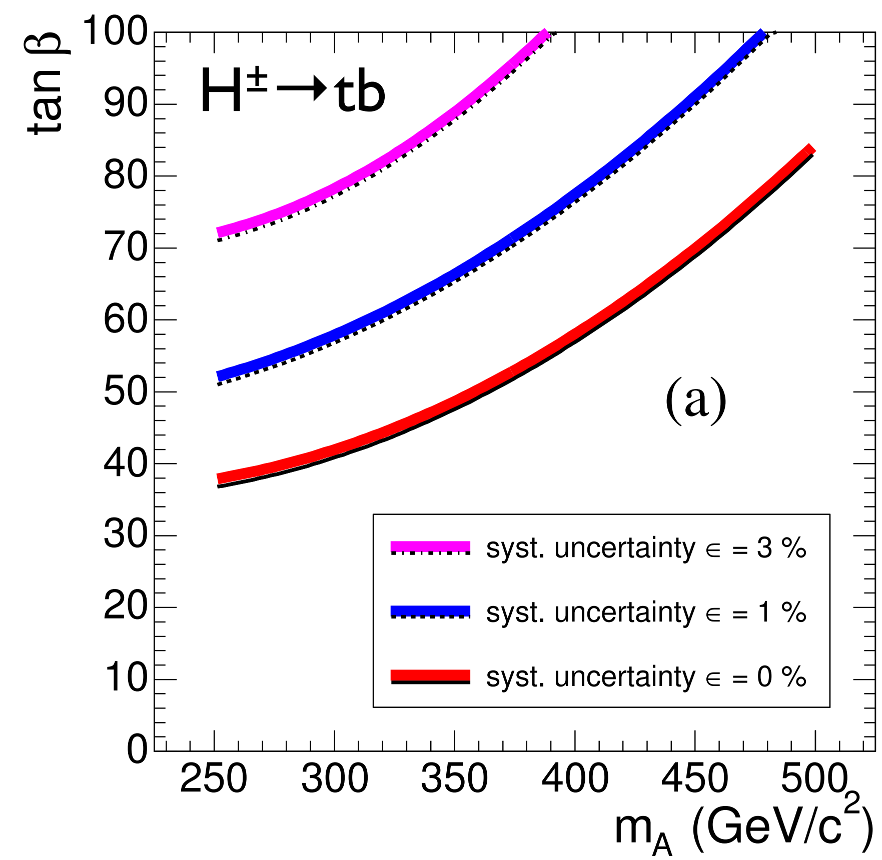


c.f. SM hh~1.42pb@100 TeV

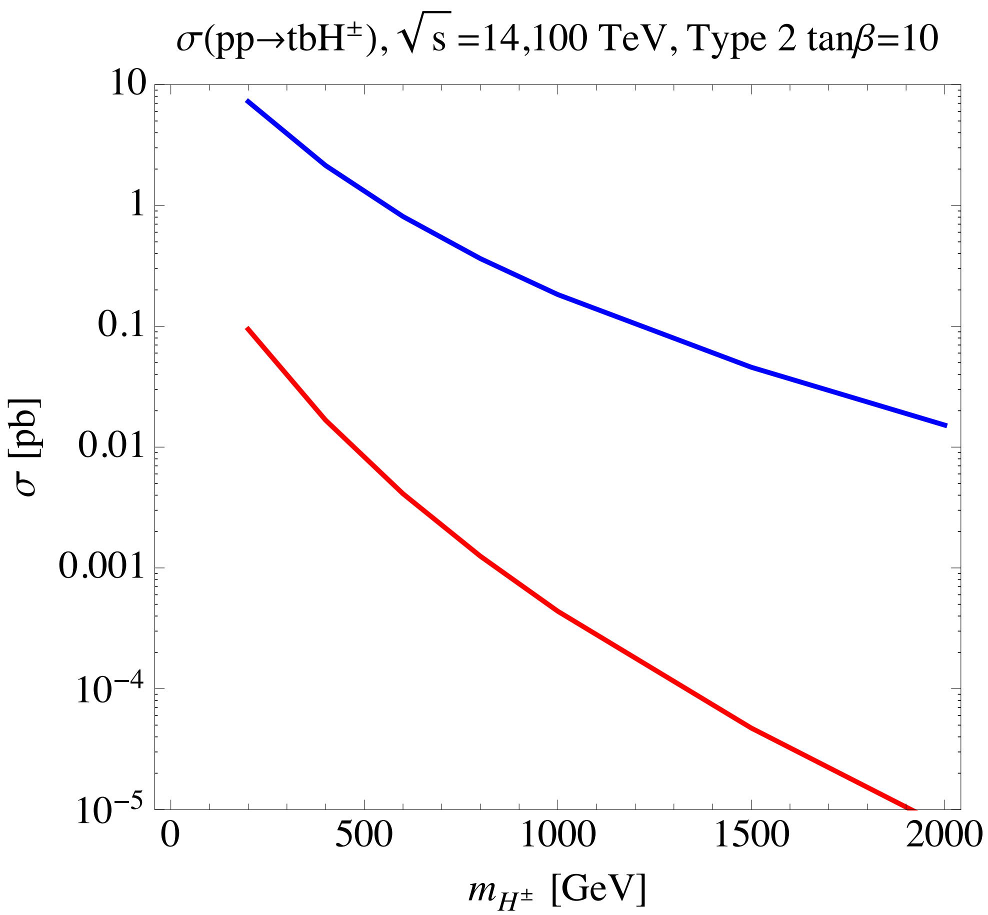


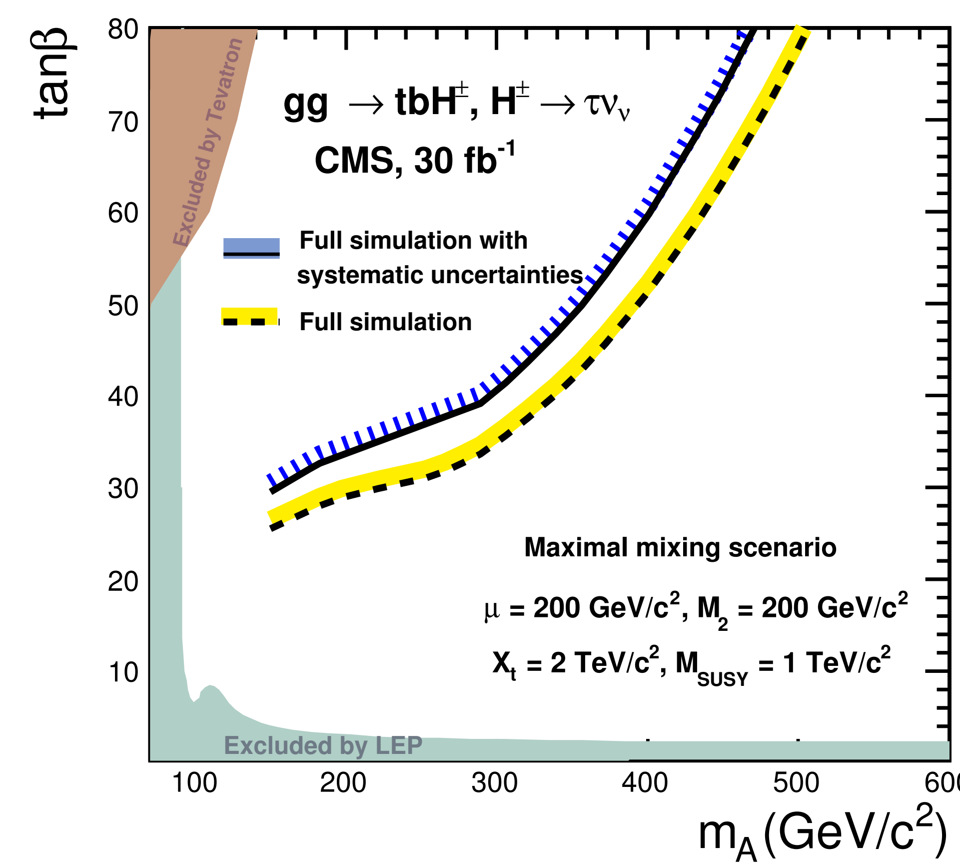
c.f. SM hh~16fb@8 TeV

$tbH^\pm \rightarrow ttbb, tb\tau\nu$



BR($H^\pm \rightarrow tb$)~1 assuming no new open scalar decays, e.g. MSSM.
BR($H^\pm \rightarrow \tau\nu$)~few% but easier final state.
Note $H^\pm \rightarrow Wh$ can also be appreciable in more general 2HDM.





No limits exist at LHC for $m_{H\pm} > m_t$; limits at 14 TeV likely to be weak based on CMS TDR.

Collider study

with E.Brownson, N.Dhingra, U.Heintz, G.Kukartsev, M.Narain, N.Parashar, J.Stupak

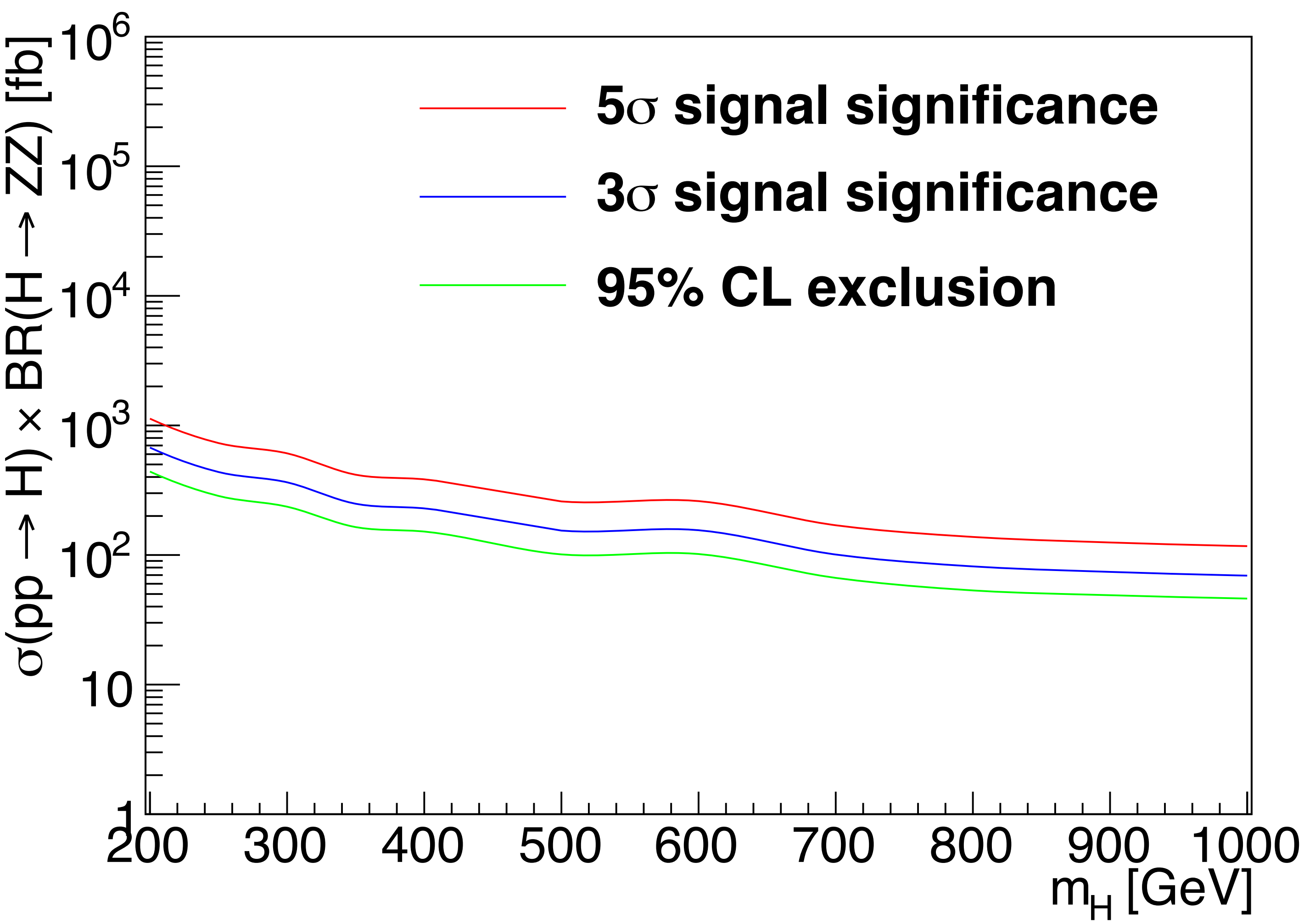
To get a sense for 100 TeV reach, investigate two promising 2HDM modes:

$H \rightarrow ZZ \rightarrow 4\ell$ $\quad$ $A \rightarrow Zh \rightarrow \ell\ell(\tau\tau+bb)$

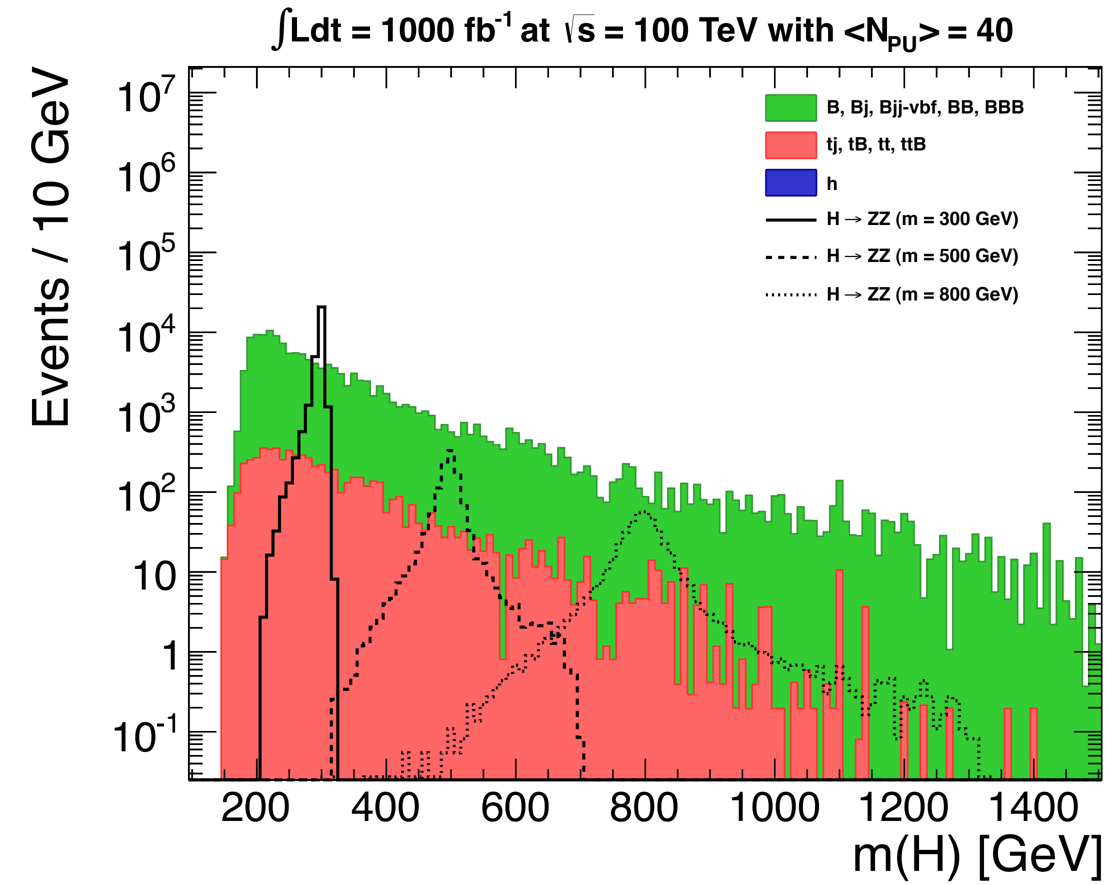
	LHC Run II	HL-LHC	HE-LHC	VLHC
$s^{1/2}$ [TeV]	14	14	33	100
L [fb^{-1}]	300	3000	3000	1000
$\langle N_{PU} \rangle$	50	140	140	40

Snowmass 2013 VLHC simulation parameters
Snowmass backgrounds, pileup, etc.

$H \rightarrow ZZ \rightarrow 4\ell$

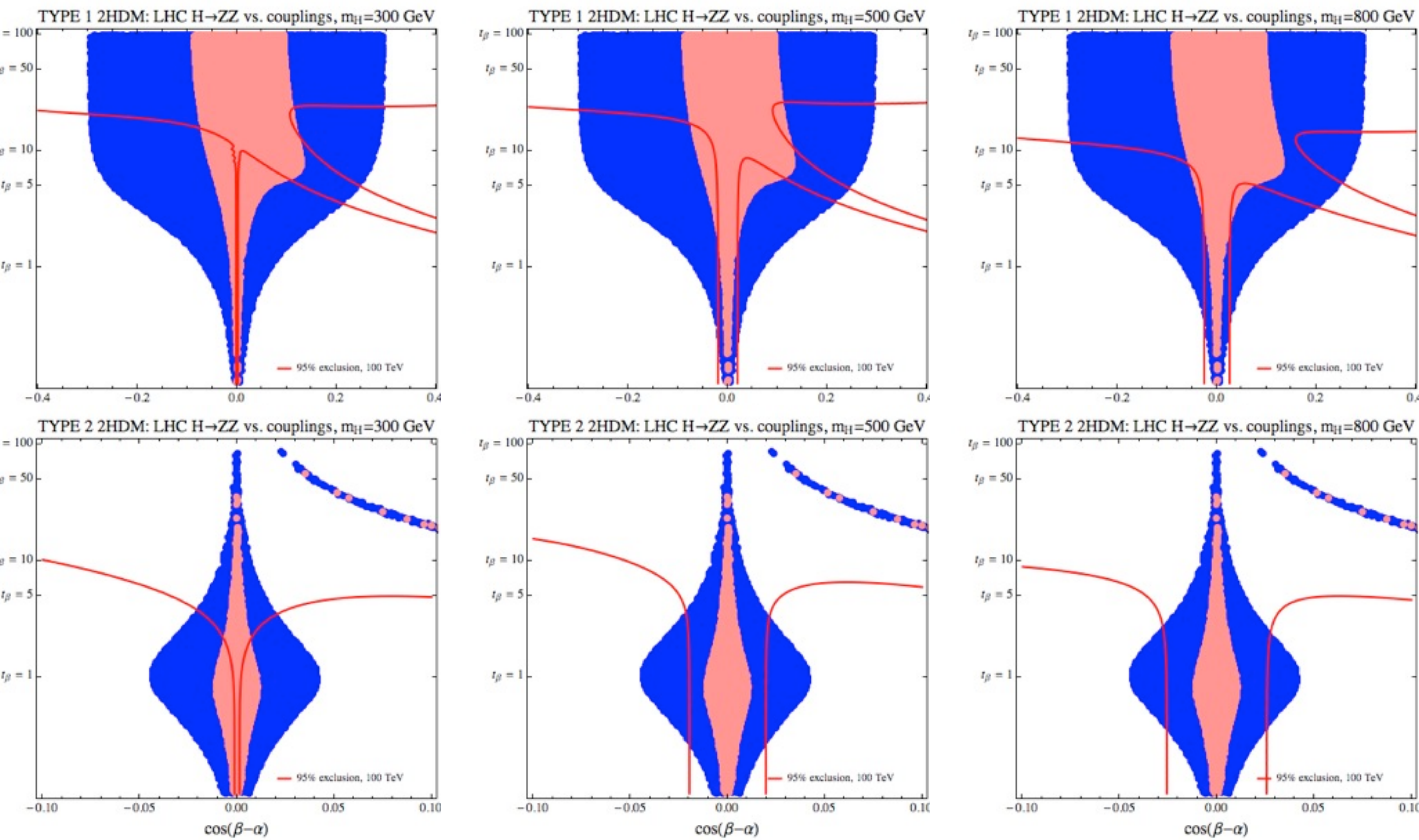


Backgrounds VV, ttV, VVV

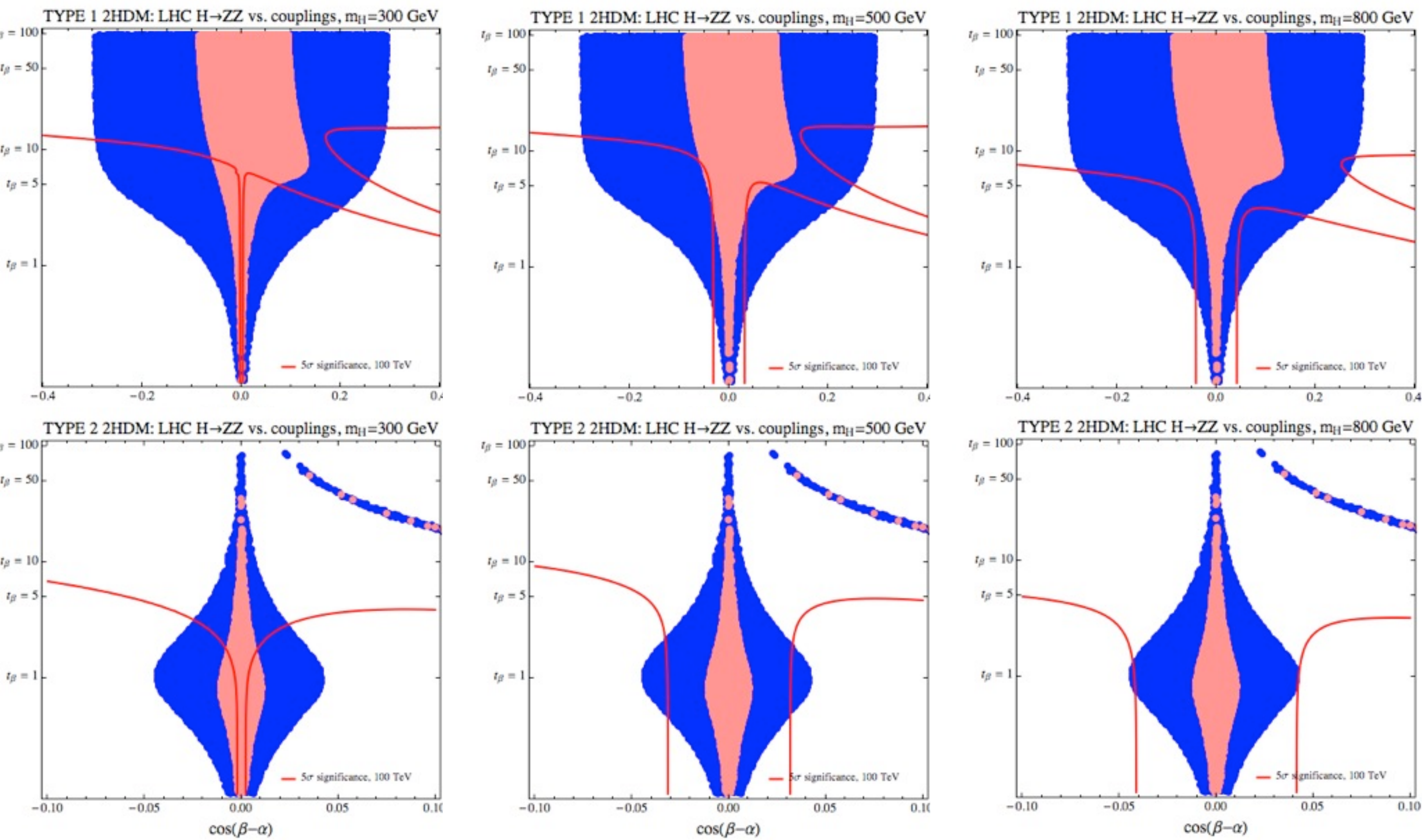


With relatively crude cuts, reach into the 100's of fb @100 TeV

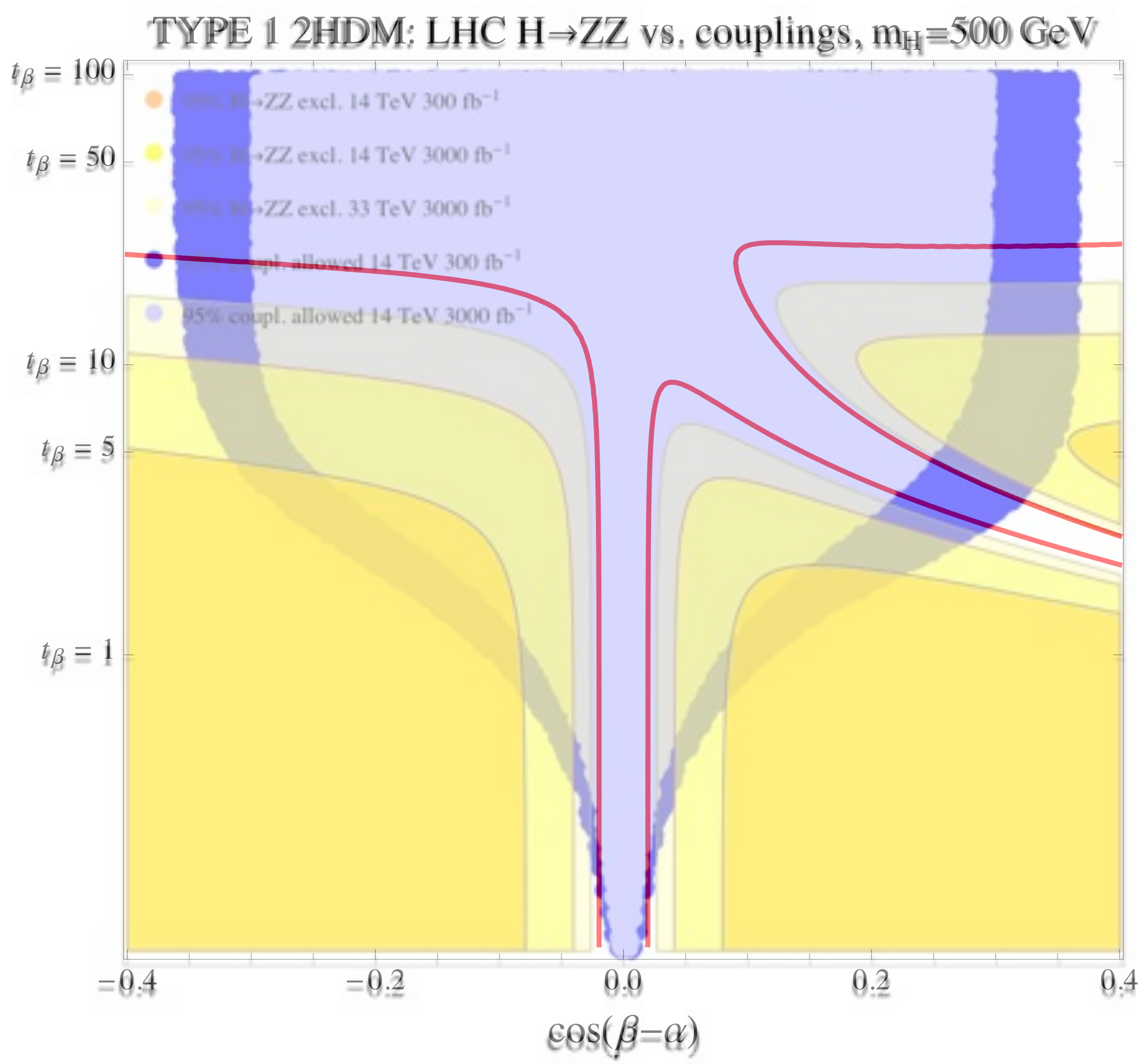
Exclusion Complementarity

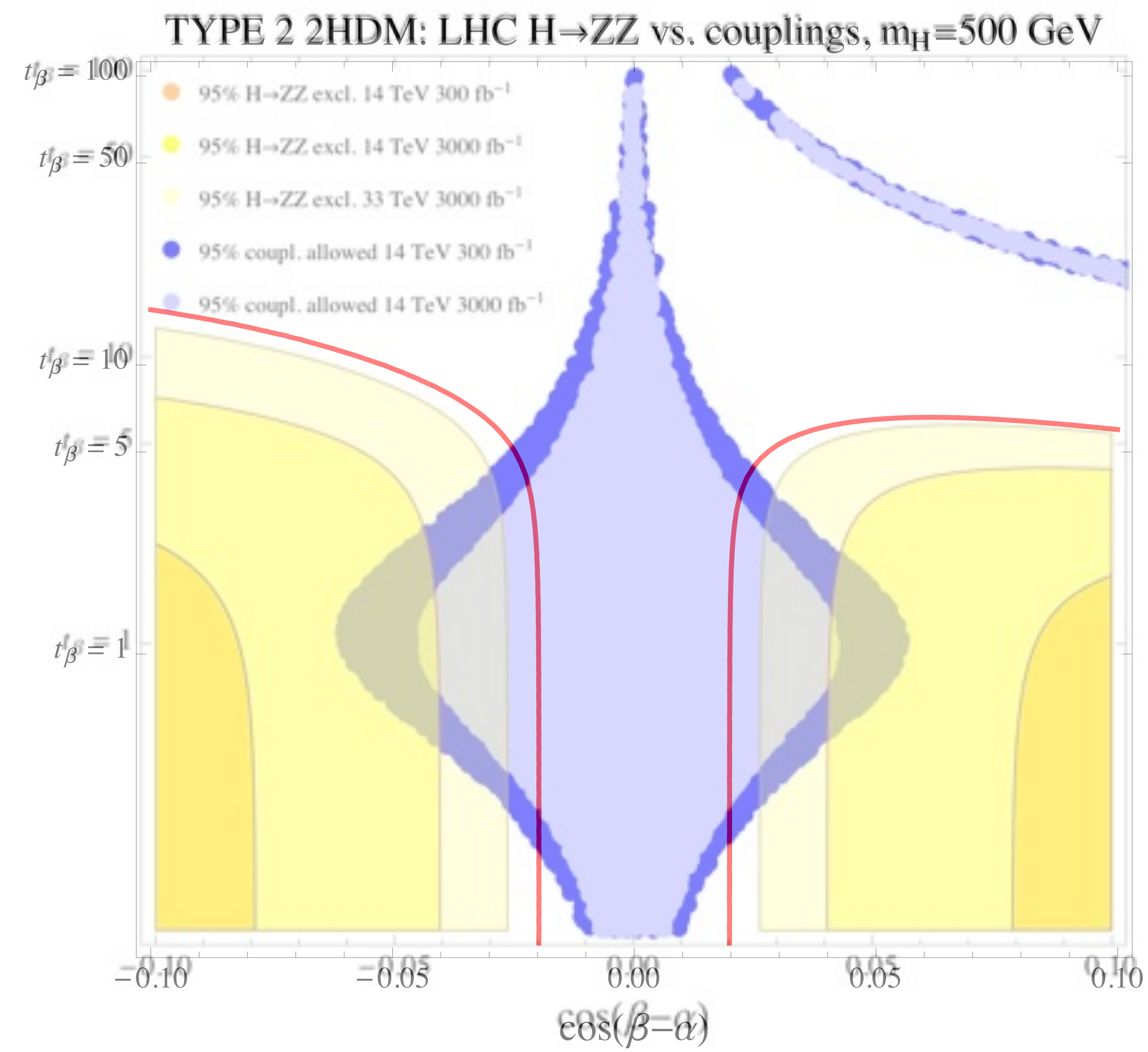


Discovery Complementarity

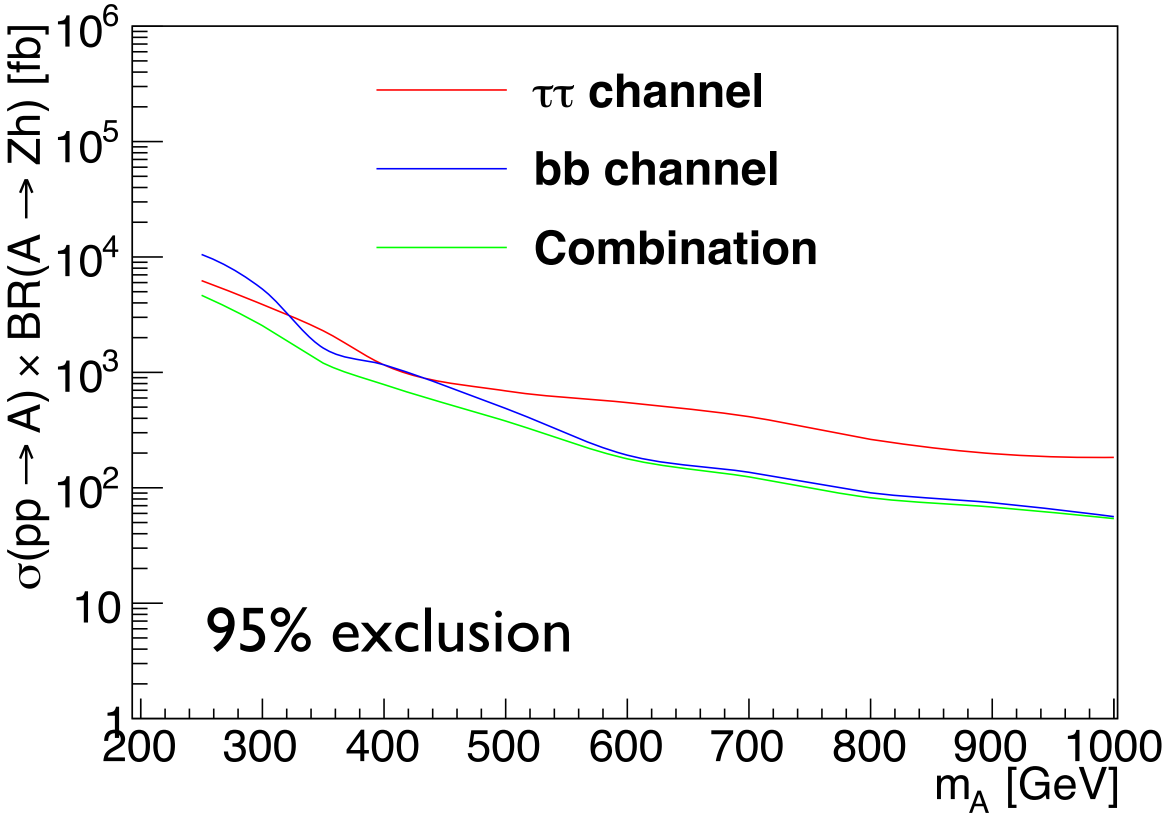


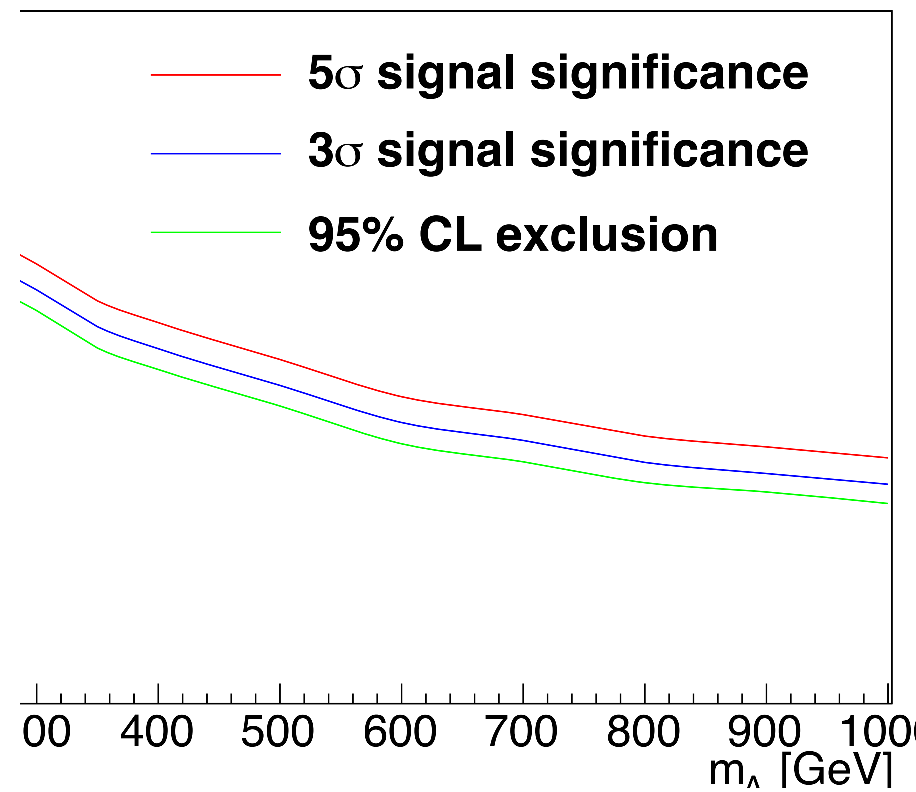
Direct complementarity



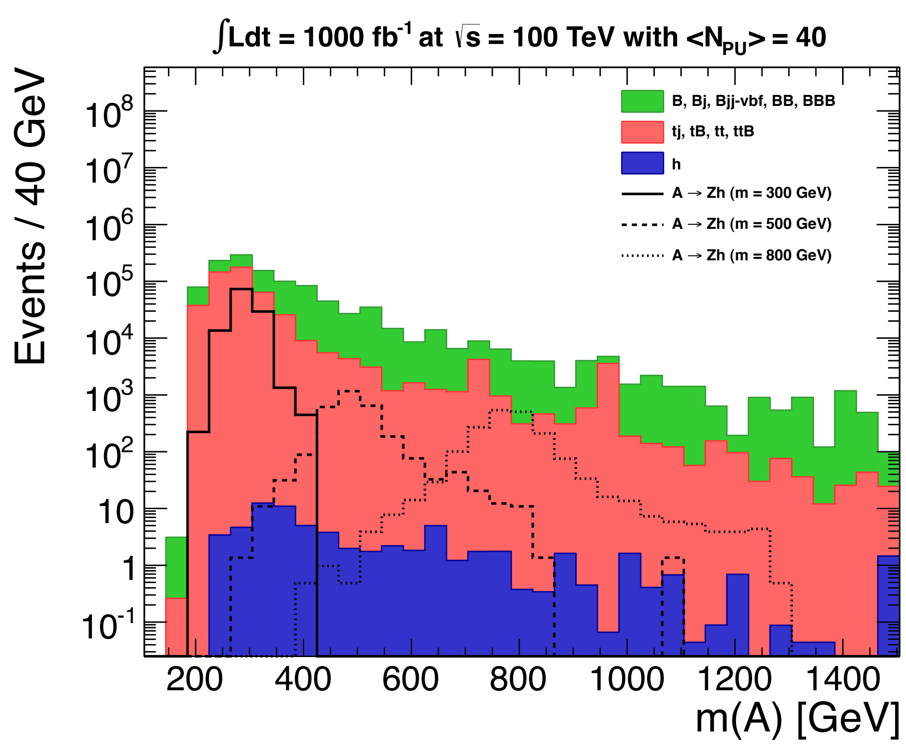


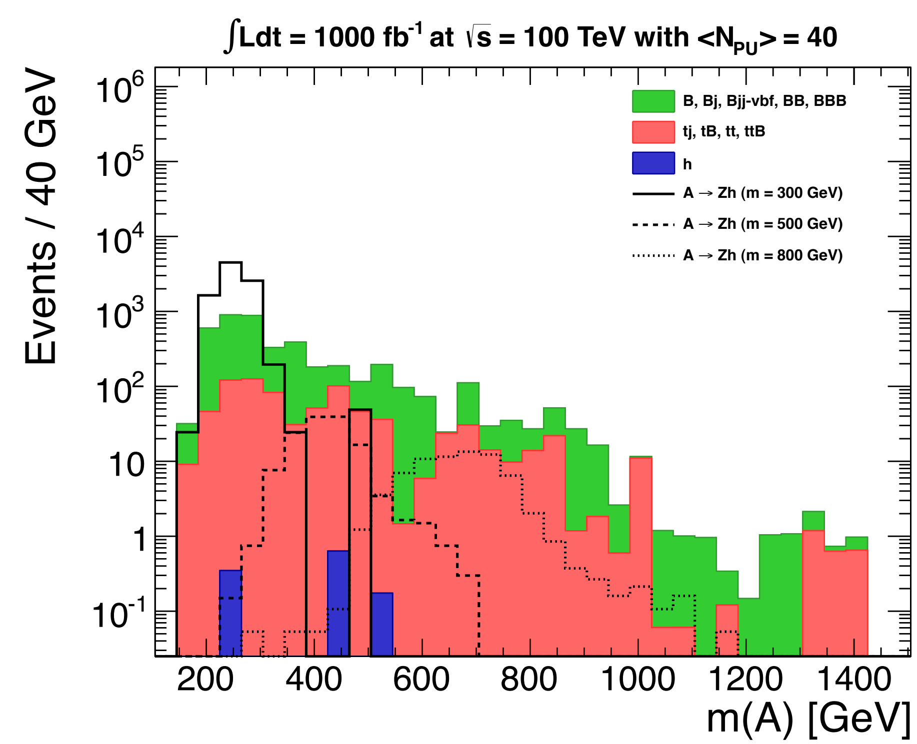
$A \to Zh \to \ell\ \ell\ (\tau\tau + bb)$



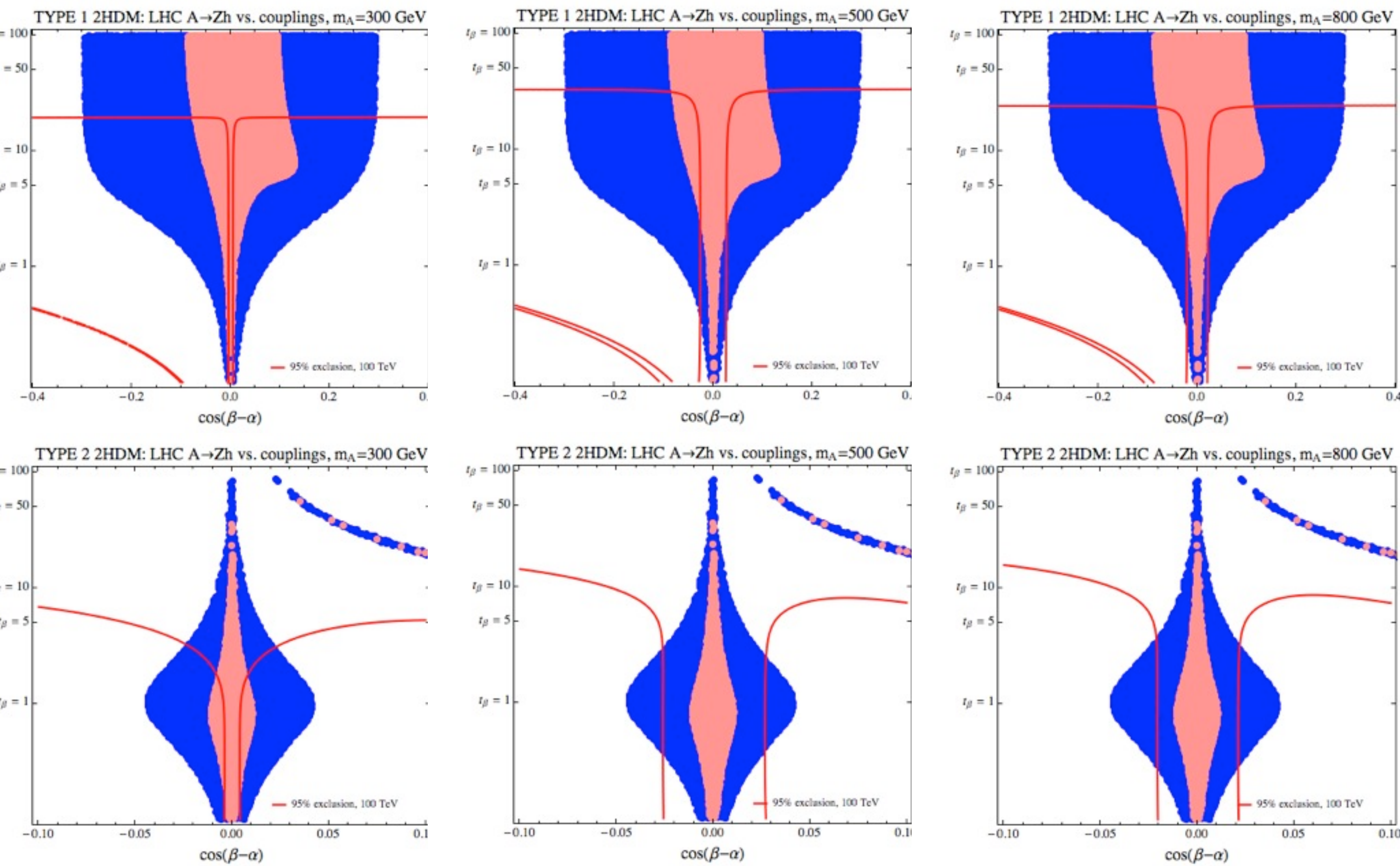


Bkgds
V, tt,
VV, ttV,
tV,VVV

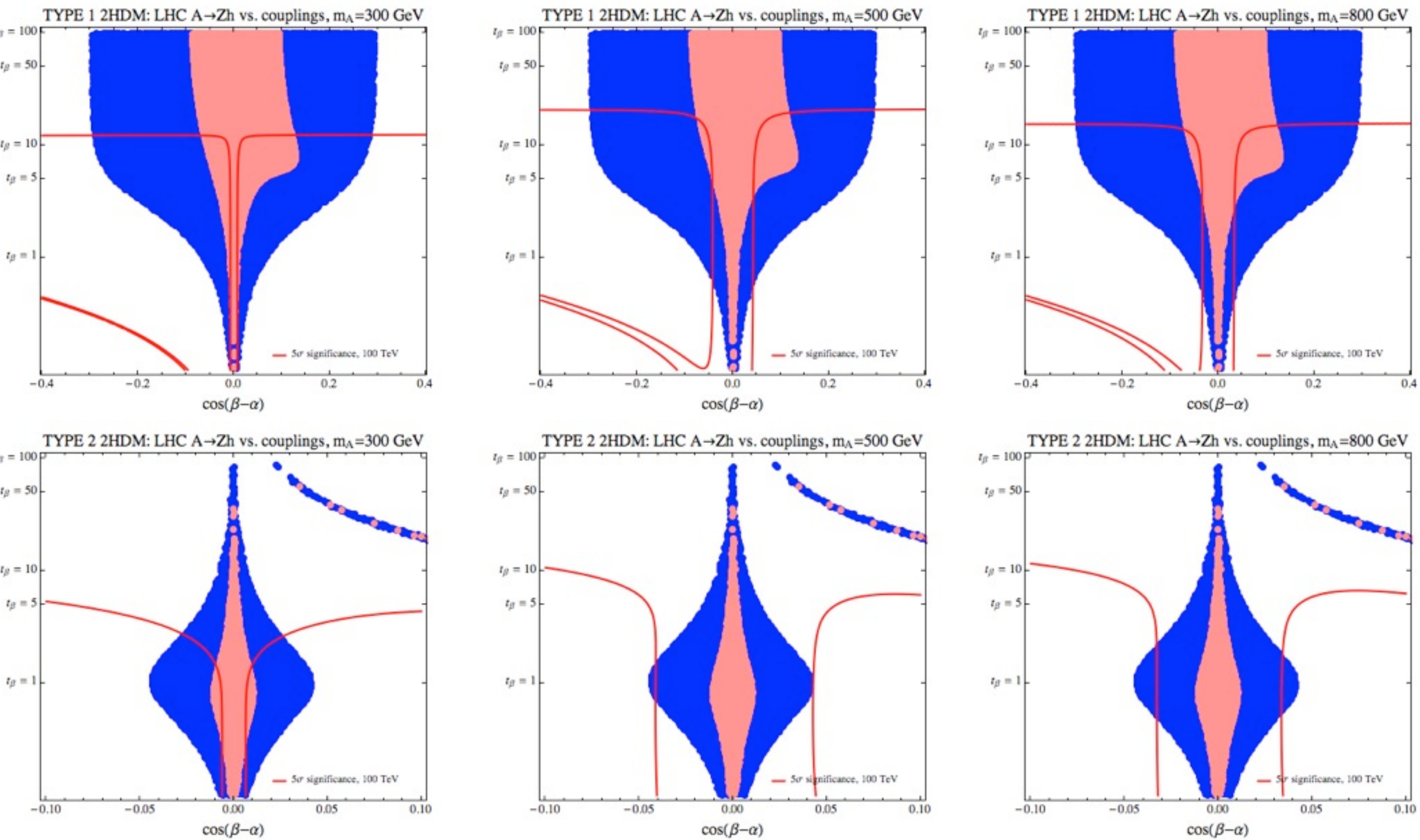




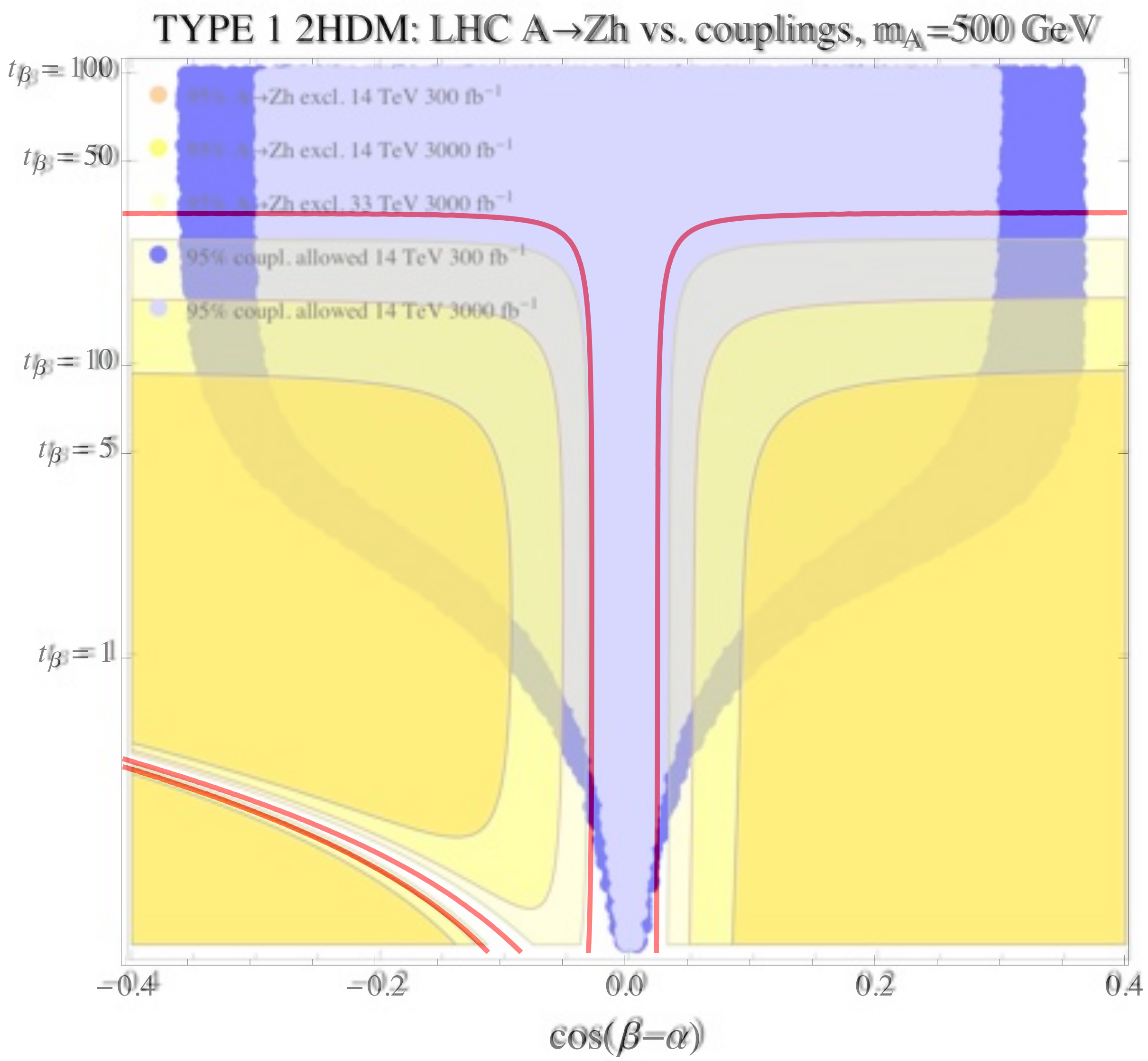
Exclusion complementarity

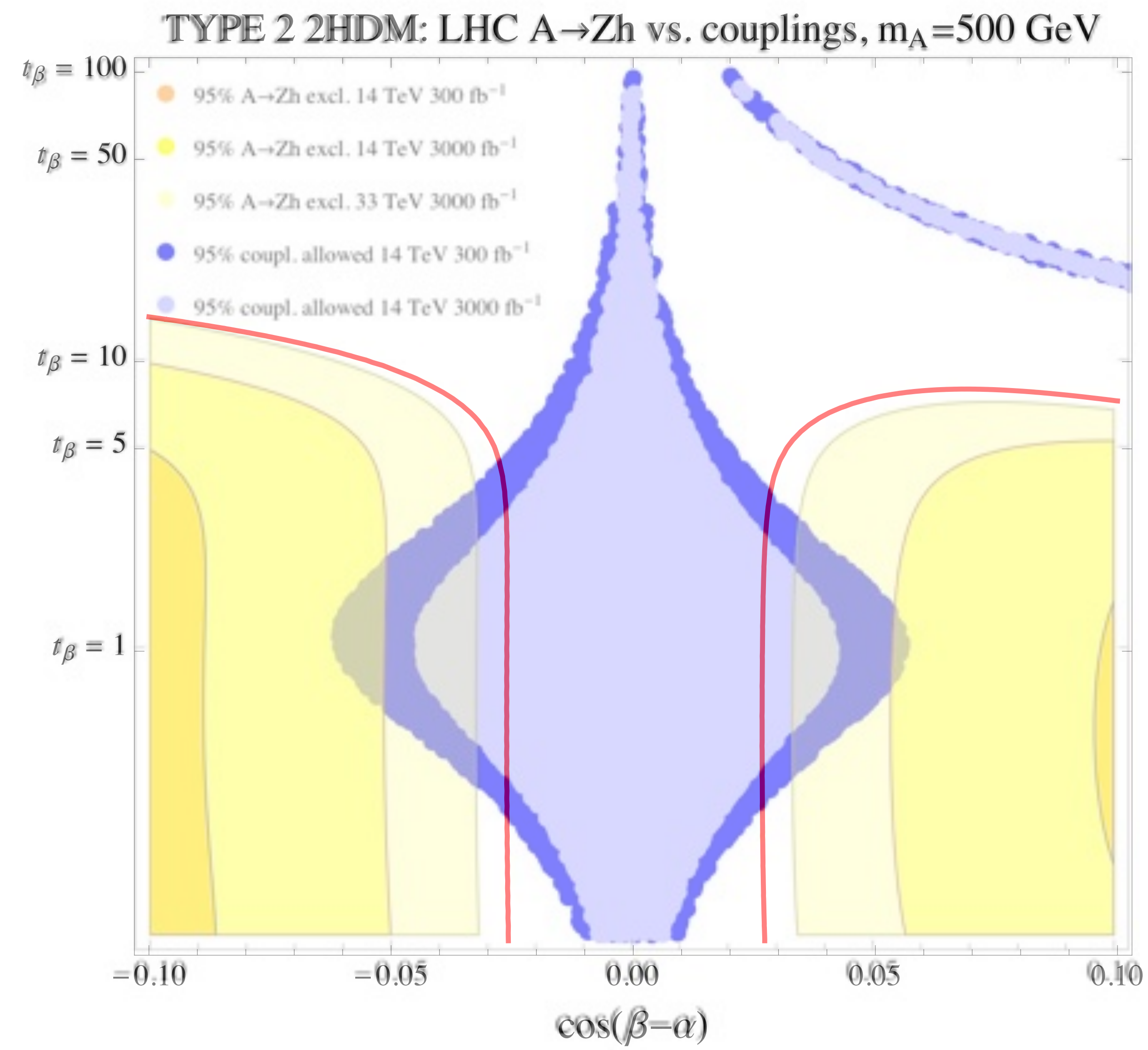


Discovery complementarity

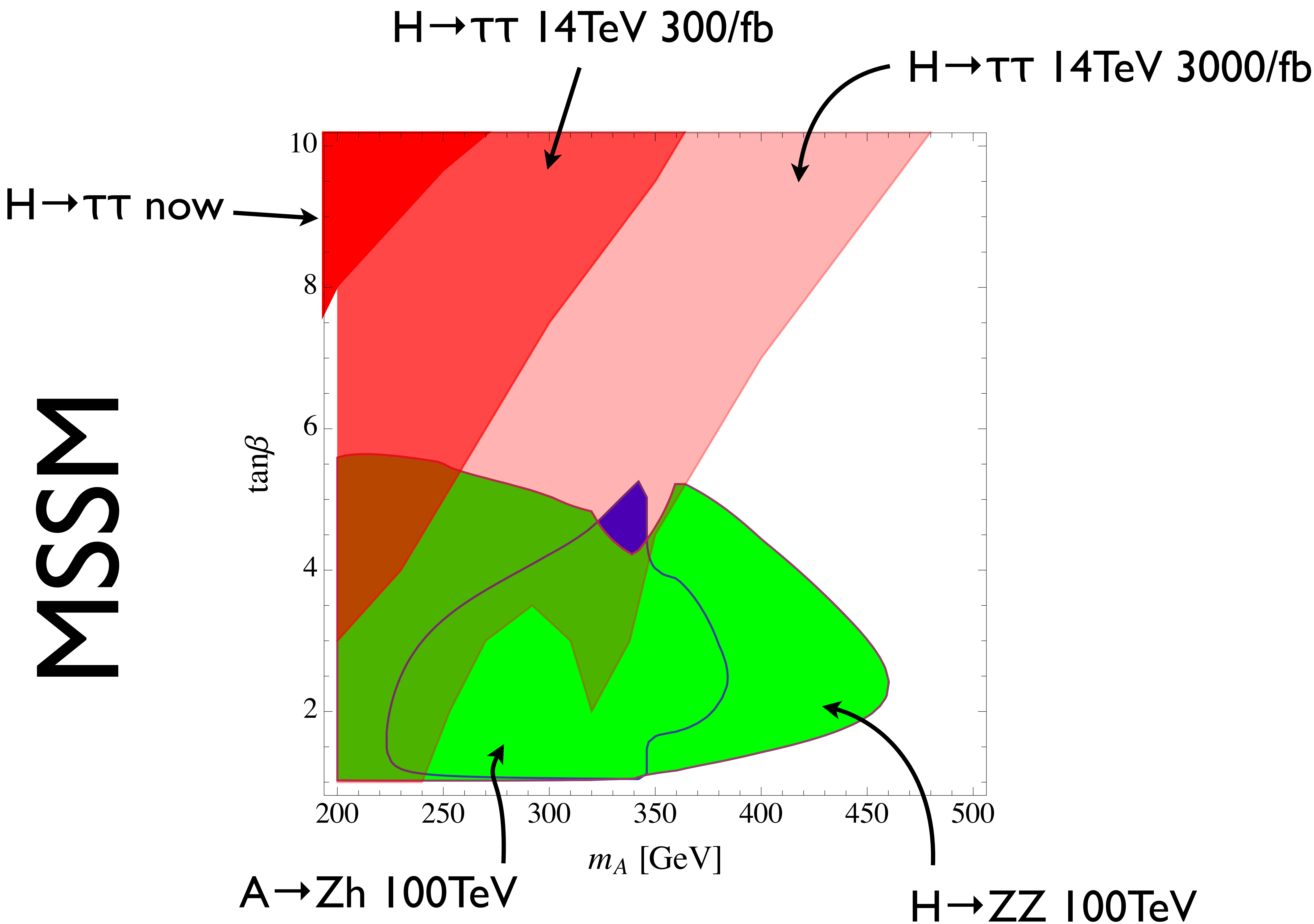


Direct complementarity

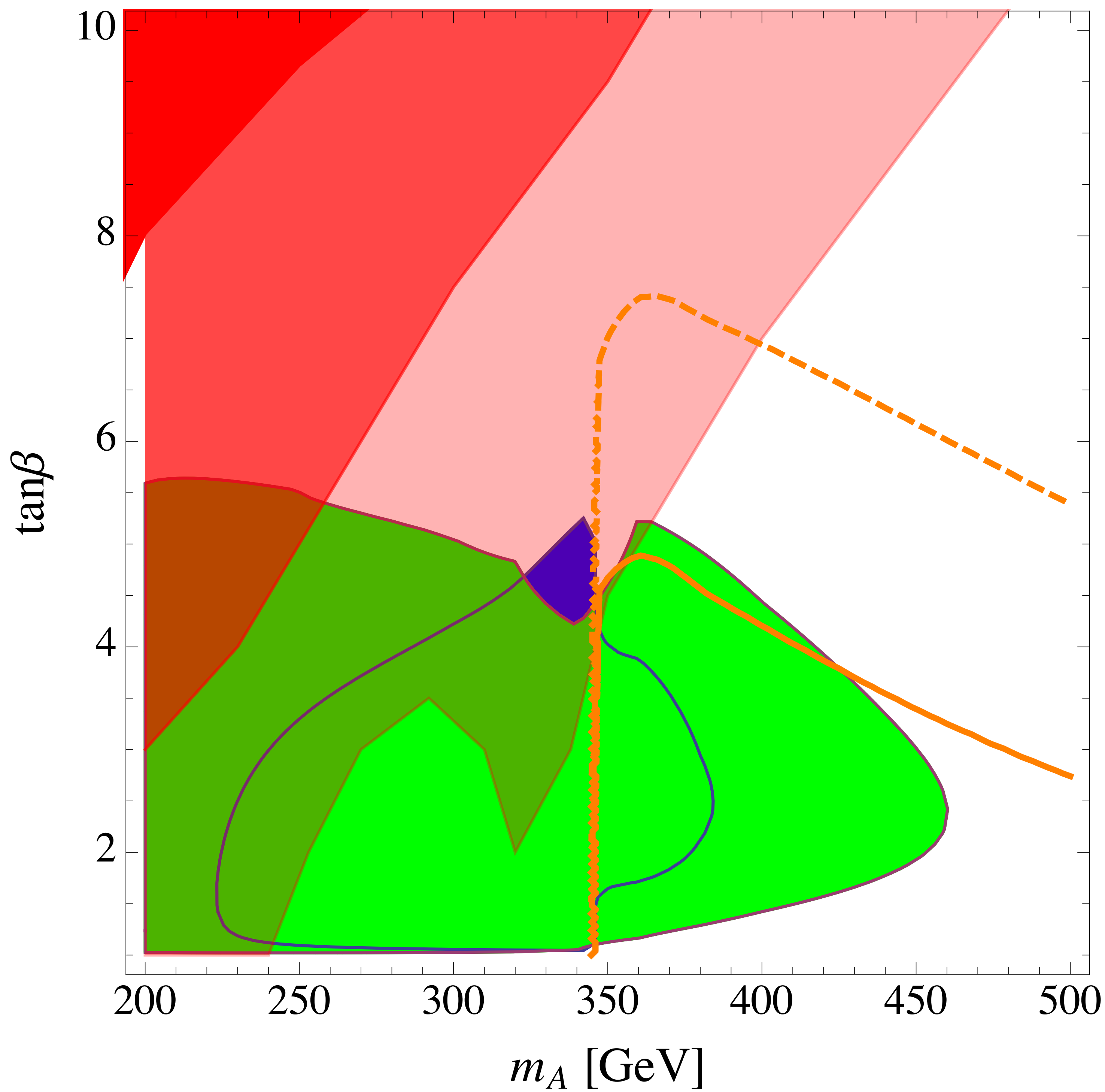




MSSM



Likely too pessimistic, but where's the signal going?



H→ττ should take care of high-tanβ region. Going to need to pick up decays into top pairs. Optimizing charged Higgs search also crucial.

$\sigma \cdot Br(gg \to A \to t\bar{t}) = 10pb$

$\sigma \cdot Br(gg \to A \to t\bar{t}) = 50pb$

Question moving forward: can we hope to see a pseudoscalar decaying to $t\bar{t}$ around SM top turnon with $\sigma \cdot Br > 10pb$ at 100 TeV?

c.f. SM ttbar ~25nb @100 TeV

Conclusions

- Strong motivation for BSM Higgses outside LHC14 reach but within 100 TeV reach in ~few TeV range.
- 100 TeV capability to pursue both alignment and decoupling.
- New opportunities at 100 TeV from enhanced top associated production: $tt\Phi$ and $tbH^{\pm}$ appreciable and provide new handles for otherwise challenging final states.
- Under-studied modes such as $\Phi \rightarrow tt$ become increasingly important at high mass given projected coupling limits.
- Excellent complementarity between coupling measurements and reach for current 100 TeV studies, demonstrates high utility of a 100 TeV BSM Higgs program.

Desiderata

Moving forward, we'll have a more complete picture from:

- Dedicated $\Phi \to \tau\tau$ study at 100 TeV.
- Dedicated $\Phi \to tt$ search at 8/14 TeV, study for 100 TeV.
- Study & exploitation of $tt\Phi$ and $tbH^{\pm}$ modes, particularly for otherwise-difficult $\Phi \to tt$ and $H^{\pm} \to tb$ decays.