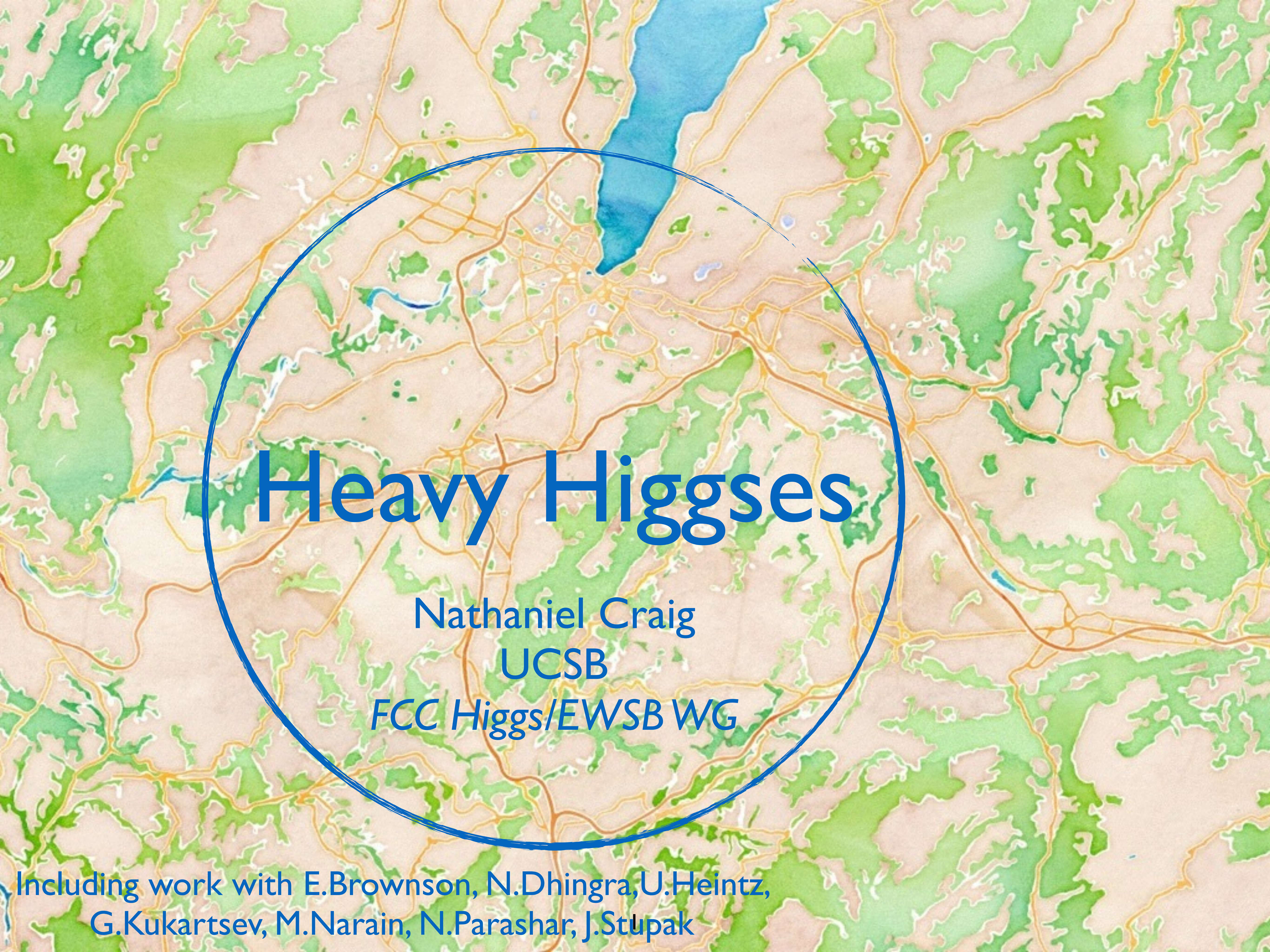


Heavy Higgses

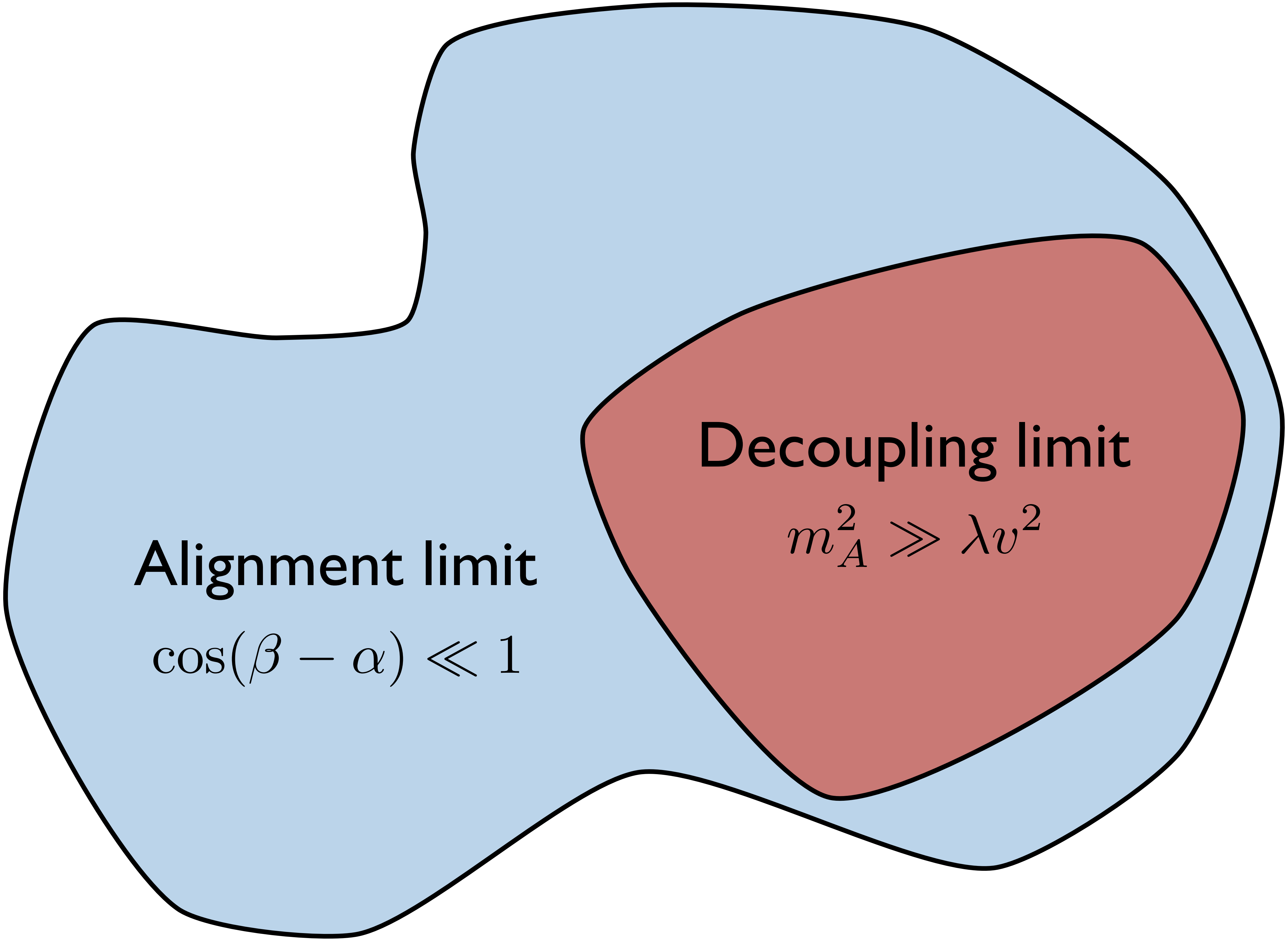
Nathaniel Craig
UCSB
FCC Higgs/EWSB WG

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

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.

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



Decoupling limit

$m_A^2 \gg \lambda v^2$

Alignment limit

$\cos(\beta - \alpha) \ll 1$

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.

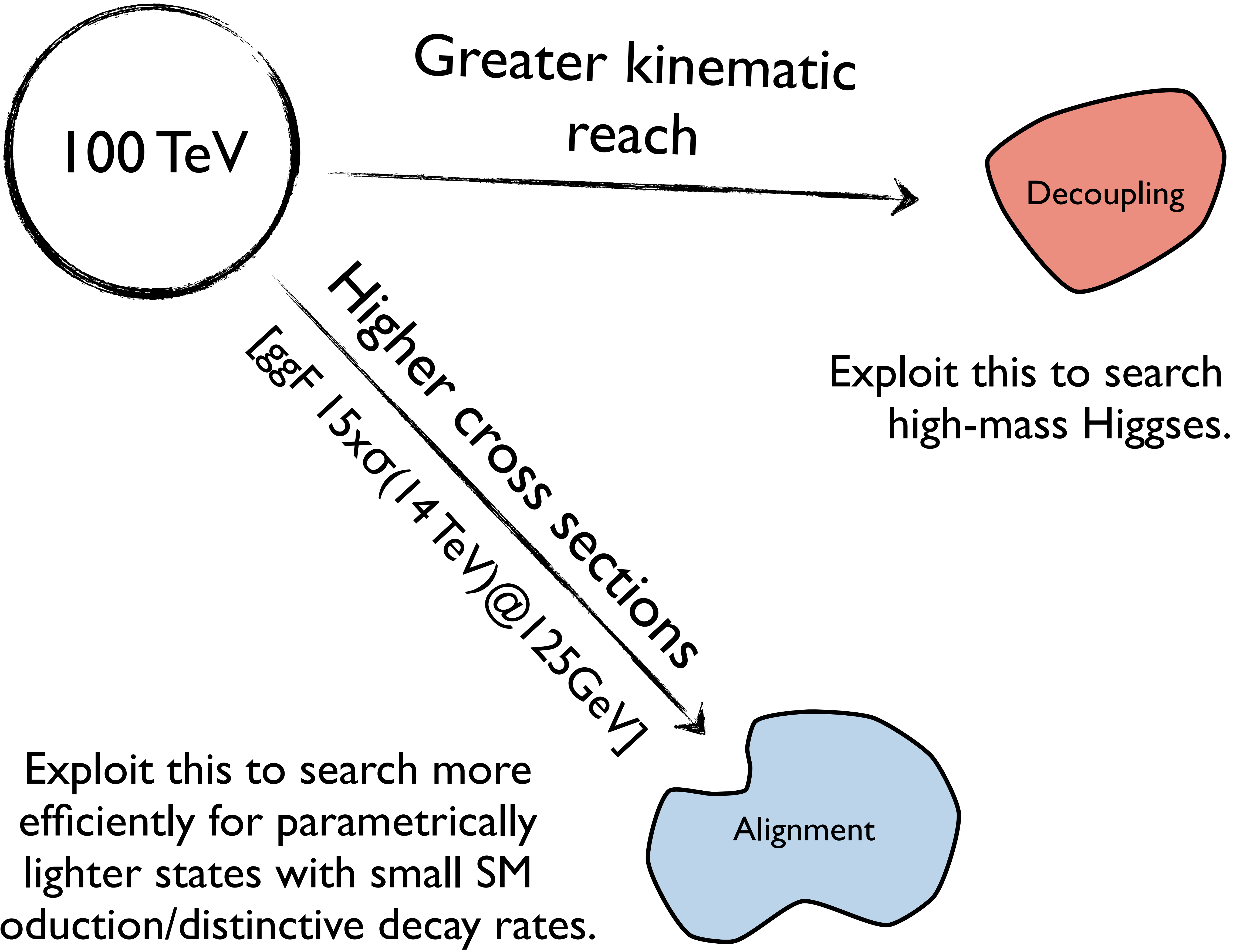
E.g. SUSY:

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

In the limit of large tanβ implies suppressed sensitivity;

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

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

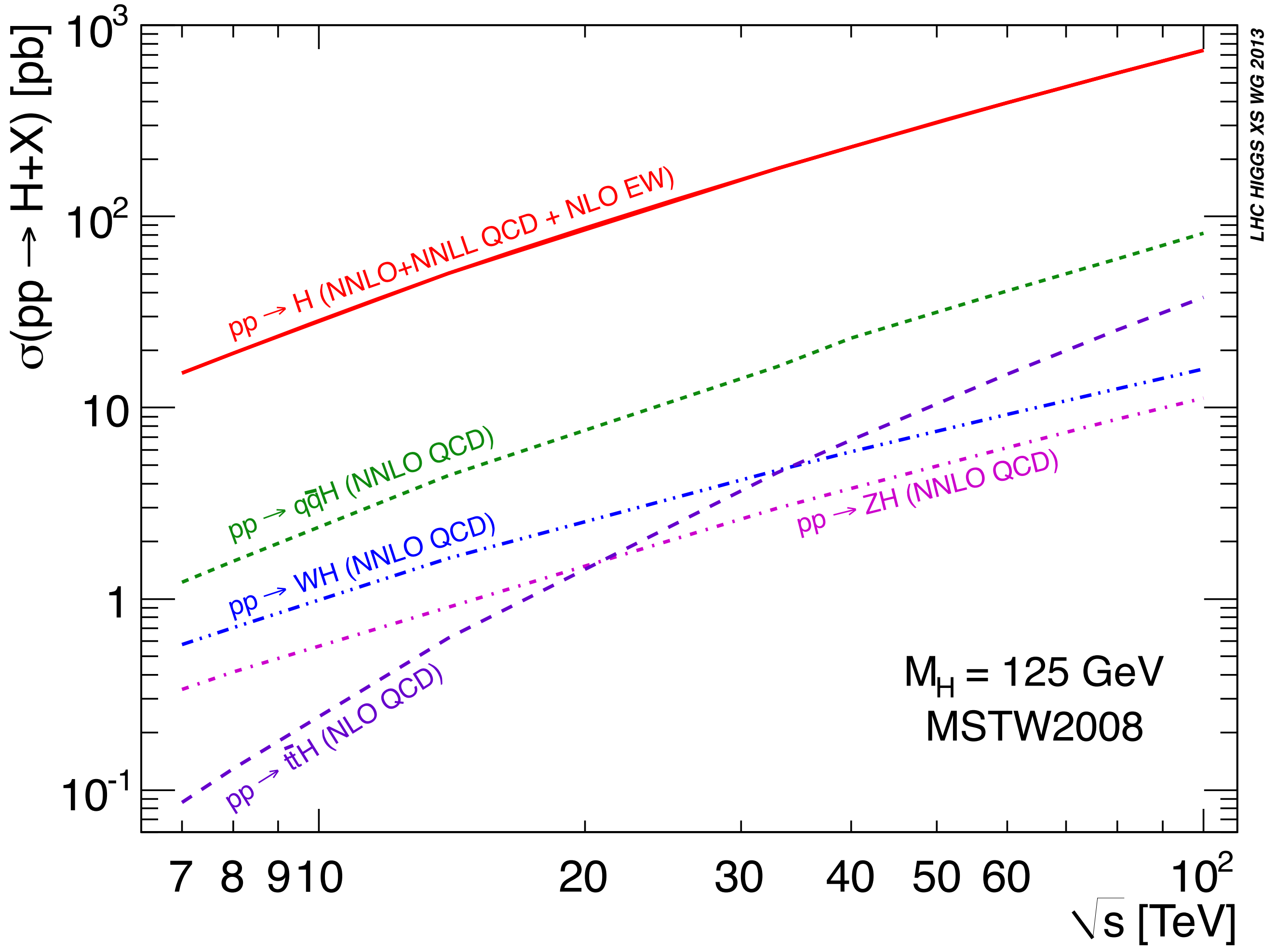
[ggF 15xσ(14 TeV)@125GeV]

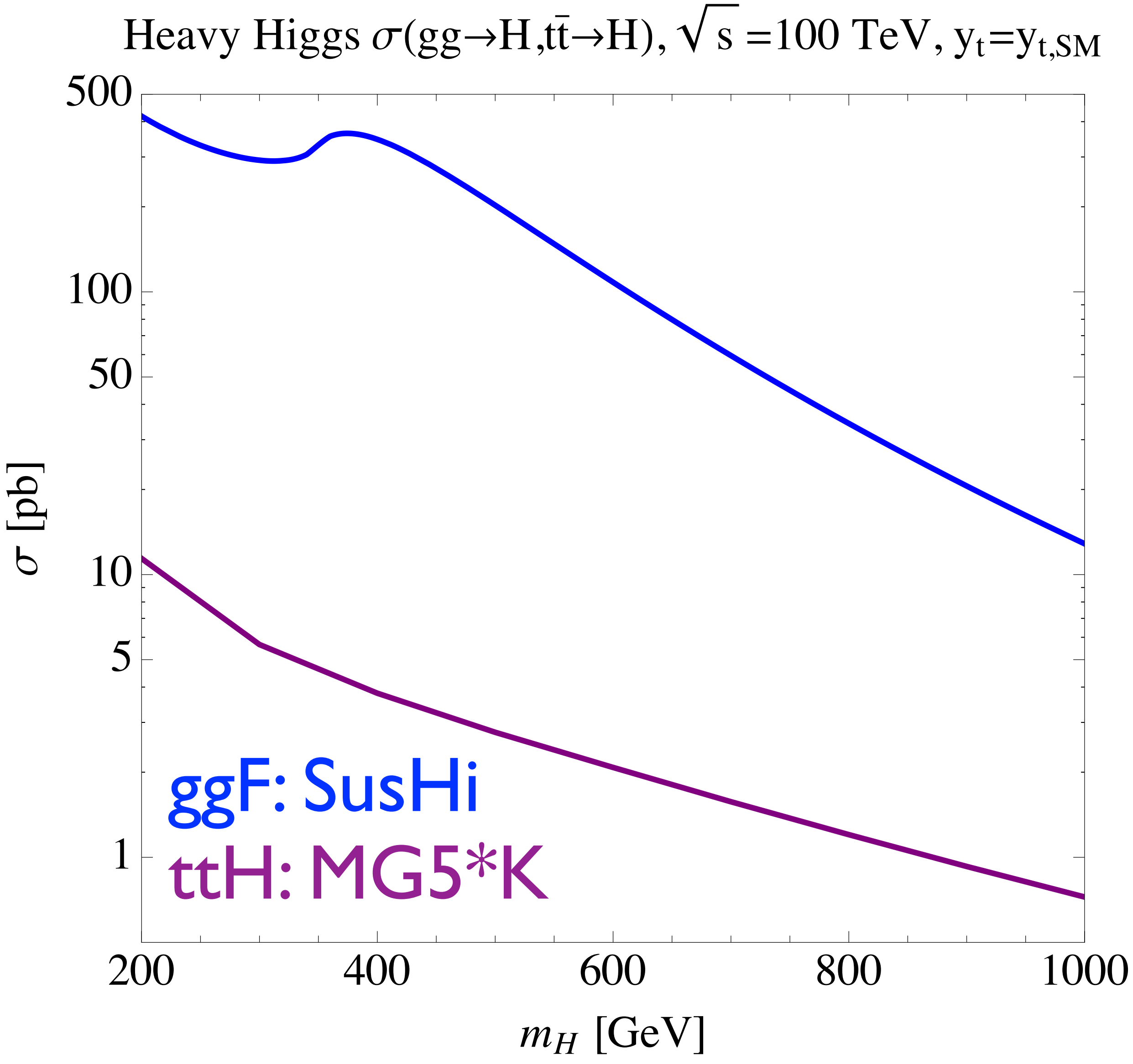
Alignment

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

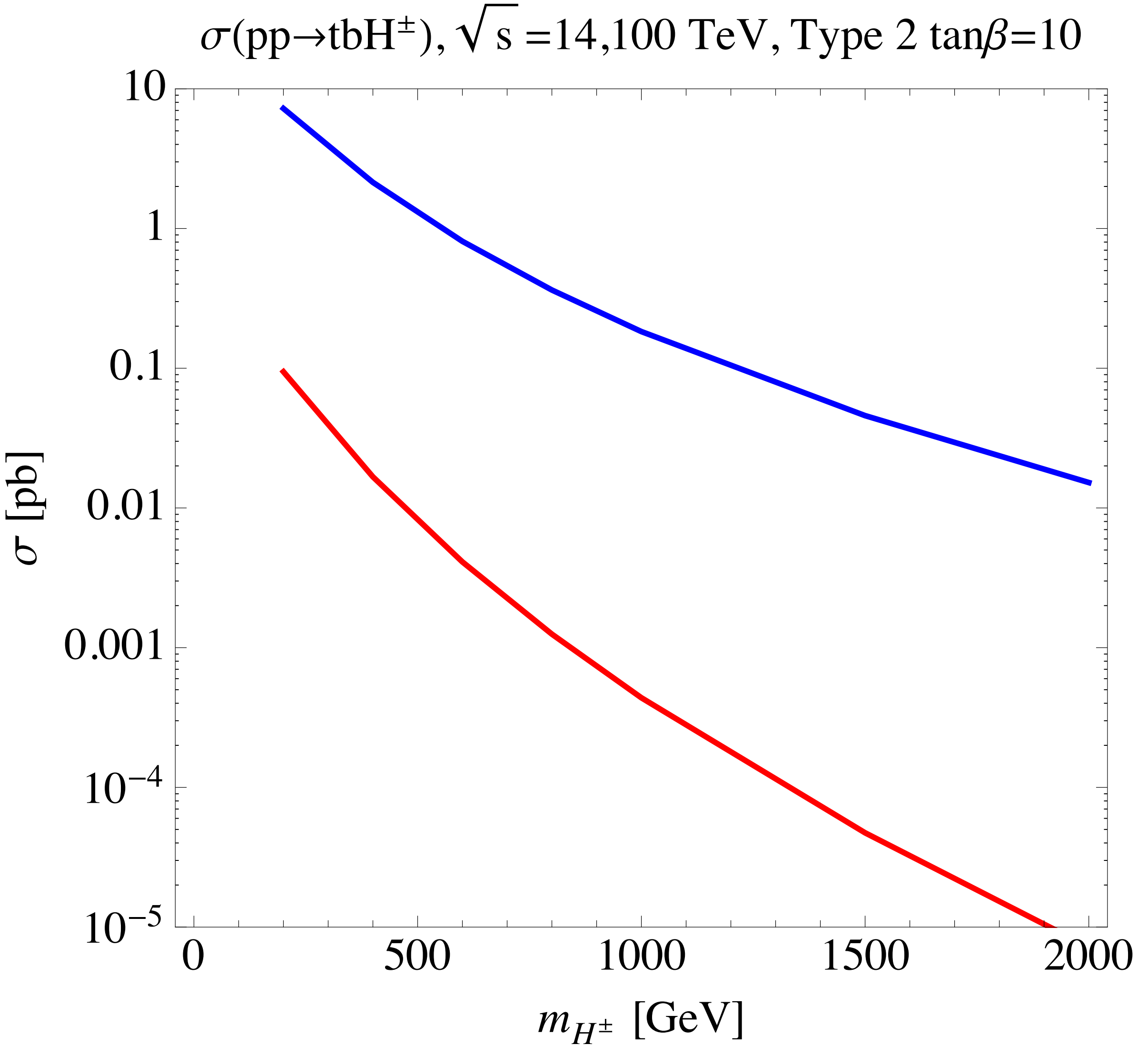




ttH: 61xσ(14 TeV); ggF: 15xσ(14 TeV)

100 TeV Opportunities

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

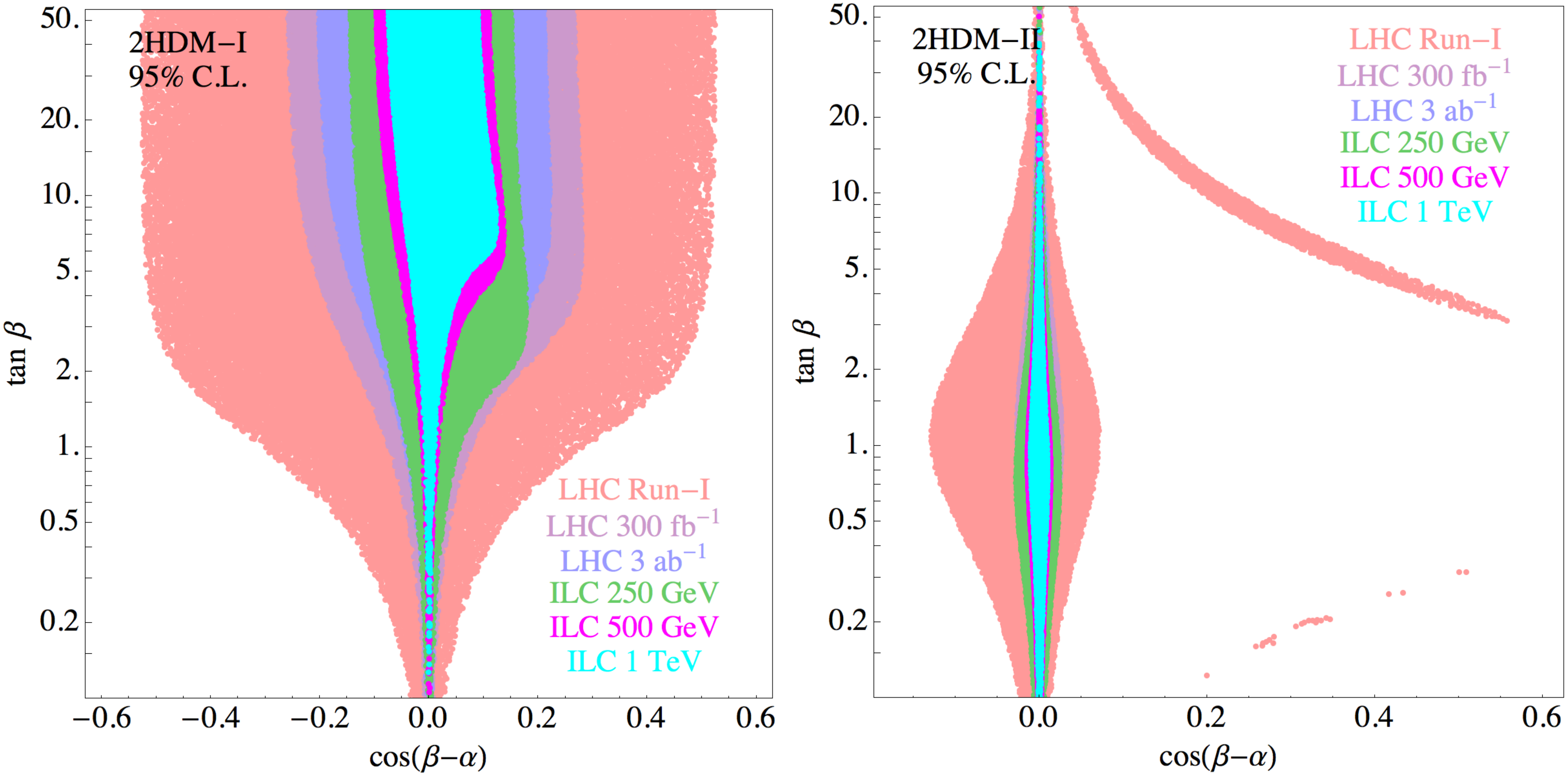


Preliminary estimate (LO MG5):
$tbH^\pm$: 80xσ(14 TeV)
@$\tan\beta=10$ $m_{H\pm}=200$ GeV.
σ >100fb to $m_{H\pm}$~TeV

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

Complementarity

[Barger, Everett, Logan, Shaughnessy 1308.0052]

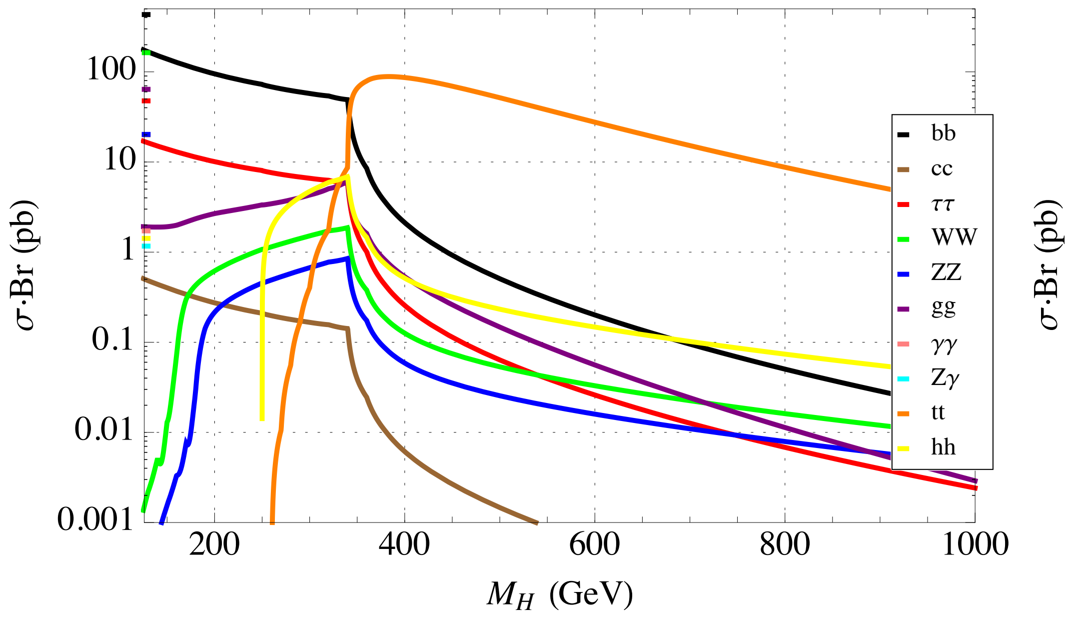


Where can we expect signs of heavy Higgses given the envelope of coupling measurements? E.g., starting the VLHC after ILC1000-level precision?

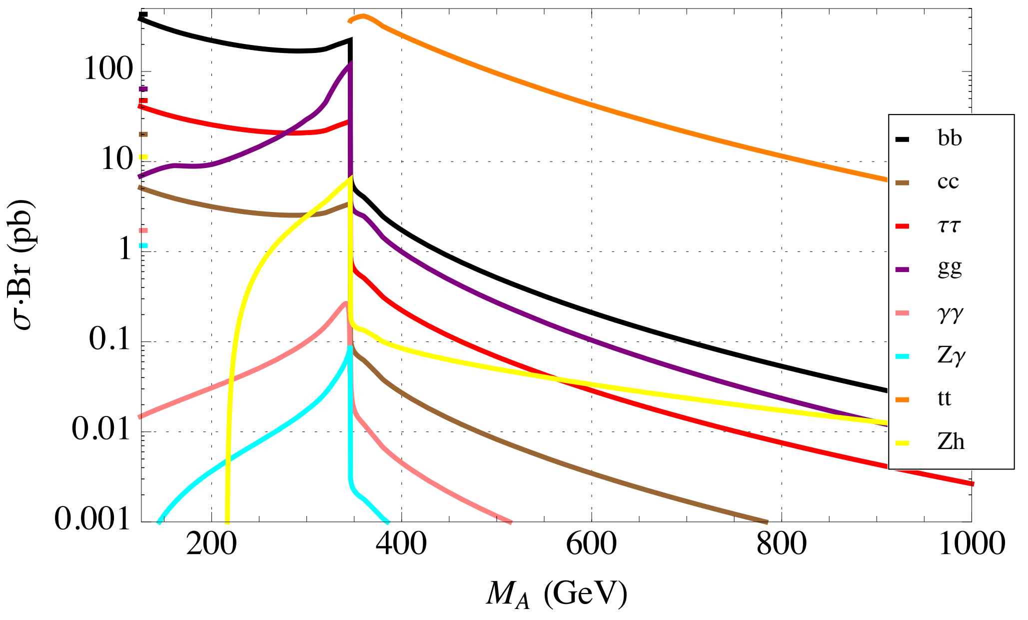
Complementarity

If observed Higgs couplings very SM-like, promising final for heavy (neutral) Higgses include tt, WW, ZZ, ττ, bb, hh, Zh.

TYPE 2: $\sigma\cdot$Br(gg→H→X), $\sqrt{s}$ =100 TeV, tanβ=2, cos$(\beta-\alpha)$=−0.01



TYPE 2: $\sigma\cdot$Br(gg→A→X), $\sqrt{s}$ =100 TeV, tanβ=2, cos$(\beta-\alpha)$=−0.01



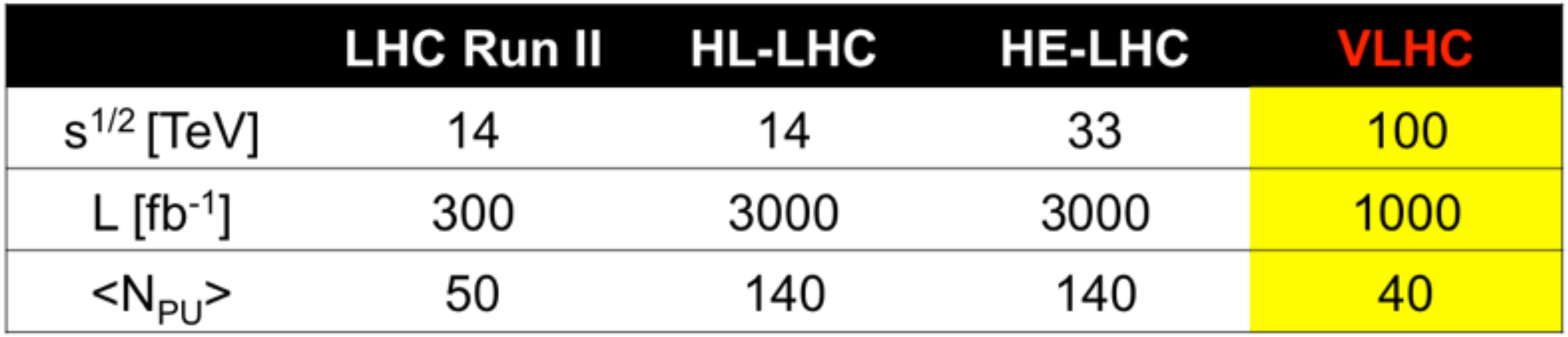
(See backup for details)

Collider study

with E.Brownson, N.Dhingra,U.Heintz, G.Kukartsev, M.Narain, N.Parashar, J.Stupak [1308.6334]

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

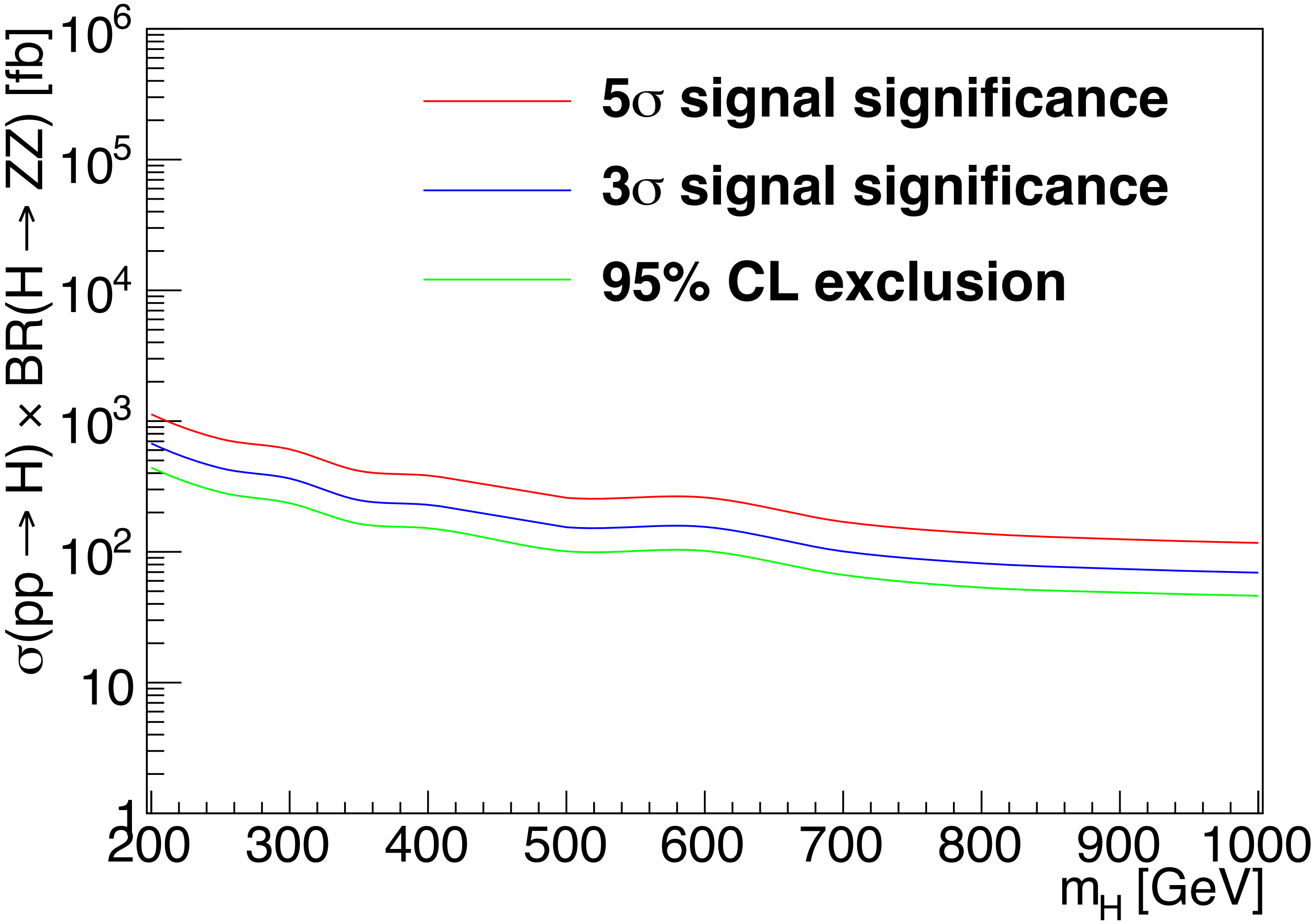
$H \to ZZ \to 4\ell$ $A \to Zh \to \ell\ell(\tau\tau+bb)$



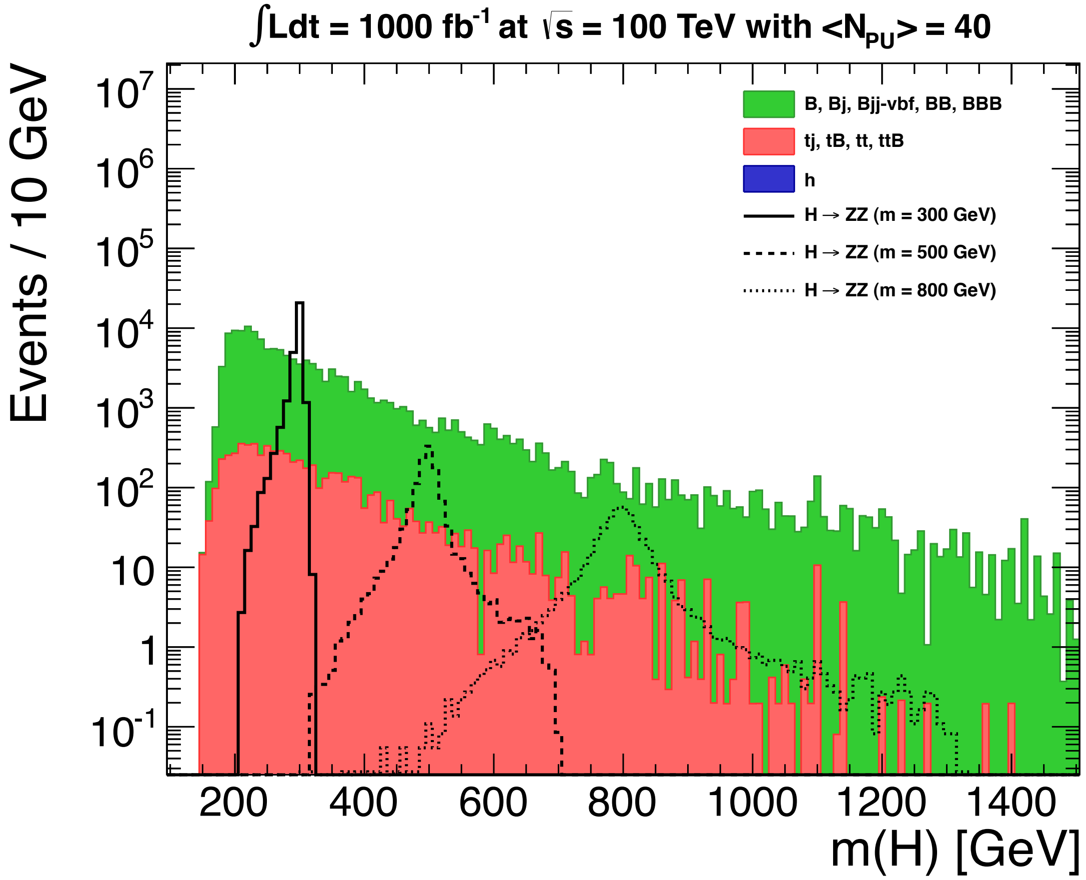
	LHC Run II	HL-LHC	HE-LHC	VLHC
$s^{1/2}$ [TeV]	14	14	33	100
L [fb^{-1}]	300	3000	3000	1000
$\langle N_{PU} \rangle$	50	140	140	40

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

H→ZZ→4ℓ



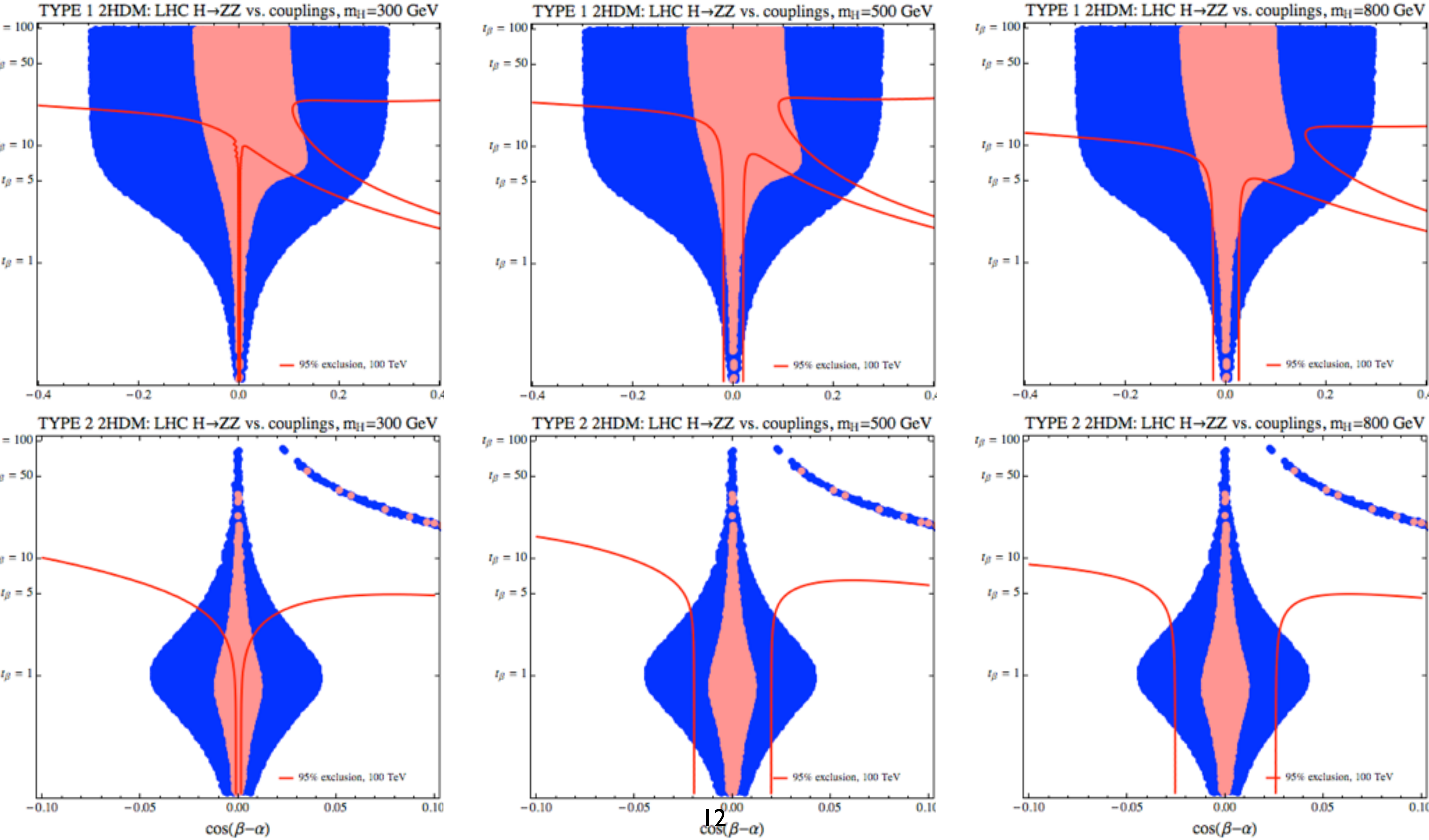
Backgrounds VV, ttV, VVV



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

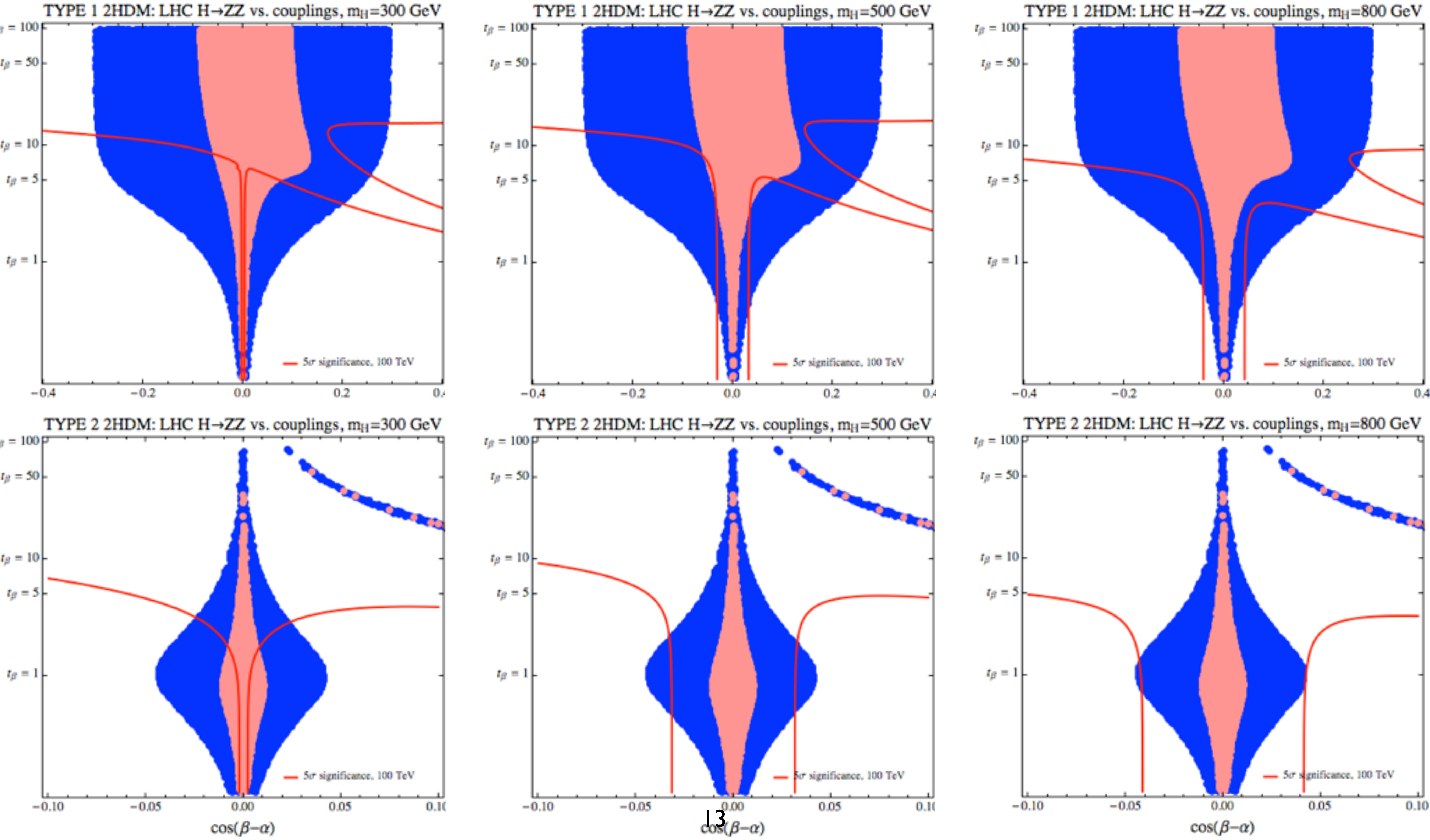
Exclusion Complementarity

(Blue: allowed by couplings after 14 TeV, 3/ab; Pink: allowed after ILC 1TeV)

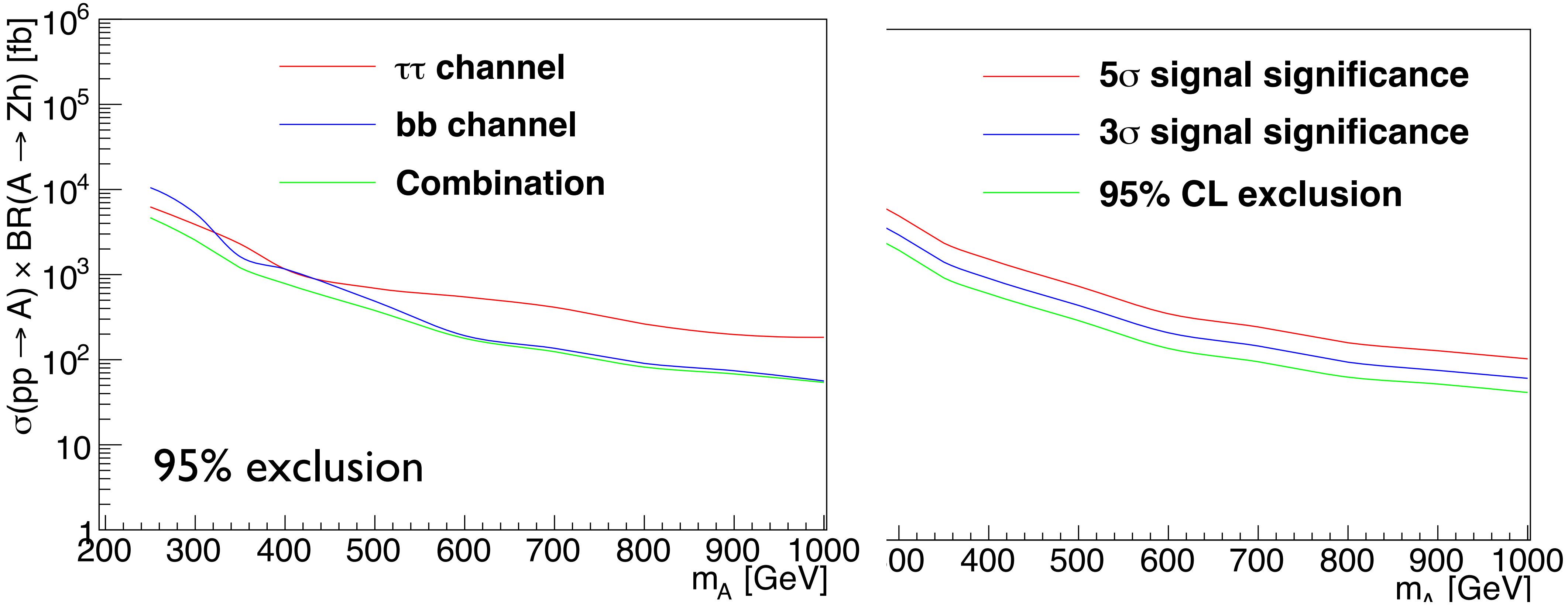


Discovery Complementarity

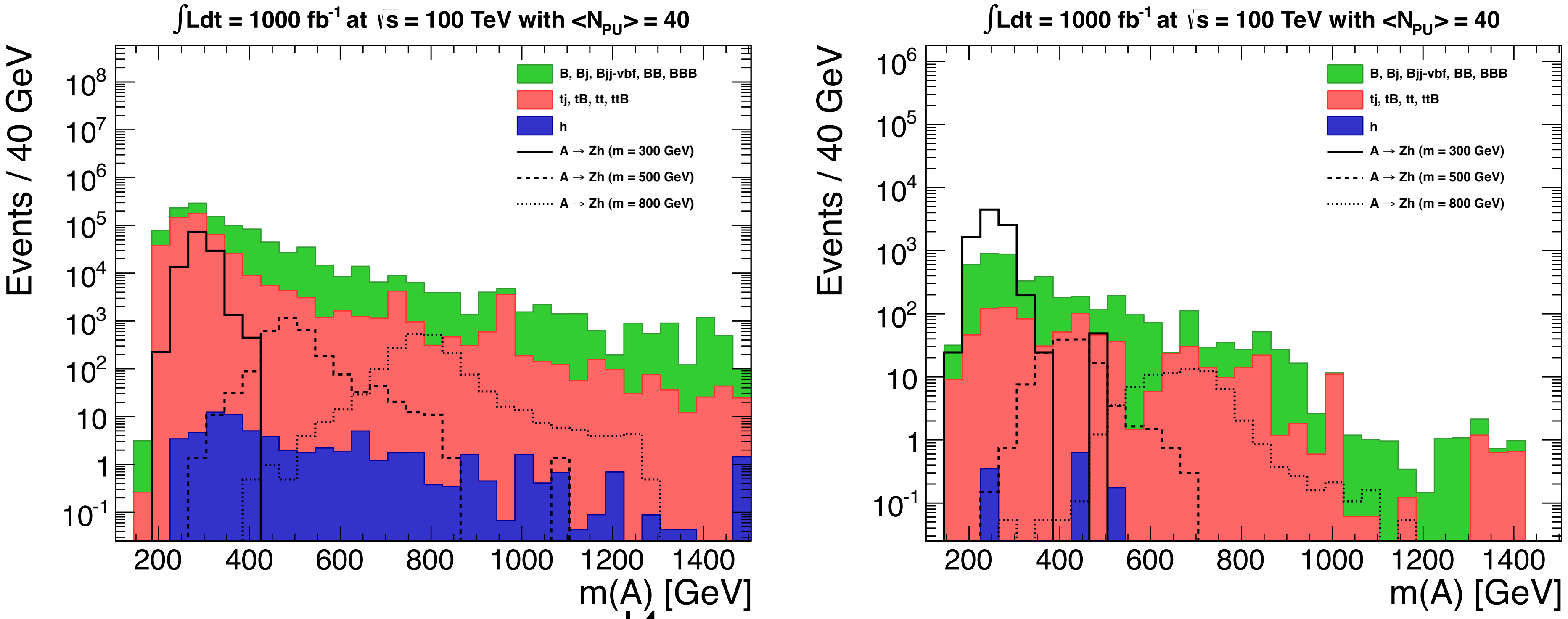
(Blue: allowed by couplings after 14 TeV, 3/ab; Pink: allowed after ILC 1TeV)



A→Zh→ℓℓ(ττ+bb)

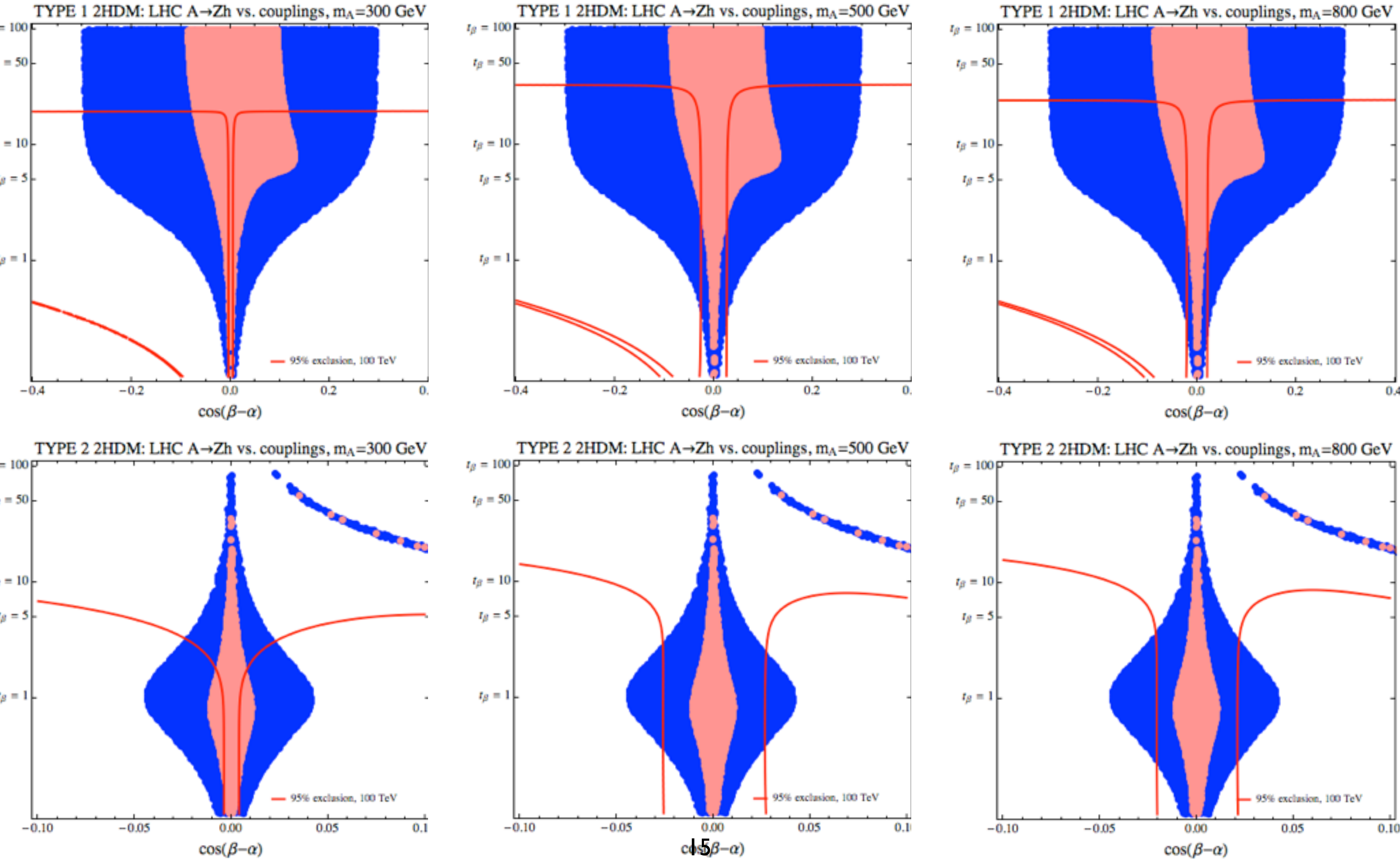


Bkgds V, tt, VV, ttV, tV, VVV



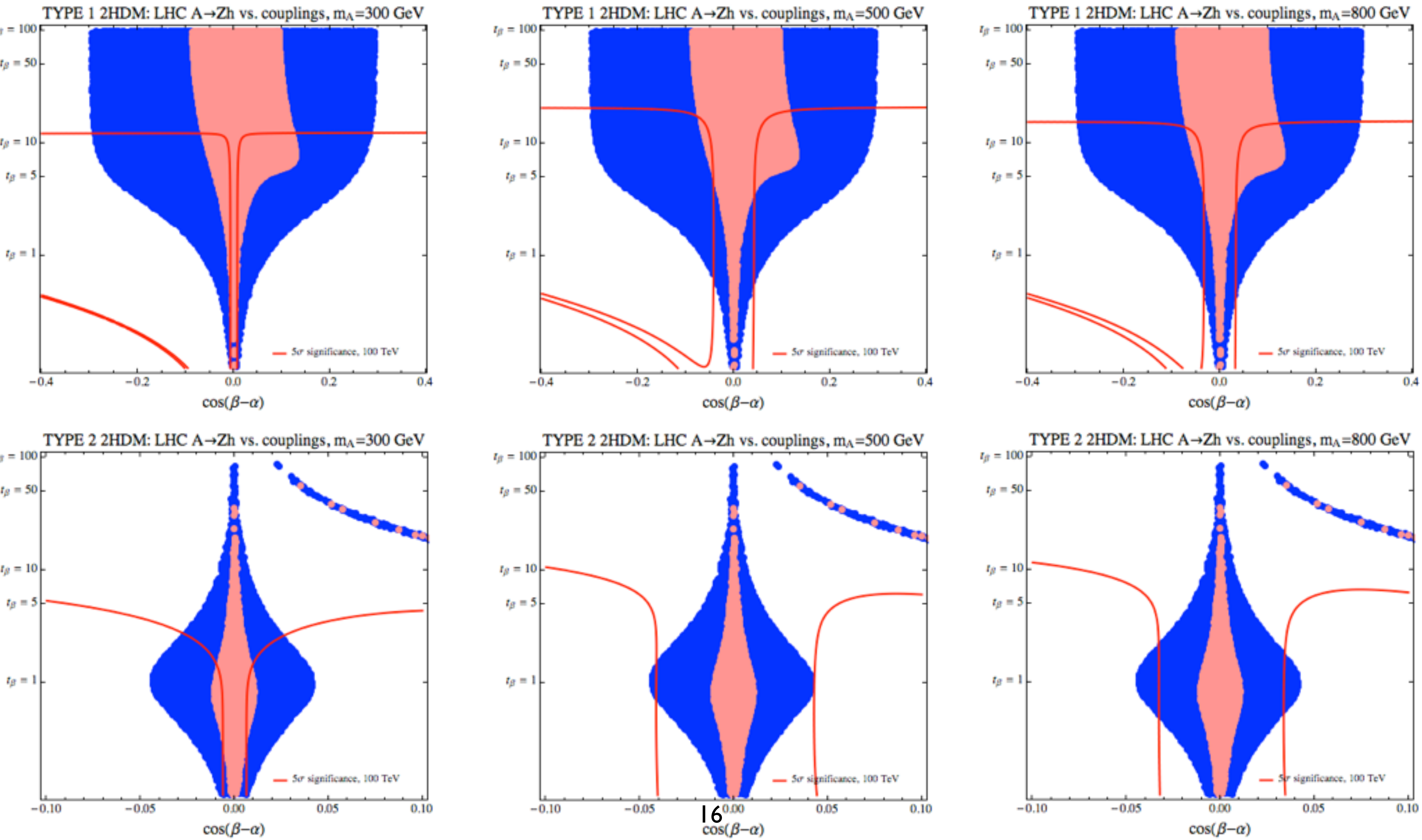
Exclusion complementarity

(Blue: allowed by couplings after 14 TeV, 3/ab; Pink: allowed after ILC 1 TeV)



Discovery complementarity

(Blue: allowed by couplings after 14 TeV, 3/ab; Pink: allowed after ILC 1TeV)



TYPE 1 2HDM: LHC A→Zh vs. couplings, m_A=300 GeV

TYPE 1 2HDM: LHC A→Zh vs. couplings, m_A=500 GeV

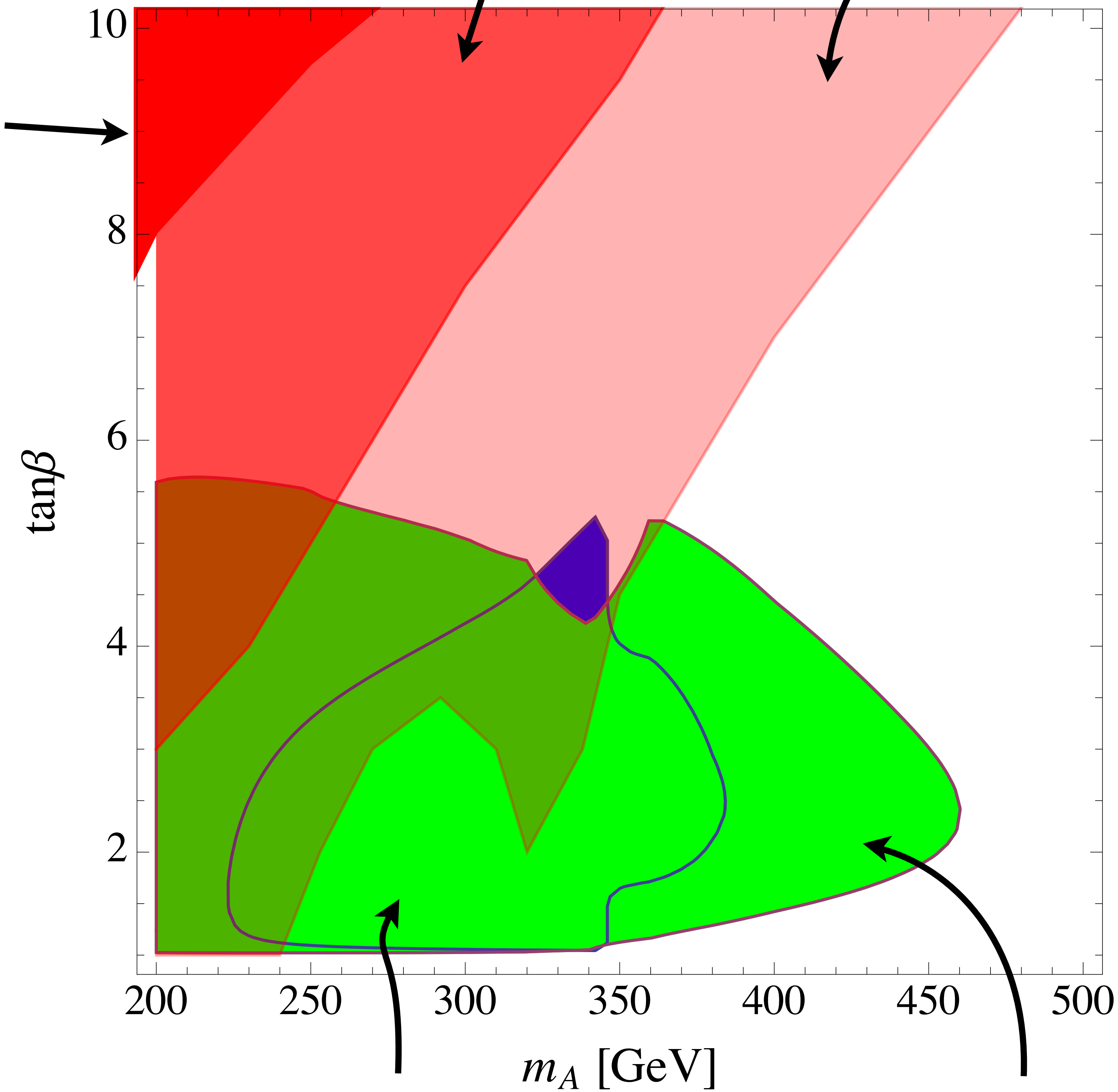
TYPE 1 2HDM: LHC A→Zh vs. couplings, m_A=800 GeV

TYPE 2 2HDM: LHC A→Zh vs. couplings, m_A=300 GeV

TYPE 2 2HDM: LHC A→Zh vs. couplings, m_A=500 GeV

TYPE 2 2HDM: LHC A→Zh vs. couplings, m_A=800 GeV

MSSM



H→ττ now

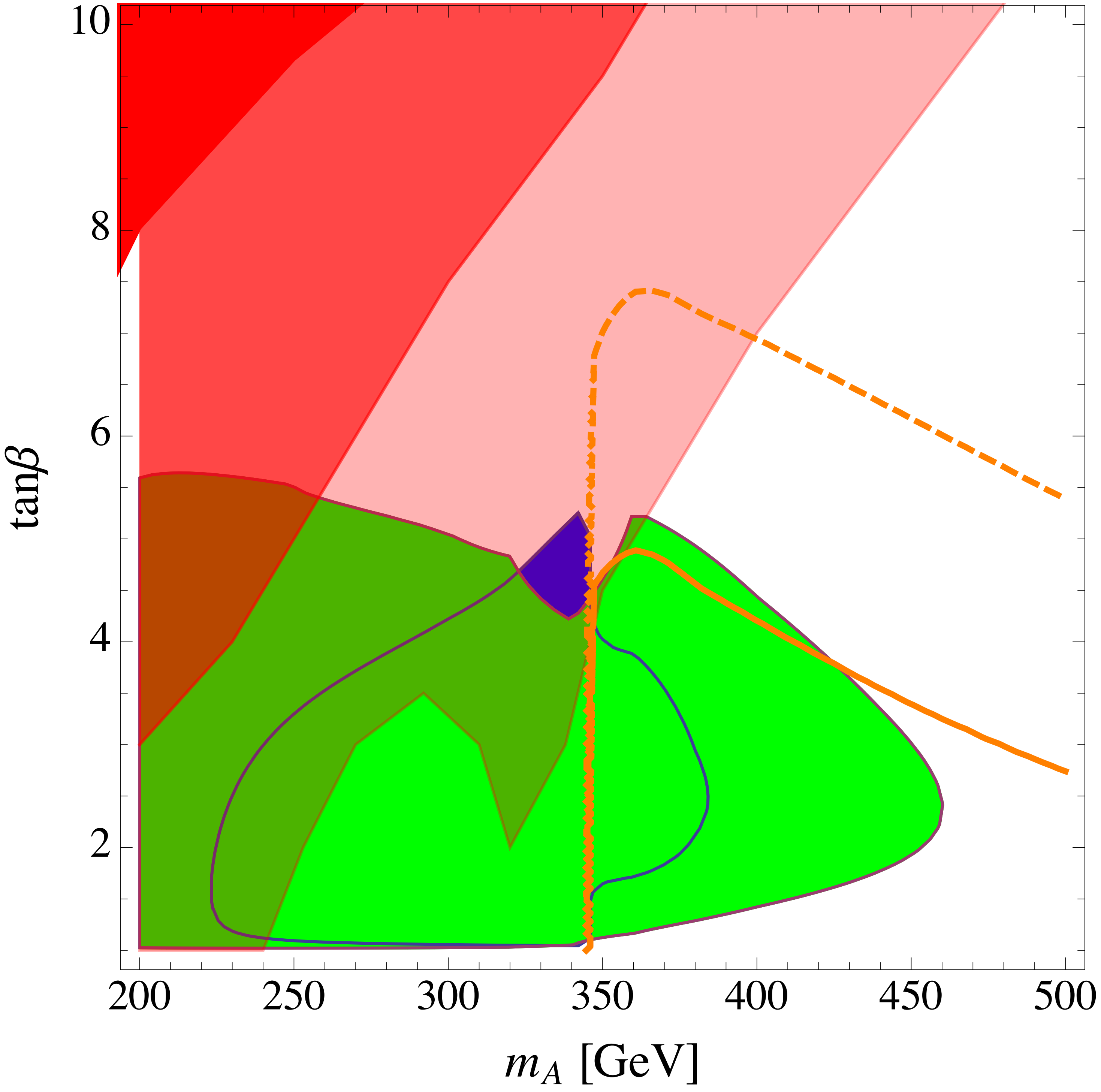
H→ττ 14TeV 300/fb

H→ττ 14TeV 3000/fb

A→Zh 100TeV

H→ZZ 100TeV

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

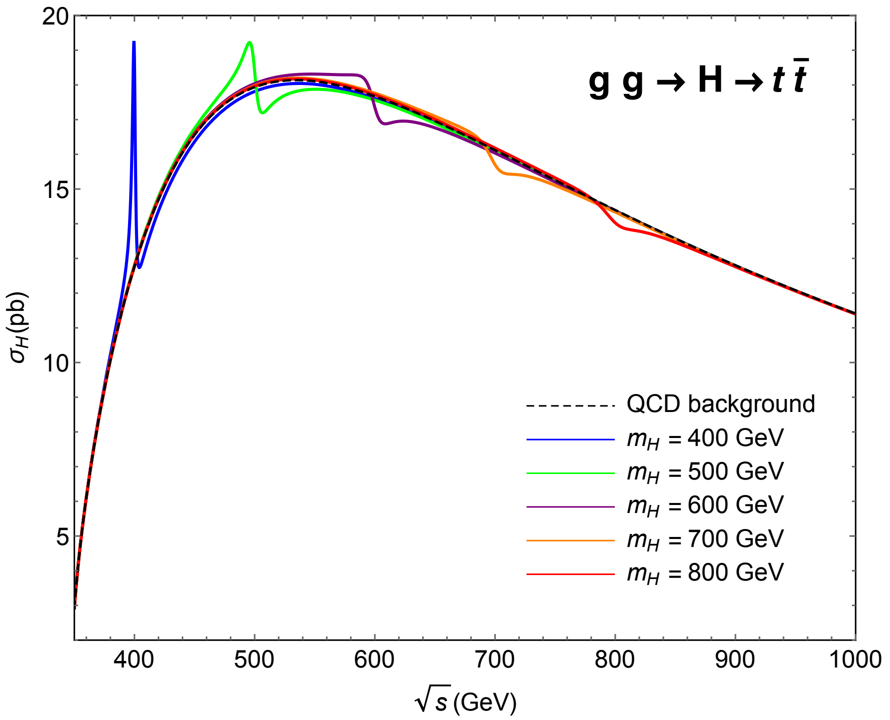


$H \to \tau\tau$ should take care of high-$\tan\beta$ region. Going to need to search for decays into top pairs. Optimizing charged Higgs search also crucial.

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

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

Challenge: interferes with SM continuum background; interference effects are dominant above 400 GeV.



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 Φ→ττ study at 100 TeV.
- Dedicated Φ→tt search at 8/14 TeV, study for 100 TeV *including interference*.
- Study & exploitation of ttΦ and tbH$^{\pm}$ modes, particularly for otherwise-difficult Φ→tt and H$^{\pm}$→tb decays.

Backup

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:

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

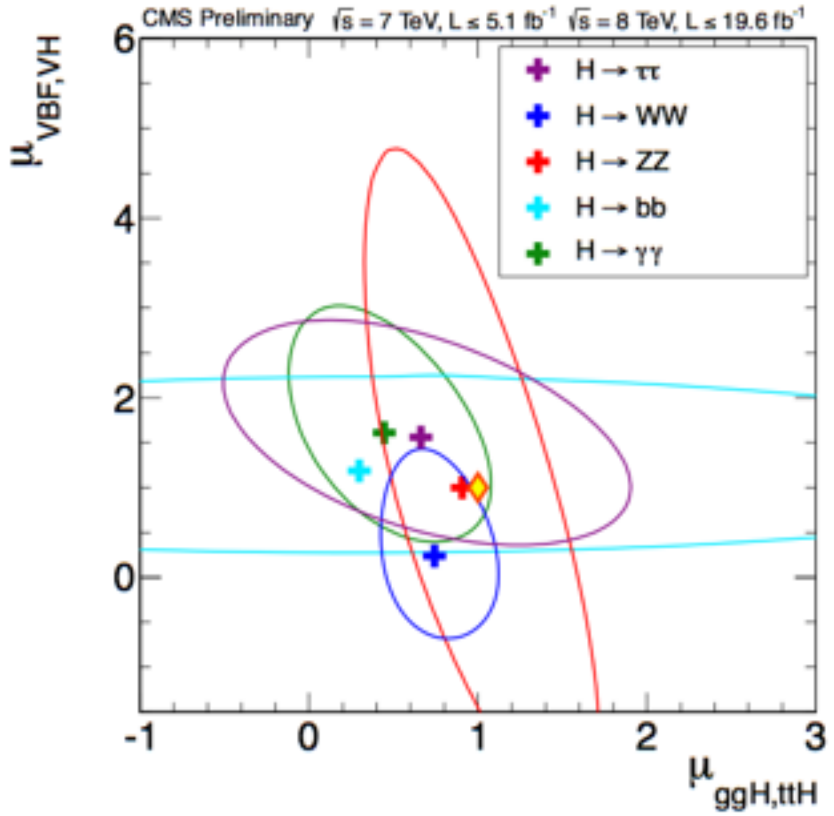
$$\alpha : \quad \begin{pmatrix} \sqrt{2}\,\mathrm{Re}(\Phi_2^0) - v_2 \\ \sqrt{2}\,\mathrm{Re}(\Phi_1^0) - v_1 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

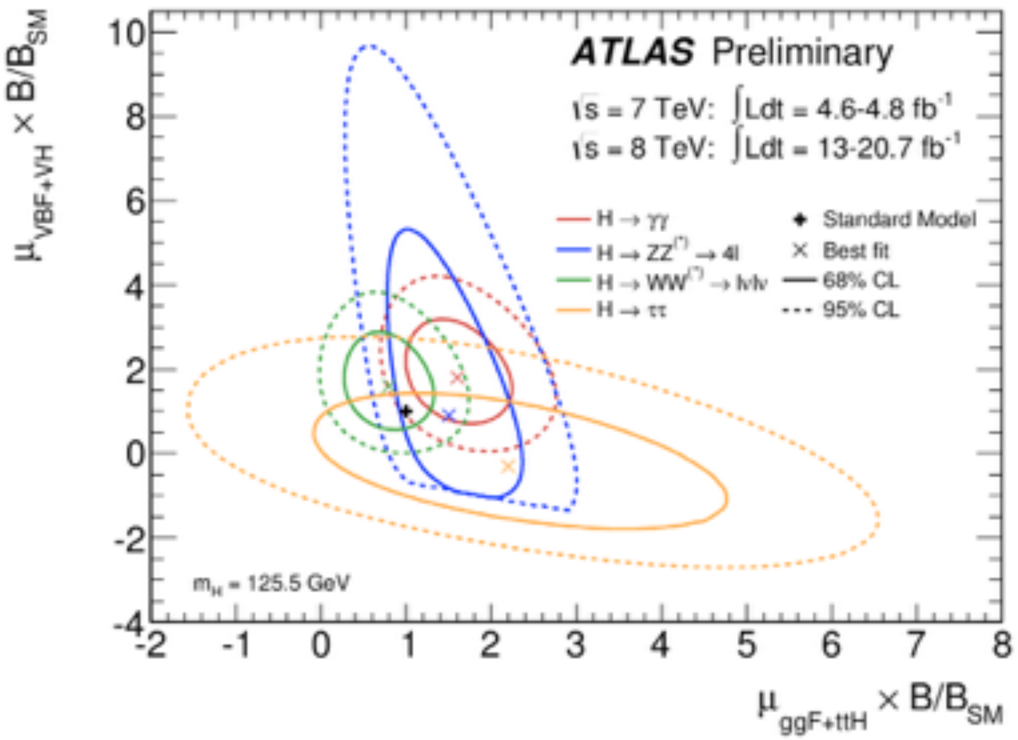
$\lambda_5, \lambda_6, \lambda_7$ (only appear in trilinear couplings)

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

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

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

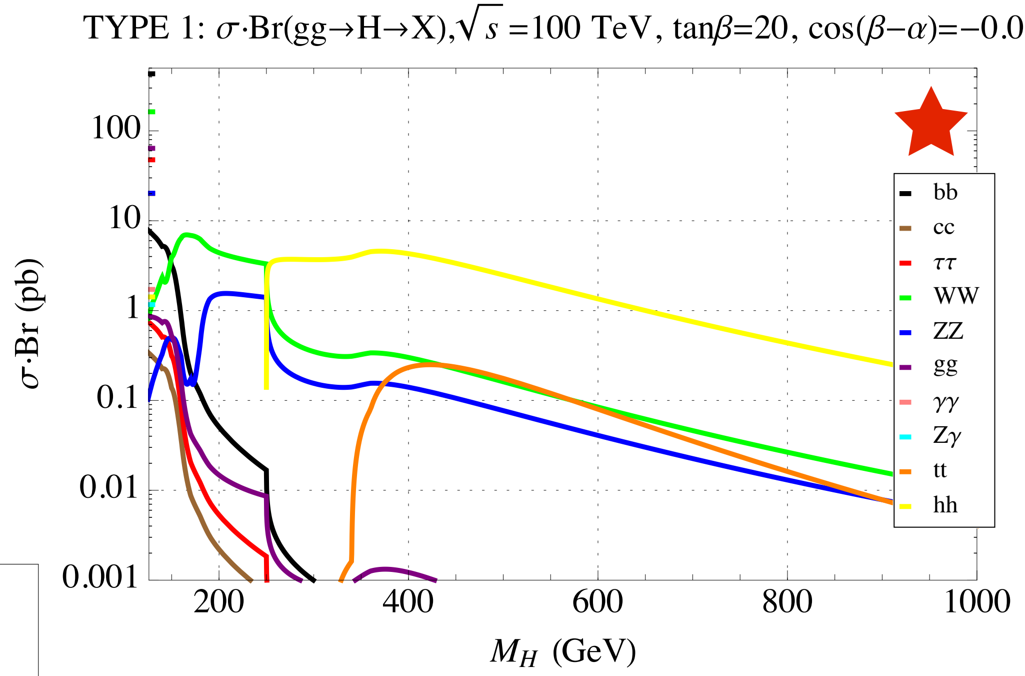
	2HDM I	2HDM II	2HDM III	2HDM IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2

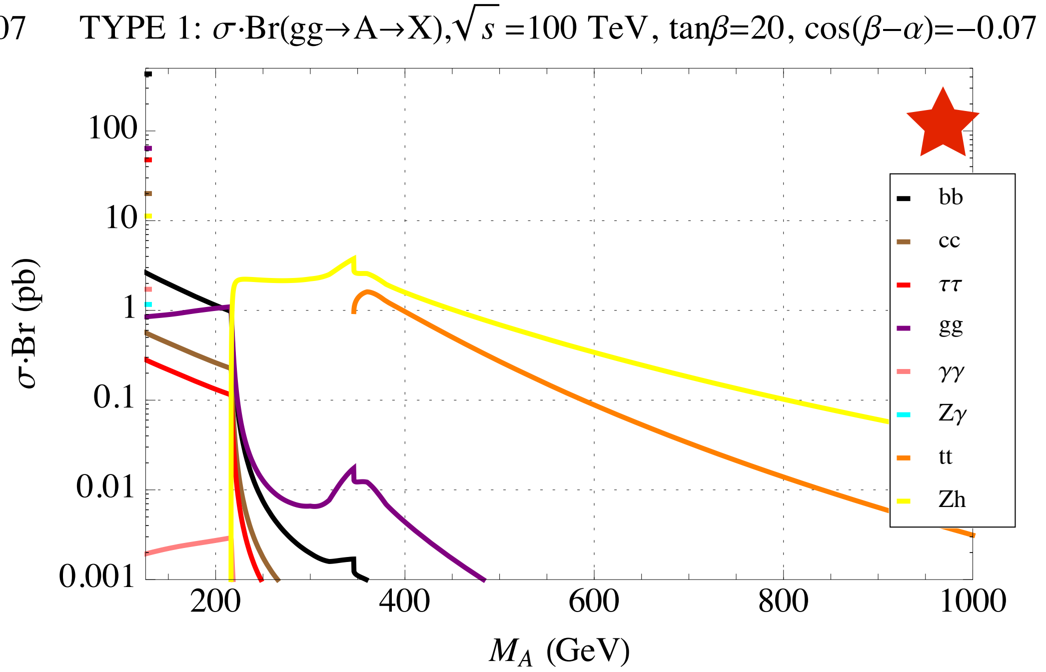
$y_{\text{2HDM}}/y_{\text{SM}}$	2HDM 1	2HDM 2
hVV	$1-\delta^2/2$	$1-\delta^2/2$
hQu	$1-\delta/t_\beta$	$1-\delta/t_\beta$
hQd	$1-\delta/t_\beta$	$1+\delta t_\beta$
hLe	$1-\delta/t_\beta$	$1+\delta t_\beta$
HVV	$-\delta$	$-\delta$
HQu	$-\delta-1/t_\beta$	$-\delta-1/t_\beta$
HQd	$-\delta-1/t_\beta$	$-\delta+t_\beta$
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.

Type I


TYPE 1: $\sigma\cdot\mathrm{Br}(gg\to H\to X)$, $\sqrt{s}$ =100 TeV, tanβ=20, cos($\beta-\alpha$)=−0.07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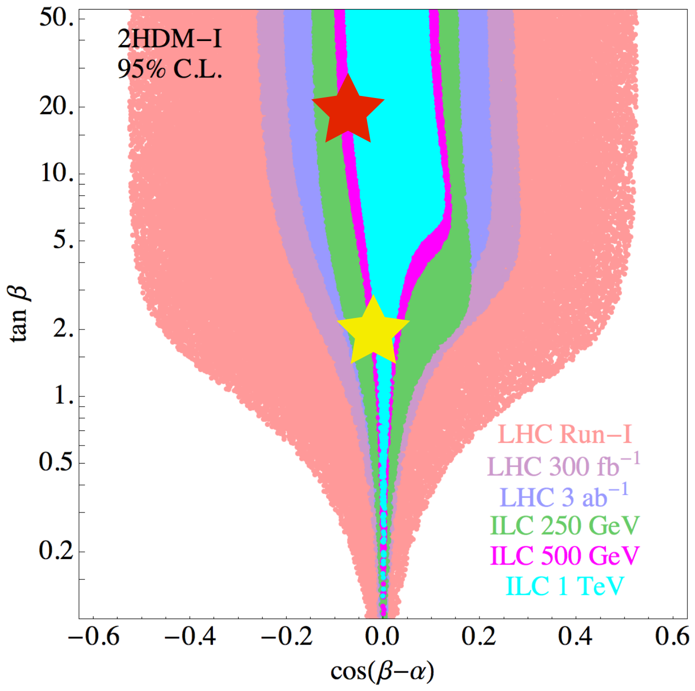
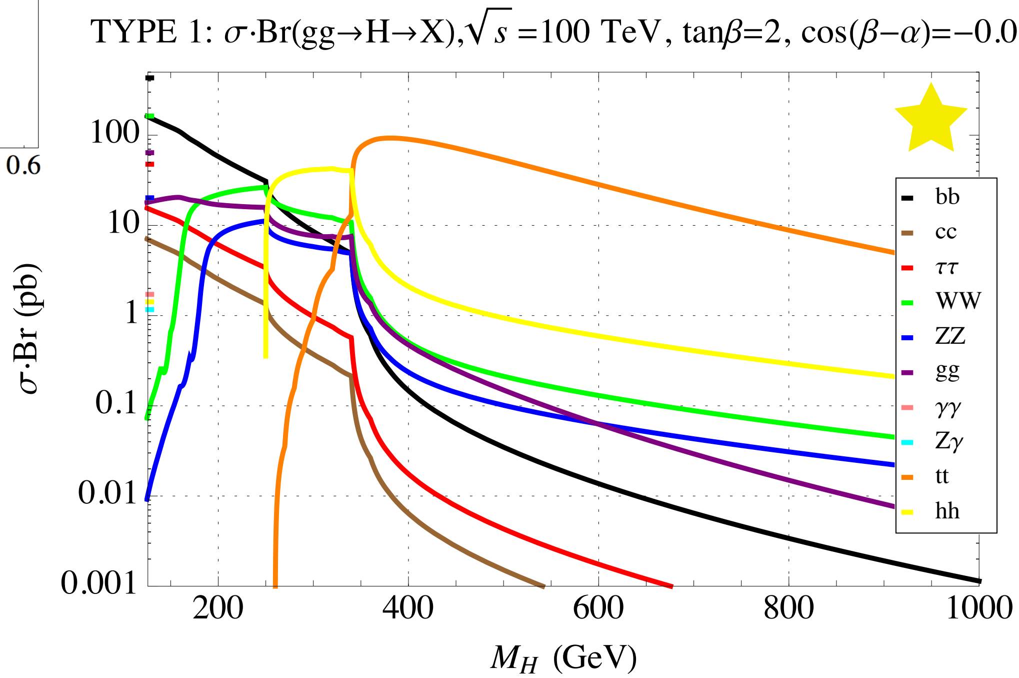
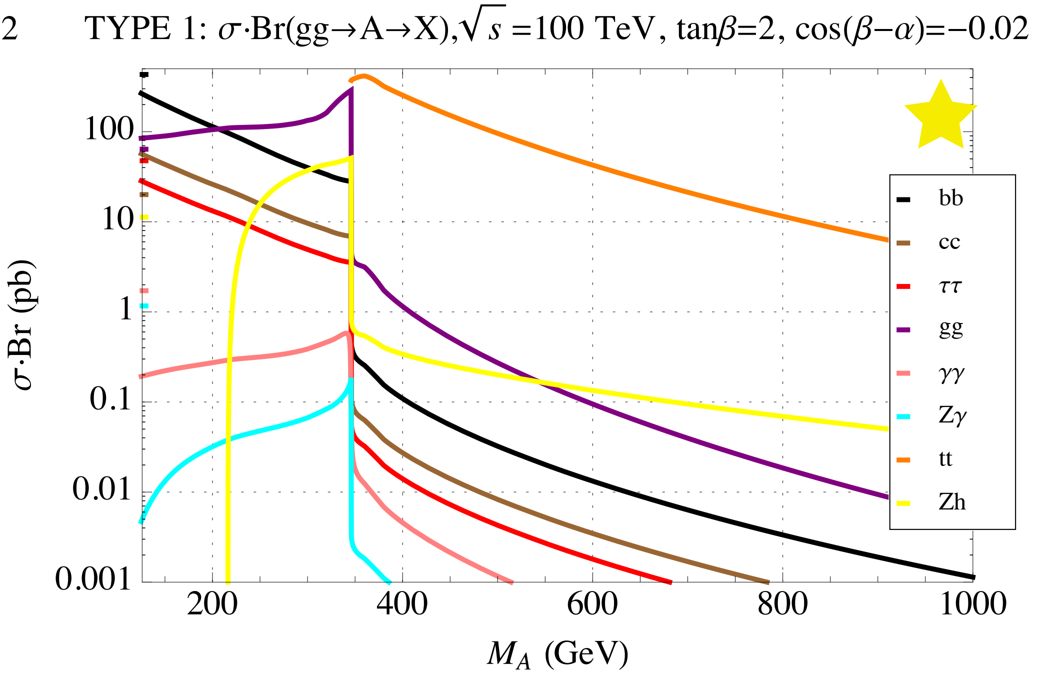


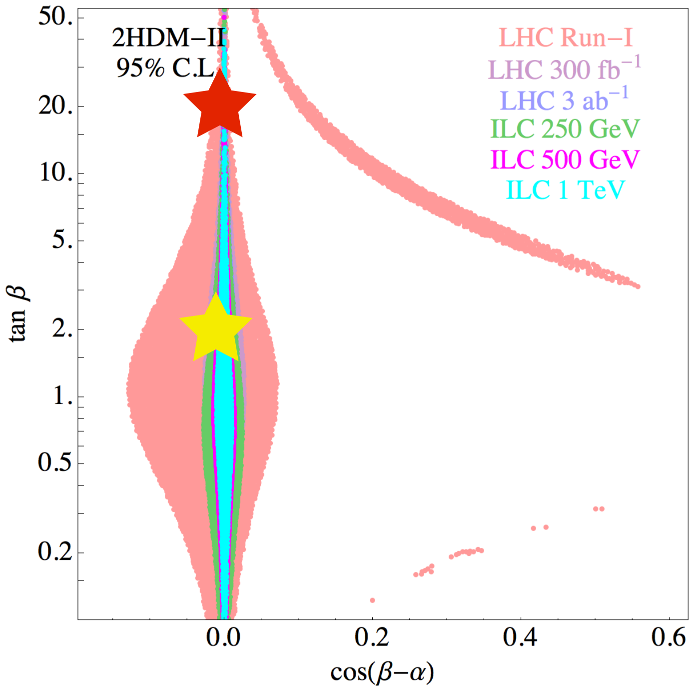
High tanβ dominated by hh, Zh, VV, tt

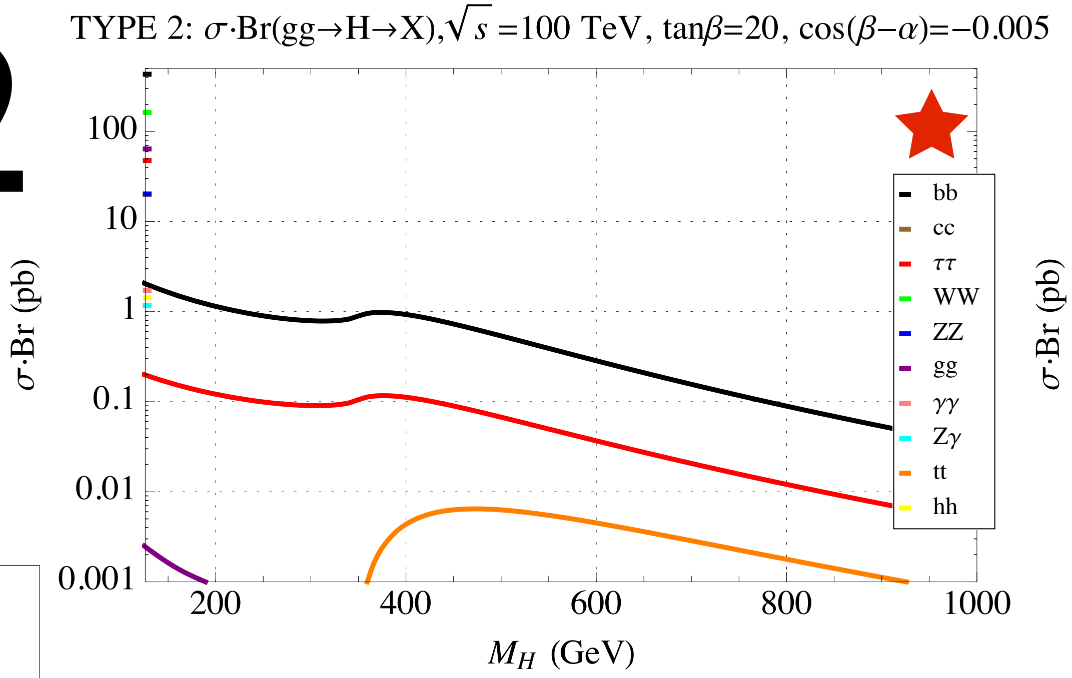

TYPE 1: $\sigma\cdot\mathrm{Br}(gg\to H\to X)$, $\sqrt{s}$ =100 TeV, tanβ=2, cos($\beta-\alpha$)=−0.02


TYPE 1: $\sigma\cdot\mathrm{Br}(gg\to A\to X)$, $\sqrt{s}$ =100 TeV, tanβ=2, cos($\beta-\alpha$)=−0.02

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

Type 2

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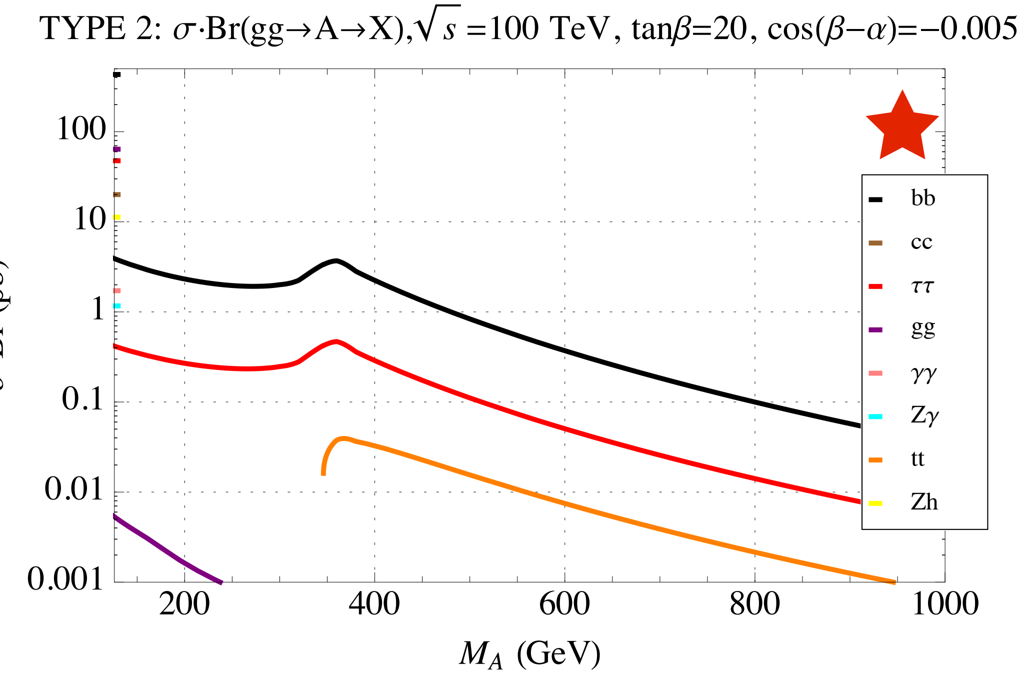
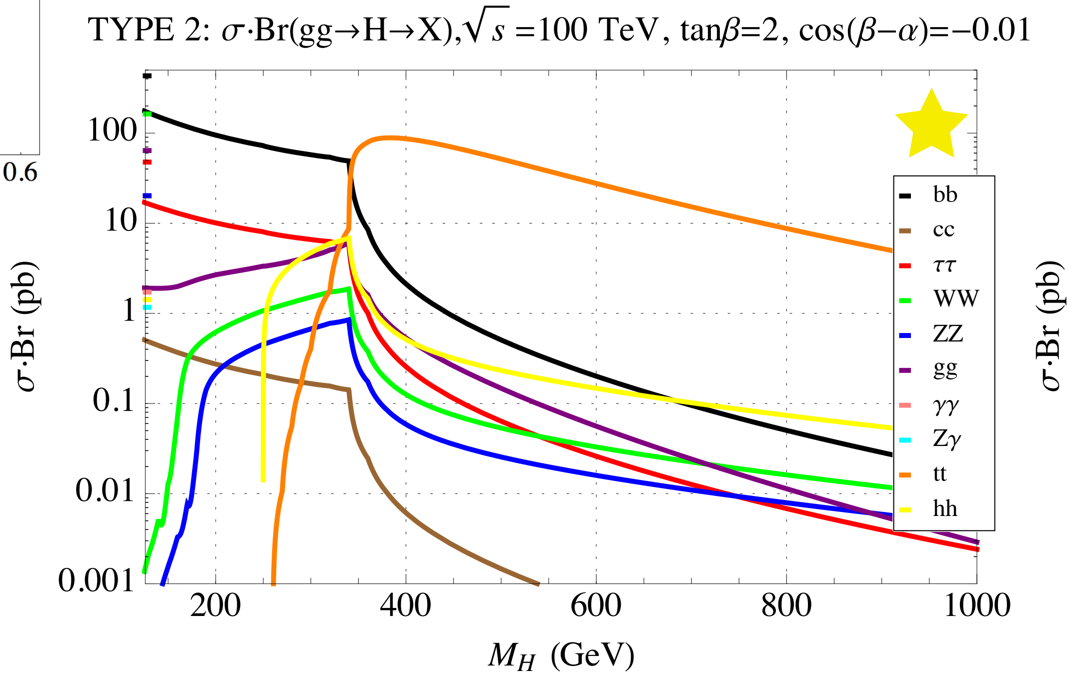

TYPE 2: $\sigma\cdot$Br(gg→A→X),$\sqrt{s}$ =100 TeV, tanβ=20, cos($\beta-\alpha$)=−0.005

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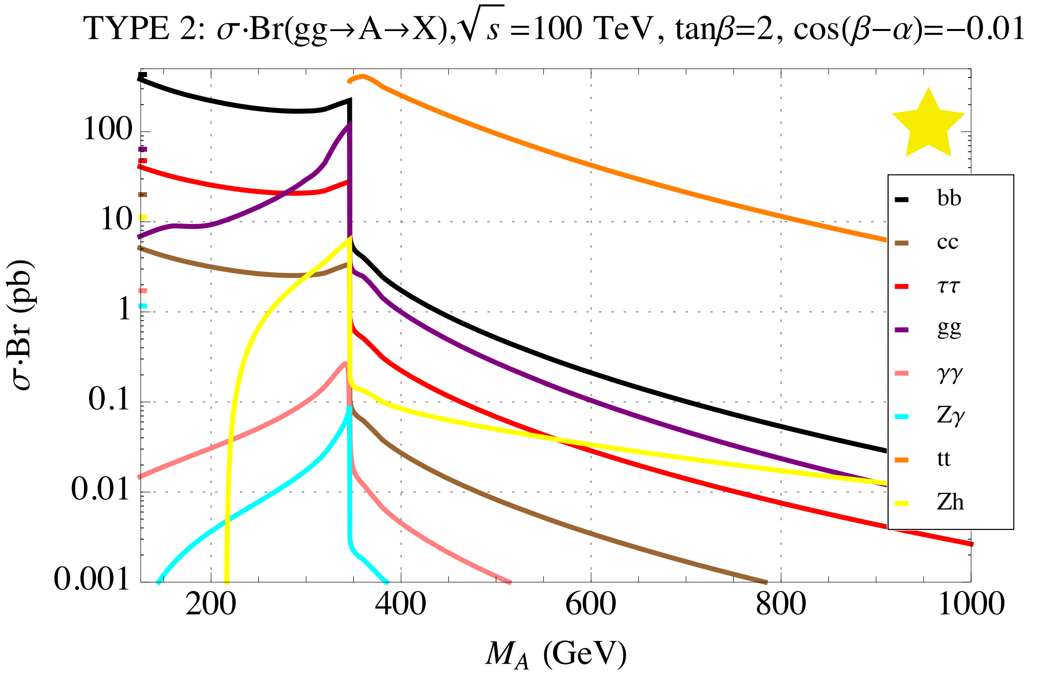
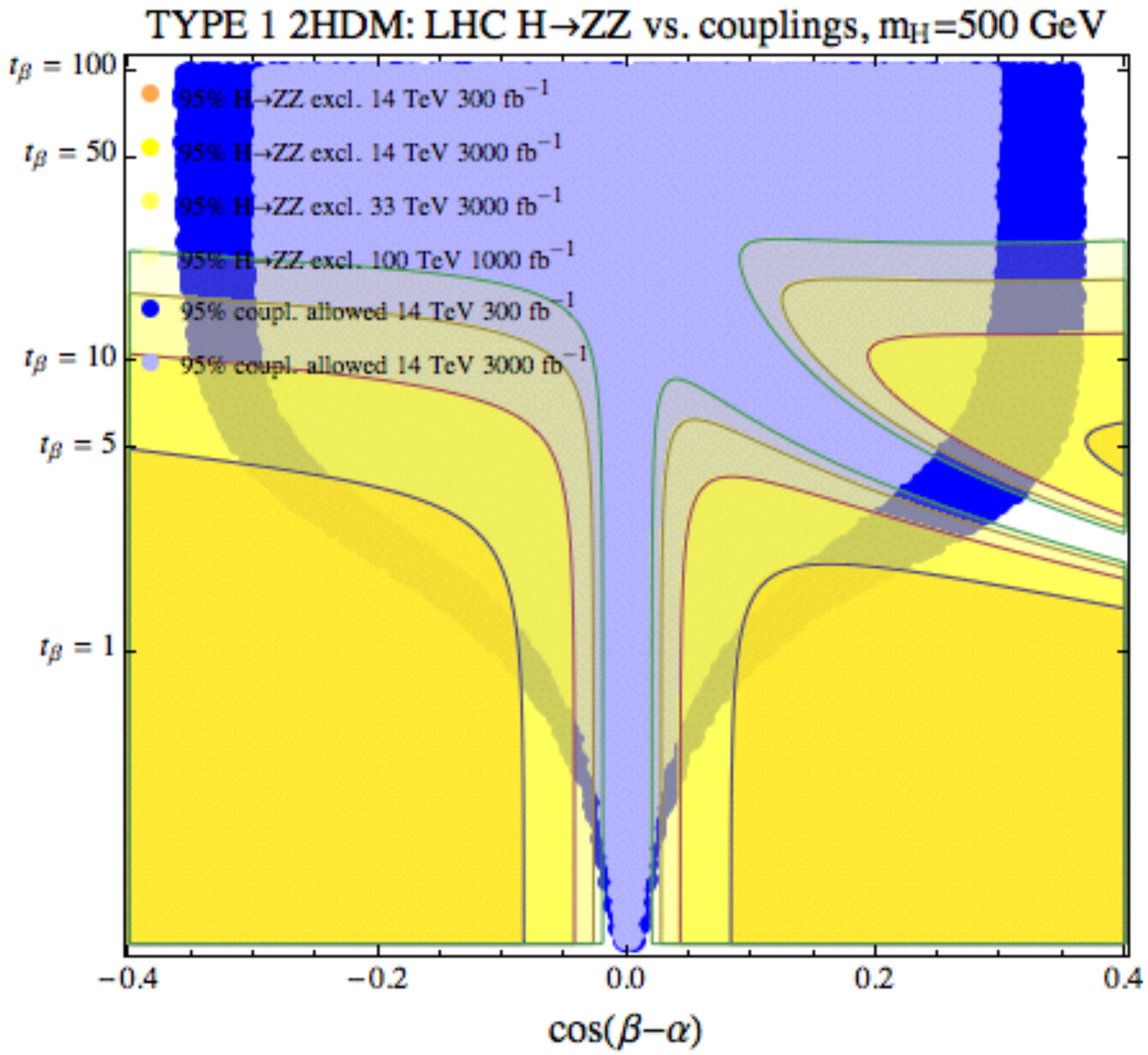
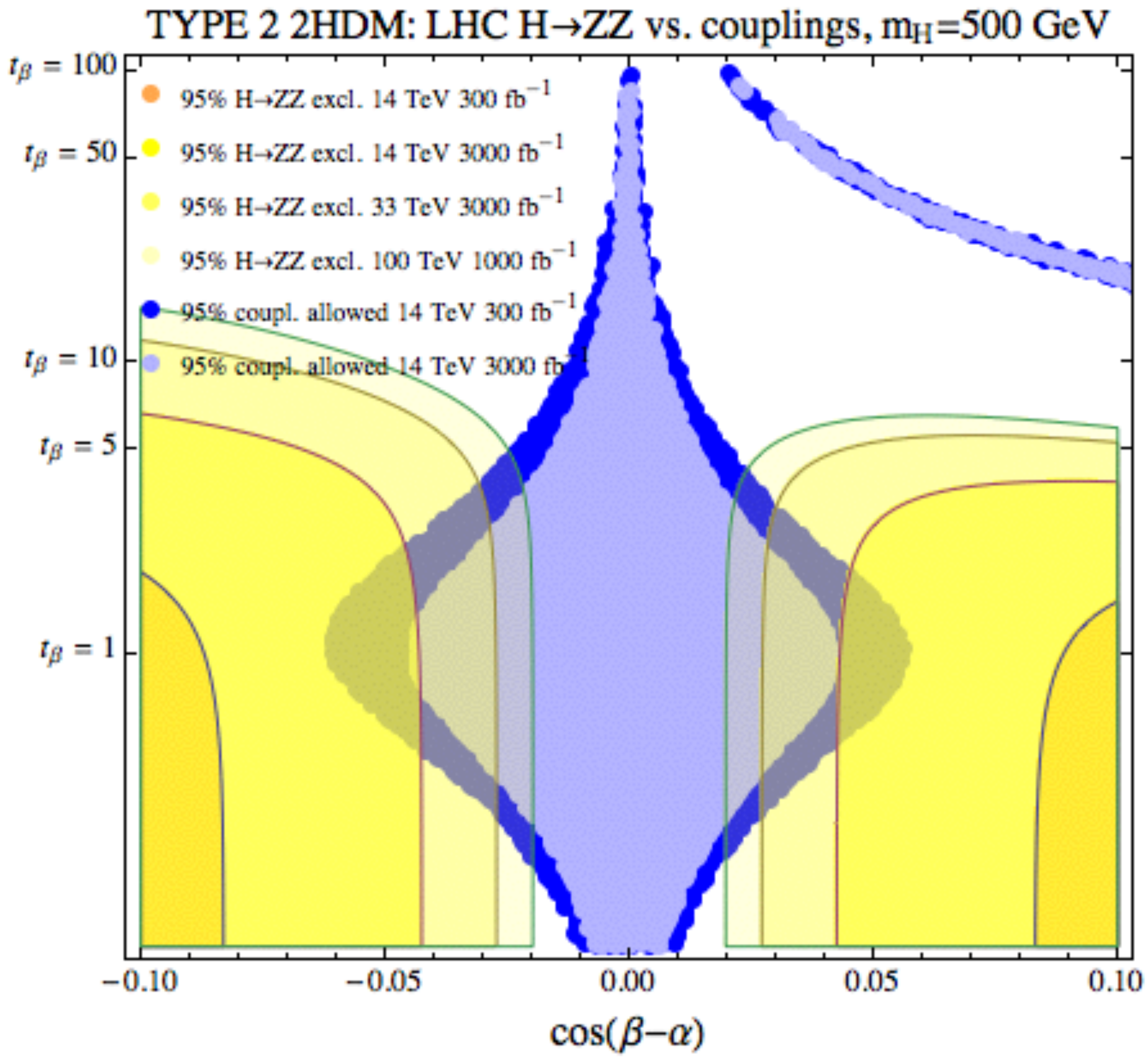

TYPE 2: $\sigma\cdot$Br(gg→A→X),$\sqrt{s}$ =100 TeV, tanβ=2, cos($\beta-\alpha$)=−0.01

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

Direct complementarity





Direct complementarity