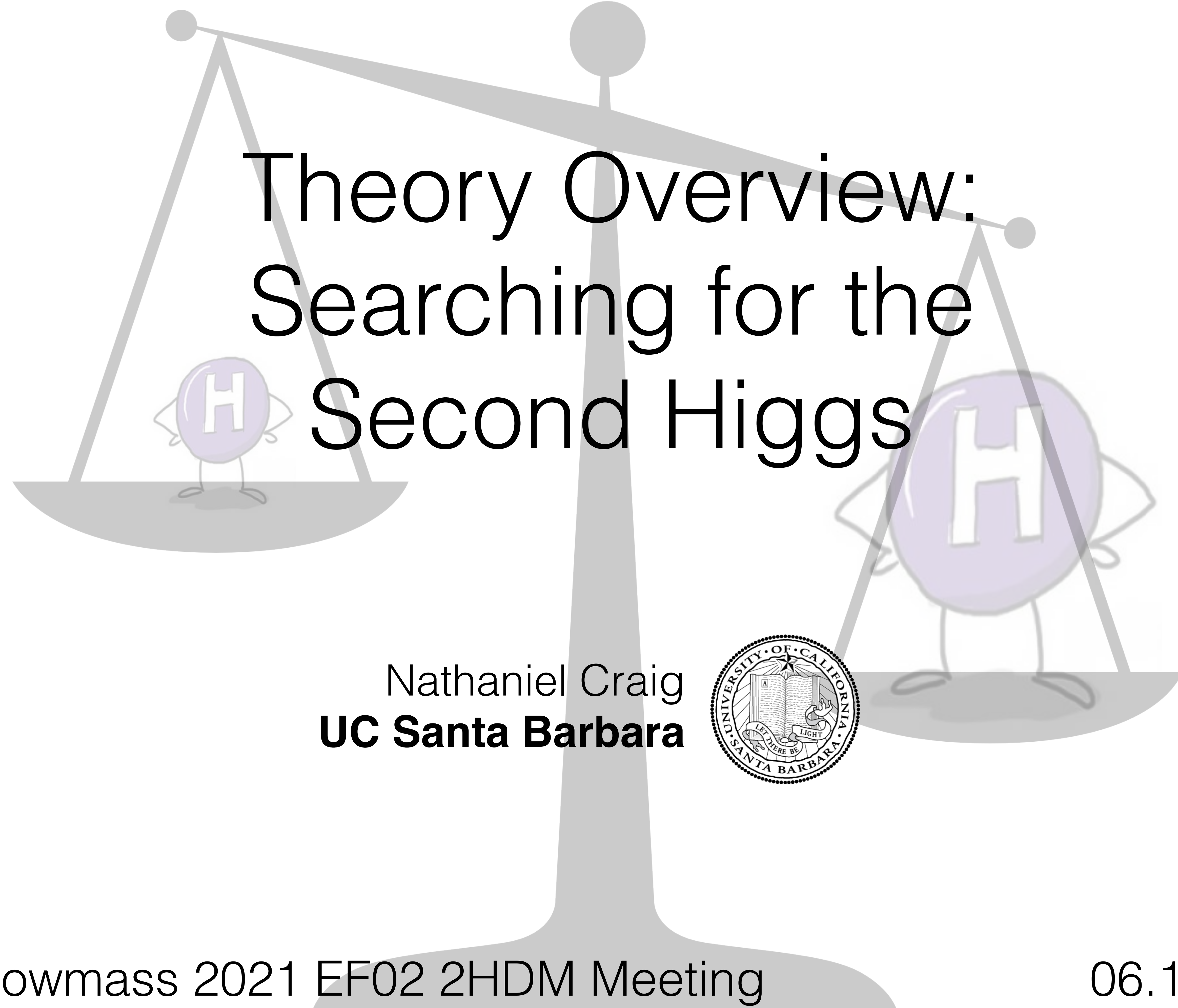

Theory Overview: Searching for the Second Higgs

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UC Santa Barbara

Snowmass 2021 EF02 2HDM Meeting

06.12.20

The Second Higgs

Additional Higgs scalars often arise
in natural theories of EWSB:

- Higgs sector of the MSSM/NMSSM…
- Little Higgs, Composite Higgs…
- Twin Higgs, Neutral Naturalness…

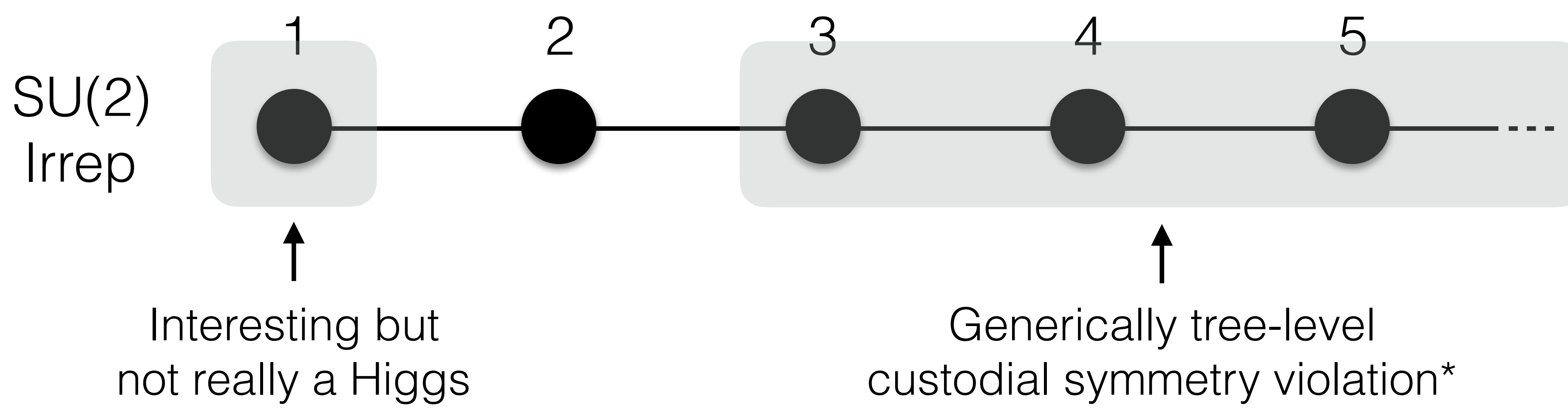
More broadly:

The spin-1/2 and spin-1 sectors of our universe
are rich in multiplicity.

Why not also the spin-0 sector?

Why 2HDM?

Add another scalar (w/ vev) to the SM…



Indirect signals of a **doublet**: $\mathcal{O}\left(\frac{v^2}{M^2}\right)$ Higgs coupling deviations

5% precision ⇔ M ≳ 1 TeV

Indirect signals of **higher reps**: $\mathcal{O}\left(\frac{v^2}{M^2}\right)$ rho parameter (w/o tuning)

.02% precision ⇔ M ≳ 17 TeV

**Georgi-Machacek model is custodial bi-triplet*

Where 2HDM?

Generically, mass scale of second Higgs only constrained by distribution of vev; can naturally be (reasonably) asymmetric.

E.g. SUSY:

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

At large tanβ, suppressed tuning:

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

Multi-TeV Higgs states consistent with naturalness in this framework. Not feasible @ 14 TeV, but within reach of 100 TeV.

Simplified parameter space

Physical d.o.f. are (8-3=5): $h, H, A, H^{\pm}$

After EWSB, 9 free params in CP-conserving potential.

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

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

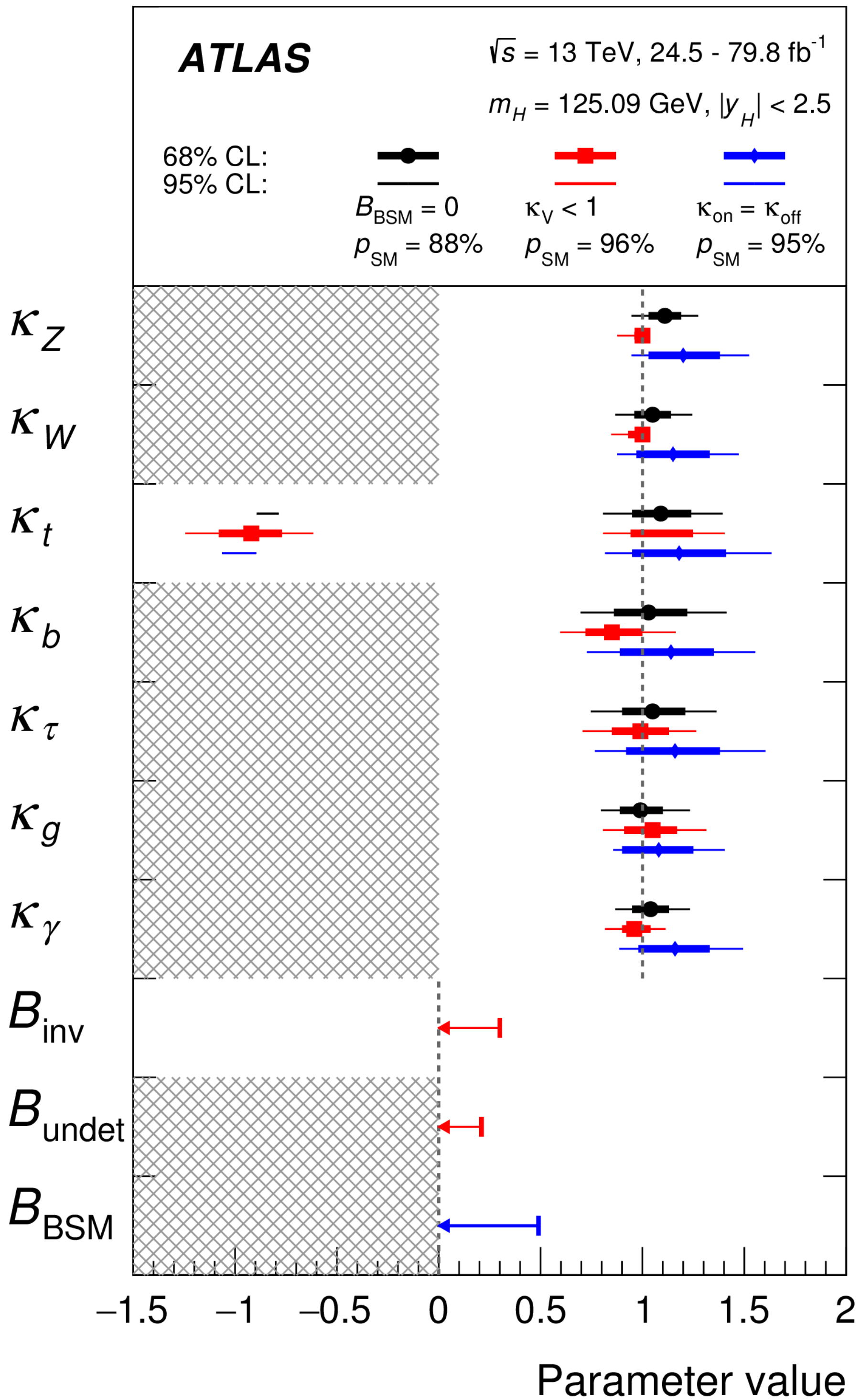
$$\alpha : \quad \begin{pmatrix} \sqrt{2}\ \mathrm{Re}(\Phi_2^0) - v_2 \\ \sqrt{2}\ \mathrm{Re}(\Phi_1^0) - v_1 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

$\lambda_5, \lambda_6, \lambda_7$ (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



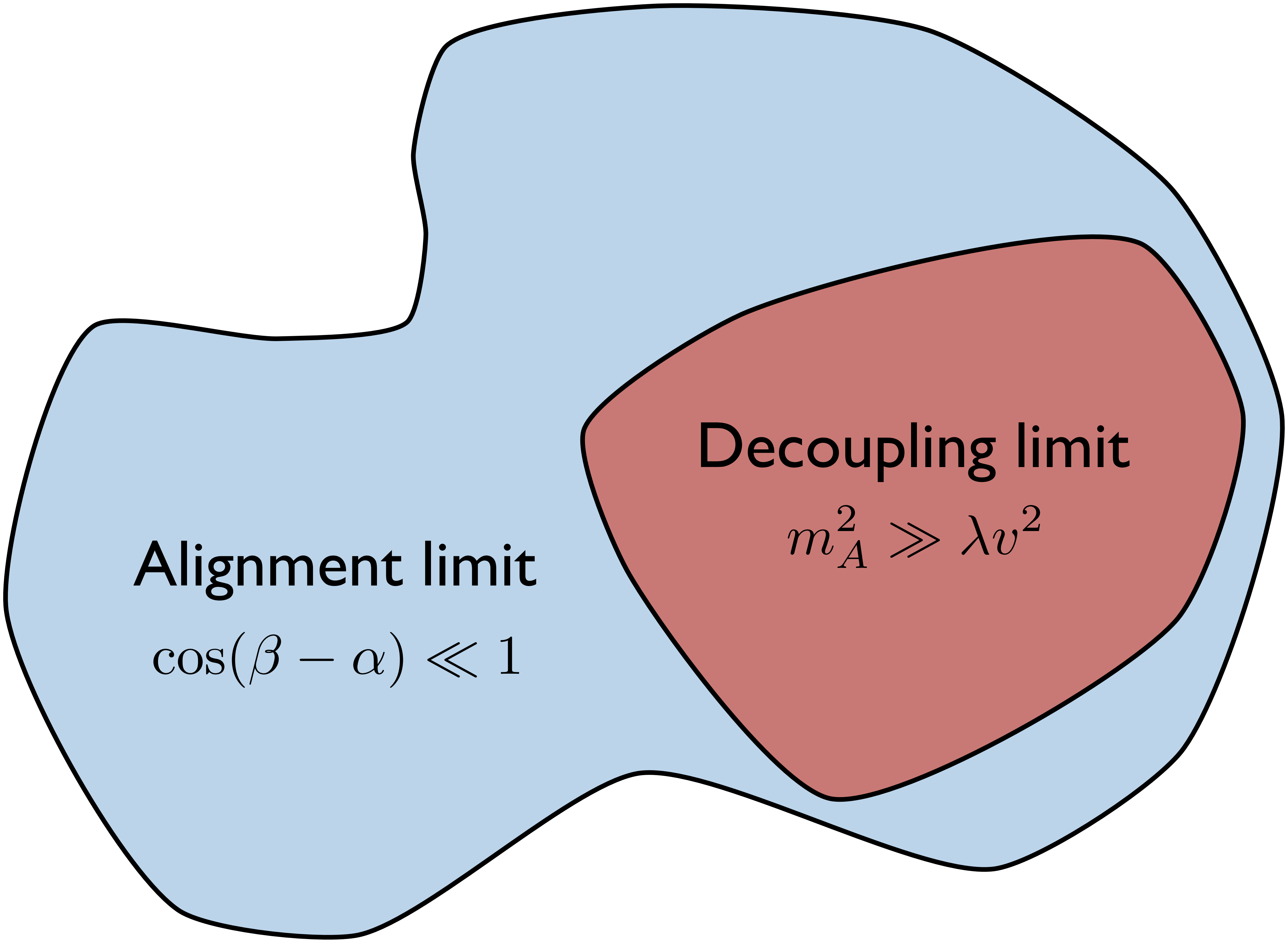
- Couplings of the observed Higgs so far approximately SM-like.
- Suggests proximity to alignment limit

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

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

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

[Haber, Gunion '02; NC, Thomas '12; NC, Galloway, Thomas '13; Carena, Low, Shah, Wagner '13]



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.
- Work at tree level, but loops matter [e.g. Chen, Han, Su, Su, Wu '18]

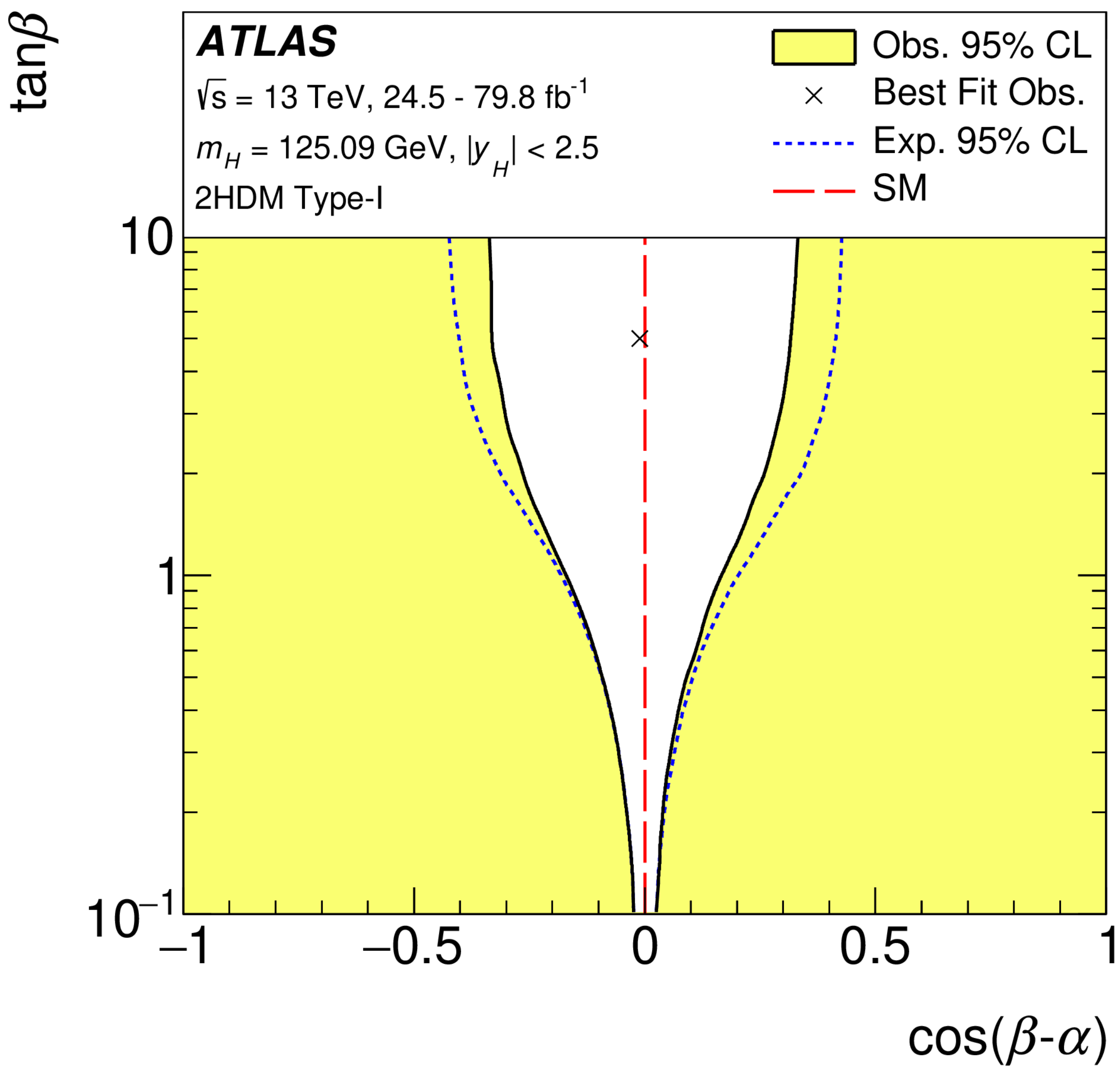
Complementarity

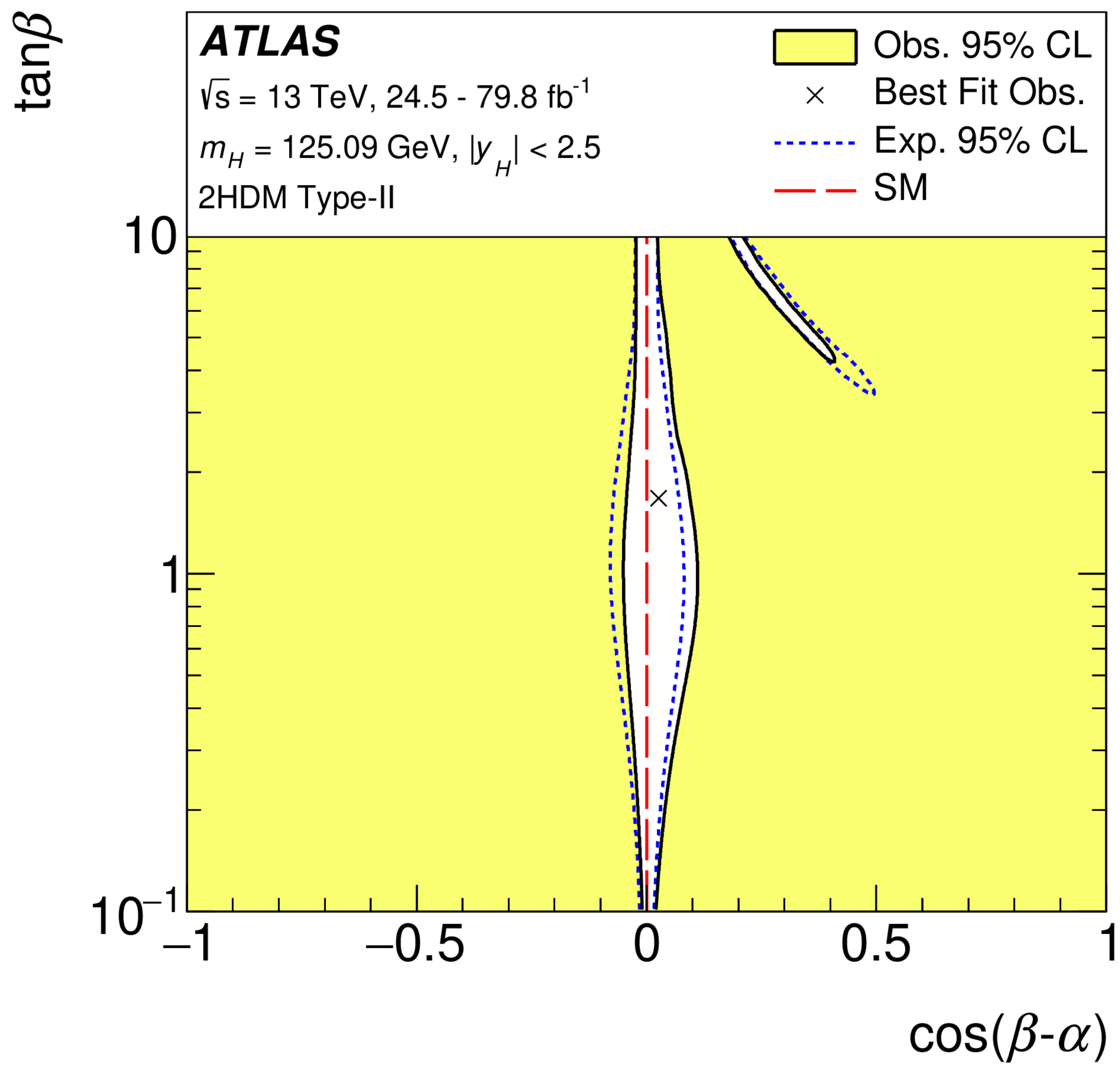
Indirect: Measure h(125)

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

Direct: Search for H/A/$H^\pm$

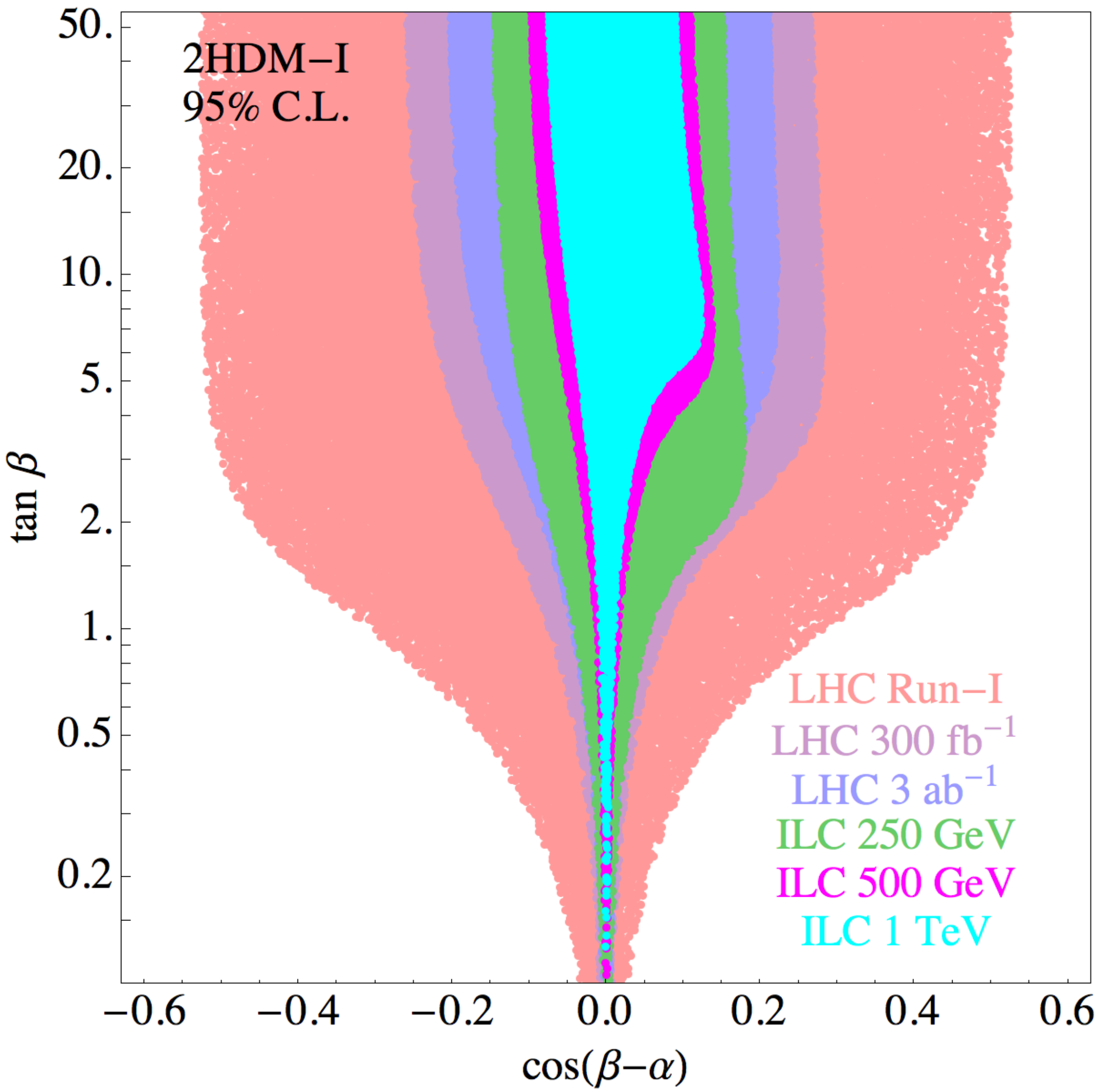
Indirect: Where now?

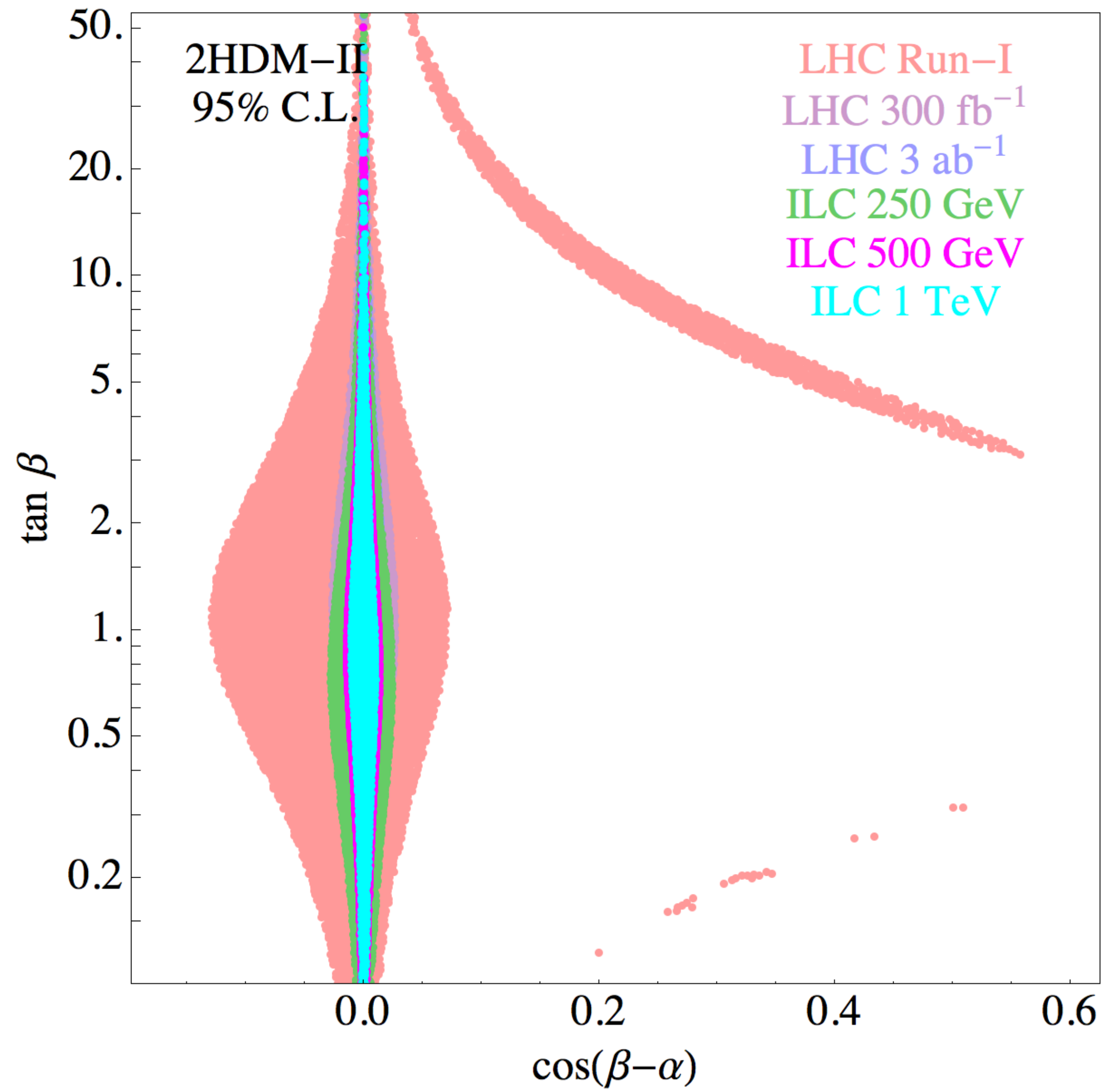




Indirect: Whither?

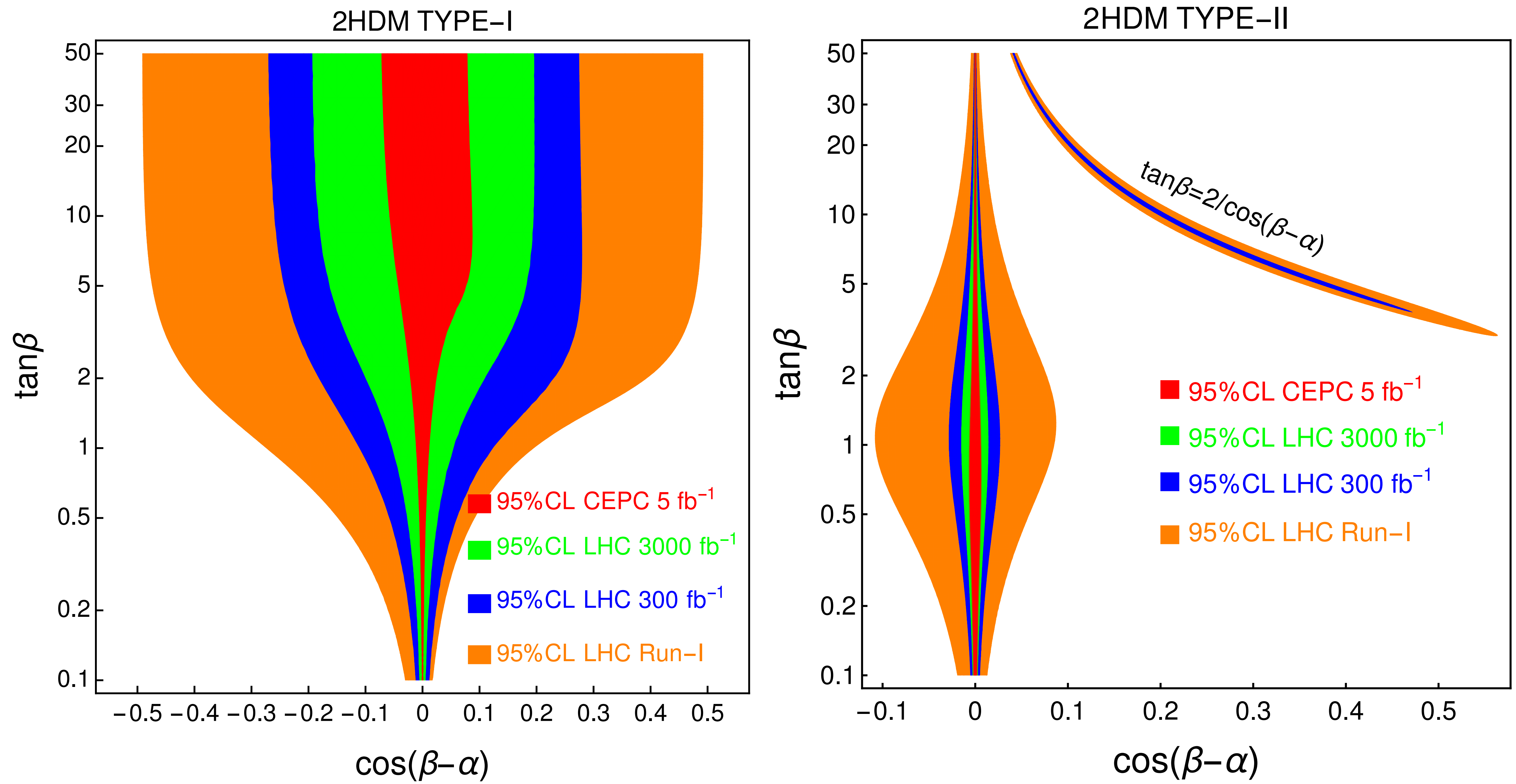
[Barger, Everett, Logan, Shaughnessy '13]





Indirect: Whither?

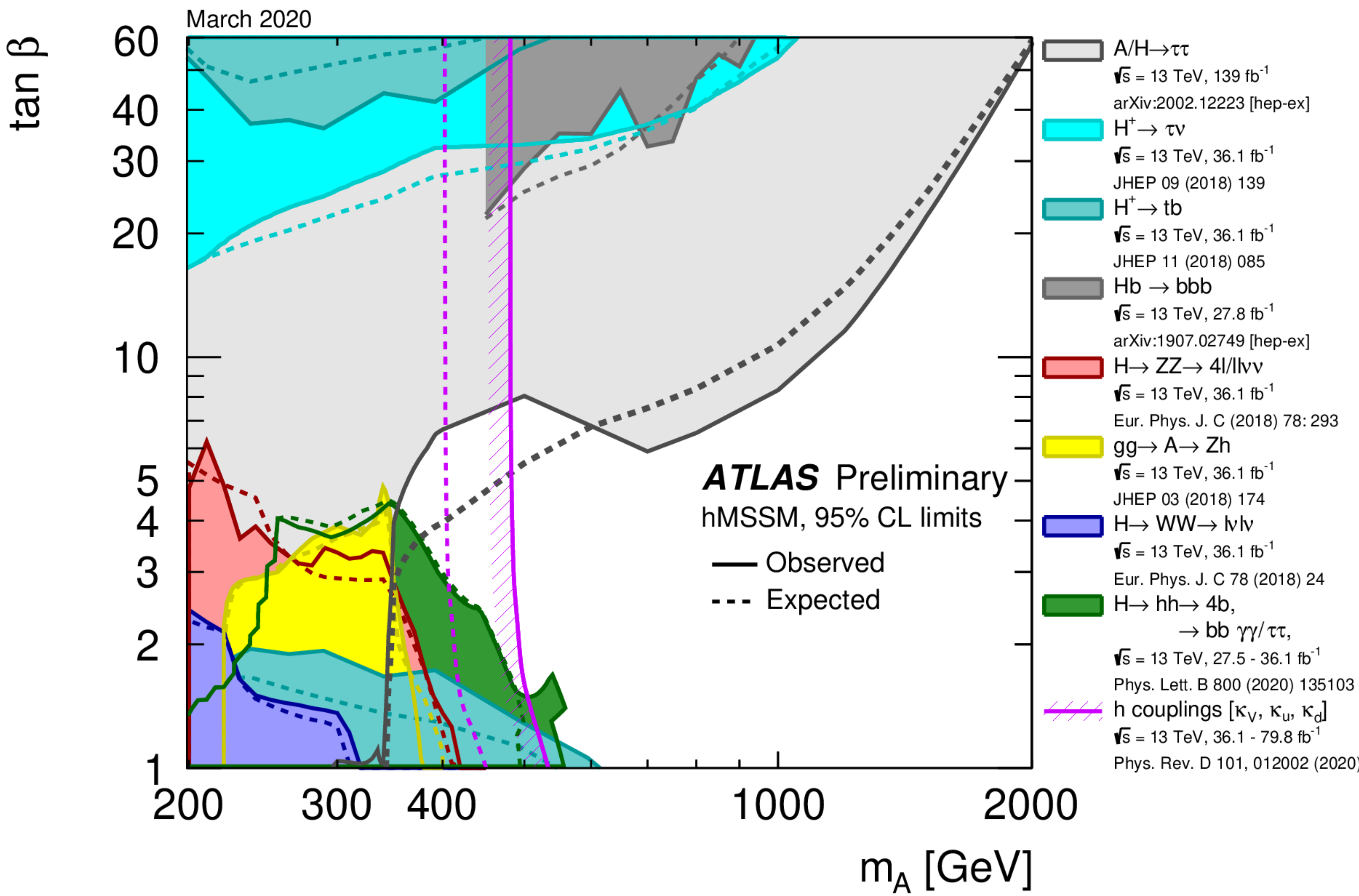
[Gu, Li, Liu, Su, Su 1709.06103]



See also: [Chen, Han, Su, Su, Wu ’18, ibid + Li ’19]

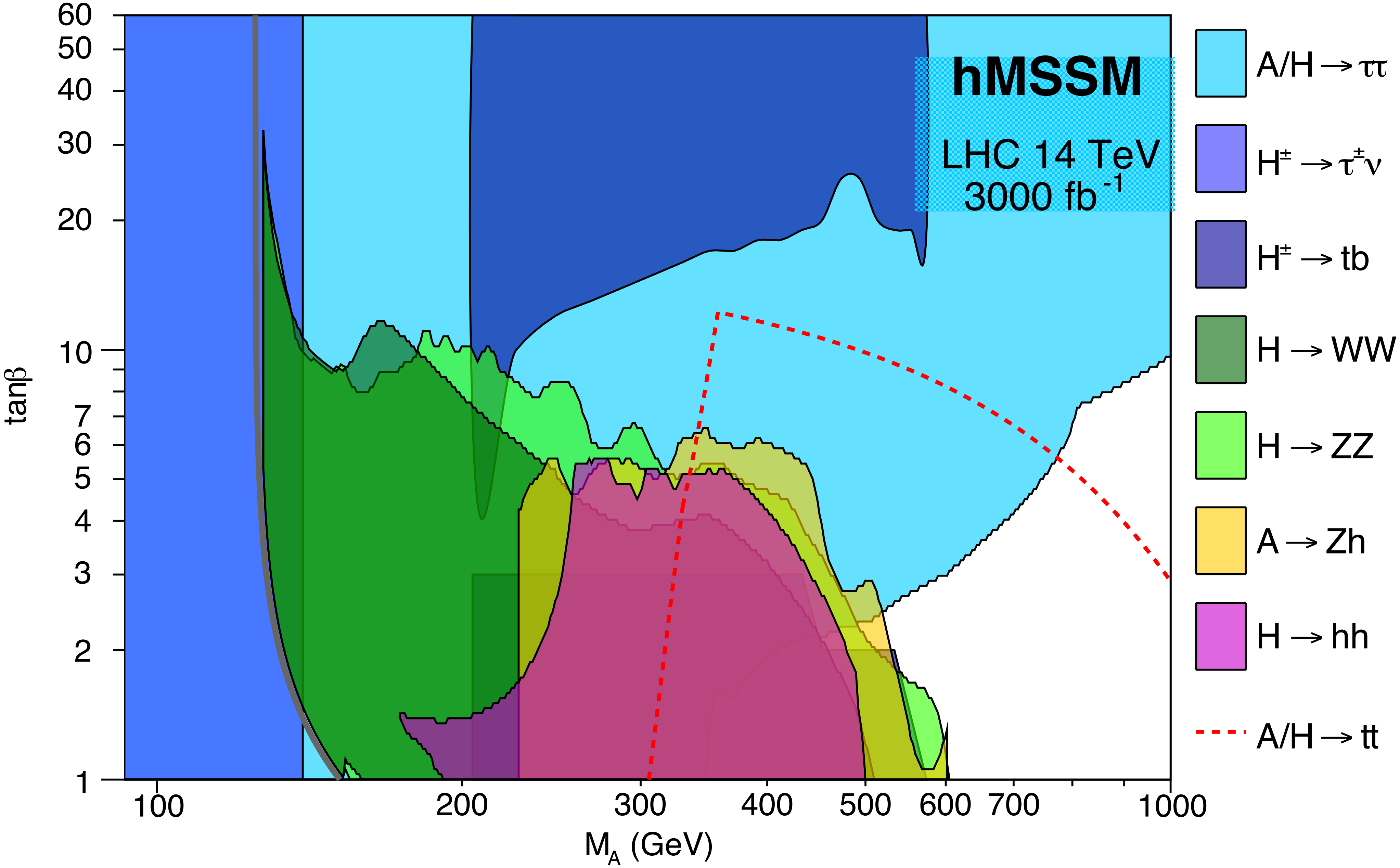
Direct: Where now?

hMSSM for illustration



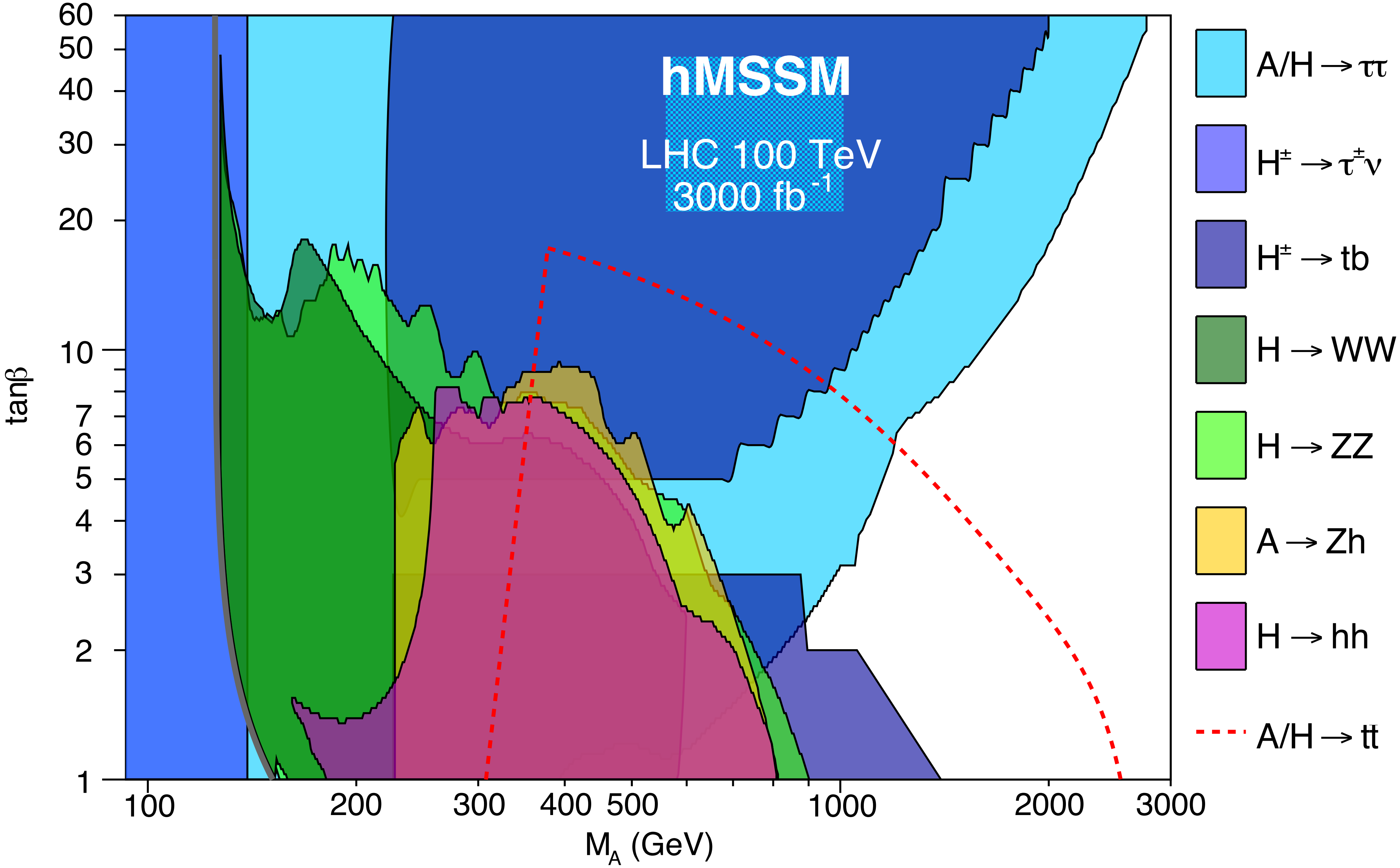
Direct: Whither?

[Baglio, Djouadi, Quevillon 1511.07853]

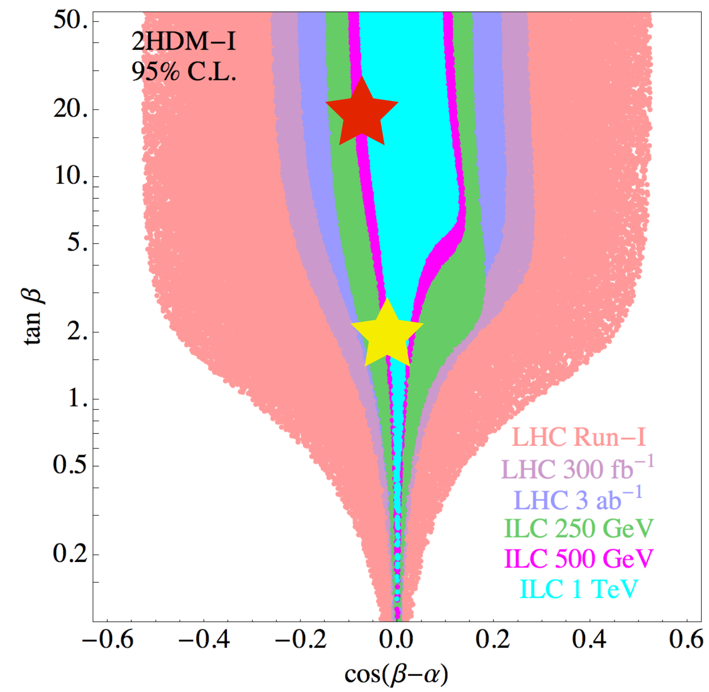


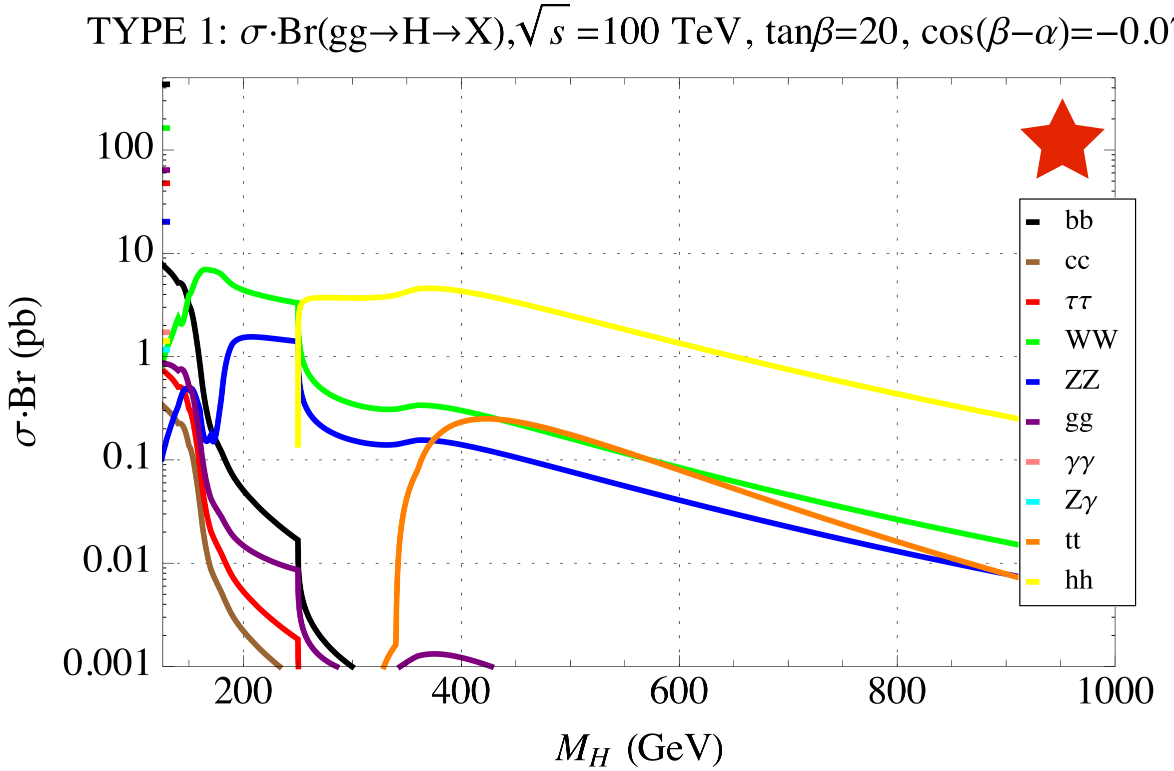
Direct: Whither?

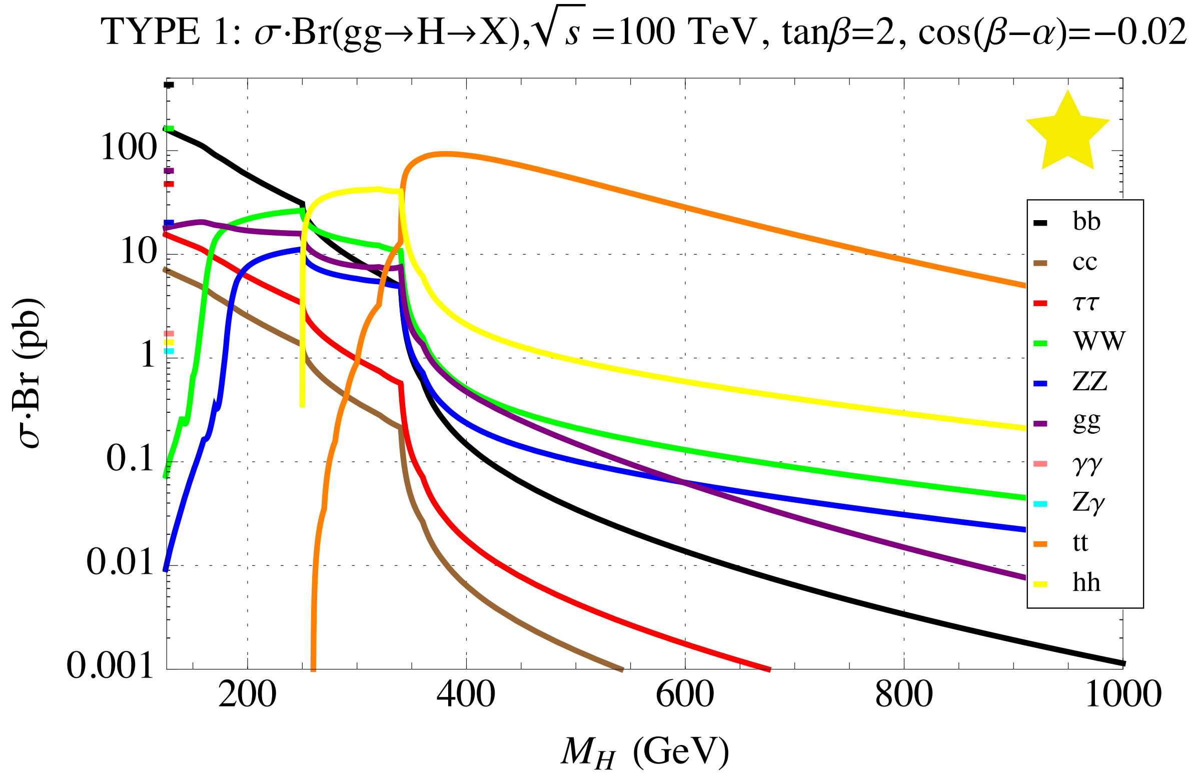
[Baglio, Djouadi, Quevillon 1511.07853]



Where's the signal?



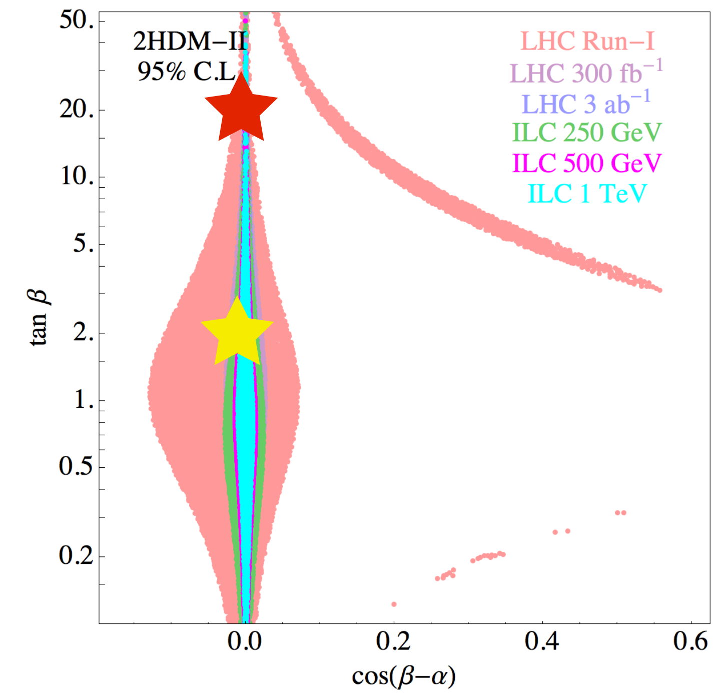


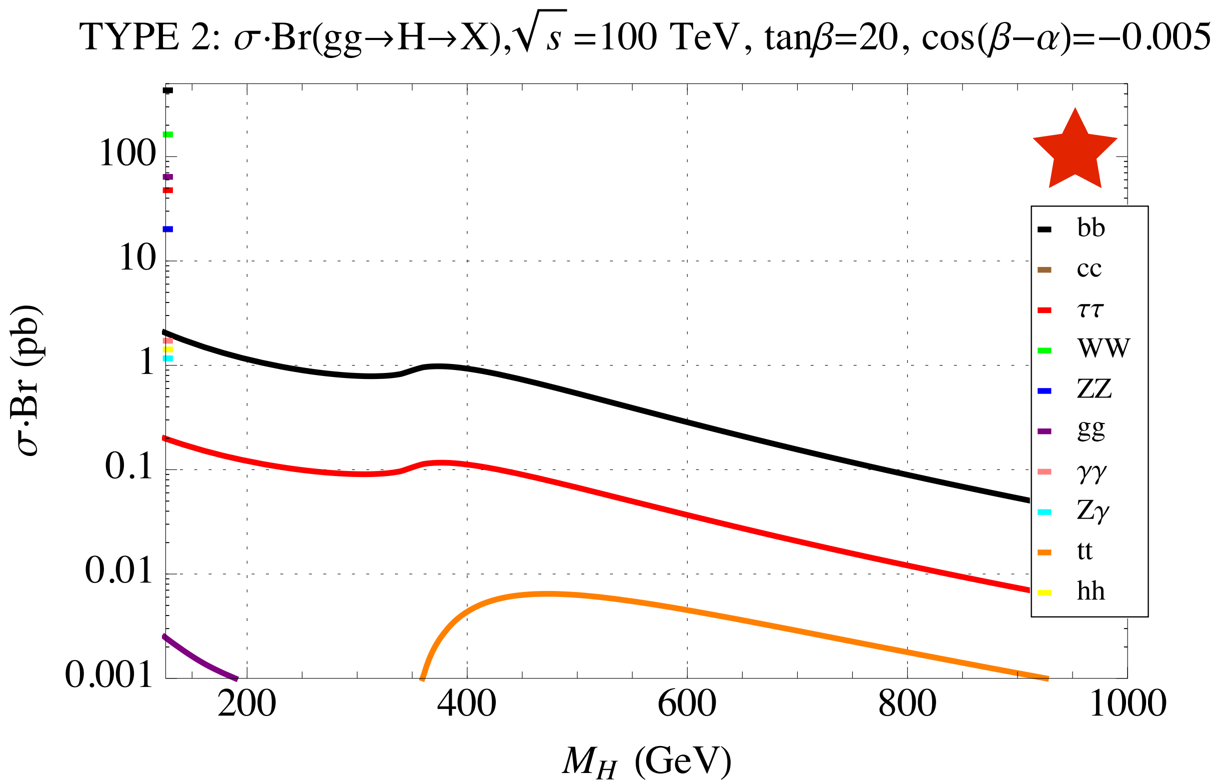


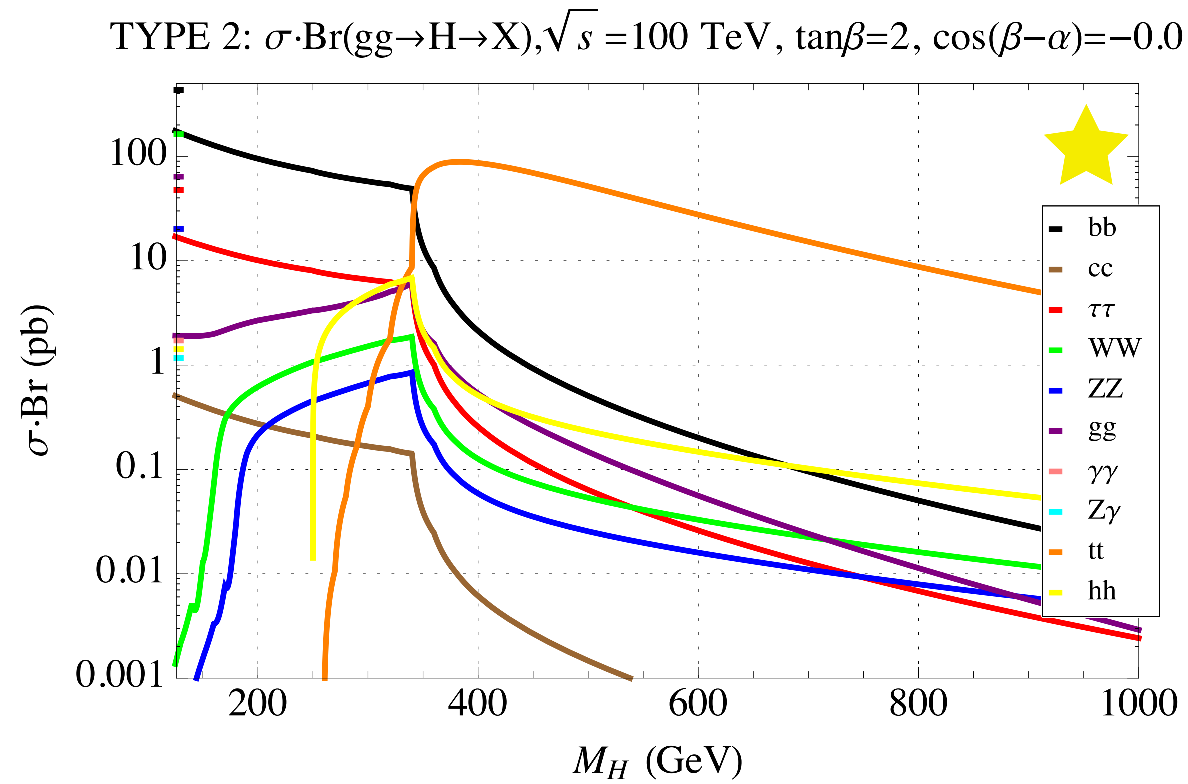
High tanβ dominated by hh, Zh, VV, tt

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

Where's the signal?







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

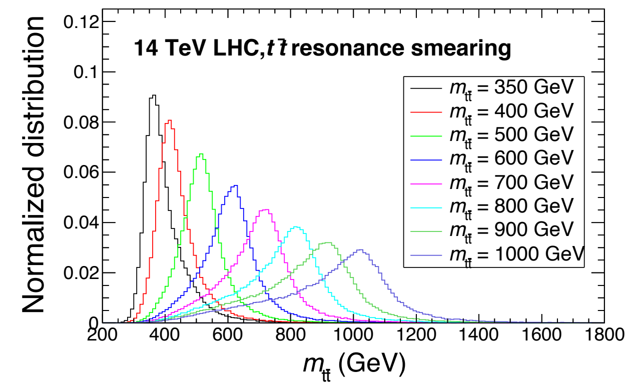
Low tanβ dominated by tt, bb; vectors suppressed by alignment

What's the problem?

[Gaemers, Hoogeveen '84; Dicus, Stange, Willenbrock '94; Barger, Han, Walker '06; NC, F. D'Eramo, P. Draper, S. Thomas, H. Zhang '15; Gori, Kim, Shah, Zurek '16; Hespel, Maltoni, Vryonidou '16; Czakon, Heymes, Mitov '16,…]

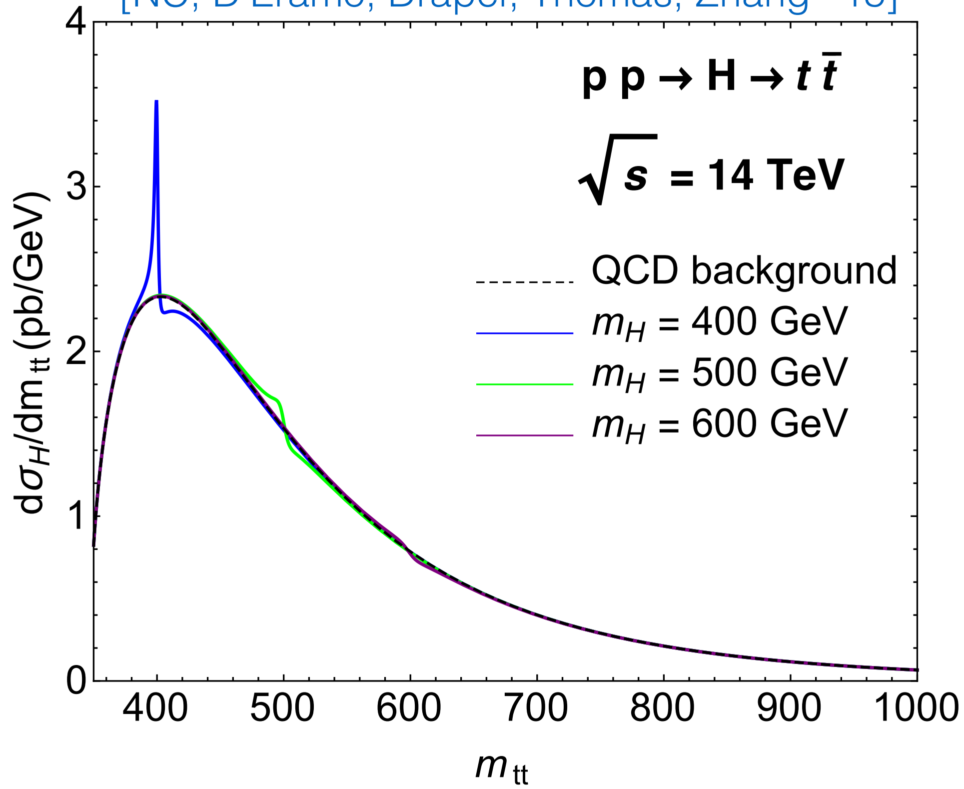
Spin-0 resonance decaying to tt interferes w/ SM tt

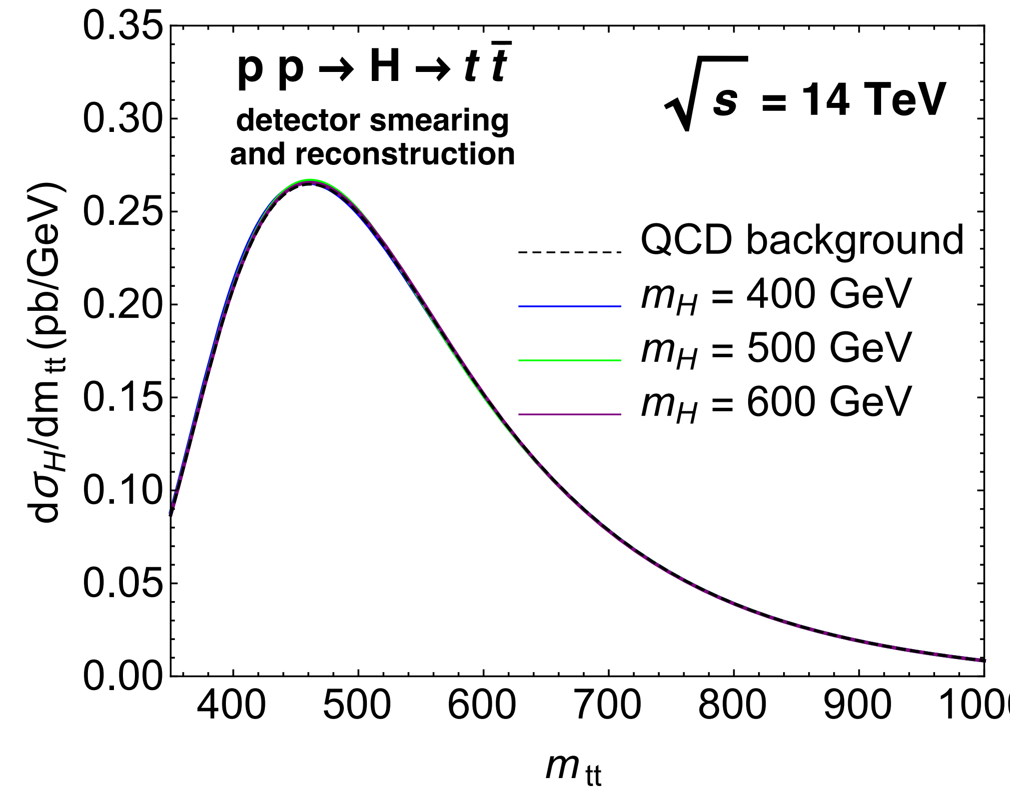
Not fatal in itself



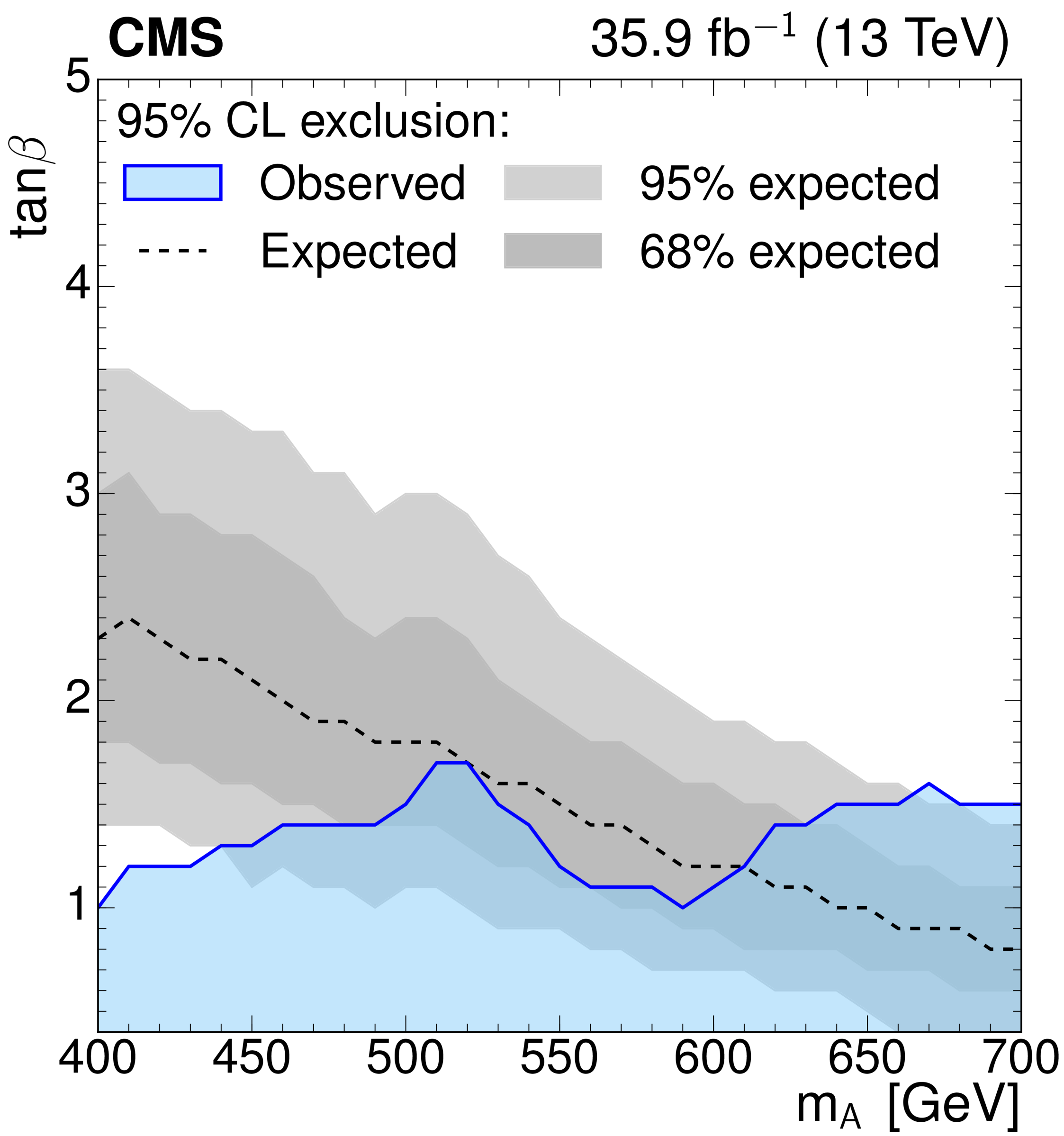
But made challenging by resolution

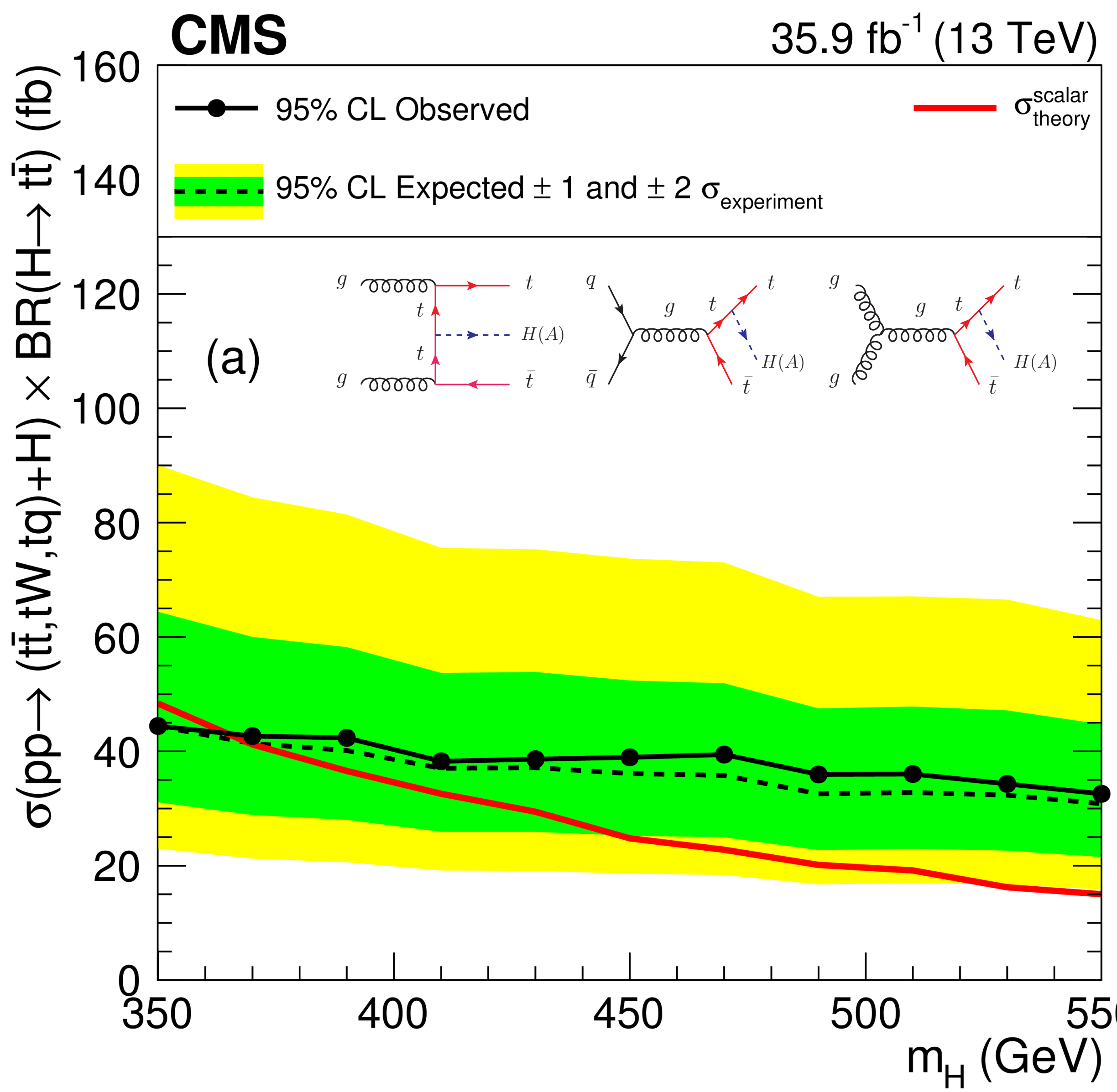
[NC, D'Eramo, Draper, Thomas, Zhang '15]



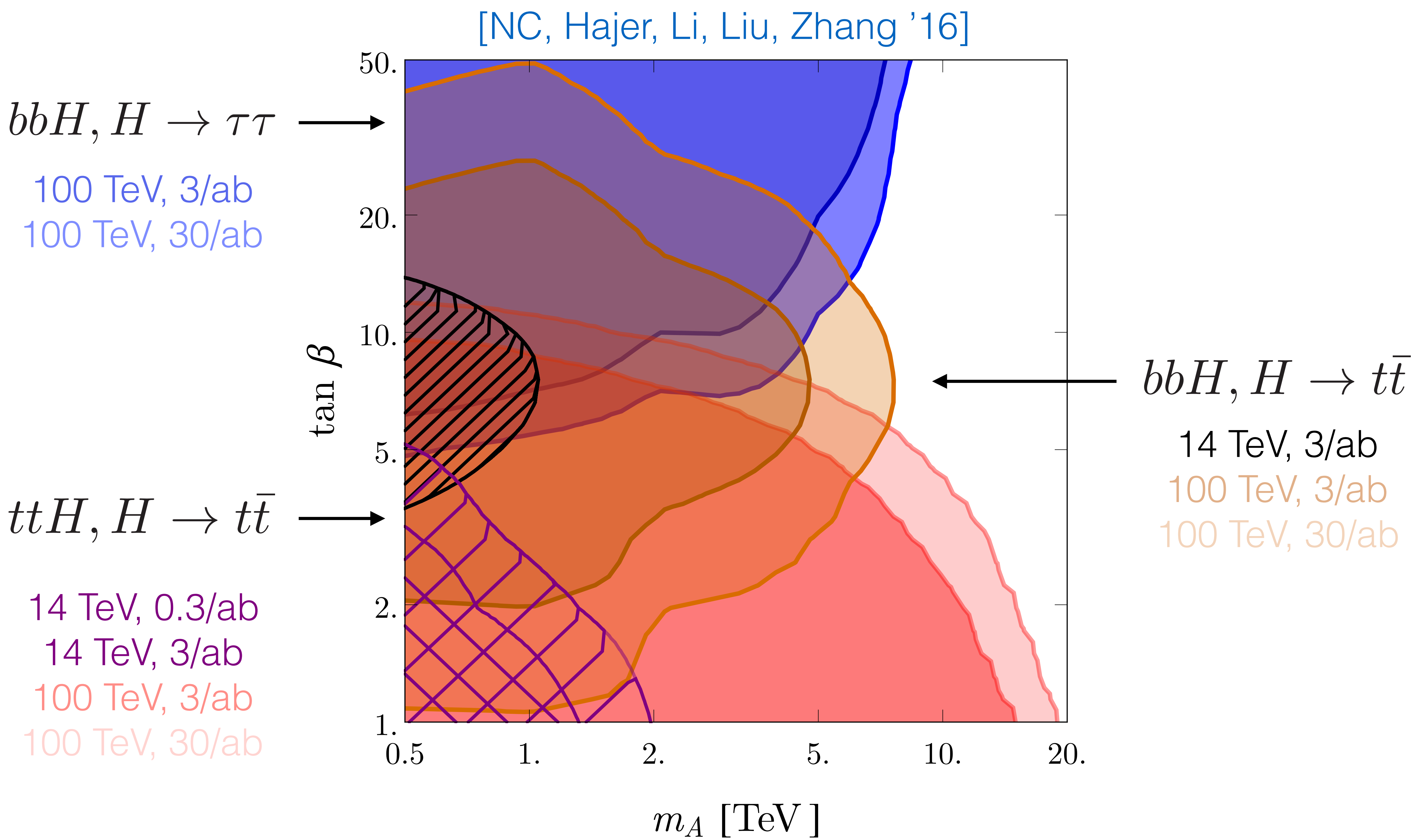


What's being done?





Where to go?


[NC, Hajer, Li, Liu, Zhang '16]
$bbH, H \to \tau\tau$
100 TeV, 3/ab
100 TeV, 30/ab
$ttH, H \to t\bar{t}$
14 TeV, 0.3/ab
14 TeV, 3/ab
100 TeV, 3/ab
100 TeV, 30/ab
$bbH, H \to t\bar{t}$
14 TeV, 3/ab
100 TeV, 3/ab
100 TeV, 30/ab
$\tan\beta$
50.
20.
10.
5.
2.
1.
0.5
1.
2.
5.
10.
20.
m_A [TeV]

More generally

Production channels (for 2HDM) in the alignment limit

Single Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^2)$	$gg \to H\,,\,A$
Single Heavy Higgs Associated Strong Production	$\mathcal{O}(g_s^4\lambda_f^2)$	$gg \to bbH\,,\,bbA\,,\,tbH^\pm\,,\,ttH\,,\,ttA$
Single Heavy Higgs Associated Weak Production	$\mathcal{O}(g_s^2 g_w^4\lambda_f^2)$	$gq \to bq'\,bH^\pm\,,\,bq\,tH\,,\,bq\,tA$
Double Heavy Higgs Weak Production	$\mathcal{O}(g_w^4)$	$q\bar{q} \to HA\,,\,HH^\pm\,,\,AH^\pm\,,\,H^+H^-$
Light + Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^4)$	$gg \to hH\,,\,hA$
Double Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^4)$	$gg \to HH\,,\,HA\,,\,AA\,,\,H^+H^-$

[NC, D'Eramo, Draper, Thomas, Zhang '15]

Heavy Higgs Cascades

Distinctive single modes may have small production rates (e.g. H±)

Dominant single modes may be hard to see (e.g. gg → H/A → tt)

Multi-mode cascades provide an opportunity (e.g. gg → H → WH±)

Organizing principle:
alignment limit.

Many multi-Higgs couplings vanish in this limit; focus on non-vanishing couplings

Multi-Higgs Couplings in the alignment limit:

- hHH
- hAA
- HHH
- HAA ←
- HH^+H^- ←
- ZAH ←
- $HW^\pm H^\mp$ ←
- $AW^\pm H^\mp$ ←

Snowmass 2021

- 2HDM are a key benchmark for future colliders, Snowmass!
- Continue exploring indirect constraints on 2HDM from Higgs factories using state-of-the-art coupling projections.
- Significant room to improve forecasting for sensitivity to tt final states at pp machines, both in ggH and ttH.
- Significant opportunities in other associated production modes, Higgs cascades.
- Challenges for pp machines largely avoided by high center-of-mass lepton colliders. Muon collider, anyone?

Thank you!