Extended Higgs Sector: A Second Doublet

John Stupak III on behalf of
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PURDUE UNIVERSITY CALUMET

CMS Compact Muon Solenoid

Introduction

- The SM contains a minimal Higgs sector
  - Many natural models predict extended Higgs sector
    - Can be described at low energy by the Two Higgs Doublet Model (2HDM)
- 2HDM
  - 5 Higgs bosons
    - h, H, A, $H^{\pm}$
  - Large parameter space, but many simplifications possible
    - No CP violation, No FCNC, MSSM quartic couplings
      - 4 2HDM types with 6 parameters: 4 masses and 2 angles (α,β)

Coupling Assignments

Type	u	d	$\ell^{\pm}$
I	Φ_2	Φ_2	Φ_2
LS			Φ_1
2*		Φ_1	
F			Φ_2

- Throughout, we interpret h(125) as the lighter of the two CP-even 2HDM scalars

*MSSM is a constrained type 2 2HDM

Probing the 2HDM (I)

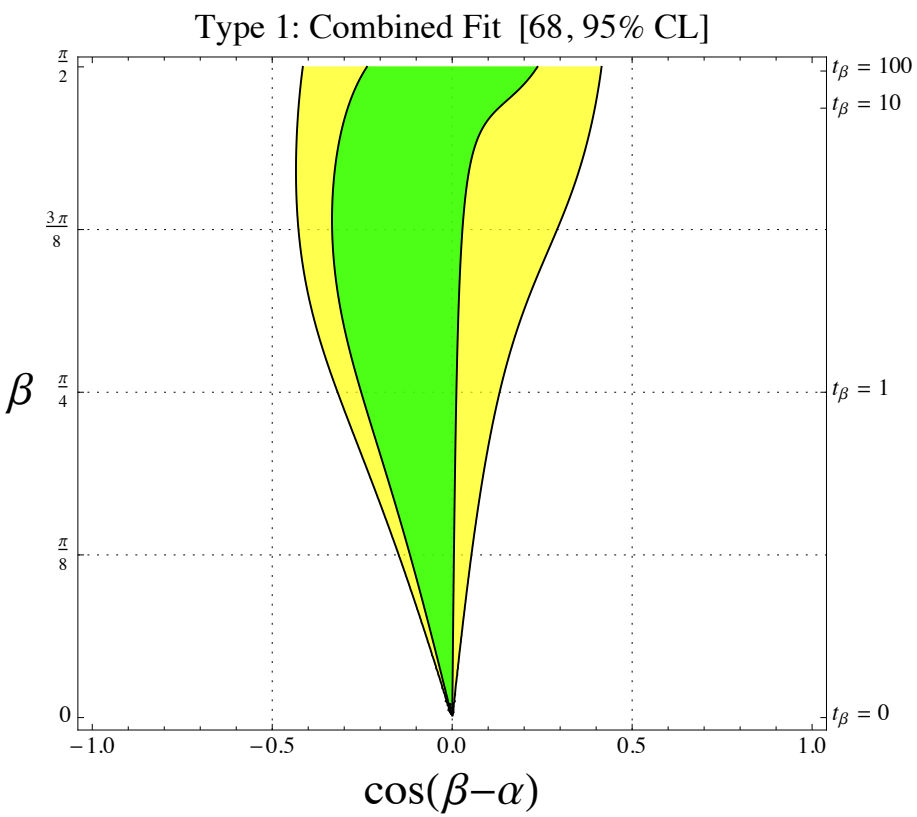
- 2 complementary strategies available to probe 2HDM:
  - Precision measurement of h(125) couplings
    - Couplings of h_{2HDM} differ from those of h_{SM}

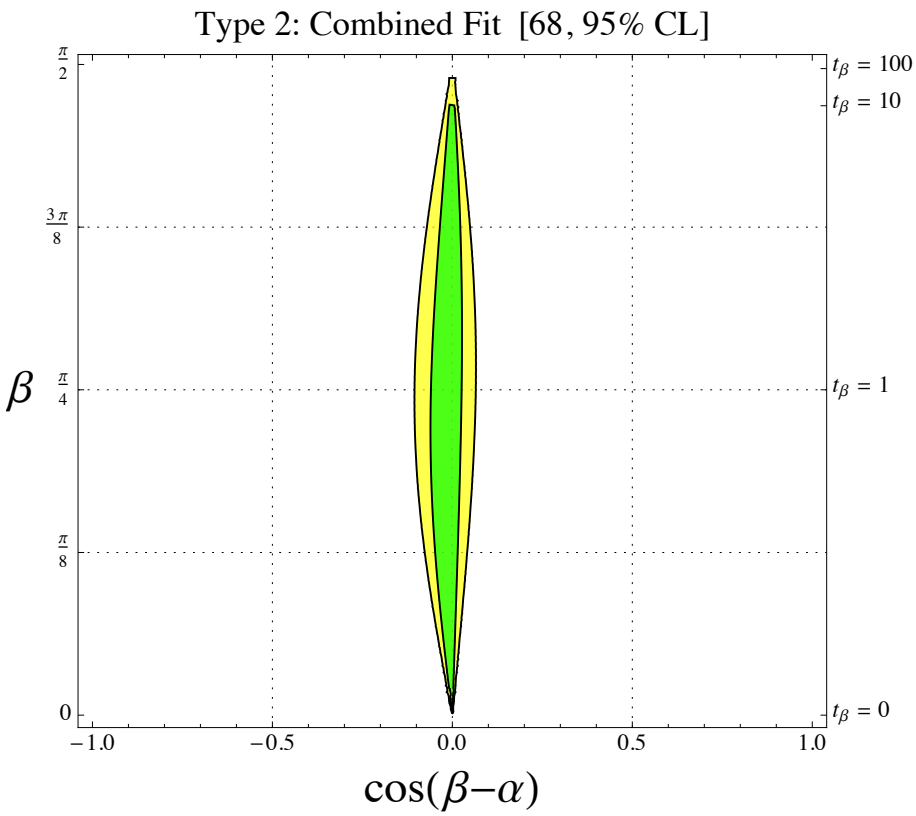
<table>
<tr><th colspan="5">y_{2HDM}/y_{SM}</th></tr>
<tr><th>Type</th><th>hVV</th><th>hQu</th><th>hQd</th><th>hLe</th></tr>
<tr><td>I</td><td rowspan="4">sin(β-α)</td><td rowspan="4">sin(β-α) + cos(β-α)/tan(β)</td><td rowspan="2">sin(β-α) + cos(β-α)/tan(β)</td><td>sin(β-α) + cos(β-α)/tan(β)</td></tr>
<tr><td>LS</td><td rowspan="2">sin(β-α) – cos(β-α)*tan(β)</td></tr>
<tr><td>2</td><td rowspan="2">sin(β-α) – cos(β-α)*tan(β)</td></tr>
<tr><td>F</td><td>sin(β-α) + cos(β-α)/tan(β)</td></tr>
</table>

    - h(125) coupling measurements can constrain 2HDM
      - But not sensitive in alignment limit (AL) - for cos(β-α)=0, all $y_{2HDM}/y_{SM}=1$

h(125) Couplings Constraints

[Craig, Galloway, Thomas: 1305.2424]



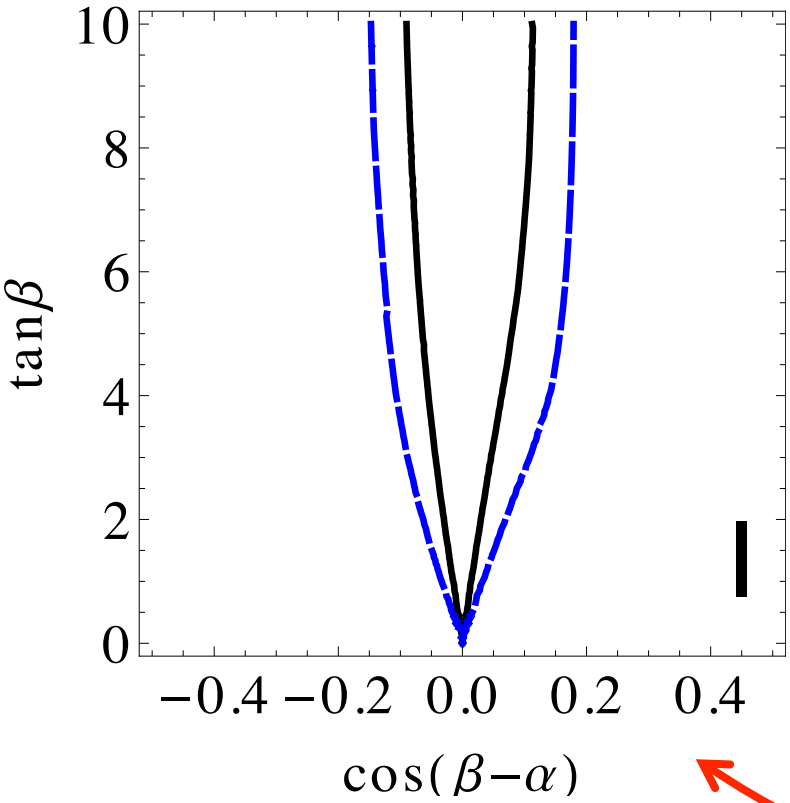


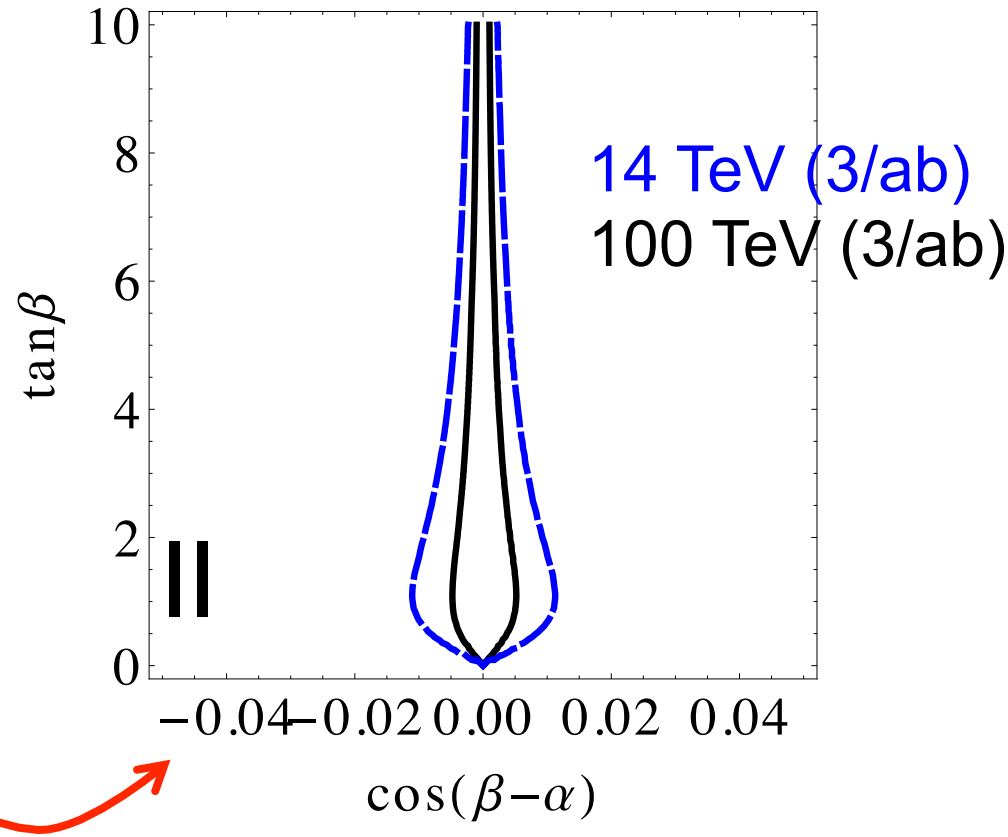
Since h(125) is SM-like, nature can't be too far from the AL

Couplings @ 100 TeV

Assuming we do not observe deviations from SM:

[Chen: SLAC Workshop]





NB: scales

Probing the 2HDM (II)

- 2 strategies available to probe 2HDM:
  - Precision measurement of h(125) couplings
  - Direct search for additional scalars
    - Best to focus on production through gluon fusion
      - HVV coupling proportional to cos(β-α) ➔ VBF and AP suppressed
      - No AVV tree-level coupling ➔ No VBF or AP
    - Potential decays:
      - H ➔ tt, hh, ZZ, WW, bb, ττ, γγ *Suppressed near AL
      - A ➔ tt, Zh, bb, ττ, γγ
    - Cleaner decays also happen to be suppressed near AL
      - But can still have significant BR quite close

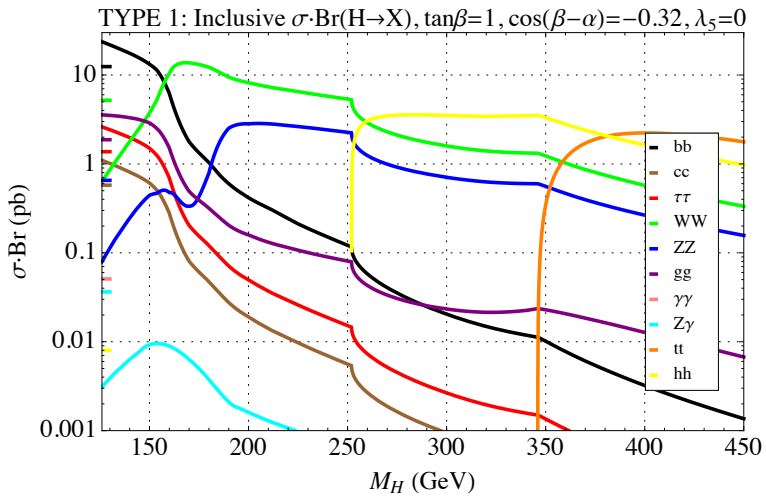
Mass Dependence

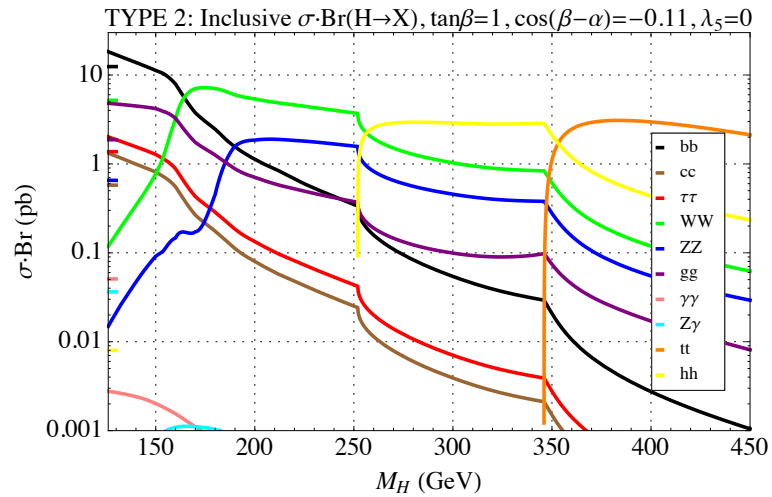
NB: 14 TeV

[Craig, Galloway, Thomas: 1305.2424]

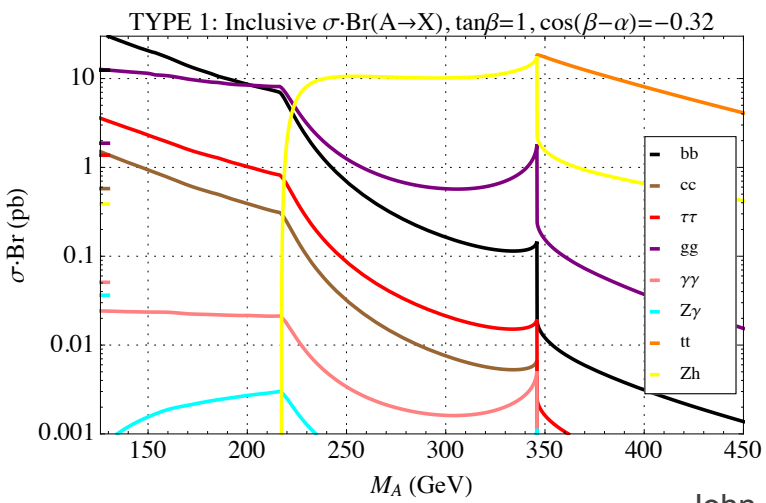
Just inside allowed region from coupling measurements

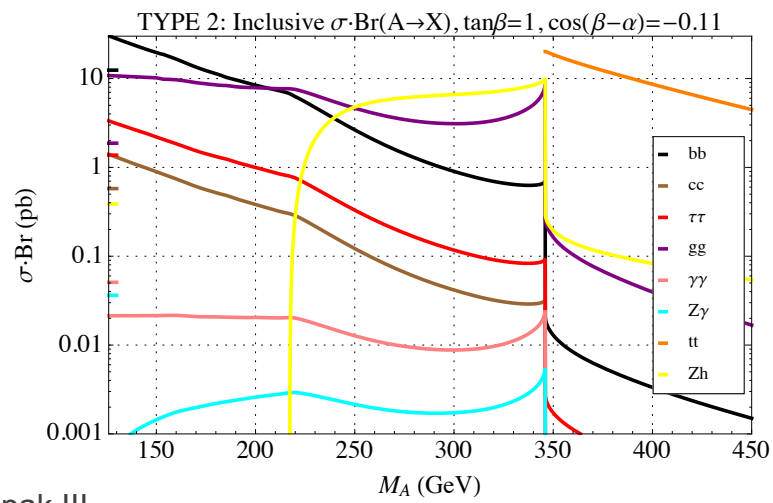
H:





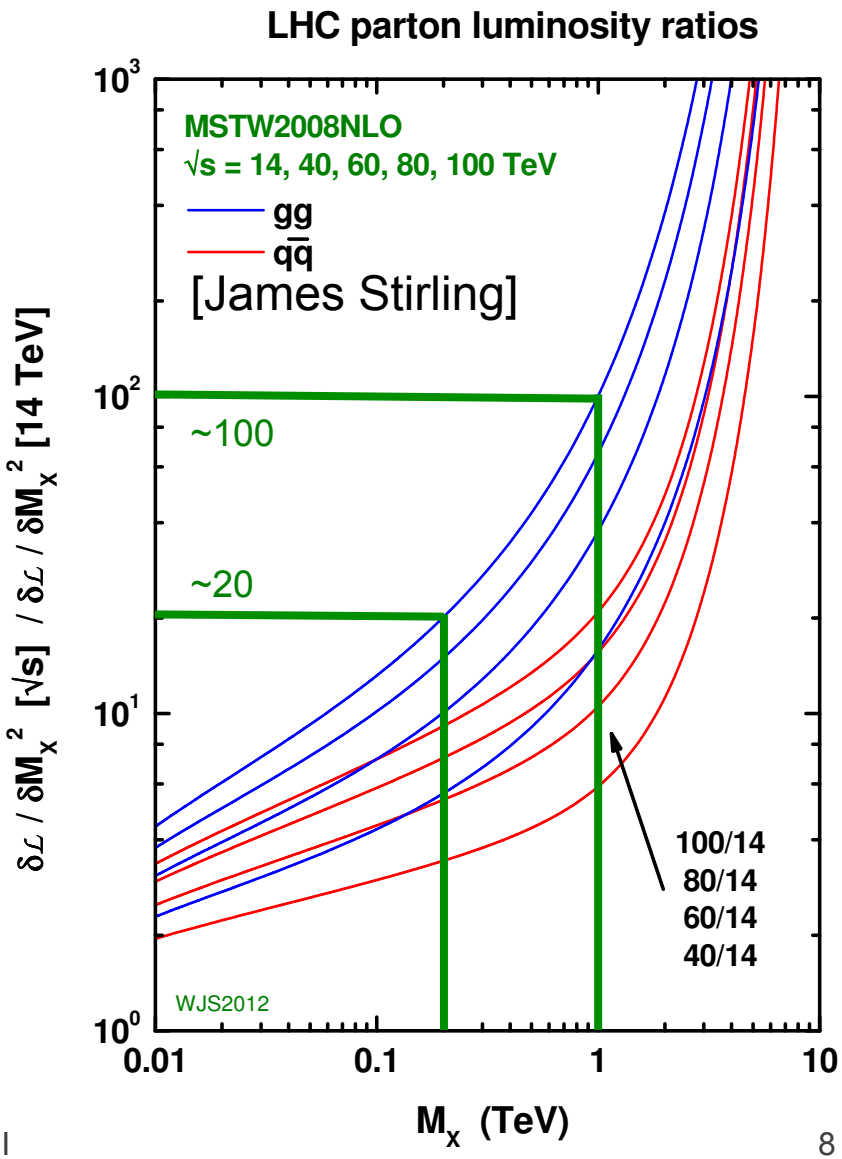
A:





Parton Luminosity

- Large gain in gluon fusion cross section at 100 TeV compared to 14 TeV
  - Factor ~20 (~100) for m_{gg} = 200 GeV (1 TeV)

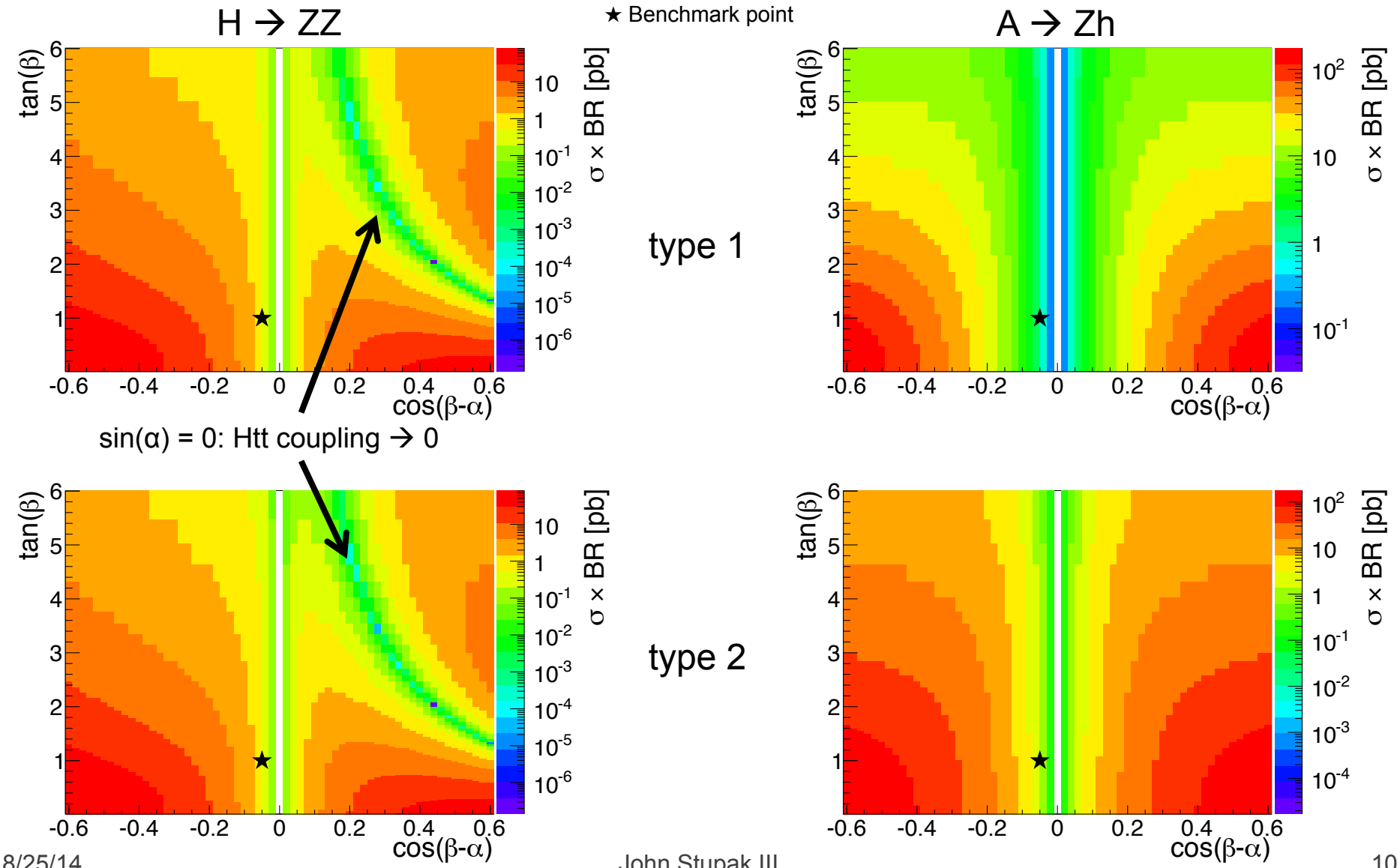


Search Strategy

- We chose to focus on:
  - $H \rightarrow ZZ \rightarrow 4\ell$
  - $A \rightarrow Zh \rightarrow \ell\ell + bb/\tau\tau$
- Leptons provide trigger and background rejection
- Fully reconstructible
- Reasonable BR across much of parameter space
  - Exception: the AL

Cross Section × BR

m = 500 GeV



Signal and Background Simulation

- Assumed run conditions:

[http://www.snowmass2013.org/tiki-index.php?page=EF+Facilities+List]

	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

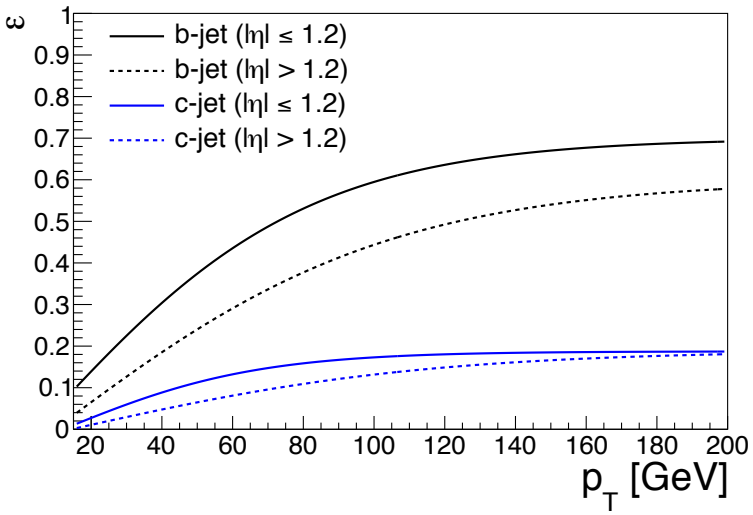
- Background MC
  - Madgraph + Bridge + Pythia + Delphes*
    - S_T-binned background samples
      - Normalized to NLO cross sections**
- Signal MC
  - Madgraph + Pythia + Delphes*
  - SM NLO gluon fusion cross sections and BRs rescaled by 2HDM LO coupling dependence on α, β

*Delphes parameterized detector simulation with generic "LHC-like" Snowmass detector

**Sub-dominant backgrounds at LO

Trigger and Object Selection

- Trigger
  - Assume thresholds remain similar to LHC
  - Require: $p_T(\ell_1) > 30$ GeV OR
    $p_T(\ell_1) > 20$ GeV AND $p_T(\ell_2) > 10$ GeV
- Object selection
  - lepton (e, μ)
    - $p_T > 5$ GeV
    - $|\eta| < 2.5$
    - Relative isolation < 10% (ρ corrected)
  - τ (hadronic)
    - $p_T > 20$ GeV
    - $|\eta| < 2.5$
    - 65% efficiency
    - 0.4% mistag rate
  - b-jet
    - $p_T > 20$ GeV
    - $|\eta| < 2.5$
    - 70% (60%) efficiency for $|\eta| \leq 1.2$ ($|\eta| > 1.2$)
    - 0.1% light jet mis-tag rate



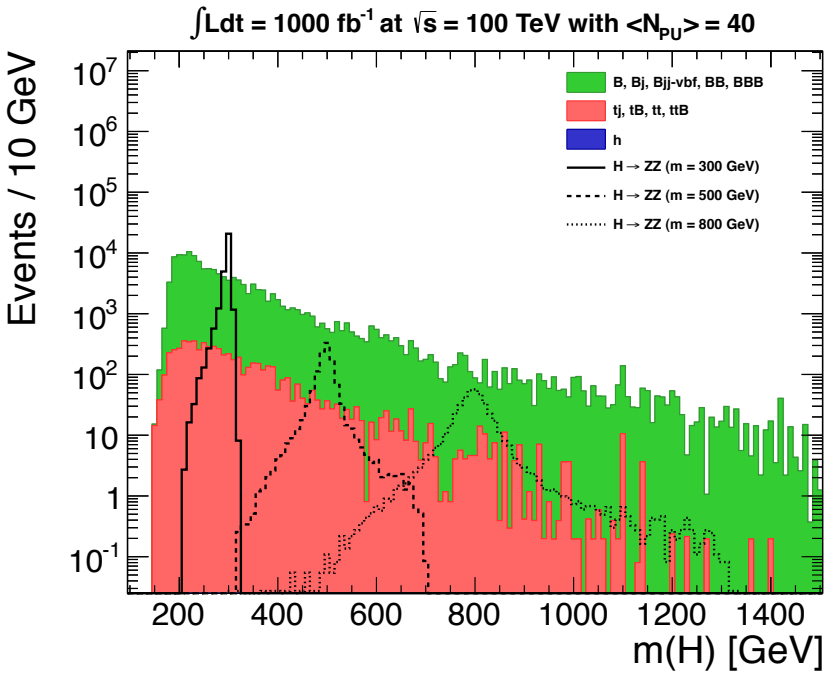
$H \rightarrow ZZ \rightarrow 4\ell$

Event Selection

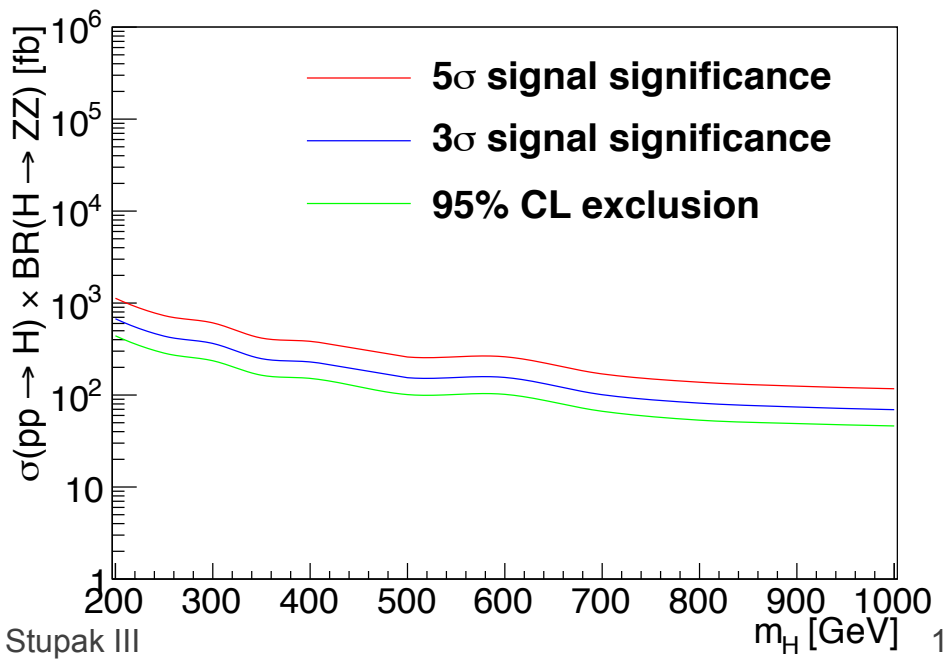
- Exactly 4 leptons
- 2 Z candidates
  - Opposite sign (OS), same flavor (SF) lepton pair
  - 80 GeV < $m(Z_1)$ < 100 GeV
  - 60 GeV < $m(Z_2)$ < 120 GeV

Sample	Selected Events
ZZ	1.3×10^5
ttZ	6.1×10^3
ZZZ	1.8×10^3
Total Background	$\mathbf{1.4 \times 10^5}$
Signal (m = 500 GeV)	1.2×10^3
Signal (m = 800 GeV)	450

Results

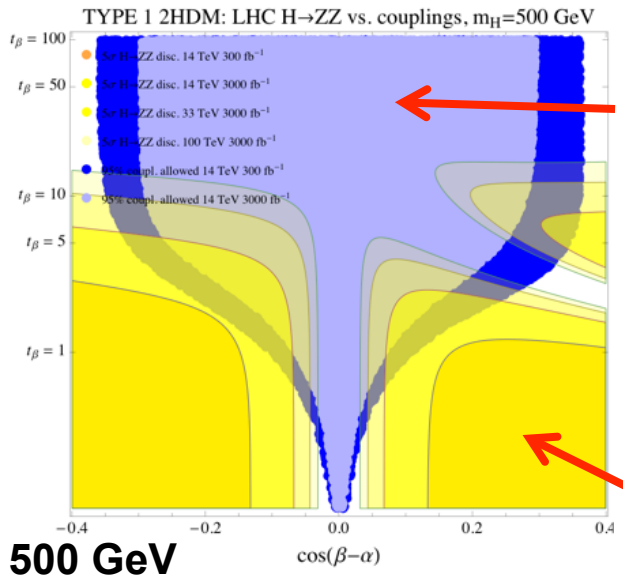


- Use to determine σ×BR which can be excluded or yield observation/discovery
  - Assume uniform 20% background systematic uncertainty



- Compare to σ×BR for each point in parameter space (next slide)

Complementarity

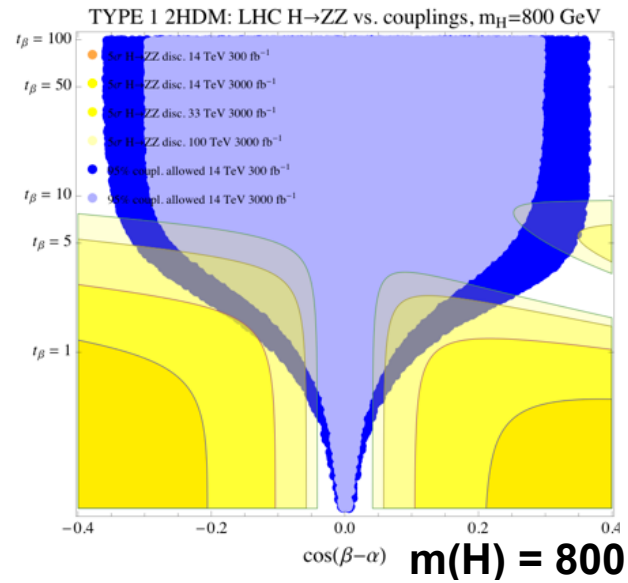


m(H) = 500 GeV

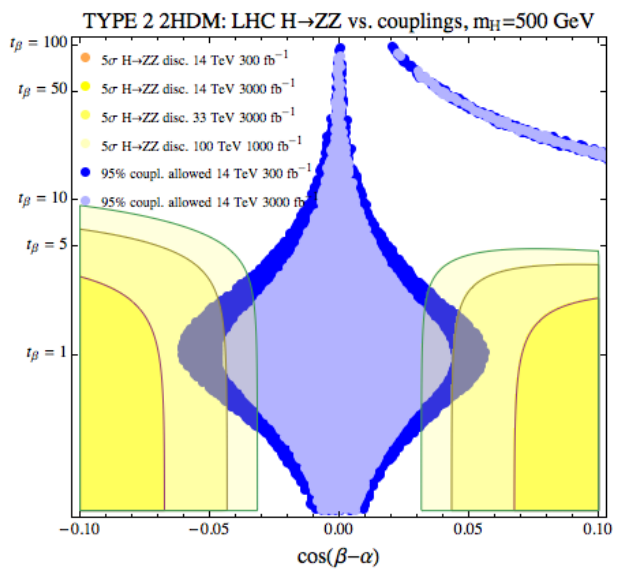
allowed by HL-LHC
(in absence of observed deviations from SM)

type 1

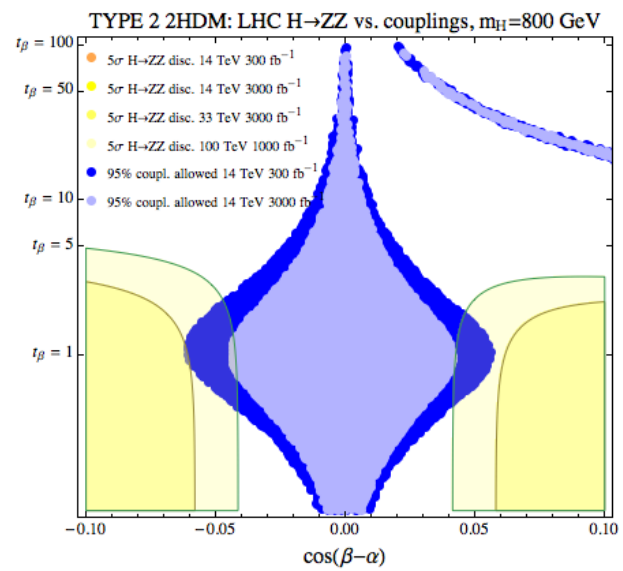
discoverable by direct search



m(H) = 800 GeV



type 2

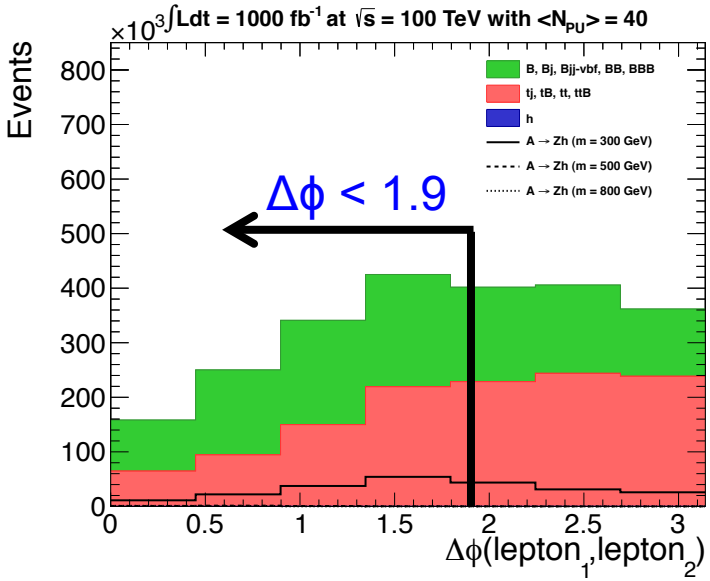


$A \rightarrow Zh \rightarrow \ell\ell + bb/\tau\tau$

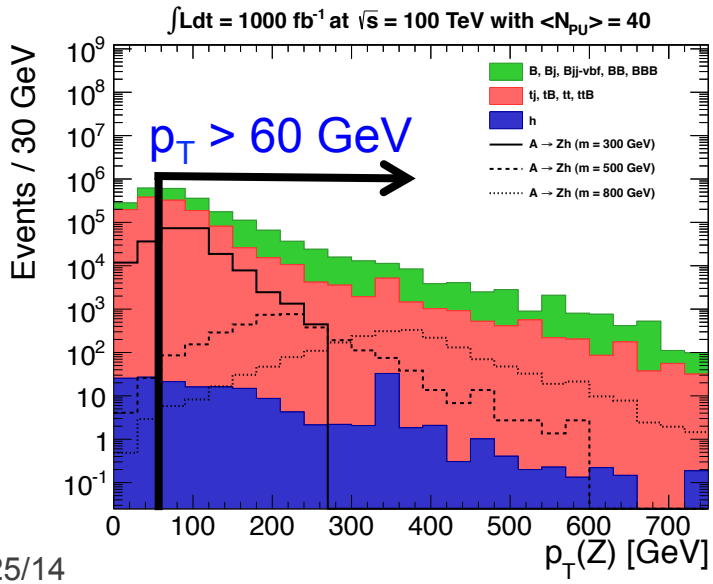
Event Pre-Selection

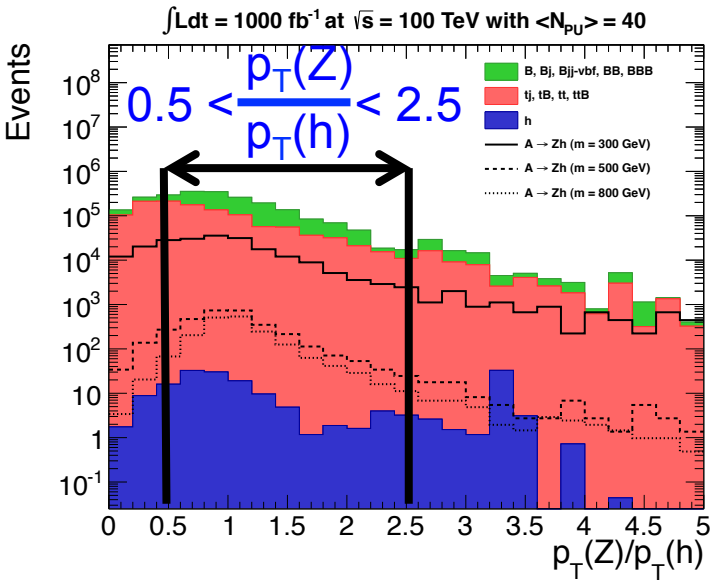
Channel	
bb	**ττ**
Exactly 2 b-jets	Exactly 2 τ leptons
Fewer than 2 τ leptons	Fewer than 2 b−jets
<u>h candidate</u> • 90 GeV < m(bb) < 150 GeV	• 55 GeV < m(ττ) < 125 GeV
Exactly 2 leptons	
<u>Z candidate</u> • OSSF lepton pair • 80 GeV < m(Z) < 100 GeV	

Pre-Selection Kinematics



- Apply additional selection cuts to enhance signal sensitivity
  - $\Delta\Phi(\ell_1, \ell_2) < 1.9$
  - $p_T(Z) > 60$ GeV
  - $0.5 < p_T(Z)/p_T(h) < 2.5$

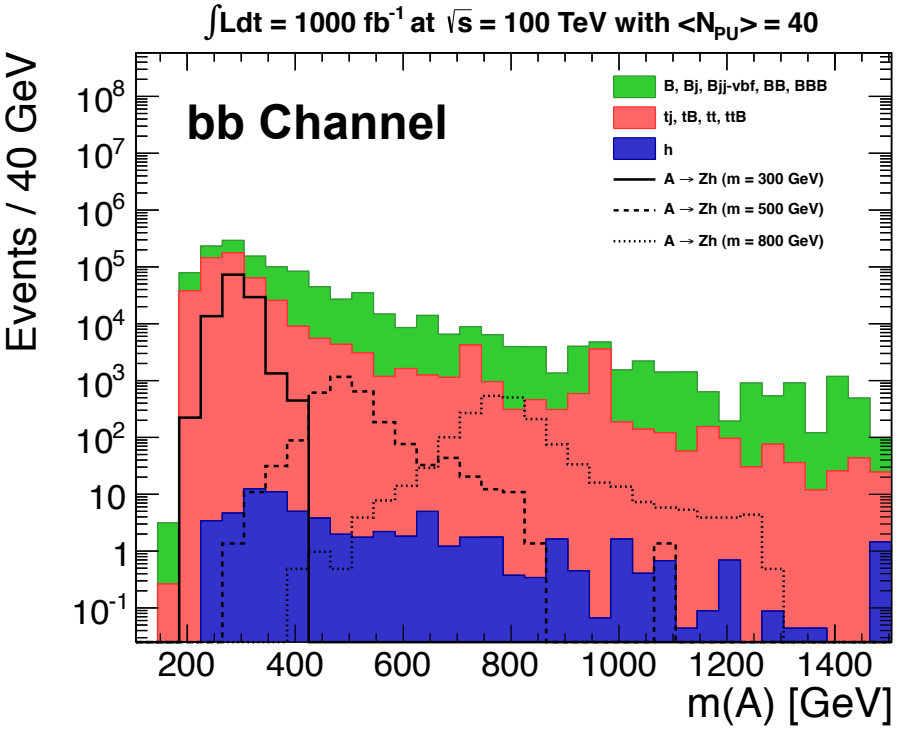


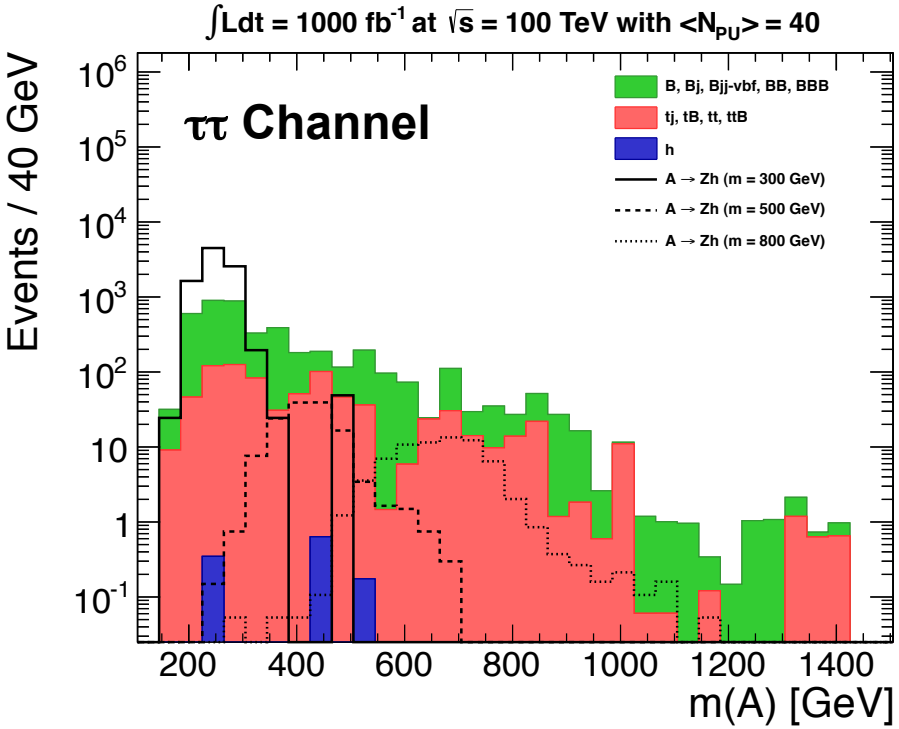


Selected Events

Sample	Selected Events	
	bb Channel	**$\tau\tau$ Channel**
Z	6.2×10^5	-
tt	4.4×10^5	-
ttZ	2.8×10^4	790
ZZ	2.4×10^4	3.3×10^3
tZ	2.2×10^4	-
ZZZ	-	250
Total Background	$\mathbf{1.1 \times 10^6}$	$\mathbf{4.3 \times 10^3}$
Signal (m = 500 GeV)	2.9×10^3	140
Signal (m = 800 GeV)	1.9×10^3	70

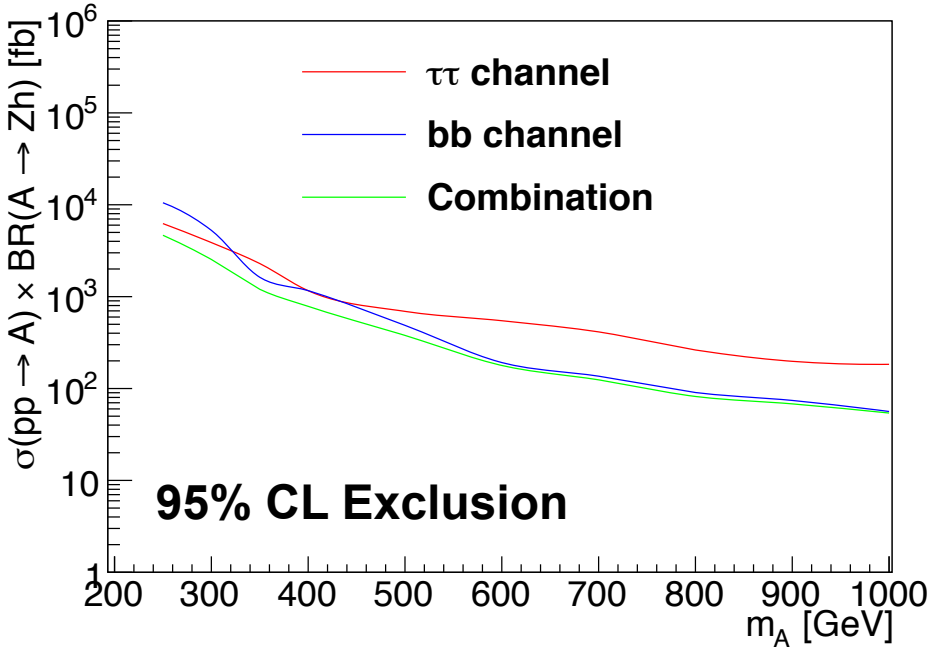
Event Kinematics

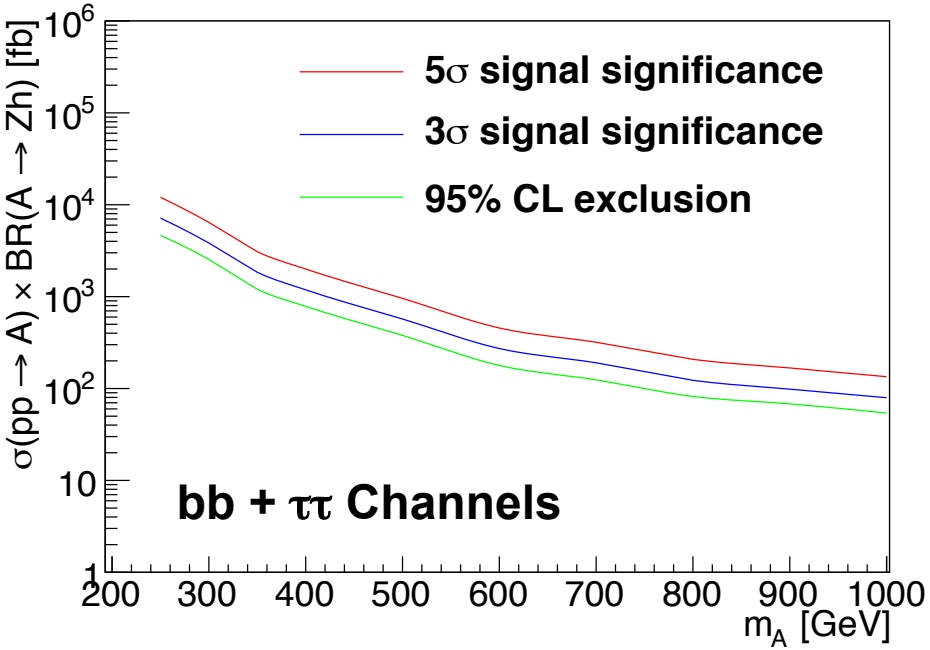




- Use to determine σ×BR which can be excluded or yield observation/discovery
  - Assume uniform 20% background systematic uncertainty

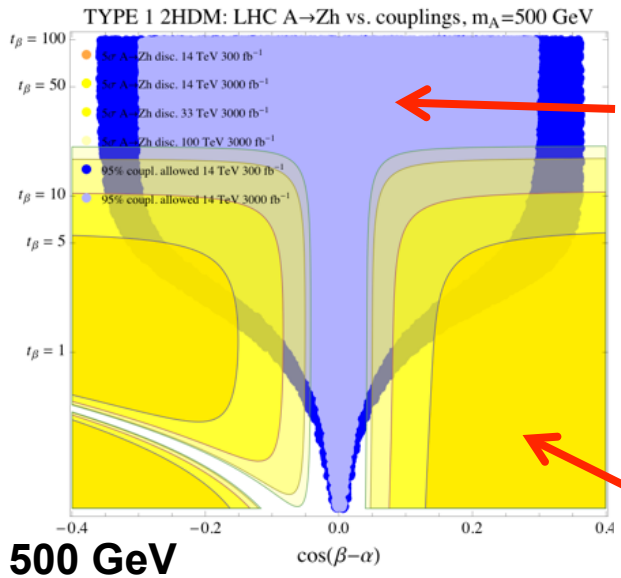
Results





- ττ (bb) channel more sensitive at small (large) m(A)
- Low mass A harder to exclude/discover than H

Complementarity

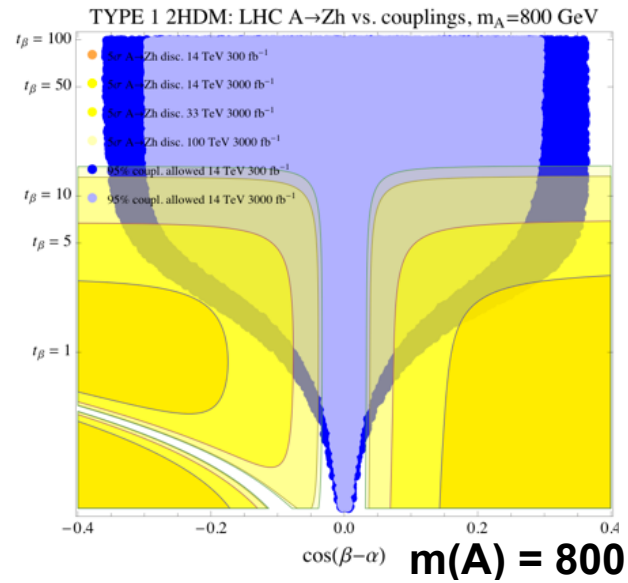


m(A) = 500 GeV

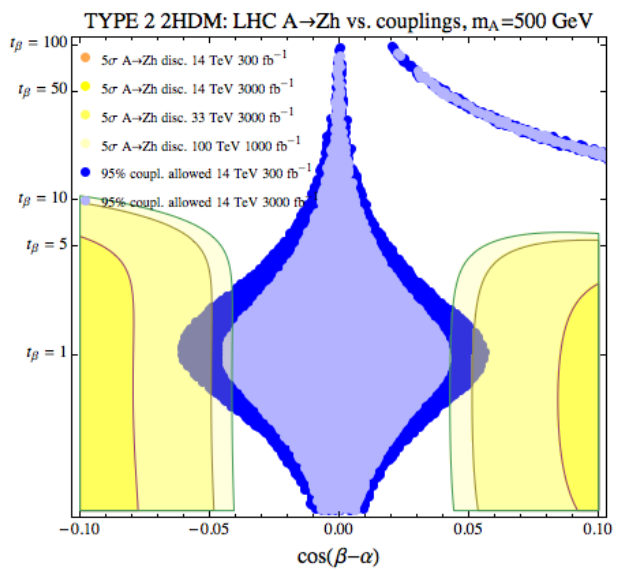
allowed by HL-LHC
(in absence of observed deviations from SM)

type 1

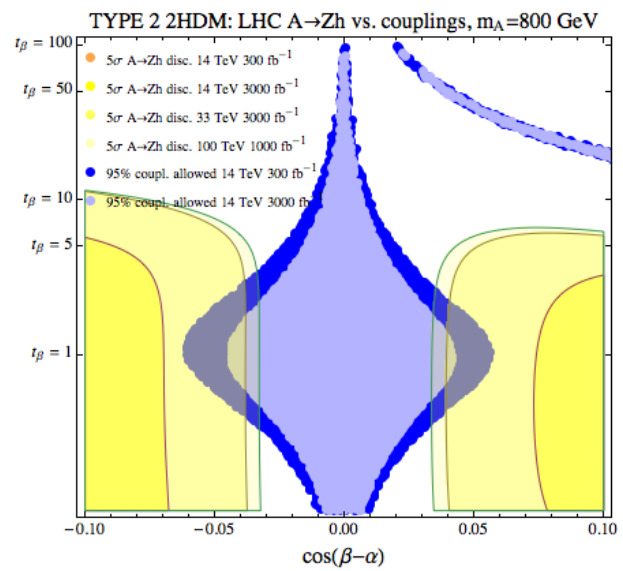
discoverable by direct search



m(A) = 800 GeV



type 2



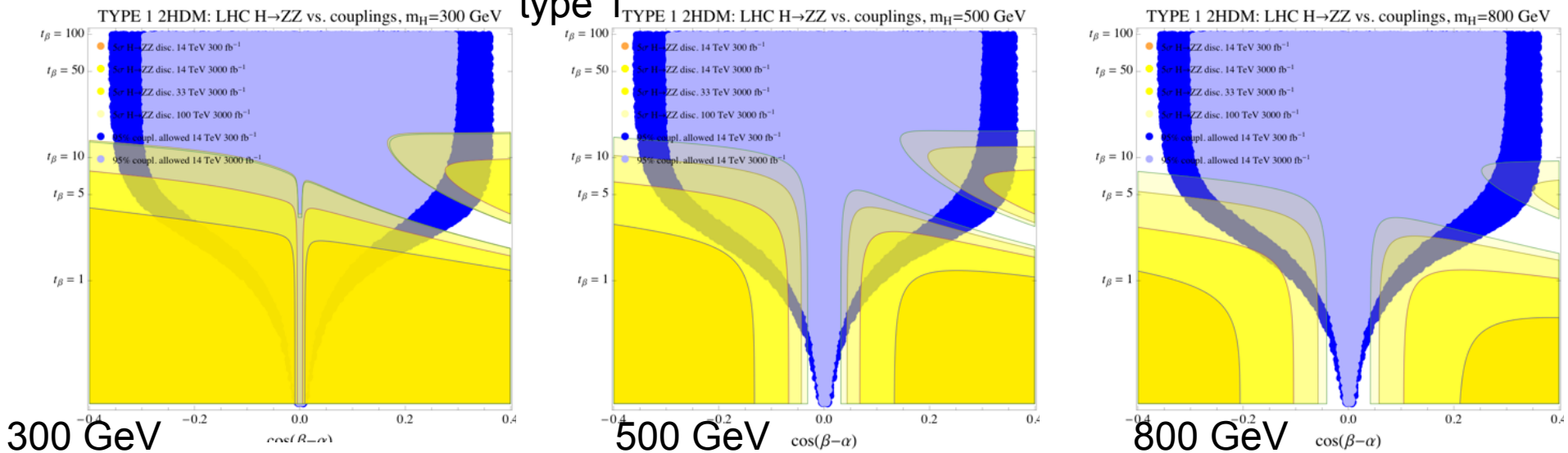
Conclusions

- Important to fully explore the Higgs sector
  - Is h(125) alone?
- Precision measurement of h(125) couplings can constrain parameter space of the 2HDM
  - Little (no) sensitivity near (at) alignment limit
- Direct search at a 100 TeV pp collider offers unique potential to probe regions of parameter space near the alignment limit
  - More info in 1308.6334
- Important to pursue both coupling measurements and direct search - Complementary

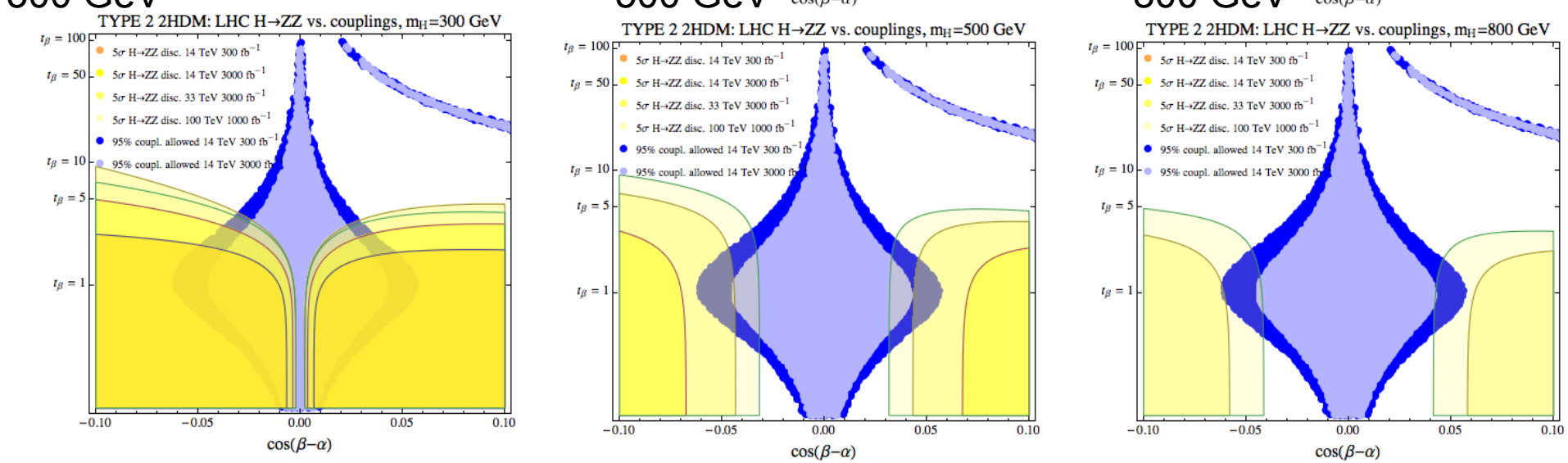
Backup

H → ZZ (5σ)

type 1



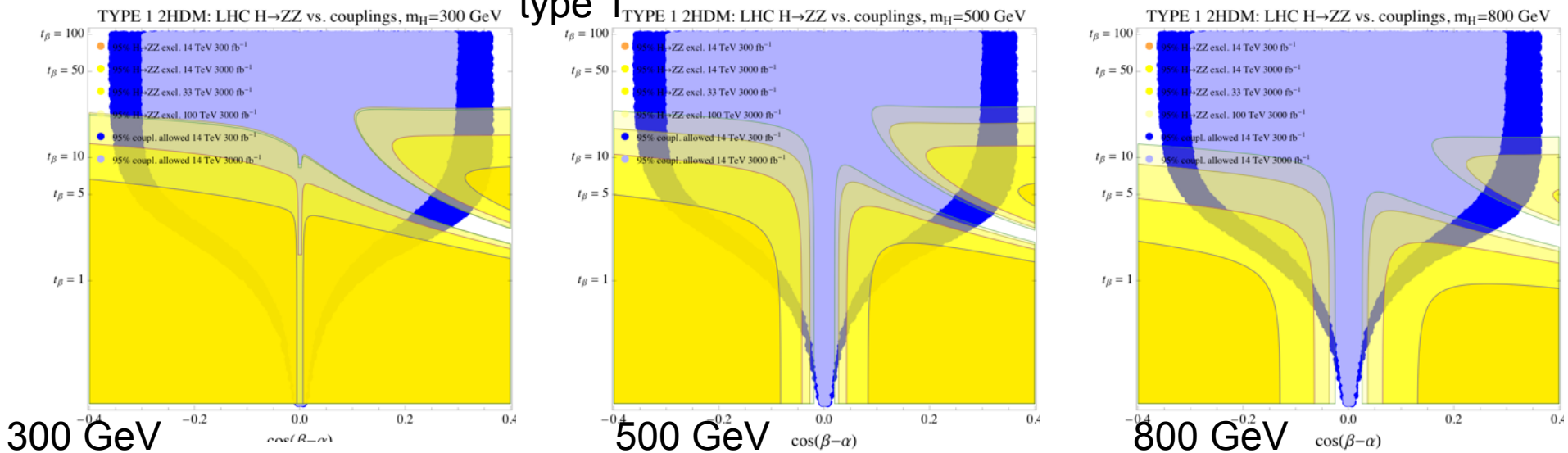
300 GeV 500 GeV 800 GeV



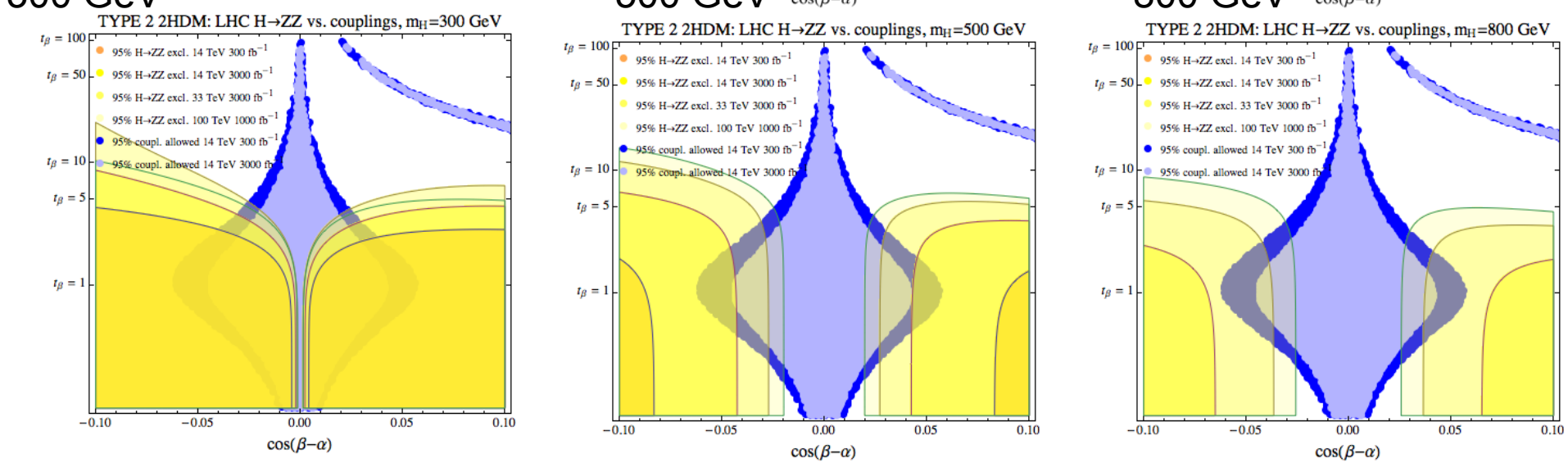
type 2

H → ZZ (95% CL)

type 1



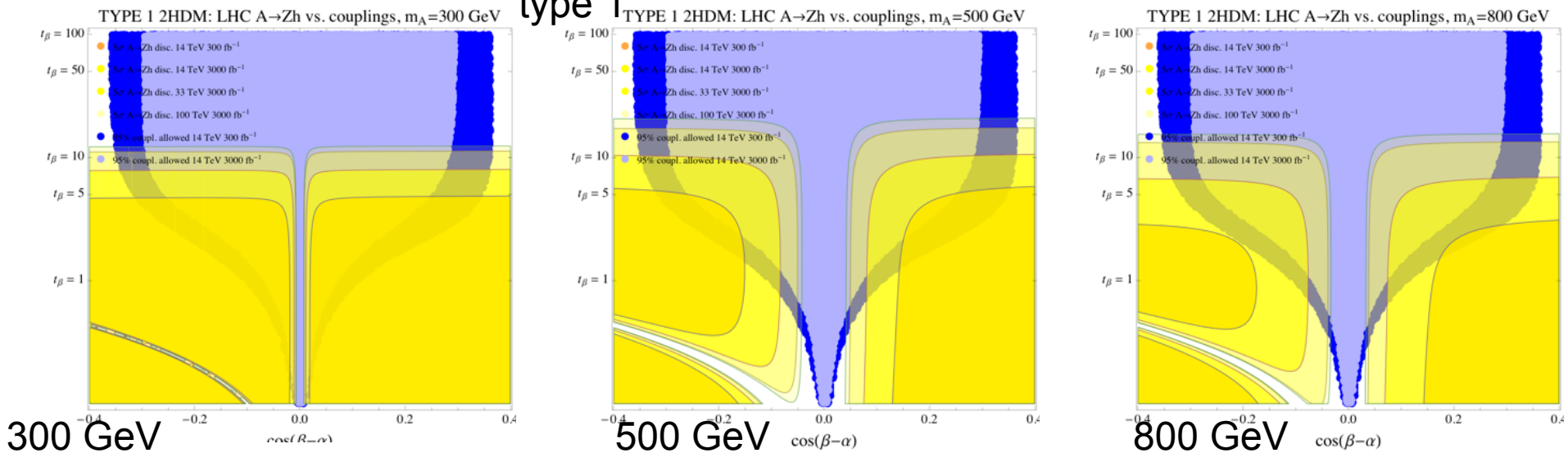
300 GeV 500 GeV 800 GeV



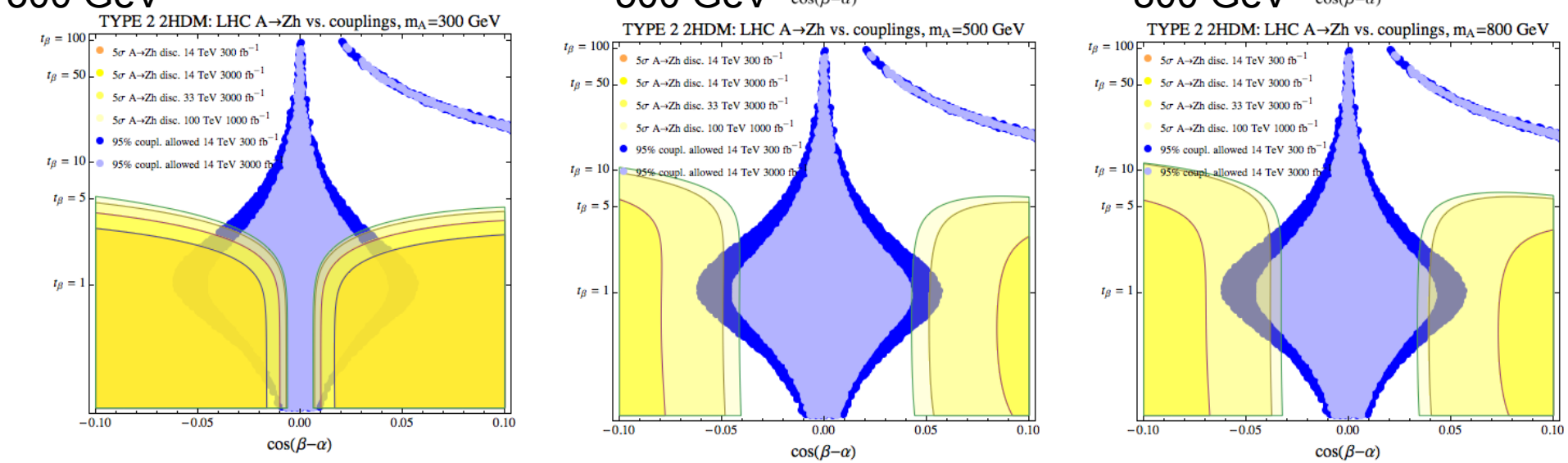
type 2

A → Zh (5σ)

type 1



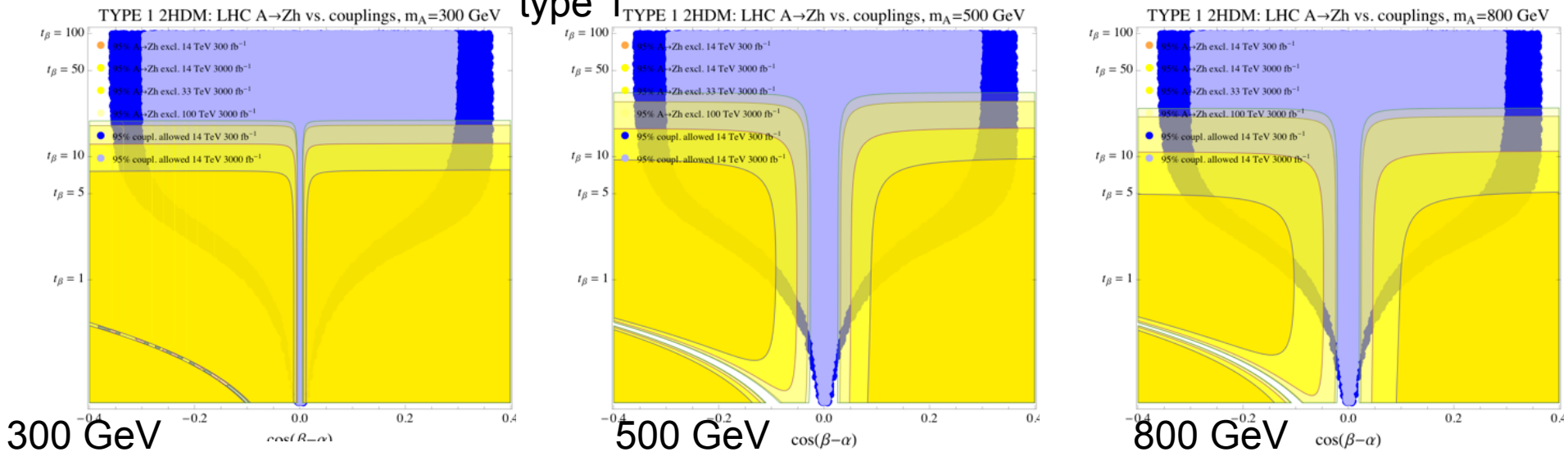
300 GeV 500 GeV 800 GeV



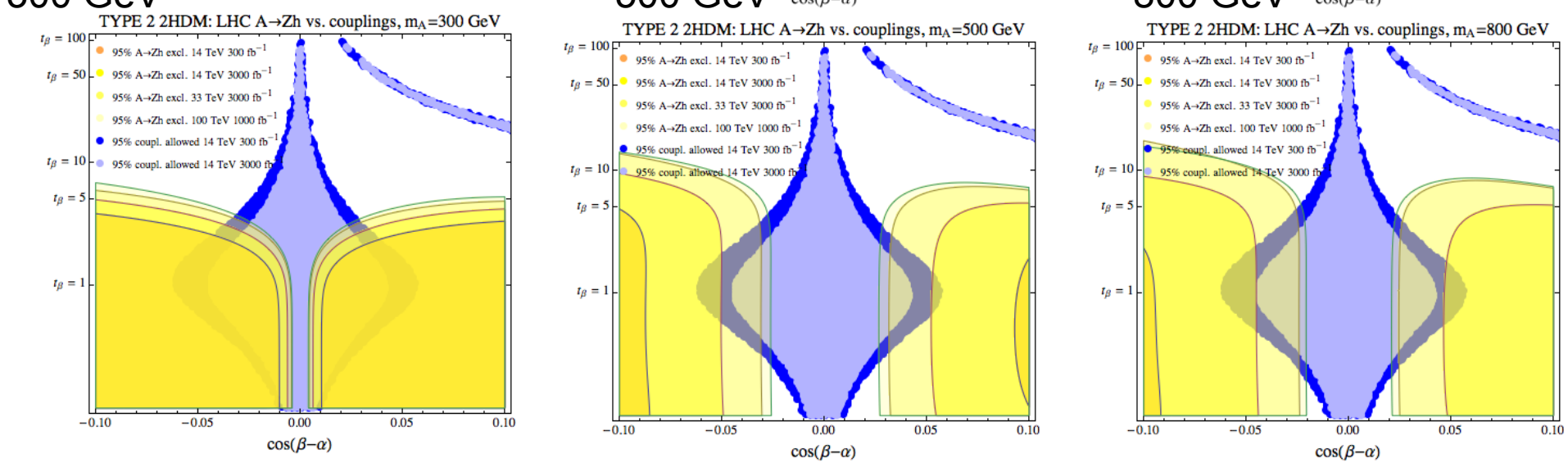
type 2

A → Zh (95% CL)

type 1



300 GeV 500 GeV 800 GeV



type 2

2HDM Coupling Strengths

[Craig, Galloway, Thomas]

$y_{2\mathrm{HDM}}/y_{\mathrm{SM}}$	2HDM 1	2HDM 2	2HDM 3 (Lepton-Specific)	2HDM 4 (Flipped)
hVV	$s_{\beta-\alpha}$	$s_{\beta-\alpha}$	$s_{\beta-\alpha}$	$s_{\beta-\alpha}$
hQu	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$
hQd	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$
hLe	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$
HVV	$c_{\beta-\alpha}$	$c_{\beta-\alpha}$	$c_{\beta-\alpha}$	$c_{\beta-\alpha}$
HQu	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$
HQd	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$
HLe	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$
AVV	0	0	0	0
AQu	$1/t_\beta$	$1/t_\beta$	$1/t_\beta$	$1/t_\beta$
AQd	$-1/t_\beta$	t_β	$-1/t_\beta$	t_β
ALe	$-1/t_\beta$	t_β	t_β	$-1/t_\beta$

[Branco, Ferreira, Lavoura, Rebelo, Sher, Silva]

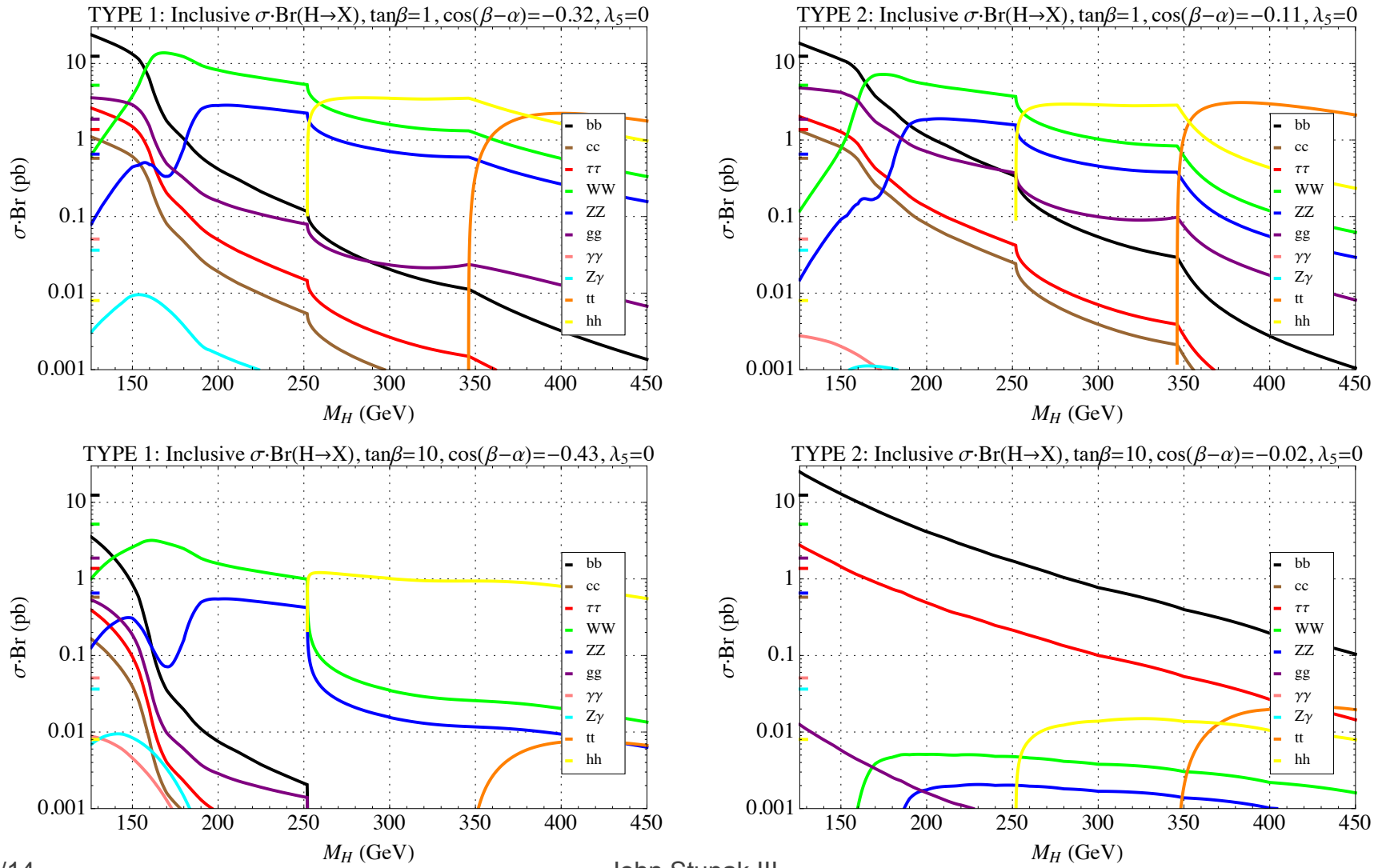
	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Equivalent

σ(H) × BR(H → X)

14 TeV

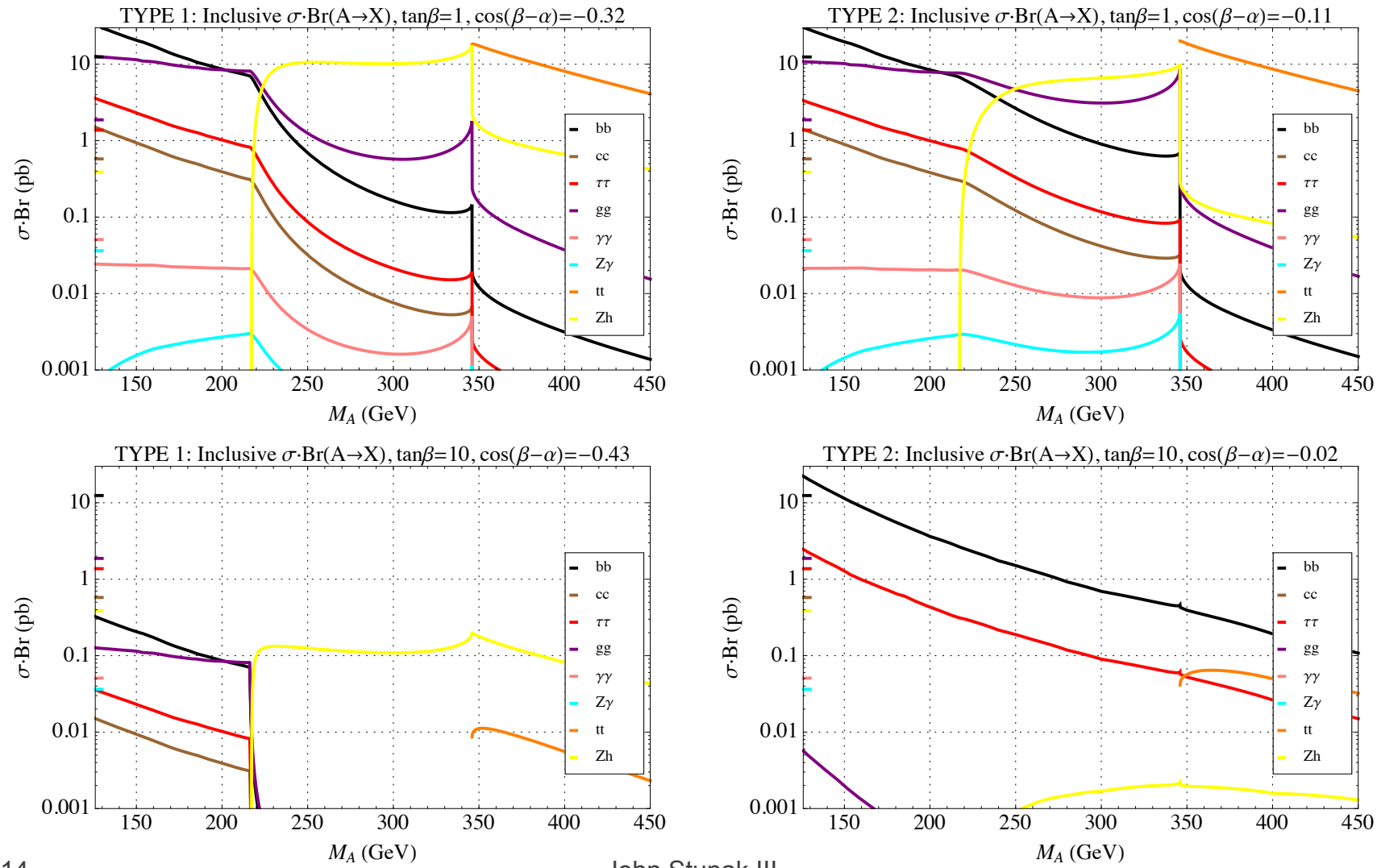
[Craig, Galloway, Thomas]



σ(A) × BR(A → X)

14 TeV

[Craig, Galloway, Thomas]



h(125) Couplings Constraints

- Most well measured:
  - ggF + decay to VV/γγ
  - VBF + decay to VV

$$\mu_{ggF} \propto \frac{y_t^2 \times y_V^2}{y_b^2}$$

$$\mu_{VBF} \propto \frac{y_V^2 \times y_V^2}{y_b^2}$$

$$y_t = y_b$$

$$\mu_{ggF} \propto y_V^2$$

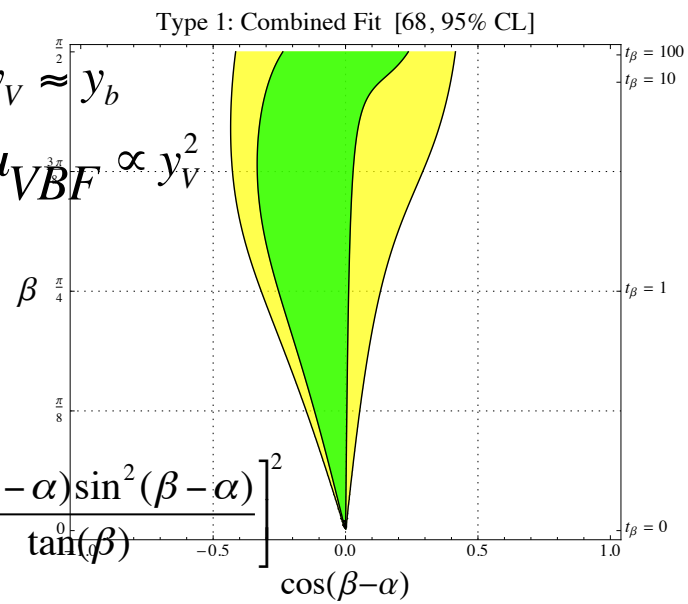
$$y_t \neq y_b$$

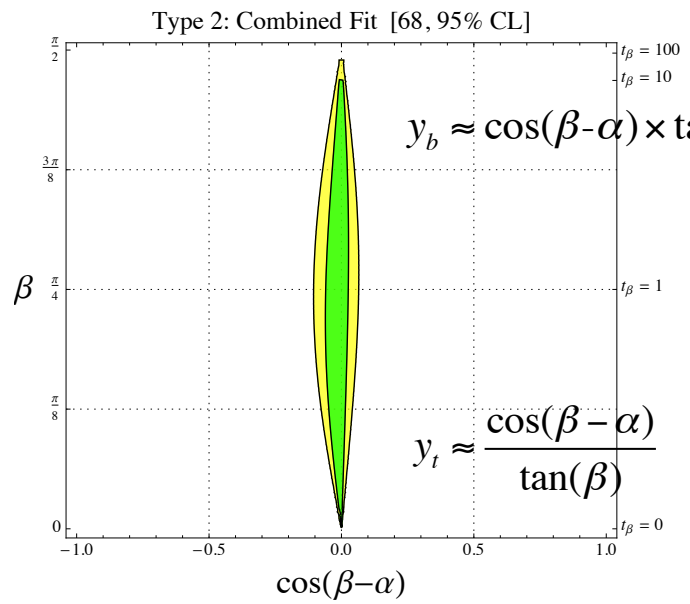
$$y_V \approx y_b$$

$$\mu_{VBF} \propto y_V^2$$

$$y_b \approx \frac{\cos(\beta-\alpha)}{\tan(\beta)}$$

$$\mu_{VBF} \propto \left[\frac{\cos(\beta-\alpha)\sin^2(\beta-\alpha)}{\tan(\beta)}\right]^2$$





$$y_b \approx \cos(\beta\text{-}\alpha) \times \tan(\beta)$$

$$y_t \approx \frac{\cos(\beta-\alpha)}{\tan(\beta)}$$

[Craig, Galloway, Thomas]

h(125) Couplings Constraints

y_{2HDM}/y_{SM}				
Type	hVV	hQu	hQd	hLe
I	sin(β-α)	sin(β-α) + cos(β-α)/tan(β)	sin(β-α) + cos(β-α)/tan(β)	sin(β-α) + cos(β-α)/tan(β)
LS				sin(β-α) – cos(β-α)*tan(β)
2			sin(β-α) – cos(β-α)*tan(β)	
F				sin(β-α) + cos(β-α)/tan(β)

Flavor Constraints

[Mahmoudi, Stal: 0907.1791]

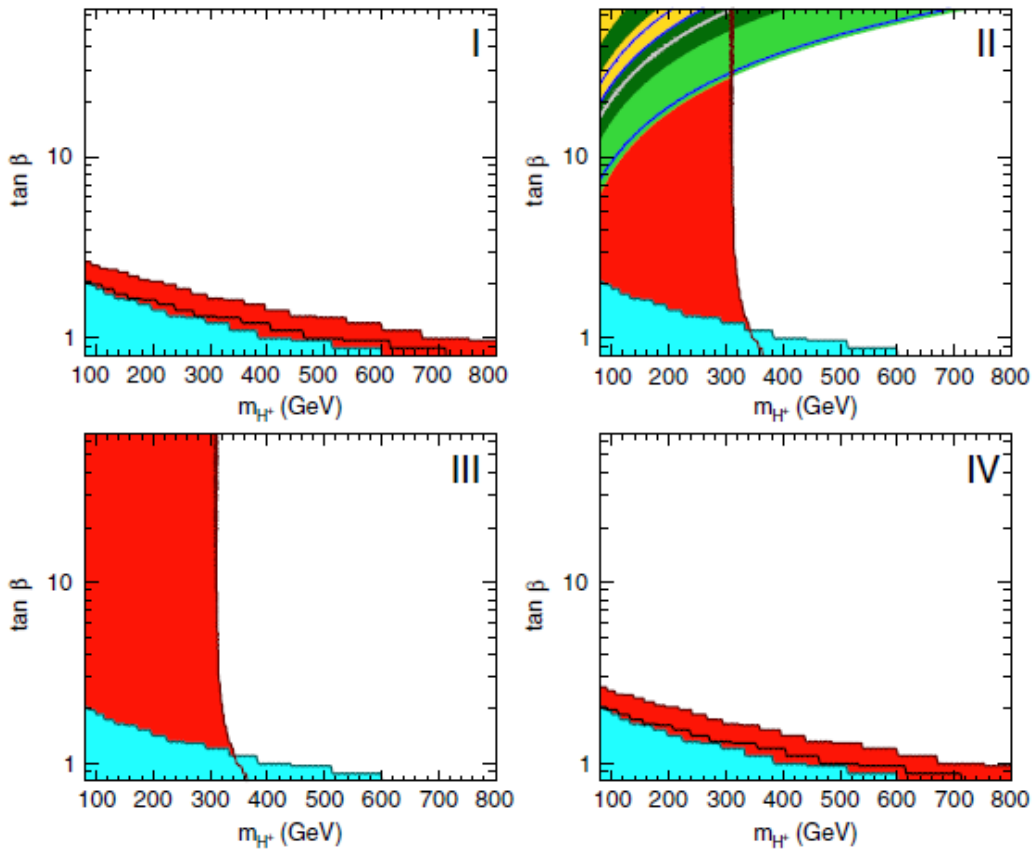


FIG. 10 (color online). Excluded regions of the $(m_{H^+}, \tan\beta)$ parameter space for Z_2-symmetric 2HDM types. The color coding is as follows: $\mathrm{BR}(B \to X_s\gamma)$ (red), Δ_{0-} (black contour), ΔM_{B_d} (cyan), $B_u \to \tau\nu_\tau$ (blue), $B \to D\tau\nu_\tau$ (yellow), $K \to \mu\nu_\mu$ (gray contour), $D_s \to \tau\nu_\tau$ (light green), and $D_s \to \mu\nu_\mu$ (dark green). The white region is not excluded by any of these constraints.