

2HDM Studies

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Looking for extended EWSB

- We've discovered one SM-like Higgs, but there is considerable room for additional degrees of freedom associated with EWSB.
- A strongly motivated scenario! Naturalness often implies extended Higgs sector.
- Two Higgs doublet models provide an effective description for many such EWSB extensions:
 - Higgs sector of MSSM,
 - Various Twin Higgs models,
 - Composite Higgs models (e.g. $SO(6)/SO(4)\times SO(2)$)
 - ...

Looking for extended EWSB

Three (EF) avenues to pursue:

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.

Also have complementarity with intensity frontier!

A simplified parameter space

- Need to develop an efficient search strategy. The 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 h, H, A, H^\pm

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

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

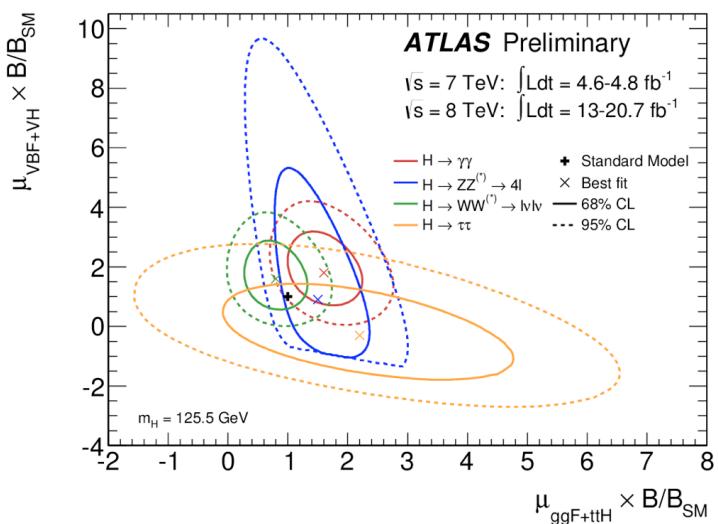
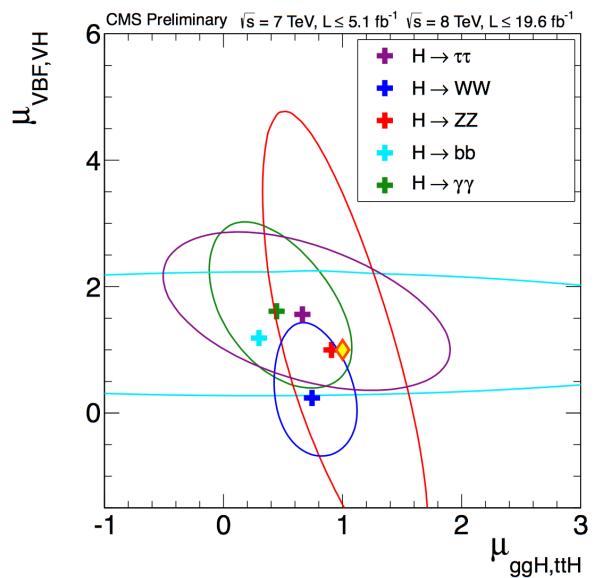
$$m_h, m_H, m_A, m_{H^\pm} \quad \tan \beta \equiv \langle \Phi_2 \rangle / \langle \Phi_1 \rangle$$

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

$$\lambda_5, \lambda_6, \lambda_7 \quad (\text{only appear in trilinear couplings})$$

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 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

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

A simplified parameter space

	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

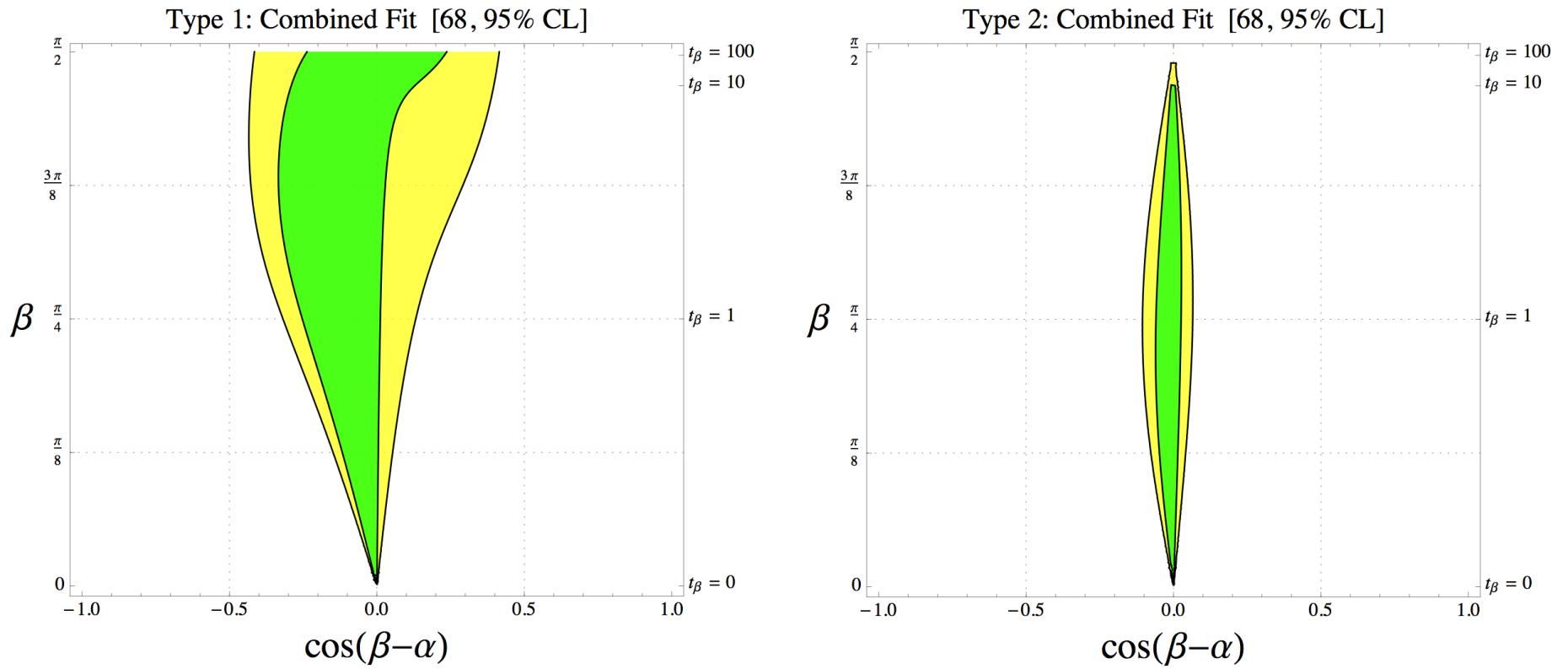
$y_{\text{2HDM}}/y_{\text{SM}}$	2HDM 1	2HDM 2
hVV	$1 - \delta^2/2$	$1 - \delta^2/2$
hQu	$1 - \delta/t_\beta$	$1 - \delta/t_\beta$
hQd	$1 - \delta/t_\beta$	$1 + \delta t_\beta$
hLe	$1 - \delta/t_\beta$	$1 + \delta t_\beta$
HVV	$-\delta$	$-\delta$
HQu	$-\delta - 1/t_\beta$	$-\delta - 1/t_\beta$
HQd	$-\delta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

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

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

- 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



Construct a fit to couplings of SM-like Higgs in terms of tree-level 2HDM parameter space. Provides a useful benchmark for the signal expectations of extra scalars.

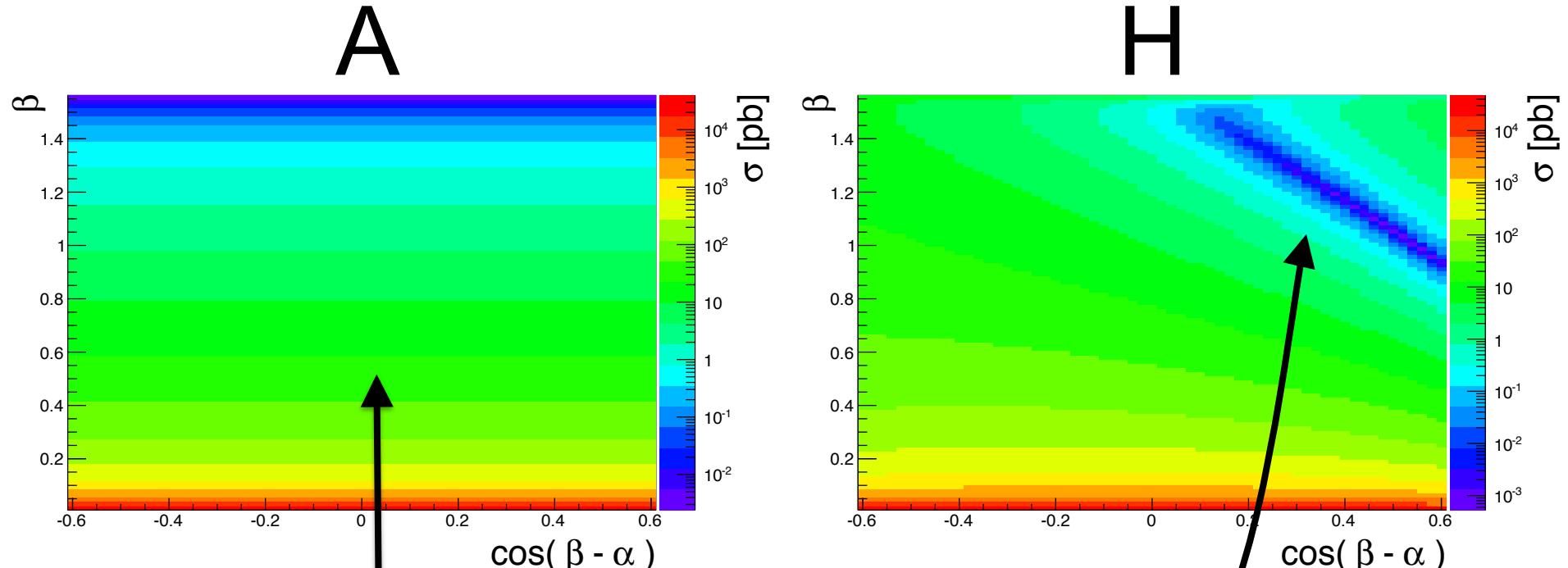
Neutral Bosons of 2HDM

- 2HDM predicts scalar H and pseudo-scalar A
- Our plan
 - Consider these decays:
 - $H \rightarrow ZZ$
 - $A \rightarrow Zh$ (Hopefully more if time permits)
 - Scan parameter space (α, β)
 - Determine expected limits and significance for:
 - $s^{1/2} = 14$
 - $Ldt = 300 \text{ fb}^{-1}, \langle N_{PU} \rangle = 50$
 - $Ldt = 3000 \text{ fb}^{-1}, \langle N_{PU} \rangle = 140$
 - $s^{1/2} = 33 \text{ TeV}$

Cross Sections *BR

- Two Higgs Doublet models are a complicated model-space
 - 3 important parameters: α , β , g_{Hhh}
 - Choose MSSM-like g_{Hhh} to simplify parameter space
 - Cross section and branching ratios still complicated functions of α , β
- Choose ~ 2 benchmark points which demonstrate the range of potential Physics in 2HDM parameter-space and which make strong case for future hadron collider

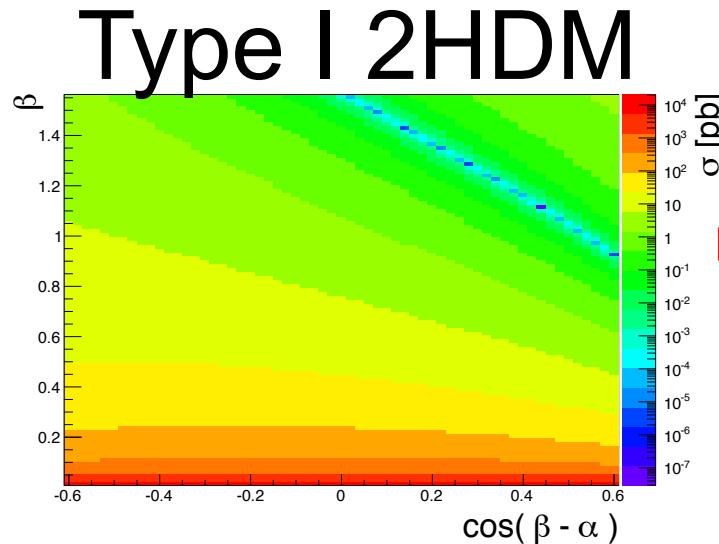
14 TeV Cross Section



- A cross section flat in $\cos(\beta-\alpha)$
- H cross section has a “trough”

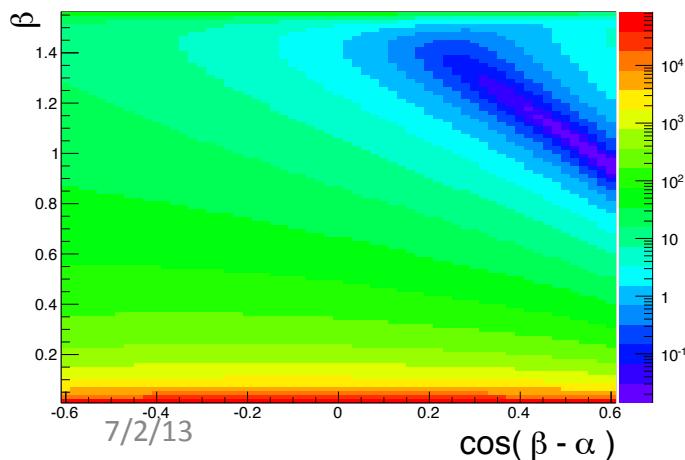
H Cross Section “Trough”

Trough size
insensitive to $m(H)$
for type I 2HDM



$m(H) = 500$ GeV

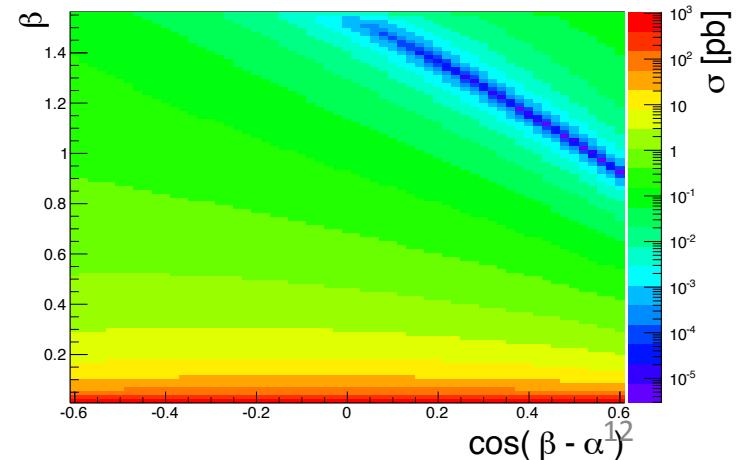
$m(H) = 200$ GeV



Type II 2HDM

Trough shrinks
with increasing
 $m(H)$ for type II
2HDM

$m(H) = 900$ GeV

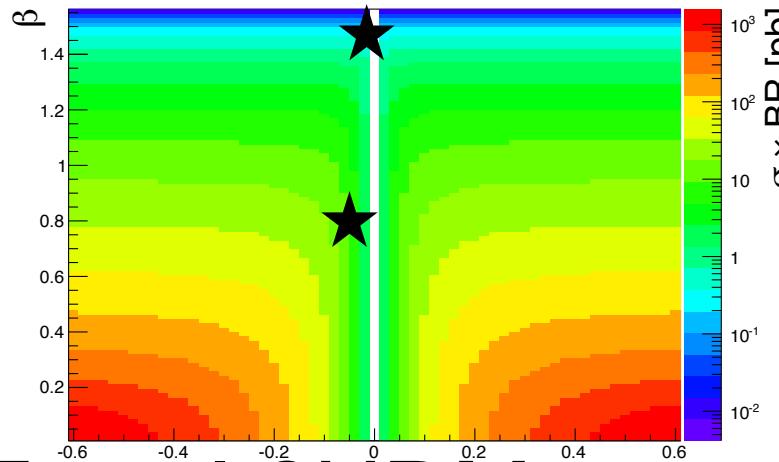


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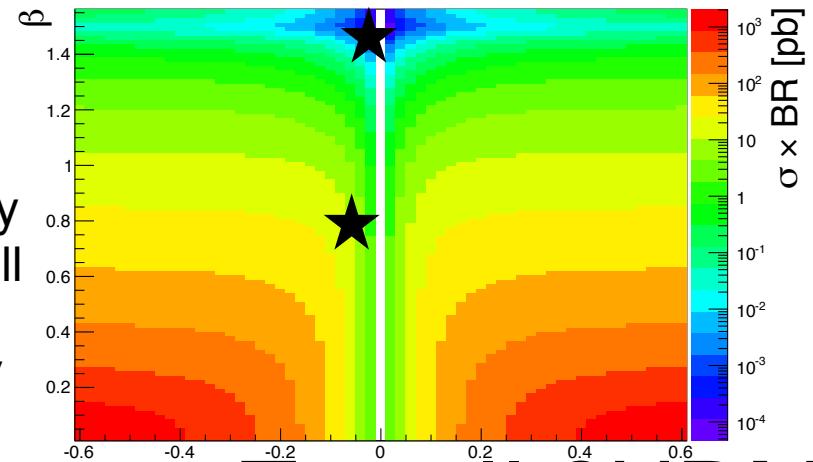
$$\sigma(A) * \text{BR}(A \rightarrow Z\gamma)$$

$$m(A) = 300 \text{ GeV}$$

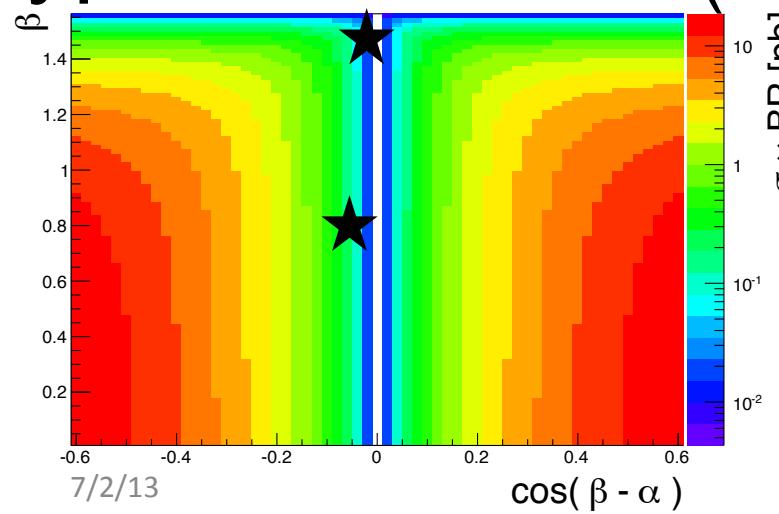


Type I 2HDM

Qualitatively
similar for all
masses
 $\leq 300 \text{ GeV}$

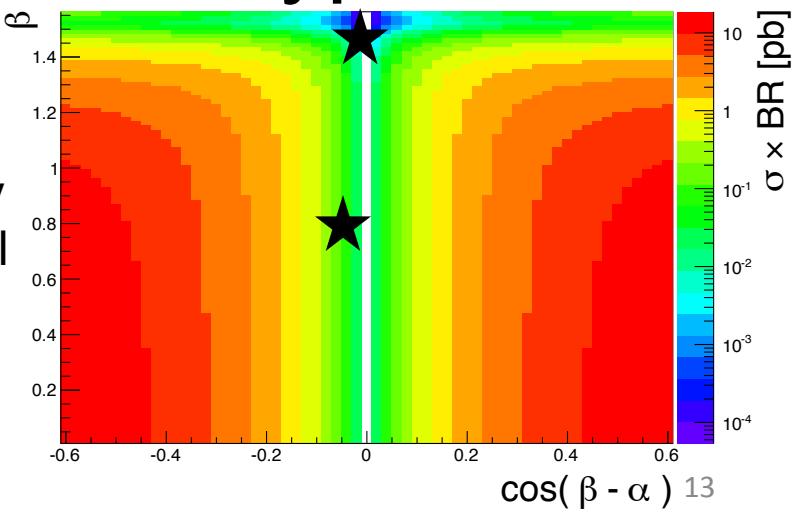


Type II 2HDM



$m(A) = 350 \text{ GeV}$

Qualitatively
similar for all
masses
 $\geq 350 \text{ GeV}$

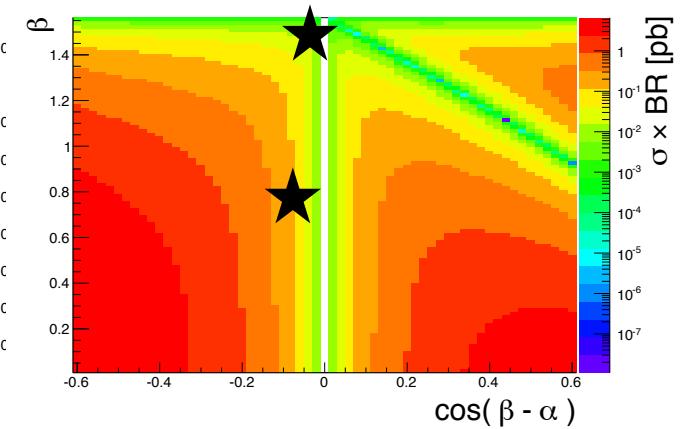
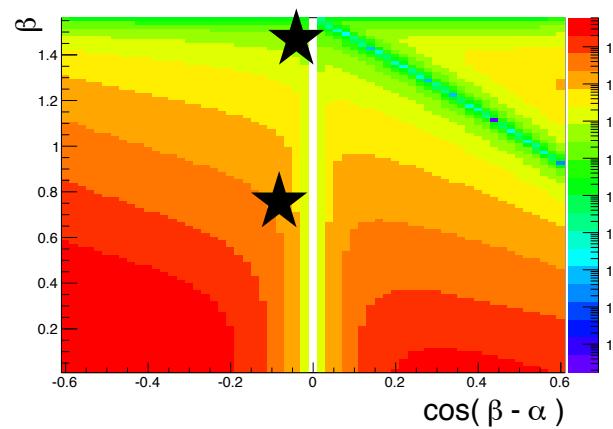
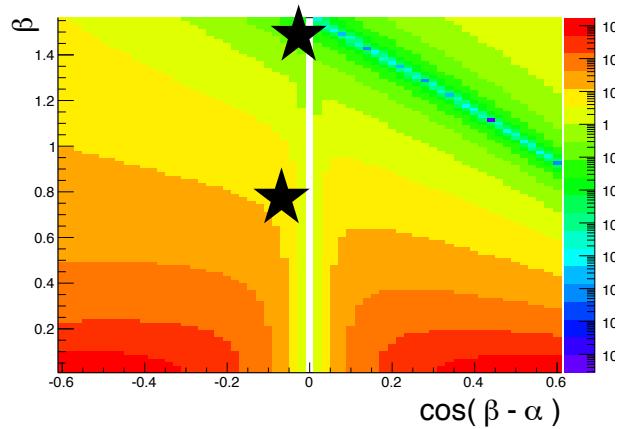


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$$\sigma(H) * BR(H \rightarrow WW)$$

Type I 2HDM

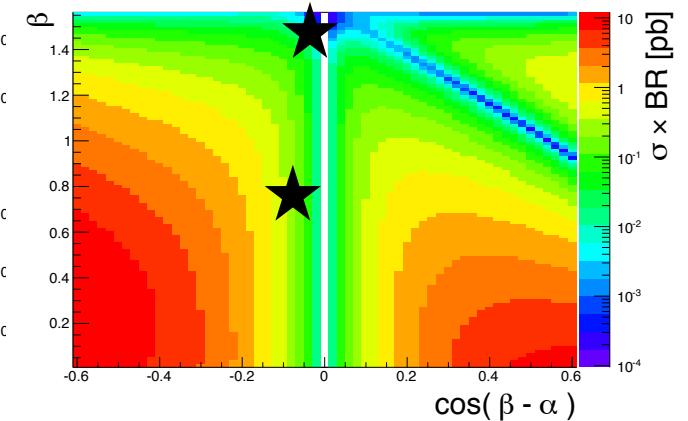
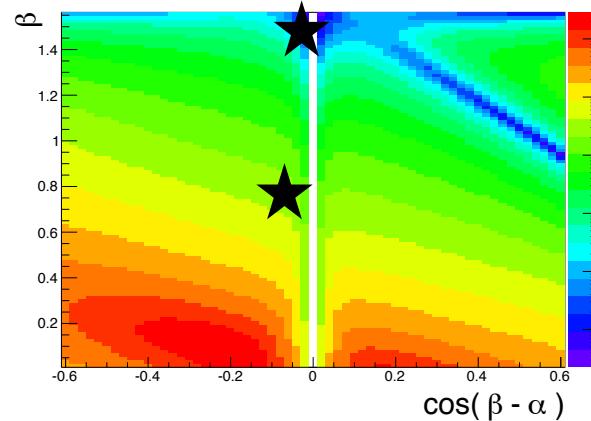
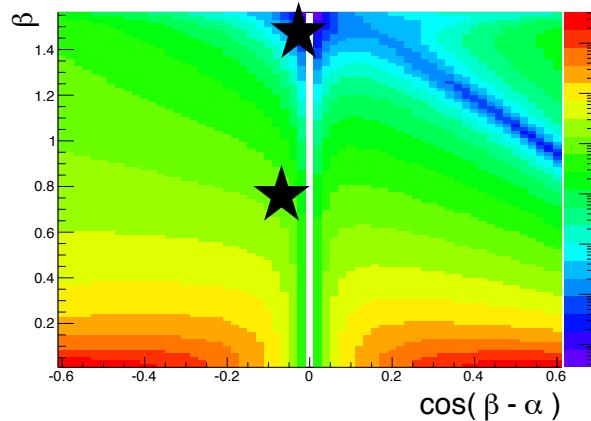


$m(H) = 250$ GeV

$m(H) = 350$ GeV

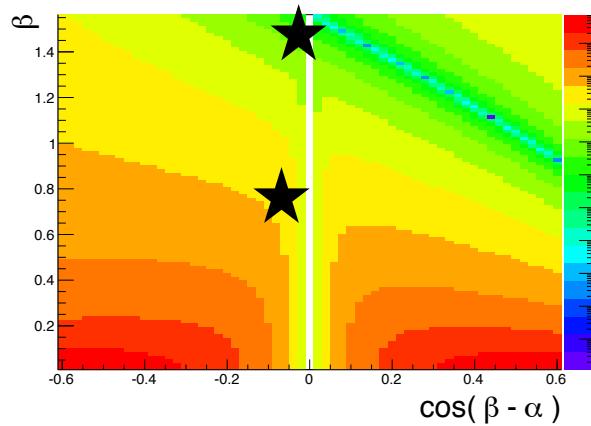
$m(H) = 450$ GeV

Type II 2HDM

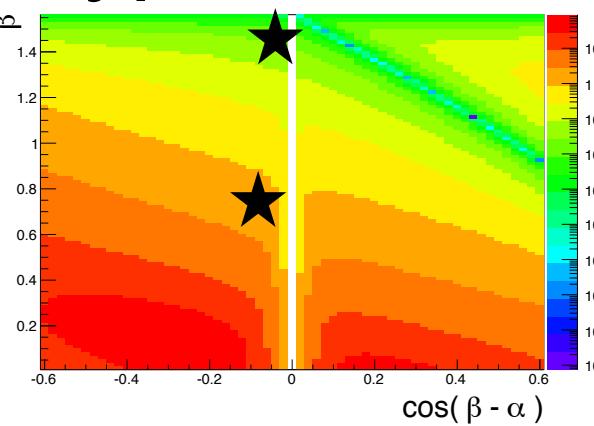


$$\sigma(H) * BR(H \rightarrow ZZ)$$

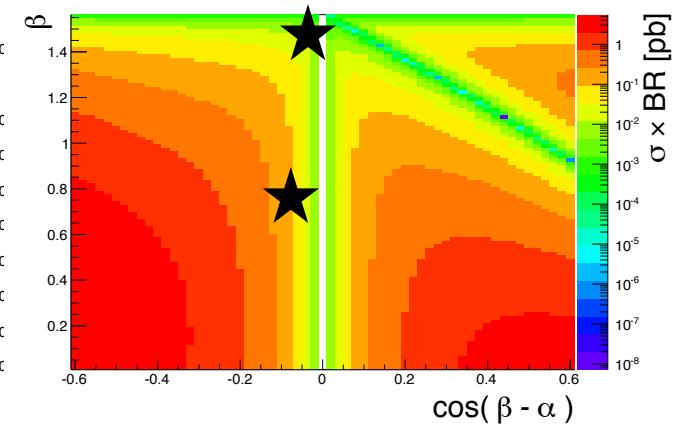
Type I 2HDM



$m(H) = 250$ GeV

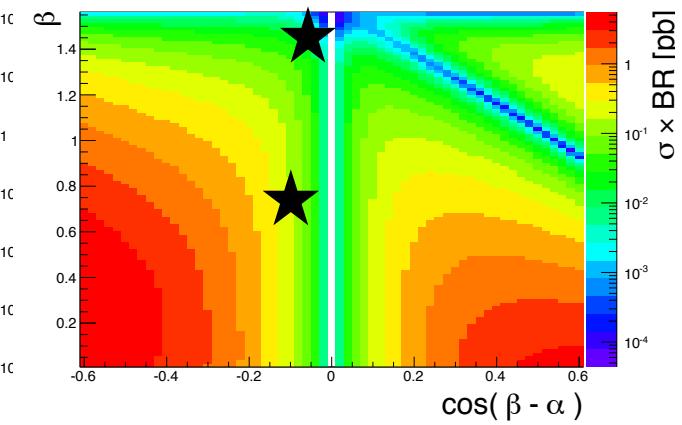
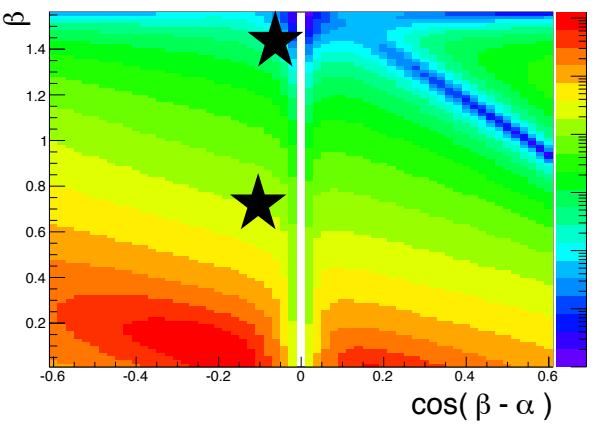
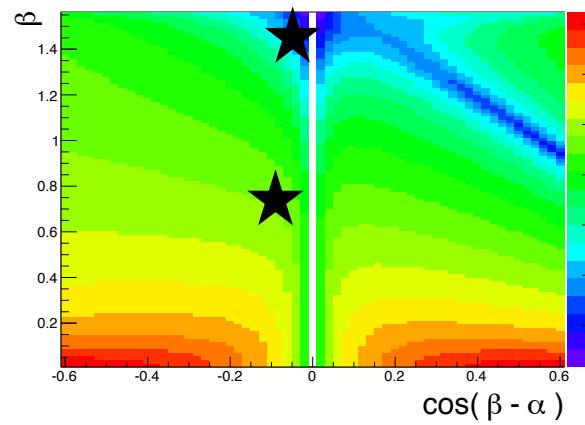


$m(H) = 300$ GeV



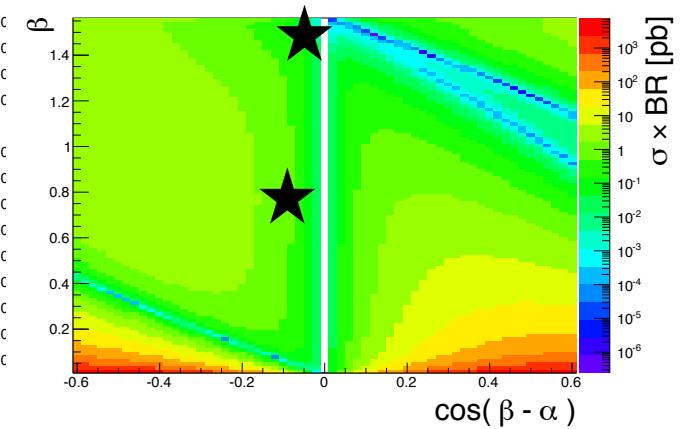
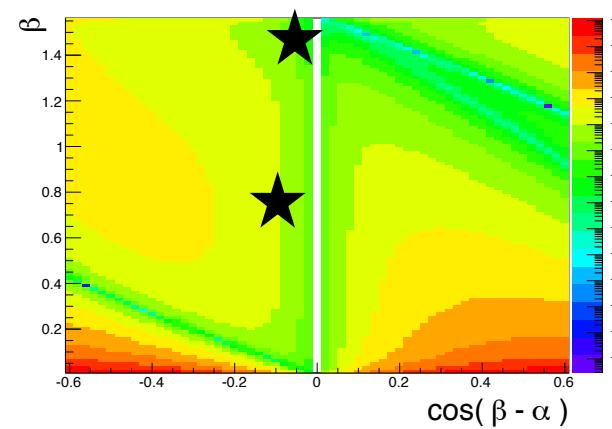
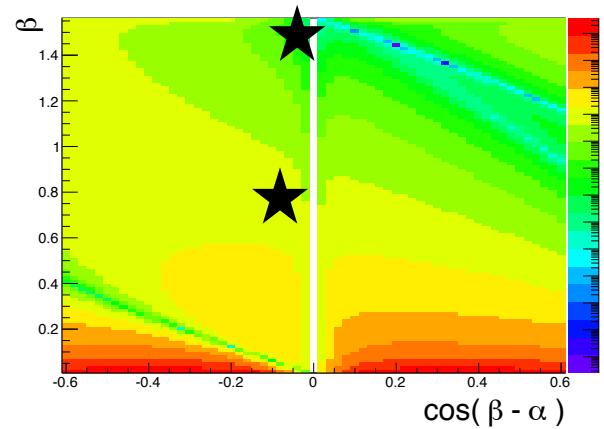
$m(H) = 400$ GeV

Type II 2HDM



$$\sigma(H) * \text{BR}(H \rightarrow hh)$$

Type II 2HDM



$m(H) = 300 \text{ GeV}$

$m(H) = 400 \text{ GeV}$

$m(H) = 450 \text{ GeV}$

Choosing benchmark points

- Choose ~2 benchmark points which show off potential of future hadron colliders
 - Also which demonstrate range of potential Physics scenarios
 - Cross section falls with increasing β
 - Nathaniel proposed:
 - Benchmark point 1: $\cos(\beta-\alpha), \beta = -0.01, 1.471$
 - Benchmark point 2: $\cos(\beta-\alpha), \beta = -0.05, 0.7854$
- Larger $|\cos(\beta-\alpha)| \rightarrow$ Larger BR($A \rightarrow Z\gamma$)
Larger $|\cos(\beta-\alpha)| \rightarrow$ Larger BR($H \rightarrow VV$)
Smaller $\beta \rightarrow$ Larger σ

$H \rightarrow ZZ \rightarrow 4\ell$

- Consider
 - $E = 14 \text{ TeV}$
 - No Pile Up
 - 300 fb^{-1}
- Object Selection
 - Lepton
 - $p_T > 5 \text{ GeV}$
 - $\eta < 2.5$
 - Z
 - OSSF lepton pair
 - $60 < m_{\ell\ell} < 120$

modeled loosely after CMS $H \rightarrow ZZ \rightarrow 4\ell$ search:

<https://twiki.cern.ch/twiki/bin/viewauth/CMS/HiggsZZ4l2012HGP>

Cutflow (13 TeV Inclusive nTuples)

Lepton Trigger:
 $p_T(\text{lepton}_1) > 30 \text{ GeV}$
 or

$p_T(\text{lepton}_1) > 20 \text{ GeV}$ and $p_T(\text{lepton}_2) > 10 \text{ GeV}$

	Presel	Lepton Trigger	$n(\text{lepton}) = 4$	$n(Z) \geq 1$	$n(Z) = 2$
B	1.15E+10	3.80E+09	0.00E+00	0.00E+00	0.00E+00
BB	1.87E+07	6.63E+06	5.95E+03	5.93E+03	4.34E+03
BBB	8.57E+04	2.42E+04	2.39E+01	2.38E+01	2.78E+01
H					
t					
tt	1.55E+08	3.44E+07	0.00E+00	0.00E+00	0.00E+00
tB	3.66E+05	1.05E+05	1.74E+02	1.64E+02	
ttB	3.66E+05	1.05E+05	1.74E+02	1.64E+02	7.12E+01
ttBB	3.48E+03	1.37E+03	2.14E+00	1.48E+00	2.04E-01
Total					
Background	1.17E+10	3.84E+09	6.32E+03	6.28E+03	4.44E+03

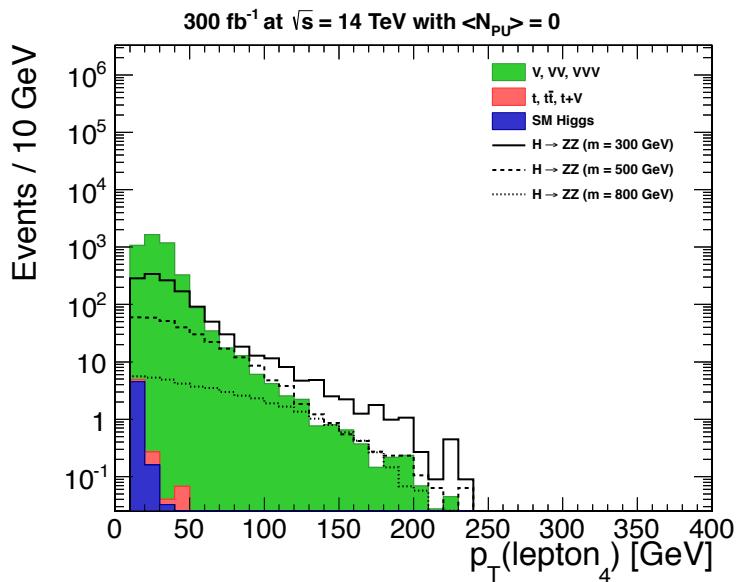
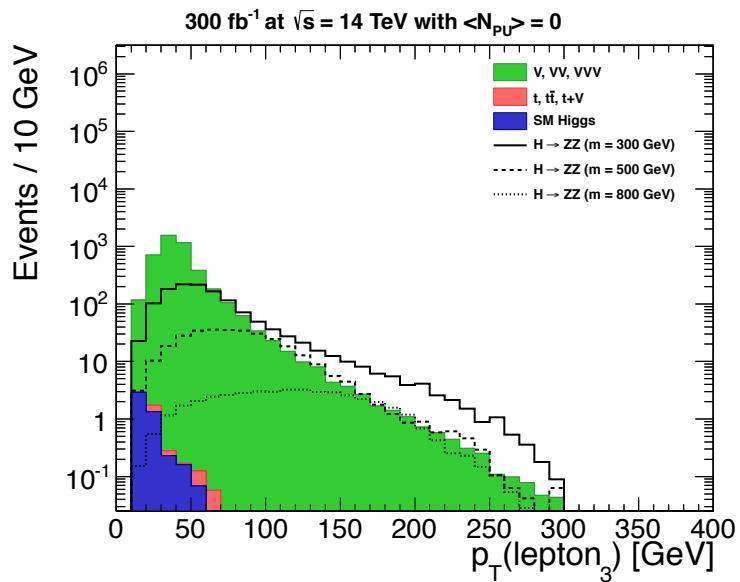
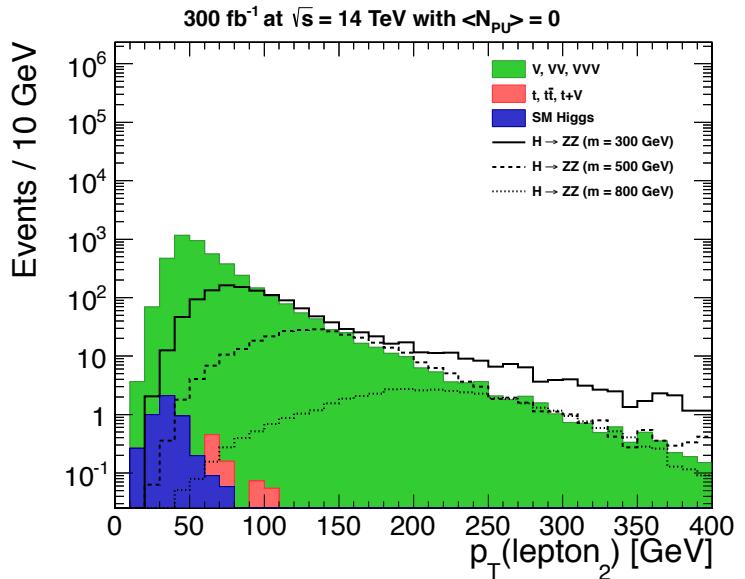
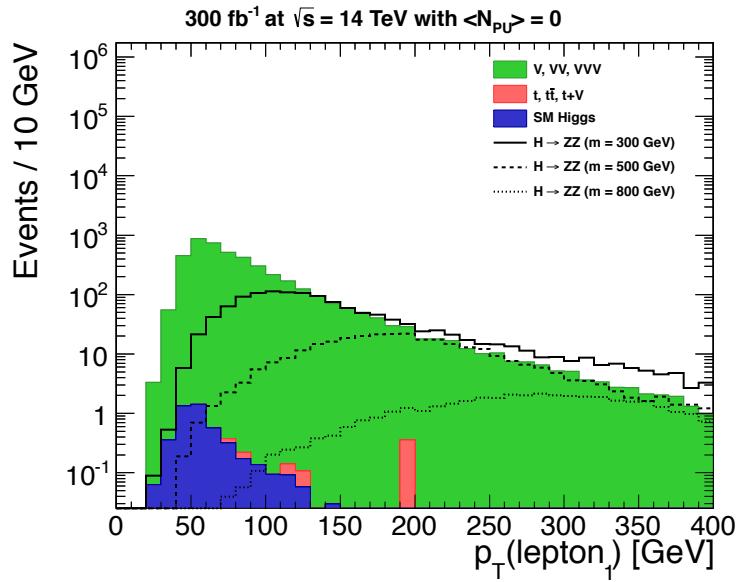
Cutflow (14 TeV H_T Binned nTuples)

Lepton Trigger:
 $p_T(\text{lepton}_1) > 30 \text{ GeV}$
 or

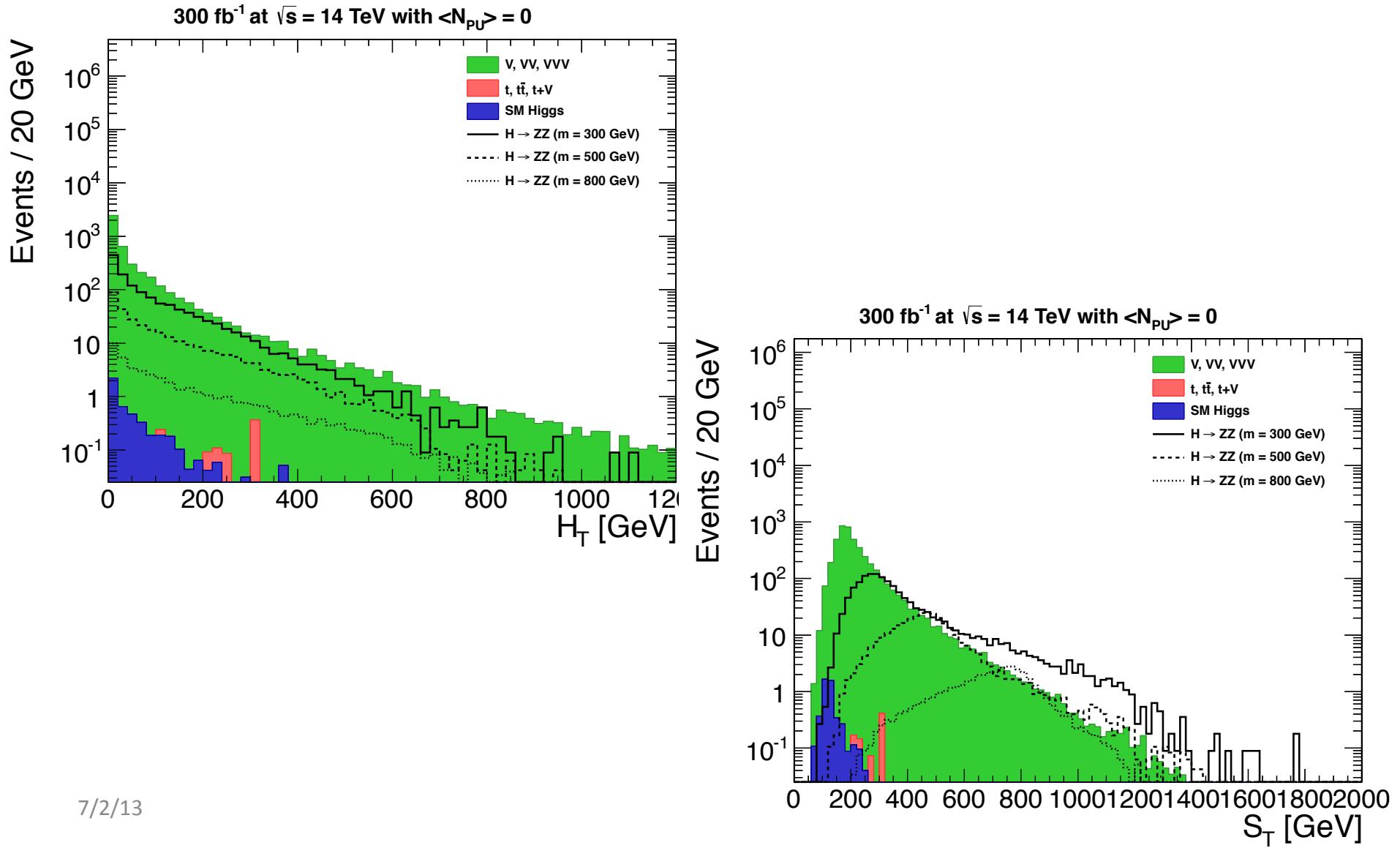
$p_T(\text{lepton}_1) > 20 \text{ GeV}$ and $p_T(\text{lepton}_2) > 10 \text{ GeV}$

	Presel	Lepton Trigger	$n(\text{lepton}) = 4$	$n(Z) \geq 1$	$n(Z) = 2$
B	8.86E+10	4.83E+09	1.34E+00	3.59E-02	0.00E+00
BB	1.12E+08	1.27E+07	6.02E+03	5.99E+03	4.49E+03
BBB	8.19E+05	1.30E+05	1.57E+02	1.52E+02	7.08E+01
H	4.47E+07	2.78E+06	8.35E+01	8.07E+01	5.43E+00
t	2.14E+07	5.32E+06	1.12E+00	9.62E-03	7.44E-04
tt	2.15E+08	4.98E+07	5.52E+00	0.00E+00	0.00E+00
tB	2.14E+07	5.32E+06	1.12E+00	9.62E-03	7.44E-04
ttB					
ttBB					
Total Background	8.90E+10	4.91E+09	6.27E+03	6.23E+03	4.56E+03
HT Binned / Inclusive	7.62 ?	1.28 ?	0.99	0.99	1.03 ²⁰

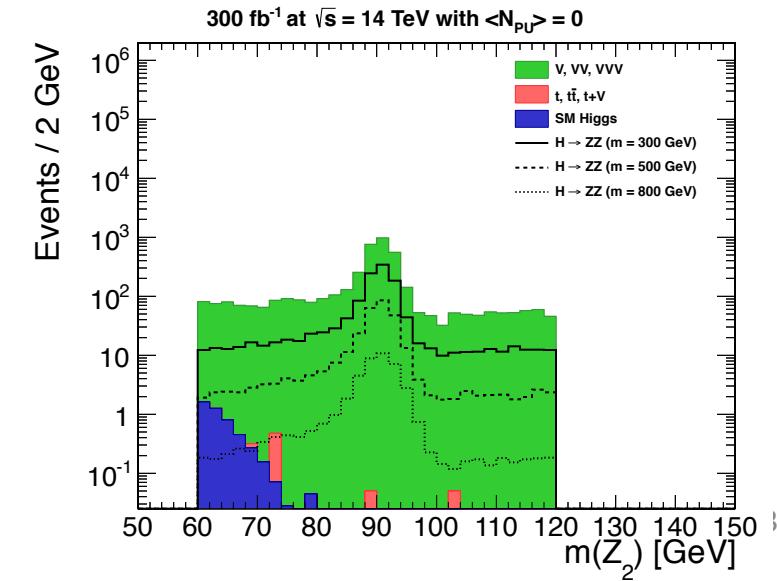
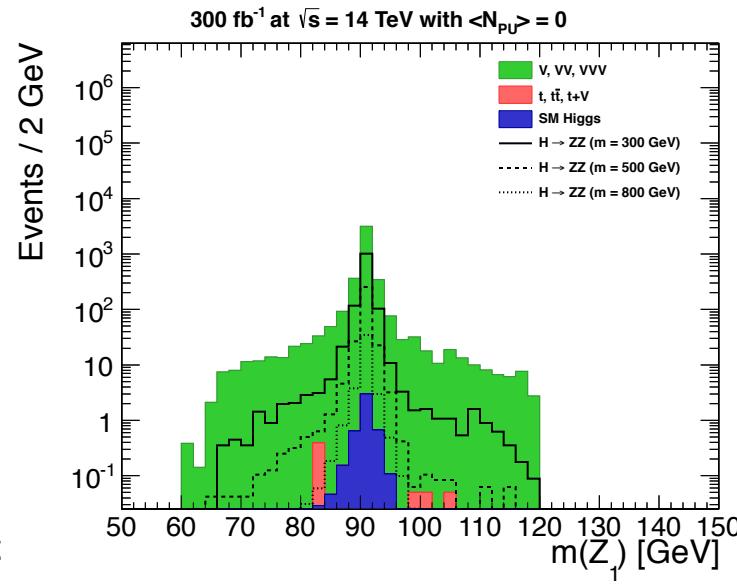
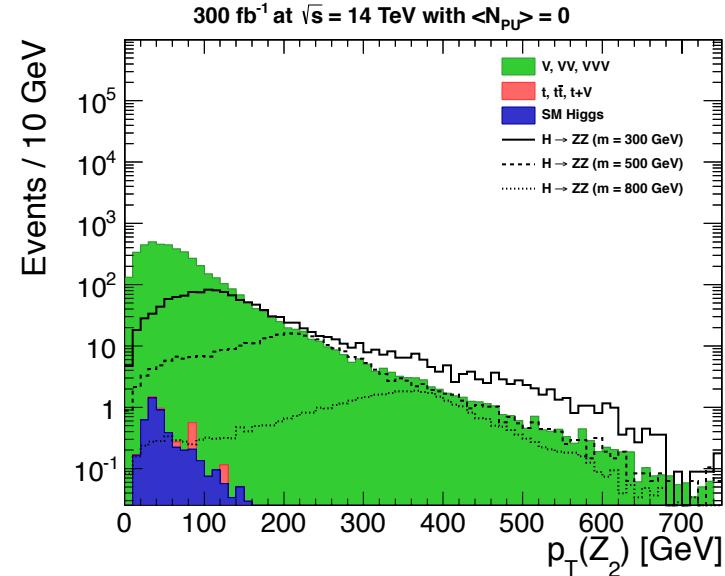
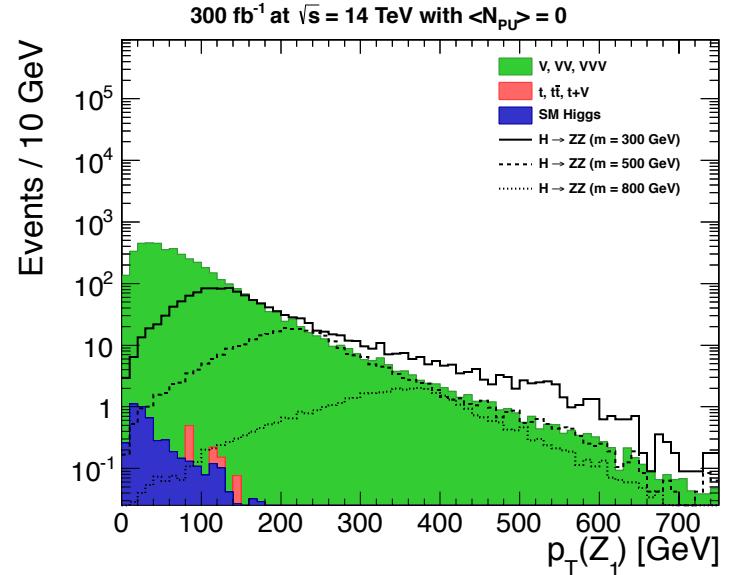
Lepton p_T



S_T, H_T Distributions

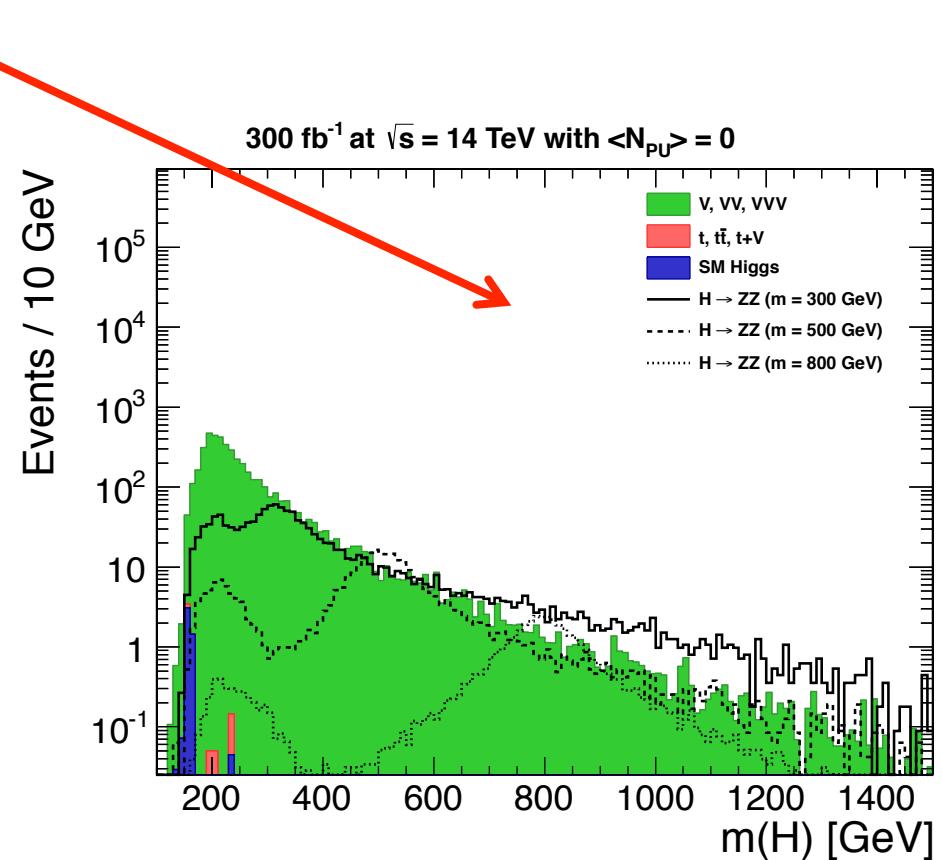


Z p_T & Mass



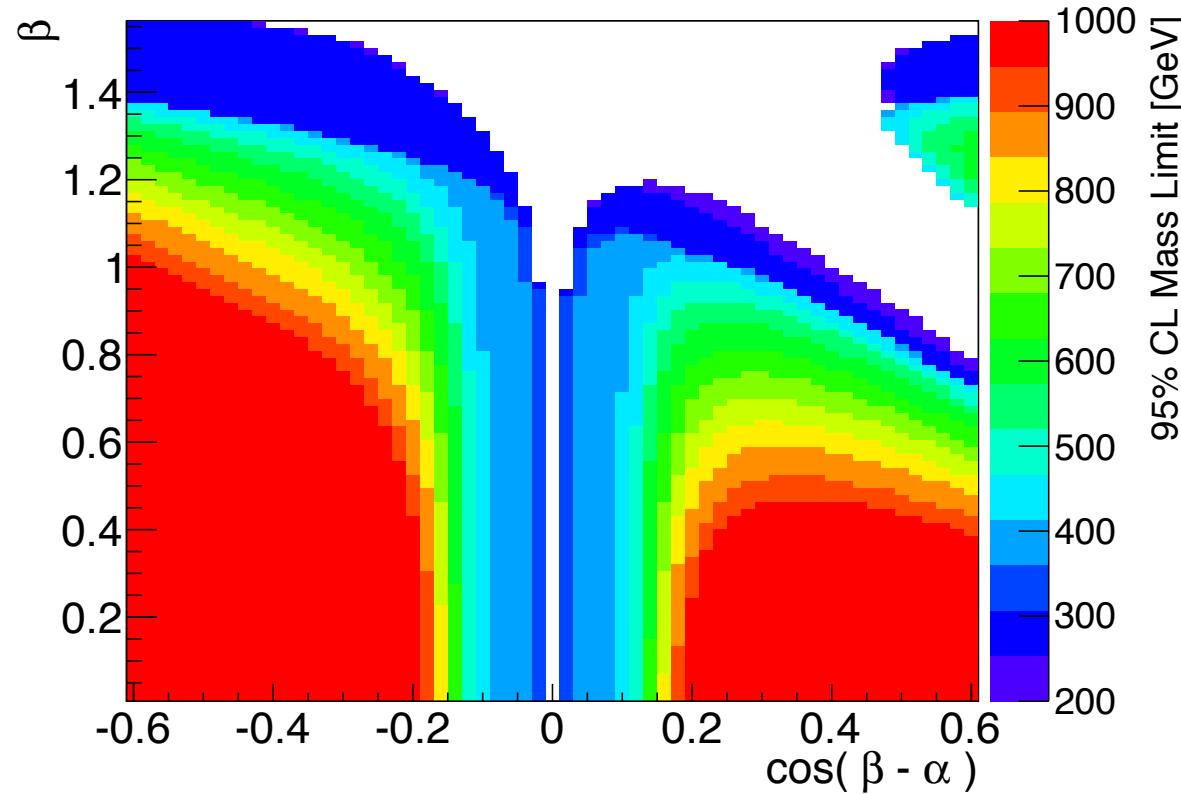
Preliminary $H \rightarrow ZZ \rightarrow 4\ell$ Results

- Baseline event selection
 - Require 2 OS-SF lepton pairs in Z mass window
- Currently optimizing cut thresholds to enhance sensitivity
 - S_T , $p_T(\ell_1)$, $p_T(Z_1)$, $p_T(Z_2)$



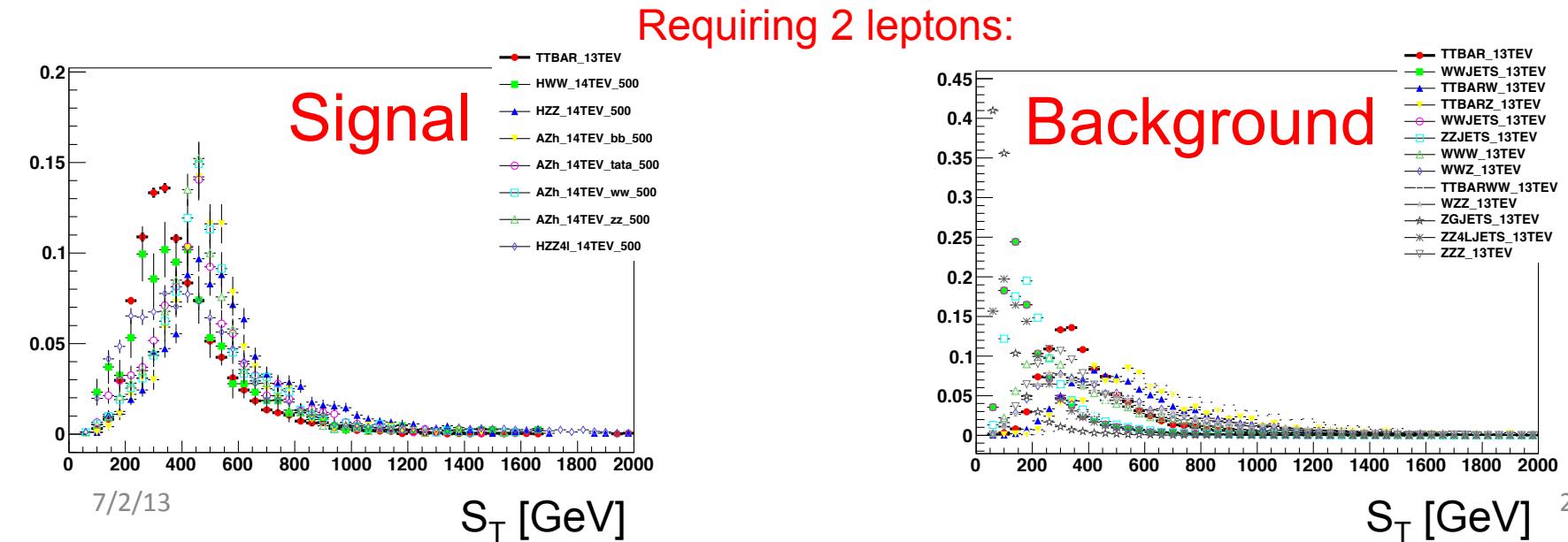
Preliminary $H \rightarrow ZZ \rightarrow 4\ell$ Results

Expected Limits: 300 fb^{-1} 14 TeV 0 PU



Preliminary A \rightarrow Zh Results

- Complicated matrix of final states
 - $Z \rightarrow \ell\ell, Z \rightarrow nn, Z \rightarrow jj$
 - $h \rightarrow ZZ, h \rightarrow WW, h \rightarrow bb, h \rightarrow tt$
- Considering multi-lepton final states
 - Work ongoing to characterize events based on N_ℓ, N_b, N_t and determine most sensitive final states → Then optimize cuts



A → Zh

- Understand the sensitivities
- All tables sorted in order of decreasing:

$$\frac{S}{\sqrt{S + B + (0.2B)^2}}$$

- highlight in red: reason to disqualify a final state from consideration
- Final states with low sensitivity are excluded
- Convention: nXY_nAB = event contains exactly Y particles of type X and B of type A
 - L = lepton
 - B = b-jet
 - T = τ

$A \rightarrow Zh$ ($h \rightarrow ZZ$)

Too few expected signal events

	nL2 nT3	nL4 nT2	nL5	nL4 nB1	nL4 nB2	nL3 nB2	nL3 nB1 nT1	nL4
AZh_14TEV_zz_500_NoPileUp	7.46E-01	3.73E-01	1.49E+00	4.85E+00	3.73E-01	1.49E+00	3.73E-01	4.22E+01
S/sqrt(S+B+(B*20%)^2)	7.51E-01	5.98E-01	5.34E-01	2.10E-01	1.23E-01	5.61E-02	4.30E-02	3.35E-02

4 lepton final state gives the best sensitivity

$A \rightarrow Zh$ ($h \rightarrow WW$)

Fake τ/b

	nL4_nT1	nL3_nT1	nL3_nB1	nL4
AZh_14TEV_ww_500_NoPileUp	3.04E+00	5.16E+01	9.42E+01	1.88E+02
S/sqrt(S+B+(B*20%)^2)	2.69E-01	2.20E-01	1.56E-01	1.50E-01

3 lepton + τ/b and 4 lepton final states gives the best sensitivity

$A \rightarrow Z h$ ($h \rightarrow \tau\tau$)

Fake τ/b

	nL3_nT2	nL3_nT1	nL2_nT3	nL3_nB1_nT1	nT4	nL2_nT2
AZh_14TEV_tata_500_NoPileUp	2.68E+00	2.51E+02	8.93E-01	5.36E+00	1.96E+01	2.19E+02
S/sqrt(S+B+(B*20%)^2)	1.11E+00	1.07E+00	8.38E-01	5.98E-01	5.26E-01	4.00E-01

3 lepton + τ lepton final state gives the best sensitivity

$A \rightarrow Z h$ ($h \rightarrow bb$)

Fake τ/b

	nT1_nB5	nL2_nB4	nB4	nB5	nT3_nB1	nL2_nB2_nT1	nT2_nB2	nT2_nB3	nL2_nB2
AZh_14TEV_bb_500_NoPileUp	8.15E+00	1.63E+01	2.41E+03	8.15E+01	2.45E+01	2.45E+01	2.12E+02	8.15E+00	3.15E+03
S/sqrt(S+B+(B*20%)^2)	3.77E-01	1.43E-01	6.03E-02	6.00E-02	4.66E-02	2.09E-02	1.97E-02	1.88E-02	1.56E-02

4 b-jet final state gives the best sensitivity

Classification of Modes

- Single-most sensitive final state for each mode:

Higgs decay	Final State	$S/\sqrt{S+B+(B*20\%)^2}$
$h \rightarrow ZZ$	4 lepton	0.03
$h \rightarrow WW$	3 lepton + τ	0.2
$h \rightarrow \tau\tau$	3 lepton + τ	1.1
$h \rightarrow bb$	4 b-jet	0.06

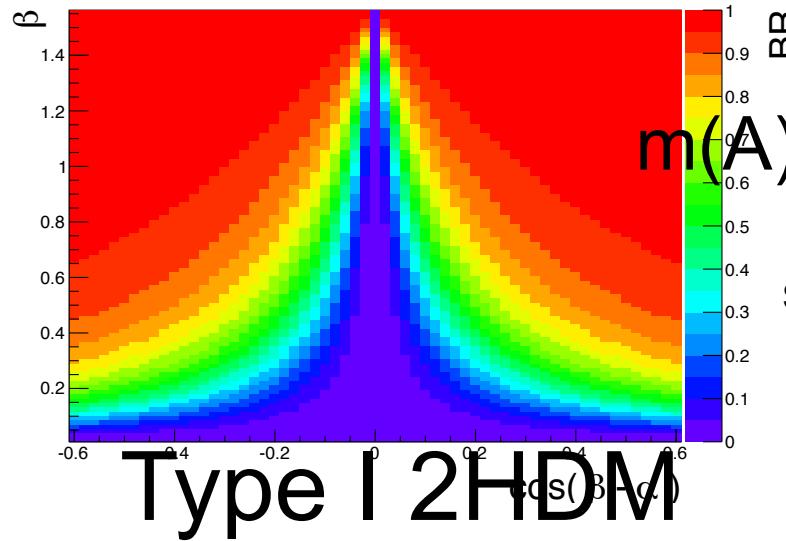
- $h \rightarrow \tau\tau$ mode has the most sensitivity
 - focus on $h \rightarrow \tau_h \tau_h$ with $Z \rightarrow \ell\ell/\tau_h \tau_h$ (invariant mass analysis)
 - Also include $h \rightarrow \tau\tau$ with $Z \rightarrow \tau\tau$, where one τ decays leptonically (cut-and-count analysis)

Conclusions

- Still lot to do:
 - extend to PU 50 and 140
 - 33 TeV
- Cannot really cover all the channels. Put effort in selecting the high impact channels to study
- $H \rightarrow ZZ \rightarrow 4l$;
- $A \rightarrow Zh$, $h \rightarrow \tau_h \tau_h$ with $Z \rightarrow \ell\ell/\tau_h \tau_h; \tau_h \tau_h bb$
- generic multilepton analysis for $A \rightarrow Zh$

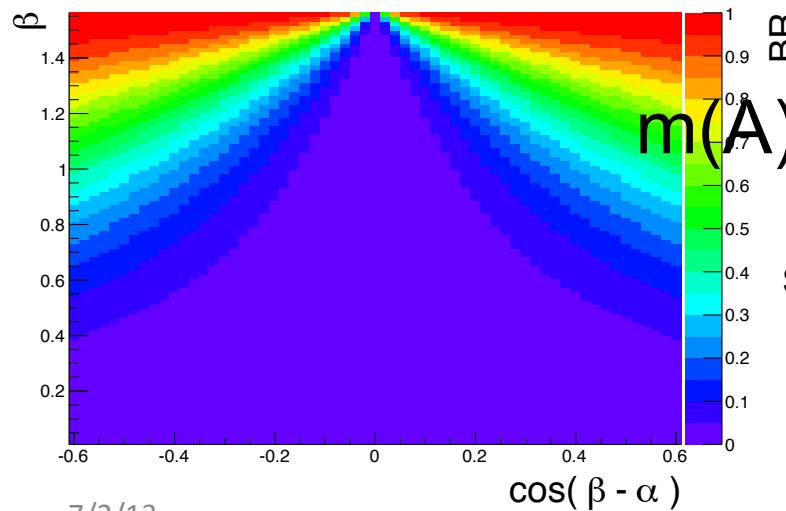
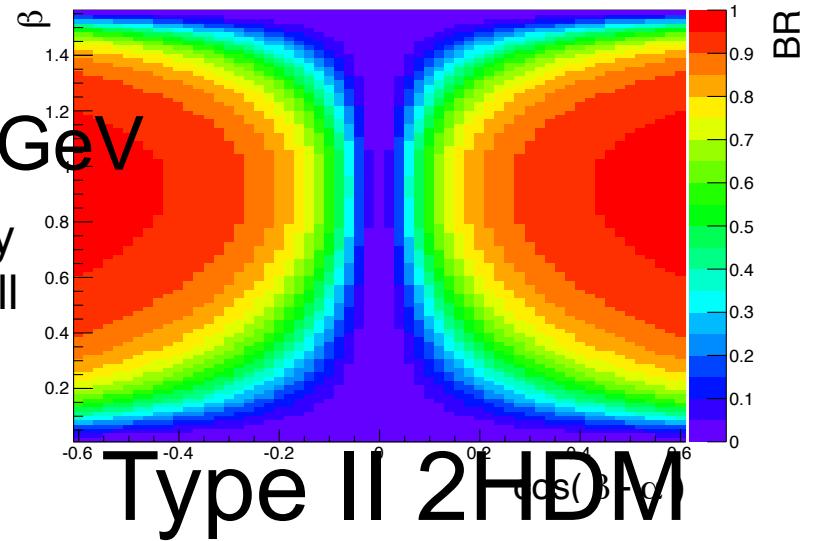
Backup

$\text{BR}(A \rightarrow Z h)$

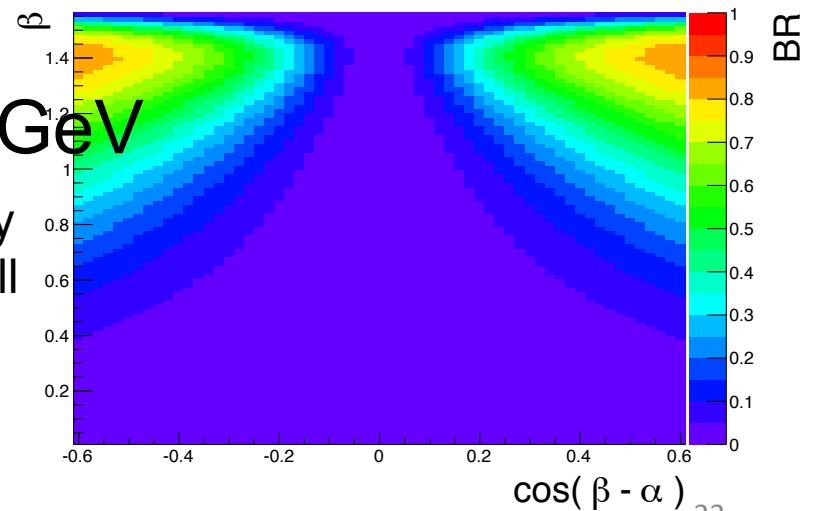


$m(A) = 300 \text{ GeV}$

Qualitatively
similar for all
masses
 $\leq 300 \text{ GeV}$

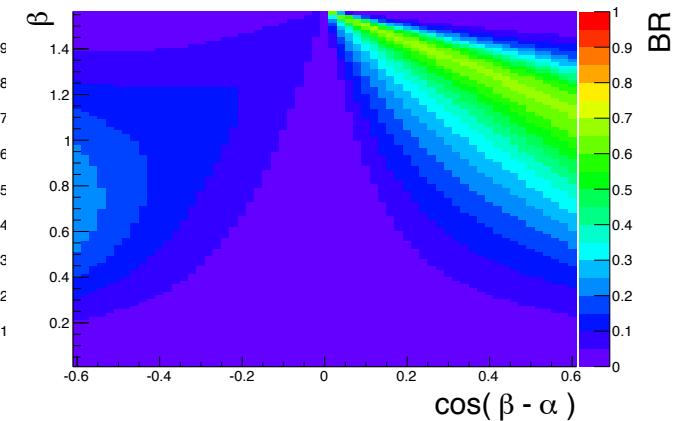
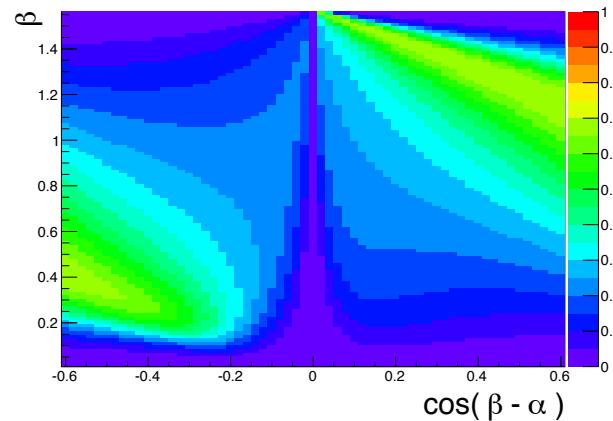
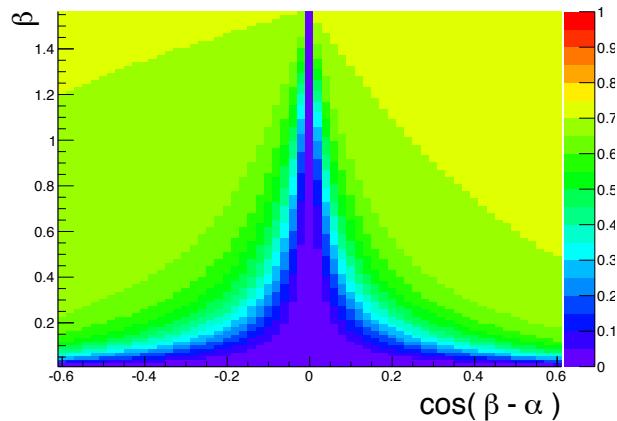


Qualitatively
similar for all
masses
 $\geq 350 \text{ GeV}$



$\text{BR}(\text{H} \rightarrow \text{WW})$

Type I 2HDM

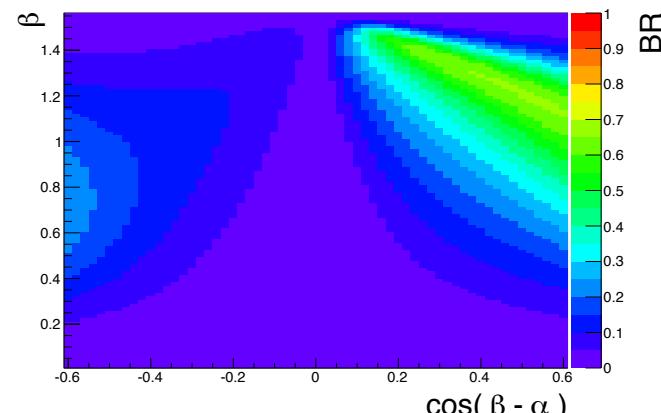
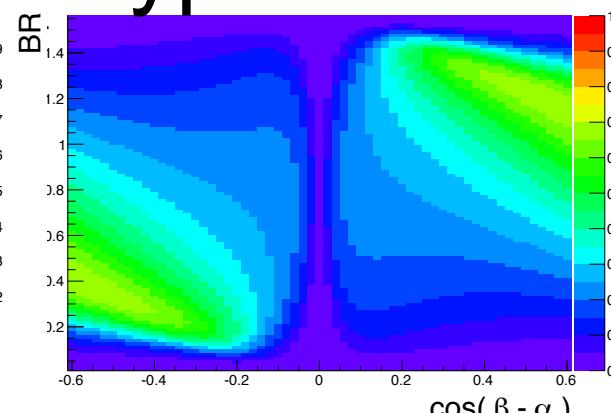
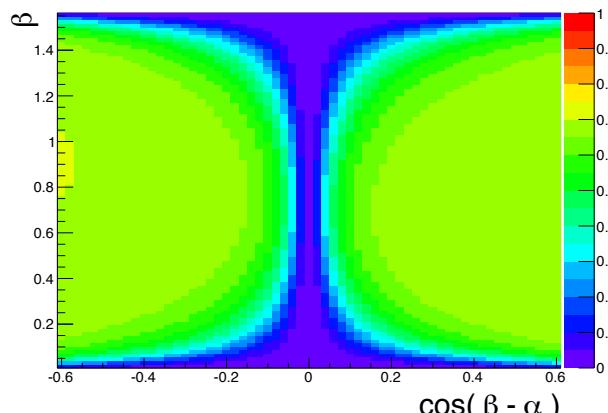


$m(\text{H}) = 250 \text{ GeV}$

$m(\text{H}) = 300 \text{ GeV}$

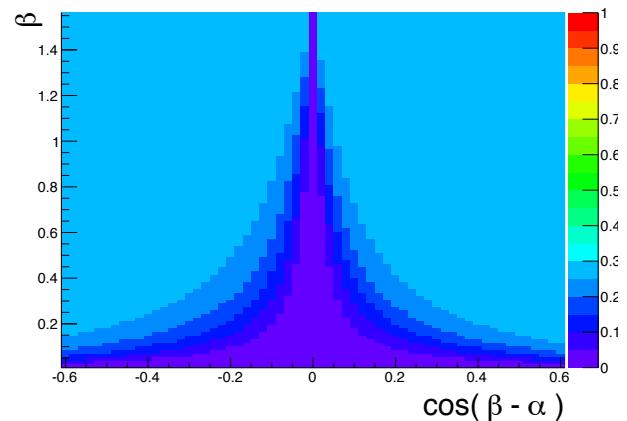
$m(\text{H}) = 600 \text{ GeV}$

Type II 2HDM

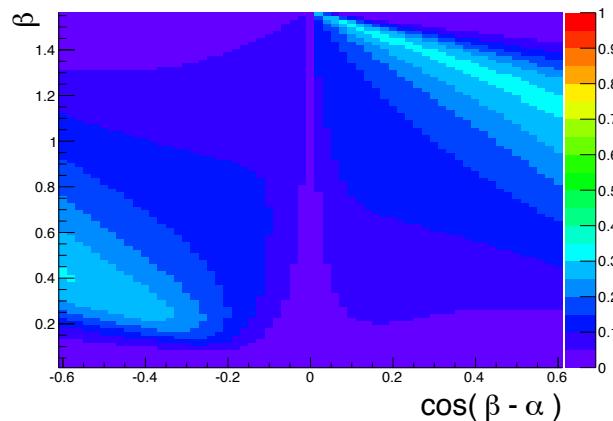


$\text{BR}(\text{H} \rightarrow \text{ZZ})$

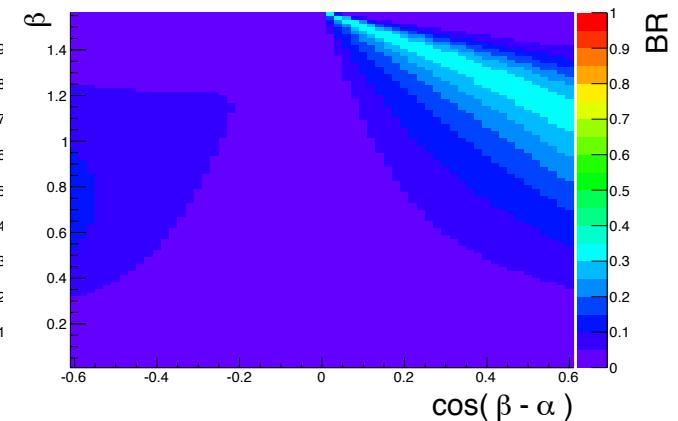
Type I 2HDM



$m(\text{H}) = 250 \text{ GeV}$

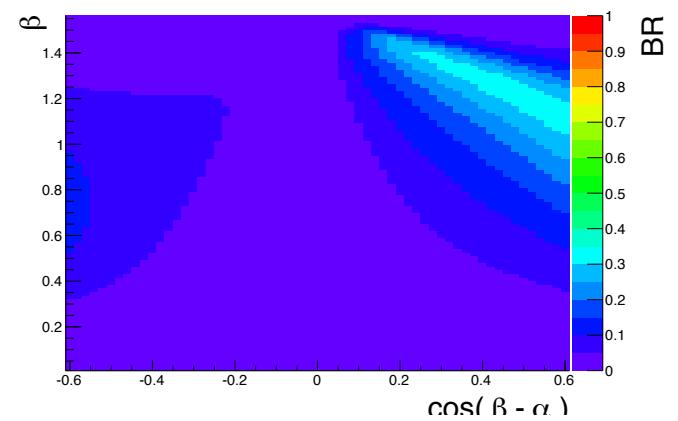
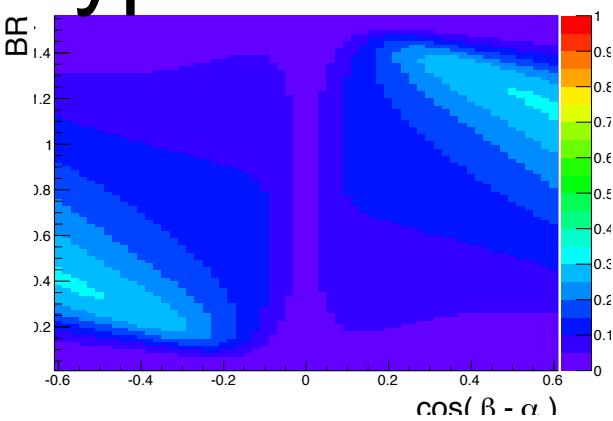
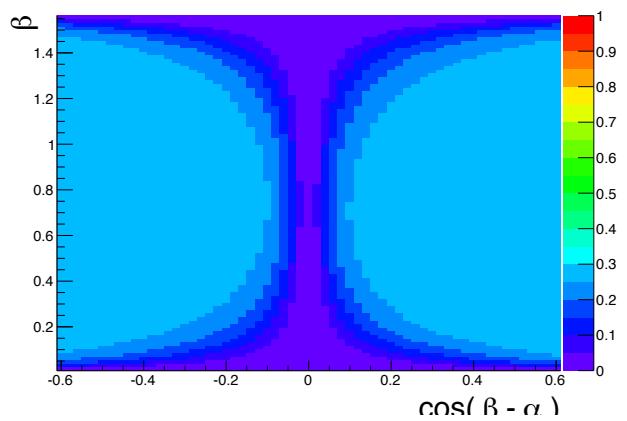


$m(\text{H}) = 300 \text{ GeV}$

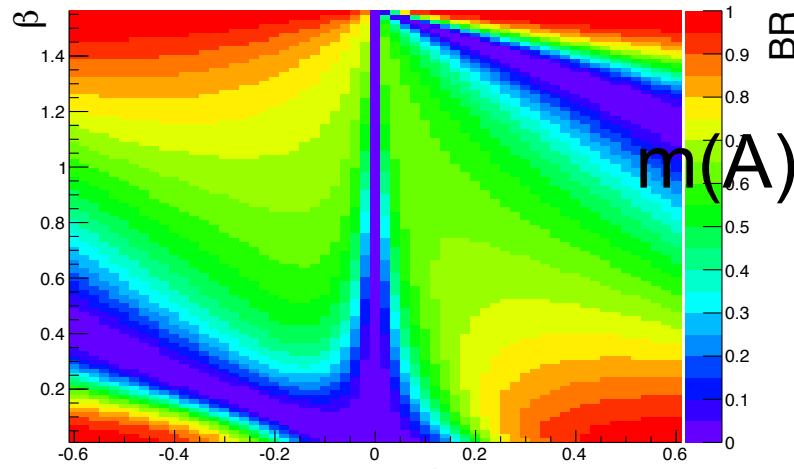


$m(\text{H}) = 600 \text{ GeV}$

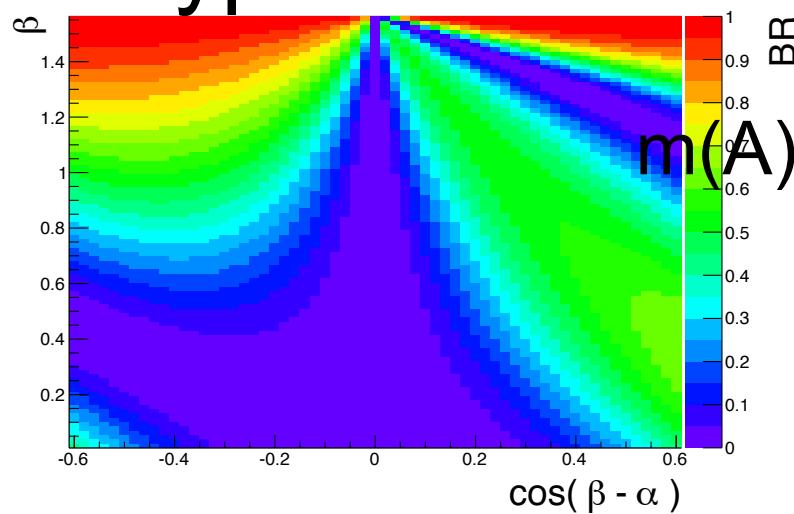
Type II 2HDM



$\text{BR}(\text{H} \rightarrow \text{hh})$

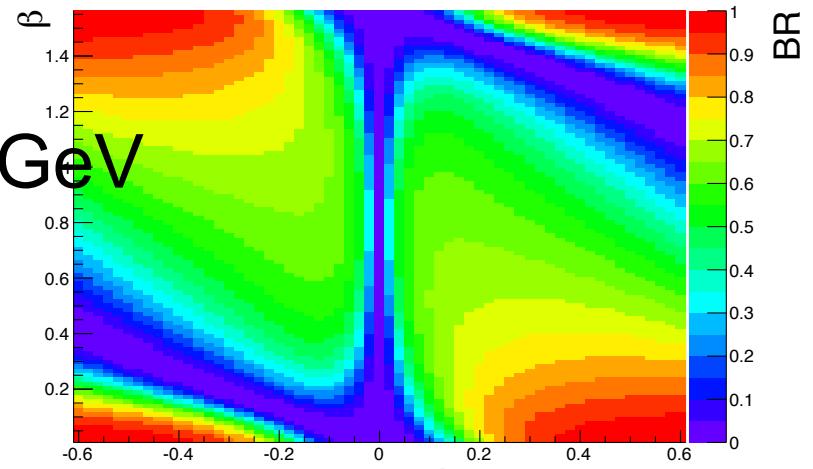


Type I 2HDM

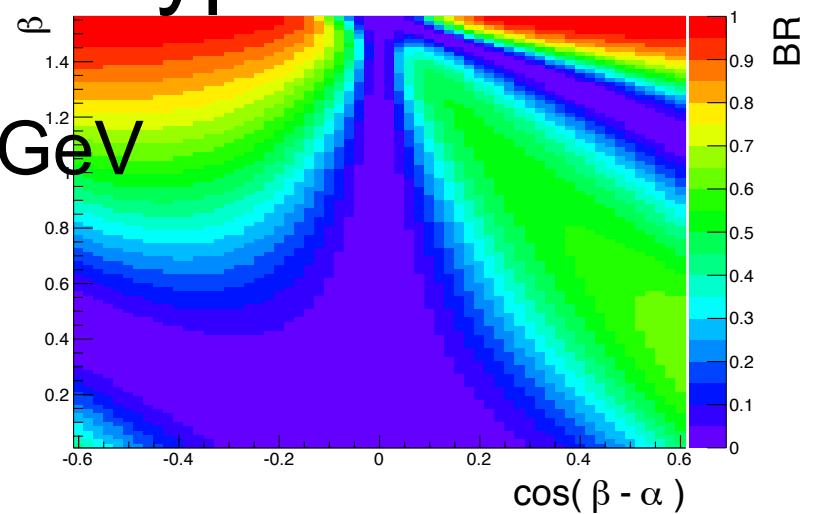


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$m(A) = 300 \text{ GeV}$



Type II 2HDM



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