Search Sensitivity for Heavy Neutral Higgs Bosons at a 100 TeV Hadron Collider

John Stupak III on behalf of
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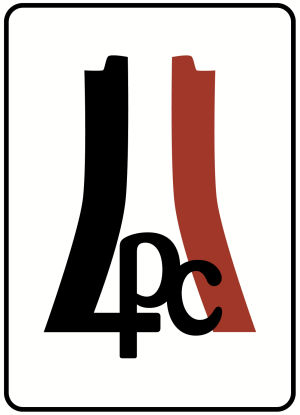
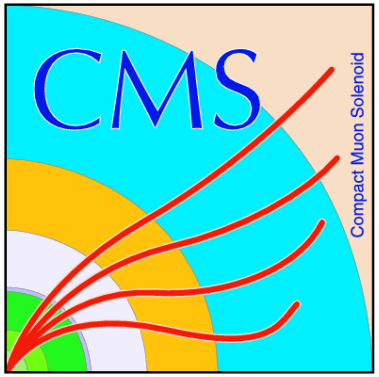
PURDUE UNIVERSITY CALUMET





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

Coupling Assignments

2HDM types

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

    - No CP violation, No FCNC, MSSM quartic couplings
      - 4 2HDM types with 6 parameters: 4 masses and 2 angles (α,β)
- Will assume throughout that h(125) is the lighter of the CP-even 2HDM scalars
- Will focus on search sensitivity for H and A

Probing the 2HDM (I)

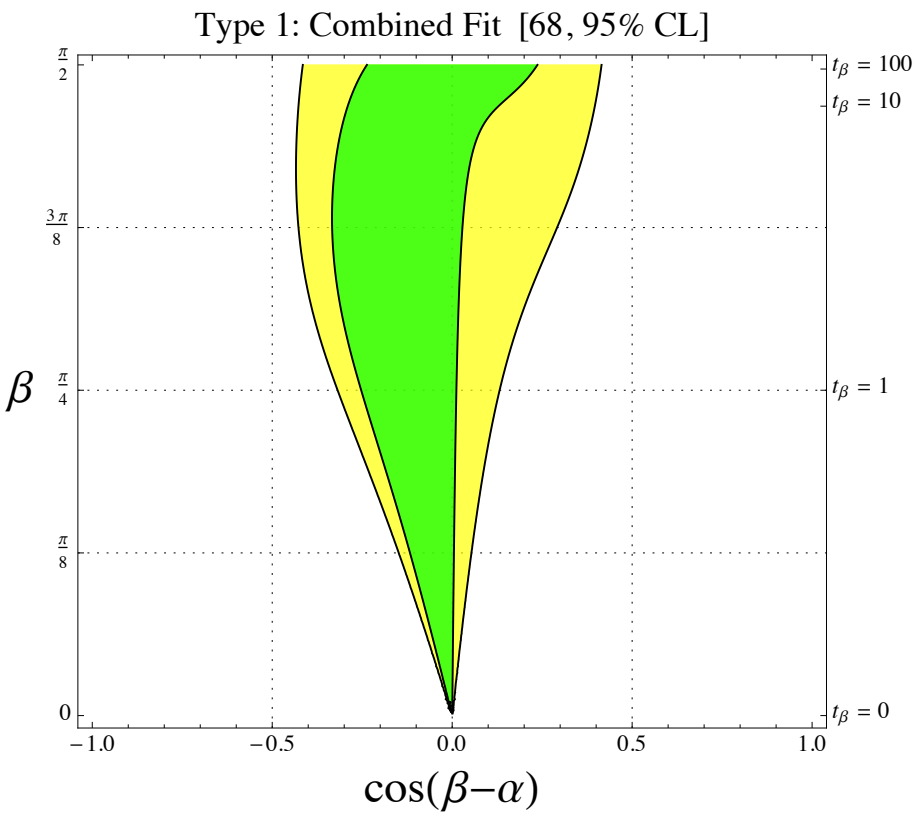
- 2 complementary strategies available to probe 2HDM:
  - Precision measurement of h(125) couplings
    - Couplings of h_{2HDM} differ from those of h_{SM}

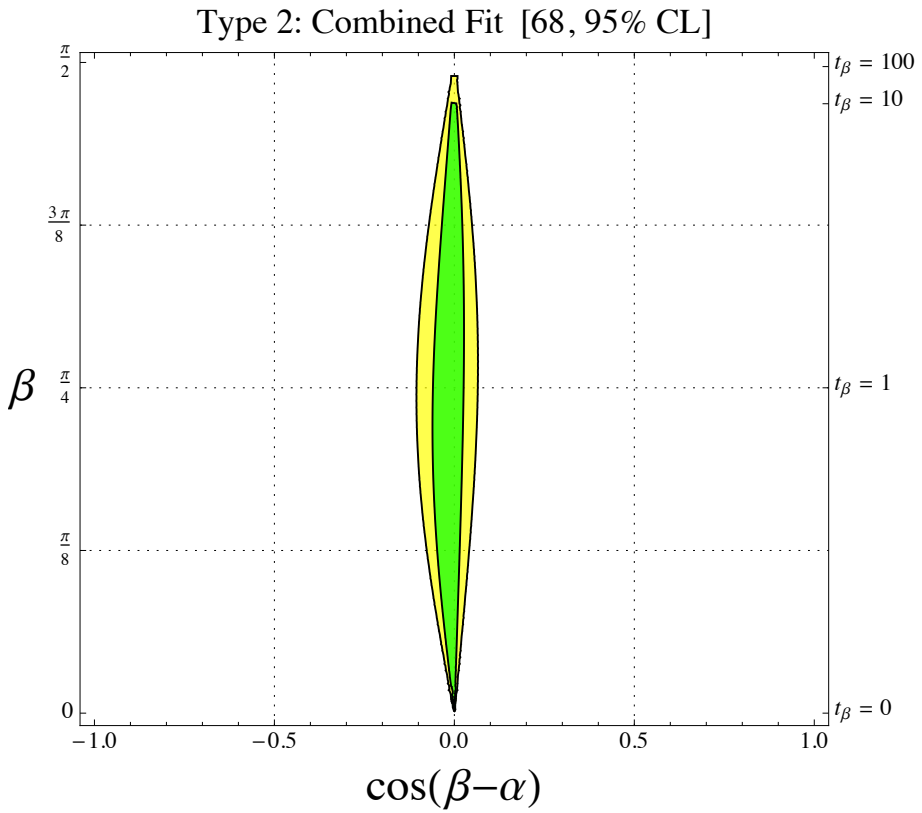
y_{2HDM}/y_{SM}	hVV	hQu	hQd	hLe
I	sin(β-α)	sin(β-α) + cos(β-α)/tan(β)	sin(β-α) + cos(β-α)/tan(β)	sin(β-α) + cos(β-α)/tan(β)
LS				sin(β-α) – cos(β-α)*tan(β)
2			sin(β-α) – cos(β-α)*tan(β)	
F				sin(β-α) + cos(β-α)/tan(β)

    - 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]





- If nature can be described by a 2HDM, must be fairly close to AL

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
    - Scalars generally prefer to decay to heaviest kinematically accessible final state
      - Allowed decays:
        - H ➔ tt, hh, ZZ, WW, bb, ττ, γγ
        - A ➔ tt, Zh, bb, ττ, γγ
      - Cleaner decays also happen to be suppressed near AL
        - But can still have significant BR quite close to AL
    - We focus on search for gluon fusion production with H ➔ ZZ and A ➔ Zh

*Suppressed near AL

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
$<N_{PU}>$	50	140	140	40

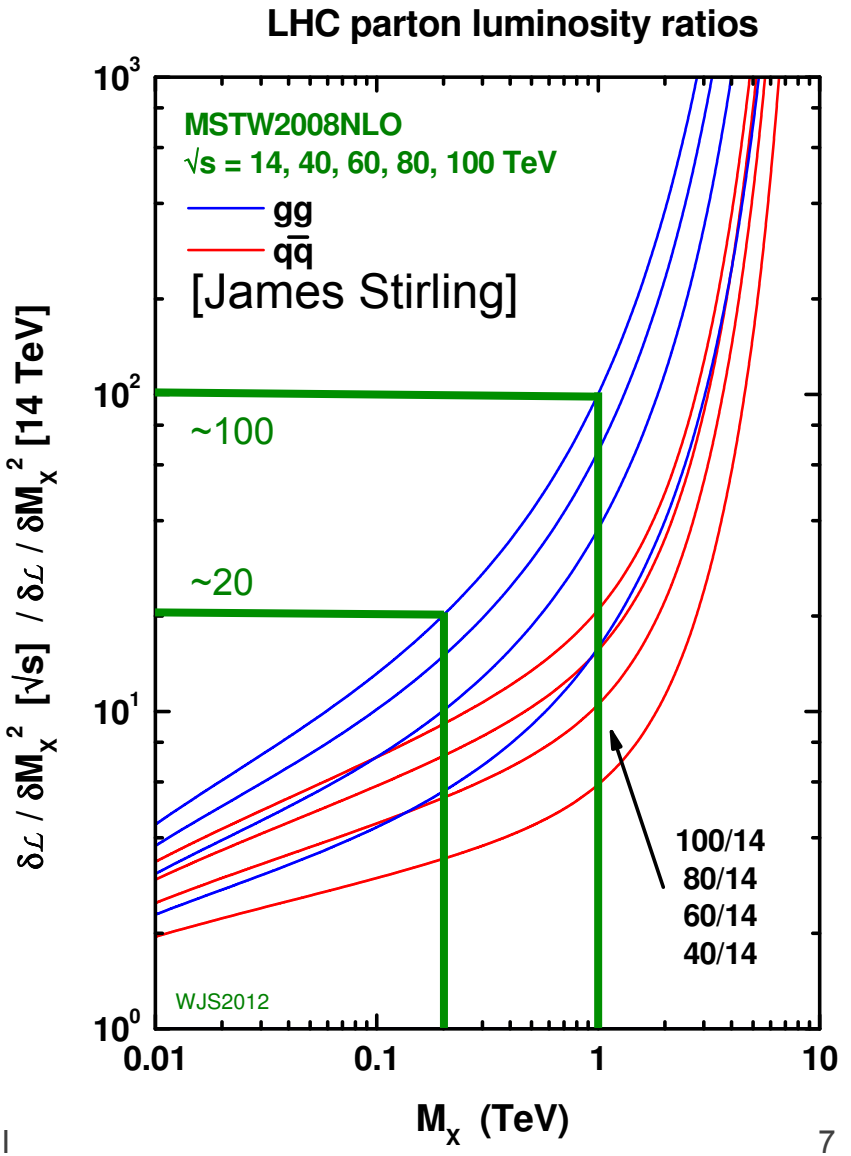
- Background MC
  - Madgraph + Bridge + Pythia + Delphes*
    - S_T-binned background samples
      - Normalized to NLO cross sections**
- Signal MC
  - Madgraph + Pythia + Delphes*
  - SM NLO gluon fusion cross sections and BRs rescaled by 2HDM LO coupling dependence on α, β

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

**Sub-dominant backgrounds at LO

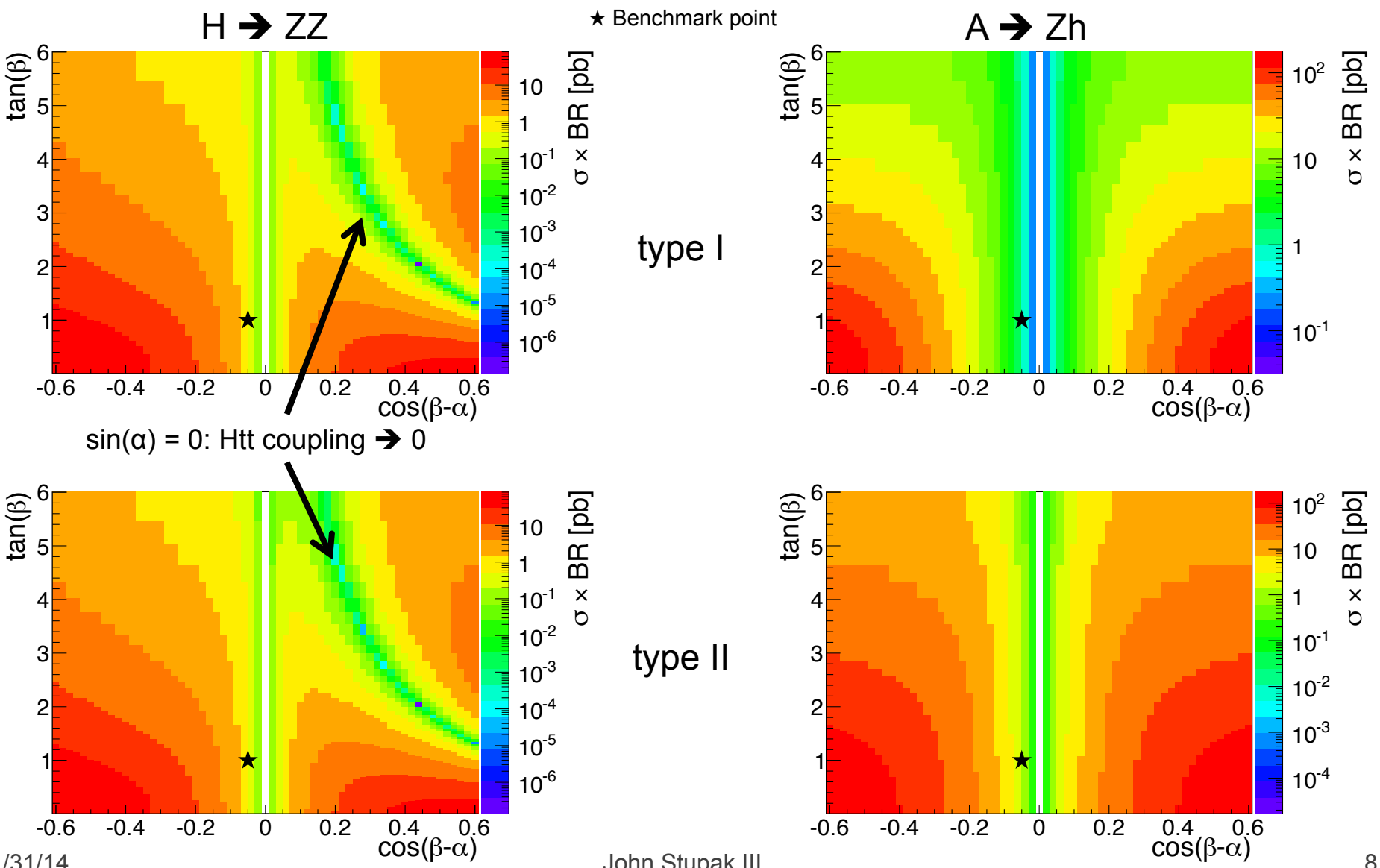
Parton Luminosity

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



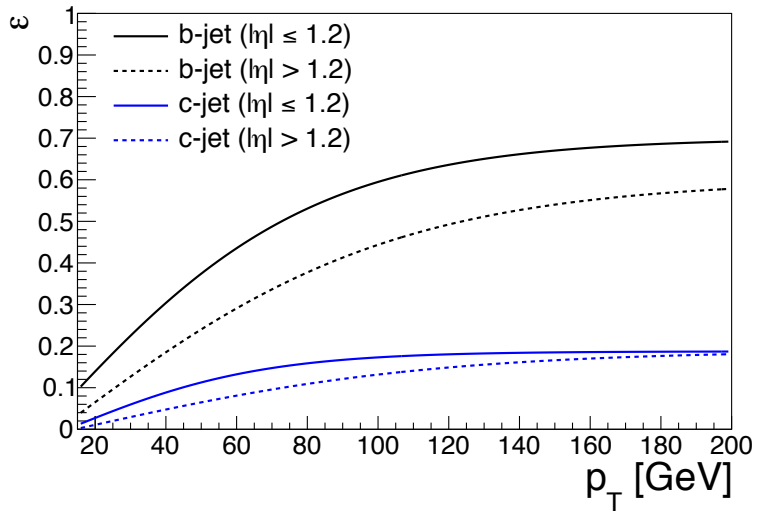
Cross Section × BR

m = 500 GeV



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%
  - τ
    - $p_T > 20$ 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→ZZ→4ℓ

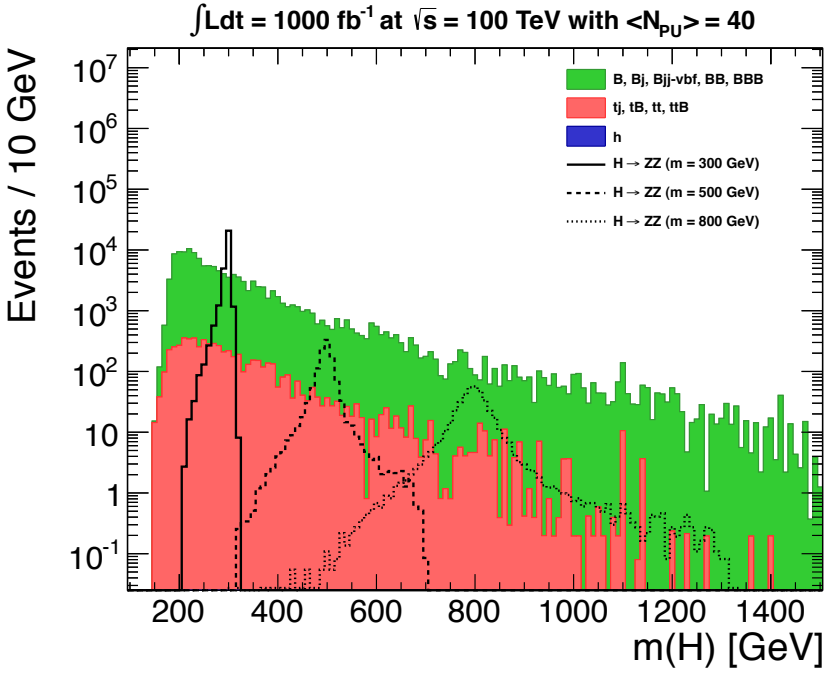
Event Selection

- 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

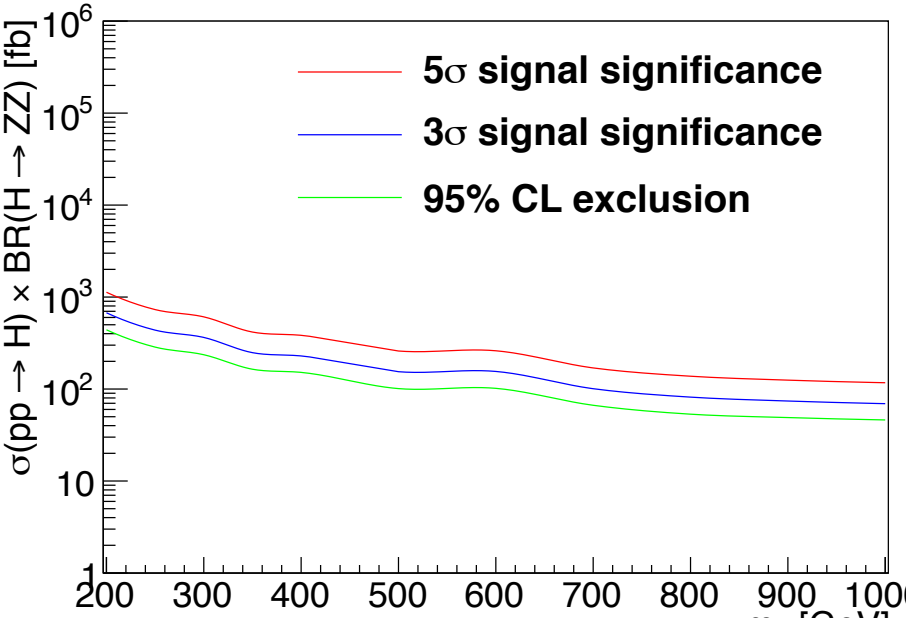
t = top, anti-top
B = $W^{\pm}$, Z

Sample	Selected Events
BB	1.3×10^5
ttB	6.1×10^3
BBB	1.8×10^3
Total Background	**1.4×10^5**
Signal (m = 500 GeV)	1.2×10^3
Signal (m = 800 GeV)	450

Results

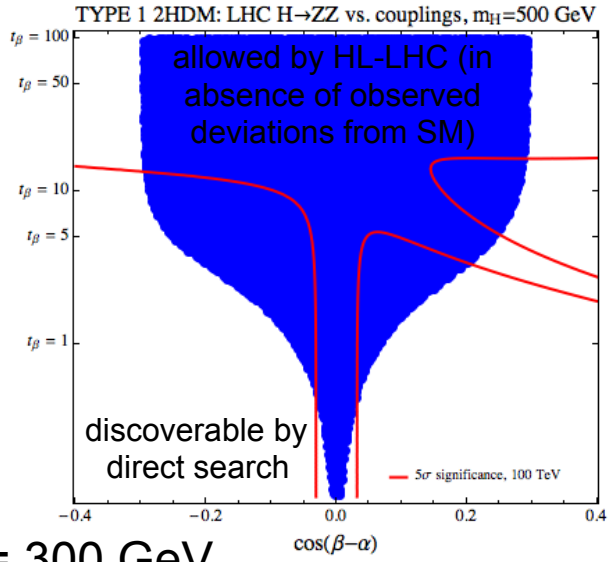


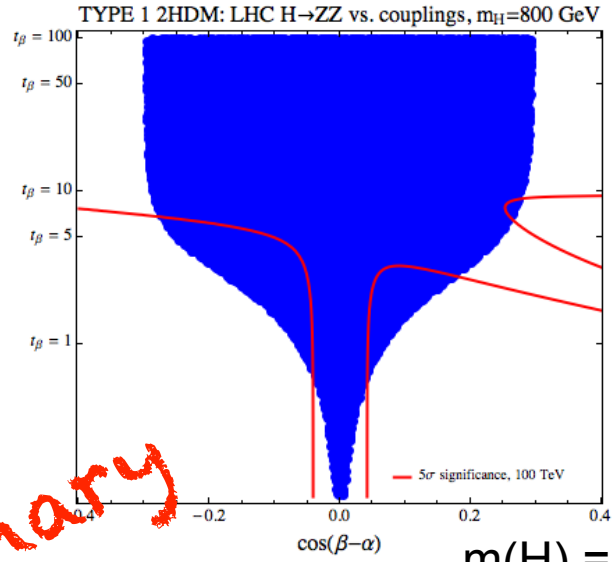
- Use to determine σ×BR which can be excluded or yield observation/discovery
  - Assume uniform 20% background systematic uncertainty



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

2D Results



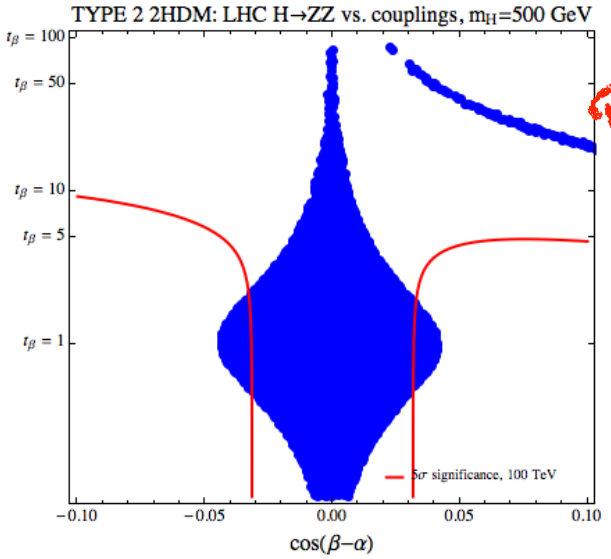


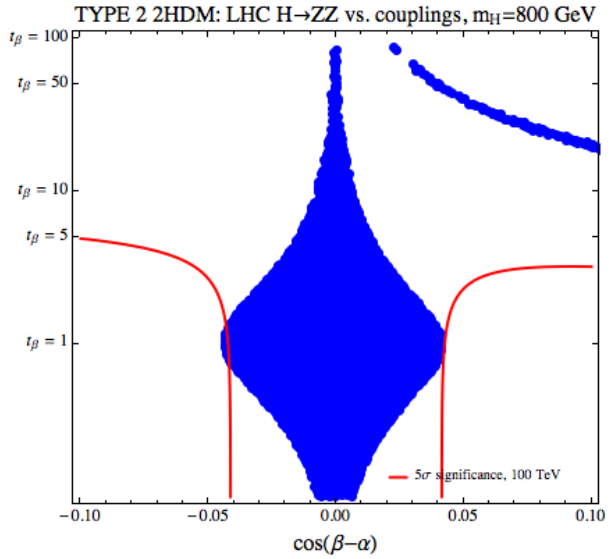
type I

m(H) = 300 GeV

m(H) = 500 GeV

Preliminary





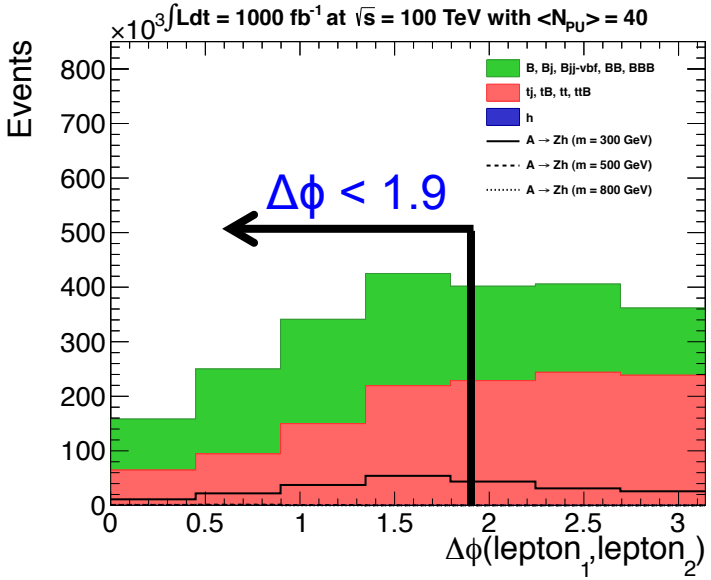
type II

A→Zh→$\ell\ell$+bb/$\tau\tau$

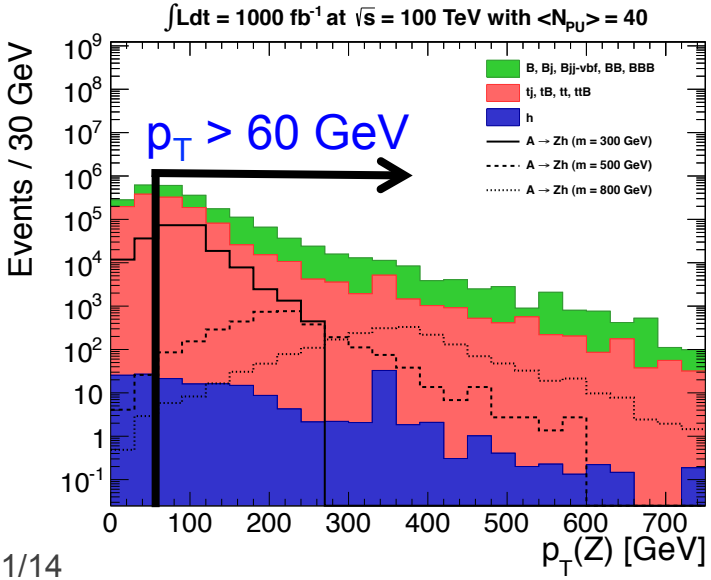
Event Pre-Selection

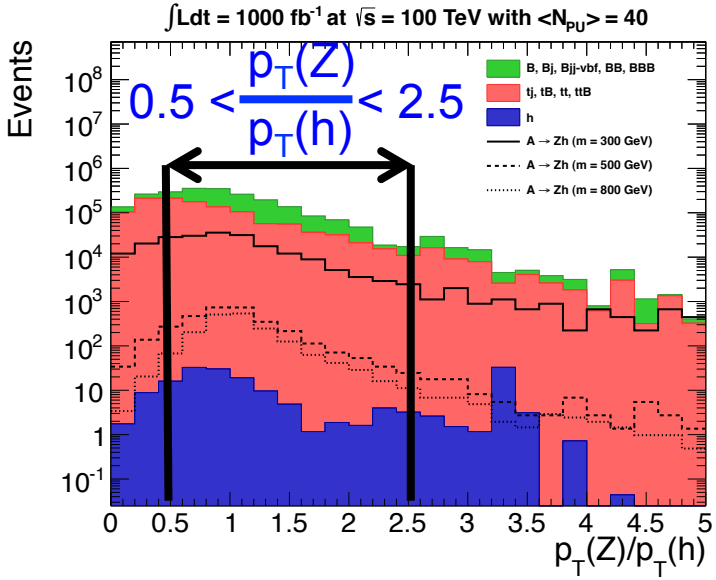
Channel	
bb	**ττ**
Exactly 2 b-jets	Exactly 2 τ leptons
Fewer than 2 τ leptons	Fewer than 2 b−jets
Exactly 2 leptons	
Z candidate • OSSF lepton pair • 80 GeV < m(Z) < 100 GeV	
h candidate	
• 90 GeV < m(bb) < 150 GeV	• 55 GeV < m(ττ) < 125 GeV

Pre-Selection Kinematics



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



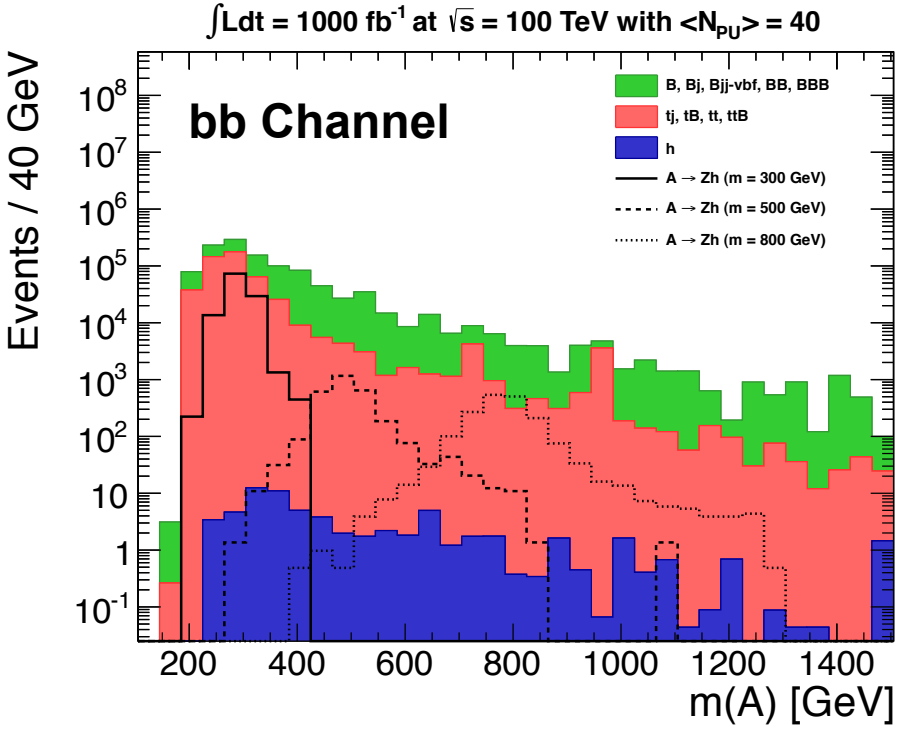


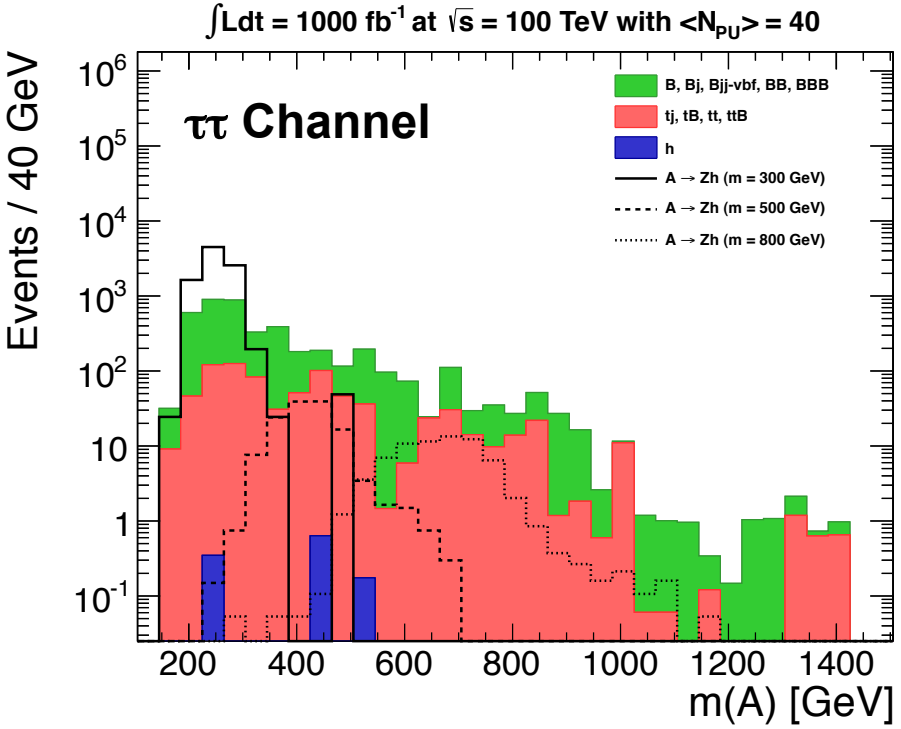
Selected Events

t = top, anti-top
B = $W^{\pm}$, Z

Sample	Selected Events	
	bb Channel	**ττ Channel**
B	6.2×10^5	-
tt	4.4×10^5	-
ttB	2.8×10^4	790
BB	2.4×10^4	3.3×10^3
tB	2.2×10^4	-
BBB	-	250
Total Background	**1.1×10^6**	**4.3×10^3**
Signal (m = 500 GeV)	2.9×10^3	140
Signal (m = 800 GeV)	1.9×10^3	70

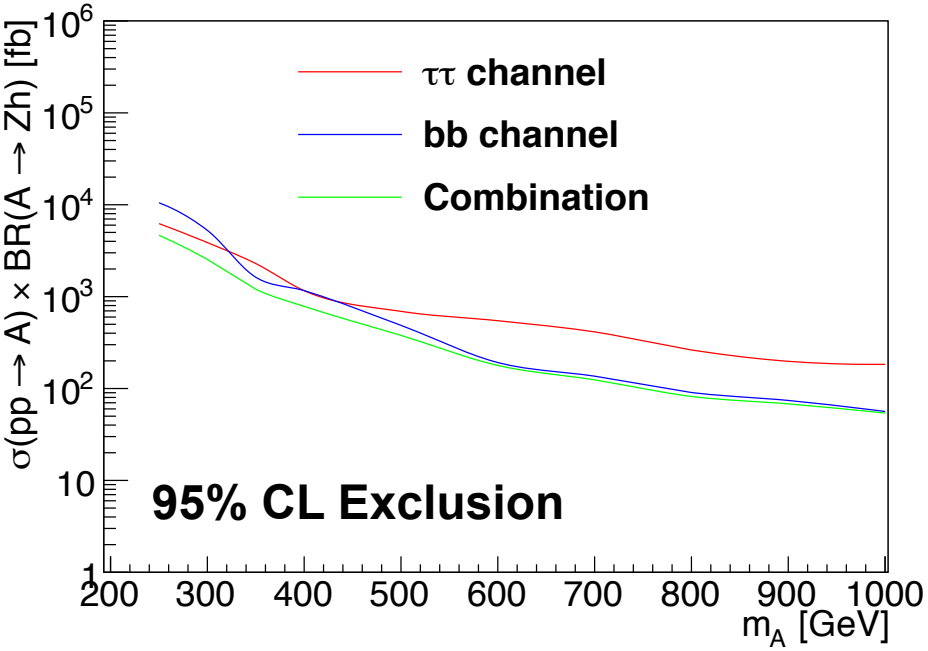
Event Kinematics

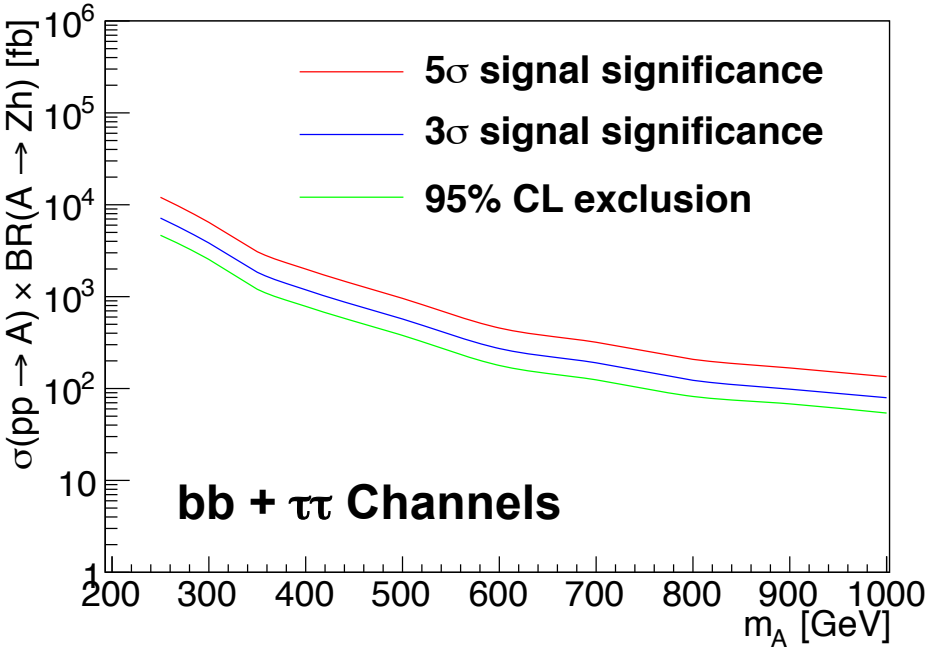




- Use to determine σ×BR which can be excluded or yield observation/discovery
  - Assume uniform 20% background systematic uncertainty

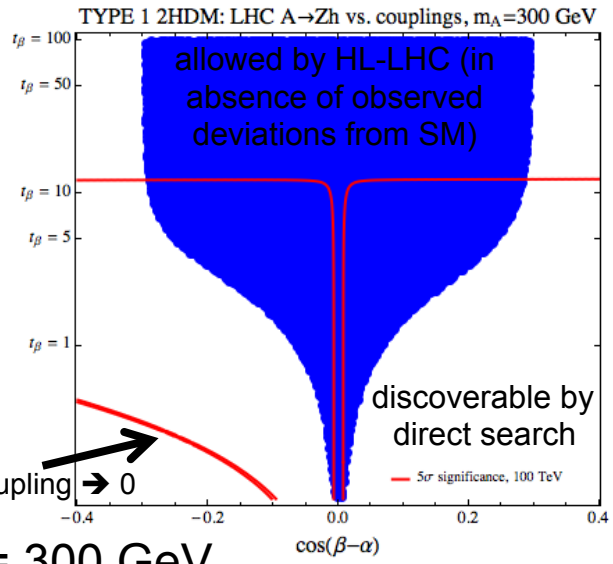
Results





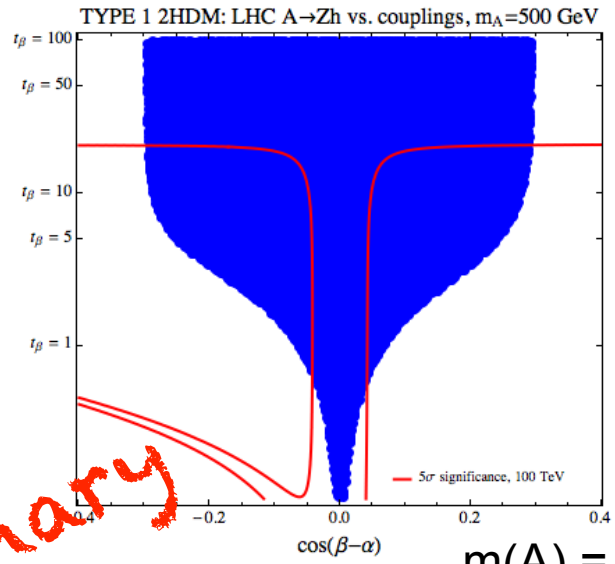
- ττ (bb) channel more sensitive at small (large) m(A)
- Low mass A harder to exclude/discover than H

2D Results



cos(α) = 0:
hbb,hττ coupling → 0

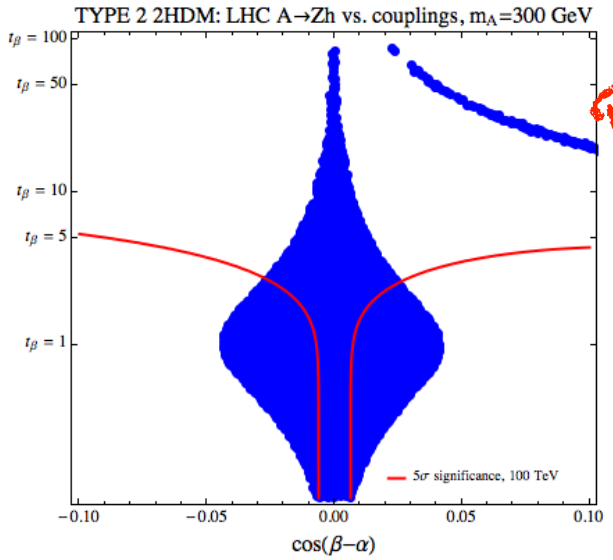
m(A) = 300 GeV



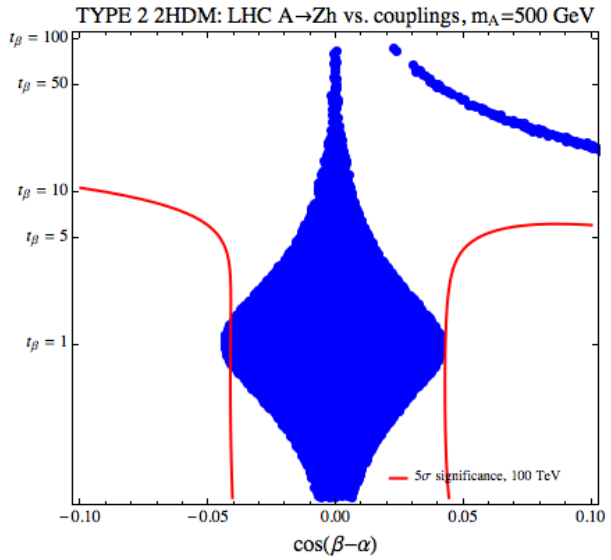
type I

m(A) = 500 GeV

Preliminary



type II



Conclusions

- Important to fully explore the Higgs sector
- 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
- Important to pursue both coupling measurements and direct search

Backup

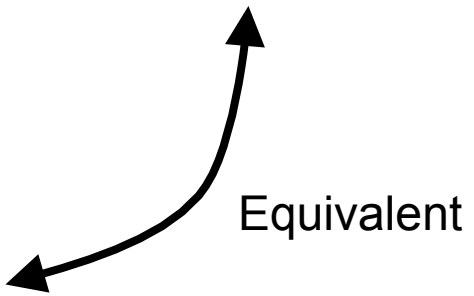
2HDM Coupling Strengths

[Craig, Galloway, Thomas]

y_{2HDM}/y_{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]

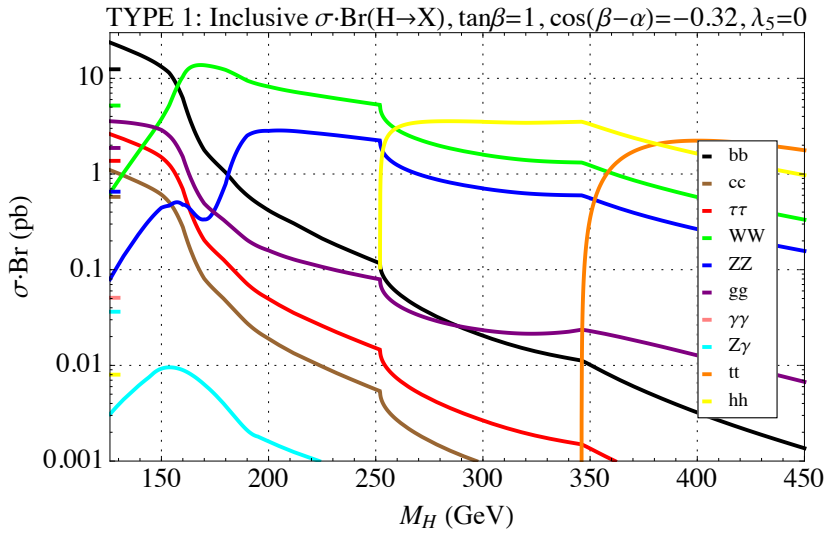
	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$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

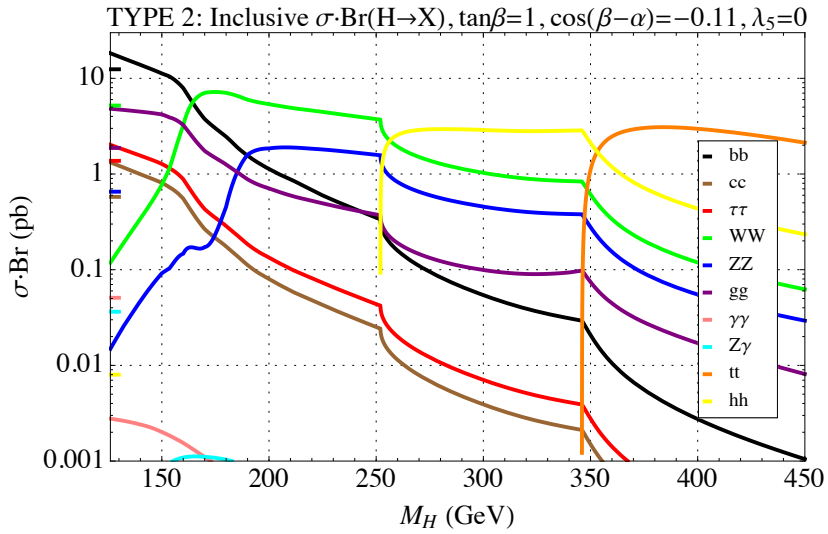


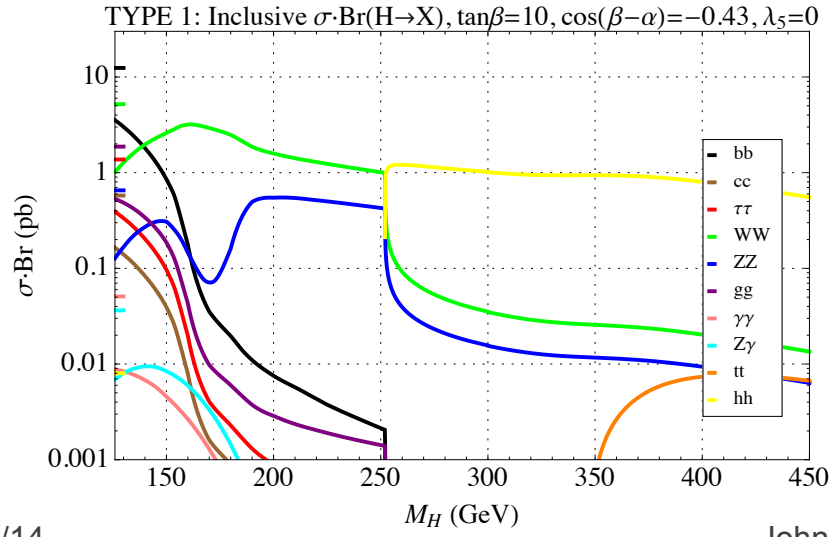
σ(H) × BR(H→X)

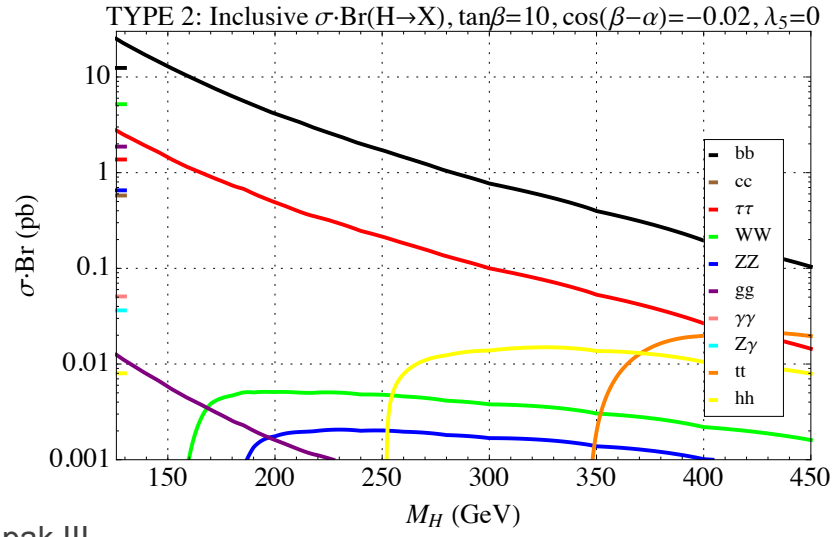
14 TeV

[Craig, Galloway, Thomas]





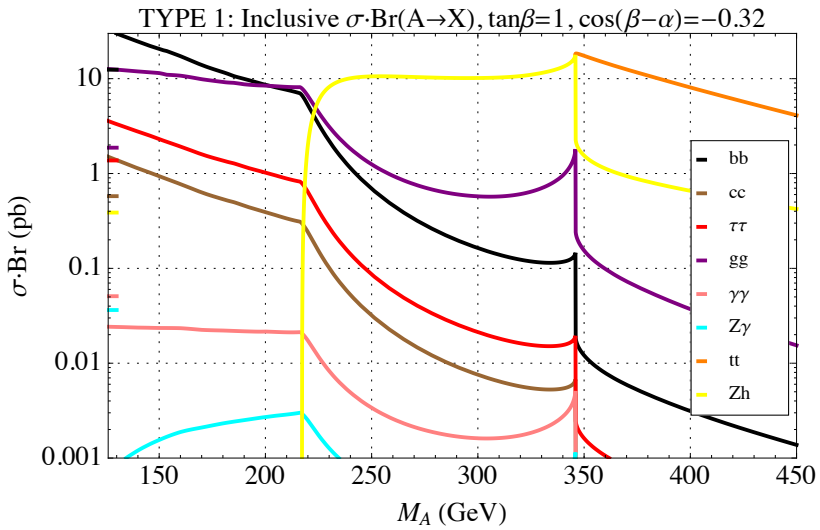


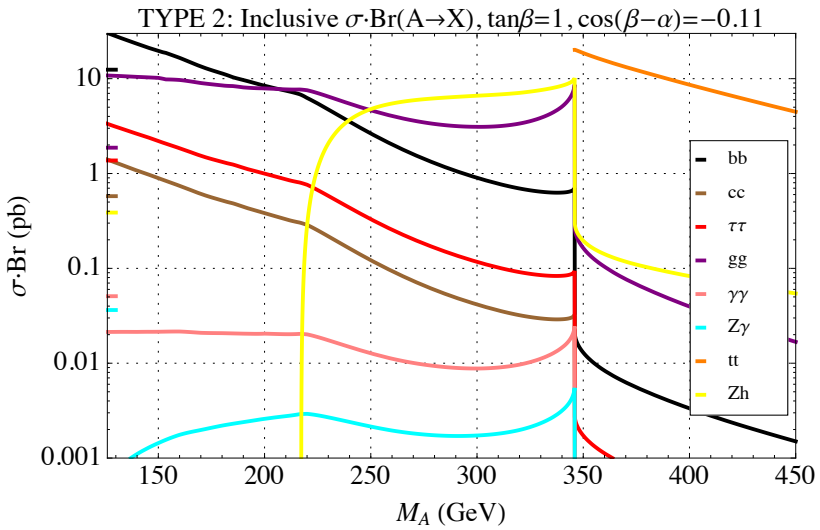


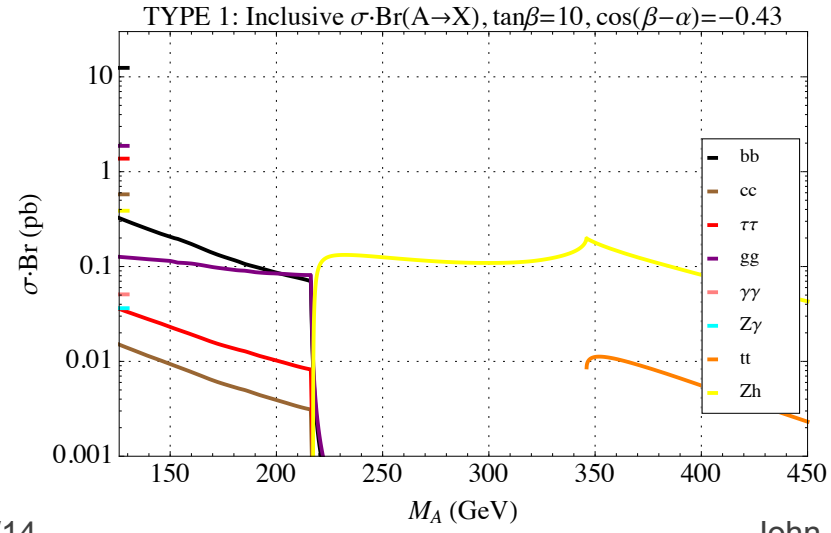
σ(A) × BR(A→X)

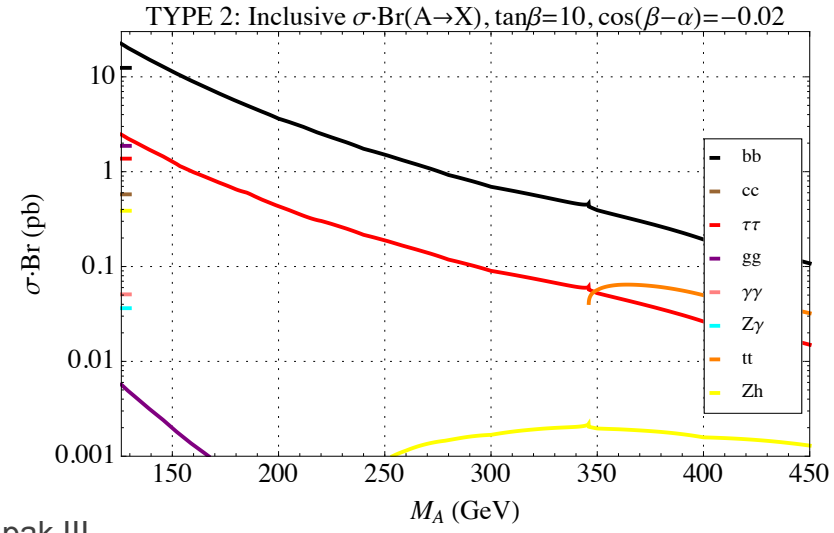
14 TeV

[Craig, Galloway, Thomas]

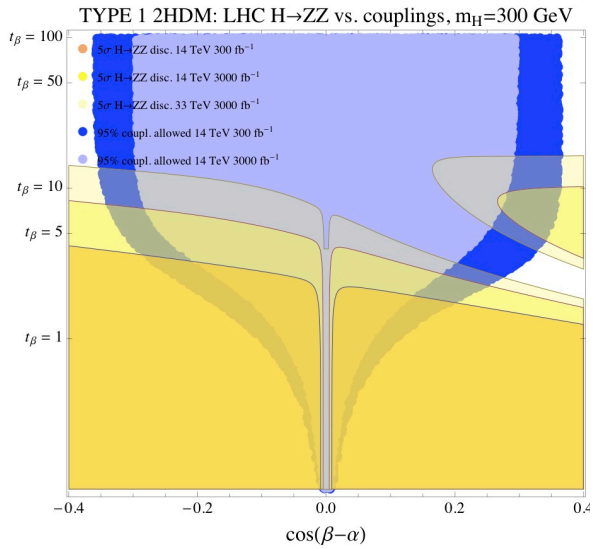


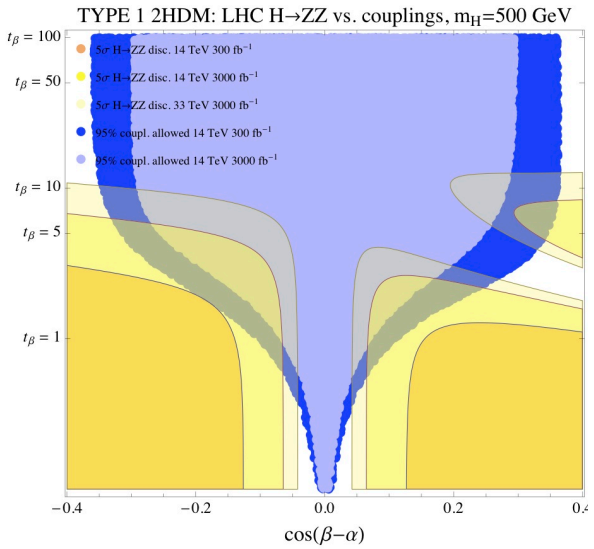


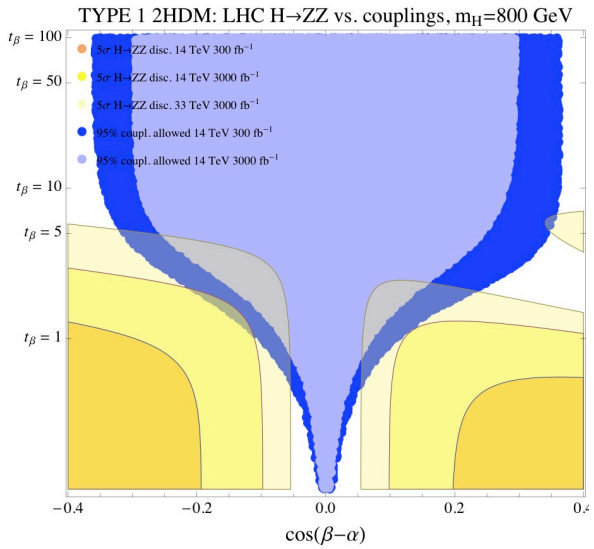




H → ZZ


TYPE 1 2HDM: LHC H→ZZ vs. couplings, m_H=300 GeV
5σ H→ZZ disc. 14 TeV 300 fb⁻¹
5σ H→ZZ disc. 14 TeV 3000 fb⁻¹
5σ H→ZZ disc. 33 TeV 3000 fb⁻¹
95% coupl. allowed 14 TeV 300 fb⁻¹
95% coupl. allowed 14 TeV 3000 fb⁻¹
t_β = 100
t_β = 50
t_β = 10
t_β = 5
t_β = 1
−0.4
−0.2
0.0
0.2
cos(β−α)


TYPE 1 2HDM: LHC H→ZZ vs. couplings, m_H=500 GeV
5σ H→ZZ disc. 14 TeV 300 fb⁻¹
5σ H→ZZ disc. 14 TeV 3000 fb⁻¹
5σ H→ZZ disc. 33 TeV 3000 fb⁻¹
95% coupl. allowed 14 TeV 300 fb⁻¹
95% coupl. allowed 14 TeV 3000 fb⁻¹
t_β = 100
t_β = 50
t_β = 10
t_β = 5
t_β = 1
−0.4
−0.2
0.0
0.2
cos(β−α)


TYPE 1 2HDM: LHC H→ZZ vs. couplings, m_H=800 GeV
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5σ H→ZZ disc. 14 TeV 3000 fb⁻¹
5σ H→ZZ disc. 33 TeV 3000 fb⁻¹
95% coupl. allowed 14 TeV 300 fb⁻¹
95% coupl. allowed 14 TeV 3000 fb⁻¹
t_β = 100
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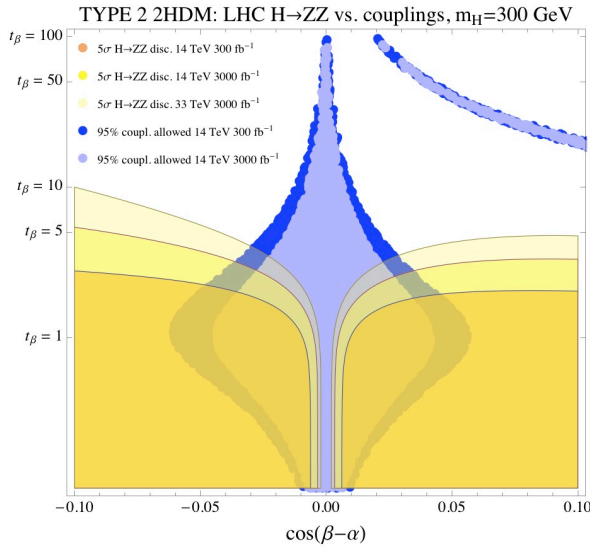
t_β = 5
t_β = 1
−0.4
−0.2
0.0
0.2
cos(β−α)


TYPE 2 2HDM: LHC H→ZZ vs. couplings, m_H=300 GeV
5σ H→ZZ disc. 14 TeV 300 fb⁻¹
5σ H→ZZ disc. 14 TeV 3000 fb⁻¹
5σ H→ZZ disc. 33 TeV 3000 fb⁻¹
95% coupl. allowed 14 TeV 300 fb⁻¹
95% coupl. allowed 14 TeV 3000 fb⁻¹
t_β = 100
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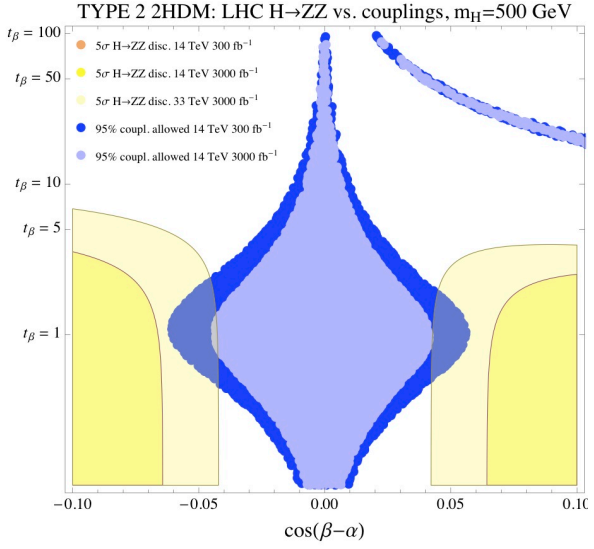
t_β = 10
t_β = 5
t_β = 1
−0.10
−0.05
0.00
0.05
cos(β−α)


TYPE 2 2HDM: LHC H→ZZ vs. couplings, m_H=500 GeV
5σ H→ZZ disc. 14 TeV 300 fb⁻¹
5σ H→ZZ disc. 14 TeV 3000 fb⁻¹
5σ H→ZZ disc. 33 TeV 3000 fb⁻¹
95% coupl. allowed 14 TeV 300 fb⁻¹
95% coupl. allowed 14 TeV 3000 fb⁻¹
t_β = 100
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t_β = 5
t_β = 1
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−0.05
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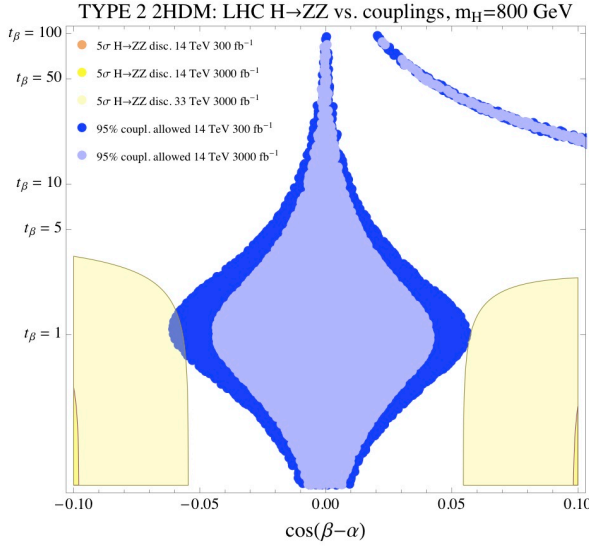
0.05
cos(β−α)


TYPE 2 2HDM: LHC H→ZZ vs. couplings, m_H=800 GeV
5σ H→ZZ disc. 14 TeV 300 fb⁻¹
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95% coupl. allowed 14 TeV 300 fb⁻¹
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t_β = 100
t_β = 50
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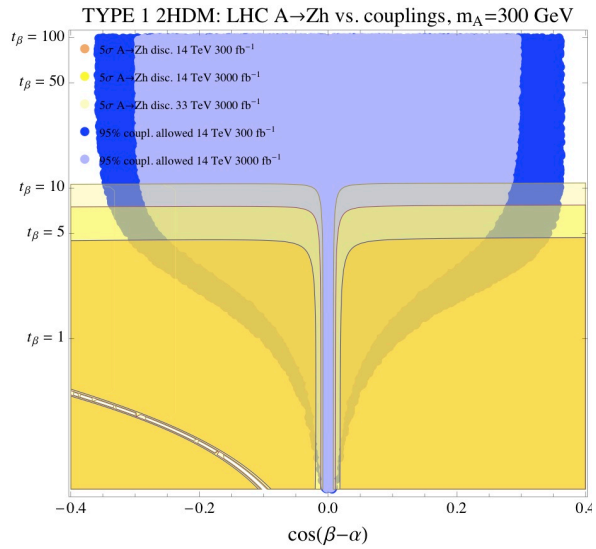
t_β = 5
t_β = 1
−0.10
−0.05
0.00
0.05
cos(β−α)

A → Zh


TYPE 1 2HDM: LHC A→Zh vs. couplings, m_A=300 GeV
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5σ A→Zh disc. 14 TeV 3000 fb⁻¹
5σ A→Zh disc. 33 TeV 3000 fb⁻¹
95% coupl. allowed 14 TeV 300 fb⁻¹
95% coupl. allowed 14 TeV 3000 fb⁻¹
tβ = 100
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tβ = 10
tβ = 5
tβ = 1
−0.4
−0.2
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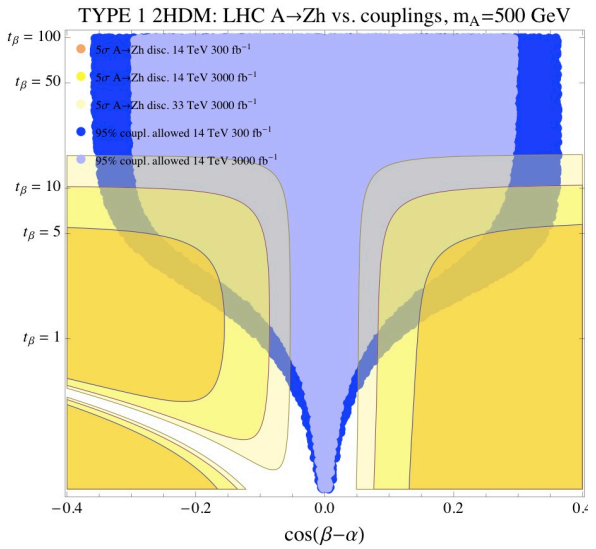
cos(β−α)


TYPE 1 2HDM: LHC A→Zh vs. couplings, m_A=500 GeV
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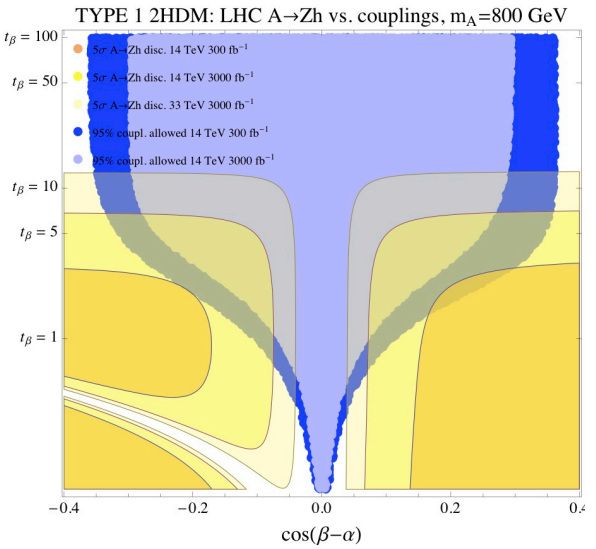
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−0.4
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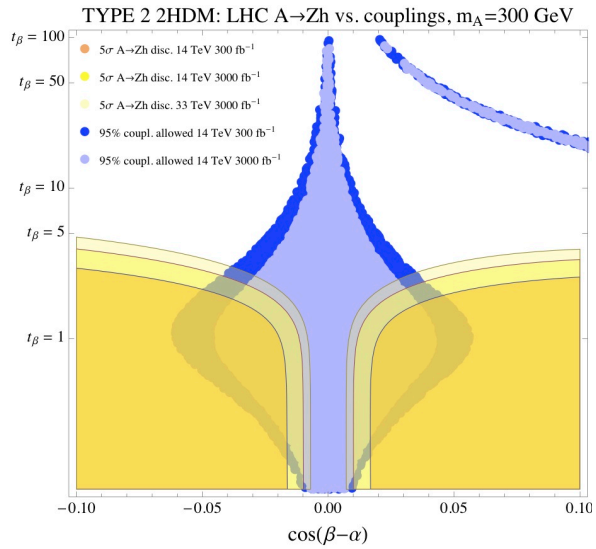
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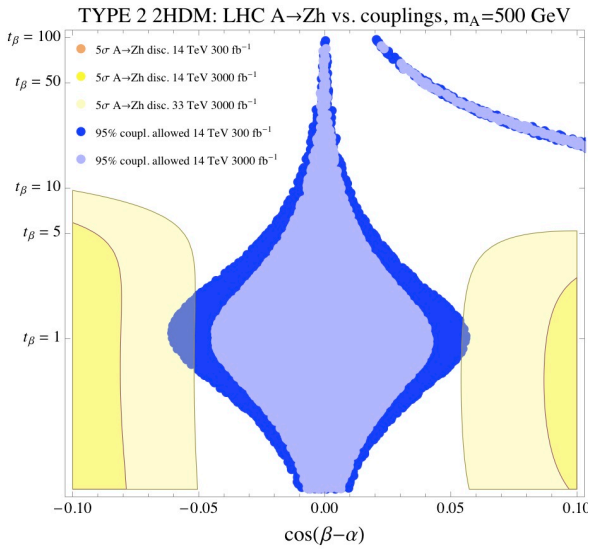
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tβ = 1
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0.00
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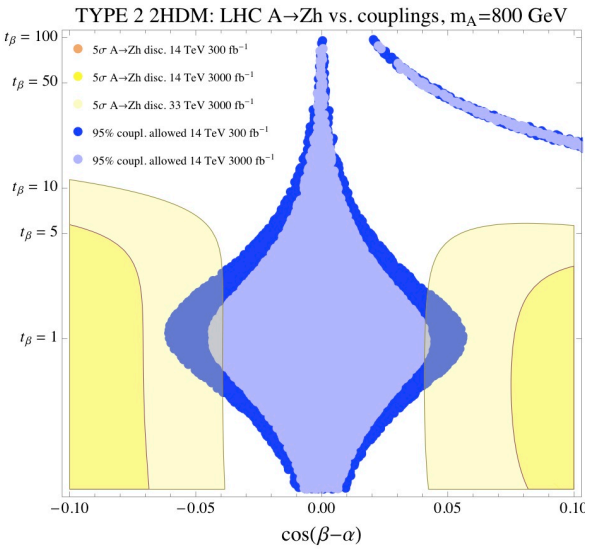
cos(β−α)


TYPE 2 2HDM: LHC A→Zh vs. couplings, m_A=800 GeV
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5σ A→Zh disc. 33 TeV 3000 fb⁻¹
95% coupl. allowed 14 TeV 300 fb⁻¹
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