Searching for Additional Higgs Bosons via Higgs Cascades

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Motivation

SM does not explain everything:

- Neutrino masses
- Dark matter
- EW scale unstable under quantum corrections
- etc.

A lot of new physics requires an extended Higgs sector.

Two Higgs Doublet Model

$$\tan\beta = v_2/v_1, \text{ with } v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}$$

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$$

Additional physical states: $H^{\pm}$, H^0, A^0

Two Higgs Doublet Model

Couplings to gauge bosons:

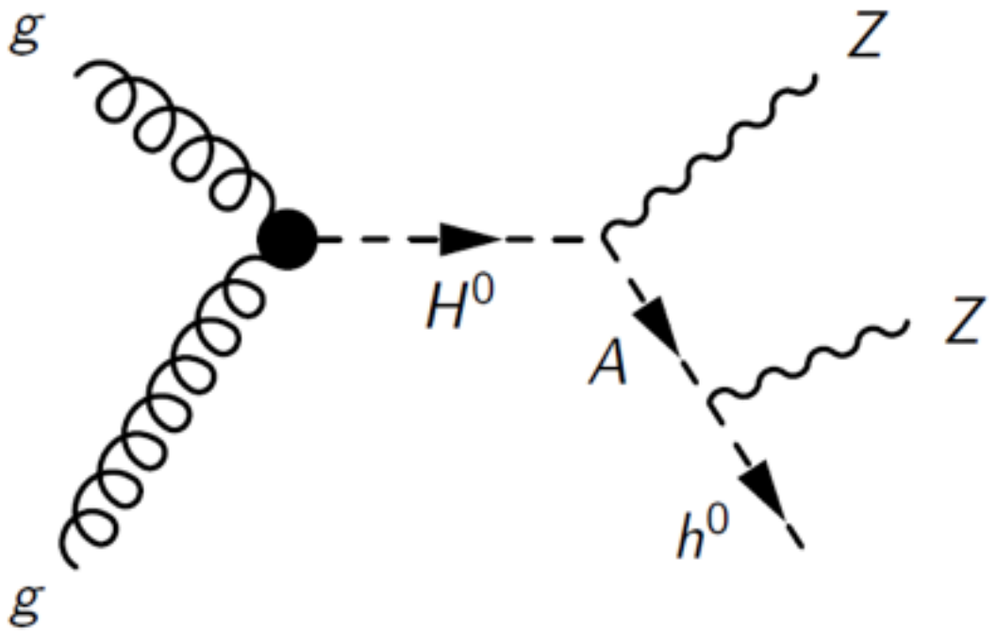
$$AhZ \propto \cos(\beta-\alpha), \qquad AHZ \propto \sin(\beta-\alpha),$$
$$hZZ \propto \sin(\beta-\alpha), \qquad HZZ \propto \cos(\beta-\alpha).$$

Couplings to fermions:

- Type I $\qquad ffh \propto \dfrac{\cos\alpha}{\sin\beta}, \qquad ffH \propto \dfrac{\sin\alpha}{\sin\beta}, \qquad ffA \propto \cot\beta$

- Type II
$$uuh \propto \frac{\cos\alpha}{\sin\beta}, \qquad ddh,\ \ell\ell h \propto \frac{\sin\alpha}{\cos\beta},$$
$$uuH \propto \frac{\sin\alpha}{\sin\beta}, \qquad ddH,\ \ell\ell H \propto \frac{\cos\alpha}{\cos\beta},$$
$$uuA \propto \cot\beta, \qquad ddA,\ \ell^+\ell^- A \propto \tan\beta.$$

Event Topology



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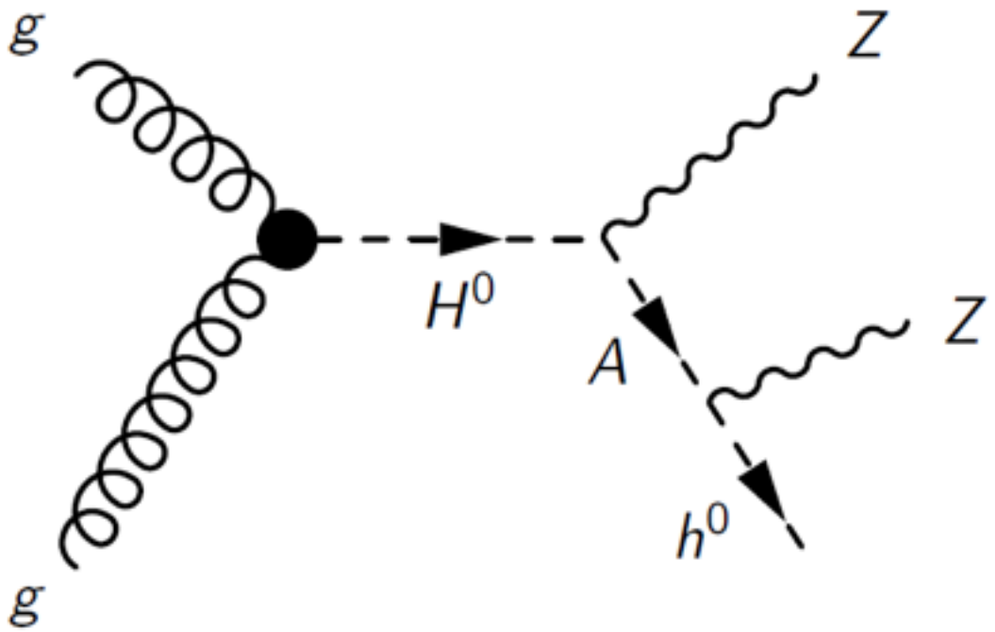

$A \to t\bar{t}$ closed
$H \to ZA$ and $A \to Zh$ open.

$$215 \text{ GeV} < m_A < 355 \text{ GeV}, \qquad m_H > m_A + 90 \text{ GeV}$$

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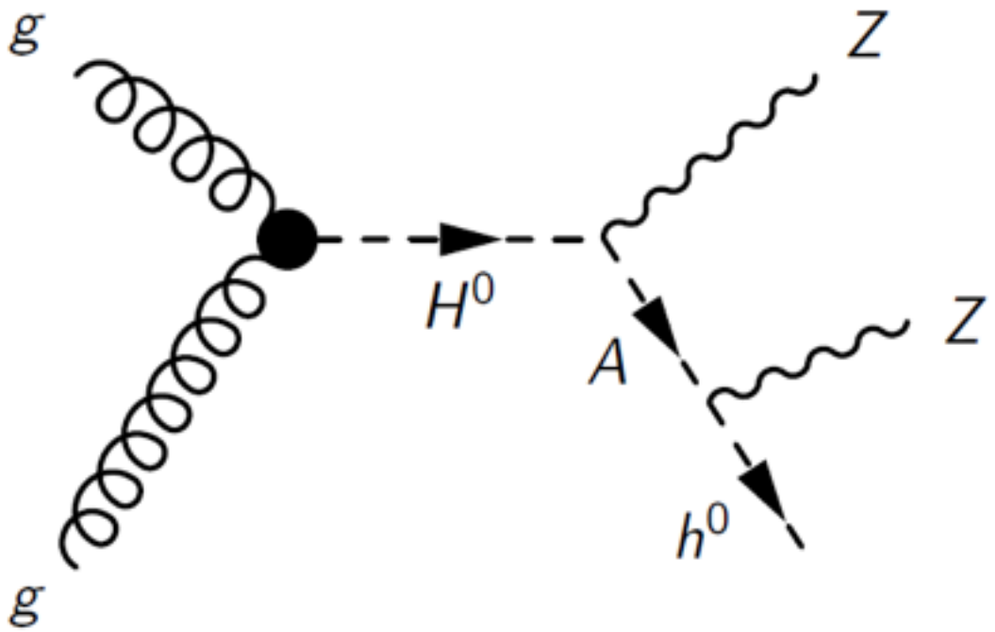

Benchmark:
$m_H = 450\ GeV$
$m_A = m_{H^\pm} = 250\ GeV$

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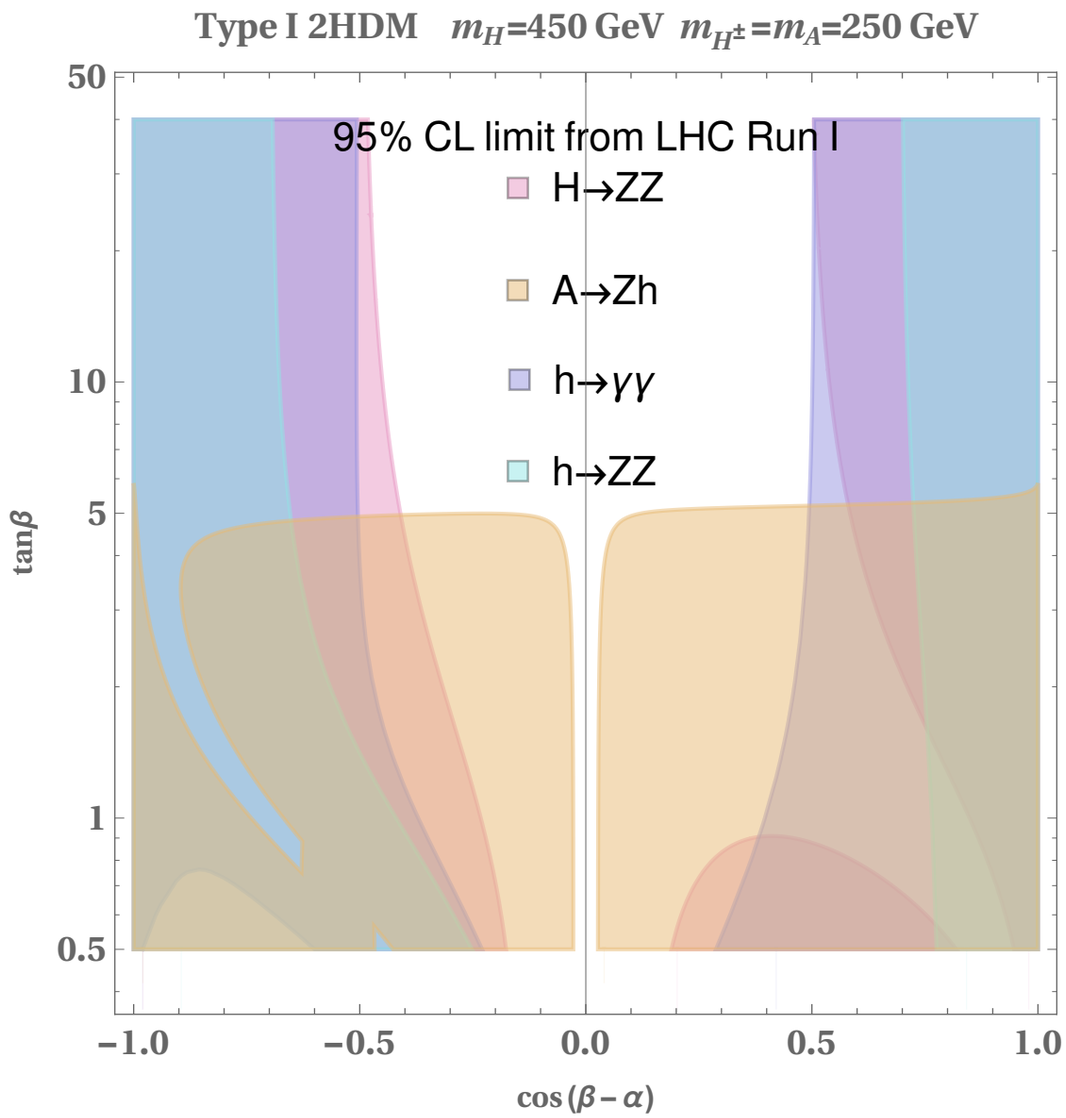
$$215\ \text{GeV} < m_A < 355\ \text{GeV}, \qquad m_H > m_A + 90\ \text{GeV}$$

Status after Run I



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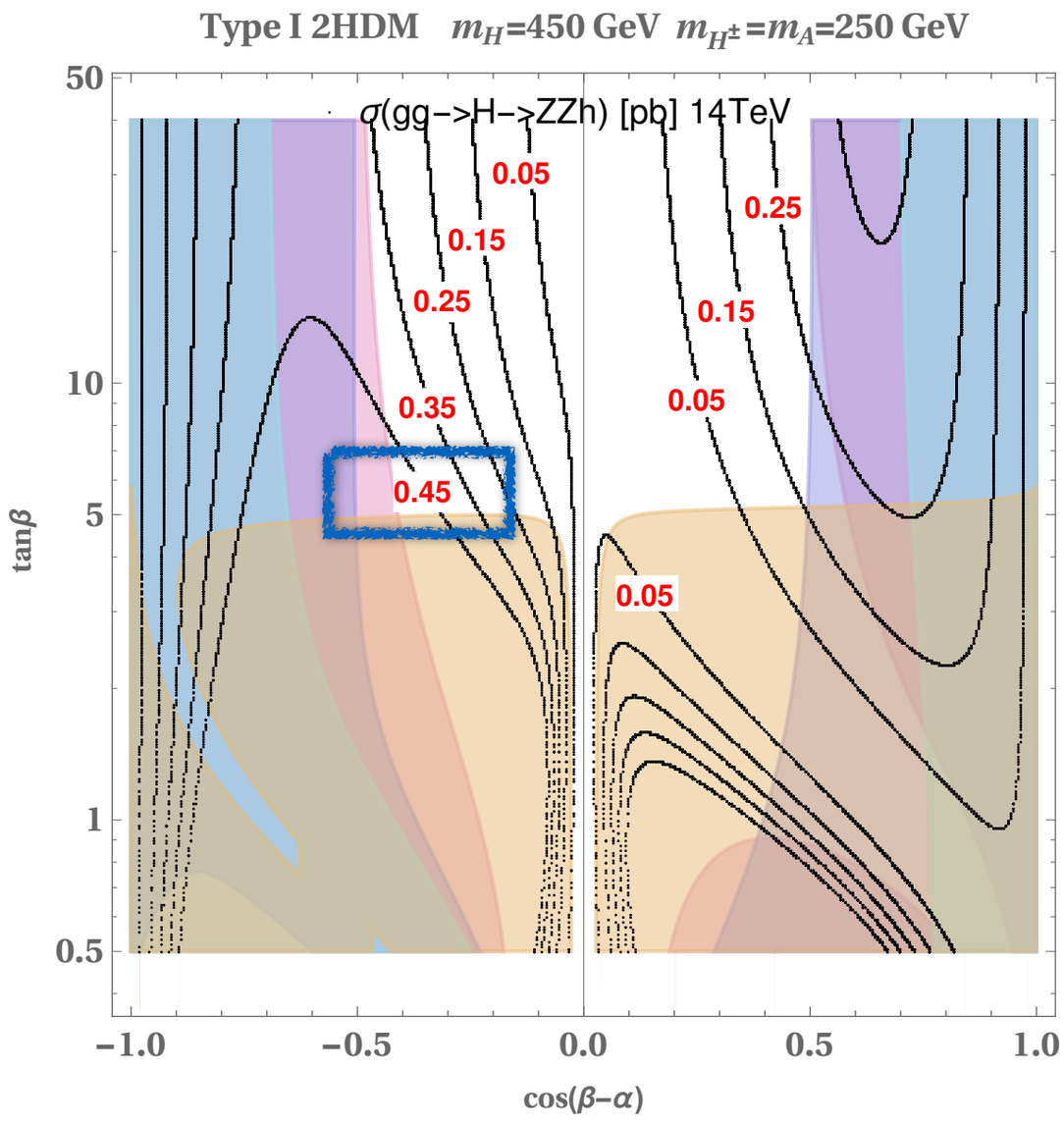

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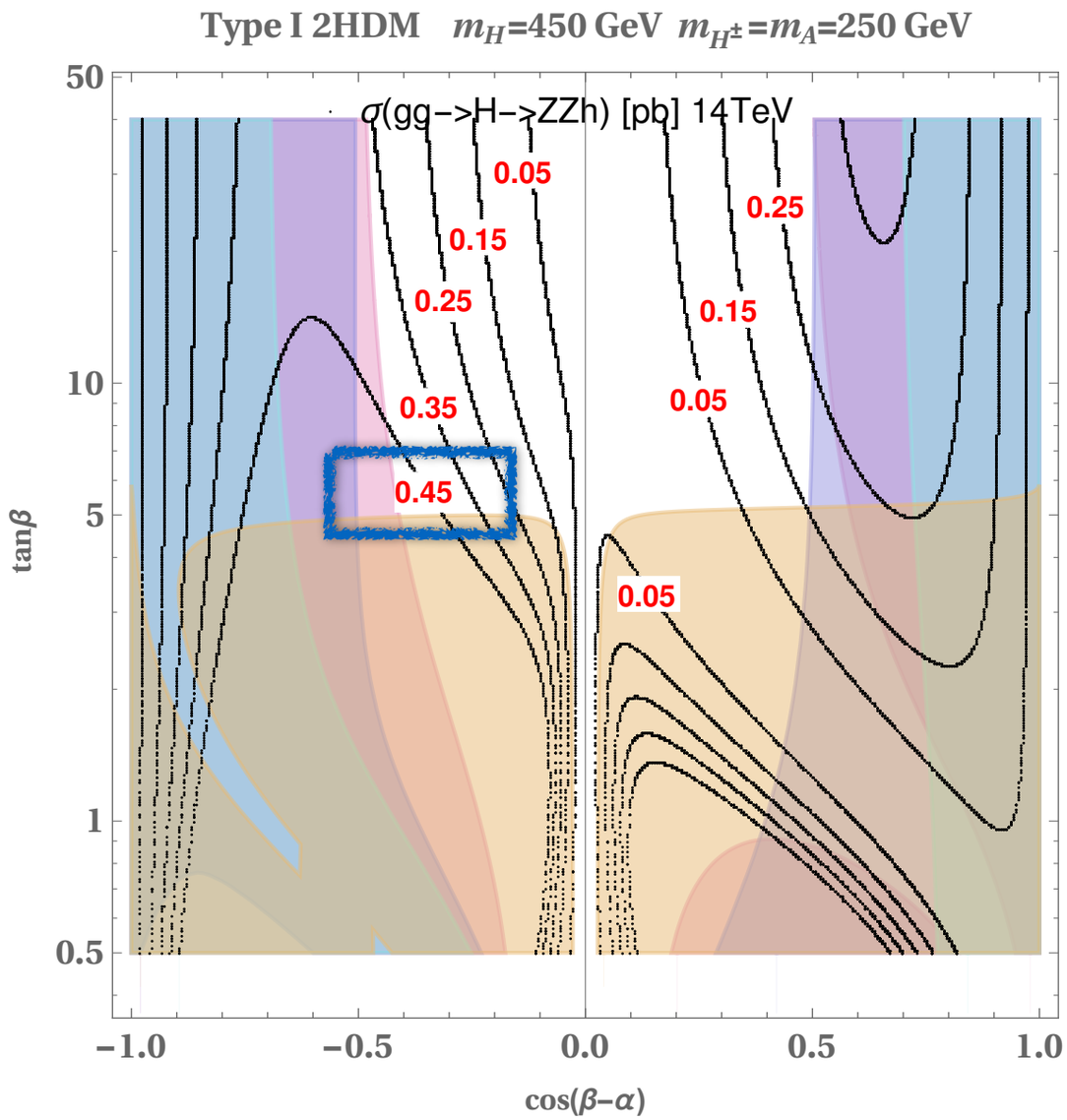

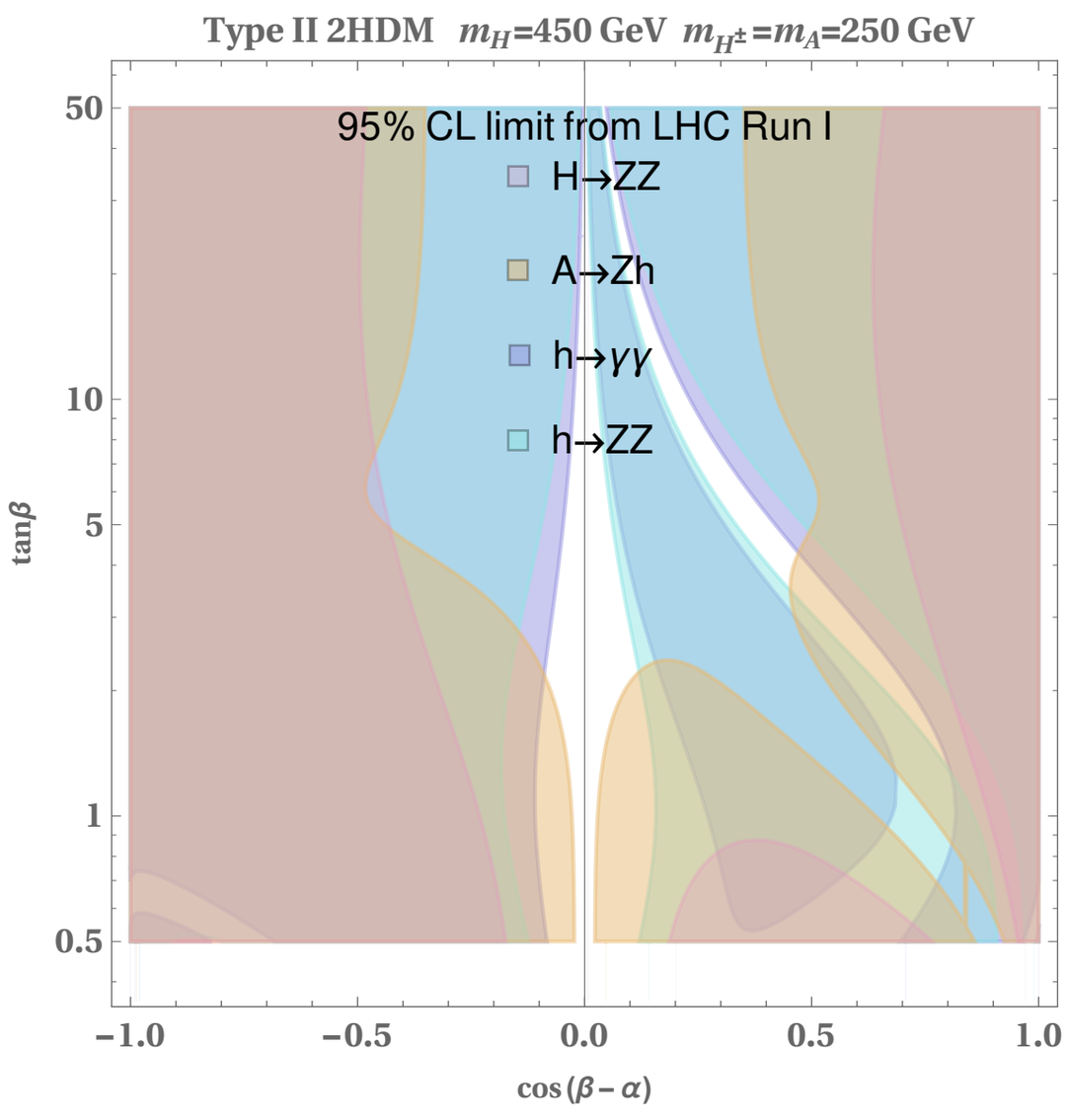

Search Channels

ZZh decay modes	Comments	Significance
$(\ell^+\ell^-)(\ell^+\ell^-)(b\bar{b})$	clean, ideal for reconstruction	11σ
$(\ell^+\ell^-)(jj)(b\bar{b})$	large signal and background	3.6σ
$(\ell^+\ell^-)(\nu\nu)(b\bar{b})$	overwhelmed by $t\bar{t}$ background	small
$(\ell^+\ell^-)(jj)(\tau_h\tau_h)$	overwhelmed by jet-faked τ background	0.7σ
$(\ell^+\ell^-)(\nu\nu)(\tau_h\tau_h)$	not enough signal yield	small
$(\ell^+\ell^-)(jj)(\gamma\gamma)$	relatively clean, small signal cross section	1.7σ
$(\nu\nu)(jj)(\gamma\gamma)$	hard to reconstruct	0.5σ
$(\ell^+\ell^-)(\nu\nu)(\gamma\gamma)$	clean but very small cross section	2.8σ
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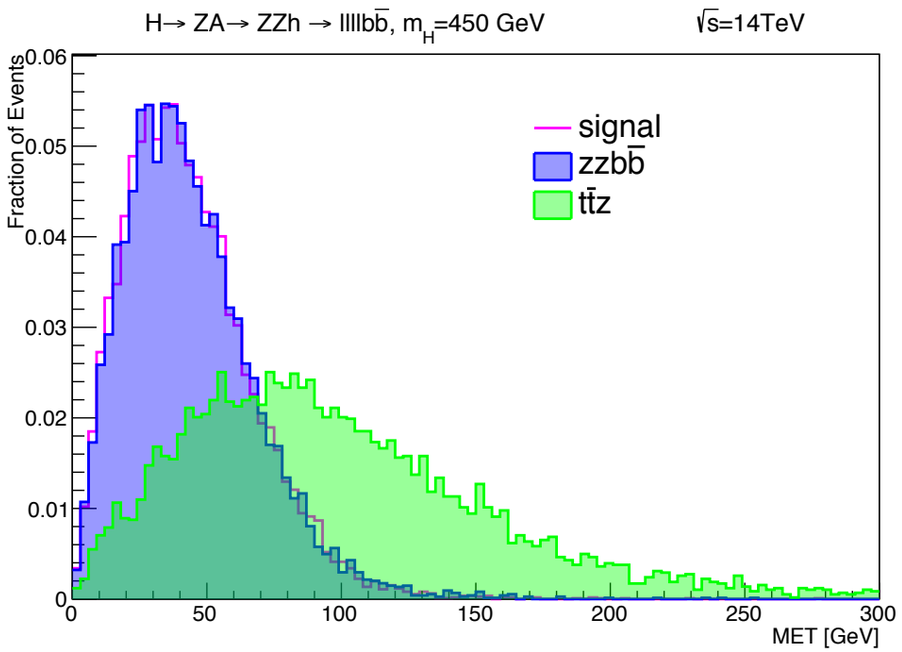
Golden Channel llllbb

- Z → ll, Z → ll, h → bb channel:
  - Main backgrounds: $ZZ + b\bar{b}$ and $t\bar{t} + Z$
  - Requirements:
    - 2 b-tagged jets
    - 2 opposite-sign same-flavor (OSSF) isolated lepton pairs.
    - $p_T(l_1) > 20\ GeV, p_T(l_2) > 15\ GeV, p_T(l_{3/4}) > 10\ GeV$
  - Kinematics
    - Mass resonance of lepton pairs, bottom pairs.
    - Missing ET
    - Reconstructed mass of pseudoscalar A and heavy higgs H.

Golden Channel llllbb



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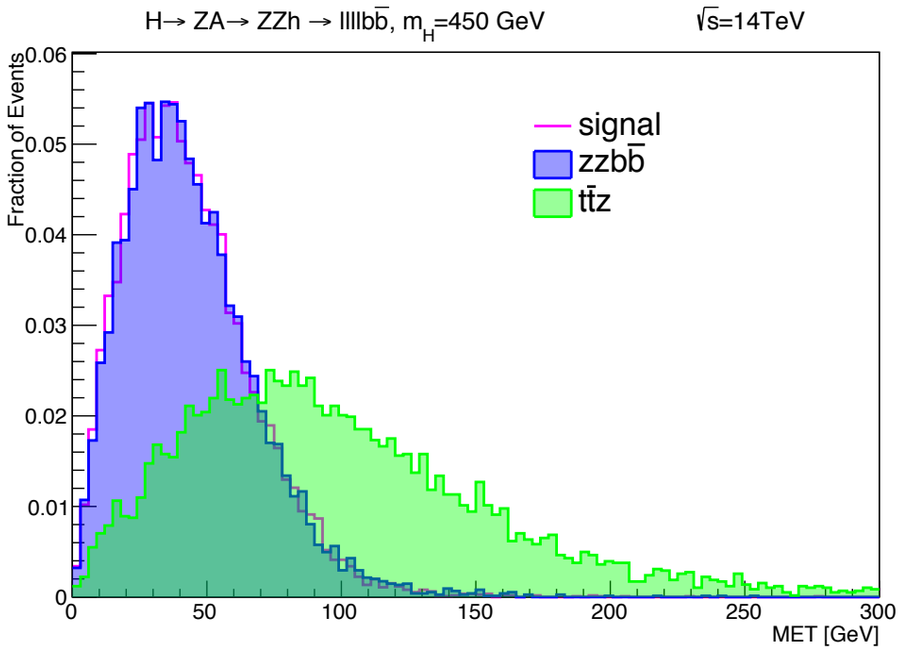

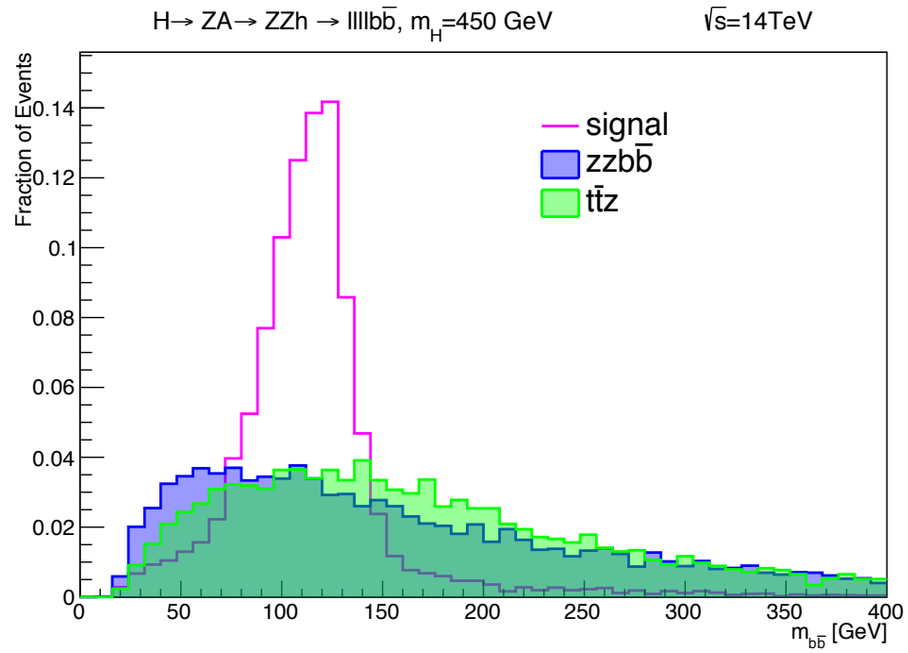

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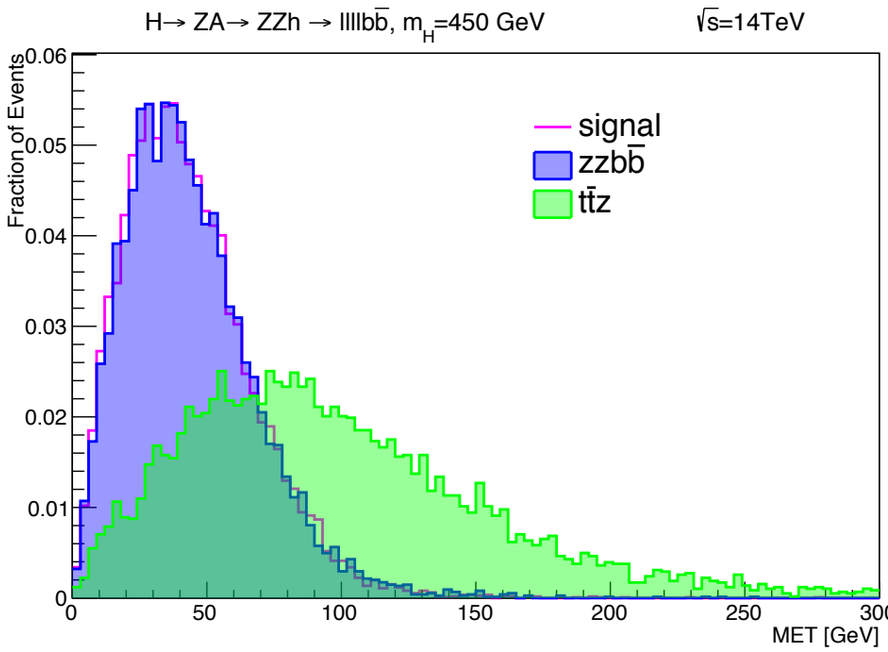

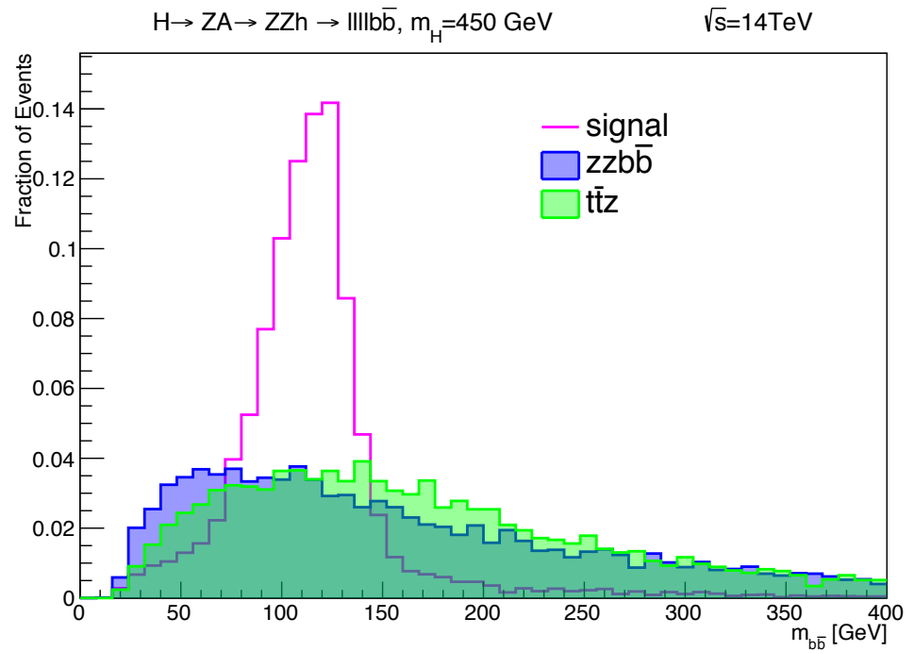

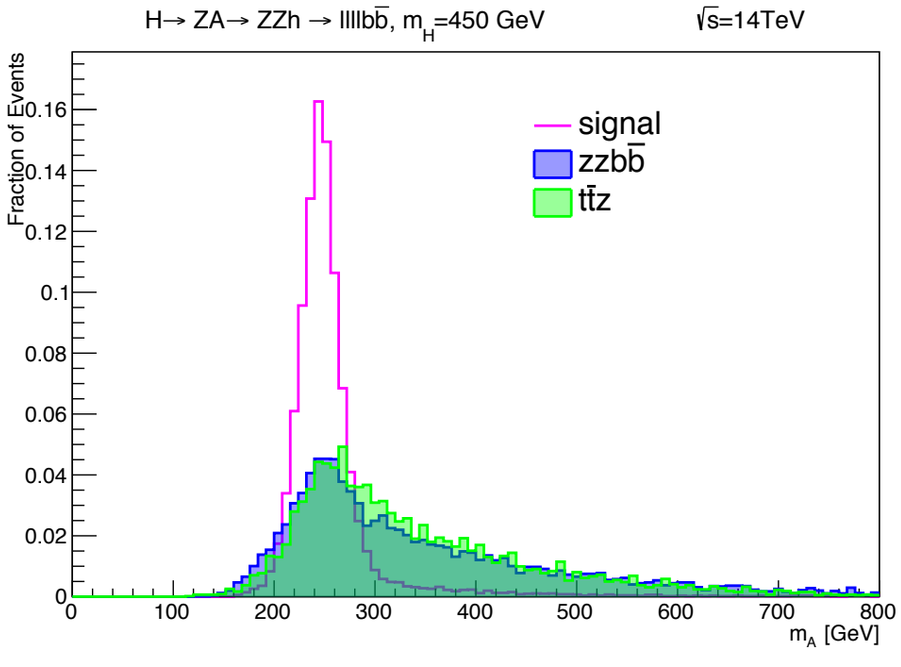

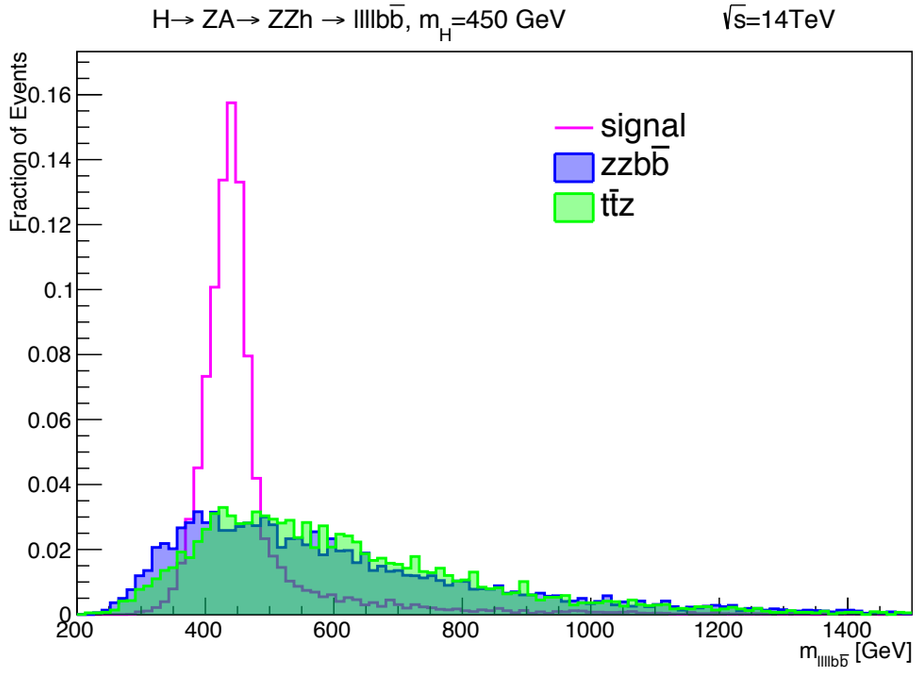

Golden Channel

# Selection	0 Initial	1 $\ell^+\ell^-\ell^+\ell^-b\bar{b}$	2 $m_{b\bar{b}}$	3 $m_{\ell^+\ell^-}$	4 $\not{E}_{\mathrm{T}}$	5 m_A	6 m_H
Signal	353	39.5	33.6	31.8	29.5	28.4	23.9
ttZ	643	37.5	14.3	3.77	1.51	1.20	0.53
$ZZb\bar{b}$	81.6	6.09	2.18	2.06	1.70	1.16	0.43
Total background	725	43.6	16.5	5.83	3.21	2.35	0.96

Cut flows after each selection. The signal and background yields are estimated for an integrated luminosity of 300/fb.

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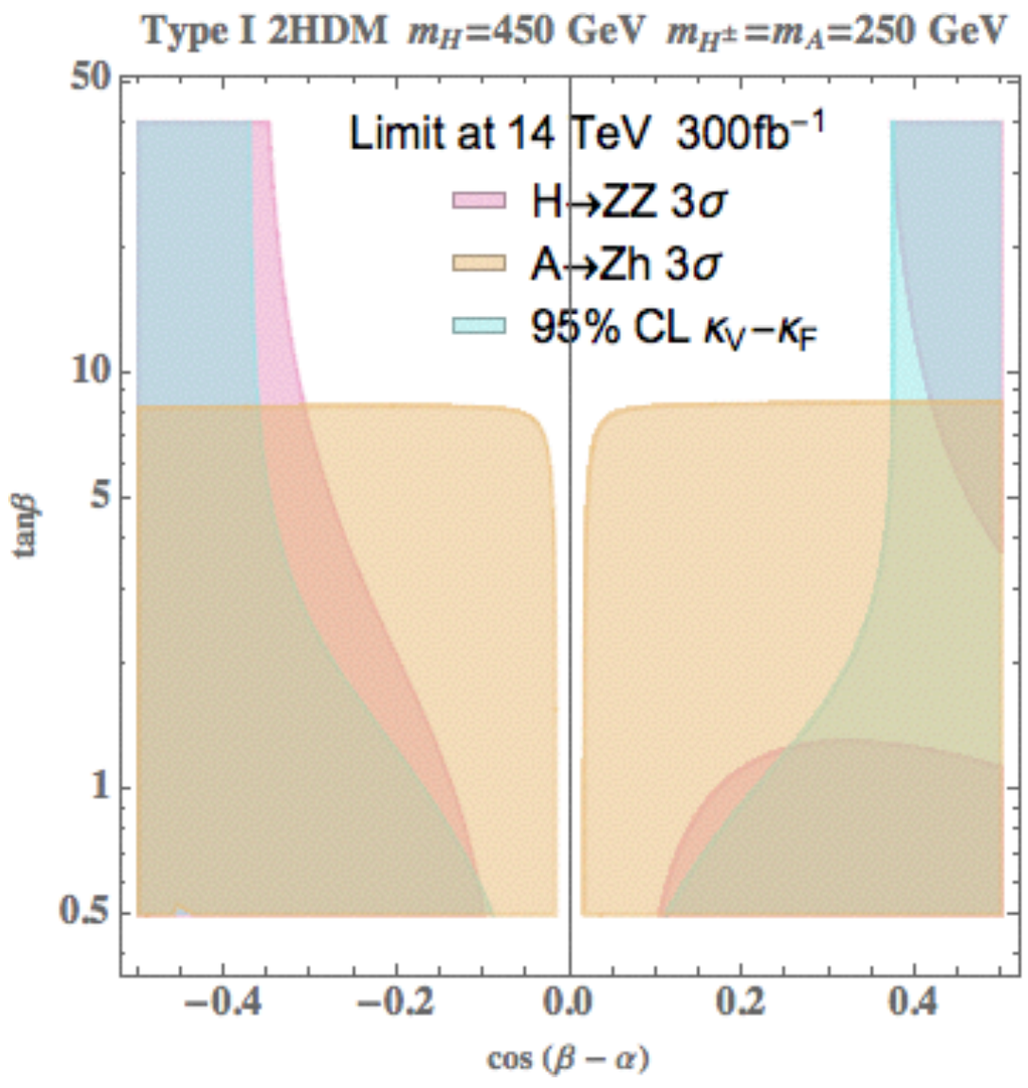
Results of Benchmark

m_A=250 GeV m_H=450 GeV σ(ZZh)=0.45pb

Channel	14 TeV 300fb^{-1}			14 TeV 3000fb^{-1}		
	Sig Yields	Bkg Yields	Significance	Sig Yields	Bkg Yields	Significance
$\ell^+\ell^-\ell^+\ell^- b\bar{b}$	24	0.96	11 σ	240	9.6	34 σ
$\ell^+\ell^- jjb\bar{b}$	495	1.9×10^4	3.6 σ	4950	1.9×10^5	11 σ
$\ell^+\ell^-\ell^+\ell^- + \not{E}_T$	9.7	18	2.1 σ	97	180	6.6 σ
$\ell^+\ell^-\nu\nu\gamma\gamma$	2.1	0.14	2.8 σ	21	1.4	9.1 σ
$\ell^+\ell^- jj\gamma\gamma$	5.7	9.6	1.7 σ	57	96	5.3 σ

Combining channels give 3σ (5σ) significance at 24/fb (54/fb)

Results of Benchmark



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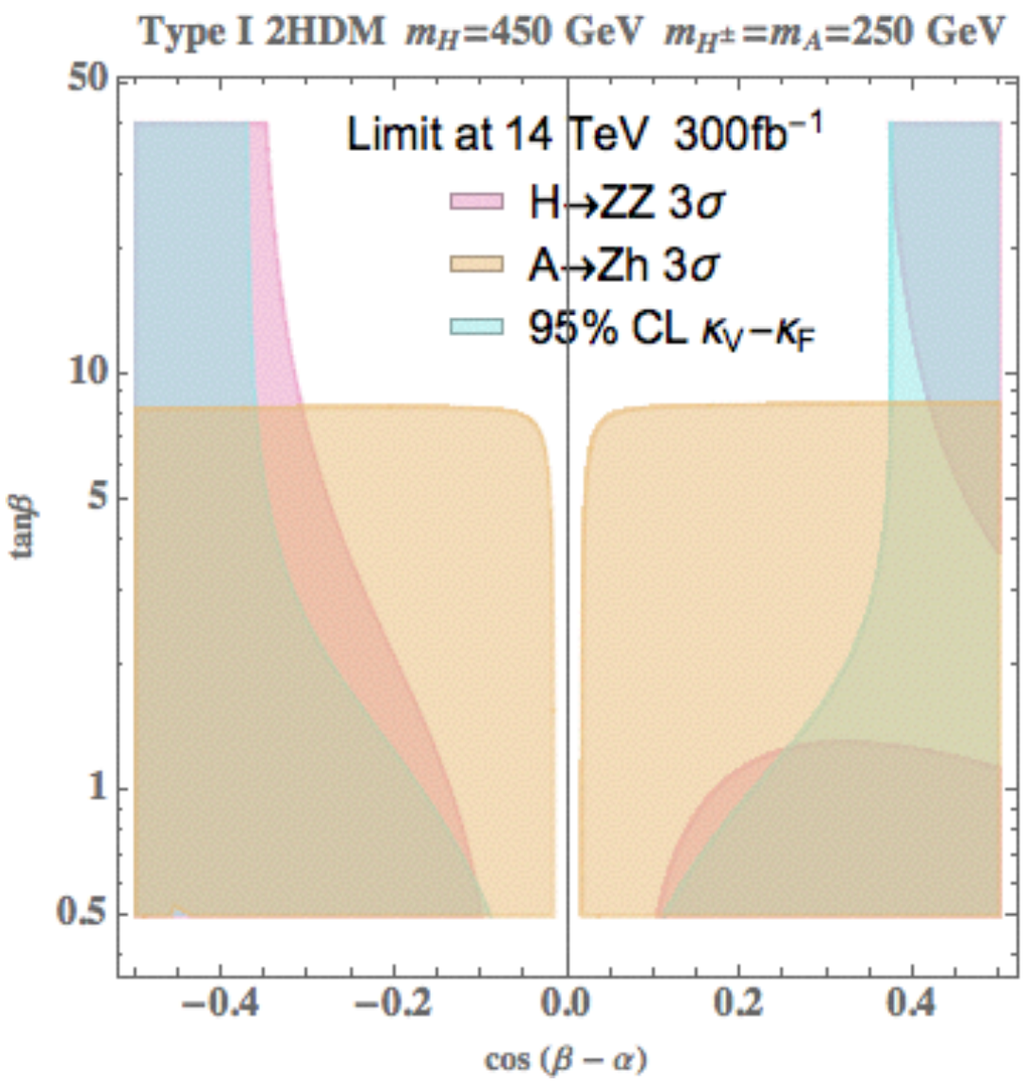

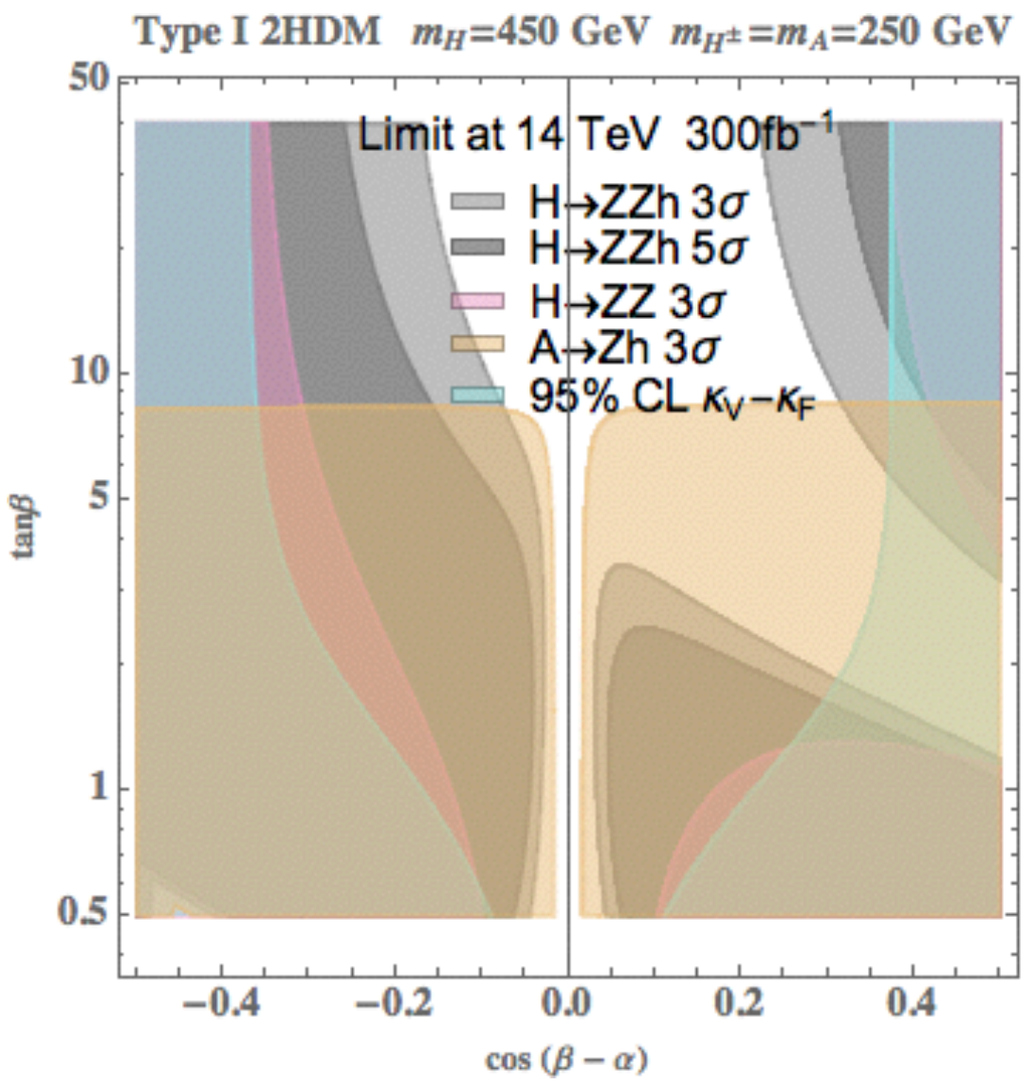

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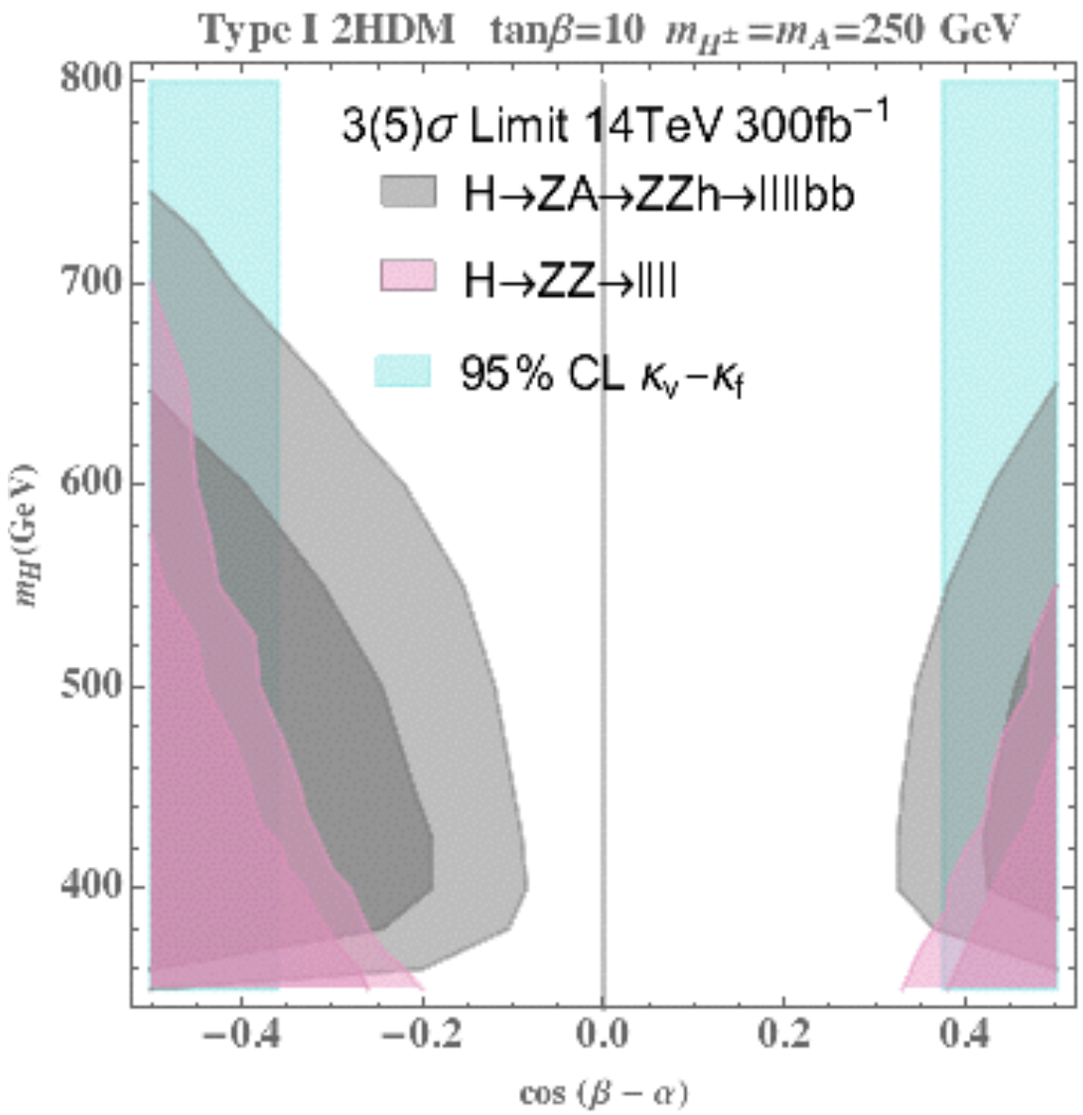
Mass Scan of m_H



m_A=250 GeV tanβ=10

Conclusion

- $gg \rightarrow H \rightarrow ZA \rightarrow ZZh$ could be the discovery mode for additional Higgs boson at LHC Run-II.
- For the benchmark $m_H = 450$ GeV and $m_A = 250$ GeV, the channel llllbb performs the best, with 11σ for 300/fb at 14 TeV.
- At 14 TeV the search is competitive with direct H searches and can be the most sensitive probe of 2HDM type I at high $\tan\beta(\geq 8)$.
- The mass reach persists for values up to 650 GeV.
- The searches for ZZh are highly motivated at LHC Run-II.

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Thanks!