Benchmarks for 2HDM Searches @ LHC:

The Hierarchical 2HDM & EW Phase Transition

G. Dorsch, S. Huber, K. Mimasu, J. M. No

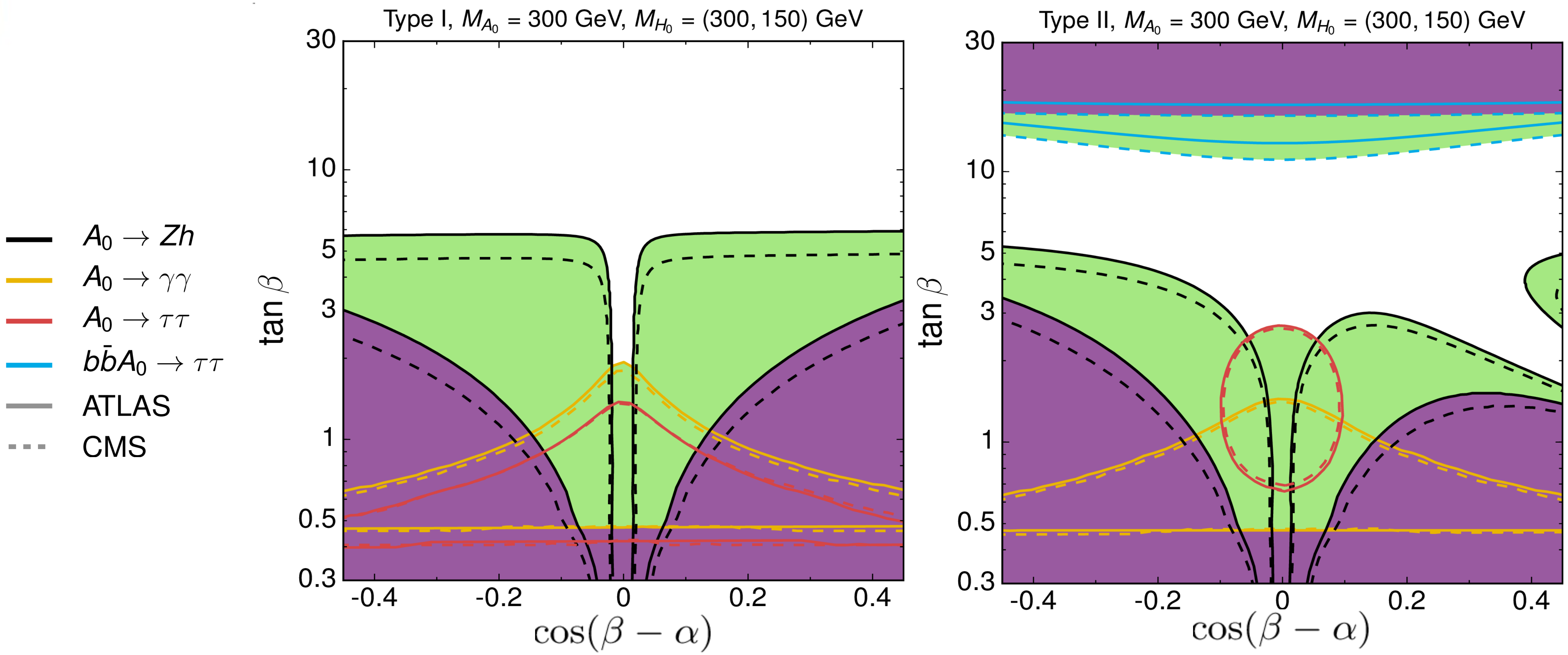
Based on 1405.5537 (PRL), 1507.xxxxx

LHCHXSWG3 Benchmarks2HDM

Mass splittings among H_0, A_0, H^+ have large impact in 2HDM phenomenology

FOR SIZABLE MASS SPLITTINGS, LIMITS FROM "STANDARD" LHC SEARCHES MAY BE SIGNIFICANTLY WEAKENED

e.g. $m_{A_0} - m_{H_0} > m_Z$ $A_0 \to H_0\, Z$ channel open BR to other decay channels drastically reduced



SusHi (NNLO) + 2HDMC

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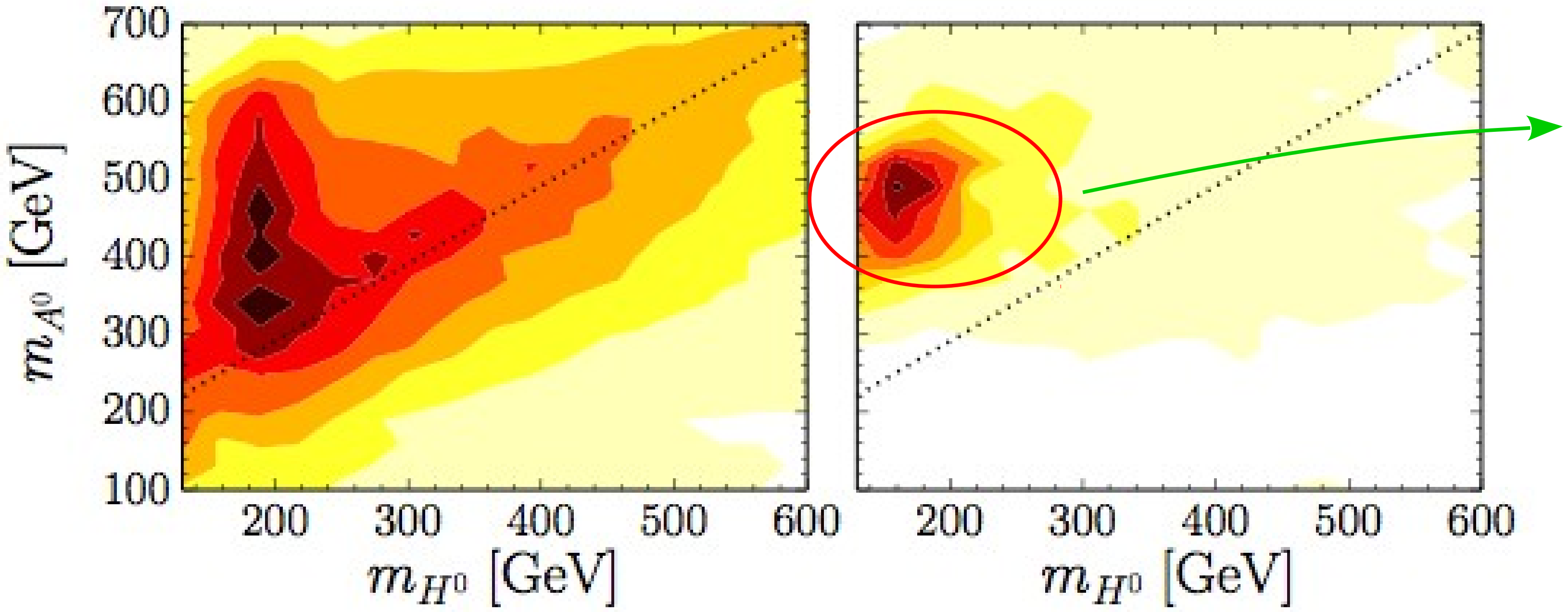
Mass splittings among H_0, A_0 Important for 2HDM Cosmology

A SIZABLE $m_{A_0} - m_{H_0}$ FAVOURS A FIRST ORDER EW PHASE TRANSITION

ELECTROWEAK BARYOGENESIS POSSIBLE WITHIN **2HDM**

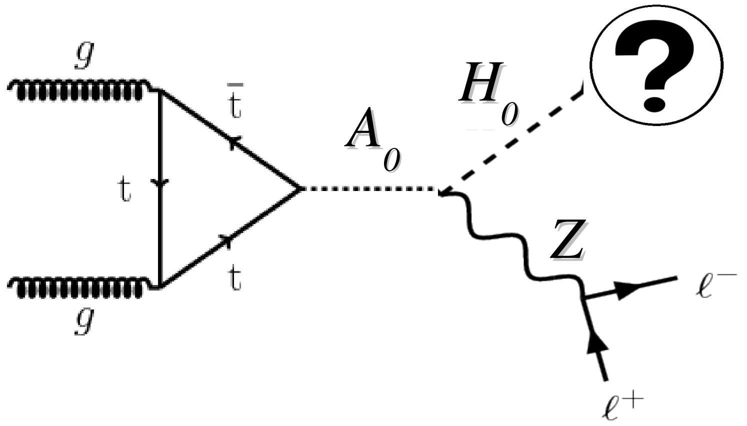


$m_{A_0} - m_{H_0} \sim v$

(& $m_{A_0} > 300$ GeV)

EW PHASE TRANSITION SIGNATURE

$$A_0 \rightarrow H_0\, Z$$



$\bar{b}b$

or

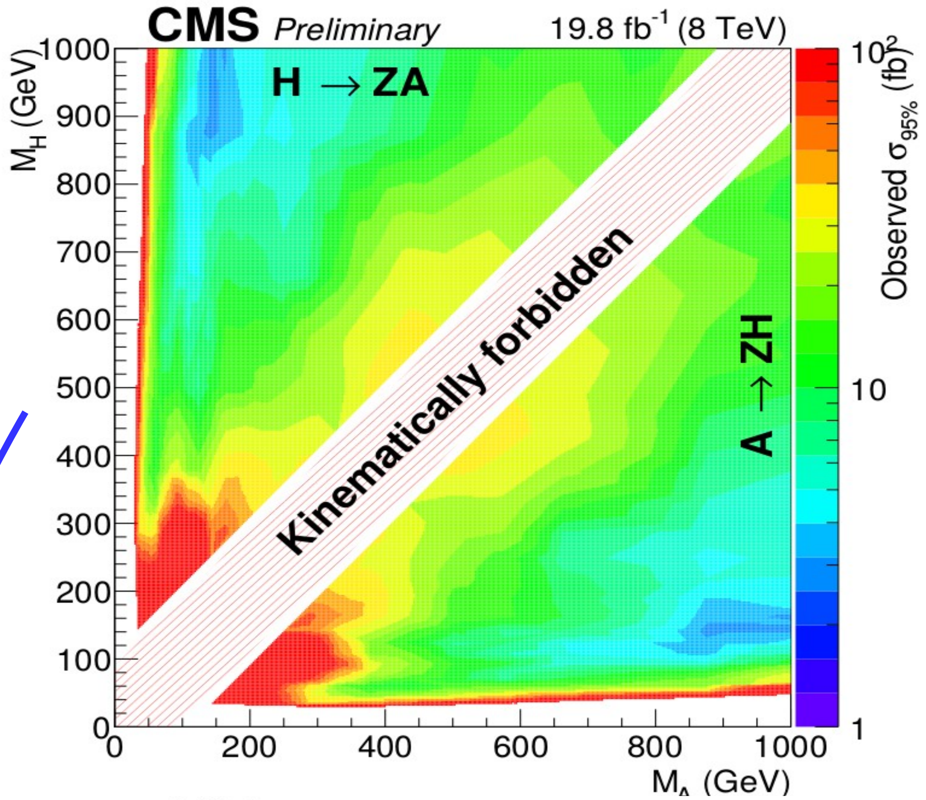
WW, ZZ

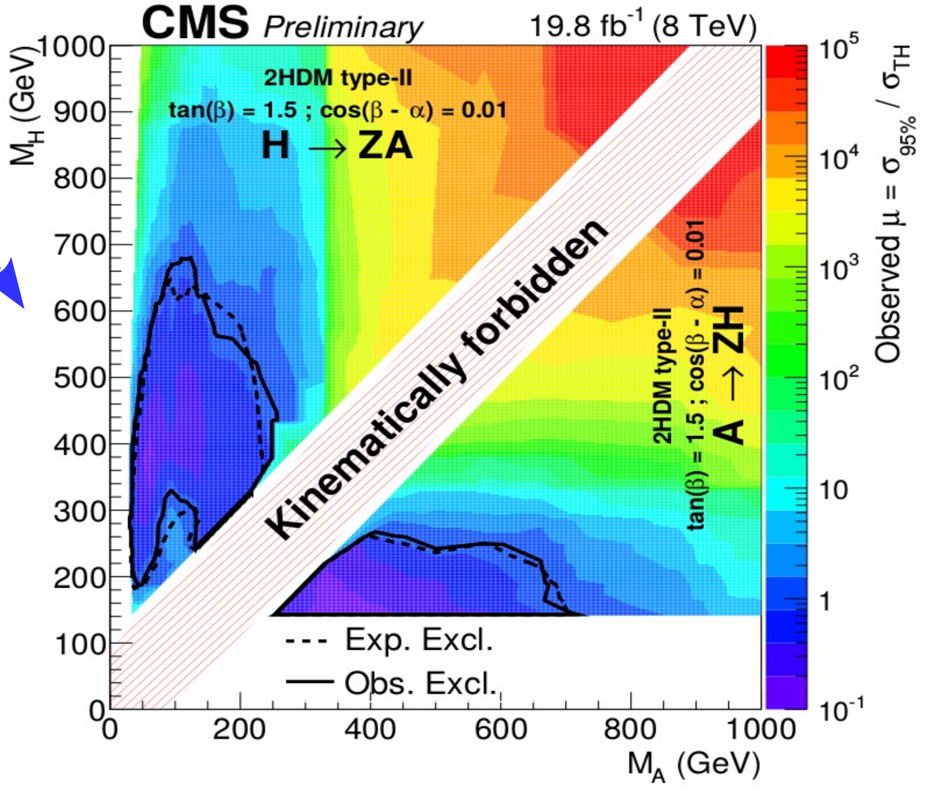
G. Dorsch, S. Huber, K. Mimasu, J. M. N, Phys. Rev. Lett. ***113*** *(2014) 211802*

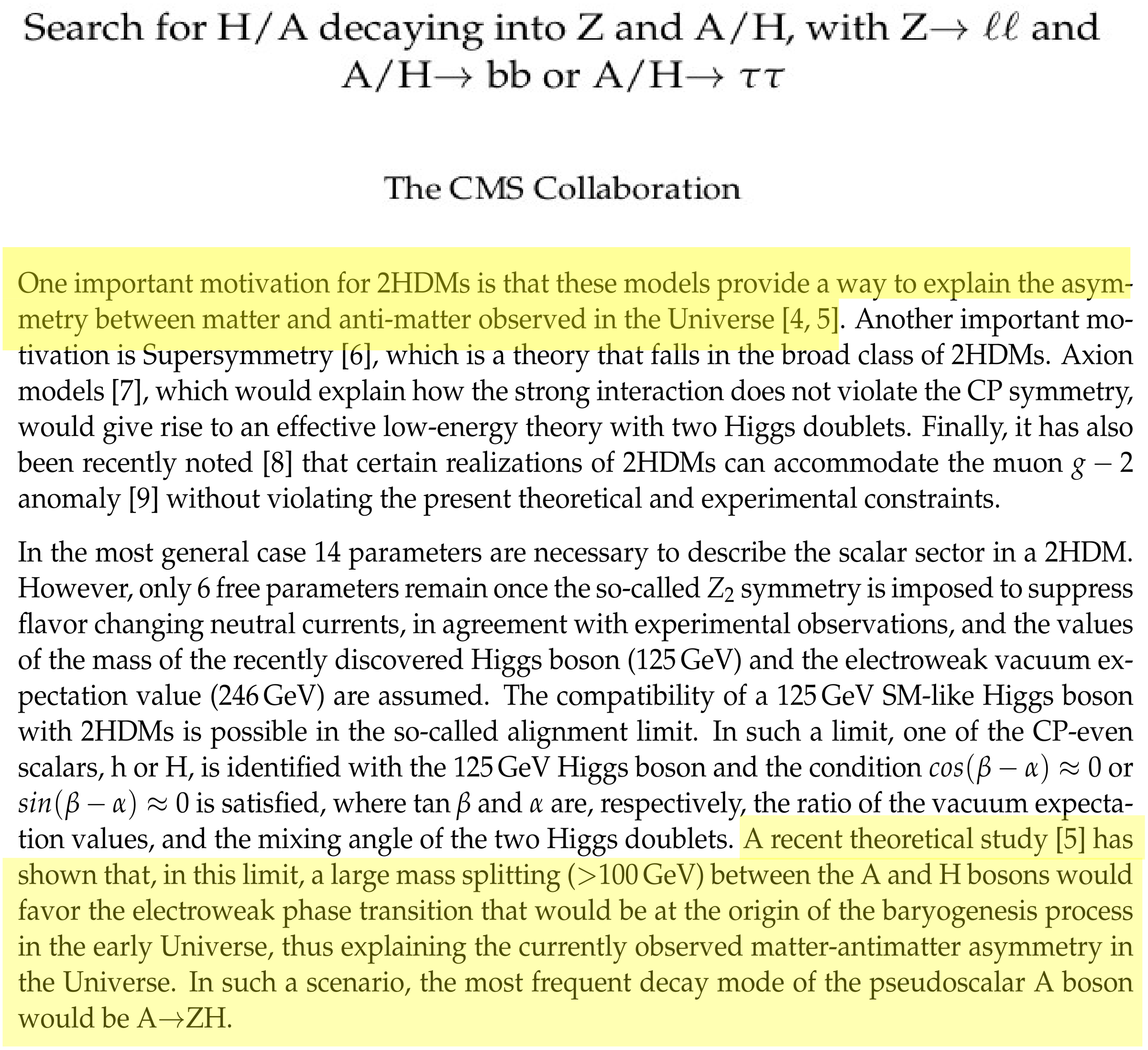
Such search(es) recently performed by CMS

(Meaningful constraints from LHC Run 1)

CMS-PAS-HIG-15-001







Search for H/A decaying into Z and A/H, with $Z\rightarrow \ell\ell$ and A/H→ bb or A/H→ $\tau\tau$

The CMS Collaboration

One important motivation for 2HDMs is that these models provide a way to explain the asymmetry between matter and anti-matter observed in the Universe [4, 5]. Another important motivation is Supersymmetry [6], which is a theory that falls in the broad class of 2HDMs. Axion models [7], which would explain how the strong interaction does not violate the CP symmetry, would give rise to an effective low-energy theory with two Higgs doublets. Finally, it has also been recently noted [8] that certain realizations of 2HDMs can accommodate the muon $g-2$ anomaly [9] without violating the present theoretical and experimental constraints.

In the most general case 14 parameters are necessary to describe the scalar sector in a 2HDM. However, only 6 free parameters remain once the so-called Z_2 symmetry is imposed to suppress flavor changing neutral currents, in agreement with experimental observations, and the values of the mass of the recently discovered Higgs boson (125 GeV) and the electroweak vacuum expectation value (246 GeV) are assumed. The compatibility of a 125 GeV SM-like Higgs boson with 2HDMs is possible in the so-called alignment limit. In such a limit, one of the CP-even scalars, h or H, is identified with the 125 GeV Higgs boson and the condition $cos(\beta-\alpha) \approx 0$ or $sin(\beta-\alpha) \approx 0$ is satisfied, where $\tan\beta$ and α are, respectively, the ratio of the vacuum expectation values, and the mixing angle of the two Higgs doublets. A recent theoretical study [5] has shown that, in this limit, a large mass splitting (>100 GeV) between the A and H bosons would favor the electroweak phase transition that would be at the origin of the baryogenesis process in the early Universe, thus explaining the currently observed matter-antimatter asymmetry in the Universe. In such a scenario, the most frequent decay mode of the pseudoscalar A boson would be A→ZH.

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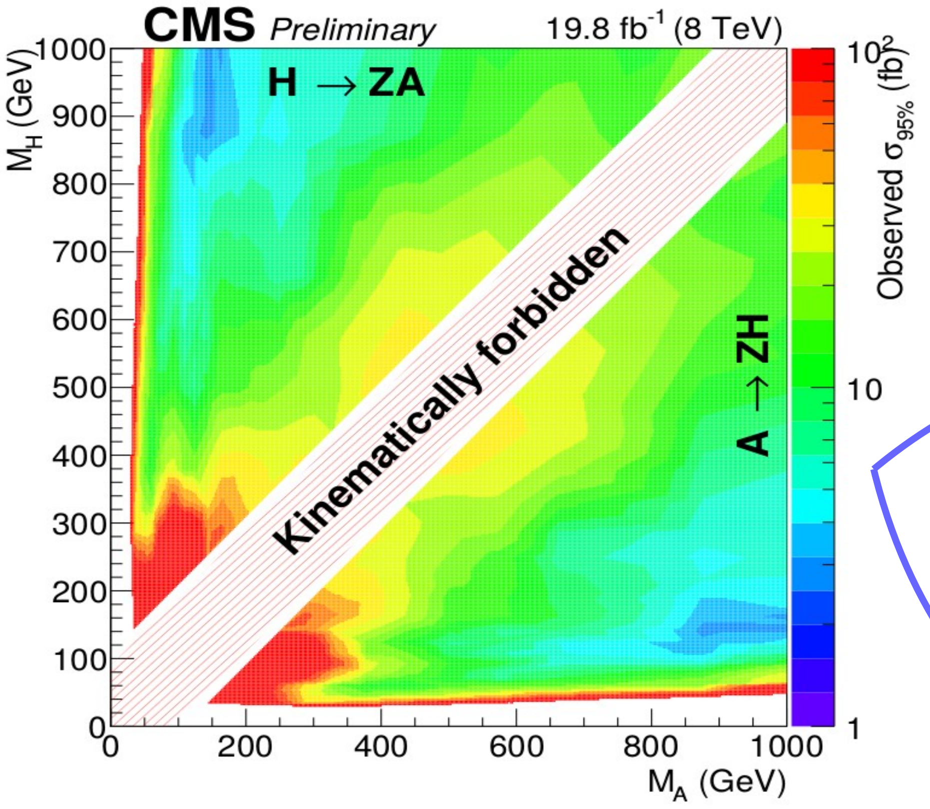

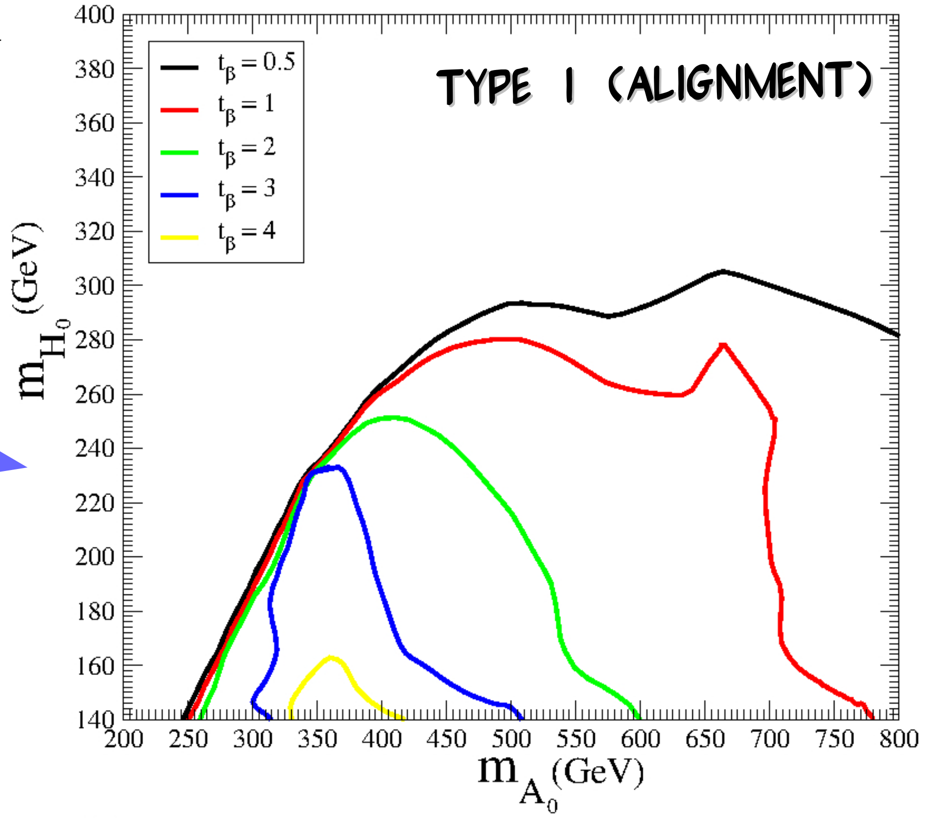

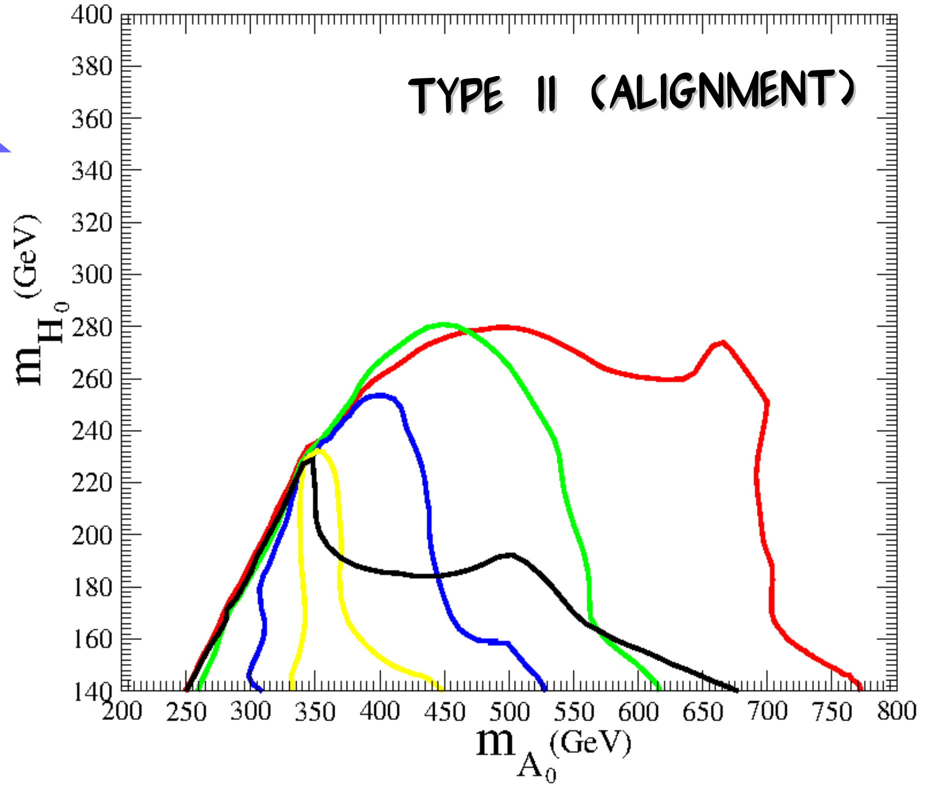

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SusHi (NNLO) + 2HDMC

This search constrains/"rules out":
→ A1, A2 from GHMN
→ BP1, BP2, BP3, BP4, BP8, BP10 from KS
→ Scenario D from HS

Benchmarks for 2HDM from the Electroweak Phase Transition

- ALL BENCHMARKS FEATURE $m_{A_0} - m_{H_0} > m_Z$

  $A_0 \to H_0 Z$ as primary signature

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- BENCHMARKS **A** → *Close to Alignment Limit* $\cos(\beta - \alpha) = 0$

  $H_0 \to \bar{b}b \;\; (m_{H_0} < 340 \text{ GeV}), \qquad H_0 \to \bar{t}t \;\; (m_{H_0} > 340 \text{ GeV})$

  H^+ needs to be close in mass to either H_0 or A_0 , due to EW Precision Observables

A1 : $m_{A_0} = m_{H^\pm} = 420 \text{ GeV} \quad m_{H_0} = 180 \text{ GeV} \quad \tan(\beta) = 3$

TYPE I $\sigma_{gg}^{A_0} = 2.795 \text{ pb} \quad Br(A_0 \to Z\, H_0) = 0.8433 \quad Br(H_0 \to \bar{b}b) = 0.711$

TYPE II $\sigma_{gg}^{A_0} = 2.837 \text{ pb} \quad Br(A_0 \to Z\, H_0) = 0.8383 \quad Br(H_0 \to \bar{b}b) = 0.899$

A2 : $m_{A_0} = 420 \text{ GeV} \quad m_{H_0} = m_{H^\pm} = 180 \text{ GeV} \quad \tan(\beta) = 3$

TYPE I $\sigma_{gg}^{A_0} = 2.795 \text{ pb} \quad Br(A_0 \to Z\, H_0) = 0.3016 \quad Br(H_0 \to \bar{b}b) = 0.711$

$Br(A_0 \to W^\pm H^\mp) = 0.642 \quad Br(H^+ \to \bar{b}t) = 0.992$

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Similar to BP1 from KS. Regarding topology and final state (bb ll), similar to BP2, BP3, BP4, BP8 from KS, and Scenario D from HS

A2 : $m_{A_0} = 420 \text{ GeV} \quad m_{H_0} = m_{H^\pm} = 180 \text{ GeV} \quad \tan(\beta) = 3$

Interesting signatures from H^+ in both Cases, similar to those Shufang will discuss (BP1-BP8).

Benchmarks for 2HDM from the Electroweak Phase Transition

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$H_0 \to W^+W^-$
- $4\ell + 2\nu$ *Final State*
- $3\ell + \nu + 2\,j$ *Final State*

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$H_0 \to ZZ$
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B. Coleppa, F. Kling, S. Su, 1404.1922

Such departure from Alignment possible for Type I (Type II in "wrong sign")

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B1 : $m_{A_0} = m_{H^\pm} = 400\ \text{GeV} \quad m_{H_0} = 180\ \text{GeV} \quad \tan(\beta) = 2 \quad \sin(\beta - \alpha) = 0.95$

$\sigma_{gg}^{A_0} = 8.158\ \text{pb} \quad Br(A_0 \to Z\,H_0) = 0.584 \quad Br(H_0 \to W^+W^-) = 0.936 \quad Br(H_0 \to ZZ) = 0.062$

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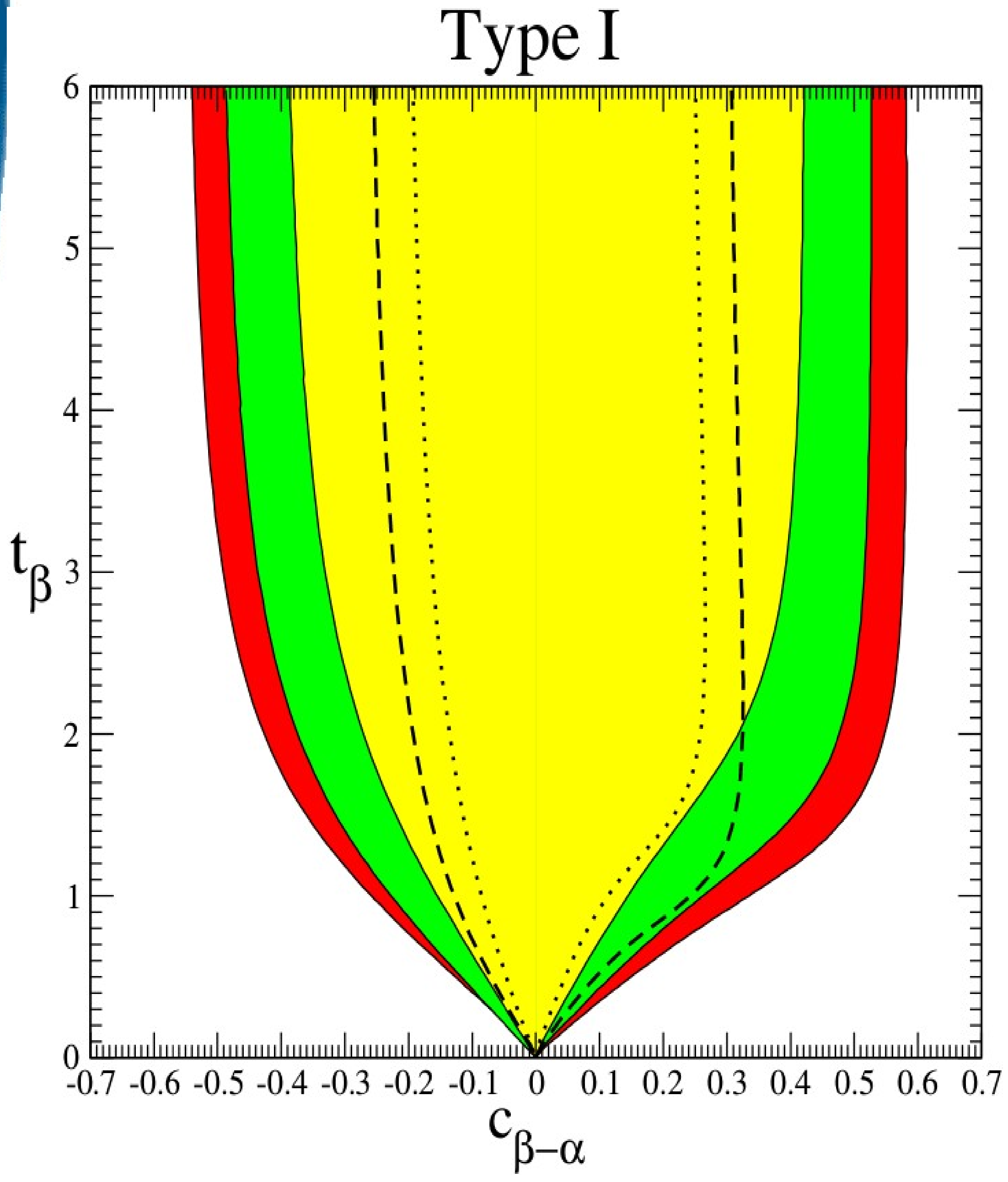
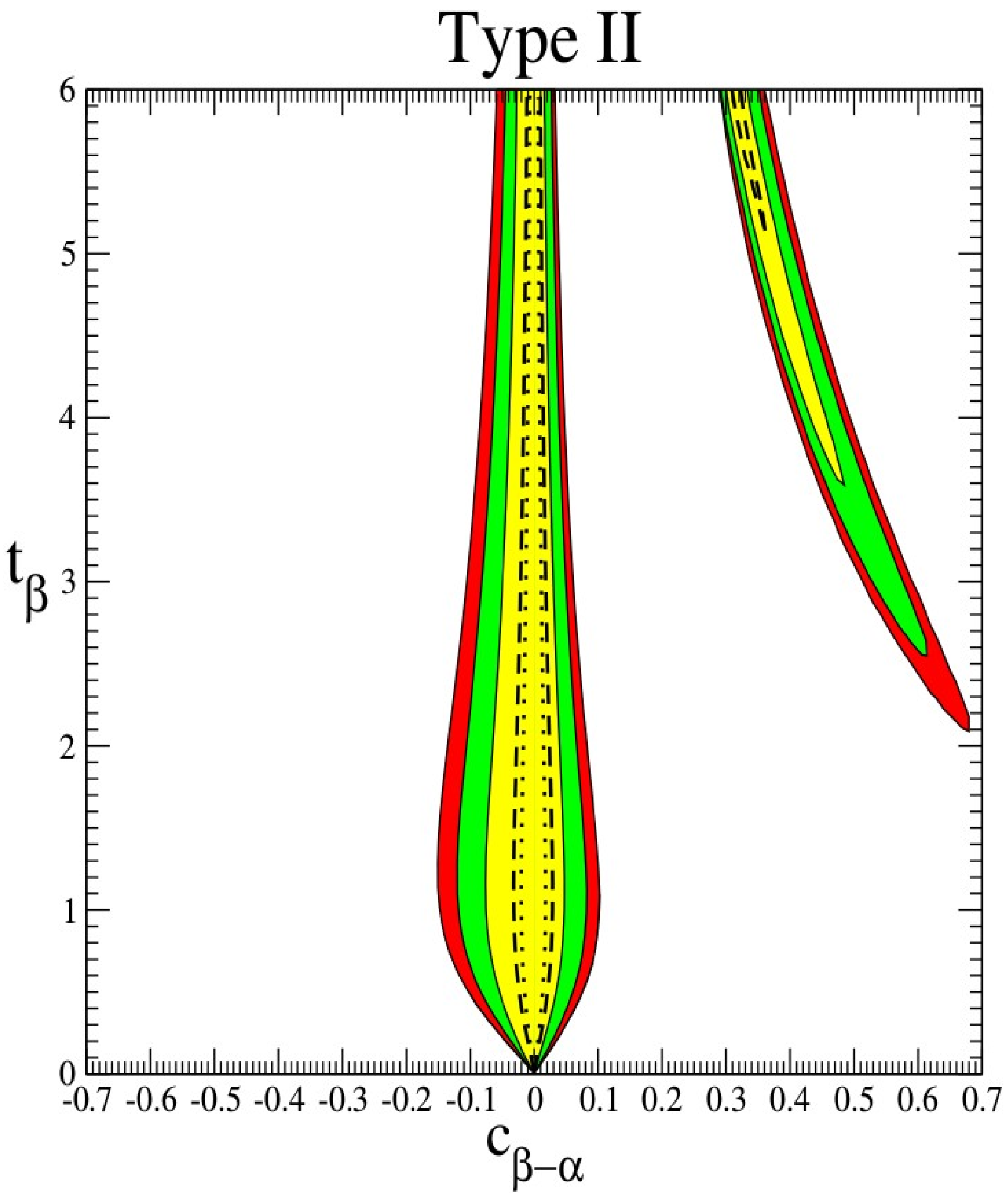
$m_{A_0} = m_{H^\pm} = 400\ \text{GeV} \quad m_{H_0} = 220\ \text{GeV} \quad \tan(\beta) = 2 \quad \sin(\beta - \alpha) = 0.95$

$\sigma_{gg}^{A_0} = 8.158\ \text{pb} \quad Br(A_0 \to Z\,H_0) = 0.446 \quad Br(H_0 \to W^+W^-) = 0.715 \quad Br(H_0 \to ZZ) = 0.285$

Back-up

Higgs Signal Strengths Fit


Type I


Type II

2HDM@LHC

LHC DISCOVERY POTENTIAL OF BENCHMARK SCENARIOS

❶ *A few words on the Analysis…*

⇨ Type I 2HDM implemented in **FeynRules** (including gluon-fusion).

⇨ Signal & relevant backgrounds generated using **MadGraph5_aMC@NLO**. Generated events passed on to **Pythia** for Parton Showering and Hadronization and subsequently to **Delphes** for detector simulation.

→ Use of NLO flat K-factors for signal (**SusHi**) and dominant backgrounds.

⇨ "Cut & Count" analysis on a small set of kinematical variables, to extract signal over background.

⇨ Determined required Integrated Luminosity at 14 TeV to achieve 5σ statistical significance via a C.L.s hypothesis test.

Only statistical uncertainties.

10% systematic uncertainty on background.

2HDM@LHC

LHC DISCOVERY POTENTIAL OF BENCHMARK SCENARIOS

❸ *Benchmark B*: $A_0 \to H_0\, Z \to W^+W^-\ell\ell \to 4\ell + 2\nu$ (α-β = 0.1π)

- ➪ Most sensitive A_0 search channel away from alignment
- ➪ $A_0 \to H_0\, Z \to ZZ\ell\ell \to 4\ell + 2j$ *also promising*

  *B. Coleppa, F. Kling, S. Su, JHEP **1409** (2014) 161*
- ➪ *Main backgrounds are* ZZ, $\underline{Zt\bar{t}\ hZ,\ ZWW}$ subdominant
- ➪ *Analysis & Event Selection similar to previous case:*
  - → 4 Isolated (cone of 0.3) leptons, same-flavour pairs. $|\eta| < 2.5\ (2.7)$ for electrons (muons)
  - → $P_T^{\ell_1} > 40$ GeV, $P_T^{\ell_{2,3,4}} > 20$ GeV.

→ *1 pair of SF leptons must reconstruct* m_Z

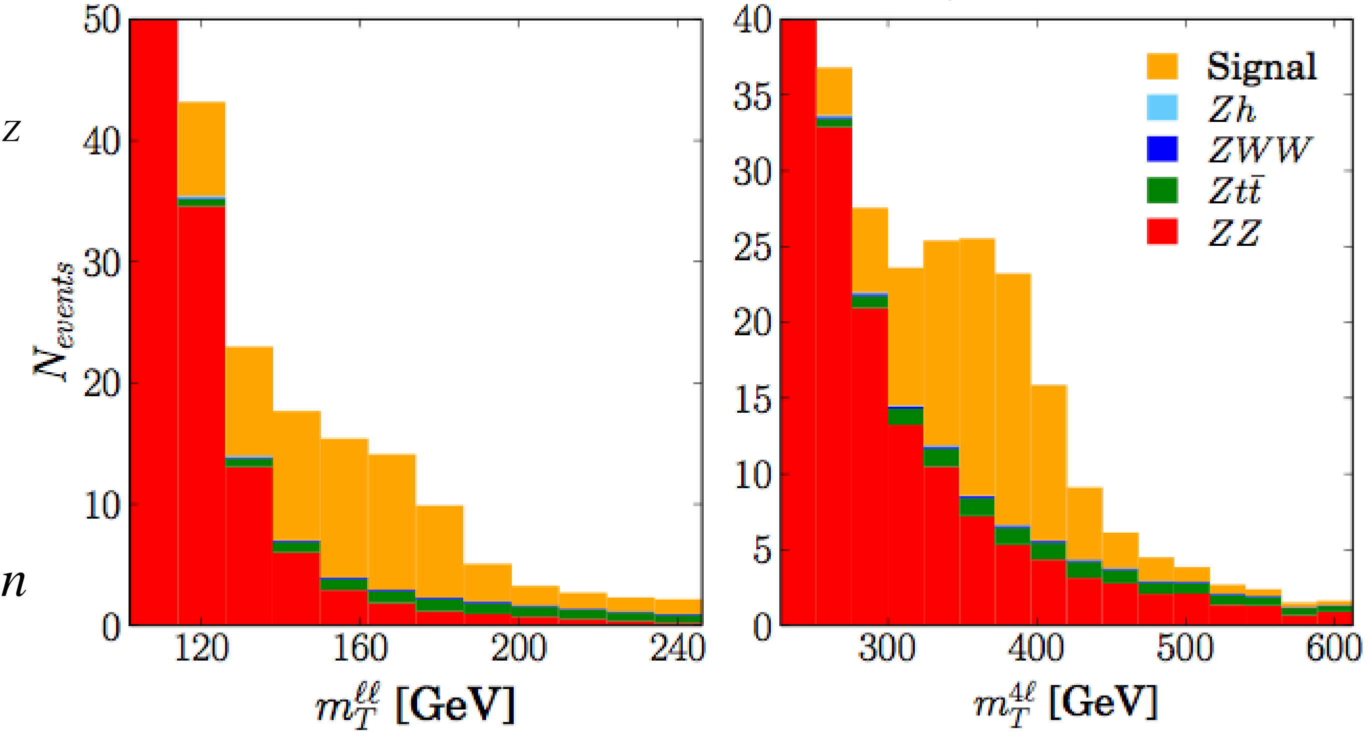
→ *Transverse mass variables*:

$$(m_T^{\ell\ell})^2 = \left(\sqrt{p_{T,\ell\ell}^2 + m_{\ell\ell}^2} + \not{p}_T\right)^2 - \left(\vec{p}_{T,\ell\ell} + \vec{\not{p}}_T\right)^2$$

$$m_T^{4\ell} = \sqrt{p_{T,\ell'\ell'}^2 + m_{\ell'\ell'}^2} + \sqrt{p_{T,\ell\ell}^2 + (m_T^{\ell\ell})^2}$$

$m_T^{4\ell} > 260$ *GeV allows for Signal Extraction*

14 TeV LHC, $\mathscr{L}$ = 60 fb^{-1}



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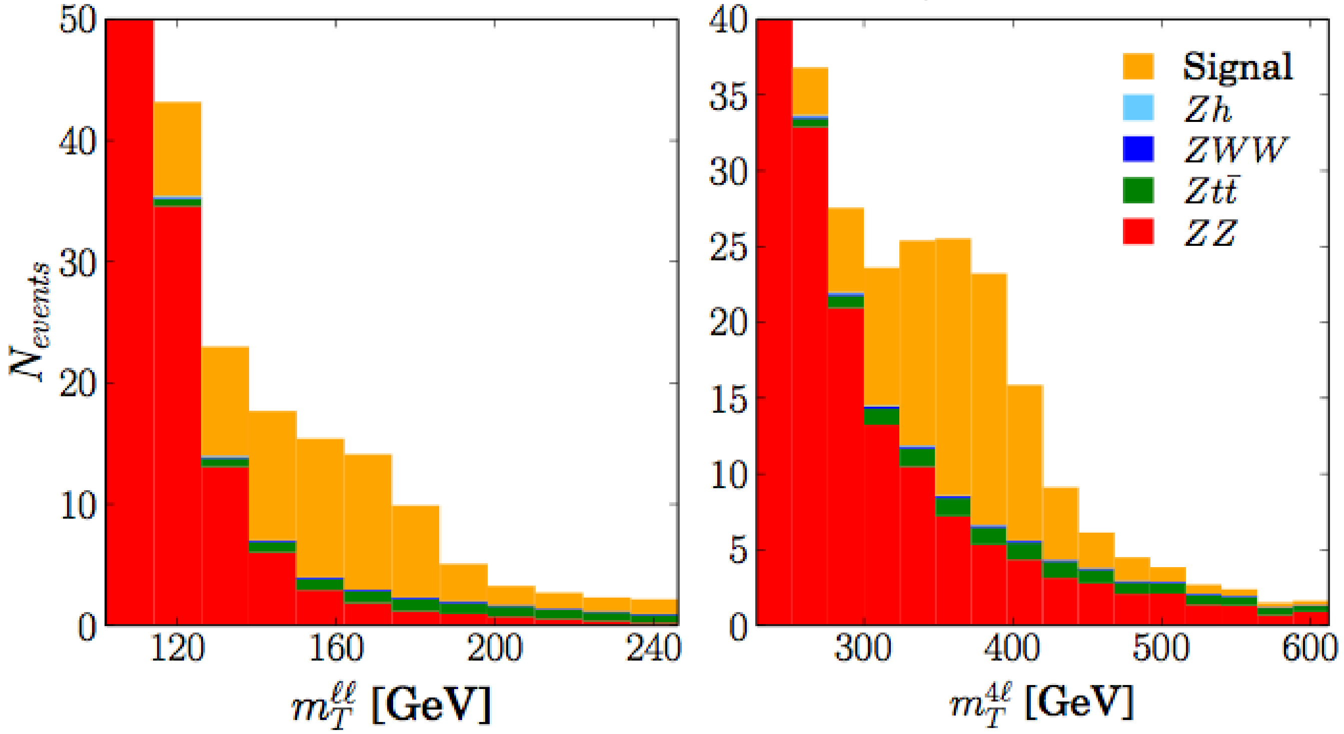
5σ signal significance for:

$\mathscr{L}$ = 60 fb^{-1} *(statistics only)*

$\mathscr{L}$ = 200 fb^{-1} *(10% systematics)*

(conservative..)

14 TeV LHC, $\mathscr{L}$ = 60 fb^{-1}



2HDM@LHC

LHC DISCOVERY POTENTIAL OF BENCHMARK SCENARIOS

❷ *Benchmark* A: $A_0 \rightarrow H_0\, Z \rightarrow \bar{b}b\, \ell\ell$ (α-β = 0.001π)

⇨ *Irreducible backgrounds are* $Z\bar{b}b,\ \bar{t}t,\ ZZ,\ hZ$

⇨ *Analysis at 14 TeV:* ***Event Selection***

→ *Anti-kT Jets with distance parameter* $R = 0.6$

→ 2 *b-tagged Jets with* |η| < 2.5

→ 2 *Isolated (within a cone of 0.3), Same-flavour leptons.* |η| < 2.5 (2.7) for electrons (muons)

→ $P_T^{\ell_1} > 40$ *GeV*, $P_T^{\ell_2} > 20$ *GeV*.

	Signal	$t\bar{t}$	$Z\,b\bar{b}$	ZZ	$Z\,h$
K-factor:	1.6	1.5	1.4	-	-
Event selection	14.6	1578	424	7.3	2.7
$80 < m_{\ell\ell} < 100$ GeV	13.1	240	388	6.6	2.5
$H_T^{bb} > 150$ GeV $H_T^{\ell\ell bb} > 280$ GeV	8.2	57	83	0.8	0.74
$\Delta R_{bb} < 2.5,\ \Delta R_{\ell\ell} < 1.6$	5.3	5.4	28.3	0.75	0.68
$m_{bb},\ m_{\ell\ell bb}$ signal region	3.2	1.37	3.2	< 0.01	< 0.02

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Invariant mass windows:

$$m_{\bar{b}b} \rightarrow (m_{H_0} - 20) \pm 30\,\mathrm{GeV}$$

$$m_{\ell\ell\bar{b}b} \rightarrow (m_{A_0} - 20) \pm 40\,\mathrm{GeV}$$

5σ signal significance for:

$\mathscr{L} \doteq 15\ fb^{-1}$ *(statistics only)*

$\mathscr{L} = 40\ fb^{-1}$ *(10% systematics)*

14 TeV LHC, $\mathscr{L}$ = 20 fb^{-1}