More Higgses at LHC:
The EW Road to Baryogenesis

Jose Miguel No, Sussex U.

Based on 1405.5537 (PRL), 1507.xxxxx with G. Dorsch, S. Huber, K. Mimasu.

Invisibles meets Visibles, 22nd June 2015

University of Sussex

MARIE CURIE ACTIONS

The SM is NOT the End of the Story...

- EW Hierarchy Problem... → Expect New Physics@TeV
- Dark Matter
- Neutrino Masses
- Matter-Antimatter Asymmetry → Baryogenesis

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$$

What is the Origin of the Baryon Asymmetry?

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What is the Origin of the Baryon Asymmetry?

<u>SAKHAROV CONDITIONS</u> *(for dynamical generation of baryon asymmetry)*

B Violation ✓ *Sphalerons*

*V. A. Kuzmin, V. A. Rubakov, M. Shaposhnikov, Phys. Lett. B**155** (1985) 36*

C/CP Violation *CKM*

Departure from Thermal Equilibrium *EW Phase Transition*

The SM is NOT the End of the Story...

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- ➪ **Matter-Antimatter Asymmetry → Baryogenesis**

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V. A. Kuzmin, V. A. Rubakov, M. Shaposhnikov, Phys. Lett. B**155** (1985) 36

C/CP Violation ✗ not enough
M. B. Gavela, P. Hernandez, J. Orloff, O. Pene, C. Quimbay, Nucl. Phys. B**430** (1994) 382

Departure from Thermal Equilibrium ✗ not enough
In the SM (m_h = 125 GeV) EW Phase Transition Smooth CrossOver
K. Kajantie, M. Laine, K. Rummukainen, M. Shaposhnikov, Phys. Rev. Lett. **77** (1996) 2887

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- C/CP Violation ?
- Departure from Thermal Equilibrium ?
  - New $\not{CP}$ Sources **EDMs**
  - EW Phase Transition **LHC**

BSM

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Departure from Thermal Equilibrium ?

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BSM

LHC Signatures Revealing
1^{st} Order EW Phase Transition

A 30s CRASH Course on the EW Phase Transition

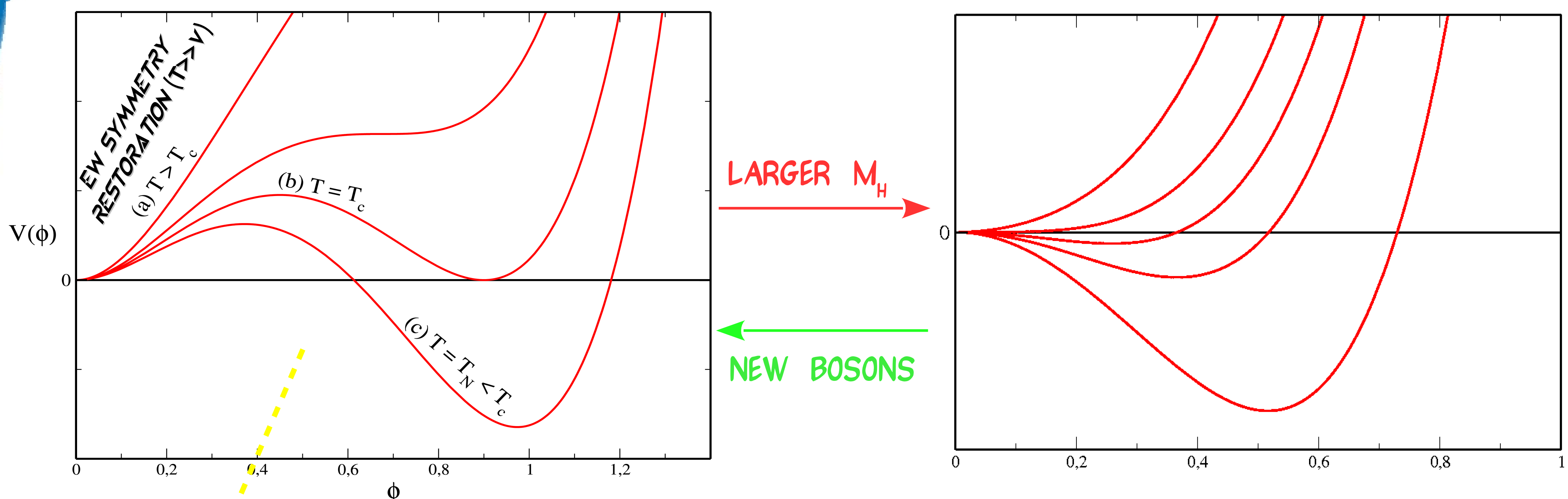
Universe Expands Adiabatically ⇨ *Equilibrium Thermal Field Theory*

Finite-T Effective Potential V(h,T) for the Higgs

$$V(h,T) \approx (a\,T^2 - \mu^2)\,h^2 - E(T)\,h^3 + \lambda(T)\,h^4$$

1st Order: $\langle\phi\rangle = \mathbf{0} \rightarrow \langle\phi\rangle = \phi(T)$ Discontinuous

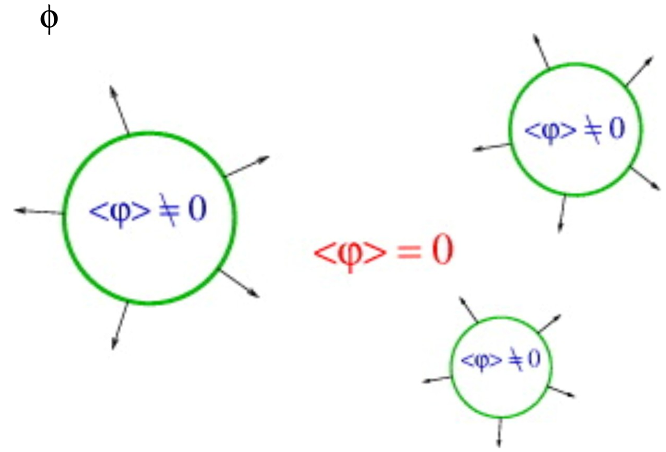
2nd Order: $\langle\phi\rangle = \mathbf{0} \rightarrow \langle\phi\rangle = \phi(T)$ Continuous



SM EW Phase Transition Smooth CrossOver for m_h > 80 GeV

K. Kajantie, M. Laine, K. Rummukainen, M. Shaposhnikov, Phys. Rev. Lett. **77** (1996) 2887

Bubble Nucleation & Growth



EW Scale Baryogenesis Needs:

- ➔ *New Bosons (EW Scale)*
- ➔ *Coupled to SM Higgs*

Strong 1st Order
EW Phase Transition

More Higgses!

Archetype Scenario: *Extended Higgs Sectors*

- SIMPLE EXTENSIONS OF THE SM
- PROVIDE MISSING INGREDIENTS FOR EW BARYOGENESIS

2HDM (Add a Second Scalar Doublet to the SM)

Goal: ***LHC signals of EW Phase Transition***

2HDM

$$V_s(\Phi_1,\Phi_2) = -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - \frac{\mu^2}{2}(\Phi_1^\dagger\Phi_2 + h.c.)$$
$$+ \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
$$+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \frac{\lambda_5}{2}\left((\Phi_1^\dagger\Phi_2)^2 + h.c.\right)$$

$\mathbb{Z}_2$ Symmetric (softly broken)

(For Simplicity, we do not consider CP Violation)

$$\Phi_1 = \begin{pmatrix} \varphi_1^+ \\ \frac{v_1+h_1+i\eta_1}{\sqrt{2}} \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \varphi_2^+ \\ \frac{v_2+h_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$$

$$H^\pm = -\sin\beta\;\varphi_1^\pm + \cos\beta\;\varphi_2^\pm \qquad h = \cos\alpha\;h_1 + \sin\alpha\;h_2$$

$$A_0 = -\sin\beta\;\eta_1 + \cos\beta\;\eta_2 \qquad H_0 = -\sin\alpha\;h_1 + \cos\alpha\;h_2$$

If $\alpha = \beta$

h is SM Higgs

- *New "Heavy" Scalars H_0* (CP-Even), A_0 (CP-Odd) *and $H^\pm$*
- *6 New Parameters* m_{H_0} m_{A_0} $m_{H^\pm}$ μ α $\tan\beta$

We Focus on Type I 2HDM (all fermions coupled to same scalar doublet)

⇨ EW PHASE TRANSITION DOES NOT DEPEND ON THE TYPE

⇨ EXPERIMENTAL CONSTRAINTS DO DEPEND ON THE TYPE

EW Phase Transition in 2HDM

➔ *Scan in* m_{H_0} m_{A_0} $m_{H^\pm}$ μ α $\tan\beta$

G. Dorsch, S. Huber, J. M. No, JHEP ***1310*** *(2013) 029*

⇨ Stability of the Effective Potential

⇨ Interface to 2HDMC & HiggsBounds → Unitarity, Perturbativity, EWPO, LEP/Tevatron/LHC Bounds

D. Eriksson, J. Rathsman, O. Stal, Comput. Phys. Commun. ***181*** *(2010) 189*

P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, K. Williams, Comput. Phys. Commun. ***181*** *(2010) 138*

⇨ Flavour Constraints (mainly $b \to s\,\gamma$)

⇨ Global Fit to light Higgs Properties → Constraints on β-α and tanβ

C. Chen, S. Dawson, M. Sher, Phys. Rev D ***88*** *(2013) 015018*

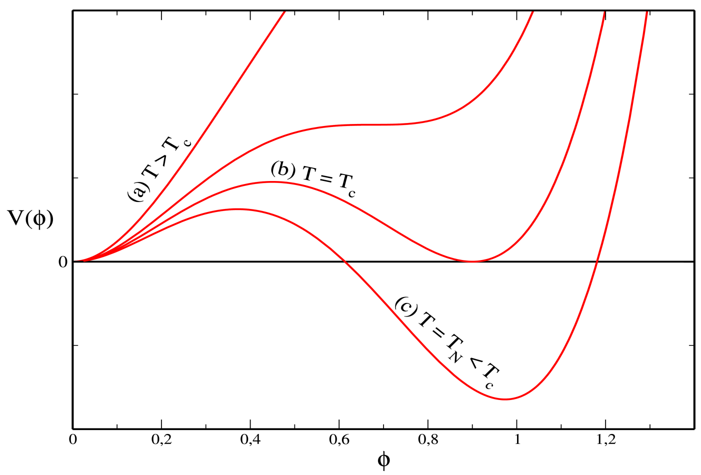
G. Belanger, D. Dumont, U. Ellwanger, J. F Gunion, S. Kraml, Phys. Rev D ***88*** *(2013) 075008*

N. Craig, F. D'Eramo, P. Draper, S. Thomas, H. Zhang, 1504.04630

Points satisfying all above constraints are **"Physical"**

➔ *Strength of the EW Phase Transition:*

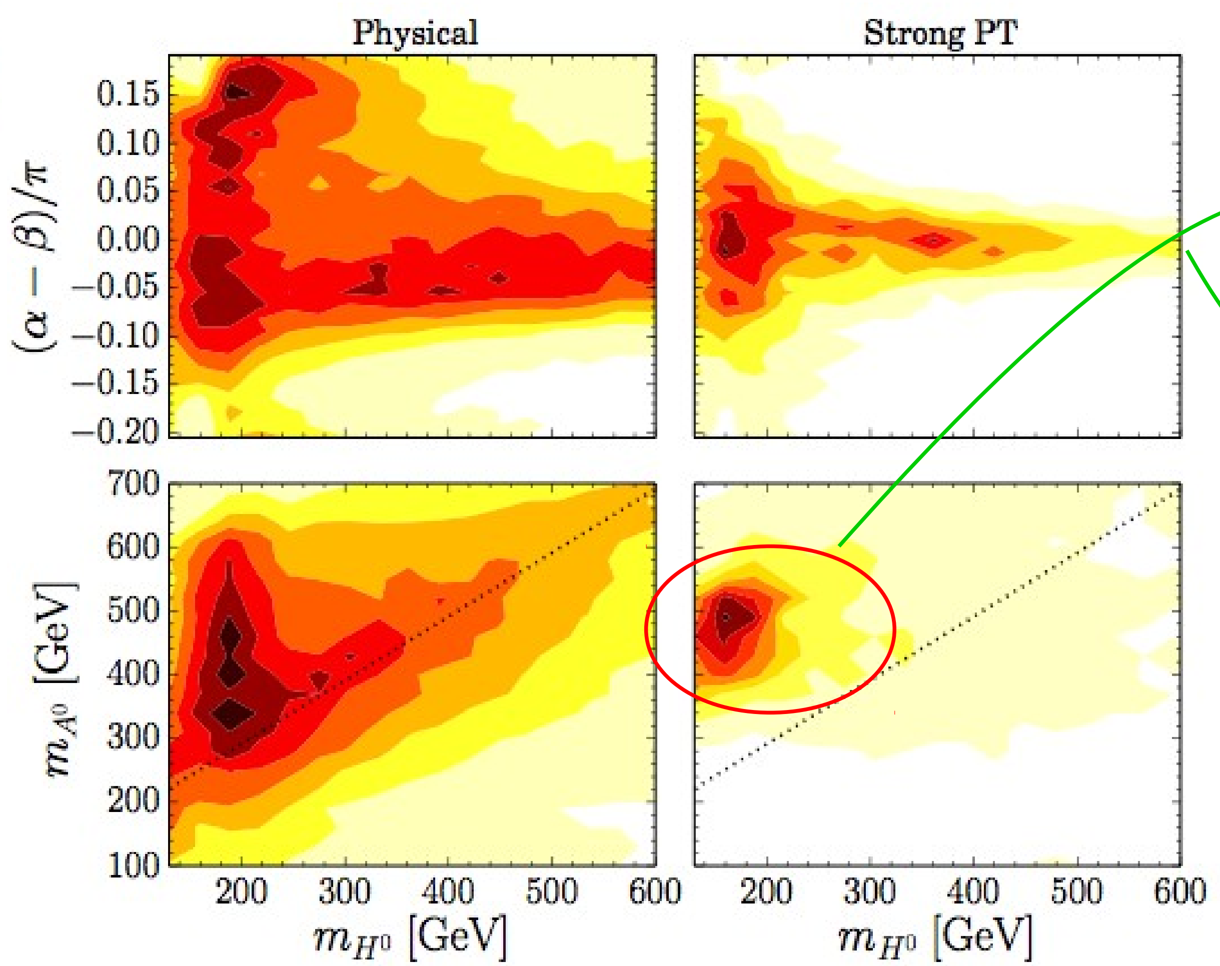
⇨ Daisy Resummed 1-loop Thermal Eff. Potential $V_{\rm eff}(\phi, T)$



EW Phase Transition in 2HDM

Strong EW Phase Transition (vs Physically Allowed)

G. Dorsch, S. Huber, K. Mimasu, J. M. No, Phys. Rev. Lett. ***113*** *(2014) 211802*



- $m_{A_0} - m_{H_0} \sim v$
  (& $m_{A_0} > 300$ GeV)
- $m_{H_0} < 250$ GeV

(Small $\alpha - \beta$ and $\tan\beta \gtrsim 1$)

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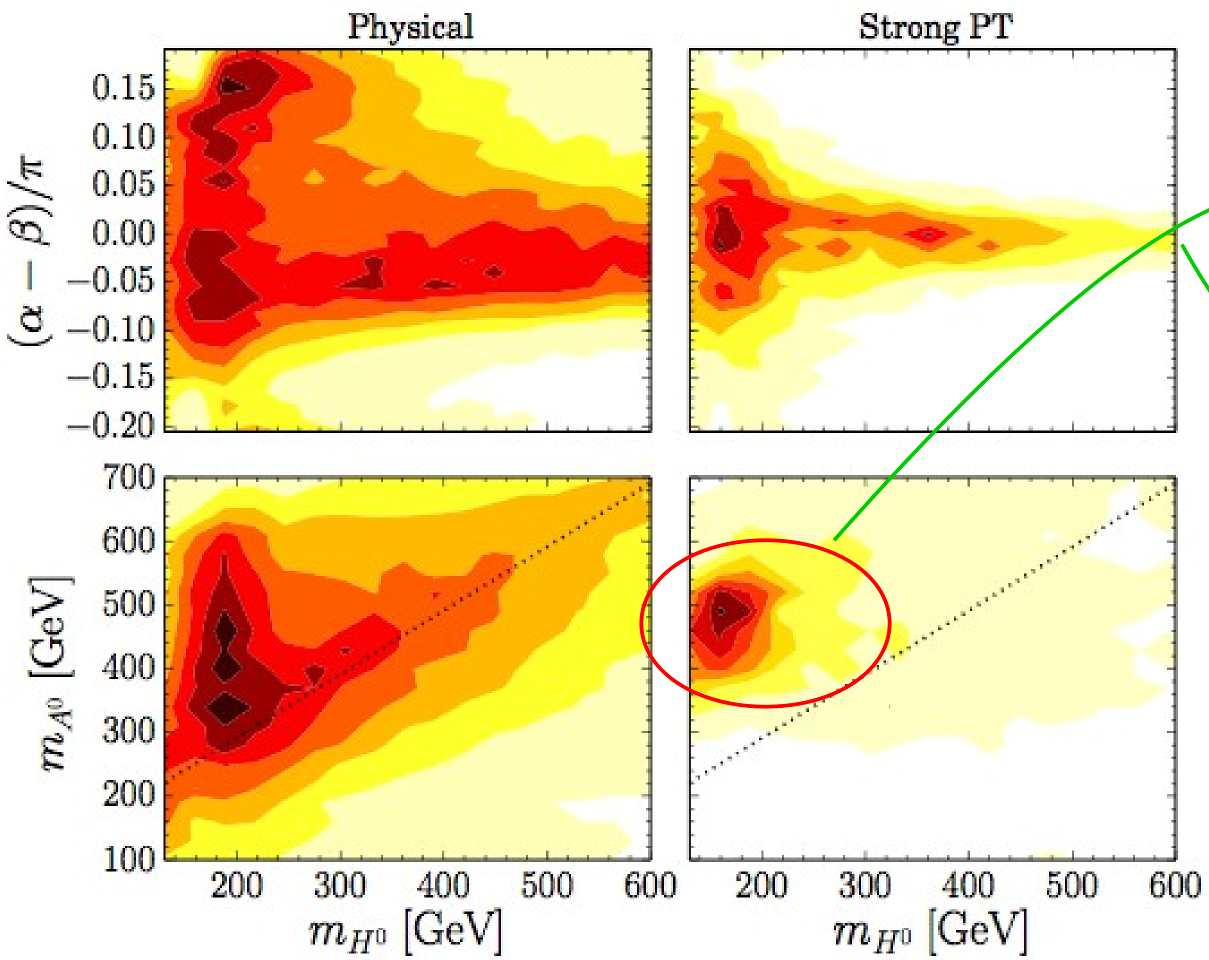


- $m_{A_0} - m_{H_0} \sim v$ (& $m_{A_0} > 300$ GeV)
- $m_{H_0} < 250$ GeV

(Small α - β and tanβ ≳ 1)

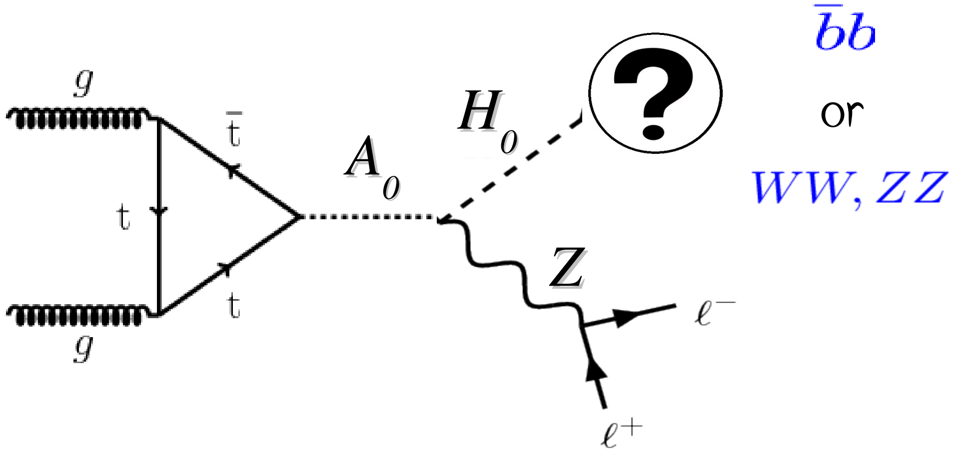
Impact on 2HDM Searches at LHC!

New Decay Channels $\phi_i \rightarrow V\, \phi_j$

(not widely considered: Not Accessible in MSSM)

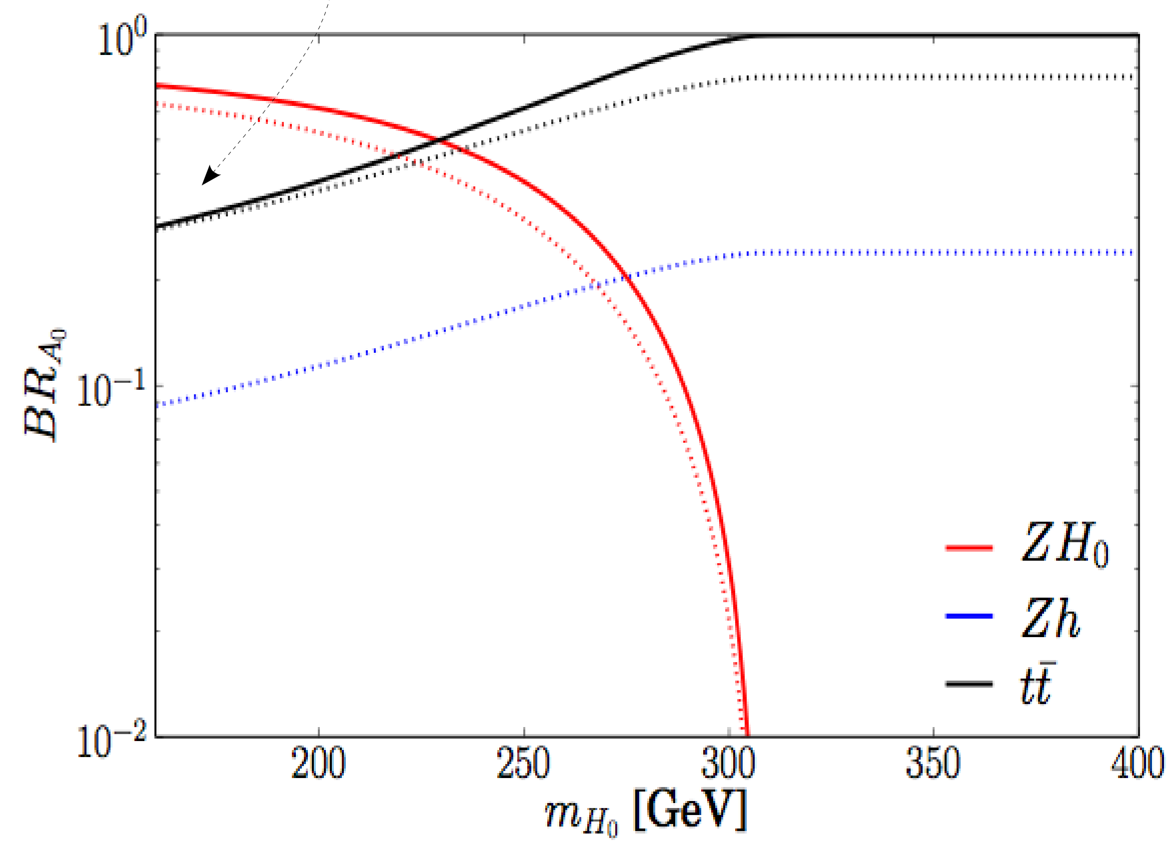
EW PHASE TRANSITION SIGNATURE

$$A_0 \rightarrow H_0\, Z$$



EW Phase Transition in 2HDM@LHC

- *Decay* $A_0 \to H_0\, Z$ *Dominant for* $m_{A_0} - m_{H_0} \sim v$



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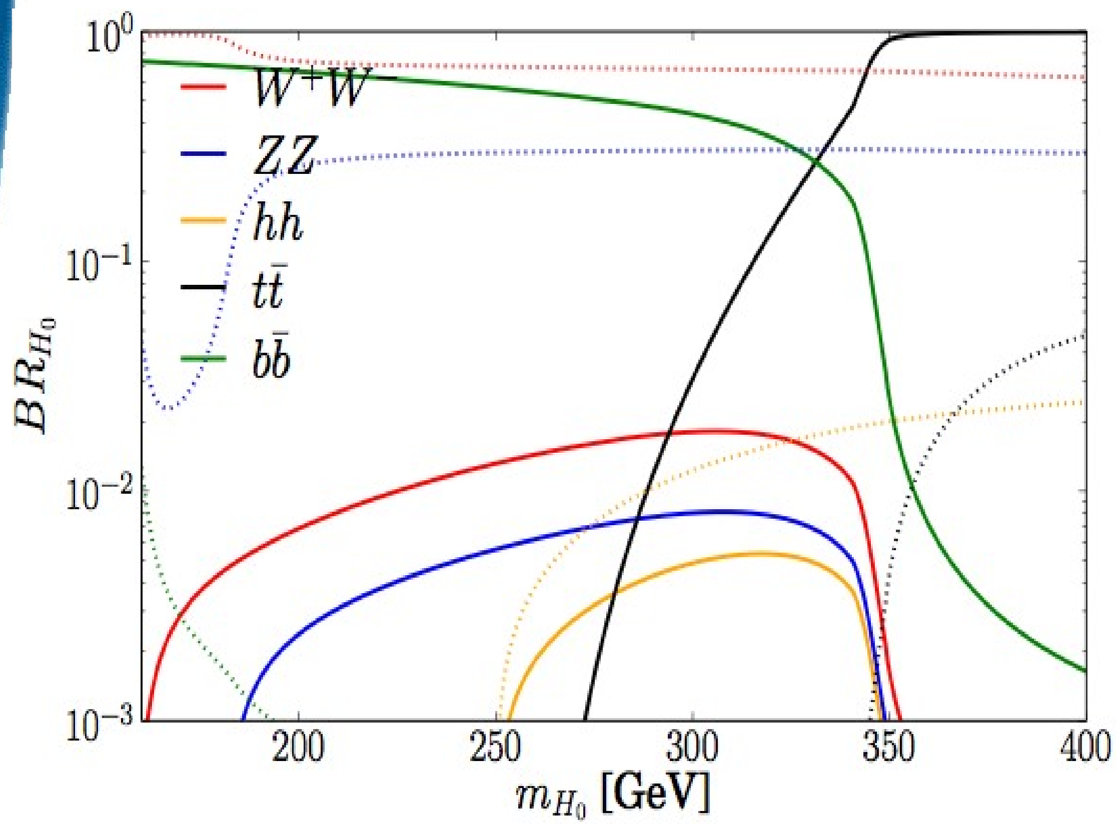
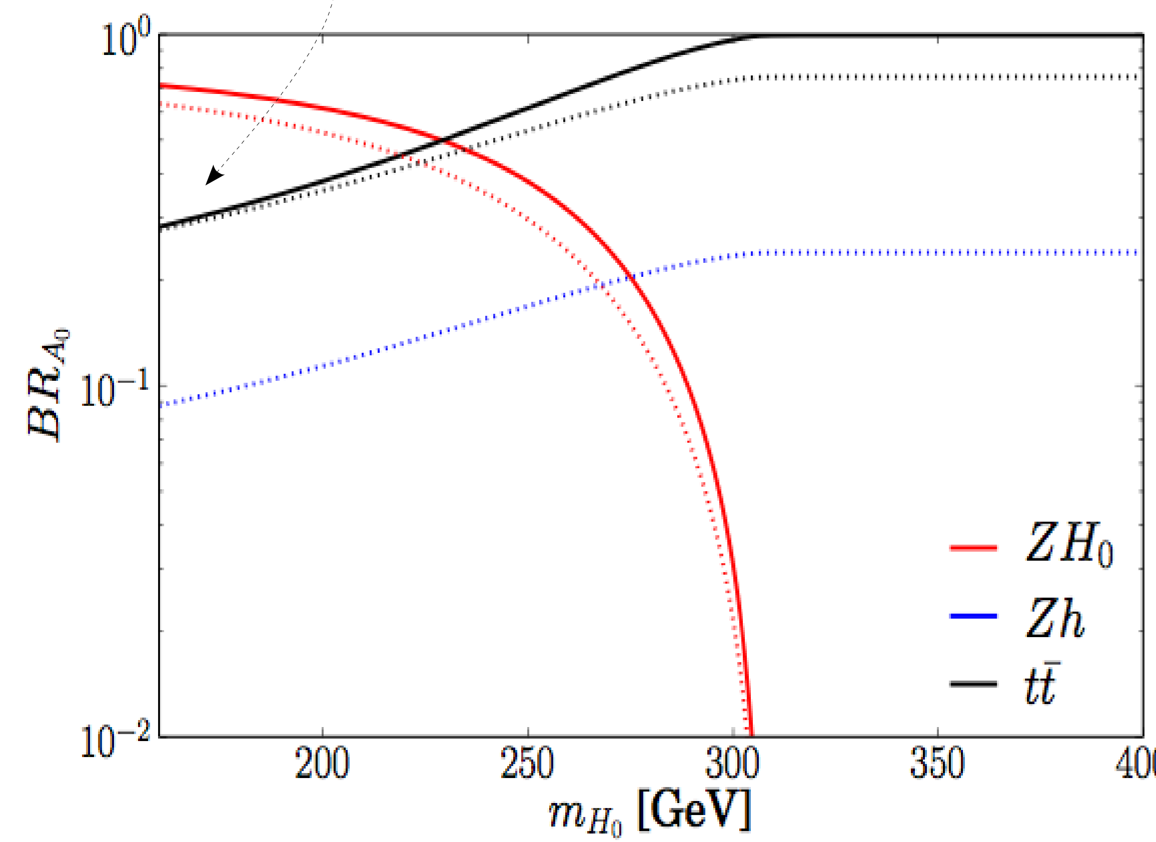
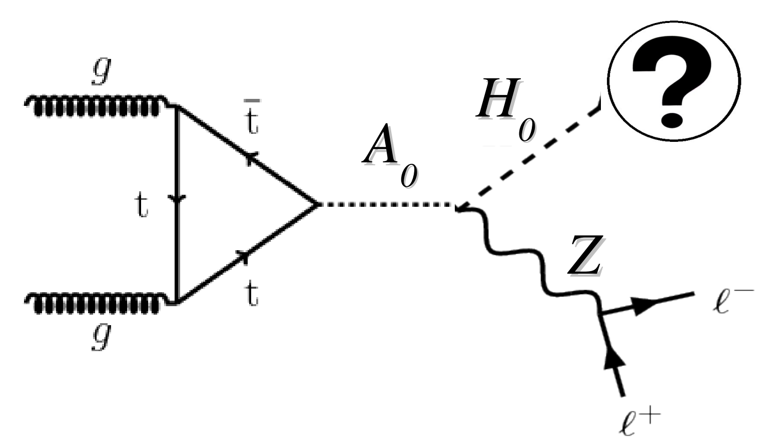




- *Simple Benchmarks for a Strong EW Phase Transition:*

  $m_{A_0} = m_{H^\pm} = 400,\ m_{H_0} = 180,\ \mu = 100$

  $\tan\beta = 2$ (controls $gg \to A_0$ production)



- *Search Strategy Dictated by Dominant Decay Mode of* H_0

  —— *A*: α-β = *0.001π* (aligned) $\bar{b}b$

  ········ *B*: α-β = *0.1π* (non-aligned) WW, ZZ

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

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* $|\eta| < 2.5$

→ 2 *Isolated (within a cone of 0.3), Same-flavour leptons.* $|\eta| < 2.5$ (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
$H_T^{\rm bb} > 150$ GeV, $H_T^{\ell\ell{\rm bb}} > 280$ 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:

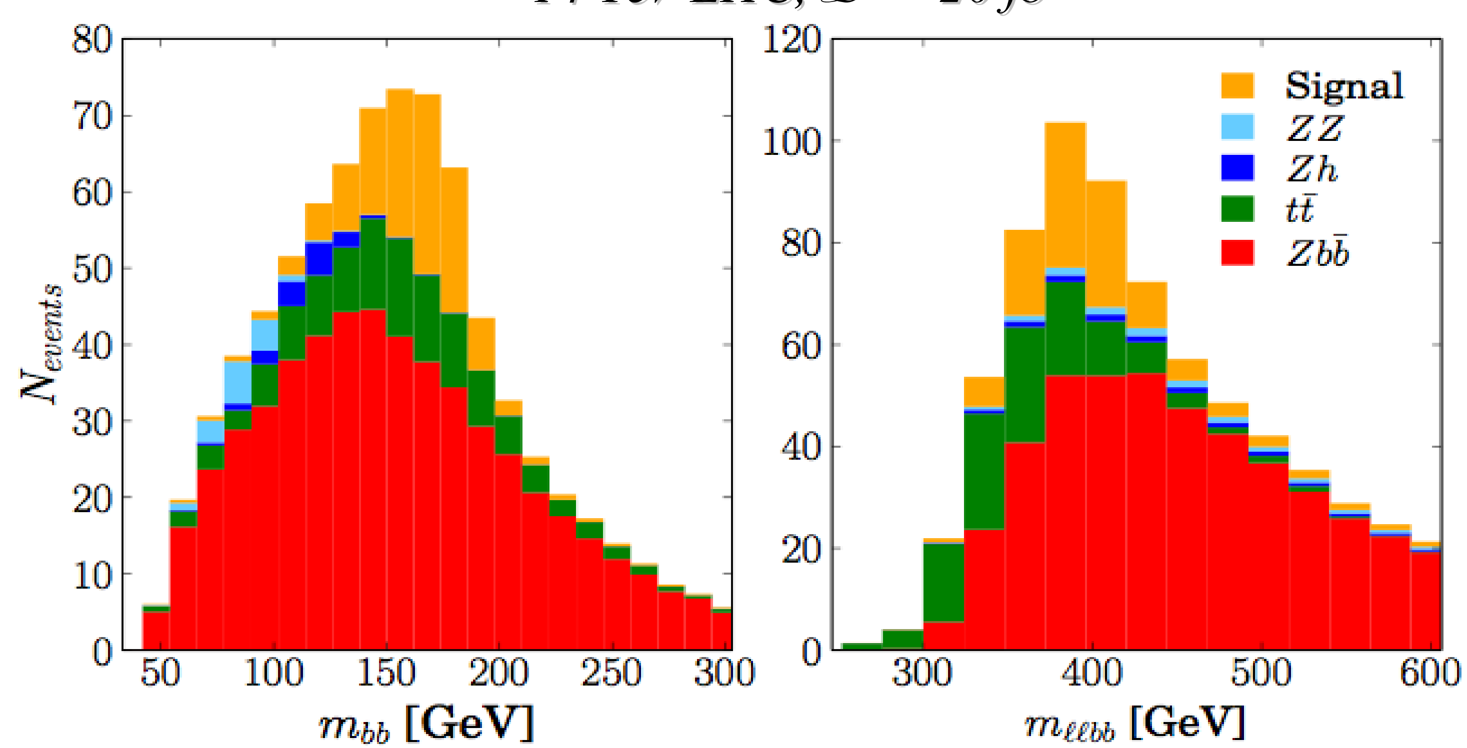
$$m_{\bar{b}b} \to (m_{H_0} - 20) \pm 30\,\text{GeV}$$
$$m_{\ell\ell\bar{b}b} \to (m_{A_0} - 20) \pm 40\,\text{GeV}$$

5σ signal significance for:

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

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

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



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, $Zt\bar{t}$ hZ, ZWW subdominant
- ⇨ *Analysis & Event Selection similar to previous case:*
  - → 4 Isolated (cone of 0.3) leptons, same-flavour pairs. |η| < 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

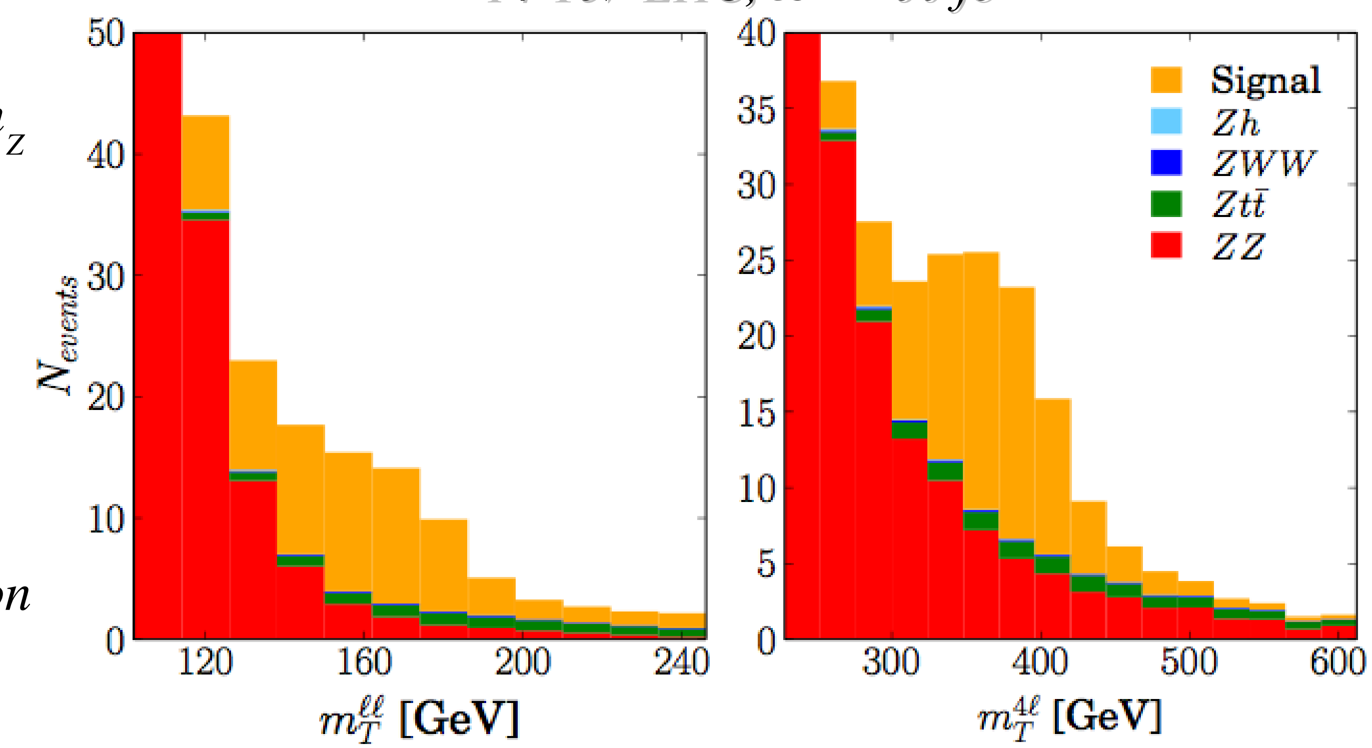
→ *Transverse mass variables*:

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

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

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

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



2HDM@LHC

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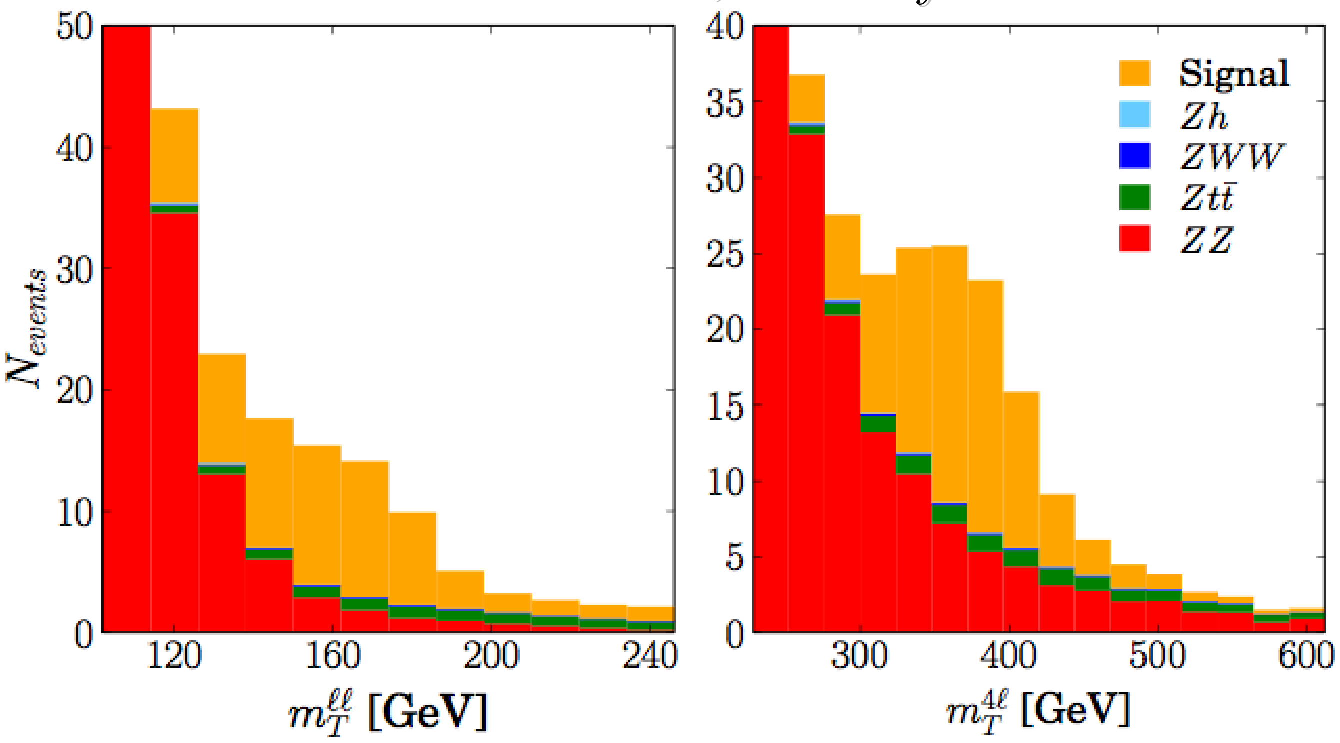
5σ signal significance for:

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

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

(conservative...)

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



Remarks on “Standard” 2HDM LHC Searches

$A_0 \to H_0\,Z$ channel Open → BR to other decay channels drastically reduced

LIMITS FROM STANDARD LHC SEARCHES SIGNIFICANTLY WEAKENED....

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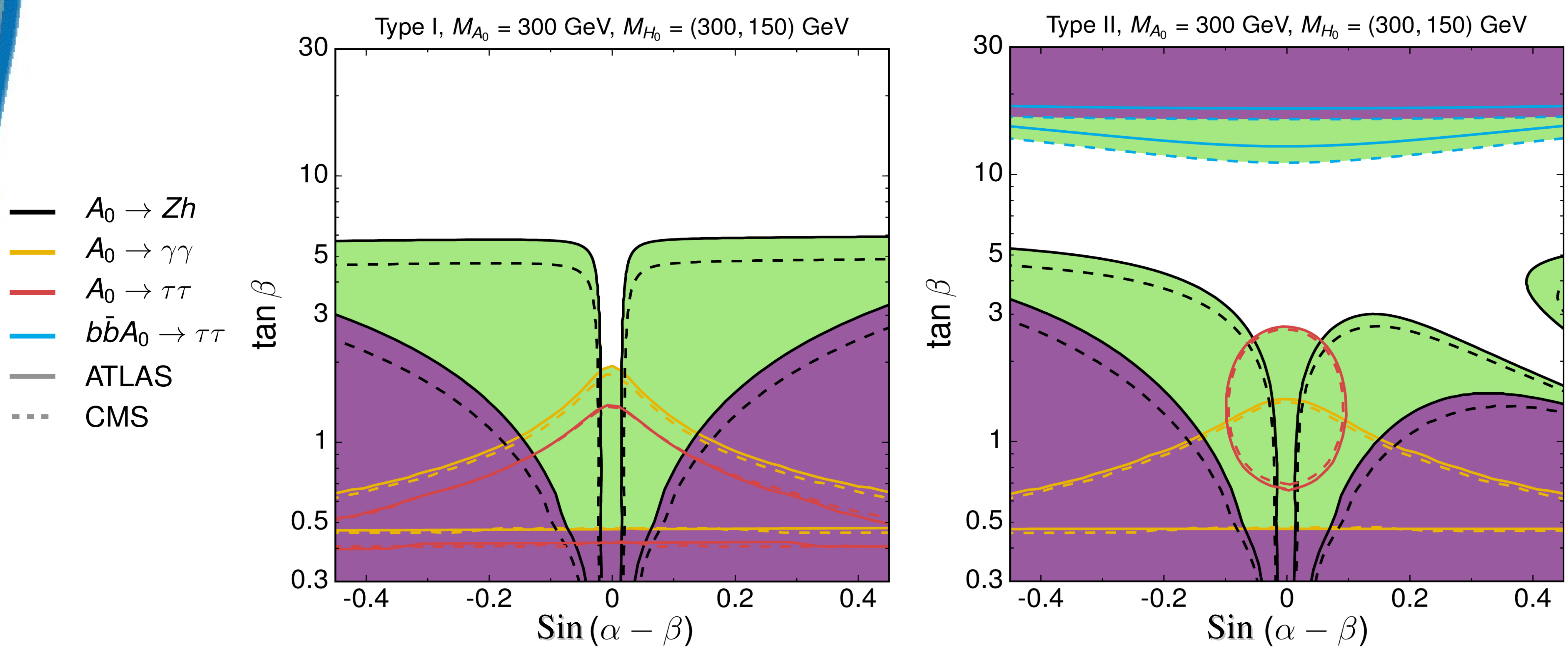
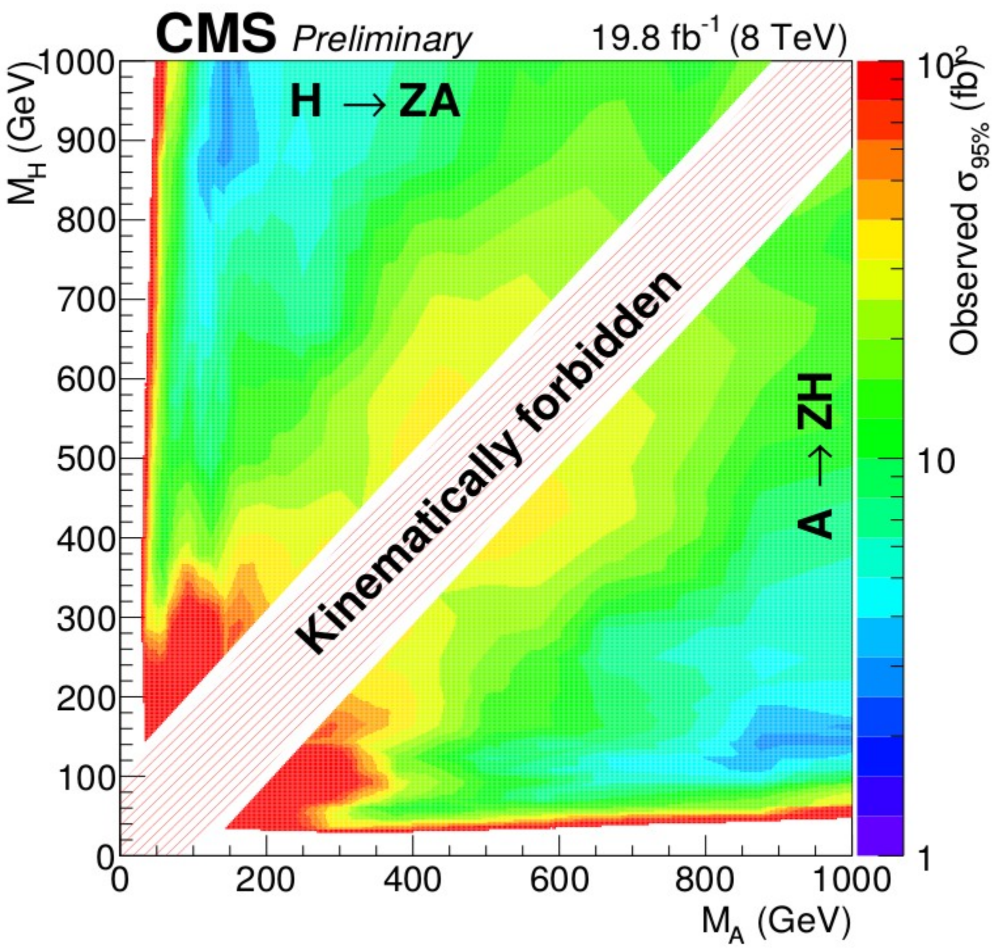


New Searches "Fill in the Gap"

CMS-PAS-HIG-15-001



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

The CMS Collaboration

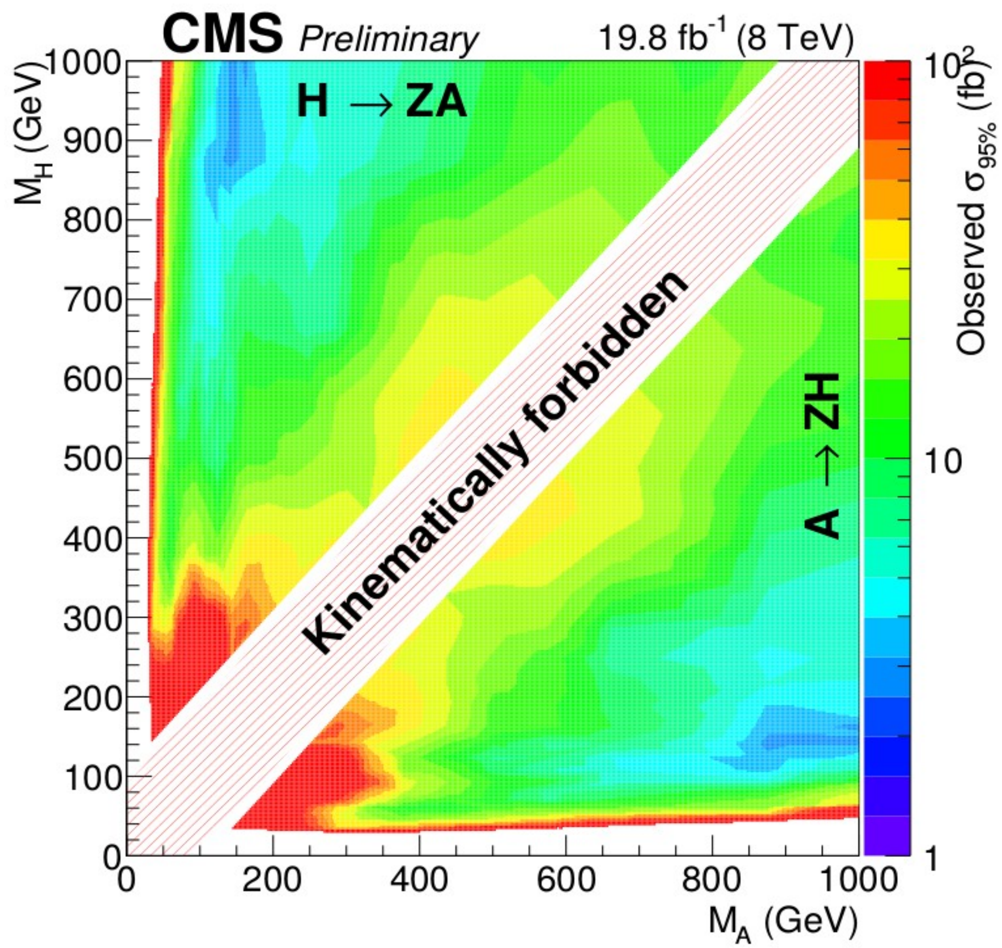
One important motivation for 2HDMs is that these models provide a way to explain the asymmetry between matter and anti-matter observed in the Universe [4, 5]. Another important motivation is Supersymmetry [6], which is a theory that falls in the broad class of 2HDMs. Axion models [7], which would explain 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.

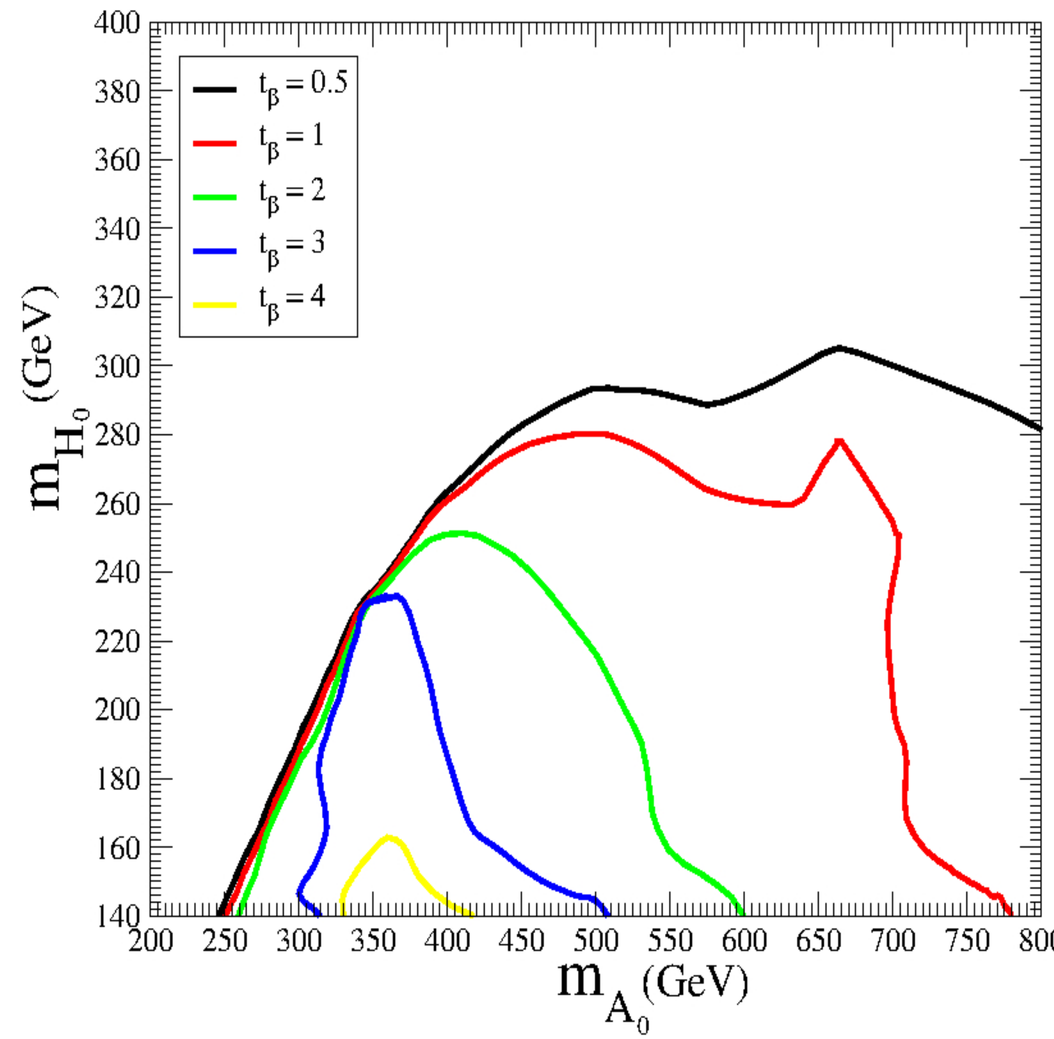
In the most general case 14 parameters are necessary to describe the scalar sector in a 2HDM. However, only 6 free parameters remain once the so-called Z_2 symmetry is imposed to suppress flavor changing neutral currents, in agreement with experimental observations, and the values of the mass of the 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.

Meaningful constraints from LHC Run 1

New Searches "Fill in the Gap"

CMS-PAS-HIG-15-001





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Meaningful constraints from LHC Run 1

Conclusions

- Extended Higgs Sectors are Archetype Scenarios for a Connection between EW Cosmology & LHC physics

EW PHASE TRANSITION

2HDM:

EW Phase Transition Signature

$$\underline{A_0 \rightarrow H_0\, Z} \rightarrow \bar{b}b\, \ell\ell$$

$$\underline{A_0 \rightarrow H_0\, Z} \rightarrow W^+W^-\ell\ell \rightarrow 4\ell + 2\nu$$

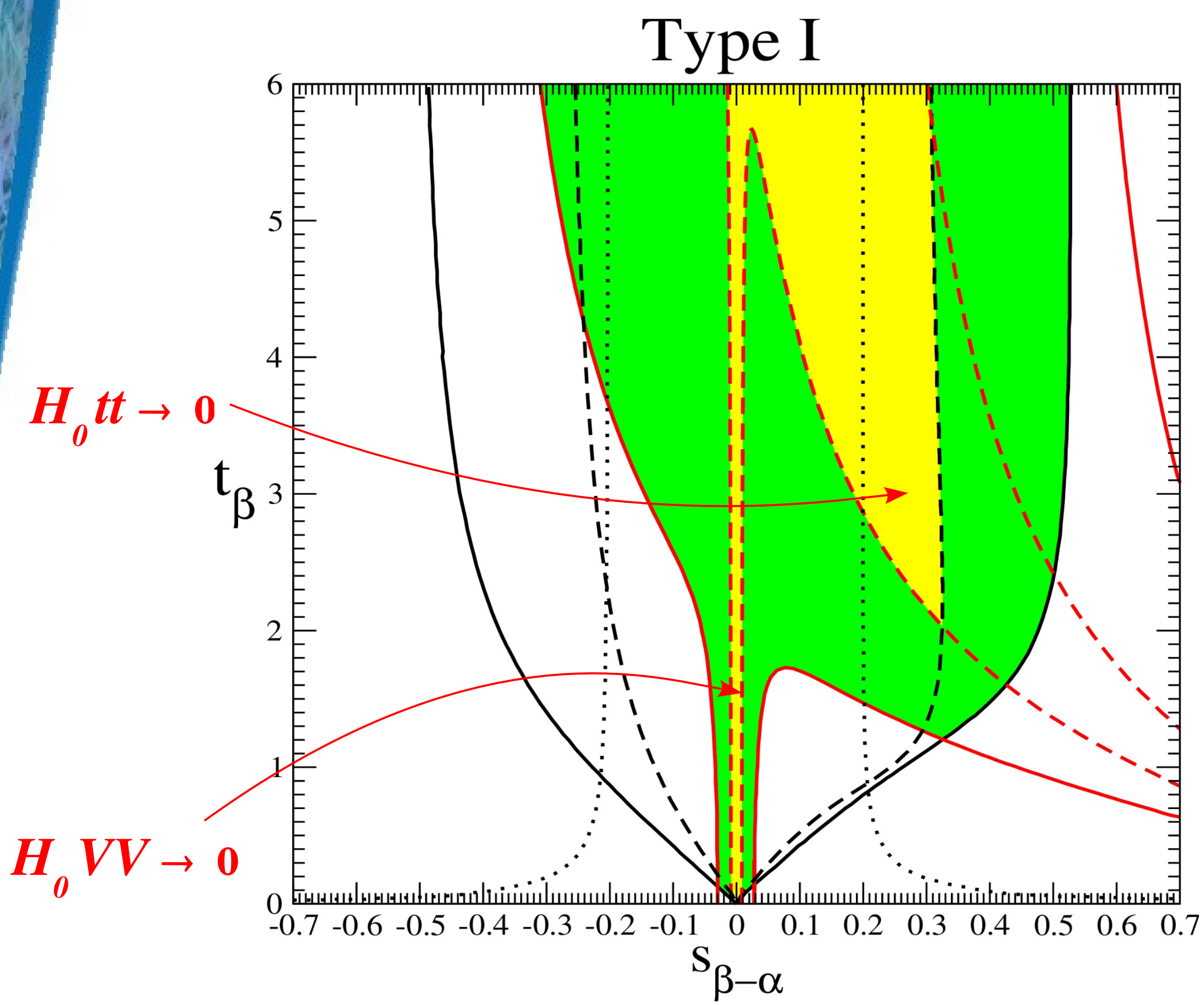
- For these "Hierarchical" 2HDM, Standard LHC searches become less efficient

- Promising Prospects for $A_0 \rightarrow H_0\, Z$ Searches at LHC14

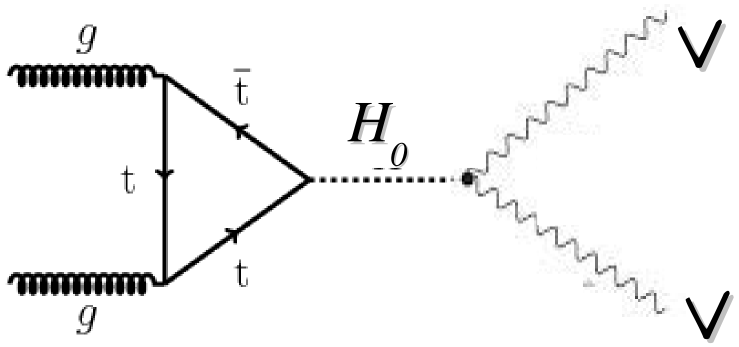
Back-up

Remarks on “Standard” 2HDM LHC Searches

EW Phase Transition LHC Searches fill region where standard 2HDM LHC searches are not as sensitive



$(m_{H_0} = 200 \text{ GeV})$



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Measurements of light Higgs couplings