More Higgses at LHC:
The EW Road to Baryogenesis

Jose Miguel No, Sussex U.

Based on 1305.6610 (JHEP), 1405.5537 (PRL), 1506.xxxxx
with G. Dorsch, S. Huber, K. Mimasu.

Rencontres de Blois, 2nd 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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<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*

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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 CP̸ Sources *EDMs*
- EW Phase Transition *LHC*

BSM

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Departure from Thermal Equilibrium ?

New C̸P̸ Sources → EDMs

EW Phase Transition → LHC

BSM

LHC Signatures Revealing 1st Order EW Phase Transition

EW Phase Transition

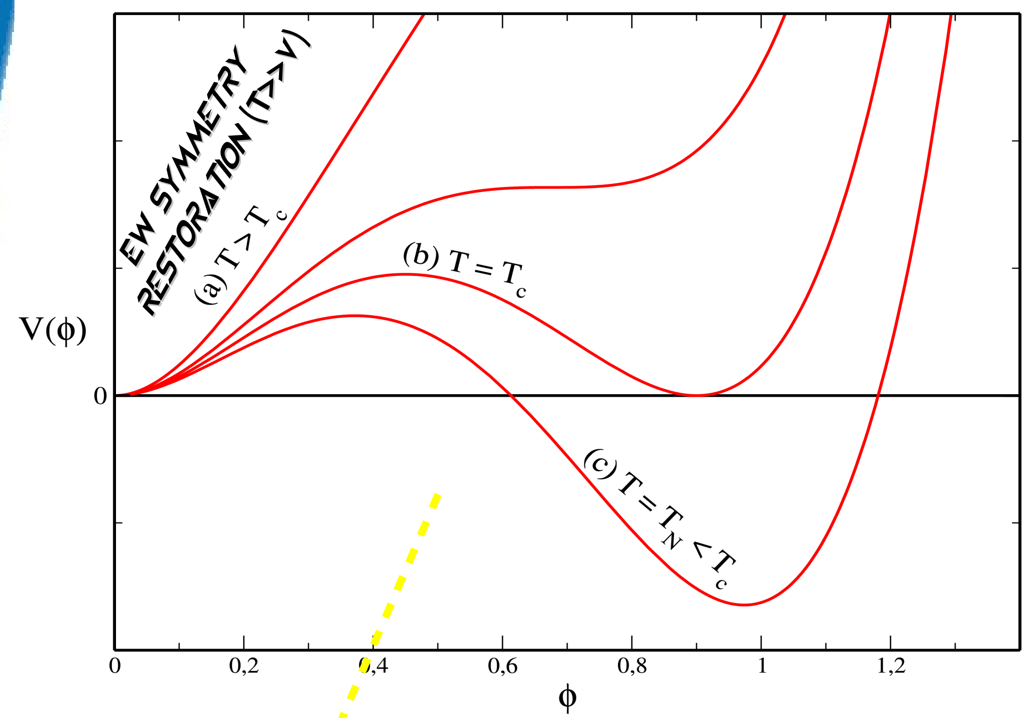
Universe Expands Adiabatically ⇨ *Equilibrium Thermal Field Theory*

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:

$\langle\phi\rangle = 0 \rightarrow \langle\phi\rangle = \phi(T)$ Discontinuous

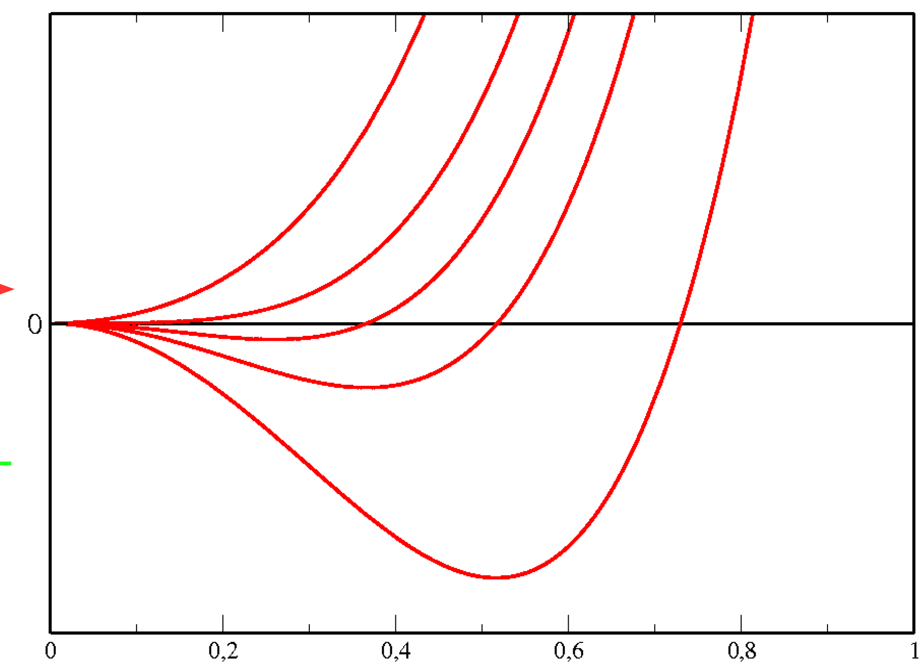


LARGER M_H →

← NEW BOSONS

2nd Order:

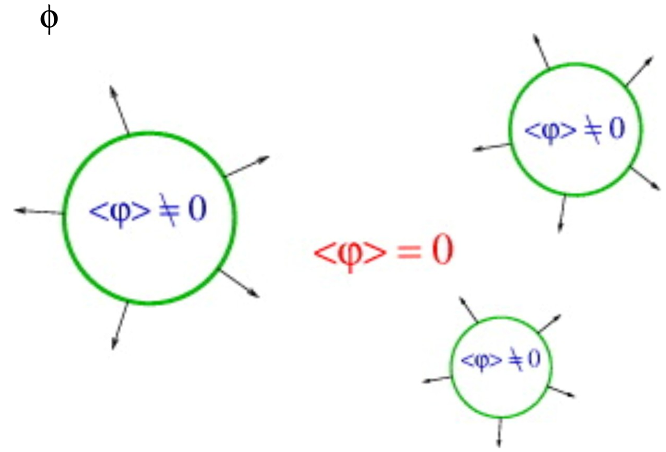
$\langle\phi\rangle = 0 \rightarrow \langle\phi\rangle = \phi(T)$ Continuous



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

Archetype Scenario: Extended Higgs Sectors

More Higgses!

- 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

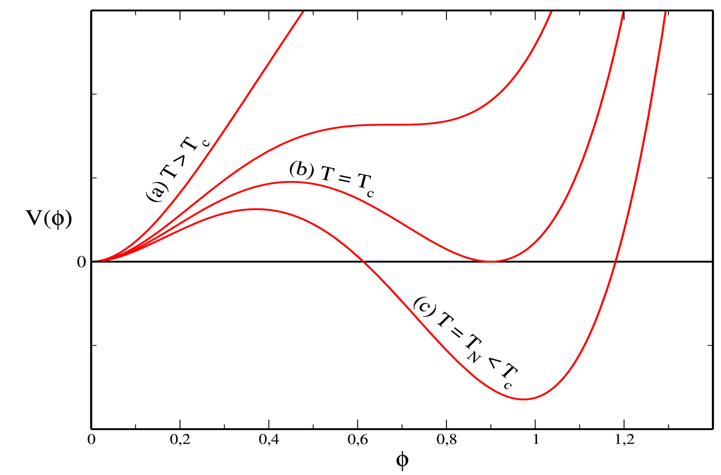
- Flavour Constraints (mainly $b \to s\gamma$)
- Global Fit to light Higgs Properties → Constraints on β−α and tanβ

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:*

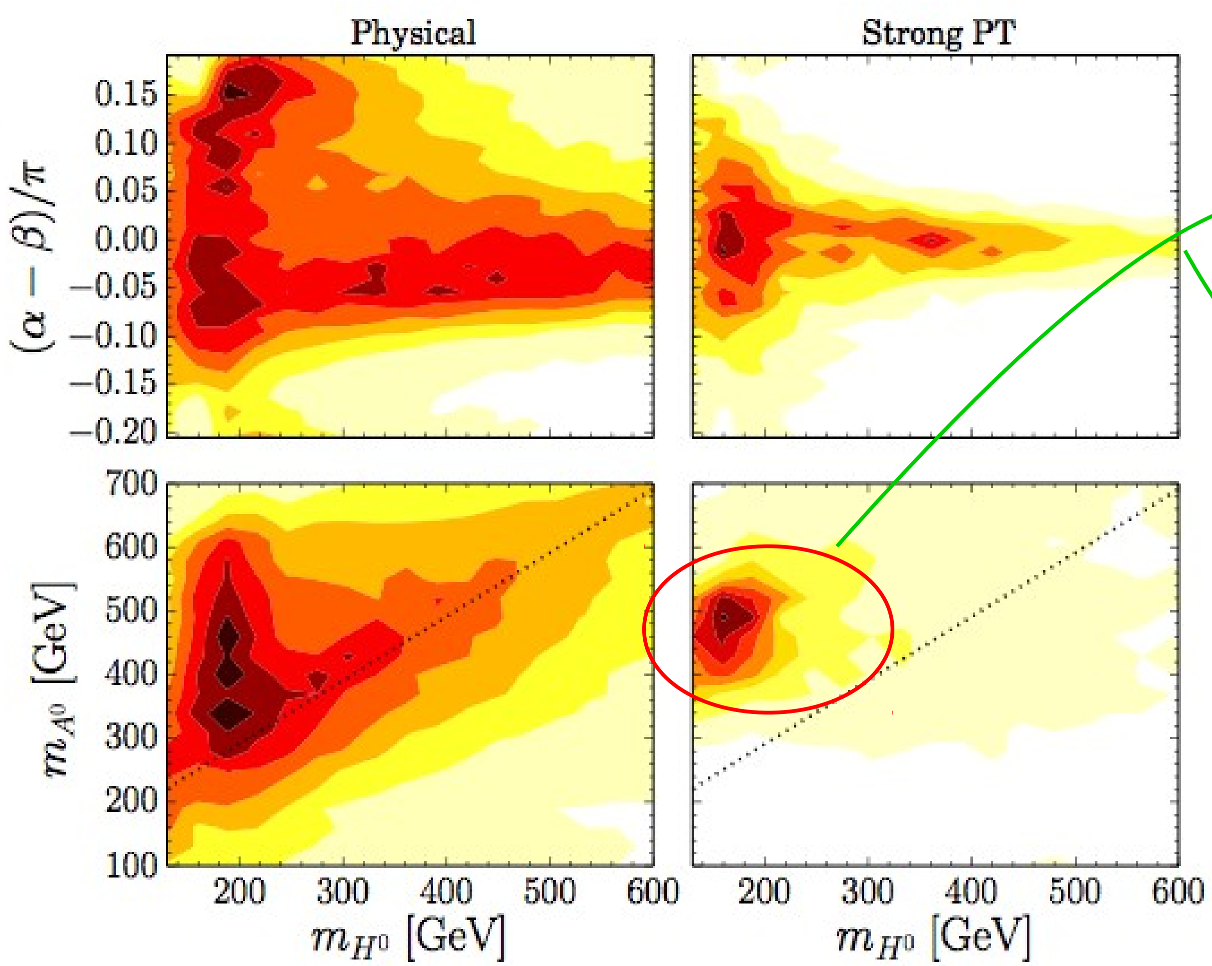
- Daisy Resummed 1-loop Thermal Eff. Potential $V_{\rm eff}(\phi, T)$



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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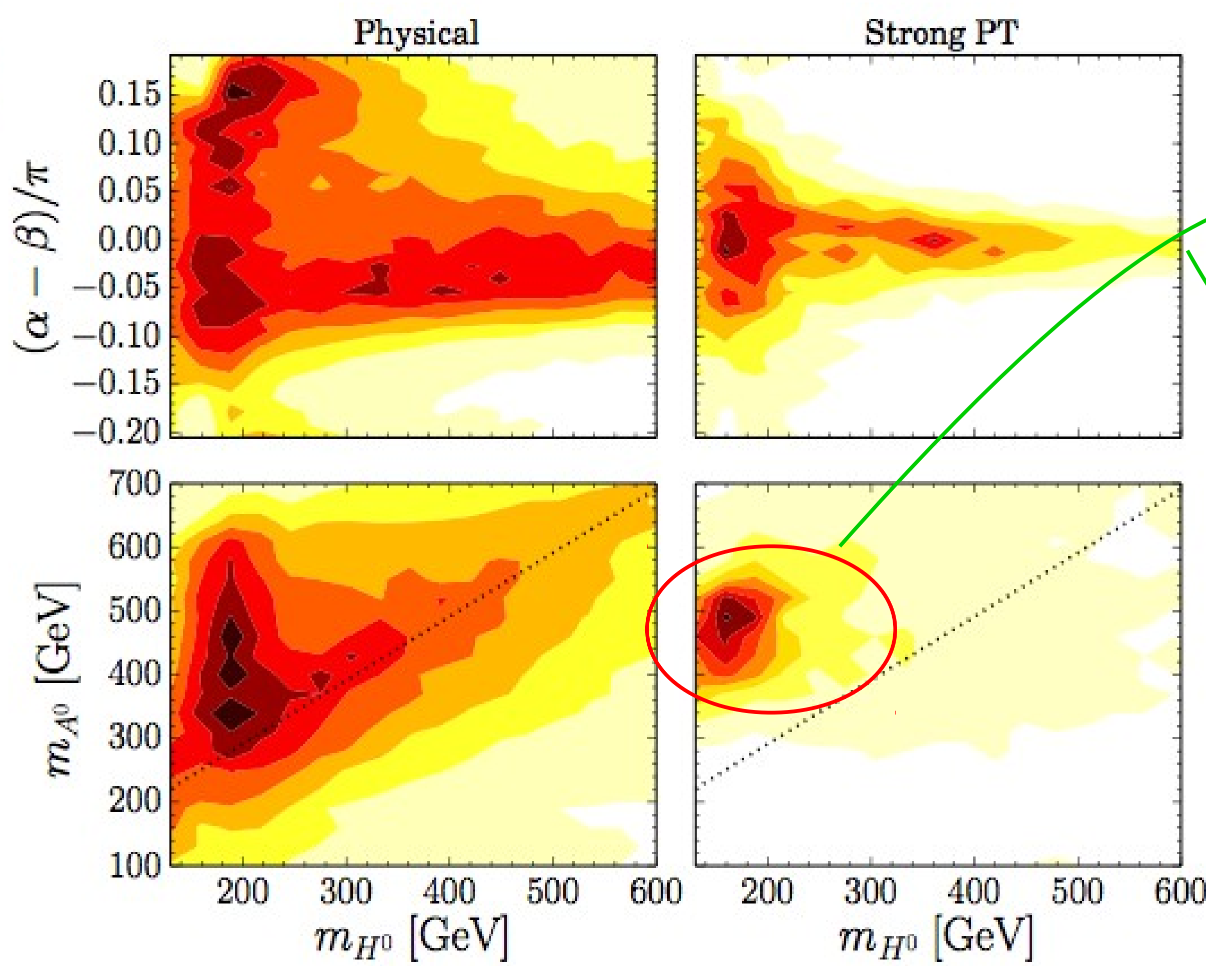

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(Small $\alpha - \beta$ and $\tan\beta \gtrsim 1$)

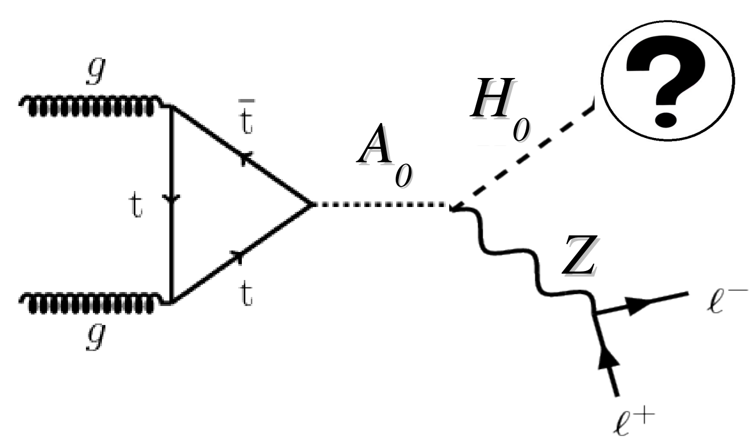
Impact on 2HDM Searches at LHC!

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

(not widely considered: Not Accessible in MSSM)

EW PHASE TRANSITION SIGNATURE

$$A_0 \rightarrow H_0\, Z$$



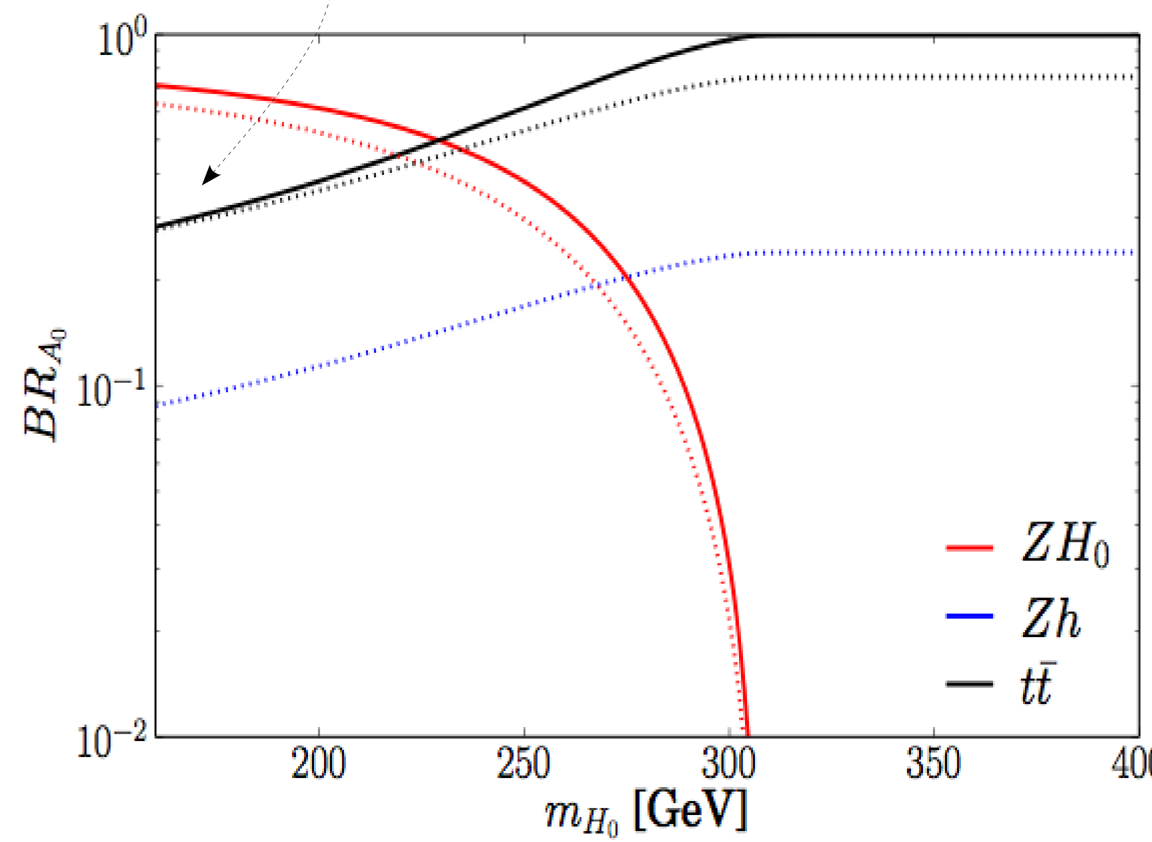
$\bar{b}b$

or

WW, ZZ

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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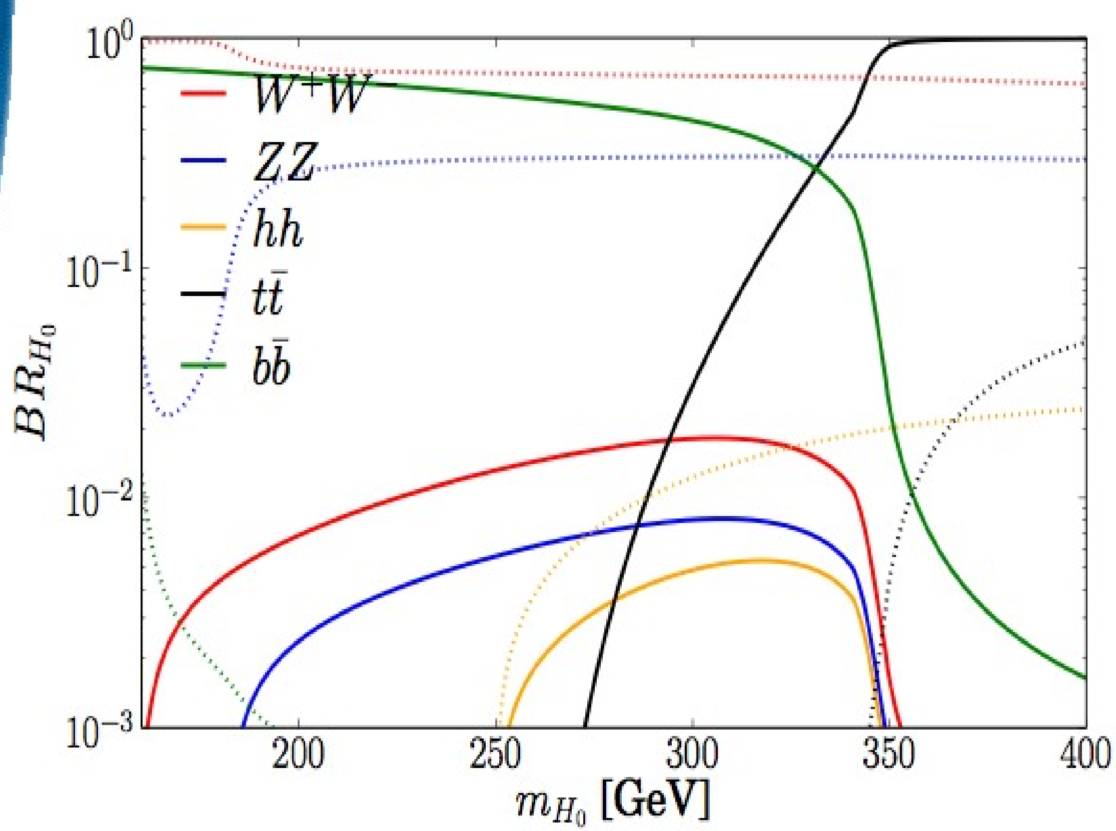
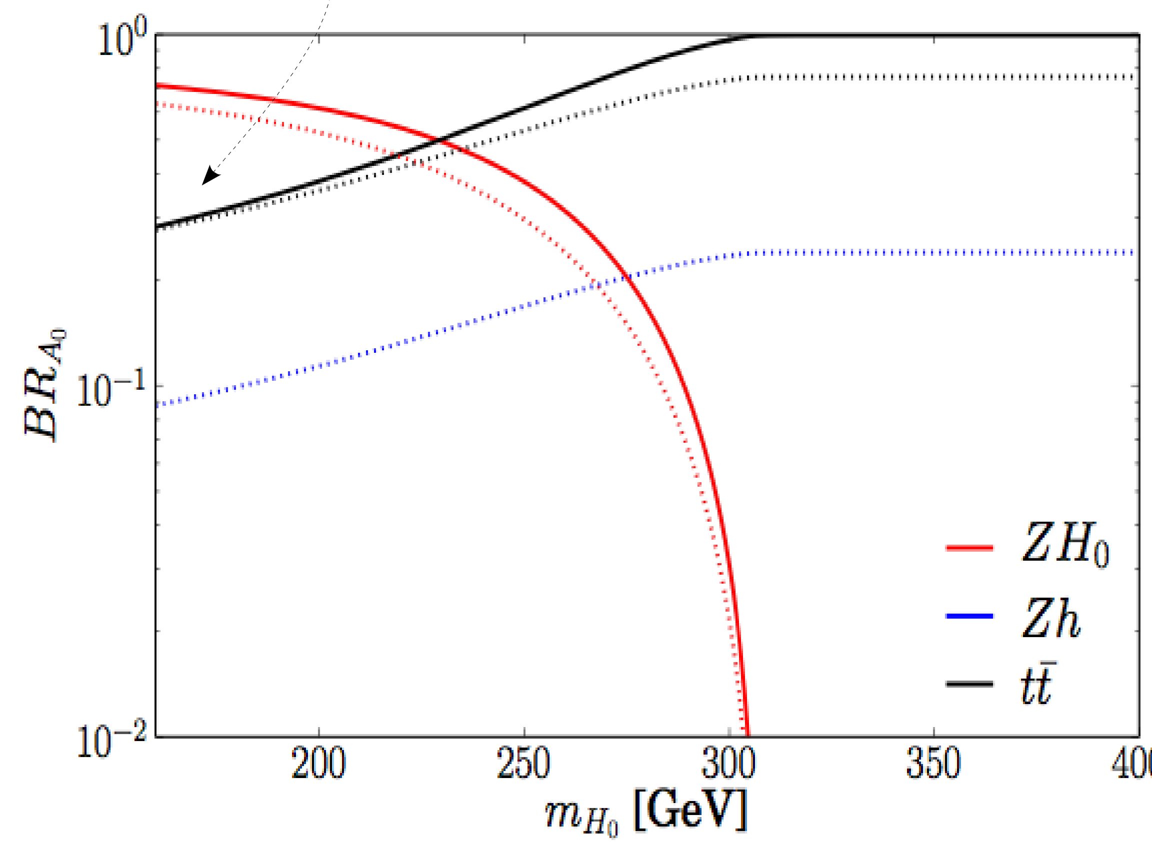
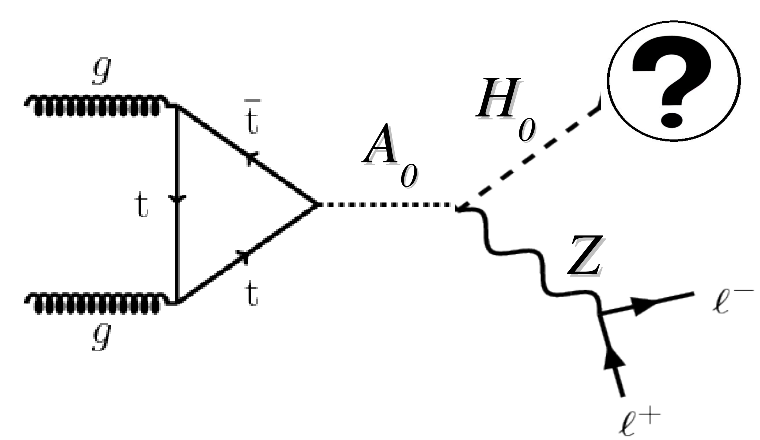




- *Simple Benchmarks for a Strong EW Phase Transition:*

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

  $\tan\beta = 2$ (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: $A_0 \to H_0\, Z \to \bar{b}b\, \ell\ell$ (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*.

K-factor:	1.6	1.5	1.4	-	-
	Signal	$t\bar{t}$	$Z\,b\bar{b}$	ZZ	$Z\,h$
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:

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

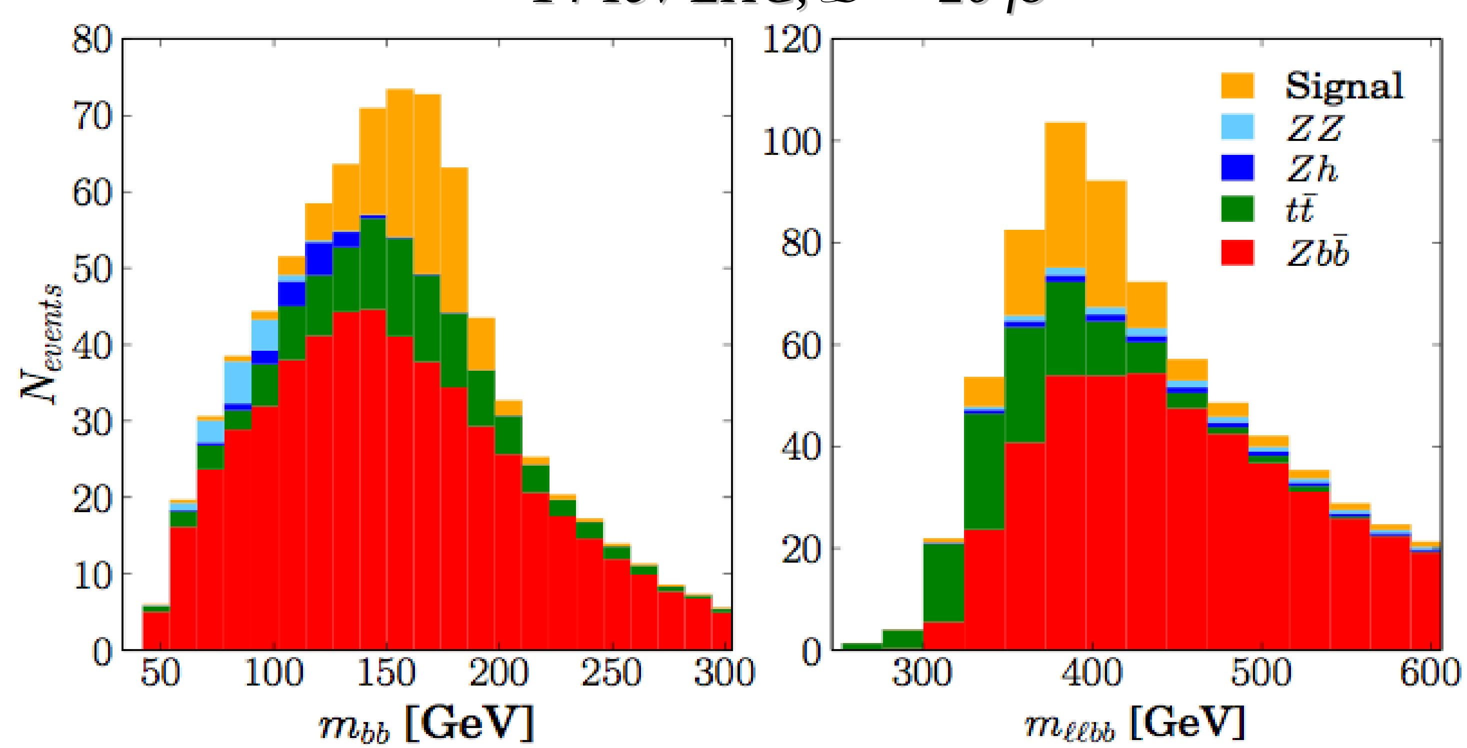
$$m_{\ell\ell\bar{b}b} \rightarrow (m_{A_0} - 20) \pm 40\,\mathrm{GeV}$$

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*$^{-1}$



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

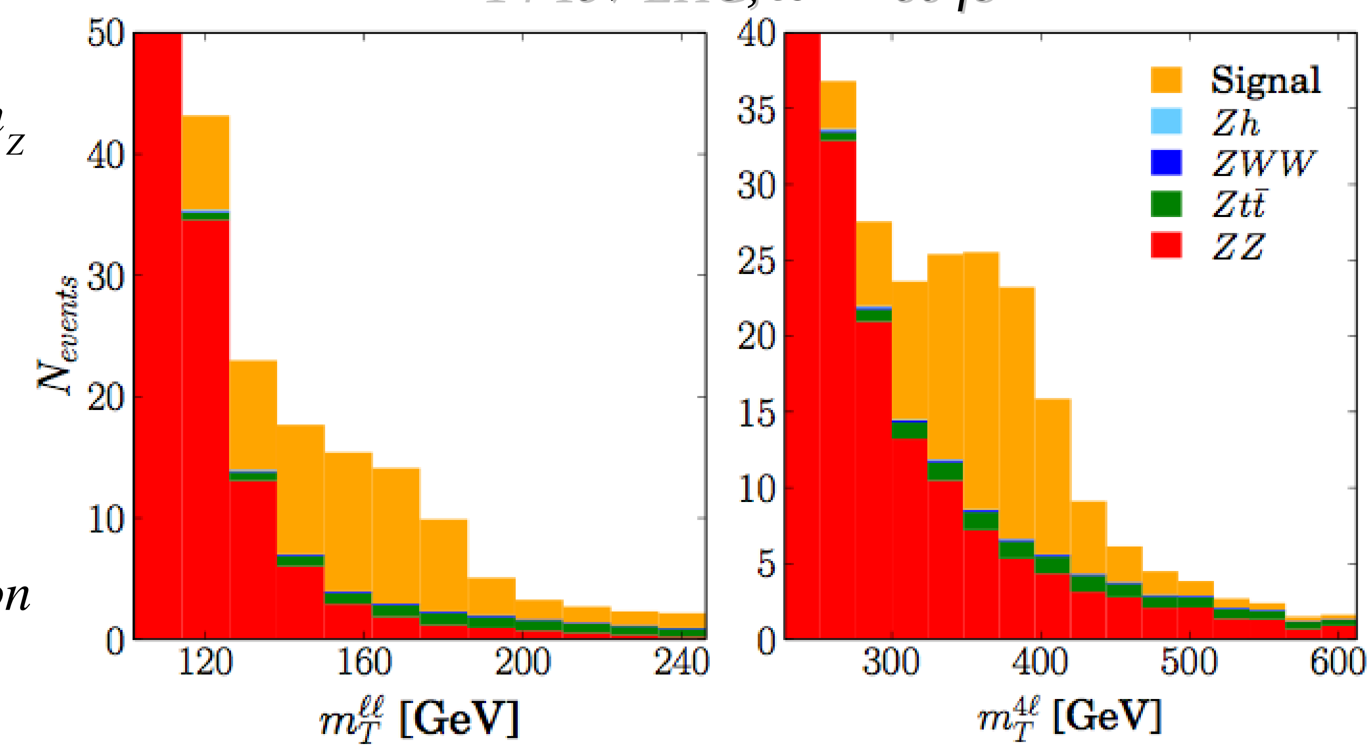
→ *Transverse mass variables*:

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

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

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

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



2HDM@LHC

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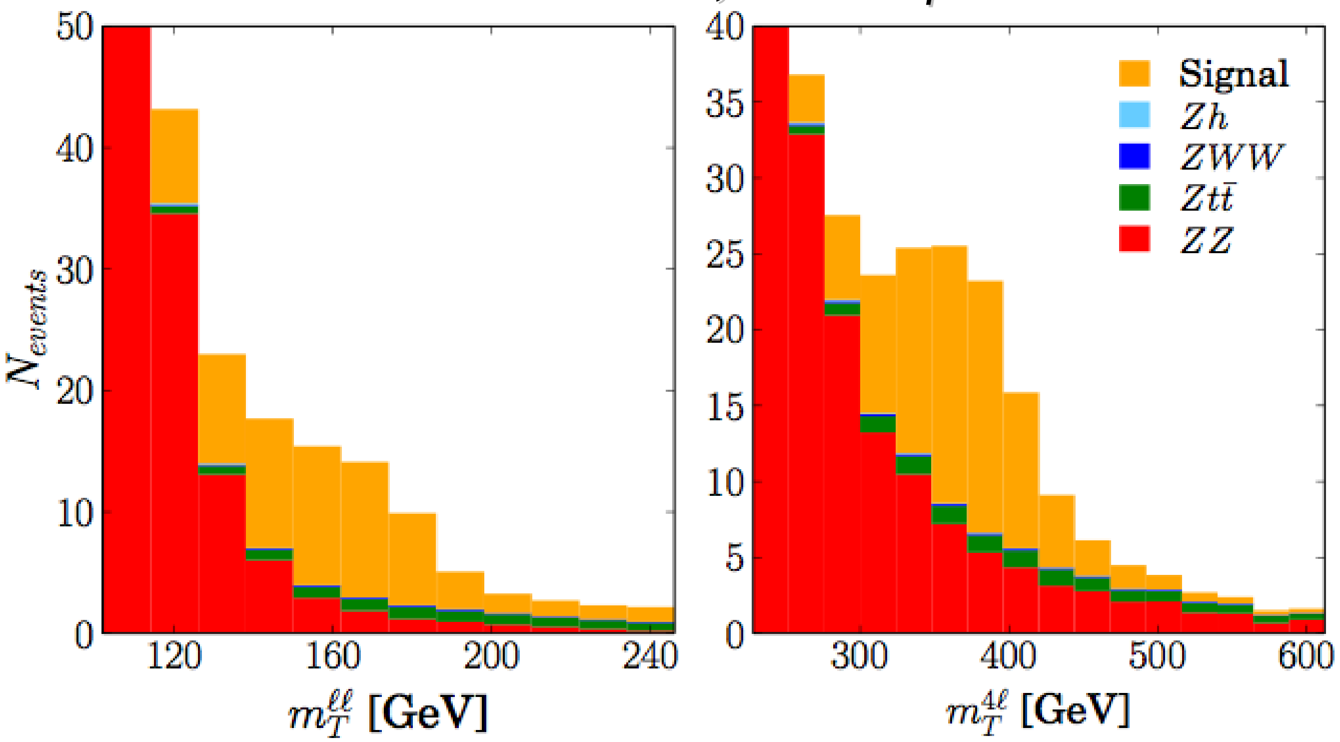
5σ signal significance for:

$\mathscr{L}$ = 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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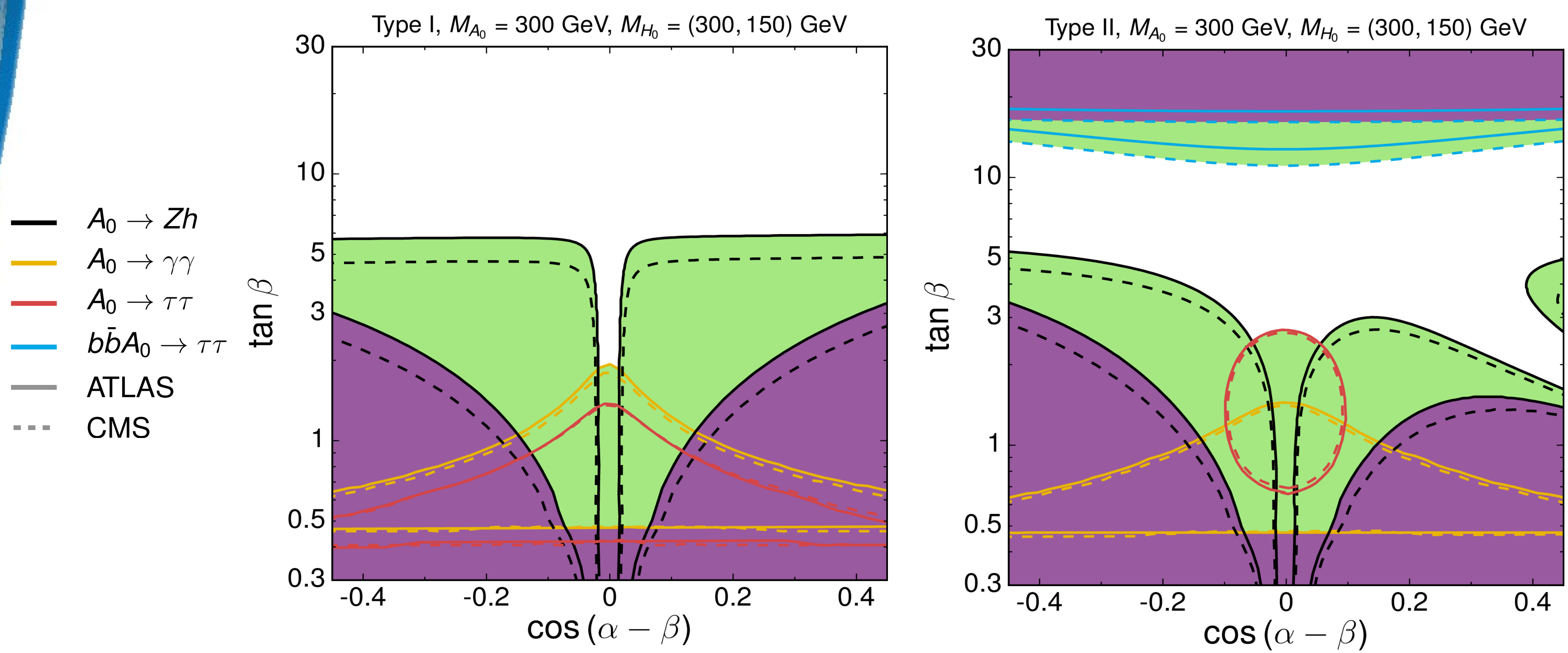

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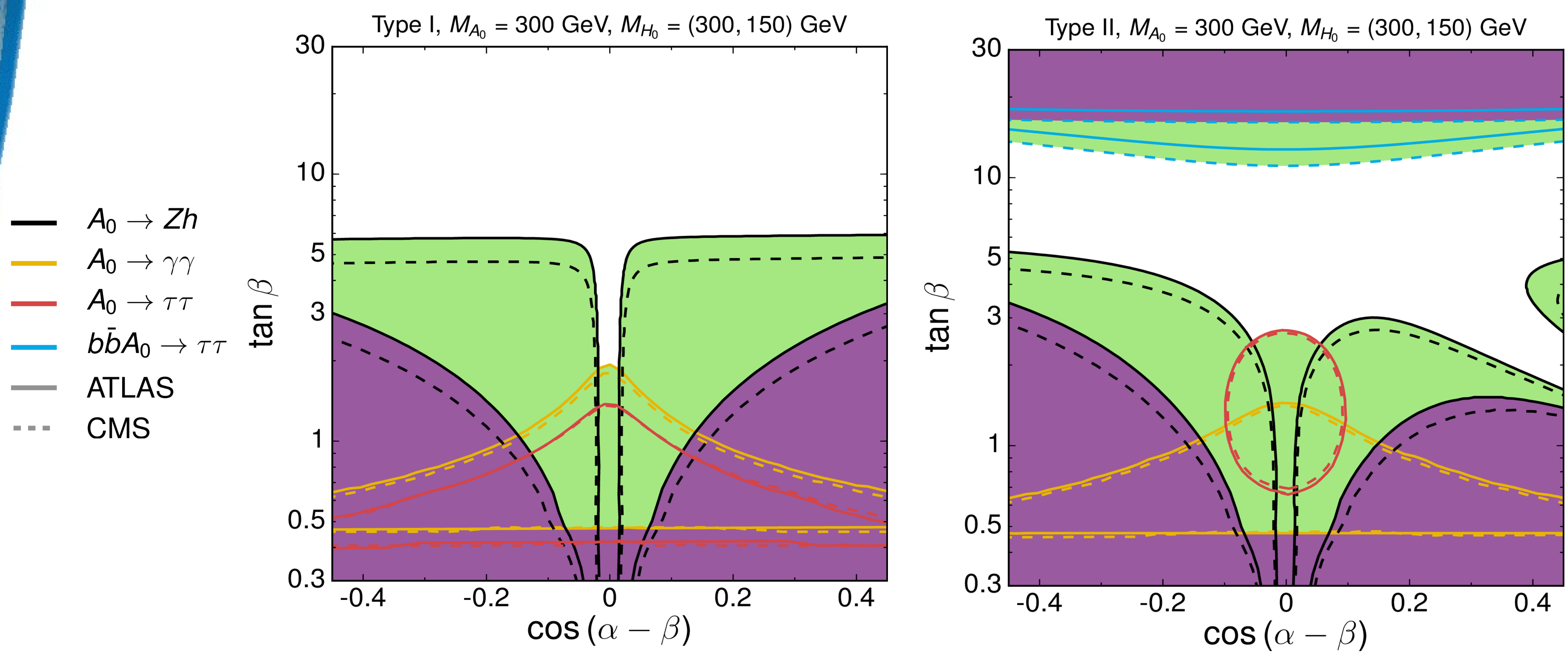


NEW $A_0 \to H_0\, Z$ SEARCHES COULD "FILL IN THE GAPS"

CMS-PAS-HIG-15-001

Conclusions

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

EW PHASE TRANSITION

2HDM:

EW Phase Transition Signature

$$A_0 \to H_0\, Z \to \bar{b}b\, \ell\ell$$

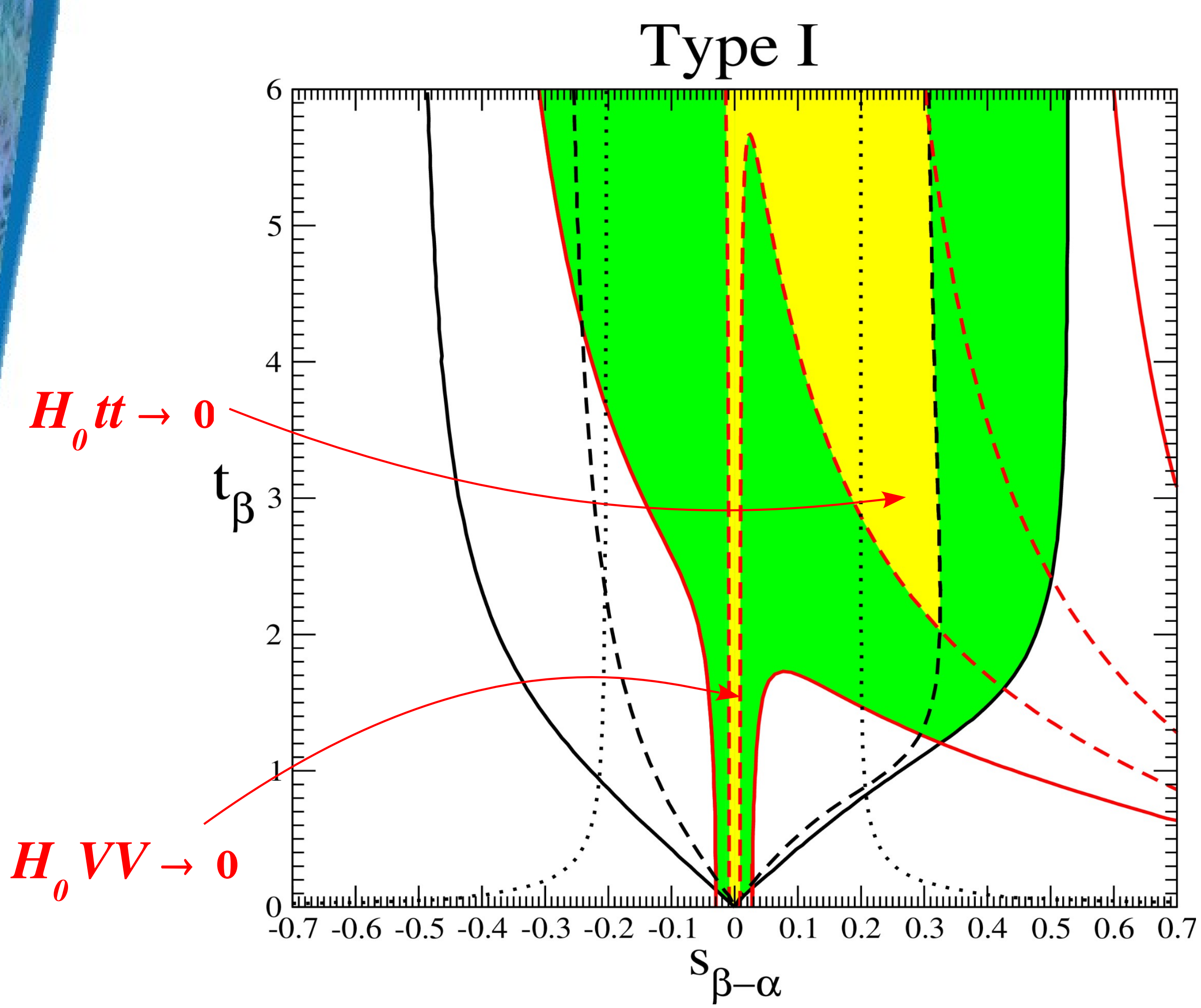
$$A_0 \to H_0\, Z \to W^+W^-\ell\ell \to 4\ell + 2\nu$$

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

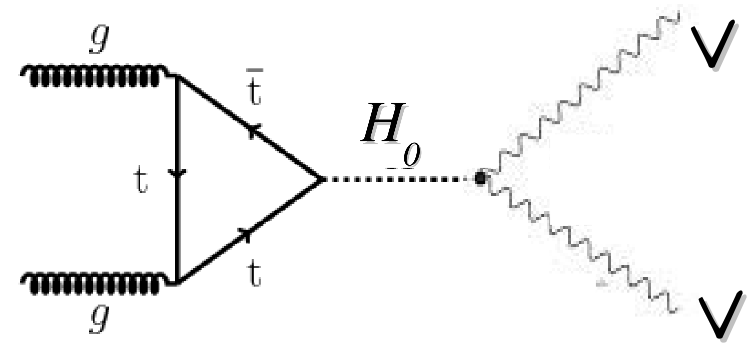
- Promising Prospects for $A_0 \to H_0\, Z$ Searches at LHC14

Remarks on "Standard" 2HDM LHC Searches

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



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



+

Measurements of light Higgs couplings