The LHC Connection to EW Cosmology

(2HDMs, the Electroweak Phase Transition & the decay $A_0 \to Z H_0$)

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In collaboration with G. Dorsch, S. Huber, K. Mimasu

Physics Challenges in the face of LHC14, IFT UAM/CSIC, Madrid, September 2014

University of Sussex

MARIE CURIE ACTIONS

Outline

❶ Motivation

Matter-antimatter Asymmetry: Baryogenesis at Electroweak Scale
Cosmology of EW Symmetry Breaking

❷ An Archetype Scenario: Extended Higgs Sectors

2HDMs: a *simple* paradigm for the EW Phase Transition & Baryogenesis

The LHC Connection:

⇨ A "*smoking gun*" signature: $A_0 \to H_0 Z$

⇨ Benchmarks for LHC searches: $\bar{b}b\,\ell\ell$ and $W^+W^-\ell\ell \to 4\ell\,2\nu$ channels

Promising discovery prospects in the upcoming 14 TeV run!

Comment on other Scenarios: **Higgs Portal**

❸ Conclusions, Outlook & Debate

Motivations

What is the Origin of the Baryon Asymmetry?

- ⇨ Leptogenesis
- ⇨ Baryogenesis at EW Scale
- ⇨ ...

SM

<u>Sakharov Conditions</u>

B Violation ✓
C & CP Violation ✗
Departure from Thermal Equilibrium ✗

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→ New CP Sources

→ First Order EW Phase Transition:
New Bosons at EW Scale

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TESTABLE!

BSM

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B Violation ✓
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New CP Sources — ***EDMs***

First Order EW Phase Transition:
New Bosons at EW Scale — **LHC**

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Possible Connection to Naturalness

N. Craig, C. Englert, M. McCullough, Phys. Rev. Lett. ***111*** *(2013) 121803*

... sphalerons are shut-off by the EW Phase Transition

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Cosmology of Electroweak Symmetry Breaking?

(Nature of the EW Phase Transition)

Arquetype Scenarios: **2HDM**

Extended Higgs Sectors can provide the Missing Ingredients for Baryogenesis

➔ *Adding a Second Scalar Doublet to the SM:*

$\mathbb{Z}_2$ Symmetric (softly broken) 2HDM

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

- New bosons coupled to SM Higgs contribute to thermal eff. potential → Strong First Order EW Phase Transition
- New Sources of CP Violation (I will not discuss it here)
- Simple Extension of the SM, Testable at LHC
- Connection between Cosmology and Collider Physics

Arquetype Scenarios: **2HDM** (Z_2 Symmetric (softly broken))

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$$\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ v\cos\beta \end{pmatrix}$$

$$\langle\Phi_2\rangle = \begin{pmatrix} 0 \\ v\sin\beta \end{pmatrix}$$

- *For Simplicity, we do not consider CP Violation (Future Work)*
- *New "Heavy" Scalars* H_0 *(CP-Even),* A_0 *(CP-Odd) and* $H^\pm$
- *6 Parameters:* m_{H_0} m_{A_0} $m_{H^\pm}$ μ α $\tan\beta$

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- *We focus on* Type-I 2HDM (all fermions coupled to same scalar doublet)
  - ⇨ The EW Phase Transition DOES NOT depend on the Type
  - ⇨ Experimental constraints DO depend on the Type

Type	u_R	d_R	e_R
I	+	+	+
II	+	−	−
X	+	+	−
Y	+	−	+

Arquetype Scenarios: **2HDM** (Z_2 Symmetric (softly broken))

The EW Phase Transition in 2HDM

- ➔ *Monte Carlo Scan:* m_{H_0} m_{A_0} $m_{H^\pm}$ μ α $\tan\beta$
  - ⇨ *Stability of the Effective Potential at 1-loop*
  - ⇨ *Code interfaced to* 2HDMC *& HiggsBounds* → Select Points Satisfying Unitarity, Perturbativity, EWPO, Collider Bounds

*D. Eriksson, J. Rathsman, O. Stal, Comput. Phys. Commun. **181** (2010) 189*
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  F. Mahmoudi, O. Stal, Phys. Rev D **81** (2010) 035016
- ⇨ *Global Fit to light Higgs Properties* → Constraints on α and $\tan\beta$

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

Points satisfying all above constraints are "Physical"

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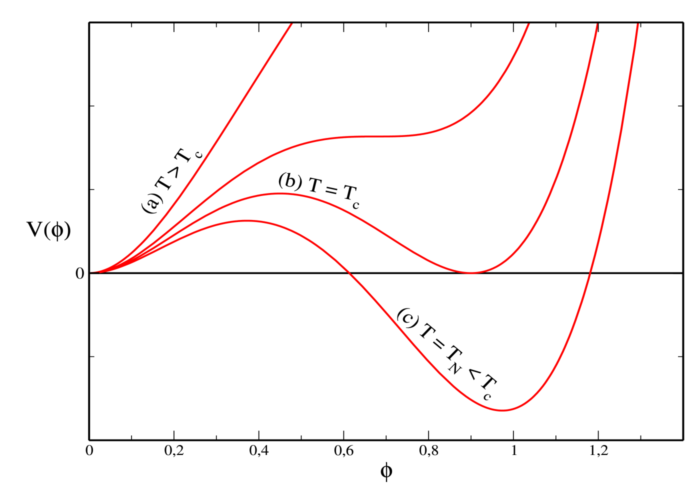
➔ *Strength of the EW Phase Transition:*

- *Daisy Resummed 1-loop Thermal Effective Potential* $V_{\mathrm{eff}}(\phi, T)$
- *Critical Temperature* T_C
- $v_C/T_C > 1$ → Strongly First Order EW Phase Transition



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The EW Phase Transition in 2HDM

***Strong EW Phase Transition* vs "*Physical*":**

- *SM-like light Higgs h*
  (Small $\alpha - \beta$ and $\tan\beta \gtrsim 1$)
  2HDM EW Phase Transition "in good shape" from measurements of Higgs properties
  G. Dorsch, S. Huber, J.M. No, JHEP **1310** (2013) 029
- *Light H_0*: $m_{H_0} < 250$ GeV
- *Large Mass Splitting* $m_{A_0} - m_{H_0} \sim v$
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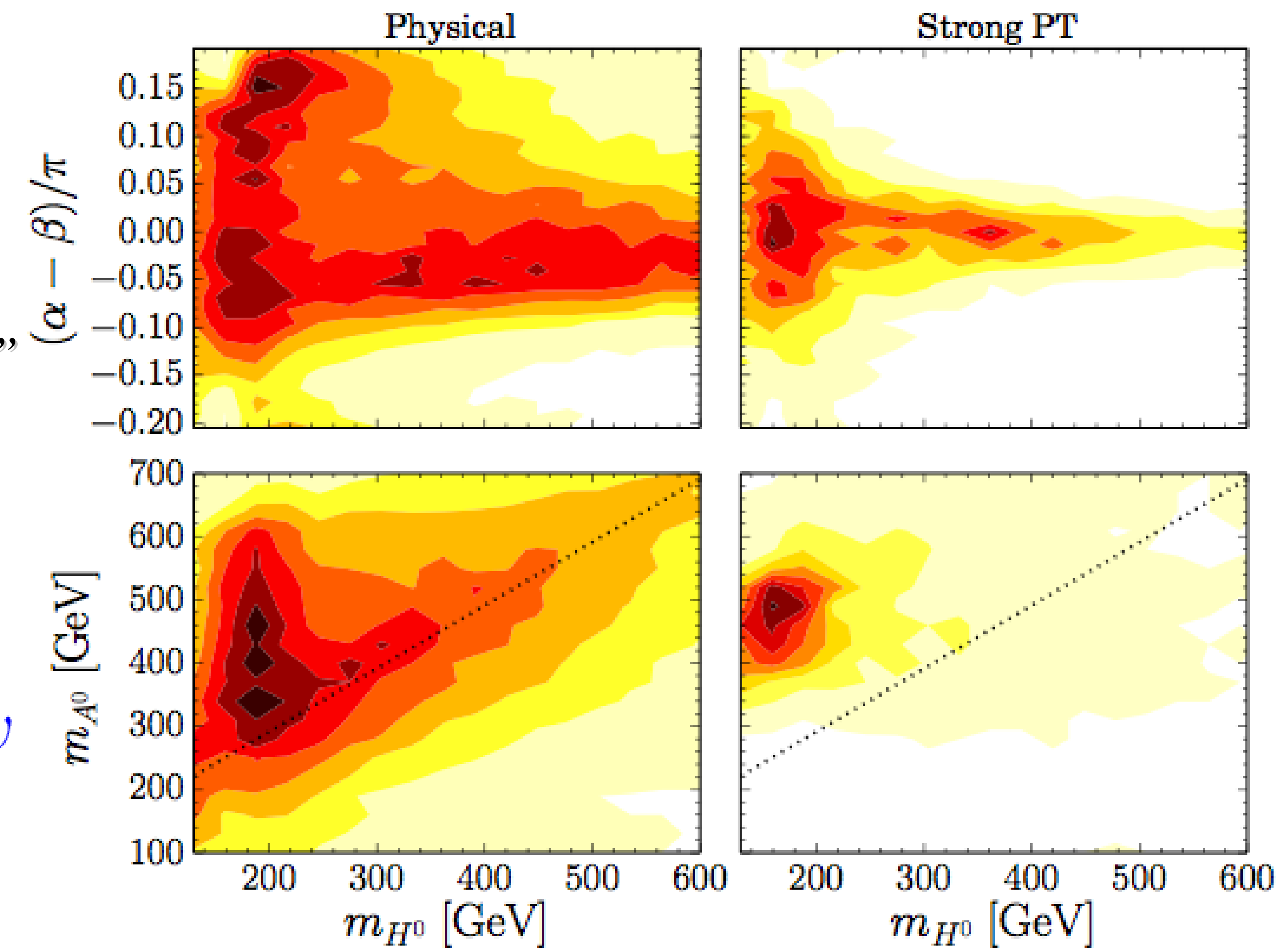

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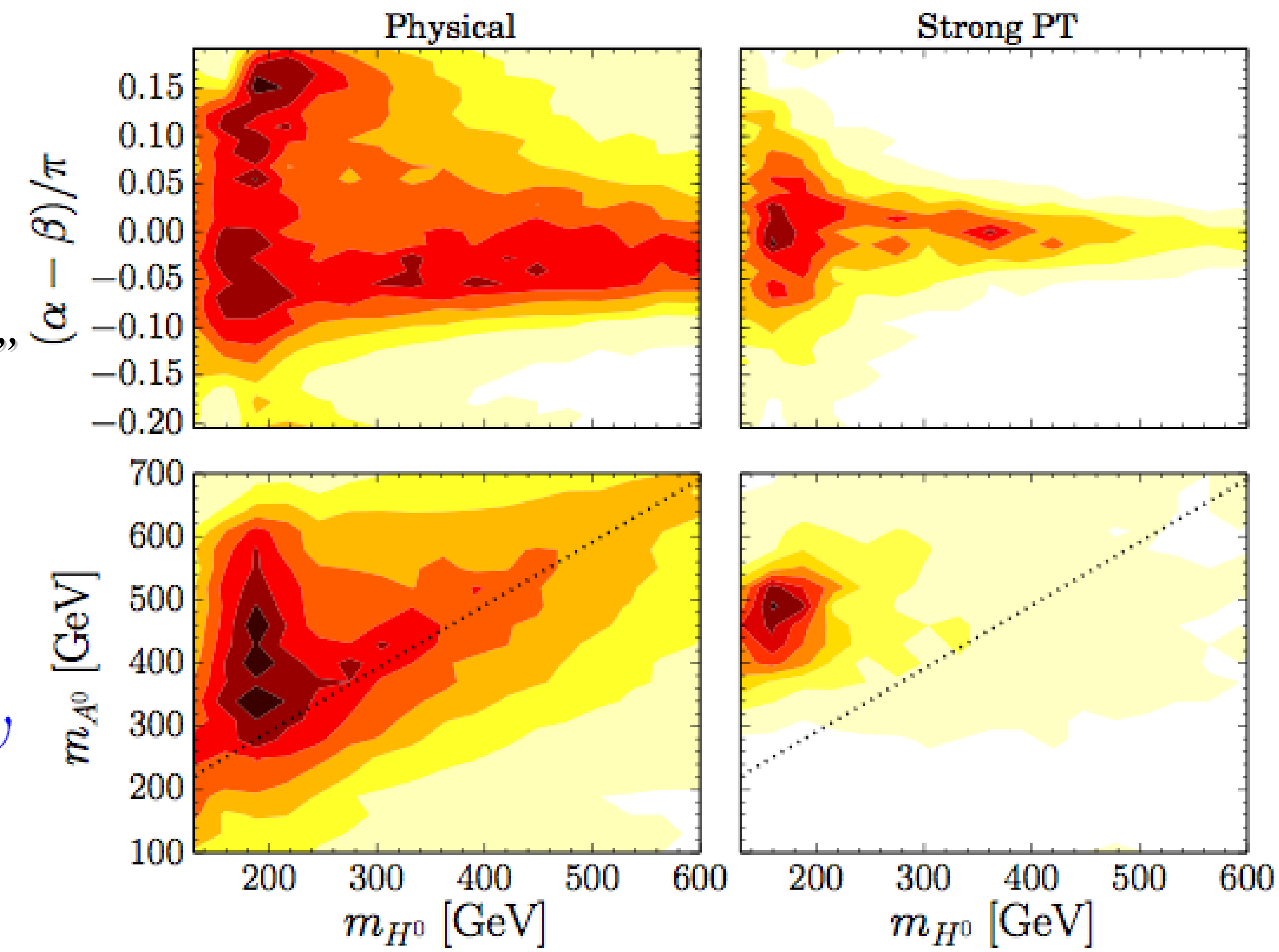

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⇨ A Strong 1st Order EW Phase Transition points towards very different 2HDM than usually considered (MSSM-like):

⇨ μ *and* v *set the overall scale. Mass Splittings set by quartic couplings* λ_i

⇨ *In MSSM,* $\Delta m \ll$ v → Large Mass Splittings $\Delta m \sim$ v Suggest Strongly Coupled UV Completions

J. Mrazek, A. Pomarol, R. Ratazzi, M. Redi, J. Serra, A. Wulzer, Nucl. Phys. B **853** (2011) 1
E. Bertuzzo, T. Ray, H. de Sandes, C. Savoy, JHEP **1305** (2013) 153

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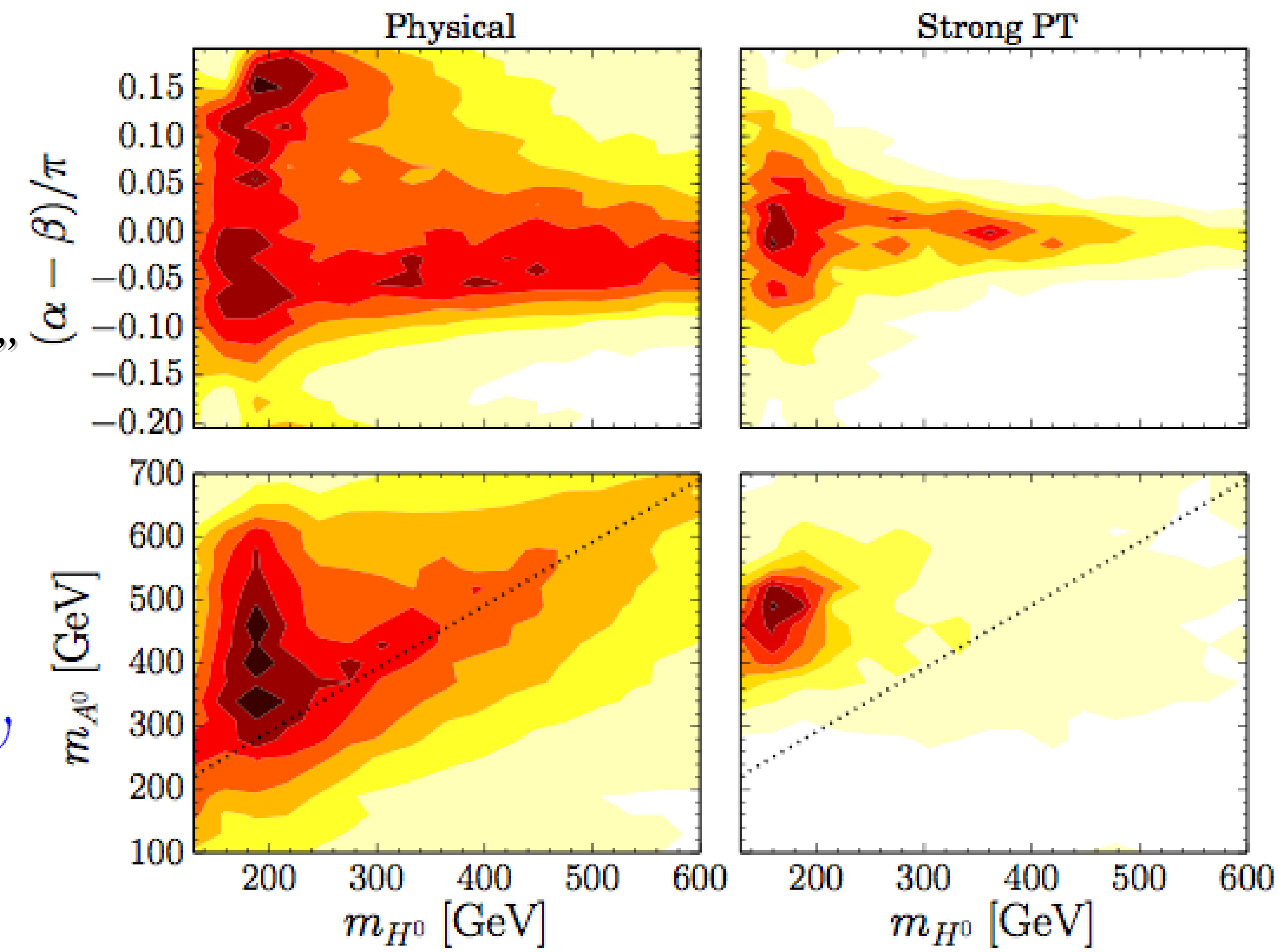

Impact on 2HDM Searches at LHC:

⇨ *H_0 searches in WW and ZZ channels are Challenging*

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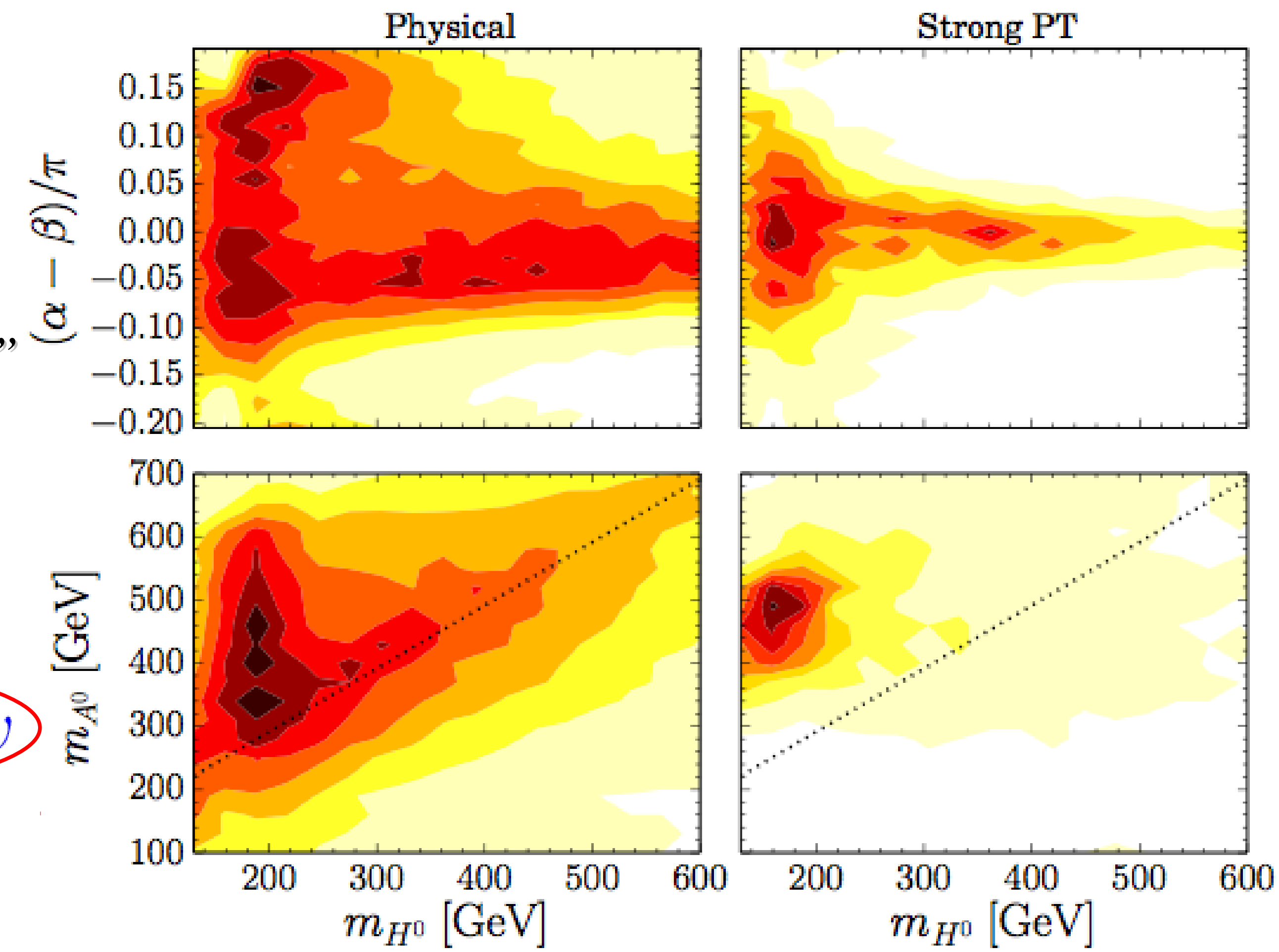

***Impact on 2HDM Searches at LHC**:*

⇨ *H_0 searches in WW and ZZ channels are Challenging*

⇨ *Opens New Decay Channels* $\phi_i \to V \phi_j$ *(not widely considered...)*
B. Coleppa, F. Kling, S. Su, arXiv:1404.1922
G. Dorsch, S. Huber, K. Mimasu, J.M. No, arXiv:1405.5537

Forbidden in MSSM-like 2HDM

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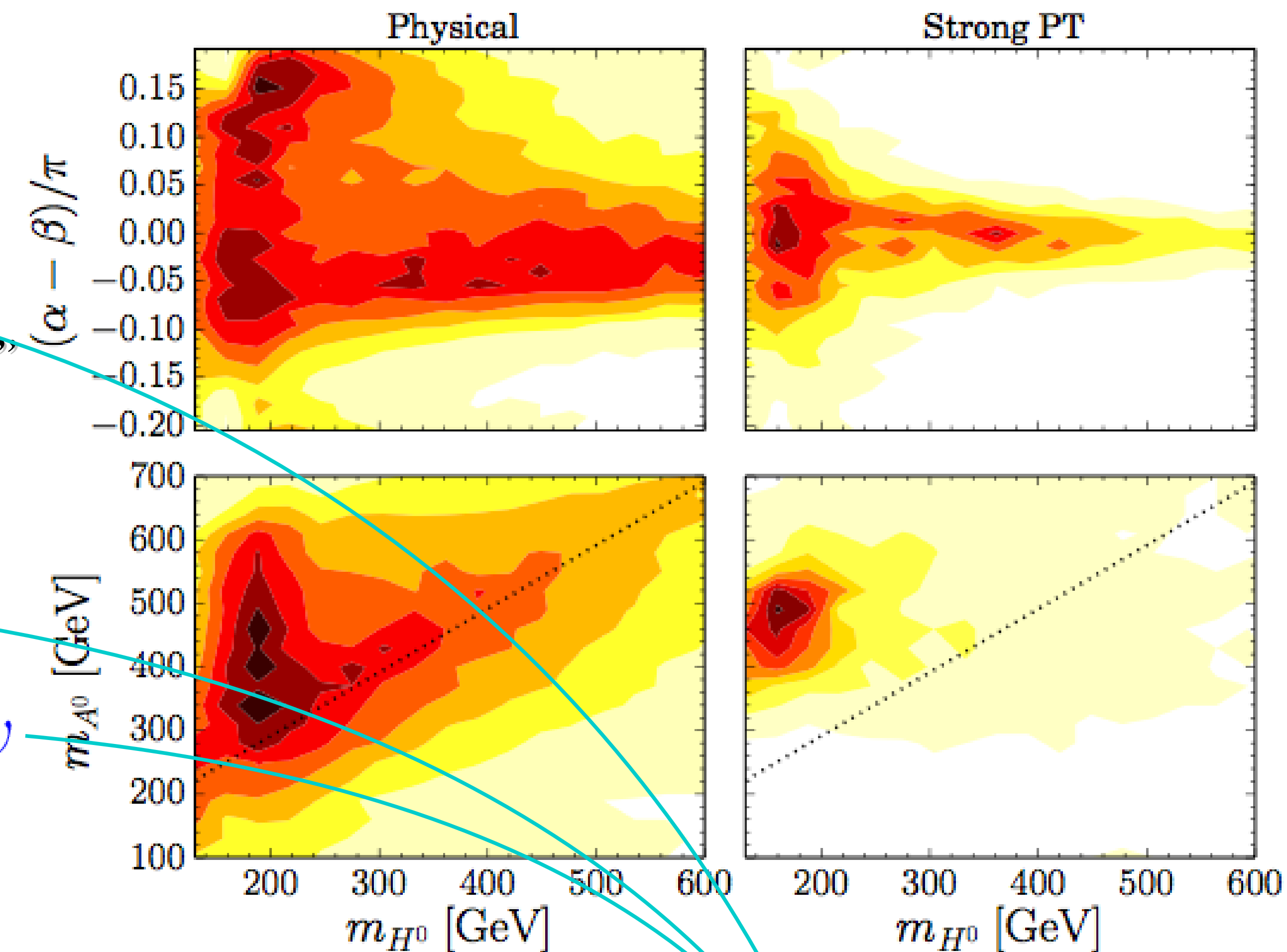

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"*smoking gun*" signature

$$A_0 \to H_0\, Z$$

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The LHC Connection: $A_0 \rightarrow H_0\, Z$

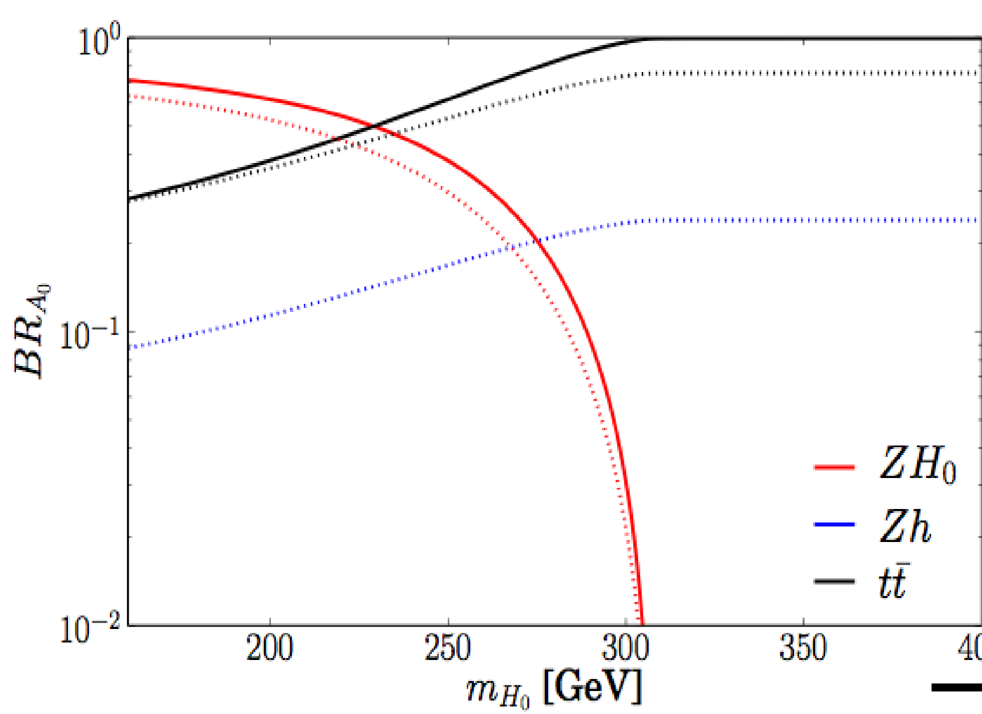
- *Decay* $A_0 \rightarrow H_0\, Z$ *Dominant for* $m_{A_0} - m_{H_0} \sim v$
  - ⇨ $A_0 \rightarrow h\, Z$ *supressed by* $\sin(\alpha - \beta)$
  - ⇨ *Competing Channels*

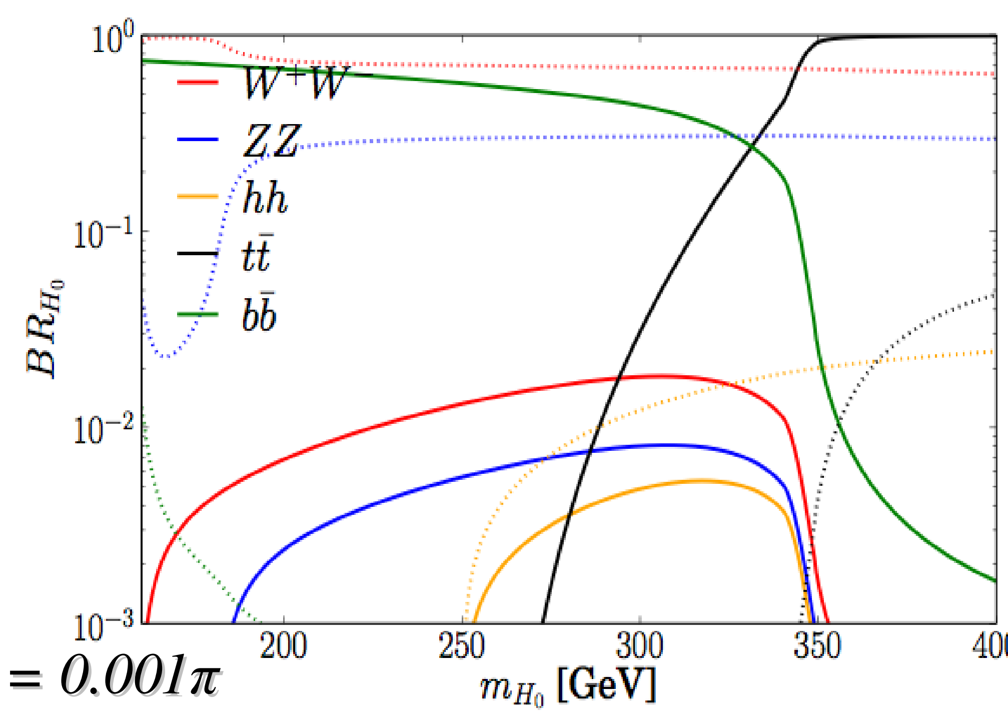
$A_0 \rightarrow \bar{t}t \sim (\tan\beta)^{-2}$

$A_0 \rightarrow H^{\pm}\, W^{\mp}$ — depends on $m_{H^{\pm}}$ (no preference from strong PT)

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

B. Coleppa, F. Kling, S. Su, arXiv:1408.4119





—— A: α-β = 0.001π

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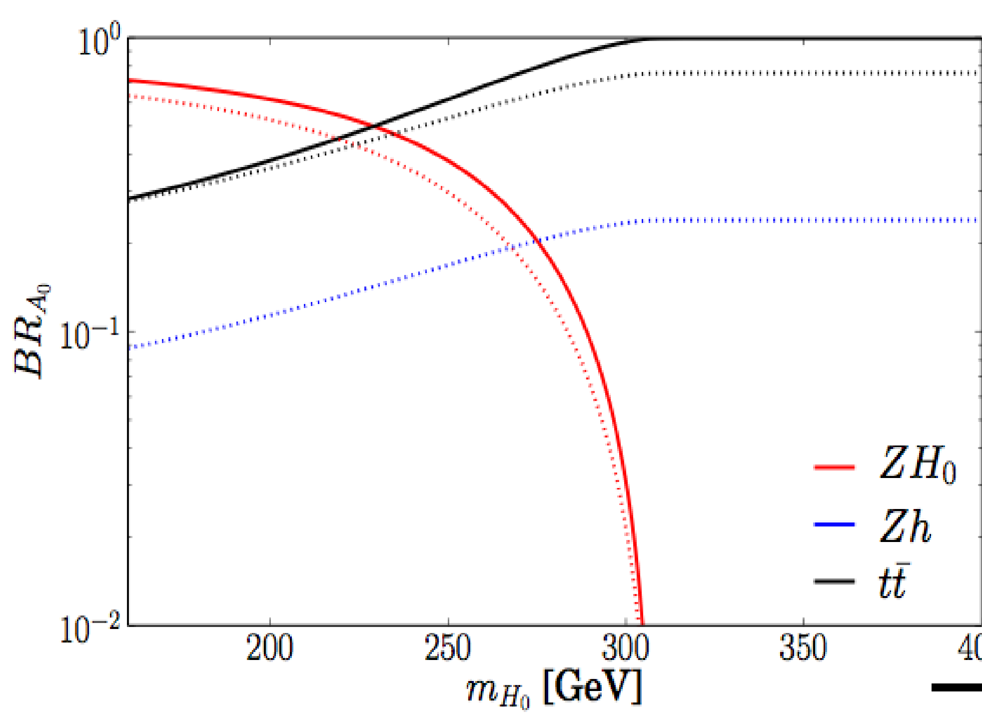
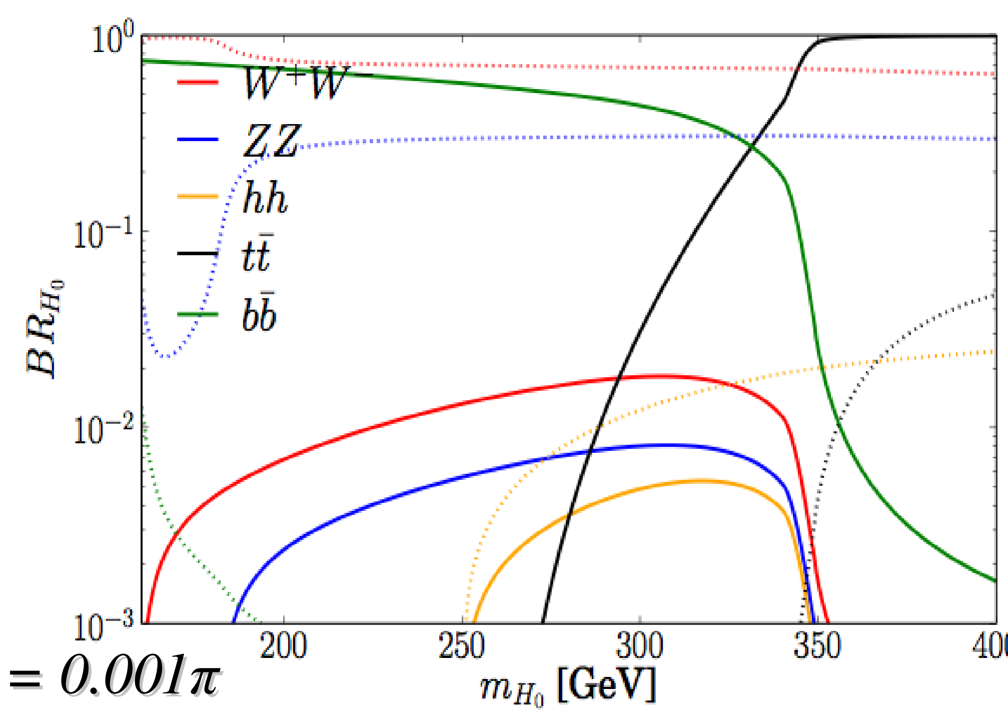
    - $A_0 \to \bar{t}t \sim (\tan\beta)^{-2}$
    - $A_0 \to H^{\pm}\, W^{\mp}$

EWPO require $m_{H^\pm} \sim m_{A_0}$ or $m_{H^\pm} \sim m_{H_0}$

closed open





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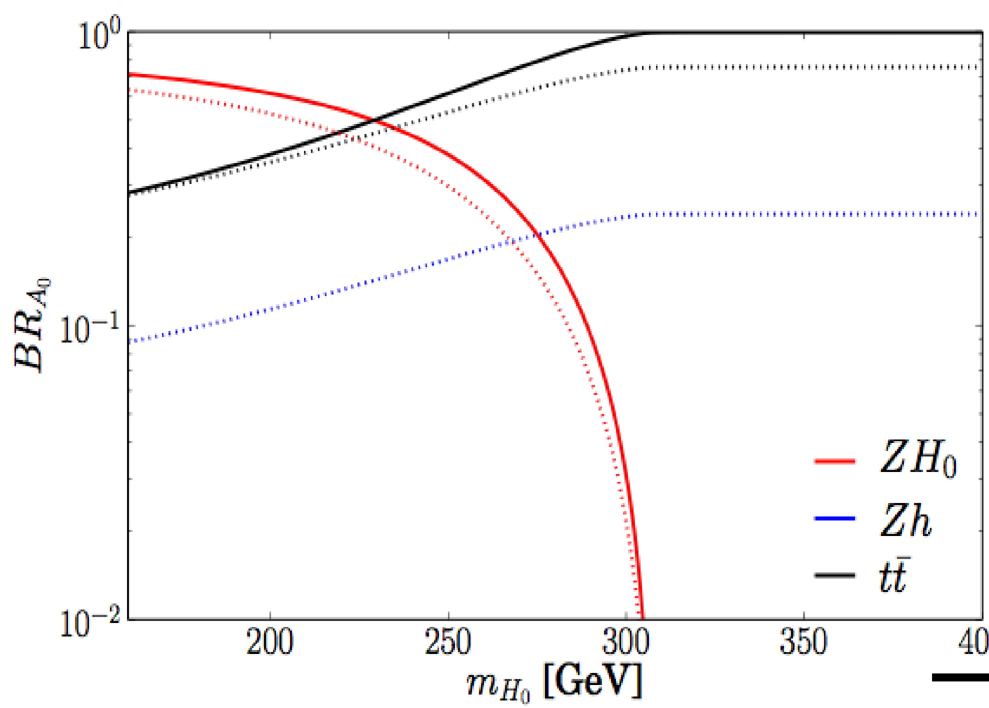
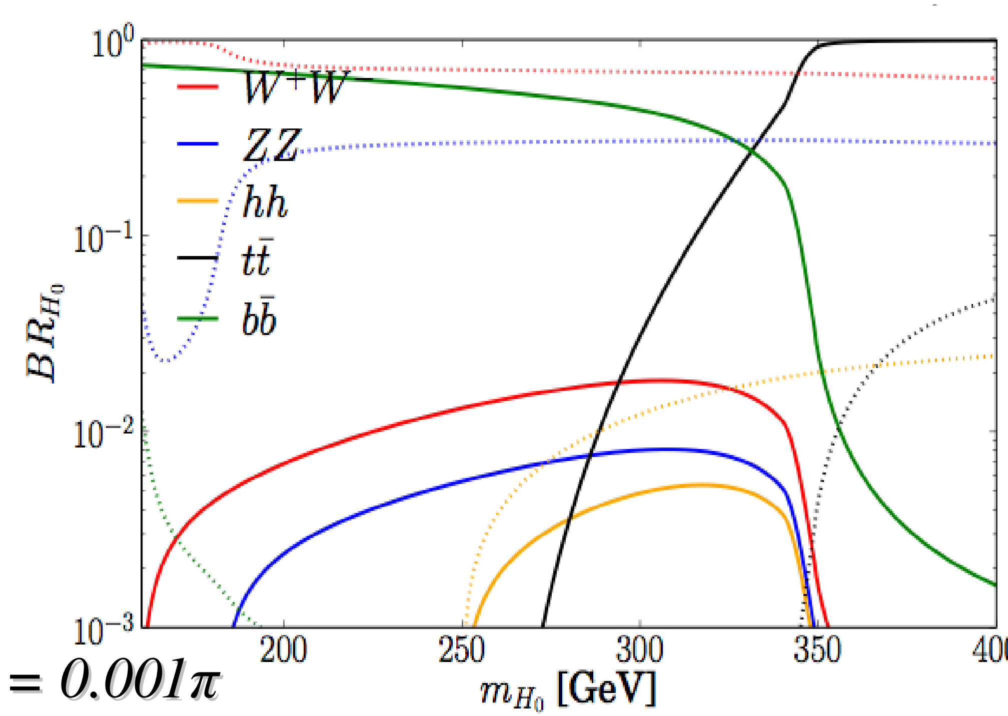
  - ⇨ *Competing Channels* → $A_0 \to \bar{t}t \sim (\tan\beta)^{-2}$, $A_0 \to H^{\pm} W^{\mp}$
- *Simple Benchmarks for a Strong EW Phase Transition*:
  $m_{A_0} = m_{H^\pm} = 400,\ m_{H_0} = 180,\ \mu = 100$ (GeV)
  $\tan\beta = 2$ (controls $gg \to A_0$ production)
- *Search Strategy Dictated by Dominant Decay Mode of* H_0
  - A: α-β = 0.001π (aligned) $\bar{b}b$
  - B: α-β = 0.1π (non-aligned) WW, ZZ





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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 a* 5σ *statistical significance via a CLs hypothesis test.*
  - *Only statistical uncertainties.*
  - *10% systematic uncertainty on background.*
- *Also considered current 8 TeV LHC data for* $\bar{b}b\,\ell\ell$

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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 (potential sensitivity already with 7-8 TeV LHC data): *Event Selection*

ATLAS-CONF-2013-079

→ *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.*

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

Arquetype Scenarios: **2HDM** (Z_2 Symmetric (softly broken))

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 (potential sensitivity already with 7-8 TeV LHC data): ***Event Selection***

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→ *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.*

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

Invariant mass windows:

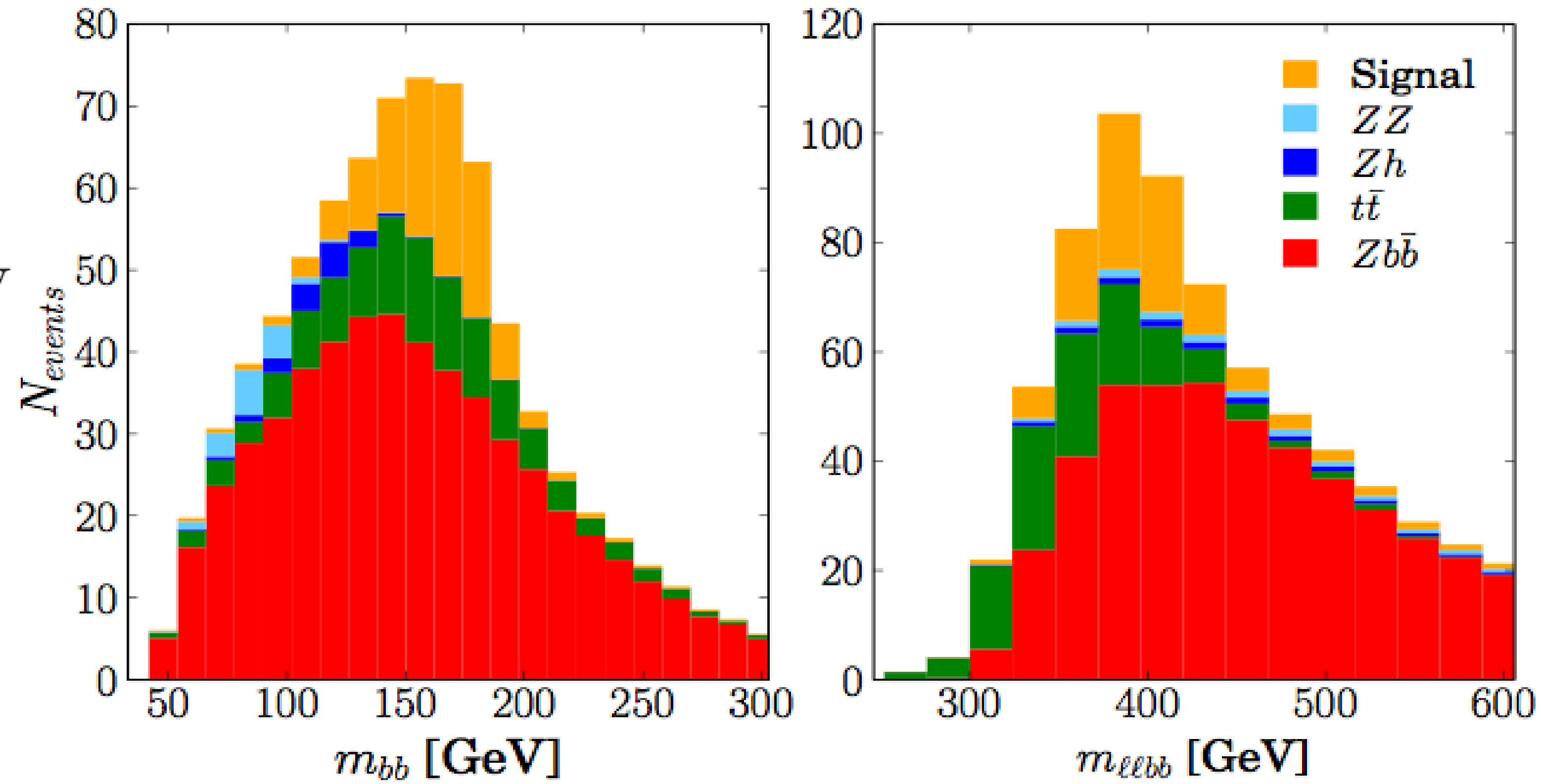
$$m_{\bar{b}b} \rightarrow (m_{H_0} - 20) \pm 30\,\mathrm{GeV}$$

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

5σ signal significance for:

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

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



Arquetype Scenarios: **2HDM** (Z_2 Symmetric (softly broken))

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.

G. Dorsch, S. Huber, K. Mimasu, J.M. No, arXiv:1405.5537

⇨ $A_0 \to H_0 Z \to ZZ\ell\ell \to 4\ell + 2j$ also promising.

B. Coleppa, F. Kling, S. Su, arXiv:1404.1922

⇨ *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.* $|\eta| <$ 2.5 (2.7) *for electrons (muons)*

→ $P_T^{\ell_1} >$ 40 *GeV*, $P_T^{\ell_{2,3,4}} >$ 20 *GeV*.

Arquetype Scenarios: **2HDM** (Z_2 Symmetric (softly broken))

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*)

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→ *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

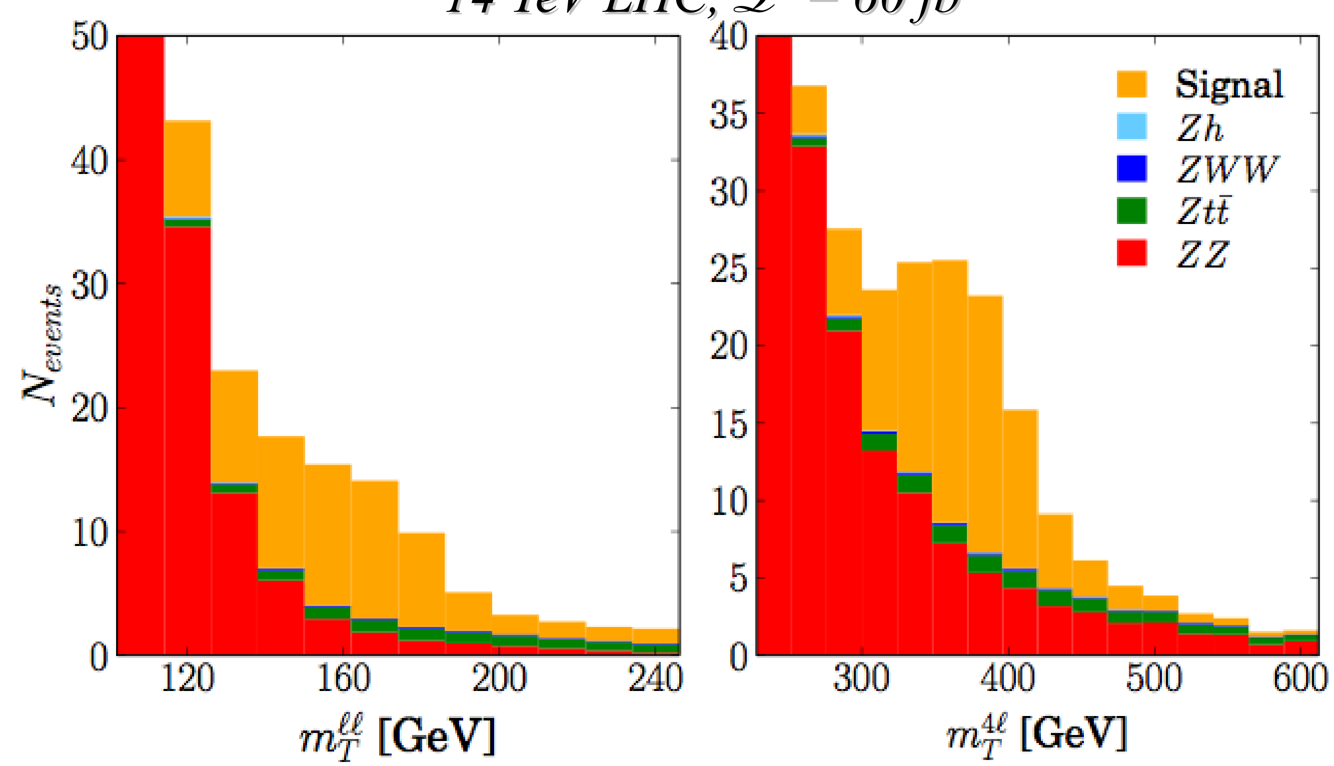
→ *Transverse mass variables*:

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

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

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

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



Arquetype Scenarios: **2HDM** (Z_2 Symmetric (softly broken))

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.
  G. Dorsch, S. Huber, K. Mimasu, J.M. No, arXiv:1405.5537
- ⇨ $A_0 \to H_0\, Z \to ZZ\ell\ell \to 4\ell + 2j$ also promising.
  B. Coleppa, F. Kling, S. Su, arXiv:1404.1922
- ⇨ *Main backgrounds are* ZZ, $Z\bar{t}t$ 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*.

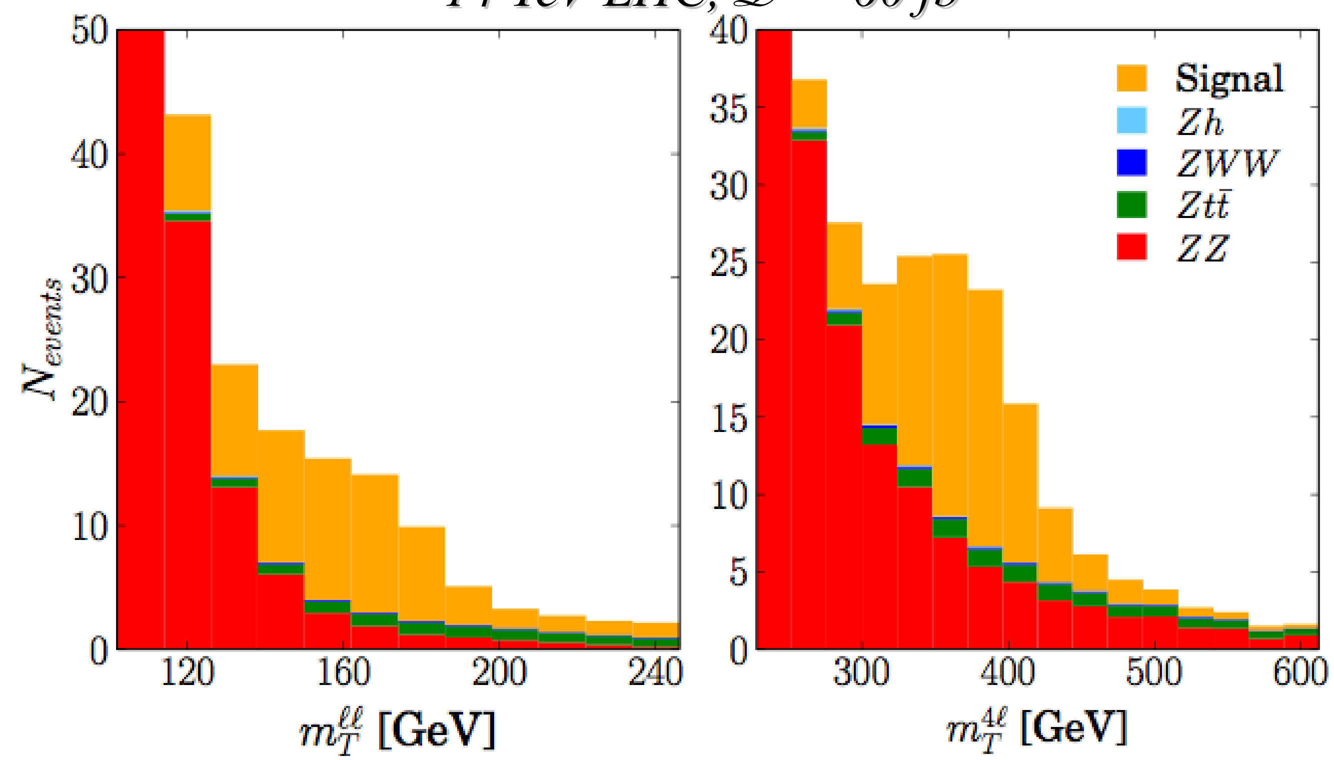
5σ signal significance for:

ℒ = 60 fb^{-1} *(statistics only)*

ℒ = 200 fb^{-1} *(10% systematics)*

(conservative...)

14 TeV LHC, ℒ = 60 fb^{-1}



Arquetype Scenarios: **Higgs Portal**

R. Schabinger, J. Wells, Phys. Rev. ***D72*** *(2005) 093007*
B. Patt, F. Wilczek, hep-ph/0605188

SM + Real Scalar Singlet S

|H|^2 unique Lorentz & Gauge Invariant term w. **d<4**

$$V(H,S) = -\mu^2\,|H|^2 + \lambda\,|H|^4 + \frac{b_2}{2}S^2 + \frac{b_4}{4}S^4 + \frac{a_1}{2}S|H|^2 + \frac{a_2}{2}S^2|H|^2 + \frac{b_3}{3}S^3$$

Singlet-Doublet Mixing

h_1 (m_1= 125 GeV), h_2

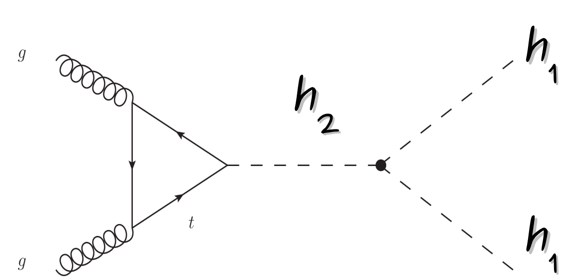
Scenarios w. Scalar Singlets can Lead to Strong 1st Order EW Phase Transition

G. Anderson, L. Hall, Phys. Rev. ***D45*** *(1992) 2685*
J. R. Espinosa, M. Quiros, Phys. Lett. B ***305*** *(1993) 98*
S. Profumo, M. Ramsey-Musolf, G. Shaughnessy, JHEP ***0708*** *(2007) 010*
J. R. Espinosa, T. Konstandin, J. M. No, M. Quiros, Phys. Rev. ***D78*** *(2008) 123528*
J. R. Espinosa, T. Konstandin, F. Riva, Nucl. Phys. ***B854*** *(2012) 592*

How to probe the EW Phase Transition at LHC?

...via Resonant Higgs Pair Production

J. M. No, M. Ramsey-Musolf, Phys. Rev. ***D89*** *(2014) 095031*



Conclusions and Outlook

⇨ *EW scale Baryogenesis as a motivation for New Physics Beyond the SM.*
(New Bosons at EW Scale ⇨ Possible Connection to Naturalness)

⇨ *Extended Higgs sectors as Archetype scenarios of such a connection between EW Cosmology and LHC Physics.*

2HDM:

→ *Simple & testable extension of the SM, capable of providing the Ingredients for EWBG missing in the SM.*

→ *A Strong First Order EW Phase Transition favours a 2HDM scenario different from the one usually considered*

SM-like light Higgs h (small $\alpha - \beta$ & $\tan\beta \gtrsim 1$)
Light H_0 ($m_{H_0} < 250$ GeV)
Large Mass Splitting $m_{A_0} - m_{H_0} \sim v$

"smoking gun"
$A_0 \to H_0\, Z$

→ *Two main search channels:* $\bar{b}b\,\ell\ell$ & $W^+W^-\,\ell\ell \to 4\ell\,2\nu$

→ *Current data could already be sensitive to this signature in* $\bar{b}b\,\ell\ell$ *final state!*

→ *"Cut & count" analysis for two benchmark shows these searches are very promising at* LHC14

Higgs Portal: *Nature of the EW Phase Transition explorable via Resonant Di-Higgs Production*

Conclusions and Outlook

⇨ *These results very much motivate taking such searches seriously at LHC*

⇨ *For 2HDM, we aim to:*

- → *Extend the present analysis beyond Benchmark scenarios*
- → *Further investigate the Sensitivity of current 7-8 TeV LHC data to these scenarios*
- → *Include Charged Higgs*: $A_0 \to H^{\pm} W^{\mp}$
- → *Include CP Violation*

ATLAS $\bar{b}b\,\ell\ell$ at 7-8 TeV

[ATLAS-CONF-2013-079]

- *Defines signal regions according to number of leptons, additional jets.*
- *Splits them according to the p_T of the Z (no m_{bb} requirement).*
- *Global fit extracts the background normalisations and signal strength of a 125 GeV SM Higgs.*
- P_T^Z *in our signal set by* $m_{A_0} - m_{H_0}$. *Signal will populate boosted kinematical region.*