Echoes of the electroweak phase transition: Discovering a second Higgs doublet via $A_0 \to ZH_0$

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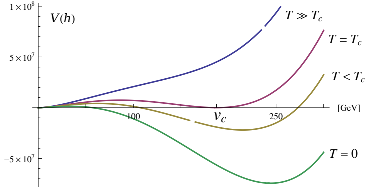
Outline

- Motivations
  - The problem of baryogenesis
  - Two-Higgs-doublet model as a viable candidate
- Electroweak phase transition in the 2HDM
- The $A_0 \to ZH_0$ as a "smoking gun" signature
- Motivating the search in $b\bar{b}\ell\ell$ and $WW\ell\ell \to 4\ell\ 2\nu$
- Collider analysis for two benchmark scenarios
  - **Promising discovery prospects in LHC 14 TeV**
- Conclusions and Outlook

Baryogenesis in the SM

- SM cannot account for observed baryon asymmetry of the Universe.
- Sakharov conditions: C, CP and B violation occurring out of equilibrium. In SM:
  - ✔ B violation unsuppressed at $T \gtrsim$ EW scale.
  - ▸ Displacement from equilibrium could be provided by a first order (i.e. discontinuous) EW phase transition.
  - ▸ To freeze out the generated BAU inside bubble, EWPT must be strongly first order (supercooling):

$$v_c/T_c \gtrsim 1.0$$



  - ✘ Not realized in the SM for $m_h \gtrsim m_W$.
  - ✘ Also, CP violation from CKM matrix insufficient!
- Baryogenesis requires BSM physics, and it is only natural to focus on extending the scalar sector.

Two-Higgs-doublet model

- Two-Higgs-doublet models are optimal candidates:
  - One of the simplest extensions of SM:
    Two $SU(2)_L$ scalar doublets: Φ_1 and Φ_2 .
  - Various heavy scalars $(h_0, H_0, A_0, H^{\pm})$ increase EWPT strength.
  - Additional source of CP violation (explicit or spontaneous).
  - Testable at LHC @ 14 TeV!
- To avoid FCNC, impose a softly broken Z_2 symmetry.

$$\mathcal{L}_{\text{Yukawa}} \supset -\overline{Q_L}\left(Y_1^t \Phi_1 + Y_2^t \Phi_2\right) t_R$$

  - This work: **Type I** $\Rightarrow$ all fermions couple to same doublet.
  - No lower bound on charged Higgs mass.
    (For Type II, $m_{H^{\pm}} > 380$ GeV from flavour constraints
    T. Hermann, M. Misiak and M. Steinhauser, JHEP **1211** *(2012) 036*)

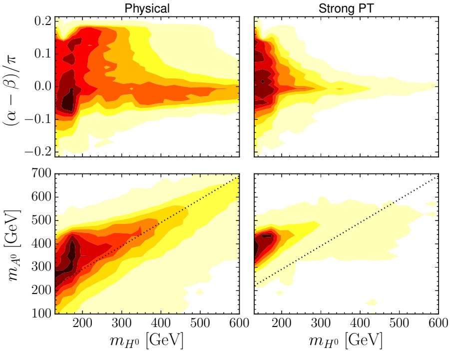
Two-Higgs-doublet model

- For simplicity, consider CP conserving case only.
  Small CPV phase does not have significant impact on EWPT.
- Theory defined by 8 physical parameters:
  - $v \approx 174$ GeV and $\mu \sim$ scale of new physics.
  - Masses: $m_{h_0} = 125$ GeV, $m_{H_0}, m_{A_0}, m_{H^\pm}$.
  - $\tan\beta = \langle\Phi_2\rangle / \langle\Phi_1\rangle$.
  - α is the mixing angle between h_0 and H_0.
    It is here defined such that $\alpha = \beta \iff h_0 = h_{\rm SM}$.
- Correct BAU obtained in special cases:
  L. Fromme, S. J. Huber and M. Seniuch, JHEP **0611** *(2006) 038*
- Scan over parameter space, imposing:
  - tree-level unitarity, perturbativity (quartics $< 2\pi$);
  - electroweak precision observables ($\Delta\rho$ most relevant);
  - flavour constraints ($b \to s\gamma$ and $B^0 - \overline{B^0}$ mixing most relevant);
  - collider bounds with HiggsBounds and HiggsSignals;
  - stability of electroweak vacuum at 1-loop up to $\Lambda = 10$ TeV.
  - If all constraints are passed, the point is deemed **physical**.

2HDM and the EWPT

- We study the EWPT by looking for the minima of the 1-loop thermal effective potential. *GCD, S. J. Huber, J. M. No, JHEP 1310 (2013) 029*
  - EW symmetry is restored at high temperatures.
  - At critical temperature T_c the potential has two degenerate minima at 0 and at v_c.
  - Phase transition is strong when $v_c/T_c > 1$.

- SM-like h_0 favoured.
- As m_{H_0} increases, strong PT requires $\langle H_0 \rangle \sim \sin(\alpha - \beta) \to 0$.
- But for $m_{H_0} \lesssim 200$ GeV, $\alpha - \beta \sim 0.1\pi$ is acceptable!
- $m_{A_0} \gtrsim 300$ GeV, with $m_{A_0} \gtrsim m_{H_0} + m_Z$.



Phenomenological consequences

- Requiring a strong PT points to a very different kind of 2HDM than usually considered in collider analyses.
  - Current heavy Higgs searches tend to be motivated by SUSY.
  - Mass splittings dictated by gauge couplings; do not exceed m_Z.
  - Thus $S_i \to Z S_j$ channel ($S_i \in H_0, A_0$) is closed.
  - H_0 searches focus on $H_0 \to WW, ZZ$ (not allowed for A_0).
  - Pseudoscalar searched for in $A_0 \to Z h_0, \tau\tau$.
- In our scenario, $m_{A_0} - m_{H_0} \gtrsim m_Z$ and $\alpha \approx \beta$.
  - Points to $A_0 \to Z H_0$, as coupling $\sim \cos(\alpha - \beta)$ is unsuppressed...
  - ...while $A_0 \to Z h_0$ is suppressed by $\sin(\alpha - \beta) \approx 0$ (in alignment limit) and due to dominance of the previous channel.
  - A competing channel would be $W^{\pm} H^{\mp}$...
  - ...but EWPO require $m_{H^{\pm}} \approx m_{H_0}$ or m_{A_0}. We pick the latter for simplicity and close this channel (strong PT is rather indifferent to this choice).

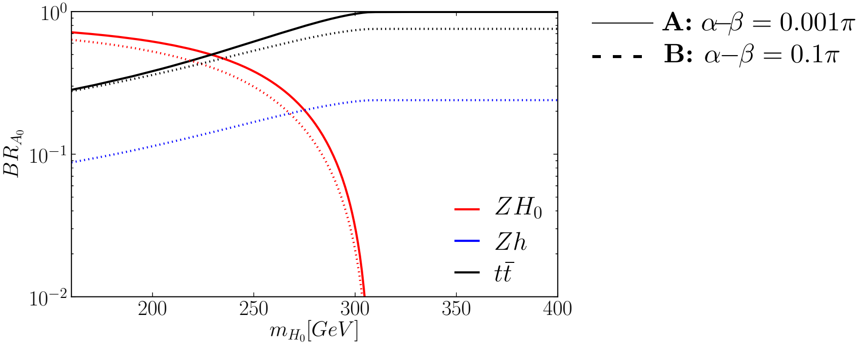
Phenomenological consequences

Benchmark scenarios

$m_{H_0} = 180$ GeV, $m_{A_0} = m_{H^\pm} = 400$ GeV, $\mu = 100$ GeV, $\tan\beta = 2$

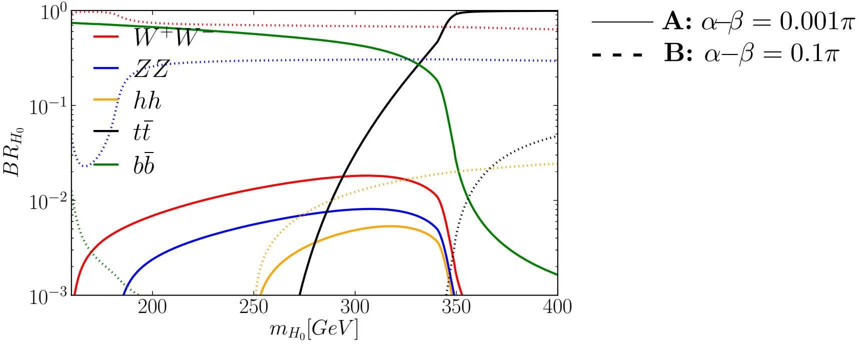
A: $\alpha - \beta = 0.001\pi$ (alignment)

B: $\alpha - \beta = 0.1\pi$ (non-alignment)



- For our benchmark points, $t\bar{t}$ and Zh_0 are always subdominant.

H_0 decays and final states



- Clear preference for $b\bar{b}$ and WW in respective scenarios.
  - Leptonic final states are clean, with lower background than hadronic channels.
  - Consider leptonic decays of Z and W.
  - A: $b\bar{b}\ell\ell$.
  - B: $WW\ell\ell \to 4\ell\ 2\nu$.

Collider analysis

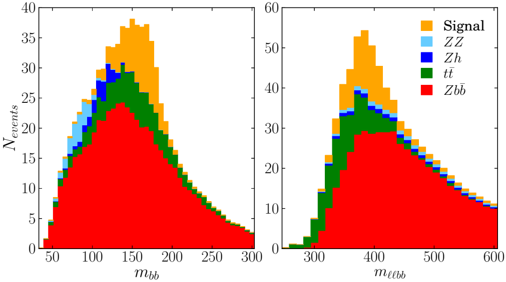
- Implemented Type I 2HDM in **FeynRules**
  - Including 5-dim effective operators for gluon fusion.
- Events generated using **MadGraph5_aMC@NLO**.
  - Passed to **Pythia** for parton showering and hadronization;
  - **Delphes** used for LHC detector simulation.
- Use K-factors for signal and dominant backgrounds to estimate NLO radiative corrections.
  - Obtained in literature for background, used **SusHi** for signal.
- "Cut and count" analysis performed on a few kinematical variables.
- Determined required luminosity at 14 TeV to achieve a (statistical only) significance of 5σ.
  - Assumed a 10% uncertainty on background expectation.

$A_0 \to ZH_0 \to b\bar{b}\ell\ell$

- Main irreducible backgrounds: $t\bar{t}$, $Zb\bar{b}$, ZZ and Zh.
- Impose cuts on $m_{\ell\ell}$, ΣP_T and ΔR.
- Look at invariant mass m_{bb} and $m_{bb\ell\ell}$.
- Significance of 5σ for $\mathcal{L} = 20$ fb^{-1}.

	Signal	$t\bar{t}$	$Z b\bar{b}$	ZZ	Zh
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

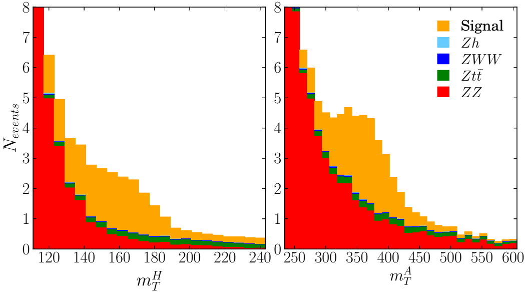
- Assuming 10% uncertainty on background increases $\mathcal{L}$ to 40 fb^{-1}.



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

$A_0 \to ZH_0 \to WW\ell\ell$

- Away from alignment, $b\bar{b}\ell\ell$ is dominated by $A_0 \to Zh_0$ but altogether low due to suppressed $BR_{A_0}(Zh_0)$.
- $WW\ell\ell$ is then the most promising channel.
- Main backgrounds: $ZZ \to 4\ell$, $Zt\bar{t}$, ZWW and Zh.
- Require one lepton pair to reconstruct Z.

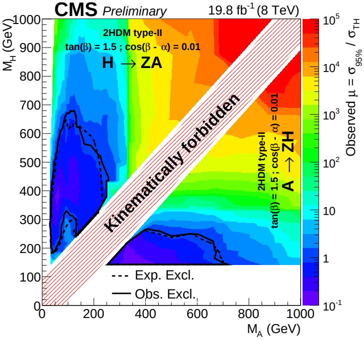


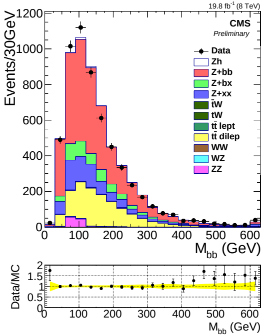
LHC 14 TeV,
$\mathcal{L} = 60\ \text{fb}^{-1}$

- A single cut on $m_{4\ell} > 260$ GeV allows for signal extraction.
- Significance of 5σ reached for $\mathcal{L} = 60\ \text{fb}^{-1}$ ($\mathcal{L} = 200\ \text{fb}^{-1}$ with 10% background uncertainty).

Prospects with 8 TeV data

- This work motivated a recent search in this channel (as well as in $H_0 \to ZA_0$) by the CMS collaboration *CMS-PAS-HIG-15-001*
- New exclusion limits; new search channel!
- Further investigation of 8 TeV data granted, and already on its way!





Conclusions and Outlook

- 2HDM is the simplest extension of SM, testable at LHC14 and can provide a strong first order phase transition required for EW baryogenesis.
- We explored the parameter space of the model, showing that a **strong PT prefers**:
  - a SM-like light h_0;
  - rather heavy pseudoscalar A_0 ($m_{A_0} \gtrsim 300$ GeV);
  - large mass splitting $m_{A_0} - m_{H_0} \gtrsim m_Z$.
- This points to an exotic phenomenology, having $A_0 \to ZH_0$ as a "smoking gun" signature.
- Our collider analysis shows that LHC 8 TeV may already be sensitive.
- At 14 TeV, potential for discovery at early stages of the run, with $\mathcal{L} = 20 - 200\ \text{fb}^{-1}$.
- We aim at extending this first analysis:
  - beyond just 2 benchmark points;
  - considering W^+H^- channel, CP violation;
  - further investigate sensitivity of current data.

Appendix: $b\bar{b}\ell\ell$ and $WW\ell\ell$

$b\bar{b}\ell\ell$

- Given potential sensibility already at 8 TeV, the 14 TeV run should be promising. *B. Coleppa, F. Kling and S. Su, arXiv:1404.1922 [hep-ph].*
- Kinematical cuts:
- Leptons should reconstruct m_Z.
- Cuts on total $H_T = \Sigma P_T$.
- ΔR between $b\bar{b}$ and $\ell\ell$.

K-factor 1.6 1.5 1.4

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Event selection	14.6	1578	424	7.3	2.7
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$WW\ell\ell$

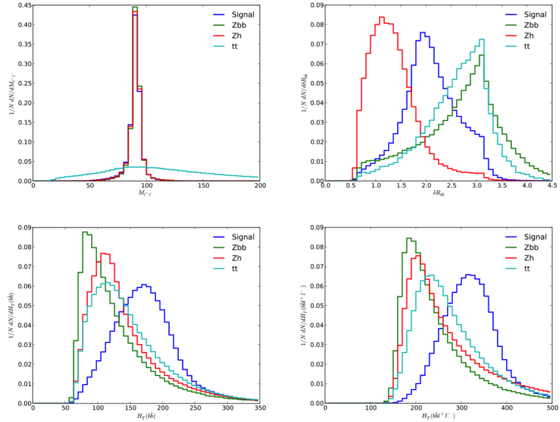
- Some information about the momenta of the two neutrinos cannot be fully deduced.
- Construct transverse mass variables sensitive to the two scalar masses.

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

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

Appendix: Distributions for $A_0 \to b\bar{b}\ell\ell$

- We employ straightforward signal selection criteria:
  - Anti-k_T jets with distance parameters $R = 0.6$.
  - b-tagging: $|\eta_b| < 2.5$.
  - $P_T^1 > 20$ GeV, $P_T^2 > 40$ GeV.
  - Leptons: $|\eta_\ell| < 2.5(2.7)$ for electrons (muons).



Appendix: 2HDM

- In CP conserving, softly broken Z_2 symmetric case:

$$
\begin{aligned}
V_{\rm tree}(\Phi_1,\Phi_2) = & -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - \frac{1}{2}\left(\mu^2\Phi_1^\dagger\Phi_2 + H.c.\right) + \\
& + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \\
& + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{1}{2}\left[\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2 + H.c.\right].
\end{aligned}
$$

- No quartic mixing terms $\Phi_1^\dagger\Phi_2$!
- In principle μ and λ_5 can be complex: **explicit CP violation!**
- Physical states:

$$
\begin{aligned}
G^+ &= \cos\beta\ \varphi_1^+ + \sin\beta\ \varphi_2^+ && \text{(charged Goldstone)},\\
H^+ &= -\sin\beta\ \varphi_1^+ + \cos\beta\ \varphi_2^+ && \text{(charged Higgs)},\\
G^0 &= \cos\beta\ \eta_1 + \sin\beta\ \eta_2 && \text{(neutral Goldstone)},\\
A^0 &= -\sin\beta\ \eta_1 + \cos\beta\ \eta_2 && \text{(CP-odd Higgs)},\\
h^0 &= \cos\alpha\ h_1 + \sin\alpha\ h_2 && \text{(lightest CP-even Higgs)},\\
H^0 &= -\sin\alpha\ h_1 + \cos\alpha\ h_2 && \text{(heaviest CP-even Higgs)}.
\end{aligned}
$$

Appendix: Z_2 symmetry

- Yukawa Lagrangean has the form

$$\mathcal{L}_{\text{Yukawa}} \supset -\overline{Q_L}\left(Y_1^n \Phi_1 + Y_2^n \Phi_2\right) n_R$$

- Avoid FCNC $\Rightarrow \mathbb{Z}_2$ symmetry:
  Each fermion type couples to one doublet only.
  S. L. Glashow and S. Weinberg, Phys. Rev. D **15** *(1977) 1958.*

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

$$\Phi_1 \to -\Phi_1, \quad \Phi_2 \to \Phi_2 \ .$$

- For PT, only top-quark needs to be considered, so all types give indistinguishable results.