The electroweak phase transition, baryogenesis and implications for collider searches

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Outline

- The problem of baryogenesis
- Electroweak phase transition
  and baryogenesis at the EW scale
- A practical example: The two-Higgs-doublet model
  - Electroweak phase transition in the 2HDM
  - $A_0 \to ZH_0$ as a "smoking gun" signature
  - Collider analysis for two benchmark scenarios

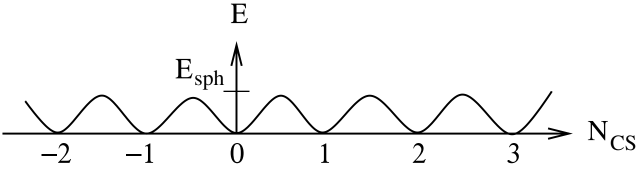
    Promising discovery prospects at LHC 13 TeV
- Conclusions and Outlook

The problem of baryogenesis

- SM cannot account for observed baryon asymmetry of the Universe:

$$\frac{n_B}{s} \approx 6.75 \times 10^{-10}.$$

- Sakharov conditions: C, CP and B violation occurring out of equilibrium. In SM:
  - ✔ B violation via $B + L$ anomaly and $SU(2)$ instantons:



  - ⋆ at $T = 0$, tunneling amplitude $\sim e^{-8\pi^2/g^2} \sim 10^{-185}$ (!)...
  - ⋆ ... but unsuppressed at $T \gtrsim$ EW scale (sphalerons).

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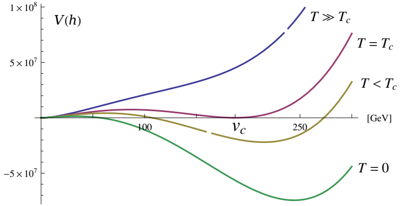
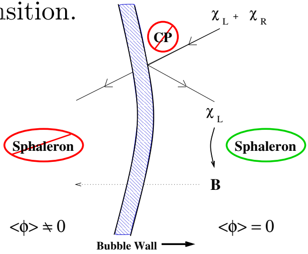
  - CP violation from CKM matrix.
  - Displacement from equilibrium could be provided by a first order (i.e. discontinuous) EW phase transition.





Morrisey and Ramsey-Musolf, New J. Phys. **14** *(2012) 125003*

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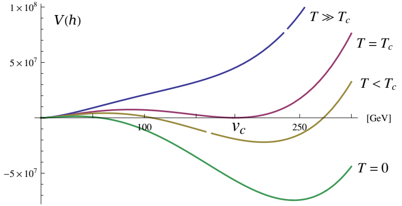

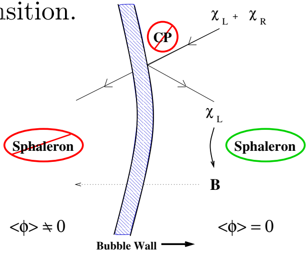

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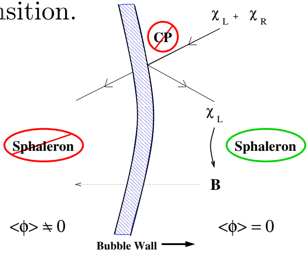
- To freeze out the generated BAU inside the bubble, EWPT must be strongly first order (supercooling):

$$v_c/T_c \gtrsim 1.0$$

✘ Not realized in the SM for $m_h \gtrsim m_W$.



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Baryogenesis requires BSM physics!

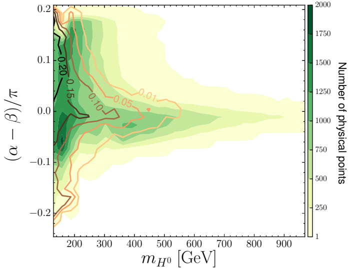
- New particles must have mass $\sim$ EW scale.
- Must have significant interactions with scalar sector.
- Therefore, the mechanism is testable at present and near future colliders!

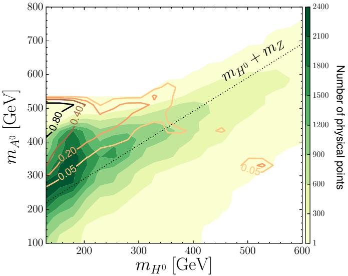
Two-Higgs-doublet model

- 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).
  - Motivated by many SM extensions (e.g. SUSY, Composite Higgs).
- 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

- SM-like light scalar favoured (alignment limit).
- $m_{A_0} \gtrsim 300$ GeV, with $m_{A_0} \gtrsim m_{H_0} + m_Z$.





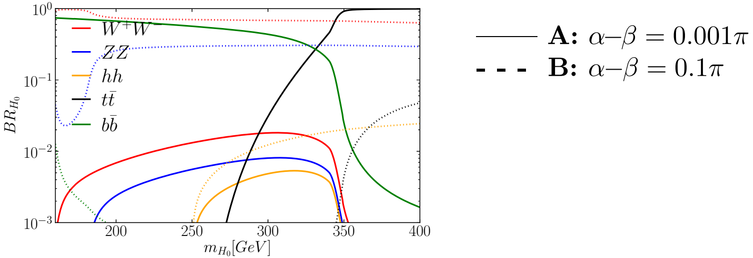
- Current heavy Higgs searches tend to be motivated by SUSY, where mass splittings are dictated by gauge couplings and do not exceed m_Z.
- Searches focus mainly on heavy Higgs $\rightarrow$ SM particle.
- In our scenario, $m_{A_0} - m_{H_0} \gtrsim m_Z$ and $\alpha \sim \beta \implies$ $A_0 \rightarrow Z H_0$ as a **smoking gun signature**!

Collider analysis

Benchmark scenarios

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

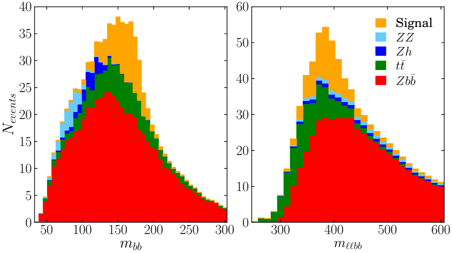
A: $\alpha - \beta = 0.001\pi$ (alignment)
B: $\alpha - \beta = 0.1\pi$ (non-alignment)



- Clear preference for $b\bar{b}$ and WW in respective scenarios.
- Final states (with leptonic decays of Z and W):
  A: $b\bar{b}\ell\ell$.
  B: $WW\ell\ell \to 4\ell\; 2\nu$.

Results

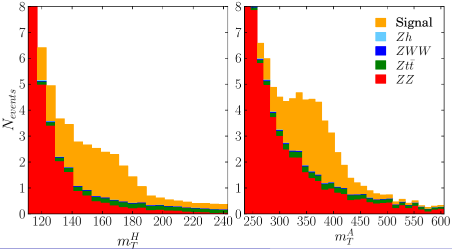
$b\bar{b}\ell\ell$ (alignment case)



LHC 13 TeV,
5σ significance for
$\mathcal{L} = 20$ fb^{-1}.

With 10% uncertainty on background: $\mathcal{L} = 40$ fb^{-1}.

$WW\ell\ell$ (non-alignment)



LHC 13 TeV,
5σ significance for
$\mathcal{L} = 60$ fb^{-1}

With 10% uncertainty on background: $\mathcal{L} = 200$ fb^{-1}.

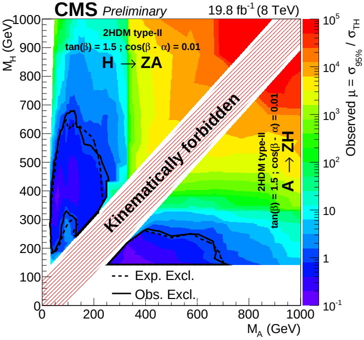
Conclusions and Outlook

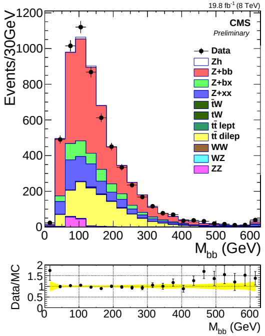
- Baryogenesis can be explained by BSM physics at the electroweak scale.
- For this purpose, the study of the electroweak phase transition is crucial.
- Cosmological observables can point to particular signatures at colliders.
- In particular, in the 2HDM:
  - A strongly first order phase transition is favored by a large splitting $m_{A_0} - m_{H_0} \gtrsim m_Z$ close to alignment limit.
  - This points to an exotic phenomenology, having $A_0 \to Z H_0$ as a "smoking gun" signature.
  - Introducing CP violation in the scalar sector opens the window for even more interesting and exotic phenomenology!

Thank you!

Appendix: Prospects with 8 TeV data

- A new search by the CMS collaboration in the channel proposed here (as well as in $H_0 \to ZA_0$) appeared shortly after this work
  CMS-PAS-HIG-15-001
- 8 TeV data is already sensitive. New exclusions!
- Further investigation of the data granted.
  To appear soon!





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

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

- Kinematical cuts:
- Leptons should reconstruct m_Z.
- Cuts on total $H_T = \Sigma P_T$.
- ΔR between $b\bar{b}$ and $\ell\ell$.
- m_{bb} in $(m_{H_0} - 20) \pm 30$ GeV
  $m_{bb\ell\ell}$ in $(m_{A_0} - 20) \pm 30$ 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

$WW\ell\ell$

- 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: 2HDM

- In CP conserving, softly broken Z_2 symmetric case:

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

- 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: $\mathbb{Z}_2$ symmetry

- Yukawa Lagrangean has the form

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

- Avoid FCNC $\implies$ $\mathbb{Z}_2$ 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	$+$	$-$	$+$

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

- For PT, only top-quark needs to be considered, so all types give indistinguishable results.
- Difference appears in phenomenological constraints only.