Baryogenesis and Gravitational Waves from the Electroweak Phase Transition

Gláuber Carvalho Dorsch

Based on the works:

JHEP 1310 (2013) 029
PRL 113 (2014) no. 21, 211802
PRD 93 (2016) no. 11, 115033
JCAP 1705 (2017) no. 05, 052
JHEP 1712 (2017) 086
JCAP 1812 (2018) no. 12, 034

Universidade Federal do Espírito Santo

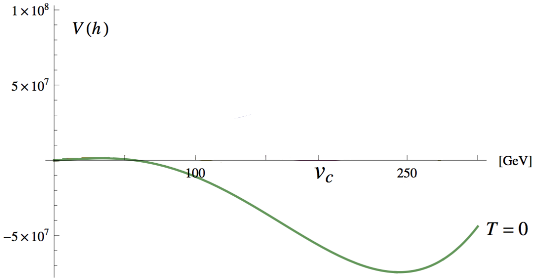
Cosmo-ufes

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

Verão Quântico 2019
Ubu — February 21st, 2019

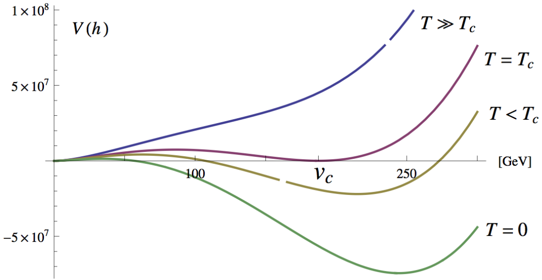
The electroweak phase transition

- Current Universe is cold, nearly empty ($T \approx 0$). Higgs mechanism proceeds as in textbooks.



The electroweak phase transition

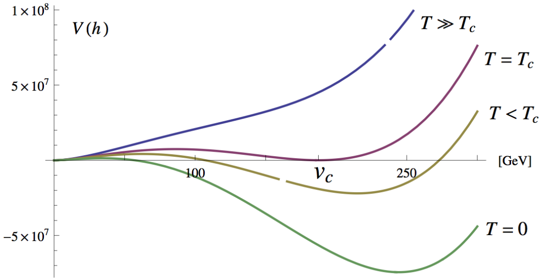
- Current Universe is cold, nearly empty ($T \approx 0$).
  Higgs mechanism proceeds as in textbooks.
- But the early Universe is hot $\Rightarrow$ Higgs immersed in plasma



The electroweak phase transition

- Current Universe is cold, nearly empty ($T \approx 0$).
  Higgs mechanism proceeds as in textbooks.
- But the early Universe is hot $\Rightarrow$ Higgs immersed in plasma
  Thermal corrections to the Higgs effective potential

$$V_{\text{eff}} \overset{\text{high T}}{\approx} V_0 + \sum_{\text{bosons}} n_i \left(\frac{T^2}{24} m_i^2 \underbrace{- \frac{T}{12\pi} m_i^3}_{\text{bosons only}} + \ldots \right) + \sum_{\text{fermions}} n_i \left(\frac{T^2}{48} m_i^2 + \ldots \right)$$

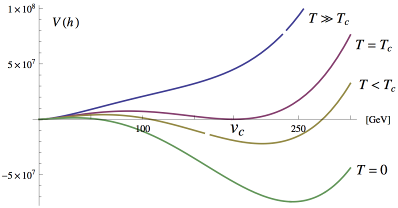


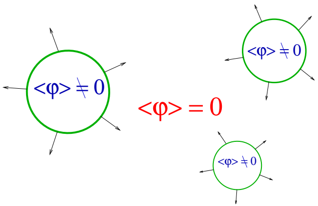
The electroweak phase transition

- Current Universe is cold, nearly empty ($T \approx 0$).
  Higgs mechanism proceeds as in textbooks.
- But the early Universe is hot $\Rightarrow$ Higgs immersed in plasma
  Thermal corrections to the Higgs effective potential

$$V_{\text{eff}} \overset{\text{high T}}{\approx} V_0 + \sum_{\text{bosons}} n_i \left(\frac{T^2}{24} m_i^2 \underbrace{- \frac{T}{12\pi} m_i^3}_{\text{bosons only}} + \ldots \right) + \sum_{\text{fermions}} n_i \left(\frac{T^2}{48} m_i^2 + \ldots \right)$$

- Barrier between vacua $\Longrightarrow$ sym. breaking through tunneling
  Bubbles! The early Universe "boils" (first order phase transition)!





Baryogenesis

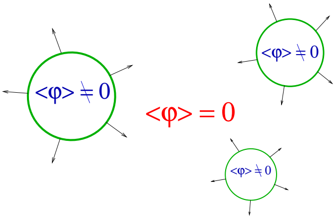
- The Universe has a matter-antimatter asymmetry: $\frac{n_B}{s} \approx 6.1 \times 10^{-10}$.

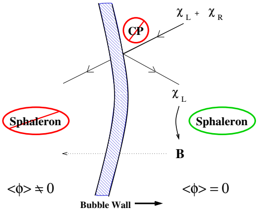
Still unexplained!

- Sakharov conditions:
  - B violation;
  - C violation, otherwise $\Gamma(X \to Y + B) = \Gamma(\overline{X} \to \overline{Y} + \overline{B})$;
  - CP violation, else

$$\Gamma(X \to q_L q_L) + \Gamma(X \to q_R q_R) = \Gamma(\overline{X} \to \overline{q}_R \overline{q}_R) + \Gamma(\overline{X} \to \overline{q}_L \overline{q}_L);$$

  - Displacement from equilibrium, else $\langle B \rangle \equiv$ constant.





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

Baryogenesis

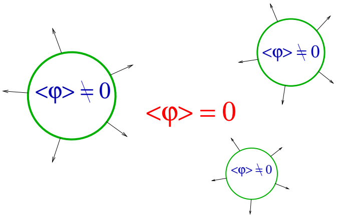
- The Universe has a matter-antimatter asymmetry: $\frac{n_B}{s} \approx 6.1 \times 10^{-10}$.

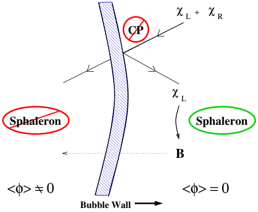
Still unexplained!

- Sakharov conditions:
  - ✔ B violation in SM 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);
  - ▸ C violation, otherwise $\Gamma(X \to Y + B) = \Gamma(\overline{X} \to \overline{Y} + \overline{B})$;
  - ▸ CP violation, else

$$\Gamma(X \to q_L q_L) + \Gamma(X \to q_R q_R) = \Gamma(\overline{X} \to \bar{q}_R \bar{q}_R) + \Gamma(\overline{X} \to \bar{q}_L \bar{q}_L);$$

  - ▸ Displacement from equilibrium, else $\langle B \rangle \equiv$ constant.





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

Baryogenesis

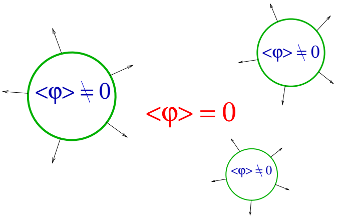
- The Universe has a matter-antimatter asymmetry: $\frac{n_B}{s} \approx 6.1 \times 10^{-10}$.

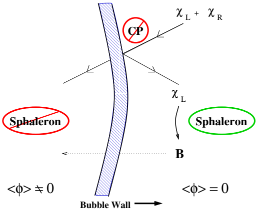
Still unexplained!

- Sakharov conditions:
  - ✔ B violation in SM 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);
  - ✔ C violation from weak interactions;
  - ▸ CP violation, else

$$\Gamma(X \to q_L q_L) + \Gamma(X \to q_R q_R) = \Gamma(\overline{X} \to \bar{q}_R \bar{q}_R) + \Gamma(\overline{X} \to \bar{q}_L \bar{q}_L);$$

  - ▸ Displacement from equilibrium, else $\langle B \rangle \equiv$ constant.





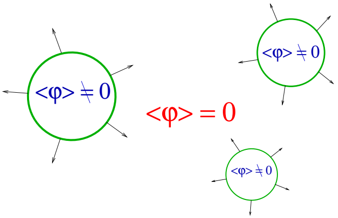
Morrisey and Ramsey-Musolf, New J. Phys. **14** *(2012) 125003*

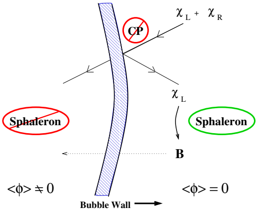
Baryogenesis

- The Universe has a matter-antimatter asymmetry: $\frac{n_B}{s} \approx 6.1 \times 10^{-10}$.

Still unexplained!

- Sakharov conditions:
  - ✔ B violation in SM 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);
  - ✔ C violation from weak interactions;
  - ✘ CP violation from CKM matrix insufficient!
  - ▸ Displacement from equilibrium, else $\langle B \rangle \equiv$ constant.





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

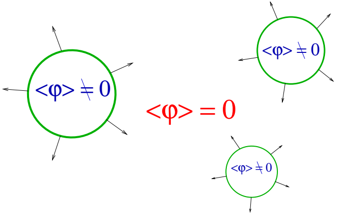
Baryogenesis

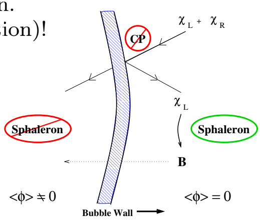
- The Universe has a matter-antimatter asymmetry: $\frac{n_B}{s} \approx 6.1 \times 10^{-10}$.

Still unexplained!

- Sakharov conditions:
  - ✔ B violation in SM 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);
  - ✔ C violation from weak interactions;
  - ✘ CP violation from CKM matrix insufficient!

  - ✘ Sphalerons are in equilibrium w.r.t. Hubble expansion. In SM, sym. breaking is a crossover (no phase transition)!





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

Baryogenesis

- The Universe has a matter-antimatter asymmetry: $\frac{n_B}{s} \approx 6.1 \times 10^{-10}$.

Still unexplained!

- Sakharov conditions:
  - ✔ B violation in SM 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);
  - ✔ C violation from weak interactions;
  - ✘ CP violation from CKM matrix insufficient!

  - ✘ Sphalerons are in equilibrium w.r.t. Hubble expansion. In SM, sym. breaking is a crossover (no phase transition)!

Baryogenesis requires BSM physics.

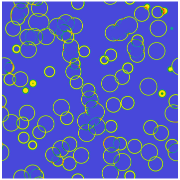
Gravitational waves

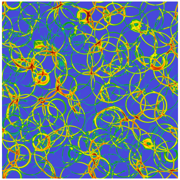
- Collision of bubbles breaks spherical symmetry!
  GW sources:
  - Kinetic energy of scalar field(s) in bubble wall (envelope approx.);
  - acoustic oscillations in the fluid;
  - turbulence.
- Density parameter for GW:

$$\Omega_{\rm GW} = \frac{\langle \dot{h}_{ij}(\mathbf{x})\dot{h}^{ij}(\mathbf{x})\rangle}{12H^2} \quad \xrightarrow{\text{Fourier}} \quad \frac{d\Omega_{\rm GW}}{d\ln k} = \frac{1}{12H^2}\frac{k^3}{2\pi^2}P_{\dot{h}}(\mathbf{k},t)$$

$$\text{with } \langle \dot{h}_{ij}(\mathbf{k},t)\,\dot{h}^{ij}(\mathbf{k}',t)\rangle = (2\pi)^3\,\delta(\mathbf{k}+\mathbf{k}')\,P_{\dot{h}}(\mathbf{k},t)$$

- Long distances ($k \lesssim k_*$), sources causally disconnected $\implies \Omega_{\rm GW} \sim k^3$.
  Total GW energy is finite, so spectrum decreases for $k \gtrsim k_*$.
  Exact behaviour depends on source details.





Hindmarsh, Huber, Rummukainen and Weir Phys. Rev. D **92**, *123009*

Gravitational waves

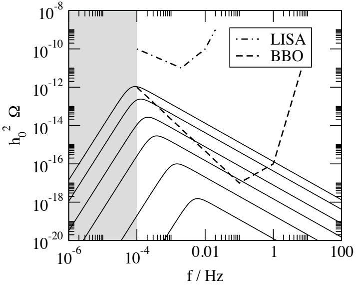
- After redshift, the peak amplitude and frequency scale as:

$$h^2\Omega_{\rm GW} = \underbrace{1.67\times 10^{-5}\times\left(\frac{g_*}{100}\right)^{-1/3}}_{\text{redshift}} \left(\frac{\kappa\alpha}{1+\alpha}\right)^2 (H_*\tau)\,(H_*R_*)\times \underbrace{\widetilde{\Omega}_{\rm GW}}_{\substack{\text{dimensionless,}\\ \text{encodes source}\\ \text{details}}}$$

$$f = 16.5\times 10^{-3}\ \text{mHz}\ \left(\frac{g_{s*}}{100}\right)^{1/6} \frac{T_*}{100\ \text{GeV}} \left(\frac{f_*}{H_*}\right)$$

  - $\alpha \equiv \frac{\text{energy released}}{\text{total energy in radiation}}$; (computed from eff. potential);
  - $\kappa \equiv$ efficiency in converting free energy to kinetic energy;
  - $\tau \equiv$ duration of source;
  - $R_* \equiv$ typical bubble radius $\approx v_w \beta^{-1}$.
  - In practice, we compute $\beta \equiv$ characteristic timescale of EWPT;

$$\Gamma = \Gamma_*\, e^{-\beta\,(t-t_*)}$$



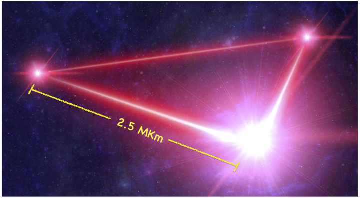
Huber and Konstandin, JCAP **0809** *(2008) 022*

- Typically $f_* \simeq \beta \sim \mathcal{O}(10^2)\, H_*$.

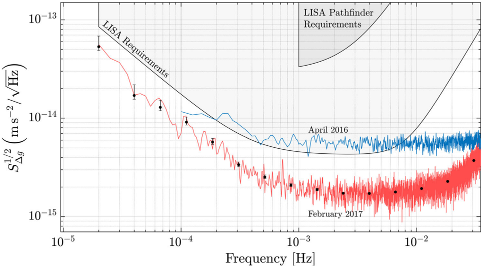

LISA
Laser Interferometer Space Antenna

LISA: Laser Interferometer Space Antenna

- 3 free-falling spacecrafts preserving equilateral shape while orbiting the sun(!) at 50 MKm from Earth ("close" to Mars).
- Sensitive to variations of 1 part in 10^{22} arm lengths.
- Viability successfully tested at LISA Pathfinder mission.
  Two cubic test masses $M \simeq 2$ Kg of size $l = 46$ mm separated by $L = 376$ mm.
  Pathfinder probed how well these test masses can be put in free fall.



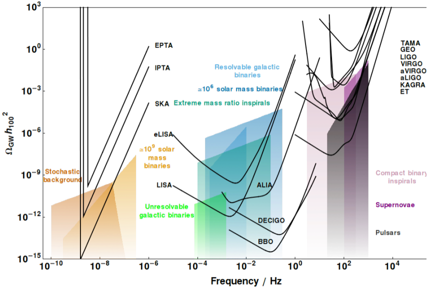
LISA Pathfinder, PRL **120**, *061101 (2018)*



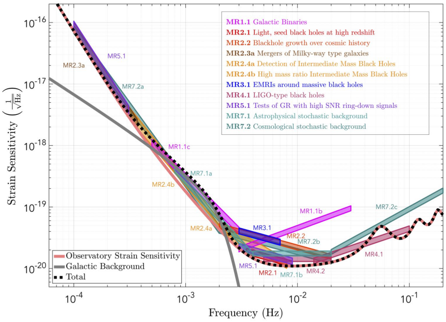
LISA: Laser Interferometer Space Antenna

- Launch planned for 2034 (possibly earlier).
- Gravity much weaker than electromagnetic interaction
  $\Longrightarrow$ gravitons decouple much earlier than photons from plasma!
- Detection of such cosmological GWs will give us access to the Universe at 10^{-12} s after Big Bang (CMB: 300,000 years)!
- Compare spectrum to prediction $\Longrightarrow$ GW as tests for BSM physics!

Moore et al., CQG **32(1)***:015014 (2015)*



LISA Mission Proposal L3



Enough with generalities... a concrete example

Two-Higgs-doublet model

- Two-Higgs-doublet models are minimal SM extensions:
  - 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.
  - Motivated by many SM extensions (e.g. SUSY, Composite Higgs).
  - Additional source of CP violation (explicit or spontaneous).

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

$$\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ v_2\, e^{i\xi} \end{pmatrix}$$

- Two field-redefinition-independent complex phases related by a minimization condition:

$$\delta_1 = 2\phi - \psi, \qquad \delta_2 = \phi - \psi - \xi,$$

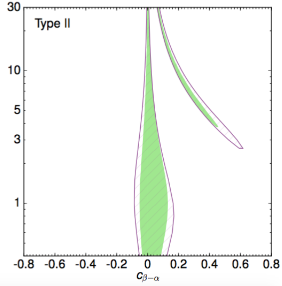
$$|\mu^2| \sin(\delta_1 - \delta_2) = v^2 \sin\beta \cos\beta\, |\lambda_5| \sin(\delta_1 - 2\delta_2).$$

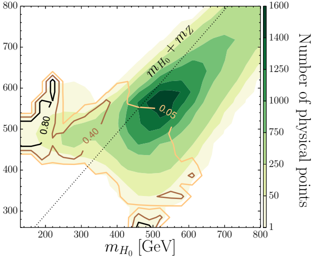
- Important parameters:

$\not{CP}$ phase:	$\delta_1 - \delta_2$
Scalar masses:	$m_{h^0} = 125$ GeV, m_{H^0}, m_{A^0}, $m_{H^\pm}$
Mass scale of Φ_2:	$M^2 \equiv \text{Re}(\mu^2)/\sin(2\beta)$
Mixing angles:	$\tan\beta$, $\beta - \alpha$ (sets departure of h^0 from h_{SM})

Constraints and phase transition in 2HDMs

- Higgs signals constraints require approximate *alignment* ($h^0 \approx h_{\rm SM}$)
  This also favors a strong EWPT.
- EW precision observables enforce an approx. degeneracy, $\boxed{m_{H^\pm} \approx m_{A^0} \text{ or } m_{H^0}}$
- For Type II, $\overline{B} \to X_s \gamma$ constrains $m_{H^\pm} \geq 480$ GeV
  Misiak et al., PRL **114** *(2015) no. 22 221801*
- We scanned a wide range of parameter space. A strongly first order phase transition prefers a large mass splitting
  $m_{A^0} \gtrsim m_{H^0} + m_Z$ with $m_{A_0} \gtrsim 400$ GeV
  GCD, Huber, No, JHEP **1310** *(2013) 029*
  GCD, Huber, Mimasu, No, PRL **113** *(2014) 21, 211802*

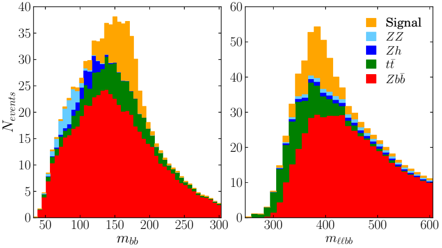




Phenomenological consequences

GCD, Huber, Mimasu, No, PRL **113** *(2014) no. 21, 211802*

- Requiring a strong EWPT points to a very different kind of 2HDM than usually considered in collider analyses.
  - Most searches were motivated by SUSY, where scalar mass splittings $\lesssim m_Z$. Thus $S_i \to Z S_j$ channel ($S_i \in \{H_0, A_0\}$) is closed.
  - Many searches focus on $H_0 \to WW, ZZ$ (not allowed for A_0).
  - Pseudoscalar searched for in $A_0 \to Zh_0, \tau\tau$.
- Our scenario favours $A_0 \to ZH_0$.
  (decay to Zh_0 is suppressed when $h_0 \approx h_{\rm SM}$).
- We did a dedicated study on the detectability of these heavy scalars via $A_0 \to ZH_0 \to b\bar{b}\ell\ell$ and $WW\ell\ell$.



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

Phenomenological consequences

- A year and a half later…

CMS-HIG-15-001

CERN-EP/2016-039
2016/08/26

Search for neutral resonances decaying into a Z boson and a pair of b jets or τ leptons

The CMS Collaboration*

Abstract

A search is performed for a new resonance decaying into a lighter resonance and a Z boson. Two channels are studied, targeting the decay of the lighter resonance into either a pair of oppositely charged τ leptons or a $b\bar{b}$ pair. The Z boson is identified via its decays to electrons or muons. The search exploits data collected by the CMS experiment at a centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 19.8 fb^{-1}. No significant deviations are observed from the standard model expectation and limits are set on production cross sections and parameters of two-Higgs-doublet models.

Published in Physics Letters B as doi:10.1016/j.physletb.2016.05.087.

Phenomenological consequences

- A year and a half later… …and still later…

CERN-EP/2016-039
2016/08/26

CMS-HIG-15-001

Search for neutral resonances decaying into a Z boson and a pair of b jets or τ leptons

The CMS Collaboration*

Abstract

A search is performed for a new resonance decaying into a lighter resonance and a Z boson. Two channels are studied, targeting the decay of the lighter resonance into either a pair of oppositely charged τ leptons or a $\mathrm{b\bar{b}}$ pair. The Z boson is identified via its decays to electrons or muons. The search exploits data collected by the CMS experiment at a centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 19.8 fb^{-1}. No significant deviations are observed from the standard model expectation and limits are set on production cross sections and parameters of two-Higgs-doublet models.

Published in Physics Letters B as `doi:10.1016/j.physletb.2016.05.087`.

Phys. Lett. B 783 (2018) 392
DOI: 10.1016/j.physletb.2018.07.006

CERN-EP-2018-030
2nd August 2018

Search for a heavy Higgs boson decaying into a Z boson and another heavy Higgs boson in the $\ell\ell bb$ final state in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

A search for a heavy neutral Higgs boson, A, decaying into a Z boson and another heavy Higgs boson, H, is performed using a data sample corresponding to an integrated luminosity of 36.1 fb^{-1} from proton–proton collisions at $\sqrt{s}$ = 13 TeV recorded in 2015 and 2016 by the ATLAS detector at the Large Hadron Collider. The search considers the Z boson decaying to electrons or muons and the H boson into a pair of b-quarks. No evidence for the production of an A boson is found. Considering each production process separately, the 95% confidence-level upper limits on the $pp \to A \to ZH$ production cross-section times the branching ratio $H \to bb$ are in the range of 14–830 fb for the gluon–gluon fusion process and 26–570 fb for the b-associated process for the mass ranges 130–700 GeV of the H boson and 230–800 GeV of the A boson. The results are interpreted in the context of two-Higgs-doublet models.

Gravitational wave spectrum

GCD, Huber, Konstandin, No, JCAP **1705** *(2017) no.05, 052*

- For thermal transitions the dominant contribution to GWs comes from acoustic oscillations in the plasma after collisions.
- Active even after phase transition is complete ($H_*\tau \to 1$).
- Relevant parameters: energy released (α_n) and duration of source activity

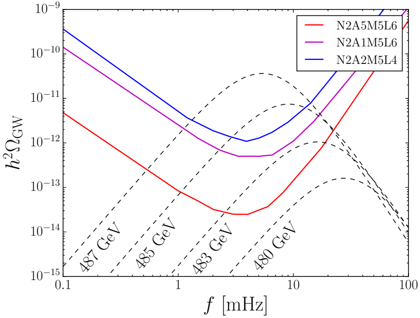
$$\alpha_n = \left(\frac{T}{4}\frac{d\Delta V}{dT} - \Delta V\right)/\rho_{\rm rad}, \qquad \frac{\Gamma}{\mathcal{V}} \sim e^{-S_3/T_n + \beta\,(t-t_n)} \implies \frac{\beta}{H_*} = T_n \left.\frac{dS_3}{dT}\right|_{T_n}.$$

- From numerical simulations the spectrum is estimated to behave as:

$$h^2\Omega_{\rm sw} \simeq 2.65\times 10^{-6}\, \overbrace{v_w \left(\frac{H_*}{\beta}\right)}^{\sim H_* R} \left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{\frac{1}{3}}$$

$$f_{\rm sw} \simeq 1.9\times 10^{-2}\,{\rm mHz}\, \frac{1}{v_w}\left(\frac{\beta}{H_*}\right)\left(\frac{T}{100\,{\rm GeV}}\right)\left(\frac{100}{g_*}\right)^{\frac{1}{6}}$$

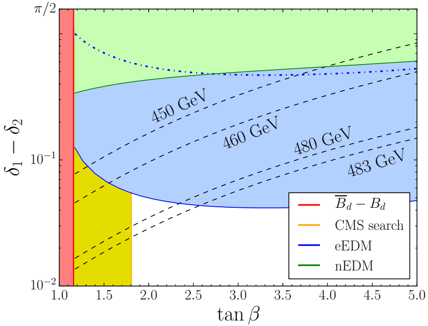
m_{A^0} [GeV]	v_n/T_n	$L_w T_n$	α_n	β/H^*	v_w
480	4.00	1.72	0.11	757.32	0.3
483	4.36	1.56	0.14	564.24	0.35
485	4.68	1.44	0.18	439.55	0.45
487	5.12	1.31	0.25	316.08	$\approx c_s$



EDM constraints and the BAU

GCD, Huber, Konstandin, No, JCAP **1705** *(2017) no.05, 052*

- In 2HDMs, contributions to EDMs enter already at 2-loop (Barr-Zee diagrams, Weinberg 3-gluon operator)
  Experimental bounds place tight constraints on $\not{C}\not{P}$ phase.



- Regarding the BAU, full computation involves solving Boltzmann eqs. including all relevant scattering rates.
- The results are expected to scale as

$$\frac{\eta}{\eta_{\text{obs}}} \sim \left(\frac{v_n}{T_n}\right)^4 \frac{1}{L_w T_n} \frac{\Delta\theta_{\text{CP}}}{(1+\tan^2\beta)}$$

$$\theta_{\text{CP}} \equiv \text{Arg}(v_1^* v_2)$$

- A caveat: new ACME II eEDM constraints,

$$|d_e^{\text{ACME II}}| < 1.1 \times 10^{-29}\, e \cdot \text{cm}$$ *Nature* **562** *(2018) no.7727, 355-360*

compared to $|d_e^{\text{ACME I}}| < 8.9 \times 10^{-29}\, e \cdot \text{cm}$.

Conclusions and Outlook

- We live in a golden age for Cosmology (precision measurements, GW detection, new experiments in sight...)
- Cosmological observations can be used to constrain BSM Particle Physics.
  The Early Universe reached higher energies than any accelerator we could dream of building in the foreseeable future.
- The Universe might have undergone a first order phase transition in the electroweak epoch ($T \approx 100$ GeV).
  Relics include BAU and a stochastic GW spectrum detectable at LISA!
- The study of this process provides a rich Particle-Cosmology interface.
  EW epoch $\longrightarrow$ EW scale (detectable at current colliders!)
- We have shown a concrete example in the case of 2HDMs.
  Study of EWPT lead to exploration of thus far neglected search channels!

Conclusions and Outlook

- We live in a golden age for Cosmology (precision measurements, GW detection, new experiments in sight. . .)
- Cosmological observations can be used to constrain BSM Particle Physics.
  The Early Universe reached higher energies than any accelerator we could dream of building in the foreseeable future.
- The Universe might have undergone a first order phase transition in the electroweak epoch ($T \approx 100$ GeV).
  Relics include BAU and a stochastic GW spectrum detectable at LISA!
- The study of this process provides a rich Particle-Cosmology interface.
  EW epoch $\longrightarrow$ EW scale (detectable at current colliders!)
- We have shown a concrete example in the case of 2HDMs.
  Study of EWPT lead to exploration of thus far neglected search channels!

THANK YOU!

Appendix: Cosmological redshift

- Adiabatic expansion, $s \propto a^3 g_s T_3 \equiv$ constant, so

$$\frac{a_*}{a_0} = \left(\frac{g_{s0}}{g_{s*}}\right)^{1/3} \frac{T_0}{T_*} \qquad \left[H_* = \sqrt{\frac{\pi^2 g_*}{90}} \frac{T_*^2}{M_{\rm Pl}}\right]$$

- The frequency redshifts as

$$\boxed{f = f_* \left(\frac{a_*}{a_0}\right) = 16.5 \times 10^{-3}\ \text{mHz}\ \left(\frac{g_{s*}}{100}\right)^{1/6} \frac{T_*}{100\ \text{GeV}} \left(\frac{f_*}{H_*}\right)}$$

after replacing $T_0 \approx 2.725$ K and $g_0 \approx 3.91$.

- Energy density scales as a^{-4} and $\rho_c \propto H^2$, so

$$\Omega_{\rm GW} \equiv \frac{\rho_{\rm GW}}{\rho_c} = \Omega_{\rm GW*} \left(\frac{a_*}{a_0}\right)^4 \left(\frac{H_*}{H_0}\right)^2$$

$$\boxed{h^2 \Omega_{\rm GW} = 1.67 \times 10^{-5} \cdot \left(\frac{g_*}{100}\right)^{-1/3} \left(\frac{\kappa\alpha}{1+\alpha}\right)^2 (H_*\tau)\,(H_* R)\,\widetilde{\Omega}_{\rm GW}}$$

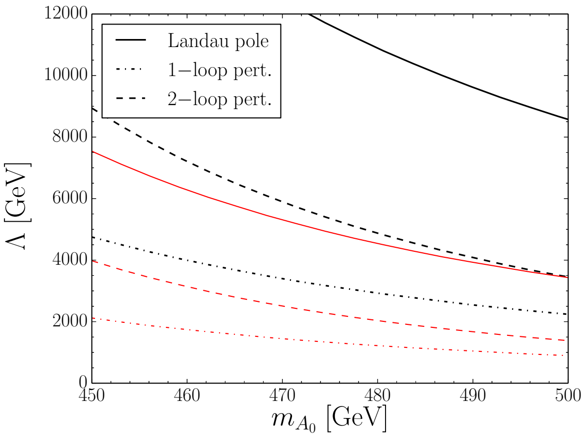
where we used $H_0 \equiv h \times 100 \frac{\text{km}}{\text{s Mpc}}$ ($h \approx 0.67 - 0.70$).

Appendix: 2HDM perturbativity analysis

- A strong PT typically requires large couplings.
  The most extreme case here considered has

$$\lambda_1 = \lambda_2 \simeq 0.2578, \qquad \lambda_3 \simeq 6.762, \qquad \lambda_4 = \lambda_5 \simeq -3.252.$$

- Solve RGE $\Rightarrow$ Landau pole and $\max(\lambda_i(\Lambda)) \geq 4\pi$.



Appendix: 2HDM

- In CP conserving, softly broken Z_2 symmetric case:

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

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

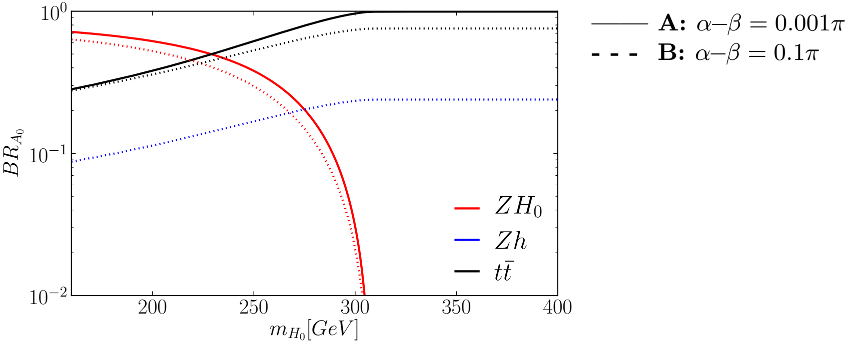
$$\begin{aligned}
G^+ &= \cos\beta\ \varphi_1^+ + \sin\beta\ \varphi_2^+ && \text{(charged Goldstone)},\\
H^+ &= -\sin\beta\ \varphi_1^+ + \cos\beta\ \varphi_2^+ && \text{(charged Higgs)},\\
G^0 &= \cos\beta\ \eta_1 + \sin\beta\ \eta_2 && \text{(neutral Goldstone)},\\
A^0 &= -\sin\beta\ \eta_1 + \cos\beta\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

Appendix: Benchmark and Branching Ratios

Benchmark scenarios

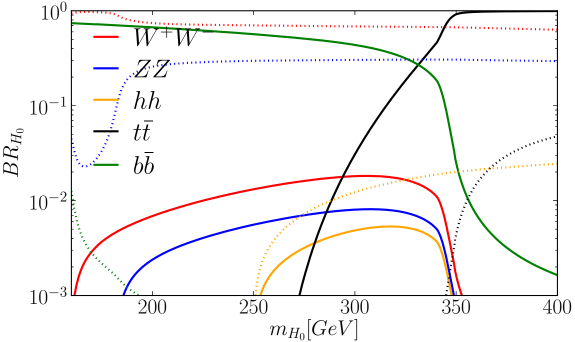
$$m_{H_0} = 180 \text{ GeV}, \; m_{A_0} = m_{H^\pm} = 400 \text{ GeV}, \; \mu = 100 \text{ GeV}, \; \tan\beta = 2$$

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



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

Appendix: H_0 decays and final states



—— **A:** $\alpha - \beta = 0.001\pi$
- - - **B:** $\alpha - \beta = 0.1\pi$

- 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.
  - Final states:
    A: $b\bar{b}\ell\ell$.
    B: $WW\ell\ell \to 4\ell\ 2\nu$.

Appendix: 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.

Appendix: Wall velocity

- Wall velocity is computed from scalar fields' EOM:

$$\Box\phi + \frac{dV}{d\phi} + \sum_n \frac{dm_n^2}{d\phi} \int \frac{d^3p}{(2\pi)^3} \frac{1}{2E_n} \Bigg(\underbrace{f_n^{\rm eq}(\mathbf{p},x)}_{\text{thermal contribution}} + \underbrace{\delta f_n(\mathbf{p},x)}_{\text{friction}} \Bigg) = 0$$

- Perturbations δf_n computed from Boltzmann eq.

$$\left(p_\mu \partial^\mu + \tfrac{1}{2}\partial_\mu m^2 \partial_{p_\mu}\right) f(x^\mu, p_i) = \underbrace{\text{collision terms}}_{\substack{\text{rates computed}\\ \text{from underlying}\\ \text{fundamental theory}}}$$

- Tricky for theories with many interactions and multiple scalar fields!

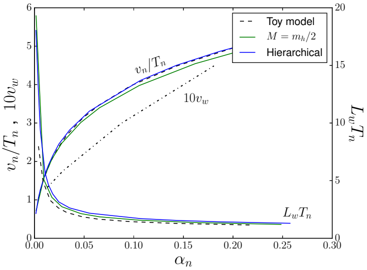
Appendix: Estimating v_w in 2HDMs

- For 2HDMs we estimate the wall velocity using a simplified model. Four additional scalars get their masses from the Higgs according to

$$m_s^2 = \kappa^2 \frac{\langle h \rangle^2}{2} \quad \text{(no self-interactions).}$$

Comparable to a 2HDM in alignment limit, $\tan\beta = 1$ and $M = m_h/\sqrt{2}$.

- Determine friction coefficient η at runaway point and extrapolate using $\eta \sim \exp(-\sqrt{v/T})$ as found in MSSM scenarios.



$$\alpha_n \equiv \frac{\rho_{\text{released}}}{\rho_{\text{rad}}}$$

v_n/T_n	α_n	v_w
1.819	0.013	0.132
2.535	0.029	0.175
3.727	0.088	0.300
4.599	0.181	0.449

We can *exclude detonations* even for very strong transitions!