Collider and Gravitational Wave Complementarity in Exploring the Singlet Extension of the Standard Model

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based on arXiv:1812.09333 [JHEP]
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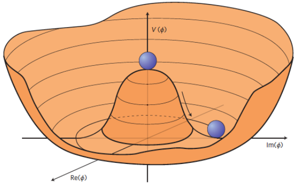
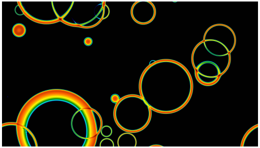
Outline

Introduction

- The Higgs potential is still largely unknown
- New scalars may provide an insight into the EWPT in the early universe
- Baryogensis through a strongly first order EWPT $\Rightarrow$ SM + S
- GWs produced by bubble nucleation and expansion
- Complementarity between GWs and colliders

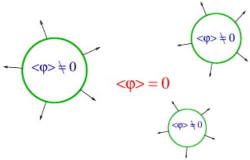


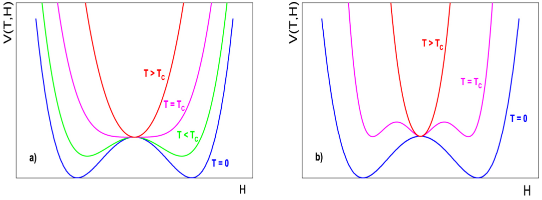


Electroweak Phase Transition

EWPT

- Essential step in EWBG by providing an out of equilibrium environment
- Electroweak symmetry restoration at high T
- Strongly first order phase transition proceeds through bubble nucleation
  - Requires $\left.\frac{v_h(T)}{T}\right|_{T=T_n} \gtrsim 1$
- Dynamics of nucleated bubbles in the plasma will generate GW





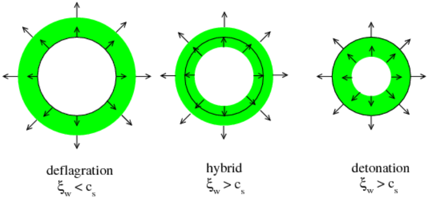
2nd Order PT

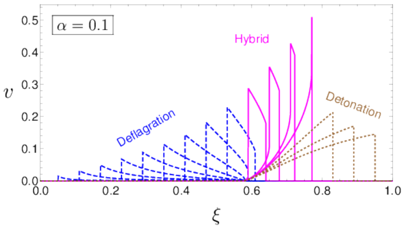
1st Order PT

Hydrodynamics

Hydrodynamics [1]

- EWBG ⇒ subsonic v_w
- GWs ⇒ large v_w
- v_+ instead of v_w enters EWBG calculations: $v_+ = 0.05$
- Detonation mode will not work





Velocity Profile

$$2\frac{v}{\xi} = \frac{1 - v\xi}{1 - v^2}\left[\frac{\mu^2}{c_s^2} - 1\right]\partial_\xi v$$

[1] arXiv:1004.4187

Gravitational Waves

Gravitational Waves

Full Spectrum

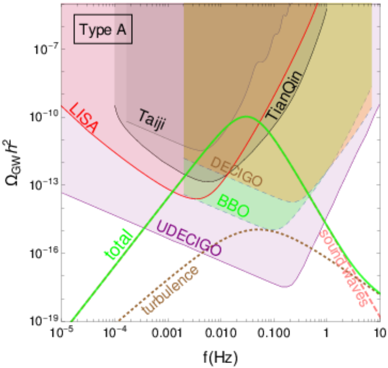
$$h^2\Omega_{GW} = h^2\Omega_{col} + h^2\Omega_{sw} + h^2\Omega_{turb}$$

Sound Wave

$$h^2\Omega_{sw} = 2.65 \times 10^{-6} \left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_\nu \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} \times v_w \left(\frac{f}{f_{SW}}\right)^3 \left(\frac{7}{4+3(f/f_{SW})^2}\right)^{7/2}$$

$$f_{sw} = 1.9 \times 10^{-5} \frac{1}{v_w}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\text{ GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

- $T_* = T_n(1+\kappa_T\alpha)^{1/4}$
- $h^2\Omega_{col}$ can be neglected



$$\text{SNR} = \sqrt{\delta \times \mathcal{T} \int_{f_{min}}^{f_{max}} df \left[\frac{h^2\Omega_{GW}(f)}{h^2\Omega_{exp}}\right]^2}$$

Model

xSM: SM + S [3]

Potential

$$V_0(H,S) = -\mu^2 H^\dagger H + \lambda(H^\dagger H)^2 + \frac{a_1}{2}H^\dagger HS + \frac{a_2}{2}H^\dagger HS^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

- $H^T = (G^+, (v_{ew} + h + iG^0)/\sqrt{2})$ and $S = v_s + s$
- μ^2 and b_2 replaced by model parameters using minimization condition (v_{ew}, v_s)
- Rotate (h, s) into physical basis (h_1, h_2) by mixing angle θ
- Free parameters of model $\Rightarrow (v_s, m_{h_2}, \theta, b_3, b_4)$
- Tadpole basis $< S >= 0$: $V \rightarrow V^{'} = V + b_1 S$ [2]

[2] arXiv:1701.08774

[3] arXiv:0705.2425,1407.5342, and 1701.04442

Effective Potential [4]

$V_{eff} = V_0 + V_T$ in high-T expansion

$$V_{eff}(h, s, T) = -\frac{1}{2}[\mu^2 - \Pi_h(T)]h^2 + \frac{1}{2}[b_2 + \Pi_s(T)]s^2 + \frac{1}{4}\lambda h^4 + \frac{1}{4}a_1 h^2 s + \frac{1}{4}a_2 h^2 s^2 + \frac{b_3}{3}s^3 + \frac{b_4}{4}s^4$$

Thermal Masses

$$\Pi_h(T) = \left(\frac{2m_W^2 + m_z^2 + 2m_t^2}{4v^2} + \frac{\lambda}{2} + \frac{a_2}{24}\right)T^2$$

$$\Pi_s(T) = \left(\frac{a_2}{6} + \frac{b_4}{4}\right)T^2$$

Phase Transition Patterns

(a) $(0,0) \to (v_H \neq 0, v_S \neq 0)$

(b) $(0,0) \to (v_H = 0, v_S \neq 0) \to (v_H \neq 0, v_S \neq 0)$

(c) $(0,0) \to (v_H \neq 0, v_s = 0) \to (v_H \neq 0, v_S \neq 0)$

[4] High-T expansion - arXiv:1101.4665

Results

Constraints

Bounded from below

$$\lambda > 0,\; b_4 > 0,\; a_2 \geq -2\sqrt{\lambda b_4}$$

Stability

$$\frac{\partial V}{\partial \phi_i} = 0, \text{ and } \frac{\partial^2 V}{\partial \phi_i \partial \phi_j} > 0,\; \phi_{i,j} = h, s$$

Higgs Signal Strength

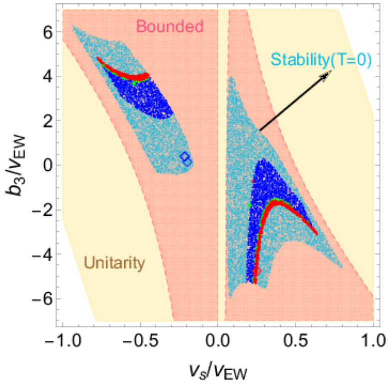
Higgs signal strength: $\mu_H = \cos^2\theta \Rightarrow |\sin\theta| > 0.33$

Perturbative Unitarity S Matrix

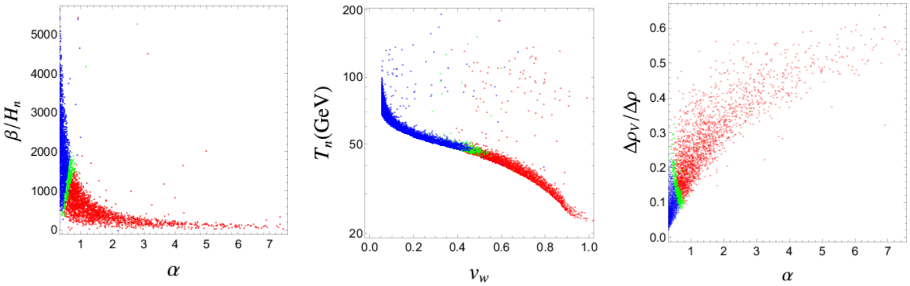
Eigenvalues of S greater than $(1/2 \times 16\pi)$

Electroweak Precision Measurements

$$\left.\begin{array}{l} m_W^{exp} = 80.385 \pm 0.015 \text{ GeV} \\ \text{S,T, and U} \end{array}\right\} (\theta, m_{h_2})$$

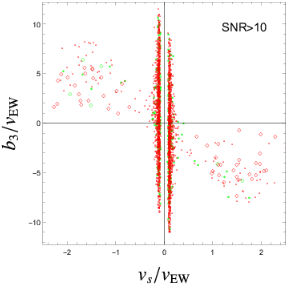


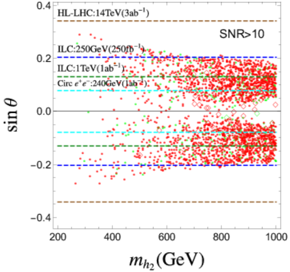
EWPT and GW

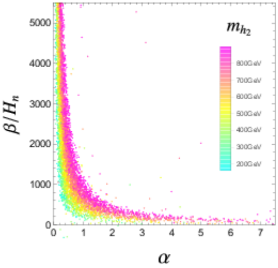


- EWPT Type: (A) 99 %, (B) 1 %, (C) 0 %
- LISA: SNR < 10 (blue - 28 %), 10 < SNR < 50 (green - 50%),and SNR > 50 (red - 22 %)
- Larger α and smaller $\beta \Rightarrow$ larger SNR

Parameter Space Giving Detectable GW



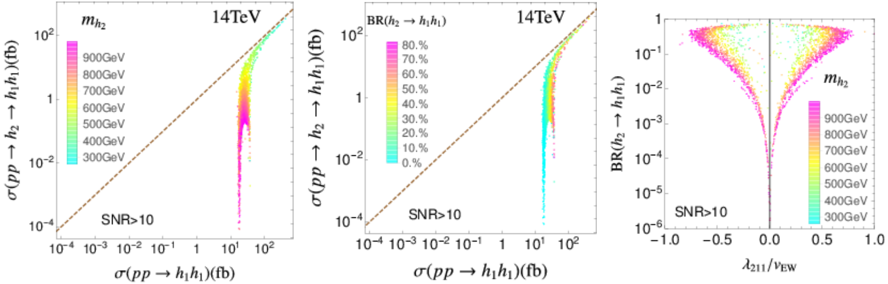




arXiv:1407.5342

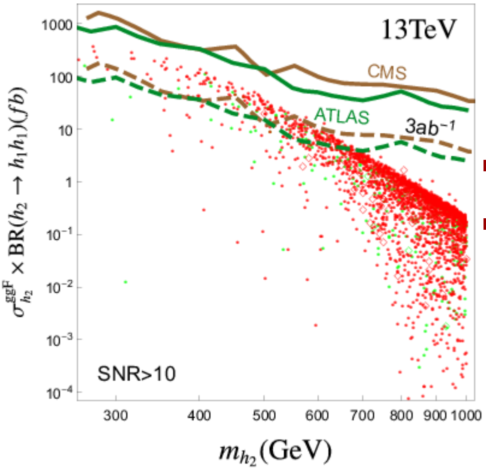
- Bounded from below: 20 GeV $\lesssim |v_s| \lesssim$ 50 GeV
- Larger m_{h_2} preferred
- W-mass constraint: $\theta \lesssim 0.2$

Correlation with Double Higgs Production Searches



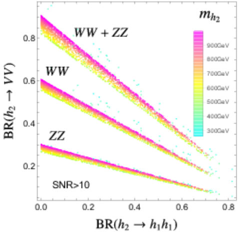
- $\Gamma_{h_2} = \sin^2\theta\Gamma_{SM}(h_2 \to X_{SM}) + \Gamma(h_2 \to h_1h_1)$
- $\sigma(pp \to h_1h_1) = \sigma(pp \to h_2)BR(h_2 \to h_1h_1)$
- Large m_{h_2} $\Rightarrow$ small Br($h_2 \to h_1h_1$) $\Rightarrow$ small $\sigma(pp \to h_2 \to h_1h_1)$

Correlation with Double Higgs Production Searches

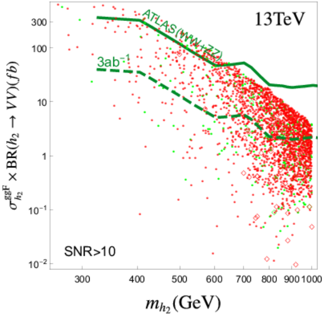


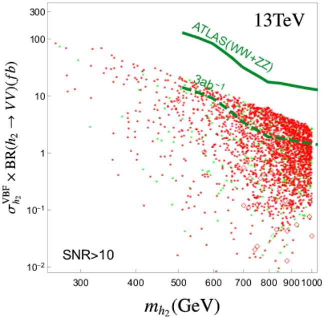
- SNR > 50 (red) and 50 > SNR > 10 (green)
- $m_{h_2} \lesssim 500$ GeV can be probed by both 3 ab^{-1} (13 TeV) HL-LHC and space-based GW detectors

Diboson Resonance Searches

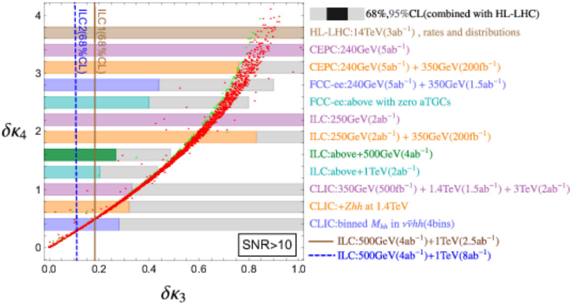


- SNR > 50 (red) and 50 > SNR > 10 (green)
- Most of h_2 decays in WW, ZZ, and $h_1 h_1$ channels
- HL-LHC will probe large fraction of parameter space in ggF and VBF channels





Higgs Cubic and Quartic Couplings



arXiv:1711.03978

- SNR > 50 (red) and SNR > 10 (green)
- Precise measurements can be used to reconstruct the Higgs potential
- $\Delta\mathcal{L} = -\frac{1}{2}\frac{m_{h_1}^2}{v}(1+\delta\kappa_3)h_1^3 - \frac{1}{8}\frac{m_{h_1}^2}{v^2}(1+\delta\kappa_4)h_1^4$
- Correlation given by $\delta\kappa_4 \approx \eta\delta\kappa_3$ for $\eta \in (2,4)$

Conclusion

Conclusion

- Electroweak Phase Transitions lead to a GW spectrum
- Singlet-extended SM Higgs sector offers a wide range of parameter space with large SNR at LISA
- Di-Higgs searches can probe lighter masses at HL-LHC
- Weak diboson resonance searches can probe a large fraction of the parameter space
- Modification to Higg's cubic and quartic couplings
- Main features of the parameter space: 20 GeV $\lesssim |v_s| \lesssim$ 50 GeV, $\theta \lesssim 0.2$, $\delta\kappa_4 \approx (2-4)\delta\kappa_3$, and large m_{h_2} preferred for SNR

Some References

- W-mass: arXiv:1203.0275
- Higgs signal strength: arXiv:1606.02266, and arXiv:1801.00794
- Sound waves: arXiv:1504.03291

EWPT Definitions

- Key parameters: T_c, T_n, α, β, and v_w

Euclidean Action of the critical bubble

$$S_3(\vec{\phi}, T) = 4\pi \int r^2 dr \left[\frac{1}{2} \left(\frac{d\vec{\phi}(r)}{dr} \right)^2 + V(\vec{\phi}, T) \right]$$

$$\frac{d\vec{\phi}(r)}{dr}\Big|_{r=0} = 0, \quad \vec{\phi}(r = \infty) = \vec{\phi}_{out}$$

Inverse time duration of PT

$$\beta = H_n T_n \frac{d(S_3/T)}{dT}\Big|_{T_n}$$

Bubble Nucleation Rate

$$\Gamma \sim \mathcal{A}(T) e^{-S_3/T}$$

Bubble Nucleation

$$\int_0^{t_n} \Gamma V_H(T) dt = \int_{T_n}^{\infty} \frac{dT}{T} \left(\frac{2\xi M_{pl}}{T} \right)^4 e^{-S_3/T} = \mathcal{O}(1)$$

$$\frac{S_3(T)}{T} \approx 140$$

Vacuum energy released from PT

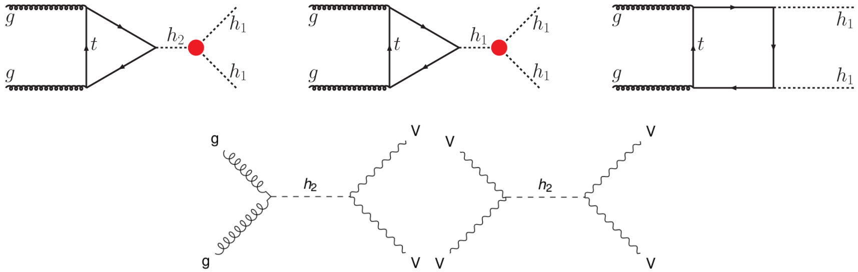
$$\alpha = \frac{\Delta\rho}{\rho_R} = \frac{1}{\rho_R} \left[-V(\vec{\phi}_b, T) + T \frac{\partial V(\vec{\phi}_b, T)}{\partial T} \right] \Big|_{T=T_n}$$

W-mass Constraint

arXiv:1406.1043v2

- W mass calculated from experimentally measured values of G_F, m_Z, and $\alpha(0)$
- Functions relating these parameters depends on the loop calculations to the vector boson self-energies

Feynman Diagrams for Double Higgs Production and Weak Boson Pairs



Double Higgs Production Channels

CMS

- 35.9 fb^{-1} at 13 TeV
- di-Higgs decay channels: $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}b\bar{b}$, and $b\bar{b}WW/ZZ$
- arXiv:1811.09689 for recent combination

ATLAS

- 36.1 fb^{-1} at 13 TeV
- Di-Higgs decay channels: $\gamma\gamma b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}b\bar{b}$, WW^*WW^*, and $b\bar{b}WW^*$
- "Combination of searches for Higgs boson pairs in pp collisions at 13 TeV with the ATLAS experiment." for recent combination

- Cross sections calculated at NNLO-NNLL for gluon fusion

Diboson-Resonances

- ATLAS combined results at 13 TeV with 36 fb^{-1} data
- VBF at NNLO
- ggF at NNLO-NNLL
- Decay channels: $WZ \to qqqq, l\nu qq, l\nu ll$, $WW \to qqqq, l\nu qq, l\nu l\nu$, $ZZ \to qqqq, \nu\nu qq, llqq, ll\nu\nu, llll$, and $WH \to qqbb, l\nu bb$, $ZH \to qqbb, \nu\nu bb, llbb$, and $l\nu, ll$
- arXiv:1808.02380

Higgs Cubic and Quartic Deviations at Lepton Colliders

- (Higgsstrahlung): $e^+e^- \to hZ$
- (WW-fusion): $e^+e^- \to \nu\bar{\nu}h$
- (WW-pair production): $e^+e^- \to WW$
- Higgs decays into ZZ^*, WW^*, $\gamma\gamma$, $Z\gamma$, gg, $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$, and $\mu^+\mu^-$
- Global Analysis: arXiv:1711.03978

Perturbative Unitarity S-Matrix

- Eleven $2 \rightarrow 2$ channels
- Charge neutral channels $(h_1 h_1, h_2 h_2, h_1 h_2, h_1 Z, h_2 Z, ZZ, W^+ W^-)$
- Charge-1 channels $(h_1 W^+, h_2 W^+, ZW^+)$
- Charge-2 channels $(W^+ W^-)$
- Leading partial wave amplitudes of these scatterings are given collectively by a symmetric matrix $S = S_0 \bigoplus S_1 \bigoplus S_2$