COLLIDER AND GRAVITATIONAL WAVE COMPLEMENTARITY IN EXPLORING THE SINGLET EXTENSION OF THE STANDARD MODEL

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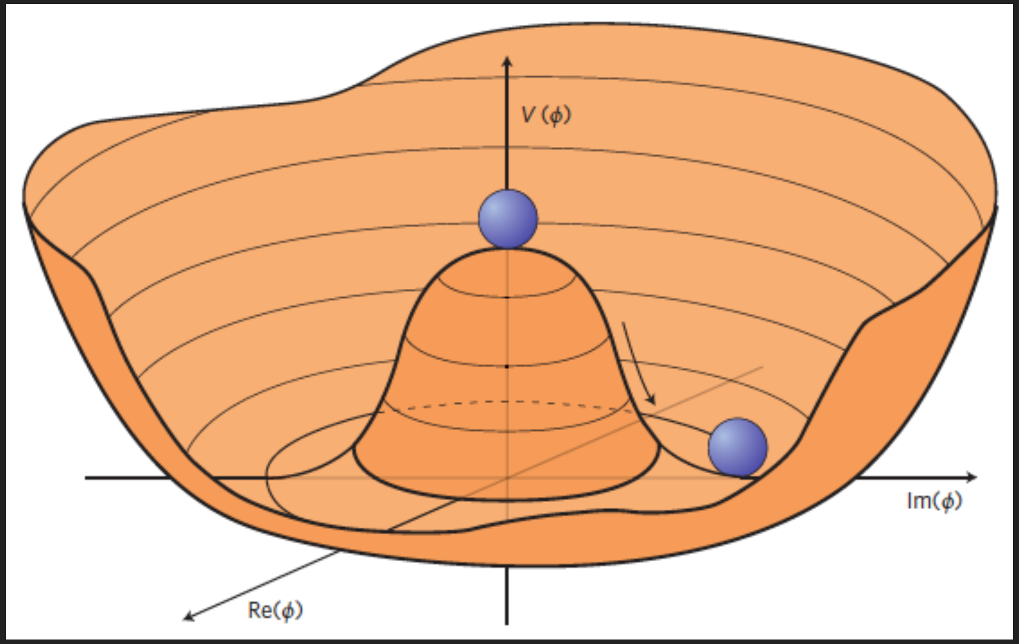
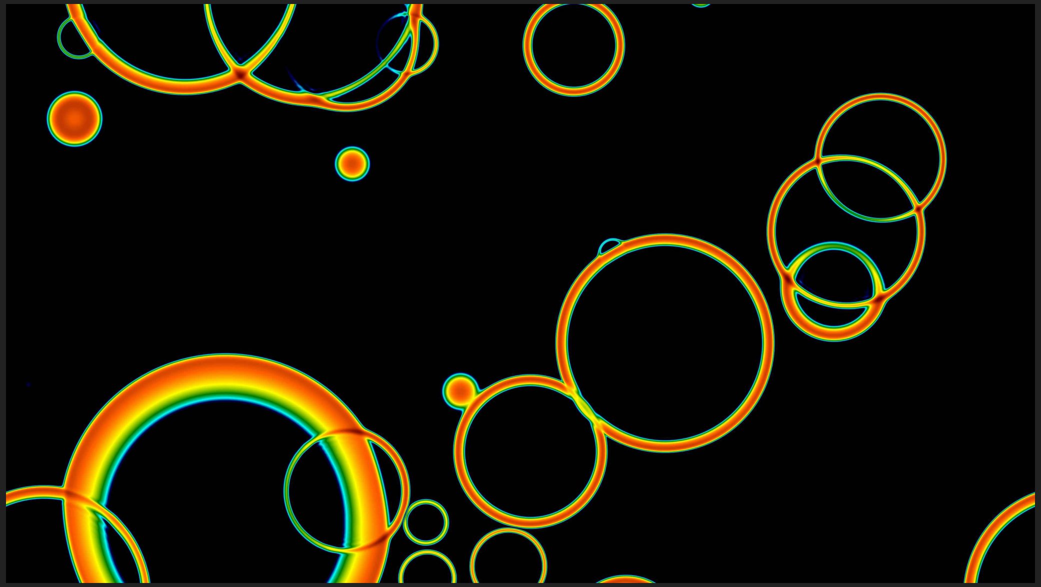
Introduction

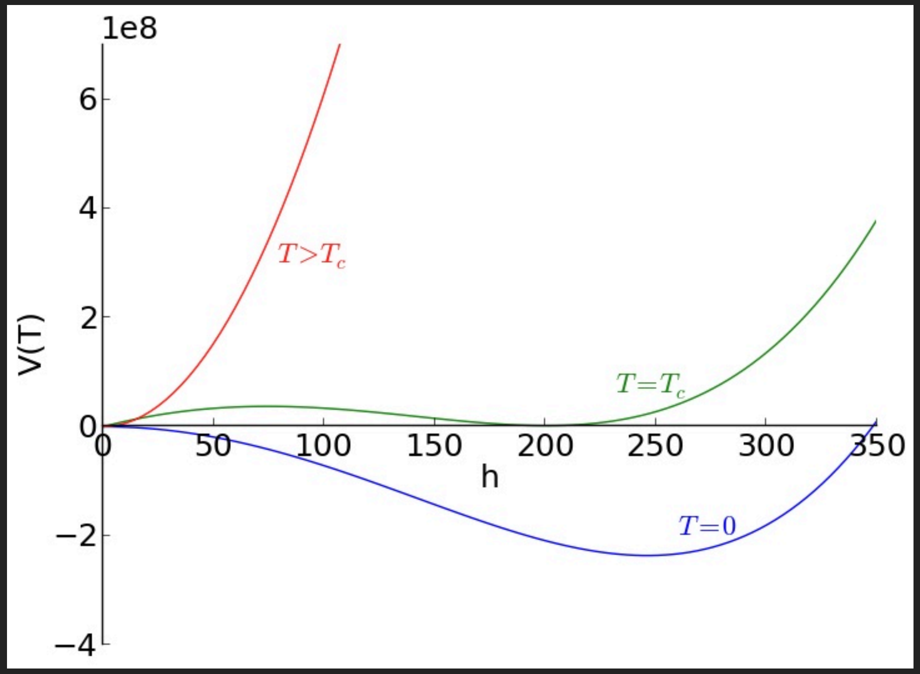
- Possible hidden Higgs sector
- New scalars may provide an insight into the EWPT in the early universe
- Baryogenesis through a strongly first electroweak phase transition → SM + S
- GW's produced by bubble nucleation and expansion
- Complementarity between GW's and colliders

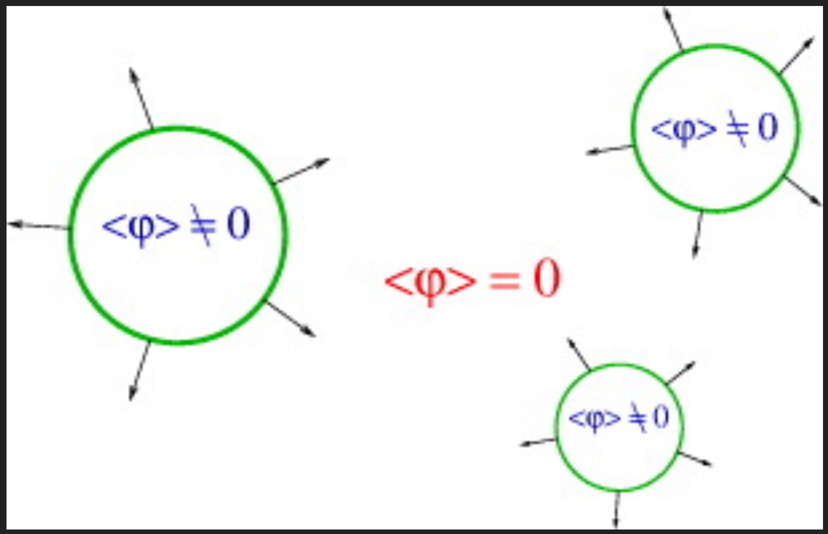




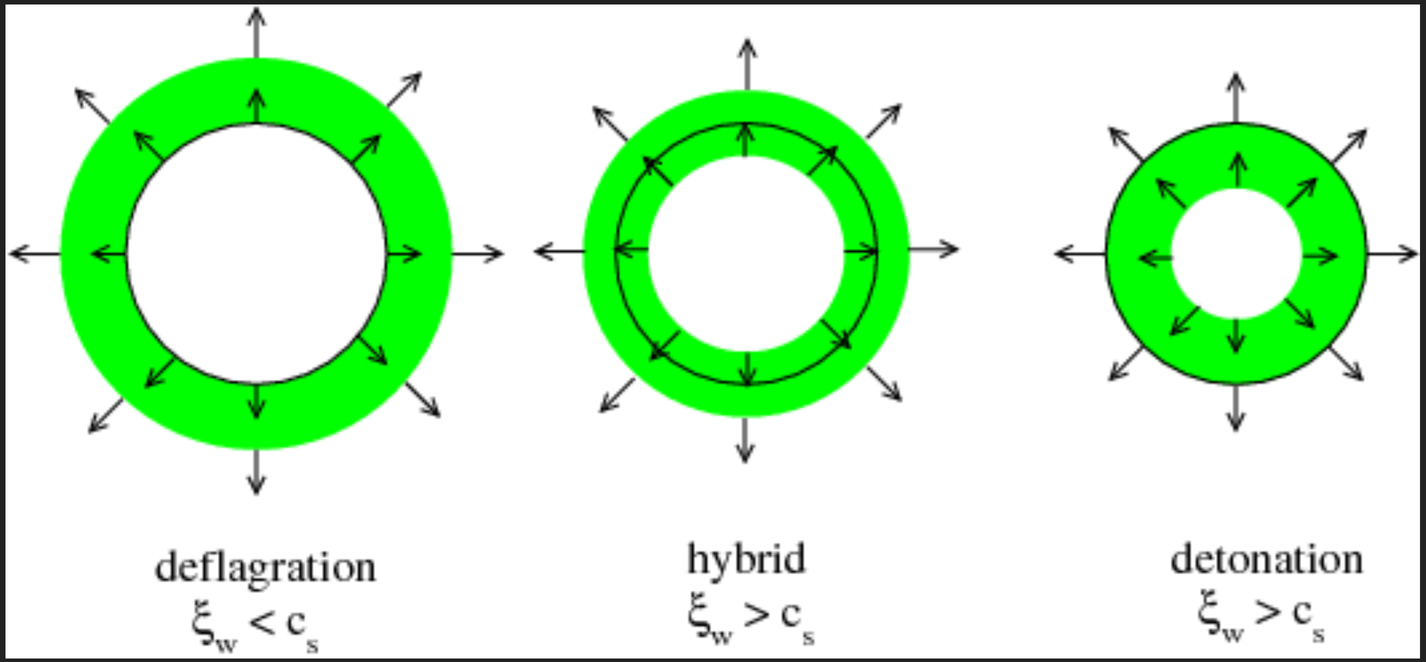
Electroweak Phase Transition

- 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 $\rightarrow \frac{v_h}{T}\Big|_{T=T_n} \gtrsim 1$
- Dynamics of nucleated bubbles in the plasma will generate GW's



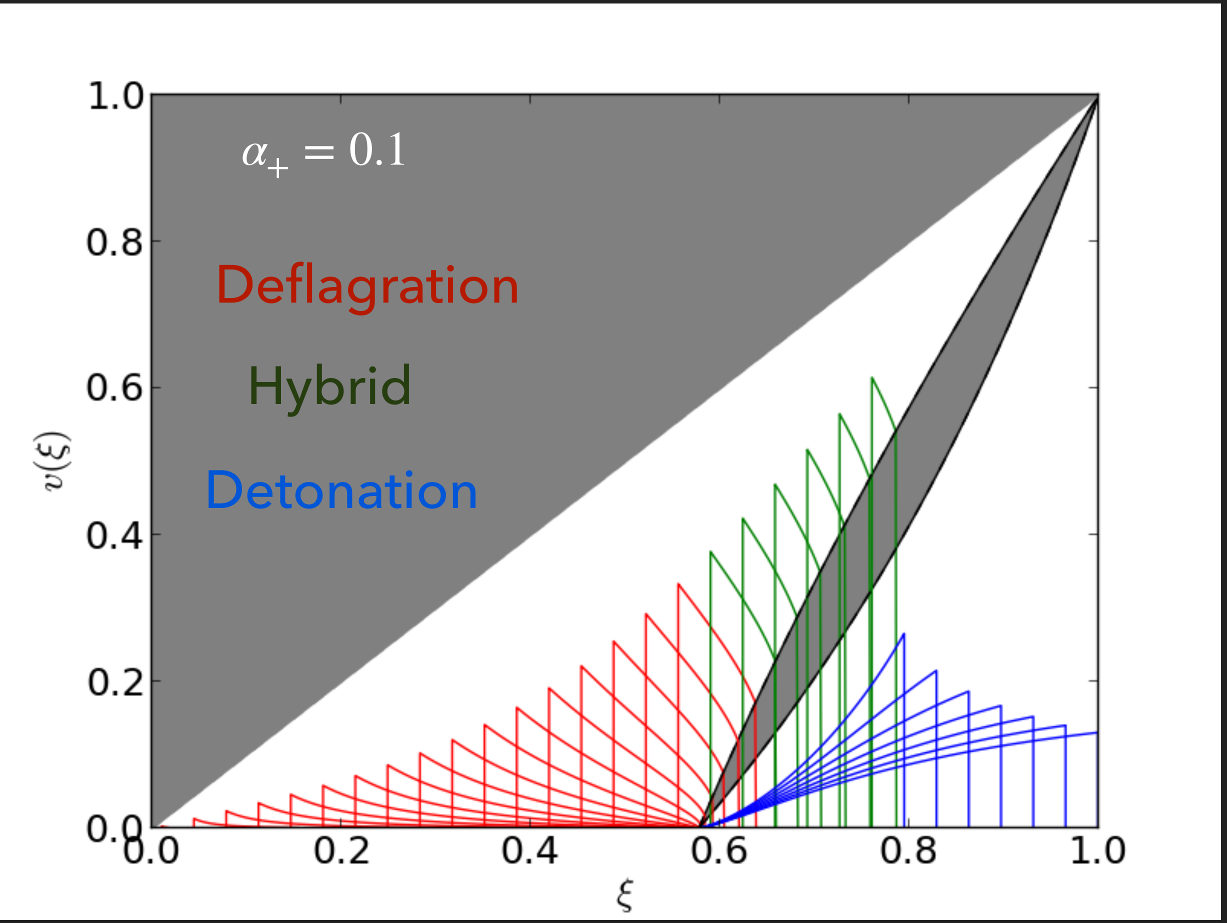


Hydrodynamics



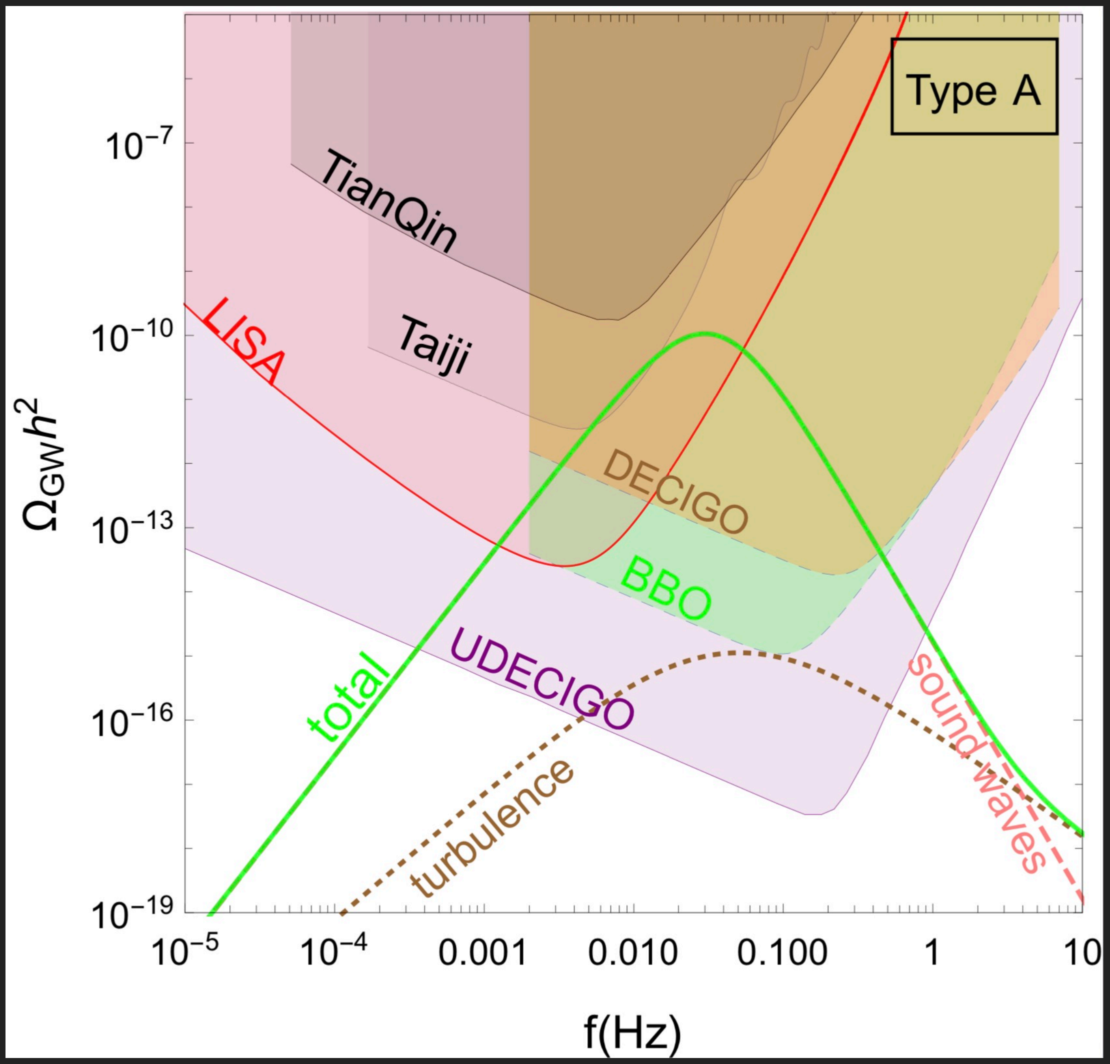
- EWBG → subsonic v_w
- GW → large v_w
- v_+ enters EWBG calculations: $v_+ = 0.05$
- Detonation mode will not work

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



Gravitational Waves

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



- Main contribution

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

- where

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

$$T_* = T_n(1+\kappa_T \alpha)^{1/4}$$

- Signal to Noise

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

Model: SM + S

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

$$H^T = \left(G^\dagger, (v_{ew} + h + iG^0)/\sqrt{2} \right) \quad S = v_s + s$$

- 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 $< S > = 0 : V' = V + b_1 S$

Effective Potential

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

- 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) $(0,0) \to (v_h \neq 0, v_s = 0) \to (v_h \neq 0, v_s \neq 0)$

Constraints

- Bounded from below

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

- Stability

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

- Perturbative Unitarity S Matrix

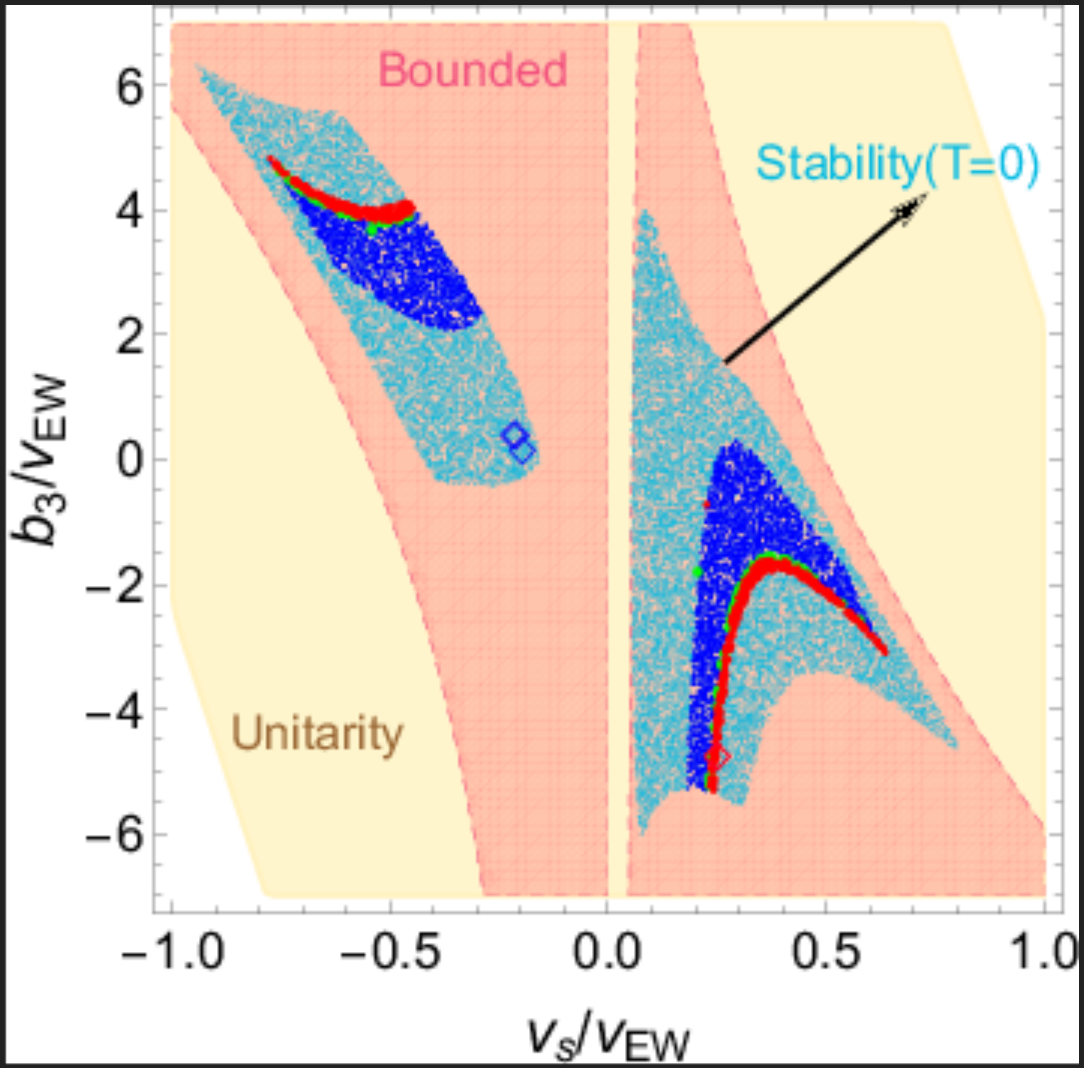
$$\text{Eigenvalues of S matrix greater than } \frac{1}{2} \times 16\pi$$

- Higgs Signal Strength

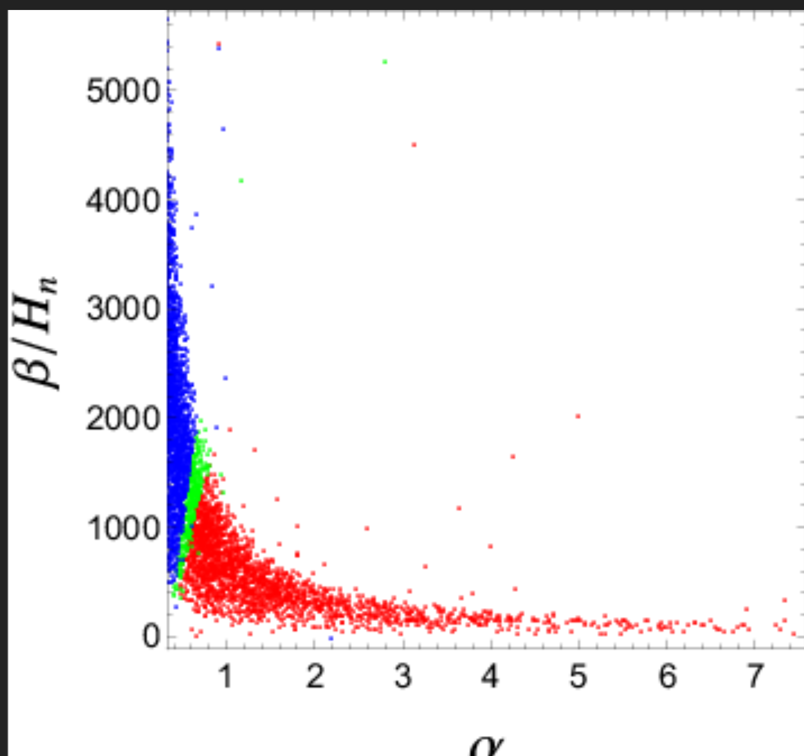
$$\mu_h = \cos^2\theta \Rightarrow |\sin\theta| > 0.33$$

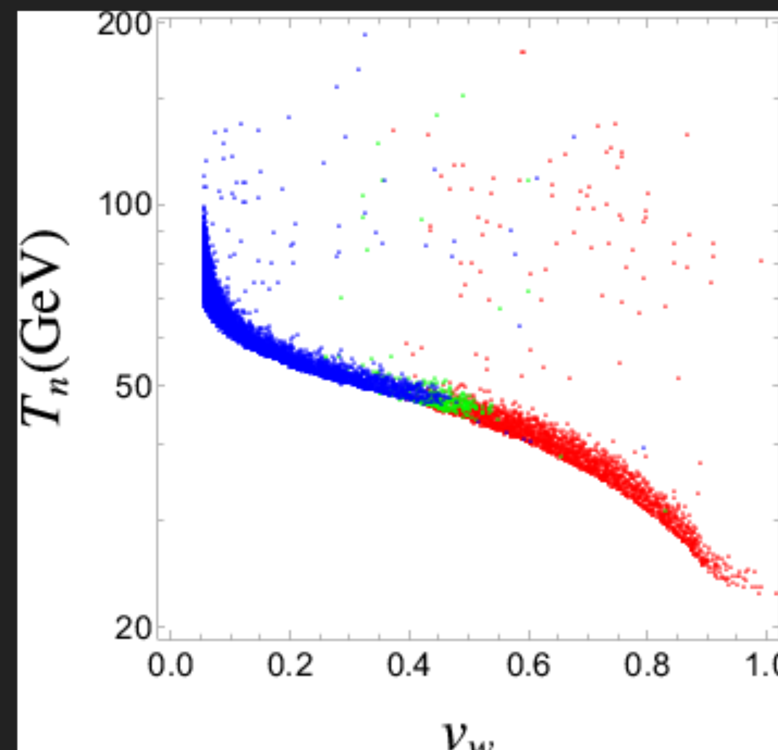
- Electroweak Precision Measurements

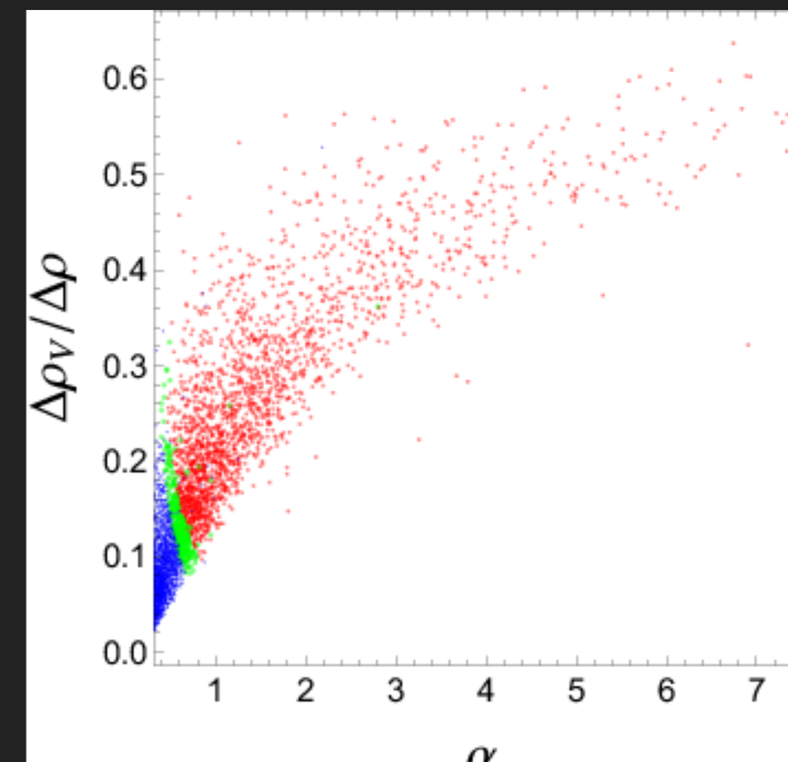
$$\left.\begin{array}{c} m_w^{exp} = 80.385 \pm 0.015 \\ \text{S,T, and U} \end{array}\right\} \left(\theta, m_{h_2}\right)$$



EWPT and SNR

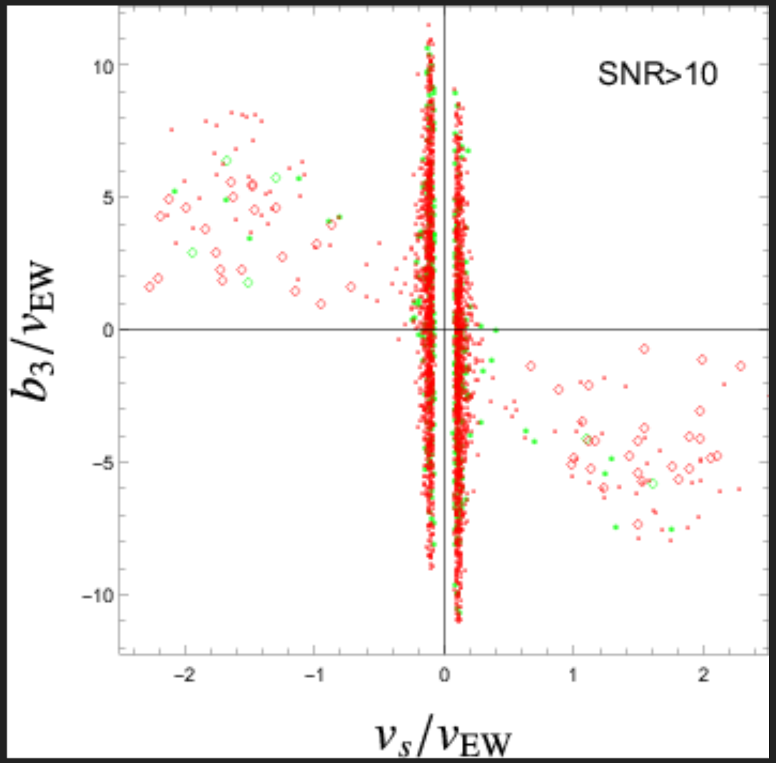


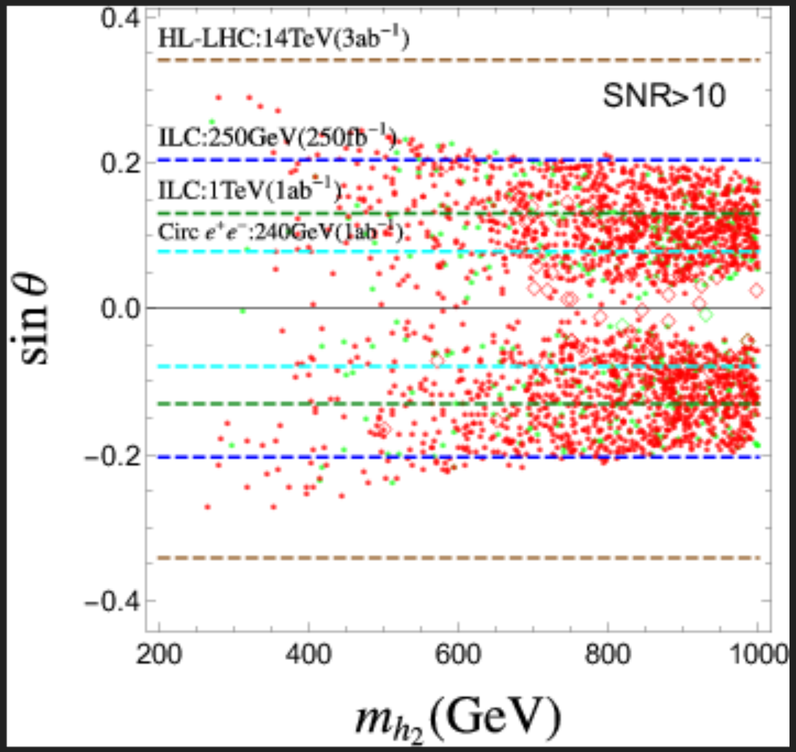


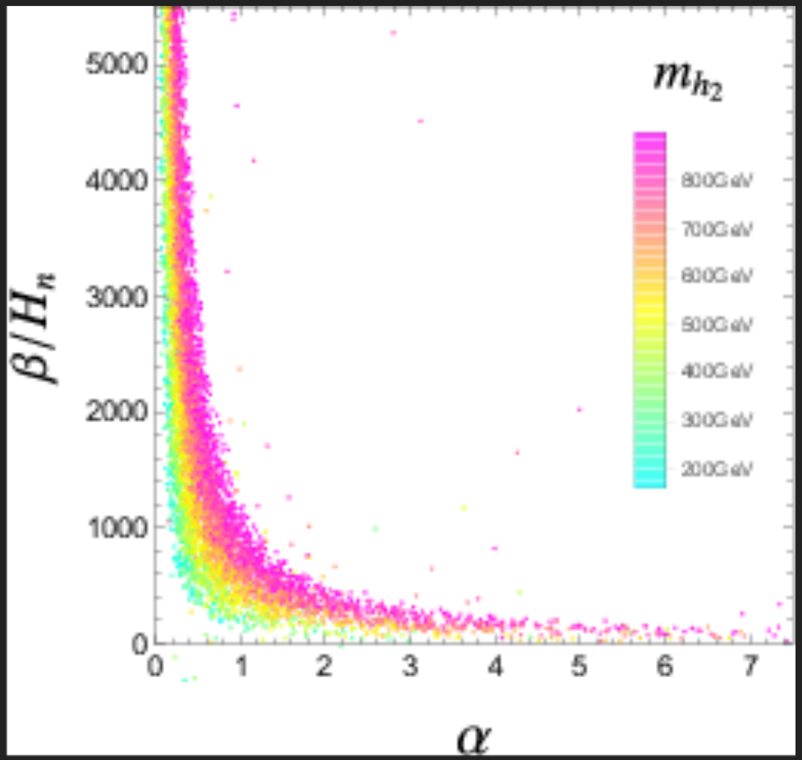


- EWPT type: (a) 99 % (b) 1 % (c) 0 %
- LISA: SNR < 10 (blue - 28 %), 10 < SNR < 50 (green - 50 %), and SNR > 50 (red - 22 %)
- Larger α and smaller $\beta \Rightarrow$ larger SNR
- Faster bubble wall $\Rightarrow$ larger SNR

Parameter Space Giving Detectable GW's

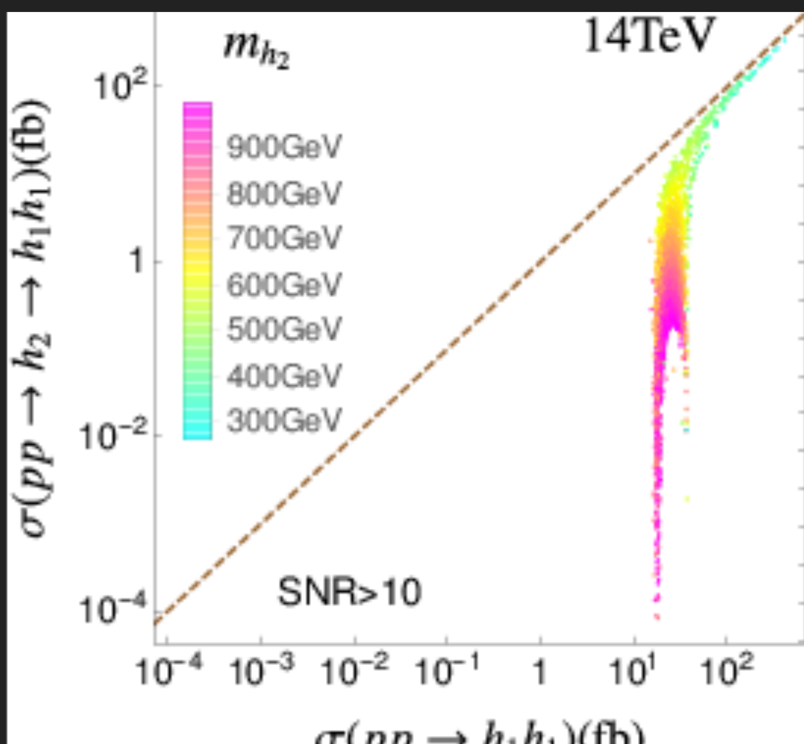


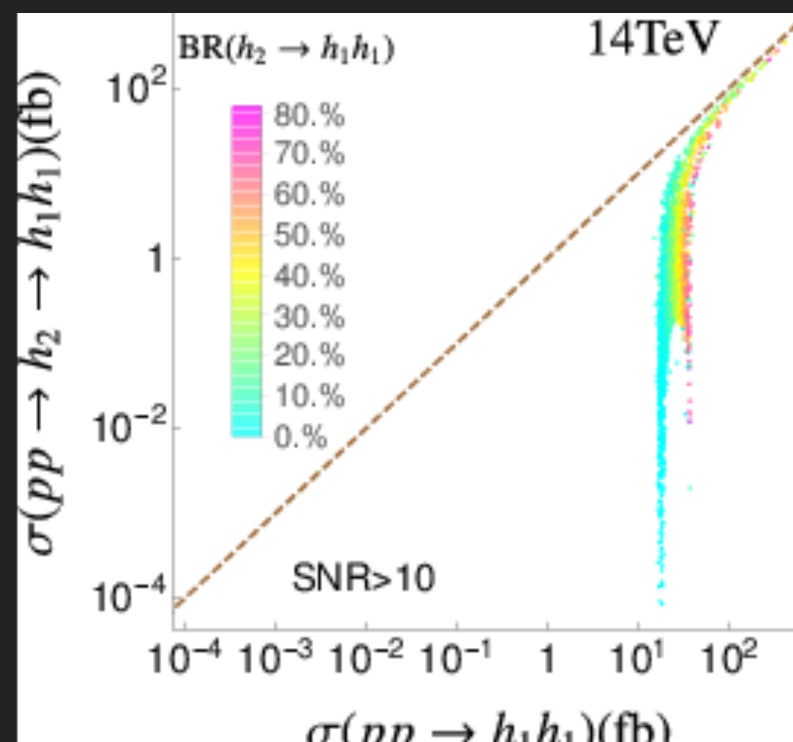


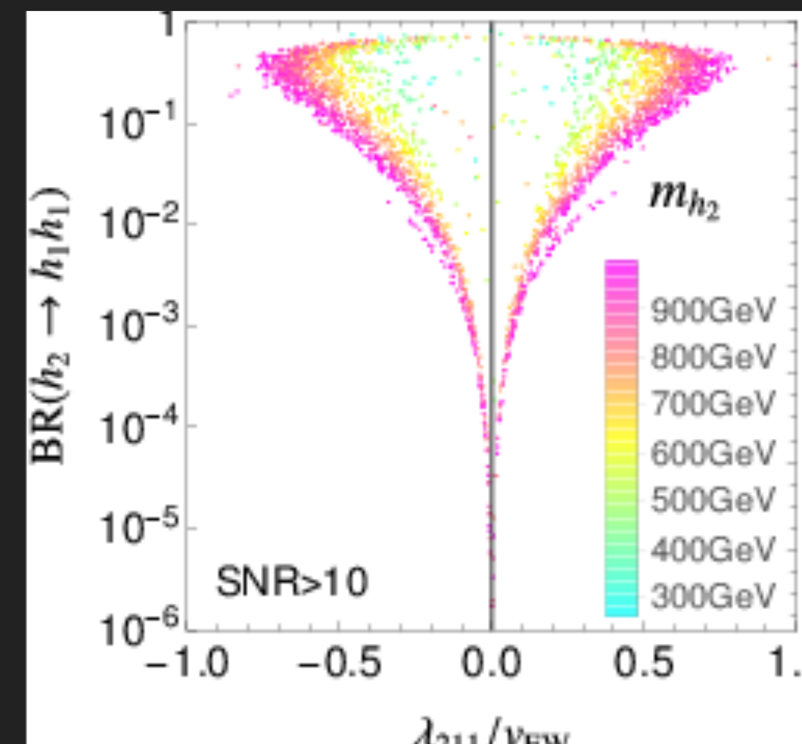


- Bounded from below: 20 GeV $\lesssim |v_s| \lesssim 50$ GeV
- Larger m_{h_2} preferred
- W-mass constraint: $\theta \lesssim 0.2$

Correlation with Double Higgs Production

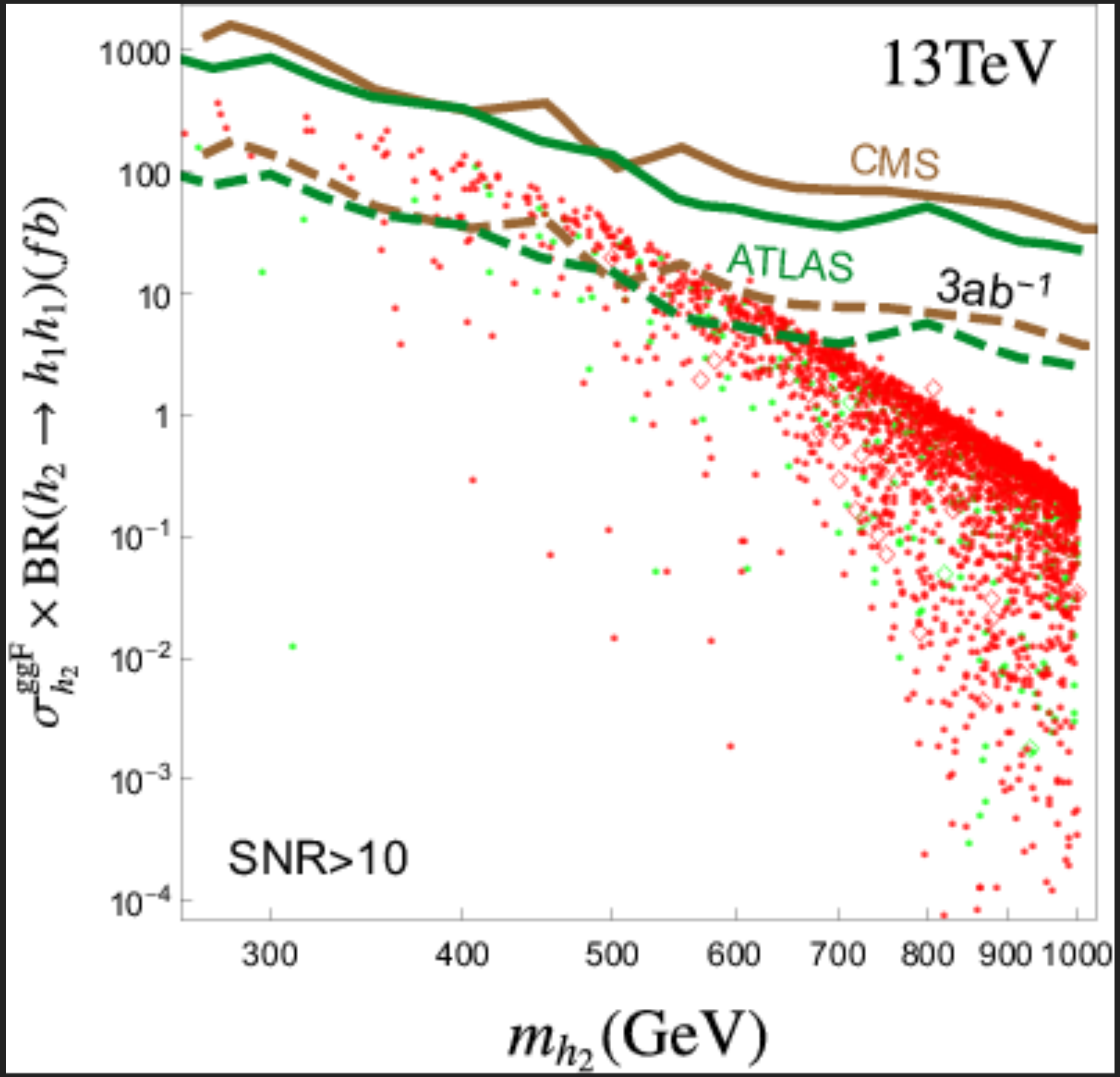






- $\Gamma_{h_2} = \sin^2\theta \Gamma_{SM}(h_2 \to X_{SM}) + \Gamma(h_2 \to h_1 h_1)$
- $\sigma(pp \to h_1 h_1) = \sigma(pp \to h_2) Br(h_2 \to h_1 h_1)$
- Large m_{h_2} $\Rightarrow$ small $Br(h_2 \to h_1 h_1)$ $\Rightarrow$ small $\sigma(pp \to h_2 \to h_1 h_1)$

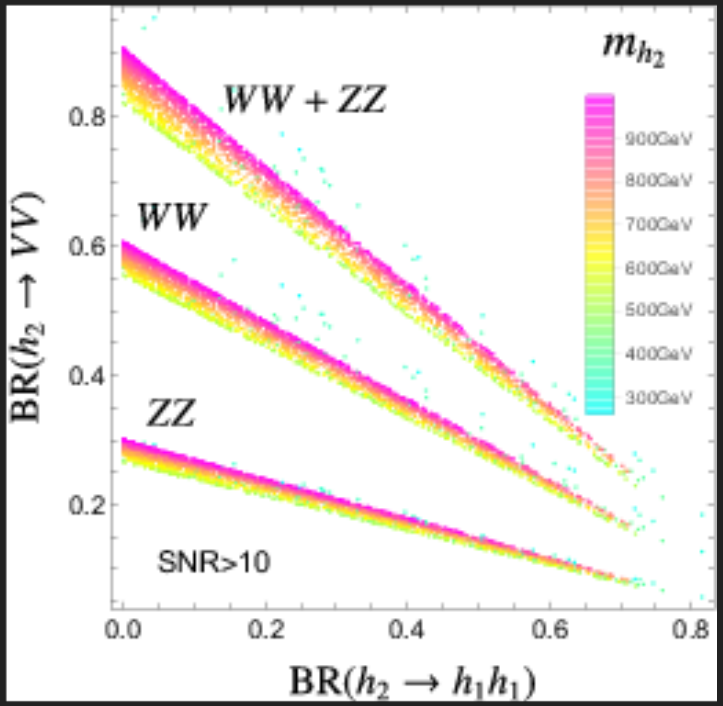
Correlation with Double Higgs Production Searches

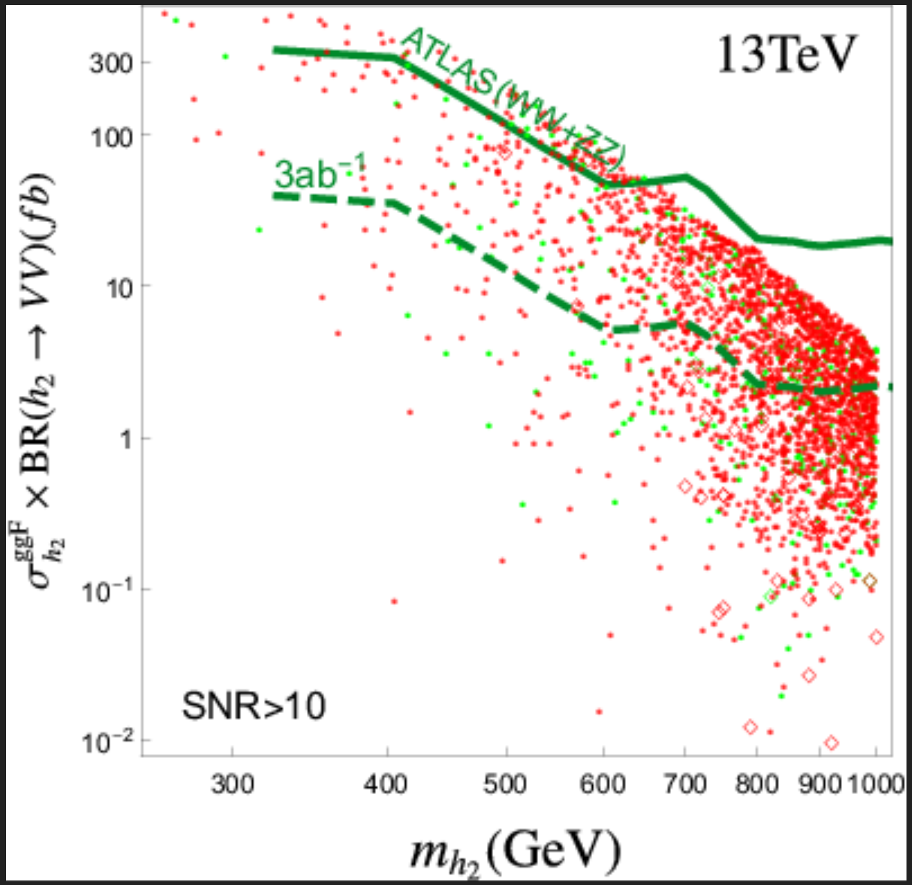


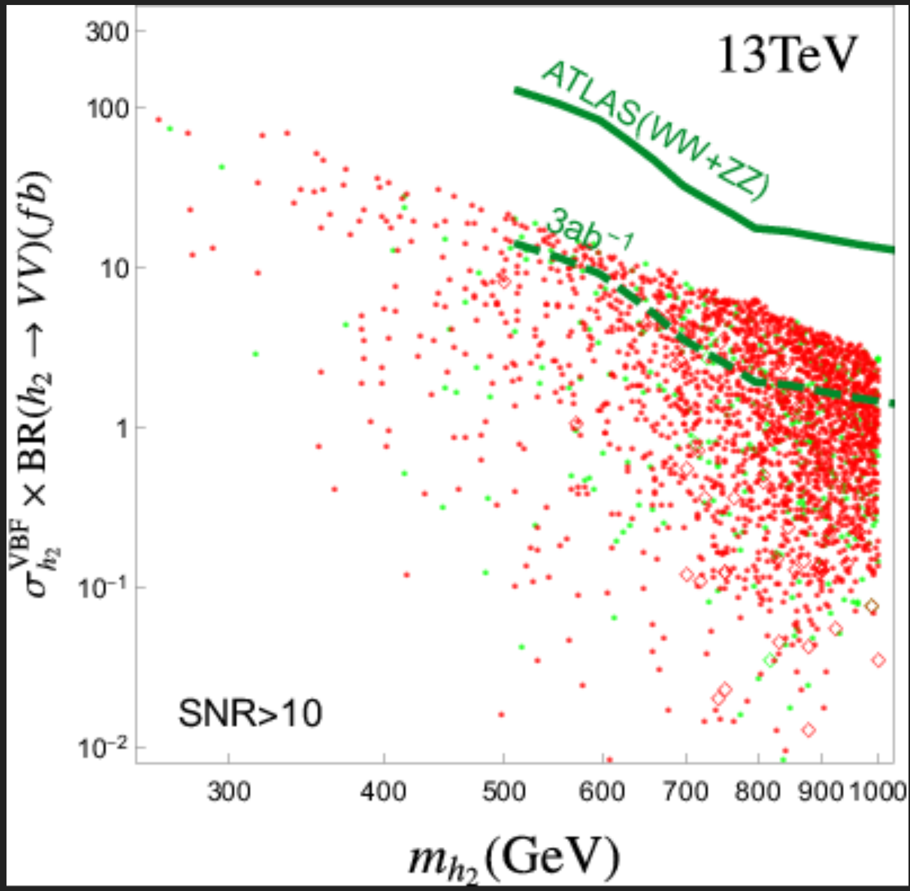
- SNR > 50 (red)
- 10 > SNR > 50 (green)
- $m_{h_2} \lesssim 500$ can be probed by both 3 ab^{-1} (13 TeV) HL-LHC and space based GW detectors

Diboson Resonant Searches

- SNR > 50 (red)
- 10 < SNR < 50 (green)
- h_2 primarily decays through VV and $h_1 h_1$ channels

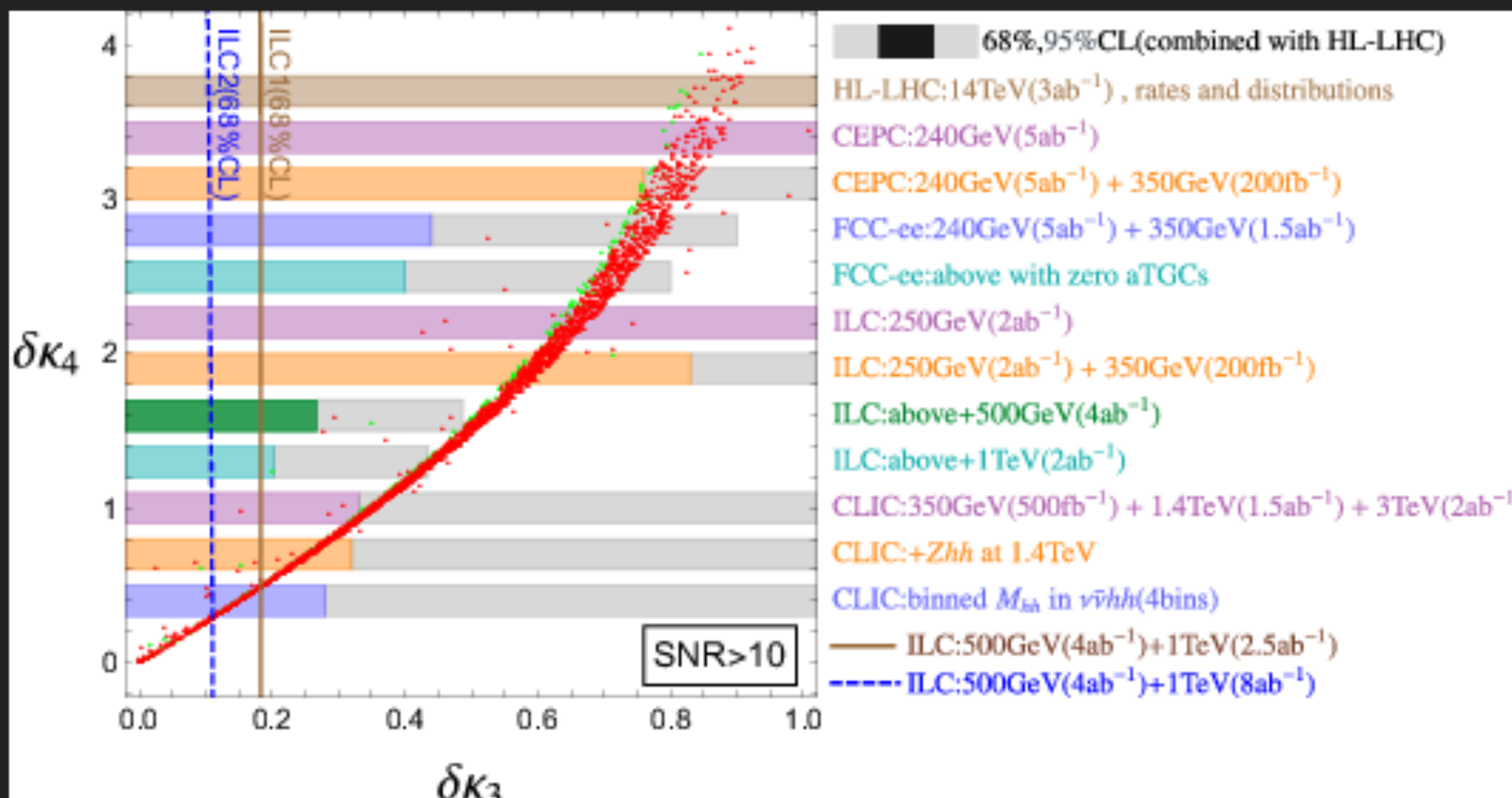






Higgs Cubic and Quartic Couplings

$$\Delta\mathscr{L} = -\frac{m_{h_1}}{2v}(1+\delta\kappa_3)h_1^3 - \frac{m_{h_1}}{8v^2}(1+\delta\kappa_4)h_1^4$$



- SNR > 50 (red) and 10 < SNR < 50 (green)
- Precise measurements can be used to reconstruct the Higgs potential
- Correlation given by $\delta\kappa_4 \approx \eta\delta\kappa_3$ for $\eta \in (2,4)$

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 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} proffered for SNR but not for colliders

Some References

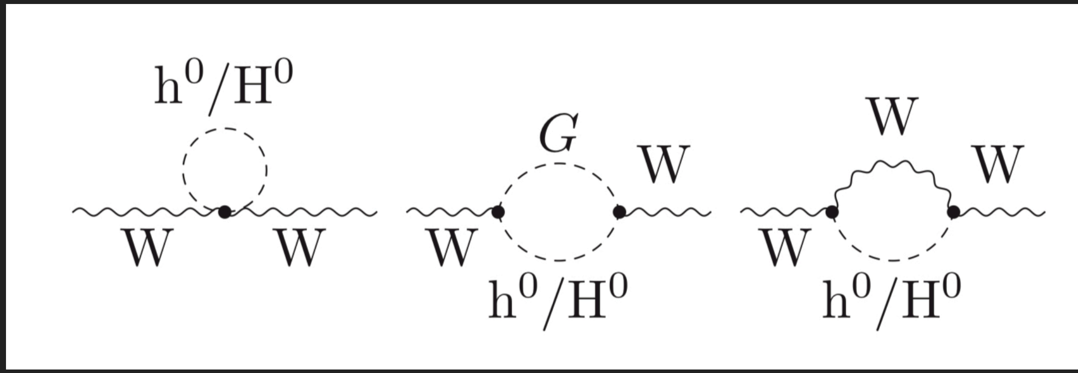
- Velocity Profile: arXiv:1004.4187
- W-mass: arXiv:1203.0275
- Higgs signal strength: arXiv:1606.02266, and arXiv:1801.00794
- Sound waves: arXiv:1504.03291

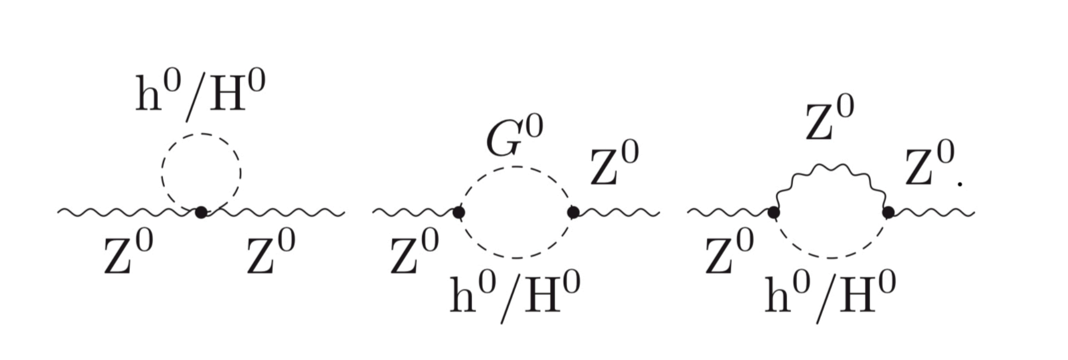
EWPT Definitions

- Key parameters: T_C, T_n, β, α, v_w
- Tunneling Rate: $\Gamma \sim \mathscr{A}(T)e^{-S_3/T}$
- Euclidean action of the critical bubble: $S_3(\vec{\phi},T) = 4\pi\int r^2 dr\left[\frac{1}{2}\left(\frac{d\vec{\phi}(r)}{dr}\right)^2 + V(\vec{\phi},T)\right]\frac{d\vec{\phi}(r)}{dr}\Big|_{r=0} = 0,\ \vec{\phi}(r=\infty) = \vec{\phi}_{out}$
- Bubble nucleation: $\int_0^{t_n}\Gamma V_H(T)dt = \int_{T_n}^{\infty}\frac{dT}{T}\left(\frac{2\xi M_{pl}}{T}\right)^4 e^{-S_3/T} = \mathscr{O}(1),\ \frac{S_3(T)}{T}\approx 140$
- Inverse time duration: $\beta = H_n T_n \frac{d(S_3/T)}{dT}\Big|_{T_n}$
- Energy released during PT: $\alpha = \frac{\Delta\rho}{\rho_R} = \frac{1}{\rho_R}\left[-V(\vec{\phi}_b,T) + T\frac{\partial V(\vec{\phi}_b,T)}{\partial T}\right]\Big|_{T=T_n}$

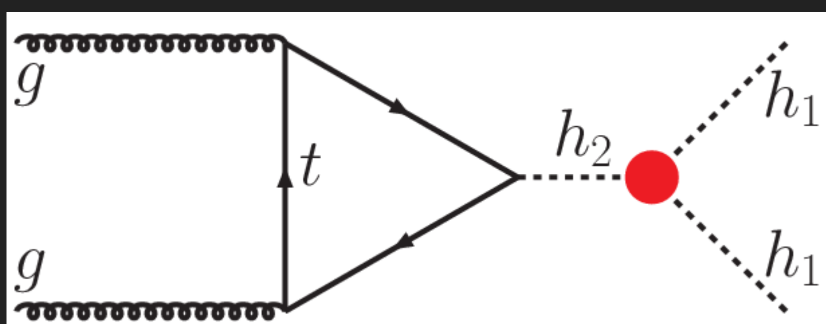
W-mass Constraint

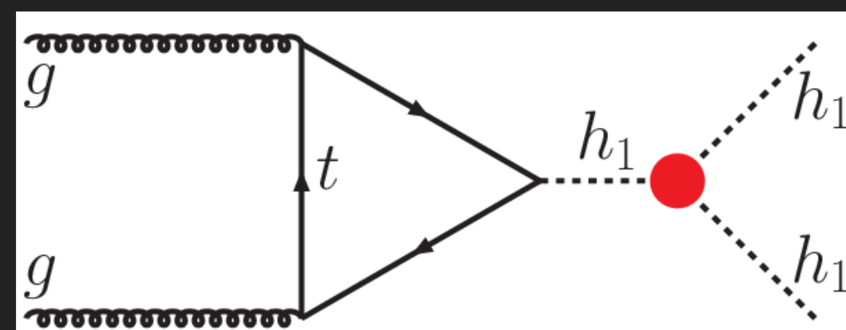
- W mass calculated from experimentally measured values of GF , mZ , and α(0)
- Functions relating these parameters depends on the loop calculations to the vector boson self-energies

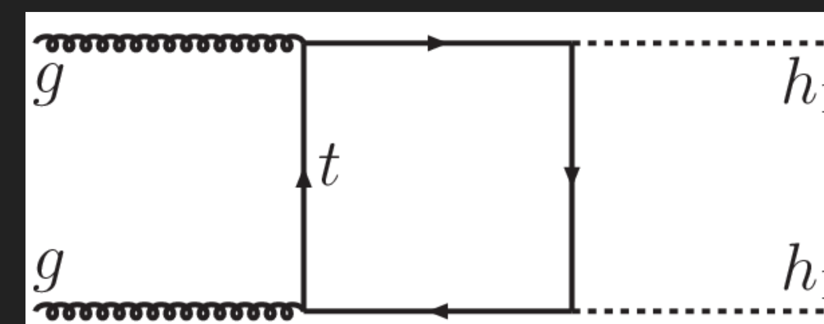


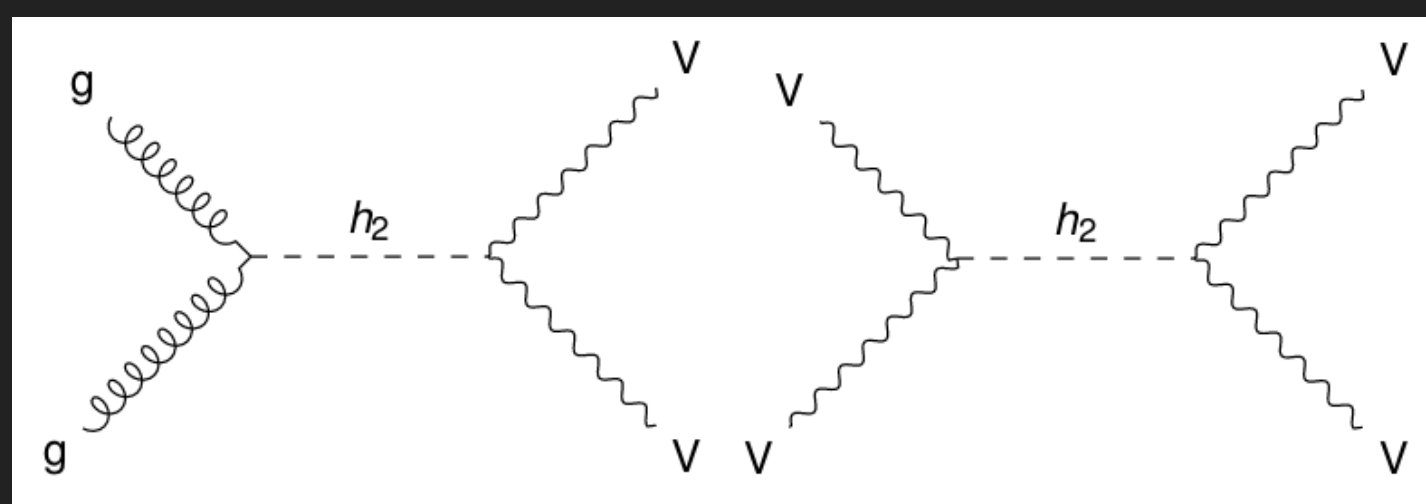


Feynman Diagrams for Di-Higgs Production and Weak Boson Pairs









Di-Higgs Production Channels

CMS

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

Atlas

- $36.1\ \mathrm{fb}^{-1}$ at 13 TeV
- Di-Higgs decay channels: $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^{+}\tau^{-}$, $bb\bar{b}\bar{b}$, $WW^{*}WW^{*}$, 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

Di-Boson Resonances

- ATLAS combined results at 13 TeV with 36 fb−1 data
- VBF at NNLO
- ggF at NNLO-NNLL
- Decay channels: WZ → qqqq, lvqq, lvll, WW → qqqq, lvqq, lvlv,
- ZZ → qqqq, vvqq, llqq, llvv, llll, and WH → qqbb, lvbb, ZH → qqbb, vvbb, llbb, and lv, ll
- arXiv:1808.02380

Higgs Cubic and Quartic Couplings 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 $2 \to 2$ channels
- Charge neutral channels: $(h_1h_1, h_2h_2, h_1h_2, h_1Z, h_2Z, ZZ, W^+W^-)$
- Charge-1 channels: (h_1W^+, h_2W^+, ZW^+)
- Charge-2 channels: (W^+W^-)
- Leading partial wave amplitude of these smatterings are given collectively by a symmetric matrix: $S = S_0 \oplus S_1 \oplus S_2$