First Order Electroweak Phase Transitions in the SM with a Singlet Extension

Anthony Hooper

UNIVERSITY *of* NEBRASKA–LINCOLN

Particle Physics on the Plains:
University of Kansas
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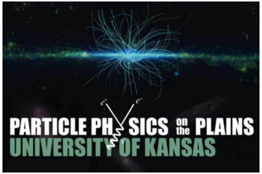
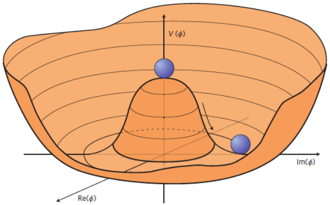


in collaboration with
Peisi Huang
Carlos Wagner

Motivation and higgs' measurements



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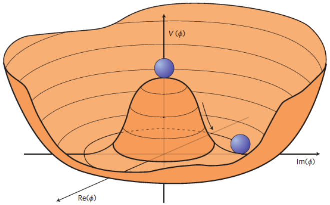

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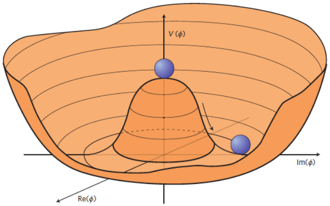

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Vacuum expectation value (vev)

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Higgs boson mass

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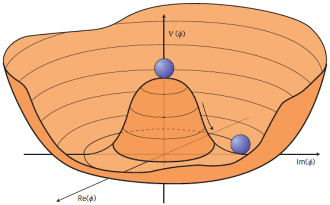

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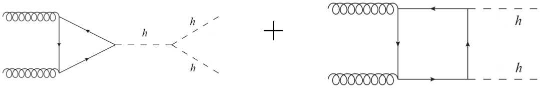

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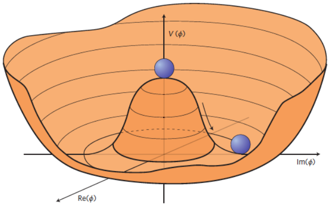

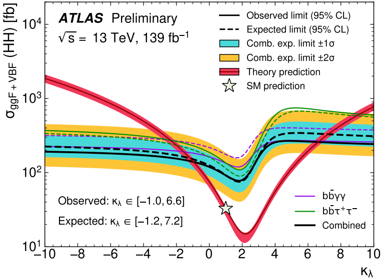

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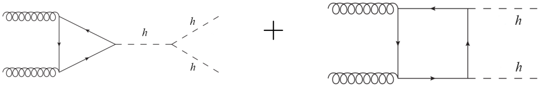

[1]ATL-PHYS-PROC-2022-044

Adding a real scalar singlet

- Matter-antimatter inequality
- Dark matter
- etc...

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$$V = V_h(\phi_h) + V_{hs}(\phi_h, \phi_s) + V_s(\phi_s),$$

where $\phi_h = \begin{pmatrix} 0 \\ h + v \end{pmatrix}$ and $\phi_s = (s + v_s)$, and v and v_s are the vevs of ϕ_h and ϕ_s, respectively.

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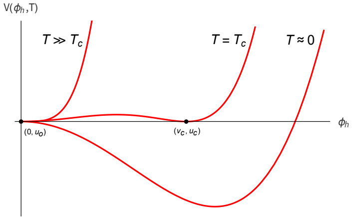
Adding a first order phase transition

First Order



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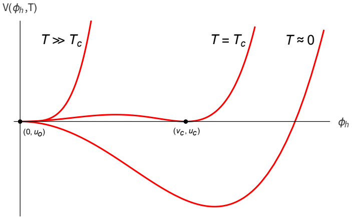

Supports electroweak baryogenesis

sets the energy scale to levels we can measure

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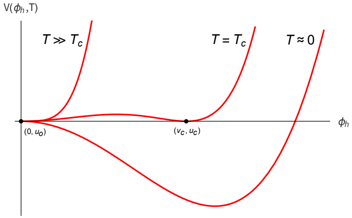
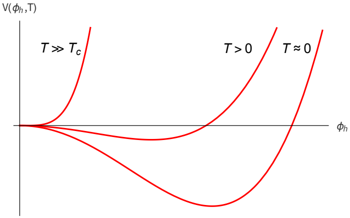


Smooth Crossover

(SM behavior)



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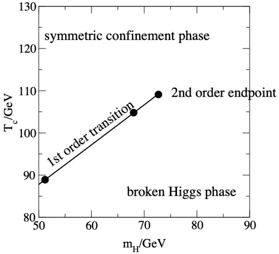

[2] arXiv:0010275

Adding a temperature component

$$V_{eff}(h, s, T) = V_0(h, s) + V_{CW}(h, s) + V_T(h, s, T)$$

V_{CW} - Coleman-Weinberg (CW) potential, V_T - finite temperature contribution

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$V_{CW} = V_1(h, s) + V_1^{c.t.}$

$$V_1 = \sum_i n_i \frac{m_i^4}{64\pi^2}\left(log\frac{m_i^2}{\Lambda^2} - C_i\right)$$

where $i = h_1, h_2, \chi_{1,2,3}, W^{\pm}, Z, t,$

n_i is degrees of freedom for each particle,

m_i^2 are the free-field dependent masses in the Landau gauge

C_i is $3/2$ for scalars and fermions and $5/6$ for gauge bosons,

and Λ is the renormalization scale.

Adding a temperature component

The thermal contribution is given by

$$V_T(h, s, T) = \frac{T^4}{2\pi^2} \sum_i n_i J_{\mp} \left(\frac{m_i(h, s, T)}{T} \right)$$

where the J function is defined as

$$J_{\mp}(y) = \pm \int_0^{\infty} dx\, x^2 \log \left(1 \mp e^{-\sqrt{x^2+y^2}} \right)$$

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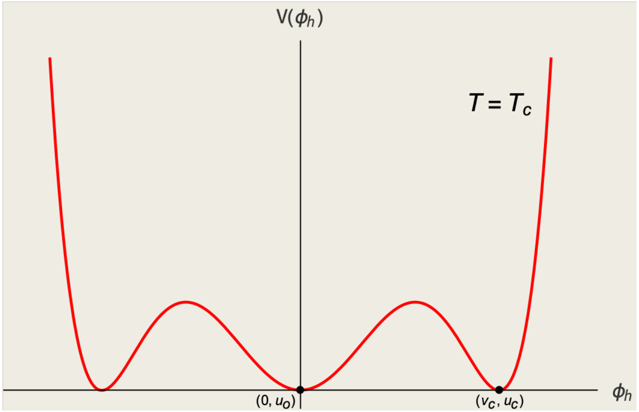
Thermally-corrected masses:

$$m_i^2(h, s) \to m_i^2(h, s) + \Pi_i(T)$$

Imposing conditions at the critical temperature



degenerate requirement:

$$V_{eff}(0, u_o, T_c) = V_{eff}(v_c, u_c, T_c)$$

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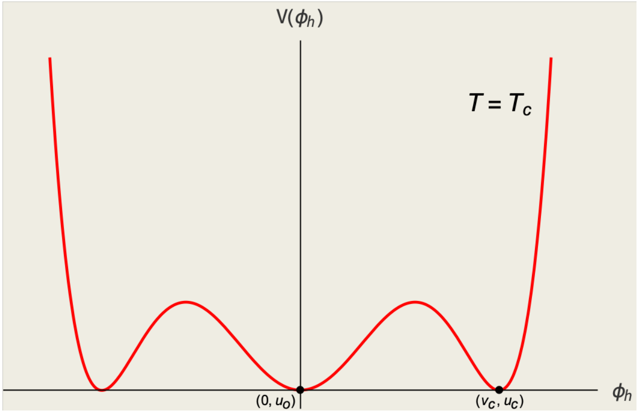

degenerate requirement:

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minimization requirement:

$$h = 0 : \quad \left.\frac{\partial V_{eff}(h, s, T_c)}{\partial s}\right|_s = 0$$

$$h = v_c : \quad \left.\frac{\partial V_{eff}(h, s, T_c)}{\partial h}\right|_b = 0$$

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where $s = (h, s) \to (0, u_o)$ and $b = (h, s) \to (v_c, u_c)$ are the critical points and are global minimums.

Conventional criteria: $v_c/T_c \gtrsim 1$

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FindBounce - a Mathematica package to calculate the bounce. (Assuming thin wall bubbles)[6]

$$\Gamma \simeq Ae^{-B}(1+\mathcal{O}(\hbar))$$

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[3] arXiv:2002.00881

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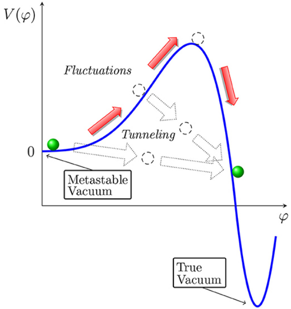
If the barrier is low enough, then thermal fluctuations can drive tunneling to occur during the nucleation of bubbles at the PT.



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[4] arXiv:1809.06923

Outline

Mixing Angle

$$V_o = \frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + t_s s + a_{hs} h^2 s + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{2}\lambda_{hs} h^2 s^2 + \frac{1}{4}\lambda_s s^4$$

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$$R(\theta)\mathcal{M}^2 R^{-1}(\theta) = \begin{pmatrix} m_h^2 & 0 \\ 0 & m_s^2 \end{pmatrix} \implies \begin{cases} h_1 = h\cos\theta + s\sin\theta \\ h_2 = s\cos\theta - h\sin\theta \end{cases}$$

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$$hff = (h_1 \cos\theta - h_2 \sin\theta) ff \implies \begin{cases} \sigma(pp \to h_1) = \cos^2\theta \sigma_{SM}(pp \to h_1) \\ \sigma(pp \to h_2) = \sin^2\theta \sigma_{SM}(pp \to h_2) \end{cases}$$

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CMS Global Signal Strength: $\mu = 1.002 \pm 0.057 \implies \cos^2\theta > 0.89 \quad$ (95% C.L.)

[5] arXiv:2207.00043

Reparametrizing

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In the basis (h, s), the mass squared matrix is

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Solve for μ_h^2, μ_s^2, a_{hs}, and t_s in terms of λ_h, λ_{hs}, λ_s, m_s, v_s, m_h, v;

$$\mu_h^2 = -v^2\lambda_h \pm \frac{v_s}{v}\Delta + v_s^2\lambda_{hs}$$

$$\mu_s^2 = m_h^2 + m_s^2 - 2v^2\lambda_h - v^2\lambda_{hs} - 3v_s^2\lambda_s$$

$$a_{hs} = \mp\frac{1}{2v}\Delta - v_s\lambda_{hs}$$

$$t_s = -v_s(m_h^2 + m_s^2 - 2v^2\lambda_h - v^2\lambda_{hs} - 2v_s^2\lambda_s) \pm \frac{v\Delta}{2}$$

where $\Delta = \sqrt{(m_h^2 - 2v^2\lambda_h)(2v^2\lambda_h - m_s^2)}$

Reparametrizing

Solve for μ_h^2, μ_s^2, a_{hs}, and t_s in terms of λ_h, λ_{hs}, λ_s, m_s, v_s, m_h, v;

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where $\Delta = \sqrt{(m_h^2 - 2v^2\lambda_h)(2v^2\lambda_h - m_s^2)}$

Ranges of the new parameters

$$\begin{aligned} \text{Stability conditions :} \quad & \lambda_h, \lambda_s \in [0, 4\pi/3], \quad \lambda_{hs} \in [-\sqrt{\lambda_h\lambda_s}, 4\pi/3] \\ \text{singlet mass :} \quad & m_s \le m_h/2 \quad \text{or} \quad 2m_h \le m_s \\ \text{singlet vev :} \quad & |v_s| \lesssim 1\ TeV \end{aligned}$$

[6] arXiv:1701.08774

Trilinear Couplings

$$V(h_1, h_2) \supset \frac{\lambda_{111}}{3!} h_1^3 + \frac{\lambda_{211}}{2!} h_2 h_1^2 + \frac{\lambda_{122}}{2!} h_2^2 h_1 + \frac{\lambda_{222}}{3!} h_2^3$$

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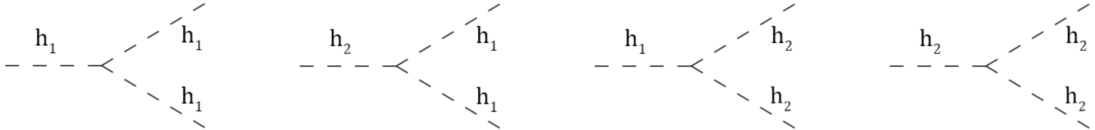

$$\lambda_{111}^0 = \frac{\partial^3 V_o(h_1, h_2)}{\partial h_1^3} = \frac{3m_h^2}{v} \cos^3\theta \left(1 + \frac{2v}{m_h^2}(v\lambda_{hs} + v_s\lambda_s \tan\theta) \tan^2\theta\right)$$

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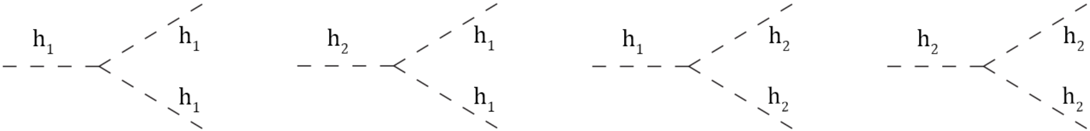
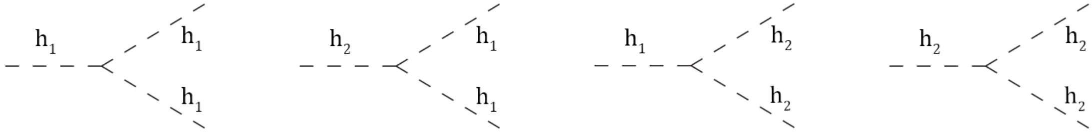


$$\lambda_{111}^0 = \frac{\partial^3 V_o(h_1, h_2)}{\partial h_1^3} = \frac{3m_h^2}{v} \cos^3\theta \left(1 + \frac{2v}{m_h^2} (v\lambda_{hs} + v_s \lambda_s \tan\theta) \tan^2\theta\right)$$

$$\lambda_{211}^0 = \frac{\partial^3 V_o(h_1, h_2)}{\partial h_1^2 \partial h_2} = -(c_\theta^2 - 2s_\theta^2)(m_s^2 - m_h^2)c_\theta^2 s_\theta / v + 6(\lambda_s v_s s_\theta - \lambda_h v c_\theta)c_\theta s_\theta + 2\lambda_{hs} v(2c_\theta^2 - s_\theta^2)s_\theta$$

Trilinear Couplings

$$V(h_1,h_2) \supset \frac{\lambda_{111}}{3!}h_1^3 + \frac{\lambda_{211}}{2!}h_2 h_1^2 + \frac{\lambda_{122}}{2!}h_2^2 h_1 + \frac{\lambda_{222}}{3!}h_2^3$$



$$\lambda^0_{111} = \frac{\partial^3 V_o(h_1,h_2)}{\partial h_1^3} = \frac{3m_h^2}{v}\cos^3\theta\left(1 + \frac{2v}{m_h^2}\left(v\lambda_{hs} + v_s\lambda_s \tan\theta\right)\tan^2\theta\right)$$

$$\lambda^0_{211} = \frac{\partial^3 V_o(h_1,h_2)}{\partial h_1^2 \partial h_2} = -(c_\theta^2 - 2s_\theta^2)(m_s^2 - m_h^2)c_\theta^2 s_\theta/v + 6(\lambda_s v_s s_\theta - \lambda_h v c_\theta)c_\theta s_\theta + 2\lambda_{hs}v(2c_\theta^2 - s_\theta^2)s_\theta$$

$$\lambda^0_{122} = \frac{\partial^3 V_o(h_1,h_2)}{\partial h_1 \partial h_2^2} = -(s_\theta^2 - 2c_\theta^2)(m_s^2 - m_h^2)c_\theta s_\theta^2/v + 6(\lambda_s v_s c_\theta + \lambda_h v s_\theta)c_\theta s_\theta + 2\lambda_{hs}v(c_\theta^2 - 2s_\theta^2)c_\theta$$

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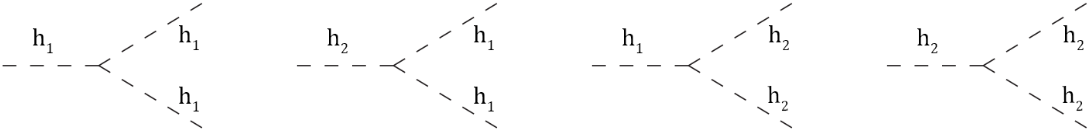
$$V(h_1,h_2) \supset \frac{\lambda_{111}}{3!}h_1^3 + \frac{\lambda_{211}}{2!}h_2 h_1^2 + \frac{\lambda_{122}}{2!}h_2^2 h_1 + \frac{\lambda_{222}}{3!}h_2^3$$



$$\lambda_{111}^0 = \frac{\partial^3 V_o(h_1,h_2)}{\partial h_1^3} = \frac{3m_h^2}{v}\cos^3\theta\left(1 + \frac{2v}{m_h^2}(v\lambda_{hs} + v_s\lambda_s\tan\theta)\tan^2\theta\right)$$

$$\kappa = \frac{\lambda_{111}}{\lambda_{111}^{SM}}$$

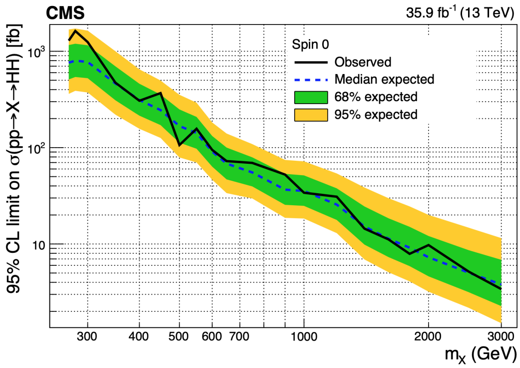
where $\lambda_{111}^{SM} = 3m_h^2/v$

$$\lambda_{211}^0 = \frac{\partial^3 V_o(h_1,h_2)}{\partial h_1^2\partial h_2} = -(c_\theta^2 - 2s_\theta^2)(m_s^2 - m_h^2)c_\theta^2 s_\theta/v + 6(\lambda_s v_s s_\theta - \lambda_h v c_\theta)c_\theta s_\theta + 2\lambda_{hs}v(2c_\theta^2 - s_\theta^2)s_\theta$$

$$\lambda_{122}^0 = \frac{\partial^3 V_o(h_1,h_2)}{\partial h_1\partial h_2^2} = -(s_\theta^2 - 2c_\theta^2)(m_s^2 - m_h^2)c_\theta s_\theta^2/v + 6(\lambda_s v_s c_\theta + \lambda_h v s_\theta)c_\theta s_\theta + 2\lambda_{hs}v(c_\theta^2 - 2s_\theta^2)c_\theta$$

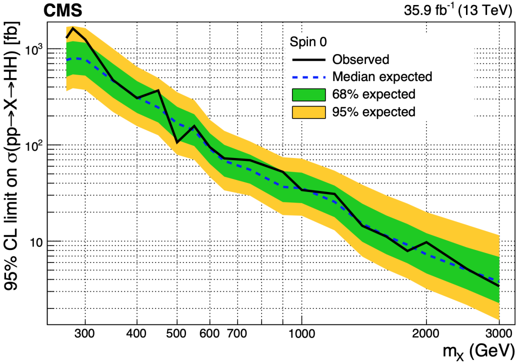
$$\lambda_{111} = \lambda_{111}^0 + \Delta\lambda_{111}^{1-loop}$$

Resonance Constraint



[7] arXiv:1811.09689

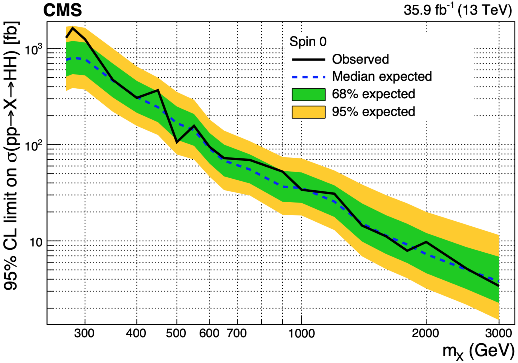
Resonance Constraint



$$\sigma(pp \rightarrow h_2 \rightarrow h_1 h_1) \approx \sigma(pp \rightarrow h_2) BR(h_2 \rightarrow h_1 h_1)$$

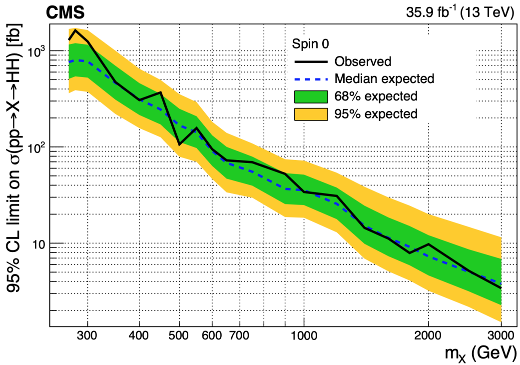
[7] arXiv:1811.09689

Resonance Constraint



$$\sigma(pp \to h_2 \to h_1 h_1) \approx \sigma(pp \to h_2) BR(h_2 \to h_1 h_1)$$
$$= \sin^2\theta \sigma_{SM}(pp \to h_2) BR(h_2 \to h_1 h_1)$$

[7] arXiv:1811.09689



$$BR(h_2 \to h_1 h_1) = \frac{\Gamma(h_2 \to h_1 h_1)}{\Gamma(h_2)}$$

where

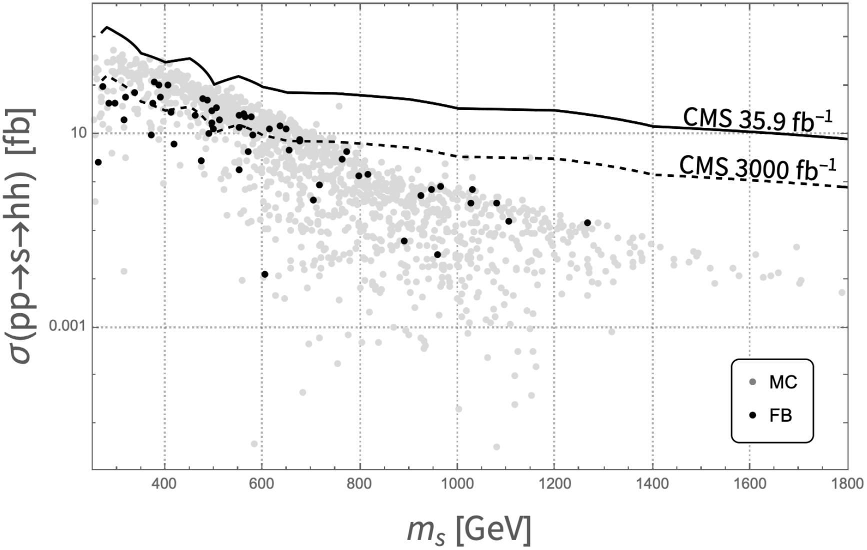
$$\Gamma(h_2 \to h_1 h_1) = \frac{\lambda_{211}^2}{32\pi m_s}\sqrt{1 - \frac{4m_h^2}{m_s^2}}$$

$$\Gamma(h_2) = \Gamma(h_2 \to h_1 h_1) + \sin^2\theta \Gamma_{SM}(h_2 \to X_{SM})$$

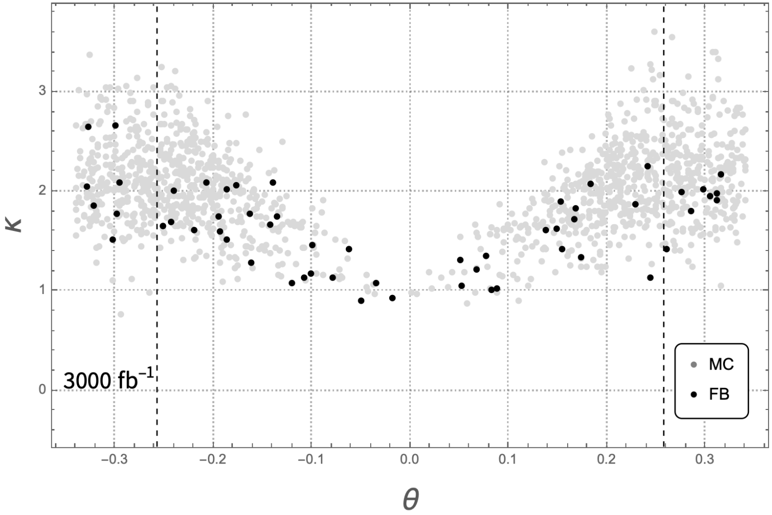
$$\begin{aligned}\sigma(pp \to h_2 \to h_1 h_1) &\approx \sigma(pp \to h_2) BR(h_2 \to h_1 h_1) \\ &= \sin^2\theta \sigma_{SM}(pp \to h_2) BR(h_2 \to h_1 h_1)\end{aligned}$$

[7] arXiv:1811.09689

Resonance Decay Results

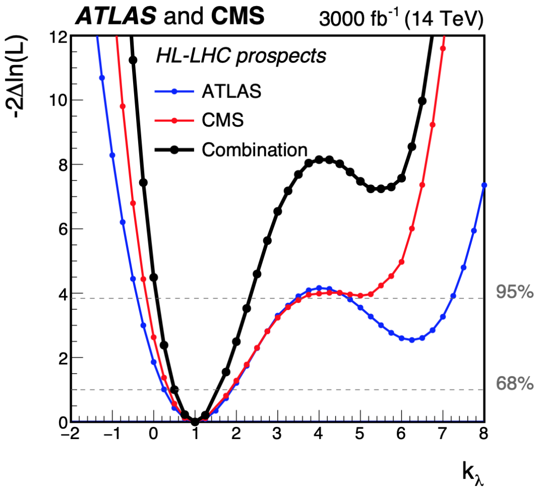


Higgs Trilinear Coupling



[8] CMS PAS FTR-18-011

Higgs Trilinear Coupling versus the Mixing Angle

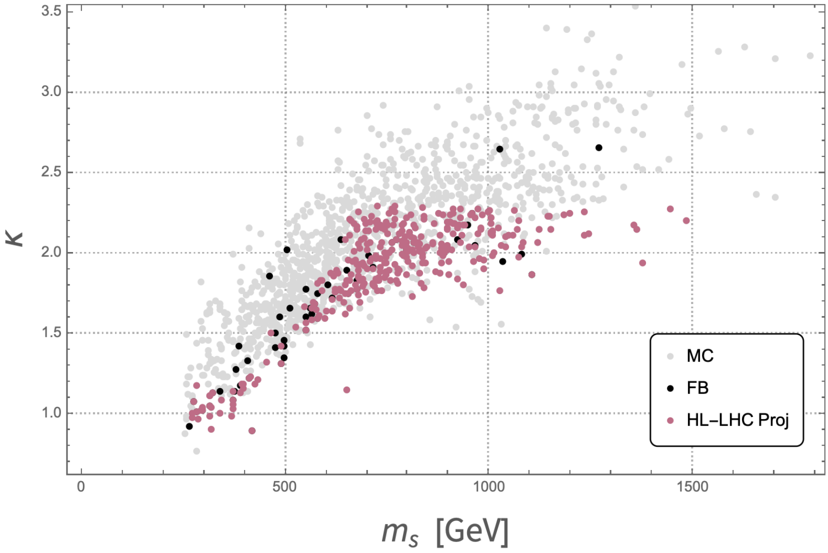


Combined:

$$0.1 < \kappa_\lambda < 2.3 \quad (95\%\ \text{C.L.})$$

[9] arXiv:1902.00134

Higgs Trilinear Coupling versus the Singlet Mass



Types of Decays

$$m_s < \frac{m_h}{2} \quad \Longrightarrow \quad \Gamma(h_2) = s_\theta^2 \sum \Gamma_{SM}(h_2 \to X_{SM}) \Longrightarrow \tau \propto \frac{1}{s_\theta^2}$$

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- $\theta = 0 \implies$ No Decays

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- $c\tau \gtrsim 0.1\, mm \implies |\theta| \lesssim 10^{-3.5} \implies$ Long-Lived Particles

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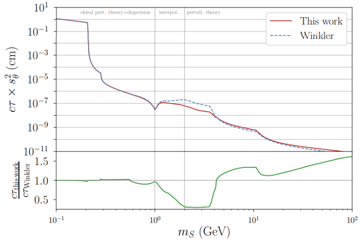

[10] arXiv:2012.07864

Types of Decays

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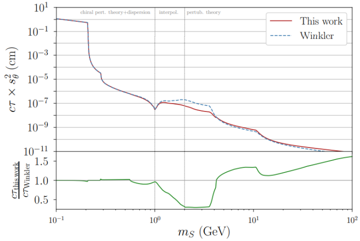
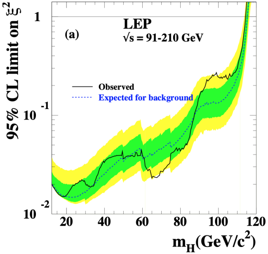


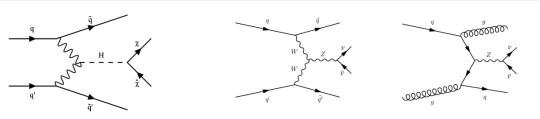


$\xi^2 = s_\theta^2$

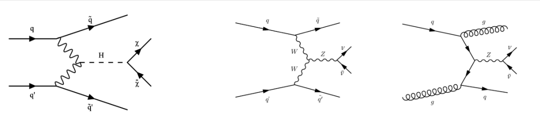
[10] arXiv:2012.07864

[11] arXiv:0306033

Experimental Constraints - Invisible Decays

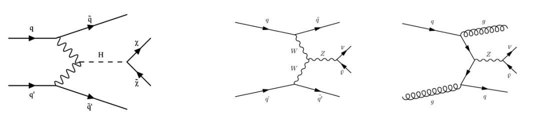


Experimental Constraints - Invisible Decays



$$BR(h \to inv) \approx BR(h \to ss)$$

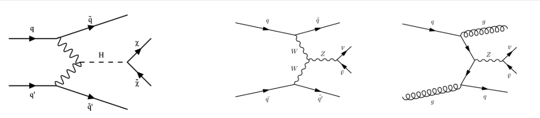
Experimental Constraints - Invisible Decays

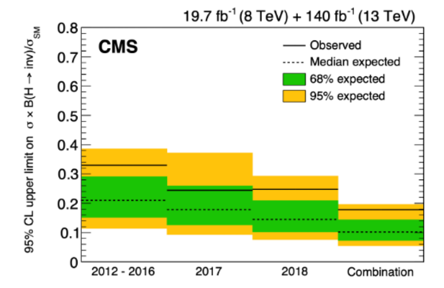


$$BR(h \to inv) \approx BR(h \to ss)$$
$$= \frac{\Gamma(h \to ss)}{\Gamma(h \to ss) + \cos^2\theta \Gamma_{SM}(h)}$$

$$\Gamma(h \to ss) = \frac{\lambda_{hss}^2}{32\pi m_h}\sqrt{1 - \frac{4m_s^2}{m_h^2}}$$

Experimental Constraints - Invisible Decays





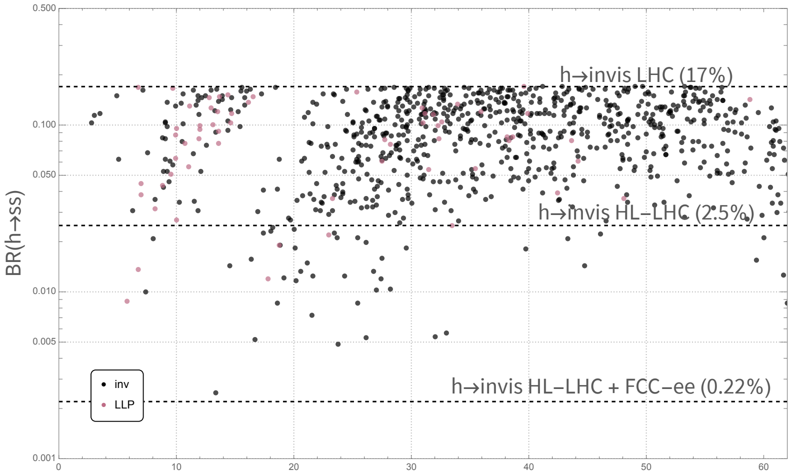
$$BR(h \to inv) \approx BR(h \to ss) = \frac{\Gamma(h \to ss)}{\Gamma(h \to ss) + \cos^2\theta \Gamma_{SM}(h)}$$

$$\Gamma(h \to ss) = \frac{\lambda_{hss}^2}{32\pi m_h}\sqrt{1 - \frac{4m_s^2}{m_h^2}}$$

$$BR(h \to ss) \leq 17\% \implies \lambda_{hss} \lesssim 5\,\mathrm{GeV}$$

[12] arXiv:1509.00672

BR($h \to ss$) versus Singlet Mass

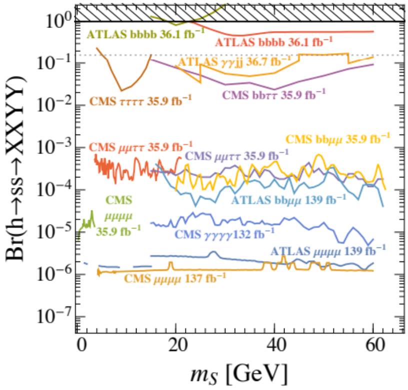


m_s [GeV]

[9] arXiv:1902.00134
[13] arXiv:1905.03764

Exotic Decay Constraints

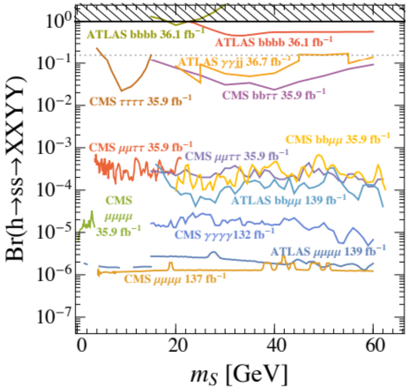
$h \to ss \to XXYY$



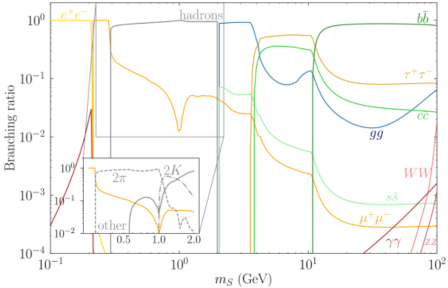
[14] arXiv:2203.08206

Exotic Decay Constraints

$h \to ss \to XXYY$



$BR(s \to XX)$



$\Longrightarrow \quad BR(h \to ss)$

[14] arXiv:2203.08206
[15] arXiv:2012.07864

Exotic Decay Results

$$BR(h \to ss) = \frac{\Gamma(h \to ss)}{\Gamma(h \to ss) + \cos^2\theta \Gamma_{SM}(h)} \qquad \Gamma(h \to ss) = \frac{\lambda_{hss}^2}{32\pi m_h}\sqrt{1 - \frac{4m_s^2}{m_h^2}}$$

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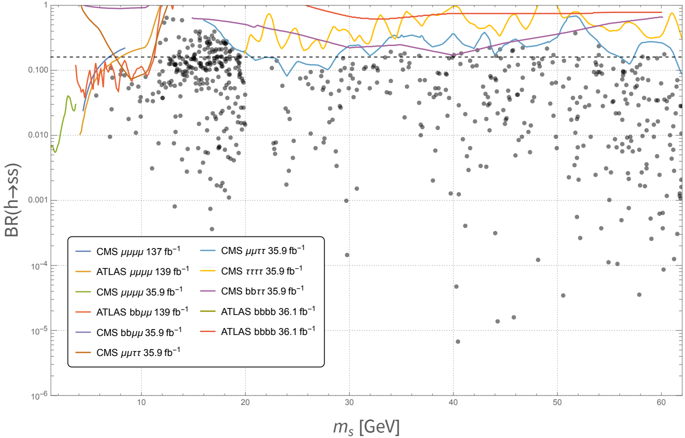
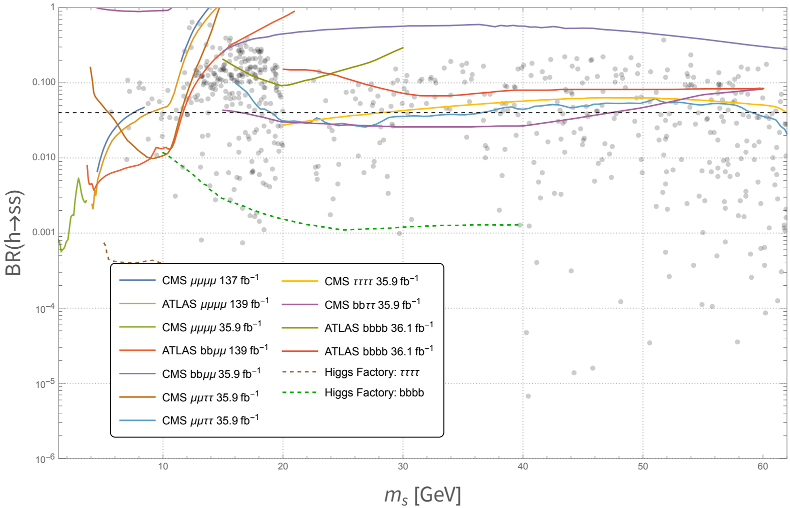
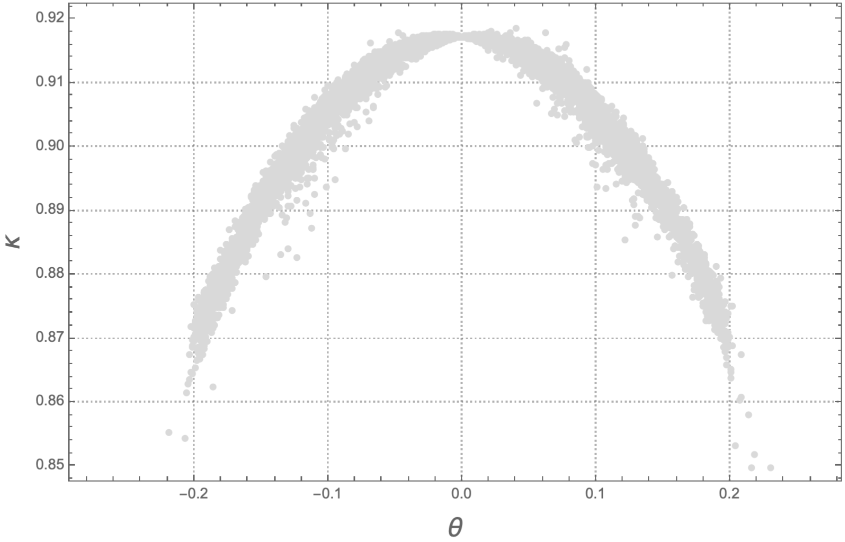


Exotic Decay Signature for Future Colliders

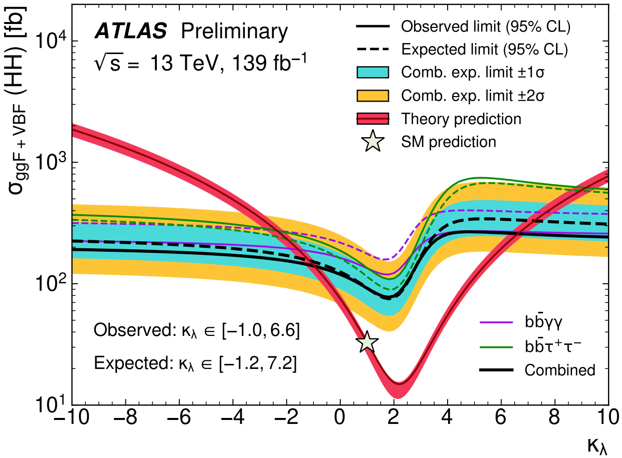


[16] arXiv:2203.08206

Higgs Trilinear Coupling versus Mixing Angle



Concluding Remarks



heavy singlets $(2m_h < m_s)$:

$$0.9 < \kappa < 3.6$$

light singlets $(2m_s < m_h)$:

$$0.85 < \kappa < 0.92$$

Thank you!

Counter Terms

$$V_1^{c.t.} = \frac{1}{2}\delta\mu_h^2 h^2 + \frac{1}{4}\delta\lambda_h h^4 + \delta t_s s + \delta a_{hs} h^2 s + \frac{1}{2}\delta\lambda_{hs} h^2 s^2 + \frac{1}{2}\delta\mu_s^2 s^2 + \frac{1}{3}\delta a_s s^3 + \frac{1}{4}\delta\lambda_s s^4 + \delta\Lambda$$

$$\left.\frac{\partial\left(V_1 + V_1^{c.t.}\right)}{\partial h}\right|_b = 0 \qquad \left.\frac{\partial\left(V_1 + V_1^{c.t.}\right)}{\partial s}\right|_b = 0 \qquad \left.\frac{\partial^2\left(V_1 + V_1^{c.t.}\right)}{\partial s \partial h}\right|_b = 0$$

$$\left.\frac{\partial^2\left(V_1 + V_1^{c.t.}\right)}{\partial h^2}\right|_b = 0 \qquad \left.\frac{\partial^2\left(V_1 + V_1^{c.t.}\right)}{\partial s^2}\right|_b = 0 \qquad \left.\frac{\partial^3\left(V_1 + V_1^{c.t.}\right)}{\partial s^3}\right|_b = 0$$

$$\left.\frac{\partial\left(V_1 + V_1^{c.t.}\right)}{\partial s}\right|_s = 0 \qquad \left.\left(V_1 + V_1^{c.t.}\right)\right|_b = 0 \qquad \left.\left(V_1 + V_1^{c.t.}\right)\right|_b = 0$$

$$b = (v, v_s) \qquad s = (0, u_s)$$

where u_s is the global minimum at $h = 0$.

Mass Terms

$$m^2_{h_1,h_2}(h,s) = \frac{\mu_h^2 + 3\lambda_h h^2 + \lambda_{hs} s^2 + 2a_{hs}s + \mu_s^2 + \lambda_{hs}h^2 + 3\lambda_s s^2}{2} \pm \frac{\sqrt{((\mu_h^2 + 3\lambda_h h^2 + \lambda_{hs}s^2 + 2a_{hs}s) - (\mu_s^2 + \lambda_{hs}h^2 + 3\lambda_s s^2))^2 + (4h(a_{hs} + \lambda_{hs}s))^2}}{2}$$

$$m_W^2 = \frac{g^2}{4}h^2 \qquad m_Z^2 = \frac{g^2 + g'^2}{4}h^2 \qquad m_t^2 = \frac{y_t^2}{2}h^2$$

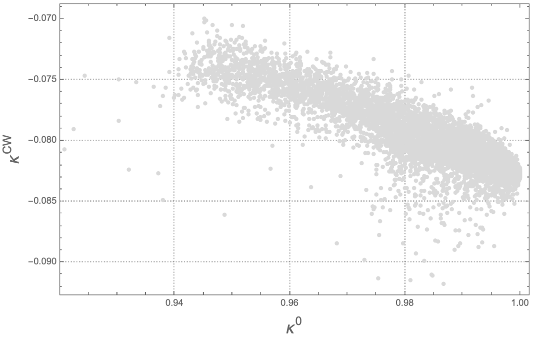
$$m_\chi^2(h,s) = \mu_h^2 + \lambda_h h^2 + \lambda_{hs}s^2 + 2a_{hs}s$$

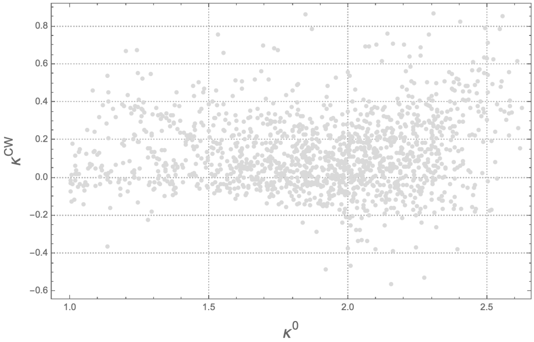
$$\mathcal{M}^2 \to \mathcal{M}^2 + \begin{pmatrix} \frac{1}{48}(9g^2 + 3g'^2 + 2(6y_t^2 + 12\lambda_h + 2\lambda_{hs}))T^2 & 0 \\ 0 & \frac{1}{12}(4\lambda_{hs} + 3\lambda_s)T^2 \end{pmatrix}$$

$$m_W^2 \to m_W^2 + \frac{11}{6}g^2T^2 \qquad m_\chi^2 \to m_\chi^2 + \left(\frac{3}{16}g^2 + \frac{1}{16}(g')^2 + \frac{1}{4}y_t^2 + \frac{1}{2}\lambda_h + \frac{1}{12}\lambda_{hs}\right)T^2$$

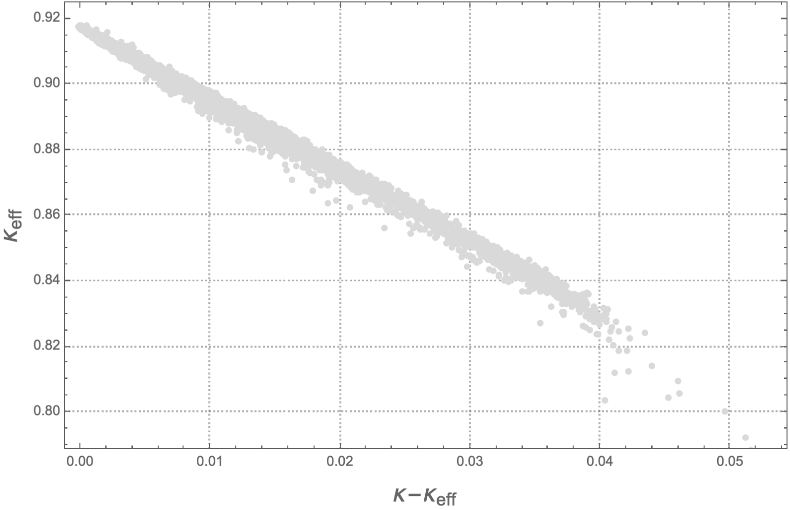
$$\mathcal{M}^2_{Z/\gamma} = \begin{pmatrix} \frac{1}{4}g^2h^2 + \frac{11}{6}g^2T^2 & -\frac{1}{4}gg'h^2 \\ -\frac{1}{4}gg'h^2 & \frac{1}{4}g'^2h^2 + \frac{11}{6}g'^2T^2 \end{pmatrix}$$

1-Loop Trilinear Corrections





Effective κ



Comparison to $\mathbb{Z}_2$ Models

$$V_o = \frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \cancel{t_s} s + \cancel{a_{hs}} h^2 s + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{2}\lambda_{hs} h^2 s^2 + \frac{1}{4}\lambda_s s^4$$

$$\mathcal{M}^2 = \left.\begin{pmatrix} \frac{\mathrm{d}^2 V_o}{\mathrm{d}h^2} & \frac{\mathrm{d}^2 V_o}{\mathrm{d}h\mathrm{d}s} \\ \frac{\mathrm{d}^2 V_o}{\mathrm{d}h\mathrm{d}s} & \frac{\mathrm{d}^2 V_o}{\mathrm{d}s^2} \end{pmatrix}\right|_{\substack{h\to v \\ s\to v_S}} = \begin{pmatrix} 2v^2\lambda_h & 2\cancel{a_{hs}} v + 2vv_s\lambda_{hs} \\ 2\cancel{a_{hs}} v + 2vv_s\lambda_{hs} & \mu_s^2 + v^2\lambda_{hs} + 3v_s^2\lambda_s \end{pmatrix}$$

Comparison to $\mathbb{Z}_2$ Models

$$V_o = \frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \cancel{t_s} s + \cancel{a_{hs}} h^2 s + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{2}\lambda_{hs} h^2 s^2 + \frac{1}{4}\lambda_s s^4$$

$$\mathcal{M}^2 = \begin{pmatrix} \frac{\mathrm{d}^2 V_o}{\mathrm{d}h^2} & \frac{\mathrm{d}^2 V_o}{\mathrm{d}h\mathrm{d}s} \\ \frac{\mathrm{d}^2 V_o}{\mathrm{d}h\mathrm{d}s} & \frac{\mathrm{d}^2 V_o}{\mathrm{d}s^2} \end{pmatrix}\Bigg|_{\substack{h \to v \\ s \to v_S}} = \begin{pmatrix} 2v^2\lambda_h & 2\cancel{a_{hs}}v + 2vv_s\lambda_{hs} \\ 2\cancel{a_{hs}}v + 2vv_s\lambda_{hs} & \mu_s^2 + v^2\lambda_{hs} + 3v_s^2\lambda_s \end{pmatrix}$$

$\mathbb{Z}_2$ Case:
No SSB $\implies$ $v_s = 0, \qquad \theta = 0$

Comparison to $\mathbb{Z}_2$ Models

$$V_o = \frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \cancel{t_s} s + \cancel{a_{hs}} h^2 s + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{2}\lambda_{hs} h^2 s^2 + \frac{1}{4}\lambda_s s^4$$

$$\mathcal{M}^2 = \left.\begin{pmatrix} \frac{\mathrm{d}^2 V_o}{\mathrm{d}h^2} & \frac{\mathrm{d}^2 V_o}{\mathrm{d}h\mathrm{d}s} \\ \frac{\mathrm{d}^2 V_o}{\mathrm{d}h\mathrm{d}s} & \frac{\mathrm{d}^2 V_o}{\mathrm{d}s^2} \end{pmatrix}\right|_{\substack{h\to v \\ s\to v_S}} = \begin{pmatrix} 2v^2\lambda_h & 2\cancel{a_{hs}}v + 2vv_s\lambda_{hs} \\ 2\cancel{a_{hs}}v + 2vv_s\lambda_{hs} & \mu_s^2 + v^2\lambda_{hs} + 3v_s^2\lambda_s \end{pmatrix}$$

$\mathbb{Z}_2$ Case:

No SSB $\implies$ $v_s = 0, \qquad \theta = 0$

SSB $\implies$ $v_s \neq 0, \qquad \theta = 0 \quad \textit{iff} \quad \lambda_{hs} = 0$

Comparison to $\mathbb{Z}_2$ Models

$$V_o = \frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \cancel{t_s} s + \cancel{a_{hs}} h^2 s + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{2}\lambda_{hs} h^2 s^2 + \frac{1}{4}\lambda_s s^4$$

$$\mathcal{M}^2 = \begin{pmatrix} \frac{\mathrm{d}^2 V_o}{\mathrm{d}h^2} & \frac{\mathrm{d}^2 V_o}{\mathrm{d}h\mathrm{d}s} \\ \frac{\mathrm{d}^2 V_o}{\mathrm{d}h\mathrm{d}s} & \frac{\mathrm{d}^2 V_o}{\mathrm{d}s^2} \end{pmatrix}\Bigg|_{\substack{h\to v \\ s\to v_S}} = \begin{pmatrix} 2v^2\lambda_h & 2\cancel{a_{hs}} v + 2vv_s\lambda_{hs} \\ 2\cancel{a_{hs}} v + 2vv_s\lambda_{hs} & \mu_s^2 + v^2\lambda_{hs} + 3v_s^2\lambda_s \end{pmatrix}$$

$\mathbb{Z}_2$ Case:

No SSB $\implies$ $v_s = 0, \qquad \theta = 0$

SSB $\implies$ $v_s \neq 0, \qquad \theta = 0 \quad \textit{iff} \quad \lambda_{hs} = 0$

General Case:

$\theta = 0 \quad \textit{iff} \quad a_{hs} + v_s\lambda_{hs} = 0$