

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

Anthony Hooper

UNIVERSITY *of* NEBRASKA-LINCOLN

Particle Physics on the Plains:

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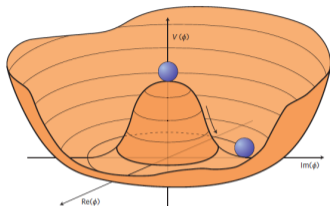


in collaboration with

Peisi Huang

Carlos Wagner

Motivation and higgs' measurements



$$V_{Higgs}^{SM} = \frac{1}{4} \lambda_h (\phi_h^\dagger \phi_h)^2 - \frac{1}{2} |\mu^2| (\phi_h^\dagger \phi_h)$$



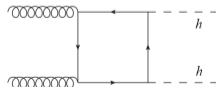
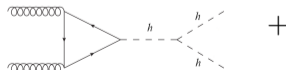
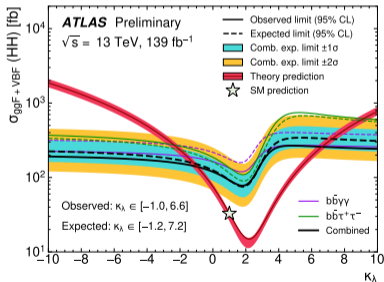
Vacuum expectation value (vev)



Higgs boson mass



Higgs self-coupling



¹ATL-PHYS-PROC-2022-044

Adding a real scalar singlet



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

New particles or interactions are needed!

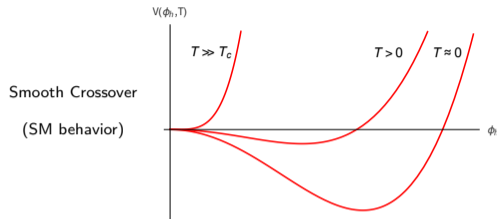
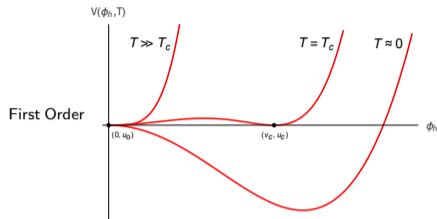
Add a field that only interacts directly with the higgs field and itself, *i.e.* a real scalar singlet

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

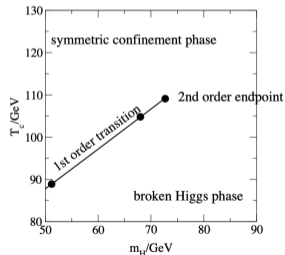
where $\phi_h = \begin{pmatrix} 0 \\ h + v \end{pmatrix}$ and $\phi_s = (s + v_s)$,
and v and v_s are the vevs of ϕ_h and ϕ_s ,
respectively.

$$V(h, s) = \frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + t_s s + a_{hs} h^2 s + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{2}\lambda_{hs} h^2 s^2 + \frac{1}{3} a_s s^3 + \frac{1}{4}\lambda_s s^4$$

Adding a first order phase transition



Supports electroweak baryogenesis
sets the energy scale to levels we can measure



²arXiv:0010275

Adding a temperature component

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

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

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

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

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

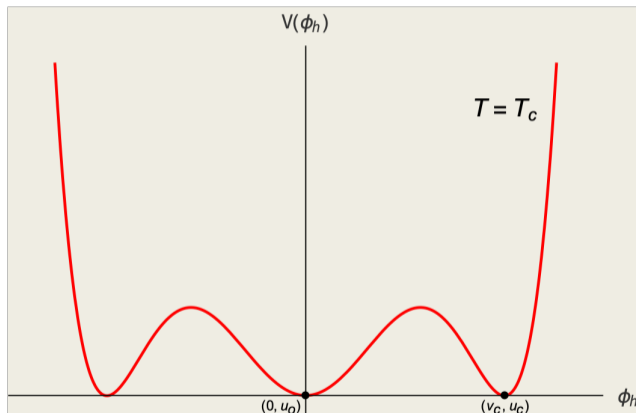
$$J_{\mp}(y) = \pm \int_0^{\infty} dx x^2 \log \left(1 \mp e^{-\sqrt{x^2+y^2}} \right)$$

with the upper and lower sign referring to bosons and fermions, respectively.

Thermally-corrected masses:

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

Imposing conditions at the critical temperature



degenerate requirement:

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

minimization requirement:

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

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

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

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

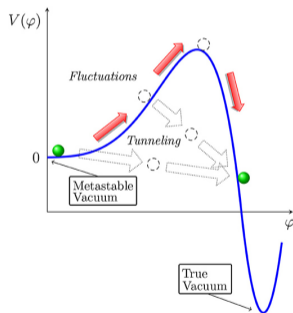
Conventional criteria: $v_c/T_c \gtrsim 1$

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

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

where B is the "bounce".

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



³arXiv:2002.00881

⁴arXiv:1809.06923

Outline

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 - Invisible Channel
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Mixing Angle

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

$$\mathcal{M}^2 = \left(\begin{array}{cc} \frac{d^2 V_o}{dh^2} & \frac{d^2 V_o}{dh ds} \\ \frac{d^2 V_o}{dh ds} & \frac{d^2 V_o}{ds^2} \end{array} \right) \Bigg|_{\substack{h \rightarrow v \\ s \rightarrow v_s}} = \left(\begin{array}{cc} 2v^2 \lambda_h & 2a_{hs} v + 2v v_s \lambda_{hs} \\ 2a_{hs} v + 2v v_s \lambda_{hs} & \mu_s^2 + v^2 \lambda_{hs} + 3v_s^2 \lambda_s \end{array} \right)$$

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

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

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

⁵arXiv:2207.00043

Reparametrizing

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

Minimum Equations: $\left. \frac{dV_o}{dh} \right|_{\substack{h \rightarrow v \\ s \rightarrow u}} = 0$ $\left. \frac{dV_o}{ds} \right|_{\substack{h \rightarrow v \\ s \rightarrow u}} = 0$

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

$$\mathcal{M}^2 = \left(\begin{array}{cc} \frac{d^2 V_o}{dh^2} & \frac{d^2 V_o}{dh ds} \\ \frac{d^2 V_o}{dh ds} & \frac{d^2 V_o}{ds^2} \end{array} \right) \bigg|_{\substack{h \rightarrow v \\ s \rightarrow v_s}} = \left(\begin{array}{cc} 2v^2 \lambda_h & 2a_{hs} v + 2vv_s \lambda_{hs} \\ 2a_{hs} v + 2vv_s \lambda_{hs} & \mu_s^2 + v^2 \lambda_{hs} + 3v_s^2 \lambda_s \end{array} \right)$$

$$\text{Diag}[\mathcal{M}^2] = \left(\begin{array}{cc} m_h^2 & 0 \\ 0 & m_s^2 \end{array} \right)$$

Similarity invariance of the trace:

Determinant properties of rotational matrices:

$$\begin{aligned} \text{tr}(\mathcal{M}^2) &= \text{tr}(\text{Diag}[\mathcal{M}^2]) \\ \det(\mathcal{M}^2) &= \det(\text{Diag}[\mathcal{M}^2]) \end{aligned}$$

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 ;

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

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

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

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

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

Ranges of the new parameters

Stability conditions : $\lambda_h, \lambda_s \in [0, 4\pi/3]$, $\lambda_{hs} \in [-\sqrt{\lambda_h \lambda_s}, 4\pi/3]$

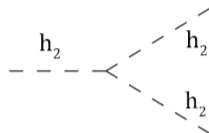
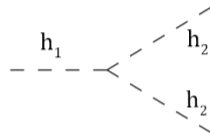
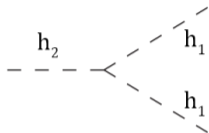
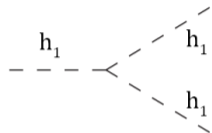
singlet mass : $m_s \leq m_h/2$ or $2m_h \leq m_s$

singlet vev : $|v_s| \lesssim 1 \text{ TeV}$

⁶arXiv:1701.08774

Trilinear Couplings

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



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

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

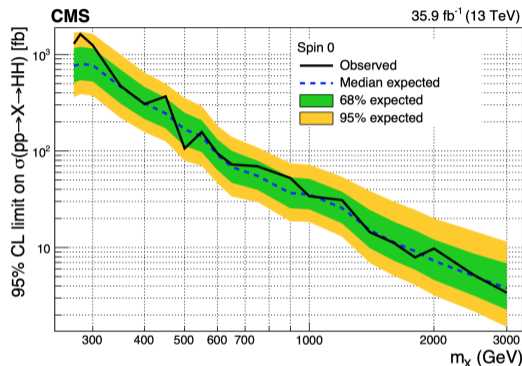
$$\text{where } \lambda_{111}^{SM} = 3m_h^2/v$$

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

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

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

Resonance Constraint



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

where

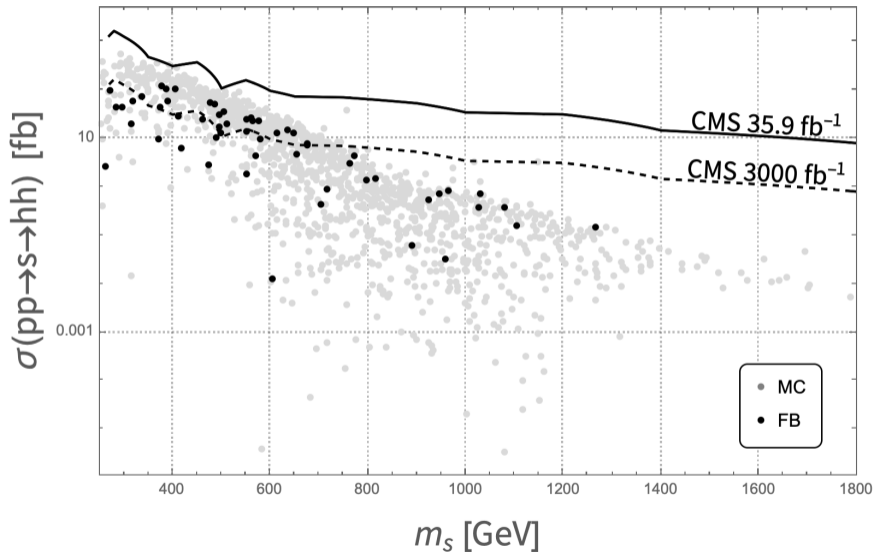
$$\Gamma(h_2 \rightarrow h_1 h_1) = \frac{\lambda_{211}^2}{32\pi m_s} \sqrt{1 - \frac{4m_h^2}{m_s^2}}$$

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

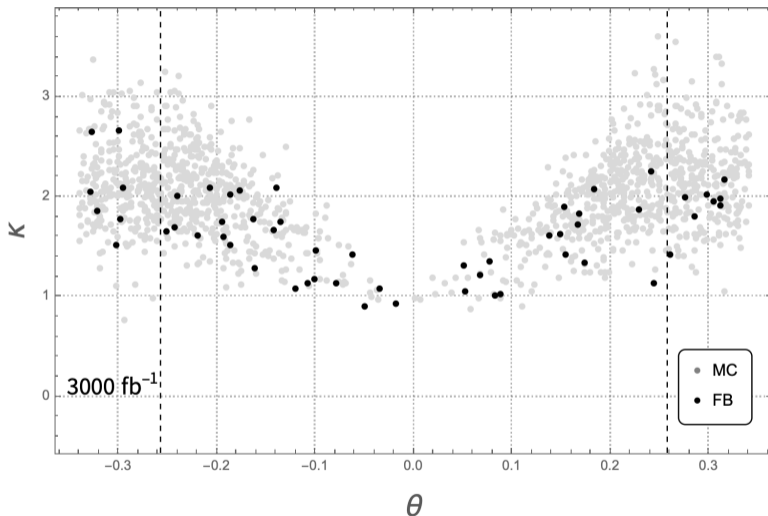
$$\begin{aligned} \sigma(pp \rightarrow h_2 \rightarrow h_1 h_1) &\approx \sigma(pp \rightarrow h_2) BR(h_2 \rightarrow h_1 h_1) \\ &= \sin^2 \theta \sigma_{SM}(pp \rightarrow h_2) BR(h_2 \rightarrow h_1 h_1) \end{aligned}$$

⁷arXiv:1811.09689

Resonance Decay Results

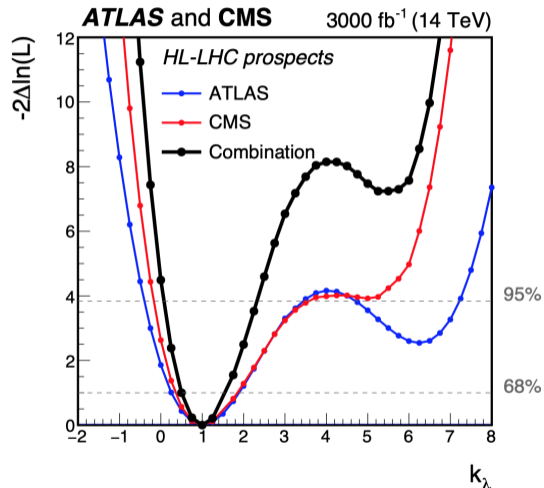


Higgs Trilinear Coupling



⁸CMS PAS FTR-18-011

Higgs Trilinear Coupling versus the Mixing Angle

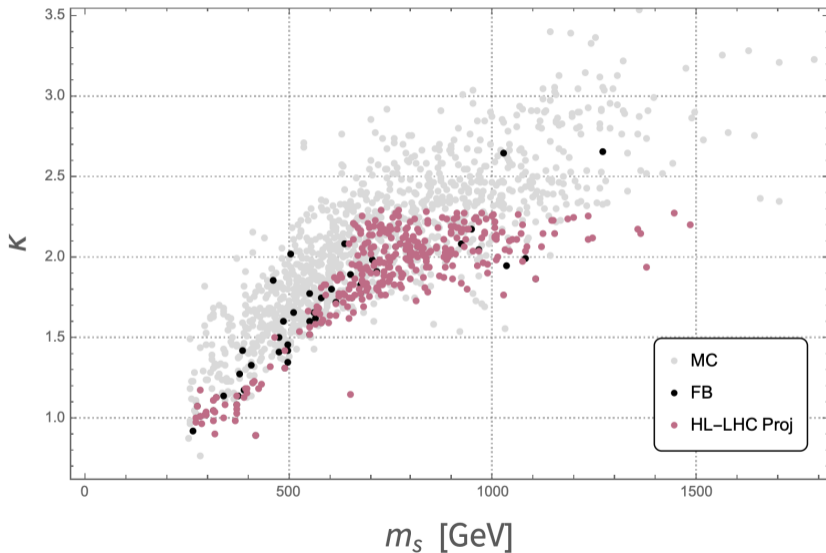


Combined:

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

⁹arXiv:1902.00134

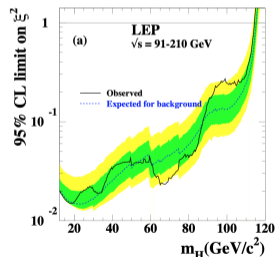
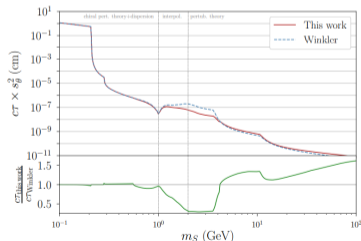
Higgs Trilinear Coupling versus the Singlet Mass



Types of Decays

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

- ⊙ $\theta = 0 \implies$ No Decays
- ⊙ $c\tau \gtrsim 0.1 \text{ mm} \implies |\theta| \lesssim 10^{-3.5} \implies$ Long-Lived Particles
- ⊙ $c\tau \lesssim 0.1 \text{ mm} \implies |\theta| \gtrsim 10^{-3.5} \implies$ Exotic Decays

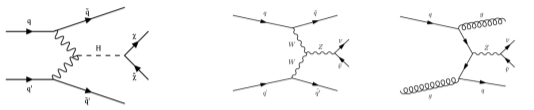


$$\xi^2 = s_\theta^2$$

¹⁰ arXiv:2012.07864

¹¹ arXiv:0306033

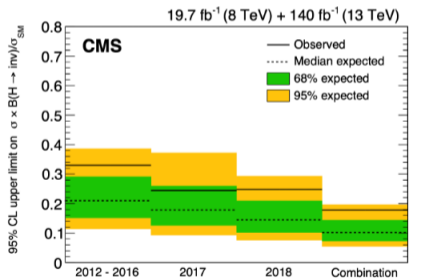
Experimental Constraints - Invisible Decays



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

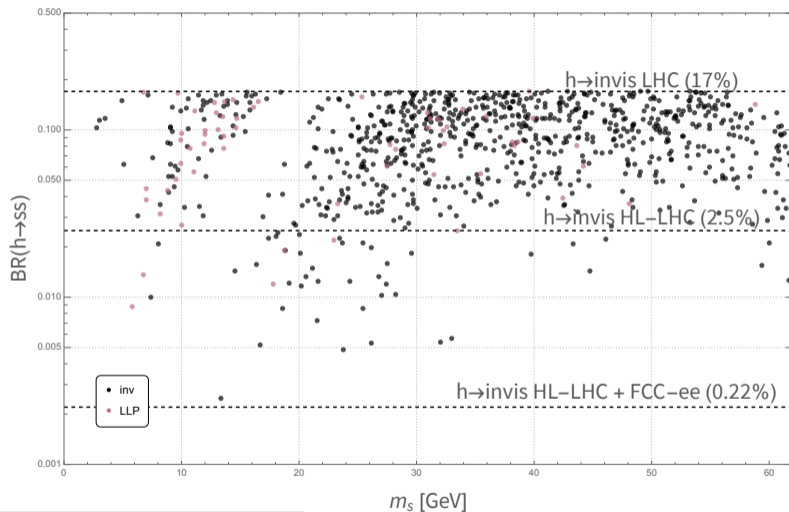
$$\Gamma(h \rightarrow ss) = \frac{\lambda_{hss}^2}{32\pi m_h} \sqrt{1 - \frac{4m_s^2}{m_h^2}}$$

$$BR(h \rightarrow ss) \leq 17\% \implies \lambda_{hss} \lesssim 5 \text{ GeV}$$



¹²arXiv:1509.00672

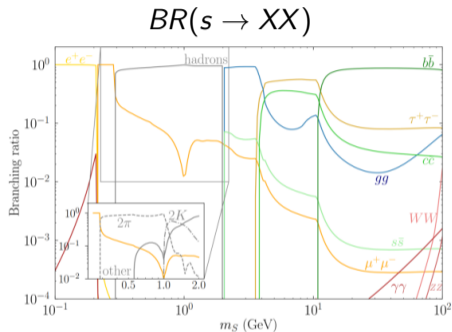
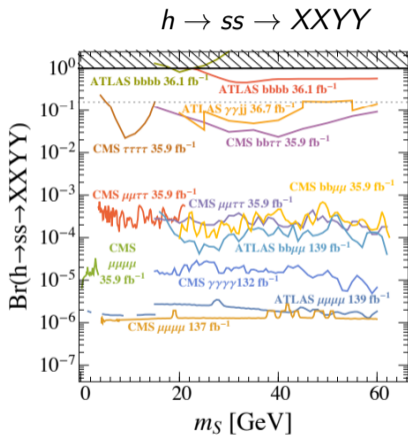
BR($h \rightarrow ss$) versus Singlet Mass



⁹arXiv:1902.00134

¹³arXiv:1905.03764

Exotic Decay Constraints



$$\implies BR(h \rightarrow ss)$$

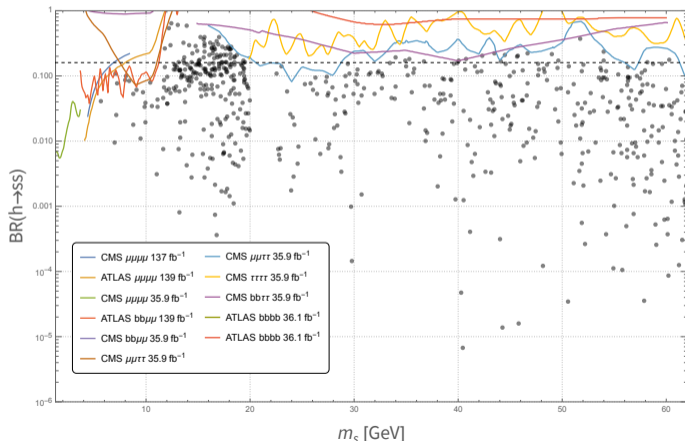
¹⁴arXiv:2203.08206

¹⁵arXiv:2012.07864

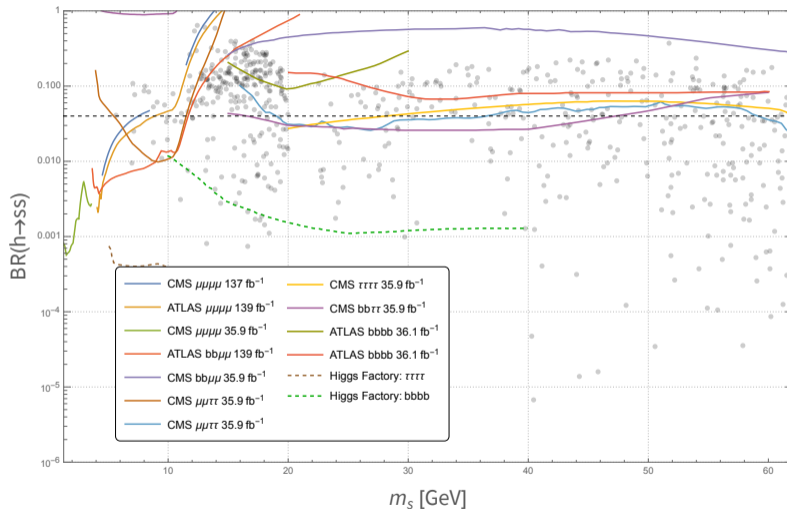
Exotic Decay Results

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

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

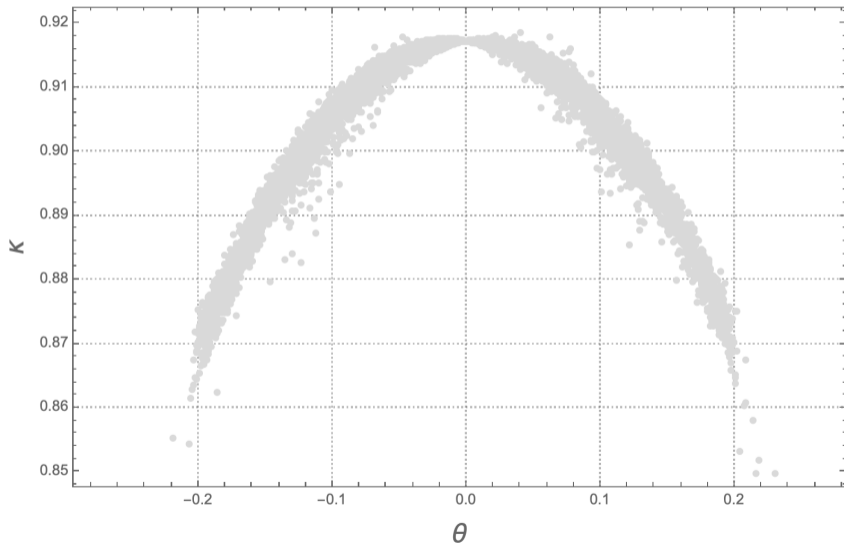


Exotic Decay Signature for Future Colliders

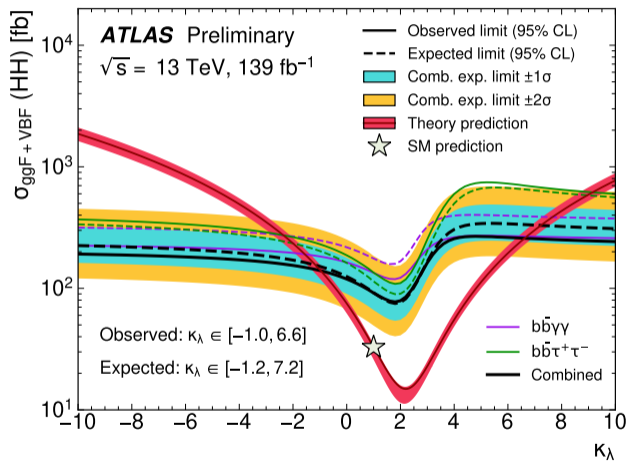


¹⁶arXiv:2203.08206

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

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

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

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

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

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

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

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

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

$$(V_1 + V_1^{c.t.})|_b = 0$$

$$(V_1 + V_1^{c.t.})|_b = 0$$

$$b = (v, v_s)$$

$$s = (0, u_s)$$

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

Mass Terms

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

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

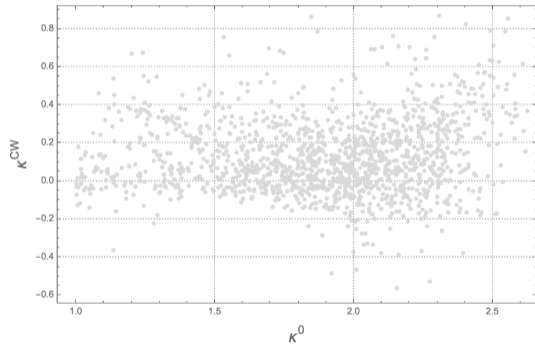
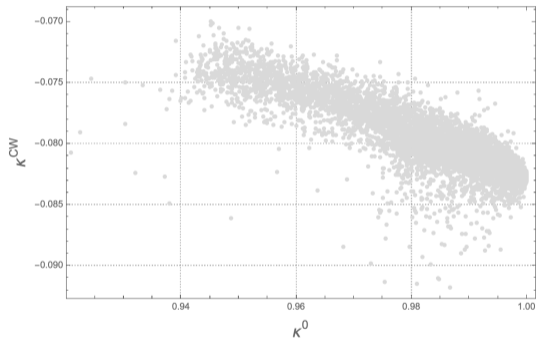
$$m_\chi^2(h, s) = \mu_h^2 + \lambda_h h^2 + \lambda_{hs} s^2 + 2a_{hs} s$$

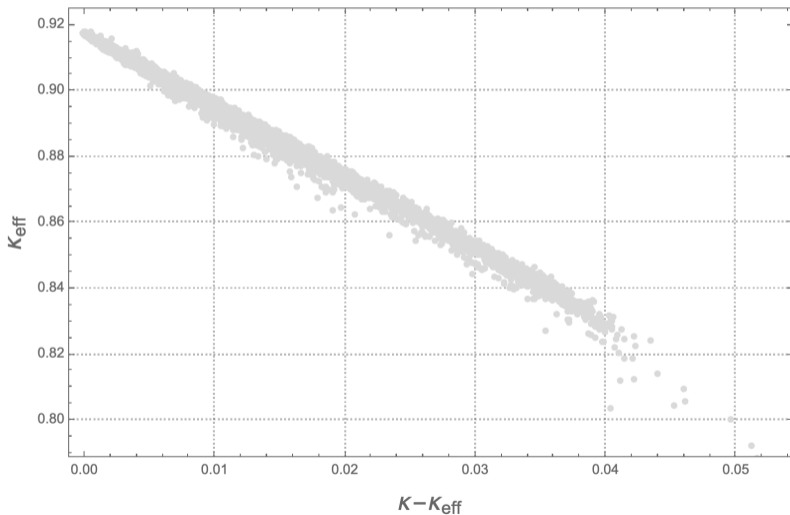
$$\mathcal{M}^2 \rightarrow \mathcal{M}^2 + \begin{pmatrix} \frac{1}{48}(9g^2 + 3g'^2 + 2(6y_t^2 + 12\lambda_h + 2\lambda_{hs}))T^2 & 0 \\ 0 & \frac{1}{12}(4\lambda_{hs} + 3\lambda_s)T^2 \end{pmatrix}$$

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

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

1-Loop Trilinear Corrections





Comparison to \mathbb{Z}_2 Models

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

$$\mathcal{M}^2 = \left(\begin{array}{cc} \frac{d^2 V_o}{dh^2} & \frac{d^2 V_o}{dhds} \\ \frac{d^2 V_o}{dhds} & \frac{d^2 V_o}{ds^2} \end{array} \right) \Bigg|_{\substack{h \rightarrow v \\ s \rightarrow v_s}} = \begin{pmatrix} 2v^2 \lambda_h & 2\cancel{a_{hs}}v + 2vv_s \lambda_{hs} \\ 2\cancel{a_{hs}}v + 2vv_s \lambda_{hs} & \mu_s^2 + v^2 \lambda_{hs} + 3v_s^2 \lambda_s \end{pmatrix}$$

\mathbb{Z}_2 Case:

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

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

General Case:

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