BSM Higgs Decoupling Scenarios In Light Of Unitarity Constraints

Kunal Kumar

Carleton University

PHENO 2014 SYMPOSIUM - MAY 6, 2012

(ongoing work with H. E. Logan)

Motivation

- If future measurements of the higgs couplings do not show significant deviations and no new particles are discovered we might be in the decoupling limit of a SM extension
- Unitarity Constraints provide a model independent link between higgs coupling deviations and the scale below which New Physics must appear
- In a specific model and it isn't necessary that the higgs couplings approach SM values as slowly as allowed by unitarity (faster decoupling implies NP shows up earlier)
- Studying scalar, fermion and gauge boson extensions can help us find features that are directly related to NP appearing much earlier vs closer to the bound due to Unitarity

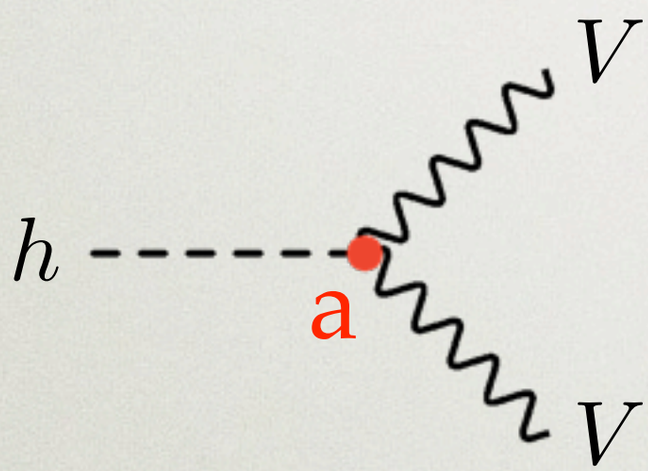
Motivation

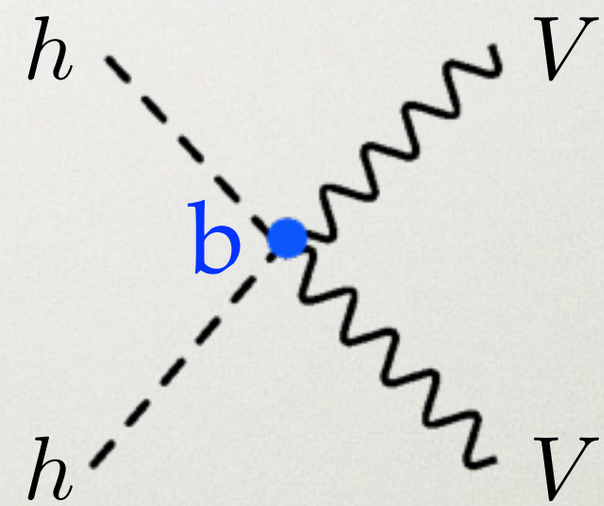
- In addition we can identify models in which a higgs coupling is always enhanced or suppressed or allows for both enhancement and suppression
- An understanding of these aspects of SM extensions should aid in distinguishing between potential NP models

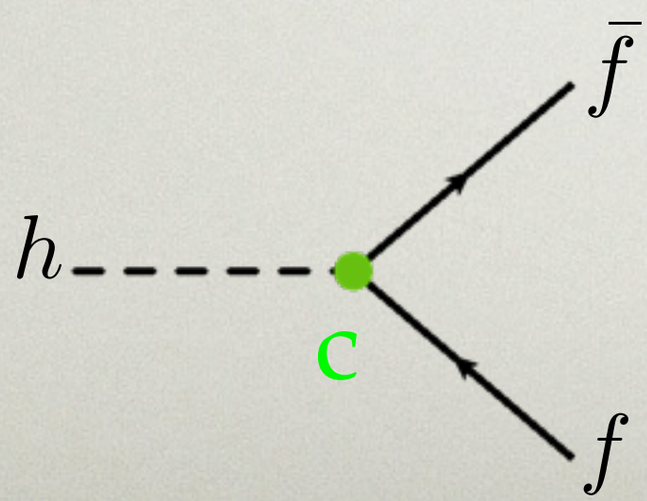
Parametrization of couplings

$$\mathcal{L} \supset \quad k_V M_V^2 V_\mu^* V^\mu \left[1 + a_V \frac{2h}{v_{\rm SM}} + b_V \frac{h^2}{v_{\rm SM}^2}\right] - m_f \bar{f} f \left[1 + c_f \frac{h}{v_{\rm SM}}\right]$$

$$- \frac{1}{2} M_h^2 h^2 \left[1 + d_3 \frac{h}{v_{\rm SM}} + d_4 \frac{h^2}{4 v_{\rm SM}^2}\right]$$







a, b, c : multiplicative factors by which the SM couplings are modified

Unitarity Limits

- $2 \longrightarrow 2$ scattering involving longitudinal V (W or Z), f, h

$$V_L V_L \to V_L V_L : |1 - a^2| < 8\pi \frac{v^2}{s}$$

$$V_L V_L \to hh : |b - a^2| < \frac{16\pi}{\sqrt{3}} \frac{v^2}{s}$$

$$f\bar{f} \to V_L V_L : |1 - ac| < \frac{16\pi}{3} \frac{v}{m_f} \frac{v}{\sqrt{s}}$$

- In the above $v = 246 \text{ GeV}$
- these inequalities determine the scale below which EFT is valid
- and the scale below which NP must appear

Scale below which NP enters

$$V_L V_L \to V_L V_L : |1 - a^2| < 8\pi \frac{v^2}{s}$$

$$V_L V_L \to hh : |b - a^2| < \frac{16\pi}{\sqrt{3}} \frac{v^2}{s}$$

$$f\bar{f} \to V_L V_L : |1 - ac| < \frac{16\pi}{3} \frac{v}{m_f} \frac{v}{\sqrt{s}}$$

$\sqrt{s}$ (TeV)	0.1	0.01
$\lvert 1 - a^2 \rvert$	4 TeV	12 TeV
$\lvert 1 - ac \rvert$	$59 \ \frac{m_t}{m_f}$ TeV	$590 \ \frac{m_t}{m_f}$ TeV
$\lvert b - a^2 \rvert$	4 TeV	13 TeV

- large deviations lower the NP scale upper bound
- *a, b* are more sensitive to the NP scale upper bound

Unitarity Limits

$$V_L V_L \to V_L V_L : |1 - a^2| < 8\pi \frac{v^2}{s}$$

$$V_L V_L \to hh : |b - a^2| < \frac{16\pi}{\sqrt{3}} \frac{v^2}{s}$$

$$f\bar{f} \to V_L V_L : |1 - ac| < \frac{16\pi}{3} \frac{v}{m_f} \frac{v}{\sqrt{s}}$$

Model Independent Power laws for deviations in couplings

$$hVV : |1 - a| \approx \mathcal{O}(v^2/s)$$

$$hhVV : |1 - b| \approx \mathcal{O}(v^2/s)$$

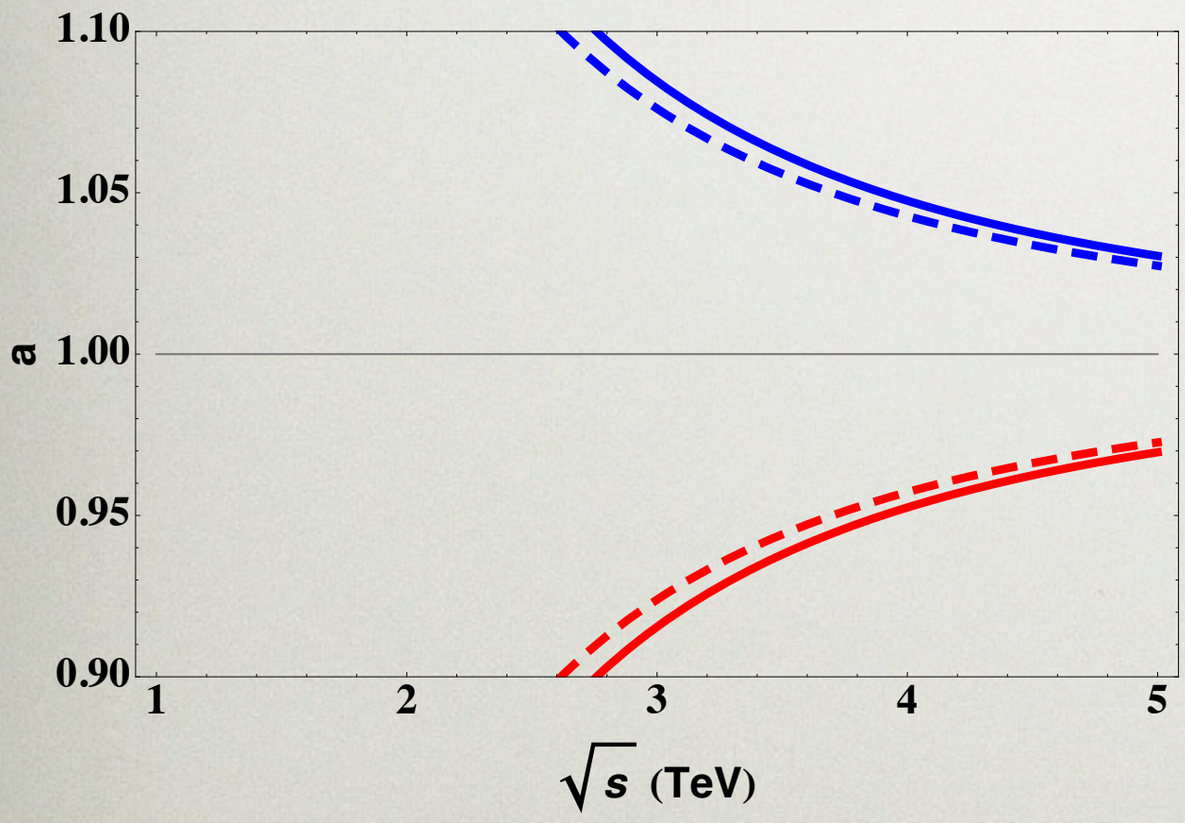
$$h\bar{f}f : |1 - c| \approx \mathcal{O}(v/\sqrt{s})$$

"Saturation" of Power Laws

- In models with a decoupling limit we can express coupling deviations in powers of $v/M_{\rm new}$

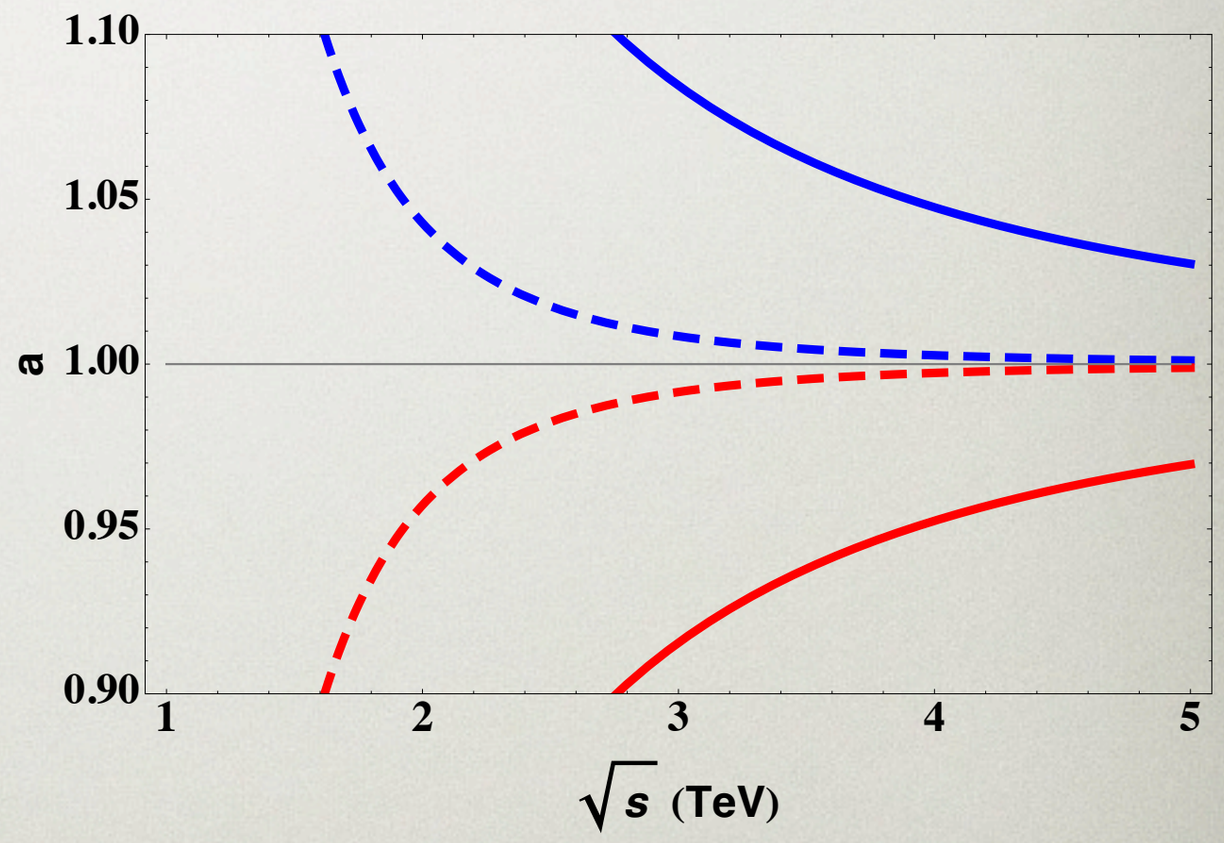
Model X

$$hVV : |1-a| \approx \mathcal{O}(v^2/M_{\rm new}^2)$$



Model Y

$$hVV : |1-a| \approx \mathcal{O}(v^4/M_{\rm new}^4)$$



Unitarity Limit $hVV : |1-a| \approx \mathcal{O}(v^2/s)$

Power Laws in Specific Models

- Scalar Sector Extensions
- Fermion Sector Extensions
- Gauge Boson Sector Extensions

Extended Scalar Sector - Type II 2HDM

CP-conserving potential with softly broken Z2

$$\mathcal{V}_{\text{gen}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right]$$
$$+ \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)$$
$$+ \left\{ \frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right)\right]\left(\Phi_1^\dagger \Phi_2\right) + \text{h.c.} \right\}.$$

J.F. Gunion, H.E. Haber [PRD 67, 075019]

$$a \approx 1 - \frac{\hat{\lambda}^2 v^4}{2\, m_A^4},$$
$$b = 1,$$
$$c \approx 1 + \frac{\hat{\lambda} v^2}{m_A^2} \times \begin{cases} \cot\beta & \text{for up type fermions} \\ -\tan\beta & \text{for down type fermions} \end{cases}$$

- *a, b* and *c* do not saturate unitarity limit power law

- Are there scalar sector extensions for which this is possible?

Extended Scalar Sector - SM + singlet

- Simplest extension of Higgs sector with interesting phenomenology when mixing is allowed or forbidden

e.g. :V. Barger et al. [arXiv:0706.4311]

$$V = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2 + \frac{1}{2}\mu^2 s^2 + \lambda_1 s^4 + \lambda_2 s^2\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right) + M_1 s\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right) + M_2 s^3$$

- s does not get a non-zero vev because $\mu^2 > 0$
- Discovered higgs is a mixture of SM doublet higgs field ϕ and a real singlet scalar

$$h = \phi\cos\theta - s\sin\theta$$
$$H = \phi\sin\theta + s\cos\theta$$

- Solving for mass eigenstates

$$M^2_{h,H} = \lambda v^2 + \frac{1}{2}\mu^2 \mp \sqrt{\left(\lambda v^2 - \frac{1}{2}\mu^2\right)^2 + M_1^2 v^2}$$

Extended Scalar Sector - SM + singlet

- Power laws for coupling modifications $$a = c = \cos\theta \approx 1 - \frac{M_1^2 v^2}{2\mu^4}$$ $$b = \cos^2\theta \approx 1 - \frac{M_1^2 v^2}{\mu^4}$$

- Decoupling limit where only μ is taken large does not saturate *a, b* or *c*
- Alternatively we could scale μ and M_1
- M_1 can scale at most linearly with μ $$|M_1|/\sqrt{\mu^2} \lesssim 5.78$$
- To see this note that $$\lambda = \frac{m_h^2}{v^2} + \frac{M_1^2}{2(\mu^2 - 2m_h^2)}$$
- And it has an upper bound from Unitarity and BFB constraints

$$\boxed{\lambda \in \left(0, \frac{16\pi}{3}\right)} \qquad \lambda_1 \in \left(0, \frac{4\pi}{3}\right) \qquad \lambda_2 \in \left(-\frac{8\pi}{3}, 8\pi\right)$$

Extended Scalar Sector - SM + singlet

$$V = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2 + \frac{1}{2}\mu^2 s^2 + \lambda_1 s^4 + \lambda_2 s^2\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right) + M_1 s\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right) + M_2 s^3$$

- When M1 is scaled linearly with μ : *a* and *b* saturate power law
- *a, b* and *c* are all suppressed compared to SM
- *c* does not saturate UL power law

$$a = c = \cos\theta \approx 1 - \frac{M_1^2 v^2}{2\mu^4}$$

$$b = \cos^2\theta \approx 1 - \frac{M_1^2 v^2}{\mu^4}$$

- Are there scalar sector extensions where *a* and *b* are not necessarily suppressed or where *c* saturates UL power law?

Extended Scalar Sector - Georgi-Machacek

H. Georgi, M. Machacek [NPB 262,463 (1985)]

- Proposed in 1985 as a possible scenario for EWSB
- As we will see this model can generate $a, b > 1$
- Contains the SM doublet along with a complex triplet (Y=2) and a real triplet (Y=0) arranged so as to preserve custodial SU(2)

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ -\phi^{+*} & \phi^{0} \end{pmatrix} \qquad X = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{+*} & \xi^{0} & \chi^{+} \\ \chi^{++*} & -\xi^{+*} & \chi^{0} \end{pmatrix}$$

$$\langle \Phi \rangle = \frac{v_\phi}{\sqrt{2}} 1_{2\times 2} \qquad \langle X \rangle = v_\chi 1_{3\times 3}$$

- The scalar vevs are constrained from the W boson mass

$$v^2 = v_\phi^2 + 8 v_\chi^2$$

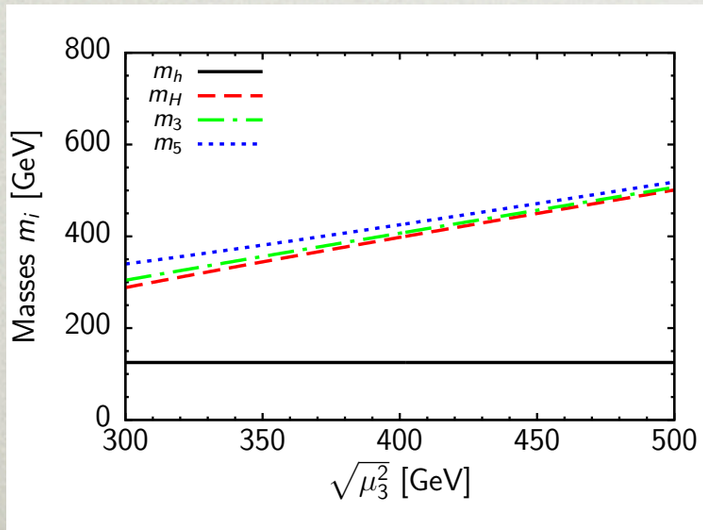
Extended Scalar Sector - Georgi-Machacek

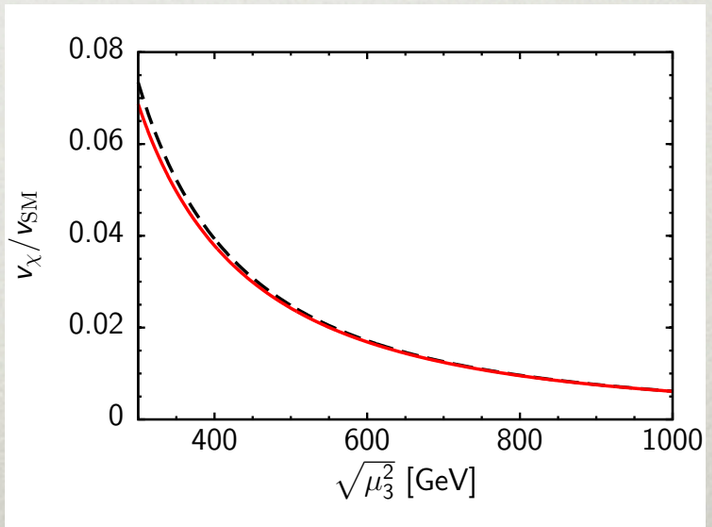
- Most general custodial SU(2) preserving potential

$$V(\Phi, X) = \frac{\mu_2^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{\mu_3^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 + \lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X)$$
$$+\lambda_3\mathrm{Tr}(X^\dagger X X^\dagger X) + \lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)\mathrm{Tr}(X^\dagger t^a X t^b)$$
$$-M_1\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)(UXU^\dagger)_{ab} - M_2\mathrm{Tr}(X^\dagger t^a X t^b)(UXU^\dagger)_{ab}.$$

Hartling, KK, Logan[arXiv: 1404.2640]; Aoki, Kanemura [PRD 77,095009]; Chiang, Yagyu [JHEP 1301, 026]

- Has a decoupling limit as μ_3 is made large
- All new scalar masses get large with μ_3 , v_ϕ approaches SM vev, v_χ tends to zero





Figs from: Hartling, KK, Logan[arXiv: 1404.2640]

Extended Scalar Sector - Georgi-Machacek

- *a,b* and *c* do not saturate power laws
- If M_1 is scaled linearly with μ_3

  a and *b* saturate power laws

$$a = \cos\theta \frac{v_\phi}{v} - \frac{8}{\sqrt{3}} \sin\theta \frac{v_\chi}{v} \approx 1 + \frac{3}{8} \frac{M_1^2 v^2}{\mu_3^4}$$

$$b = \cos^2\theta + \frac{8}{3} \sin^2\theta \approx \left(1 + \frac{5}{4} \frac{M_1^2 v^2}{\mu_3^4}\right)$$

$$c = \cos\theta \frac{v}{v_\phi} \approx 1 - \frac{1}{8} \frac{M_1^2 v^2}{\mu_3^4}$$

- Reason for M_1 increasing at most linearly is similar to SM + singlet case
- λ_1 increases with increase in M_1/μ_3 and is bounded from unitarity

$$\lambda_1 \approx \frac{m_h^2}{8v^2} + \frac{3}{32} \frac{M_1^2}{\mu_3^2} \qquad \lambda_1 \in \left(-\frac{1}{3}\pi, \frac{1}{3}\pi\right) \simeq (-1.05, 1.05)$$

- Therefore $|M_1|/\sqrt{\mu_3^2} \lesssim 3.3$

Extended Scalar Sector - Georgi-Machacek

- *a* and *b* saturate power laws
- *a* and *b* are **enhanced** compared to SM
- c does not saturate power laws

$$a = \cos\theta \frac{v_\phi}{v} - \frac{8}{\sqrt{3}} \sin\theta \frac{v_\chi}{v} \approx 1 + \frac{3}{8} \frac{M_1^2 v^2}{\mu_3^4}$$

$$b = \cos^2\theta + \frac{8}{3} \sin^2\theta \approx \left(1 + \frac{5}{4} \frac{M_1^2 v^2}{\mu_3^4}\right)$$

$$c = \cos\theta \frac{v}{v_\phi} \approx 1 - \frac{1}{8} \frac{M_1^2 v^2}{\mu_3^4}$$

- A feature that leads to saturation of *a* and *b* in scalar sector extensions is the presence of a dimensionful parameter (e.g. M_1) that is the coefficient of a term trilinear in scalar fields

$$V = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2}\right)^2 + \frac{1}{2}\mu^2 s^2 + \lambda_1 s^4 + \lambda_2 s^2 \left(\Phi^\dagger \Phi - \frac{v^2}{2}\right) + M_1 s \left(\Phi^\dagger \Phi - \frac{v^2}{2}\right) + M_2 s^3$$

- Do fermion extensions saturate the power law for *c* ?

Extended Fermion Sector

- Adding new vector-like top partners $\boxed{\chi_{L,R} \sim (3,1)_{2/3}}$

eg: KK, R. V.-Morales,F. Yu [PRD 86,113002]

- Mass terms for top and top partners

$$\mathcal{L} \supset -y_t \tilde{H} \bar{Q}_L t_R - y_L \tilde{H} \bar{Q}_L \chi_R - M \bar{\chi}_L \chi_R + \text{ h.c.}$$

- In the (t, χ) basis the (non-diagonal) mass and interaction matrices are

$$\hat{M} = \begin{pmatrix} m & \xi_L \\ 0 & M \end{pmatrix} \qquad \hat{N}_h = \begin{pmatrix} m & \xi_L \\ 0 & 0 \end{pmatrix}$$

where $\xi_L = \dfrac{y_L v}{\sqrt{2}} \qquad m = \dfrac{y_t v}{\sqrt{2}}$

Extended Fermion Sector

- After switching to basis of mass eigenstates $\mathbf{t} \equiv (t_1, t_2)$

$$\mathcal{L} \supset -\bar{\mathbf{t}} \left(\hat{M}_D + \frac{h}{v} \hat{V}_h \right) P_R \, \mathbf{t} + \text{ h.c.}$$

$$\hat{M}_D = \hat{L} \hat{M} \hat{R}^\dagger \qquad \hat{V}_h = \hat{L} \hat{N}_h \hat{R}^\dagger$$

- The 1,1 entry of $\hat{V}_h$ gives us the $ht\bar{t}$ coupling
- This model has a decoupling limit as *M* is made large
- Assuming $\frac{\xi_L}{M}, \frac{m}{M} \ll 1$

$$c = \frac{m}{m_t} \left(1 - \frac{3}{2} \frac{\xi_L^2}{M^2} \right) \approx 1 - \frac{y_L^2}{2} \frac{v^2}{M^2}$$

- while $a = b = 1$

- Doesn't saturate power law for *c* as well

Extended Gauge Boson Sector

- For completeness we consider the effect of an extended gauge boson sector

bi-doublet $\downarrow$ $\langle\Delta\rangle$ doublet under $SU(2)_1$ $\downarrow$ $\langle\phi\rangle$

$$SU(2)_1 \times SU(2)_2 \times U(1)_Y \longrightarrow SU(2)_W \times U(1)_Y \longrightarrow U(1)_{\rm em}$$

B. A. Dobrescu, A. D. Peterson [arXiv:1312.1999]

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}\left(v_\phi + \phi_r^0 + i\phi_i^0\right) \end{pmatrix} \qquad \Delta = \begin{pmatrix} \eta^0 & \chi^+ \\ \eta^- & \chi^0 \end{pmatrix} = \langle\Delta\rangle + \begin{pmatrix} \frac{1}{\sqrt{2}}\left(\eta_r^0 + i\eta_i^0\right) & \chi^+ \\ \eta^- & \frac{1}{\sqrt{2}}\left(\chi_r^0 + i\chi_i^0\right) \end{pmatrix}$$

$$\langle\Delta\rangle \downarrow \frac{v_\Delta}{2}\,\mathrm{diag}\,(1,1)$$

- Most general CP conserving potential with the Z_2 symmetry $\Delta \leftrightarrow \tilde{\Delta}$

$$V = m_\Phi^2 \Phi^\dagger\Phi + \frac{\lambda_\Phi}{2}\left(\Phi^\dagger\Phi\right)^2 + (m_\Delta^2 + \lambda_0 \Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \frac{\lambda_\Delta}{2}\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 - \frac{\tilde{\lambda}}{2}\left|\mathrm{Tr}(\Delta^\dagger\tilde{\Delta})\right|^2$$
$$- \left[\frac{\tilde{\lambda}'}{4}\left(\mathrm{Tr}(\Delta^\dagger\Delta)\right)^2 + \mathrm{h.c.}\right]$$

Extended Gauge Boson Sector

- Of the 12 fields in the bi-doublet and doublet : 6 are "eaten" by gauge bosons
- Of the remaining 6 there are 4 odd under Z_2 : $H^0, A^0, H^\pm$
- And 2 are even under Z_2 : h^0, H'^0

masses proportional to v_Δ

- Decoupling limit corresponds to making v_Δ large
- In terms of the original doublet and bi-doublet fields

125 GeV boson $\longrightarrow$ $h^0 = \phi_r^0 \cos\alpha_h - \frac{1}{\sqrt{2}}\left(\chi_r^0 + \eta_r^0\right) \sin\alpha_h$

$$H'^0 = \phi_r^0 \sin\alpha_h + \frac{1}{\sqrt{2}}\left(\chi_r^0 + \eta_r^0\right) \cos\alpha_h$$

- In general there is an effect on *a,b,c* from mixing between the two Z2 even scalars
- Since we want to isolate the effect of the additional bosons we choose this mixing angle α_h to be zero

Extended Gauge Boson Sector

Calculating a_W, a_Z, b_W, b_Z

- Generated by the scalar kinetic terms : $(D_\mu \Phi)^\dagger D_\mu \Phi + \mathrm{Tr}\left[(D_\mu \Delta)^\dagger D_\mu \Delta\right]$
- where $D_\mu = \partial_\mu - i g_Y Y B_\mu - i g_1 \vec{T}_1 \cdot \vec{W}_{1\mu} - i g_2 \vec{T}_2 \cdot \vec{W}_{2\mu}$
- Defining $t_{\theta_0} = g_1/g_2$

$a_W = 1 + \frac{v^2}{v_\Delta^2} s_{\theta_0}^2$	$a_Z = 1 + \frac{v^2}{v_\Delta^2} s_{\theta_0}^2 (1 + t_{\theta_W}^2 c_{\theta_0}^2 (1 - 2 t_{\theta_0} s_{\theta_0}^2))$
$b_W = 1$	$b_Z = 1 + \frac{v^2}{v_\Delta^2} t_{\theta_W}^2 s_{\theta_0}^2 c_{\theta_0}^2 (1 - 2 t_{\theta_0} s_{\theta_0}^2)$

- a_W can be enhanced like in GM model while couplings to Z may be enhanced or suppressed depending on t_{θ_0}
- The fermion coupling modification again does not saturate unitarity power law

$$c = \frac{v}{v_\phi} = 1 - \frac{v^2}{v_\Delta^2} s_{\theta_0}^2$$

- Always suppressed

Results

- Extended Scalar Sectors (SM+s, GM) can saturate *a* and *b* power laws when there is a trilinear term whose dimensionful coefficient can be made large
- Further discrimination is possible based on whether *a* and *b* can be enhanced in a model (e.g. Georgi-Machacek)
- None of the extensions (to our knowledge) saturate the power the law for *c*
- Gauge Boson Sector extensions that enhance *a* and *b* are possible as well