Playing With Color and The Higgs Portal: A Study of $gg \to h$

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Punch Line

- Lots of new physics can hide in $gg \to h$ while still appearing like a SM Higgs
- Allowing for the Higgs to mix with a new scalar opens up a whole new class of possible contributions
- Even if we see a cross section $\sim$ SM we can not assume it is a SM Higgs
- A host of new states with masses $\sim v_h$ could be ‘hiding’ in gluon fusion

Overview

- Why study $gg \to h$?
- The Higgs Portal and Higgs Mixing
- Production of s_1 and s_2
- Review of $gg \to h$ in SM
- Effects New Colored States and Higgs Mixing
- Ongoing/Future Work
- Conclusions

Why study $gg \to h$?

- Beginning to see hints of a resonance in the $\gamma\gamma$, WW and $b\bar{b}$ GeV decay modes
- Interpreted as SM Higgs these rates are above SM expectation but well within 1σ
- Crucial step in this interpretation is calculating the SM Higgs production cxn which at LHC is dominated by gluon fusion
- Relies on assumption that dominant contribution comes from top quark loop and in particular m_t only comes from EWSB
- But Yukawa couplings have yet to be measured and in addition fermion masses are only a byproduct of the Higgs mechanism
- Thus the gluon fusion mode does not directly probe the Higgs mechanism responsible for $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$

Why study $gg \to h$?

- Implies that LHC Higgs searches can be skewed by presence of new colored particles which contribute to $gg \to h$ loop
- Excess can also be interpreted as a scalar mass eigenstate which arises from mixing between SM Higgs and new scalar state
- Both effects can generically be part of extended color sectors, in particular if new colored states obtain mass from new scalar vev
- This new scalar can mix with the SM Higgs through the ‘Higgs portal’ once it obtains a vev
- We consider a broad class of new physics insertions, allowing for ‘direct’ alterations of $gg \to h$ loop, as well as new effects induced through ‘Higgs-mixing’, to be present simultaneously

The Higgs Portal and Higgs Mixing

- $H^\dagger H$ is the lowest mass dimension operator in the SM which is both gauge and Lorentz invariant
- Can combine with BSM operators of arbitrary mass dimension

$$\mathcal{L}_{hp} \supset \lambda_{hp} \mathcal{O}_{NP} H^\dagger H$$

- Will typically be suppressed by new physics scale unless $\mathcal{O}_{NP} \sim \Phi^\dagger \Phi$ (or a pure NP and SM scalar singlet)
- New colored states can enter $gg \to h$ loop directly through $\mathcal{L}_{hp}$
- Considering renormalizable interactions, only colored scalars may contribute through $\mathcal{L}_{hp}$
- We refer to this class of contributions as ‘direct’ NP effects
- Direct contributions may also arise from fermion mixing with SM top quark (and/or bottom), though not through $\mathcal{L}_{hp}$

The Higgs Portal and Higgs Mixing

- Can also have indirect ‘Higgs-mixing’ induced contributions
- This mixing can be generated through

$$\begin{aligned} \mathcal{L} &\supset \lambda_{hp} H^\dagger H \Phi^\dagger \Phi \\ &\sim \lambda_{hp} v_h v_\phi h \phi, \end{aligned}$$

- New colored states coupling to ϕ can now contribute to gluon fusion regardless if they couple to the SM Higgs (*h*)
- Can allow for a larger class of states, including new fermions and massive colored vectors to contribute at the renormalizable level
- There are now two physical scalars in the spectrum leading to interesting phenomenology which has been studied previously

R. Gupta, J. Wells: 1110.0824/ Schabinger, Wells: 0509209

The Higgs Portal and Higgs Mixing

- This mixing will lead to the scalar mass matrix

$$m^2_{\text{scalar}} = \begin{pmatrix} m_h^2(v_h(\lambda_{hp})) & -\lambda_{hp} v_h(\lambda_{hp}) v_\phi(\lambda_{hp}) \\ -\lambda_{hp} v_h(\lambda_{hp}) v_\phi(\lambda_{hp}) & m_\phi^2(v_\phi(\lambda_{hp})) \end{pmatrix}$$

- The coupled vevs depend explicitly on λ_{hp} and are found by solving the full scalar potential including Higgs portal interaction
- Can diagonalize the mass matrix to obtain the mass eigenstates

$$\begin{aligned} s_1 &= h\cos\theta - \phi\sin\theta \\ s_2 &= h\sin\theta + \phi\cos\theta \end{aligned}$$

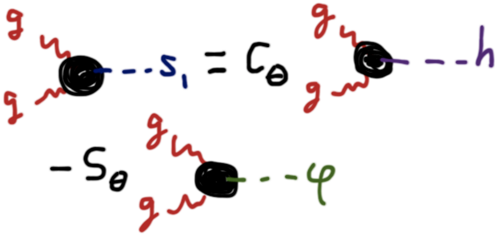
- We can define the Higgs-mixing angle as

$$\tan 2\theta = \frac{-2\lambda_{hp} v_h v_\phi}{m_\phi^2 - m_h^2}$$

- We can see that λ_{hp} controls sign of θ

Production of s_1 and s_2

- Now instead of h production we have s_1 and s_2 production,



- The amplitudes for $s_{1,2}$ production can be decomposed in terms of gauge eigenstate production as,

$$\begin{aligned}\mathcal{M}(gg \to s_1) \;=\; & c_\theta \left[\mathcal{M}(gg \xrightarrow[scalars]{} h) + \mathcal{M}(gg \xrightarrow[fermions]{} h) + \mathcal{M}(gg \xrightarrow[vectors]{} h)\right] \\ - \; & s_\theta \left[\mathcal{M}(gg \xrightarrow[scalars]{} \phi) + \mathcal{M}(gg \xrightarrow[fermions]{} \phi) + \mathcal{M}(gg \xrightarrow[vectors]{} \phi)\right]\end{aligned}$$

- Interference effects controlled by sign s_θ and hence λ_{hp}

Production of s_1 and s_2

- Scalars, fermions, or vectors can contribute to loop

$$\begin{aligned}\mathcal{M}(gg \xrightarrow[scalars]{} s_1) &= c_\theta \left[\sum_i \mathcal{M}(gg \xrightarrow[\eta_i]{} h) + \sum_j \mathcal{M}(gg \xrightarrow[\eta_j]{} h)\right] \\ &- s_\theta \left[\sum_j \mathcal{M}(gg \xrightarrow[\eta_j]{} \phi) + \sum_k \mathcal{M}(gg \xrightarrow[\eta_k]{} \phi)\right]\end{aligned}$$

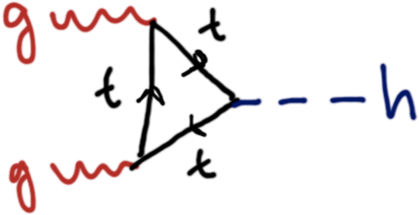
- New states may couple to h, ϕ or both
- We can write the relative rate for s_1 vs SM h production as,

$$\epsilon_{gg} \equiv \frac{|\mathcal{M}(gg \to s_1)|^2}{\left|\mathcal{M}(gg \xrightarrow[SM]{} h)\right|^2} = \frac{|c_\theta \mathcal{M}(gg \to h) - s_\theta \mathcal{M}(gg \to \phi)|^2}{\left|\mathcal{M}(gg \xrightarrow[SM]{} h)\right|^2} = c_\theta^2 \left|\mathcal{Z}_{ggh} - t_\theta \mathcal{Z}_{gg\phi}\right|^2$$

- Can have either suppression or enhancement relative to SM rate in contrast to 'standard' Higgs-mixing scenarios

Review of $gg \to h$ in SM

- As is well known occurs primarily through top quark loop



- The amplitude is contained by $SU(3)_c$ gauge invariance to have the form,

$$i\mathcal{M}^{ab}_{SM} = i\left(\frac{\alpha_s}{\pi v_h}\right) C(r)\delta^{ab}\epsilon_{1\mu}\epsilon_{2\nu}\left(p_1^\nu p_2^\mu - \frac{m_h^2}{2}g^{\mu\nu}\right) F_{SM}(\tau)$$

- Does not decouple in limit $\tau = m_h^2/4m_t^2 \to 0$
- Similarly for a sequential fourth generation which leads to an enhancement of production rate of ~ 9

Review of $gg \to h$: 'Decoupling'

- The decoupling feature of the SM amplitude is a consequence of EWSB
- Mass in loop propagator is the same as in *hff* coupling
- Any other particle which obtains mass only from EWSB will have this feature
- Typically a new state with a mass not from EWSB will decouple
- But new state may be associated with a BSM sector defined by some scale Λ_{BSM}
- For a renormalizable theory, we take this to be the VEV, v_ϕ of new scalar ϕ
- ϕ then endows new contributions to $gg \to s_{1,2}$ with 'non'-decoupling property
- If v_ϕ is $\sim v_h$ it is possible effects will be large enough to be observed at LHC

Colored Scalar w/ no Higgs Mixing

- We can first consider a colored scalar with no VEV
- Has been examined in various recent studies

Dobrescu et. al: 1112.2208, Batell et. al: 1112.5180, Bai et. al: 1112.1964

- Mass shifted after EWSB

$$\mathcal{L}_S = |D_\mu S|^2 - m_0^2 S^\dagger S - \kappa |S^\dagger S|^2 - \lambda_{hp} S^\dagger S H^\dagger H$$

$$m_S^2 \equiv m_0^2 + \lambda_{hp} v_h^2$$

- The amplitude is of the same form as SM

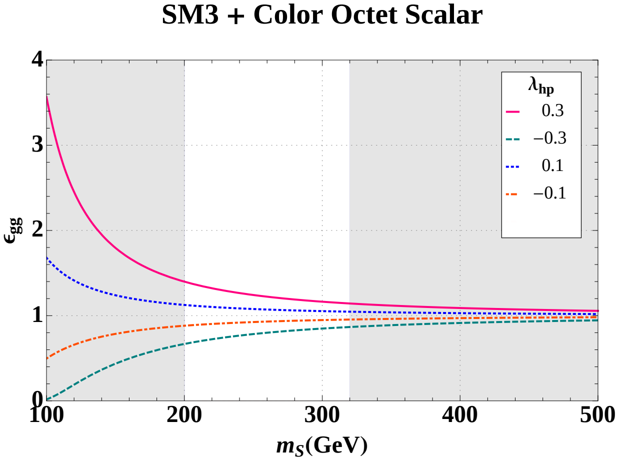
$$i\mathcal{M}_S^{ab} = i\left(\frac{\alpha_s}{\pi v_h}\right)\left(\frac{C(r_S)\lambda_{hp} v_h^2}{4m_S^2}\right)\delta^{ab}\epsilon_{1\mu}\epsilon_{2\nu}(p_1^\nu p_2^\mu - \frac{m_h^2}{2}g^{\mu\nu})F_S(\tau_S)$$

- Decouples as $m_S \to \infty$ unless $m_0^2 = 0$
- Can write relative production rate as

$$\epsilon_{gg} = \frac{\left|\sum_f \left(\frac{C(r_f)}{v_h} F_{SM}(\tau_f)\right) + \frac{C(r_s)\lambda_{hp} v_h}{4m_S^2} F_S(\tau_S)\right|^2}{\left|\sum_f \left(\frac{C(r_f)}{v_h} F_{SM}(\tau_f)\right)\right|^2}$$

Colored Scalar: Results(Preliminary)

- The relative rate for h production ($m_h = 125$ GeV)



- Sign λ_{hp} determines enhancement or suppression
- Effect decouples as m_S gets large
- ATLAS / CMS bounds from di-jet pairs allow for $\sim 200 - 320$ GeV

Colored Fermions

- Can have exotic fermions which mix with SM top quark

$$\mathcal{L} \supset -y_t H \overline{Q}_L t_R - y_R H \overline{\Psi}_L t_R - M \overline{\Psi}_L \Psi_R + h.c.$$

$$\mathcal{L} \supset -\bar{\mathbf{t}} \left(\hat{M}_D + \tfrac{h}{v_h} \hat{V}_h \right) P_R \; \mathbf{t} + h.c.$$

- Again the amplitude is of the same form

$$i\mathcal{M}_F^{ab} = i \left(\frac{\alpha_s}{\pi v_h} \right) \left(\frac{V_{ii}}{m_{F_i}} \right) C(r) \delta^{ab} \epsilon_{1\mu} \epsilon_{2\nu} \left(p_1^{\nu} p_2^{\mu} - \frac{m_h^2}{2} g^{\mu\nu} \right) F_F(\tau_{F_i})$$

- Can also add Higgs-mixing simultaneously

$$\epsilon_{gg} = \frac{c_\theta^2 \left| \sum\limits_{i=t_1,t_2} \left(\frac{C(r_{F_i})}{v_h} \left(\frac{V_{h\,ii}}{m_{F_i}} \right) F_F(\tau_{F_i}) \right) - t_\theta \sum\limits_{i=t_1,t_2} \left(\frac{C(r_{F_i})}{v_\phi} \left(\frac{V_{\phi\,ii}}{m_{F_i}} \right) F_F(\tau_{F_i}) \right) \right|^2}{\left| \sum\limits_f \left(\frac{C(r_f)}{v_h} F_{SM}(\tau_f) \right) \right|^2}$$

Colored Vectors: 'Coloron' Model

- Color gauge sector is extended to $SU(3)_1 \otimes SU(3)_2$ and spontaneously broken to $SU(3)_c$ by vev of bi-fundamental Φ

Hill, E. Simmons: 0203079 / Bai, Dobrescu: 1012.5814

- Need to solve full scalar potential including Higgs portal

$$\begin{aligned} V_{tot} &= V(\Phi) + V(H) + V_{hp} \\ &- m_\Phi^2 \ \mathrm{Tr}(\Phi^\dagger\Phi) - \mu_\Phi(\det\Phi + h.c.) + \tfrac{\lambda_\Phi}{2}\left[\mathrm{Tr}(\Phi\Phi^\dagger)\right]^2 + \tfrac{\kappa_\Phi}{2}\ \mathrm{Tr}(\Phi\Phi^\dagger\Phi\Phi^\dagger) \\ &- m_H^2|H|^2 + \lambda_H|H|^4 \\ &- \lambda_{hp}|H|^2\ \mathrm{Tr}(\Phi^\dagger\Phi) \end{aligned}$$

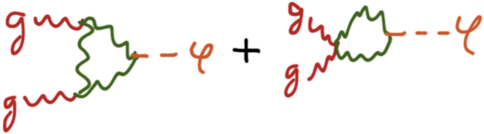
$$\langle\Phi\rangle = \frac{v_\phi}{\sqrt{6}}\mathbb{I}_3 = \frac{\mu_\Phi + \sqrt{\mu_\Phi^2 + \left(2(3\lambda_\Phi+\kappa_\Phi) - \frac{3\lambda_{hp}^2}{\lambda_H}\right)\left(2m_\Phi^2 + \frac{\lambda_{hp}m_H^2}{\lambda_H}\right)}}{\left(2(3\lambda_\Phi+\kappa_\Phi) - \frac{3\lambda_{hp}^2}{\lambda_H}\right)}\mathbb{I}_3$$

$$\langle H\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_h \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \sqrt{\frac{m_H^2}{\lambda_H} + \frac{\lambda_{hp}v_\phi}{2\lambda_H}} \end{pmatrix}$$

- We see that the vevs are coupled through λ_{hp}

Colored Vectors: ‘Coloron’ Model

- Calculation of colored vector contribution similar to *h* $\to \gamma\gamma$ through a *W* loop



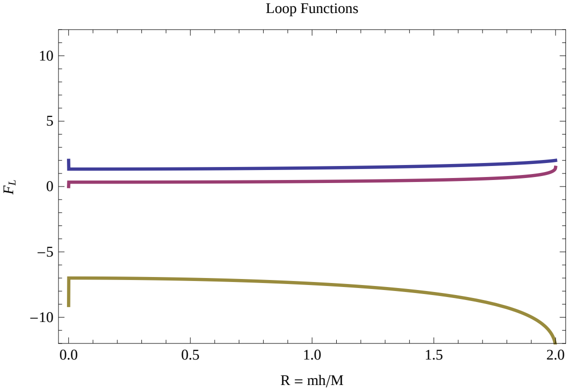
- We compute the amplitude in both the unitary and Feynman gange

$$i\mathcal{M}_V^{ab} = i\left(\frac{\alpha_s}{\pi v_\phi}\right)\left(\frac{C(r)}{4}\right)\delta^{ab}\epsilon_{1\mu}\epsilon_{2\gamma}\left(p_1^\gamma p_2^\mu - \frac{m_{s_1}^2}{2}g^{\mu\gamma}\right)F_{G'}(\tau_{G'})$$

- This amplitude does not decouple when $m_{G'} \to \infty$ or $m_{G'} \to 0$
- Once EWSB occurs and ϕ and *h* mix, this ‘non’-decoupling will transfer to s_1 and s_2 production

Colored Vectors: ‘Coloron’ Model

- A colored vector can have much larger effects than the fermion and scalar cases due to magnitude of ‘loop function’



- Furthermore, for color octet there is an additional factor of 3 coming from Casimir compared to 1/2 for SM contribution
- So vector contribution is naively $\sim$ 30 times the SM contribution
- Suppression from Higgs mixing can make this $\sim$ 1

Colored Vectors: ‘Coloron’ Model

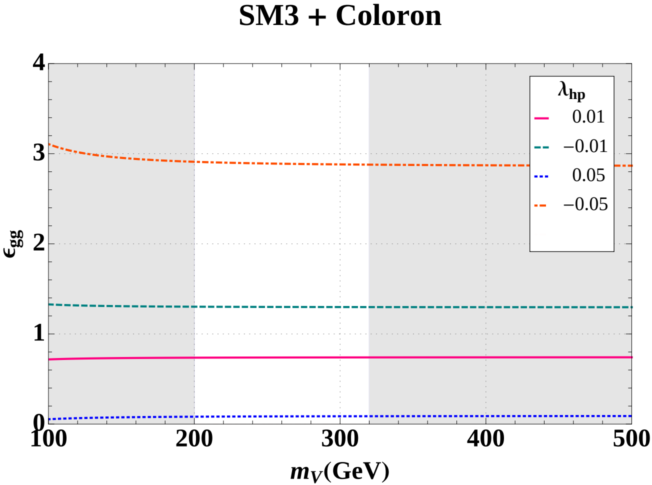
- The Coloron model also generically includes a physical scalar G_H coming from the $SU(3)_c$ octet component of Φ
- We consider the G' and G_H contributions in turn as well as their simultaneous effects
- The relative rate including both contributions can be written as

$$\epsilon_{gg} = \frac{c_\theta^2 \left| \sum_f \left(\frac{C(r_f)}{v_h} F_{SM}(\tau_f) \right) - t_\theta \left(\frac{C(r_{G'})}{4v_\phi} F_{G'}(\tau_{G'}) + \frac{C(r_{G_H})}{4v_\phi} \left(\frac{\frac{2}{3} m^2_{\phi_I} + m^2_{\phi_R}}{m^2_{G_H}} \right) F_{G_H}(\tau_{G_H}) \right) \right|^2}{\left| \sum_f \left(\frac{C(r_f)}{v_h} F_{SM}(\tau_f) \right) \right|^2}$$

- In the Coloron model, one must also ensure scalar potential is still stable for a given point in parameter space

Coloron Model: Results(Preliminary)

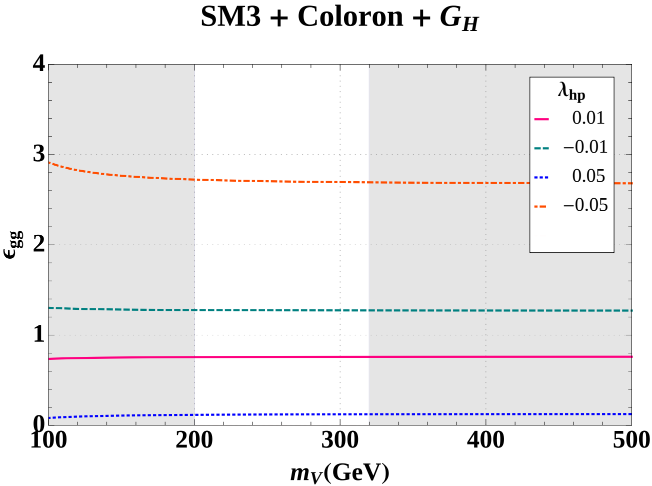
- The relative rate for s_1 production ($m_{s_1} = 125$ GeV, $v_\phi = 325$ GeV)



- Smaller λ_{hp} required as well as opposite sign compared to scalar
- Does not decouple as vector mass taken large

Coloron Model: Results(Preliminary)

- $m_{s_1} = 125$ GeV, $v_\phi = 325$ GeV, $m_{G_H} = 200$ GeV



- Contribution dominated by G' loop which interferes destructively with G_H loop (due to sign of loop function)

Conclusion/Ongoing Work

- There can be an interplay between Higgs mixing and effects of new colored states which conspire to give $\sim$ SM production cxn.
- Currently examining effects on s_2 production
- Exotic fermion case and extending analysis to higher masses
- Also examining effects on decays as well
- We examine general new physics effects on Higgs production
- Many new effects could be hiding in gluon fusion
- A scalar with $\sim$ SM cxn. does not guarantee SM Higgs
- We need to exhaust all possibilities before proclaiming a SM Higgs

Chicago, May 6

- Oh and also, don’t travel from Chicago!