2>3 VBS and Higg Self-coupling Measurements

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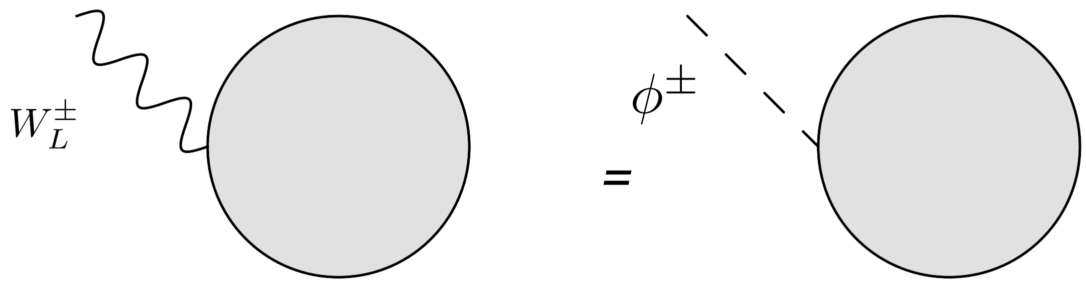
New approaches to measure Higgs self-couplings?

1. Higgs field in SM: Higgs boson and would-be Goldstone bosons form a SU(2) doublet:

$$\Phi^{\pm} = \begin{pmatrix} \phi^{\pm} \\ \frac{1}{\sqrt{2}}(h + i\phi^0) \end{pmatrix}$$

2. Goldstone equivalence theorem



3. 2 >3 VBS: $V_L V_L \to V_L V_L h$ and $V_L V_L \to hhh$

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- SMEFT:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \ldots$$

$$\mathcal{L}_{\rm dim-6} = \frac{1}{\Lambda^2}\left(-c_6(\Phi^\dagger\Phi)^3 + c_{\Phi_1}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + c_{\Phi_2}(\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)\right.$$
$$+ c_{\Phi^2W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + c_{\Phi^2B^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + c_{\Phi^2WB}\Phi^\dagger\tau^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$\left.+ c_{W^3}\epsilon^{abc}W^{a\nu}_\mu W^{b\rho}_\nu W^{b\mu}_\rho\right)$$

- Focus: c_6 and c_{Φ_1}

- Both lepton colliders and hadron colliders in different energies

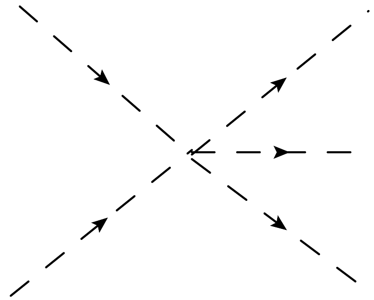
2 Amplitudes

$$M(W_L W_L \to W_L W_L h) \simeq M(\phi\phi \to \phi\phi h)$$

(Focus on c6)

- 1. No propagator

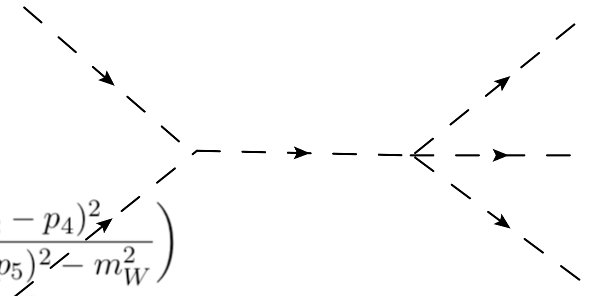
$(\Phi^\dagger\Phi)^3$ operator:



$$\mathcal{A}_0^{\phi^+\phi^-\to\phi^+\phi^- h} = \lambda_{(\phi^+\phi^-)^2 h} = -12 C_6 v i$$

Since C_6 is suppressed by $\frac{1}{\Lambda^2}$, $\mathcal{A}_0 \sim \frac{v}{\Lambda^2}$.

- 2. One propagator.



$$\begin{aligned}\mathcal{A}_1^{BSM} \simeq & -i2C_{\Phi_1}\frac{m_h^2}{v}\left(\frac{(p_1+p_2)^2}{(p_4+p_5)^2-m_W^2}+\frac{(p_1+p_2)^2}{(p_3+p_5)^2-m_W^2}+\frac{(p_1-p_3)^2}{(p_2-p_5)^2-m_W^2}+\frac{(p_2-p_4)^2}{(p_1-p_5)^2-m_W^2}\right)\\ & -iC_{\Phi_1}\frac{m_h^2}{v}\left(\frac{(p_1+p_2)^2}{(p_3+p_4)^2-m_h^2}+\frac{(p_3+p_4)^2}{(p_1+p_2)^2-m_h^2}+\frac{(p_1-p_3)^2}{(p_2-p_4)^2-m_h^2}+\frac{(p_2-p_4)^2}{(p_1-p_3)^2-m_h^2}\right) \quad (8)\end{aligned}$$

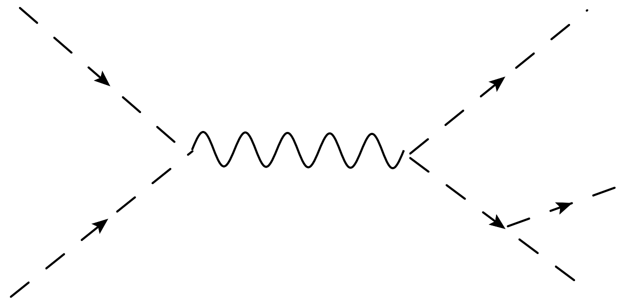
So we have $\mathcal{A}_1^{BSM} \sim \frac{v}{\Lambda^2}$.

2 Amplitudes

Feynman diagrams

- 3. Two propagators.

$$A_2 \simeq A_2^a + A_2^b + A_2^c \sim \frac{v}{\Lambda^2} + \frac{v}{E^2}$$



- Summary:

$$\mathcal{A}(W_L^+ W_L^- \to W_L^+ W_L^- h) = \mathcal{A}^{\rm SM} + \mathcal{A}^{\rm BSM}$$

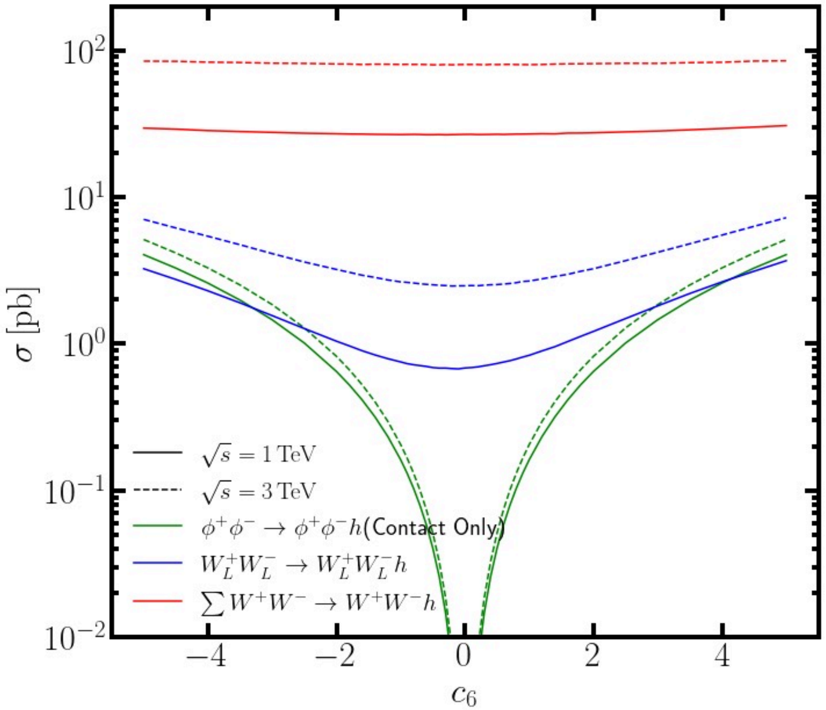
$$\mathcal{A}^{\rm SM} \simeq \frac{v}{E^2} \qquad \mathcal{A}^{\rm BSM} \simeq \frac{v}{\Lambda^2}$$

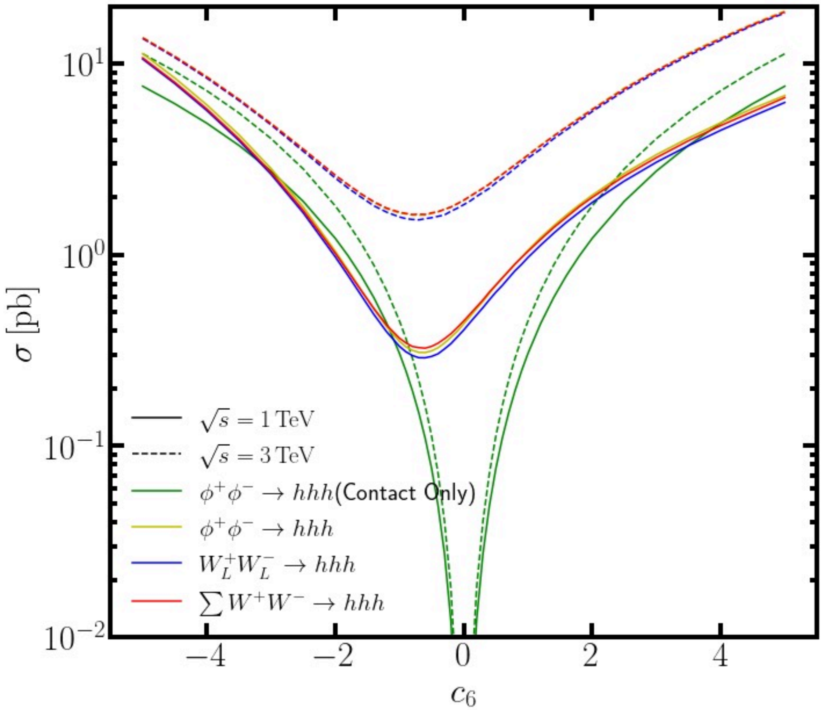
$$\frac{\mathcal{A}^{BSM}}{\mathcal{A}^{SM}} \sim \frac{E^2}{\Lambda^2}$$

3 Cross section

Cross section: $V_L V_L \to V_L V_L h$ & $V_L V_L \to hhh$

- Plots with c6



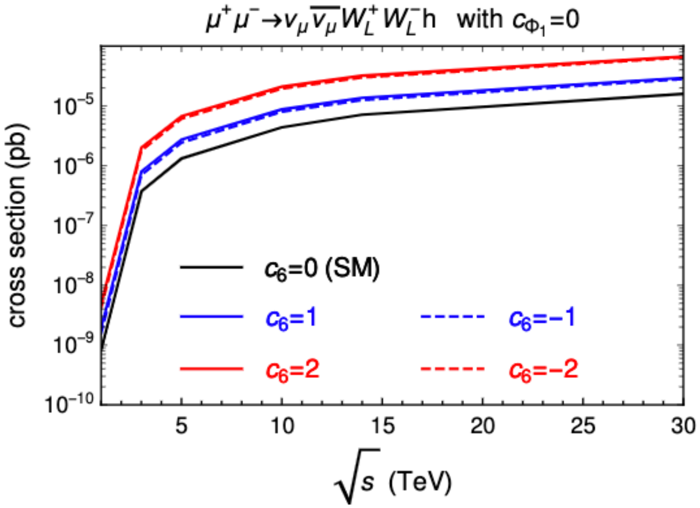


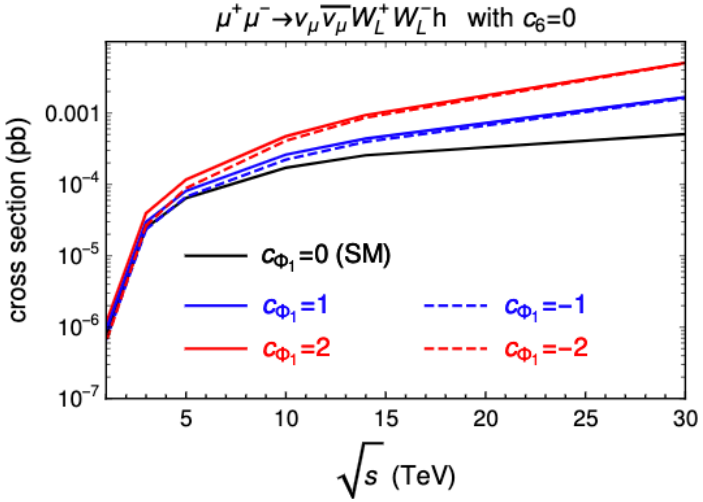
4. Full Simulation in colliders

- Problems:
- 1. transverse pols. dominate cross section
- 2. Enhancement of cross section of $V_L V_L \to V_L V_L h$ is partly cancelled by log enhancement of SM cross section.

- Solutions:
- 1.Select longitudinal pols only for final states
- 2. Make PT cuts for final vector bosons and HIggs

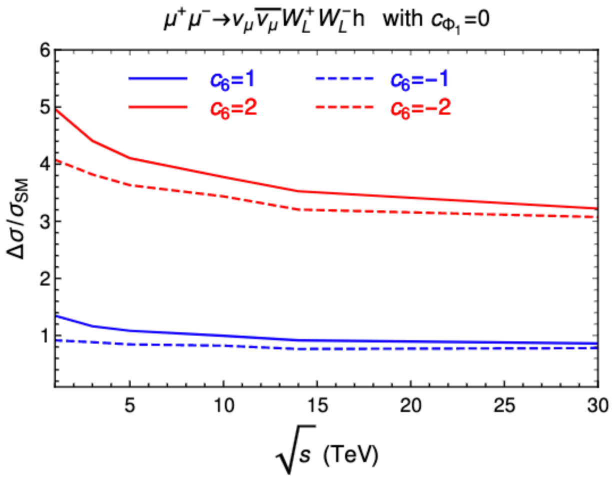
Cross sections vs energy: $l^+l^- \to \bar{\nu}\nu W_L^+ W_L^- h$

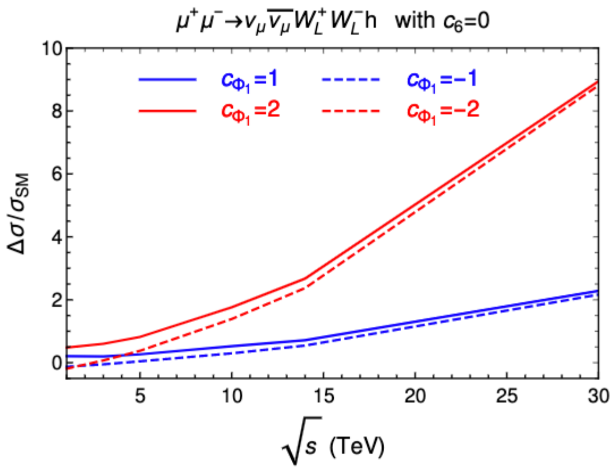




Small SM cross sections until 5 TeV

Only muon colliders satisfy

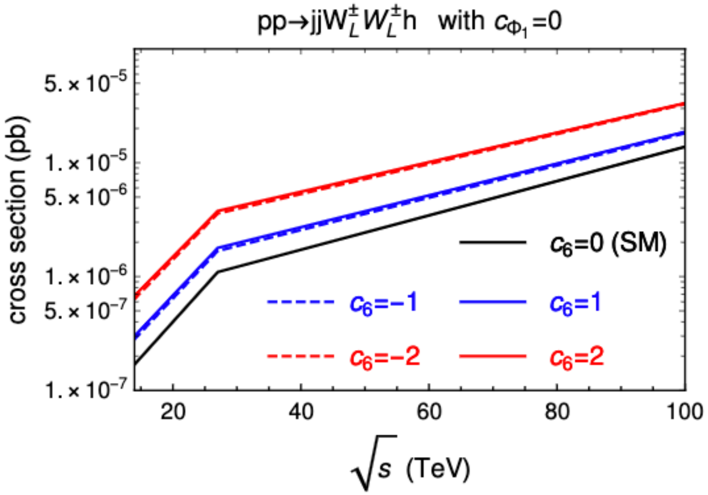


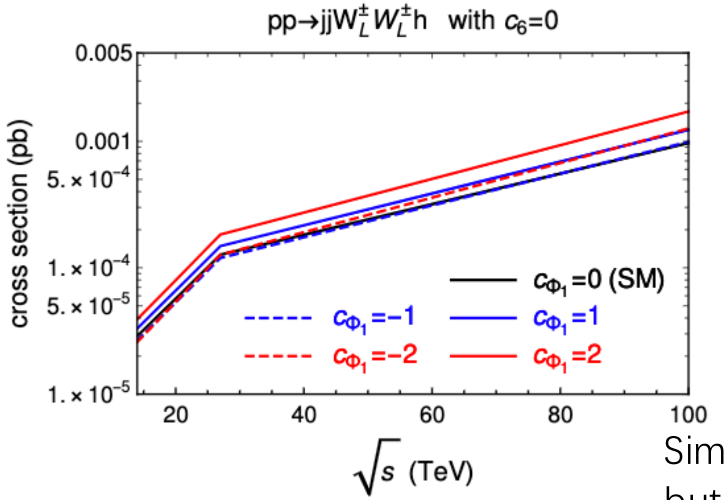


Enhancment:

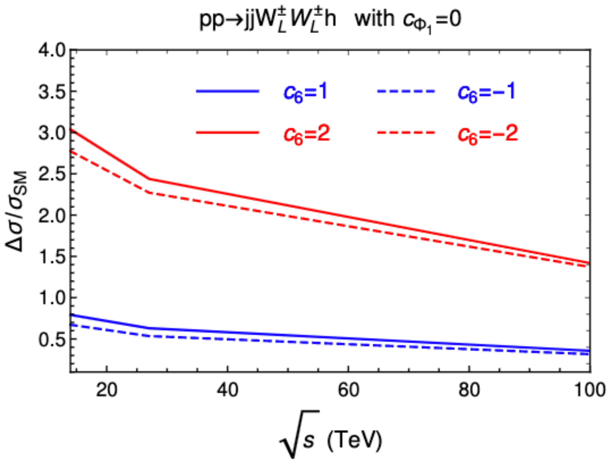
1. Low energy: larger for c6 than cPhi1
2. High energy: larger for

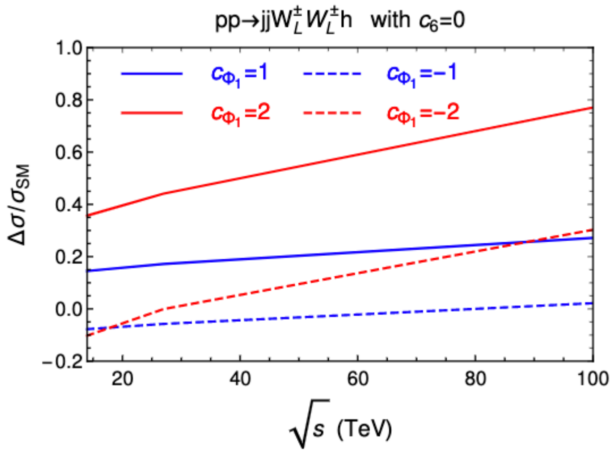
$$pp \to jjW_L^+W_L^-h$$



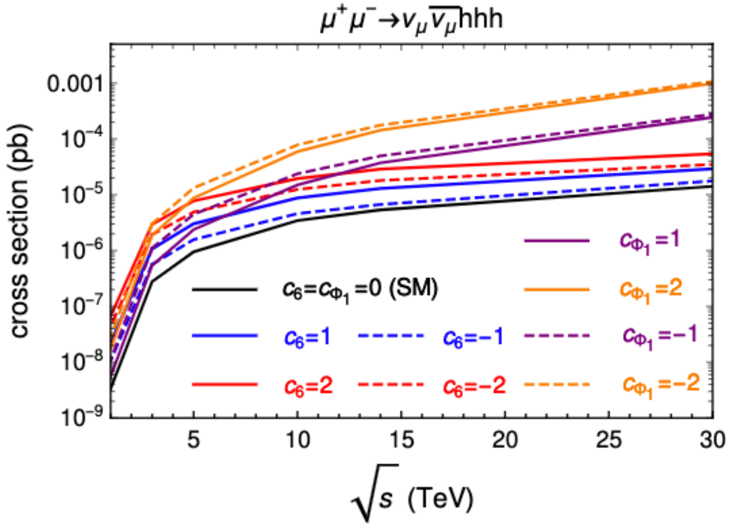


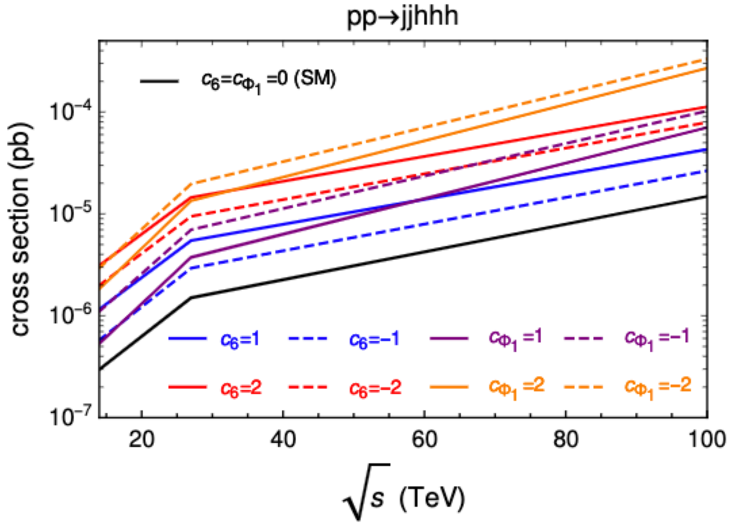
Similar to $l^+l^- \to \bar{\nu}\nu W_L^+W_L^-h$
but smaller in cross sections and
enhancement



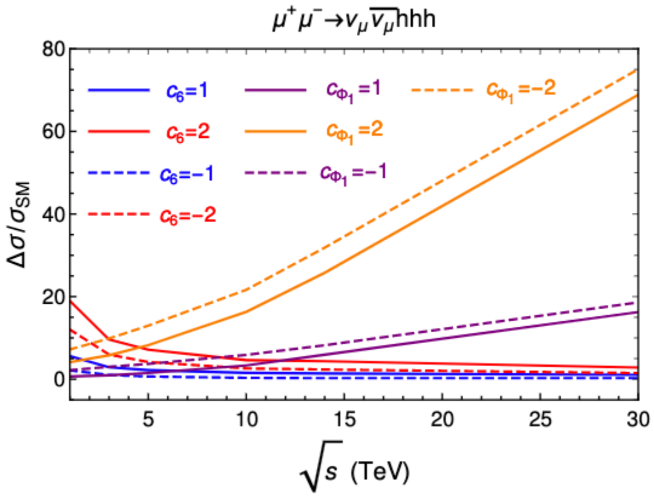


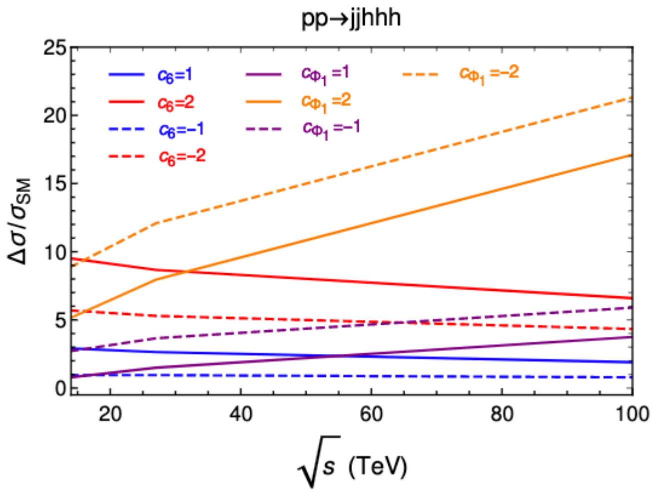
$l^+l^- \to \bar{\nu}\nu hhh$ and $pp \to jjhhh$





Cross sections smaller than wwh.





Enhancement larger than wwh.

Conclusions

- 2>3 VBS is an excellent channel to measure Higgs self-coupling, but only in high energy.

- 1.In high energy, Amplitudes of $V_LV_L \to V_LV_Lh$ or hhh: $\frac{\mathcal{A}^{BSM}}{\mathcal{A}^{SM}} \sim \frac{E^2}{\Lambda^2}$
- 2.Origin: 5-point scalar vertices from c6 operator.
- 3.Behavior of cross section follows for $pp \to jjhhh$/ $l^+l^- \to v_l\bar{v}_L hhh$
- 4.Cuts are needed for $pp \to jjW_L^{\pm}W_L^{\pm}h$ / $l^+l^- \to v_l\bar{v}_l W_L^+W_L^-h$
- 5. More analysis to come.