Measuring Higgs Boson Self-couplings with 2→3 VBS Processes

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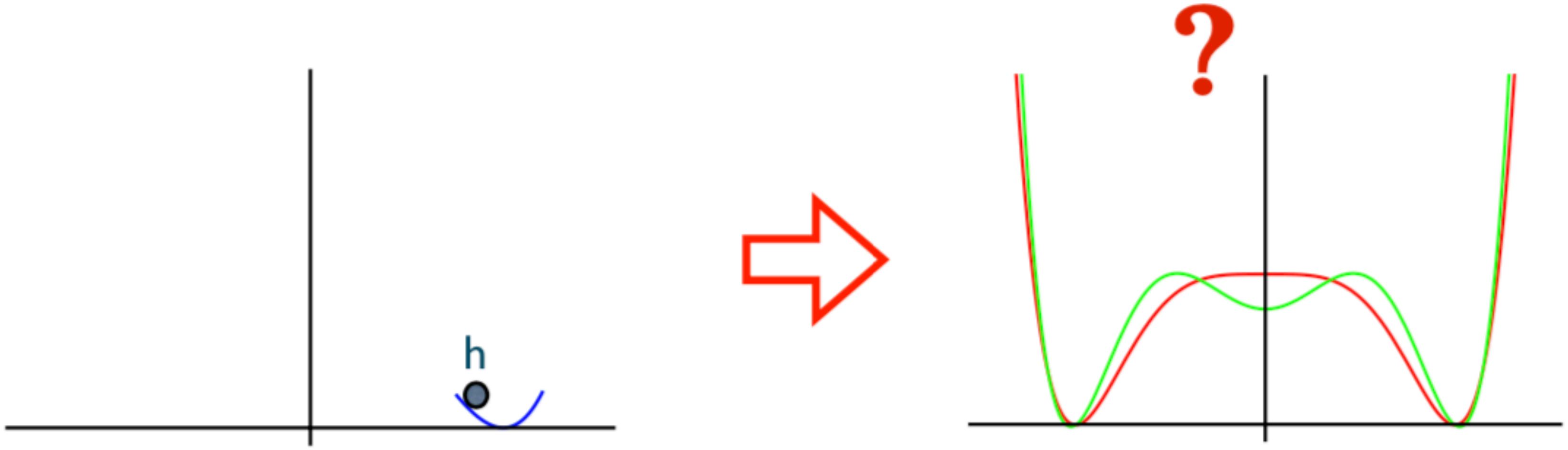
Higgs Self-couplings

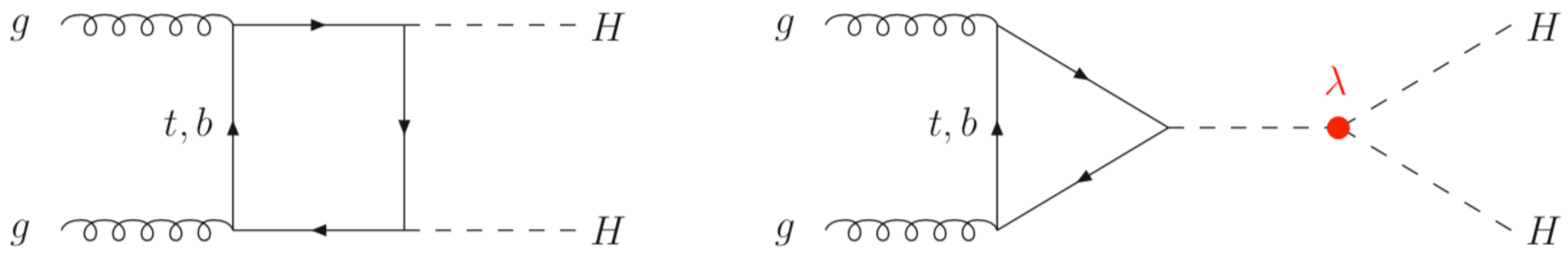
- Higgs Potential: Direct related to origin of EW symmetry breaking
- Goal: measure Higgs self-couplings precisely



$$V(h) = m_h^2 h^\dagger h + \frac{1}{2}\lambda(h^\dagger h)^2,$$

$$V(h) = ?$$

Main Channel to measure Higgs self-couplings at LHC: gg> HH



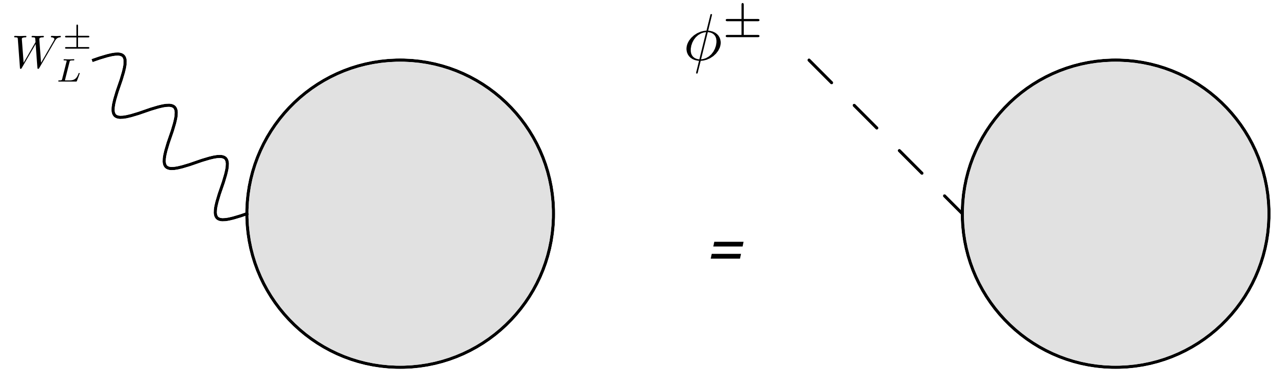
Feynman diagrams in SM

New channels and new approaches?

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



- Parameterization scheme: SMEFT.

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

- Related to Higgs physics

$$\mathcal{L} = \mathcal{L}_{\rm SM} - c_6(\Phi^\dagger\Phi)^3 + c_{\Phi_1}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + c_{\Phi_2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)^*(\Phi^\dagger \overleftrightarrow{D}_\mu\Phi)$$
$$+c_{W^3}\epsilon^{abc}W_\mu^{a\nu}W_\nu^{b\rho}W_\rho^{b\mu} + c_{\Phi^2W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + c_{\Phi^2B^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu}$$
$$+c_{\Phi^2WB}\Phi^\dagger\tau^a\Phi W^a_{\mu\nu}B^{\mu\nu} \qquad (1)$$

- c_6 and c_{Φ_1} modify Higgs potential

1812.09299

- Measuring Higgs couplings with longitudinal external states.

Higgs Couplings without the Higgs

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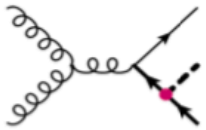
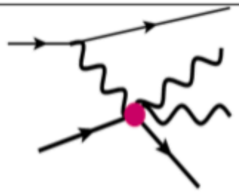
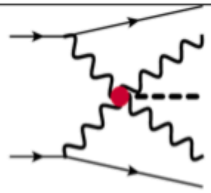
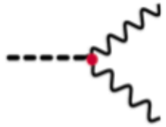
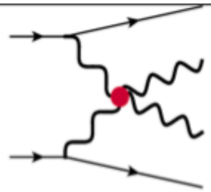
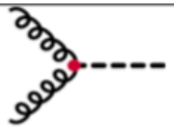
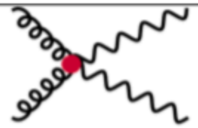
$$\kappa_t : pp \to jt + V_L V_L' \quad (4)$$
$$(e^+e^- \to ll + \{tbW_L, tbZ_L, ttW_L, ttZ_L\})$$
$$\kappa_\lambda : pp \to jjh + V_L V_L',\ (e^+e^- \to llhV_L V_L') \quad (5)$$
$$pp \to jj + 4V_L,\ (e^+e^- \to ll\,4V_L) \quad (6)$$
$$\kappa_{\gamma\gamma, Z\gamma} : pp \to jj + V'V,\ (e^+e^- \to llV'V) \quad (7)$$
$$\kappa_V : pp \to jj + V_L V_L',\ (e^+e^- \to llV_L V_L') \quad (8)$$
$$\kappa_g : pp \to W_L^+ W_L^-, Z_L Z_L,\ (e^+e^- \to lljj) \quad (9)$$

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

Kinda follow-up to this paper.

2 → 3 Vector Boson Scattering:

- 1. $V_L V_L \to V_L V_L h$: $W_L^+ W_L^- \to W_L^+ W_L^- h$
- $V_L V_L \to hhh$: $W_L^+ W_L^- \to hhh$
- 2. Next: a). Amplitudes in high energy limit
- b). Simulation: cross sections in colliders

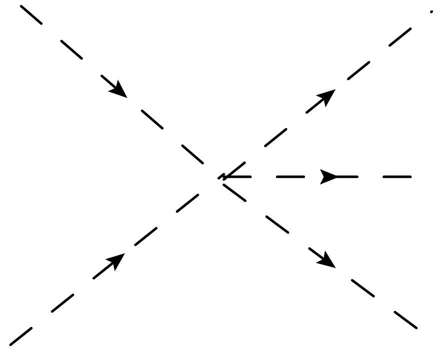
2 Amplitudes

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

(Focus on c6)

- 1. No propagator

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



$$\mathcal{A}_0^{\phi^+\phi^-\to\phi^+\phi^-h} = \lambda_{(\phi^+\phi^-)^2h} = -12C_6vi$$

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

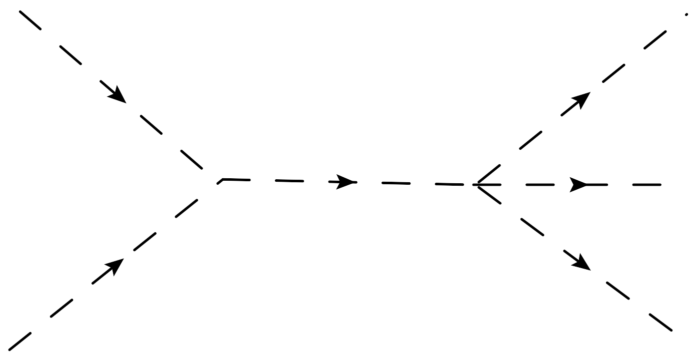
Main entrance to modify Higgs coupling, the effect has to be strong.
(Amplitude sensitive to .)

Same for $\phi^+\phi^- \to hhh$ ($W_L^+W_L^- \to hhh$)

2. Amplitudes

Feynman diagrams

- 2. One propagator. 8 diagrams.



$$A_1 = \mathcal{M}'_4 \frac{i}{q^2 - m^2} \mathcal{M}'_3$$

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

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

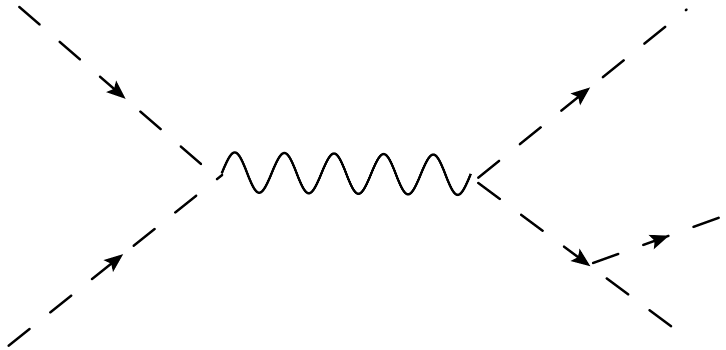
$\phi^+\phi^- \to hhh$: effective number of diagrams = 4.

2 Amplitudes

Feynman diagrams

- 3. Two propagators. Full amplitude complicated, scaling simple.

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



- 47 diagrams (not conclusive).
-
- Effective no. of diagrams for $\phi^+\phi^- \to hhh$: 8

Summary of the amplitude

$$\mathcal{A}(W_L^+W_L^- \to W_L^+W_L^-h) = \mathcal{A}^{\rm SM} + \mathcal{A}^{\rm BSM} \tag{13}$$

with

$$\mathcal{A}^{\rm SM} \simeq \frac{v}{E^2} \qquad \mathcal{A}^{\rm BSM} \simeq \frac{v}{\Lambda^2} \tag{14}$$

The ratio between BSM and SM is approximately

$$\frac{\mathcal{A}^{BSM}}{\mathcal{A}^{SM}} \sim \frac{E^2}{\Lambda^2} \tag{15}$$

3.Cross section

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

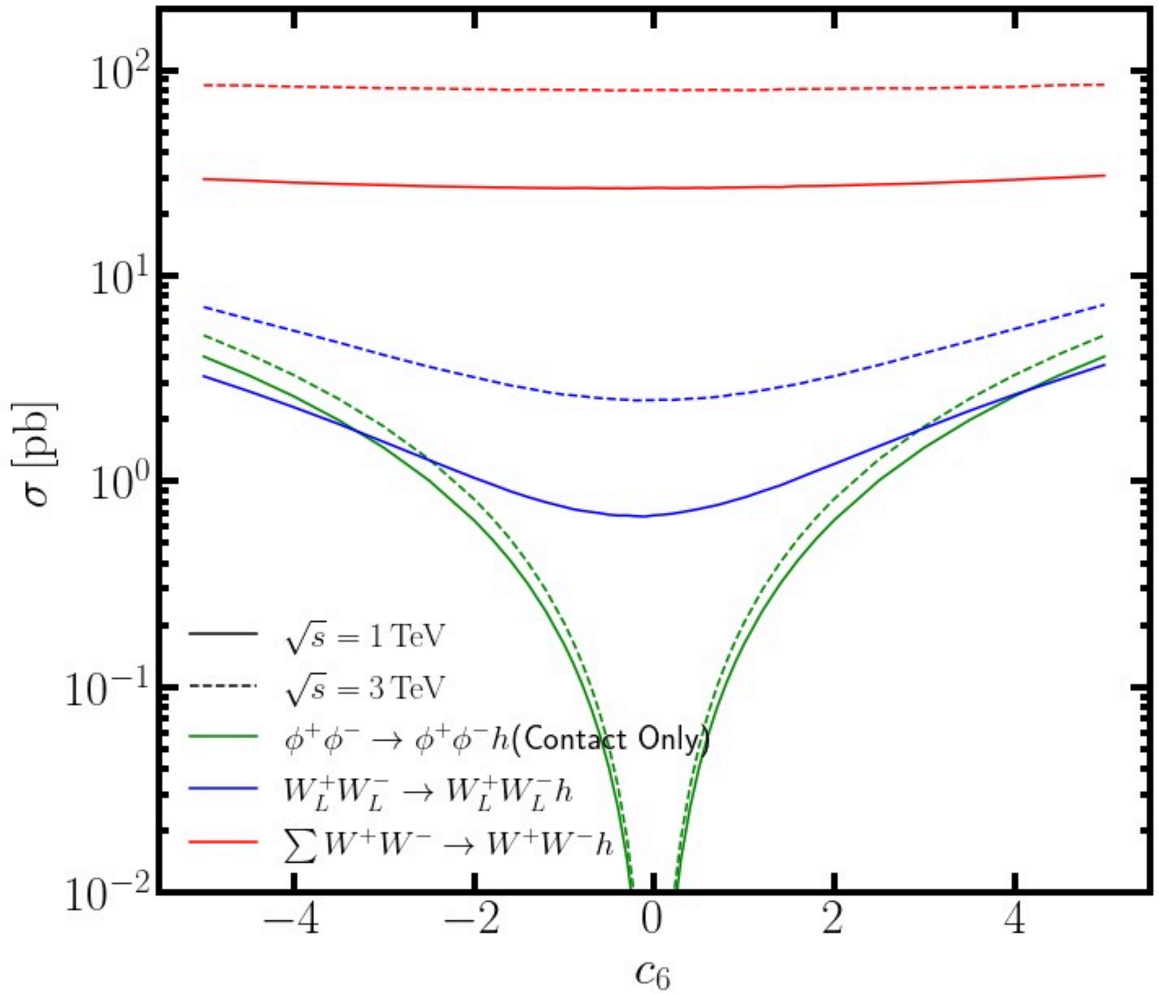
- Additional factors:
- 1) Log enhancement from infrared singularities (soft, and collinear)

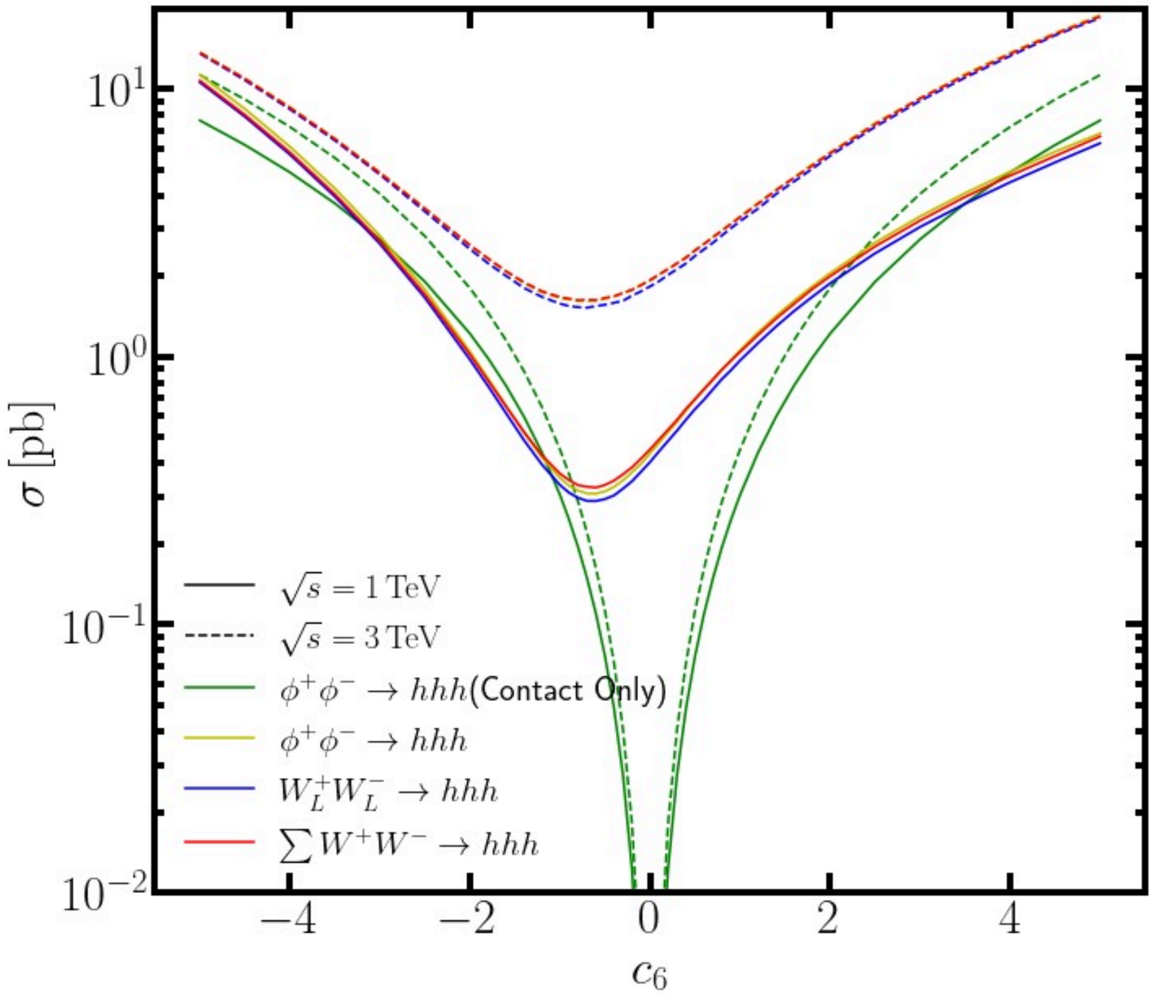
- Sensitivity to new physics don' t necessary translate to cross sections

3 Cross section

Cross section: $V_LV_L \to V_LV_Lh$& $V_LV_L \to hhh$

- Plots with c6 (C6=c6/Λ^2), $\Lambda = 1$TeV)





4. Full Simulation:

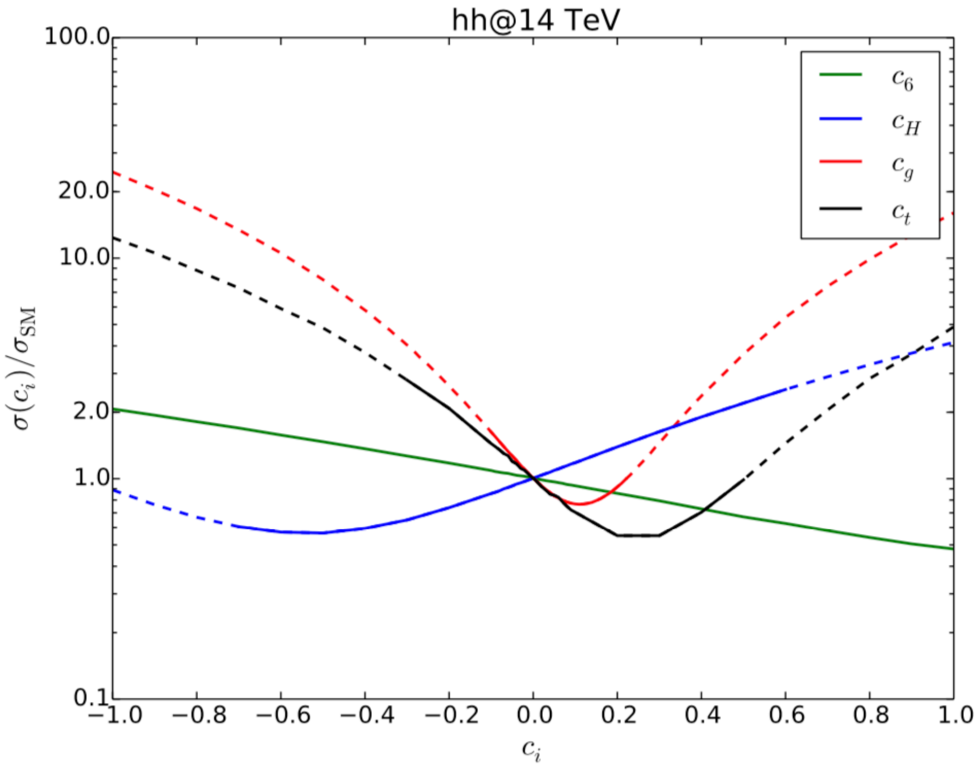
- 1.Processes on lepton colliders and proton colliders:

$$l^+l^- \to \nu_l\bar{\nu}_l W_L^+ W_L^- h \qquad l^+l^- \to \nu_l\bar{\nu}_l hhh \tag{4.1}$$

$$pp \to jjW_L^\pm W_L^\pm h \qquad pp \to jjhhh \tag{4.2}$$

- 2.Select for longitudinal polarizations

4. Full Simulation: Comparison with $pp > hh$



Taken from arxiv: 1910.00012v2

$$c_6' \in [-1.0, 1.0],\ c_H' \in [-0.8, 0.6],$$

Translate to

$$c_6 \in [-1.8, 1.8] \qquad c_{\Phi_1} \in [-6.6, 5.0]$$

Choice of range

$$c_6 \in [-2, 2] \qquad c_{\Phi_1} \in [-2, 2]$$

4. Full Simulation: $\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu W_L^+ W_L^- h$

Dependence on c6:

Cross sections (pb) for $\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu W_L^+ W_L^- h$ ($c_{\Phi_1}=0$, Scheme 2)					
c_6	-2	-1	0	1	2
1 TeV, cut 1	$4.17\cdot10^{-9}$	$1.57\cdot10^{-9}$	$8.22\cdot10^{-10}$	$1.93\cdot10^{-9}$	$4.90\cdot10^{-9}$
3 TeV, cut 1	$1.79\cdot10^{-6}$	$6.98\cdot10^{-6}$	$3.71\cdot10^{-7}$	$8.01\cdot10^{-7}$	$2.00\cdot10^{-6}$
5 TeV, cut 1	$6.10\cdot10^{-6}$	$2.43\cdot10^{-6}$	$1.32\cdot10^{-6}$	$2.74\cdot10^{-6}$	$6.72\cdot10^{-6}$
10 TeV, cut 1	$1.94\cdot10^{-5}$	$7.98\cdot10^{-6}$	$4.38\cdot10^{-6}$	$8.74\cdot10^{-6}$	$2.09\cdot10^{-5}$
14 TeV, cut 1	$2.99\cdot10^{-5}$	$1.25\cdot10^{-5}$	$7.11\cdot10^{-6}$	$1.36\cdot10^{-5}$	$3.22\cdot10^{-5}$
30 TeV, cut 1	$6.45\cdot10^{-5}$	$2.82\cdot10^{-5}$	$1.58\cdot10^{-5}$	$2.95\cdot10^{-5}$	$6.68\cdot10^{-5}$

Dependence on : c_{Φ_1}

Cross sections (pb) for $\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu W_L^+ W_L^- h$ ($c_6=0$, Scheme 2)					
c_{Φ_1}	-2	-1	0	1	2
1 TeV, cut 0	$6.23\cdot10^{-7}$	$6.70\cdot10^{-7}$	$7.69\cdot10^{-7}$	$9.27\cdot10^{-7}$	$1.14\cdot10^{-6}$
3 TeV, cut 0	$2.65\cdot10^{-5}$	$2.34\cdot10^{-5}$	$2.47\cdot10^{-5}$	$2.96\cdot10^{-5}$	$3.95\cdot10^{-5}$
5 TeV, cut 0	$8.85\cdot10^{-5}$	$6.71\cdot10^{-5}$	$6.43\cdot10^{-5}$	$8.13\cdot10^{-5}$	$1.17\cdot10^{-4}$
10 TeV, cut 0	$4.09\cdot10^{-4}$	$2.22\cdot10^{-4}$	$1.71\cdot10^{-4}$	$2.61\cdot10^{-4}$	$4.72\cdot10^{-4}$
14 TeV, cut 0	$8.63\cdot10^{-4}$	$3.95\cdot10^{-4}$	$2.56\cdot10^{-4}$	$4.38\cdot10^{-4}$	$9.39\cdot10^{-4}$
30 TeV, cut 0	$4.97\cdot10^{-3}$	$1.60\cdot10^{-3}$	$5.07\cdot10^{-4}$	$1.66\cdot10^{-3}$	$5.04\cdot10^{-3}$

Dependence on c6:

1. $\sigma/\sigma_{\mathrm{SM}} > 4$
2. Requires PT cuts to reduce SM cross sections:

   $p_T(W^\pm) > 150$ **GeV and** $p_T(h) > 150$ **GeV.**

3. $\sigma_{\mathrm{SM}} < 10^{-5} pb$ until 30 TeV

Dependence on c_{Φ_1}:

1. $\sigma/\sigma_{\mathrm{SM}} > 10$
2. No pT cuts required
3. $\sigma_{\mathrm{SM}} < 10^{-5} pb$ until 3 TeV

   $\sigma_{\mathrm{SM}} < 10^{-4} pb$ until 10 TeV

4. Full Simulation: $pp \to jjW_L^{\pm}W_L^{\pm}h$

Cross sections (pb) for $pp \to j_F j_F W_L^{\pm} W_L^{\pm} h$ (Scheme 2, $c_{\Phi_1} = 0$)					
c_6	-2	-1	0	1	2
14 TeV, cut 2	$6.35 \cdot 10^{-7}$	$2.81 \cdot 10^{-7}$	$1.68 \cdot 10^{-7}$	$3.01 \cdot 10^{-7}$	$6.79 \cdot 10^{-7}$
27 TeV, cut 2	$3.58 \cdot 10^{-6}$	$1.68 \cdot 10^{-6}$	$1.09 \cdot 10^{-6}$	$1.78 \cdot 10^{-6}$	$3.76 \cdot 10^{-6}$
100 TeV, cut 2	$3.28 \cdot 10^{-5}$	$1.82 \cdot 10^{-5}$	1.38×10^{-5}	1.87×10^{-5}	$3.34 \cdot 10^{-5}$

Cross sections (pb) for $pp \to j_F j_F W_L^{\pm} W_L^{\pm} h$ (Scheme 2, $c_6 = 0$)					
c_{Φ_1}	-2	-1	0	1	2
14 TeV, cut 3	$2.58 \cdot 10^{-5}$	$2.65 \cdot 10^{-5}$	$2.88 \cdot 10^{-5}$	$3.29 \cdot 10^{-5}$	$3.90 \cdot 10^{-5}$
27 TeV, cut 3	$1.27 \cdot 10^{-4}$	$1.20 \cdot 10^{-4}$	$1.27 \cdot 10^{-4}$	$1.49 \cdot 10^{-4}$	$1.83 \cdot 10^{-4}$
100 TeV, cut 3	$1.26 \cdot 10^{-3}$	$9.91 \cdot 10^{-4}$	$9.70 \cdot 10^{-4}$	$1.23 \cdot 10^{-3}$	$1.72 \cdot 10^{-3}$

Dependence on c6:

1. $\sigma/\sigma_{\rm SM} > 3$

2. Requires PT cuts to reduce SM cross sections:

$p_T(W^{\pm}) > 150$ **GeV and** $p_T(h) > 150$ **GeV.**

3. $\sigma_{\rm SM} < 10^{-5} pb$ until 100 TeV

4. Full Simulation: $\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu hhh$

Cross sections (pb) for $\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu hhh$ ($c_{\Phi_1} = 0$, Scheme 2)					
c_6	-2	-1	0	1	2
1 TeV, cut 0	$4.42 \cdot 10^{-8}$	$1.06 \cdot 10^{-8}$	$3.39 \cdot 10^{-9}$	$2.25 \cdot 10^{-8}$	$6.76 \cdot 10^{-8}$
3 TeV, cut 0	$1.93 \cdot 10^{-6}$	$5.66 \cdot 10^{-7}$	$2.78 \cdot 10^{-7}$	$1.08 \cdot 10^{-6}$	$2.94 \cdot 10^{-6}$
5 TeV, cut 0	$4.91 \cdot 10^{-6}$	$1.57 \cdot 10^{-6}$	$9.50 \cdot 10^{-7}$	$3.03 \cdot 10^{-6}$	$7.74 \cdot 10^{-6}$
10 TeV, cut 0	$1.25 \cdot 10^{-5}$	$4.59 \cdot 10^{-6}$	$3.46 \cdot 10^{-6}$	$8.75 \cdot 10^{-6}$	$1.95 \cdot 10^{-5}$
14 TeV, cut 0	$1.80 \cdot 10^{-5}$	$6.70 \cdot 10^{-6}$	$5.38 \cdot 10^{-6}$	$1.30 \cdot 10^{-5}$	$2.88 \cdot 10^{-5}$
30 TeV, cut 0	$3.50 \cdot 10^{-5}$	$1.77 \cdot 10^{-5}$	$1.41 \cdot 10^{-5}$	$2.92 \cdot 10^{-5}$	$5.42 \cdot 10^{-5}$

Cross sections (pb) for $\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu hhh$ ($c_6 = 0$, Scheme 2)				
c_{Φ_1}	-2	-1	1	2
1 TeV, cut 0	$2.78 \cdot 10^{-8}$	$1.08 \cdot 10^{-8}$	$5.56 \cdot 10^{-9}$	$1.73 \cdot 10^{-8}$
3 TeV, cut 0	$3.01 \cdot 10^{-6}$	$1.11 \cdot 10^{-6}$	$5.43 \cdot 10^{-7}$	$1.89 \cdot 10^{-6}$
5 TeV, cut 0	$1.33 \cdot 10^{-5}$	$4.47 \cdot 10^{-6}$	$2.38 \cdot 10^{-6}$	$8.76 \cdot 10^{-6}$
10 TeV, cut 0	$7.83 \cdot 10^{-5}$	$2.38 \cdot 10^{-5}$	$1.50 \cdot 10^{-5}$	$5.97 \cdot 10^{-5}$
14 TeV, cut 0	$1.77 \cdot 10^{-4}$	$4.97 \cdot 10^{-5}$	$3.73 \cdot 10^{-5}$	$1.44 \cdot 10^{-4}$
30 TeV, cut 0	$1.07 \cdot 10^{-3}$	$2.77 \cdot 10^{-4}$	$2.44 \cdot 10^{-4}$	$9.86 \cdot 10^{-4}$

Table 2: The same as Table 1 except for the $\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu hhh$ process.

Dependence on c6 and c_{Φ_1}:

1. $\sigma/\sigma_{\rm SM} > 3$
2. No PT cuts required
3. $\sigma_{\rm SM} < 10^{-5} pb$ until 30 TeV

4. Full Simulation: $pp \to jjhhh$

Cross sections (pb) for $pp \to j_F j_F hhh$ (Scheme 2, $c_{\Phi_1} = 0$).					
c_6	-2	-1	0	1	2
14 TeV, cut 3	$1.99 \cdot 10^{-6}$	$5.77 \cdot 10^{-7}$	$2.97 \cdot 10^{-7}$	$1.16 \cdot 10^{-6}$	$3.12 \cdot 10^{-6}$
27 TeV, cut 3	$9.46 \cdot 10^{-6}$	$2.93 \cdot 10^{-6}$	$1.50 \cdot 10^{-6}$	$5.48 \cdot 10^{-6}$	$1.45 \cdot 10^{-5}$
100 TeV, cut 3	$7.91 \cdot 10^{-5}$	$2.65 \cdot 10^{-5}$	$1.48 \cdot 10^{-5}$	$4.30 \cdot 10^{-5}$	$1.13 \cdot 10^{-4}$

Cross sections (pb) for $pp \to j_F j_F hhh$ (Scheme 2, $c_6 = 0$).				
c_{Φ_1}	-2	-1	1	2
14 TeV, cut 3	$2.94 \cdot 10^{-6}$	$1.10 \cdot 10^{-6}$	$5.33 \cdot 10^{-7}$	$1.83 \cdot 10^{-6}$
27 TeV, cut 3	$1.97 \cdot 10^{-5}$	$6.99 \cdot 10^{-6}$	$3.75 \cdot 10^{-6}$	$1.35 \cdot 10^{-5}$
100 TeV, cut 3	$3.31 \cdot 10^{-4}$	$1.02 \cdot 10^{-4}$	$7.04 \cdot 10^{-5}$	$2.69 \cdot 10^{-4}$

Table 4: The same as Table 3 except for the $pp \to j_F j_F hhh$ process.

Dependence on c6 and c_{Φ_1}:

1. $\sigma/\sigma_{\mathrm{SM}} > 6$
2. No PT cuts required
3. $\sigma_{\mathrm{SM}} < 10^{-5} pb$ until 100 TeV

Conclusions

- In high energy, Amplitudes of $V_L V_L \to V_L V_L h$ or hhh: $\frac{\mathcal{A}^{BSM}}{\mathcal{A}^{SM}} \sim \frac{E^2}{\Lambda^2}$
- Origin: 5-point scalar vertices from c6 operator.
- Behavior of cross section follows for $pp \to jjhhh$ $l^+ l^- \to v_l \bar{v}_L hhh$
- Cuts are needed for $pp \to jjW_L^{\pm} W_L^{\pm} h$ $l^+ l^- \to v_l \bar{v}_l W_L^+ W_L^- h$
- Cross sections only large enough for future muon colliders and 100 TeV pp colliders for c6 dependence