VLVL → VLVLh and Higg Self-coupling Measurements

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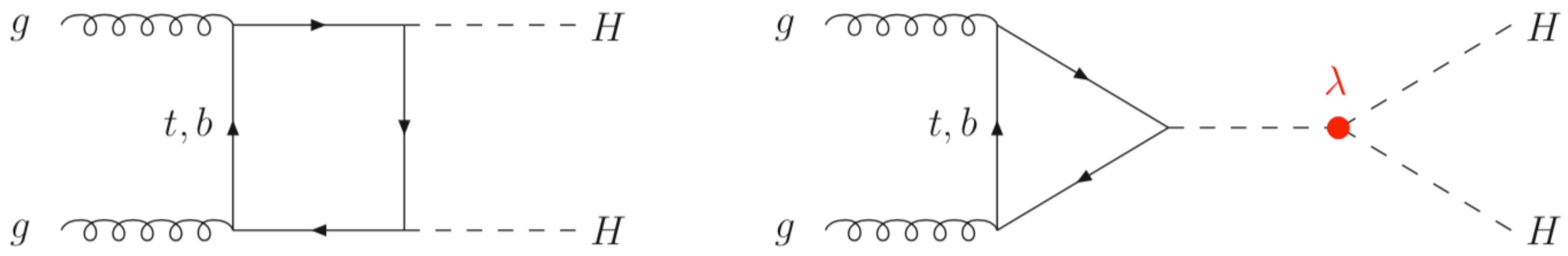
\\\\ Main Channel to measure Higgs self-couplings at LHC: gg> HH



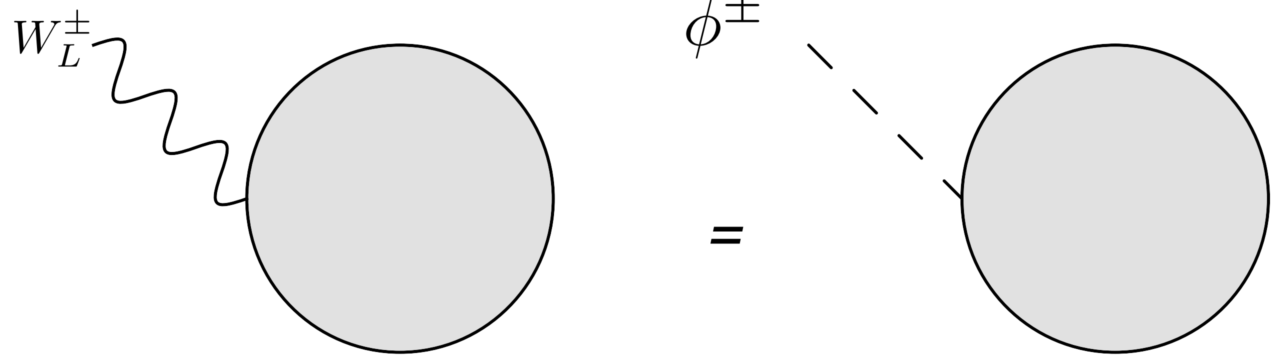
Feynman diagrams in SM

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



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- Measuring Higgs couplings with longitudinal external states.

Higgs Couplings without the Higgs

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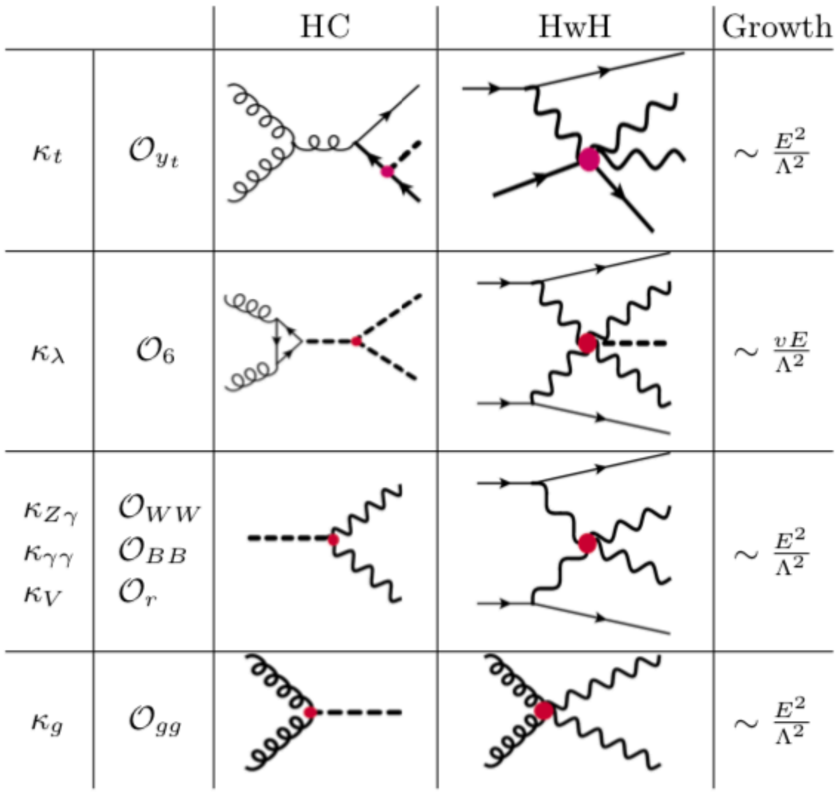
$$\kappa_t : pp \to jt + V_L V_L' \quad (4)$$
$$(e^+e^- \to ll + \{tbW_L, tbZ_L, ttW_L, ttZ_L\})$$
$$\kappa_\lambda : pp \to jjh + V_L V_L', \; (e^+e^- \to llhV_L V_L') \quad (5)$$
$$pp \to jj + 4V_L, \; (e^+e^- \to ll\,4V_L) \quad (6)$$
$$\kappa_{\gamma\gamma, Z\gamma} : pp \to jj + V'V, \; (e^+e^-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



Kinda follow-up to this paper.

- Parameterization scheme: SMEFT.

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

- Related to Higgs physics

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

- Higgs potential

$$V(\Phi^\dagger\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda_h(\Phi^\dagger\Phi)^2 + C_6(\Phi^\dagger\Phi)^3$$

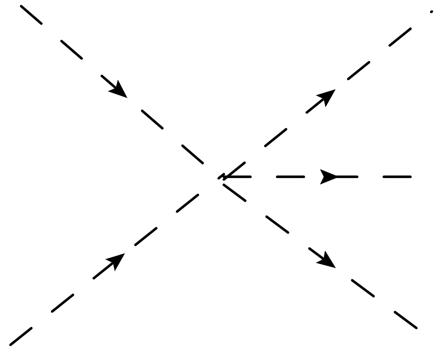
2 Amplitudes

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

(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 $\frac{1}{\Lambda^2}$, $\mathcal{A}_0 \sim \frac{v}{\Lambda^2}$.

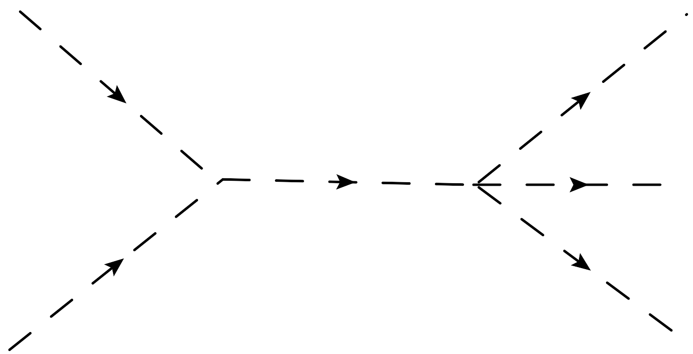
Main entrance to modify Higgs coupling, the effect has to be strong.
(Amplitude sensitive to .)

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

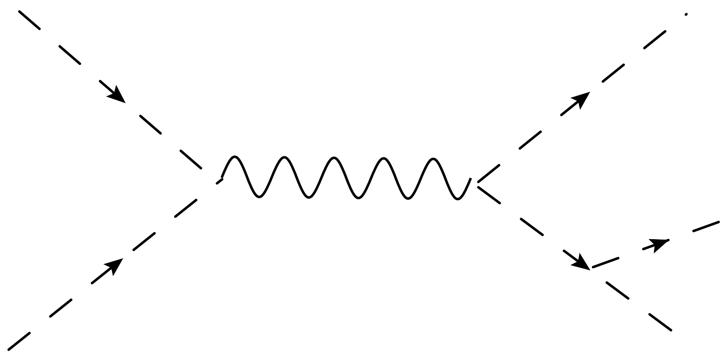
$\phi^+\phi^- \to hhh$: effective number of diagrams = 4.

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

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

with

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

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

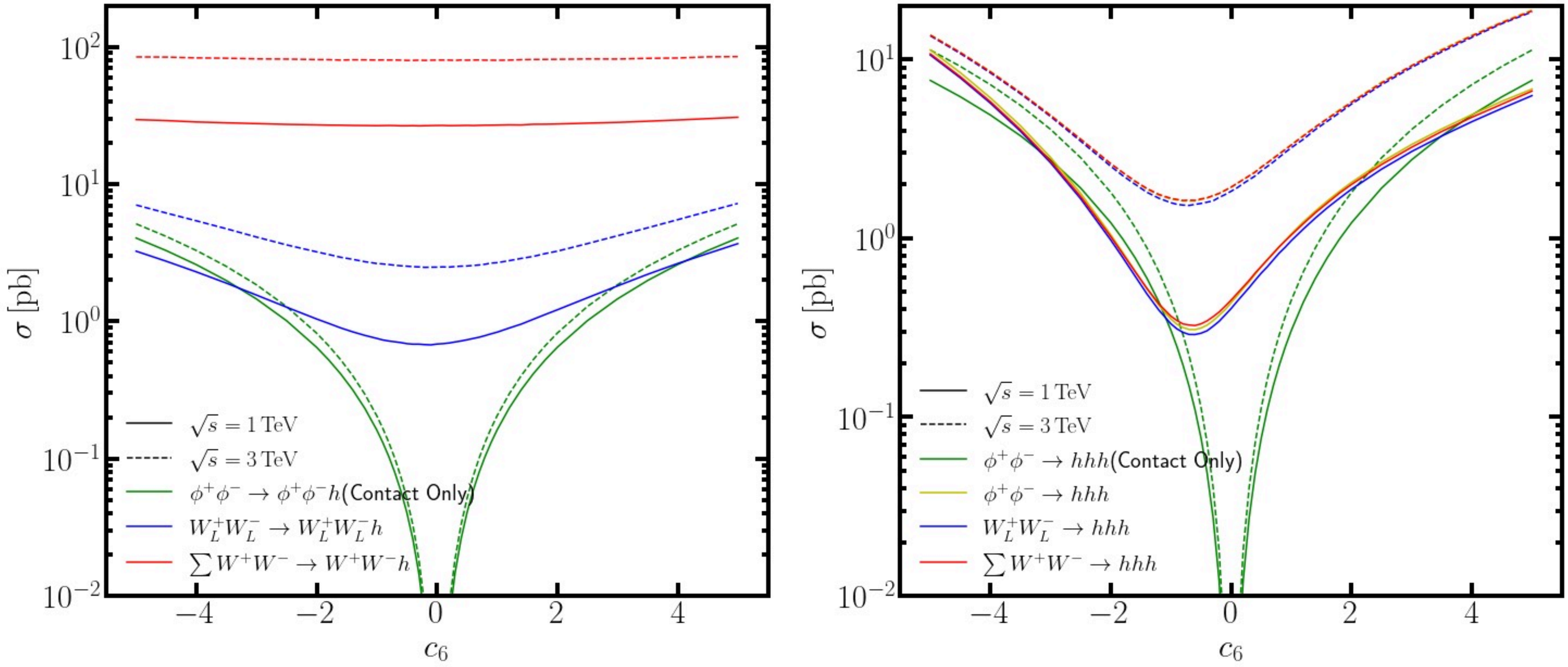
- Two additional factors:
- 1) Log enhancement from infrared singularities (soft, and collinear)
- 2) No. of diagrams (Only one diagram for C6)

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

3 Cross section

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

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



4. Full Simulation

$$pp \to jjhhh$$

p p > j j hhh with only basic cut : delta_eta_jj > 2.5

	14TeV	27TeV	100TeV
c6=1	4.741E-06	1.617E-05	9.126E-05
c6=-1	2.798E-05	5.531E-05	0.0002836
c6=2	3.874E-06	1.669E-05	0.0001202
c6=-2	4.425E-05	0.0001177	0.0004233

- 14 TeV: Only ~ 10 events at c6=-2,
- For h> bbar: 100 *0.6^3 ~ only 3-4 events
- 27 TeV: ~ 3000 events for c6=-2. (Assuming integrated luminosity is 3000fb^-1)
- h> bbar: 3000*0.6^3 ~ 600 events
- Very small SM cross sections: clean channel, but only in higher energies.

4. Simulation

HL-LHC

- $pp \to jjW_L^{\pm}W_L^{\pm}h$

File no.	C6.	Cross section (pb) (sqrts=14TeV)
0	0	2.854e-05 ± 7.3e-08
2	**-2**	**2.99e-05 ± 5.7e-08**

- 1. No significant enhancement for c6=-2.
- 2. only ~ 100 events
- For w+> l+ v; h> bbar: 100 *0.2^2*0.6 ~ only 2-3 events
- 3. Similarly for $l^+l^- \to v_l\bar{v}_lW_L^+W_L^-h$ at sqrts <= 1TeV
- 4. Needs cuts to reduce log enhancement from SM.

4. Simulation

Madgraph Simulation: VV →VVh

- Ongoing investigation. Example:

$$e^+e^- \to \nu_e \bar{\nu}_e W_L^+ W_L^- h$$

File no.	C6.	Cross section cut16(sqrts=14TeV)
0	0	1.781e-07 ± 2.4e-09
1	-1	4.129e-06 ± 8.2e-09

- m_{ll}^2 >0.3TeV. pT(w+/w-)>0.6TeV, pT(h)>0.6TeV

Conclusions

- VBS with 3-final states provide excellent channels for measuring higgs self-couplings, especially deviation of Higgs potential in future high energy colliders:

- 1.In high energy, Amplitudes of $V_L V_L \to V_L V_L h$ or hhh: $\frac{\mathcal{A}^{BSM}}{\mathcal{A}^{SM}} \sim \frac{E^2}{\Lambda^2}$
- 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 to come.