MEASURING HIGGS BOSON SELF-COUPLINGS WITH 2 $\to$ 3 VBS

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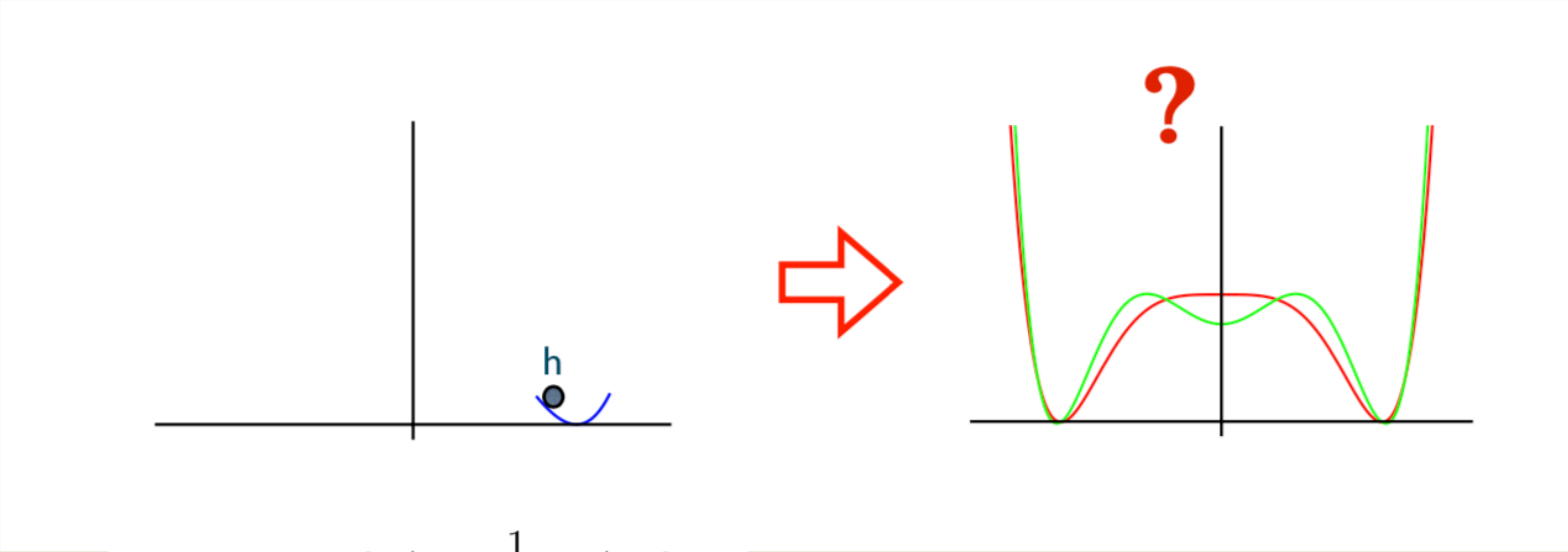
Focus:Higgs Self-couplings

1. Motivation

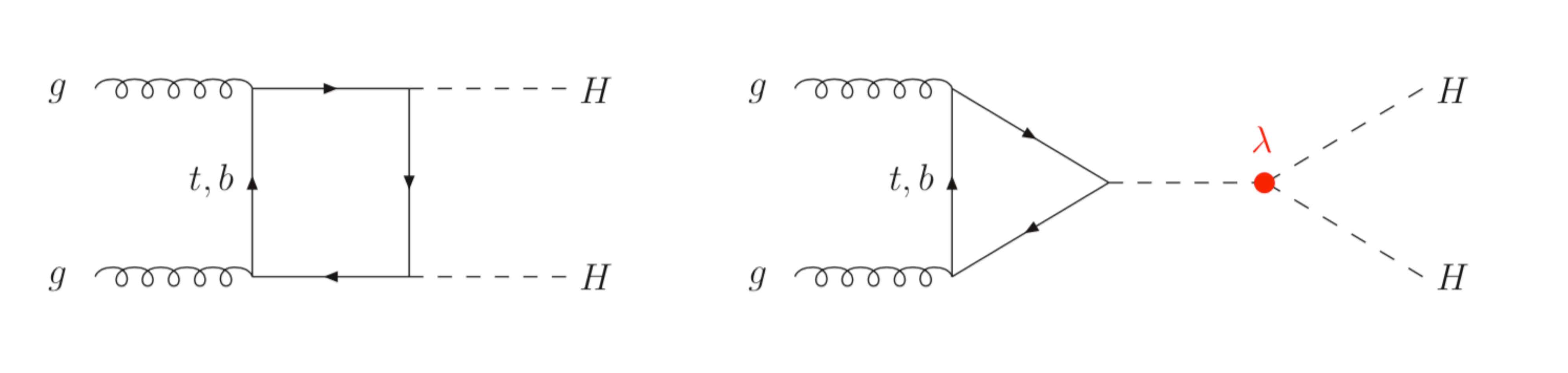
- Higgs Potential: Direct related to origin of EW symmetry breaking



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

$$V(h) = ?$$

Main Channel for Higgs self-coupling measurement at LHC: gg> HH



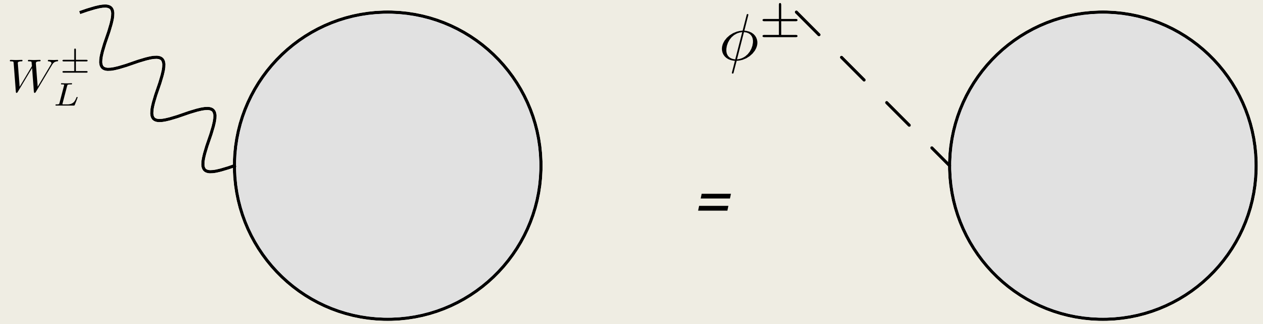
Usually take multiple Higgs final states.

Another approach:

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

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

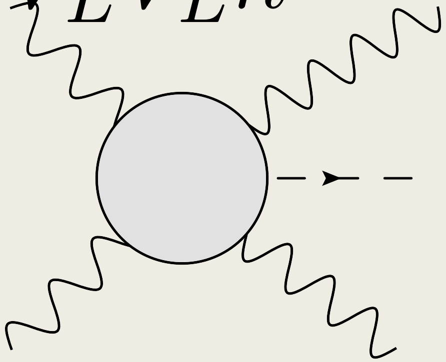
2. Goldstone equivalence theorem



3. New approach: Measuring Higgs couplings through V_L.

Our focus: 2>3 Vector Boson Scattering

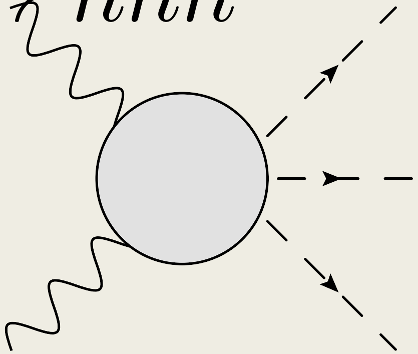
$$V_L V_L \to V_L V_L h$$



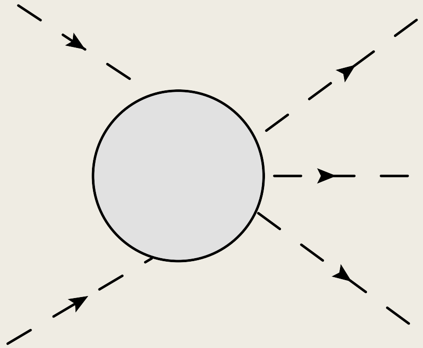
Proposed by Henning et.al.
in arxiv: 1812.09299 (Phys. Rev. Lett. **123**, 181801)

When E ≫m

$$V_L V_L \to hhh$$



$$\simeq$$



Take Goldstone equivalence (GET)

- Parameterization scheme: SMEFT.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i \mathcal{O}_i}{\Lambda^2} + \mathcal{O}(\frac{1}{\Lambda^3})$$

- Dim-6 operators related to Higgs physics

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

- Under GET, only $\mathcal{O}_6,\ \mathcal{O}_{\Phi_1}$ contribute to the Higgs self-coupling(s). Our focus.

2>3 VBS amplitude in high energy

- In high energy limit, new physics is very sensitive to new physics for $V_L V_L \to V_L V_L h$ & $V_L V_L \to hhh$

- The amplitudes behave as $\frac{\mathcal{A}^{BSM}}{\mathcal{A}^{SM}} \sim \frac{E^2}{\Lambda^2}$

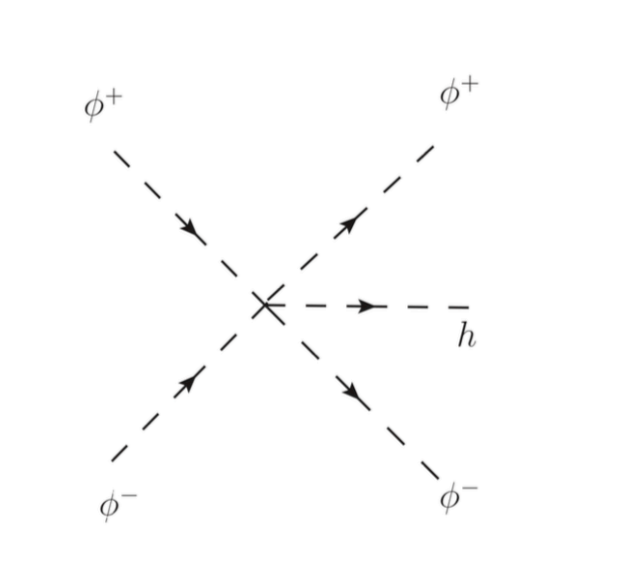
Feynman diagrams

- 1. No propagator: only one diagram

$$\mathcal{A}_0^{\phi^+\phi^-\to\phi^+\phi^-h} = \lambda_{(\phi^+\phi^-)^2h} = 12ic_6\frac{v}{\Lambda^2}$$

$$\mathcal{A}_0^{\phi^+\phi^-\to hhh} = \lambda_{\phi^+\phi^-h^3} = 18ic_6\frac{v}{\Lambda^2}$$

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

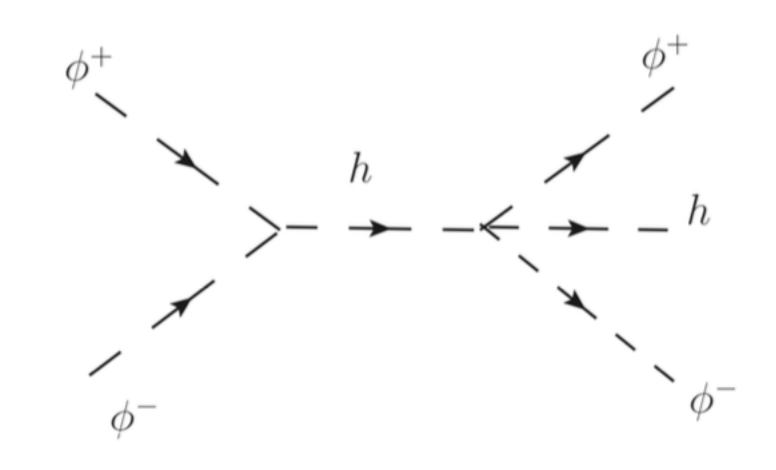


a. Only BSM contribution.

b. The dominant diagram for c_6

Feynman diagrams

- 2. One propagator.



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

$$-iC_{\Phi_1}\frac{m_h^2}{v}\left(\frac{(p_1+p_2)^2}{(p_3+p_4)^2-m_h^2}+\frac{(p_3+p_4)^2}{(p_1+p_2)^2-m_h^2}+\frac{(p_1-p_3)^2}{(p_2-p_4)^2-m_h^2}+\cdots (p_1-p_3)^2-m_h^2\right)$$

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

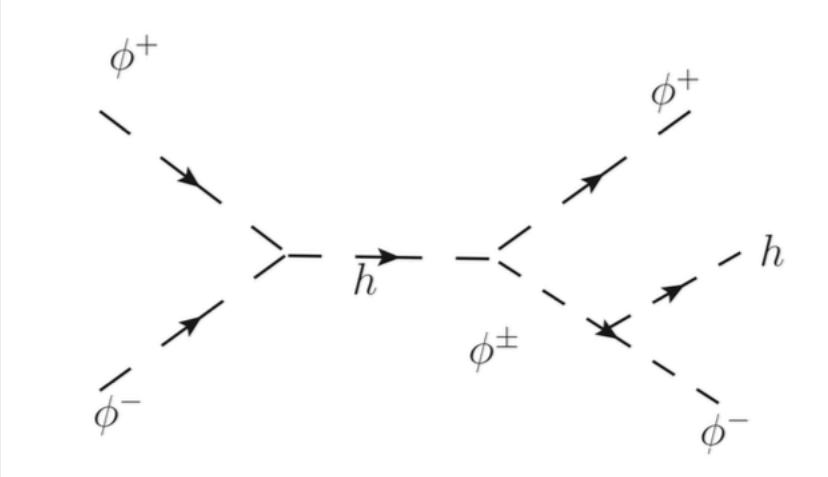
$$\mathcal{A}_1^{SM} \sim \frac{v}{E^2}.$$

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

Feynman diagrams

- Two propagators.

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



- A_2^a : two scalars.

$$\mathcal{A}_2^{a,\mathrm{BSM}} \sim \frac{v^3}{\Lambda^2 E^2} .$$

$$\mathcal{A}_2^{a,\mathrm{SM}} \sim \frac{v^3}{E^4} ,$$

- A_2^b: one scalar and one vector boson. Only SM

$$\mathcal{A}_2^{b,SM} \sim \frac{v}{E^2}$$

- A_2^c: two vector bosons. Only SM: $\mathcal{A}_2^c \sim \frac{v}{E^2} .$

Total Amplitudes in High Energy

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

with

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

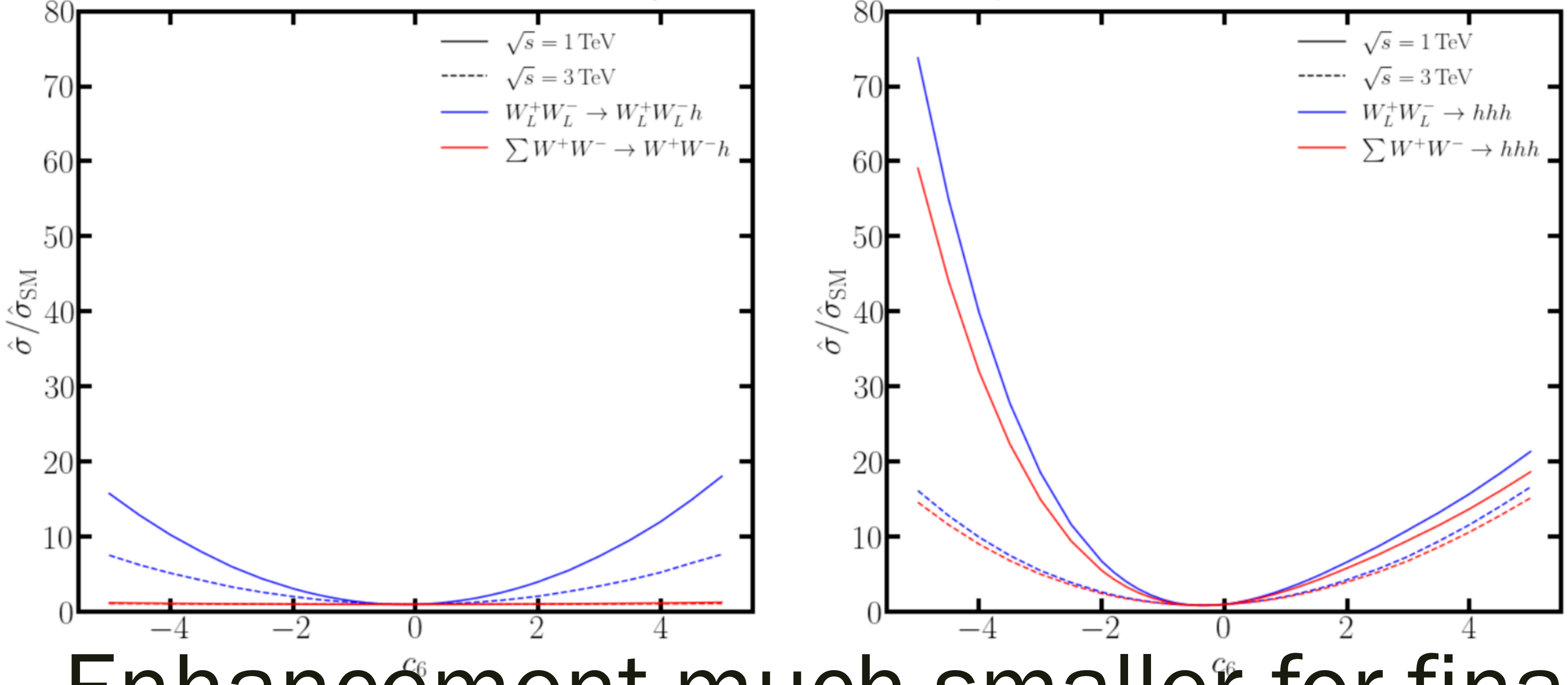
The ratio between BSM and SM is approximately

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

SM has logarithmic enhancement at low P_T from infrared singularities (soft, and collinear)

3.2 Partonic cross section

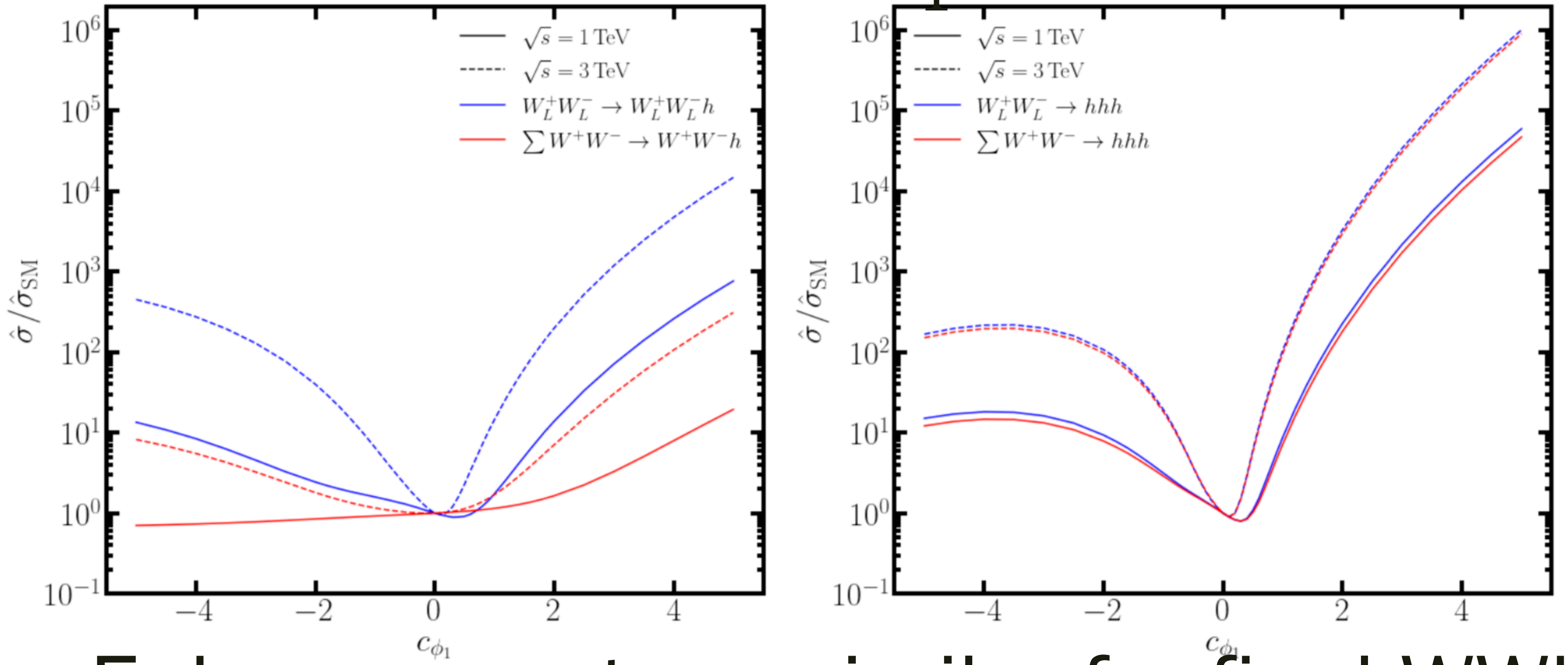
σ/σ_{SM} v.s. c_6



Enhancement much smaller for final WWh.

Figure 5: $\hat{\sigma}/\hat{\sigma}_{SM}$ for $W^+W^- \to W^+W^-h$ and $W^+W^- \to hhh$ as functions of c_6.

σ/σ_{SM} v.s. c_{Φ_1}



Enhancement are similar for final WWh and final hhh.

Figure 7: $\hat{\sigma}/\hat{\sigma}_{\rm SM}$ for $W^+W^- \to W^+W^-h$ and $W^+W^- \to hhh$ as functions of c_{Φ_1}.

3.2 Full Processes

$$l^+l^- \to \nu_l\bar{\nu}_l W_L^+ W_L^- h \qquad l^+l^- \to \nu_l\bar{\nu}_l hhh$$
$$pp \to jjW_L^\pm W_L^\pm h \qquad pp \to jjhhh$$

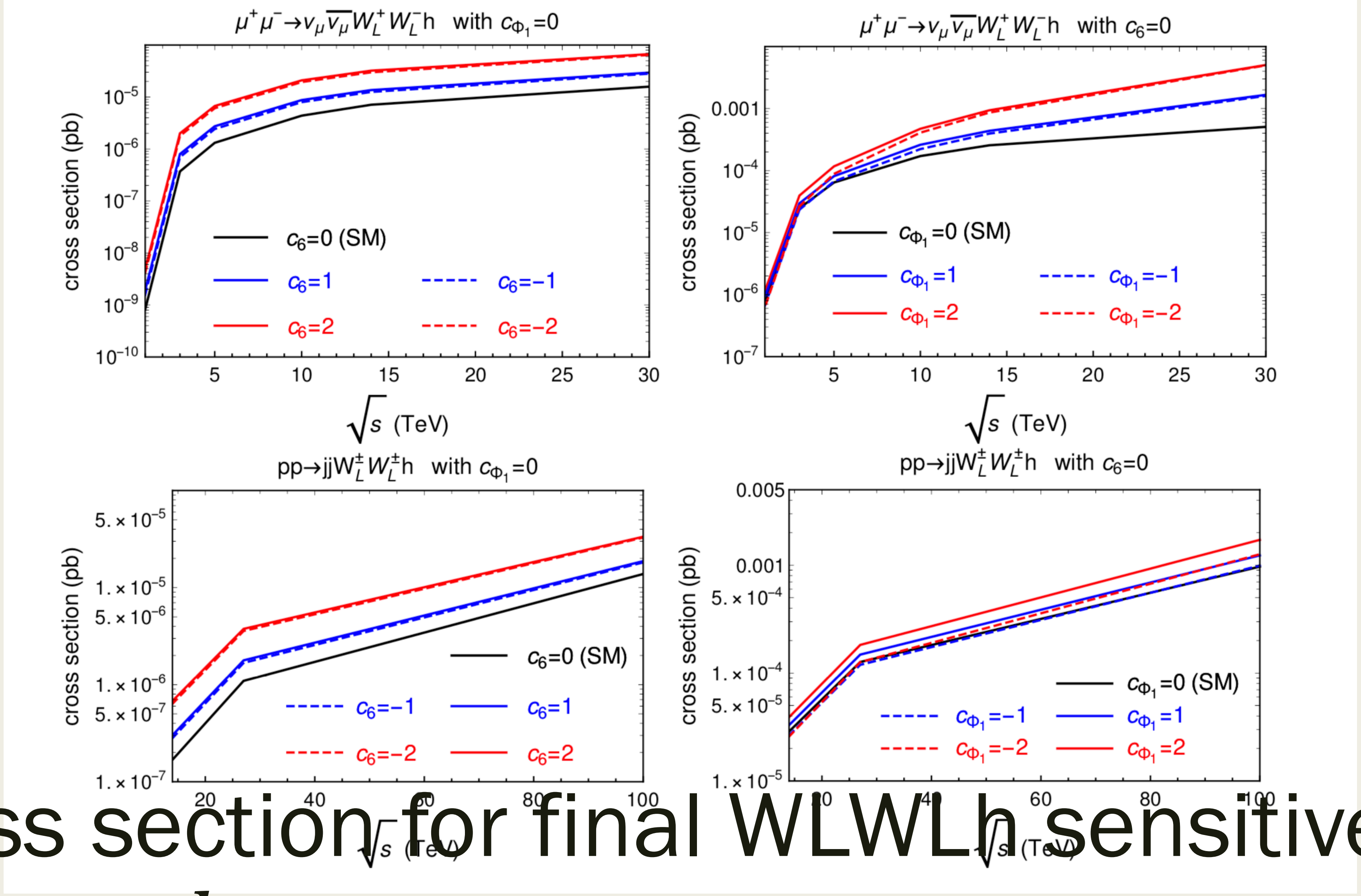
Lepton colliders: 1-30 TeV

Hadron colliders: 14, 27, 100 TeV

Simulation:

1. Select final vector bosons to be longitudinal
2. Impose PT cuts on final VL to reduce SM background.

3.2 Full Processes: simulation results



Cross section for final WLWLh sensitive to c_6 and c_{Φ_1}.

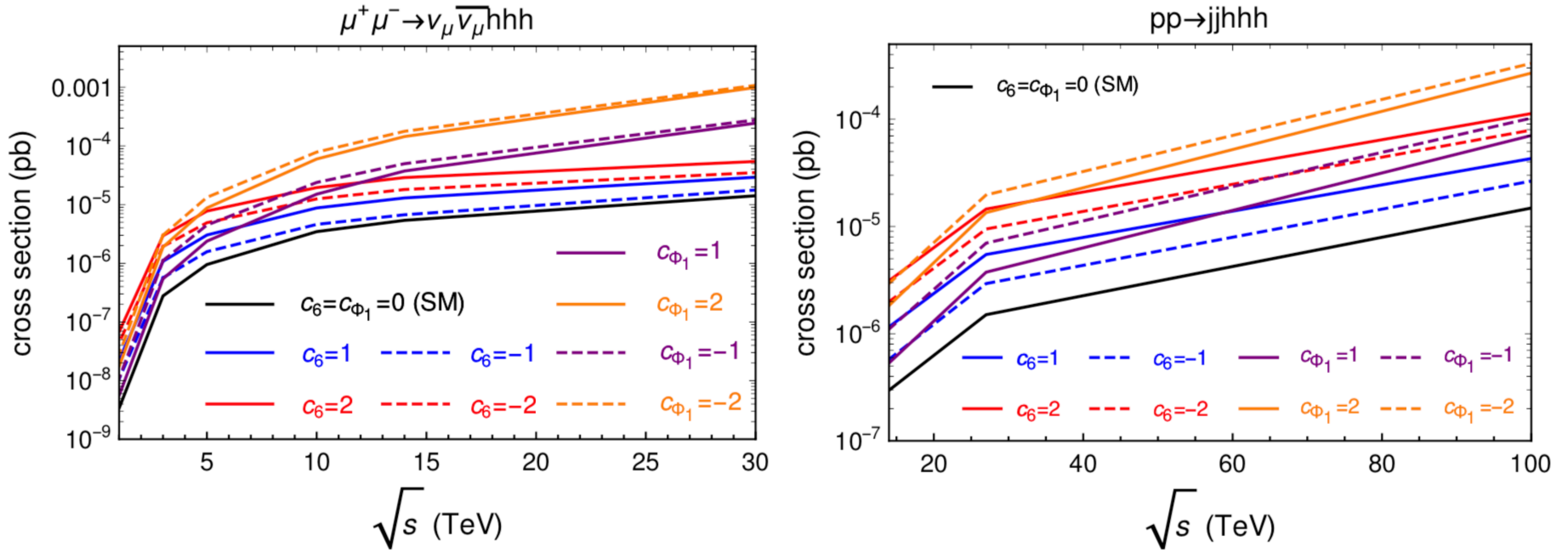


Figure 9: The vary of cross sections for $c_6 = \pm1, \pm2$ with $c_{\Phi_1} = 0$ and $c_{\Phi_1} = \pm1, \pm2$ with $c_6 = 0$ for $\mu^+\mu^- \to \nu_\mu\overline{\nu}_\mu hhh$ from $\sqrt{s} = 1$ to 30 TeV (left panel) and $pp \to jjhhh$ from $\sqrt{s} = 14$ to 100 TeV (right panel).

Cross section for final hhh sensitive to c_6 *and* c_{Φ_1}.

3.2 Constraints on c_6 *and* c_{Φ_1}

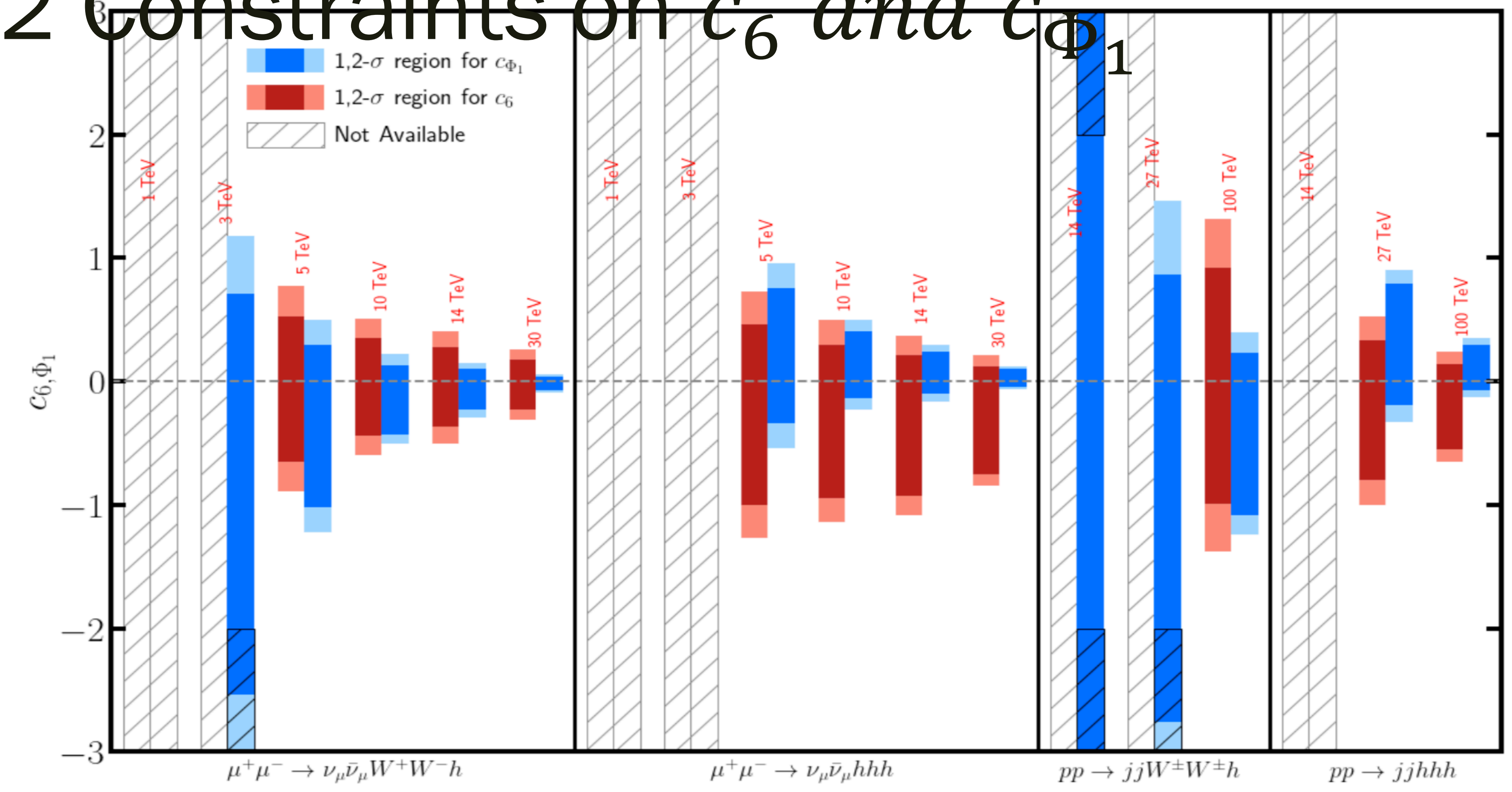


Figure 12: The allowed region for c_6 (red) and c_{Φ_1} (blue) from different channels. The darker color indicates the 1-σ region, while lighter one indicates the 2-σ region. The hatched region are not available either due to low event rate or beyond $[-2, 2]$.

- Naive estimation: no decay, no background analysis.

Conclusions

- 2→3 VBS includes: $V_L V_L \to V_L V_L h, V_L V_L \to hhh$
- Amplitude of 2→3 VBS under SMEFT is very sensitive to new physics: $\frac{\mathcal{A}^{BSM}}{\mathcal{A}^{SM}} \sim \frac{E^2}{\Lambda^2}$
- Subtleties in cross sections: select long. pol.; impose PT cuts
- $W^+W^- \to W^+W^-h$ and $W^+W^- \to hhh.$ are good channels to measure Higgs self-couplings, in 100 TeV pp collider, and especially future muon colliders.