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

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Based on 2105.11500, 2112.12507

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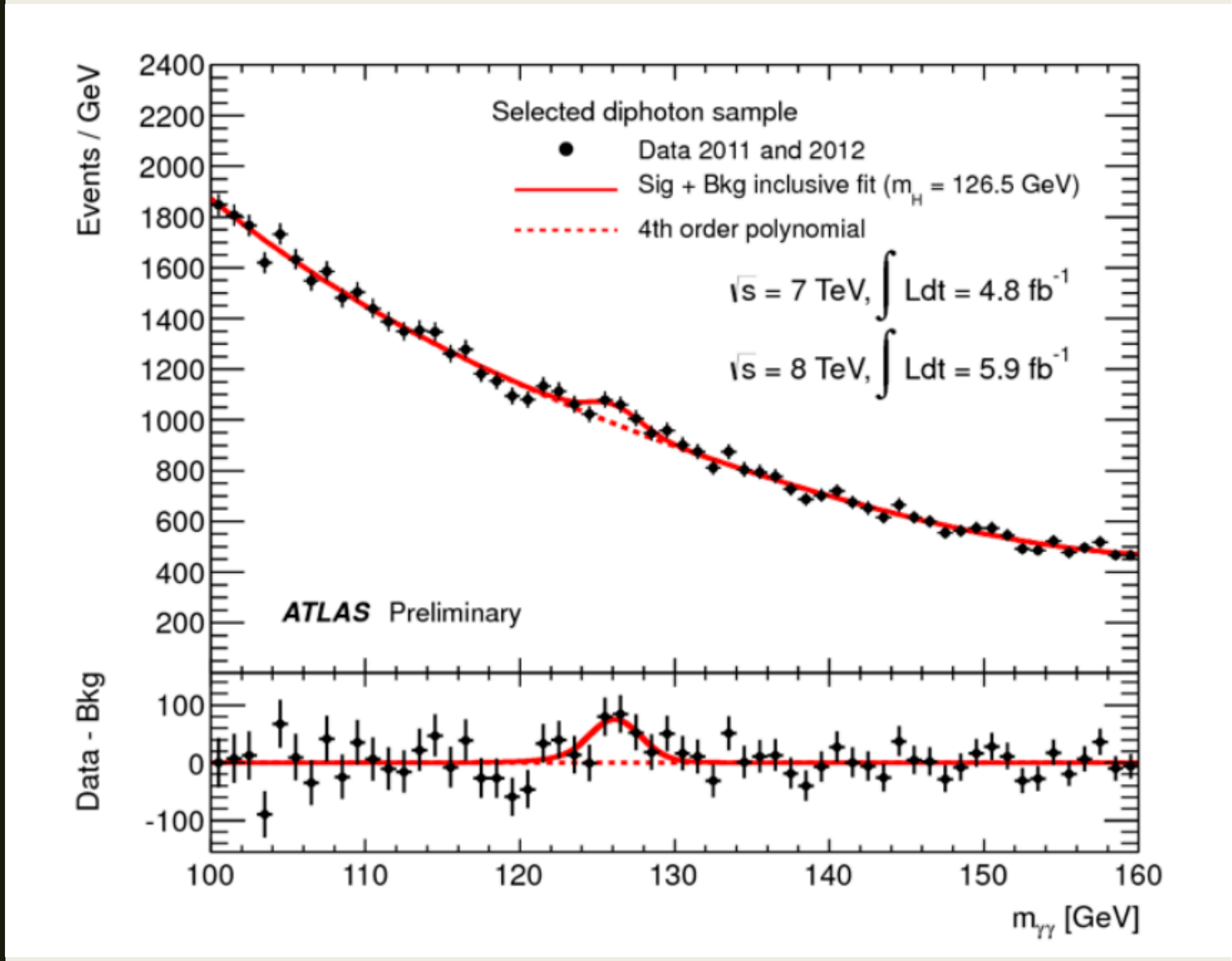
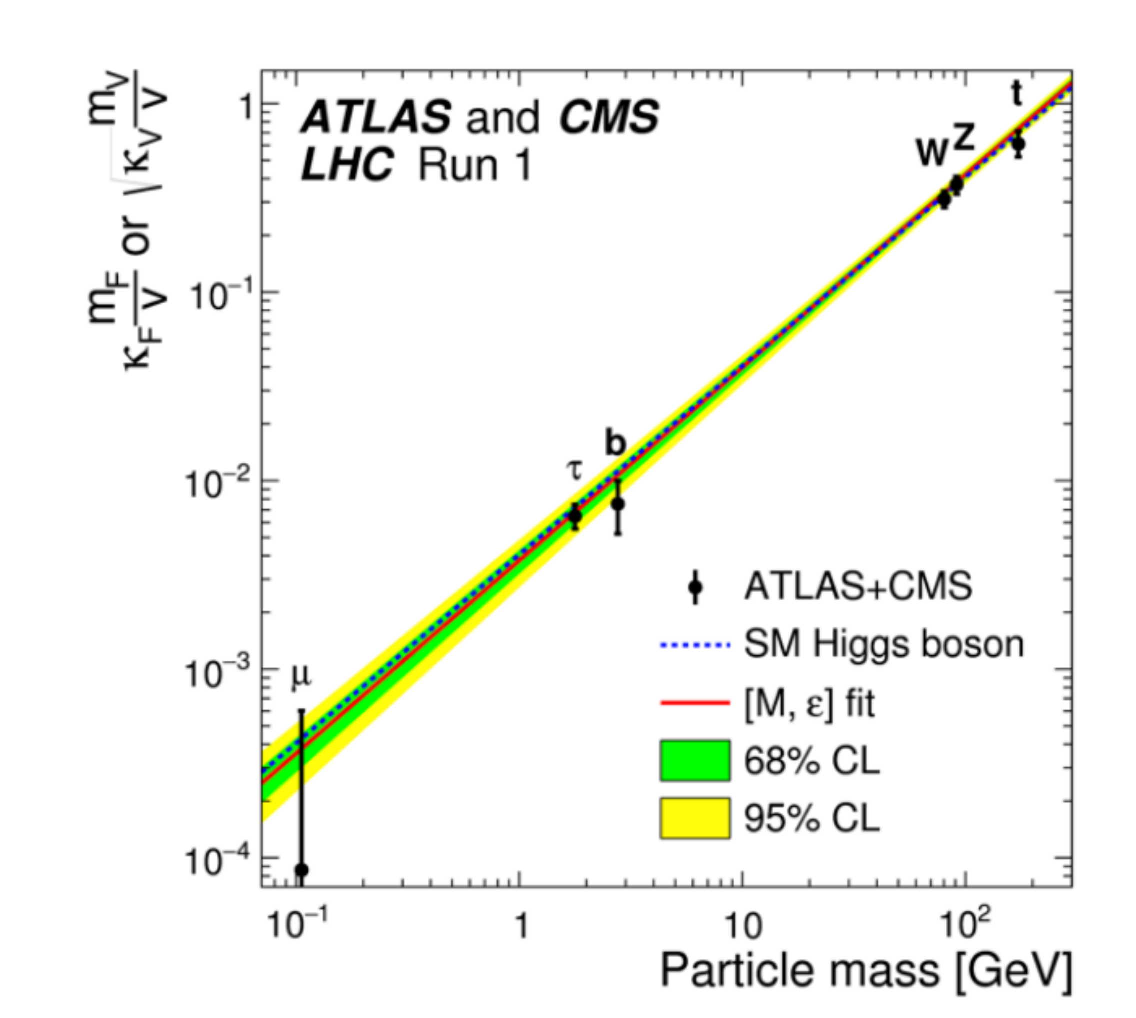
OUTLINE

- 1. Motivation
- 2. Physical Analysis and Strategy
- 3. Simulation and results

Higgs Discovery – Completion of SM

1. Motivation



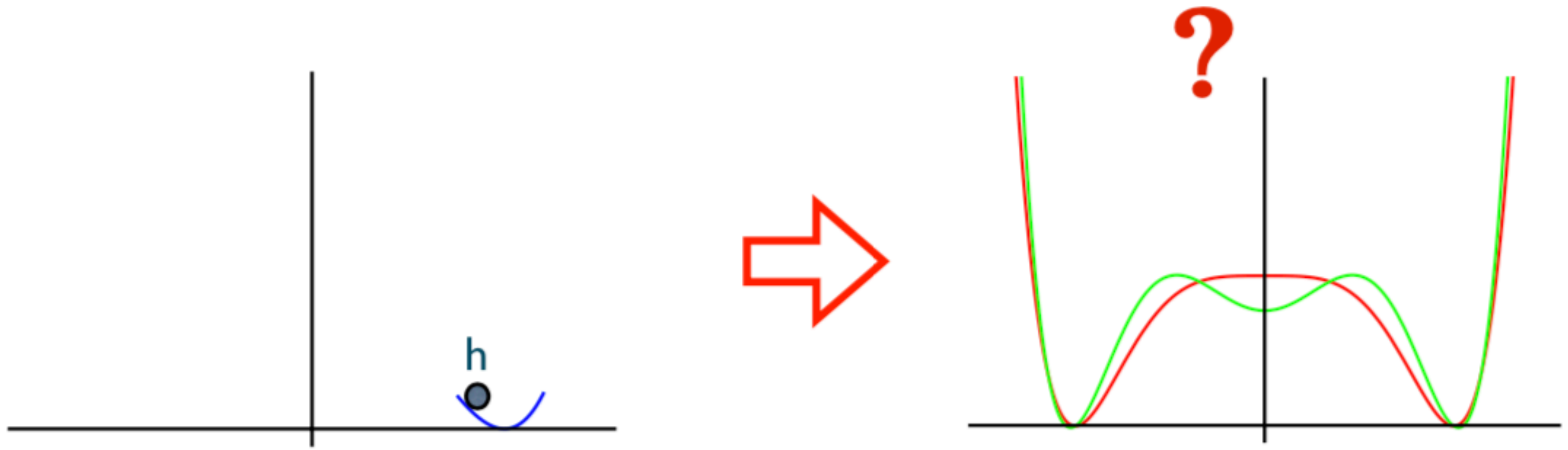


$$pp \to h \to \gamma\gamma$$

UNFINISHED BUSINESS:

1. Motivation

- Many Higgs couplings haven't been not measured precisely
- Higgs self-couplings still haven't been not measured at all.
- Direct related the shape of Higgs Potential, and therefore the origin of EW symmetry breaking



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

$$V(h) = ?$$

New Colliders

- Hadron collider: HE-LHC(27 TeV), 100 TeV and etc.

  1902.04070, *1902.00134*, *1607.01831*

- e+e- collider:

  250 GeV-260 GeV: ILC, CEPC *1810.09037*, *1903.01629*
  1-5 TeV: CLIC

  hep-ph/0412251

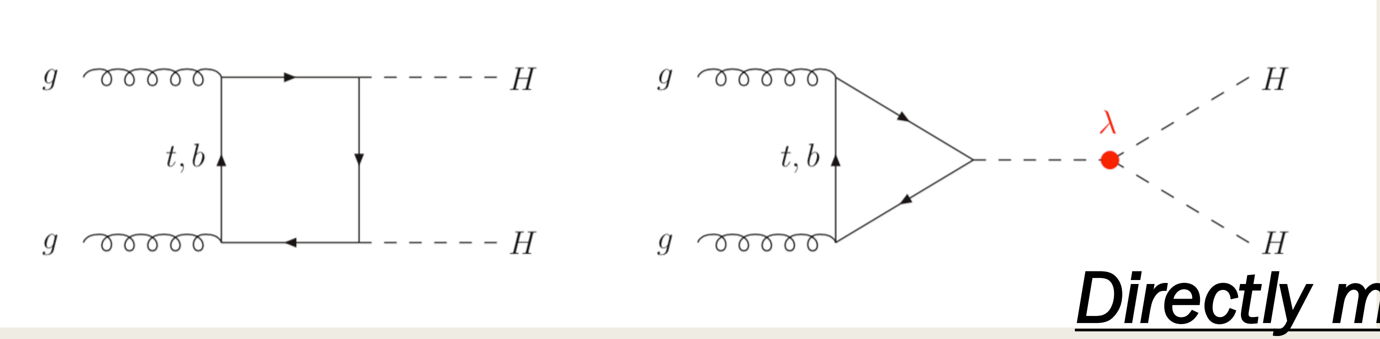
- Muon collider

  3、10、14 TeV *2103.14043*, *2303.08533*

  High energy & clean environment

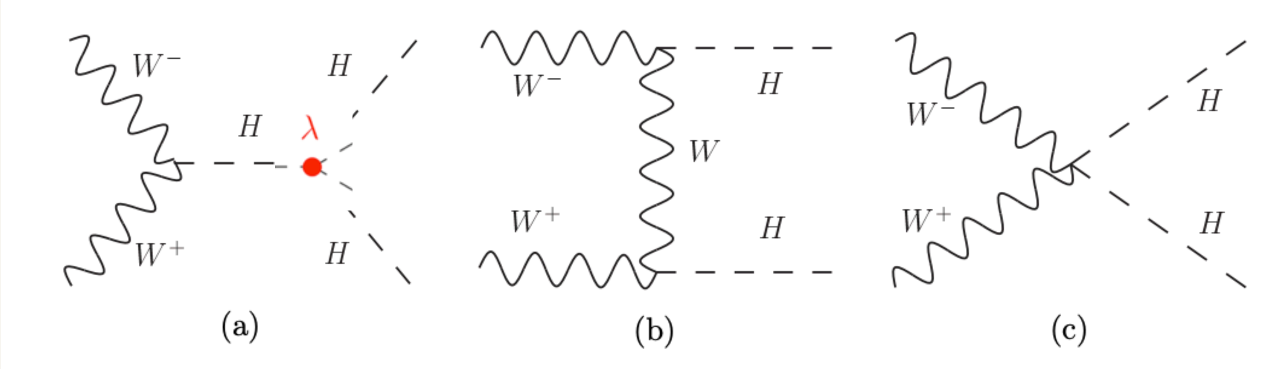
Main Channel for Higgs self-coupling measurement

- LHC: $gg \rightarrow hh\,(pp \rightarrow hh)$



<u>Directly measuring hhh vertex</u>

- Future muon collider: $WW/ZZ \rightarrow hh\,(\mu\mu \rightarrow \nu\nu(/\mu\mu)hh)$



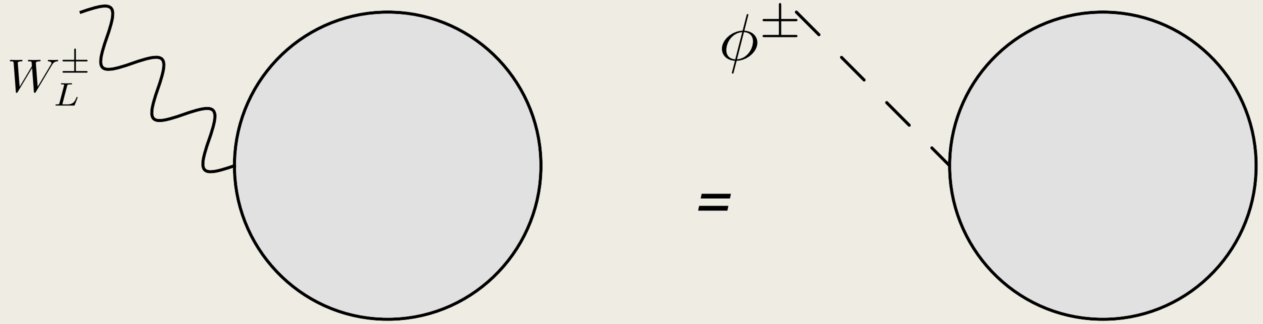
2008.12204

Another approach:

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

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

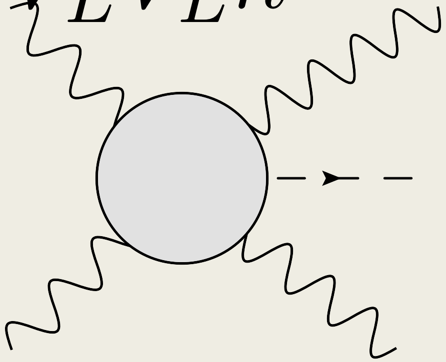
2. Goldstone equivalence theorem



3. New approach: Measuring Higgs couplings through V_L.

Our focus: 2>3 Vector Boson Scattering

$$V_L V_L \to V_L V_L h$$

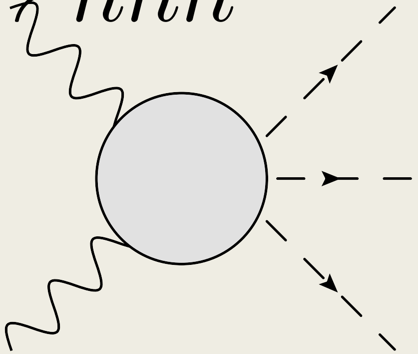


Proposed by Henning et.al.
in arxiv: 1812.09299 (Phys. Rev. Lett. **123**, 181801)

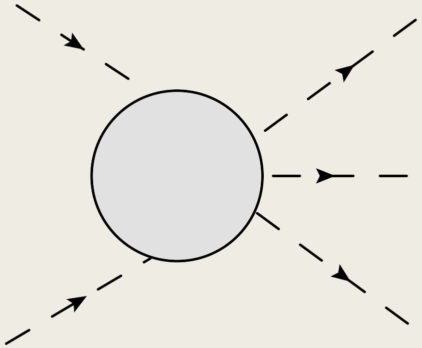
When E ≫m

$$V_L V_L \to hhh$$

2003.13628



$\simeq$



Take Goldstone equivalence (GET)

Muon collider especially suitable for this prcess

2. SMEFT and Amplitudes

- 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

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

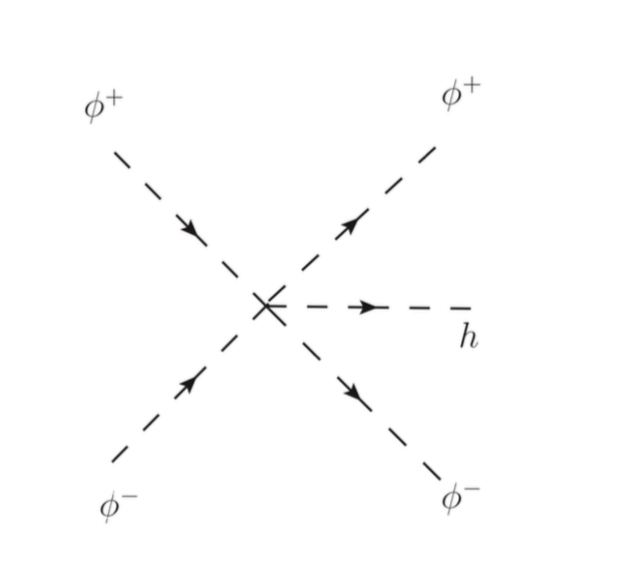
- Under GET, only $\mathcal{O}_6,\ \mathcal{O}_{\Phi_1}$ contribute to the Higgs self-coupling(s). Our focus.

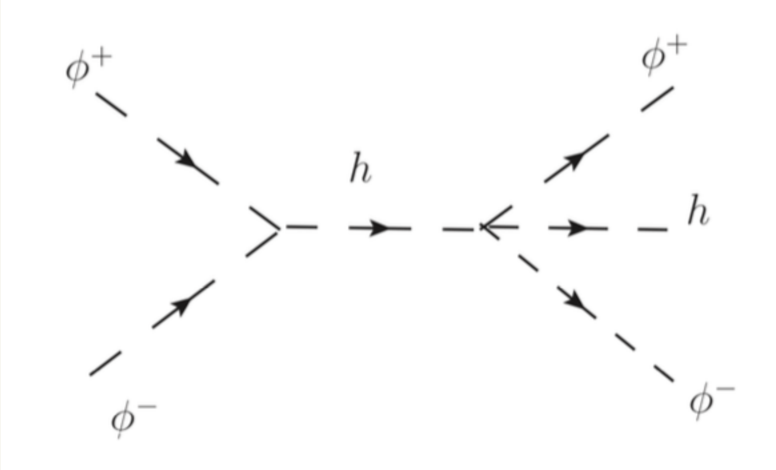
2>3 VBS amplitude in high energy

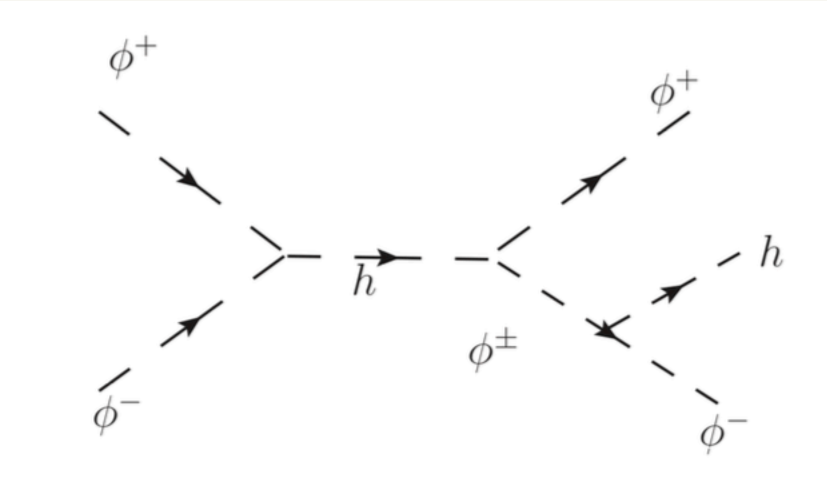
- In high energy limit, new physics is very sensitive to new physics for $V_L V_L \to V_L V_L h$ & $V_L V_L \to hhh$

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

Feynman diagrams(GET)







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

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

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

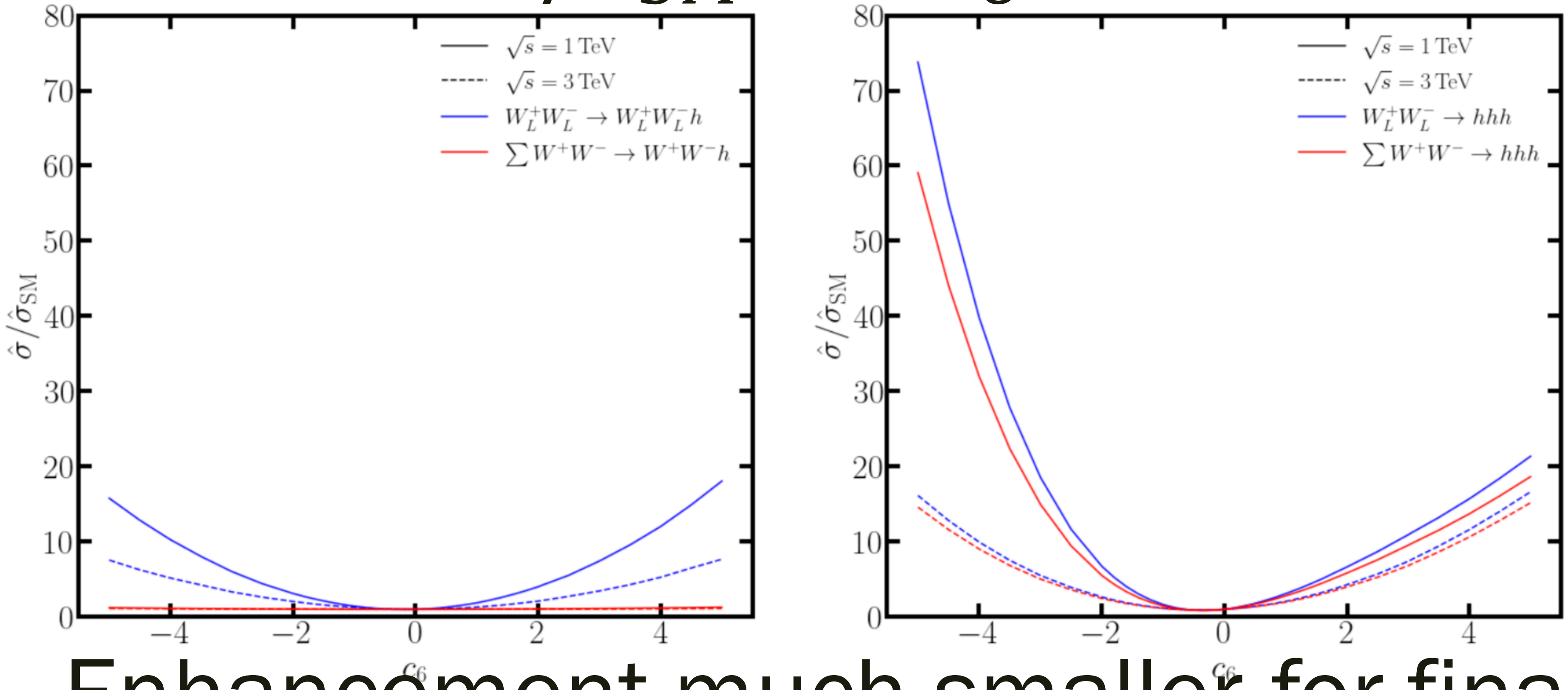
$$A_2 \simeq A_2^a + A_2^b + A_2^c \sim \frac{v}{\Lambda^2} + \frac{v}{E^2}$$

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

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

3.2 Partonic cross section

σ/σ_{SM} v.s. c_6



Enhancement much smaller for final WWh.

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

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

<u>**Simulation settings:**</u>

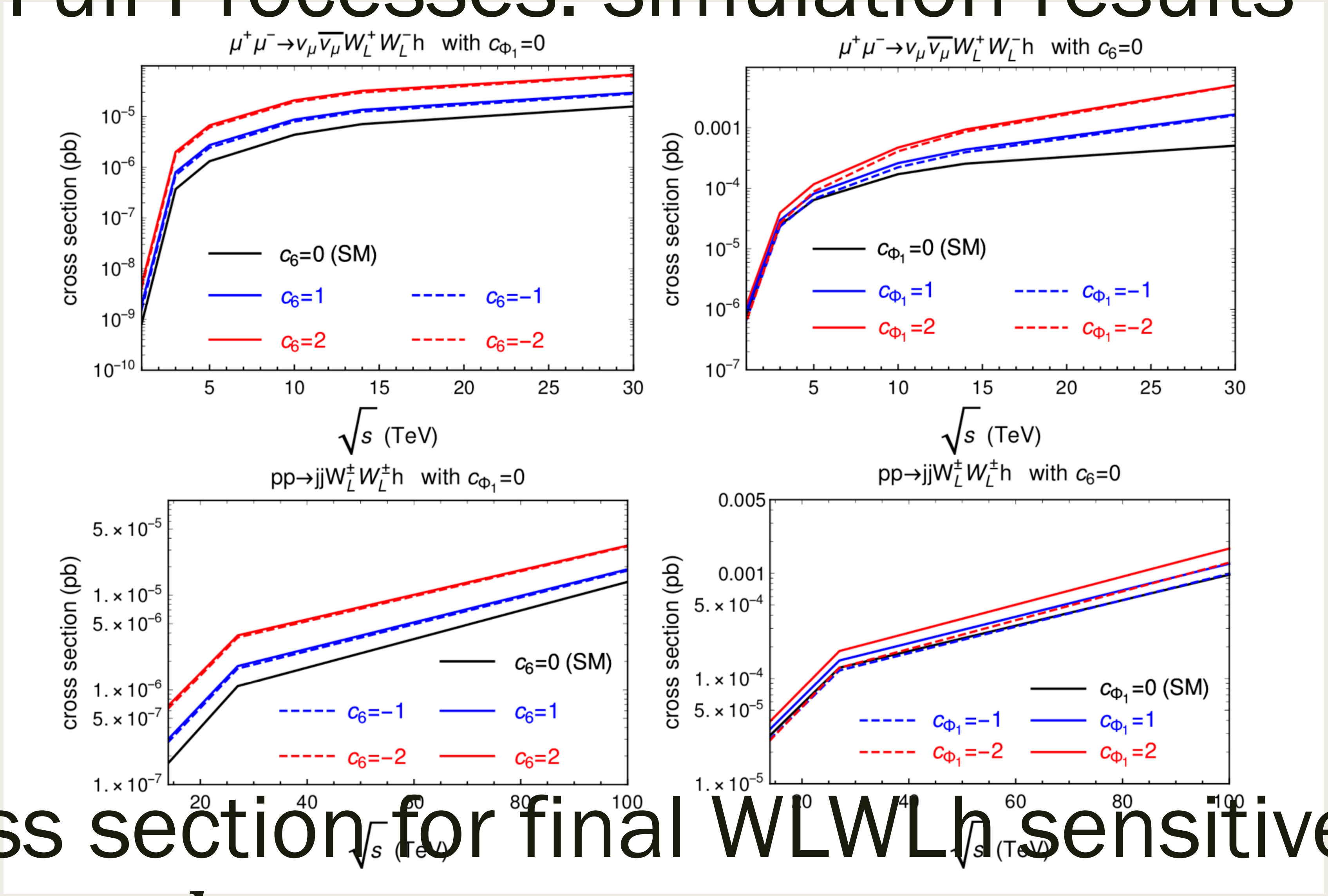
1. Select final vector bosons to be longitudinal
2. Impose PT cuts on final VL to reduce SM background.

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

Table 1: The cross section for $\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu W_L^+ W_L^- h$ with $c_{\Phi_1} = 0$ at different c.m. energies. Five benchmark points of c_6 are displayed in different columns. The cuts $m_{\nu\nu} > 150$ GeV, $p_T(W,h) > 150$ GeV are implemented to obtain these cross sections.

Cross sections (pb) for $\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu W^+ W^- h$ with $c_{\Phi_1} = 0$					
c_6	-2	-1	0	1	2
1 TeV	2.87×10^{-8}	2.51×10^{-8}	2.37×10^{-8}	2.44×10^{-8}	2.73×10^{-8}
3 TeV	2.04×10^{-5}	1.90×10^{-5}	1.85×10^{-5}	1.88×10^{-5}	2.01×10^{-5}
5 TeV	8.18×10^{-5}	7.74×10^{-5}	7.60×10^{-5}	7.72×10^{-5}	8.07×10^{-5}
10 TeV	3.16×10^{-4}	3.02×10^{-4}	3.00×10^{-4}	3.02×10^{-4}	3.13×10^{-4}
14 TeV	5.29×10^{-4}	5.12×10^{-4}	5.03×10^{-4}	5.06×10^{-4}	5.29×10^{-4}
30 TeV	1.38×10^{-3}	1.31×10^{-3}	1.31×10^{-3}	1.33×10^{-3}	1.36×10^{-3}

3.2 Full Processes: simulation results



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

Background Analysis

$$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu W^+ W^- h \quad (WW \text{ fusion}) \,.$$

Channel: $W^\pm \to l^\pm v l\,; \quad W^\mp \to j j'$ $\qquad h \to b\bar{b}$

Signal: $l^\pm j j' b\bar{b} + \mathrm{MET}$

Background

$$\mu^+\mu^- \to t\bar{t}, \quad \nu_\mu \bar{\nu}_\mu t\bar{t}, \quad W^+W^-Z, \quad \nu_\mu \bar{\nu}_\mu W^+W^-Z \quad \text{and} \quad \gamma\gamma \to t\bar{t}$$

3.2 Constraints on c_6 *and* c_{Φ_1}

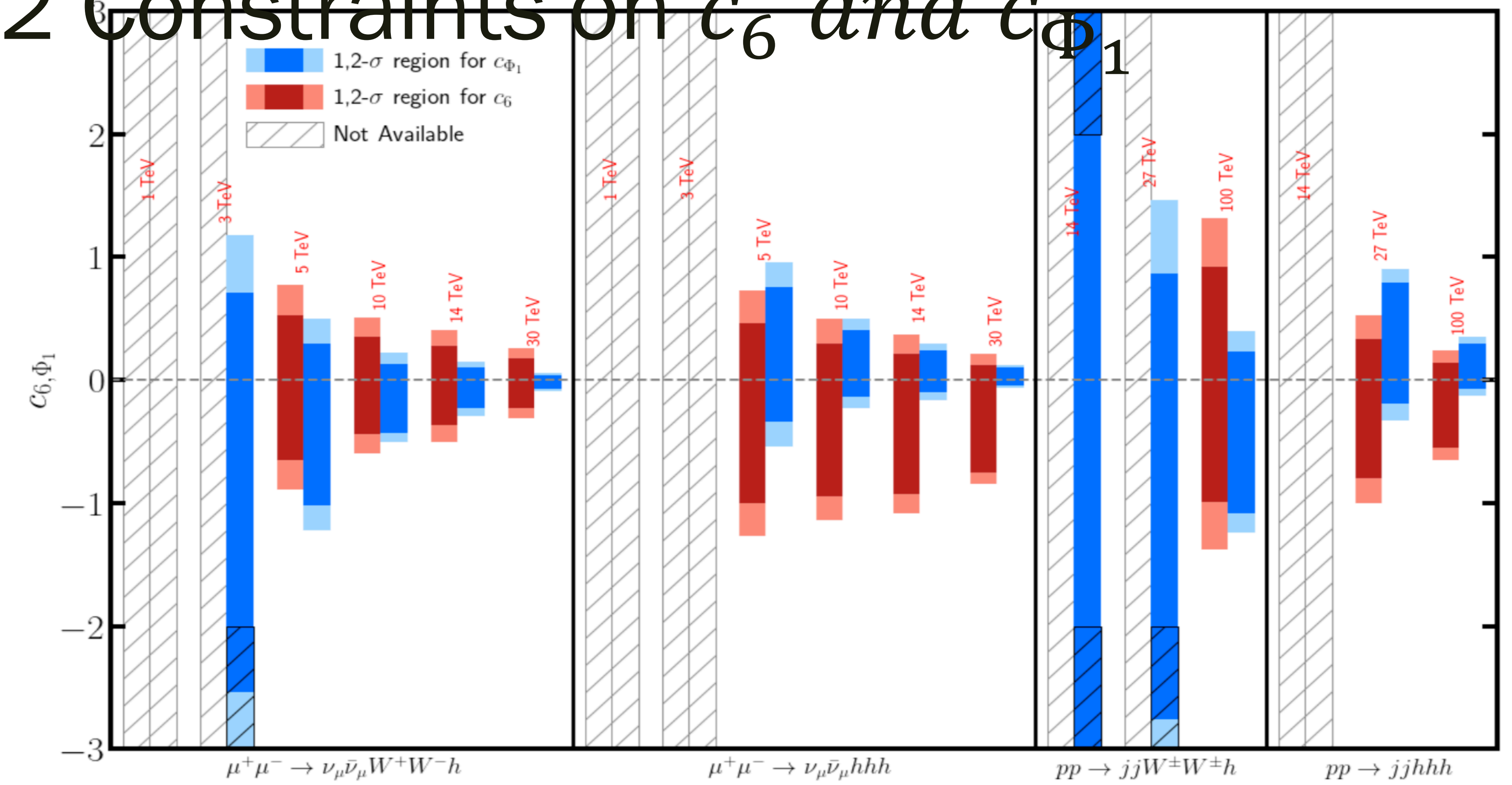


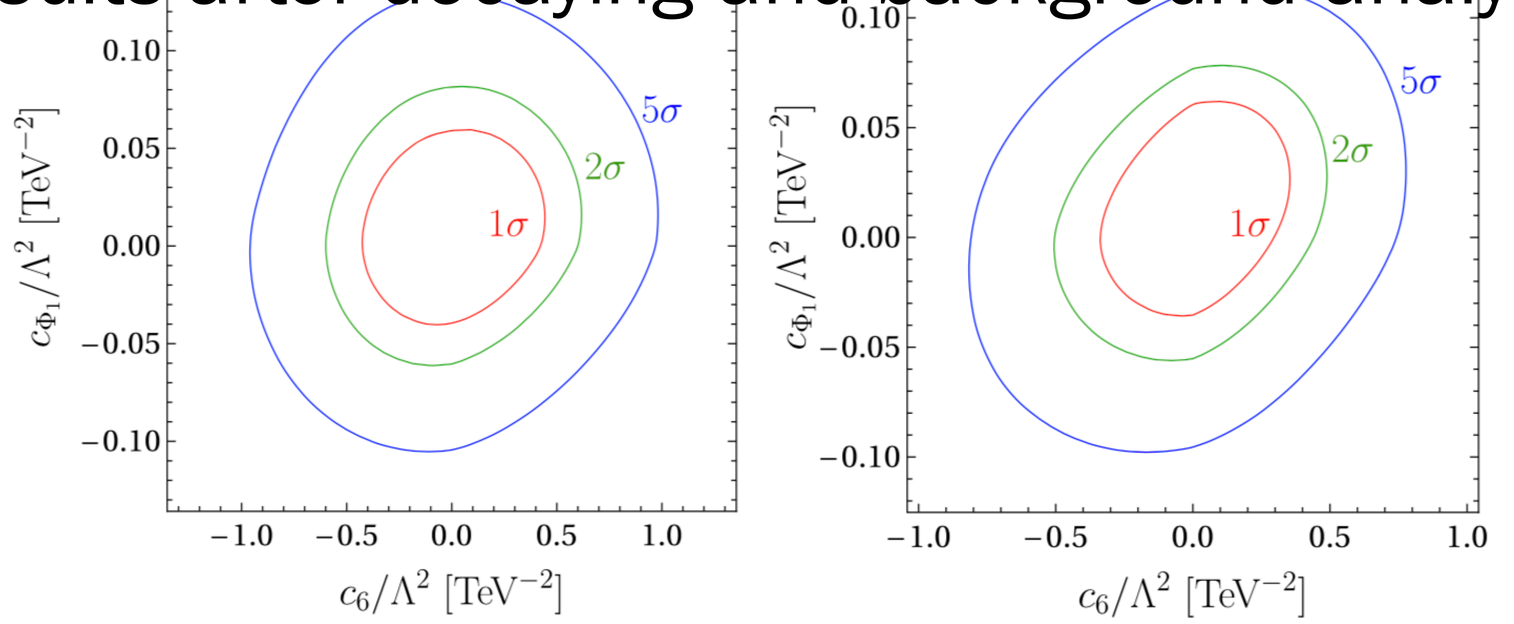
Figure 12: The allowed region for c_6 (red) and c_{Φ_1} (blue) from different channels. The darker color indicates the 1-σ region, while lighter one indicates the 2-σ region. The hatched region are not available either due to low event rate or beyond $[-2, 2]$.

Naive estimation: no decay, no background analysis.

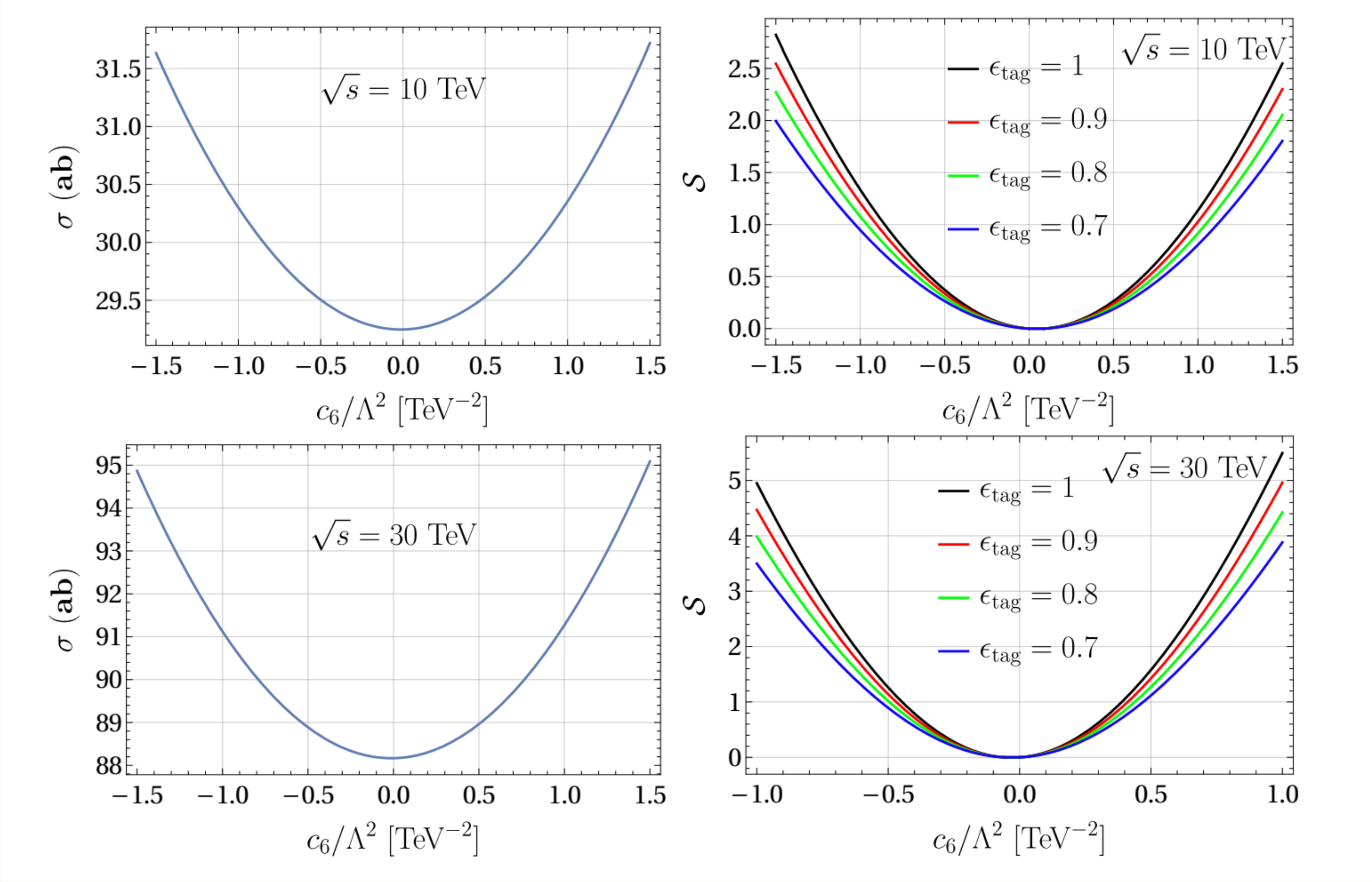
TABLE IV. The summary table of the expected sensitivities to the couplings at 1σ and 2σ for the three processes WWh, ZZh, and hhh for $\sqrt{s} = 10$ TeV and $\sqrt{s} = 30$ TeV. The tagging efficiency of longitudinal polarizations is assumed to be 100%.

Channels	$\sqrt{s}$(TeV)	coupling (TeV^{-2})	1σ	2σ
WWh	10 TeV	c_6/Λ^2	[−0.856, 0.940]	[−1.245, 1.327]
		c_{Φ_1}/Λ^2	[−0.318, 0.424]	[−0.477, 0.571]
	30 TeV	c_6/Λ^2	[−0.447, 0.389]	[−0.627, 0.569]
		c_{Φ_1}/Λ^2	[−0.0378, 0.0657]	[−0.0591, 0.0867]
ZZh	30 TeV	c_6/Λ^2	[−1.329, 1.136]	[−1.881, 1.691]
		c_{Φ_1}/Λ^2	[−0.0688, 0.0852]	[−0.103, 0.119]
hhh	10 TeV	c_6/Λ^2	[−0.926, 0.796]	[−1.316, 1.201]
		c_{Φ_1}/Λ^2	[−0.282, 0.351]	[−0.430, 0.505]
	30 TeV	c_6/Λ^2	[−0.354, 0.342]	[−0.493, 0.458]
		c_{Φ_1}/Λ^2	[−0.0324, 0.0576]	[−0.0545, 0.0760]

Results after decaying and background analysis.



Significance with varying helicity tagging efficiency



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 is very sensitive to new physics on higgs self-couplings.
- Special settings in data and analysis:
  1)select long. pol.; 2)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.
- Similar analysis can be applied to top Yukawa(working on progress)

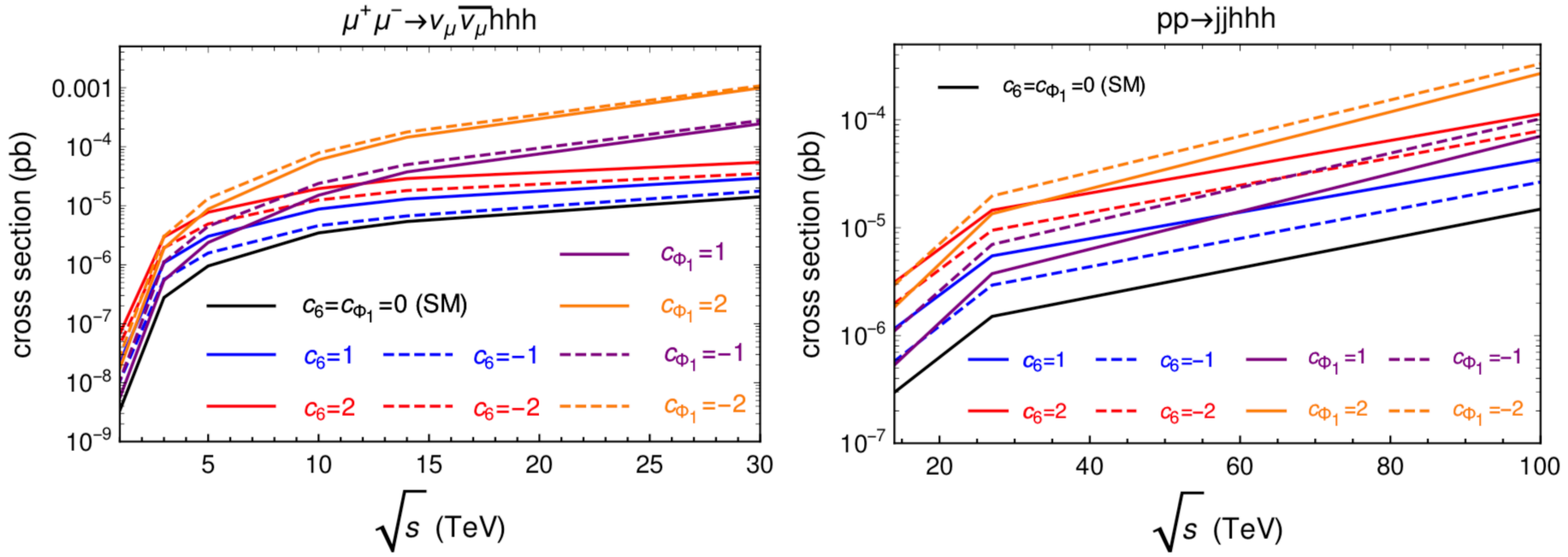


Figure 9: The vary of cross sections for $c_6 = \pm1, \pm2$ with $c_{\Phi_1} = 0$ and $c_{\Phi_1} = \pm1, \pm2$ with $c_6 = 0$ for $\mu^+\mu^- \to \nu_\mu\overline{\nu}_\mu hhh$ from $\sqrt{s} = 1$ to 30 TeV (left panel) and $pp \to jjhhh$ from $\sqrt{s} = 14$ to 100 TeV (right panel).

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