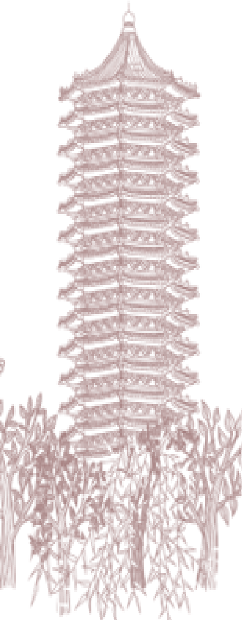
Di-Higgs boson production at lepton colliders



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Based on arXiv: 2306.xxxxx

In collaboration with Qing-Hong Cao, Kun Cheng and Yandong Liu

Higgs-Gauge couplings and unitarity

The correlation of g_{HVV} and g_{HHVV}

Higgs-Gauge Couplings ⟺ **Perturbative Unitarity**

- Giving insight to EWSB mechanism
- The deviation of Higgs-Gauge coupling can indicate New Physics BSM
- Distinguishing different realizations of Higgs mechanism (linear or nonlinear)

- Constraint the mass of Higgs boson

  B. W. Lee, C. Quigg and H. B. Thacker, Phys. Rev. Lett. 38, 883-885 (1977).
  B. W. Lee, C. Quigg and H. B. Thacker, Phys. Rev. D 16, 1519 (1977).

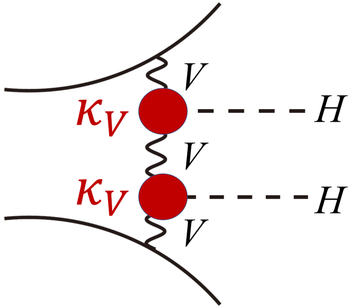
- Using the unitarity relation to bound the scale of new physics

VBF di-Higgs production process

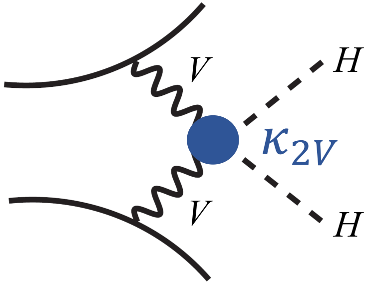
Define κ_V and κ_{2V} : $\kappa_V = \frac{g_{HVV}}{g_{HVV}^{\text{SM}}}$, $\kappa_{2V} = \frac{g_{HHVV}}{g_{HHVV}^{\text{SM}}}$

$$g_{HVV}^{\text{SM}} = \frac{2m_V^2}{v}, \quad g_{HHVV}^{\text{SM}} = \frac{2m_V^2}{v^2} \qquad v = 246\text{GeV} \quad V = W, Z$$

Three point Higgs-Gauge coupling:

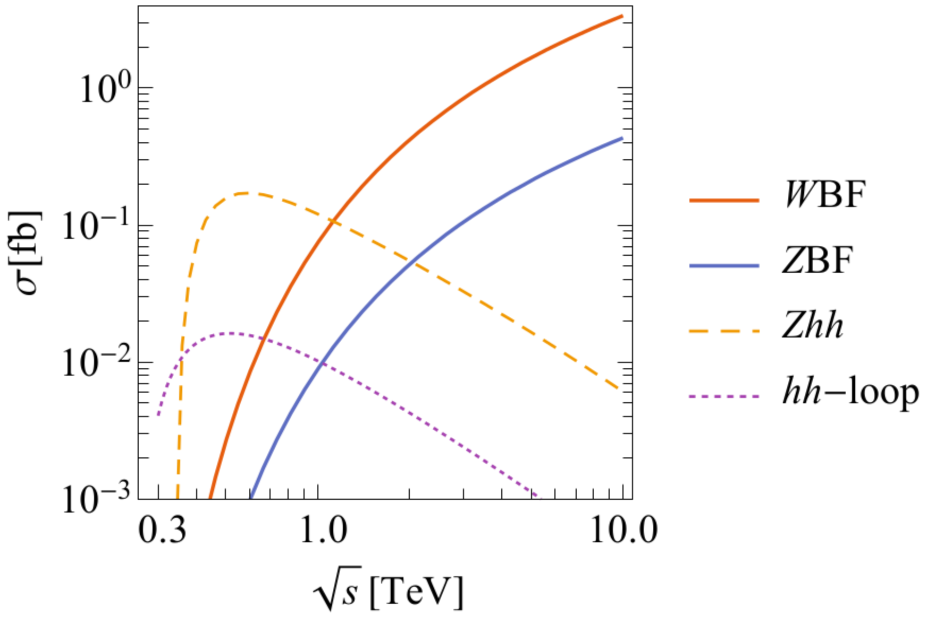


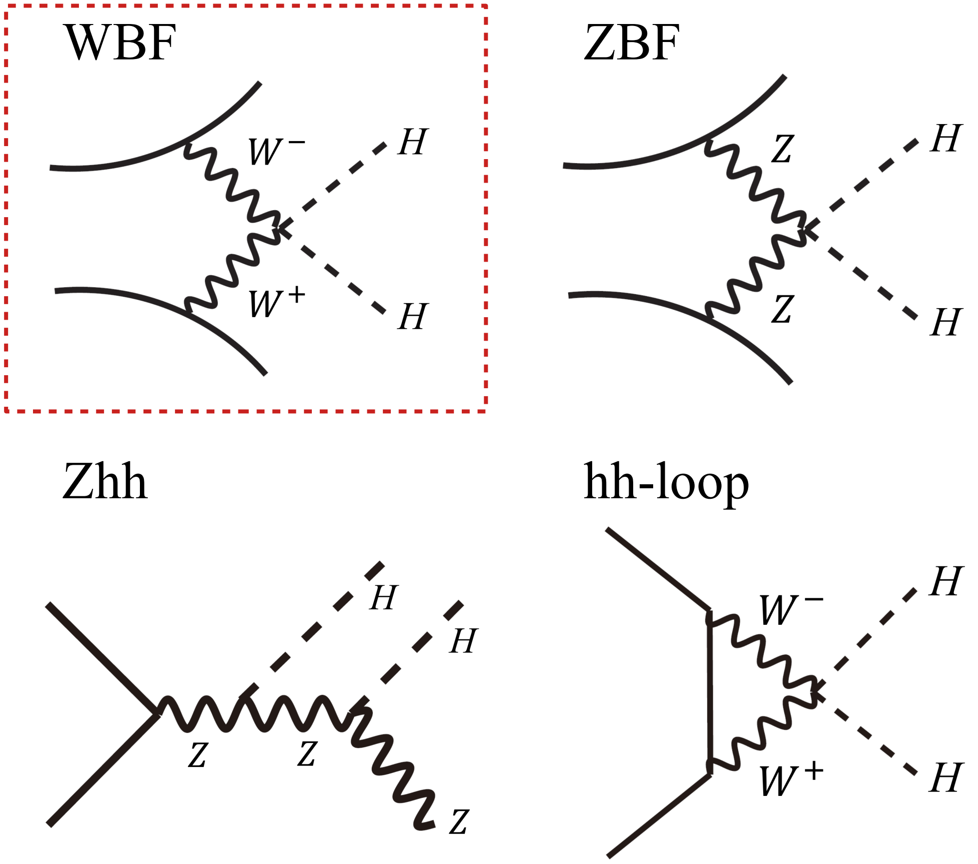
Four point Higgs-Gauge coupling:



We can use the VBF kind di-Higgs production process to measure Higgs-Gauge couplings.

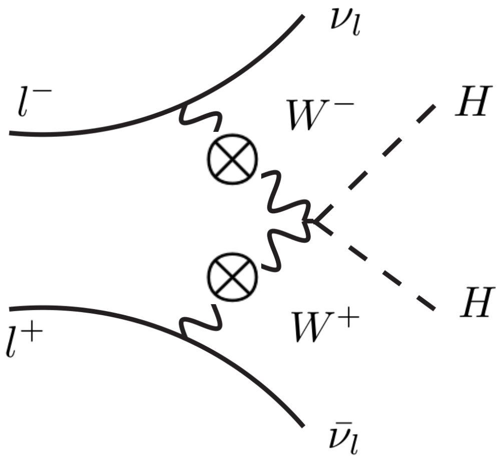
W-mediated VBF at lepton colliders





The charged current VBF process has larger cross section than the neutral current case.

Unitarity sum rule



Effective W Approximation (EWA): Full process = PDF ⊗ Subprocess

$$\sigma(l^- l^+ \to \nu_l \bar{\nu}_l HH) = \sum_{i,j} \int \mathrm{d}x_1 \mathrm{d}x_2 P^i_{W^-/l^-}(x_1) P^j_{W^+/l^+}(x_2) \sigma(W_i^- W_j^+ \to HH)$$

Here *P* is the probability distribution function, *x* is energy fraction, *i, j* are polarization indexes.

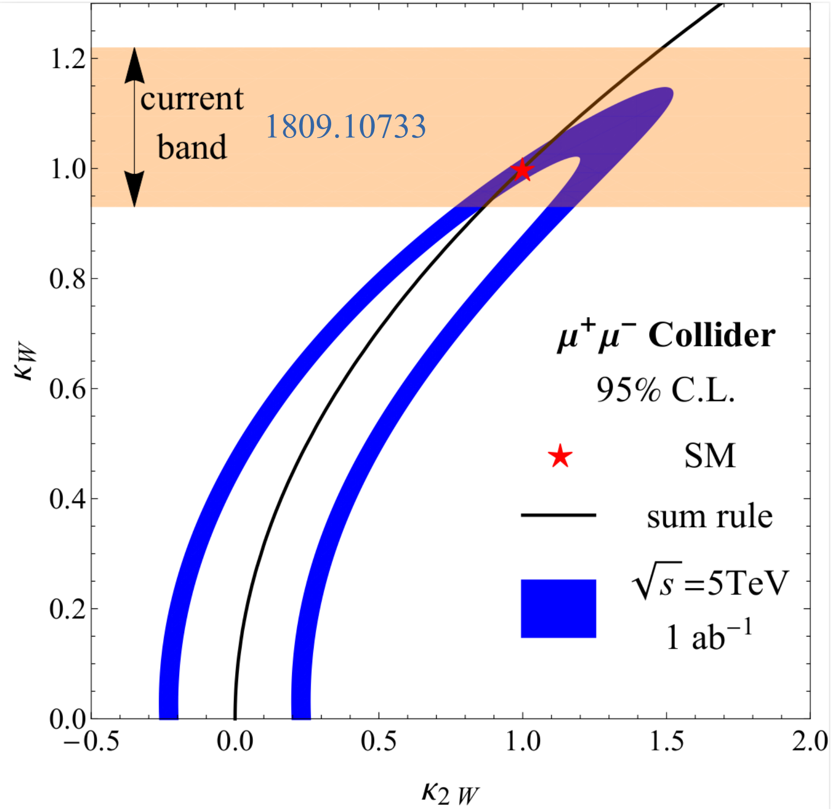
Due to the factorization, the subprocess can help to dig into the nature of the full process.

Amplitude of the subprocess (at high energy limit): $M \to \frac{s}{v^2}(\kappa_{2W} - \kappa_W^2), \quad s = E^2$

The unitarity requires the amplitude stays finite under infinite collision energy

Unitarity sum rule $$\kappa_{2W} - \kappa_W^2 = 0$$

Constraint on Higgs-Gauge couplings



We performed the simulation for the full process:

$$l^+l^- \to \bar{\nu}_l \nu_l HH$$

Define signal strength μ : $\mu \equiv \frac{\sigma(\kappa_{2W}, \kappa_W)}{\sigma_{SM}}$

95 % C.L. corresponds: $0.76 \leq \mu \leq 1.26$

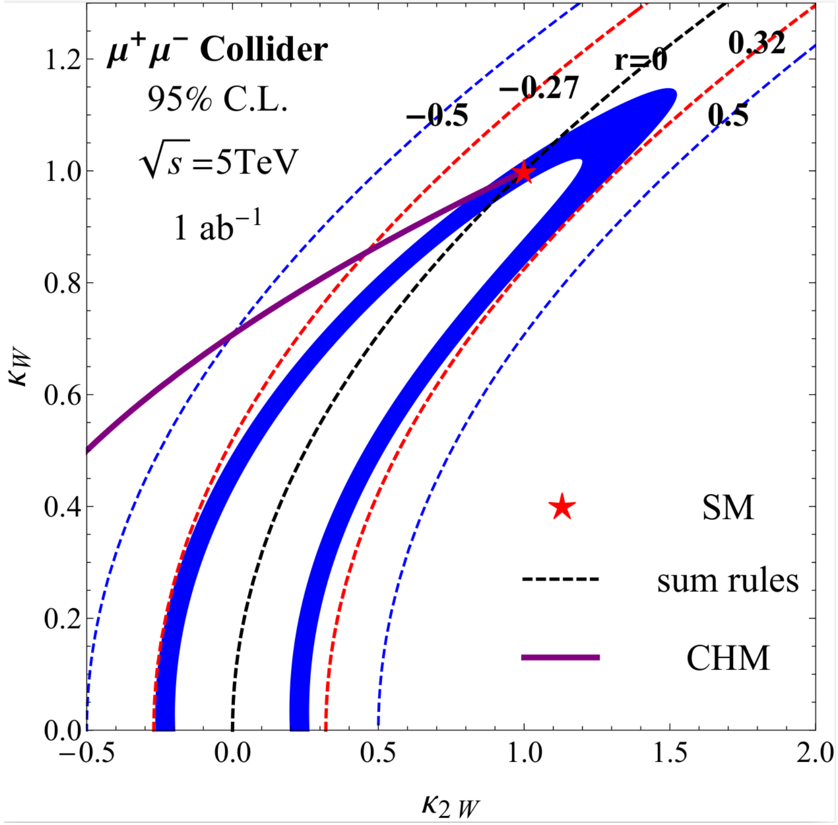
Constraint on κ_{2W} with respect to current κ_W :

$$0.93 \leq \kappa_W \leq 1.22, \quad 0.76 \leq \kappa_{2W} \leq 1.60$$

Constraint on κ_W and κ_{2W} based on the unitarity sum rule:

$$0.94 \leq \kappa_W \leq 1.05, \quad 0.89 \leq \kappa_{2W} \leq 1.11$$

Results on unitarity and CHM



r: monitor the unitarity violation effects

$$r = \kappa_{2W} - \kappa_W^2$$

Unitarity violation scale: $-0.27 \leq r \leq 0.32$

- Composite Higgs Model (CHM):

$$\kappa_W = \sqrt{1-\xi}, \quad \kappa_{2W} = 1-2\xi, \quad \xi = \frac{v^2}{f^2}$$

$$\kappa_{2W} - \kappa_W^2 = -\xi \quad \Rightarrow \quad r = -\xi$$

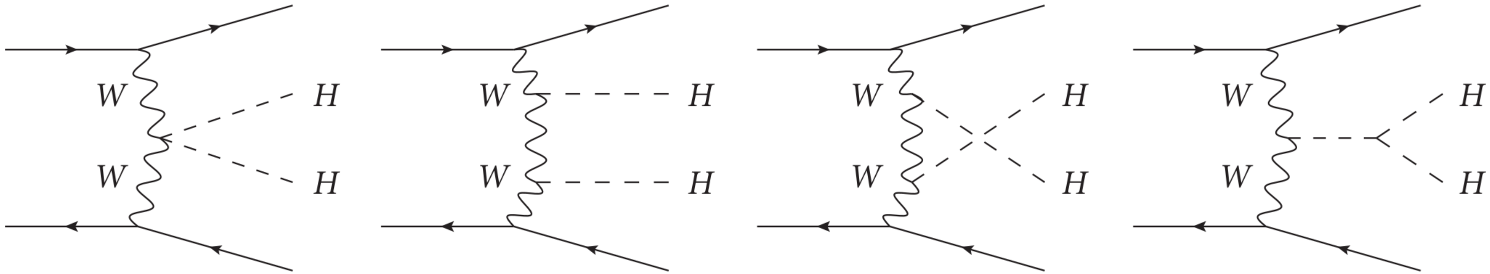
Constraint on ξ and compositeness scale f:

$$0 \leq \xi \leq 0.078, \qquad f \geq 0.88\text{TeV}$$

Summary

- Using **correlation** of κ_{2W} and κ_W to study Higgs-Gauge couplings and unitarity bound.

- Consider the ***W*-mediated Vector Boson Fusion di-Higgs** process at **lepton colliders**.



- Based on the unitarity sum rule, we get **constraint on** κ_W **and** κ_{2W} **:**

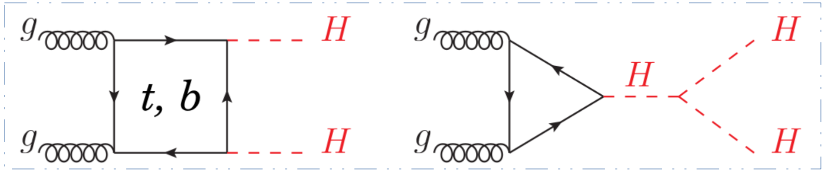
$$0.94 \leq \kappa_W \leq 1.05, \quad 0.89 \leq \kappa_{2W} \leq 1.11$$

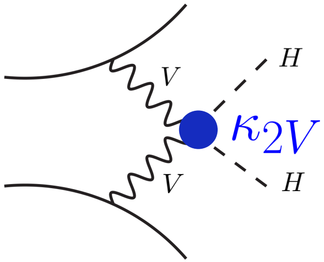
Thank you!

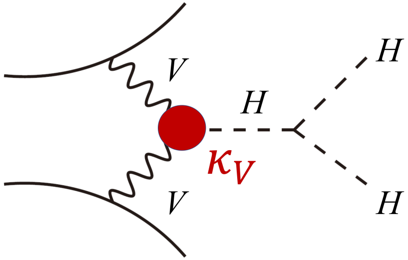
Back up

At hadron colliders:

Large background







Full simulation

TABLE I: Cut flow for the SM $\nu\bar{\nu}hh$ di-Higgs signal and backgrounds cross sections at 1 TeV electron-positron collider (left) and 5 TeV muon collider (right).

σ [ab]	pre-cuts	m_{bb} cut	HHCUT	$M_{\rm recoil}$ cut
Sig.	15.9	9.7	8.3	5.7
$\nu\nu hZ$	54.4	11.1	6.3	5.5
$\nu\nu ZZ$	73.7	9.1	3.1	2.9
$\nu W^{\pm}h$	45.2	3.9	2.3	2.3
$\nu W^{\pm}Z$	47.0	2.5	1.1	1.1
Bkg.	-	-	-	11.8

σ [ab]	pre-cuts	m_{bb} cut	HHCUT	$M_{\rm recoil}$ cut
Sig.	267.6	146.4	126.8	126.5
$\nu\nu hZ$	679.1	103.3	61.3	61.0
$\nu\nu ZZ$	936.2	82.0	25.3	25.3
$\nu W^{\pm}h$	342.7	17.9	8.9	8.9
$\nu W^{\pm}Z$	315.2	14.7	6.5	6.0
Bkg.	-	-	-	101.2

$$n^{\ell}(p_T > 10\,\text{GeV}) = 0, \quad \not{E}_T > 10\,\text{GeV},$$

$$p_T^{jet} > 15\ \text{GeV}, \quad -4.0 < \eta^{jet} < 4.0, \ \Delta R^{mn} > 0.5,$$

$$100\,\text{GeV} < m_{bb} < 150\,\text{GeV}$$

$$\chi^2(m_h, m_h) < \chi^2(m_Z, m_Z),$$

$$\chi^2(m_h, m_h) < \chi^2(m_h, m_Z).$$

$$M_{\rm recoil} \equiv \sqrt{(p_1 + p_2 - p_{h_1} - p_{h_2})^2} > 200\,\text{GeV},$$

TABLE II: Cut flow for the SM $\nu_e\bar{\nu}_\mu hh$ di-Higgs signal and backgrounds cross sections at $e\mu$ collider with $E_e = 100\,\text{GeV}$, $E_\mu = 2.5\,\text{TeV}$ (left) and $E_e = 170\,\text{GeV}$, $E_\mu = 6\,\text{TeV}$ (right).

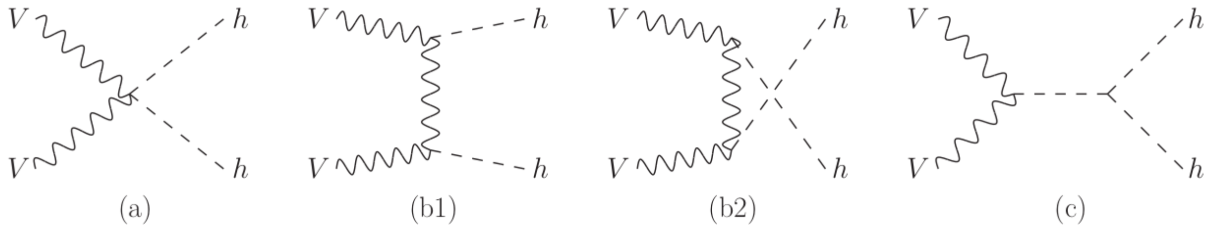
σ [ab]	pre-cuts	m_{bb} cut	HHCUT
$\nu\nu hh(\to bbbb)$	12.2	6.8	5.5
$\nu\nu hZ$	49.8	9.3	5.2
$\nu\nu ZZ$	66.1	8.3	2.8
$\nu W^{\pm}h$	36.8	2.8	1.4
$\nu W^{\pm}Z$	40.2	2.2	0.9
Bkg.	-	-	10.4

σ [ab]	pre-cuts	m_{bb} cut	HHCUT
$\nu\nu hh(\to bbbb)$	69.9	37.6	31.5
$\nu\nu hZ$	205.5	33.1	19.3
$\nu\nu ZZ$	298.1	30.6	10.4
$\nu W^{\pm}h$	143.6	9.9	6.6
$\nu W^{\pm}Z$	139.6	6.5	2.8
Bkg.	-	-	39.1

$$\chi^2(m_1, m_2) \equiv \min_{i,j,k,l} \left[(m_{b_ib_j} - m_1)^2 + (m_{b_kb_l} - m_2)^2\right]$$

$$n^{\ell}(p_T > 10\,\text{GeV}) = 0, \quad \not{E}_T > 10\,\text{GeV},$$

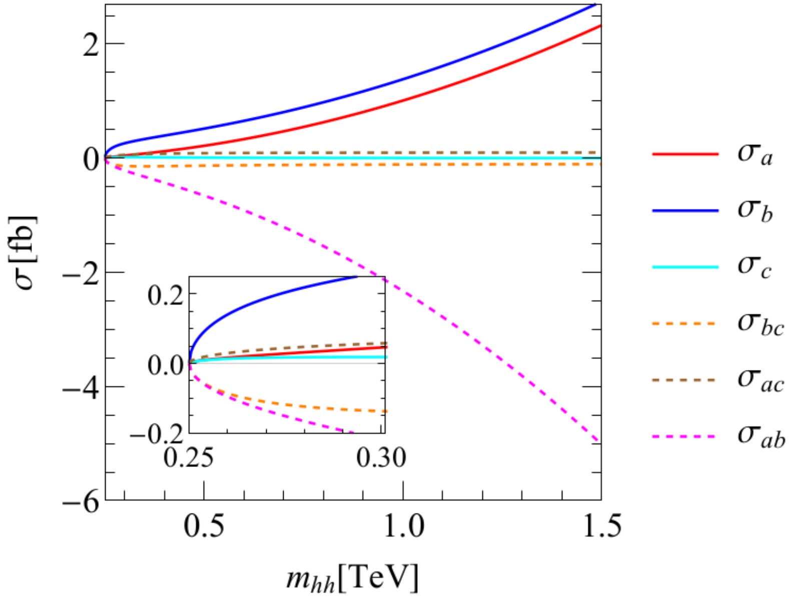
$$p_T^{jet} > 15\,\text{GeV}, -3.0 < \eta^{jet} < 5.0, \ \Delta R^{mn} > 0.5.$$

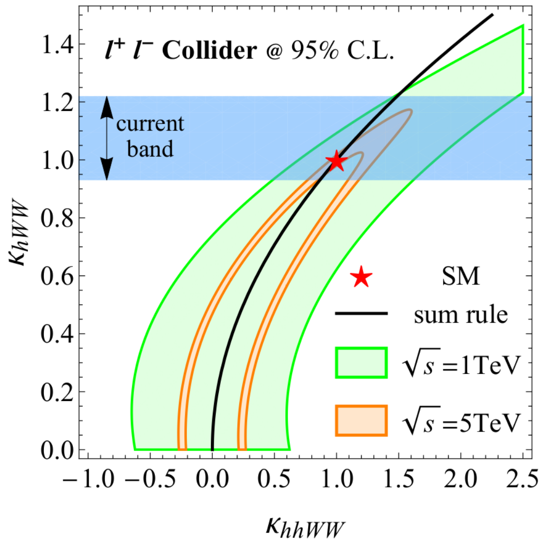


$$\sigma(W^+W^- \to hh) = \kappa_{hhWW}^2\sigma_a + \kappa_{hWW}^4\sigma_b + \kappa_{hWW}^2\kappa_h^2\sigma_c + \kappa_{hhWW}\kappa_{hWW}^2\sigma_{ab} + \kappa_{hhWW}\kappa_{hWW}\kappa_h\sigma_{ac} + \kappa_{hWW}^3\kappa_h\sigma_{bc},$$

TABLE I: Cross section of $l^-l^+ \to \nu_l\bar{\nu}_l hh$

cross section [fb]	σ_a	σ_b	σ_c	σ_{ab}	σ_{bc}	σ_{ac}
1 TeV e^+e^- collider	0.54	1.41	0.09	−1.69	−0.62	0.35
1 TeV $e\mu$ collider	0.54	1.41	0.09	−1.69	−0.62	0.35
2 TeV $e\mu$ collider	4.80	9.02	0.34	−12.72	−2.53	1.53
5 TeV $\mu^+\mu^-$ collider	41.70	56.94	0.68	−95.47	−7.38	5.17





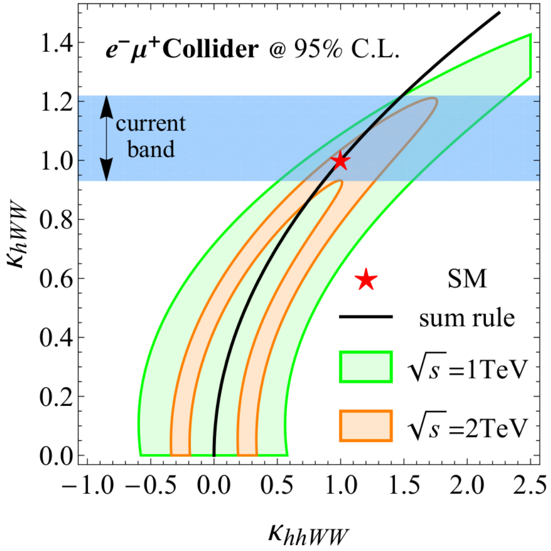


TABLE IV: Constraint on μ at 95% C.L. at different lepton colliders.

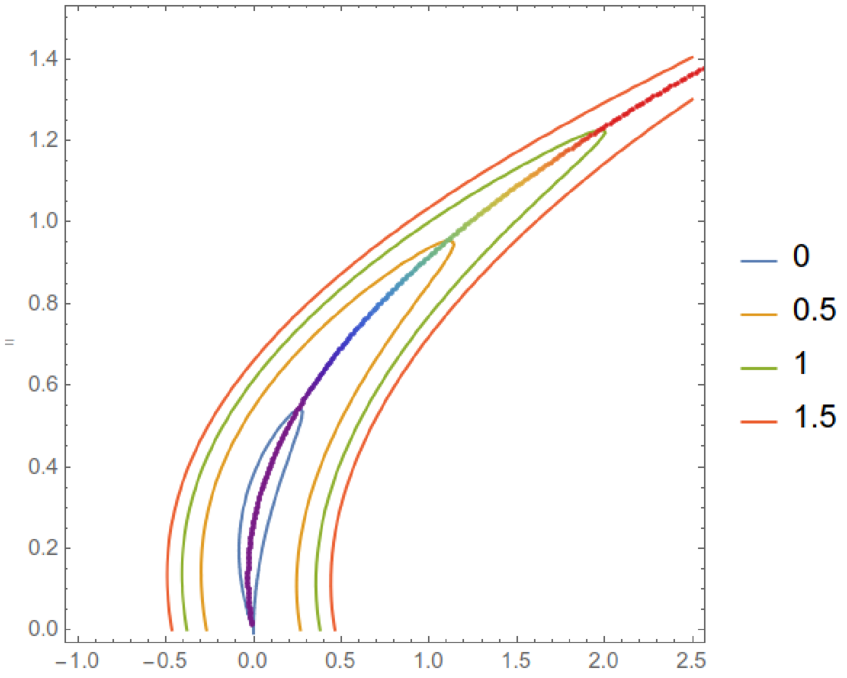
	$\sqrt{s} = 1\,\text{TeV}$ e^+e^- collider	$\sqrt{s} = 5\,\text{TeV}$ $\mu^+\mu^-$collider	$\sqrt{s} = 1\,\text{TeV}$ $e\mu$ collider	$\sqrt{s} = 2\,\text{TeV}$ $e\mu$ collider
μ	$-0.29 \le \mu \le 2.78$	$0.76 \le \mu \le 1.26$	$-0.21 \le \mu \le 2.70$	$0.50 \le \mu \le 1.58$

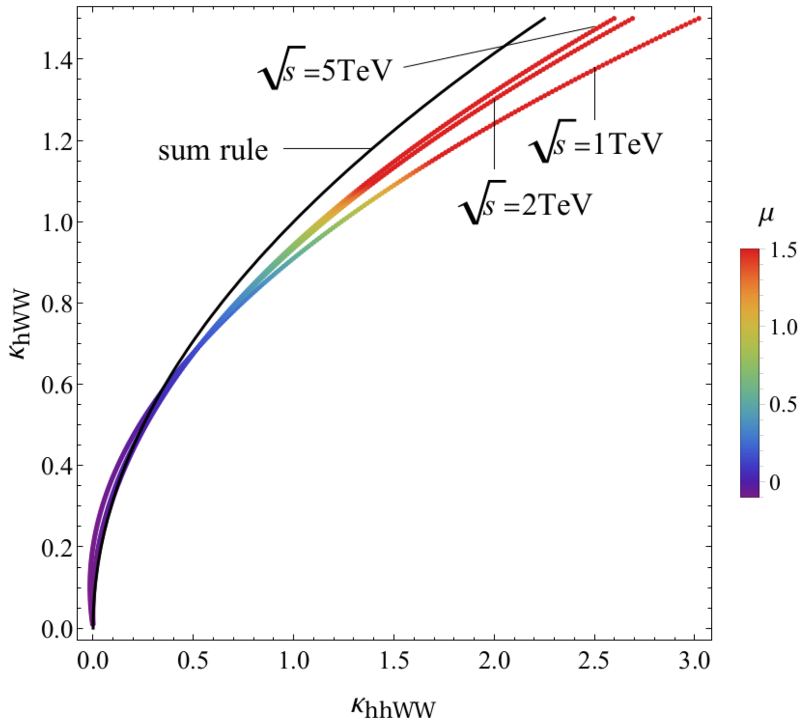
TABLE V: Constraint on κ_{hhWW} with respect to current κ_{hWW} result at 95% C.L.

	$\sqrt{s} = 1\,\text{TeV}$ e^+e^- collider	$\sqrt{s} = 5\,\text{TeV}$ $\mu^+\mu^-$collider	$\sqrt{s} = 1\,\text{TeV}$ $e\mu$ collider	$\sqrt{s} = 2\,\text{TeV}$ $e\mu$ collider
κ_{hWW}	[0.93,1.22]	[0.93,1.22]	[0.93,1.22]	[0.93,1.22]
κ_{hhWW}	[0.48,2.46]	[0.76,1.60]	[0.51,2.32]	[0.71,1.76]

TABLE VI: Constraint on κ_{hWW} and κ_{hhWW} at 95% C.L. under the unitarity sum rule

	$\sqrt{s} = 1\,\text{TeV}$ e^+e^- collider	$\sqrt{s} = 5\,\text{TeV}$ $\mu^+\mu^-$collider	$\sqrt{s} = 1\,\text{TeV}$ $e\mu$ collider	$\sqrt{s} = 2\,\text{TeV}$ $e\mu$ collider
κ_{hWW}	[0,1.23]	[0.94,1.05]	[0,1.21]	[0.86,1.10]
κ_{hhWW}	[0,1.52]	[0.89,1.11]	[0,1.48]	[0.74,1.21]


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
0
0.5
1
1.5


$\sqrt{s}$ =5TeV
sum rule
$\sqrt{s}$ =1TeV
$\sqrt{s}$ =2TeV
κ_{hWW}
κ_{hhWW}
μ
1.5
1.0
0.5
0
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0

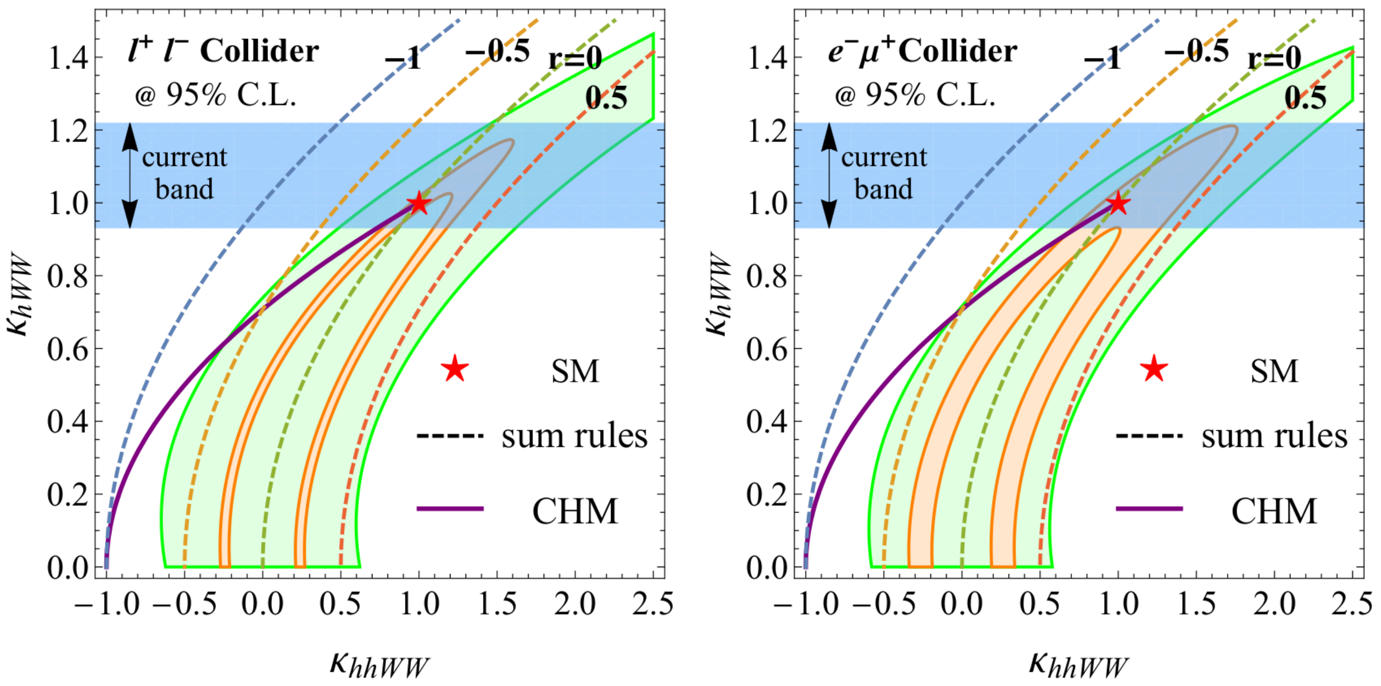
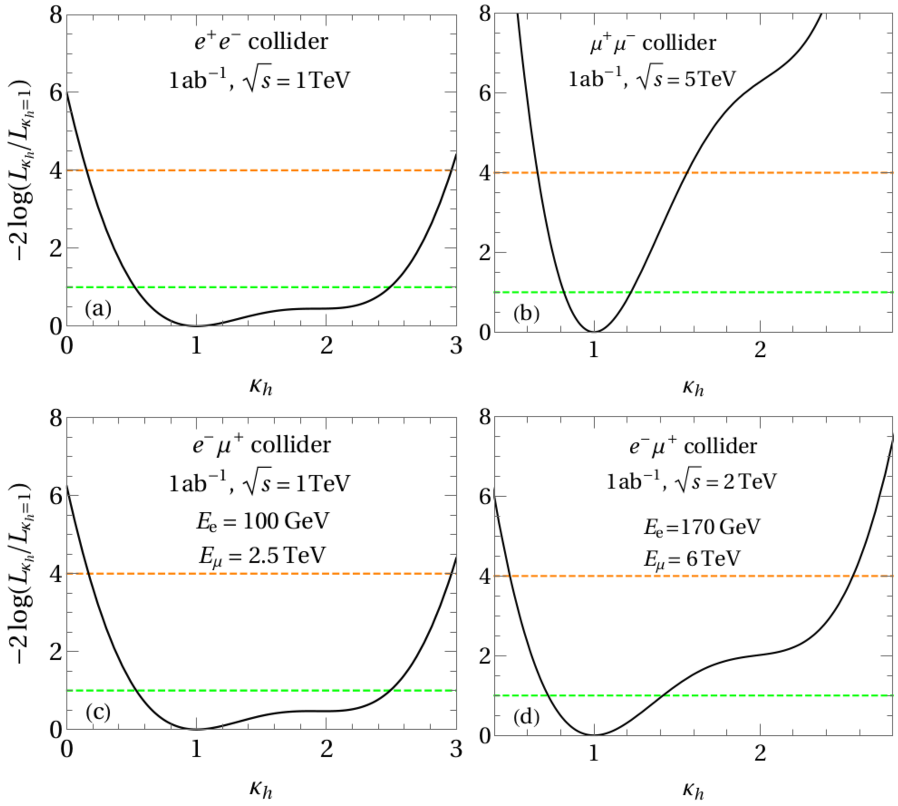
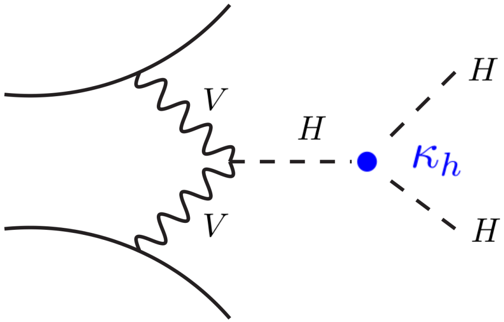


TABLE VII: Constraint on ξ at 95% C.L.

	$\sqrt{s} = 1\,\text{TeV}$ e^+e^- collider	$\sqrt{s} = 5\,\text{TeV}$ $\mu^+\mu^-$ collider	$\sqrt{s} = 1\,\text{TeV}$ $e\mu$ collider	$\sqrt{s} = 2\,\text{TeV}$ $e\mu$ collider
ξ	[0,0.62]	[0,0.078]	[0,0.53]	[0,0.166]

Results on Higgs trilinear self-couplings





	κ_h@95%C.L.
1TeVe^+e^-	[0.15,2.96]
5TeV$\mu^+\mu^-$	[0.66,1.56]

	κ_h@95%C.L.
1TeV$e\mu$	[0.17,2.96]
2TeV$e\mu$	[0.49,2.56]

$$0.66 \le \kappa_h \le 1.56$$

HL-LHC:

$$-0.18 \le \kappa_h \le 3.6$$

Previous studies on higgs gauge and self-coupling

Constraint on g_HWW: Single Higgs production and following decay

$0.93 < \kappa_{\mathrm{hWW}} < 1.22$ $0.87 < \kappa_{\mathrm{hZZ}} < 1.10$ 1809.10733

Constraint on g_HHH: Di-Higgs boson production process

$(\mathrm{ATLAS}) - 1.5 < \kappa_h < 6.7$ ATLAS Collaboration, ATLAS-CONF-2021-016 (2021)

$(\mathrm{CMS}) - 3.3 < \kappa_h < 8.5$ 2011.12373

Constraint on g_HHWW: VBF kind Di-Higgs boson production

$-1.3 < \kappa_{\mathrm{hhWW}} < 3.5$ 2011.12373

CLIC: 0.75<kh<1.45, 0.94<k2v<1.08 1901.05897

e-p collider:(1.3TeV) 0.96<kv<1.04 2207.03862