Electroweak Couplings of the Higgs Boson at a Multi-TeV Muon Collider

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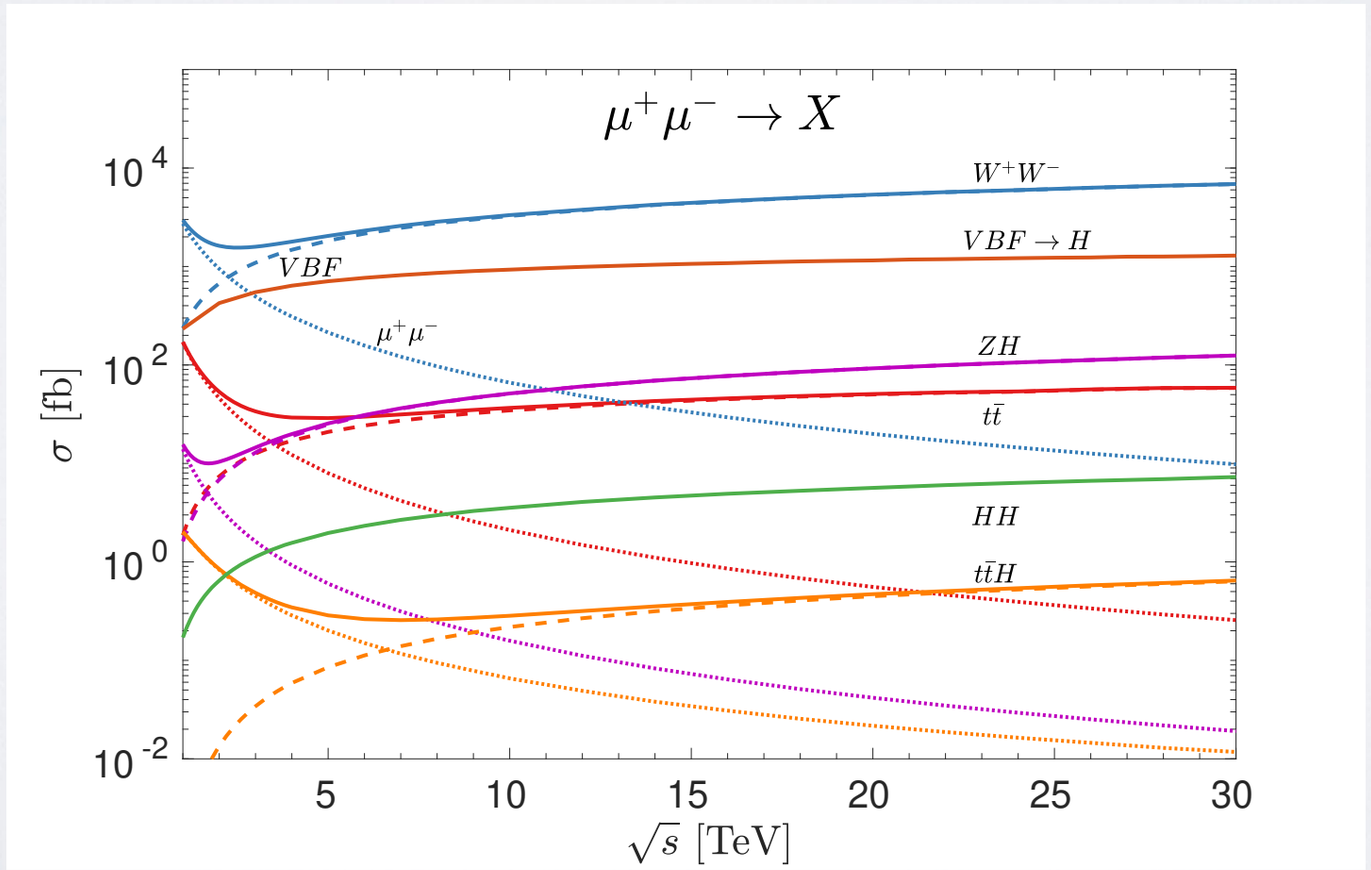
- Conclusion

Muon Collider

$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90

$$\text{Lumi.} > \frac{5 \text{ years}}{\text{time}} \left(\frac{\sqrt{s}}{10 \text{ TeV}}\right)^2 \; 2 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$$



Muon Collider

$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
σ (fb): $WW \to H$	490	700	830	950	1200
$ZZ \to H$	51	72	89	96	120
$WW \to HH$	0.80	1.8	3.2	4.3	6.7
$ZZ \to HH$	0.11	0.24	0.43	0.57	0.91

$\mathcal{O}(10^6 - 10^8)$ Higgs $\Rightarrow \mathcal{O}(10^{-3} - 10^{-4})$ precision

$\mathcal{O}(10^3 - 10^5)$ di-Higgs $\Rightarrow \mathcal{O}(10^{-2} - 10^{-3})$ precision

Higgs and BSM

$$\mathcal{L} \supset \left(M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu \right) \left(\kappa_V \frac{2H}{v} + \kappa_{V_2} \frac{H^2}{v^2} \right) - \frac{m_H^2}{2v} \left(\kappa_3 H^3 + \frac{1}{4v} \kappa_4 H^4 \right)$$

- In terms of dim-6 EFT

$$\mathcal{O}_H = \frac{c_H}{2\Lambda^2} \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi) \ , \quad \mathcal{O}_6 = -\frac{c_6 \lambda}{\Lambda^2} (\Phi^\dagger \Phi)^3$$

$$\Delta\kappa_V = -\frac{c_H}{2} \frac{v^2}{\Lambda^2} \ , \qquad \Delta\kappa_{V2} = -2 c_H \frac{v^2}{\Lambda^2},$$

$$\Delta\kappa_3 \approx -\frac{3 c_H}{2} \frac{v^2}{\Lambda^2} + c_6 \frac{v^2}{\Lambda^2} \ , \qquad \Delta\kappa_4 \approx -\frac{25}{9} c_H \frac{v^2}{\Lambda^2} + 6 c_6 \frac{v^2}{\Lambda^2}$$

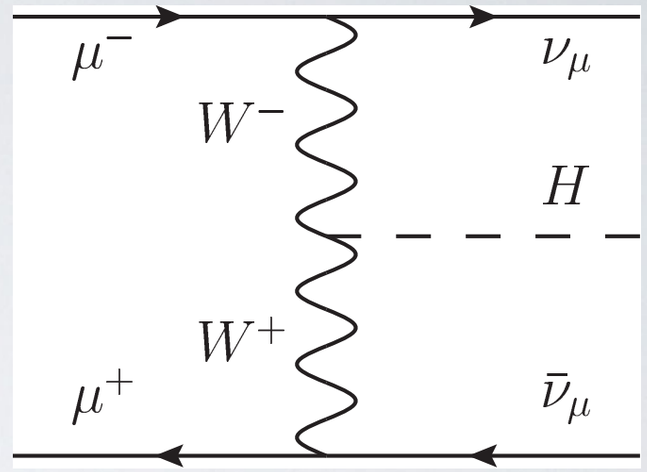
- Currently at LHC

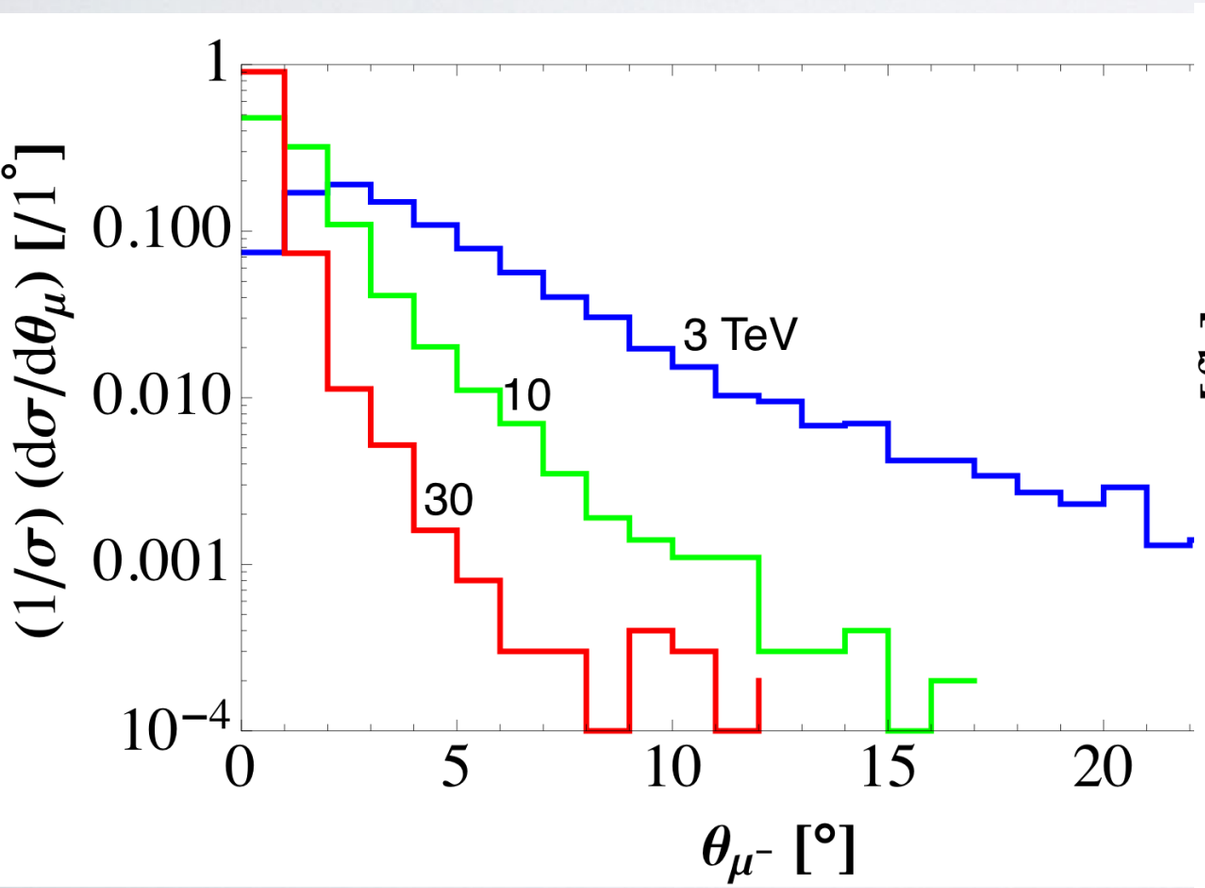
$$\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right) \sim \mathcal{O}(5\%) \qquad \text{for} \quad \Lambda \sim 1 \ \text{TeV}$$

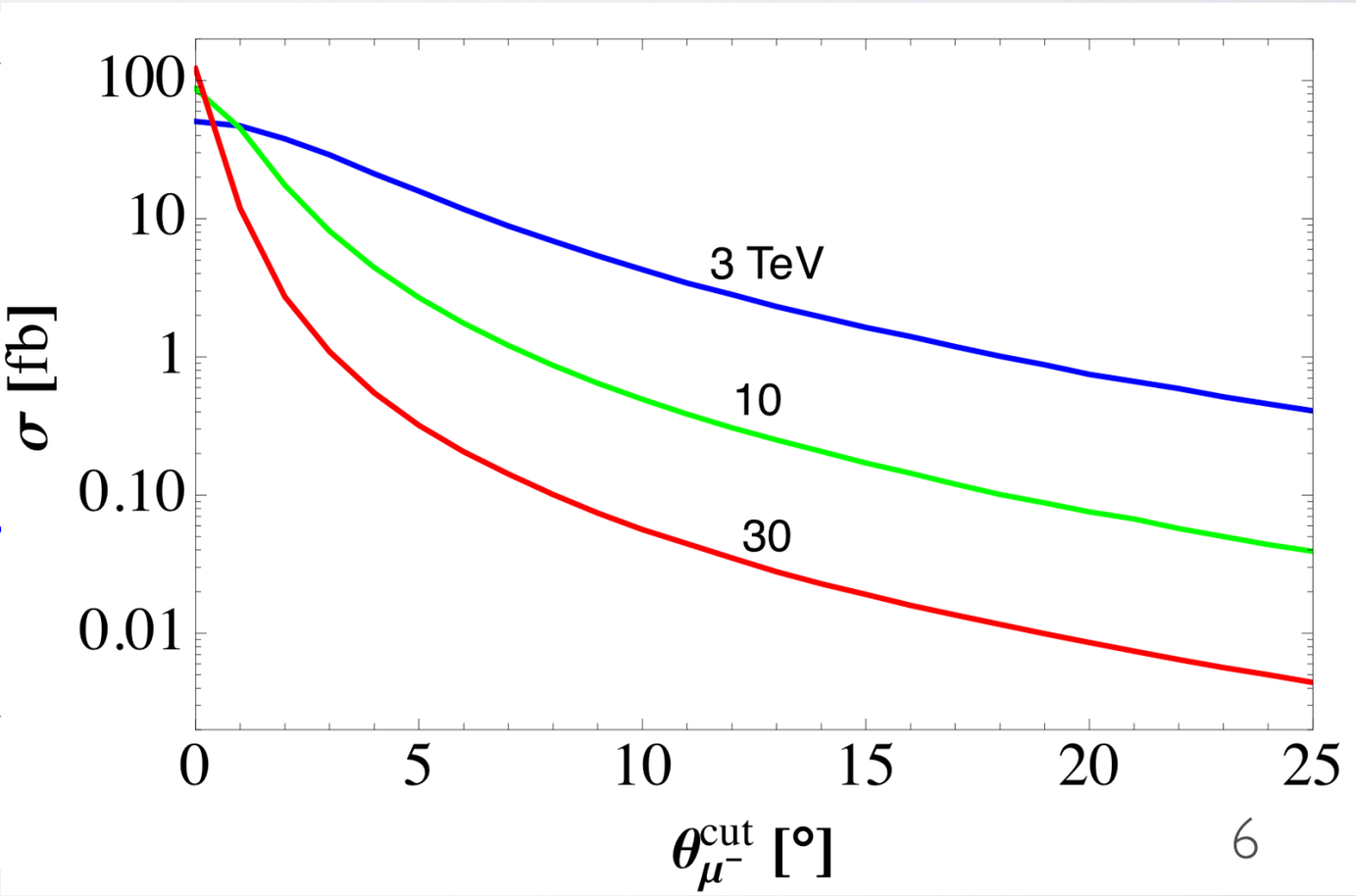
Single Higgs Production

$$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu \, H \qquad (WW \text{ fusion}),$$

$$\mu^+\mu^- \to \mu^+\mu^- \, H \qquad (ZZ \text{ fusion}).$$





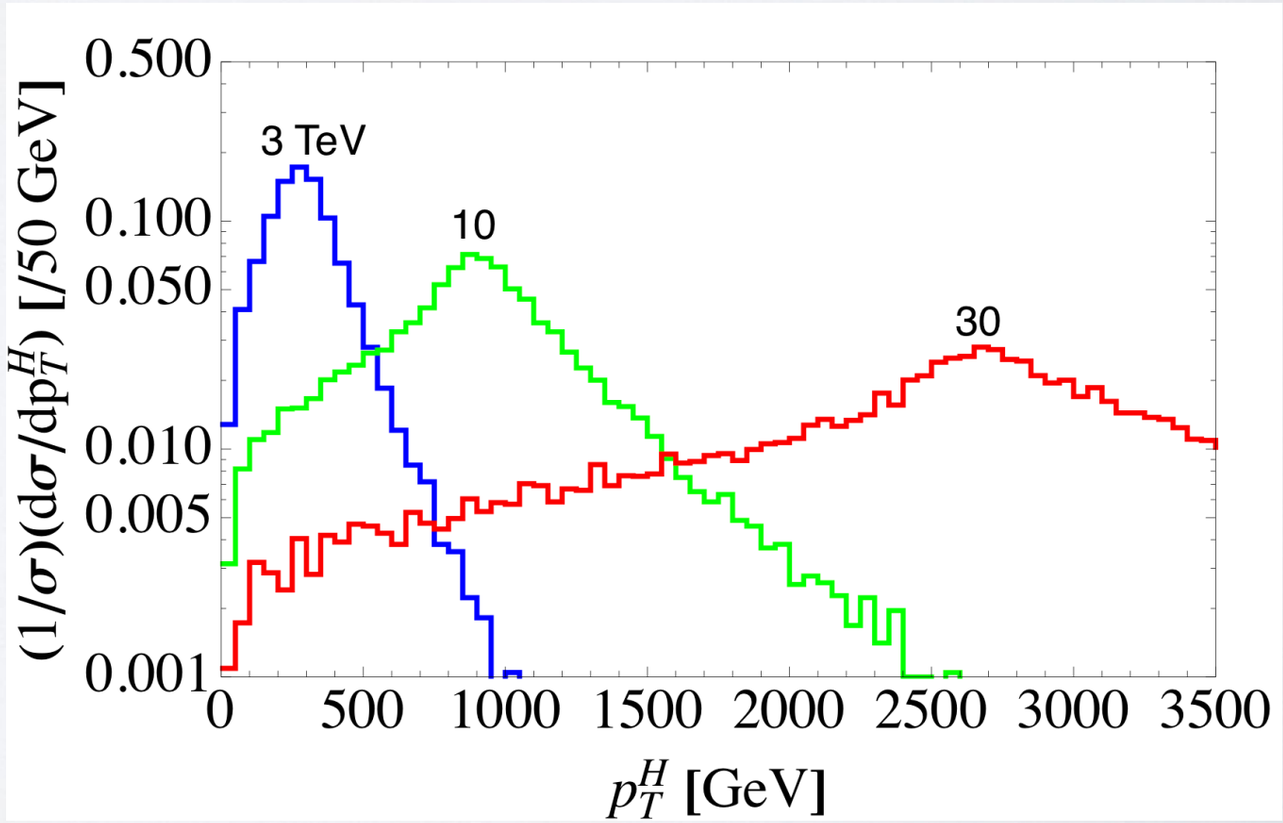


Single Higgs Production

- **Inclusive channel:** events from WW fusion and from ZZ fusion without detecting muons
- **Exclusive 1μ channel:** events from ZZ fusion with at least one muon detected.

$$10^\circ < \theta_{\mu^\pm} < 170^\circ$$

$$p_T^\mu > 0.17 E_\mu$$



Single Higgs Production

- Focus on the leading decay channel

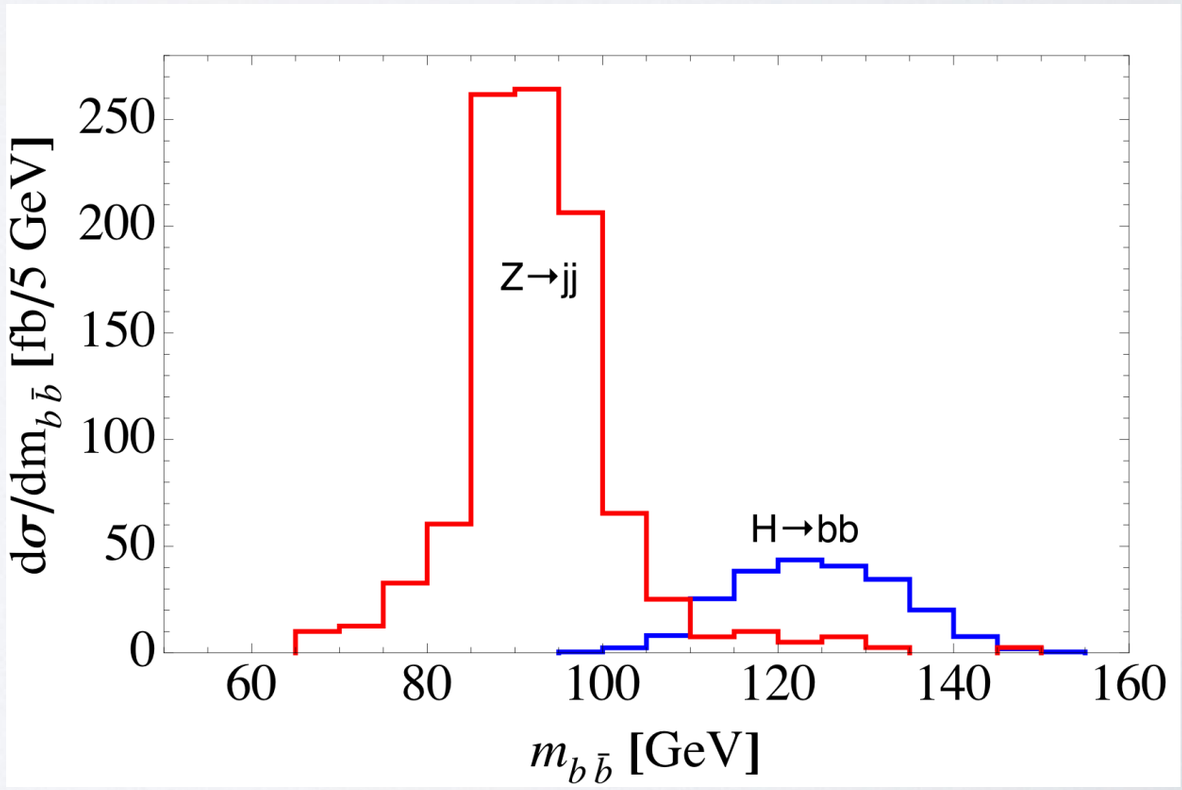
$$H \to b\bar{b}$$

$$p_T(b) > 30 \text{ GeV}, \qquad 10^\circ < \theta_b < 170^\circ,$$

$$M_{\text{recoil}} = \sqrt{(p_{\mu^+} + p_{\mu^+} - p_H)^2} > 200 \text{ GeV}$$

$$\Delta E/E = 10\%$$

$$m_{b\bar{b}} = m_H \pm 15 \text{ GeV}$$



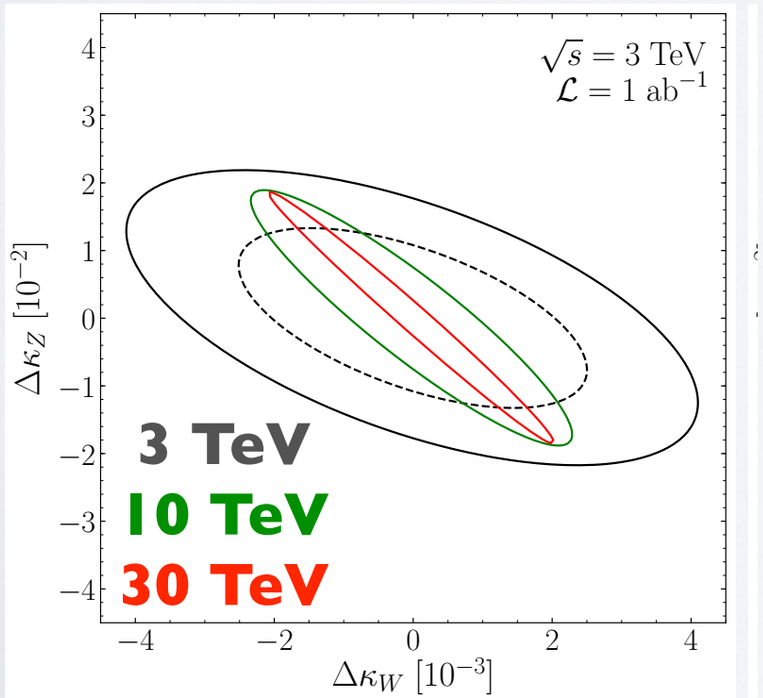
V-V-H Coupling

- Single parameter fit:

$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
$(\Delta\kappa_W)_{\mathrm{in}}$	0.26%	0.12%	0.073%	0.050%	0.023%
$(\Delta\kappa_Z)_{\mathrm{in}}$	2.4%	1.1%	0.65%	0.46%	0.20%
$(\Delta\kappa_Z)_{1\mu}$	1.7%	1.5%	1.5%	1.5%	1.5%

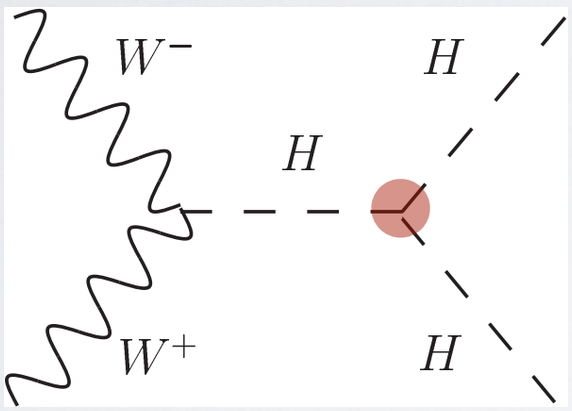
Statistical uncertainty only

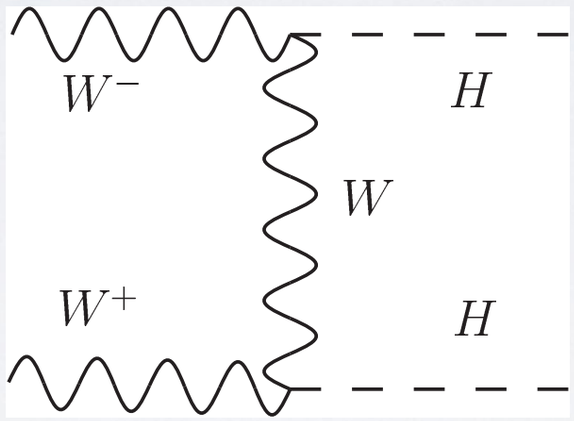
- 2D fit

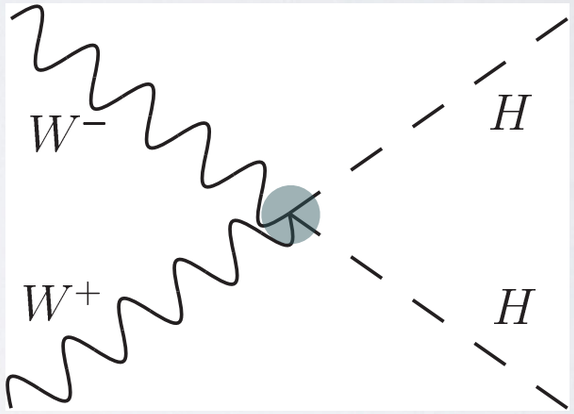


Double Higgs Production

$$\mu^+\mu^- \xrightarrow{VBF} HH + X$$







$$\mathcal{A}(W_L^+W_L^- \to HH) = \mathcal{A}_{\rm SM} + \mathcal{A}_1\Delta\kappa_{W_2} + \mathcal{A}_2\Delta\kappa_3$$

$$\mathcal{A}_{\rm SM},\ \mathcal{A}_2 \sim \text{constant} \qquad \mathcal{A}_1 \sim E^2 \qquad \text{when } E \gg M_W$$

Double Higgs Production

- Focus on the leading decay channel

$$\mathrm{BR}(4b) \simeq 34\%$$

$$p_T(b) > 30\ \mathrm{GeV}, \quad 10^\circ < \theta_b < 170^\circ, \quad \Delta R_{bb} > 0.4$$

$$\text{paired by minimizing } (m_{j_1 j_2} - m_H)^2 + (m_{j_3 j_4} - m_H)^2$$

$$|m_{jj} - m_H| < 15\ \mathrm{GeV}$$

$$M_{\mathrm{recoil}} = \sqrt{(p_{\mu^+} + p_{\mu^-} - p_{H_1} - p_{H_2})^2} > 200\ \mathrm{GeV}$$

Double Higgs Production

$$\sigma = \sigma_{\rm SM}\left[1 + r_1\Delta\kappa_{W_2} + r_2\Delta\kappa_3 + r_3\Delta\kappa_{W_2}\Delta\kappa_3 + r_4\left(\Delta\kappa_{W_2}\right)^2 + r_5\left(\Delta\kappa_3\right)^2\right]$$

- Sensitive to H-H-H in low m_{HH} region.
- Sensitive to W-W-H-H in high m_{HH} region.

m_{HH} [GeV]	$\sigma_{\rm SM}$ [ab]	r_1	r_2	r_3	r_4	r_5
$[0, 350)$	15	-2.7	-1.7	7.6	6.7	2.6
$[350, 450)$	24	-3.4	-1.2	5.2	7.8	0.95
$[450, 550)$	24	-4.0	-0.91	4.6	12	0.52
$[550, 650)$	21	-4.6	-0.70	4.7	17	0.36
$[650, 750)$	17	-5.3	-0.60	5.1	26	0.28
$[750, 950)$	24	-6.9	-0.52	6.3	46	0.23
$[950, 1350)$	23	-11	-0.47	8.7	120	0.19
$[1350, 5000)$	15	-18	-0.30	7.2	240	0.075

$\sqrt{s} = 10$ TeV

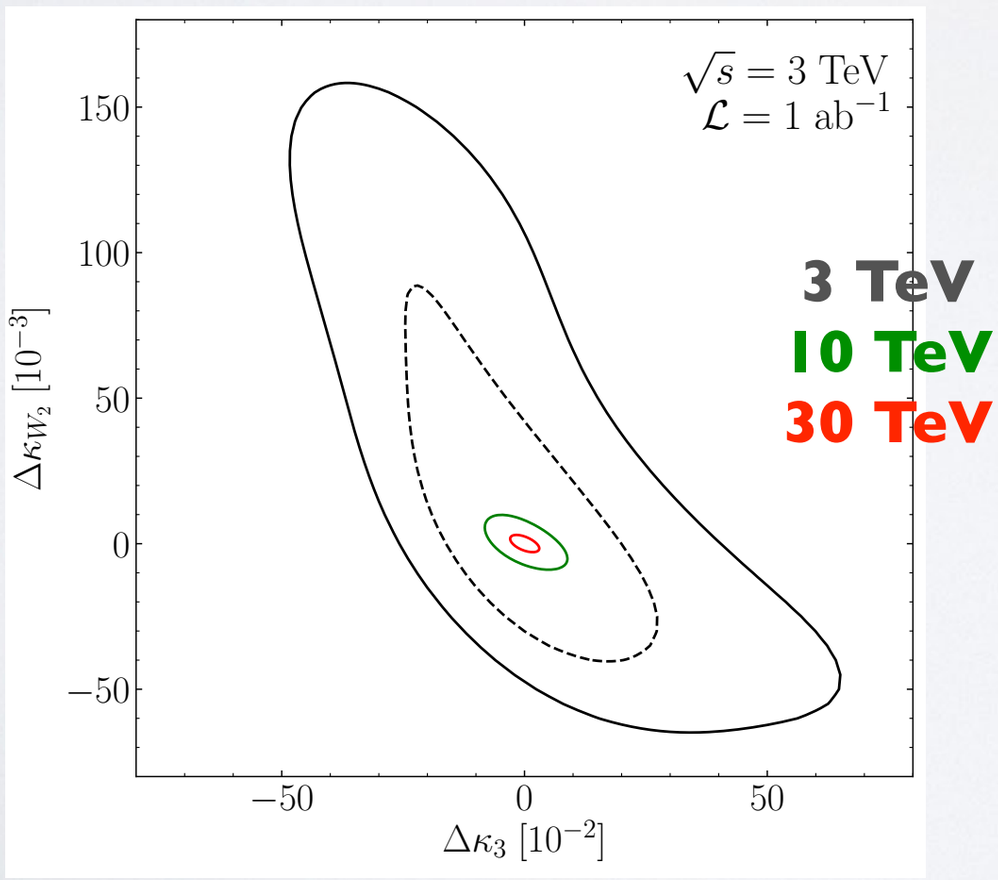
H-H-H & W-W-H-H

- Single parameter fit:

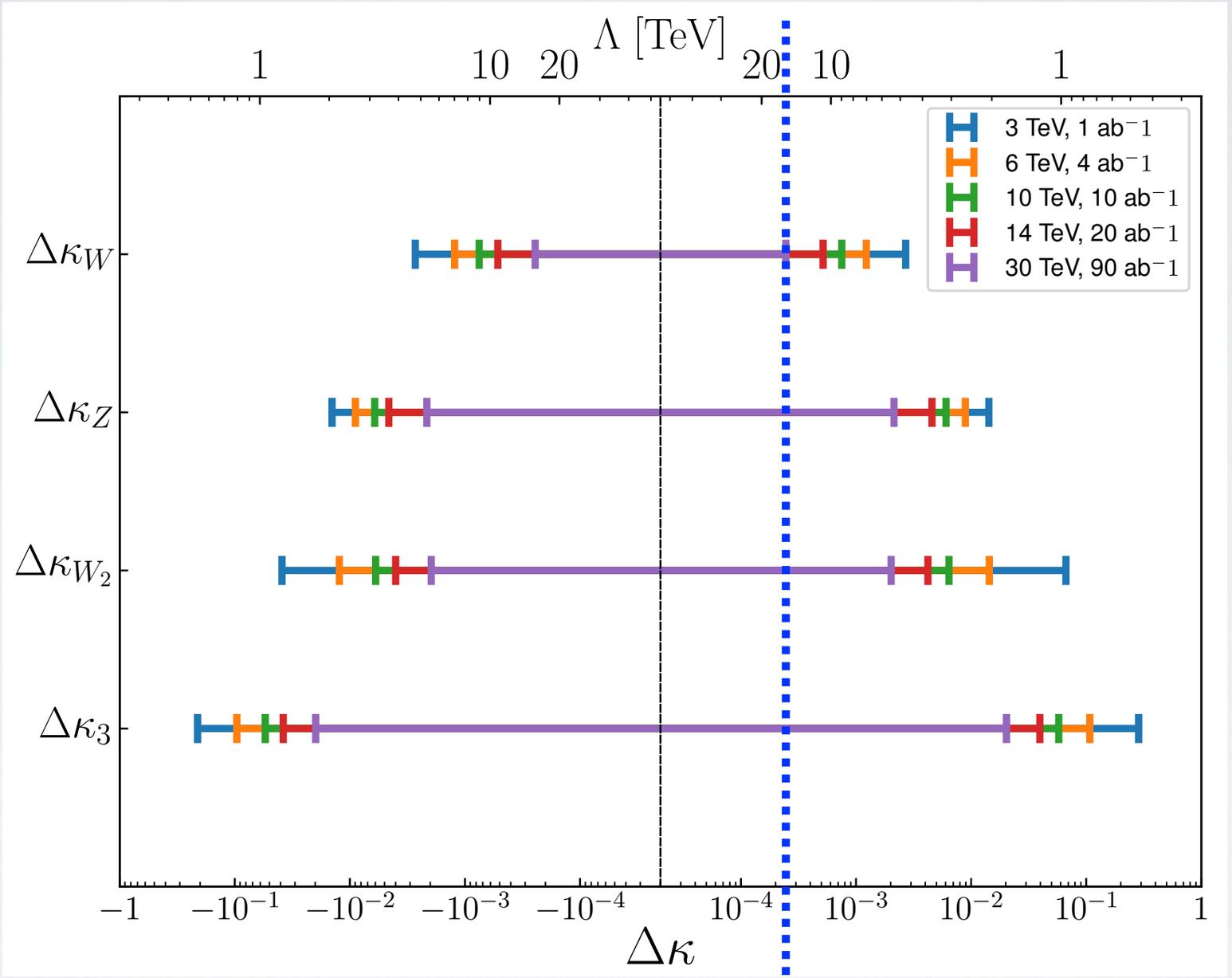
$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
$(\Delta\kappa_{W_2})_{\mathrm{in}}$	5.3%	1.3%	0.62%	0.41%	0.20%
$(\Delta\kappa_3)_{\mathrm{in}}$	25%	10%	5.6%	3.9%	2.0%

Statistical uncertainty only

- 2D fit



Result Summary



$$\Lambda \sim 1\ \mathrm{TeV}/\sqrt{16\Delta\kappa} \quad \Rightarrow \quad 10 - 20\,\mathrm{TeV}$$

Conclusion

- Great potential on Higgs precision measurement.
- Distinct/novel kinematical feature.

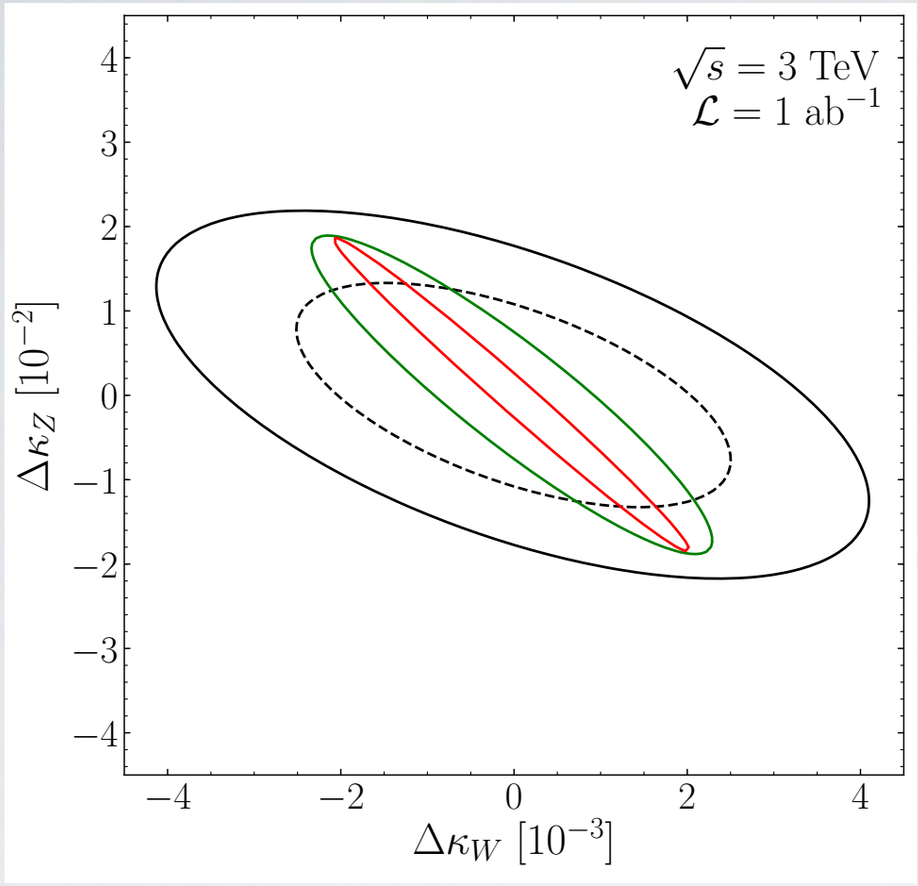
$\sqrt{s}$ (TeV)	3	6	10	14	30	Comparison	
WWH $(\Delta\kappa_W)$	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% (68% C.L.)	**CLIC**
ZZH $(\Delta\kappa_Z)$	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% (95% C.L.)	**CEPC**
$WWHH$ $(\Delta\kappa_{W_2})$	5.3%	1.3%	0.62%	0.41%	0.20%	5% , 1% (68% C.L.)	**CLIC/ FCC-hh**
HHH $(\Delta\kappa_3)$	25%	10%	5.6%	3.9%	2.0%	5% (68% C.L.)	**FCC-hh SppC**

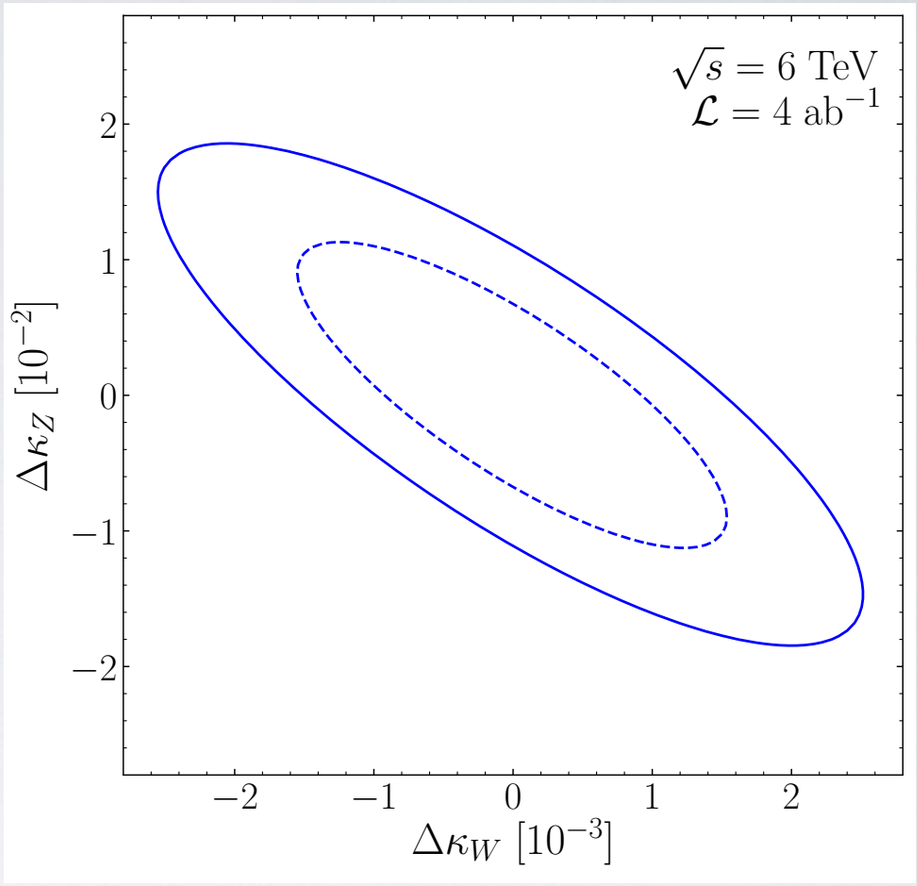
Back-ups

$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
σ (fb): $WW \to H$	490	700	830	950	1200
$ZZ \to H$	51	72	89	96	120
$WW \to HH$	0.80	1.8	3.2	4.3	6.7
$ZZ \to HH$	0.11	0.24	0.43	0.57	0.91
$WW \to ZH$	9.5	22	33	42	67
$WW \to t\bar{t}H$	0.012	0.046	0.090	0.14	0.28
$WW \to Z$	2200	3100	3600	4200	5200
$WW \to ZZ$	57	130	200	260	420

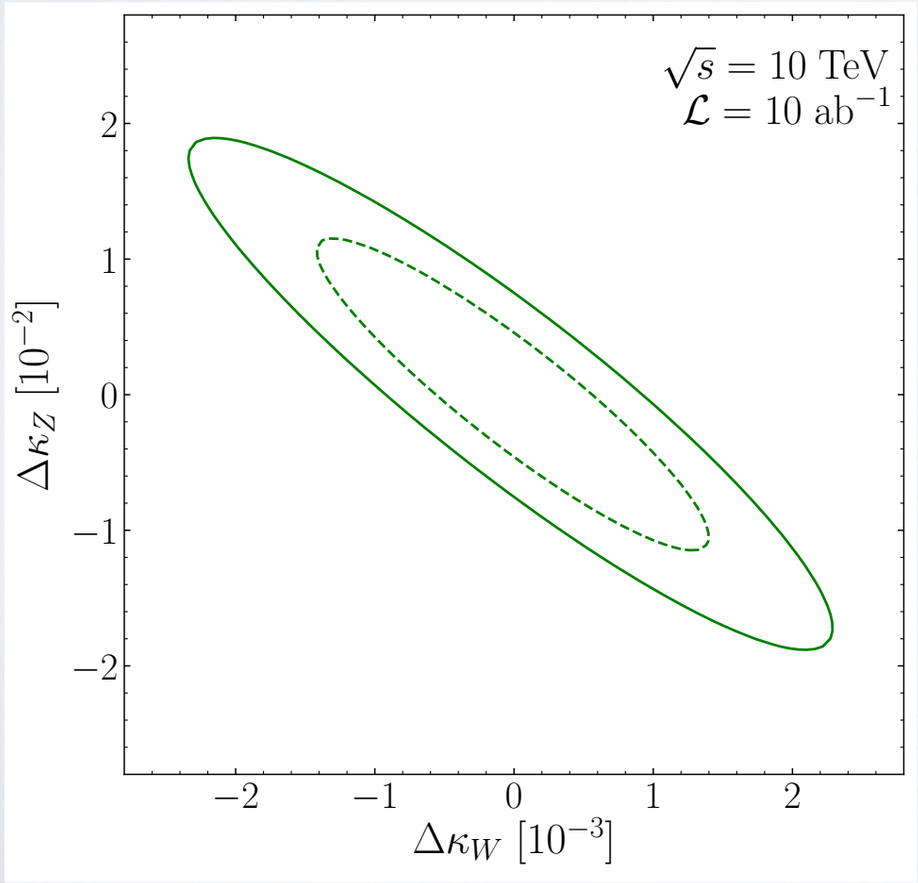
Selection Efficiencies

$\sqrt{s}$ (TeV)	3	6	10	14	30
$WW \to H:\ \epsilon_{\text{in}}$ (%)	54	46	42	39	32
$ZZ \to H:\ \epsilon_{\text{in}}$ (%)	57	49	44	41	35
Cross section σ_{in} (fb)	170	200	220	240	240
$ZZ \to H:\ \epsilon_{1\mu}$ (%)	11	2.7	0.84	0.37	0.071
Cross section $\sigma_{1\mu}$ (fb)	3.1	1.1	0.43	0.20	0.050
$VV \to HH:\ \epsilon_{hh}$ (%)	27	18	13	11	7.2
Cross section σ_{hh} (ab)	81	140	150	170	200

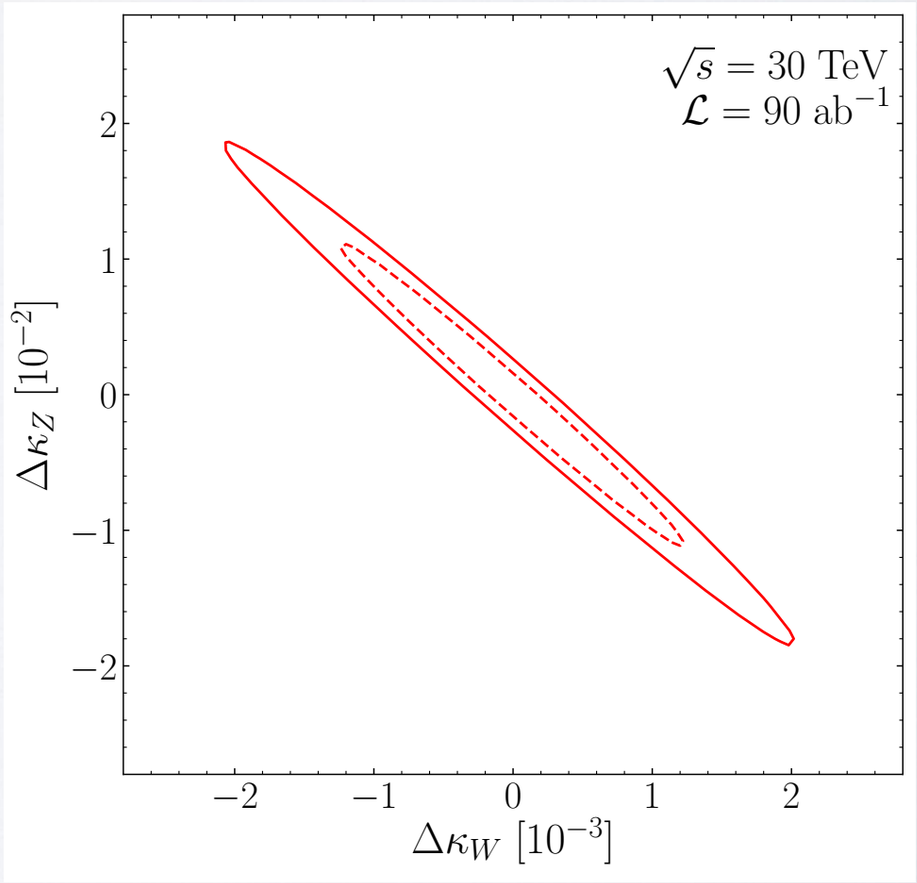

$\sqrt{s} = 3$ TeV
$\mathcal{L} = 1$ ab^{-1}
$\Delta\kappa_Z$ [10^{-2}]
$\Delta\kappa_W$ [10^{-3}]


$\sqrt{s} = 6$ TeV
$\mathcal{L} = 4$ ab^{-1}
$\Delta\kappa_Z$ [10^{-2}]
$\Delta\kappa_W$ [10^{-3}]

(a)


$\sqrt{s} = 10$ TeV
$\mathcal{L} = 10$ ab^{-1}
$\Delta\kappa_Z$ [10^{-2}]
$\Delta\kappa_W$ [10^{-3}]

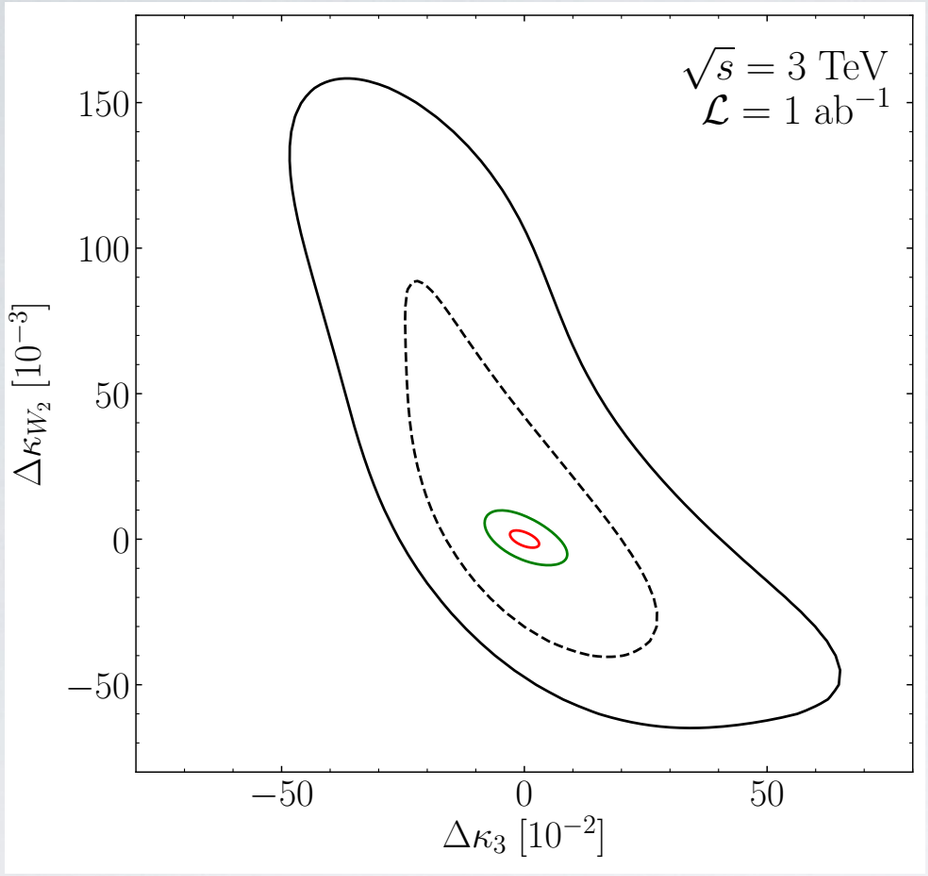
(b)

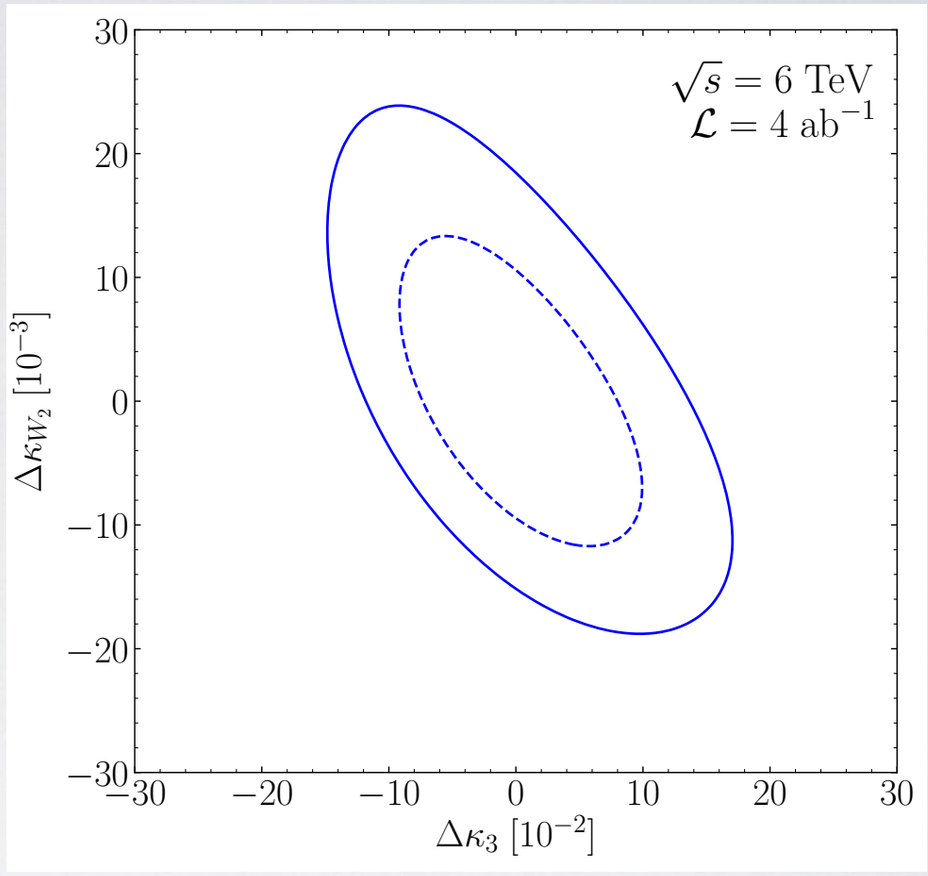

$\sqrt{s} = 30$ TeV
$\mathcal{L} = 90$ ab^{-1}
$\Delta\kappa_Z$ [10^{-2}]
$\Delta\kappa_W$ [10^{-3}]

$$\mu^+\mu^- \to HH + X$$

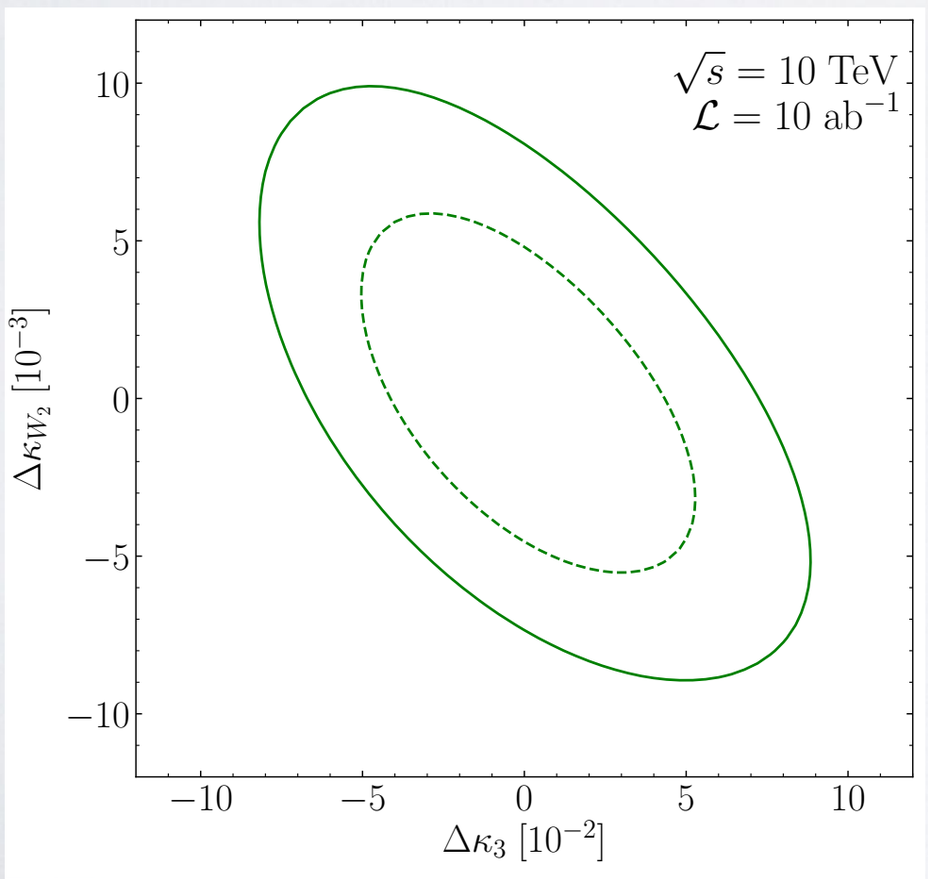
$$\sigma = \sigma_{\rm SM}\left[1 + R_1\Delta\kappa_{W_2} + R_2\Delta\kappa_3 + R_3\Delta\kappa_{W_2}\Delta\kappa_3 + R_4\left(\Delta\kappa_{W_2}\right)^2 + R_5\left(\Delta\kappa_3\right)^2\right]$$

$\sqrt{s}$ [TeV]	$\sigma_{\rm SM}$ [fb]	R_1	R_2	R_3	R_4	R_5
3 TeV	0.91	-3.5	-0.65	3.1	14	0.49
6 TeV	2.0	-3.9	-0.50	2.8	29	0.35
10 TeV	3.6	-4.3	-0.43	2.7	54	0.29
14 TeV	4.9	-4.4	-0.38	2.6	80	0.25
30 TeV	7.6	-4.4	-0.28	2.3	210	0.19

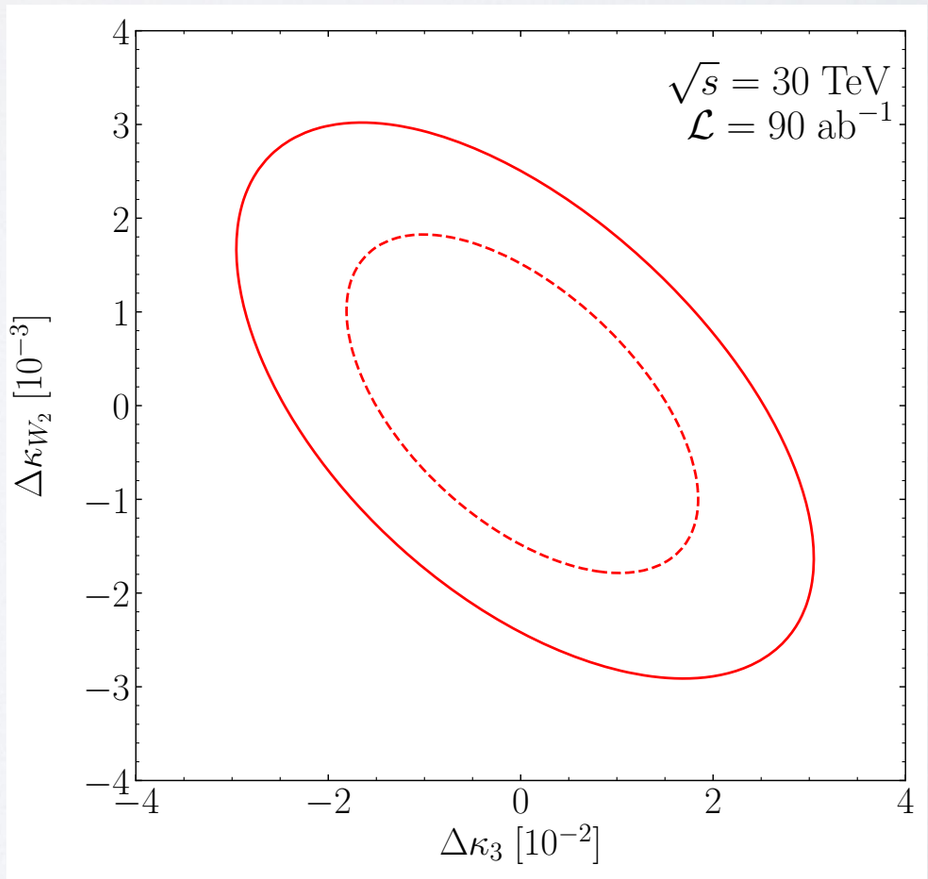

$\sqrt{s} = 3$ TeV
$\mathcal{L} = 1$ ab^{-1}
$\Delta\kappa_{W_2}$ [10^{-3}]
$\Delta\kappa_3$ [10^{-2}]
150
100
50
0
−50
−50
0
50


$\sqrt{s} = 6$ TeV
$\mathcal{L} = 4$ ab^{-1}
$\Delta\kappa_{W_2}$ [10^{-3}]
$\Delta\kappa_3$ [10^{-2}]
30
20
10
0
−10
−20
−30
−30
−20
−10
0
10
20
30

(a)


$\sqrt{s} = 10$ TeV
$\mathcal{L} = 10$ ab^{-1}
$\Delta\kappa_{W_2}$ [10^{-3}]
$\Delta\kappa_3$ [10^{-2}]
10
5
0
−5
−10
−10
−5
0
5
10

(b)


$\sqrt{s} = 30$ TeV
$\mathcal{L} = 90$ ab^{-1}
$\Delta\kappa_{W_2}$ [10^{-3}]
$\Delta\kappa_3$ [10^{-2}]
4
3
2
1
0
−1
−2
−3
−4
−4
−2
0
2
4

$$\Lambda \sim \sqrt{\frac{c_{H,6}}{\Delta\kappa}}\, v$$

$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison	
WWH $(\Delta\kappa_W)$	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [43]	CLIC
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)	
ZZH $(\Delta\kappa_Z)$	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]	CEPC
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	3.6	5.3	(95% C.L.)	
$WWHH$ $(\Delta\kappa_{W_2})$	5.3%	1.3%	0.62%	0.41%	0.20%	5% [38], 1% [24]	CLIC/ FCC-hh
$\Lambda/\sqrt{c_i}$ (TeV)	1.1	2.1	3.1	3.8	5.5	(68% C.L.)	
HHH $(\Delta\kappa_3)$	25%	10%	5.6%	3.9%	2.0%	5% [22, 23]	FCC-hh SppC
$\Lambda/\sqrt{c_i}$ (TeV)	0.49	0.77	1.0	1.2	1.7	(68% C.L.)	