CP violating top Yukawa at $\mu^-\mu^+$ collider

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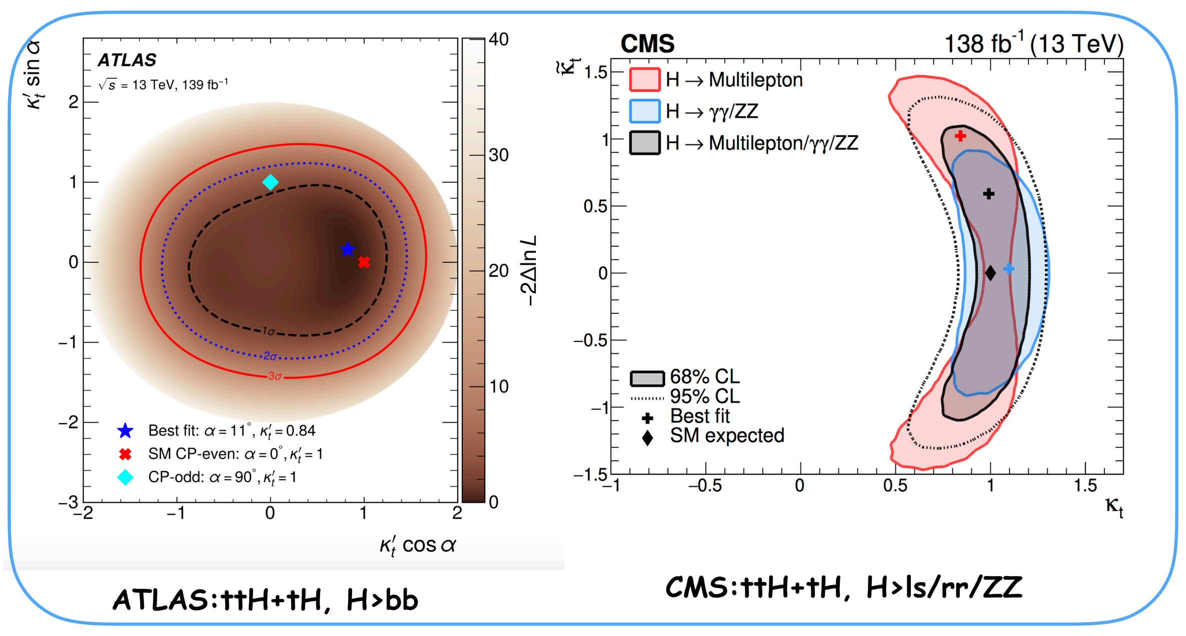
Motivations

LHC search and constraints



$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$
$$\equiv -g\phi\bar{\psi}_t(\cos\xi + i\gamma_5\sin\xi)\psi_t$$

Process	Cross section [fb]
$t\bar{t}H$	507 [53]
tHq	74.3 [53]
tHW	15.2 [87]
ggH	4.86×10^4 [53]
qqH	3.78×10^3 [53]
WH	1.37×10^3 [53]
ZH	884 [53]

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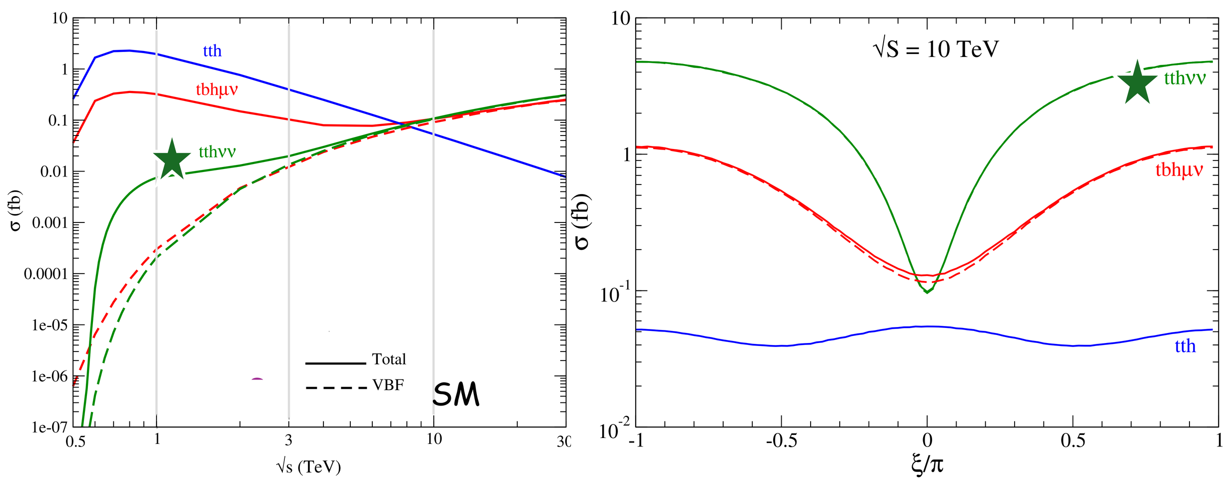
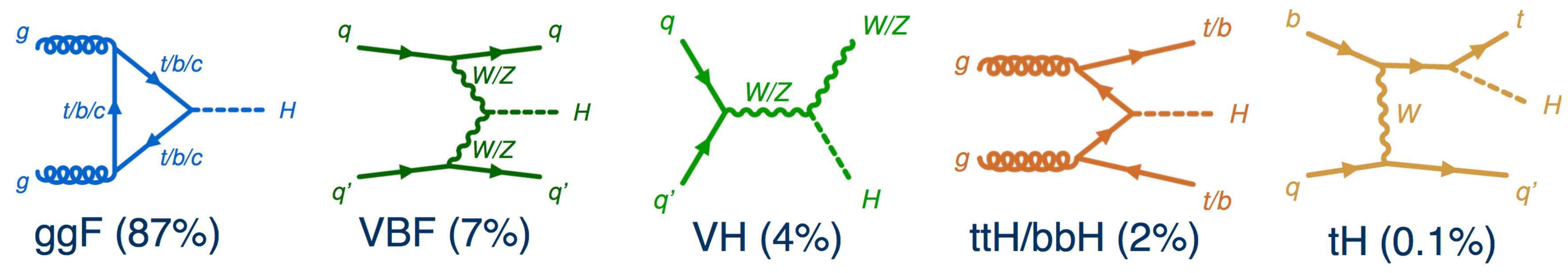
Top Yukawa processes at the muon collider



$$\mu^-\mu^+ \to \nu_\mu\bar{\nu}_\mu t\bar{t}H$$

Large cross section
&
sensitive to CPV phase



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[2]

Lagrangian

- SMEFT with dimension-6 operator in the Unitary (U) gauge

$$\mathcal{L} = -y_{\rm SM} Q^\dagger \phi t_R + \frac{\lambda}{\Lambda^2} Q^\dagger \phi t_R \phi^\dagger\phi + \text{h.c.}$$
$$Q = (t_L, b_L)^T \text{ and } \phi = ((v + H + i\pi^0)/\sqrt{2}, i\pi^-)^T$$

$$\begin{aligned}\mathcal{L}^{\rm SMEFT}_{ttH} = & -m_t t_L^\dagger t_R - g_{\rm SM}\left[(H + i\pi^0)t_L^\dagger + i\sqrt{2}\pi^- b_L^\dagger\right] t_R \\ & +(g_{\rm SM} - g e^{i\xi})\left\{ H t_L^\dagger t_R + \frac{H}{v}\left[(H + i\pi^0)t_L^\dagger + i\sqrt{2}\pi^- b_L^\dagger\right] t_R \right\} \\ & +(g_{\rm SM} - g e^{i\xi})\left\{\left[\frac{H^2 + (\pi^0)^2}{2v} + \frac{\pi^+\pi^-}{v}\right] t_L^\dagger t_R \right. \\ & \left. + \frac{H^2 + (\pi^0)^2 + 2\pi^+\pi^-}{2v^2}\left[(H + i\pi^0)t_L^\dagger + i\sqrt{2}\pi^- b_L^\dagger\right] t_R \right\} + h.c.,\end{aligned}$$

- ttHH, ttHHH for both U and FD gauge
- ttHZ, ttZZ, ttHZZ ttHWW only in FD gauge

$$g_{\rm SM} = \frac{m_t}{v} \quad \text{and} \quad g_{\rm SM} - g e^{i\xi} = \frac{\lambda v^2}{\sqrt{2}\Lambda^2}$$

- the SM Yukawa $-g_{\rm SM} H t_L^\dagger t_R + \text{h.c.}$ is replaced by $-g e^{i\xi} H t_L^\dagger t_R + \text{h.c.}$

[1]

Feynman-Diagram Gauge

- Weak bosons are 5-components $W^\pm_M = (W^\pm_\mu, \pi^\pm)$, unlike in R_ξ gauge, EOM mixes $W^\pm_\mu$ and $\pi^\pm$
- FD gauge propagator $\quad n(q)^\mu_{\rm FD} = ({\rm sgn}(q^0), -\vec{q}/|\vec{q}|)$

$$G_{MN}(q) = \frac{i}{q^2 - m^2 + i\epsilon}\begin{pmatrix} -g_{\mu\nu} + \dfrac{q_\mu n_\nu + n_\mu q_\nu}{n\cdot q} & i\dfrac{m n_\mu}{n\cdot q} \\ -i\dfrac{m n_\nu}{n\cdot q} & 1 \end{pmatrix} \qquad M, N = 0 \text{ to } 4,$$

- Helicity ±1 states don't mix with the Goldstone boson. Helicity 0 state is a mixture of

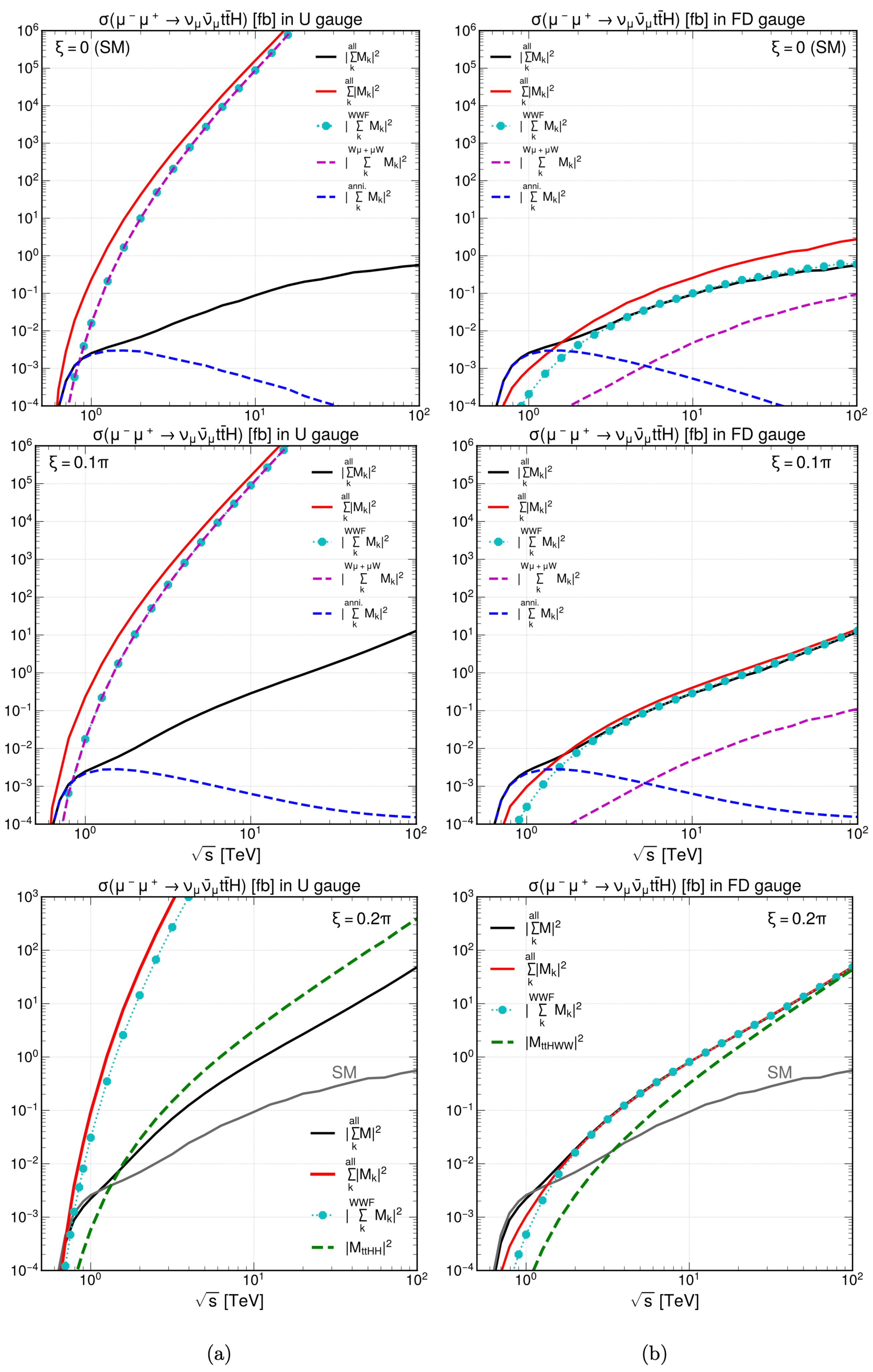
$$-\frac{Q\, n^\mu}{n\cdot q} = \epsilon^\mu(q, h=0) - \frac{q^\mu}{Q}, \quad Q = \sqrt{|q^2|}$$

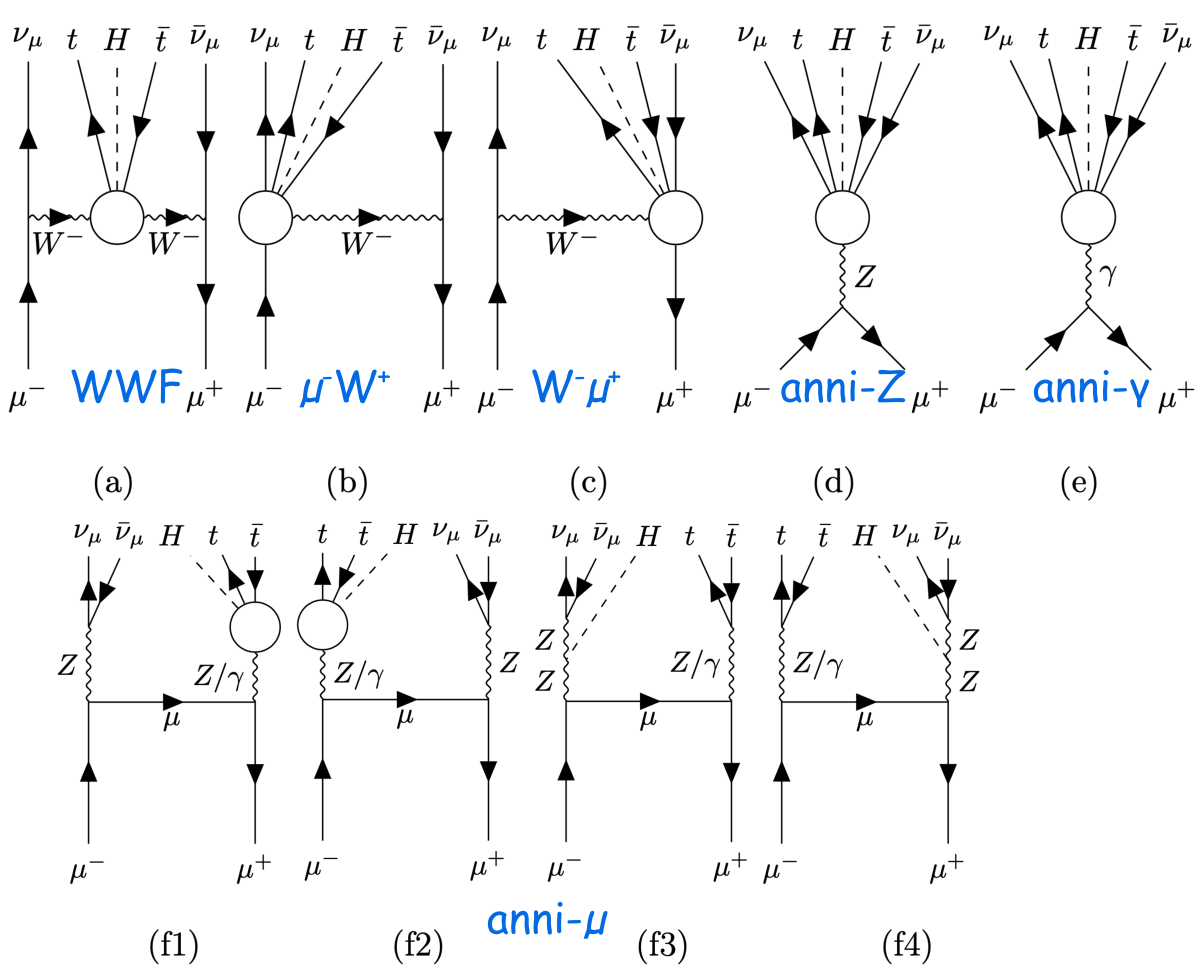
and the Goldstone boson.

- Because the Goldstone bosons are parts of the physical weak boson, all Goldstone boson vertices contribute to the scattering amplitudes in the FD gauge

[3],[4]

U gauge v.s. FD gauge

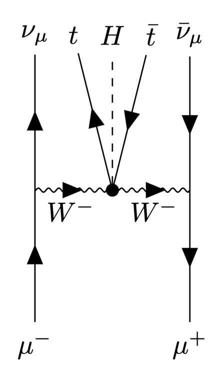




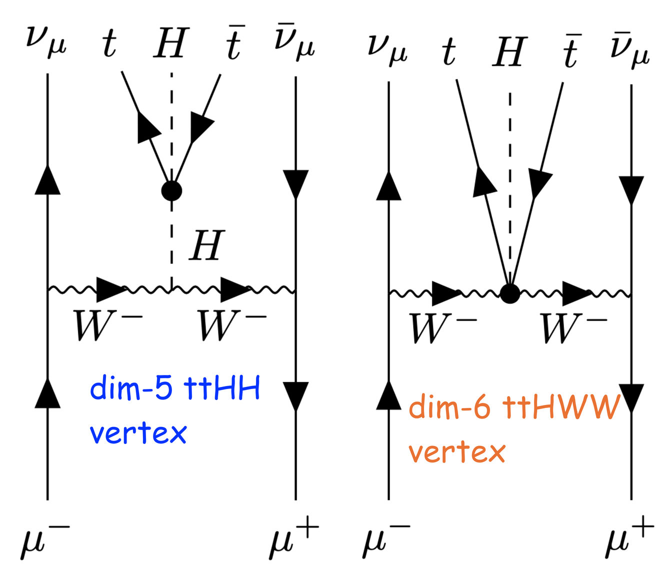
- In this process, e.g.

$$\frac{g_{\rm SM} - g e^{i\xi}}{v^2}\pi^+\pi^- H t_L^\dagger t_R + \text{h.c.}$$

contributes as



and dominates the total cross section because of its dim-6 property.



No. of diagrams	SM U	SM FD	SMEFT U	SMEFT FD
a) WWF	19	21	20	30
b) $\mu^- W^+$	11	11	11	13
c) $W^- \mu^+$	11	11	11	13
d) anni-Z	24	24	25	36
e) anni-γ	8	8	8	10
f) anni-μ	14	14	14	16
Total	87	89	89	118

[1] Vernon Barger, Kaoru Hagiwara, and Ya-Juan Zheng, 'CP-violating top-Higgs coupling in SMEFT', Phys.Lett.B 850 (2024) 138547.
[2] Morgan E. Cassidy, Zhongtian Dong, Kyoungchul Kong, Ian M. Lewis, Yanzhe Zhang and Ya-Juan Zheng, JHEP(05) (2024) 176.
[3] Junmou Chen, Kaoru Hagiwara, Junichi Kanzaki and Kentarou Mawatari, 'Helicity amplitudes without gauge cancellation for electroweak processes'Eur.Phys.J.C 83 (2023).
[4] Junmou Chen, Kaoru Hagiwara, Junichi Kanzaki, Kentarou Mawatari and Ya-Juan Zheng, 'Helicity amplitudes in light-cone and Feynman-diagram gauges'Eur.Phys.J.Plus 139 (2024).