CP violating top-Higgs coupling in SMEFT

International Workshop on Future Linear Colliders (LCWS2024)

Ya-Juan Zheng
(Iwate University)

July 10, 2024

Based on [1] Vernon Barger, Kaoru Hagiwara and YJZ, Phys.Lett.B 850 (2024) 138547.
[2] Morgan Cassidy, Zhongtian Dong, Kyoungchul Kong, Ian Lewis, Yanzhe Zhang and YJZ, JHEP05(2024) 176.
[3] Kaoru Hagiwara, Junichi, Kanzaki, Olivier Mattelaer, Kentarou Mawatari, YJZ, [arXiv:2405.01256].

Outline

- CP violating top Yukawa from effective Lagrangian
- LHC searches and e^-e^+ collider prospect
- Muon collider process
- Gauge invariant Lagrangian from a dimension-6 operator
- Unitarity constraints
- Individual diagram contributions in the Feynman-Diagram gauge

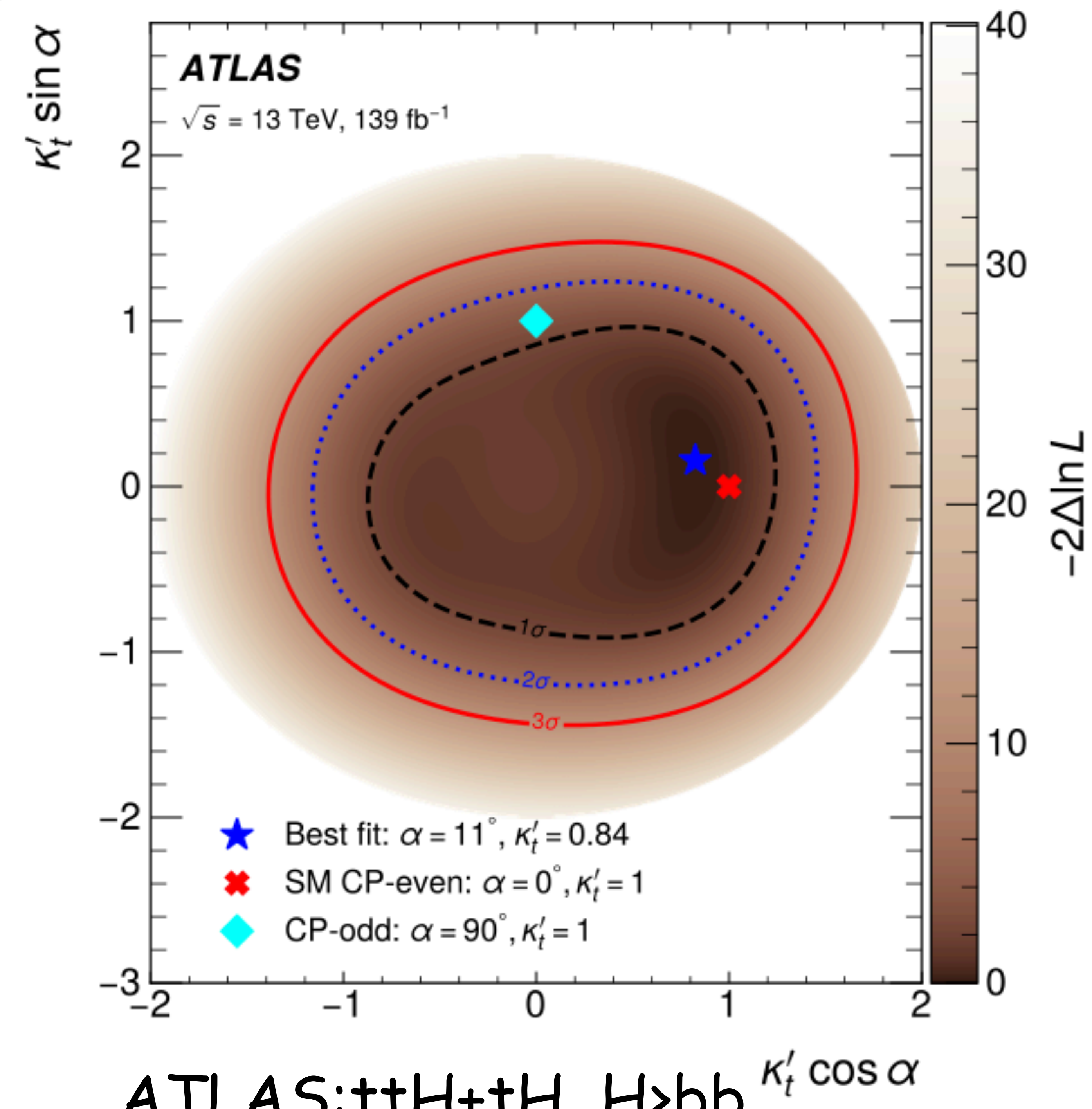
LHC searches and constraints

$$\mathcal{L}_{ttH} = -gH\bar{t}(\cos\xi + i\gamma_5 \sin\xi)t$$

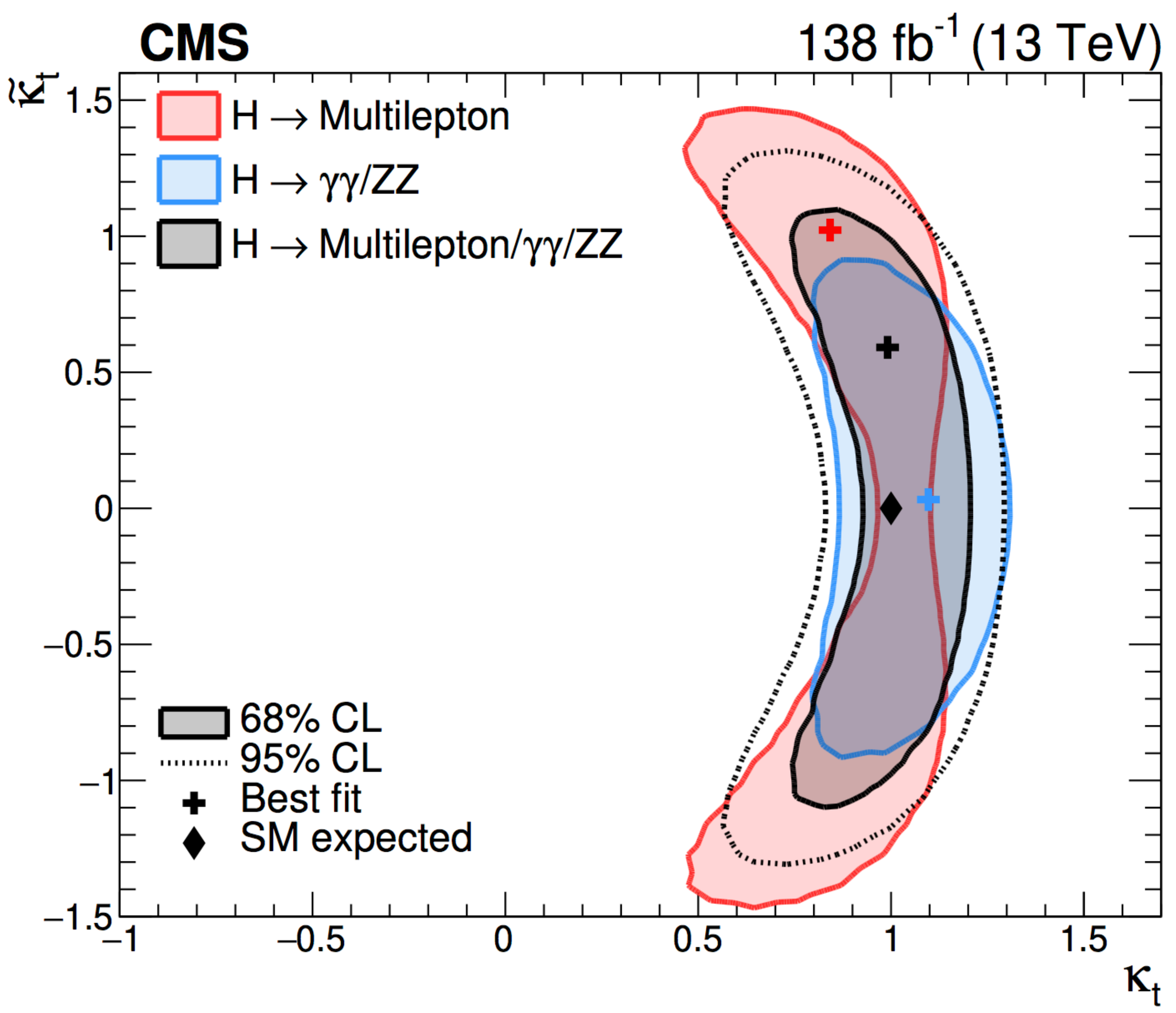
g is real and positive, $-\pi < \xi < \pi$

When $g=g_{SM}=m_t/v$, $\xi=0$ ⟶ SM

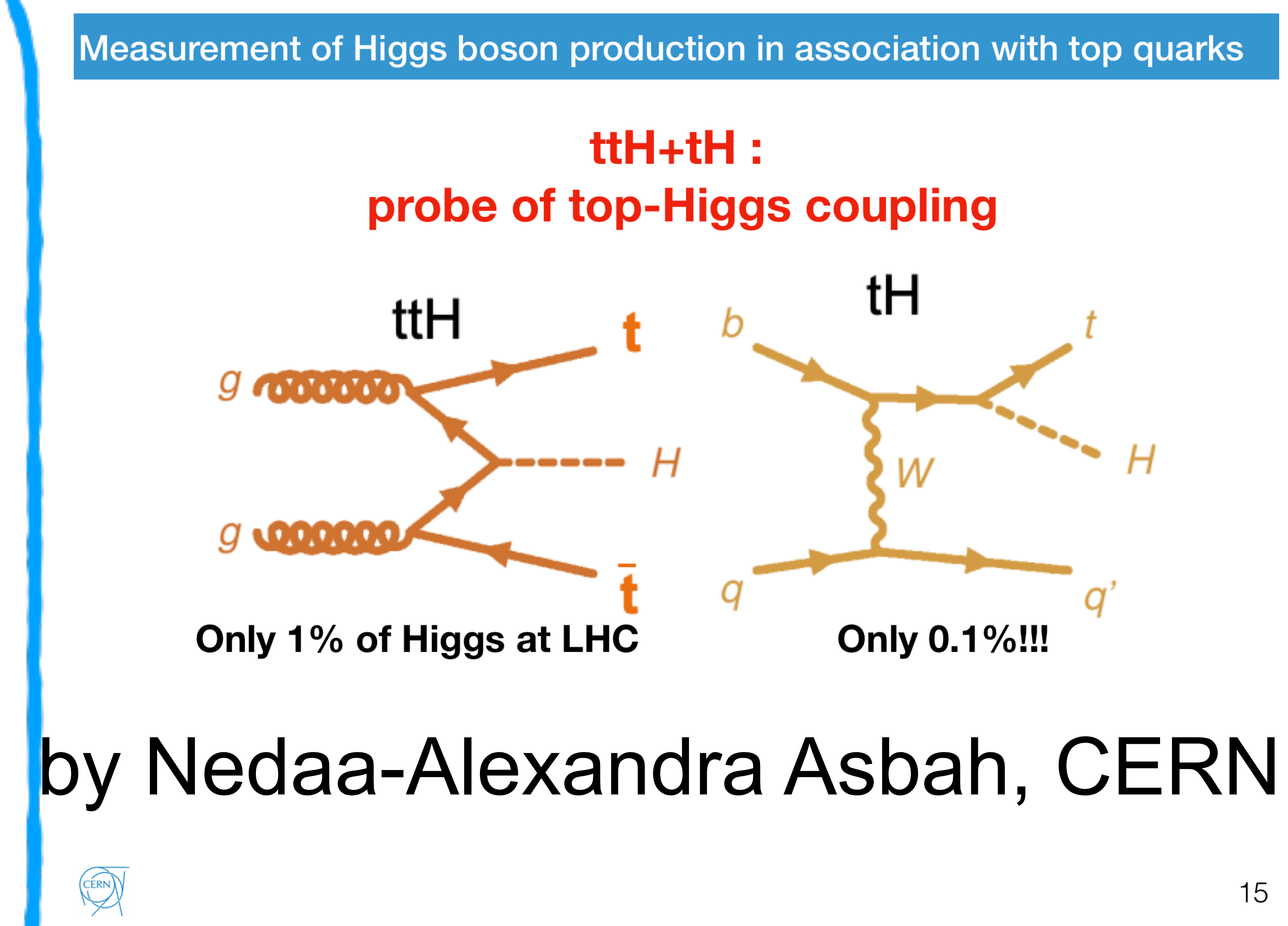
- X. Zhang, S. K. Lee, K. Whisnant, and B. L. Young, "Phenomenology of a nonstandard top quark Yukawa coupling," Phys. Rev. D 50 (1994) 7042–7047, arXiv:hep-ph/9407259.
- H. Bahl, E. Fuchs, S. Heinemeyer, J. Katzy, M. Menen, K. Peters, M. Saimpert, and G. Weiglein, "Constraining the CP structure of Higgs-fermion couplings with a global LHC fit, the electron EDM and baryogenesis," Eur. Phys. J. C 82 (2022) no. 7, 604, arXiv:2202.11753 [hep-ph].



ATLAS:ttH+tH, H>bb
arXiv:2303.05974



CMS:ttH+tH, H>ls/rr/ZZ
JHEP07(2023)092



LHC direct searches:
ATLAS best fit:11+52-73 degree

Direct measurement of a CP violating top-Higgs Yukawa Lagrangian at LHC and e^-e^+ collider

$$\mathcal{L}_{ttH} = -gH\bar{t}(\cos\xi + i\gamma_5 \sin\xi)t$$

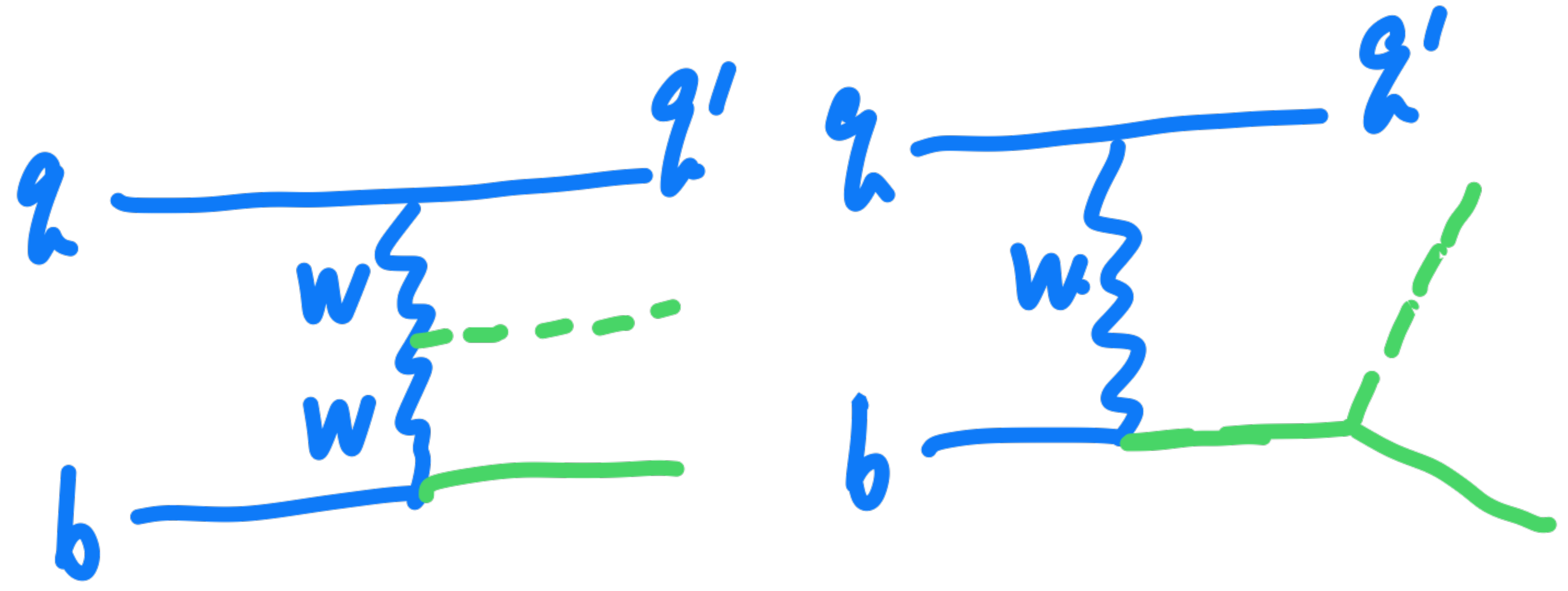
Top pair +Higgs, $pp \to ttH$

X.G.He, G.N.Li, YJZ.

Int.J.Mod.Phys.A30(2015) 25,1550156.

Single top +Higgs, $pp \to tHj$

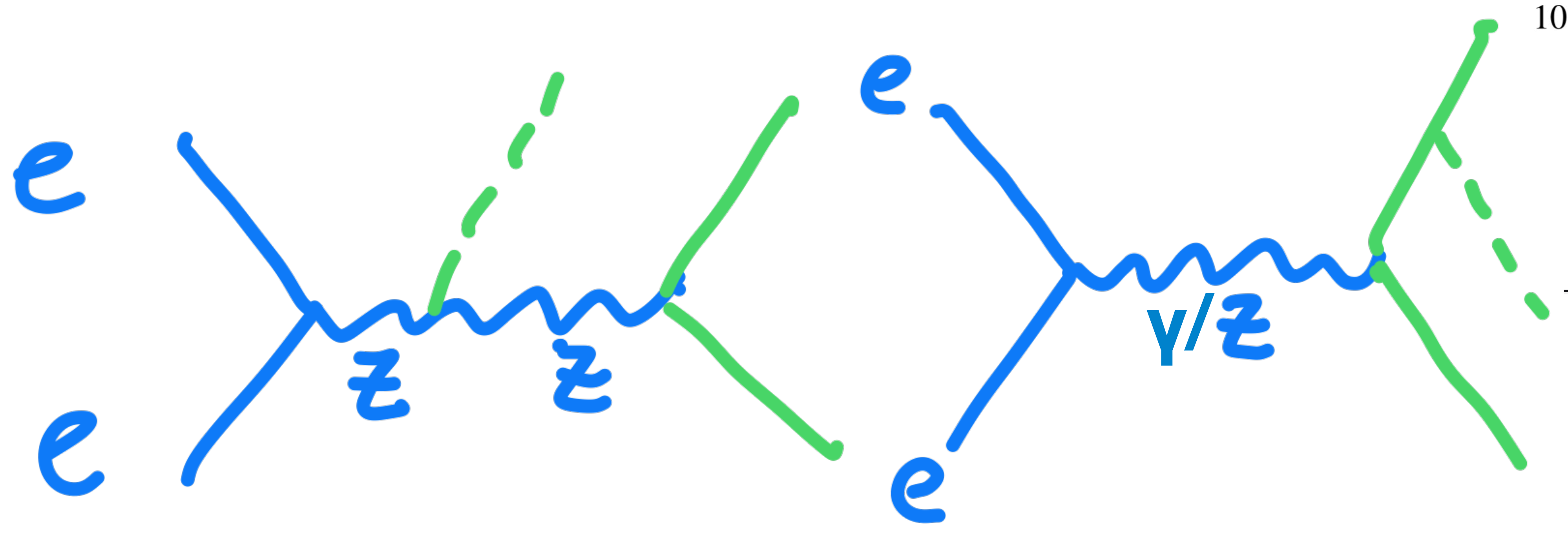
V.Barger, K. Hagiwara, YJZ.*Phys.Rev.D99(2019)3,031701, JHEP09(2020)101.*

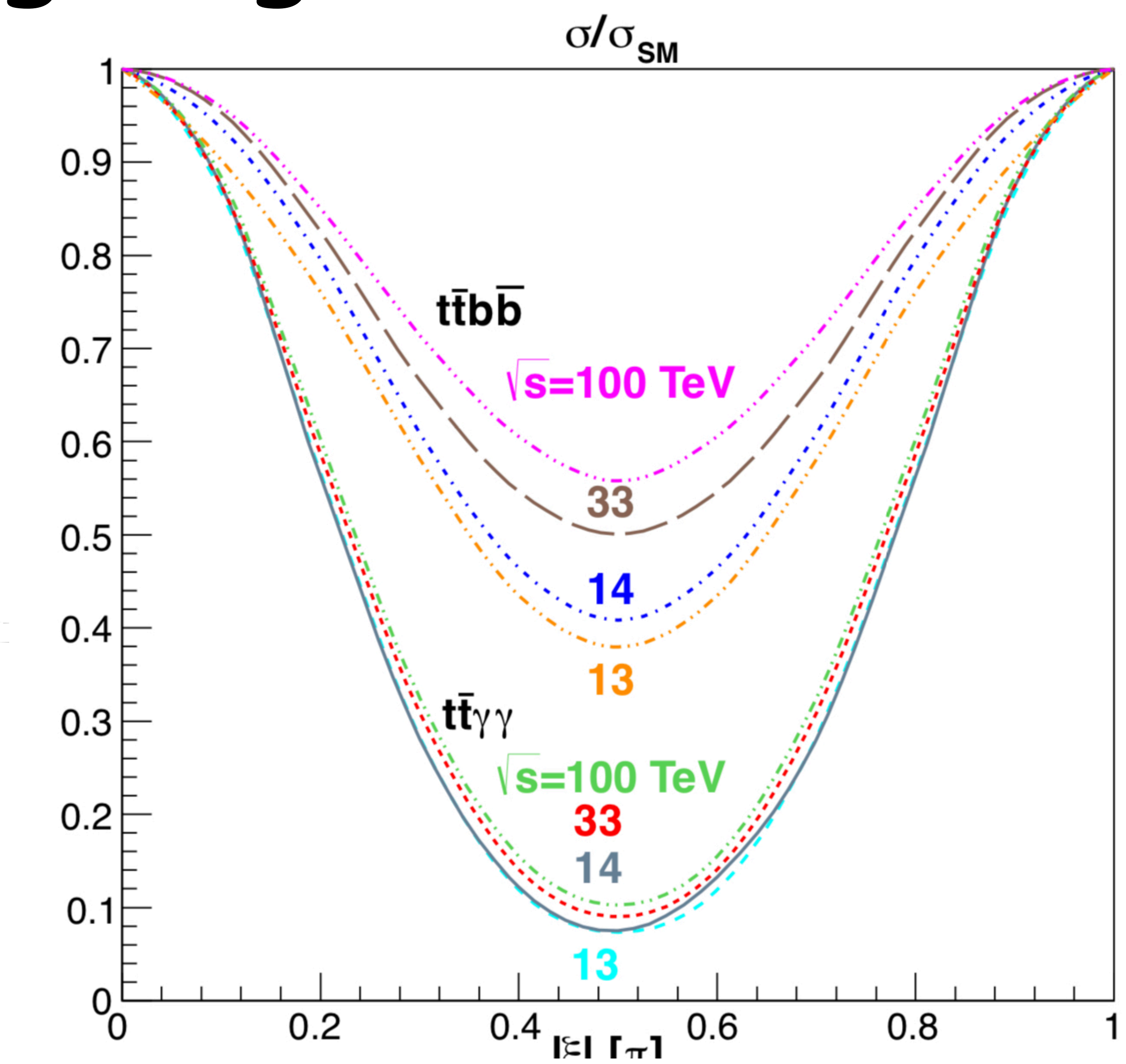


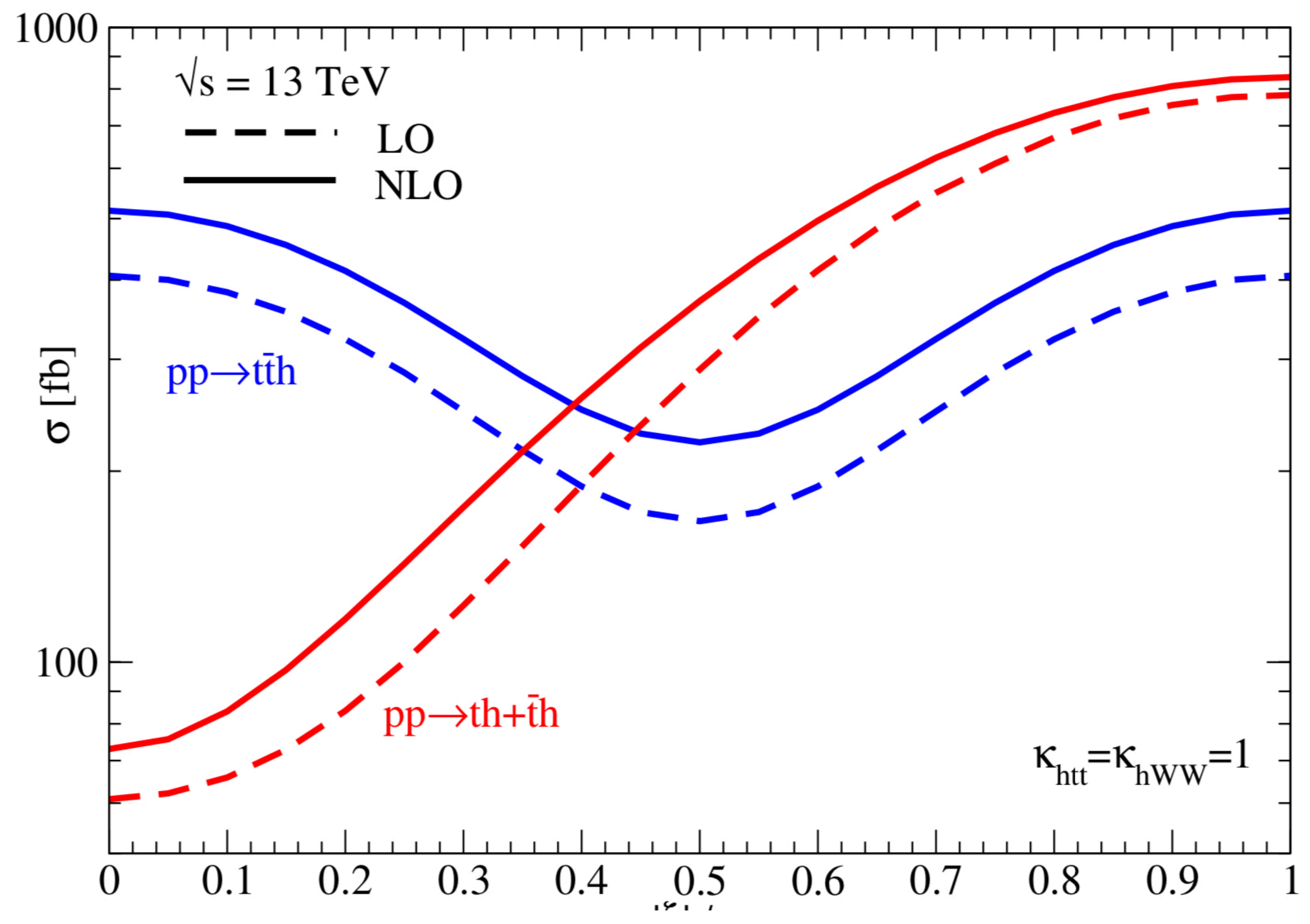
Top pair +Higgs, ee →ttH

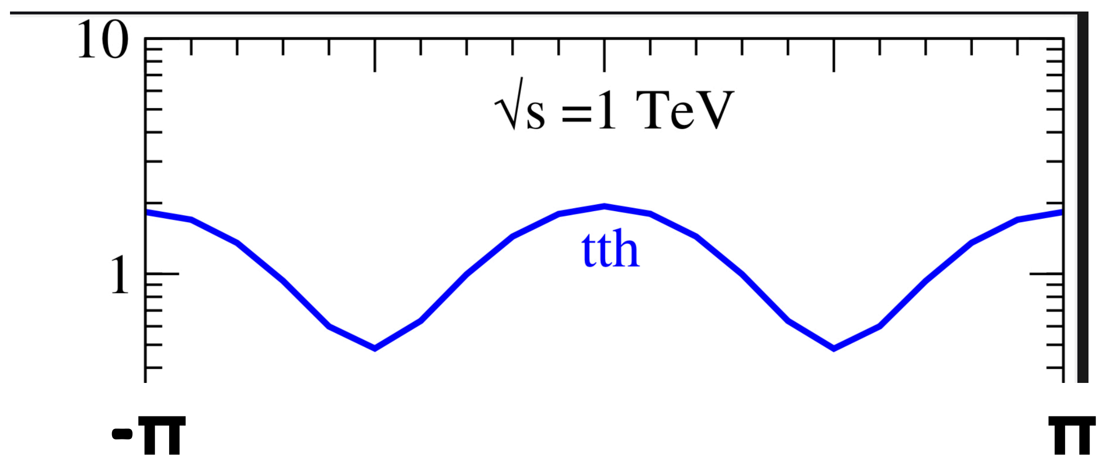
K. Hagiwara, H.Yokoya, YJZ.

JHEP02(2018)180

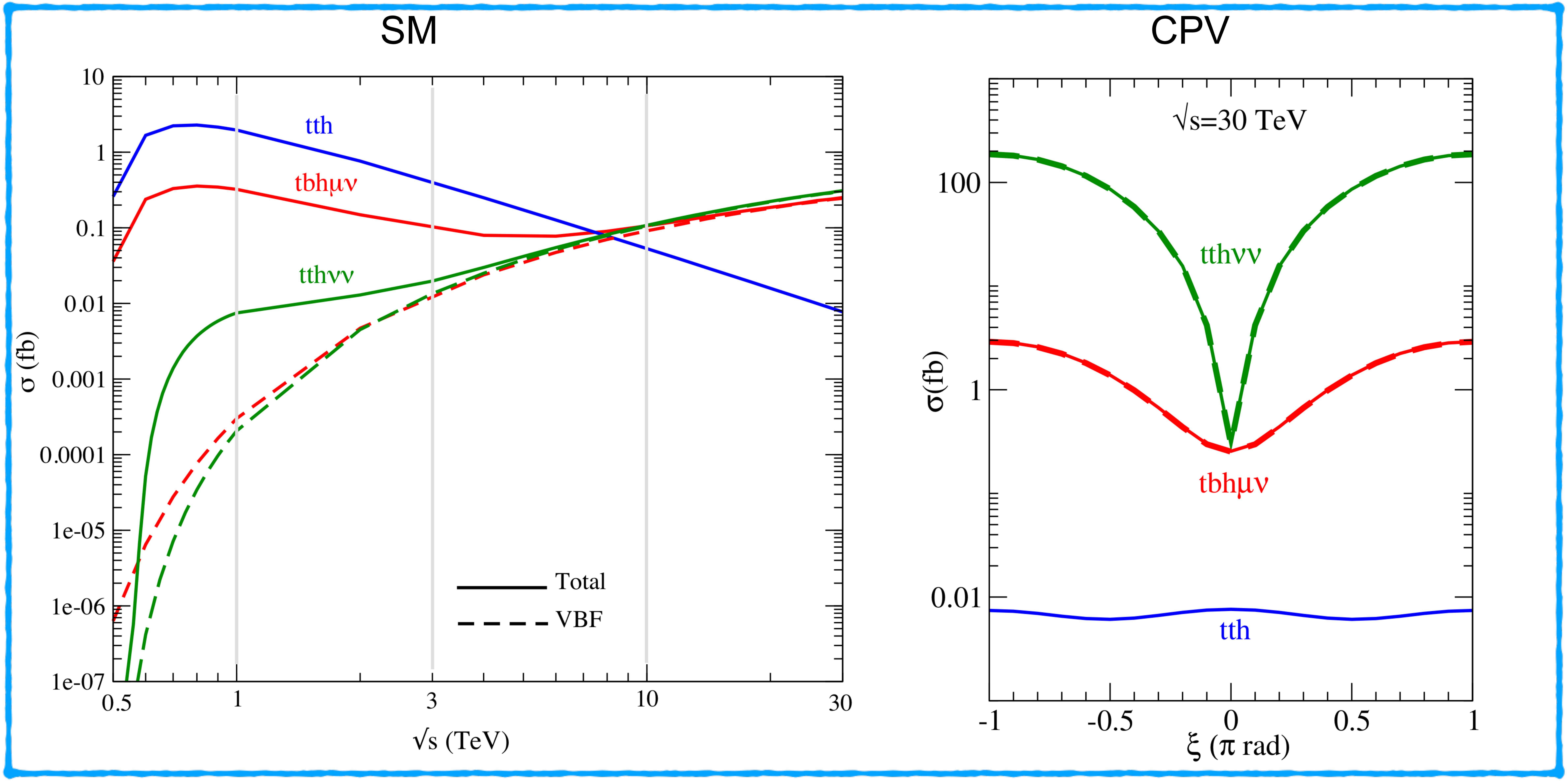




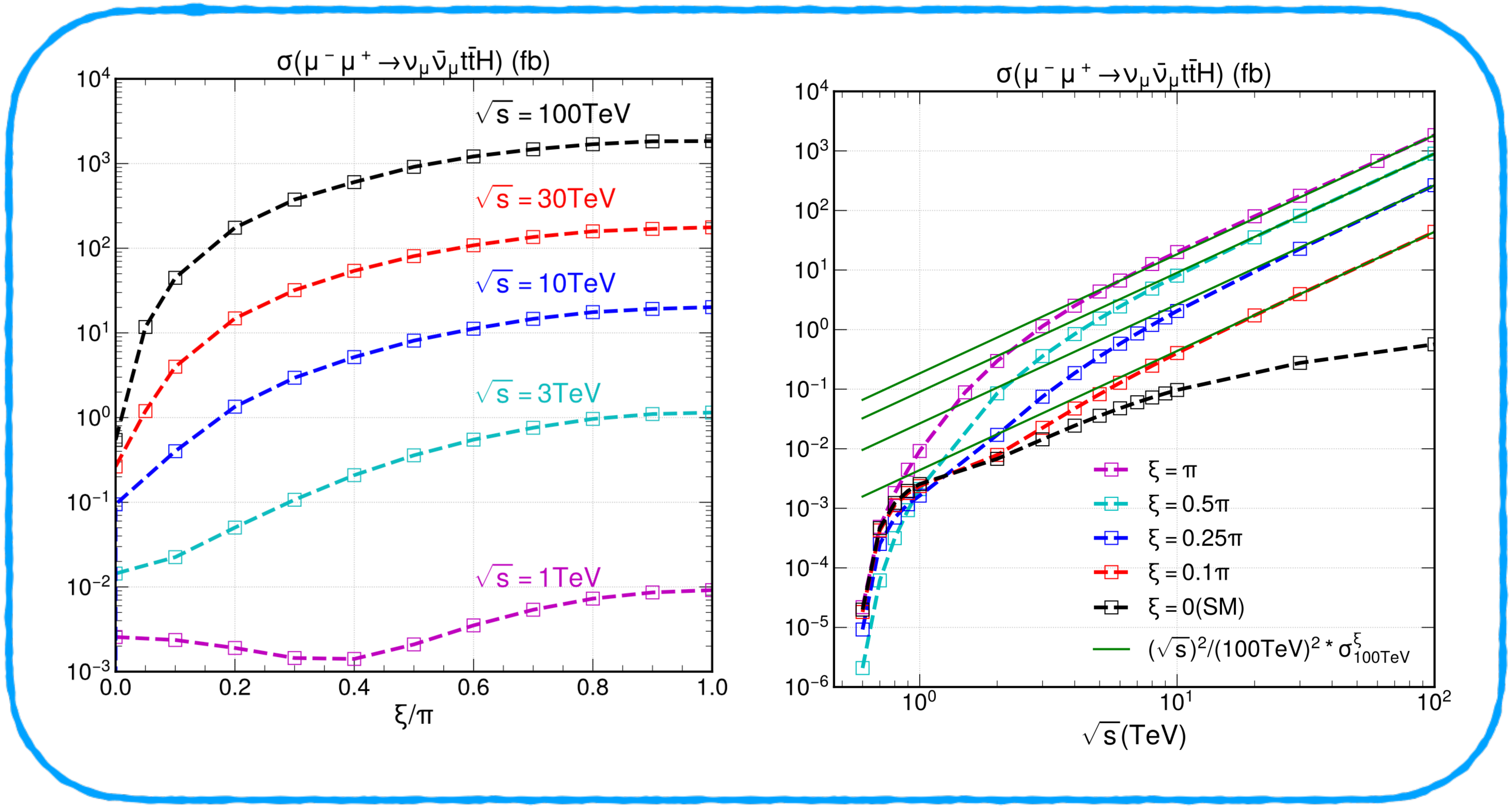


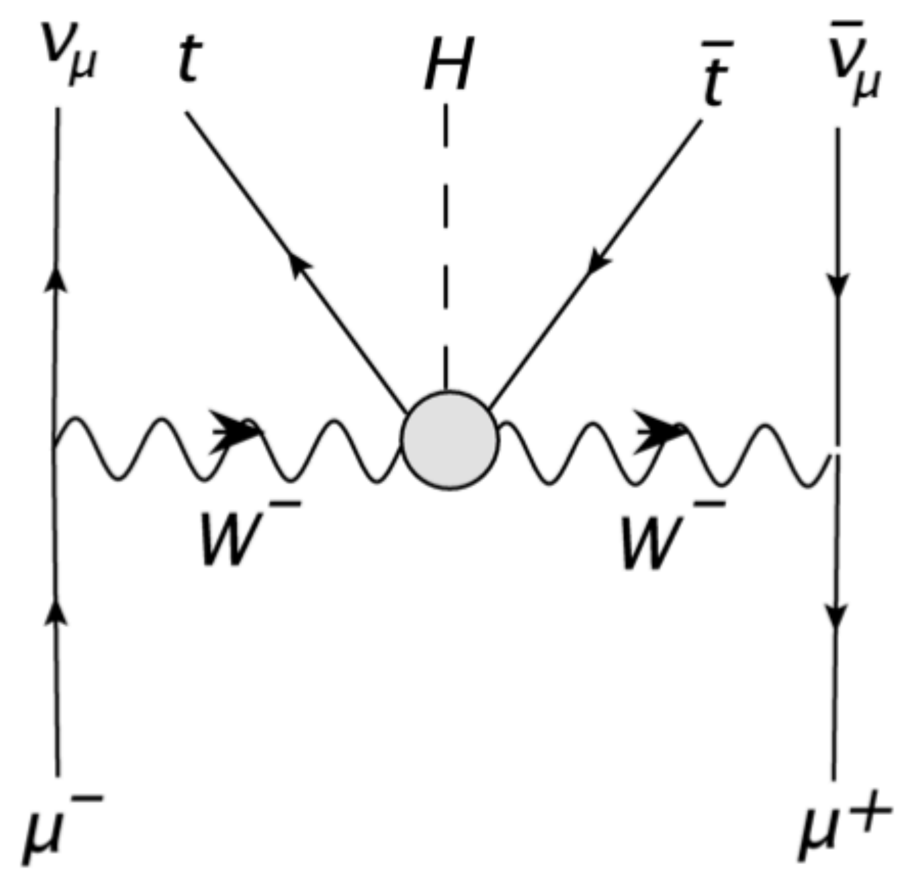


Top Yukawa processes at muon collider



M.Cassidy, Z.Dong, KC.Kong, I. Lewis, Y.Zhang, YJZ, JHEP 05 (2024) 176.

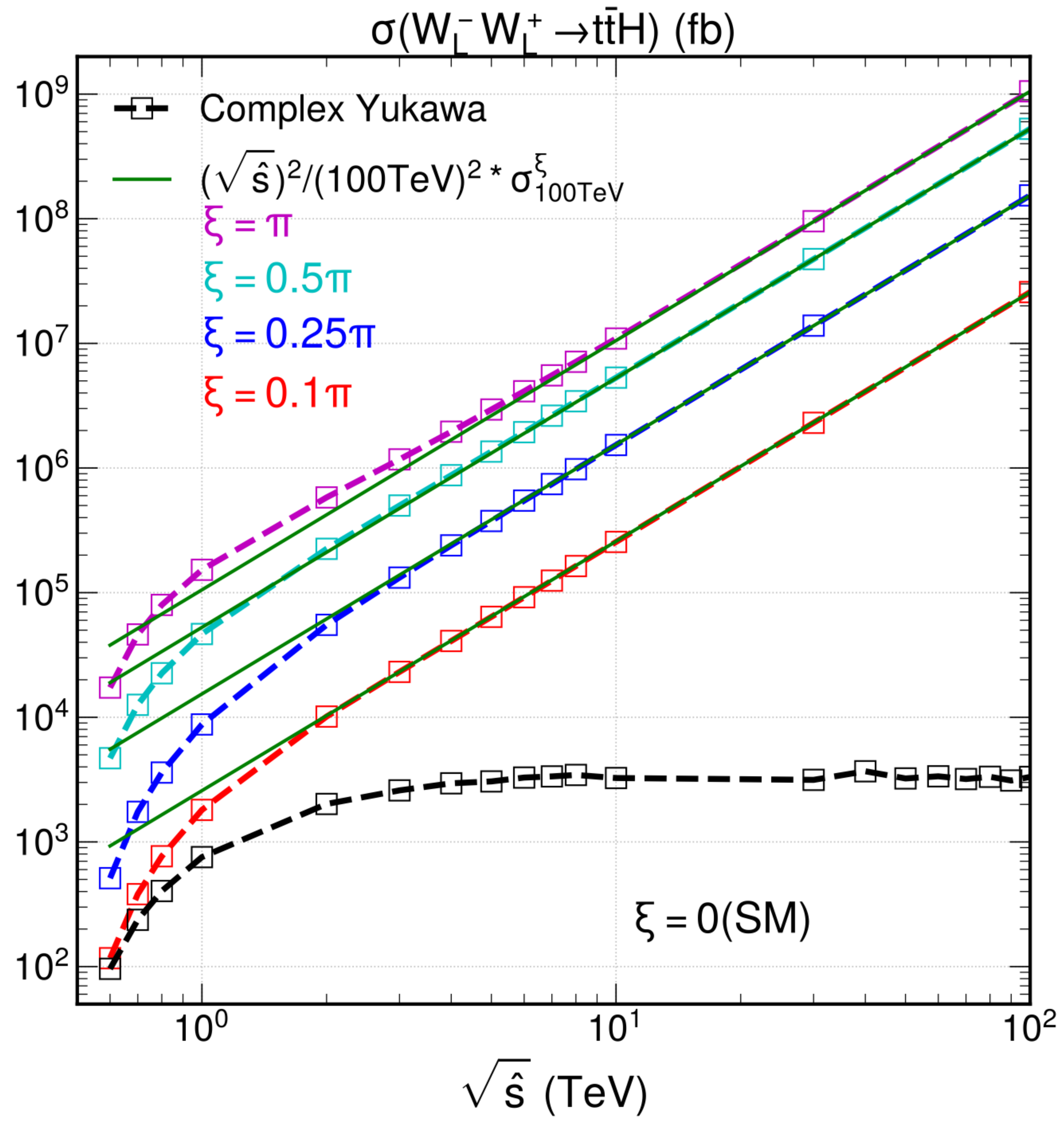




88 diagrams generated from Madgraph5, 20 diagrams are Vector Boson Fusions

Energy dependence at high energy:
BSM: quadratic growth
SM: logarithmically growth

Vector Boson Fusion



$$W^-(q, h=0)\ W^+(\bar{q}, \bar{h}=0) \to t\bar{t}H$$

quadratic energy growth from the longitudinally polarized weak boson wave functions E/m_W.

In the SM, E/m_W from individual diagram cancels after summing up, leading to the Goldstone boson equivalence theorem (GBET) as a manifestation of gauge invariance.

$$\mathcal{L}_{ttH} = -gH\bar{t}(\cos\xi + i\gamma_5 \sin\xi)t$$

Gauge invariant formulation: Models like two Higgs doublet models,etc

SMEFT

A gauge invariant top Yukawa sector:

Dimension-6 operator

$$\mathcal{L} = -y_{\rm SM} Q^\dagger \phi t_R - \frac{\lambda}{\Lambda^2} Q^\dagger \phi t_R \phi^\dagger \phi + \text{h.c.}$$

$$Q = (t_L, b_L)^T$$
$$\phi = ((v + H + i\pi^0)/\sqrt{2}, i\pi^-)^T$$

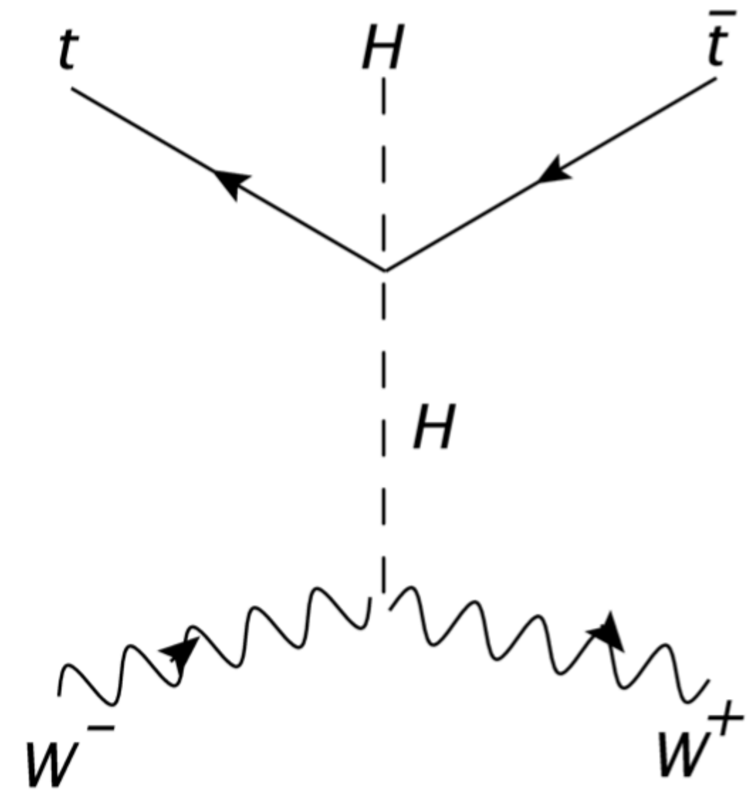
$$\mathcal{L}^{\rm SMEFT}_{ttH} = -Q^\dagger \phi t_R \left(y' - \frac{\lambda}{\Lambda^2}\left(vH + \frac{H^2 + (\pi^0)^2}{2} + \pi^+\pi^-\right) + \text{h.c.}\right.$$

$$y' = y_{\rm SM} - \frac{\lambda v^2}{2\Lambda^2}$$

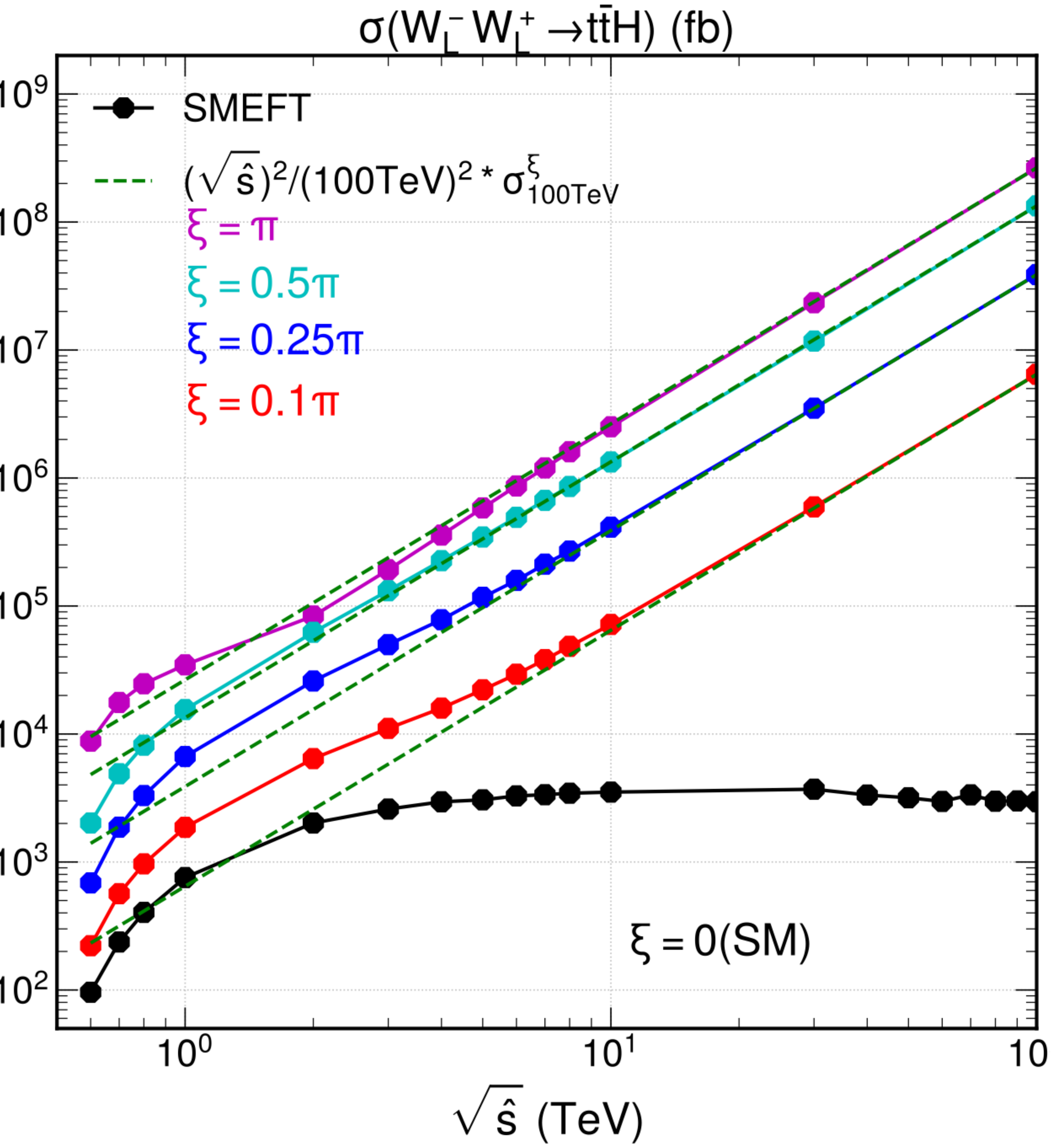
$$\begin{aligned}
\mathcal{L}^{\rm SMEFT}_{ttH} =& -m_t t_L^\dagger t_R - g_{\rm SM}\left[(H + i\pi^0)t_L^\dagger + i\sqrt{2}\pi^- b_L^\dagger\right] t_R \\
& -(ge^{i\xi} - g_{\rm SM})\left\{H t_L^\dagger t_R + \frac{H}{v}\left[(H + i\pi^0)t_L^\dagger + i\sqrt{2}\pi^- b_L^\dagger\right] t_R\right\} \\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

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

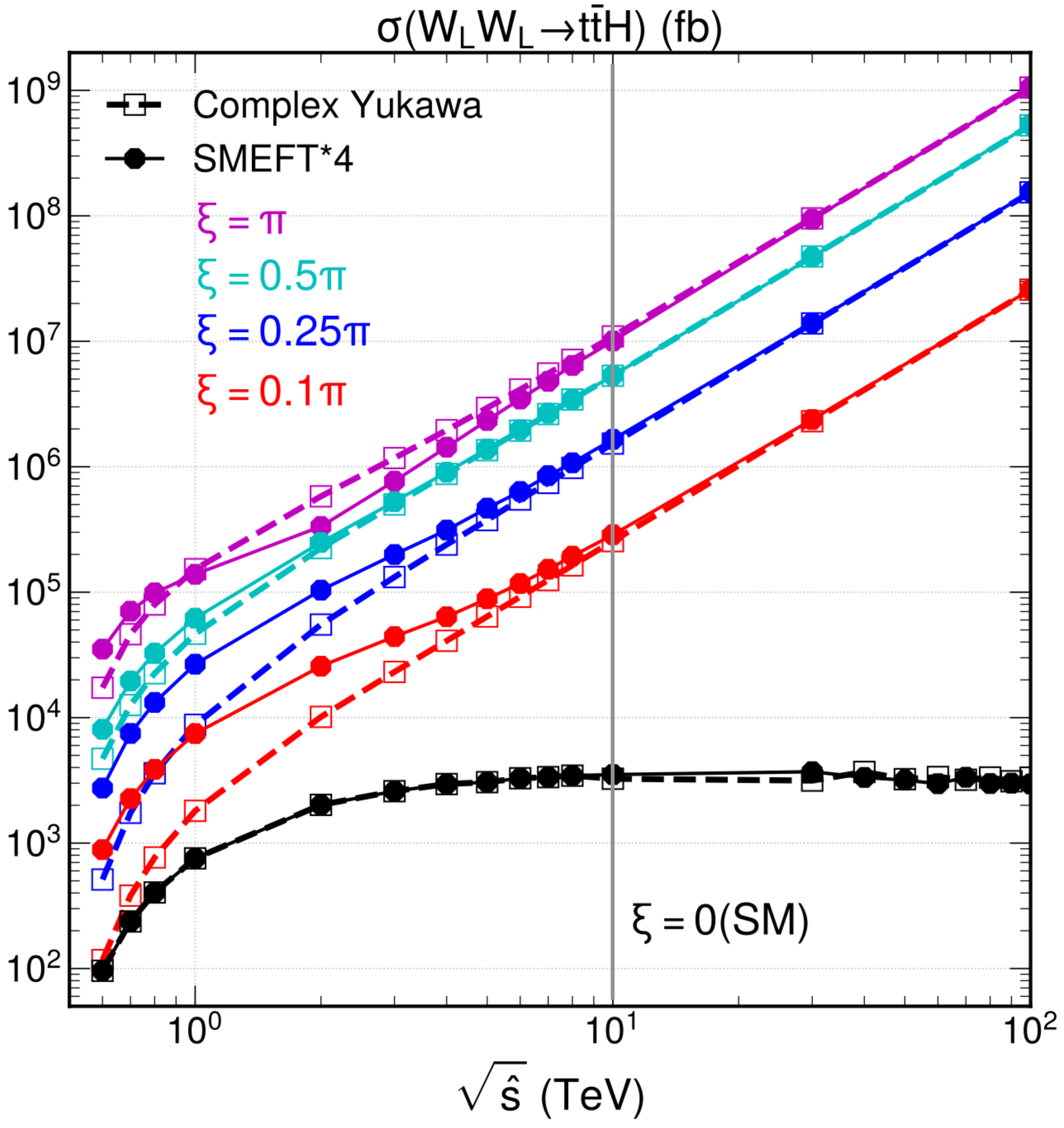
Additional ttHH and ttHHH coupling

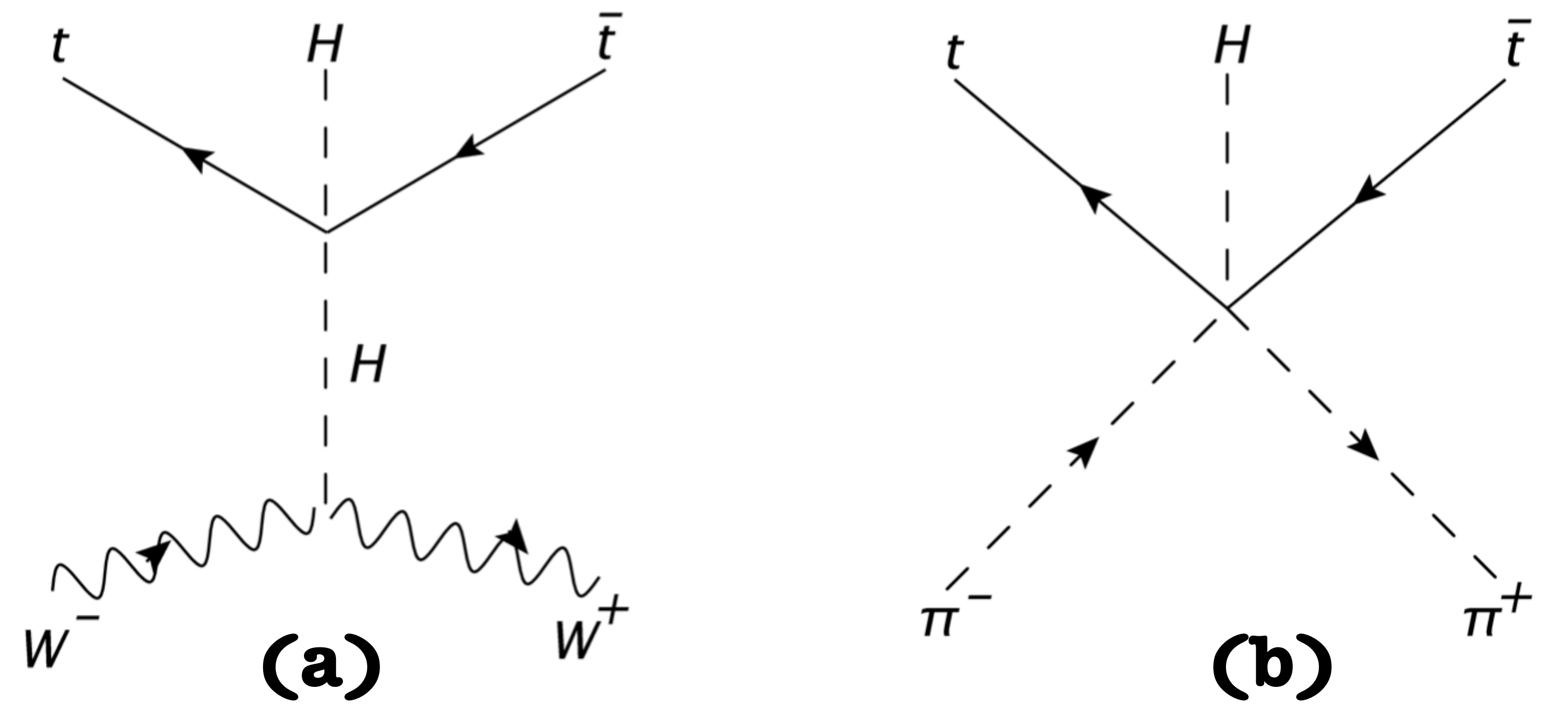


$$\mathcal{L}^{\rm SMEFT}_{ttHH} = \frac{3(g_{\rm SM} - ge^{i\xi})}{v}\frac{H^2}{2} t_L^\dagger t_R + \text{h.c.}$$



above 10 TeV





Complete amplitude in SMEFT:

$$\mathcal{M}(W_L^- W_L^+ \to t\bar{t}H)_{\rm SMEFT} = \sum_{k=1}^{20} \mathcal{M}_k + \mathcal{M}_{\rm Fig.\,\mathbf{a}}$$

$$\mathcal{M}^{\pm\pm}_{\rm Fig\,\mathbf{b}} = \frac{1}{v^2}\left[\mp 2p_t\left(g_{\rm SM} - g\cos\xi\right) - i m_{tt}\left(g\sin\xi\right)\right]$$

$$\mathcal{M}^{\pm\pm}_{\rm Fig.\,\mathbf{a}} = \frac{3}{v^2}\left[\mp 2p_t(g_{\rm SM} - g\cos\xi) - i m_{tt}(g\sin\xi)\right]\frac{(\hat{s}-2m_W^2)}{(\hat{s}-m_H^2)}$$

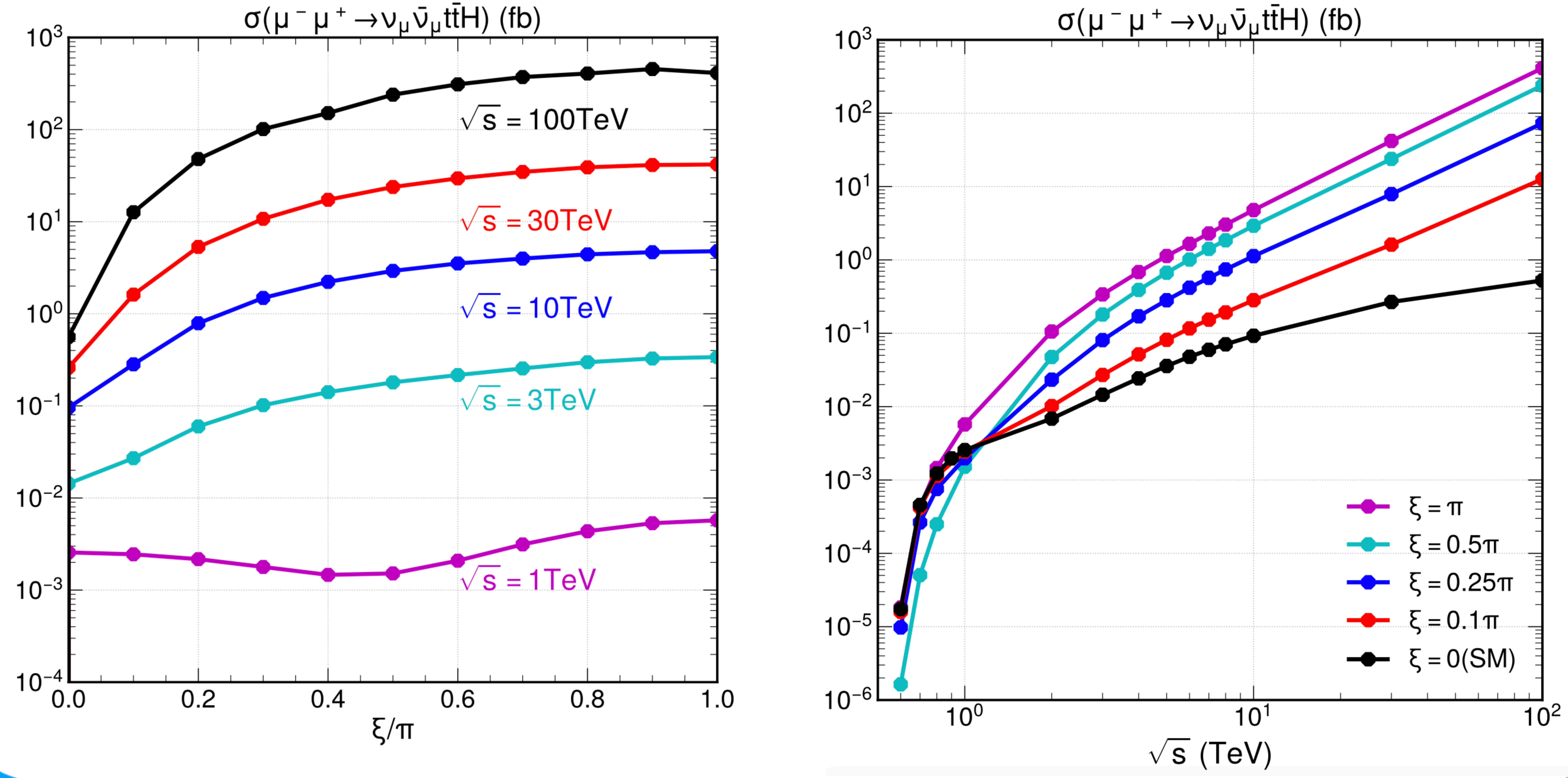
$$\mathcal{M}^{\pm\pm}_{\rm Fig.\,\mathbf{a}} = 3\mathcal{M}^{\pm\pm}_{\rm Fig.\,\mathbf{b}} \cdot \left\{1 + \mathcal{O}\left(\frac{1}{\hat{s}}\right)\right\}$$

GBET tells:

$$\sum_{k=1}^{20} \mathcal{M}_k + \mathcal{M}_{\rm Fig.\,\mathbf{a}} = \mathcal{M}_{\rm Fig.\,\mathbf{b}} \cdot \left\{1 + \mathcal{O}\left(\frac{1}{\hat{s}}\right)\right\}$$

$$\sum_{k=1}^{20} \mathcal{M}_k \approx -2\mathcal{M}_{\rm Fig.\,\mathbf{b}}$$

$$\sigma_{\rm tot}(W_L^- W_L^+ \to ttH)_{\rm SMEFT} \approx \frac{1}{4}\sigma_{\rm tot}(W_L^- W_L^+ \to ttH)_{\rm complex\ \ Yukawa}$$



Phenomenologies under study, V. Barger, K. Hagiwara, J. Kanzaki, K.Mawatari and YJZ, in preparation

Perturbative Unitarity

In the SM, $g_{SM} = m_t/v$, unitarity should be valid at all scales

When $\xi \neq 0$, perturbation unitarity can be violated at $\sqrt{s} \geq o\left(\frac{\Lambda}{\sqrt{\lambda}}\right)$ $g_{\rm SM} - g e^{i\xi} = \frac{\lambda v^2}{\sqrt{2}\Lambda^2}$

$$SS^\dagger = 1$$
$$(1 + iT)(1 - iT^\dagger) = 1$$
$$-i(T - T^\dagger) = TT^\dagger$$
$$-i < i|(T - T^\dagger)|i > = < i|TT^\dagger|i >$$
$$-i(T_{ii} - T^*_{ii}) = < i|T|f > \Phi_f < f|T^\dagger|i >$$

All final states with phase space Φ_f

Optical Theorem: $2Im(T_{ii}) = \sum_f |T_{fi}|^2 \Phi_f = 2\hat{s} \sum_f \sigma(i \to f)$

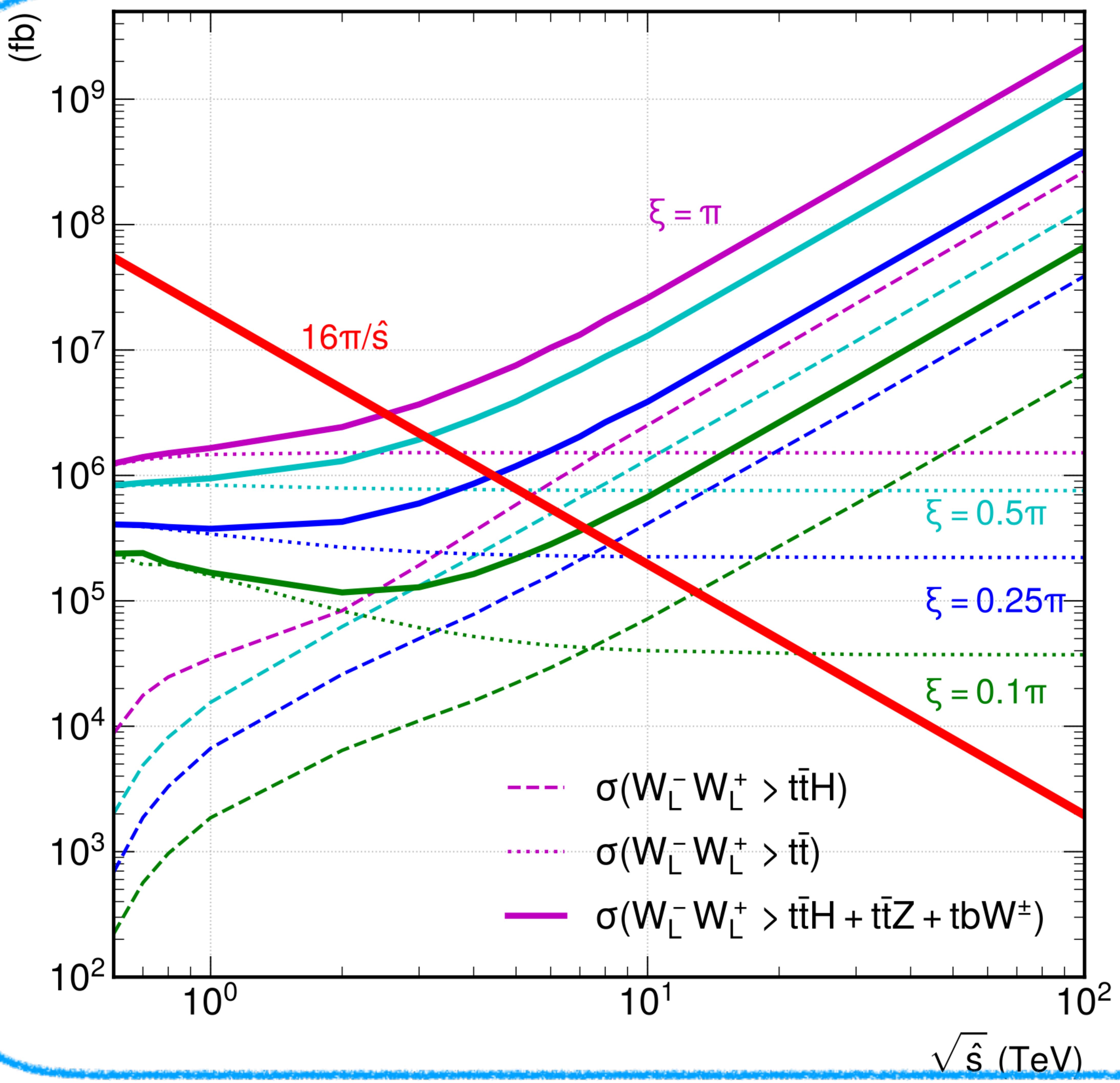
Unitarity bound: for *J=0* $2Im(T_{ii}) > |T_{ii}|^2 \frac{1}{8\pi}$ 2-body phase space

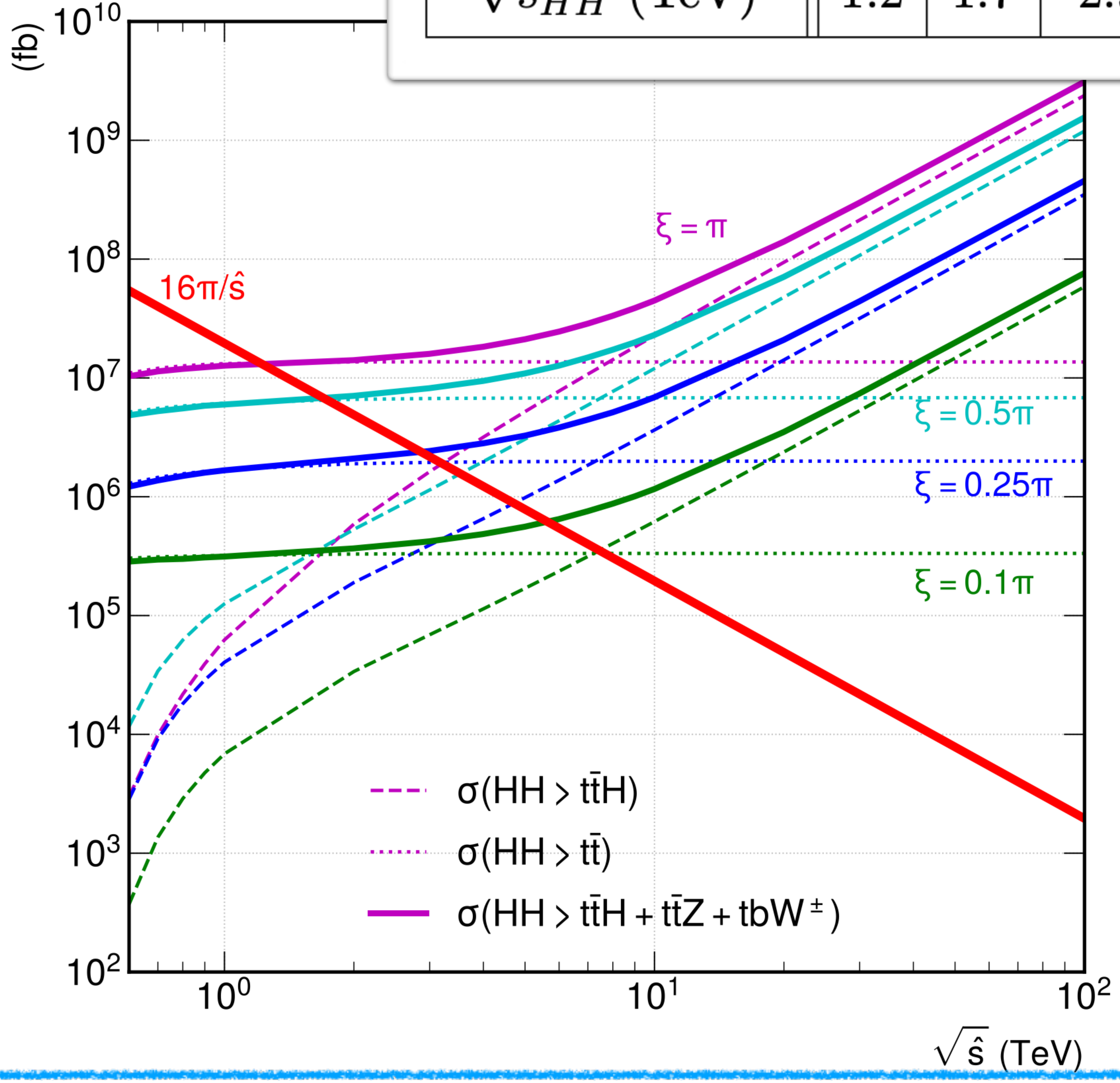
$$|T_{ii}|^2 < 16\pi Im(T_{ii}) < 16\pi |T_{ii}|$$
$$|T_{ii}| < 16\pi$$
$$2\hat{s} \sum_f \sigma(i \to f)_{J=0} = 2Im(T_{ii})_{J=0} < 32\pi$$
$$\sum_f \sigma(i \to f)_{J=0} < \frac{16\pi}{\hat{s}}$$

Unitarity bound

$$\sum_f \sigma_{\text{tot}} \left(W_L^- W_L^+ \to f; J=0 \right) < \frac{16\pi}{\hat{s}}$$

$\lvert\xi\rvert$	π	0.5π	0.25π	0.1π
$\lvert\lambda\rvert \cdot \Lambda^{-2}(\text{TeV}^{-2})$	32.9	23.2	12.6	5.14
$\sqrt{\hat{s}}_{W_L W_L}(\text{TeV})$	2.5	3.1	4.4	7.2
$\sqrt{\hat{s}}_{HH}$ (TeV)	1.2	1.7	2.9	5.6





Feynman-Diagram (FD) 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 $$n(q)^{\mu}_{\rm FD} = ({\rm sgn}(q^0), -\vec{q}/|\vec{q}|)$$

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

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

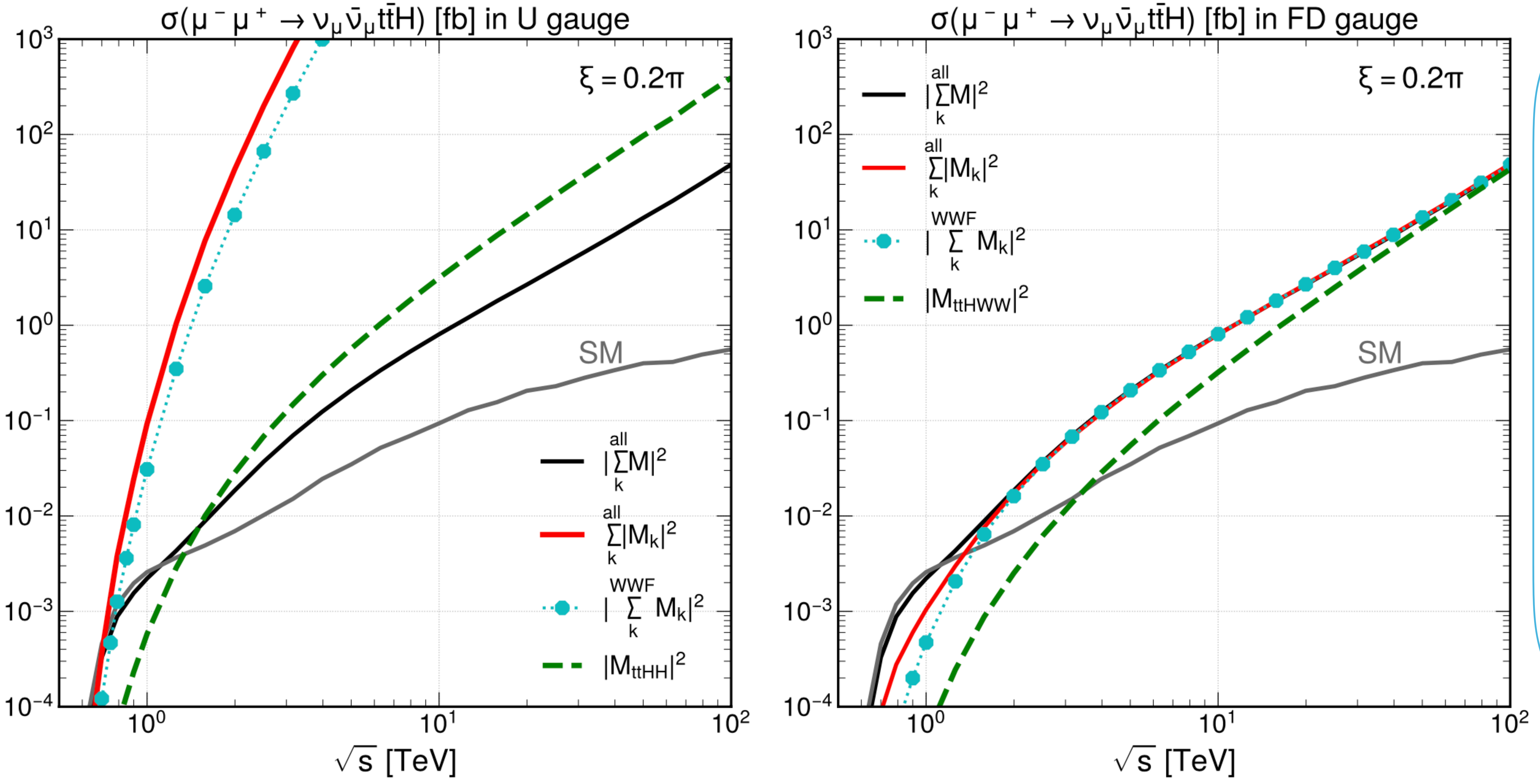
$$-\frac{Q\, n^\mu}{n\cdot q} = \epsilon^\mu(q, h=0) - \frac{q^\mu}{Q}, \quad Q = \sqrt{|q^2|}$$

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

[1] Kaoru Hagiwara, Junichi Kanzaki and Kentarou Mawatari, 'QED and QCD helicity amplitudes in Parton-shower gauge.' Eur.Phys.J.C 80(2020) 6, 584
[2] Junmou Chen, Kaoru Hagiwara, Junichi Kanzaki and Kentarou Mawatari, 'Helicity amplitudes without gauge cancellation for electroweak processes'Eur.Phys.J.C 83 (2023).
[3] 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).

FD gauge

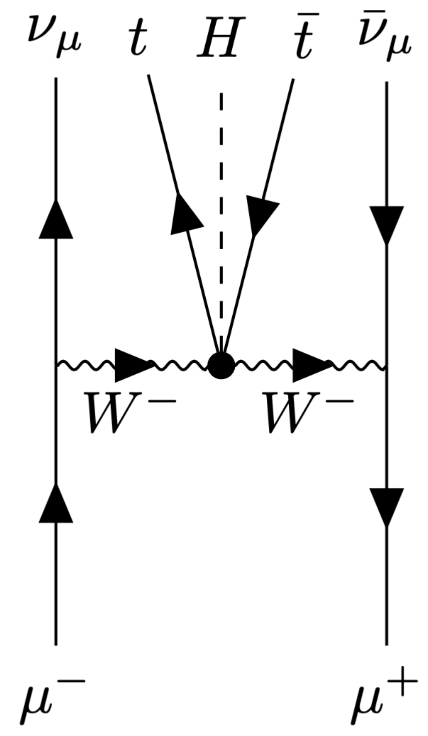


(a) (b)

- 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.

Automatic generation of FD gauge is available in Madgraph by command 'set gauge FD'.

Summary

- We identify the cause of a power law increase of the $\mu^-\mu^+ \rightarrow \nu\nu t t H$ cross section when the top Yukawa coupling is complex as due to the power law increase of the weak boson fusion sub process cross section, which is a consequence of gauge non-invariance of the dimension four Lagrangian.

- We identify the dimension-six SMEFT operator which gives a gauge invariant description for complex Yukawa coupling and confirm that the total cross section for W W → ttH satisfies the Goldstone Boson Equivalence Theorem.

- We obtain a novel perturbedive untarity bound on the SMEFT operator by summing over all 2 → 2 and 2 → 3 processes which contribute to the J=0 HH → HH amplitude.

- In the Feynman-Diagram gauge, the cross section is dominated by the WBF diagrams making the GBET manifest.