SMEFT top-quark effects on $\Delta F=2$ observable

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Based on **on-going work** with **Motoi Endo(KEK)** and **Teppei Kitahara(KIT)**

Introduction

- **FCNCの計算における標準的な有効理論**

$$\mathscr{H}_{\mathrm{eff}}^{\Delta F=2} = C_1(\bar{d}_{L,i}\gamma^\mu d_{L,j})(\bar{d}_{L,i}\gamma_\mu d_{L,j}) + C_2(\bar{d}_{R,i}d_{L,j})(\bar{d}_{R,i}d_{L,j}) + \cdots$$

-ゲージ不変性が明白ではない

-NP粒子, top, W, Z, Higgsはdecouple (NP scale > O(100)GeV)

- **Standard Model Effective Theory(SMEFT):**

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i C_i \underline{\mathcal{O}_i}$$ **(NP粒子だけdecouple)**

ゲージ不変

-ゲージ不変性が明白 **e.g. KaonにおけるΔS=2の観測量**

-operatorを評価するスケール不定性なし **e.g. LRのΔB=2の観測量**

Outline

- Introduction

  -標準的な有効理論における問題点

- SMEFTによるゲージ不変な扱い

  -Kaon系におけるゲージ不変な扱い

  [Endo, Kitahara, Mishima and Yamamoto]

- SMEFTにおけるトップクォークの量子補正

  -Left-right symmetric modelにおけるSMEFT

  On-going work with **Motoi Endo**(KEK) and **Teppei Kitahara**(KIT, TTP)

Flavor-changing Z penguin

- ε'/ε: $K_L \to \pi\pi$におけるCPを破る観測量

- SM:

  $(\varepsilon'/\varepsilon_K)_{SM} = (1.1 \pm 5.1) \times 10^{-4}$ [T.Kitahara, U.Nierste and P.Tremper]

- 実験:

  $(\varepsilon'/\varepsilon_K)_{EXP} = (16.6 \pm 2.3) \times 10^{-4}$ [NA48, KTeV]

- SMと実験値が合っていない:

  $(\varepsilon'/\varepsilon_K)_{EXP} > (\varepsilon'/\varepsilon_K)_{SM}$ at 2.8σ level

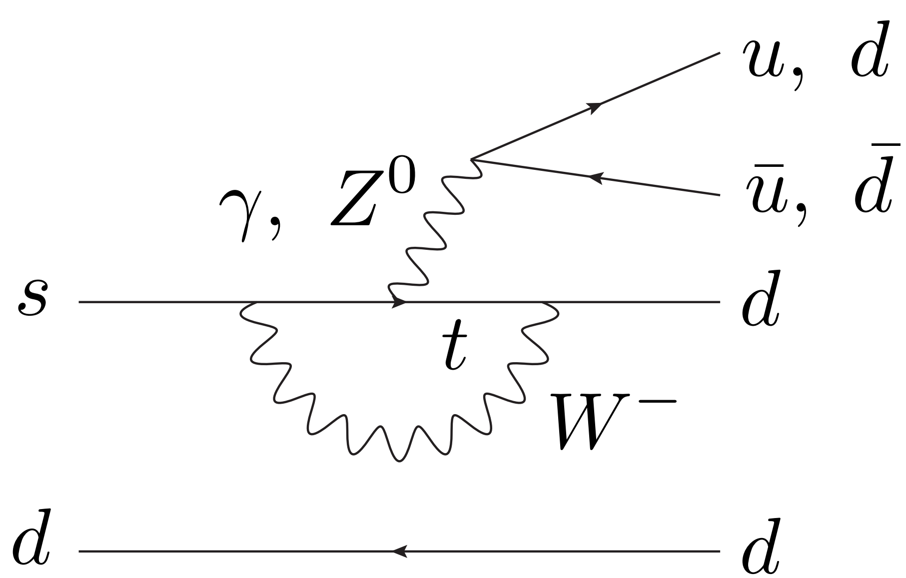
KaonにおけるSMEFT

- **ε'/εへのNPの寄与:**

$$\epsilon'/\epsilon_K \propto \left(\mathrm{Im}A_0 - \mathrm{Im}A_2/\omega_{EXP}\right) \qquad 1/\omega_{\mathrm{EXP}} = 22.46$$

decay amplitude

$$A_2 \sim$$

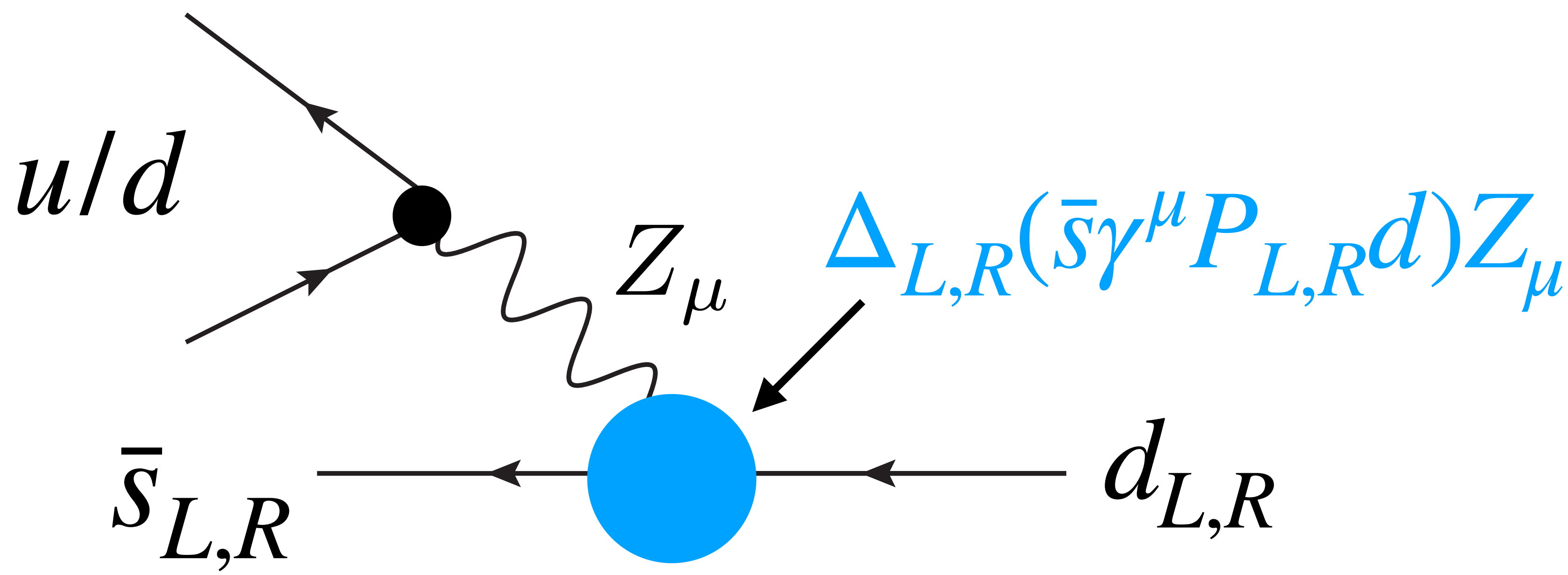


EW-penguin

- **Z-penguinへのNPの寄与は魅力的なシナリオ**

KaonにおけるSMEFT

- **Z-penguinへのNPの寄与:**



$$\mathscr{L} = \Delta_L(\bar{s}\gamma^\mu P_L d)Z_\mu + \Delta_R(\bar{s}\gamma^\mu P_R d)Z_\mu$$ **(ゲージ不変ではない)**

$$(\epsilon'/\epsilon_K)_{NP} \propto \left(s_W^2 \mathrm{Im}\Delta_L + c_W^2 \mathrm{Im}\Delta_R\right)$$

KaonにおけるSMEFT

- **SMEFT:**

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i C_i \underbrace{\mathcal{O}_i}_{\text{ゲージ不変}}$$

EWSB

$$\left.\begin{array}{l} [\mathcal{O}_{HQ}^{(1)}] = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_2 \gamma^\mu q_1) \\ [\mathcal{O}_{HQ}^{(3)}] = (H^\dagger i \overleftrightarrow{D}^a_\mu H)(\bar{q}_2 \tau^a \gamma^\mu q_1) \end{array}\right\} \longrightarrow \quad \Delta_L (\bar{s}\gamma^\mu P_L d) Z_\mu$$

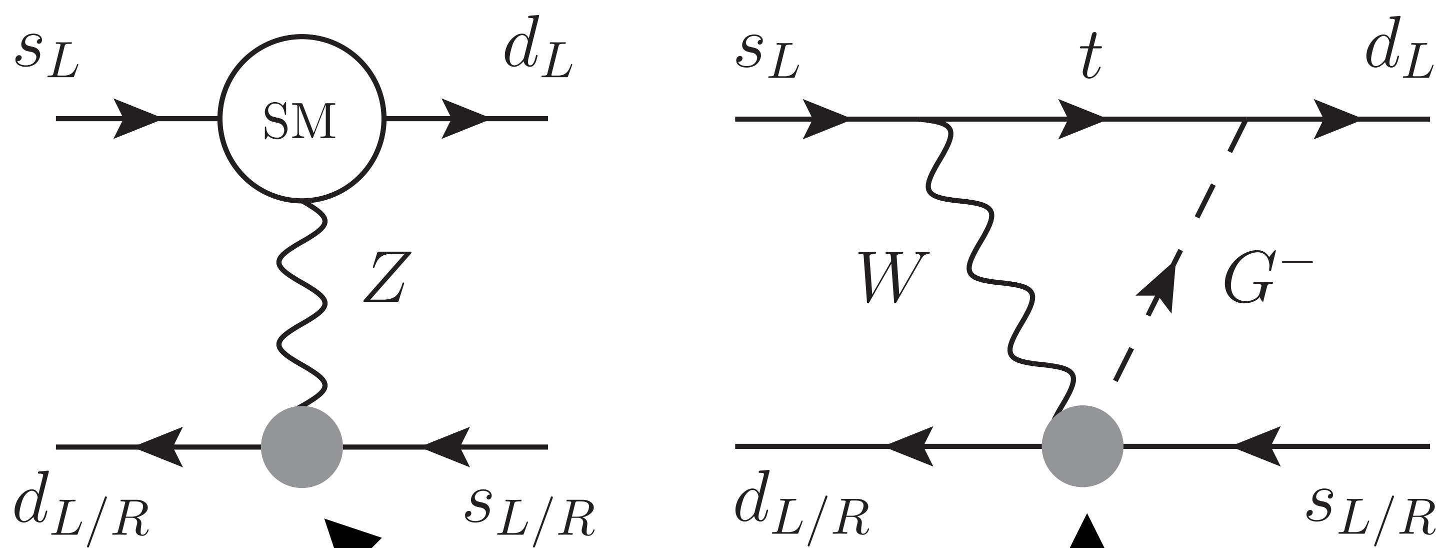
$$[\mathcal{O}_{HD}] = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{s}\gamma^\mu d) \longrightarrow \quad \Delta_R (\bar{s}\gamma^\mu P_R d) Z_\mu$$

$$\mathcal{L}_{\rm eff} = \Delta_L \left[Z_\mu - \frac{g}{M_Z} \left(W_\mu^- G^+ + W_\mu^+ G^- \right) + \cdots \right] (\bar{s}_L \gamma^\mu d_L)$$

$\Delta S = 2$ の観測量に寄与

KaonにおけるSMEFT

- **ΔS=2の観測量** $\sim \langle K^0 | \hat{H} | \bar{K}^0 \rangle$



…

$$\mathscr{L}_{\text{eff}} = \Delta_{L,R} \left[\underline{Z_\mu} - \frac{g}{M_Z} \left(\underline{W_\mu^- G^+ + W_\mu^+ G^-} \right) + \cdots \right] (\bar{s}_{L,R} \gamma^\mu d_{L,R})$$

- **SMEFTによってゲージ不変な扱いが可能**

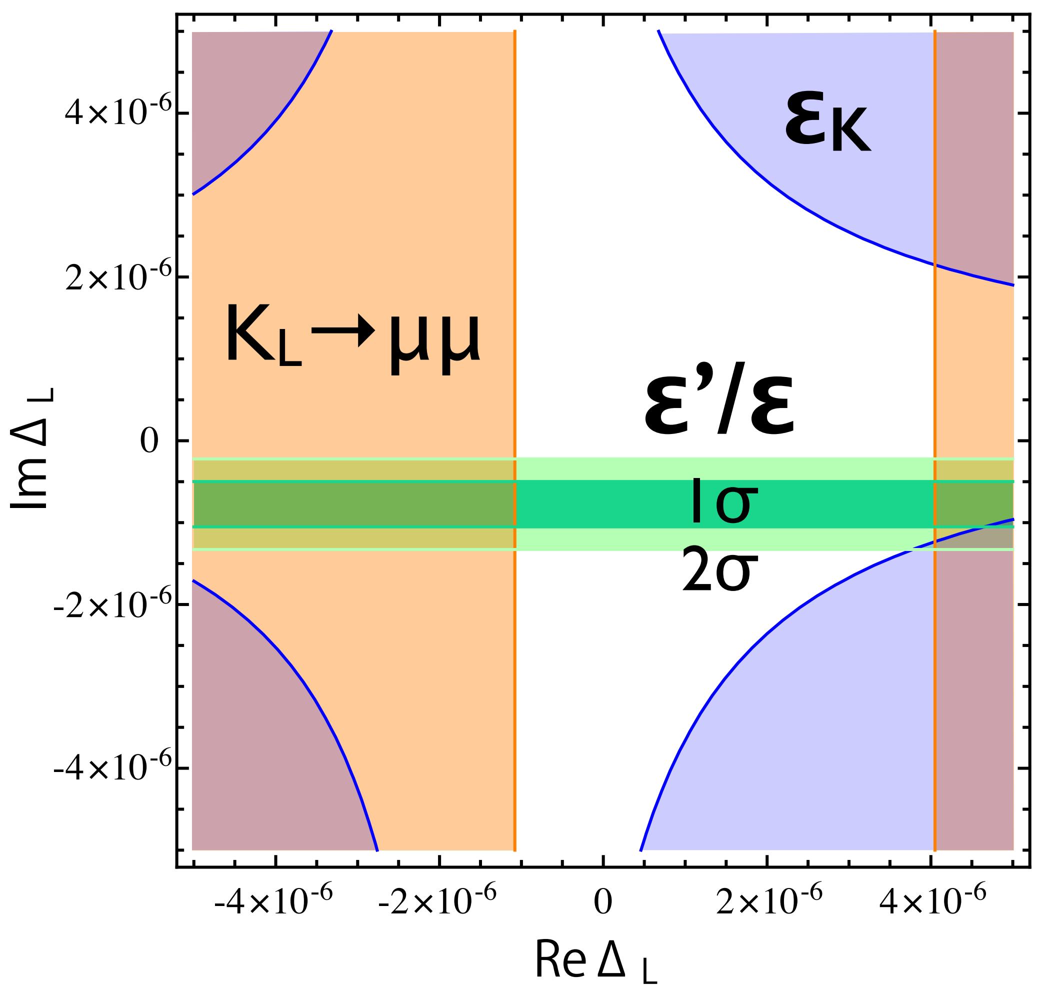
KaonにおけるSMEFT

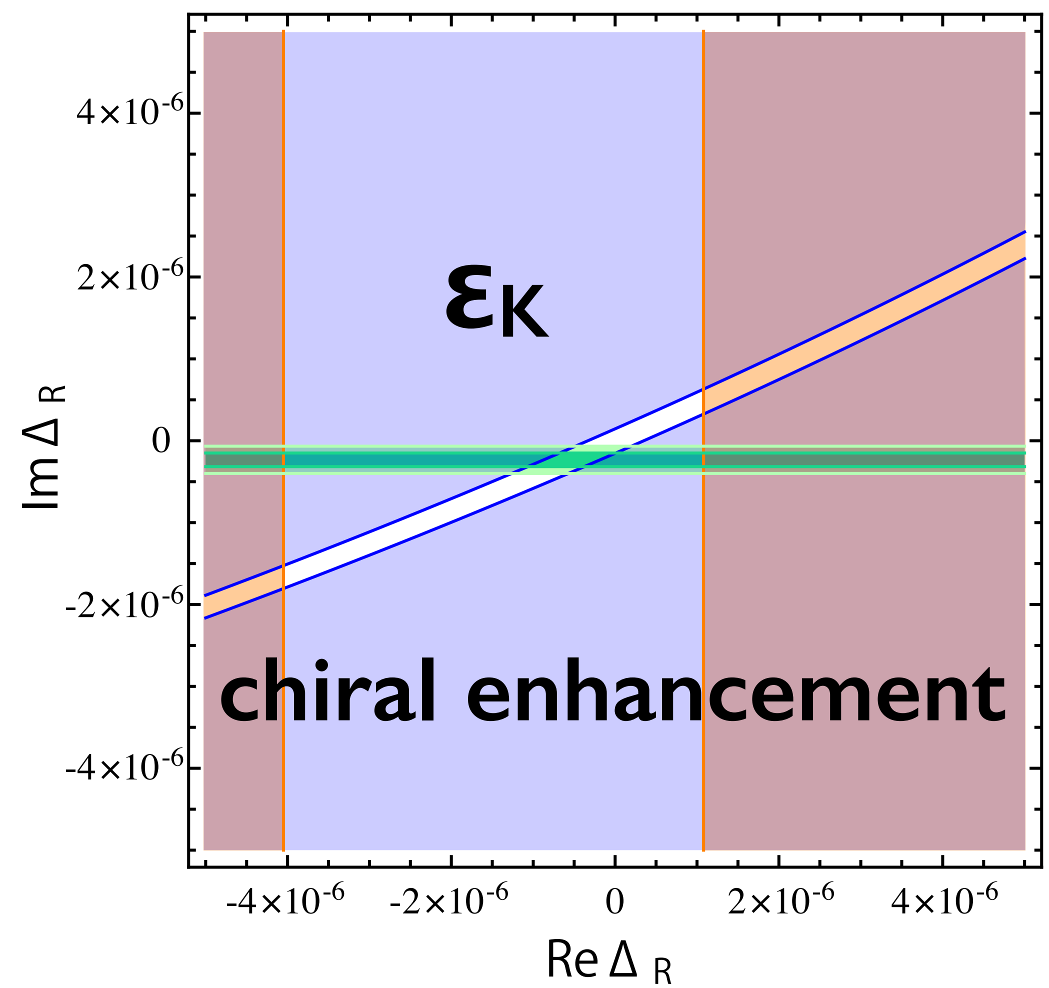
- **KaonのIndirect CP violation:**

-実験値: $|\epsilon^{\rm exp}| = (2.228 \pm 0.011) \times 10^{-3}$

-SM: $\epsilon^{\rm SM} = (2.12 \pm 0.18) \times 10^{-3}$

Δ_L **Δ_R**





$\mathscr{L} = \Delta_L(\bar{d}_L\gamma^\mu s_L)Z_\mu + \Delta_R(\bar{d}_R\gamma^\mu s_R)Z_\mu$

[Endo, Kitahara, Mishima, Yamamoto]

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- **SMEFTにおけるトップクォークの量子補正**

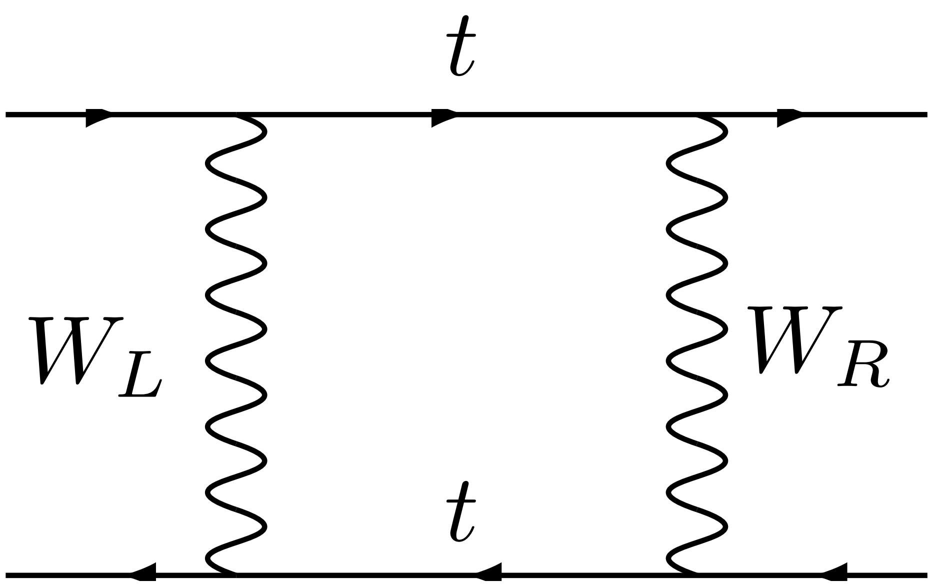
  -具体例としてLeft-right symmetric model

On-going work with **Motoi Endo(KEK) and Teppei Kitahara(KIT, TTP)**

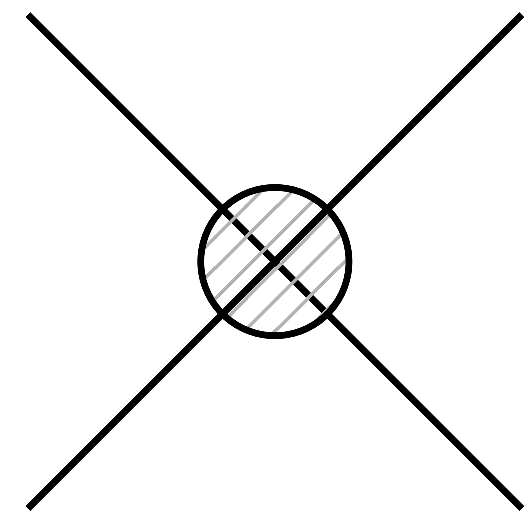
スケールの不定性

- **NP粒子とSM粒子が寄与する:**

e.g. LR model



重い粒子を積分



- **operatorをどのscaleで評価すべきかが決まらない**

Left-right symmetric model

SU(3)$_C$×SU(2)$_L$×SU(2)$_R$×U(1)$_{B\text{-}L}$ $\xrightarrow{v_R}$ SU(3)$_C$×SU(2)$_L$×U(1)$_Y$

- **Flavor-changing相互作用:**

-W$_L$, W$_R$(heavy)

$$\mathscr{L}_{\text{int}} = \frac{g_L}{\sqrt{2}}(V_L)_{ij}\bar{u}_i\gamma_\mu P_L d_j W_L^\mu + \frac{g_R}{\sqrt{2}}(V_R)_{ij}\bar{u}_i\gamma_\mu P_R d_j W_R^\mu$$

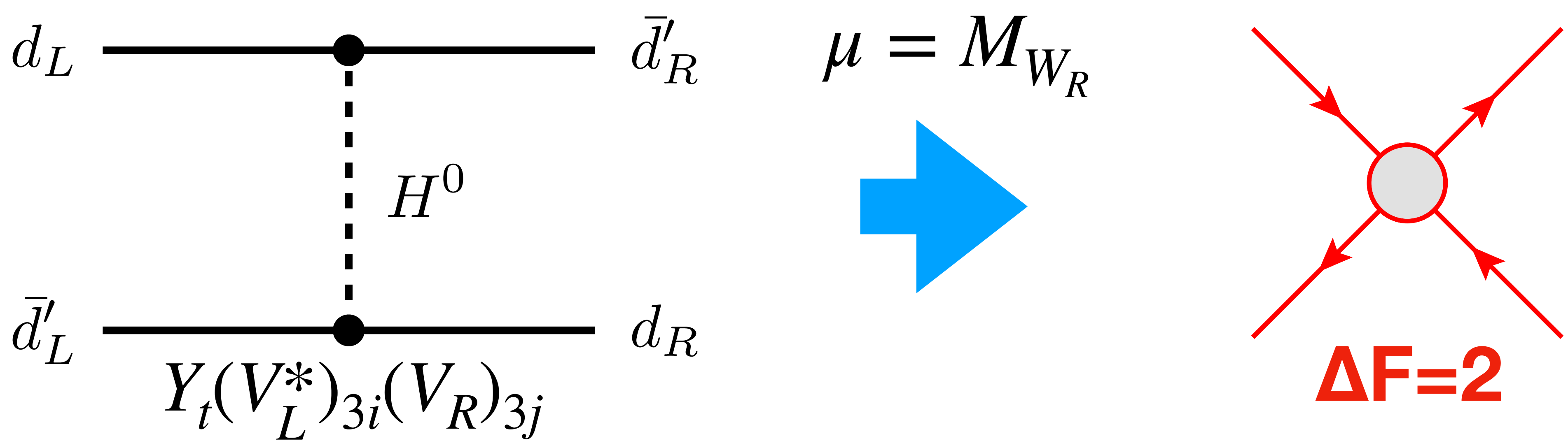
-H^0(heavy neutral higgs)

$$\mathscr{L}_{\text{int}} \simeq -\frac{\sqrt{2}}{v\cos 2\beta}\left[\bar{d}(V_L^\dagger M_u V_R)P_R d H^0 + \bar{d}(V_R^\dagger M_u V_L)P_L d (H^0)^*\right]$$

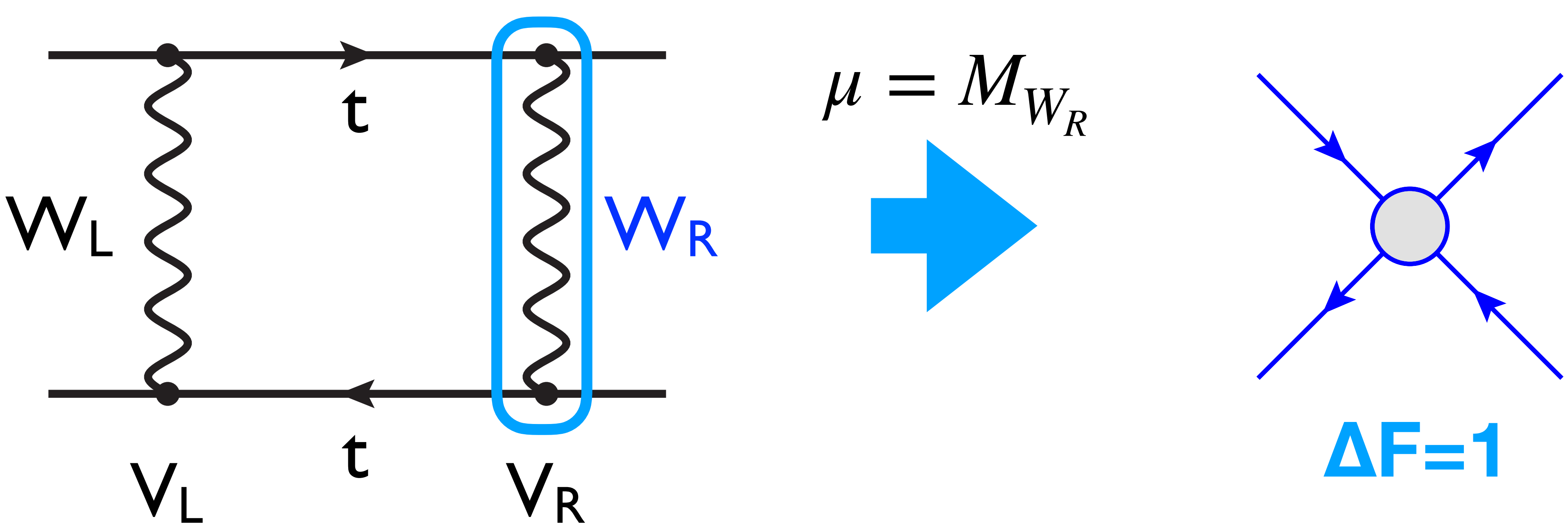
SMEFTへのmatching

- **SMEFTでの扱い:**

-ΔF=2のoperatorにtree-level matcing

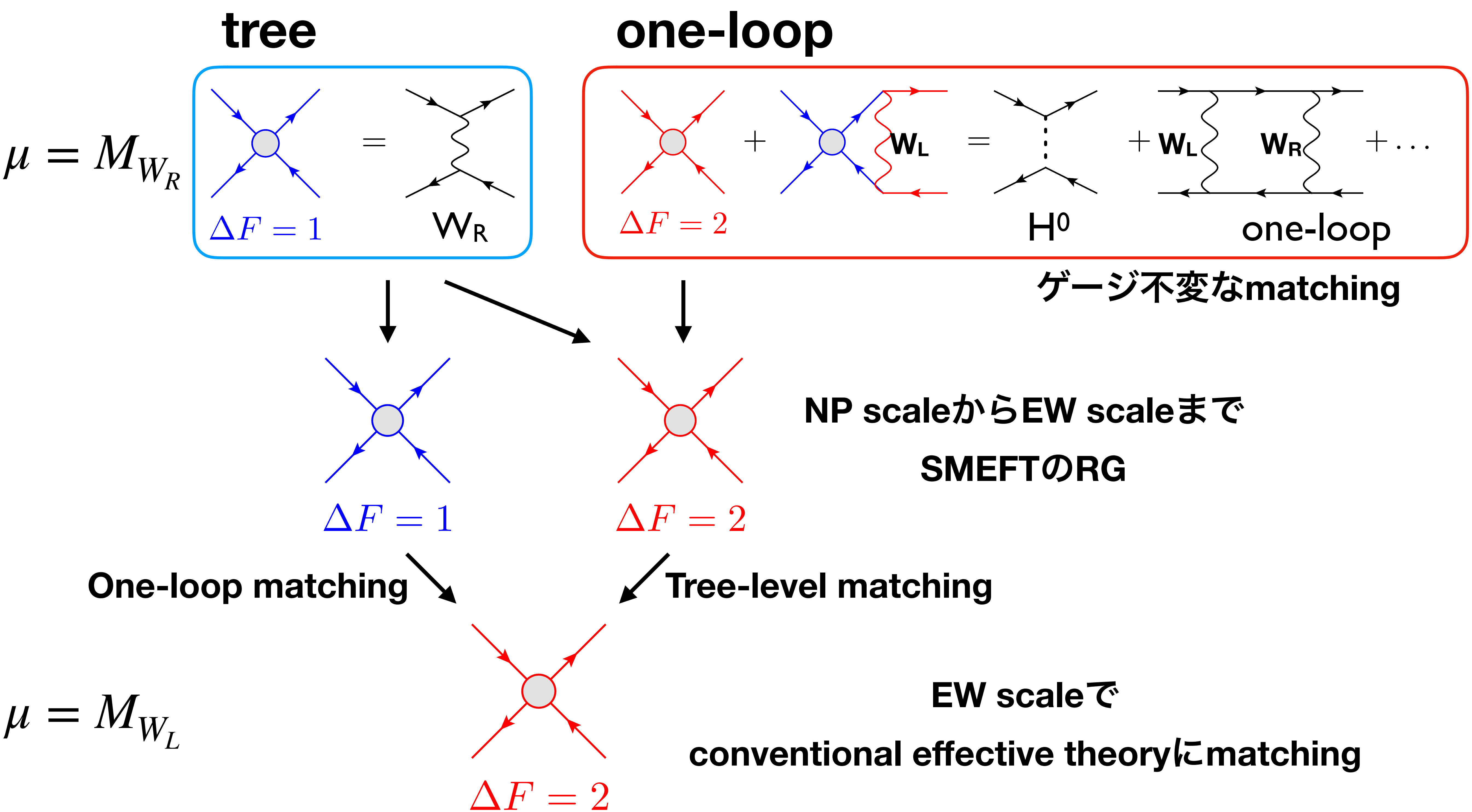


-ΔF=1のoperatorにtree-level matcing



SMEFTへのmatching

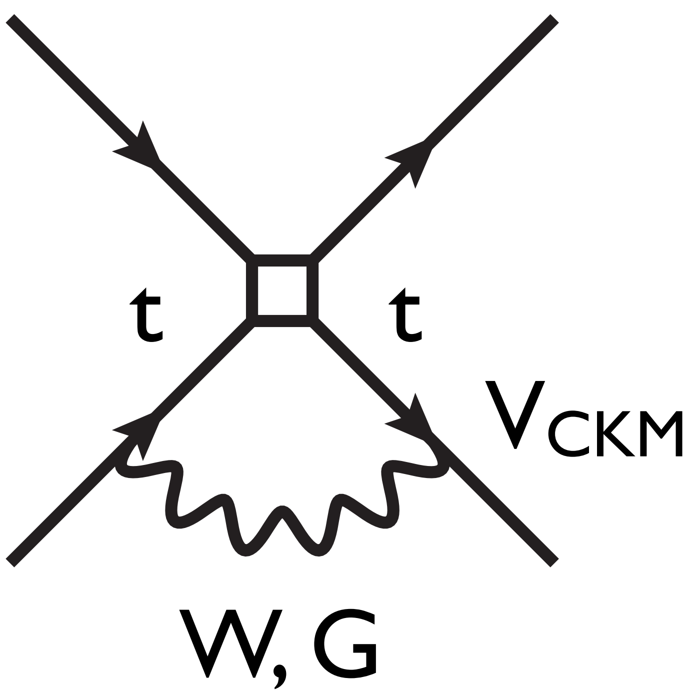
- **NP scaleでのmatching:**



SMEFTへのmatching

- **EW scaleでのmatching:**

one-loop matching

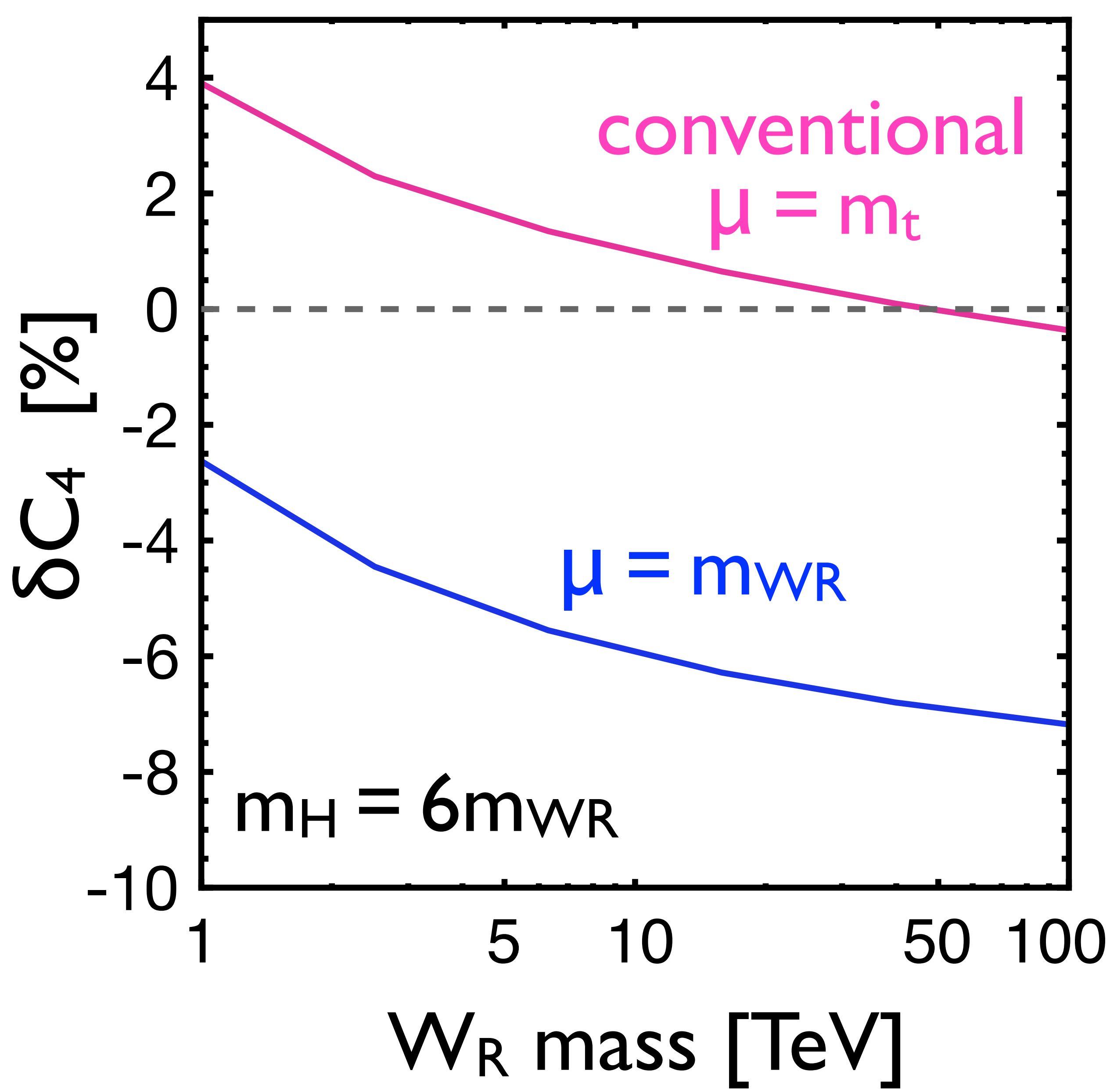


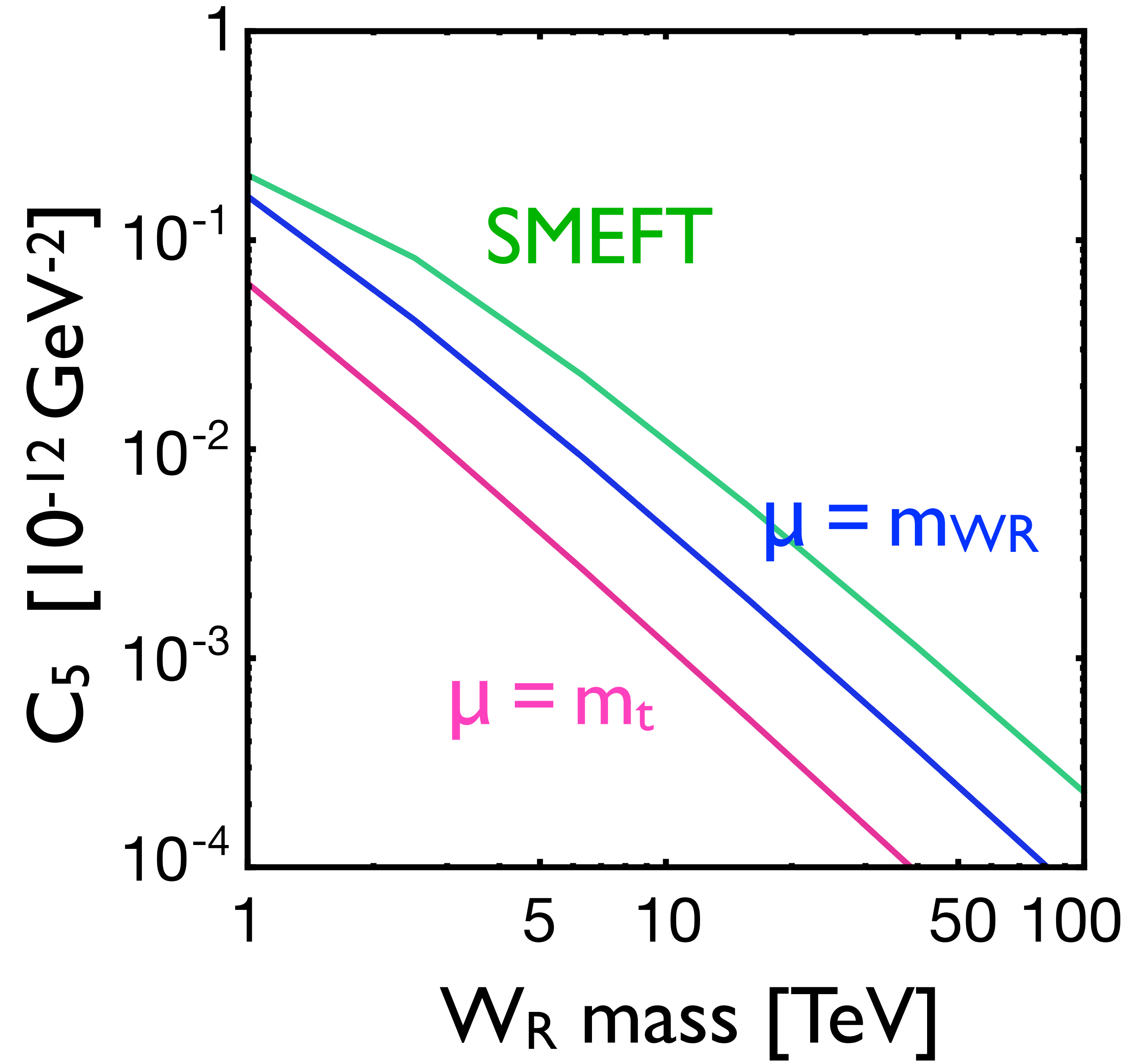
$$
\begin{aligned}
(C_4)_{ij}^{1\text{–loop}} &= \frac{\alpha\lambda_t^{ij}}{\pi s_W^2}(C_{ud}^{(8)})_{33ij} I_1(x_t,\mu_W) + \frac{2\alpha\lambda_t^{ij}}{\pi s_W^2}(C_{qd}^{(8)})_{33ij} J(x_t) \\
&\quad - \frac{\alpha}{2\pi s_W^2}\sum_{m=1}^{3}\left[\lambda_t^{im}(C_{qd}^{(8)})_{mjij} + \lambda_t^{mj}(C_{qd}^{(8)})_{imij}\right] K(x_t,\mu_W), \\
(C_5)_{ij}^{1\text{–loop}} &= \frac{2\alpha\lambda_t^{ij}}{\pi s_W^2}\left[(C_{ud}^{(1)})_{33ij} - \frac{1}{2N_c}(C_{ud}^{(8)})_{33ij} - (C_{Hd})_{ij}\right] I_1(x_t,\mu_W) \\
&\quad + \frac{4\alpha\lambda_t^{ij}}{\pi s_W^2}\left[(C_{qd}^{(1)})_{33ij} - \frac{1}{2N_c}(C_{qd}^{(8)})_{33ij}\right] J(x_t) \\
&\quad - \frac{\alpha}{\pi s_W^2}\sum_{m=1}^{3}\Bigg[\lambda_t^{im}\Big((C_{qd}^{(1)})_{mjij} - \frac{1}{2N_c}(C_{qd}^{(8)})_{mjij}\Big) \\
&\qquad\qquad + \lambda_t^{mj}\Big((C_{qd}^{(1)})_{imij} - \frac{1}{2N_c}(C_{qd}^{(8)})_{imij}\Big)\Bigg] K(x_t,\mu_W),
\end{aligned}
$$

- **SMEFTとconventionalな方法でどの程度違いがあるか?**

Result(1)

- B_SのWilson係数(μ=M_{WL}):

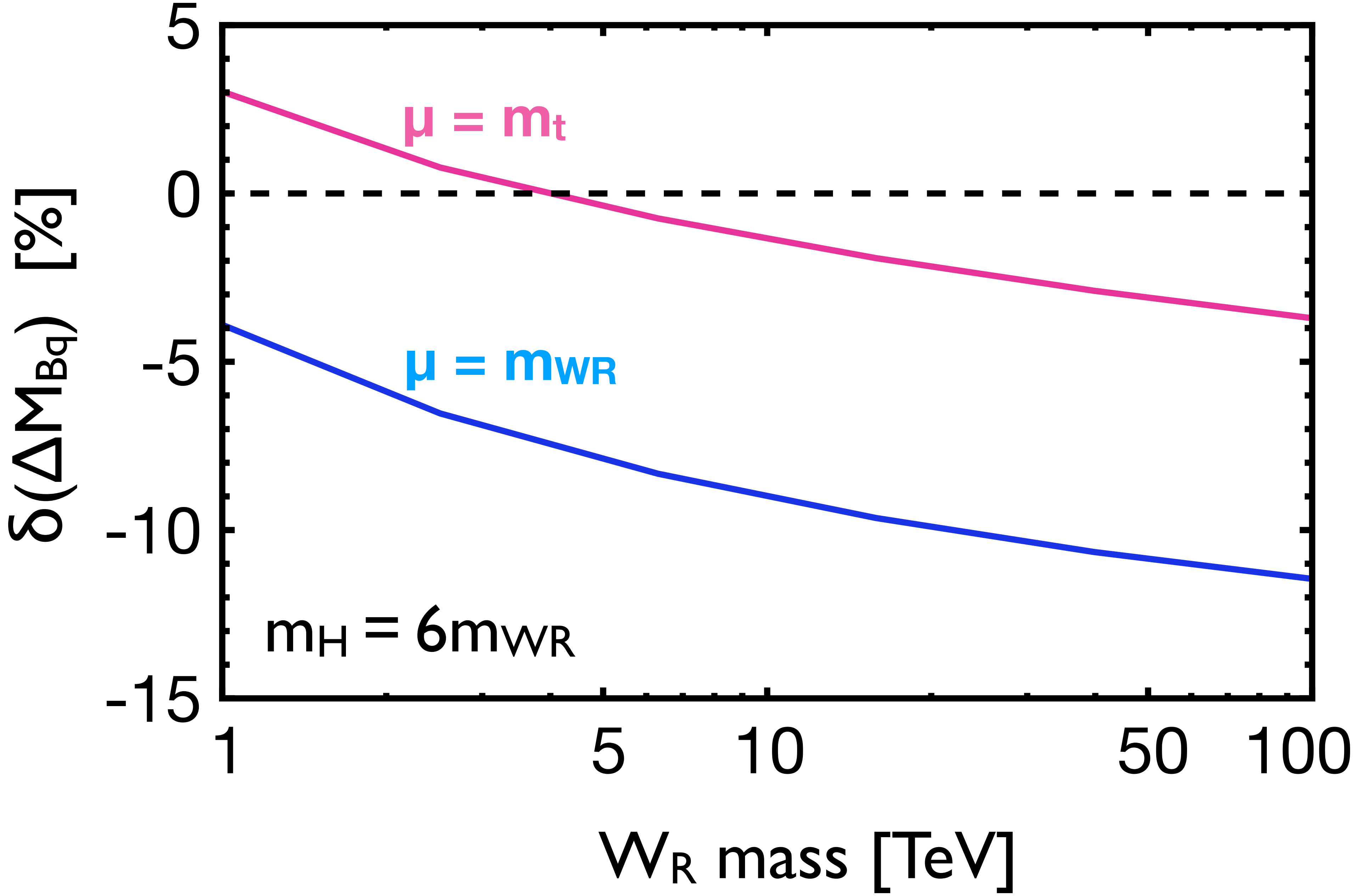




$$\delta C_4 = (C_4(M_{W_L})^{\mathrm{SMEFT}} - C_{4,\mathrm{con}}(M_{W_L})^{\mathrm{input=top,W_R}})/C_4(M_{W_L})^{\mathrm{SMEFT}}$$

Result(2)

- B中間子のmass difference:



$$\delta(\Delta M_{B_q}) = (\Delta M_{B_q})^{\rm SMEFT} - (\Delta M_{B_q})^{\rm input=top, W_R}) / (\Delta M_{B_q})^{\rm SMEFT}$$

Summary

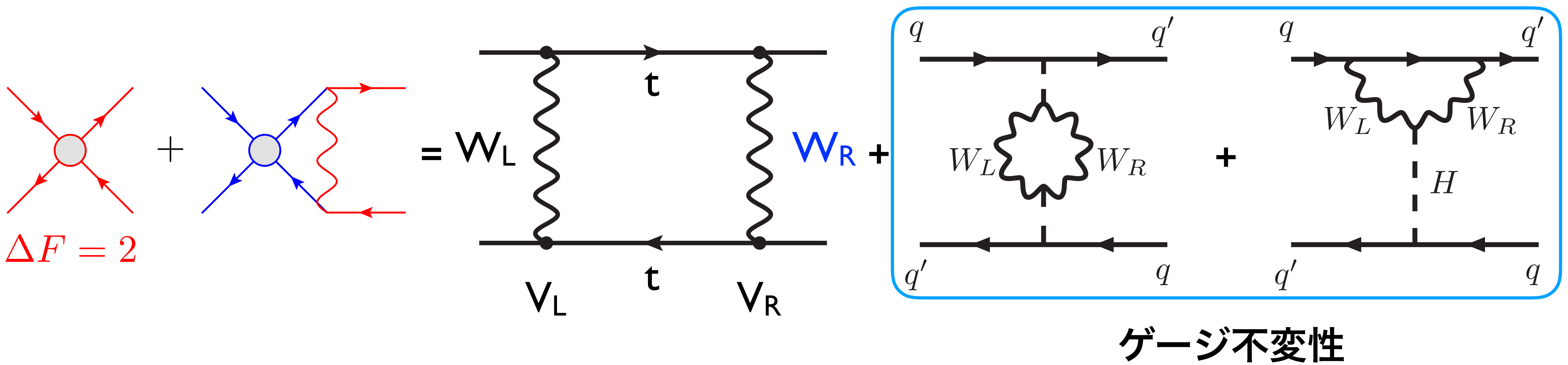
・SMEFTによってゲージ不変に物理量を扱える

・SMEFTによってスケールの不定性を改善できる

Back up slide

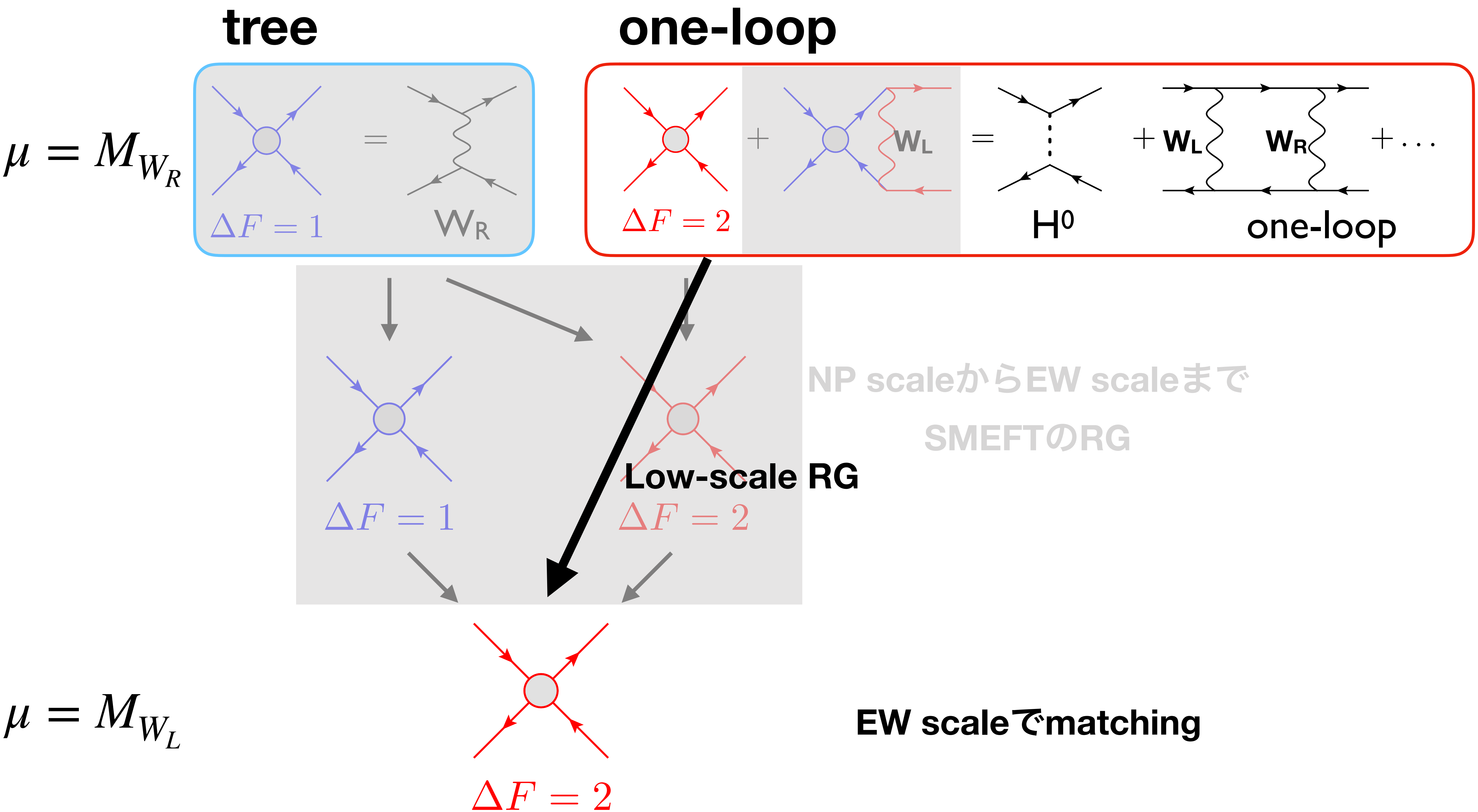
ゲージ不変なmatching

- **NP scaleでのゲージ不変なmatching:**



Conventional case

- **NP scaleでのmatching:**



KaonのCP の破れ

$$|K_S\rangle = |K_+\rangle + \epsilon\,|K_-\rangle \qquad |K_L\rangle = |K_-\rangle + \epsilon\,|K_+\rangle$$

CP を破る相互作用

$|\pi\pi\rangle$:CP even $\qquad |\pi\pi\rangle$:CP even

Direct CP violation

$$\eta_\pm \equiv \frac{\langle \pi^+\pi^-|\mathcal{H}|K_L\rangle}{\langle \pi^+\pi^-|\mathcal{H}|K_S\rangle} \qquad \eta_{00} \equiv \frac{\langle \pi^0\pi^0|\mathcal{H}|K_L\rangle}{\langle \pi^0\pi^0|\mathcal{H}|K_S\rangle}$$

$$\eta_\pm \neq \eta_{00}$$

$$\epsilon' \equiv \frac{\eta_\pm - \eta_{00}}{3}$$

ϵ'/ϵ

$$\mathrm{Re}\frac{\epsilon'}{\epsilon} = \frac{1}{6}\frac{|\eta_{\pm}|^2 - |\eta_{00}|^2}{|\eta_{\pm}|^2} = \frac{1}{6}\left(1 - \frac{\frac{\mathcal{B}(K_L \to \pi^0\pi^0)}{\mathcal{B}(K_S \to \pi^0\pi^0)}}{\frac{\mathcal{B}(K_L \to \pi^+\pi^-)}{\mathcal{B}(K_S \to \pi^+\pi^-)}}\right)$$

この量を測ることができる

$$\eta_{\pm} \equiv \frac{\langle \pi^+\pi^- | \mathcal{H} | K_L \rangle}{\langle \pi^+\pi^- | \mathcal{H} | K_S \rangle} \qquad \eta_{00} \equiv \frac{\langle \pi^0\pi^0 | \mathcal{H} | K_L \rangle}{\langle \pi^0\pi^0 | \mathcal{H} | K_S \rangle}$$

NA48実験 と KTeV実験 が測定を行った

$$(\epsilon'/\epsilon)_{exp} = (16.6 \pm 2.3) \times 10^{-4} \quad [\mathrm{PDG}]$$

ϵ'/ϵ

$$\epsilon' \equiv \frac{\eta_{\pm} - \eta_{00}}{3} \quad \eta_{00} \equiv \frac{\langle \pi^0\pi^0|\mathcal{H}|K_L\rangle}{\langle \pi^0\pi^0|\mathcal{H}|K_S\rangle} \quad \eta_{\pm} \equiv \frac{\langle \pi^+\pi^-|\mathcal{H}|K_L\rangle}{\langle \pi^+\pi^-|\mathcal{H}|K_S\rangle}$$

$$\left\langle (\pi\pi)_I|\mathcal{H}|K^0\right\rangle = A_I e^{i\delta_I} \qquad \left\langle (\pi\pi)_I|\mathcal{H}|\bar{K}^0\right\rangle = A_I^* e^{i\delta_I}$$

$$\text{Isospin} : I = 0, 2$$

$$\epsilon' \simeq \frac{1}{\sqrt{2}}\frac{\omega}{\mathrm{Re}A_0}\left(\mathrm{Im}A_0 - \frac{1}{\omega}\mathrm{Im}A_2\right)\exp\left(i\left(\frac{\pi}{2} + \delta_2 - \delta_0\right)\right)$$

$$\omega \equiv \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0}$$

ϵ'/ϵ

$$\epsilon' \simeq \frac{1}{\sqrt{2}} \frac{\omega}{\mathrm{Re}A_0} \left(\mathrm{Im}A_0 - \frac{1}{\omega} \mathrm{Im}A_2 \right) \exp\left(i \left(\frac{\pi}{2} + \delta_2 - \delta_0 \right) \right)$$

$$\epsilon = |\epsilon| \exp\left(i \mathrm{Tan}^{-1} \frac{2\Delta M}{\Delta\Gamma} \right)$$

acidental cancellation
が起きる

以下の量を評価する

$$\frac{\epsilon'}{\epsilon} \simeq \frac{1}{\sqrt{2}\,|\epsilon|_{exp}} \frac{\omega_{exp}}{(\mathrm{Re}A_0)_{exp}} \left(\mathrm{Im}A_0 - \frac{1}{\omega_{exp}} \mathrm{Im}A_2 \right)$$

The SM prediction of ϵ'_K/ϵ_K

RBC-UKQCD

$$\frac{\epsilon'_K}{\epsilon_K} \simeq \frac{1}{\sqrt{2}|\epsilon_K|}\frac{\omega_{exp}}{(\mathrm{Re}A_0)_{exp}}\left(\boxed{\mathrm{Im}A_0} - \frac{1}{\omega_{exp}}\boxed{\mathrm{Im}A_2}\right)$$

They determine $\mathrm{Im}A_0, \mathrm{Im}A_2$ by lattice QCD calculation.

The SM prediction of ϵ'_K/ϵ_K

Buras et al. A.J. Buras, M. Gorbahn, S. J¨ager and M. Jamin, JHEP 11 (2015) 202 [arXiv:1507.06345]

$$\frac{\epsilon'_K}{\epsilon_K} \simeq \frac{1}{\sqrt{2}|\epsilon_K|} \frac{\omega_{exp}}{(\mathrm{Re}A_0)_{exp}} \left(\mathrm{Im}A_0 - \frac{1}{\omega_{exp}} \mathrm{Im}A_2 \right)$$

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_{i=1}^{10} C_i(\mu) Q_i(\mu) \qquad A_I = \langle (\pi\pi)_I | \mathcal{H}_{eff} | K^0 \rangle$$

$$(\mathrm{Re}A_0)_{exp}, (\mathrm{Re}A_2)_{exp}$$

$\downarrow$ determine

$$\langle Q_2(\mu) \rangle_0 , \langle Q_2(\mu) \rangle_2$$

$\downarrow$ by using suitable relation

$$\langle Q_{4,10}(\mu) \rangle_0 , \langle Q_{1,9,10}(\mu) \rangle_2$$

$$\langle Q_i(\mu) \rangle_I \equiv \langle (\pi\pi)_I | Q_i(\mu) | K^0 \rangle$$

The SM prediction of ϵ'_K/ϵ_K

Kitahara et al.

$$\frac{\epsilon'_K}{\epsilon_K} \simeq \frac{1}{\sqrt{2}|\epsilon_K|} \frac{\omega_{exp}}{(\mathrm{Re}A_0)_{exp}} \left(\boxed{\mathrm{Im}A_0} - \frac{1}{\omega_{exp}} \boxed{\mathrm{Im}A_2} \right)$$

In addition to Buras's result they estimate subleading hadron matrix elements

$$\langle Q_3 \rangle_0 \,, \langle Q_5 \rangle_0 \,, \langle Q_7 \rangle_0$$

by using lattice QCD result.

Models solving ϵ'/ϵ anomaly

Several new physics models have been studied to explain ϵ'/ϵ anomaly

MSSM

chargino Z penguin [M.Endo, S.Mishima, D.Ueda and K.Yamamoto, PLB762(2016)493]

gluino Z penguin [M.Tanimoto and K.Yamamoto, PTEP(2016)no.12,123B02]

gluino box [T.Kitahara, U.Nierste and P.Tremper, PRL117(2016)no.9, 091802 A.Crivellin, G.D'Ambrosio, T.Kitahara and U.Nierste, 1703.05786]

Vector-like quarks [C.Bobeth, A.J.Buras, A.Celis and M.Jung, JHEP1704(2017)079]

Little Higgs Model with T-parity [M.Blanke, A.J.Buras and S.Recksiegel, EPJ.C76 (2016)no.4,182]

331 model [A.J.Buras and F.De Fazio, JHEP 1603(2016)010 & JHEP1608 (2016) 115]

Right handed current [V.Cirigliano, W.Dekens, J.de Vries and E.Mereghetti, PLB
017)1 S.Alioli, V.Cirigliano, W.Dekens, J.de Vries and E.Mereghetti, JHEP1705 (2017)086]