SMEFT effects on ΔF=2 FCNC

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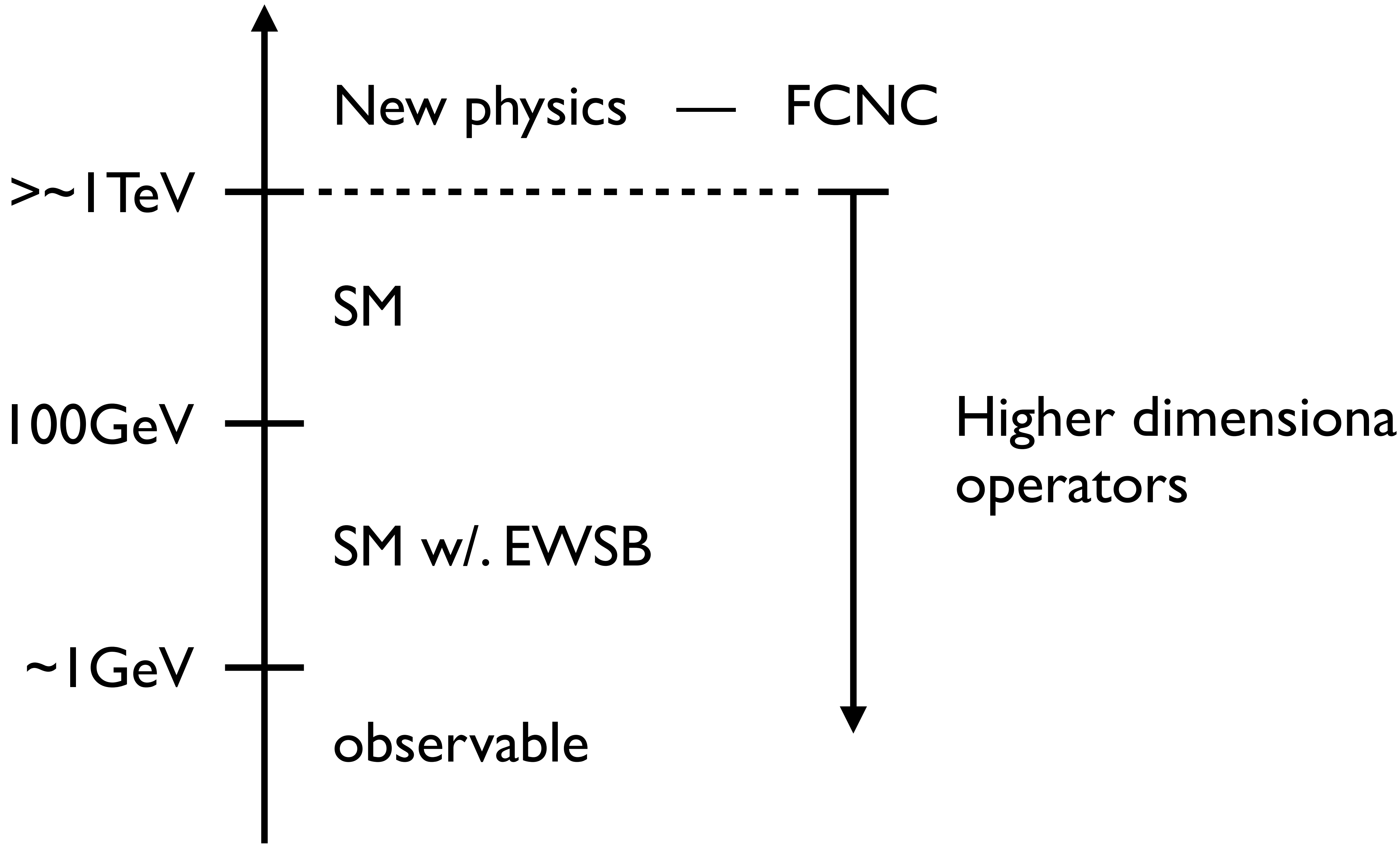
Beyond the BSM, Gunma, 2018.10.1

New physics contributions to FCNC



Conventional FCNC calculation

Higher dimensional operators

$$\mathcal{H}_{\rm eff}^{\Delta F=2} = C_1(\bar{d}_{L,i}\gamma^\mu d_{L,j})(\bar{d}_{L,i}\gamma_\mu d_{L,j})$$
$$+ C_2(\bar{d}_{R,i} d_{L,j})(\bar{d}_{R,i} d_{L,j}) + C_3(\bar{d}^\alpha_{R,i} d^\beta_{L,j})(\bar{d}^\beta_{R,i} d^\alpha_{L,j})$$
$$+ C_4(\bar{d}_{R,i} d_{L,j})(\bar{d}_{L,i} d_{R,j}) + C_5(\bar{d}^\alpha_{R,i} d^\beta_{L,j})(\bar{d}^\beta_{L,i} d^\alpha_{R,j})$$

EFT *below* EWSB, i.e., top, W, Z and H are decoupled

New physics scale > O(100)GeV — SM effective field theory (SMEFT)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i C_i \mathcal{O}_i^{d>4}$$

Are SMEFT effects be negligible?

Outline

Introduction: “Are SMEFT effects be negligible?”

SMEFT in ΔF=2 FCNC

Two models:

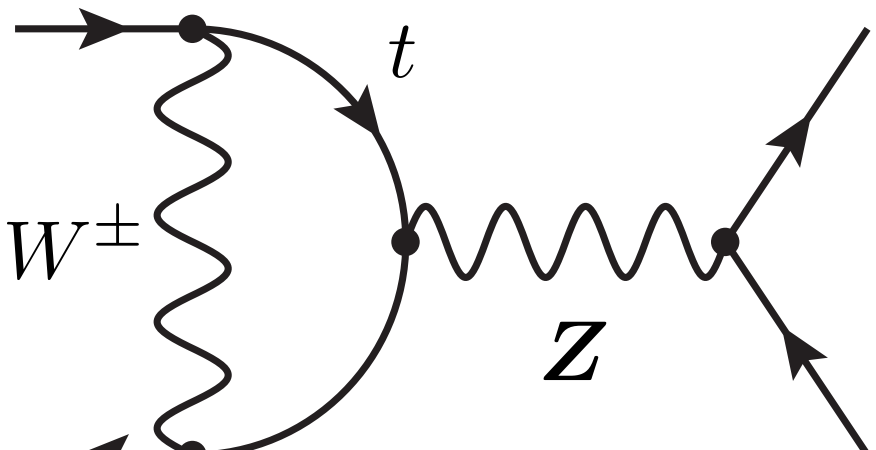
- Flavor-changing Z penguin
- Left-right model

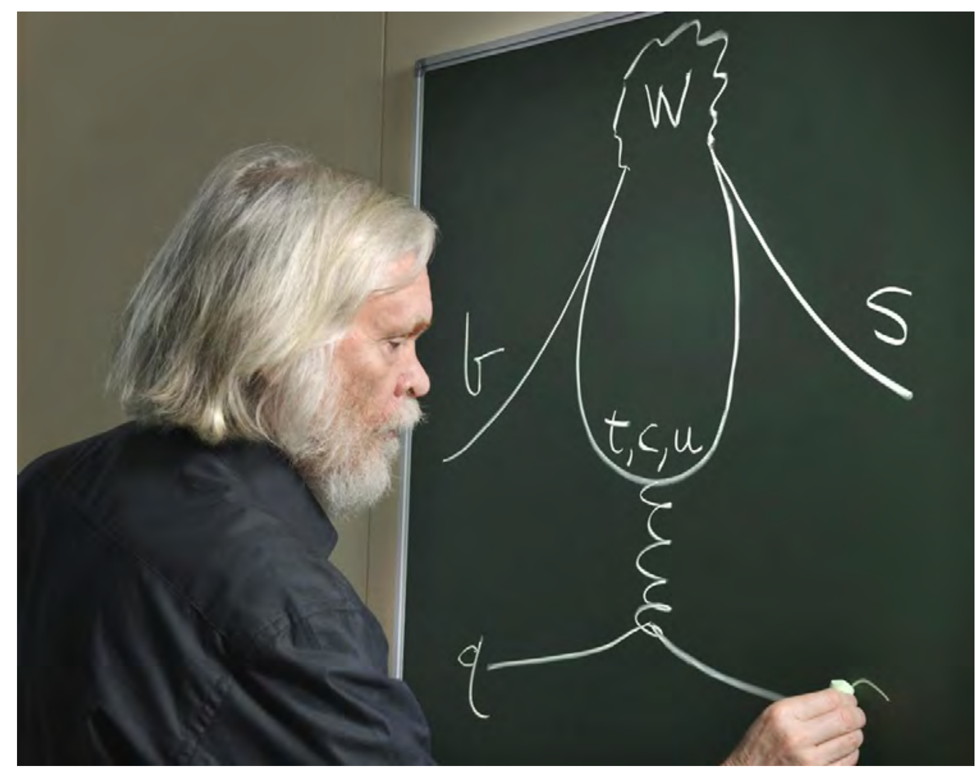
Summary

Flavor-changing Z penguin: Motivation

Sensitive to physics beyond SM — cleanest probe

FC Z-penguin



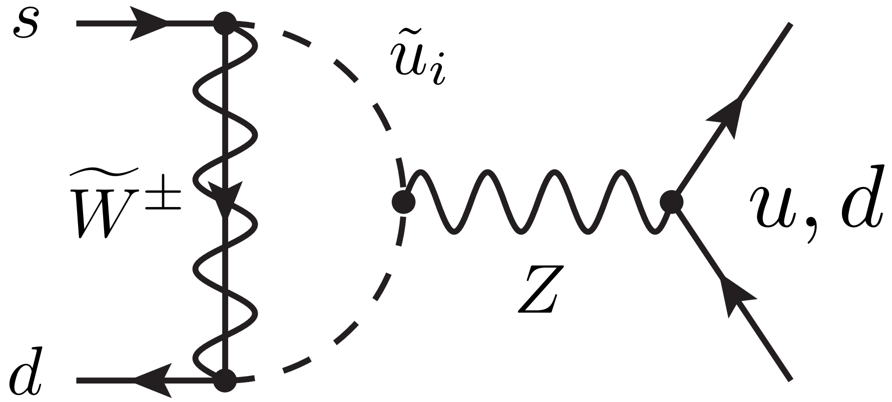


Flavor-changing Z penguin: Motivation

Sensitive to physics beyond SM — cleanest probe

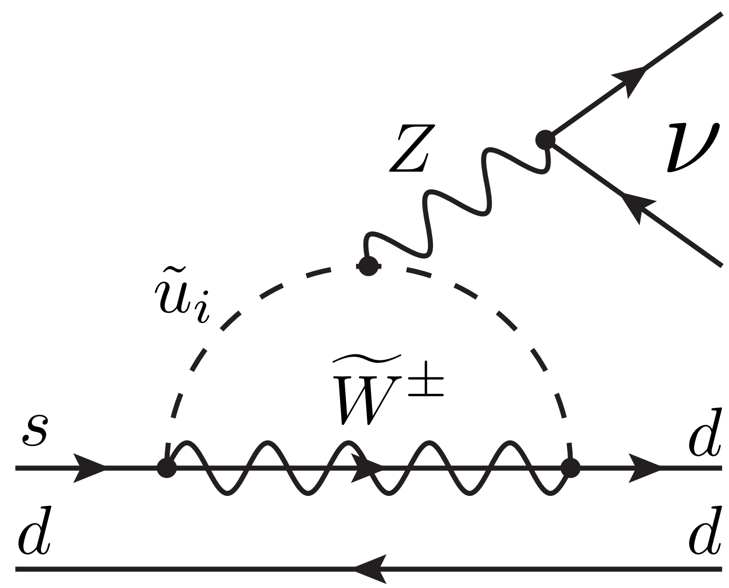
Less constrained by experiments — ε'/ε

ϵ'/ϵ $(K_L \to \pi\pi)$



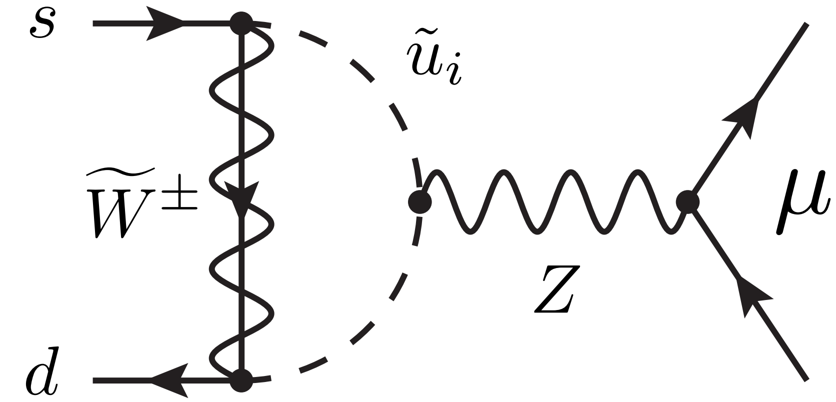
2.8σ anomaly

$K_L \to \pi^0 \nu \bar{\nu}$



KOTO

$K_S \to \mu^+ \mu^-$



LHCb

Direct CP violation of Kaon

First lattice computation of hadron matrix element

[RBC-UKQCD'15]

SM prediction (lattice + NLO)

$$(\epsilon'/\epsilon)_{\rm SM} = (1.1 \pm 5.1) \times 10^{-4}$$ [Kitahara et.al.'16]

Experimental result

$$(\epsilon'/\epsilon)_{\rm exp} = (16.6 \pm 2.3) \times 10^{-4}$$ [NA48,KTeV'90-99]

New 2.8σ discrepancy

(Near) future prospects

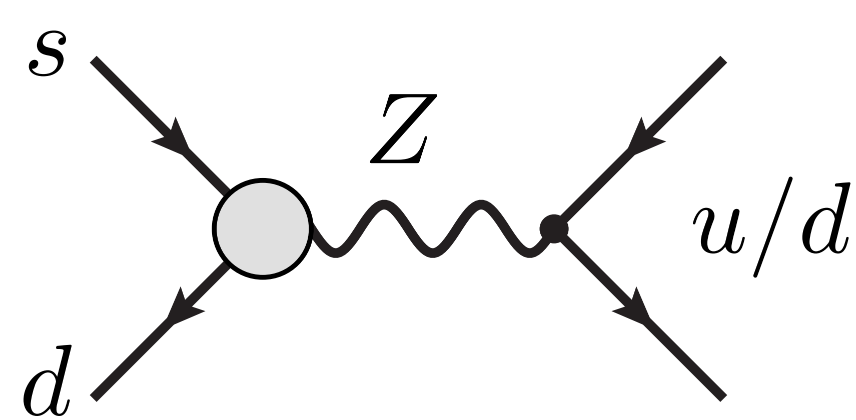
increase statistics, improve systematics, resolve δ_0, …

New physics interpretation

Flavor-changing Z penguin

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

$$(\epsilon'/\epsilon)_{\rm NP} \propto {\rm Im}\Delta_L + \frac{c_W^2}{s_W^2}{\rm Im}\Delta_R$$



Not gauge invariant under SU(2)xU(1)

— lose correlations among NP cont. in ``low-scale" EFT

Z penguin in SMEFT

SM gauge symmetric, SU(2)xU(1)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i C_i \mathcal{O}_i^{d>4}$$

EWSB

$$[\mathcal{O}_{HQ}^{(1)}] = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{q}_i \gamma^\mu q_j)$$

$$[\mathcal{O}_{HQ}^{(3)}] = (H^\dagger i \overleftrightarrow{D}_\mu^a H)(\overline{q}_i \tau^a \gamma^\mu q_j)$$

→ **Δ_L**

$$[\mathcal{O}_{HD}] = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{d}_i \gamma^\mu d_j)$$

→ **Δ_R**

Δ_L, Δ_R → ϵ'/ϵ

$$\mathcal{L}_{\rm eff} = \Delta_L \left[Z_\mu - \frac{g}{m_Z}\left(W_\mu^- G^+ + W_\mu^+ G^-\right) + \dots \right] (\overline{q}_{L,i} \gamma^\mu q_{L,j})$$

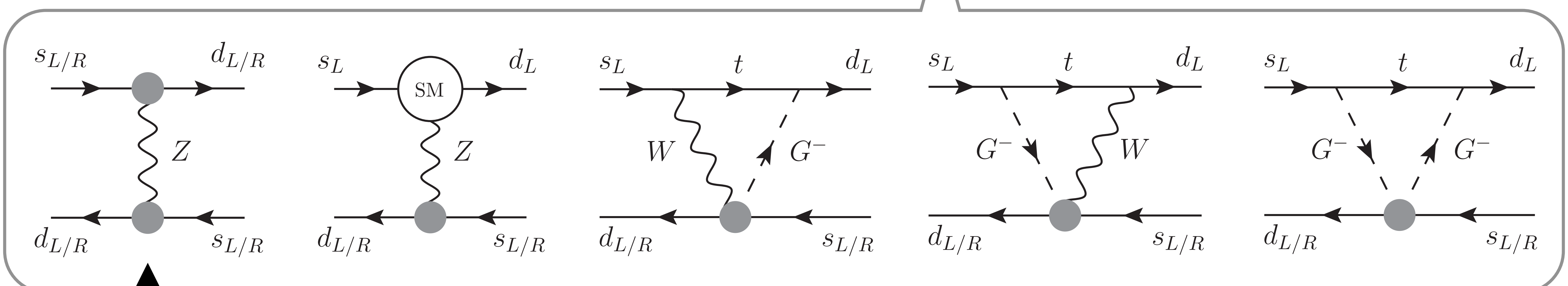
↘ ↙

ΔF=2 transitions

Indirect CP violation of Kaon

$$\epsilon = e^{i\varphi_\varepsilon}\left(\epsilon^{\rm SM} + \epsilon^{\rm NP}\right)$$

$$\mathrm{Im}\langle K^0 | H | \overline{K^0}\rangle$$



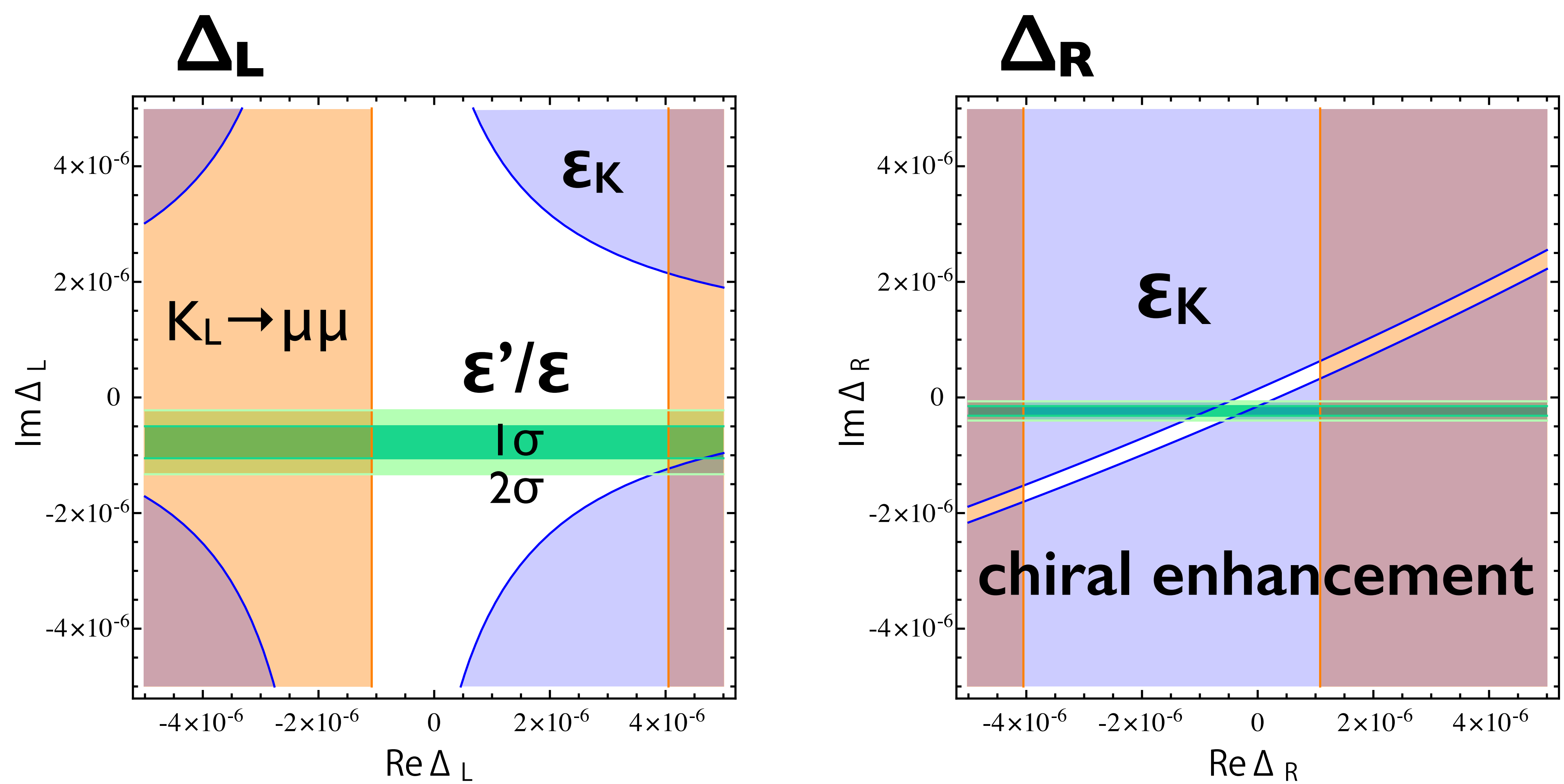
Δ_L, Δ_R

Correlate in SMEFT

Indirect CP violation of Kaon

Experimental value $|\epsilon^{\rm exp}| = (2.228 \pm 0.011) \times 10^{-3}$

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



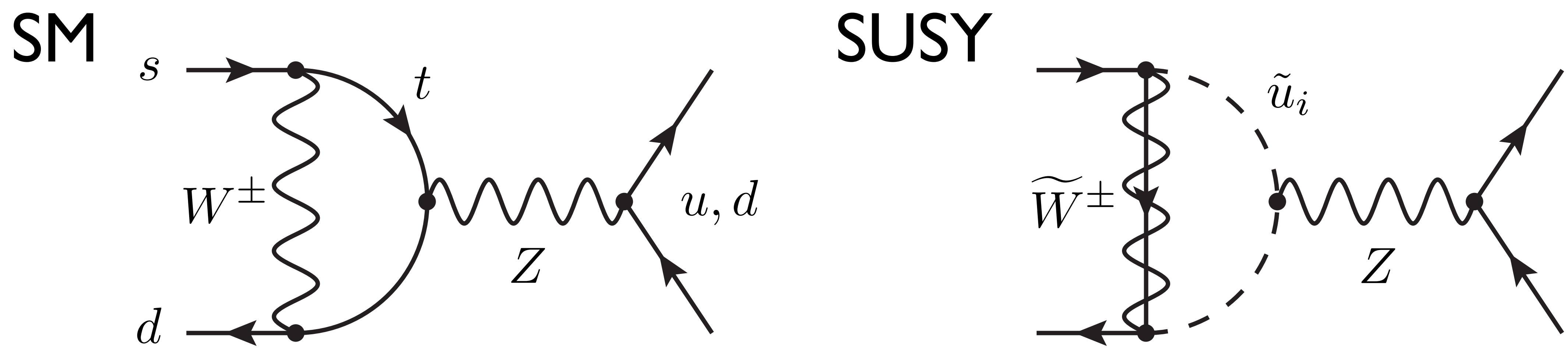
$$\mathcal{L} = \Delta_L(\bar{d}_L\gamma^\mu s_L)Z_\mu + \Delta_R(\bar{d}_R\gamma^\mu s_R)Z_\mu$$

[ME, Kitahara, Mishima, Yamamoto]

SUSY scenario

[ME,Mishima,Ueda,Yamamoto]

Left-handed contribution by **Wino** mediation



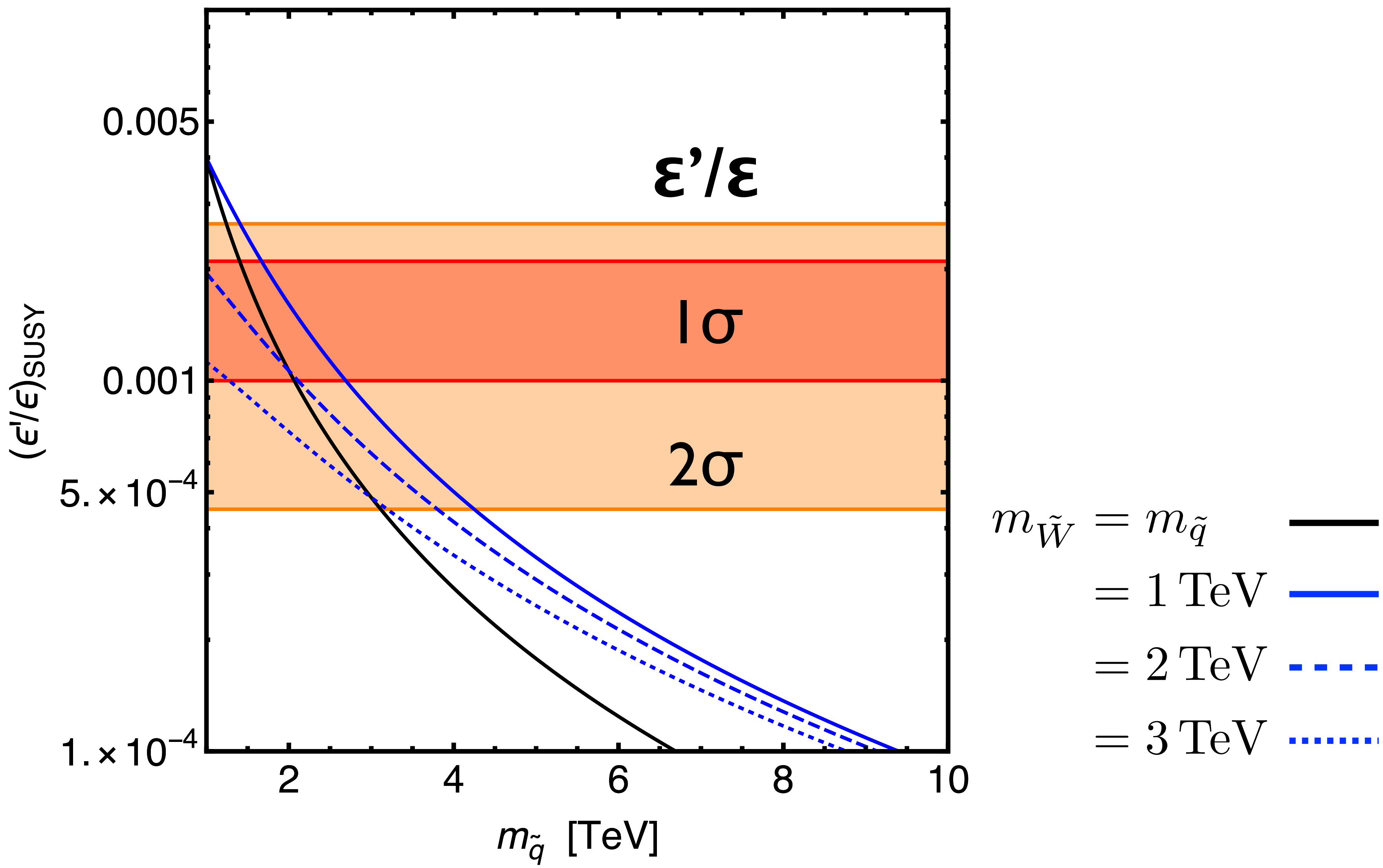
Flavor and CP violation in squark trilinear couplings

$$\left.\begin{array}{l}(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{q}_i\gamma^\mu q_j) \\ (H^\dagger i\overleftrightarrow{D}^a_\mu H)(\overline{q}_i\tau^a\gamma^\mu q_j)\end{array}\right\} \quad V = (T_U)_{i3} H_u \tilde{u}_{iL}\tilde{t}^*_R$$

How large can SUSY be?

[ME,Mishima,Ueda,Yamamoto]

Maximum SUSY contribution to ε'/ε



ε'/ε discrepancy is explained when $m_{\tilde{q}} \lesssim 4\,\mathrm{TeV}$

Outline

Introduction: “Are SMEFT effects be negligible?”

SMEFT in $\Delta F=2$ FCNC

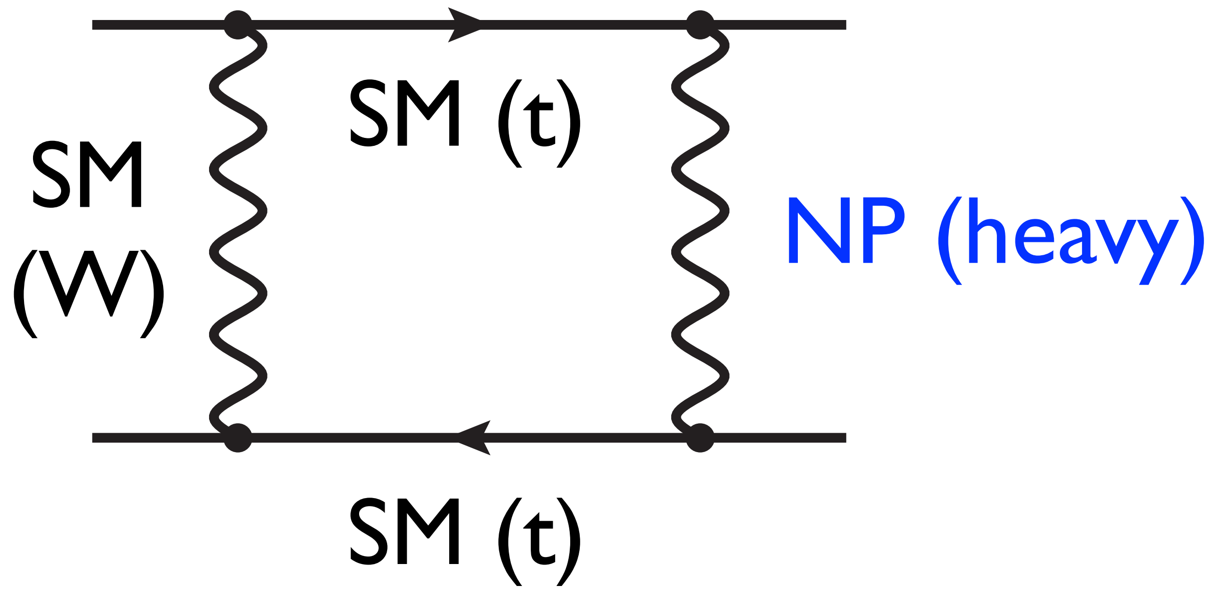
Two models:

- Flavor-changing Z penguin — tight constraint on RH coupling
- Left-right model

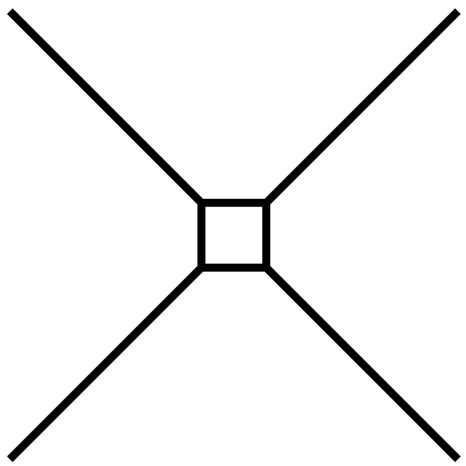
Summary

Scale uncertainty

New (heavy) and SM (light) particle contributions



conventional →



"low-scale" EFT
(t, W, … decoupled)

Q. In which scale operators should be matched?

Left-right symmetric model

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

Flavor-changing interactions

Left- and right-handed W bosons

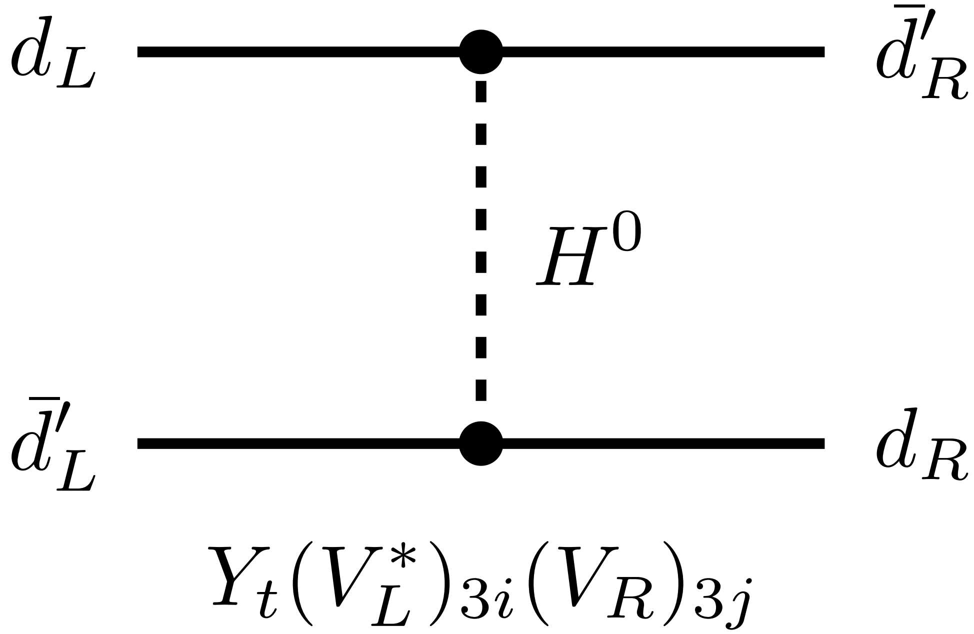
$$\mathcal{L}_{\rm int} = \frac{g_L}{\sqrt{2}}(V_L)_{ij}\bar{u}_i\gamma_\mu P_L d_j W_L^\mu + \frac{g_R}{\sqrt{2}}(V_R)_{ij}\bar{u}_i\gamma_\mu P_R d_j W_R^\mu$$

Higgs fields: $\Phi \sim (H_u, H_d)$ & Δ_R (Δ_L)

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

ΔF=2 transitions: tree level

Heavy Higgs exchange

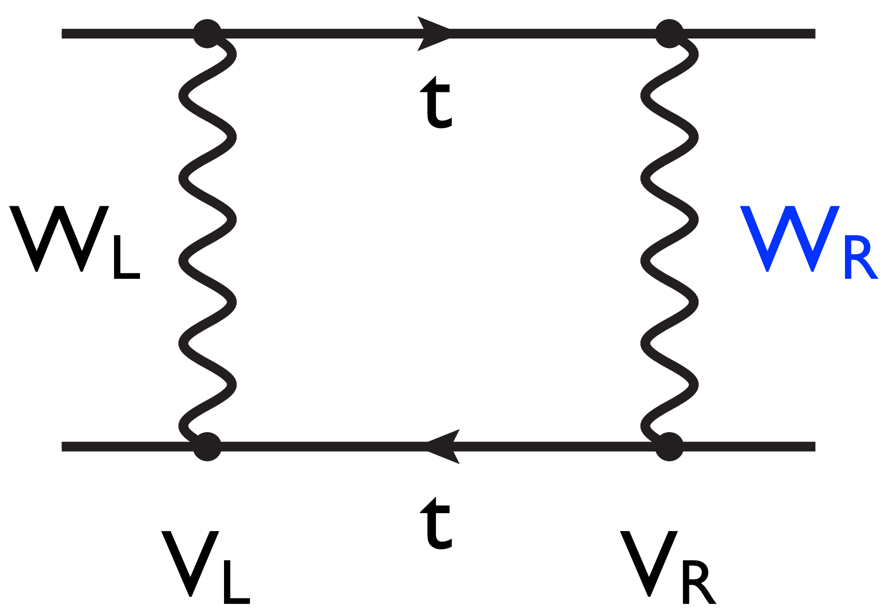


$$\sim \frac{1}{\cos^2 2\beta} \frac{Y_t^2}{m_H^2} (\lambda_{LR})_{ij} (\lambda_{RL})_{ij}$$

Input at a scale of heavy Higgs boson mass

ΔF=2 transitions: one-loop level

Left- and right-handed W bosons ($m_H > m_{WR}$)



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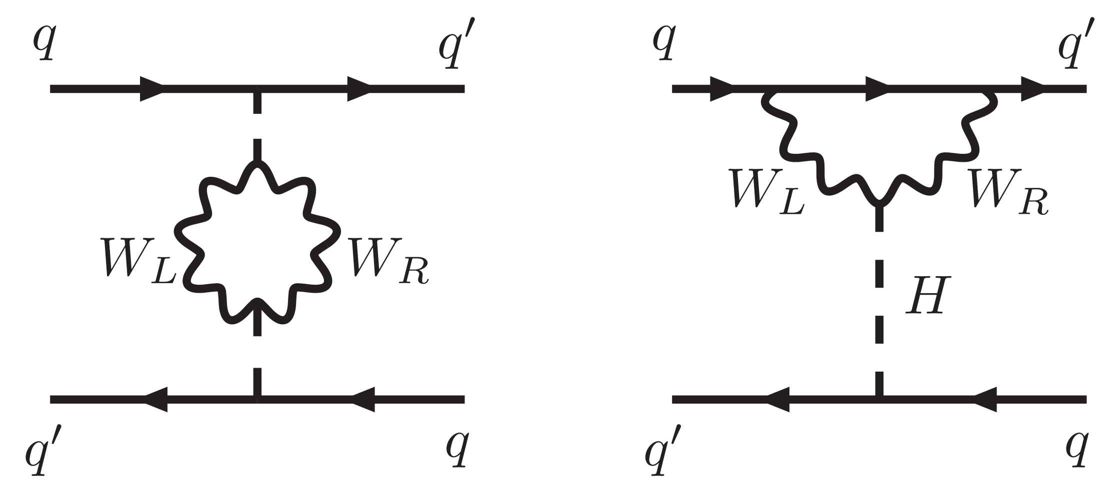


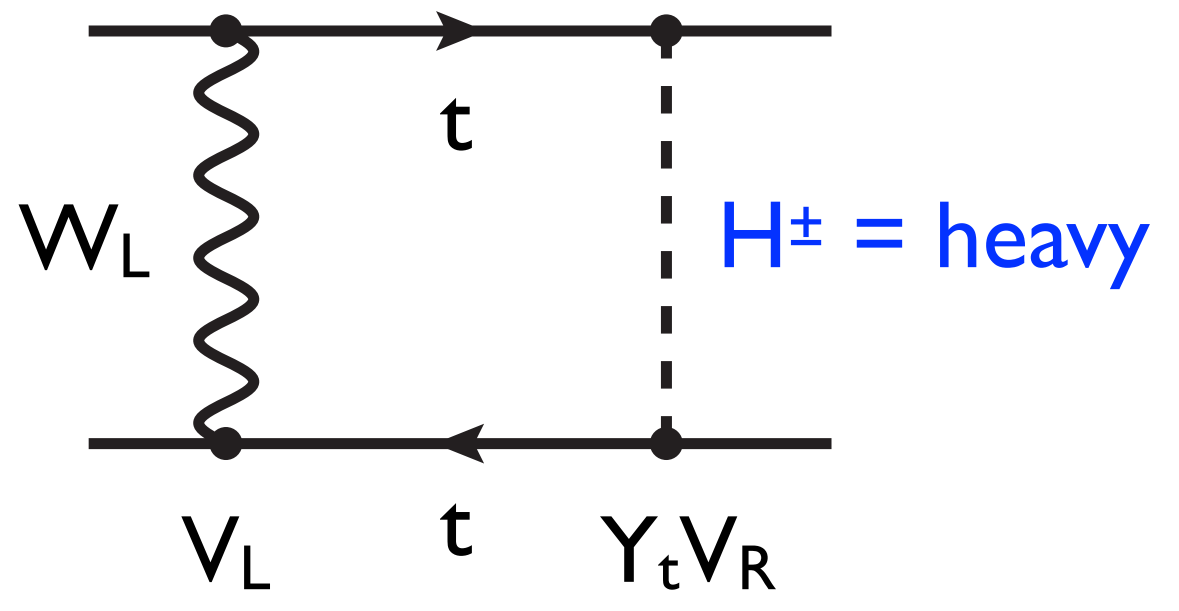
gauge invariance

Which matching scale ~ W_R? EWSB??

— **Match LR onto SMEFT operators**

ΔF=2 transitions: one-loop level

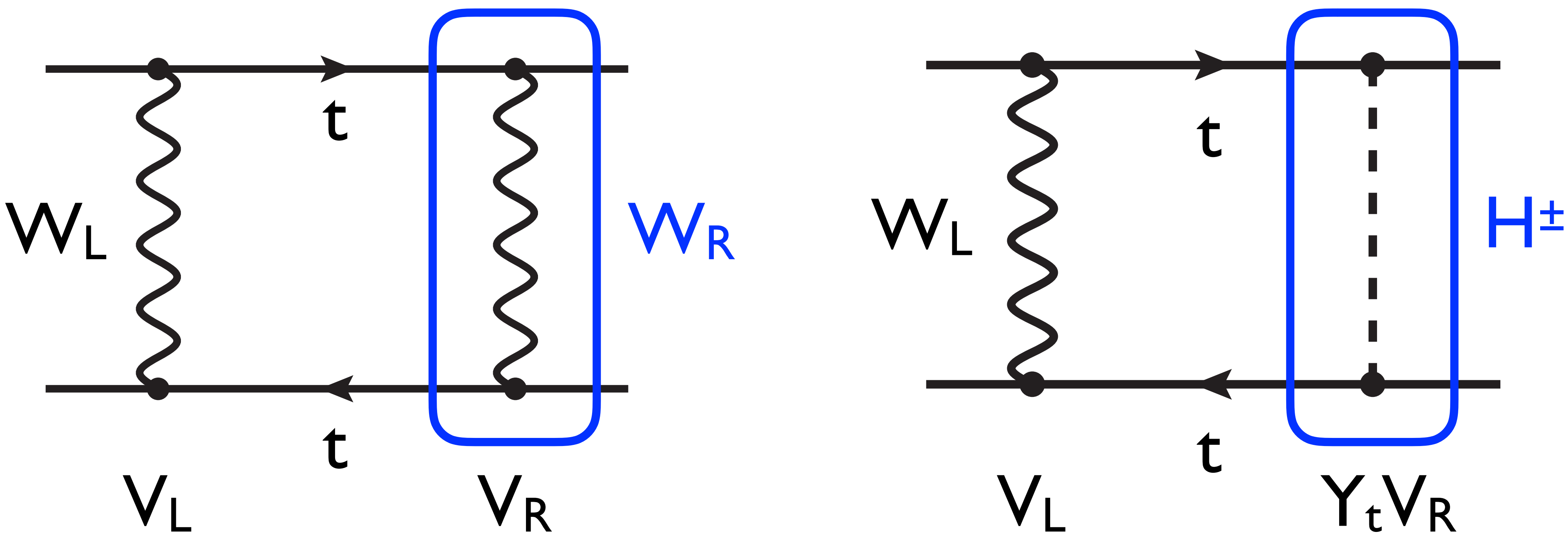
Charged Higgs ~ neutral Higgs at one-loop



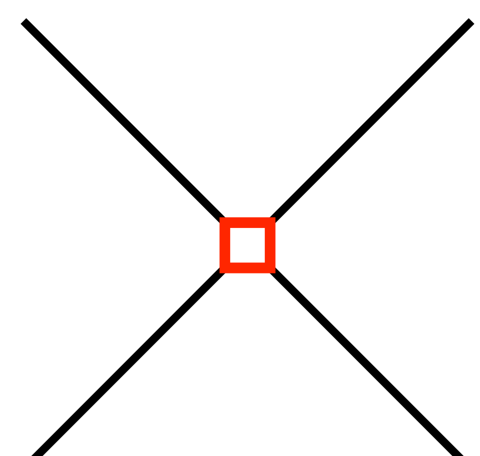
Take account in SMEFT analysis

Matching on SMEFT at LR scale

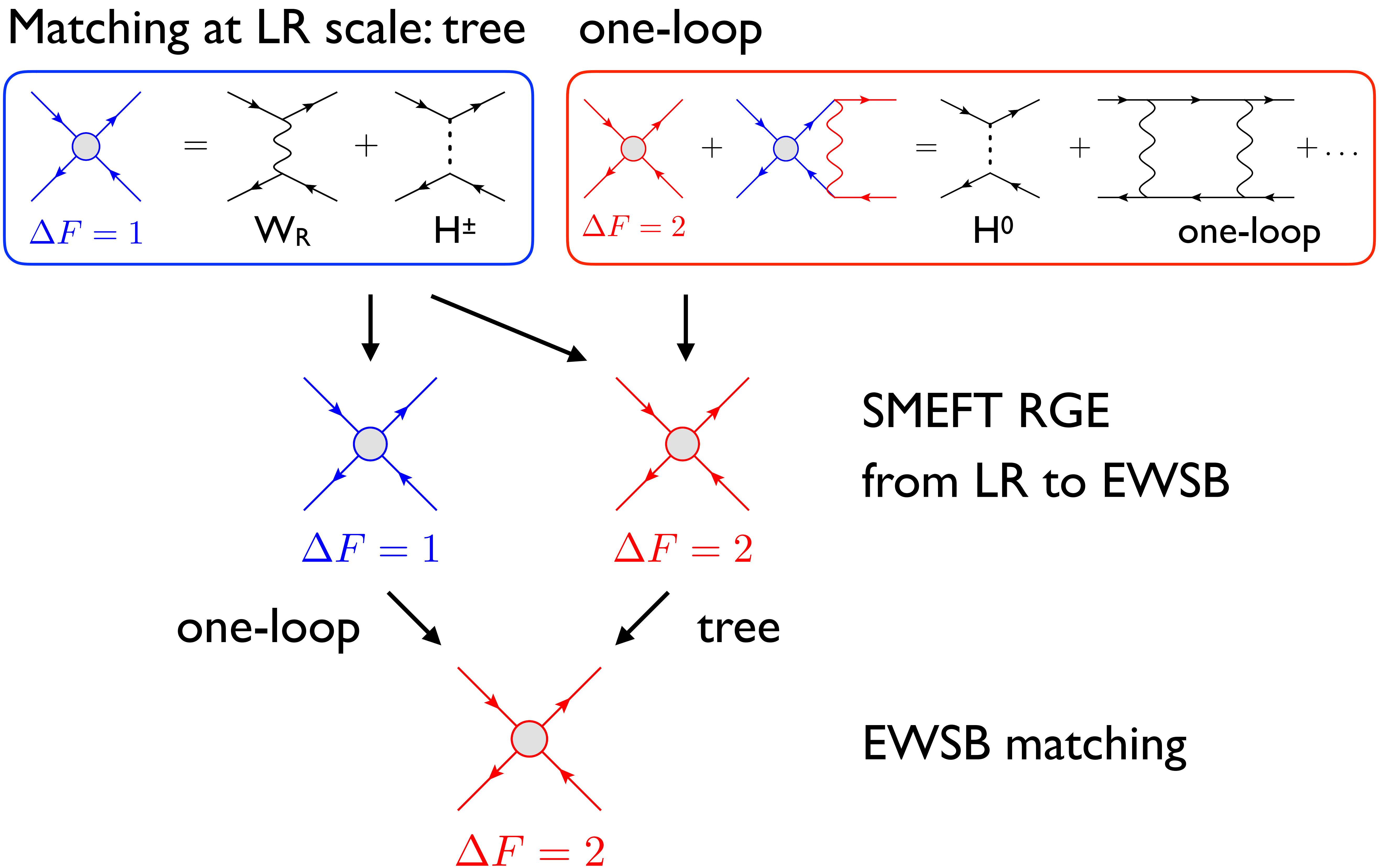
$\Delta F=1$ operators at tree level



$\Delta F=2$ operators at one-loop level

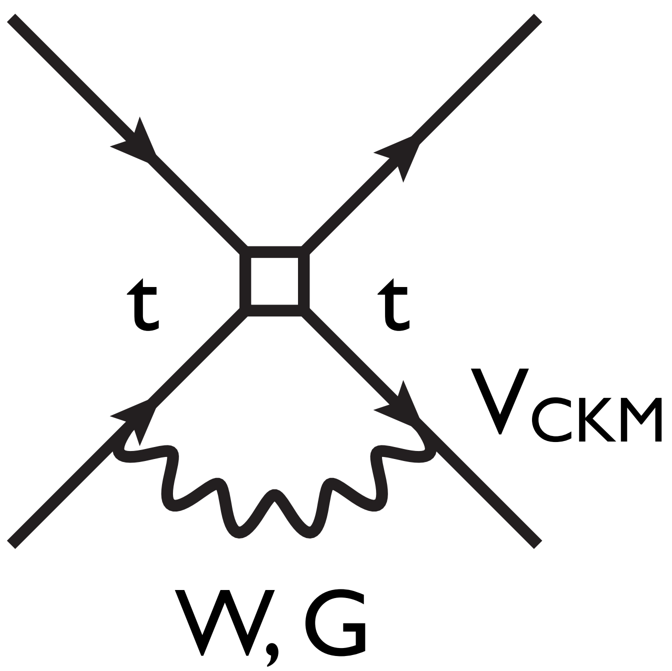


Flow chart



Matching at LR scale: tree
one-loop
$\Delta F = 1$
W_R
$H^{\pm}$
$\Delta F = 2$
H^0
one-loop
SMEFT RGE
from LR to EWSB
$\Delta F = 1$
$\Delta F = 2$
one-loop
tree
EWSB matching
$\Delta F = 2$

ΔF=1 → ΔF=2 in SMEFT



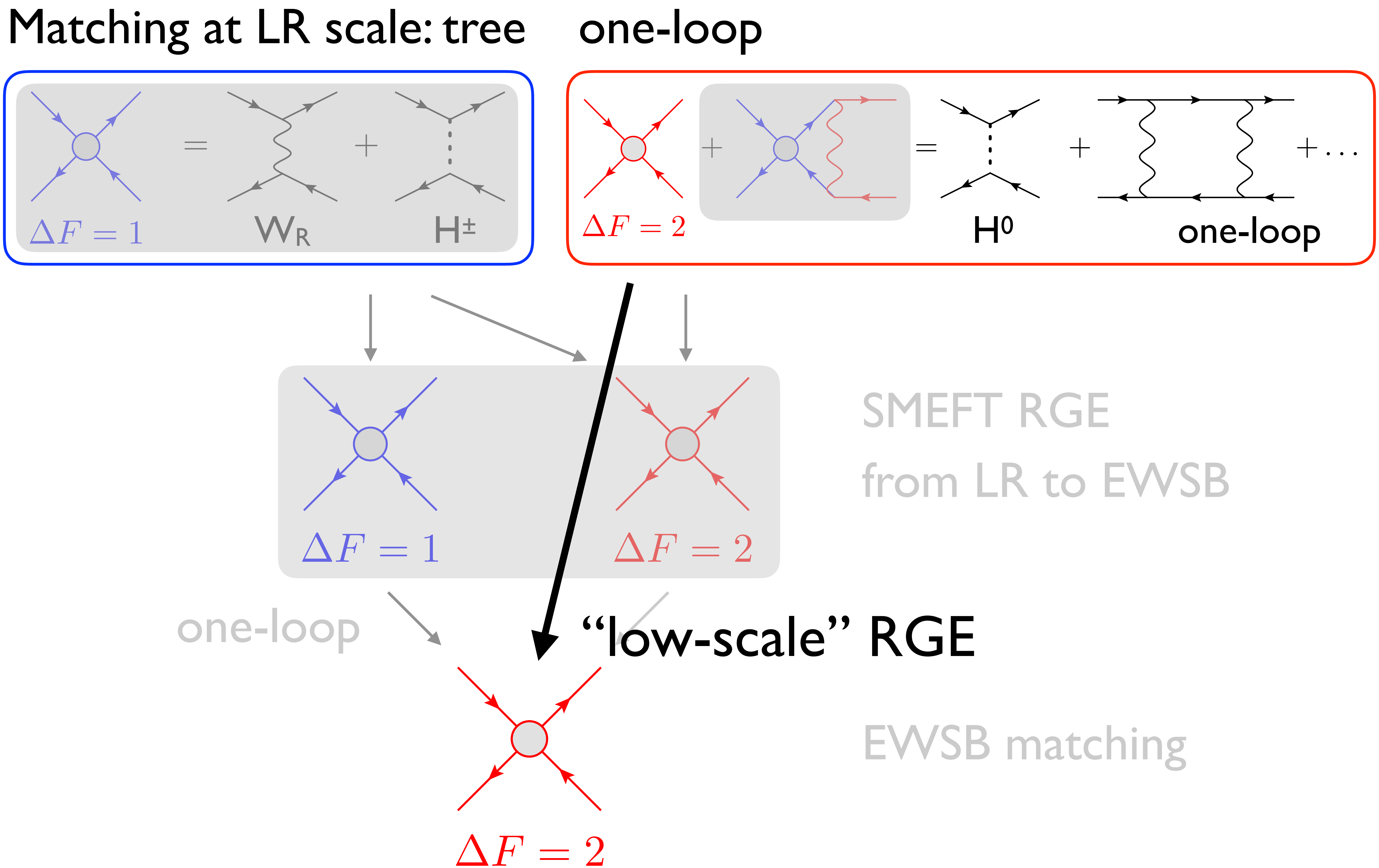
one-loop matching

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

cf. scale(μ) dependence — RGE

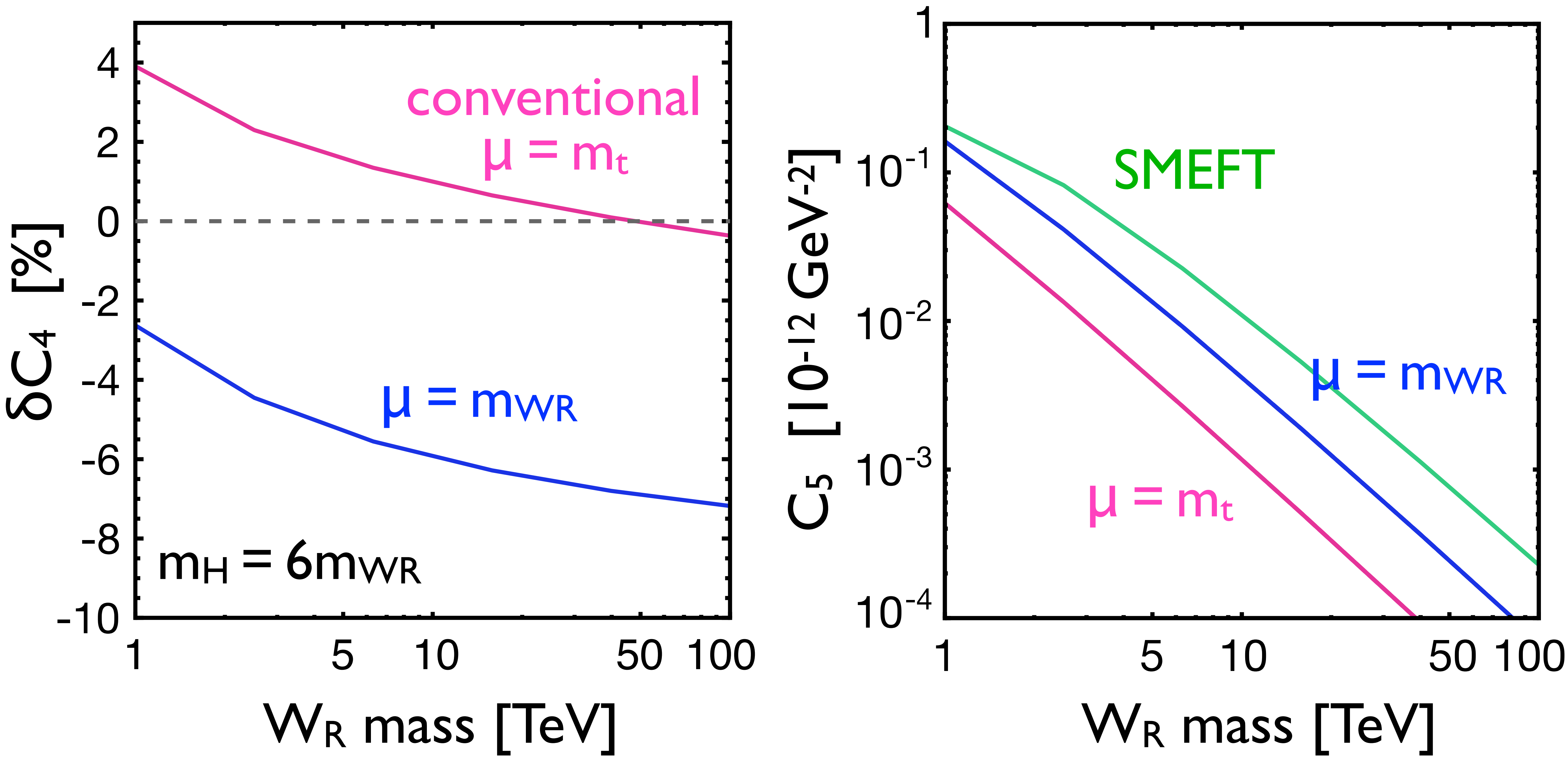
[ME,Kitahara,Ueda, preliminary]

Flow chart: conventional case



Result: Wilson coefficients

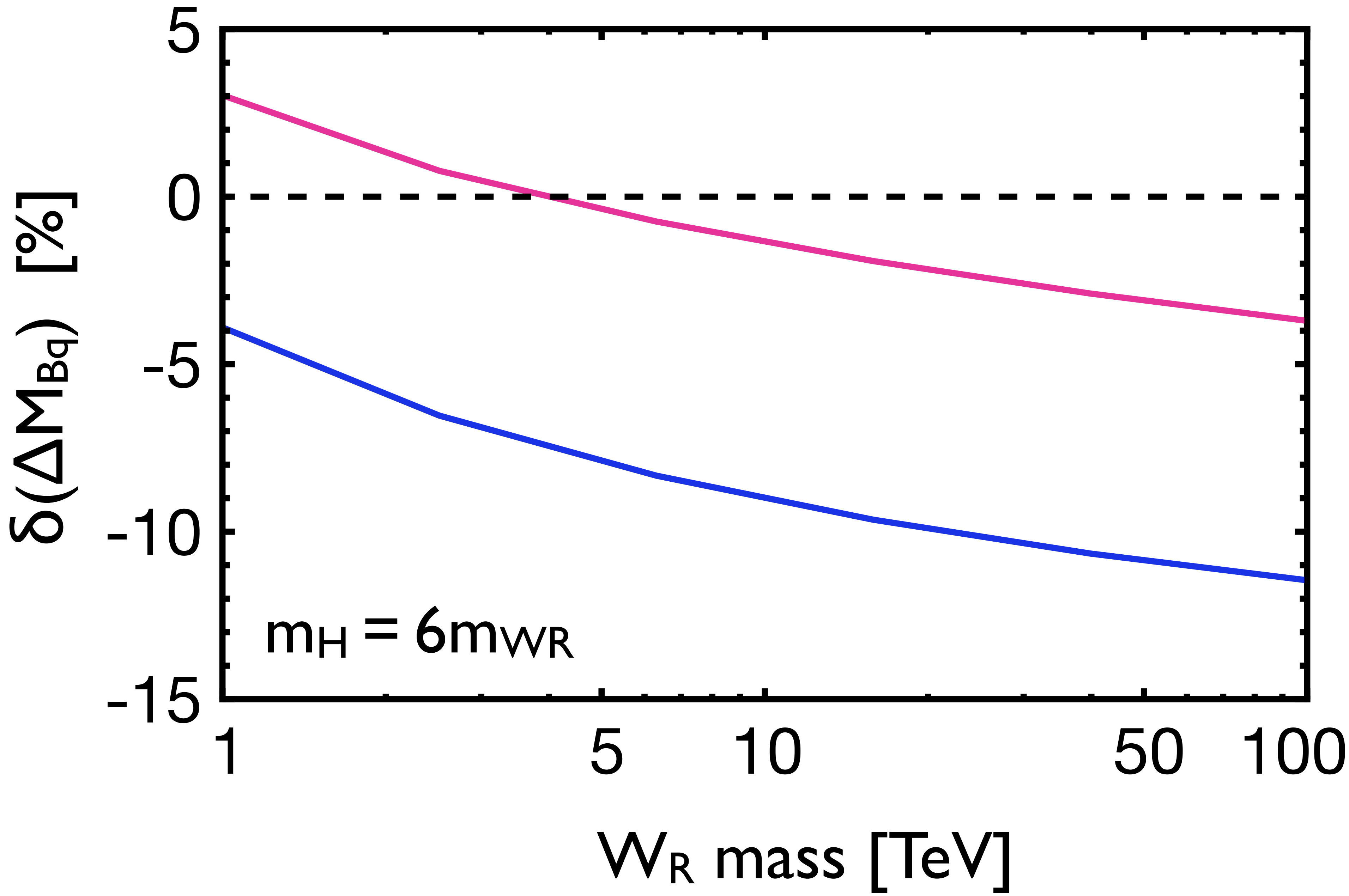
one-loop top contribution



[ME,Kitahara,Ueda, preliminary]

Result: B meson mass difference

one-loop top contribution



[ME,Kitahara,Ueda, preliminary]

Summary

SMEFT effects becomes important in LHC era.

In Z-penguin models, we obtain correlations, providing tight constraint on RH flavor-changing Z coupling.

In left-right symmetric model, SMEFT is necessary for reducing scale uncertainty.