Flavor Structure of the Three Site Higgsless Model

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Reference: MK, T. Onogi, arXiv:1006.3414

2011 Workshop
Physics Beyond the Standard Model and Particle Observable
Kobe University, Jan. 6-7, 2011

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Outline

1. Introduction, Review
2. Flavor structure
3. $b \to s\gamma$ process
4. Summary

Introduction

Higgsless models with an extra-dimension

Csaki et al. PRD69:055006(2004)

- EWSB is achieved by BCs of an extra dimension
- Tower of vector resonances appear as KK-modes of γ/Z/W, and those contribute to partially cancel the growth of $W_L W_L$ scattering amplitude at low energy

⇒ Possibility of recovering calculability at least for the LHC phenomenology study

Introduction

For the study of LHC phenomenology,

it is reasonable to consider

an effective model with only one vector resonance

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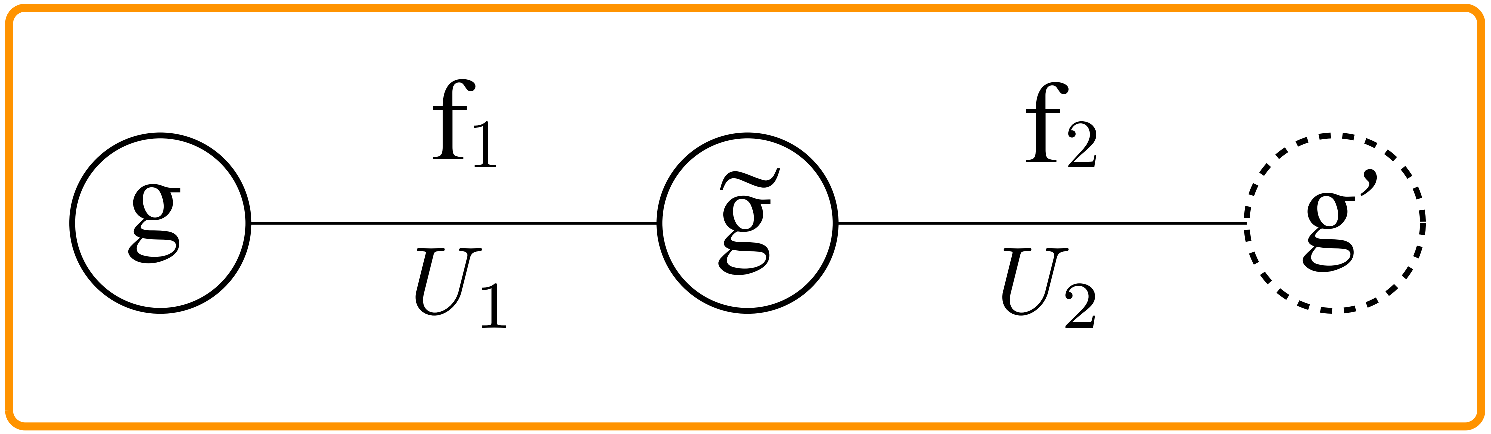
Three Site Higgsless Model

Chivukula, Coleppa, Di Chiara, Simmons, He, MK, Tanabashi, PRD 74, 075001 (2006)

Three Site Higgsless Model

Gauge sector



Four dimensional gauge invariant model which includes

- $SU(2) \times SU(2) \times U(1)$ gauge fields (Circles at 0th, 1st and 2nd sites)
- $\left(SU(2) \times SU(2)\right)/SU(2)$ non-linear sigma fields (Links) : $U_{1,2} = e^{i\pi_{1,2}/f_{1,2}}$

Three Site Higgsless Model

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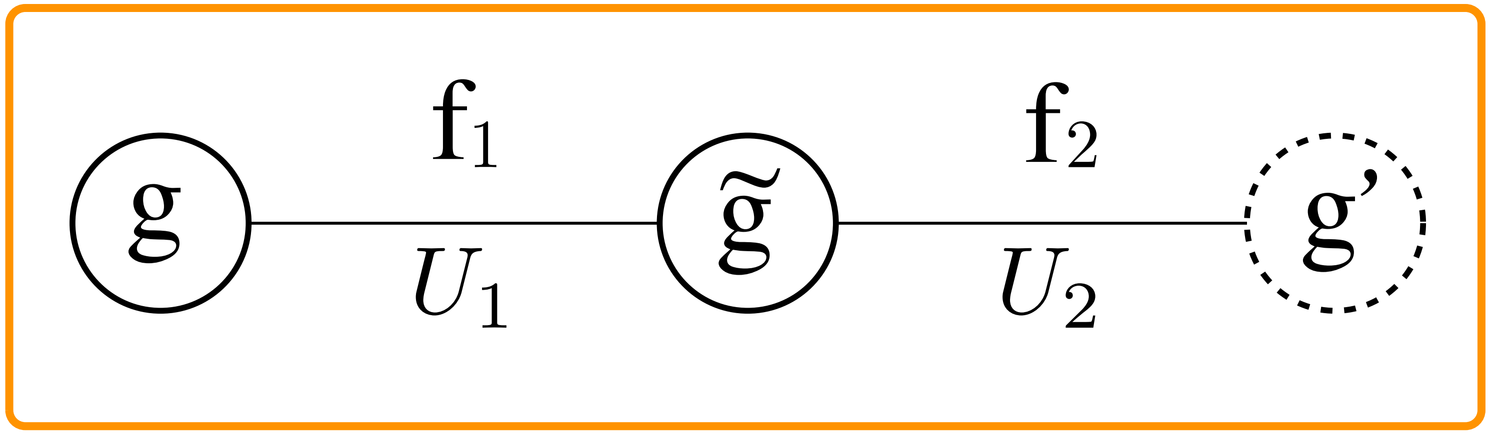

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  → γ, W, Z, W', Z'

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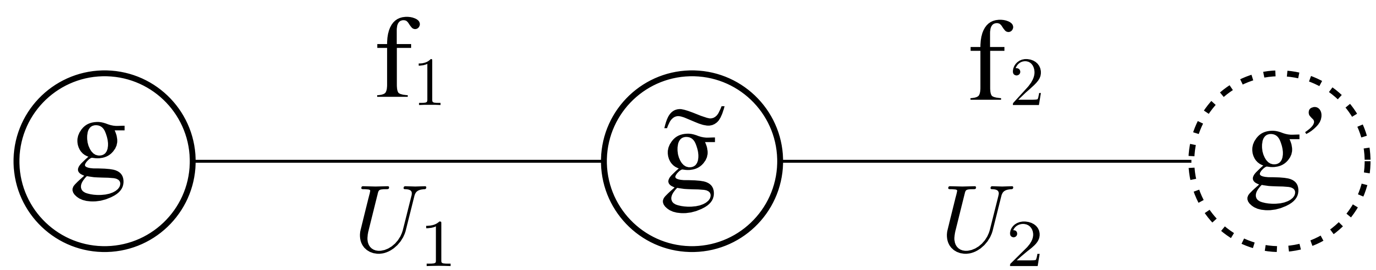
  Eaten by massive gauge fields

Three Site Higgsless Model

Gauge sector



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  Eaten by massive gauge fields

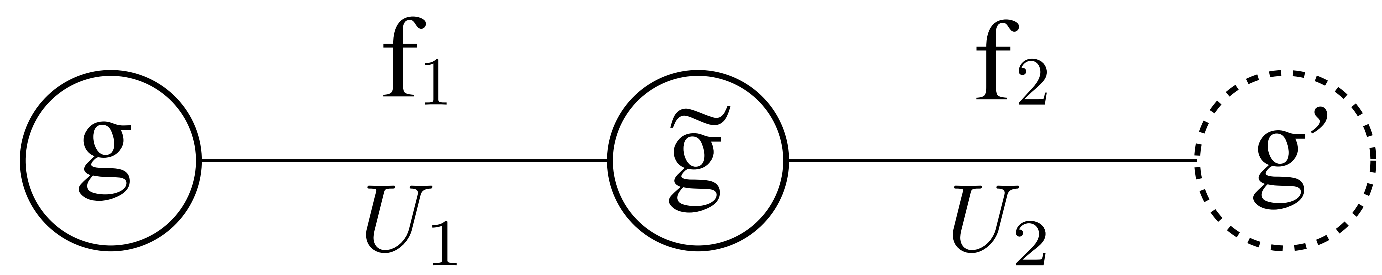
$$S = -\int d^4x \sum_{j=0}^{2} \frac{1}{2g_j^2}\left(F^j_{\mu\nu}F^{j\mu\nu}\right) + \sum_{j=1}^{2}\frac{f_j^2}{4}\left((D_\mu U_j)^\dagger (D_\mu U_j)\right)$$

$(g_0 \equiv g,\ \ g_1 \equiv \tilde{g},\ \ g_2 \equiv g')$

$$D_\mu U_j \equiv \partial_\mu U_j - iA_\mu^{j-1}U_j + iU_jA_\mu^j$$

Three Site Higgsless Model

Gauge sector



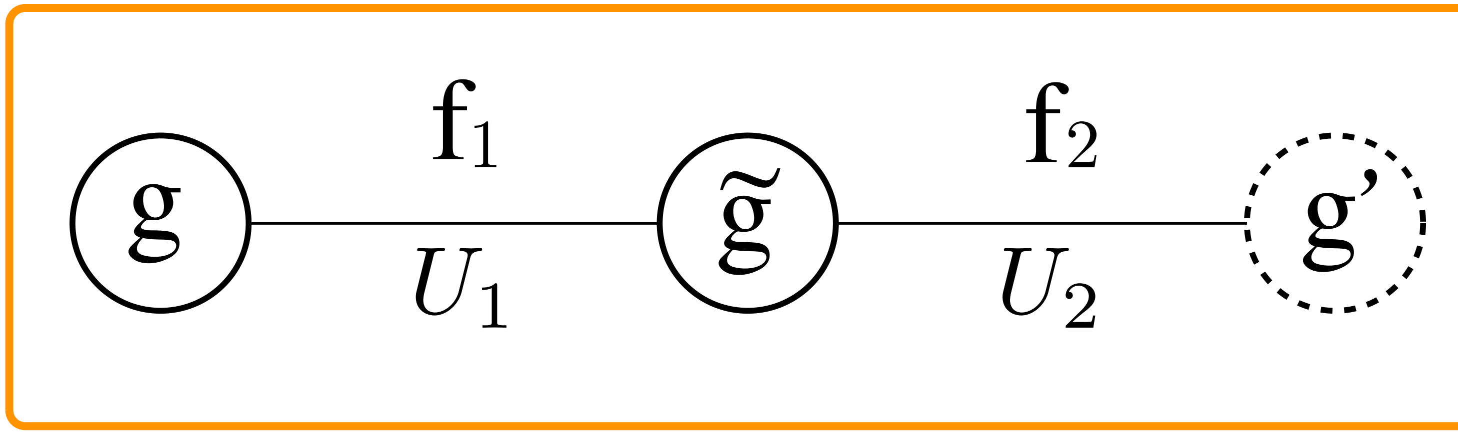
$$f_1 = f_2 \; (= f) = \sqrt{2}v$$

$$g, g' \ll \tilde{g} \quad \Longrightarrow \quad M_W, M_Z \ll M_{W'}, M_{Z'}$$

$$g/\tilde{g} \equiv x \quad (\ll 1)$$

Three Site Higgsless Model

Gauge sector



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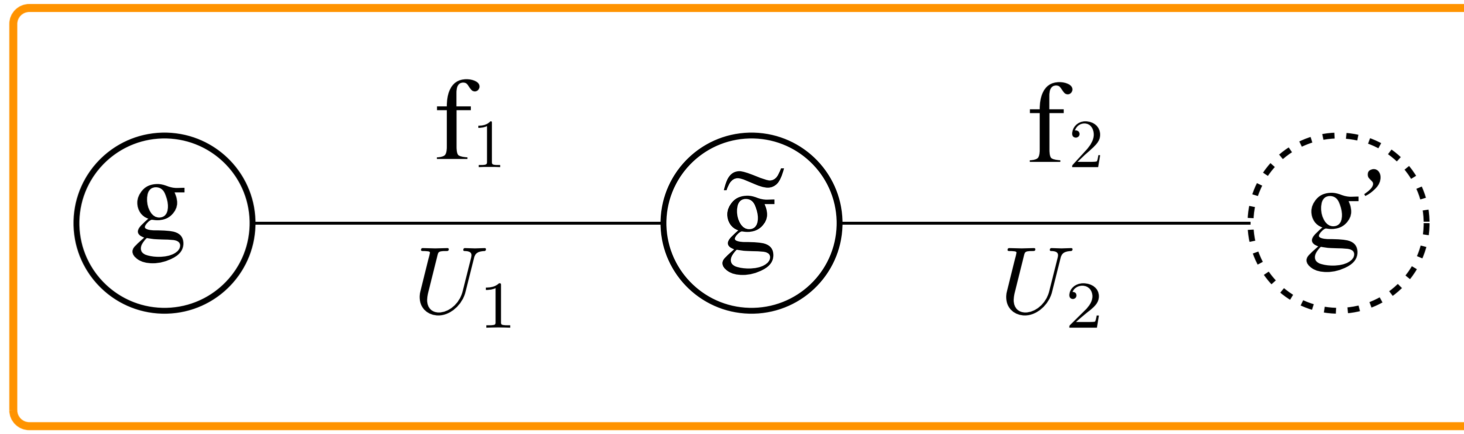
Numerically, g and g' are approximately equal to the SM SU(2) and U(1) couplings

Three Site Higgsless Model

Gauge sector

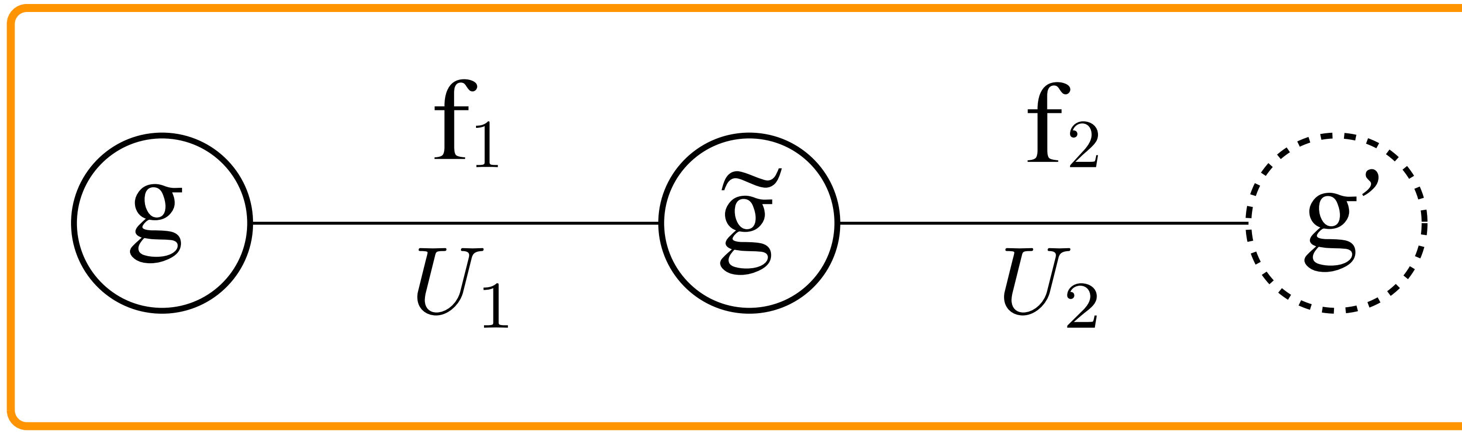


Charged gauge bosons

Mass squared matrix : $\frac{\tilde{g}^2 v^2}{2} \begin{pmatrix} x^2 & -x \\ -x & 2 \end{pmatrix}$

Three Site Higgsless Model

Gauge sector



Charged gauge bosons

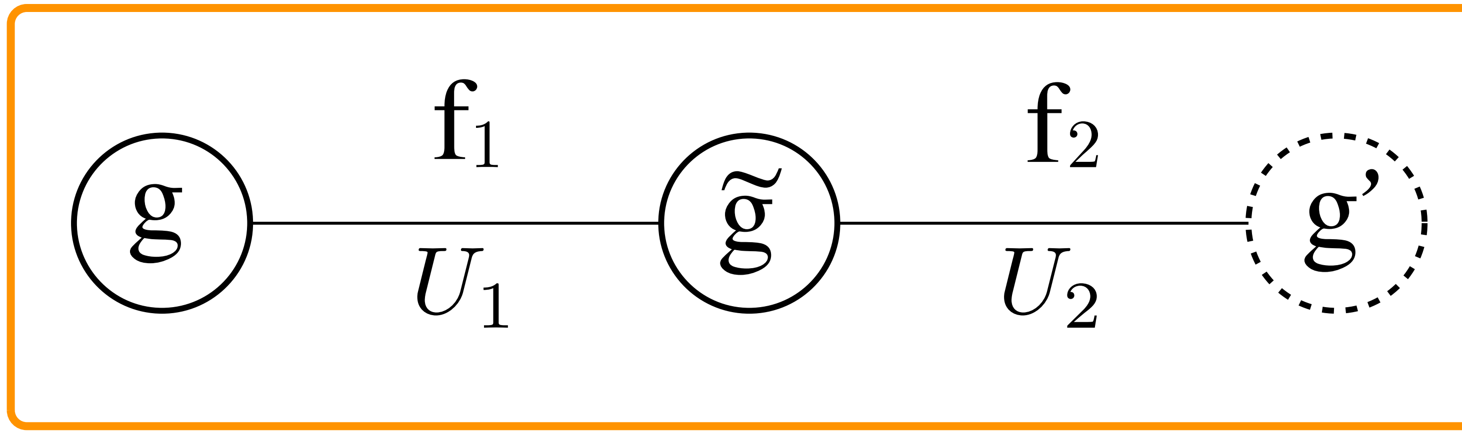
Mass squared matrix : $\frac{\tilde{g}^2 v^2}{2} \begin{pmatrix} x^2 & -x \\ -x & 2 \end{pmatrix}$

W boson $\quad M_W^2 = \left(\frac{gv}{2}\right)^2 \left[1 - \frac{x^2}{4} + \cdots\right]$

W' boson $\quad M_{W'}^2 = \left(\frac{\tilde{g}v}{2}\right)^2 \left[1 + \frac{x^2}{4} + \cdots\right]$

Three Site Higgsless Model

Gauge sector



Charged gauge bosons

Mass squared matrix : $\frac{\tilde{g}^2 v^2}{2} \begin{pmatrix} x^2 & -x \\ -x & 2 \end{pmatrix}$

$$\frac{M_W^2}{M_{W'}^2} = \frac{x^2}{4}\left[1 + O(x^2)\right]$$

W boson $\quad M_W^2 = \left(\frac{gv}{2}\right)^2 \left[1 - \frac{x^2}{4} + \cdots\right]$

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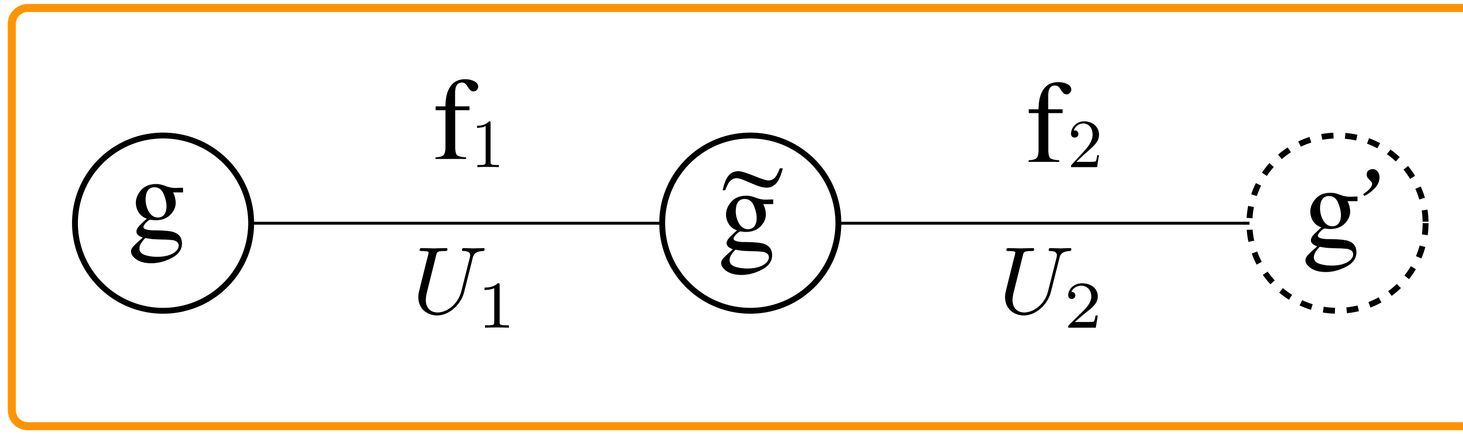
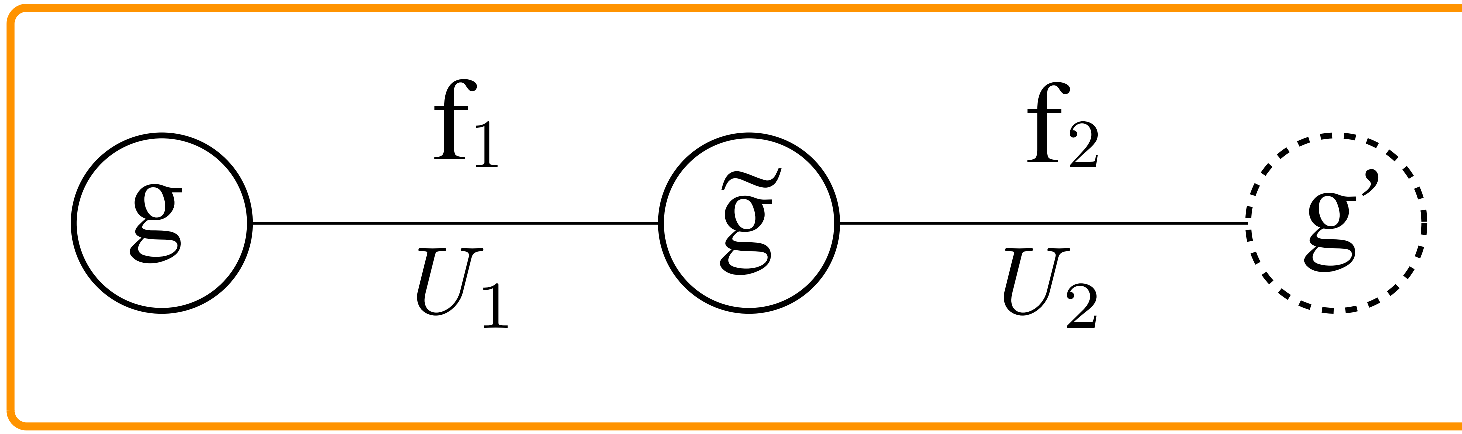


Neutral gauge bosons

Mass squared matrix : $\frac{\tilde{g}^2 v^2}{2} \begin{pmatrix} x^2 & -x & 0 \\ -x & 2 & -xt \\ 0 & -xt & x^2 t^2 \end{pmatrix}$ $\left(t \equiv \frac{g'}{g} \right)$

Three Site Higgsless Model

Gauge sector



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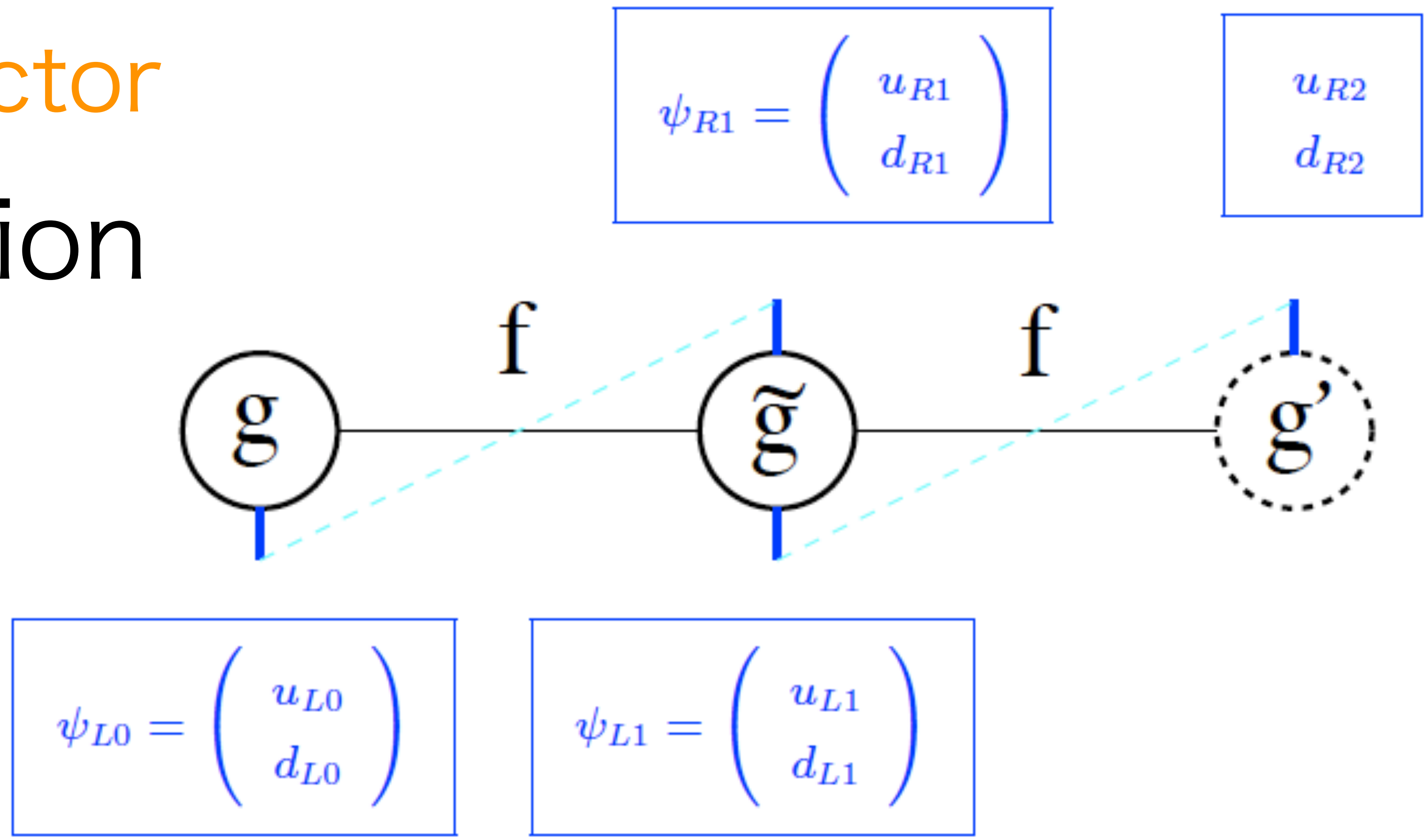
→ photon
Z boson
Z' boson

Three Site Higgsless Model

Fermion sector

1 generation



Three Site Higgsless Model

Fermion sector

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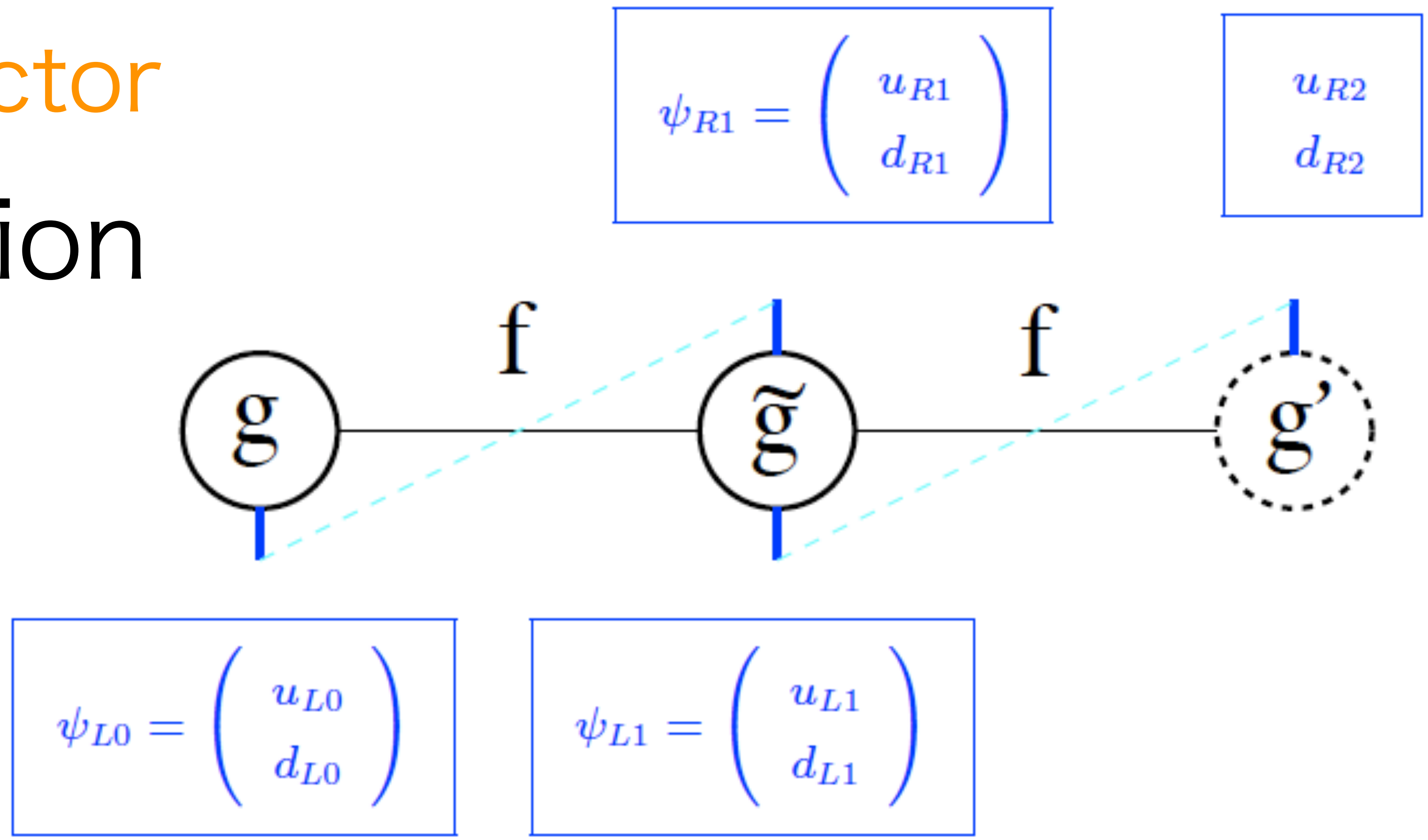


$$\mathcal{L}_{mass} = M\left[\varepsilon_L \bar{\psi}_{L0} U_1 \psi_{R1} + \bar{\psi}_{R1}\psi_{L1} + \bar{\psi}_{L1} U_2 \begin{pmatrix} \varepsilon_{uR} & \\ & \varepsilon_{dR} \end{pmatrix} \begin{pmatrix} u_{R2} \\ d_{R2} \end{pmatrix}\right] + h.c.$$

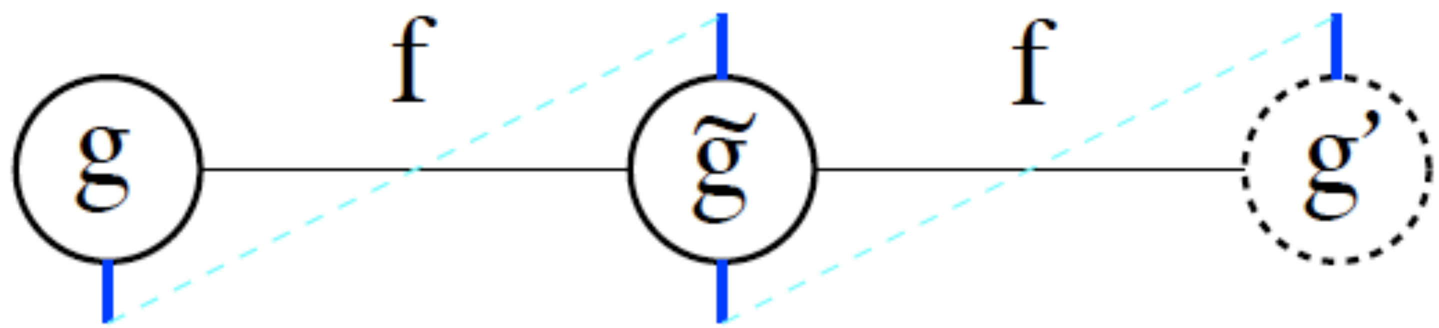
Three Site Higgsless Model

Mass eigenstate

⟺ linear combination of “site eigenstates”

$$\psi_{R1} = \begin{pmatrix} u_{R1} \\ d_{R1} \end{pmatrix}$$

$$\begin{matrix} u_{R2} \\ d_{R2} \end{matrix}$$



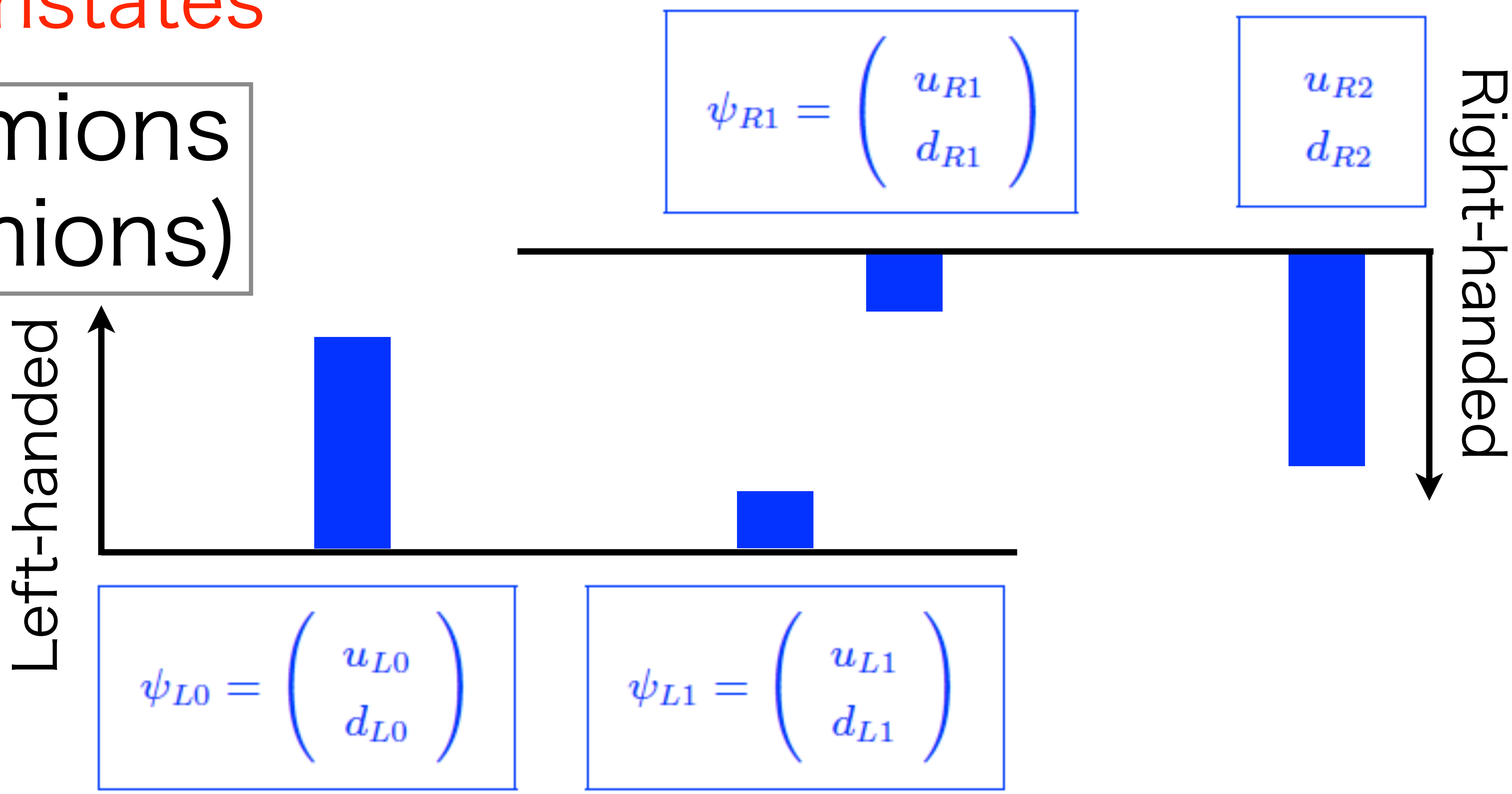
$$\psi_{L0} = \begin{pmatrix} u_{L0} \\ d_{L0} \end{pmatrix} \qquad \psi_{L1} = \begin{pmatrix} u_{L1} \\ d_{L1} \end{pmatrix}$$

$$\mathcal{L}_{mass} = M \left[\varepsilon_L \bar{\psi}_{L0} U_1 \psi_{R1} + \bar{\psi}_{R1} \psi_{L1} + \bar{\psi}_{L1} U_2 \begin{pmatrix} \varepsilon_{uR} & \\ & \varepsilon_{dR} \end{pmatrix} \begin{pmatrix} u_{R2} \\ d_{R2} \end{pmatrix} \right] + h.c.$$

Three Site Higgsless Model

"Wavefunctions" of mass eigenstates

light fermions
(SM fermions)



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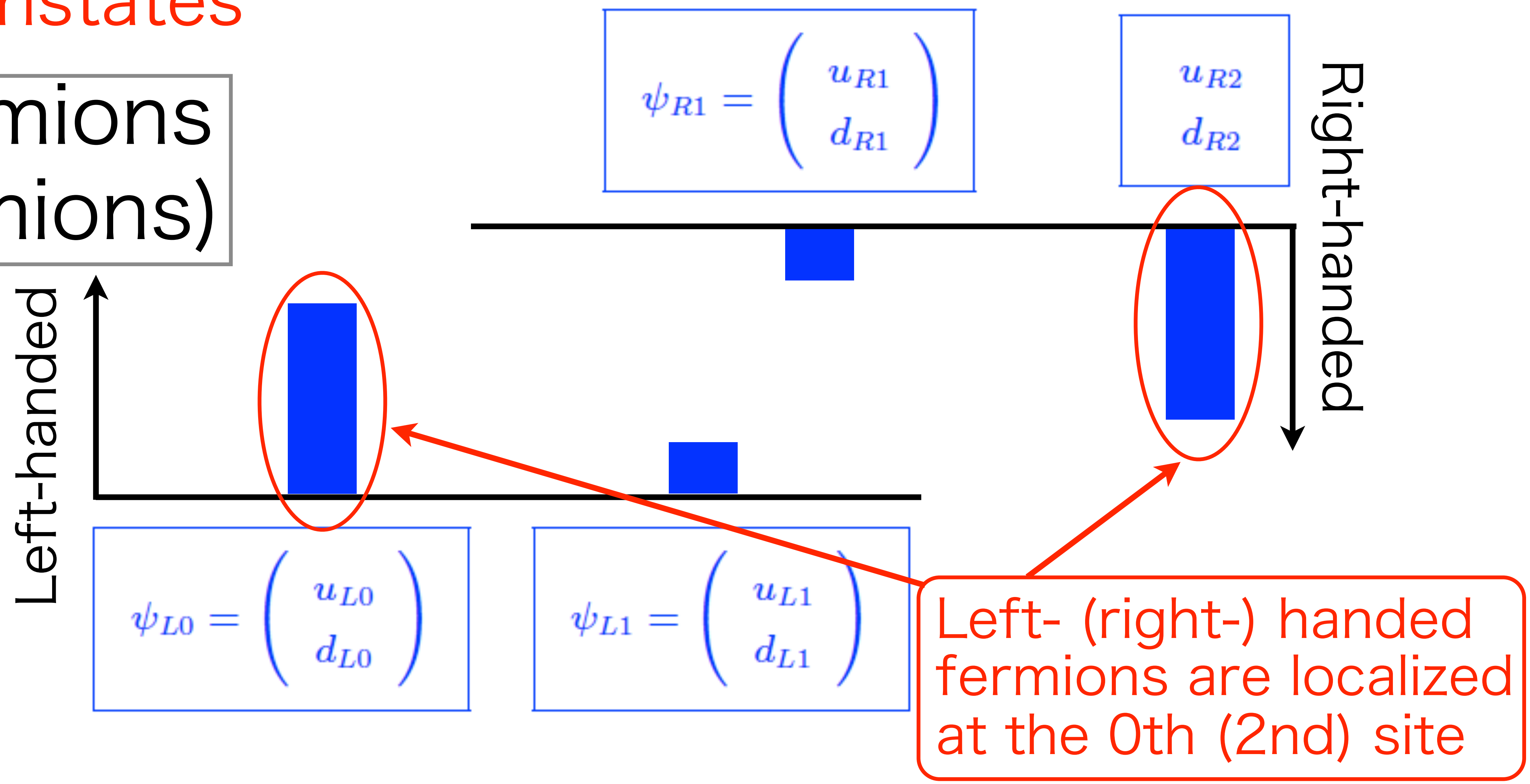

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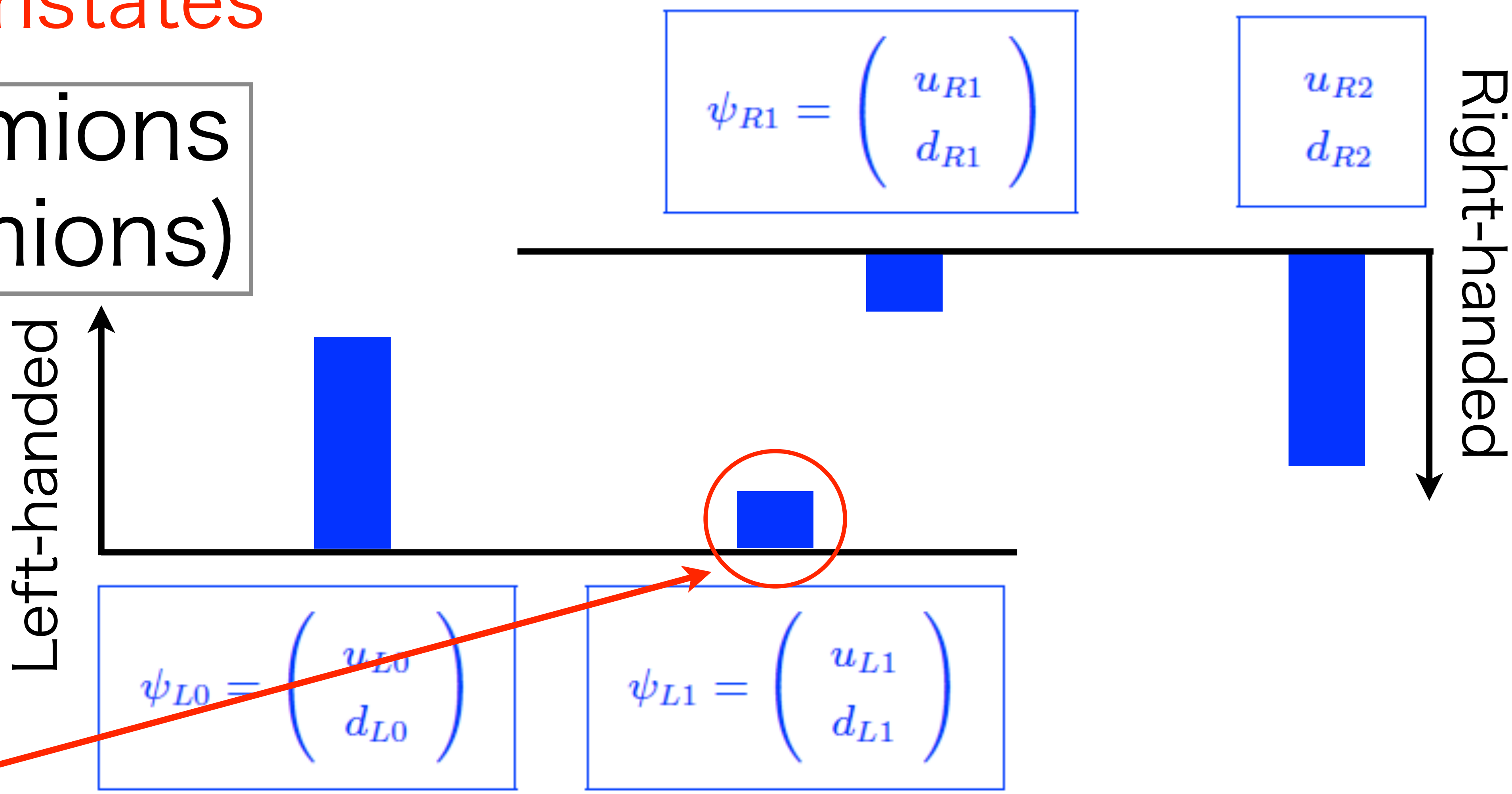

Ideal delocalization

$$\varepsilon_L \approx 2\frac{M_W^2}{M_{W'}^2}$$

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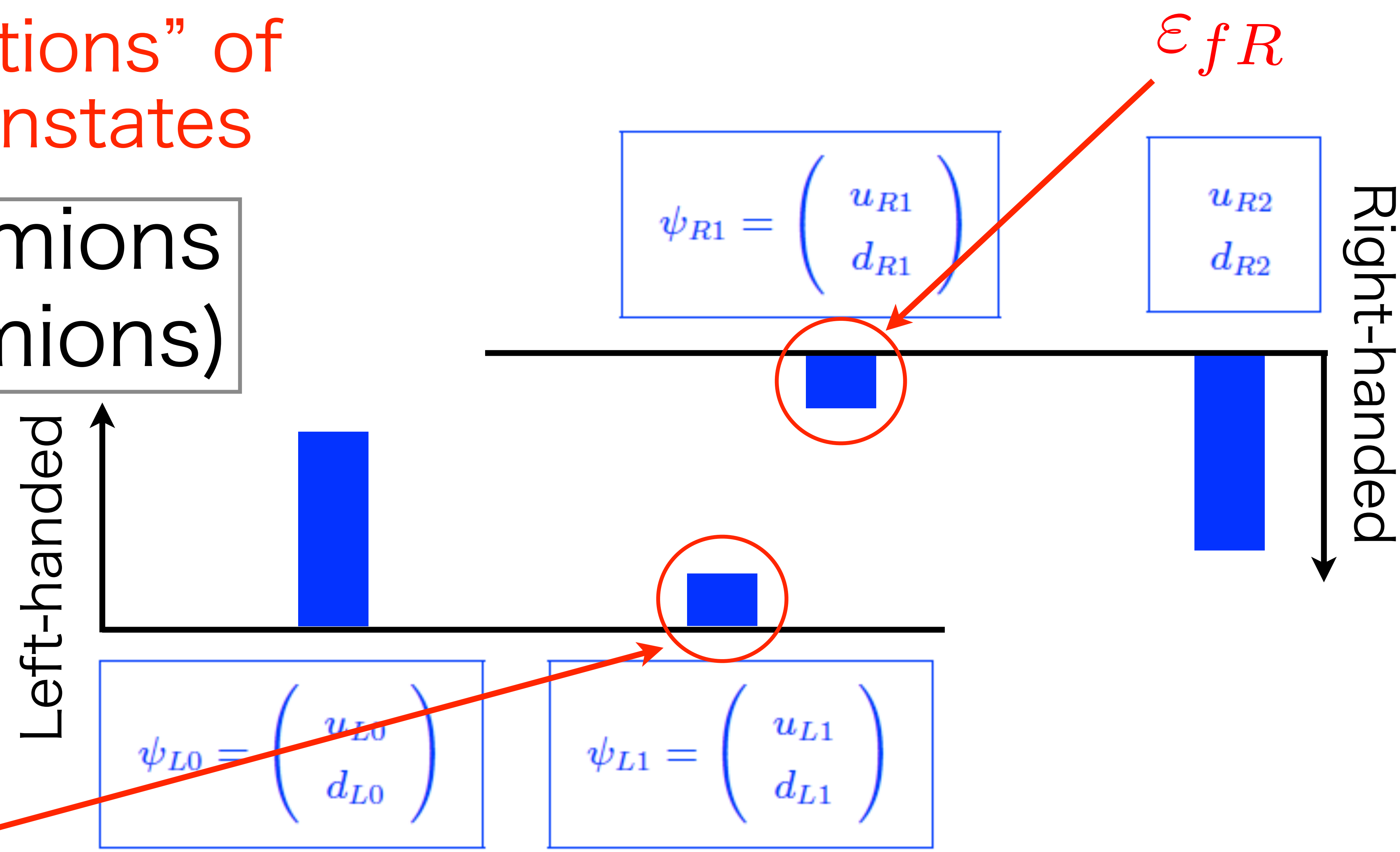

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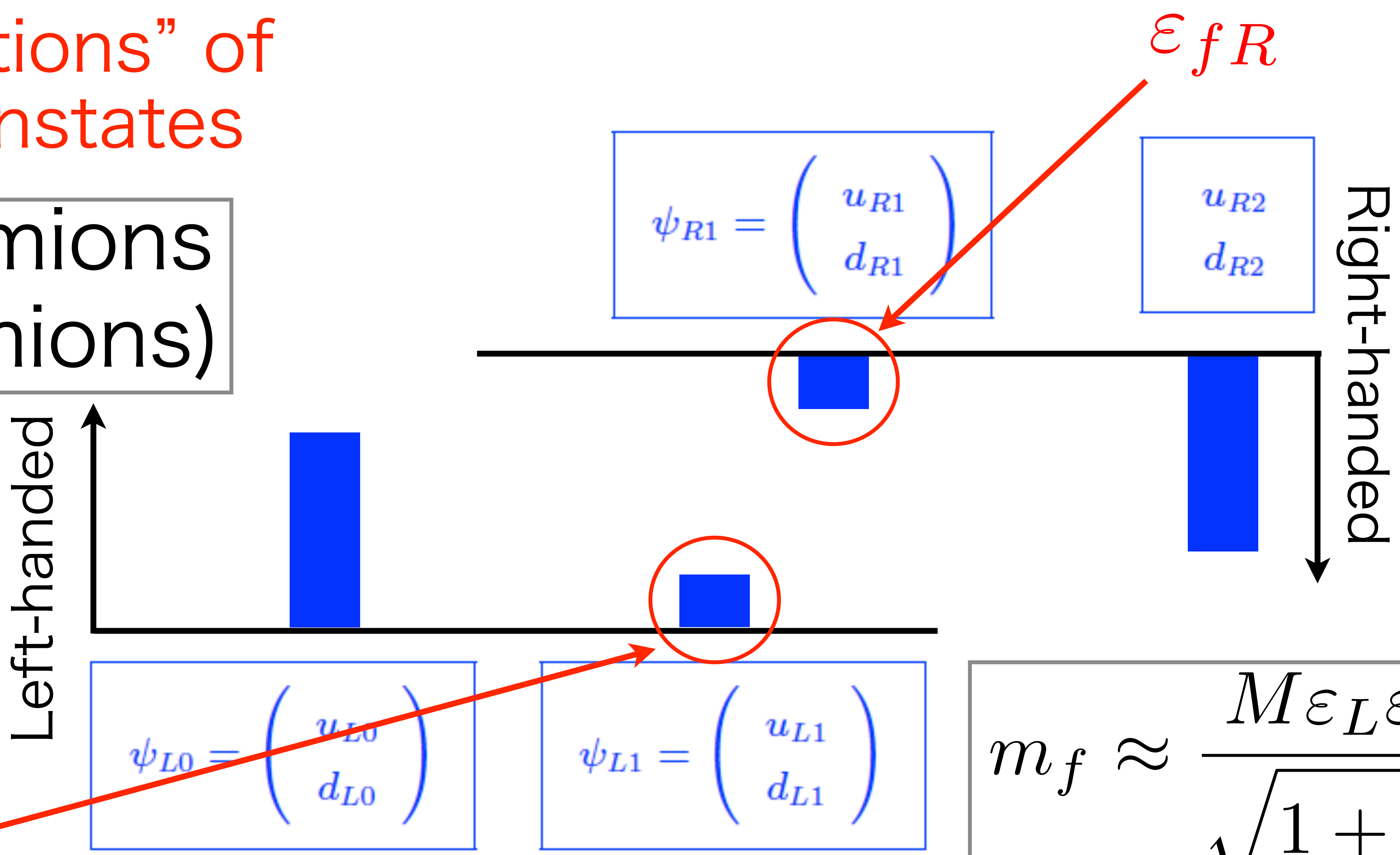

Ideal delocalization

$$\varepsilon_L \approx 2\frac{M_W^2}{M_{W'}^2}$$

$$m_f \approx \frac{M\varepsilon_L\varepsilon_{fR}}{\sqrt{1+\varepsilon_{fR}^2}}$$

$$\mathcal{L}_{mass} = M\left[\varepsilon_L \bar{\psi}_{L0} U_1 \psi_{R1} + \bar{\psi}_{R1}\psi_{L1} + \bar{\psi}_{L1} U_2 \begin{pmatrix} \varepsilon_{uR} & \\ & \varepsilon_{dR} \end{pmatrix} \begin{pmatrix} u_{R2} \\ d_{R2} \end{pmatrix}\right] + h.c.$$

Three Site Higgsless Model

"Wavefunctions" of mass eigenstates

Heavy partners

$$\psi_{R1} = \begin{pmatrix} u_{R1} \\ d_{R1} \end{pmatrix}$$

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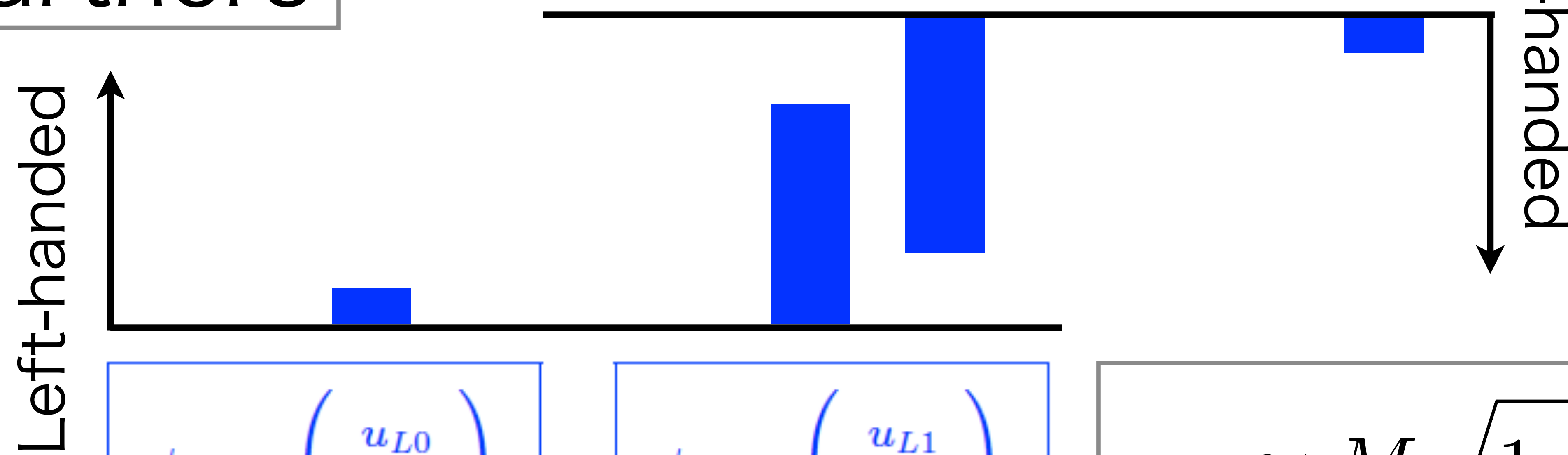

$$\psi_{L0} = \begin{pmatrix} u_{L0} \\ d_{L0} \end{pmatrix}$$

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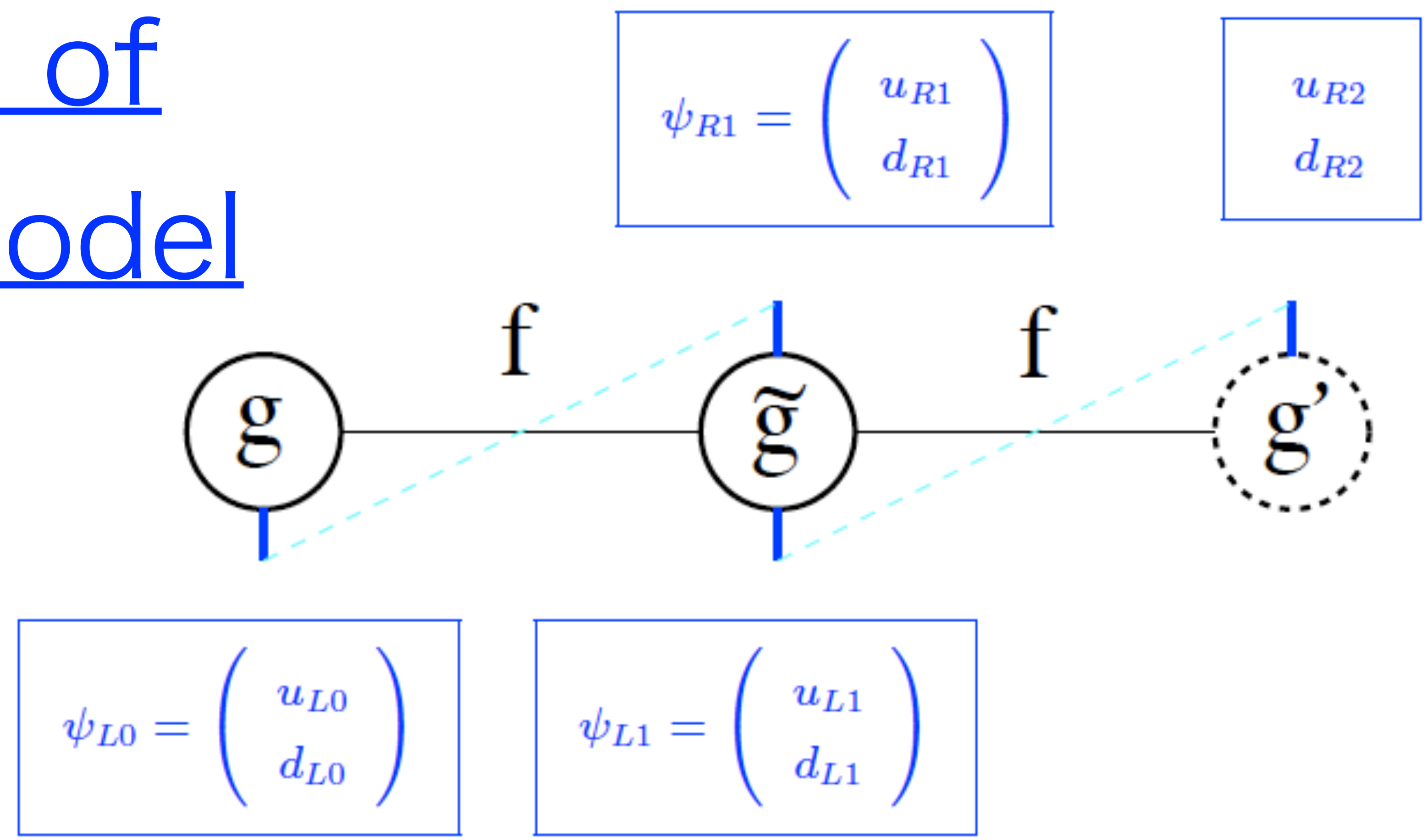
$$m_F \approx M\sqrt{1+\varepsilon_{fR}^2}$$

$$\mathcal{L}_{mass} = M\left[\varepsilon_L \bar{\psi}_{L0} U_1 \psi_{R1} + \bar{\psi}_{R1}\psi_{L1} + \bar{\psi}_{L1} U_2 \begin{pmatrix} \varepsilon_{uR} & \\ & \varepsilon_{dR} \end{pmatrix} \begin{pmatrix} u_{R2} \\ d_{R2} \end{pmatrix}\right] + h.c.$$

Flavor structure of the three-site model



Mass term: one generation

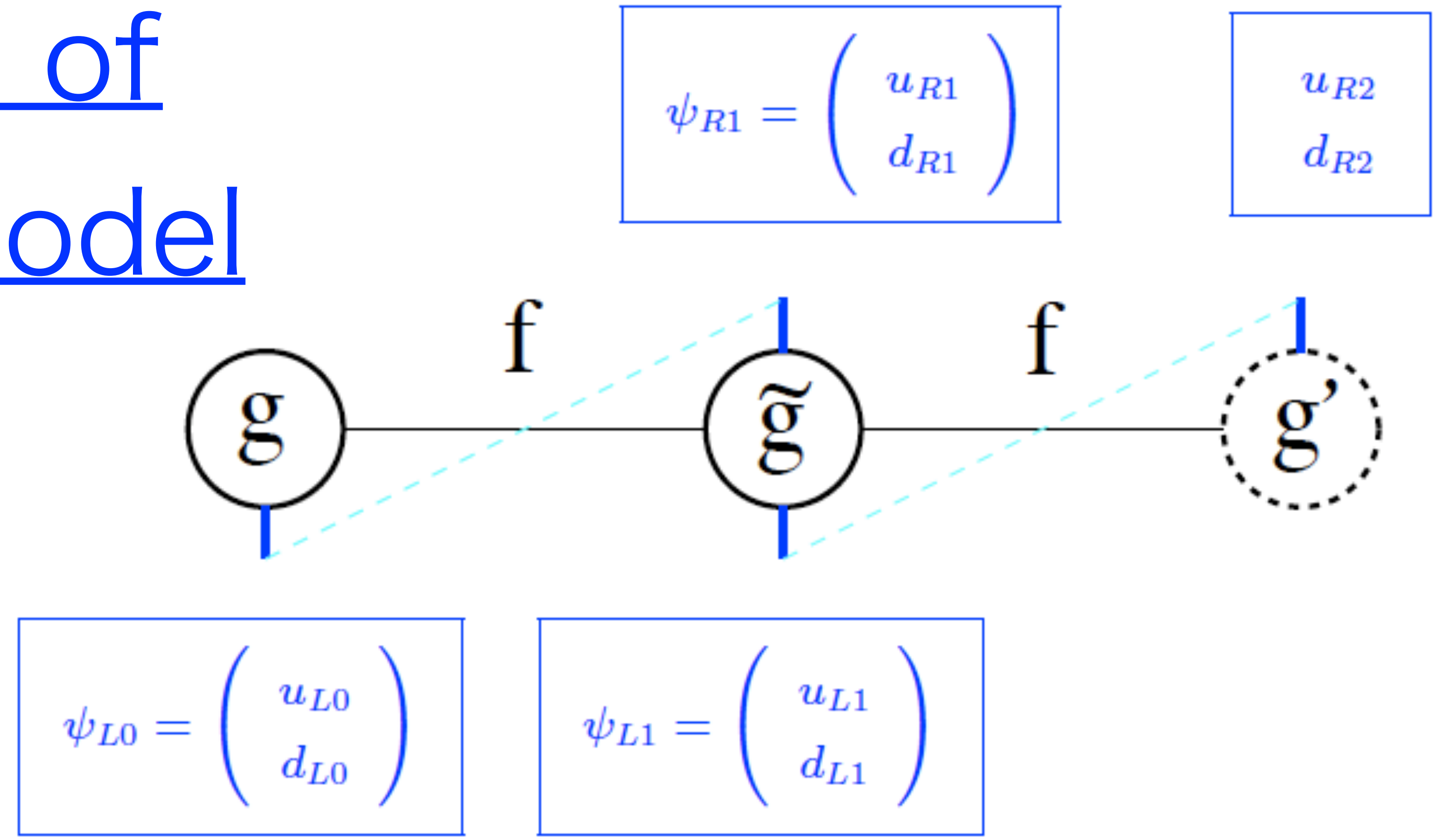
$$\begin{aligned}\mathcal{L}_{mass} \;=\; & -\sqrt{2}v \begin{pmatrix} \bar{u}_{L0} & \bar{d}_{L0} \end{pmatrix} \begin{pmatrix} \lambda & \\ & \lambda \end{pmatrix} \begin{pmatrix} u_{R1} \\ d_{R1} \end{pmatrix} \\ & -\sqrt{2}v \begin{pmatrix} \bar{u}_{R1} & \bar{d}_{R1} \end{pmatrix} \begin{pmatrix} \tilde{\lambda} & \\ & \tilde{\lambda} \end{pmatrix} \begin{pmatrix} u_{L1} \\ d_{L1} \end{pmatrix} \\ & -\sqrt{2}v \begin{pmatrix} \bar{u}_{L1} & \bar{d}_{L1} \end{pmatrix} \begin{pmatrix} \lambda'_u & \\ & \lambda'_d \end{pmatrix} \begin{pmatrix} u_{R2} \\ d_{R2} \end{pmatrix} \end{aligned}$$

+ h.c.

parameter redefinition

$$\begin{aligned} M &\equiv \sqrt{2}v\,\tilde{\lambda} \\ M\varepsilon_L &\equiv \sqrt{2}v\,\lambda \\ M\varepsilon_{fR} &\equiv \sqrt{2}v\,\lambda'_f \end{aligned}$$

Flavor structure of the three-site model



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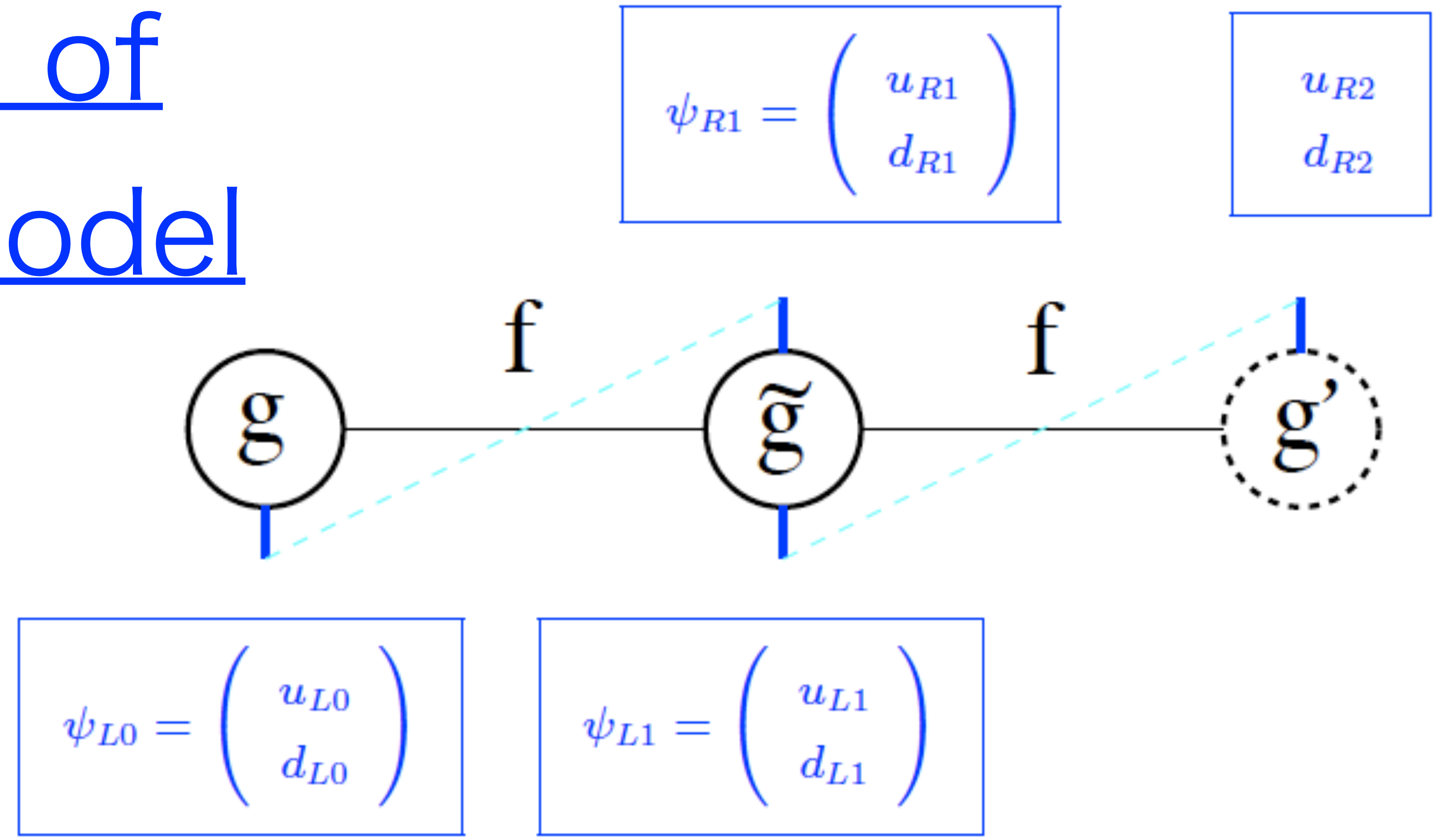
\end{aligned}
$$

+ h.c.

3-generation generalization

Flavor structure of the three-site model



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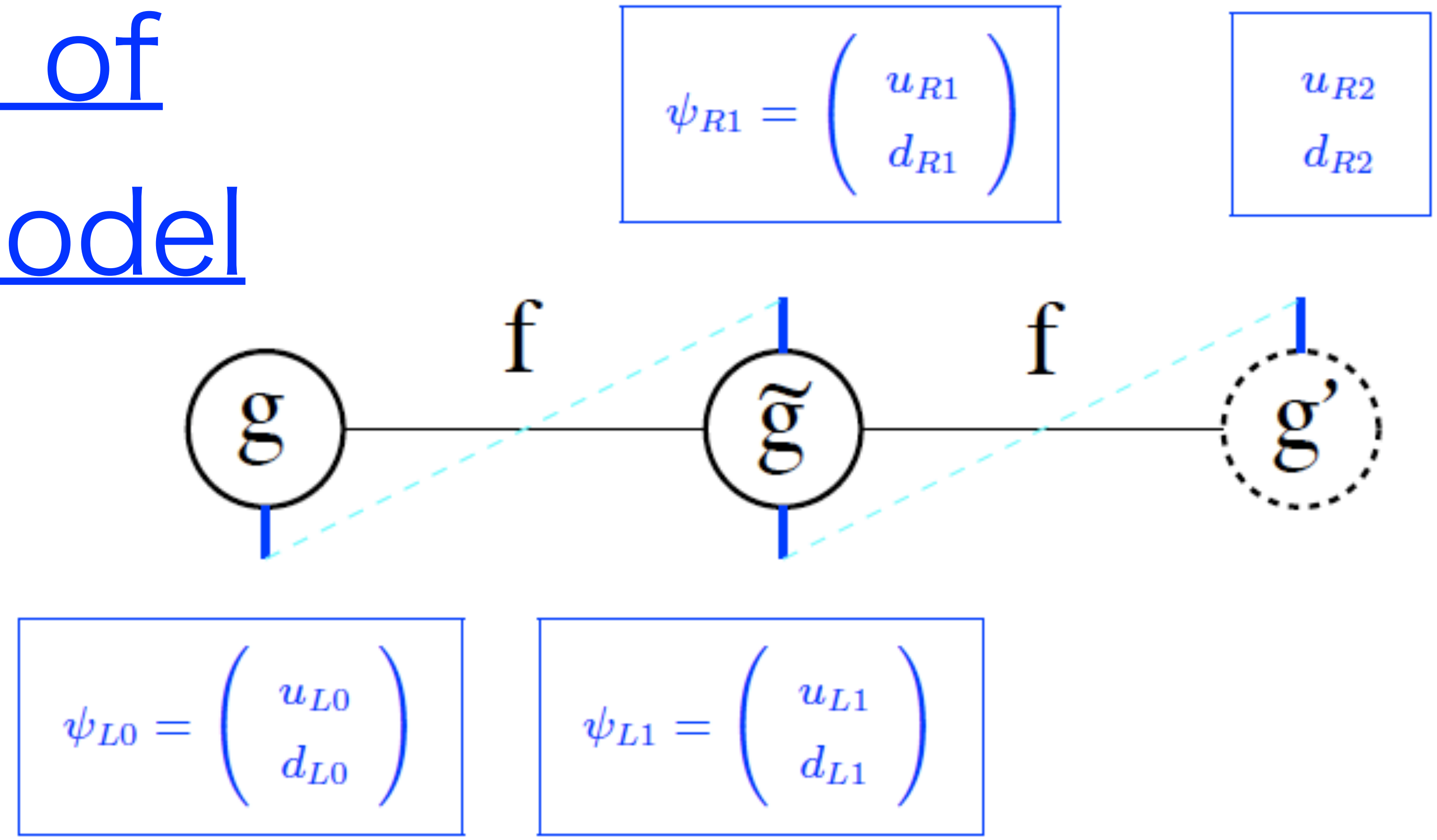
\end{aligned}
$$

+ h.c.

3-generation generalization

→ 3-vector

Flavor structure of the three-site model



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+ h.c.

3-generation generalization

→ 3x3 matrix

Generalization to 3 generations

$$\mathcal{L}_{mass} = -\sqrt{2}v \begin{pmatrix} \bar{u}_{L(0,I)} & \bar{d}_{L(0,I)} \end{pmatrix} \left(\begin{array}{c|c} \lambda\cdot\delta_{IJ} & \\ \hline & \lambda\cdot\delta_{IJ} \end{array}\right) \begin{pmatrix} u_{R(1,J)} \\ d_{R(1,J)} \end{pmatrix}$$

$$-\sqrt{2}v \begin{pmatrix} \bar{u}_{R(1,I)} & \bar{d}_{R(1,I)} \end{pmatrix} \left(\begin{array}{c|c} \tilde{\lambda}\cdot\delta_{IJ} & \\ \hline & \tilde{\lambda}\cdot\delta_{IJ} \end{array}\right) \begin{pmatrix} u_{L(1,J)} \\ d_{L(1,J)} \end{pmatrix}$$

$$-\sqrt{2}v \begin{pmatrix} \bar{u}_{L(1,I)} & \bar{d}_{L(1,I)} \end{pmatrix} \left(\begin{array}{c|c} (\Lambda'_u)_{IJ} & \\ \hline & (\Lambda'_d)_{IJ} \end{array}\right) \begin{pmatrix} u_{R(2,J)} \\ d_{R(2,J)} \end{pmatrix} + h.c.$$

$I, J = 1, 2, 3$: generation index

Generalization to 3 generations

$$
\begin{aligned}
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\end{aligned}
$$

$I, J = 1, 2, 3 \ :$ generation index

Same structure as the SM

(Λ'_u, Λ'_d : 3x3 complex)

Generalization to 3 generations

$$
\begin{aligned}
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$I, J = 1, 2, 3$: generation index

We assume no extra flavor mixing from this part

Generalization to 3 generations

$$\begin{aligned}\mathcal{L}_{mass} = & -\sqrt{2}v \begin{pmatrix} \bar{u}_{L(0,I)} & \bar{d}_{L(0,I)} \end{pmatrix} \left(\begin{array}{c|c} \lambda \cdot \delta_{IJ} & \\ \hline & \lambda \cdot \delta_{IJ} \end{array}\right) \begin{pmatrix} u_{R(1,J)} \\ d_{R(1,J)} \end{pmatrix} \\ & -\sqrt{2}v \begin{pmatrix} \bar{u}_{R(1,I)} & \bar{d}_{R(1,I)} \end{pmatrix} \left(\begin{array}{c|c} \tilde{\lambda} \cdot \delta_{IJ} & \\ \hline & \tilde{\lambda} \cdot \delta_{IJ} \end{array}\right) \begin{pmatrix} u_{L(1,J)} \\ d_{L(1,J)} \end{pmatrix} \\ & -\sqrt{2}v \begin{pmatrix} \bar{u}_{L(1,I)} & \bar{d}_{L(1,I)} \end{pmatrix} \left(\begin{array}{c|c} (\Lambda'_u)_{IJ} & \\ \hline & (\Lambda'_d)_{IJ} \end{array}\right) \begin{pmatrix} u_{R(2,J)} \\ d_{R(2,J)} \end{pmatrix} + h.c.\end{aligned}$$

$$I, J = 1, 2, 3 \;:\; \text{generation index}$$

We assume no extra flavor mixing from this part

This set-up does not induce tree-level FCNC

Still, extra source of flavor violation exists

Diagonalization

$$\mathcal{L}_{mass} = -\sqrt{2}v \begin{pmatrix} \bar{u}_{L(0,I)} & \bar{d}_{L(0,I)} \end{pmatrix} \left(\begin{array}{c|c} \lambda \cdot \delta_{IJ} & \\ \hline & \lambda \cdot \delta_{IJ} \end{array}\right) \begin{pmatrix} u_{R(1,J)} \\ d_{R(1,J)} \end{pmatrix}$$

$$-\sqrt{2}v \begin{pmatrix} \bar{u}_{R(1,I)} & \bar{d}_{R(1,I)} \end{pmatrix} \left(\begin{array}{c|c} \tilde{\lambda} \cdot \delta_{IJ} & \\ \hline & \tilde{\lambda} \cdot \delta_{IJ} \end{array}\right) \begin{pmatrix} u_{L(1,J)} \\ d_{L(1,J)} \end{pmatrix}$$

$$-\sqrt{2}v \begin{pmatrix} \bar{u}_{L(1,I)} & \bar{d}_{L(1,I)} \end{pmatrix} \left(\begin{array}{c|c} (\Lambda'_u)_{IJ} & \\ \hline & (\Lambda'_d)_{IJ} \end{array}\right) \begin{pmatrix} u_{R(2,J)} \\ d_{R(2,J)} \end{pmatrix} + h.c.$$

Introduce $V_{uL}, V_{uR}, V_{dL}, V_{dR}$ which diagonalize Λ'_u, Λ'_d

$$\underline{V_{uL}}\Lambda'_u \underline{V^\dagger_{uR}} = \begin{pmatrix} \lambda_u^{\prime(1)} & & \\ & \lambda_u^{\prime(2)} & \\ & & \lambda_u^{\prime(3)} \end{pmatrix}$$

$$\underline{V_{dL}}\Lambda'_d \underline{V^\dagger_{dR}} = \begin{pmatrix} \lambda_d^{\prime(1)} & & \\ & \lambda_d^{\prime(2)} & \\ & & \lambda_d^{\prime(3)} \end{pmatrix}$$

Diagonalization

$$\mathcal{L}_{mass} = -\sqrt{2}v \begin{pmatrix} \bar{u}_{L(0,I)} & \bar{d}_{L(0,I)} \end{pmatrix} \left(\begin{array}{c|c} \lambda \cdot \delta_{IJ} & \\ \hline & \lambda \cdot \delta_{IJ} \end{array}\right) \begin{pmatrix} u_{R(1,J)} \\ d_{R(1,J)} \end{pmatrix}$$
$$-\sqrt{2}v \begin{pmatrix} \bar{u}_{R(1,I)} & \bar{d}_{R(1,I)} \end{pmatrix} \left(\begin{array}{c|c} \tilde{\lambda} \cdot \delta_{IJ} & \\ \hline & \tilde{\lambda} \cdot \delta_{IJ} \end{array}\right) \begin{pmatrix} u_{L(1,J)} \\ d_{L(1,J)} \end{pmatrix}$$
$$-\sqrt{2}v \begin{pmatrix} \bar{u}_{L(1,I)} & \bar{d}_{L(1,I)} \end{pmatrix} \left(\begin{array}{c|c} (\Lambda'_u)_{IJ} & \\ \hline & (\Lambda'_d)_{IJ} \end{array}\right) \begin{pmatrix} u_{R(2,J)} \\ d_{R(2,J)} \end{pmatrix} + h.c.$$

Field redefinition

$$u'_{L(0,I')} = \sum_{I=1}^{3} \boxed{(V_{uL})^{I'I}} u_{L(0,I)}, \qquad d'_{L(0,I')} = \sum_{I=1}^{3} \boxed{(V_{dL})^{I'I}} d_{L(0,I)},$$
$$u'_{R(1,I')} = \sum_{I=1}^{3} \boxed{(V_{uL})^{I'I}} u_{R(1,I)}, \qquad d'_{R(1,I')} = \sum_{I=1}^{3} \boxed{(V_{dL})^{I'I}} d_{R(1,I)},$$
$$u'_{L(1,I')} = \sum_{I=1}^{3} \boxed{(V_{uL})^{I'I}} u_{L(1,I)}, \qquad d'_{L(1,I')} = \sum_{I=1}^{3} \boxed{(V_{dL})^{I'I}} d_{L(1,I)},$$
$$u'_{R(2,I')} = \sum_{I=1}^{3} \boxed{(V_{uR})^{I'I}} u_{R(2,I)}, \qquad d'_{R(2,I')} = \sum_{I=1}^{3} \boxed{(V_{dR})^{I'I}} d_{R(2,I)}.$$

Diagonalization

$$\mathcal{L}_{mass} \quad =$$

$$-\sqrt{2}v \left(\bar{u}'_{L(0,I')}(V_{uL})^{I'I} \quad \bar{d}'_{L(0,I')}(V_{dL})^{I'I} \right) \left(\begin{array}{c|c} \lambda \cdot \delta_{IJ} & \\ \hline & \lambda \cdot \delta_{IJ} \end{array} \right) \left(\begin{array}{c} (V^{\dagger}_{uL})^{JJ'} u'_{R(1,J')} \\ (V^{\dagger}_{dL})^{JJ'} d'_{R(1,J')} \end{array} \right)$$

$$-\sqrt{2}v \left(\bar{u}'_{R(1,I')}(V_{uL})^{I'I} \quad \bar{d}'_{R(1,I')}(V_{dL})^{I'I} \right) \left(\begin{array}{c|c} \tilde{\lambda} \cdot \delta_{IJ} & \\ \hline & \tilde{\lambda} \cdot \delta_{IJ} \end{array} \right) \left(\begin{array}{c} (V^{\dagger}_{uL})^{JJ'} u'_{L(1,J')} \\ (V^{\dagger}_{dL})^{JJ'} d'_{L(1,J')} \end{array} \right)$$

$$-\sqrt{2}v \left(\bar{u}'_{L(1,I')}(V_{uL})^{I'I} \quad \bar{d}'_{L(1,I')}(V_{dL})^{I'I} \right) \left(\begin{array}{c|c} (\Lambda'_u)_{IJ} & \\ \hline & (\Lambda'_d)_{IJ} \end{array} \right) \left(\begin{array}{c} (V^{\dagger}_{uR})^{JJ'} u'_{R(2,J')} \\ (V^{\dagger}_{dR})^{JJ'} d'_{R(2,J')} \end{array} \right)$$

$$+\, h.c.$$

Diagonalization

$$\mathcal{L}_{mass} = -\sqrt{2}v \begin{pmatrix} \bar{u}'_{L(0,I')} & \bar{d}'_{L(0,I')} \end{pmatrix} \begin{pmatrix} \lambda \cdot \delta_{I'J'} & \\ & \lambda \cdot \delta_{I'J'} \end{pmatrix} \begin{pmatrix} u'_{R(1,J')} \\ d'_{R(1,J')} \end{pmatrix}$$
$$-\sqrt{2}v \begin{pmatrix} \bar{u}'_{R(1,I')} & \bar{d}'_{R(1,I')} \end{pmatrix} \begin{pmatrix} \tilde{\lambda} \cdot \delta_{I'J'} & \\ & \tilde{\lambda} \cdot \delta_{I'J'} \end{pmatrix} \begin{pmatrix} u'_{L(1,J')} \\ d'_{L(1,J')} \end{pmatrix}$$
$$-\sqrt{2}v \begin{pmatrix} \bar{u}'_{L(1,I')} & \bar{d}'_{L(1,I')} \end{pmatrix} \begin{pmatrix} \lambda'^{(I')}_u \cdot \delta_{I'J'} & \\ & \lambda'^{(I')}_d \cdot \delta_{I'J'} \end{pmatrix} \begin{pmatrix} u'_{R(2,J')} \\ d'_{R(2,J')} \end{pmatrix} + h.c.$$

Diagonalized in “generation space”

Diagonalization

$$
\begin{aligned}
\mathcal{L}_{mass} \;=\; & -\sqrt{2}v \begin{pmatrix} \bar{u}'_{L(0,I')} & \bar{d}'_{L(0,I')} \end{pmatrix} \left(\begin{array}{c|c} \lambda \cdot \delta_{I'J'} & \\ \hline & \lambda \cdot \delta_{I'J'} \end{array} \right) \begin{pmatrix} u'_{R(1,J')} \\ d'_{R(1,J')} \end{pmatrix} \\
& -\sqrt{2}v \begin{pmatrix} \bar{u}'_{R(1,I')} & \bar{d}'_{R(1,I')} \end{pmatrix} \left(\begin{array}{c|c} \tilde{\lambda} \cdot \delta_{I'J'} & \\ \hline & \tilde{\lambda} \cdot \delta_{I'J'} \end{array} \right) \begin{pmatrix} u'_{L(1,J')} \\ d'_{L(1,J')} \end{pmatrix} \\
& -\sqrt{2}v \begin{pmatrix} \bar{u}'_{L(1,I')} & \bar{d}'_{L(1,I')} \end{pmatrix} \left(\begin{array}{c|c} \lambda'^{(I')}_u \cdot \delta_{I'J'} & \\ \hline & \lambda'^{(I')}_d \cdot \delta_{I'J'} \end{array} \right) \begin{pmatrix} u'_{R(2,J')} \\ d'_{R(2,J')} \end{pmatrix} + h.c.
\end{aligned}
$$

Diagonalized in “generation space”

Furthermore

diagonalization in “site space”

$$
\begin{aligned}
u''_{L(i',I')} &= \sum_{i=0}^{1} \left(U^{(I')}_{uL}\right)^{i'i} u'_{L(i,I')}, & d''_{L(i',I')} &= \sum_{i=0}^{1} \left(U^{(I')}_{dL}\right)^{i'i} d'_{L(i,I')}, \\
u''_{R(i',I')} &= \sum_{i=1}^{2} \left(U^{(I')}_{uR}\right)^{i'i} u'_{R(i,I')}, & d''_{R(i',I')} &= \sum_{i=1}^{2} \left(U^{(I')}_{dR}\right)^{i'i} d'_{R(i,I')}.
\end{aligned}
$$

SM fermions and their heavy partners

$$
\begin{aligned}
u''_{L,R(0,1)} &= u_{L,R}\,, & d''_{L,R(0,1)} &= d_{L,R}\,,\\
u''_{L,R(0,2)} &= c_{L,R}\,, & d''_{L,R(0,2)} &= s_{L,R}\,,\\
u''_{L,R(0,3)} &= t_{L,R}\,, & d''_{L,R(0,3)} &= b_{L,R}\,,\\
u''_{L,R(1,1)} &= U_{L,R}\,, & d''_{L,R(1,1)} &= D_{L,R}\,,\\
u''_{L,R(1,2)} &= C_{L,R}\,, & d''_{L,R(1,2)} &= S_{L,R}\,,\\
u''_{L,R(1,3)} &= T_{L,R}\,, & d''_{L,R(1,3)} &= B_{L,R}\,,
\end{aligned}
$$

0, 1 : KK-index

1, 2, 3 : generation index

Fermion couplings to neutral gauge bosons

e.g., T_3 part

$$\sum_{i=0}^{1}\sum_{I=1}^{3}\frac{g_i}{2}\left[\bar{u}_{L(i,I)}\gamma_\mu u_{L(i,I)} - \bar{d}_{L(i,I)}\gamma_\mu d_{L(i,I)}\right] A_i^{3\,\mu}$$

$$+\sum_{i=1}^{2}\sum_{I=1}^{3}\frac{g_i}{2}\left[\bar{u}_{R(i,I)}\gamma_\mu u_{R(i,I)} - \bar{d}_{R(i,I)}\gamma_\mu d_{R(i,I)}\right] A_i^{3\,\mu},$$

There is no tree-level FCNC term

(because of the unitarity of rotation matrices)

Left-handed Fermion couplings to charged gauge bosons

$$\sum_{I=1}^{3}\left[\frac{g_0}{\sqrt{2}}A_0^{+\,\mu}\bar{u}_{L(0,I)}\gamma_\mu d_{L(0,I)}+\frac{g_1}{\sqrt{2}}A_1^{+\,\mu}\bar{u}_{L(1,I)}\gamma_\mu d_{L(1,I)}\right]\;+h.c.,$$

Left-handed Fermion couplings to charged gauge bosons

$$\sum_{I=1}^{3}\left[\frac{g_0}{\sqrt{2}}A_0^{+\,\mu}\bar{u}_{L(0,I)}\gamma_\mu d_{L(0,I)}+\frac{g_1}{\sqrt{2}}A_1^{+\,\mu}\bar{u}_{L(1,I)}\gamma_\mu d_{L(1,I)}\right]\quad +h.c.,$$

$$=\quad\sum_{I',J'=1}^{3}\left[\frac{g_0}{\sqrt{2}}A_0^{+\,\mu}\bar{u}'_{L(0,I')}\gamma_\mu d'_{L(0,J')}+\frac{g_1}{\sqrt{2}}A_1^{+\,\mu}\bar{u}'_{L(1,I')}\gamma_\mu d'_{L(1,J')}\right]\left(V_{uL}V_{dL}^{\dagger}\right)^{I'J'}\quad +h.c.,$$

Left-handed Fermion couplings to charged gauge bosons

$$\sum_{I=1}^{3}\left[\frac{g_0}{\sqrt{2}}A_0^{+\,\mu}\bar{u}_{L(0,I)}\gamma_\mu d_{L(0,I)}+\frac{g_1}{\sqrt{2}}A_1^{+\,\mu}\bar{u}_{L(1,I)}\gamma_\mu d_{L(1,I)}\right]\;+h.c.,$$

$$=\;\sum_{I',J'=1}^{3}\left[\frac{g_0}{\sqrt{2}}A_0^{+\,\mu}\bar{u}'_{L(0,I')}\gamma_\mu d'_{L(0,J')}+\frac{g_1}{\sqrt{2}}A_1^{+\,\mu}\bar{u}'_{L(1,I')}\gamma_\mu d'_{L(1,J')}\right]\underline{\left(V_{uL}V_{dL}^{\dagger}\right)^{I'J'}}+h.c.,$$

$$|||$$

$$\left(V^{(0)}\right)^{I'J'}$$

where, $\left(V_{uL}V_{dL}^{\dagger}\right)^{I'J'}\equiv(V^{(0)})^{I'J'}\equiv\begin{pmatrix} V_{ud}^{(0)} & V_{us}^{(0)} & V_{ub}^{(0)} \\ V_{cd}^{(0)} & V_{cs}^{(0)} & V_{cb}^{(0)} \\ V_{td}^{(0)} & V_{ts}^{(0)} & V_{tb}^{(0)} \end{pmatrix}$

Left-handed Fermion couplings to charged gauge bosons

$$\sum_{I=1}^{3}\left[\frac{g_0}{\sqrt{2}}A_0^{+\,\mu}\bar{u}_{L(0,I)}\gamma_\mu d_{L(0,I)}+\frac{g_1}{\sqrt{2}}A_1^{+\,\mu}\bar{u}_{L(1,I)}\gamma_\mu d_{L(1,I)}\right]\ +h.c.,$$

$$=\sum_{I',J'=1}^{3}\left[\frac{g_0}{\sqrt{2}}A_0^{+\,\mu}\bar{u}'_{L(0,I')}\gamma_\mu d'_{L(0,J')}+\frac{g_1}{\sqrt{2}}A_1^{+\,\mu}\bar{u}'_{L(1,I')}\gamma_\mu d'_{L(1,J')}\right]\left(V_{uL}V_{dL}^{\dagger}\right)^{I'J'}+h.c.,$$

rewrite this part in terms of mass eigenstates

$$\left(V_{uL}V_{dL}^{\dagger}\right)^{I'J'} \equiv \left(V^{(0)}\right)^{I'J'}$$

where, $\left(V_{uL}V_{dL}^{\dagger}\right)^{I'J'}\equiv(V^{(0)})^{I'J'}\equiv\begin{pmatrix} V_{ud}^{(0)} & V_{us}^{(0)} & V_{ub}^{(0)} \\ V_{cd}^{(0)} & V_{cs}^{(0)} & V_{cb}^{(0)} \\ V_{td}^{(0)} & V_{ts}^{(0)} & V_{tb}^{(0)} \end{pmatrix}$

↓

site eigenmode → KK eigenmode

Left-handed Fermion couplings to W boson

$$\frac{g_L^W}{\sqrt{2}} W^{+\mu} \begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L & \bar{U}_L & \bar{C}_L & \bar{T}_L \end{pmatrix} \gamma_\mu \left(\begin{array}{c|c} V_L^{(\ell\ell)} & V_L^{(\ell h)} \\ \hline V_L^{(h\ell)} & V_L^{(hh)} \end{array} \right) \begin{pmatrix} d_L \\ s_L \\ b_L \\ D_L \\ S_L \\ B_L \end{pmatrix} + h.c.$$

Left-handed Fermion couplings to W boson

$$\frac{g_L^W}{\sqrt{2}} W^{+\mu} \begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L & \bar{U}_L & \bar{C}_L & \bar{T}_L \end{pmatrix} \gamma_\mu \left(\begin{array}{c|c} V_L^{(\ell\ell)} & V_L^{(\ell h)} \\ \hline V_L^{(h\ell)} & V_L^{(hh)} \end{array}\right) \begin{pmatrix} d_L \\ s_L \\ b_L \\ D_L \\ S_L \\ B_L \end{pmatrix} + h.c.$$

$$V_L^{(\ell\ell)} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 + \frac{\varepsilon_{tR}^2}{4(1+\varepsilon_{tR}^2)^2} x^2 + O(x^4) \end{pmatrix} V^{(0)},$$

$$V_L^{(\ell h)} = \frac{x}{2\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \frac{1+2\varepsilon_{tR}^2}{1+\varepsilon_{tR}^2} + O(x^2) \end{pmatrix} V^{(0)},$$

$$V_L^{(h\ell)} = \frac{x}{2\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \frac{1-\varepsilon_{tR}^2}{1+\varepsilon_{tR}^2} + O(x^2) \end{pmatrix} V^{(0)},$$

Left-handed Fermion couplings to W boson

$$\frac{g_L^W}{\sqrt{2}} W^{+\mu} \begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L & \bar{U}_L & \bar{C}_L & \bar{T}_L \end{pmatrix} \gamma_\mu \left(\begin{array}{c|c} V_L^{(\ell\ell)} & V_L^{(\ell h)} \\ \hline V_L^{(h\ell)} & V_L^{(hh)} \end{array} \right) \begin{pmatrix} d_L \\ s_L \\ b_L \\ D_L \\ S_L \\ B_L \end{pmatrix} + h.c.$$

$$V_L^{(\ell\ell)} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 + \frac{\varepsilon_{tR}^2}{4(1+\varepsilon_{tR}^2)^2} x^2 + O(x^4) \end{pmatrix} V^{(0)},$$

$$V_L^{(\ell h)} = \frac{x}{2\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \frac{1+2\varepsilon_{tR}^2}{1+\varepsilon_{tR}^2} + O(x^2) \end{pmatrix} V^{(0)},$$

$$V_L^{(h\ell)} = \frac{x}{2\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \frac{1-\varepsilon_{tR}^2}{1+\varepsilon_{tR}^2} + O(x^2) \end{pmatrix} V^{(0)},$$

ε_{tR} becomes a source of flavor violation

$$\varepsilon_{tR} \lesssim 0.3$$

Abe, Matsuzaki, Tanabashi
PRD78:055020, 2008

$\left(\varepsilon_{fR} \ll 1 \ (\text{for} f \neq t) \right)$

Left-handed Fermion couplings to W boson

$$\frac{g_L^W}{\sqrt{2}} W^{+\mu} \begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L & \bar{U}_L & \bar{C}_L & \bar{T}_L \end{pmatrix} \gamma_\mu \left(\begin{array}{c|c} V_L^{(\ell\ell)} & V_L^{(\ell h)} \\ \hline V_L^{(h\ell)} & V_L^{(hh)} \end{array} \right) \begin{pmatrix} d_L \\ s_L \\ b_L \\ D_L \\ S_L \\ B_L \end{pmatrix} + h.c.$$

$$V_L^{(\ell\ell)} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 + \frac{\varepsilon_{tR}^2}{4(1+\varepsilon_{tR}^2)^2} x^2 + O(x^4) \end{pmatrix} V^{(0)},$$

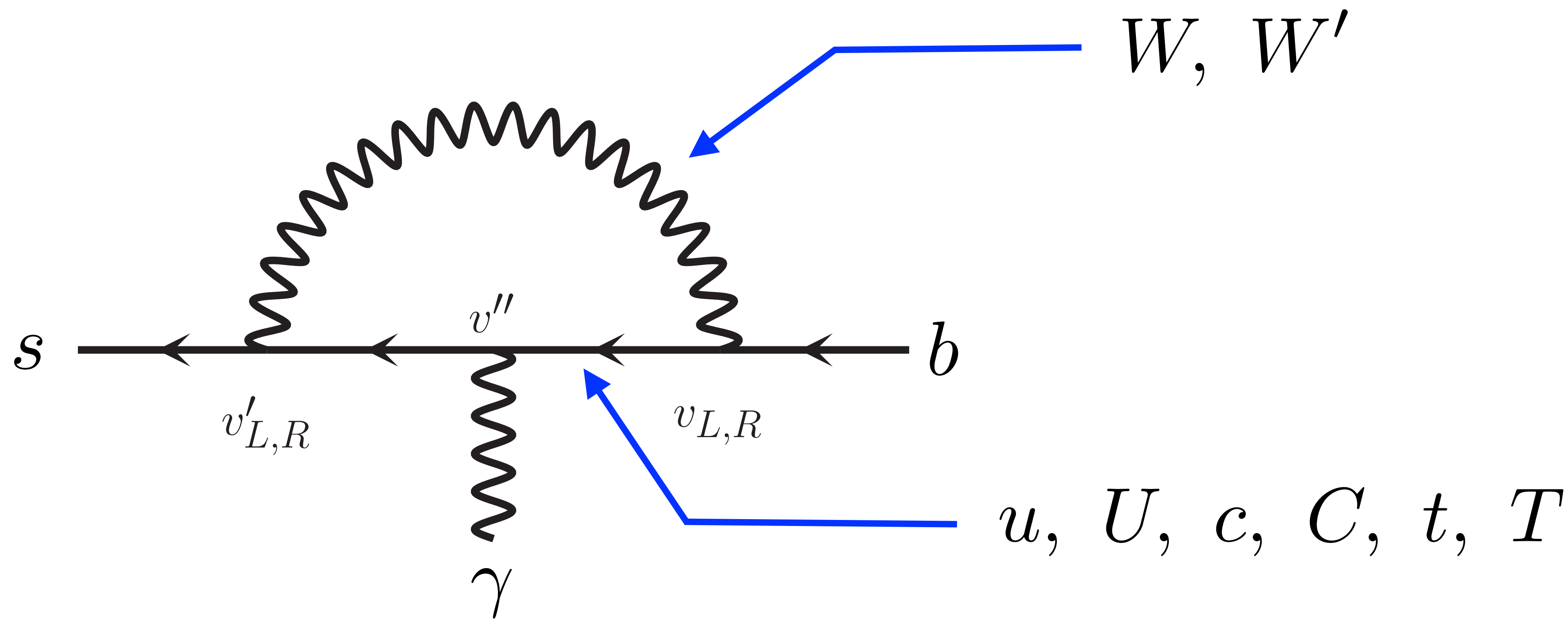
$$V_L^{(\ell h)} = \frac{x}{2\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \frac{1+2\varepsilon_{tR}^2}{1+\varepsilon_{tR}^2} + O(x^2) \end{pmatrix} V^{(0)},$$

$$V_L^{(h\ell)} = \frac{x}{2\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \frac{1-\varepsilon_{tR}^2}{1+\varepsilon_{tR}^2} + O(x^2) \end{pmatrix} V^{(0)},$$

ε_{tR} becomes a source of flavor violation

flavor physics which involve 3rd generation is interesting

$b \to s\gamma$ process in the three-site model



Effects of heavy particles do not decouple!

T. Inami and C.S. Lim, PTP 65: 297, 1981

$b \to s\gamma$ process

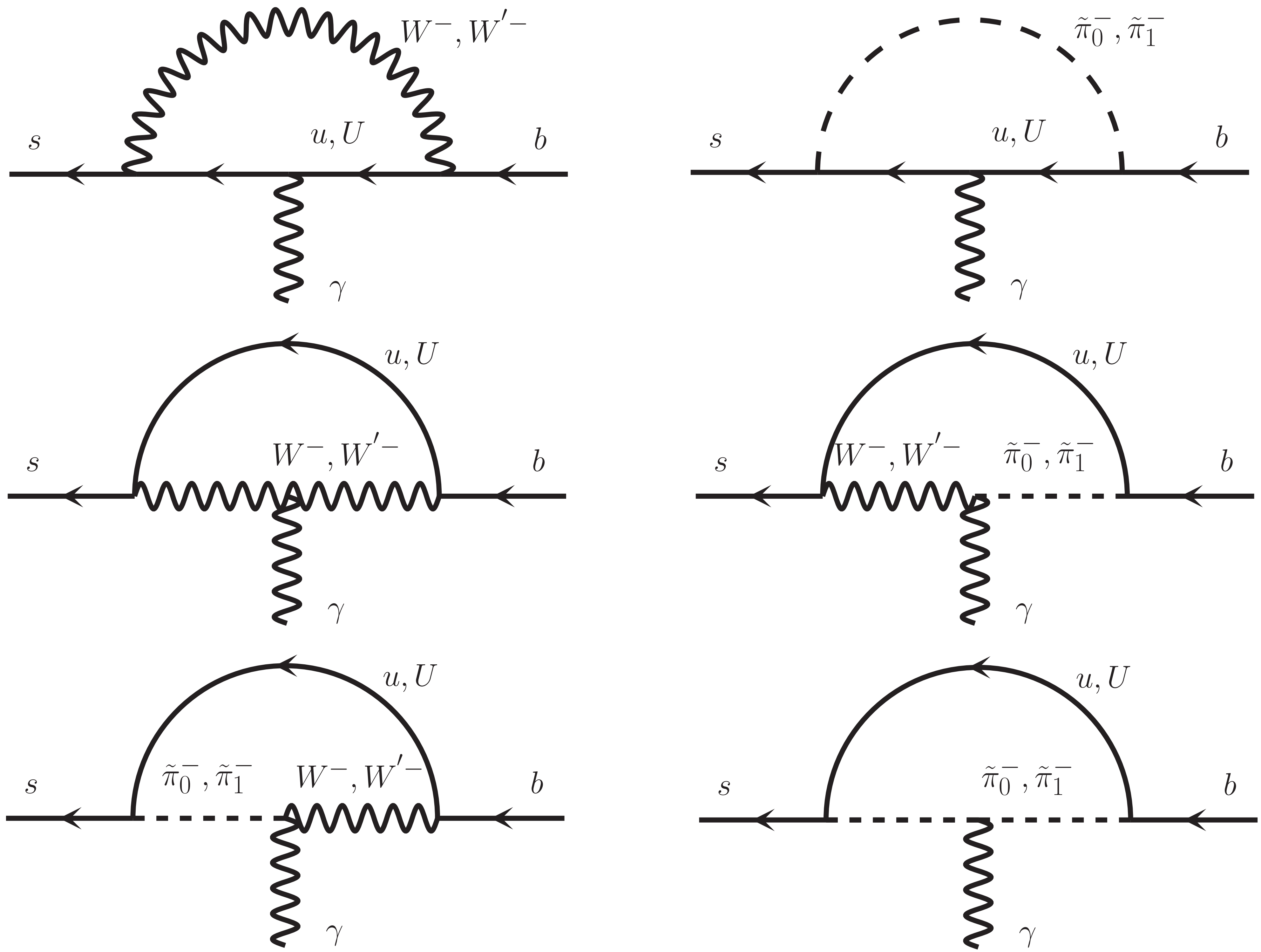
K.G. Chetyrkin, M. Misiak, M. Munz
PLB 400, 206 (1997)

$$C_7^{(0)\text{eff}}(\mu_b) = \boxed{\eta^{\frac{16}{23}} C_7^{(0)}(M_W)} + \boxed{\frac{8}{3}\left(\eta^{\frac{14}{23}} - \eta^{\frac{16}{23}}\right) C_8^{(0)}(M_W)} + \boxed{\sum_{i=1}^{8} h_i \eta^{a_i}}$$

magnetic — chromomagnetic — 4-Fermi

$$\eta = \alpha_s(M_W)/\alpha_s(\mu_b)$$

$b \to s\gamma$ process in the three-site model



$b \to s\gamma$ process in the three-site model

Three types of contributions:

1. Diagrams which also exist in the SM

$b \to s\gamma$ process in the three-site model

Three types of contributions:

1. Diagrams which also exist in the SM

⇒ take the same values as in the case of the SM because ideal delocalization guarantees SM fermions to reproduce SM couplings

$b \to s\gamma$ process in the three-site model

Three types of contributions:

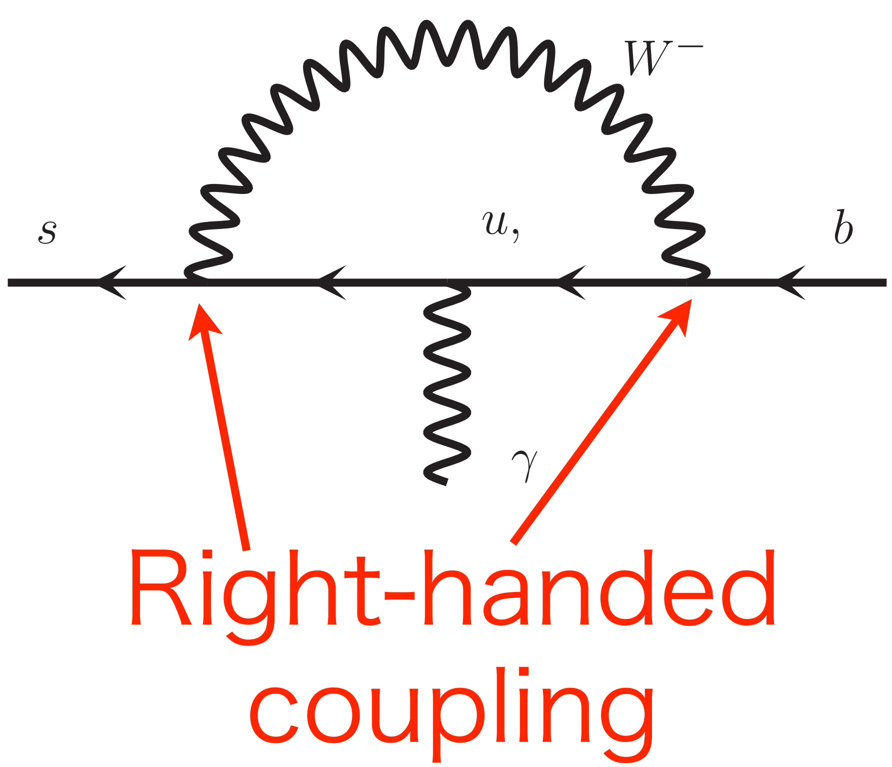
2. Diagrams which involve only SM particles, but do not exist in the SM

$b \to s\gamma$ process in the three-site model

Three types of contributions:

2. Diagrams which involve only SM particles, but do not exist in the SM

Example

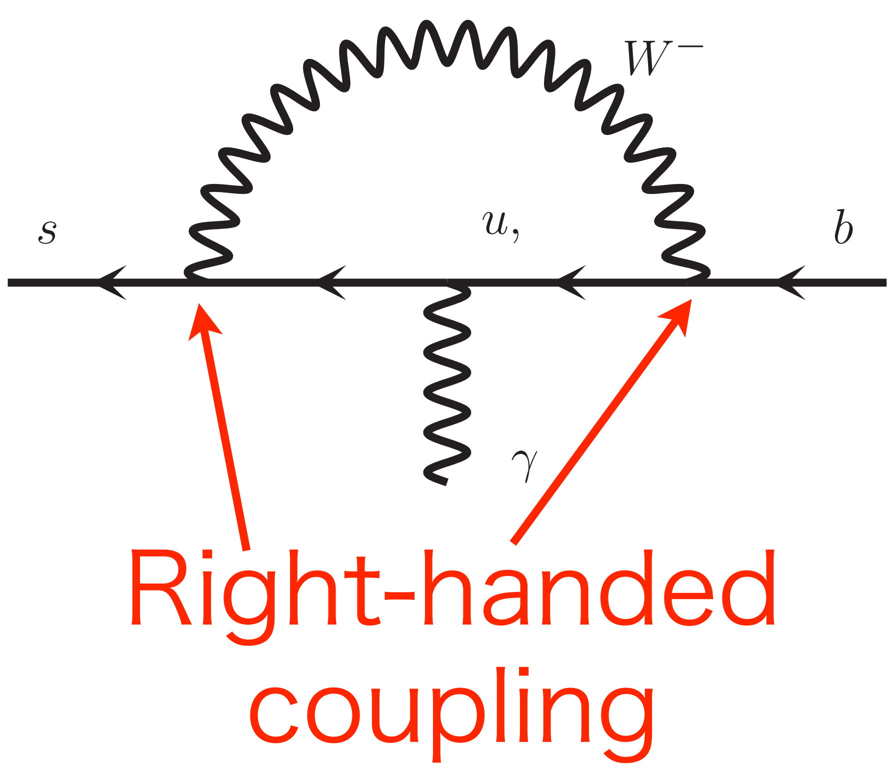


$b \to s\gamma$ process in the three-site model

Three types of contributions:

2. Diagrams which involve only SM particles, but do not exist in the SM

Example



Contribution to $C_7^{(0)}(M_W)$

$$Q_u \frac{\varepsilon_{tR}^2}{2(1+\varepsilon_{tR}^2)} \frac{1+2x_t \log x_t - x_t^2}{(x_t-1)^3}$$

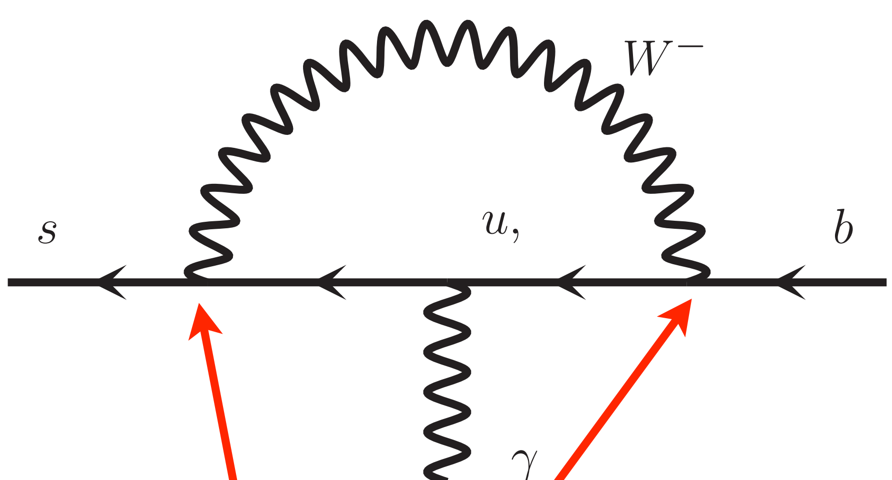
$$\left(x_t \equiv \frac{m_t^2}{m_W^2} \right)$$

$b \to s\gamma$ process in the three-site model

Three types of contributions:

2. Diagrams which involve only SM particles, but do not exist in the SM

Example



Right-handed coupling

Contribution to $C_7^{(0)}(M_W)$

$$Q_u \frac{\varepsilon_{tR}^2}{2(1+\varepsilon_{tR}^2)} \frac{1+2x_t \log x_t - x_t^2}{(x_t-1)^3}$$

vanishes when $\varepsilon_{tR} \to 0$

$$\left(x_t \equiv \frac{m_t^2}{m_W^2} \right)$$

$b \rightarrow s\gamma$ process in the three-site model

Three types of contributions:

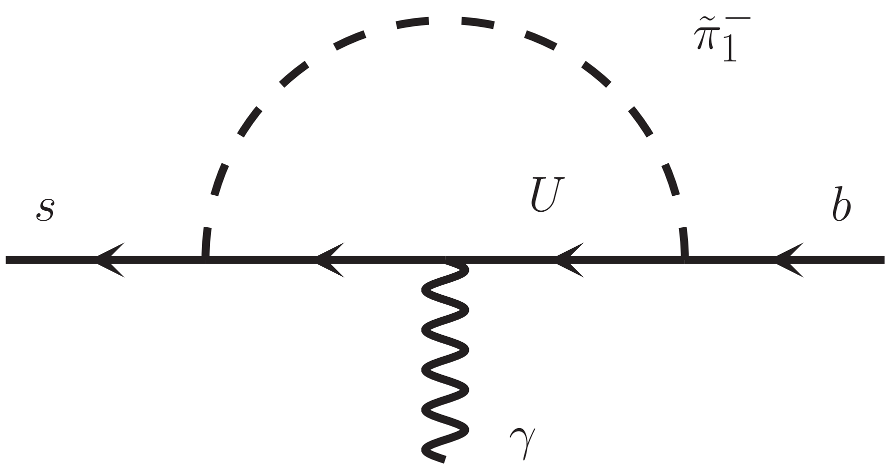
3. Diagrams which involve heavy particle(s)

$b \to s\gamma$ process in the three-site model

Three types of contributions:

3. Diagrams which involve heavy particle(s)

Example

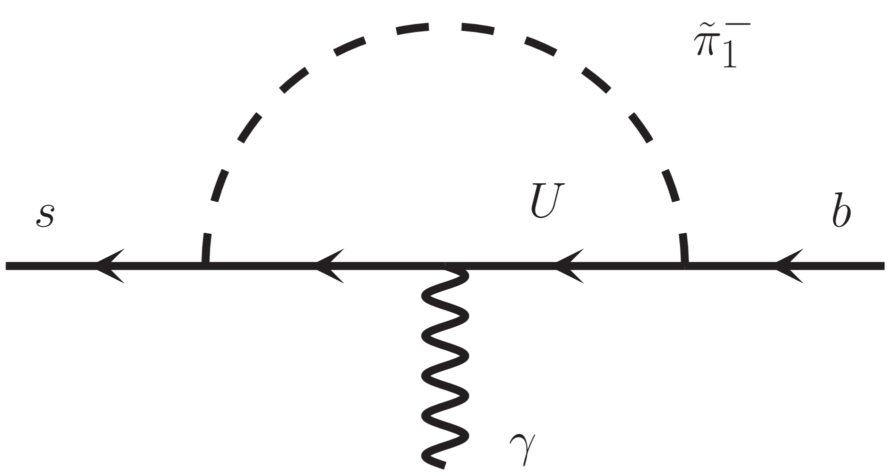


$b \to s\gamma$ process in the three-site model

Three types of contributions:

3. Diagrams which involve heavy particle(s)

Example



Contribution to $C_7^{(0)}(M_W)$

$$Q_u \left(\frac{z_t(3 - 4z_t + z_t^2 + 2\log z_t)}{16(z_t - 1)^3} - \frac{z_c(3 - 4z_c + z_c^2 + 2\log z_c)}{16(z_c - 1)^3} \right)$$

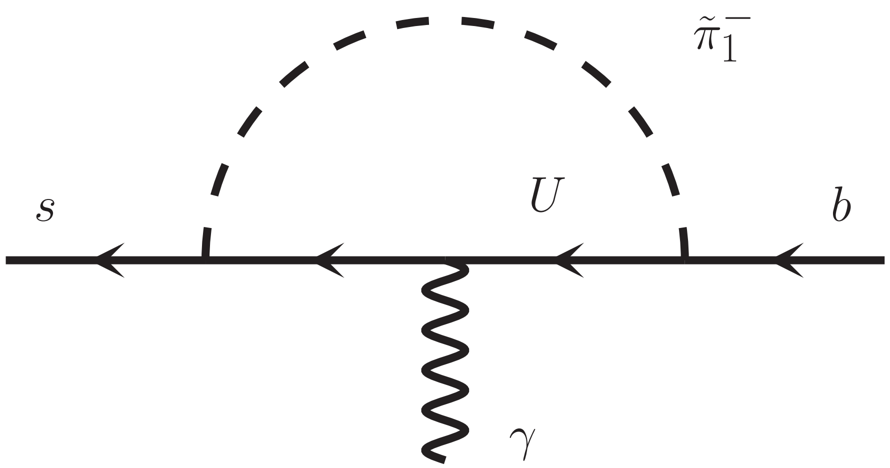
$$\left(z_t \equiv \frac{m_T^2}{m_{W'}^2},\ z_c \equiv \frac{m_C^2}{m_{W'}^2} \right)$$

$b \to s\gamma$ process in the three-site model

Three types of contributions:

3. Diagrams which involve heavy particle(s)

Example



Contribution to $C_7^{(0)}(M_W)$

$$Q_u\left(\frac{z_t(3-4z_t+z_t^2+2\log z_t)}{16(z_t-1)^3}-\frac{z_c(3-4z_c+z_c^2+2\log z_c)}{16(z_c-1)^3}\right)$$

vanishes when $\varepsilon_{tR} \to 0$

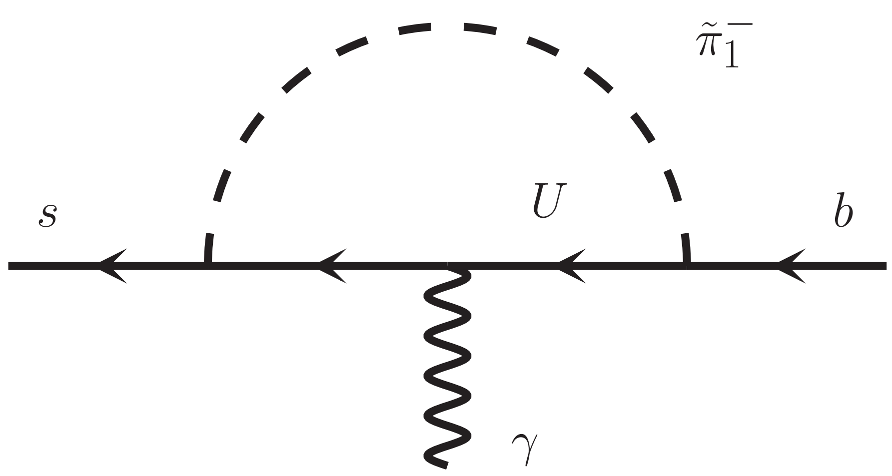
$$\left(z_t \equiv \frac{m_T^2}{m_{W'}^2},\ z_c \equiv \frac{m_C^2}{m_{W'}^2}\right)$$

$b \to s\gamma$ process in the three-site model

Three types of contributions:

3. Diagrams which involve heavy particle(s)

Example



Contribution to $C_7^{(0)}(M_W)$

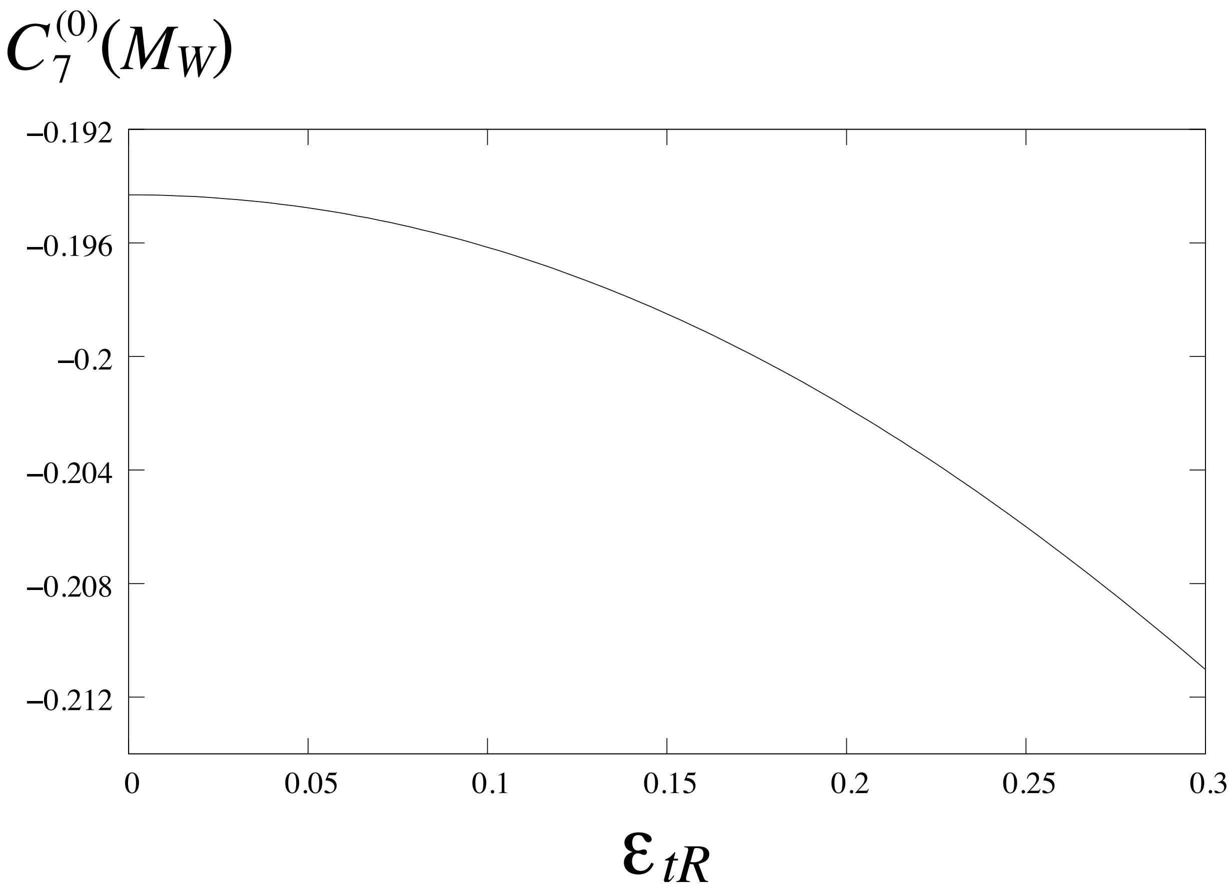
$$Q_u \left(\frac{z_t(3 - 4z_t + z_t^2 + 2\log z_t)}{16(z_t - 1)^3} - \frac{z_c(3 - 4z_c + z_c^2 + 2\log z_c)}{16(z_c - 1)^3} \right)$$

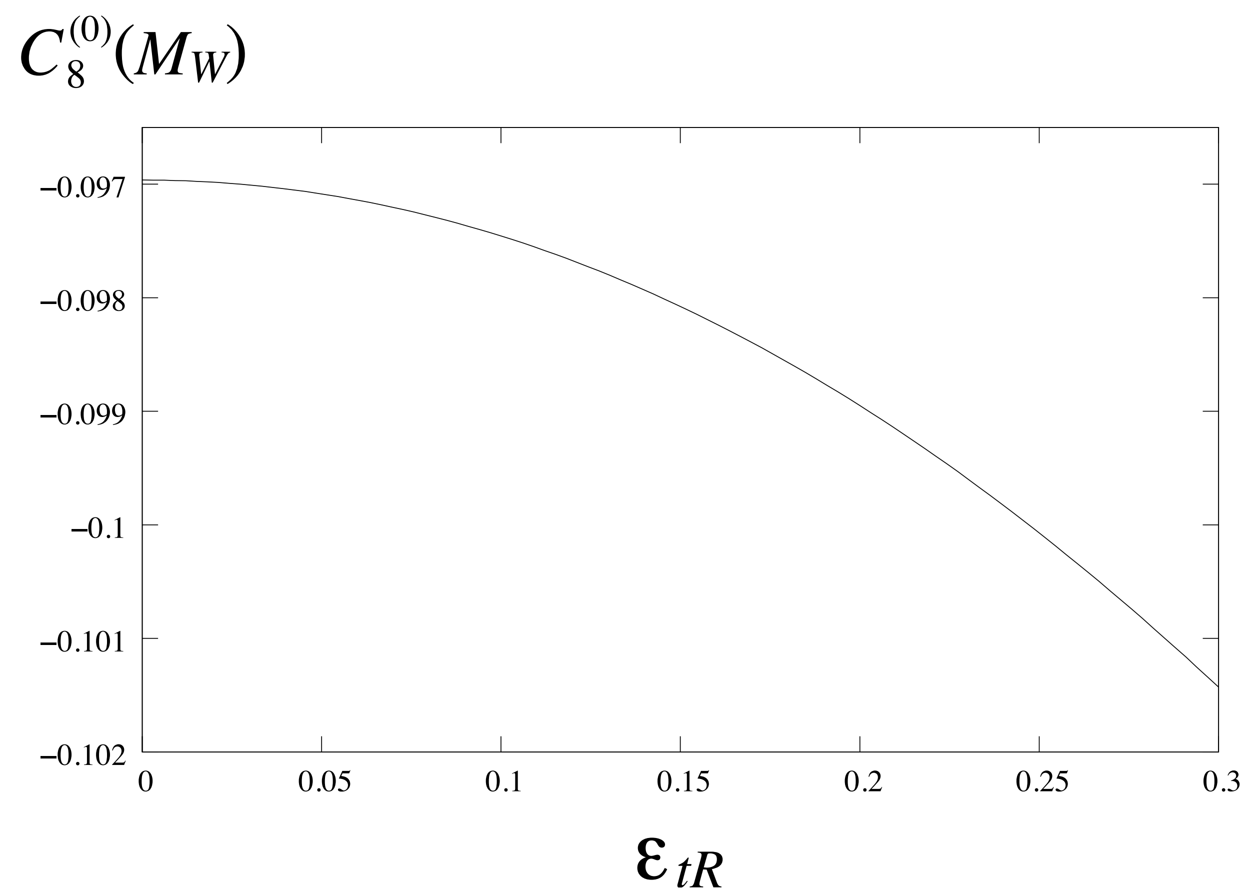
Note that each term does not vanish

vanishes when $\varepsilon_{tR} \to 0$

$$\left(z_t \equiv \frac{m_T^2}{m_{W'}^2},\ z_c \equiv \frac{m_C^2}{m_{W'}^2} \right)$$

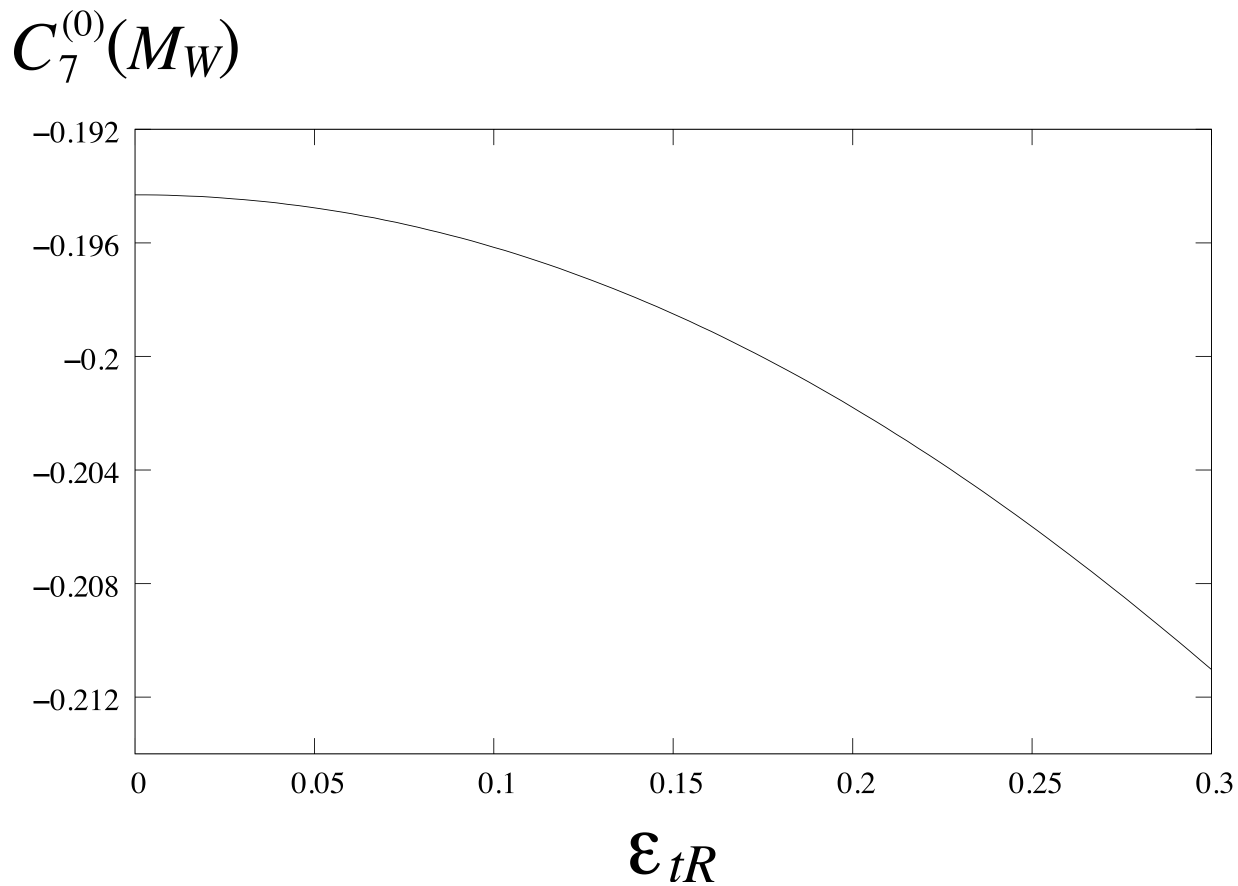
$C_7^{(0)}(M_W)$ and $C_7^{(0)}(M_W)$ as functions of ε_{tR}

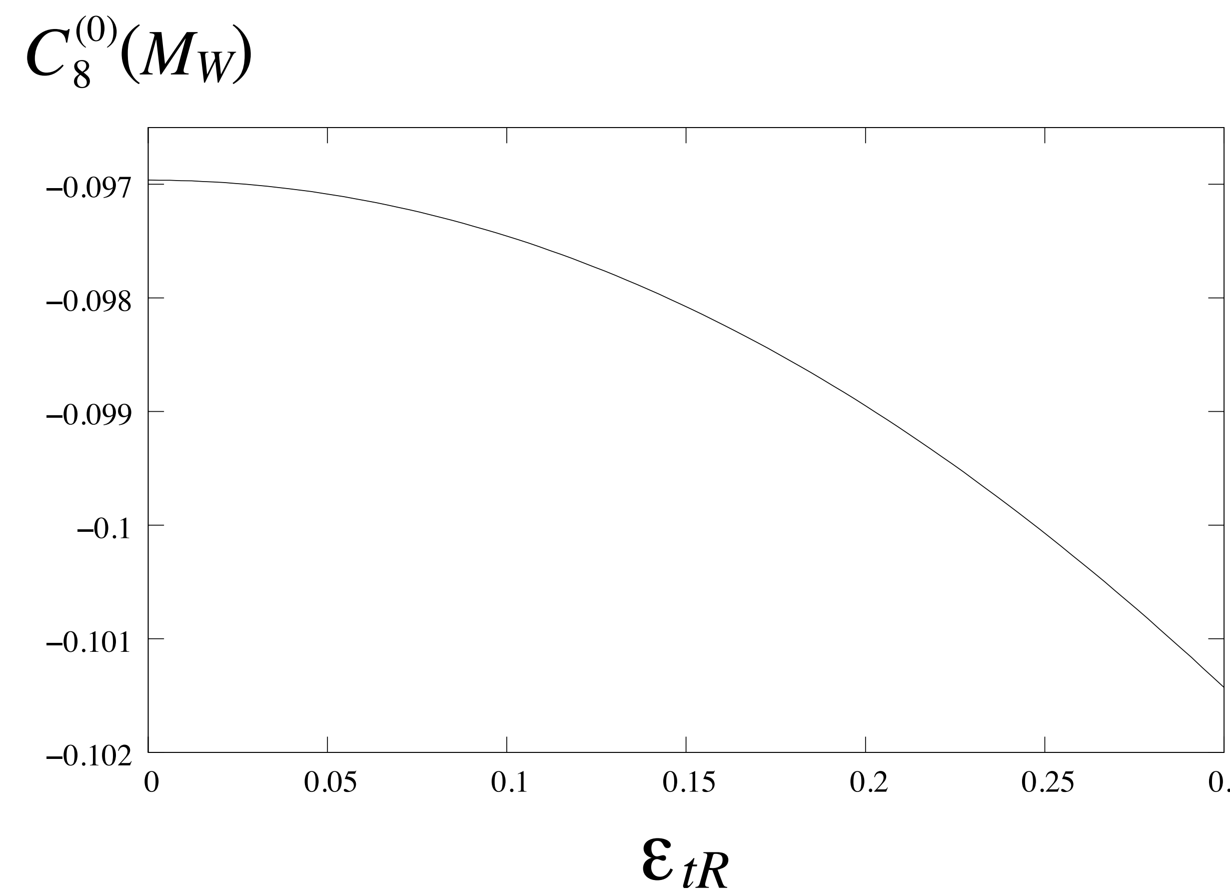




Magnitudes increase about 8.5/4.5 % from that in the SM

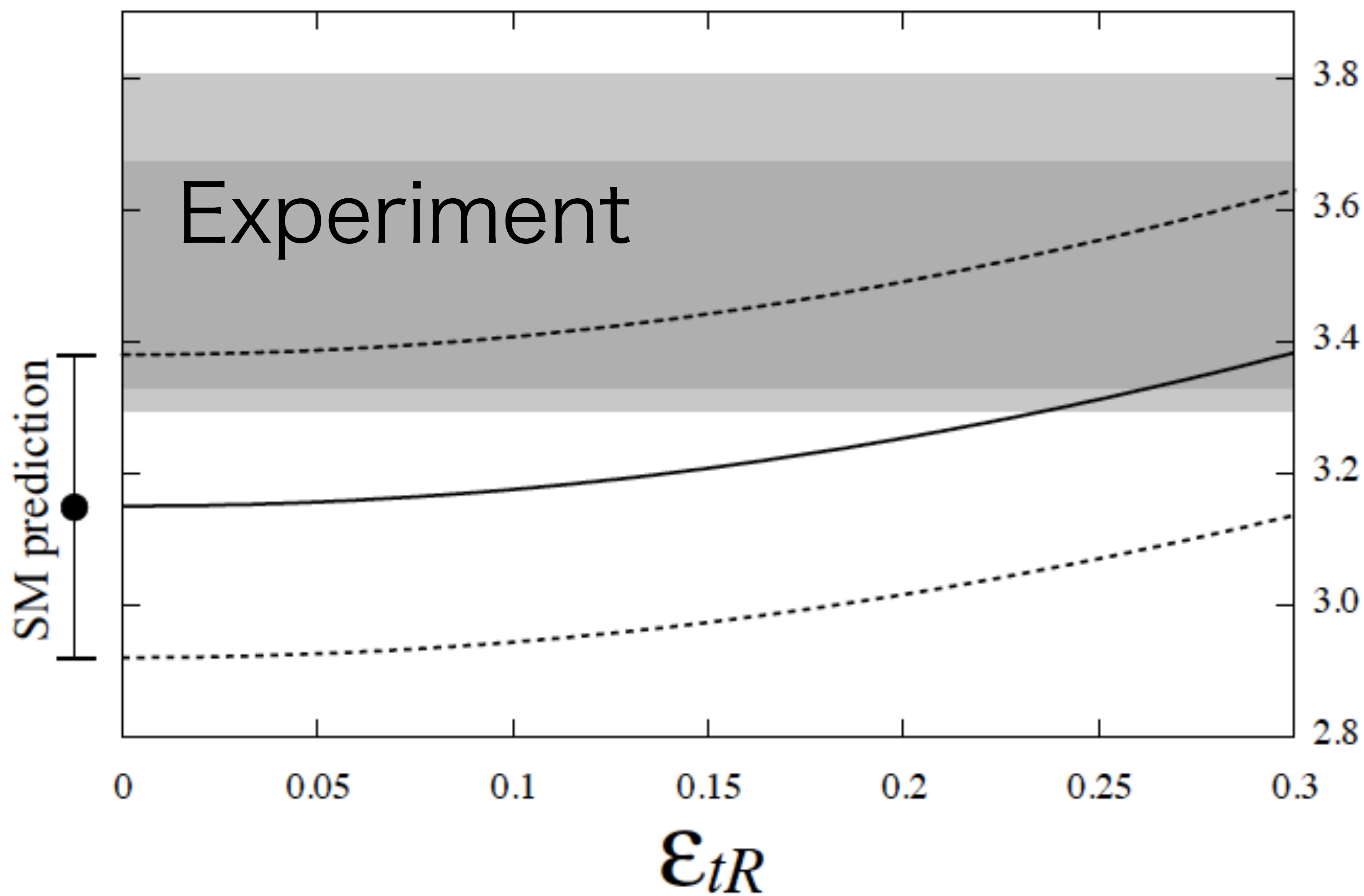
$C_7^{(0)}(M_W)$ and $C_7^{(0)}(M_W)$ as functions of ε_{tR}





$$C_7^{(0)\mathrm{eff}}(\mu_b) = \eta^{\frac{16}{23}} C_7^{(0)}(M_W) + \frac{8}{3}\left(\eta^{\frac{14}{23}} - \eta^{\frac{16}{23}}\right) C_8^{(0)}(M_W) + \sum_{i=1}^{8} h_i \eta^{a_i}$$

$B(B \to X_S \gamma) \times 10^4$ in the three-site model



～7% enhancement compared to the SM

Summary

Flavor structure was introduced to the three site Higgsless model in a way to minimize the FCNC at the tree level

We discussed the existence of the extra flavor non-universality essentially resulting from the fact that the top quark is heavy

$b \to s\gamma$ process was discussed as an example, and it was shown that the branching ratio in the three site Higgsless model takes closer value to its experimental central value