Flavor Physics in the Beyond Standard Models

Yuji Omura

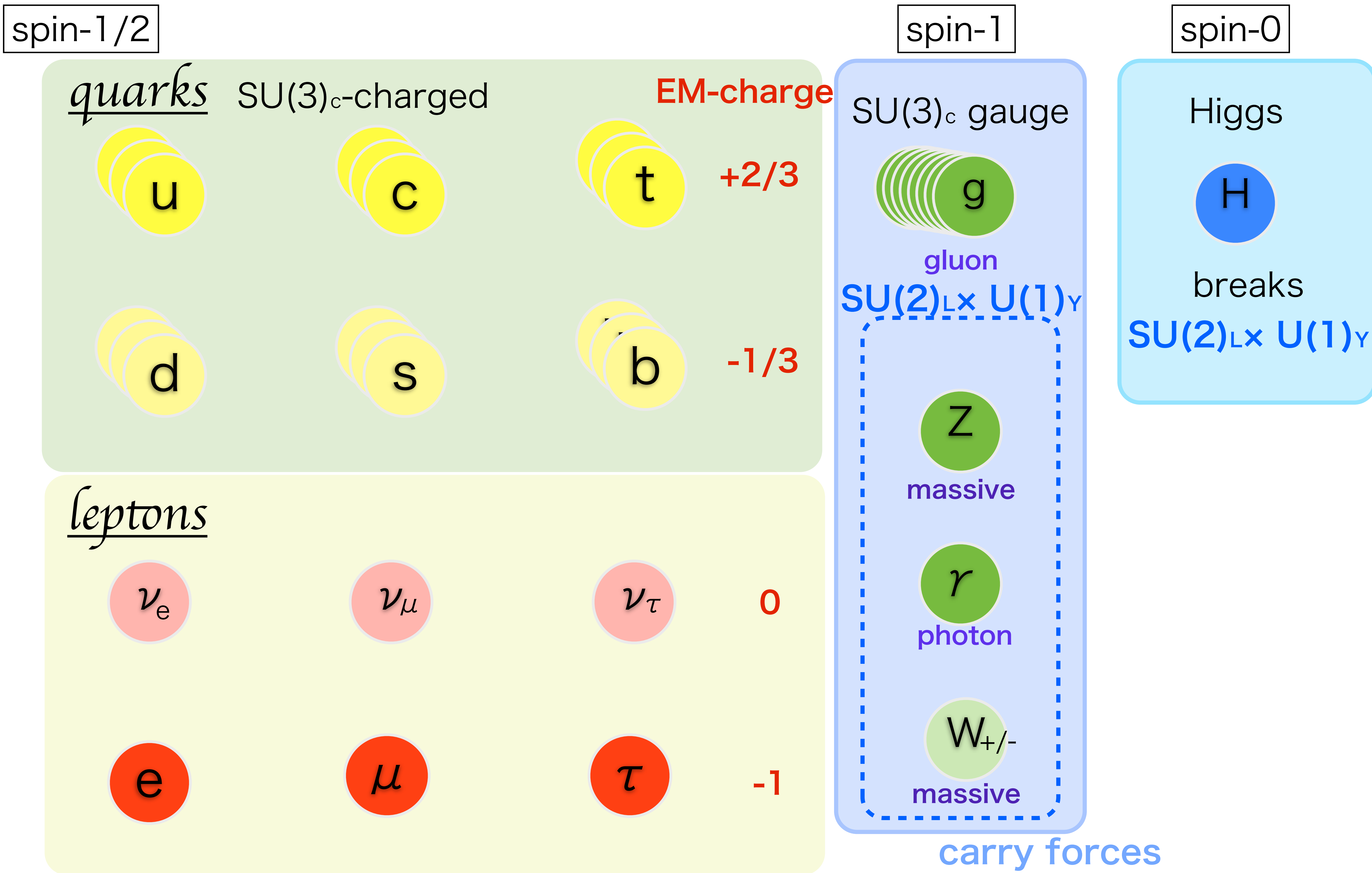
Based on PLB744 (2015) 395 with J. Hisano, Y. Muramatsu, M. Yamanaka, and (arXiv:1505.07636) with T. Kobayashi, F. Takayama, D. Yasuhara

—KMI topics—

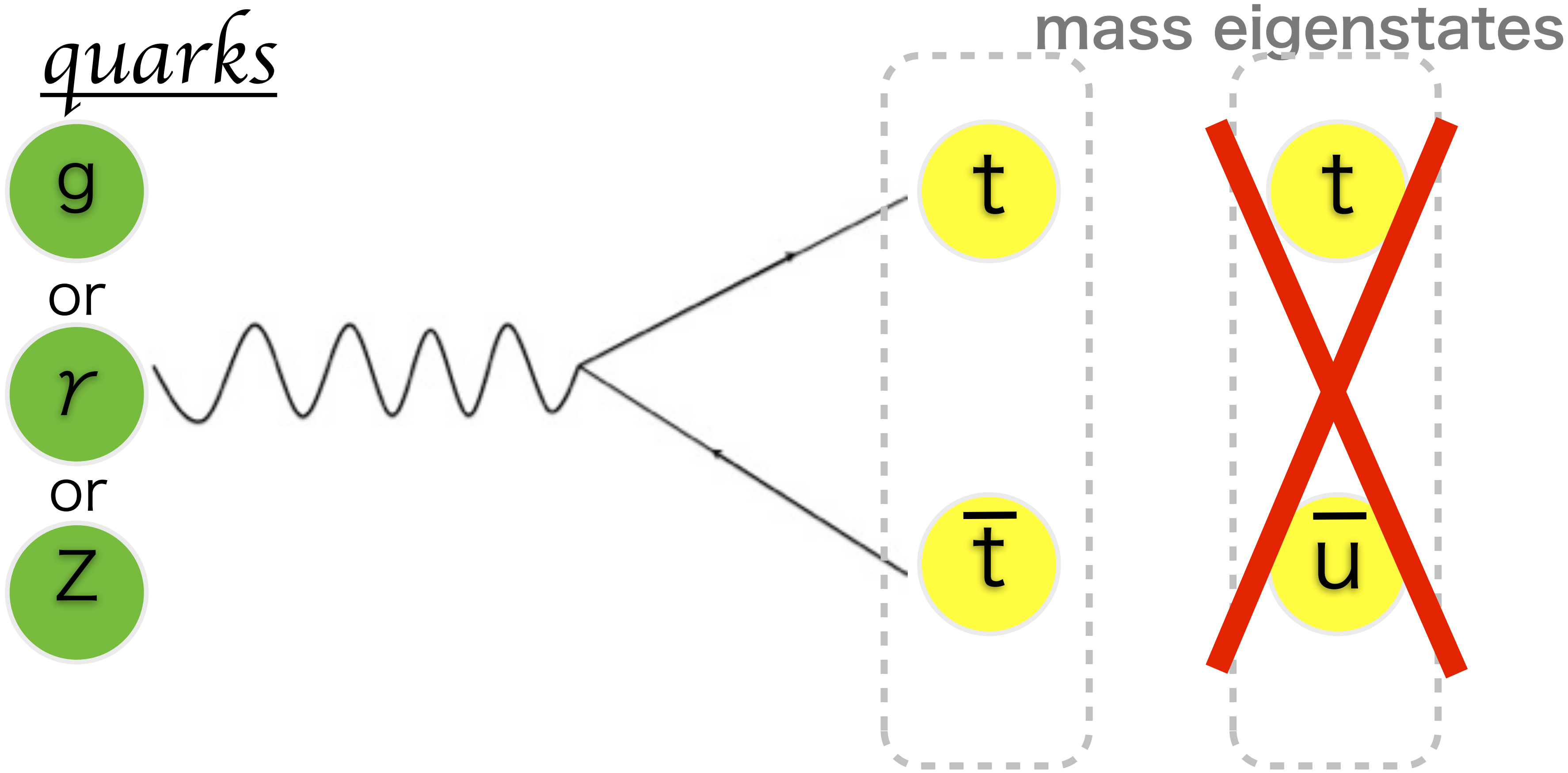
Standard Model ($SU(3)_C \times SU(2)_L \times U(1)_Y$)

is very successful in particle physics

Standard Model (SU(3)c×SU(2)L×U(1)Y)
is very successful in particle physics

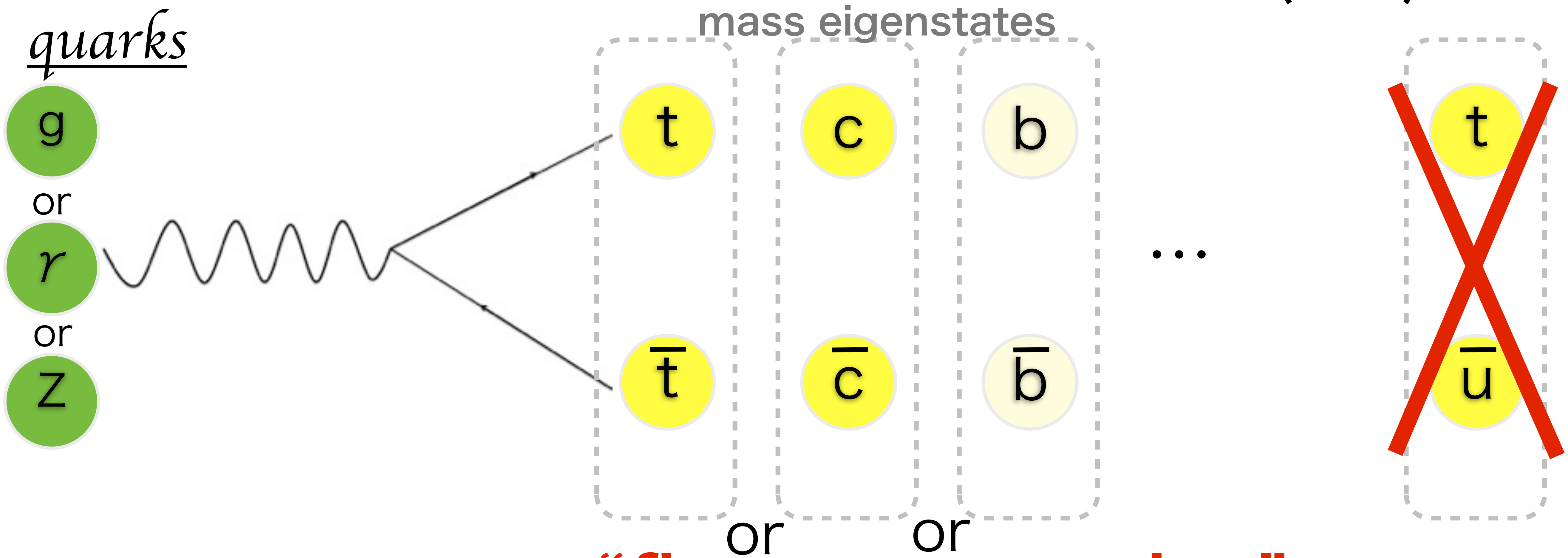


Interactions in the Standard Model (SM)



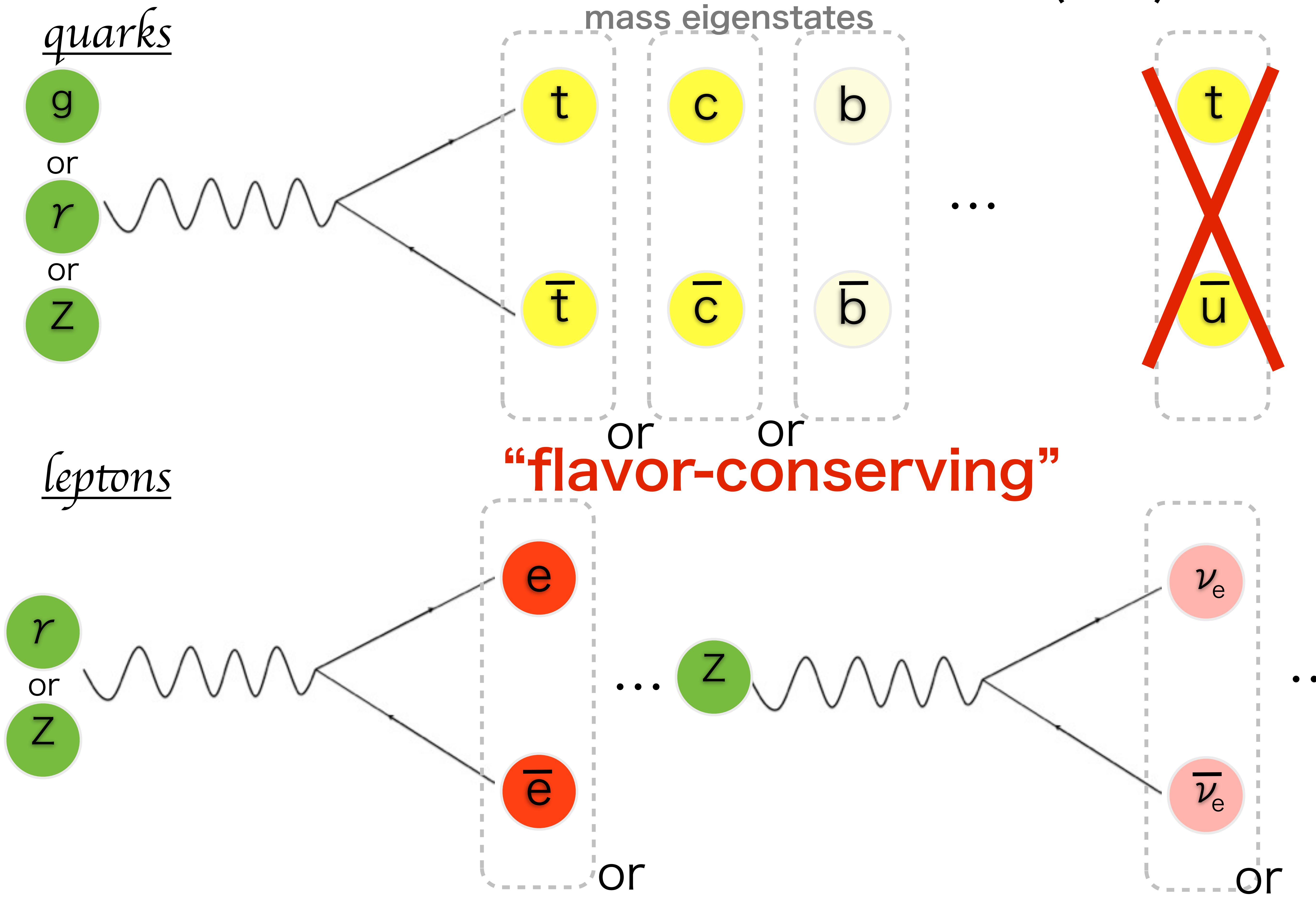
“flavor-conserving”

Interactions in the Standard Model (SM)

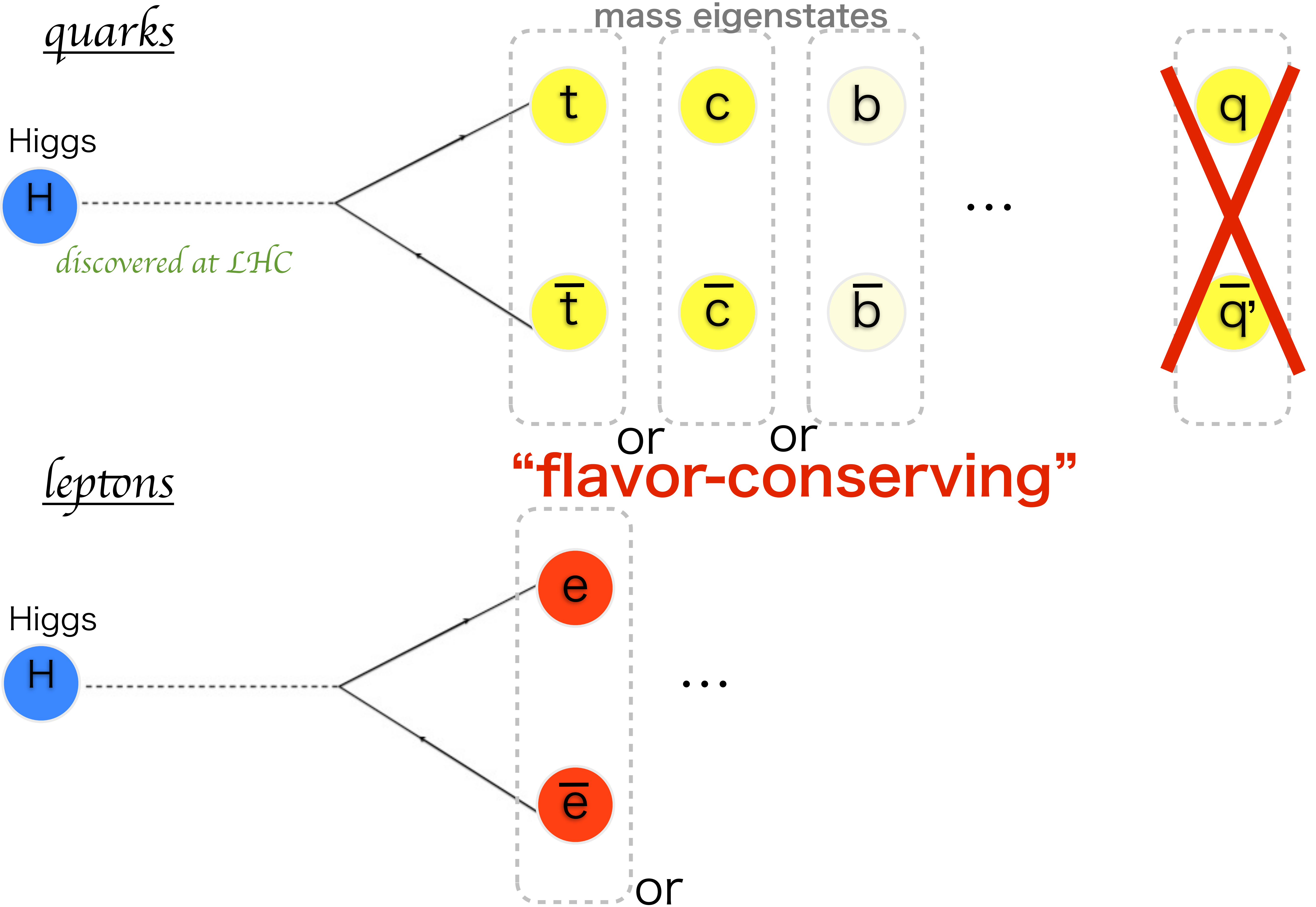


"flavor-conserving"

Interactions in the Standard Model (SM)

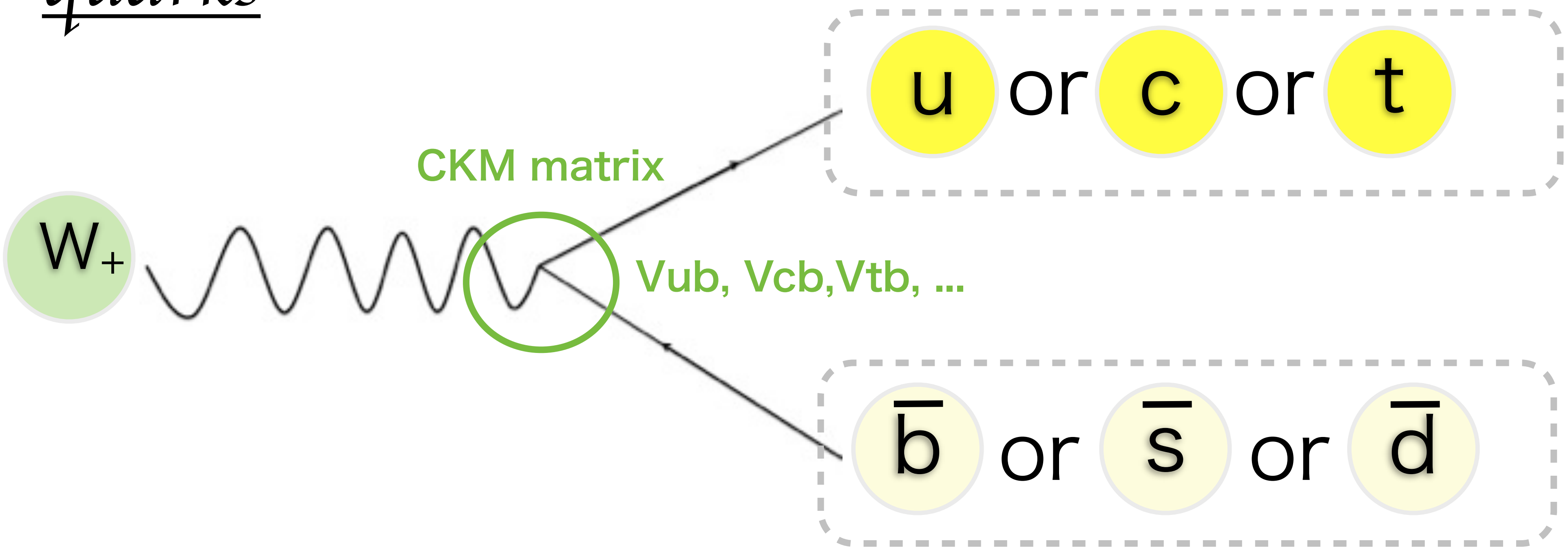


Yukawa Interactions in the SM



W-Interaction in the SM

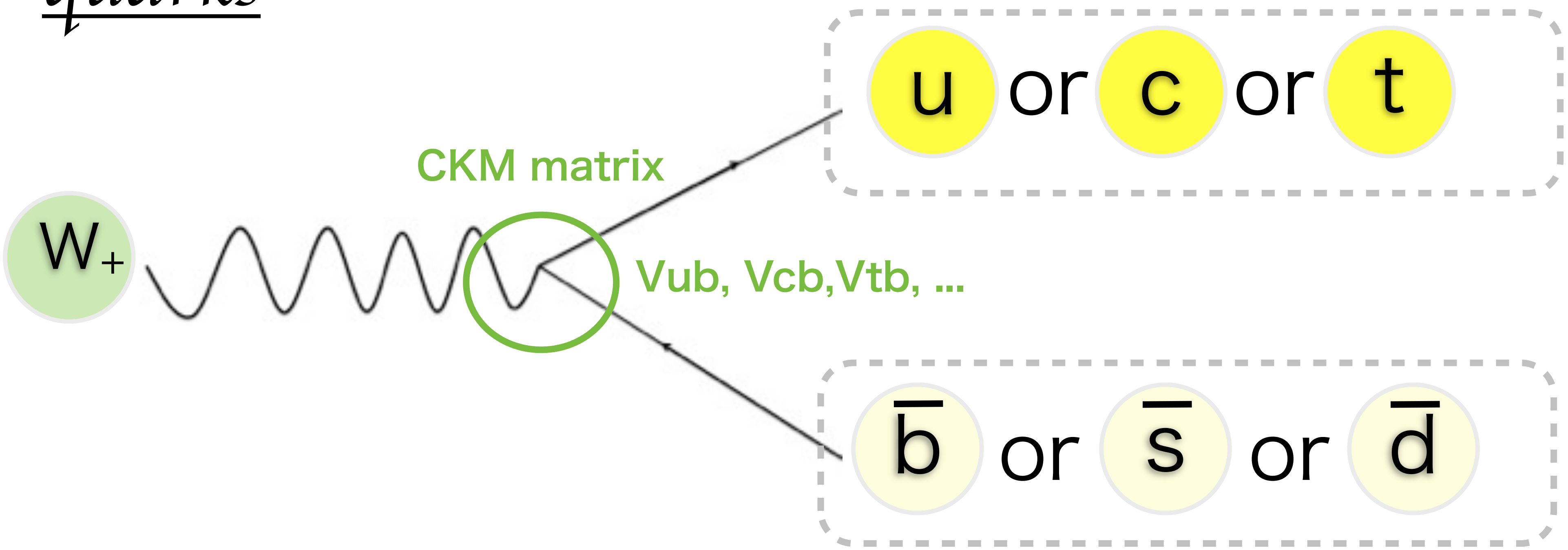
quarks



"flavor-changing"

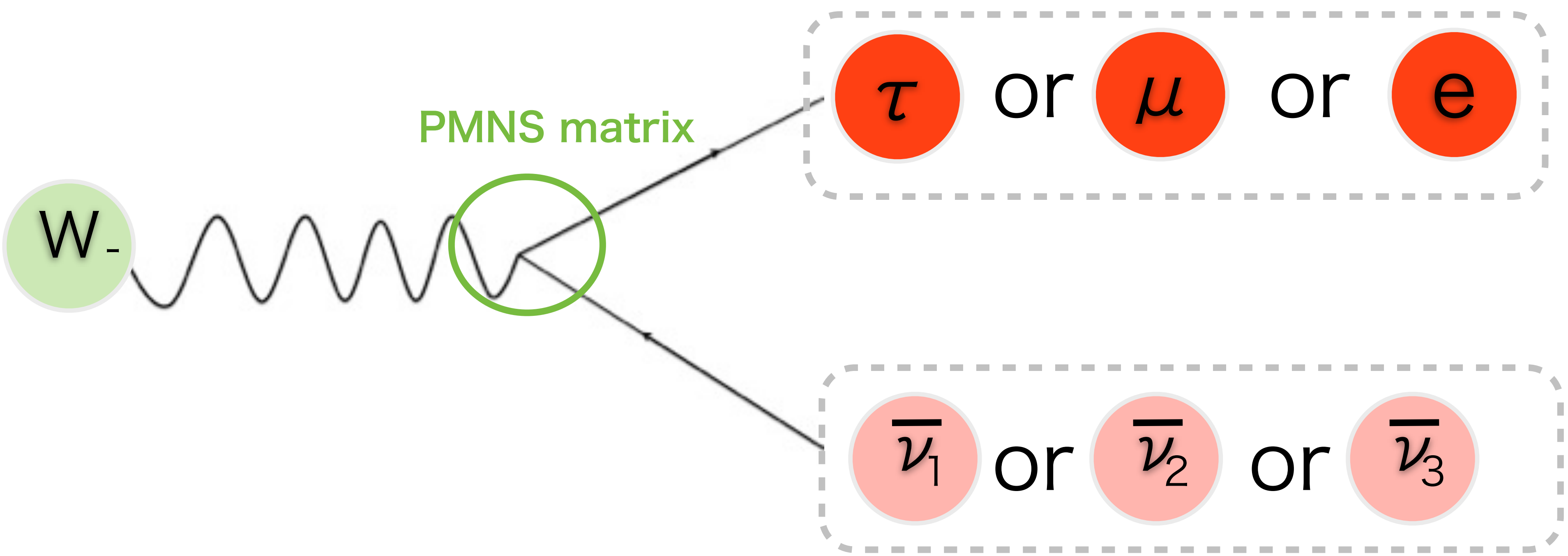
W-Interaction in the SM

quarks

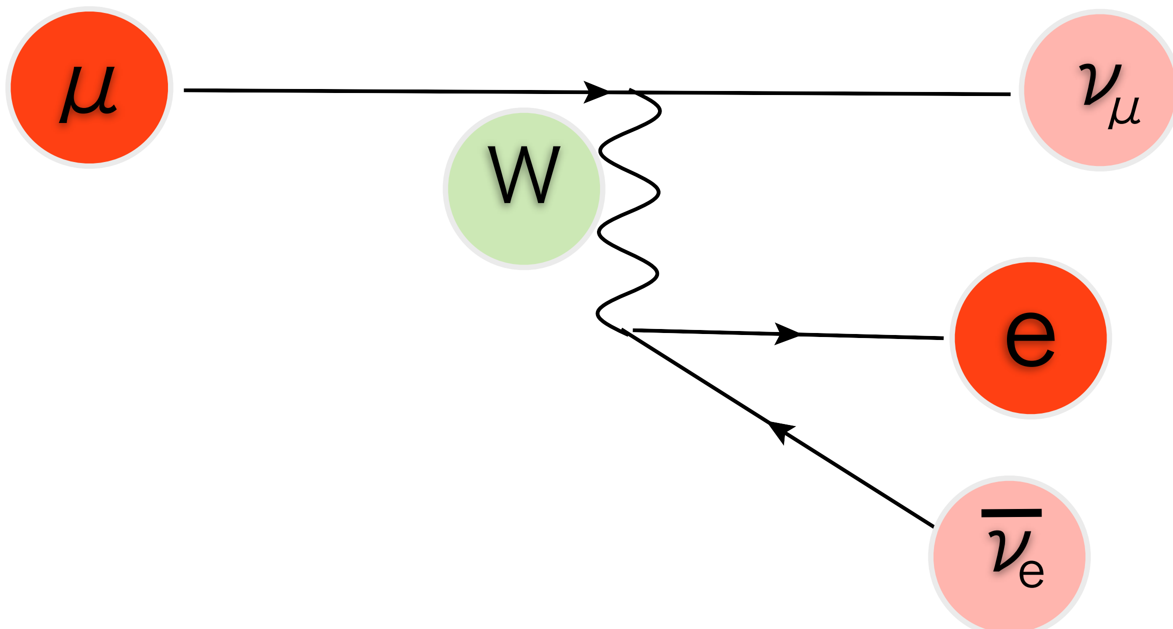


"flavor-changing"

leptons



Very tiny flavor changing processes predicted and this picture successfully describes our nature!



For instance, μ decays through W exchanging

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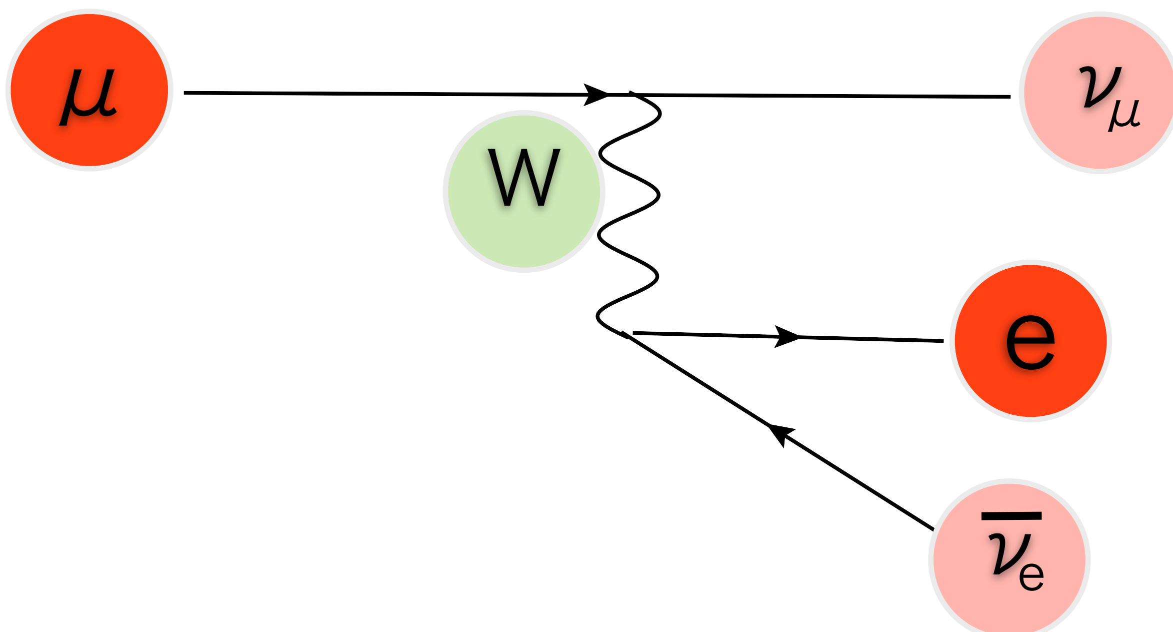

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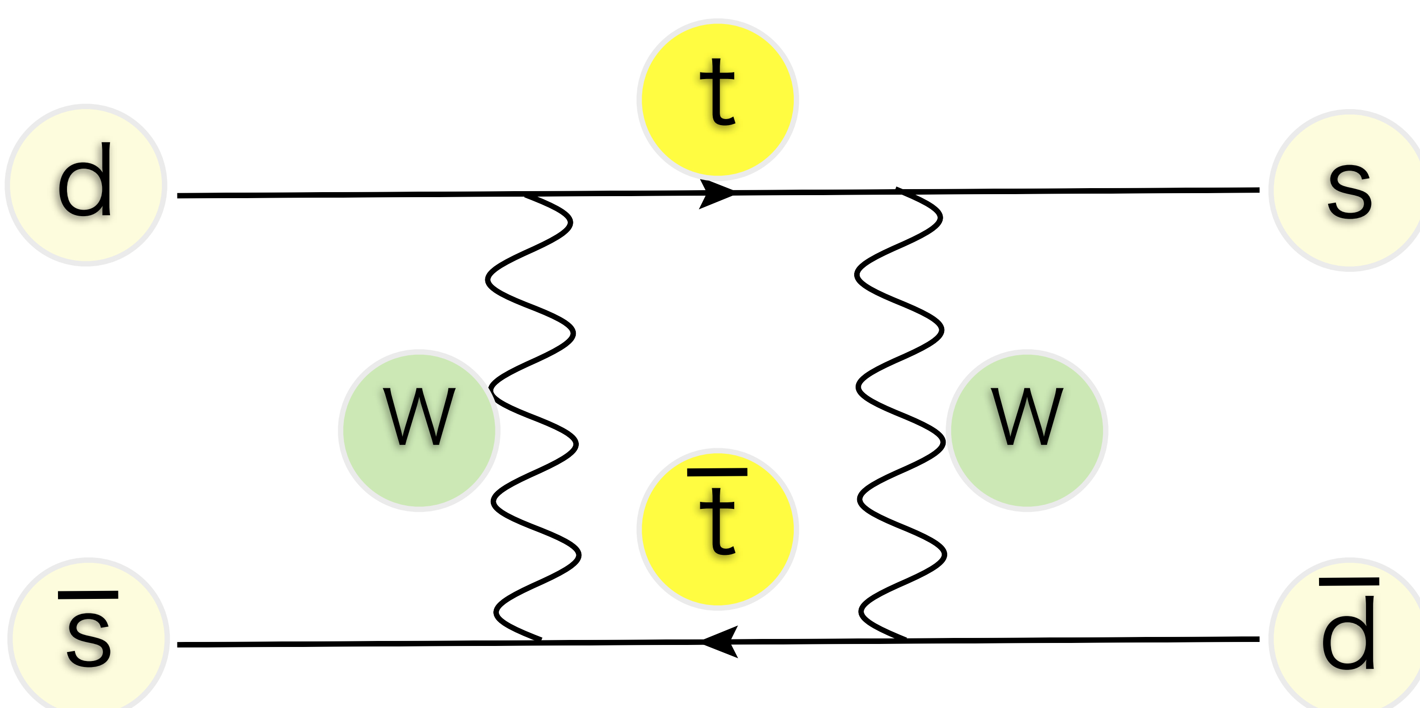
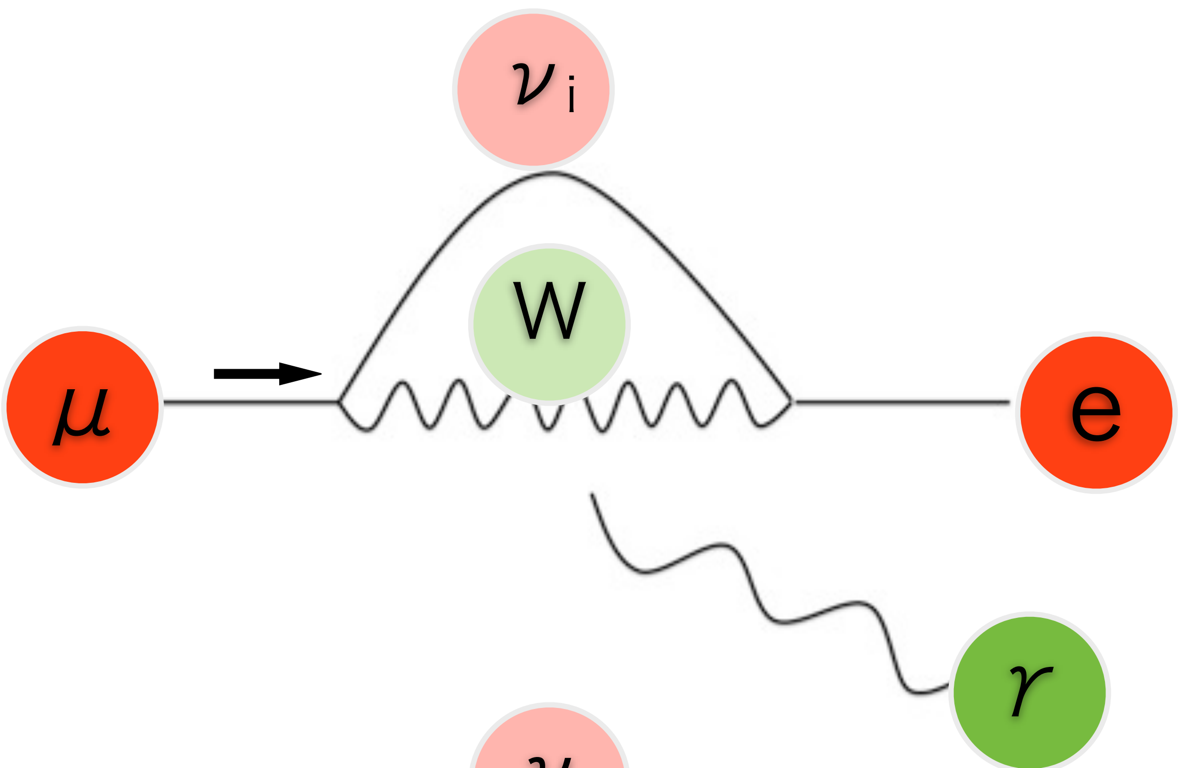


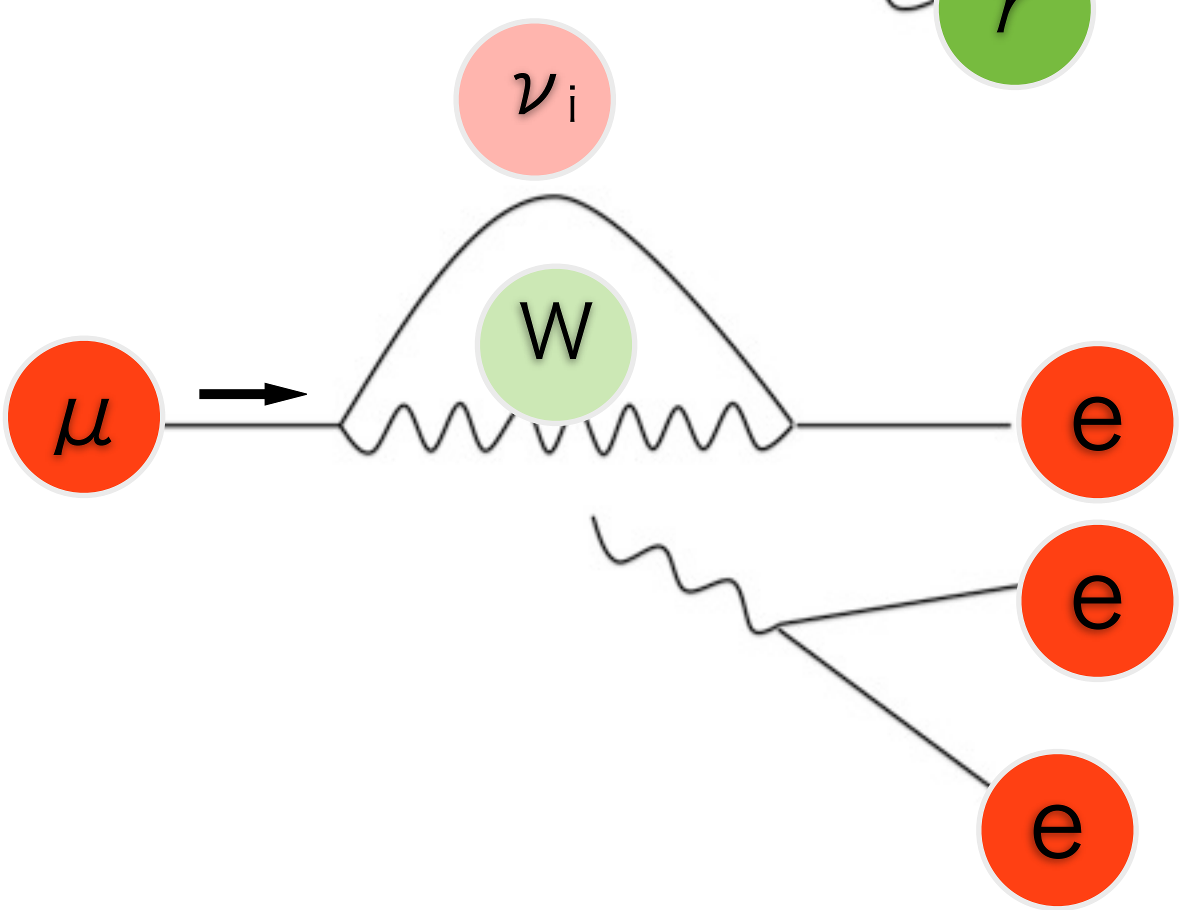
K_0-$\overline{K_0}$ mixing predicted by the one-loop, and observed actually.

Very tiny flavor changing processes predicted and this picture successfully describes our nature!



For instance, $\mu \to 3e$, $\mu \to e\,\gamma$ are very very tiny.

$$Br \propto \left| U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{m^2_W} \right|^2 \ll 10^{-50}$$



They are not still observed, and consistent with the experimental bound.

$$Br(\mu \to e\gamma) < 5.7 \times 10^{-13}$$

$$Br(\mu \to 3e) < 1.0 \times 10^{-12}$$

Is this the end of the story???

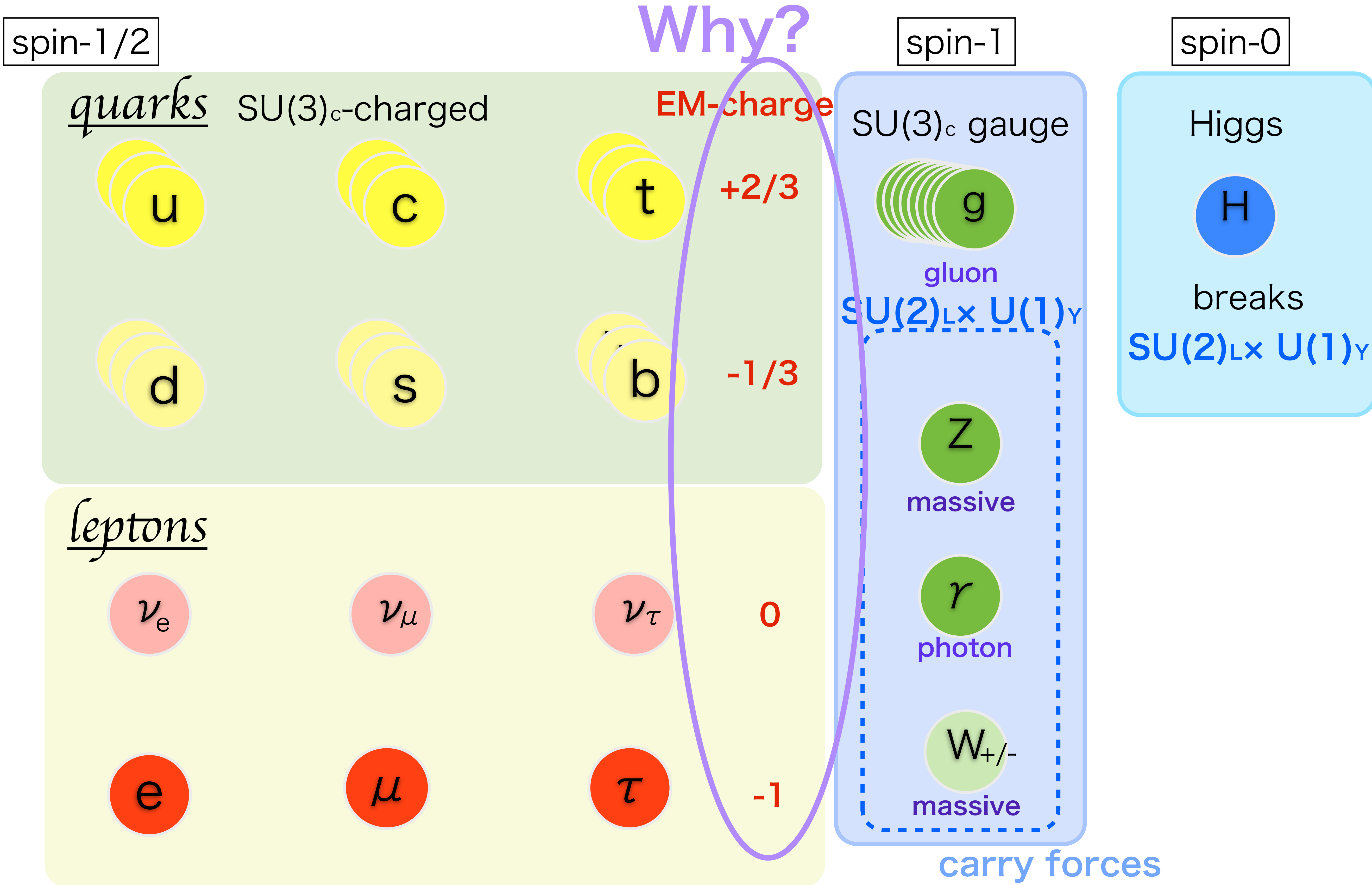
Is this the end of the story???

No, No, No!

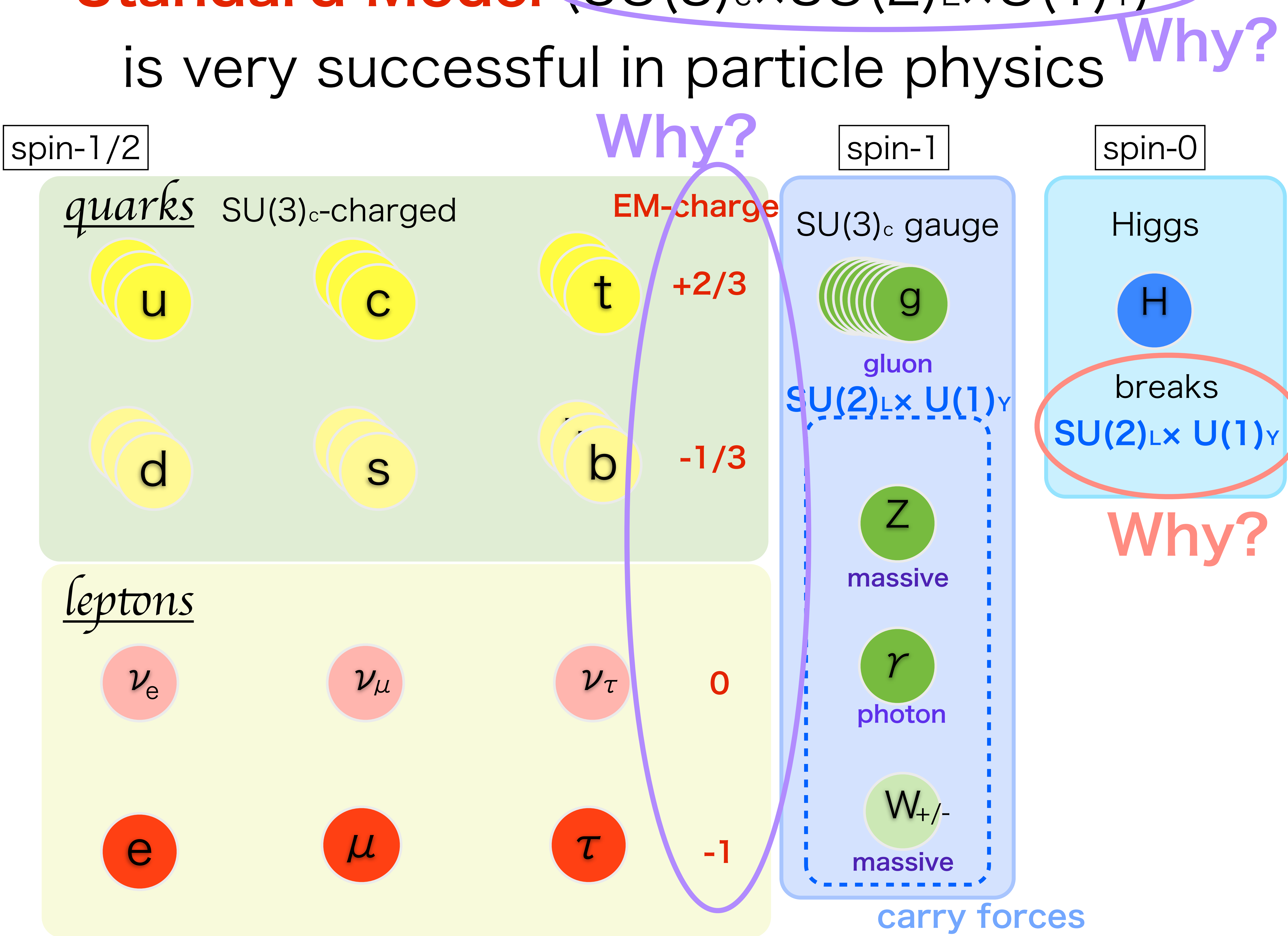
There are many “why” in the SM.

Standard Model ($SU(3)_c \times SU(2)_L \times U(1)_Y$) Why?

is very successful in particle physics



Standard Model $(SU(3)_c \times SU(2)_L \times U(1)_Y)$ is very successful in particle physics



Supersymmetry (SUSY)

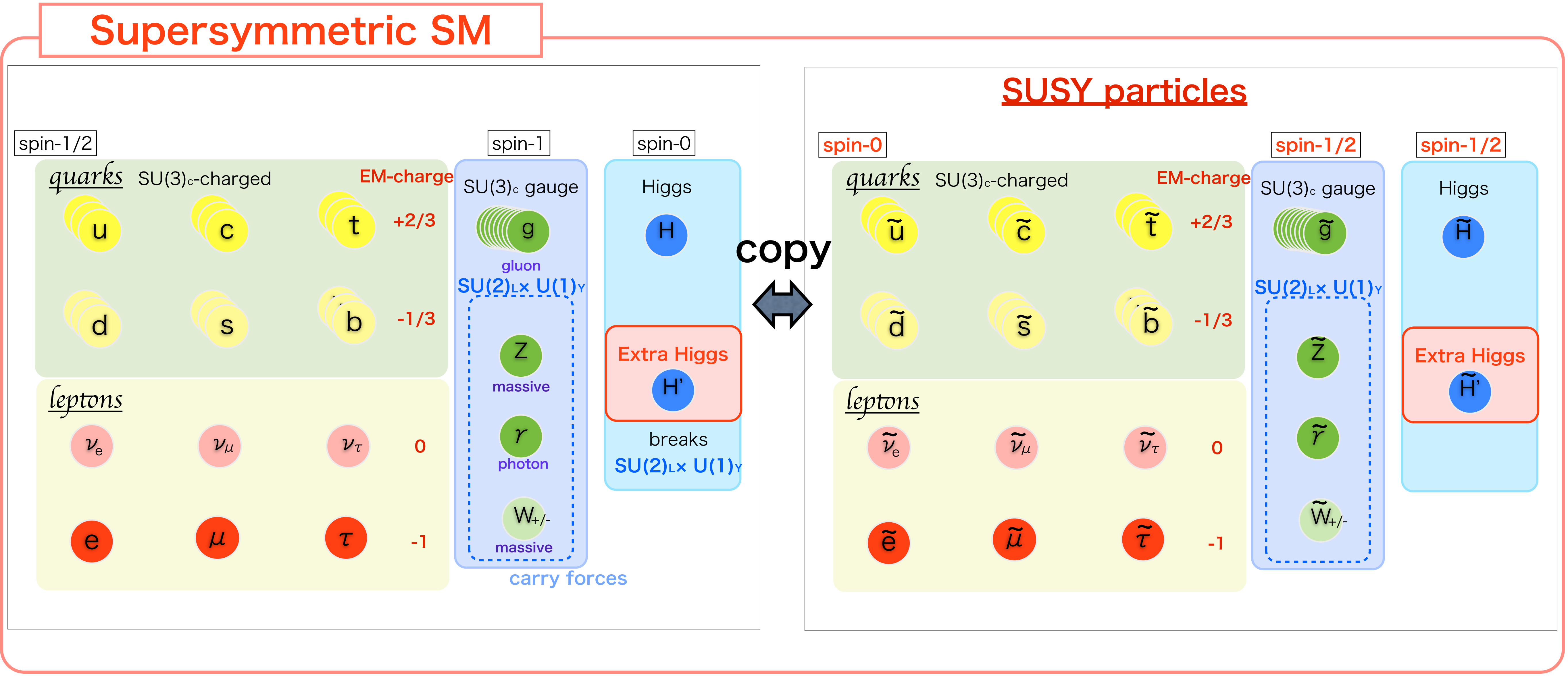
Grand Unified Theory (GUT)

are very natural explanations!

Answer to the origin of EW scale:

Supersymmetry (SUSY)

SUSY can explain why $SU(2)_L \times U(1)_Y$ breaking happen around 200 GeV



because of no quadratic divergence

nonrenormalization theorem

radiative $SU(2)_L \times U(1)_Y$ breaking

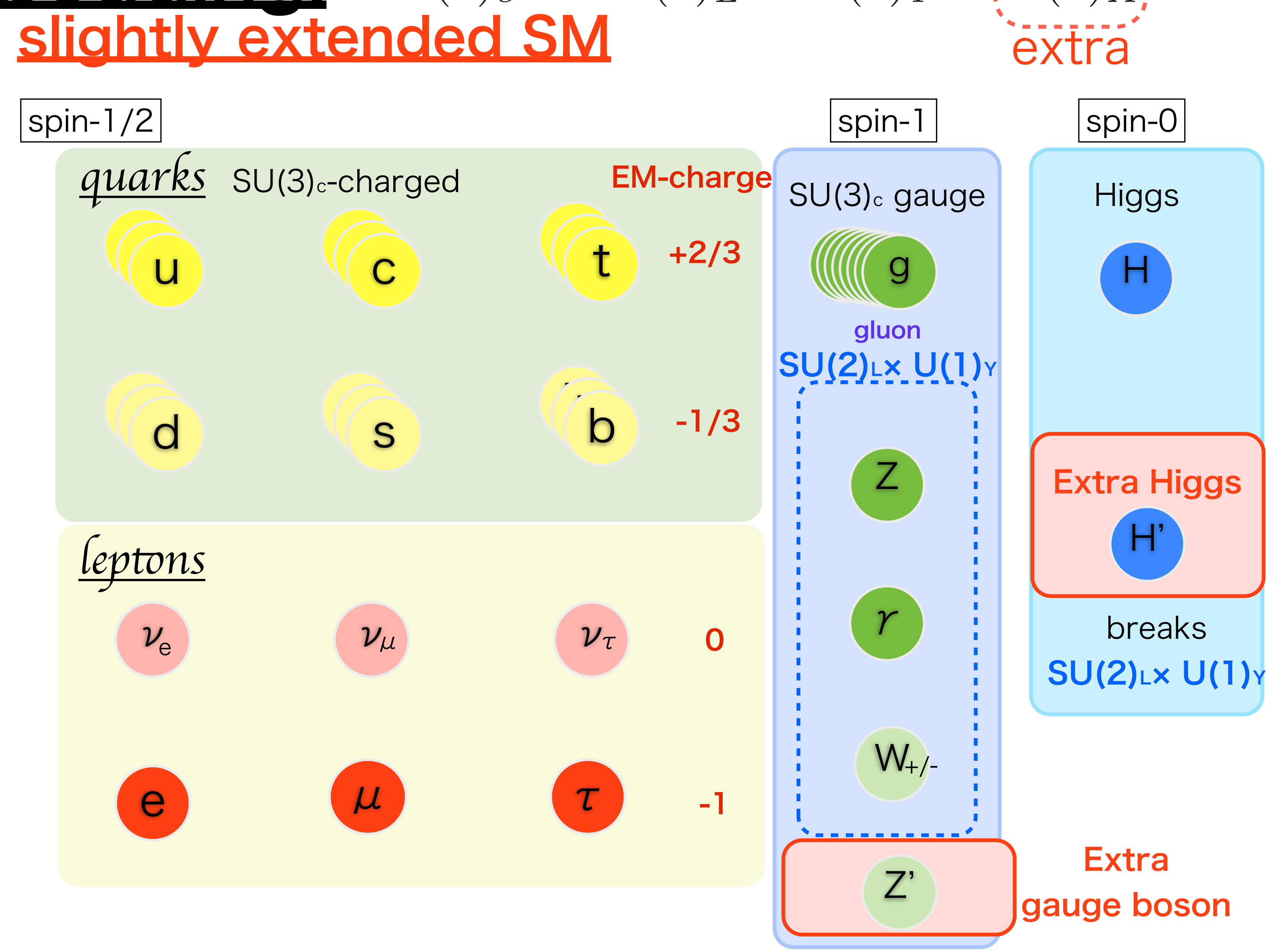
SUSY scale relates to EW scale

Answer to the origin of gauge symmetry:

Grand Unified Theory (GUT)

SM gauge groups naturally embedded into GUT

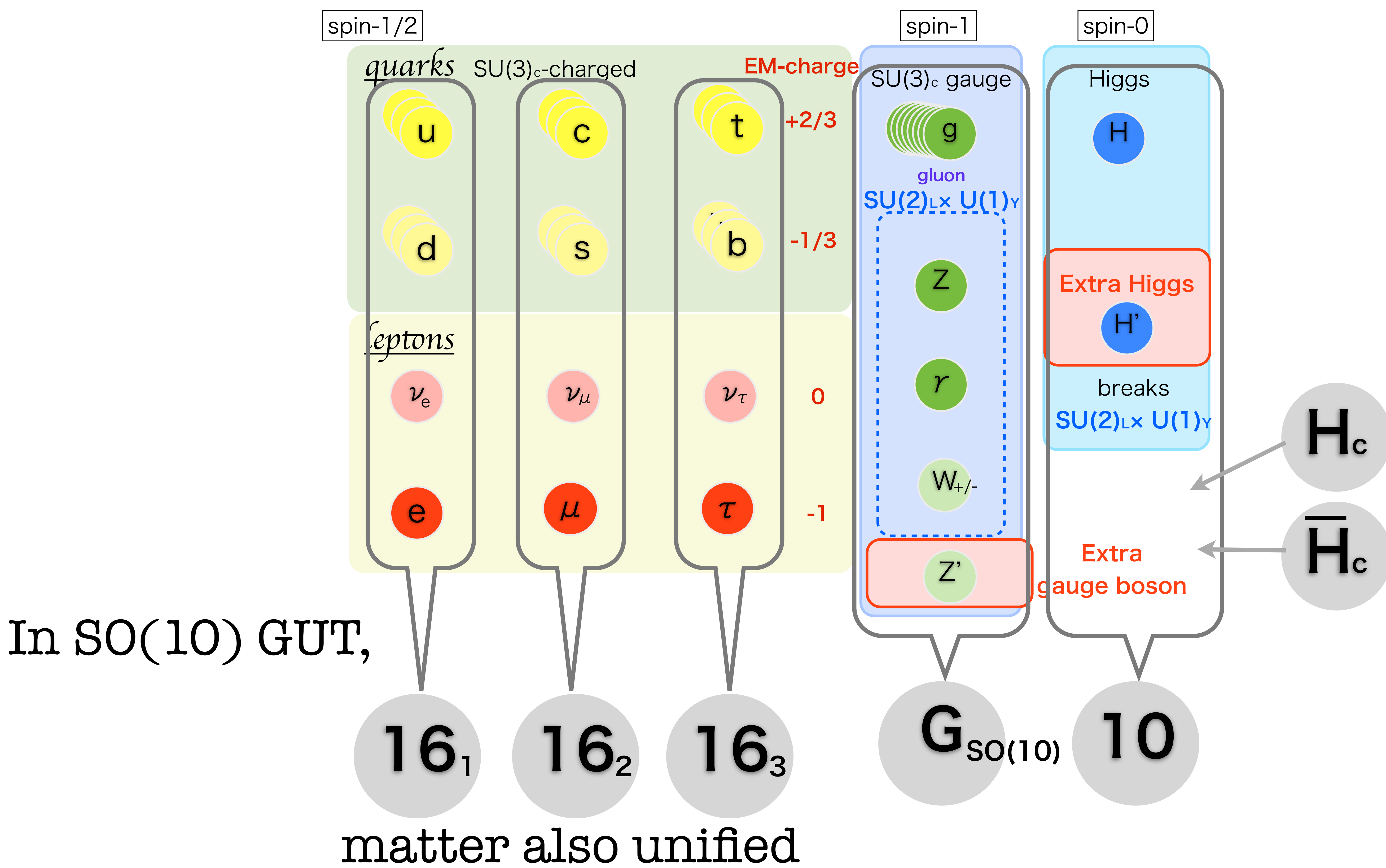
SO(10) Embedding: $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X \rightarrow SO(10)$



SM gauge groups naturally embedded into GUT

SO(10) Embedding: $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X \rightarrow SO(10)$

slightly extended SM — extra



supersymmetric SO(10) GUT looks very elegant and natural

but story is not so simple…

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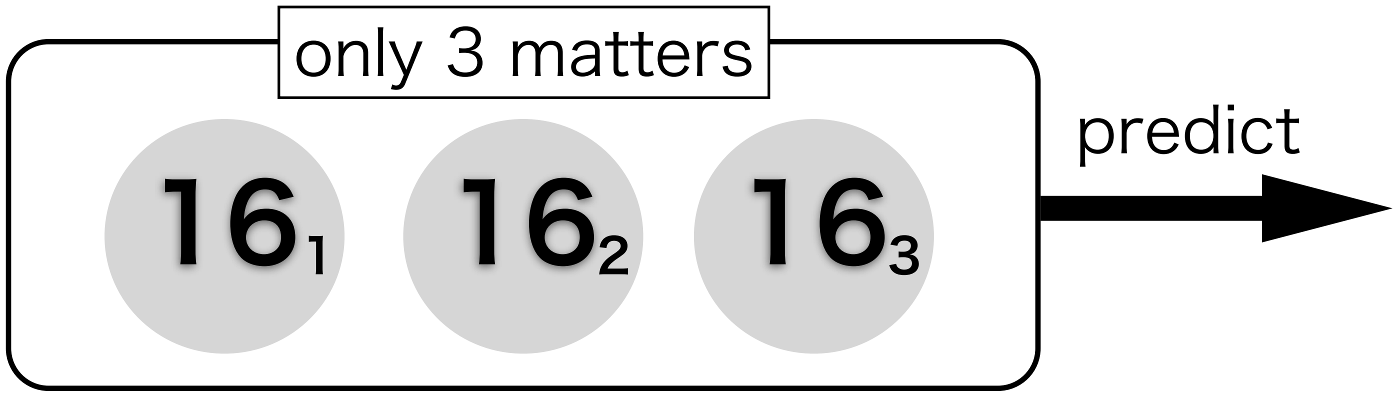
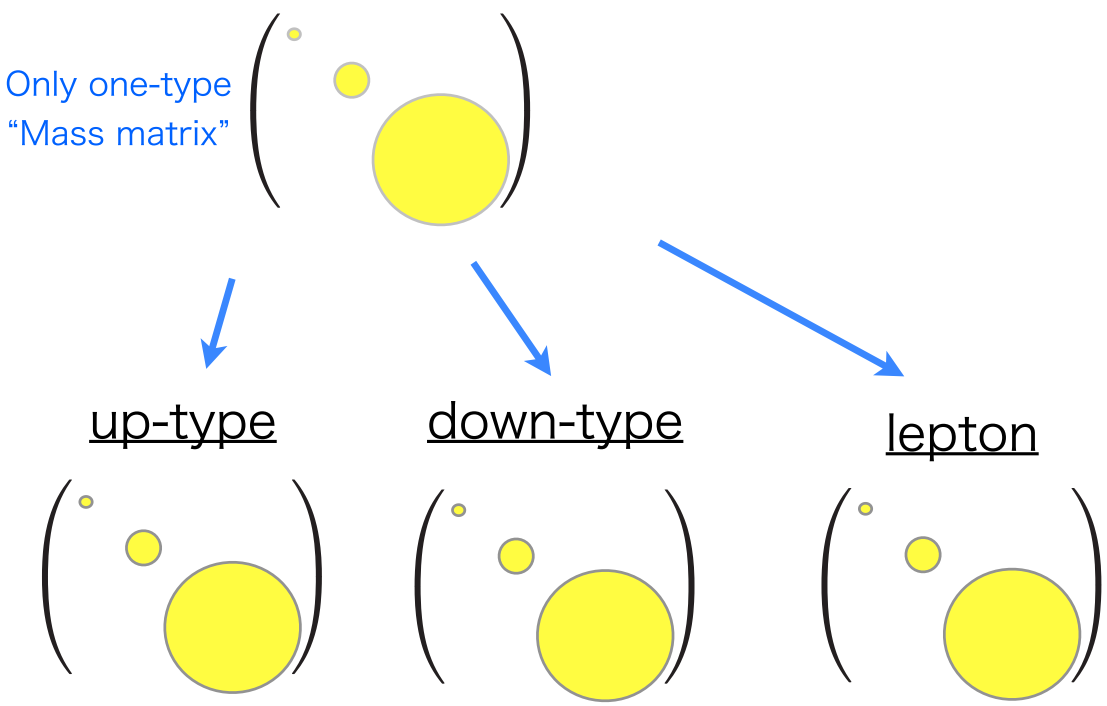


same mass matrices
of (u,c,t), (d,s,b),(e, μ , τ)

no CKM mixing

SO(10) GUT unifies quarks and leptons into **16** rep.

$W_{\rm min} = h_{ij} \mathbf{16}_i \mathbf{16}_j \mathbf{10}_H$ $\quad$ @ $\tan\beta = 1$



same mass spectrum

supersymmetric SO(10) GUT looks very elegant and natural

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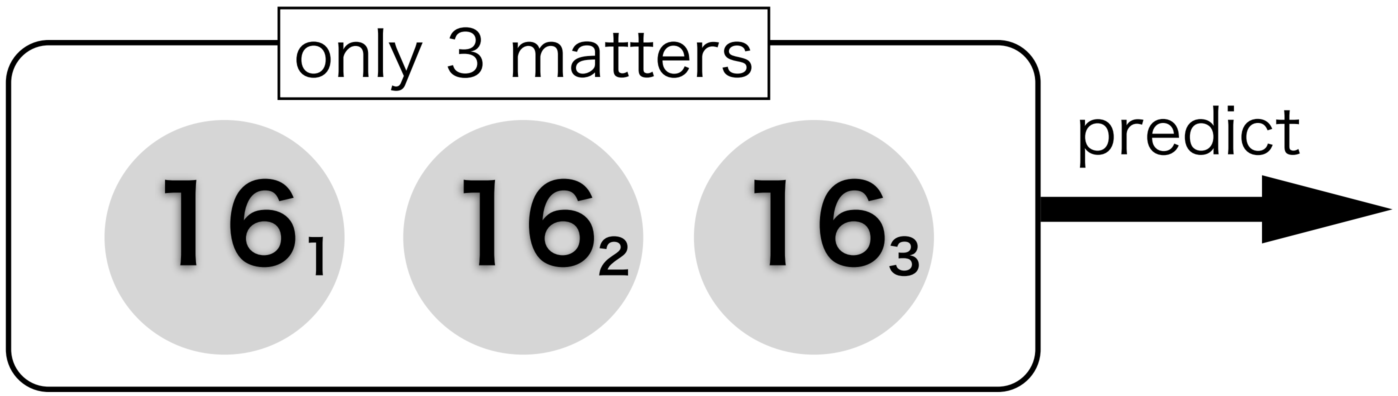

same mass matrices
of (u,c,t), (d,s,b),(e, μ , τ)

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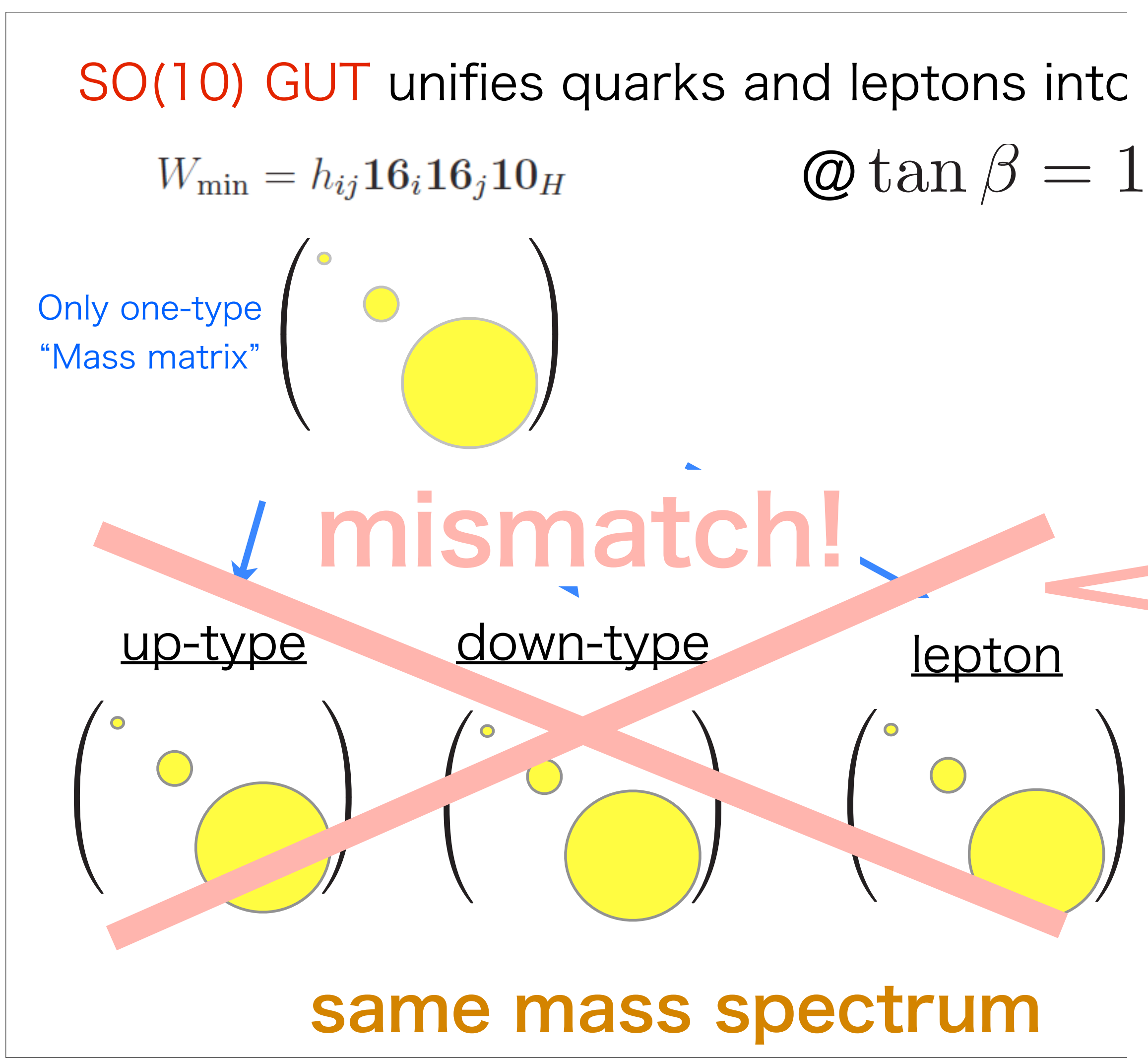
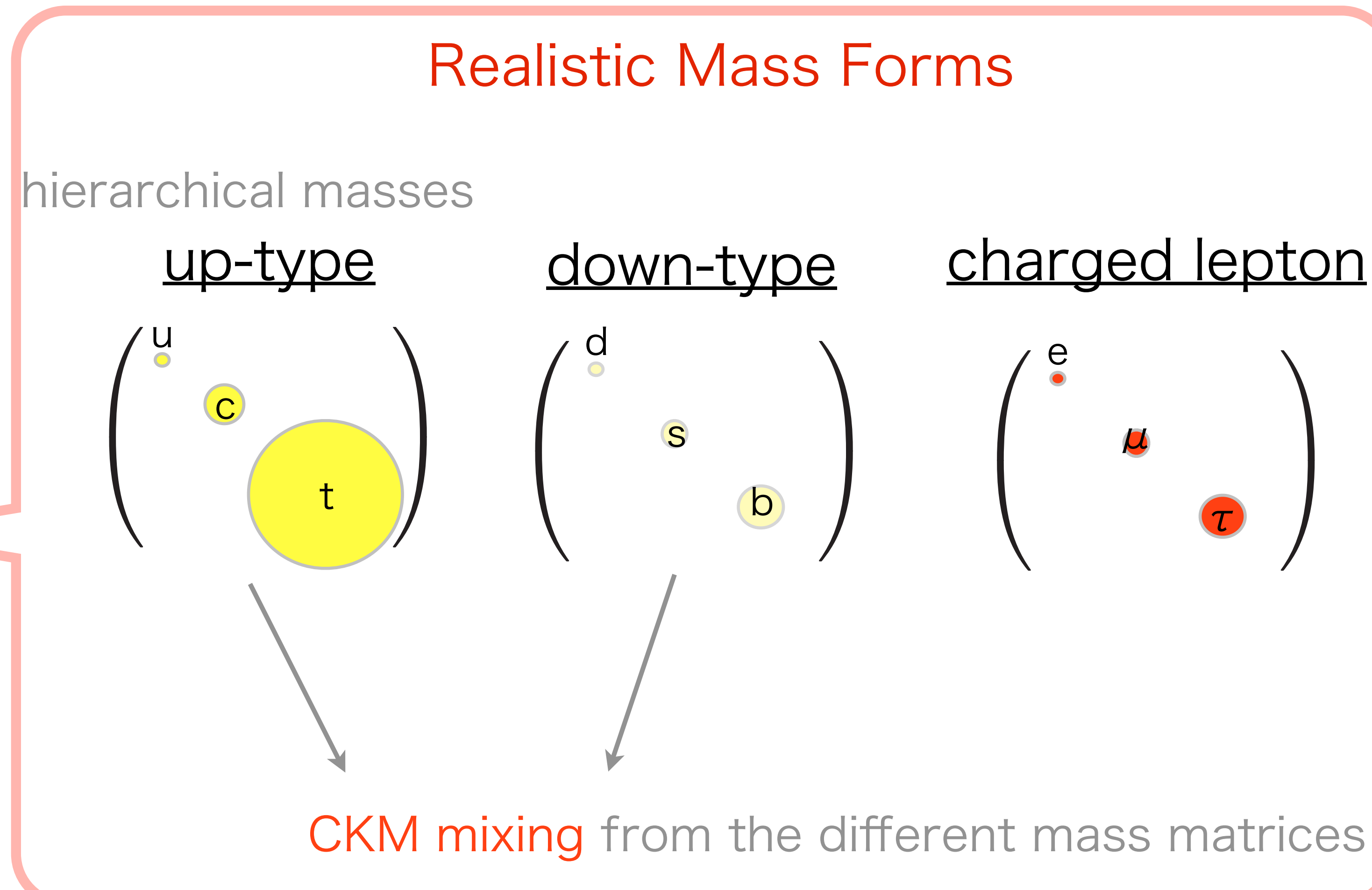
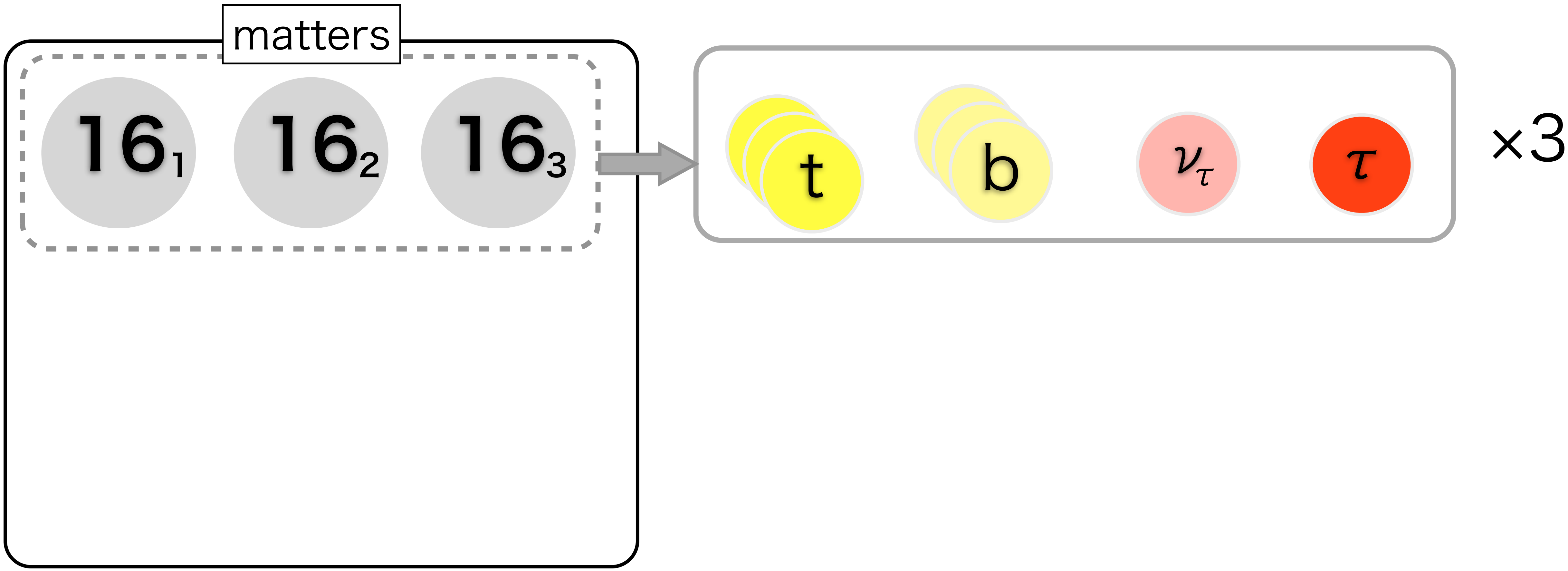




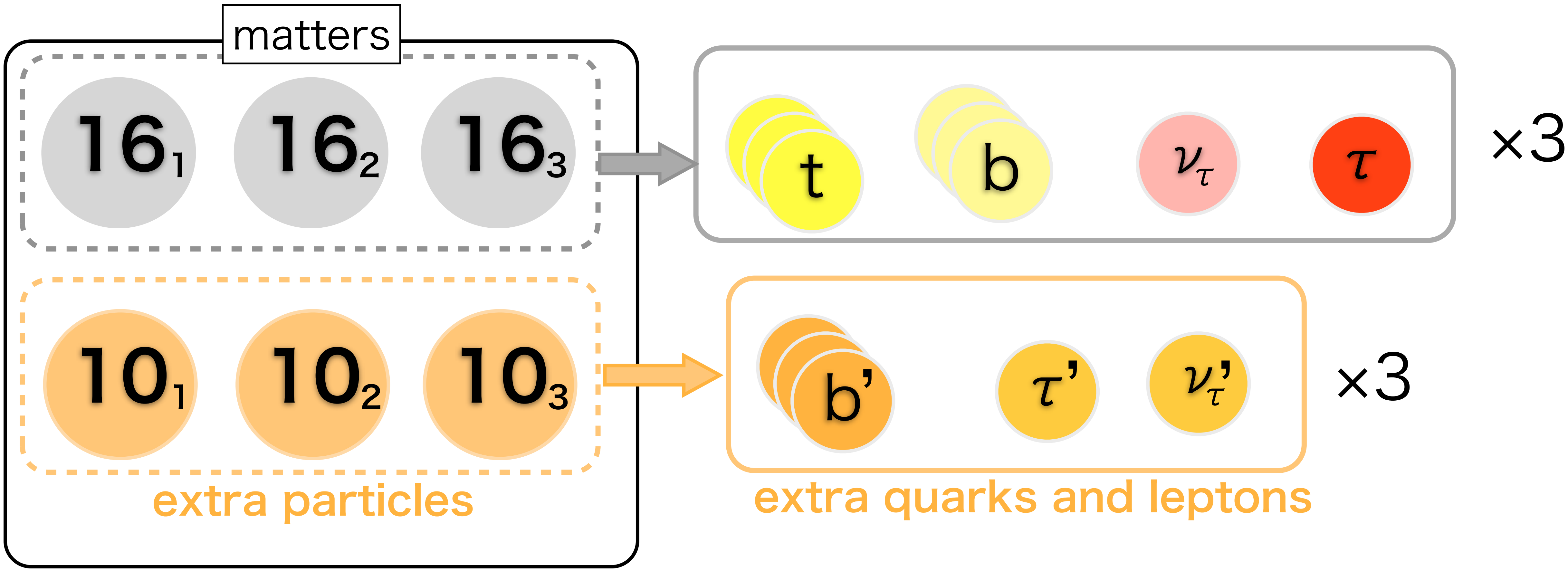
We need extra something.

minimal setup



Let me add extra matters ($\mathbf{10}_1$, $\mathbf{10}_2$, $\mathbf{10}_3$)

(YO, J. Hisano, Y. Muramatsu, M. Yamanaka)



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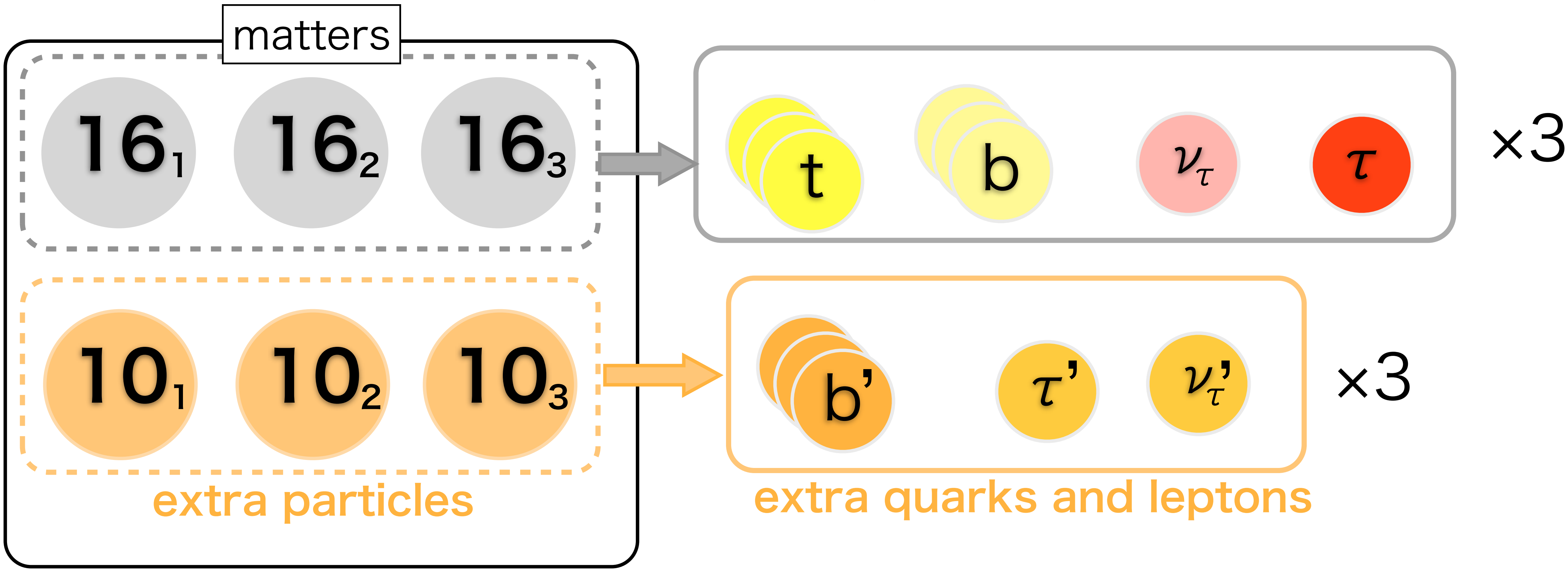


Then SM particles are given by the linear combinations:

ex)

minimal

$$|(b^c_R)_{SM} >= |b^c_R>$$

extended

$$|(b^c_R)_{SM} >= (\cos\theta_b)|b^c_R> + (\sin\theta_b)|b'^c_R>$$

realization of b mass by the mixing

minimal

$$m_b = m_t$$

$@\tan\beta = 1$

extended

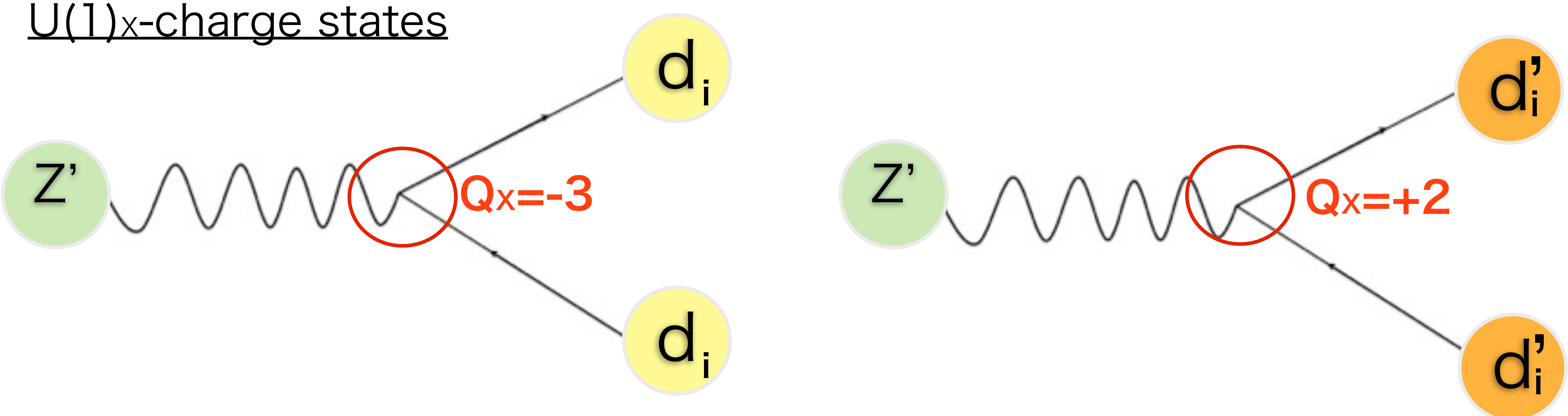
$$m_b = \left(m_t \right) \times \left(\cos\theta_b \right)$$

Crucial fact is

(YO, J. Hisano, Y. Muramatsu, M. Yamanaka)

d_i and d'_i carry different $U(1)_X$ charges
extra

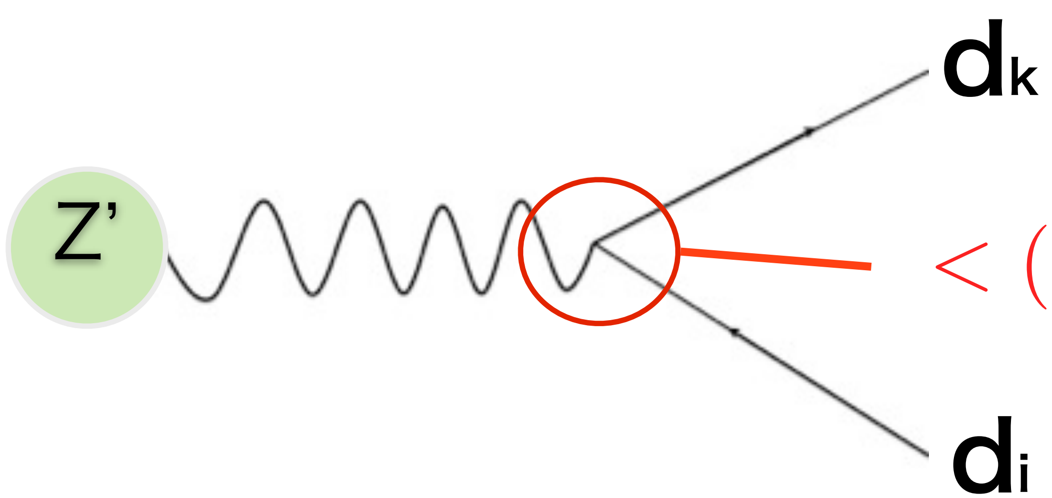
U(1)x-charge states



mass eigenstates

down-type quarks

$$|(d_R^i)_{SM}> = U_{ij}|d_R^j(-3)> + U'_{ij}|d'^j_R(+2)>$$

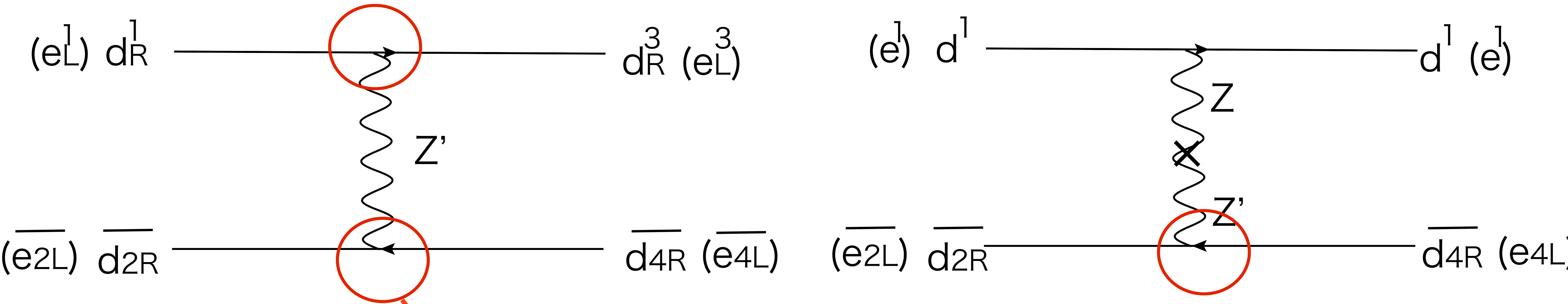


$$<(d_R^k)_{SM}|\hat{Q}_X|(d_R^i)_{SM}> \not\propto \delta_{ik}$$

Flavor violating!

Contributions to Flavor Physics

finite Z-Z' mass mixing predicted



flavor changing

almost flavor-universally

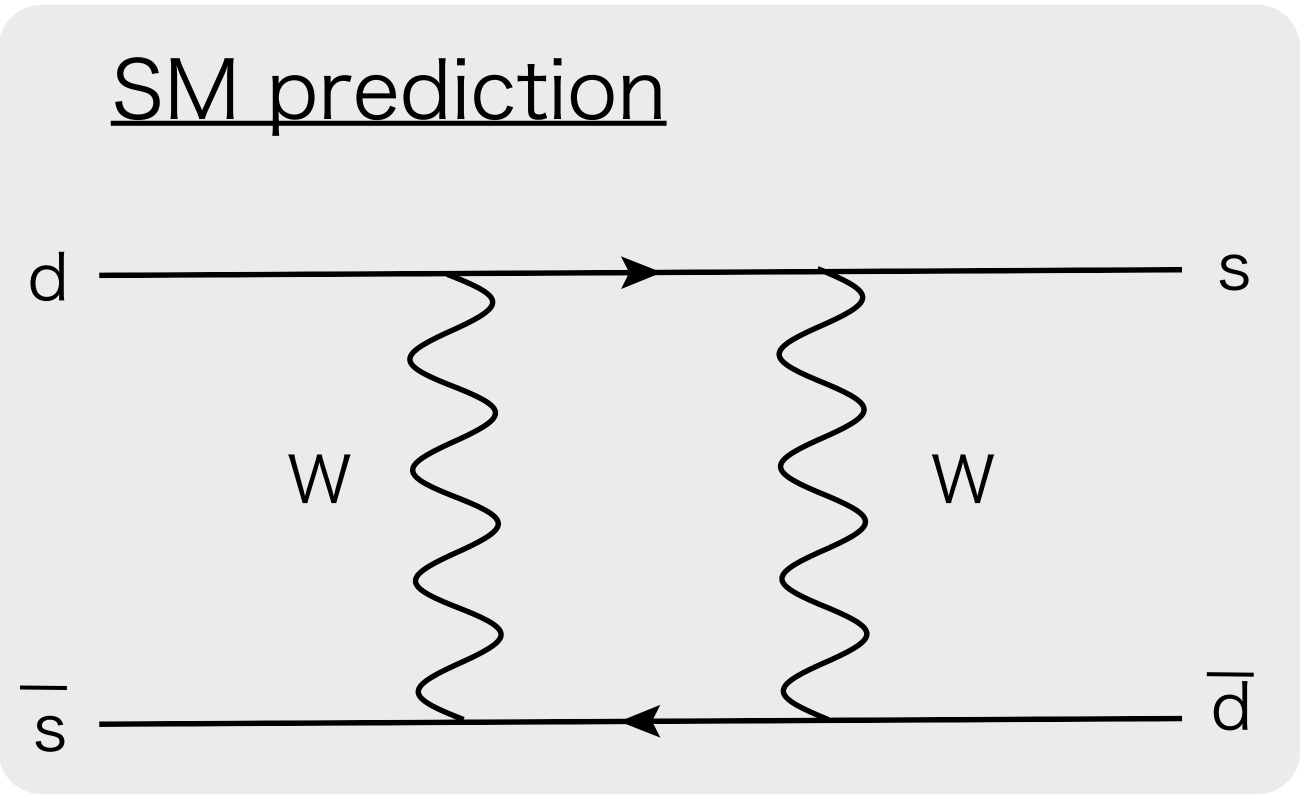
(d,s), (d,b), (s,b), (e,μ), (e,τ), (μ,τ) elements are O(1) and complex.

Very nice predictions

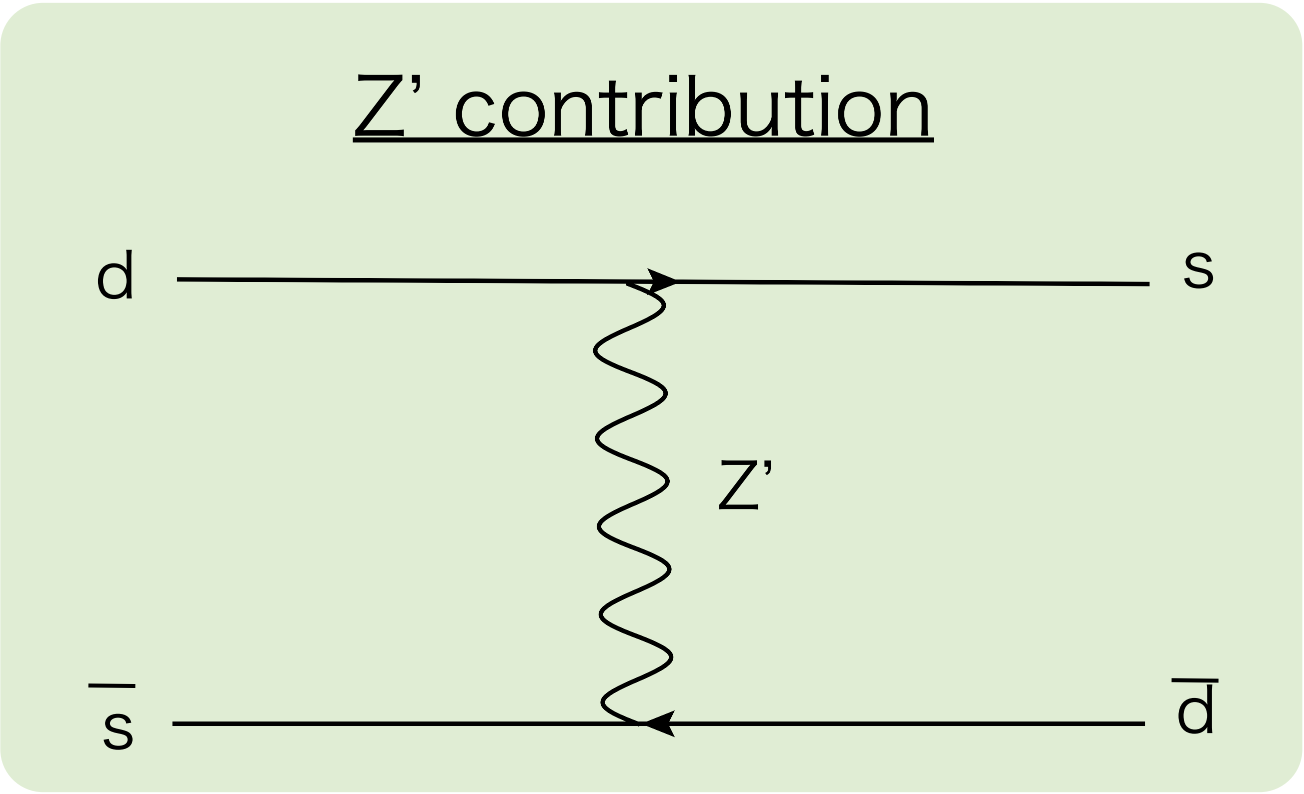
because it is usually difficult to prove GUTs.

Z' scale may be also determined by the 125 GeV Higgs
and Z' coupling is predicted by the GUT relation.
Predictability is very high!

Important processes are K system and μ physics



vs



$$\underbrace{|V_{ts}^* V_{td}|}_{K \text{ system}} \sim 5 \cdot 10^{-4} \ll \underbrace{|V_{tb}^* V_{td}|}_{B_d \text{ system}} \sim 10^{-2} < \underbrace{|V_{tb}^* V_{ts}|}_{B_s \text{ system}} \sim 4 \cdot 10^{-2}$$

K system is more sensitive to new physics

Experimental constraints on μ are stronger

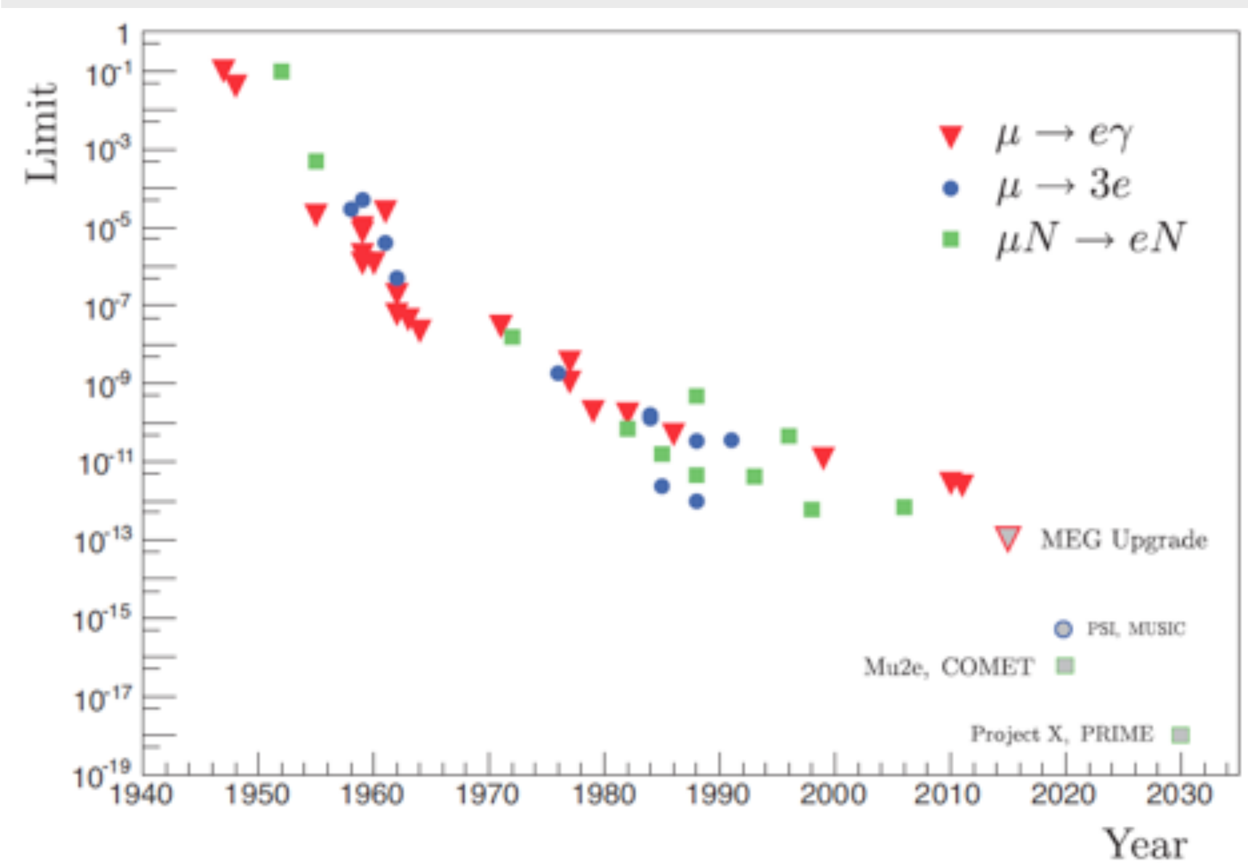
τ decay

$$\mathrm{BR}(\tau \to l_i l_j l_k) \lesssim 10^{-8}$$

$$\mathrm{BR}(\tau \to l_i \gamma) \lesssim 10^{-8}$$

(arXiv:1001.3221;0908.2381)

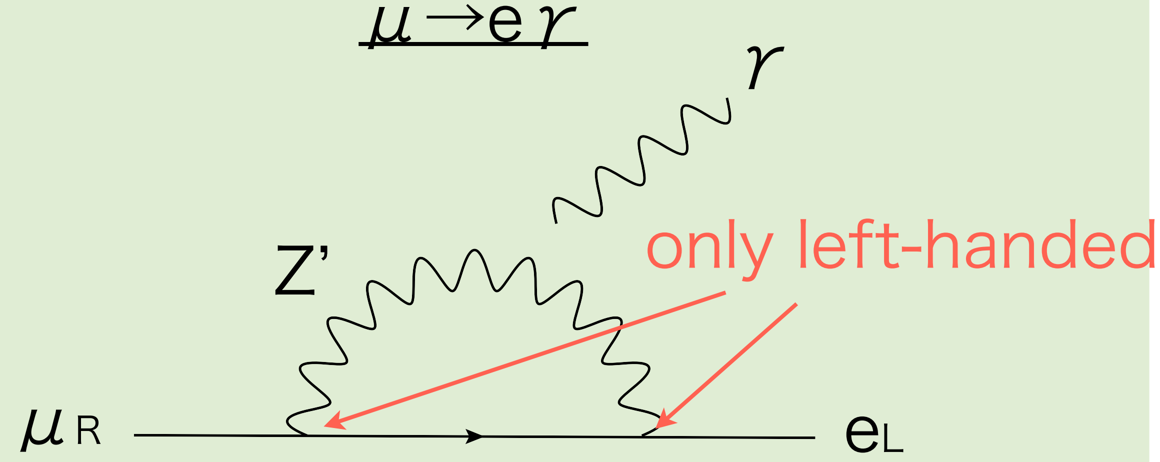
μ decay



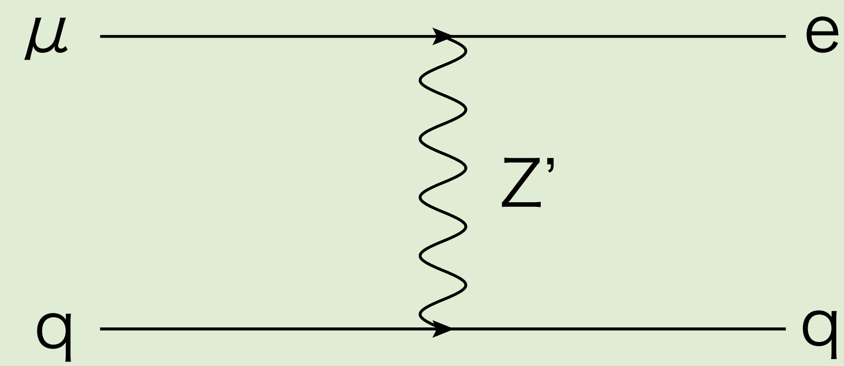
(arXiv:1307.5787)

vs

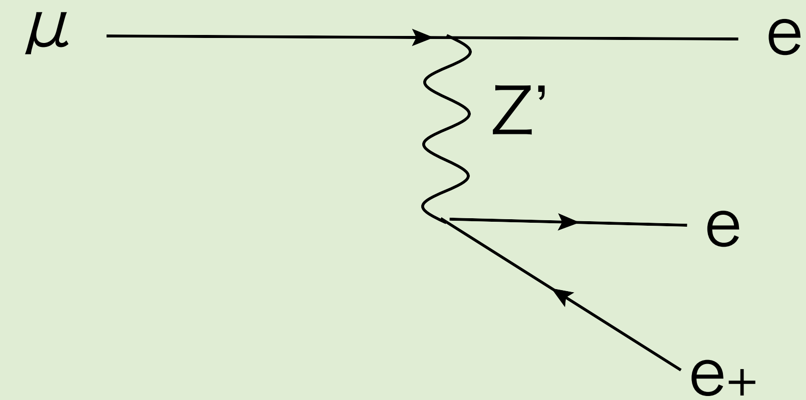
$\mu \to e\gamma$



$\mu \to e$ conversion

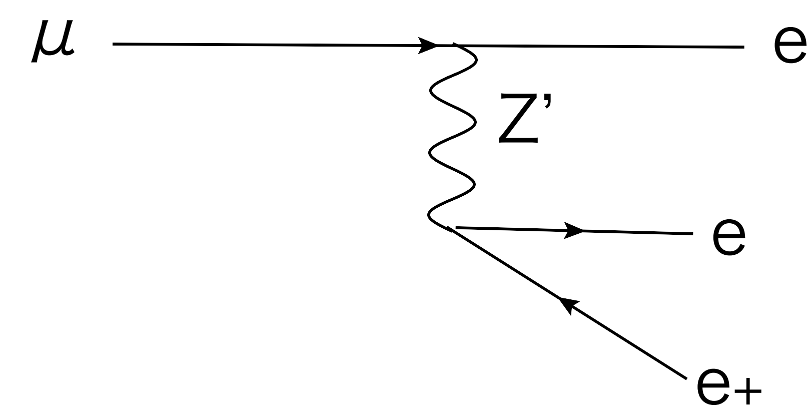


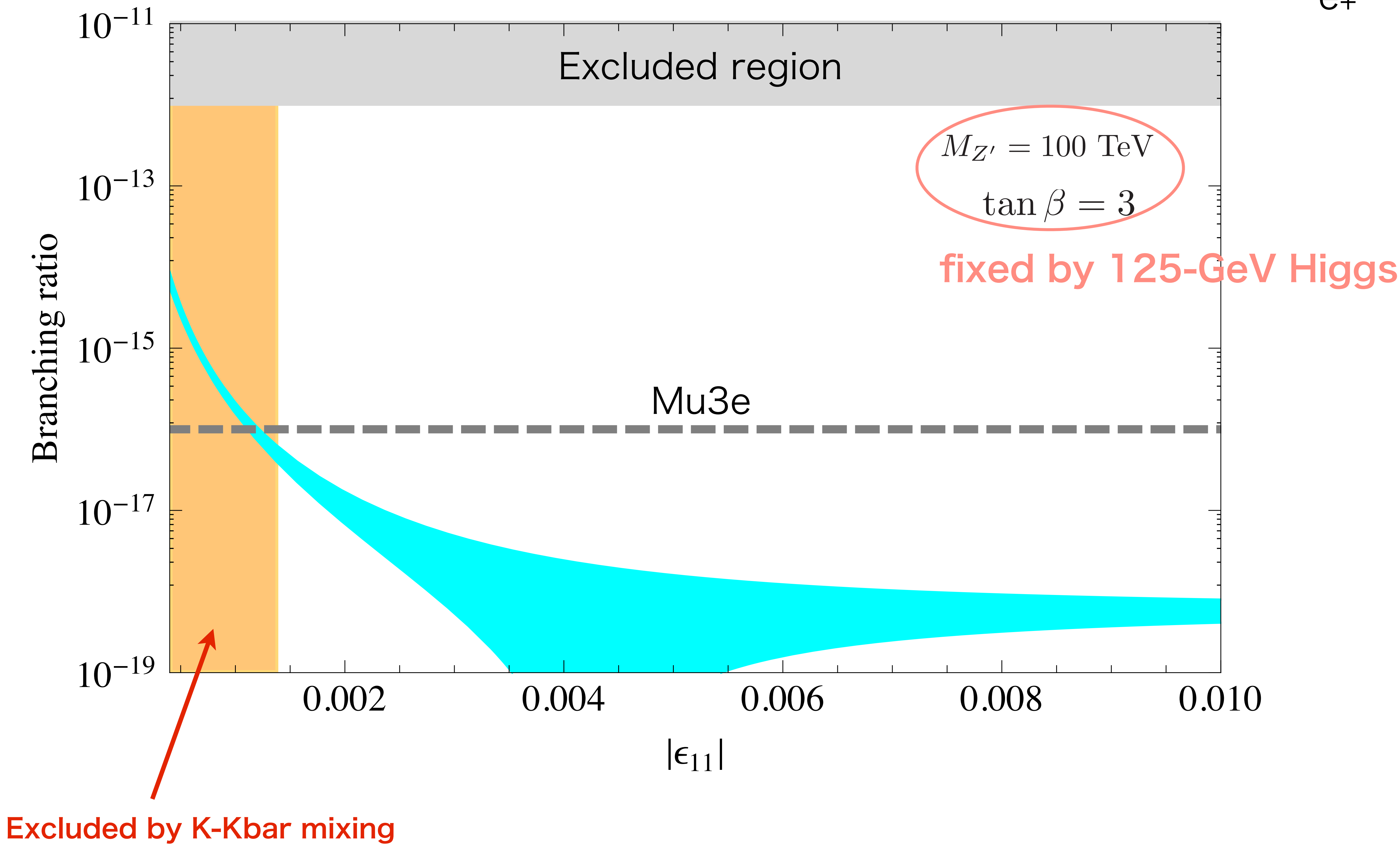
$\mu \to eee_+$



$\mu \to 3e$, μ-e conversion are most important

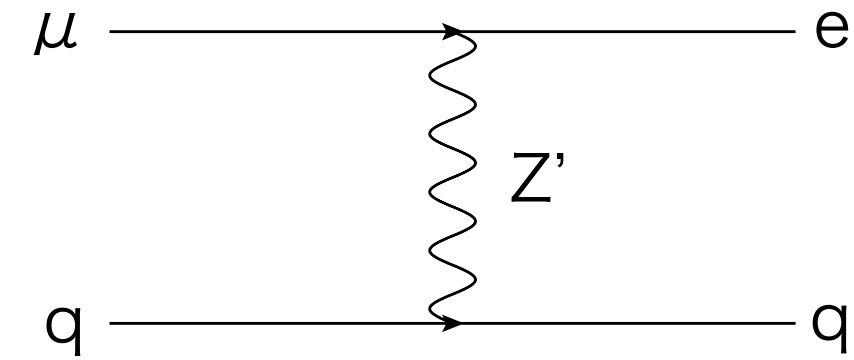
Allowed region for $\mu \to 3e$

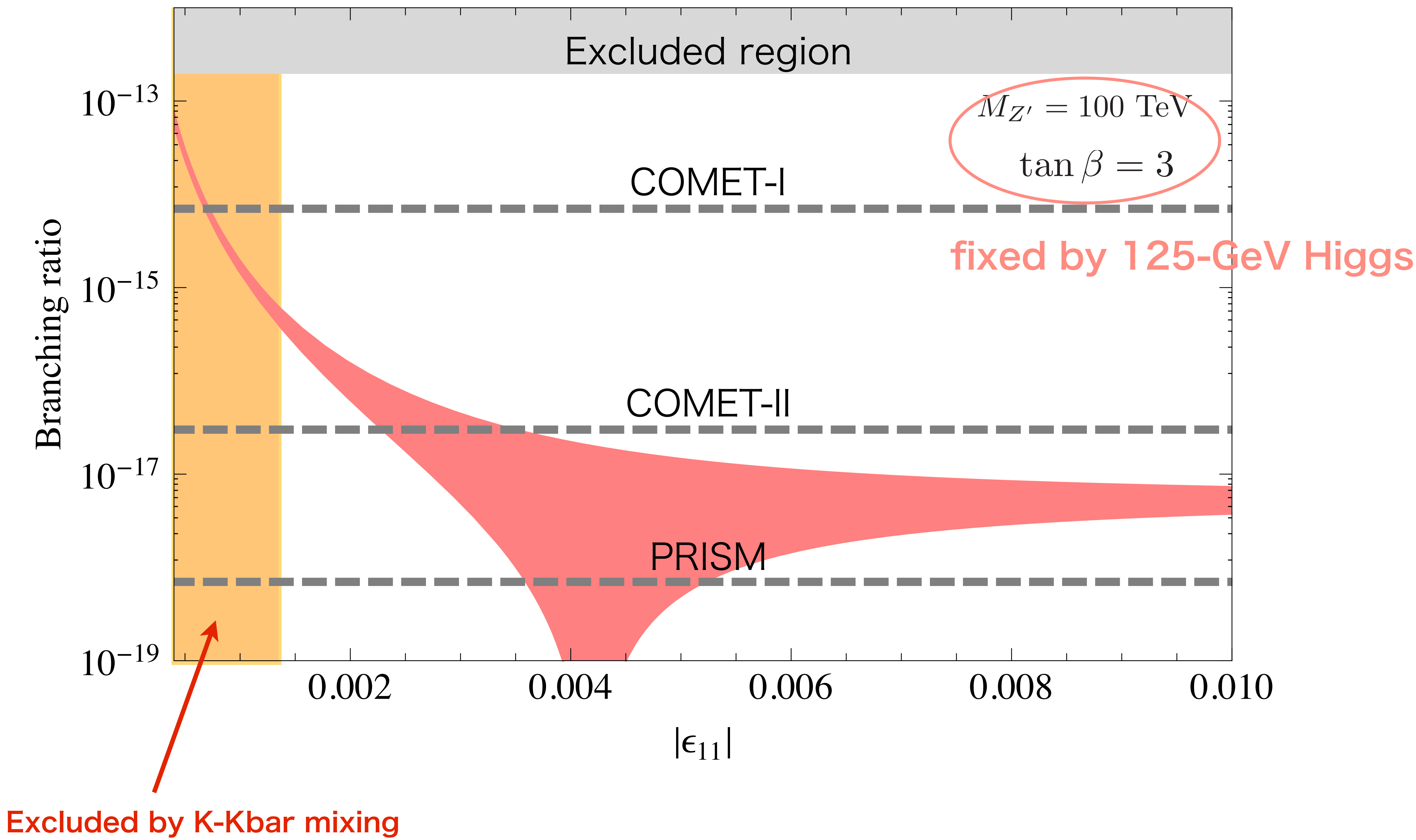




deviations of $K_L \to \mu\mu, \mu e$, $K_+ \to \pi_+ \nu\nu$ are less than O(1)%.

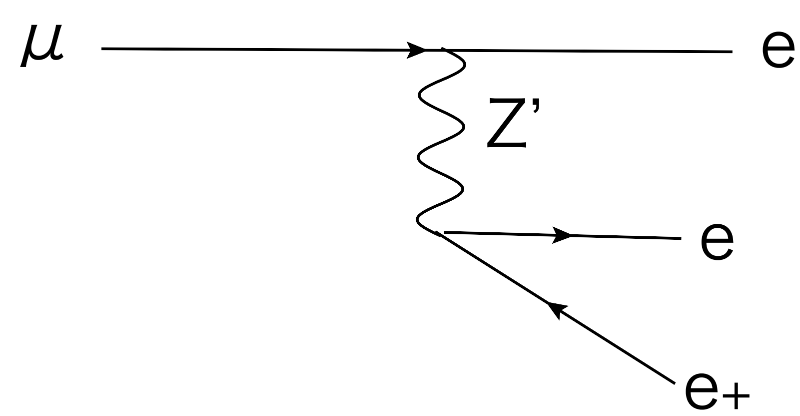
Allowed region for $\mu \to e$ in Al



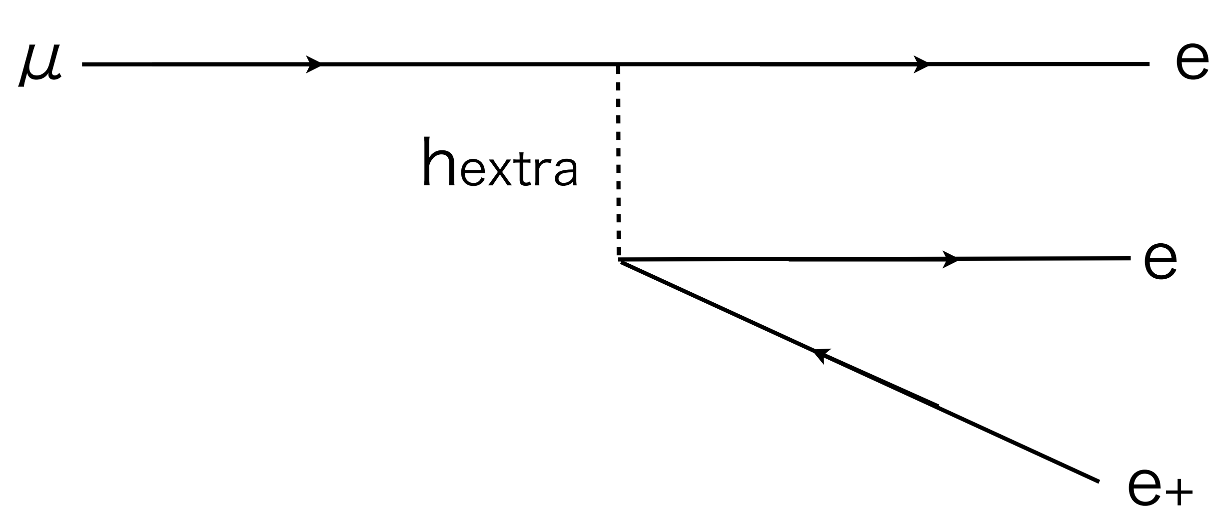


deviations of $K_L \to \mu\mu, \mu e$, $K_+ \to \pi_+ \nu\nu$ are less than O(1)%.

I introduced Z’ exchanging flavor violation



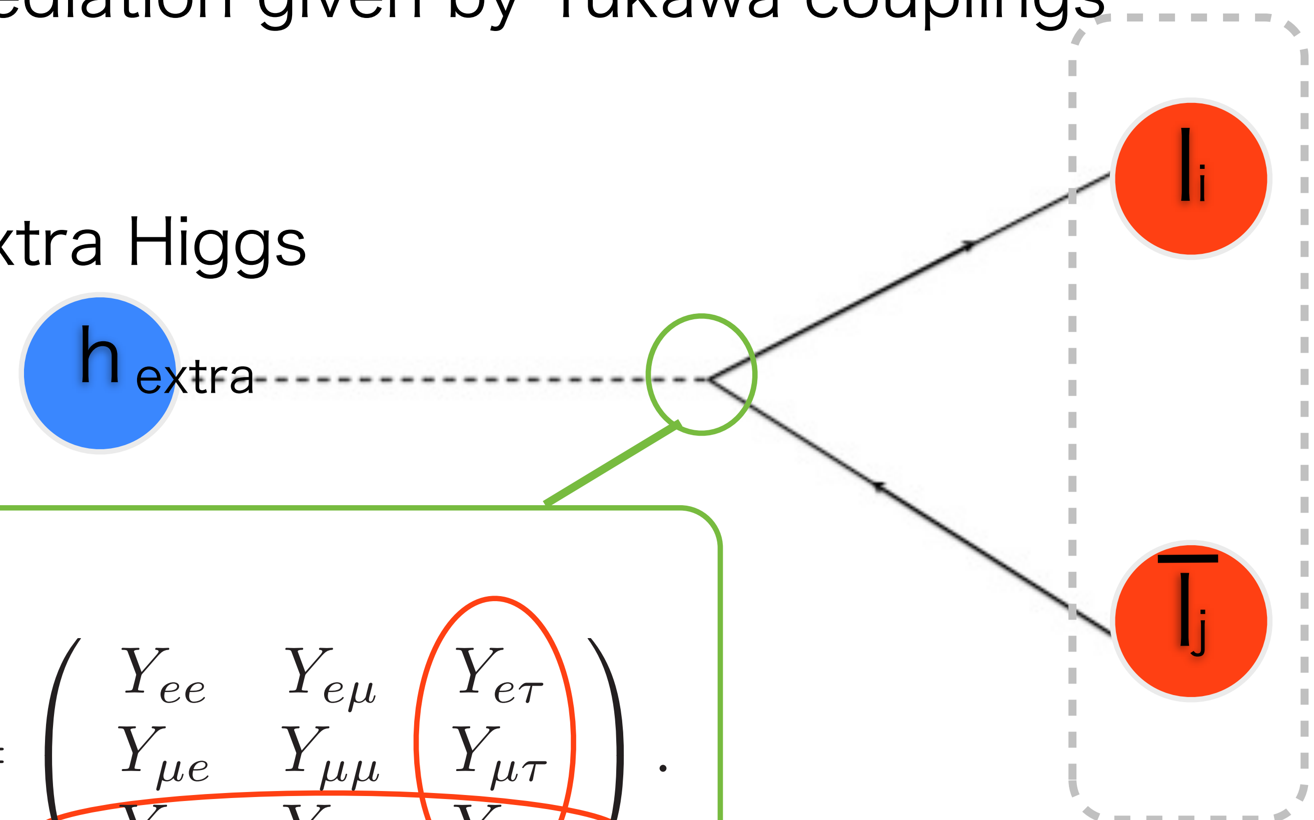
extra scalar (spin-0) exchanging flavor violation is also widely discussed in the BSMs.



Higgs mediated Flavor violation

Higgs mediation given by Yukawa couplings

Extra Higgs



$$Y_{ij} h_{\rm extra} \overline{l_L^i} l_R^j$$

$$(Y_{ij}) = \begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}.$$

tend to be large in many BSMs,
because of the mass hierarchy

The processes involving third generations (τ, b, t) are important

LFVs involving electron suppressed because of small Y_{ee}, $Y_{\mu e}$ and $Y_{e\mu}$.

1 example of the BSMs

which predict the Higgs-mediated Flavor violation.

Standard Model (SU(3)$_c$×SU(2)$_L$×U(1)$_Y$)

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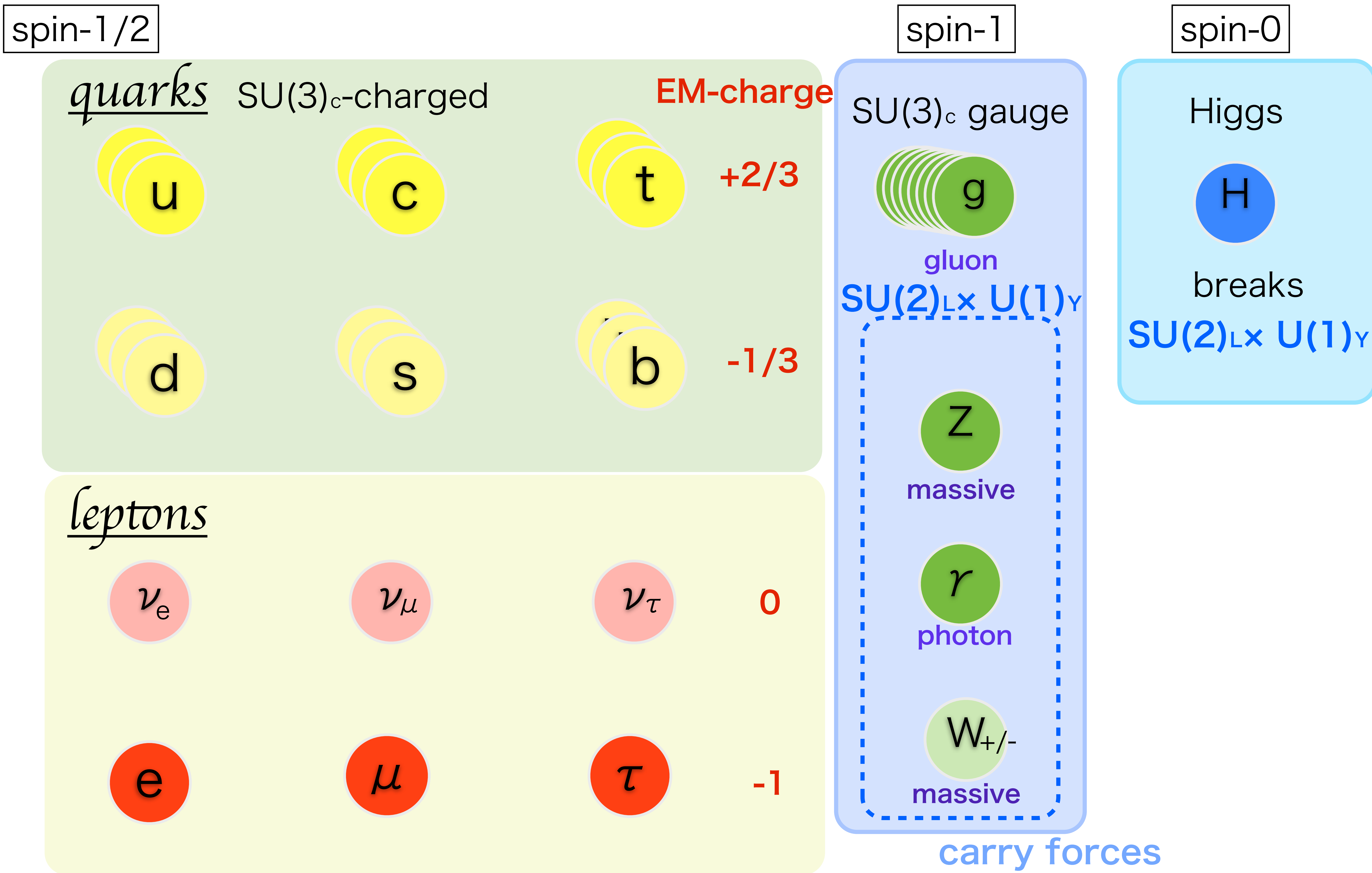
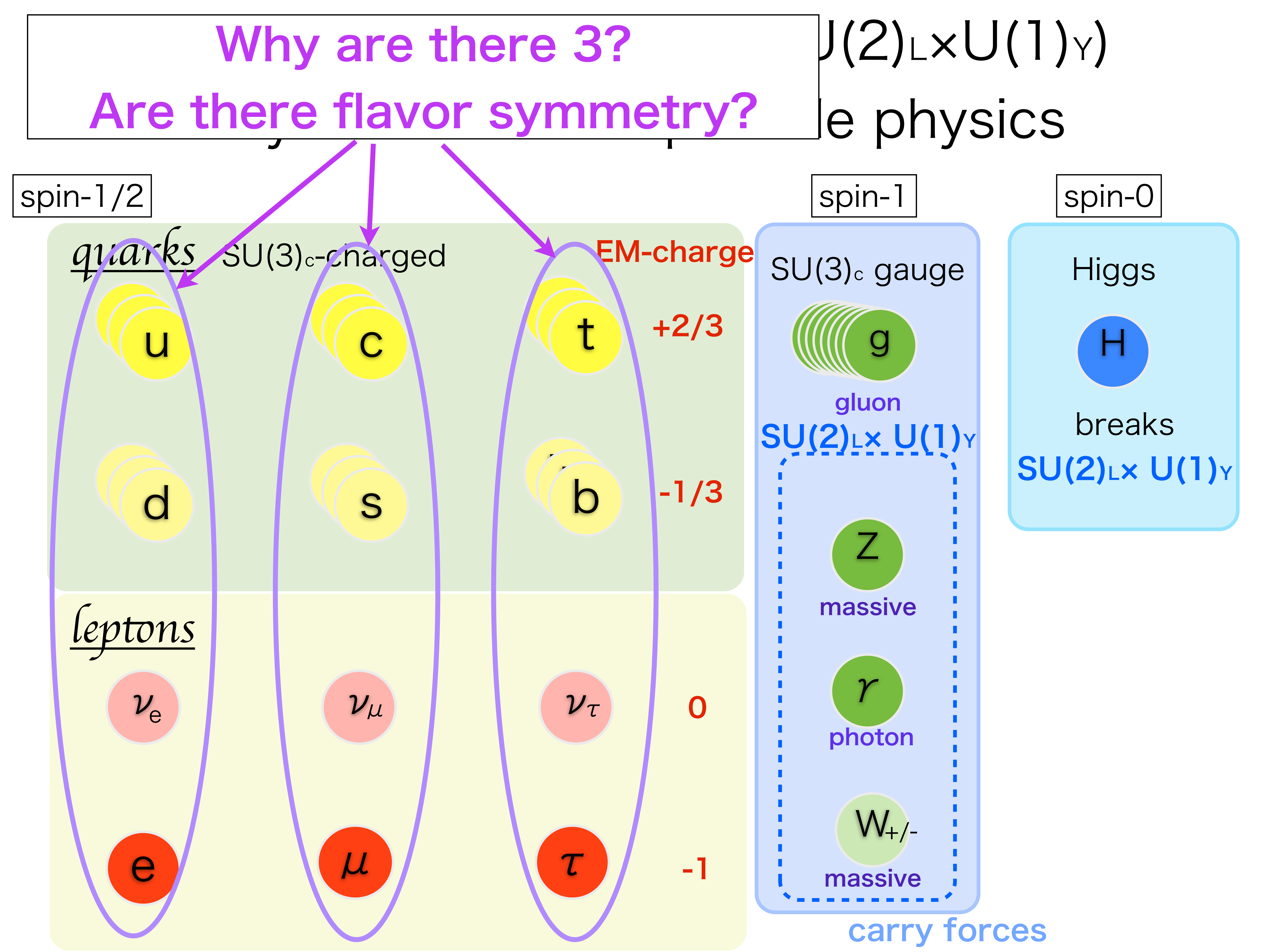
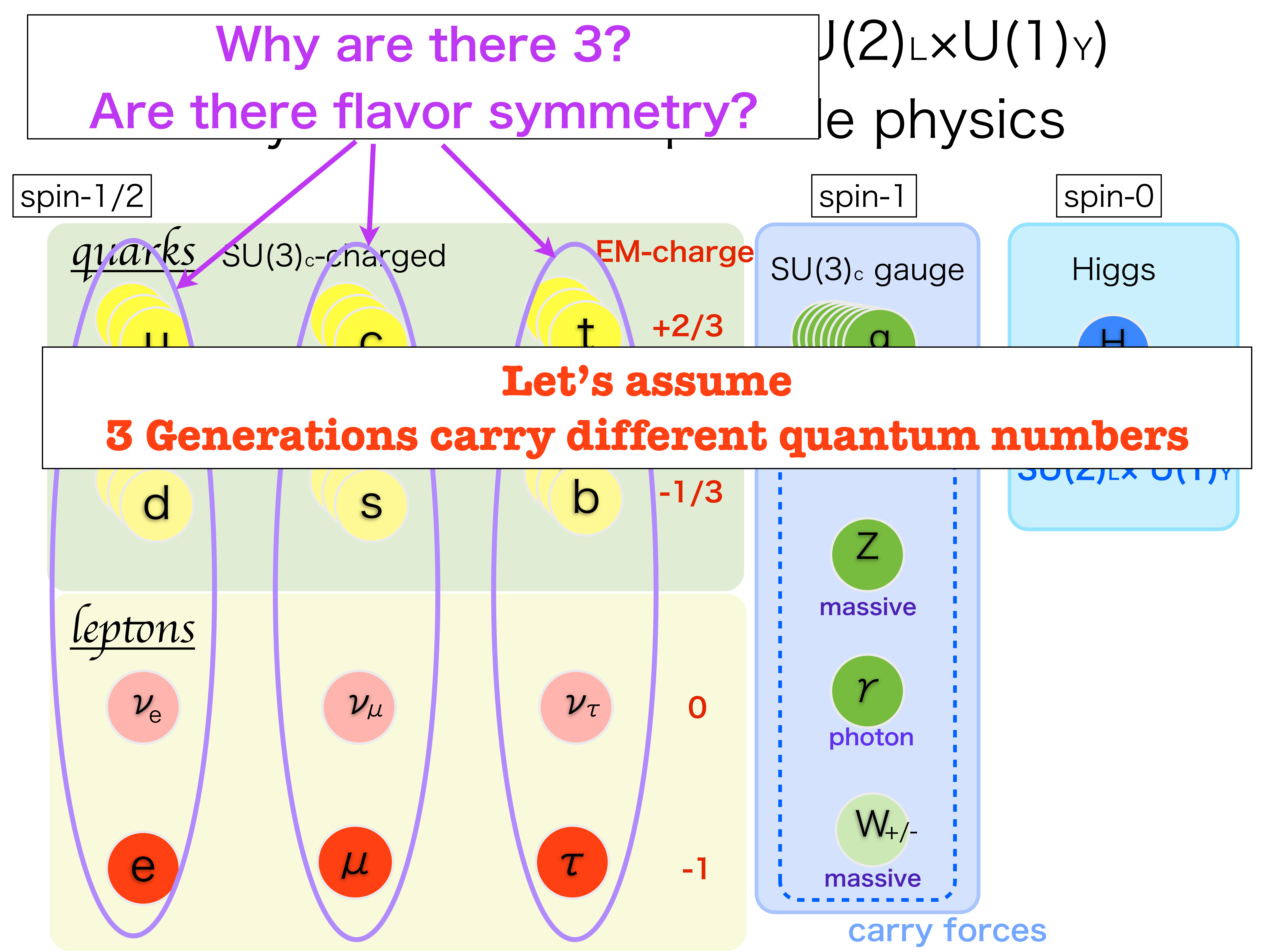




Why are there 3?
Are there flavor symmetry?
J(2)L×U(1)Y)
le physics
spin-1/2
spin-1
spin-0
quarks
SU(3)c-charged
EM-charge
u
c
t
+2/3
d
s
b
-1/3
leptons
νe
νμ
ντ
0
e
μ
τ
-1
SU(3)c gauge
g
gluon
SU(2)L× U(1)Y
Z
massive
γ
photon
W+/-
massive
carry forces
Higgs
H
breaks
SU(2)L× U(1)Y


J(2)L×U(1)Y)
le physics
Why are there 3?
Are there flavor symmetry?
spin-1/2
spin-1
spin-0
quarks
SU(3)c-charged
EM-charge
SU(3)c gauge
Higgs
u
c
t
+2/3
g
H
Let's assume
3 Generations carry different quantum numbers
d
s
b
-1/3
Z
massive
leptons
ν_e
ν_μ
ν_τ
0
photon
e
μ
τ
-1
$W_{+/-}$
massive
carry forces

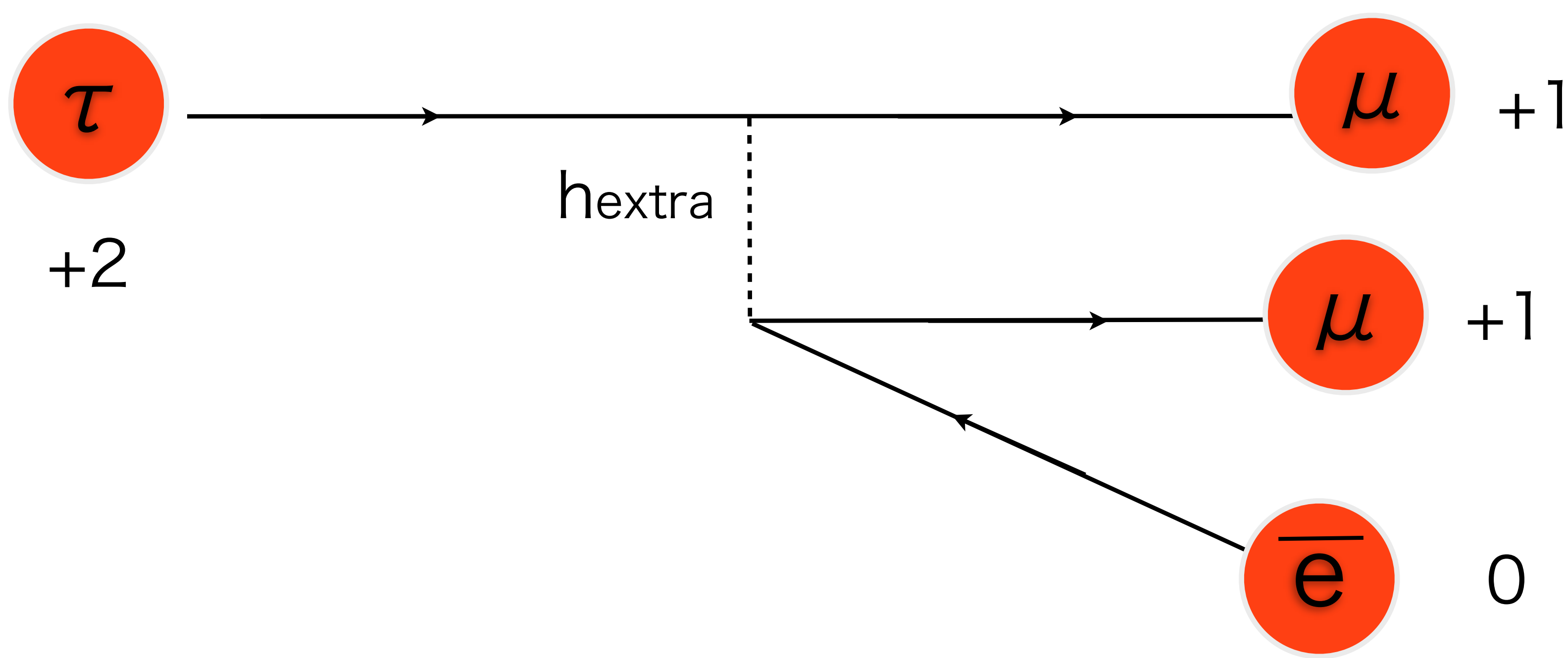
(YO, T. Kobayashi, F. Takayama, D. Yasuhara)

For example, let me assign flavor charges to leptons

	e	μ	τ	h_{extra}
flavor charges	0	+1	+2	+1

(In fact, many flavor models suggest this feature.)

prediction

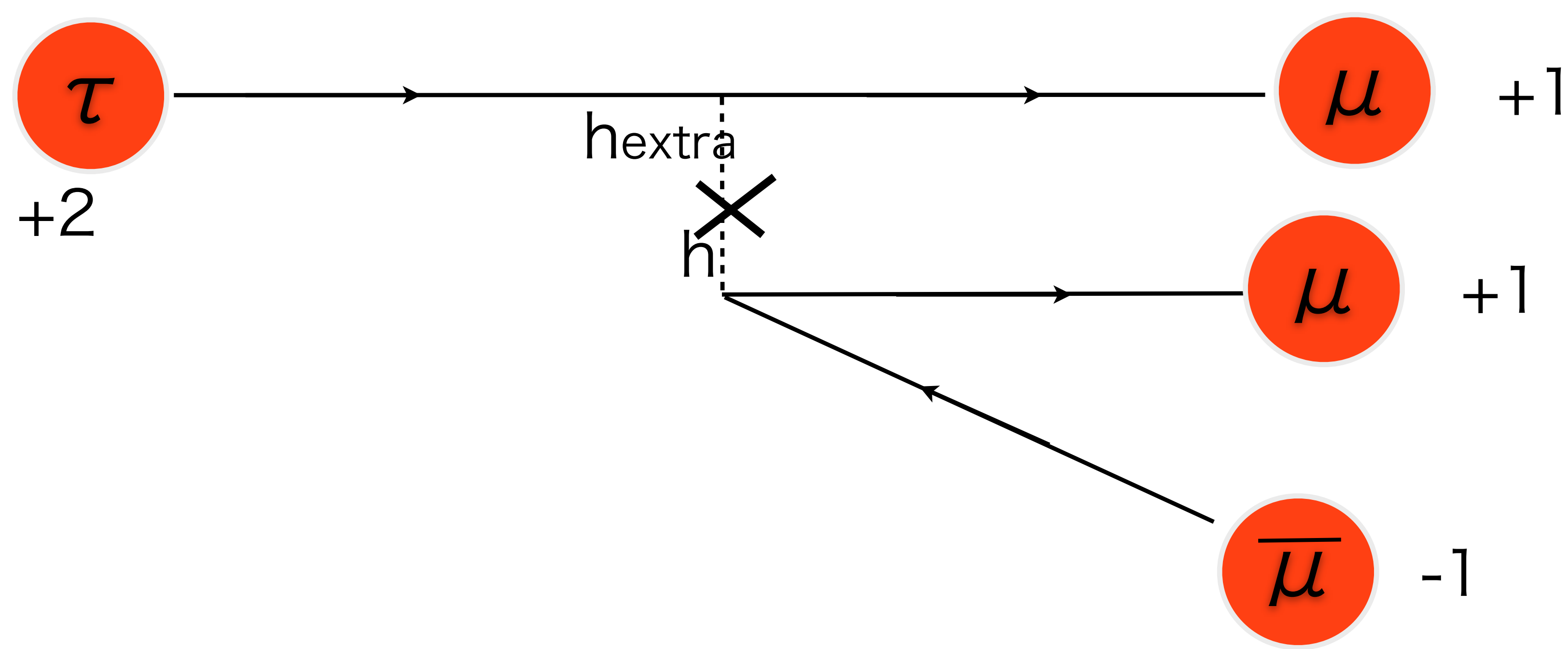


This symmetry cannot be hold in the full lagrangian,
but works very well.
(neutrino mass matrix breaks this, but the masses are quite small.)

(YO, T. Kobayashi, F. Takayama, D. Yasuhara)

The other processes are suppressed by the breaking terms in scalar potential

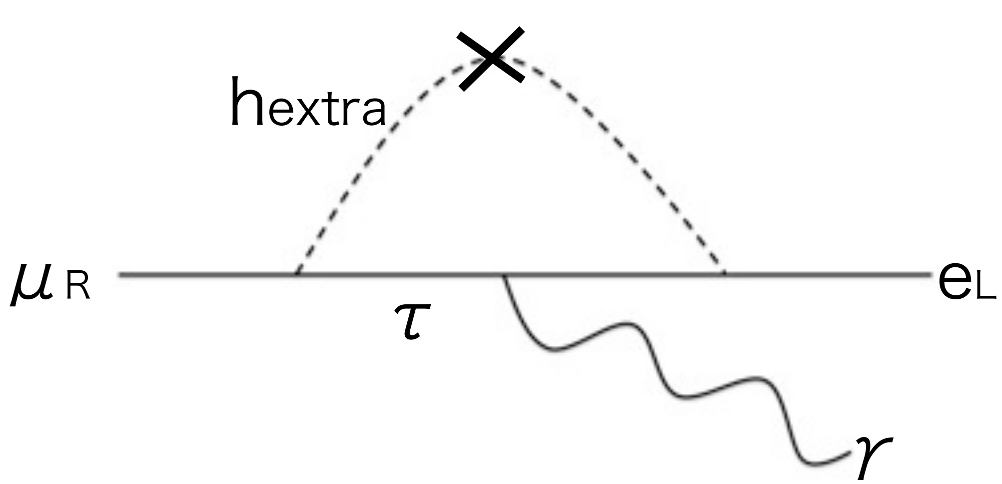
prediction



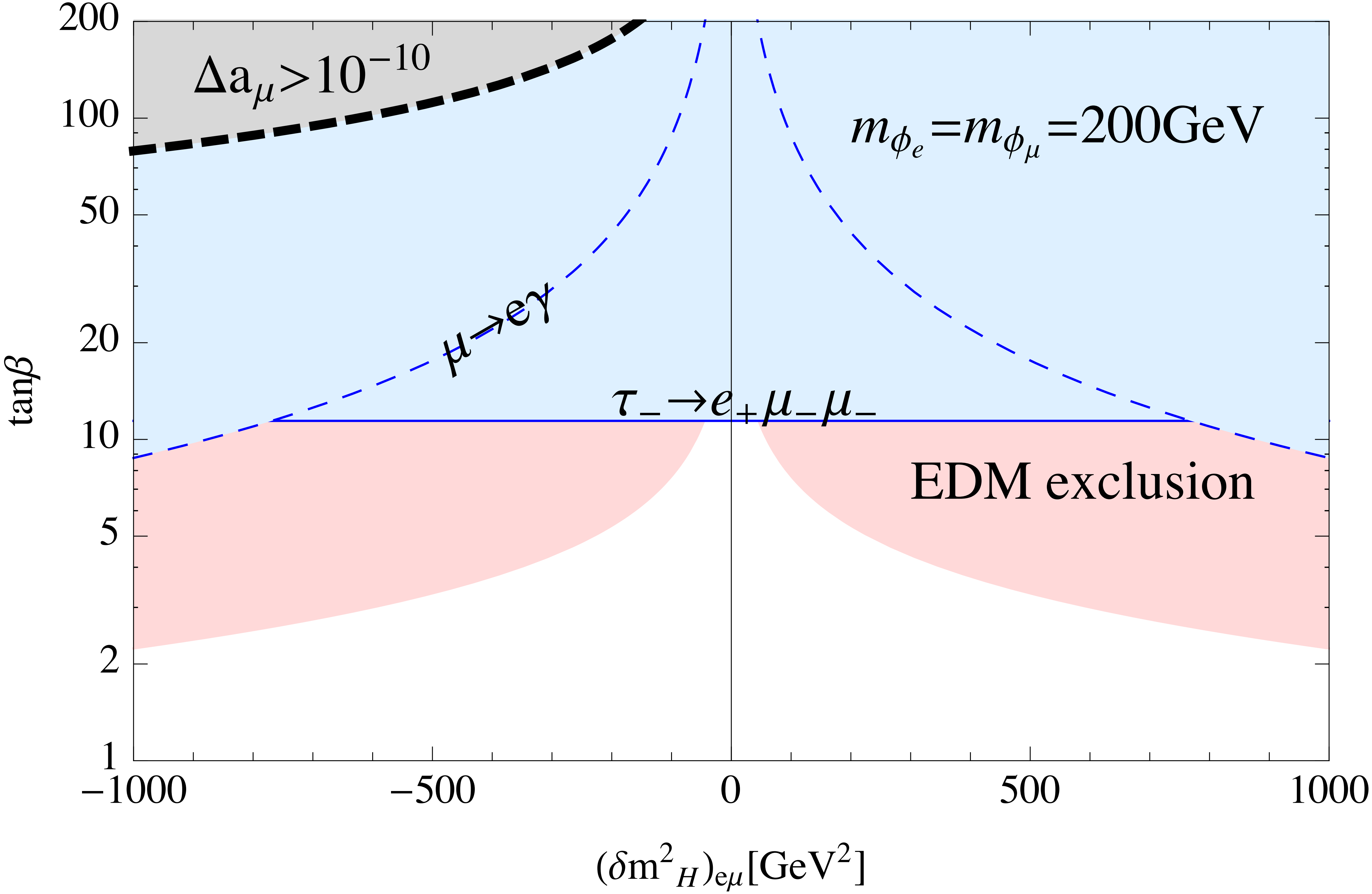
$$\mathrm{Br}(\tau^- \to 3\mu) \lesssim O(0.01) \times \mathrm{Br}(\tau^- \to e^+\mu^-\mu^-)$$

$$\mathrm{Br}(\tau^- \to 3e) \ll \mathrm{Br}(\tau^- \to e^+\mu^-\mu^-)$$

Not only τ decay, but $\mu \to e\,\gamma$ process is also important, because of large $Y_{\tau\mu}$, $Y_{e\tau}$ and τ mass enhancement.



$$\mathrm{Br}(\tau^- \to e\gamma) \lesssim \mathrm{Br}(\mu^- \to e\gamma)$$



EDM is relevant, depending on phases of Yukawa.

difficult to explain the anomaly of muon g-2.

Summary

- Higgs discovered! What is next?
- I hope it is not the end of the story.
- We are waiting for discovery of new physics.
- Flavor violations will be very good processes to find the evidence of new physics. SM predicts tiny flavor violation.

- I introduce flavor violating process in the BSMs, motivated by GUT and flavor symmetry.

- SO(10) GUT predicts flavor violating Z'
  $\rightarrow$ flavor-universally Z' coupling
  $\rightarrow$ K physics, μ physics are important.

- Flavor symmetry
  $\rightarrow$ scalar exchanging causes flavor violation
  $\rightarrow$ τ, b, t physics important.

Thank you