Hidden sector behind the CKM matrix

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based on arXiv:1703.08789,
in collaboration with Yuji Omura (KMI, Nagoya)

Dark Side of the Universe @ CTPU, IBS
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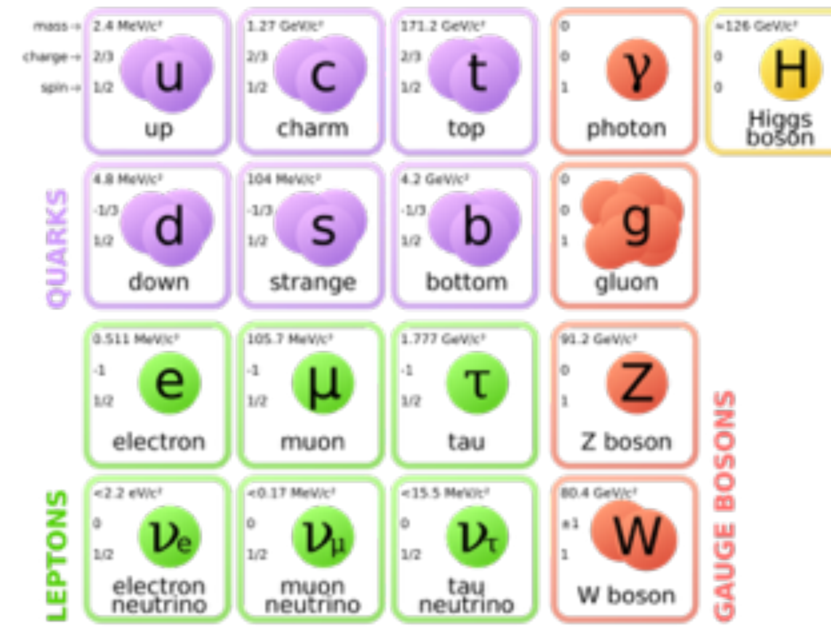
NAGOYA UNIVERSITY

Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

Introduction

In 2012, Standard model has been established by discovery of the 125GeV Higgs boson



However, there are still mysteries in nature:

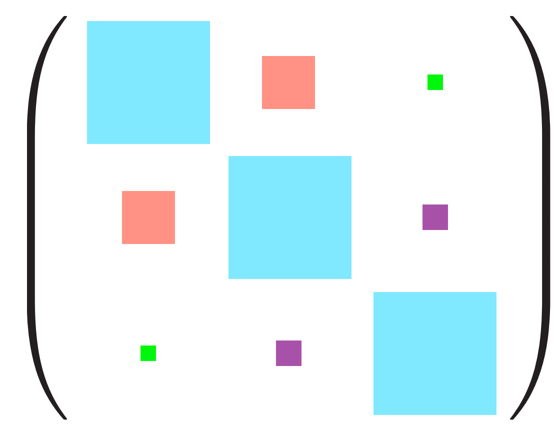
- baryon asymmetry
- dark matter & dark energy
- neutrino mass
- etc.

Flavor structure

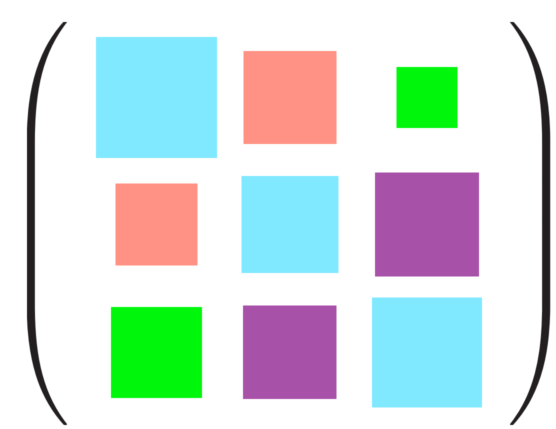
✓ 3 generations in both quarks and leptons

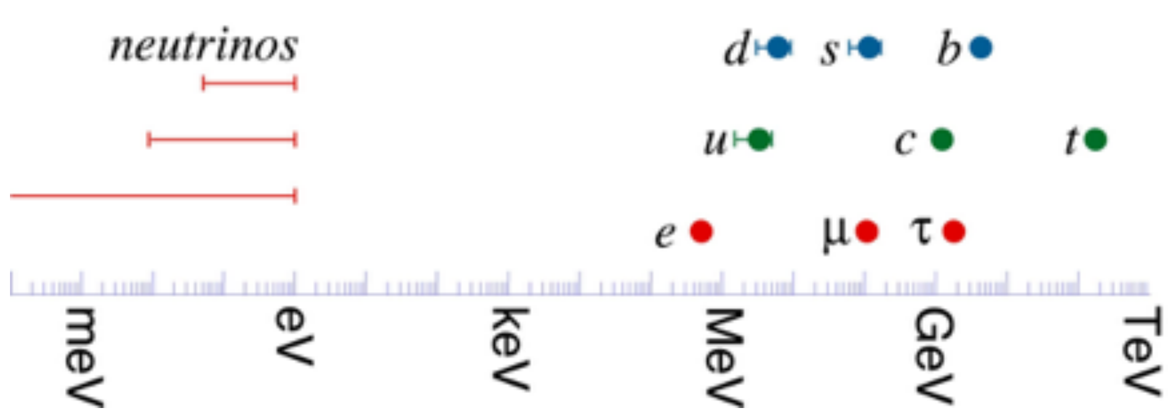
✓ mass hierarchy and flavor mixing

V_{CKM} =



V_{PMNS} =

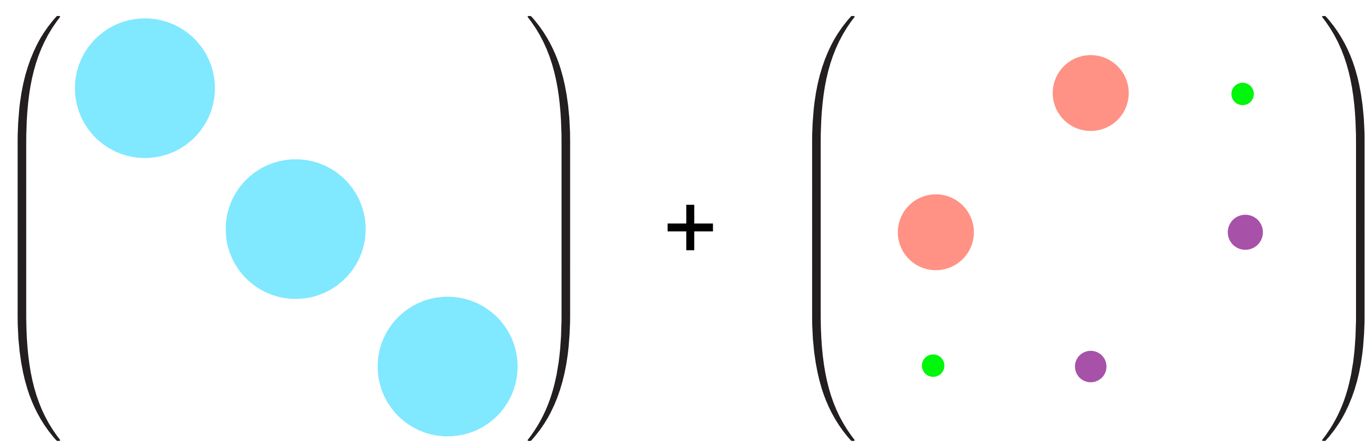




Radiative generation of quark mixing

Barbieri and Nanopoulos, PLB91, 369(1980); PLB95, 43(1980); +Wyler, PLB103, 433(1981); +Masiero, PLB104, 194(1981); E. Ma, 1311.3213; 1411.6679; Nomura and Okada, 1606.09055; SO and Omura, 1703.08789; etc.

V_{CKM} =



~unit matrix

small off-diagonal

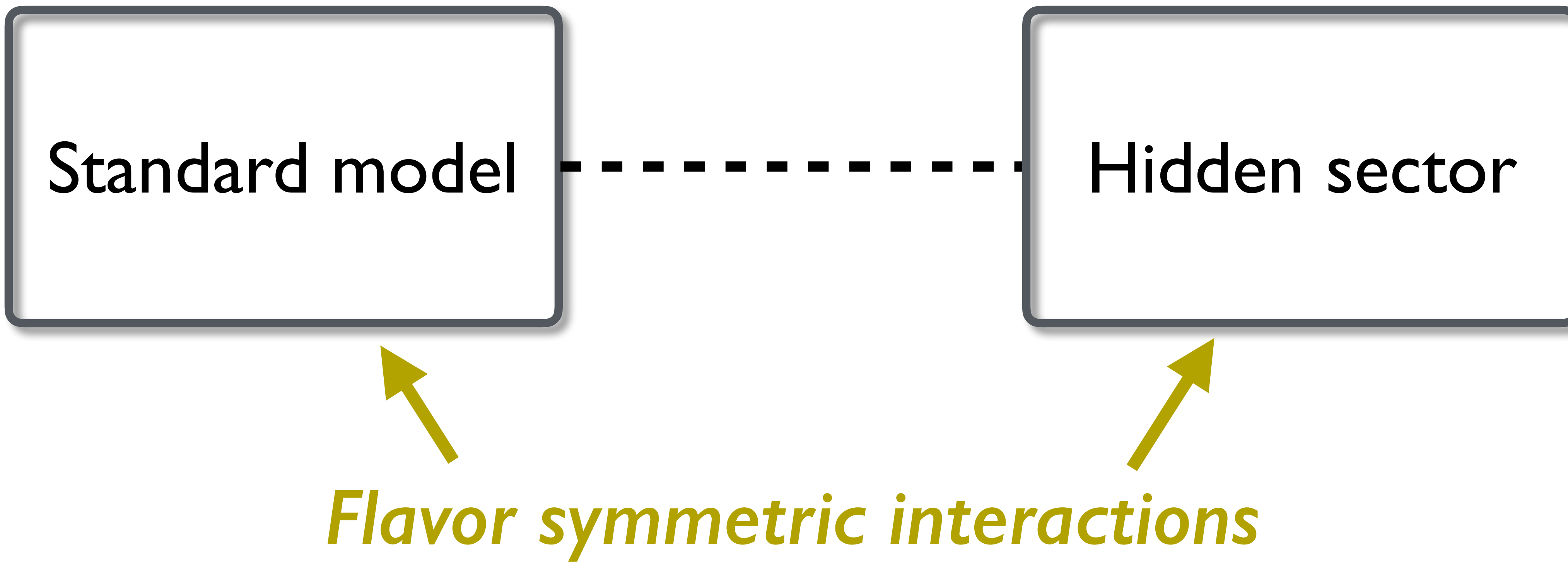
CKM =unit matrix → Flavor symmetry

Flavor symmetries are respected at high energy??

➡ radiatively generation of quark mixing

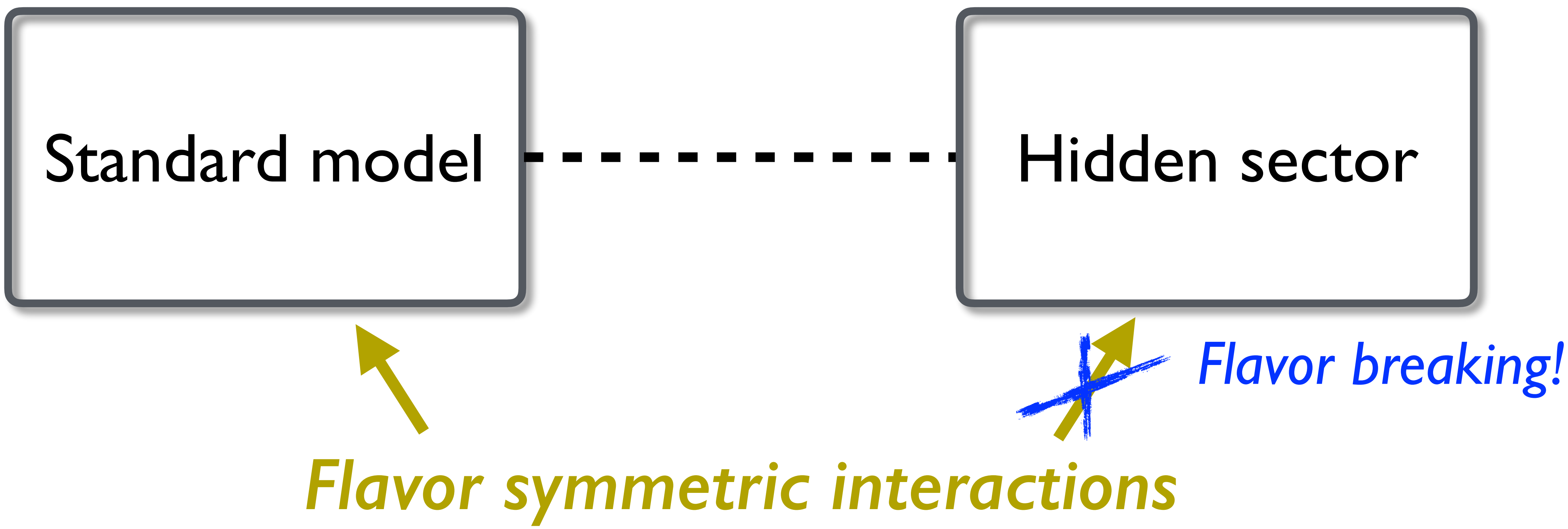
Rough sketch of generating flavor violation

@ high energy



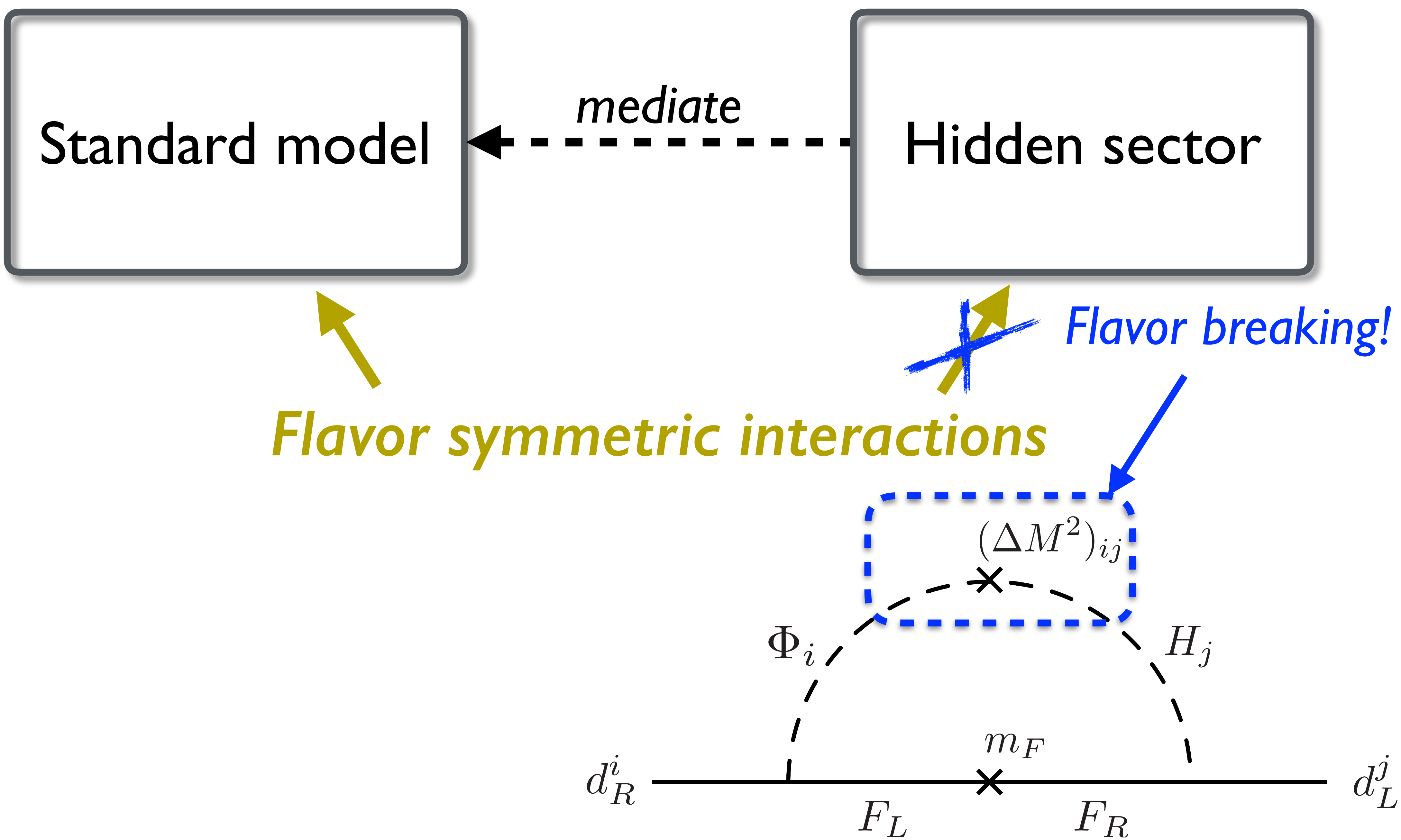
Rough sketch of generating flavor violation

above EW scale



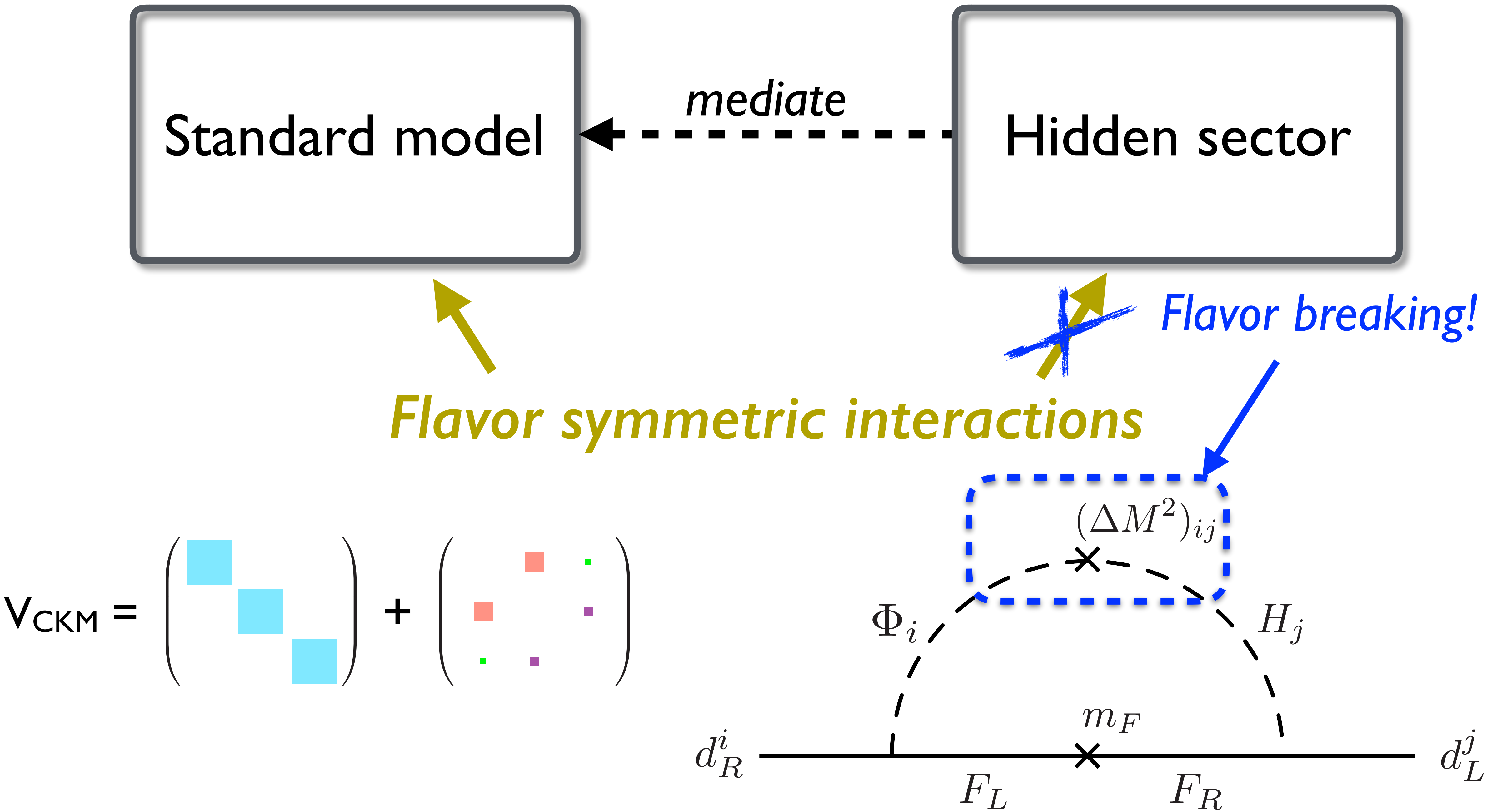
Rough sketch of generating flavor violation

<u>above EW scale</u>



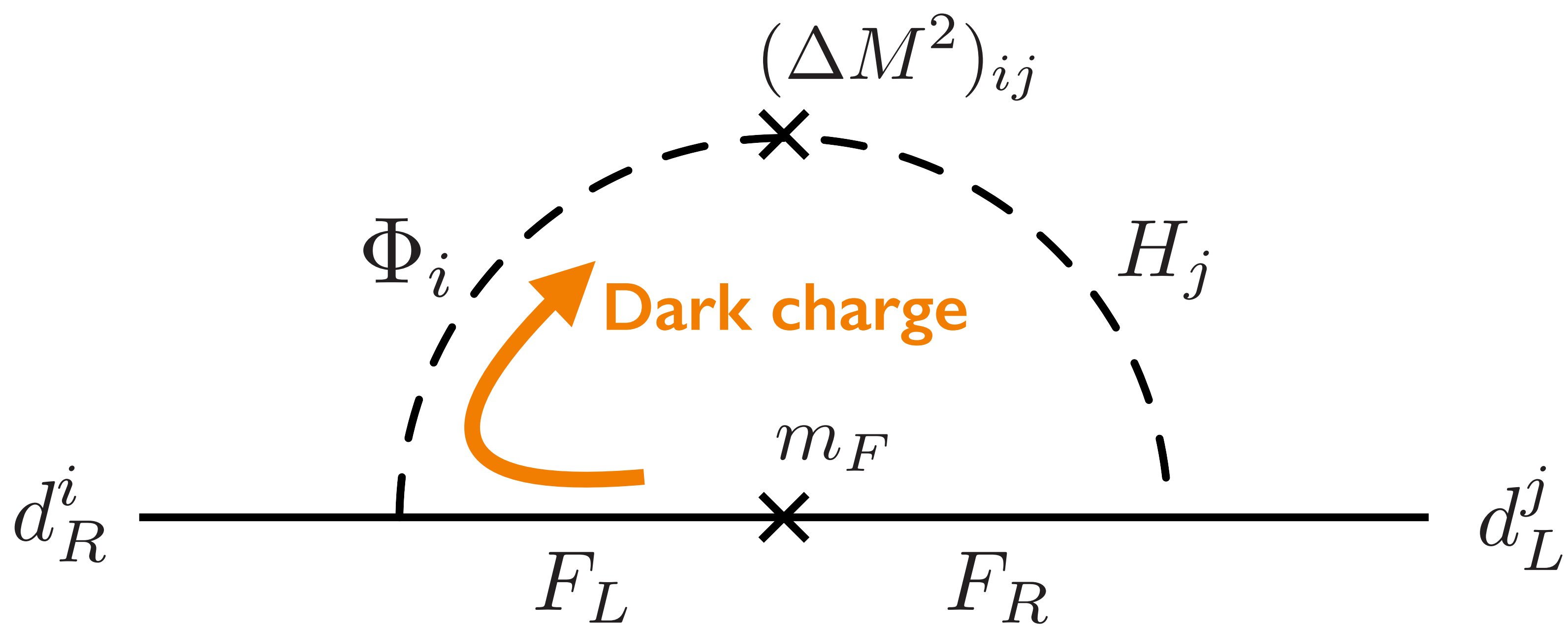
Rough sketch of generating flavor violation

above EW scale



Dark matter in the hidden sector

Flavor breaking effect is mediated at loop level:



The lightest neutral particle among Φ*i* and *Hj* can be DM candidate

(SO and Y.Omura, 1703.08789)

Setup

Setup

<Quarks and Scalars>

	Fields	spin	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	flavor charge
SM	$\hat{Q}_L^i$	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$1/6$	q_i
	$\hat{u}_R^i$	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	q_i
	$\hat{d}_R^i$	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	q_i
	H	0	$\mathbf{1}$	$\mathbf{2}$	$1/2$	0
DS	$F_{L,R}$	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	q_F
	Φ_i	0	$\mathbf{1}$	$\mathbf{1}$	0	$q_i - q_F$
	H_i	0	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$q_i - q_F$

<Yukawa couplings>

$$\mathcal{L}_{\text{yukawa}} = y_u^i \overline{\hat{Q}_L^i} \widetilde{H} \hat{u}_R^i + y_d^i \overline{\hat{Q}_L^i} H \hat{d}_R^i + \hat{\lambda}_i \overline{F_L} \Phi_i^\dagger \hat{d}_R^i + \hat{\kappa}_i \overline{\hat{Q}_L^i} H_i F_R$$

$\rightarrow$

tree level mass (diagonal):

$$(M_u^{(0)})_{ij} = \frac{y_u^i v}{\sqrt{2}} \delta_{ij}, \quad (M_d^{(0)})_{ij} = \frac{y_d^i v}{\sqrt{2}} \delta_{ij}$$

<Trilinear coupling>

$$\mathcal{L}_{\text{tri}} = \sum_i A_i \Phi_i H_i^\dagger H + h.c.$$

+ lots of quartic couplings

Setup

Assumptions

- Flavor breaking effect appears in scalar mass matrix
- Light scalars dominate the contributions to quark mixing

After flavor breaking,

$$\Phi_i \to c_\Phi^{ij} \widetilde{\Phi}_j = c_X X + \cdots$$

$$H_i \to c_H^{ij} \widetilde{H}_j = c_{H_D} H_D + \cdots$$

(X, H_D : lightest eigenstate)

Lagrangian is approximate to

$$\mathcal{L}_{\text{yukawa}}^{\text{app}} = y_u^i \overline{\hat{Q}_L^i} \widetilde{H} \hat{u}_R^i + y_d^i \overline{\hat{Q}_L^i} H \hat{d}_R^i + \lambda_i \overline{F_L} X^\dagger \hat{d}_R^i + \kappa_i \overline{\hat{Q}_L^i} H_D F_R + \ldots$$

$$\mathcal{L}_{\text{tri}}^{\text{app}} = A X H_D^\dagger H + h.c. + \ldots$$

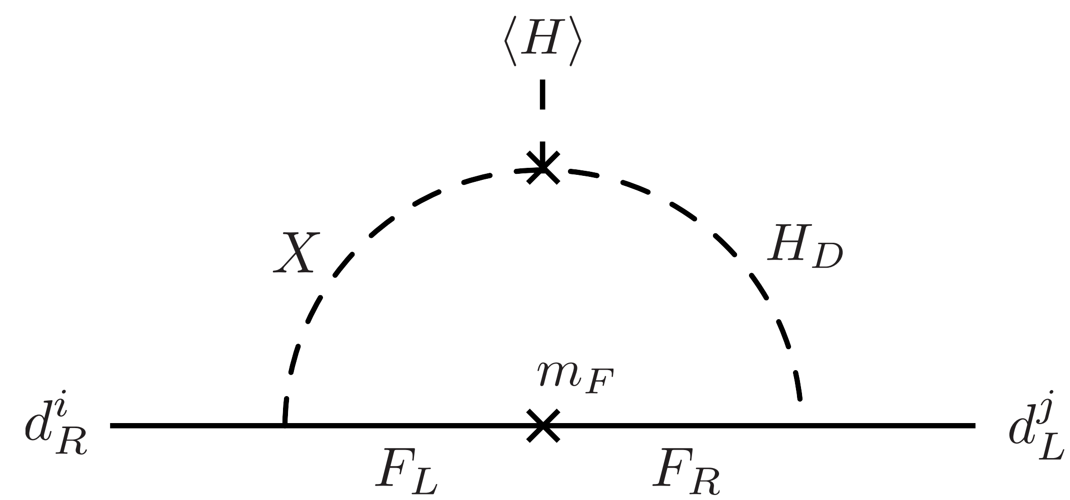
Generation of realistic yukawa couplings

How large coupling is needed ?

radiatively induced mass matrix:

$$(M_d)_{ij} = \frac{v}{\sqrt{2}} \left(y_d^i \delta_{ij} + \epsilon \kappa_i \lambda_j \right)$$

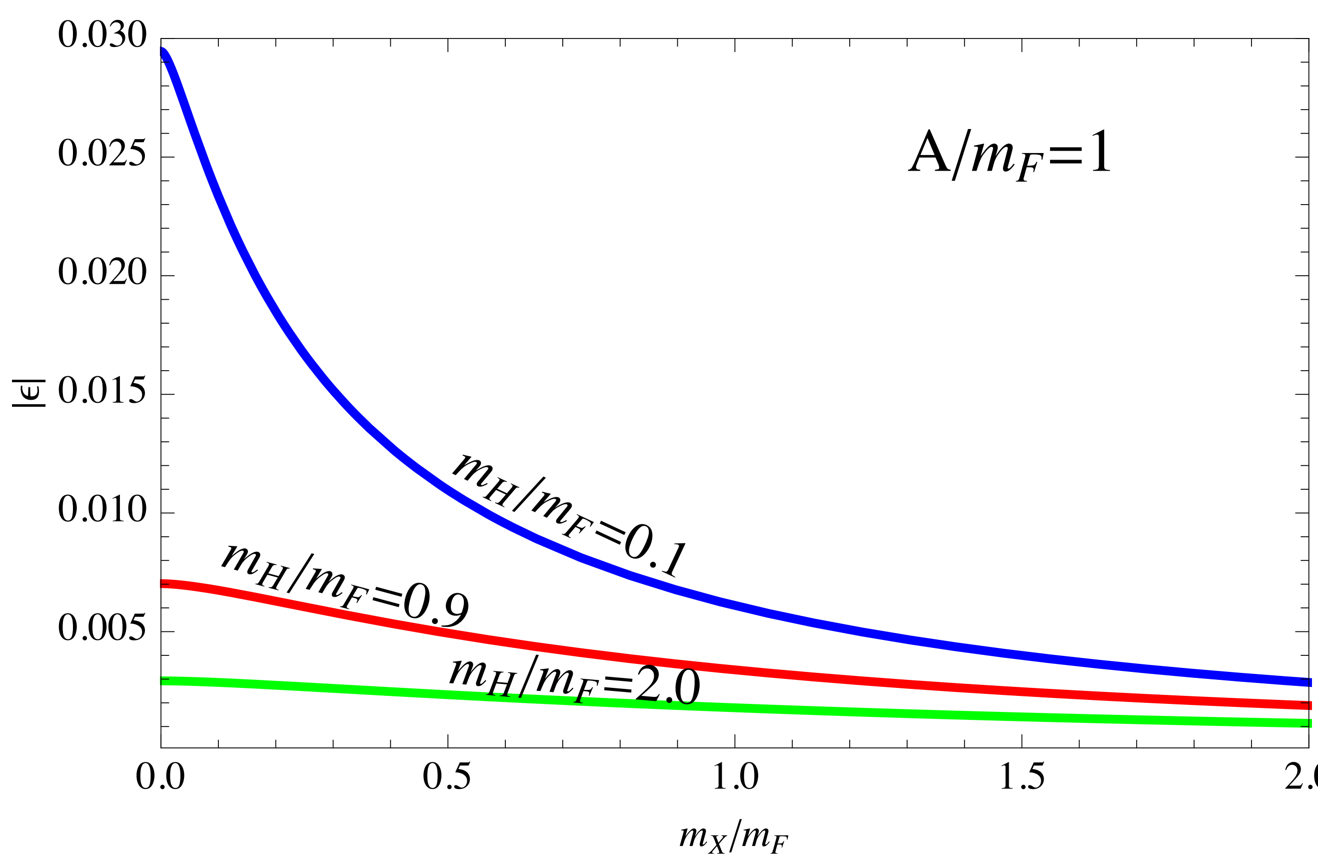
$$\epsilon = \frac{1}{16\pi^2} \frac{A}{m_F} \mathcal{Y}(m_{H_D}^2/m_F^2, m_X^2/m_F^2)$$



In mass eigenbasis,

$$(\lambda V_R^\dagger)_i \overline{F_L} X^\dagger d_R^i + (V\kappa)_i \overline{Q_L^i} H_D^0 F_R$$

$$\widetilde{\lambda}_i \equiv \lambda_j V_{Rji}^\dagger, \quad \widetilde{\kappa}_i \equiv V_{ij} \kappa_j$$



- ✓ $|\varepsilon| = O(10^{-2}) - O(10^{-3})$
- ✓ lighter scalar has more contribution
- ✓ λ's, κ's = O(1) - O(0.01) are required

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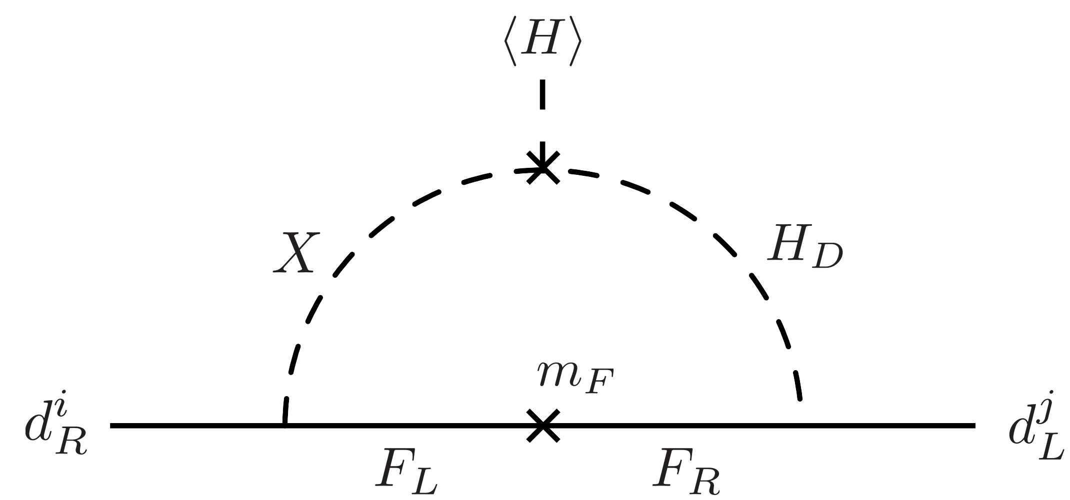

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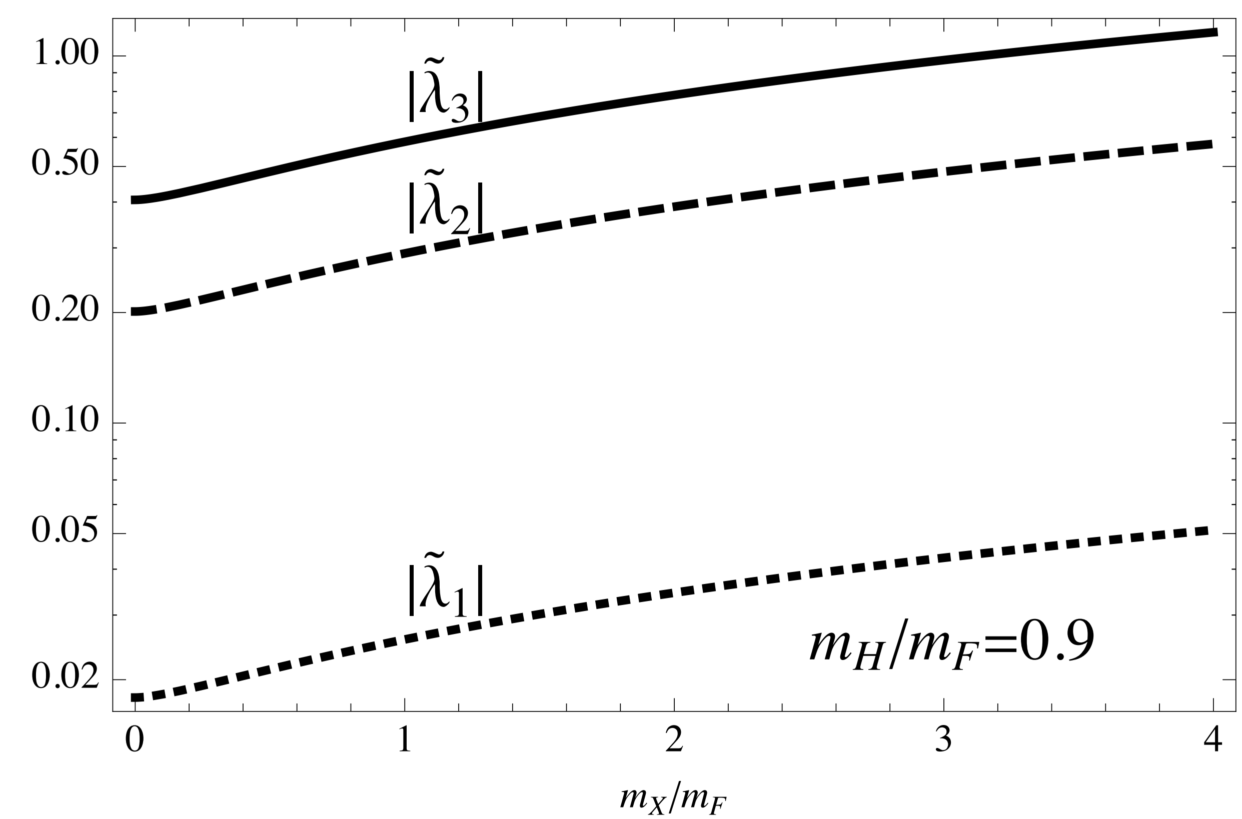

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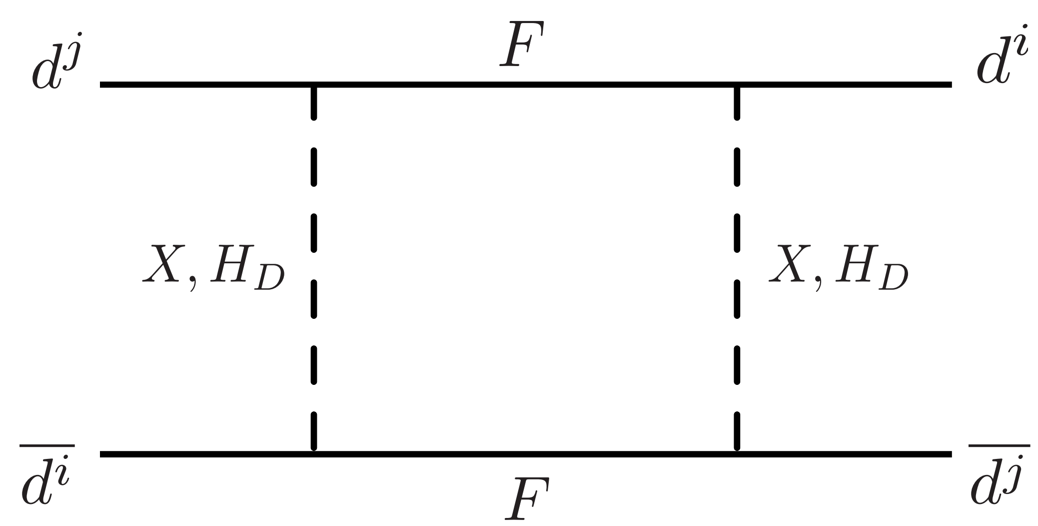
Phenomenology

Flavor and CP violation

Yukawa's are new source of flavor and CP violation

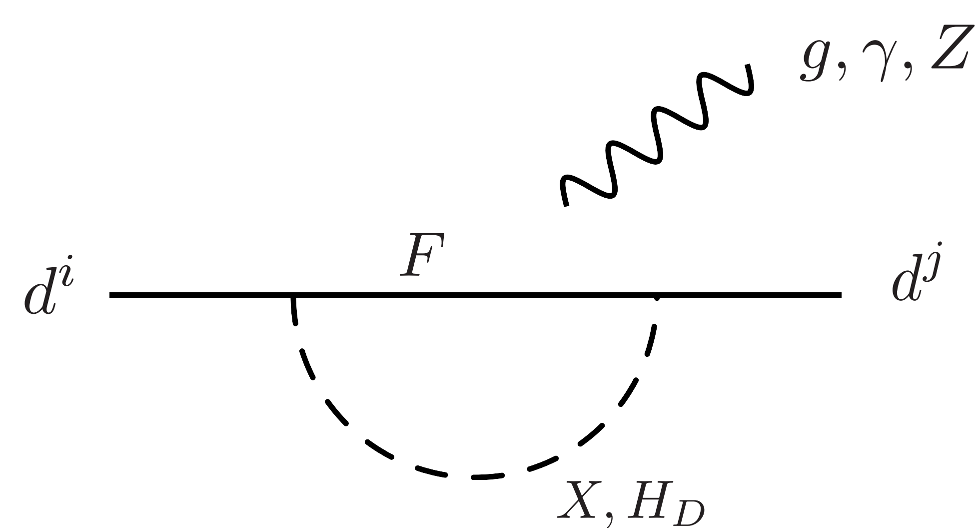
ΔF=2 processes

K0-K0 mixing
Bd-Bd mixing
Bs-Bs mixing
...



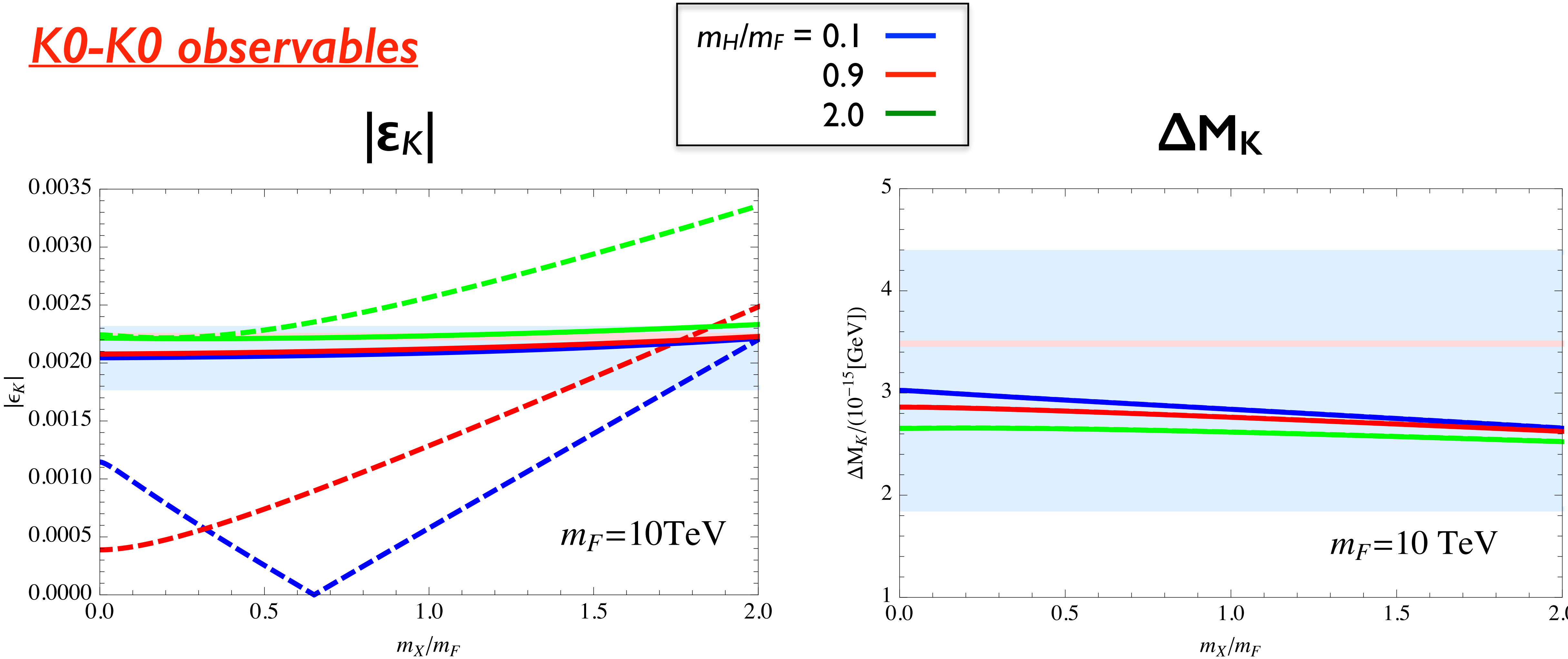
ΔF=1 processes, EDMs

b->sγ,
neutron EDM,
atom EDM,
...



ΔF=2 processes

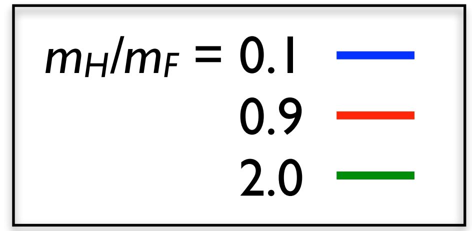
K0-K0 observables



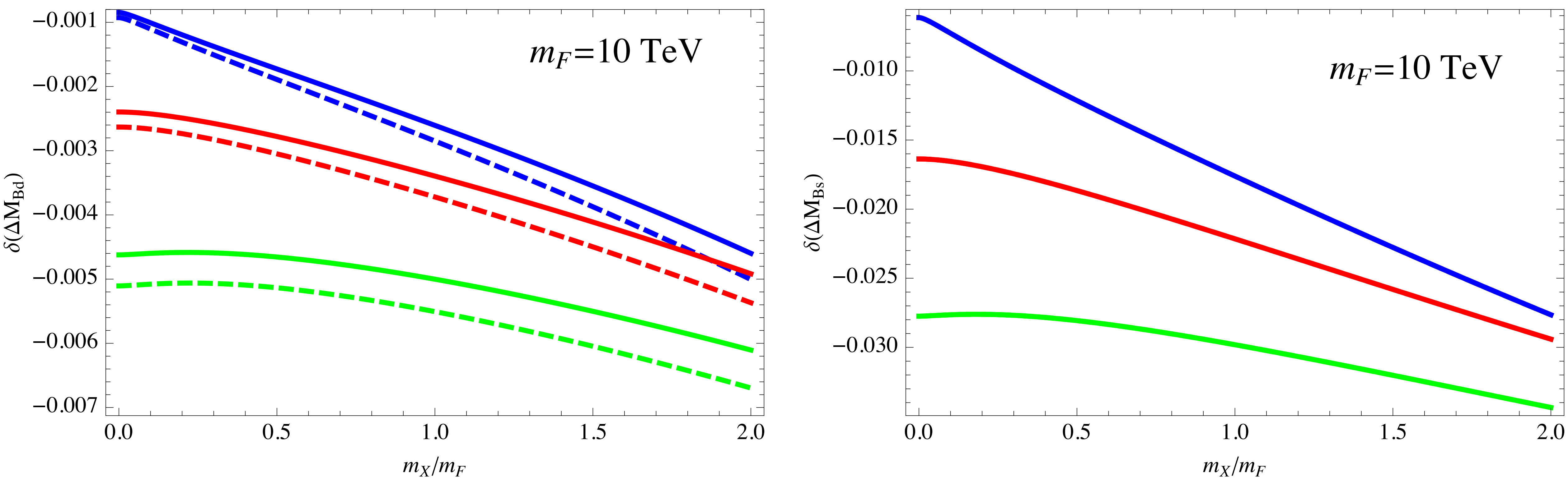
- ✓ bands: experimental result within 1σ
- ✓ lines: prediction in our model
  (solid: only CKM phase, dashed lines: +another new phase)
- ✓ $|\varepsilon_K|$ gives strongest bound, while ΔM_K has still large uncertainty
- ✓ m_F >O(10TeV) is allowed

ΔF=2 processes

B-Bbar observables



δ(ΔM_{Bd}) **δ(ΔM_{Bs})**



✓ deviations from the SM are allowed up to ~10%

✓ our model (m_F =10TeV): |δ(ΔMBd)| = O(10^{-3})

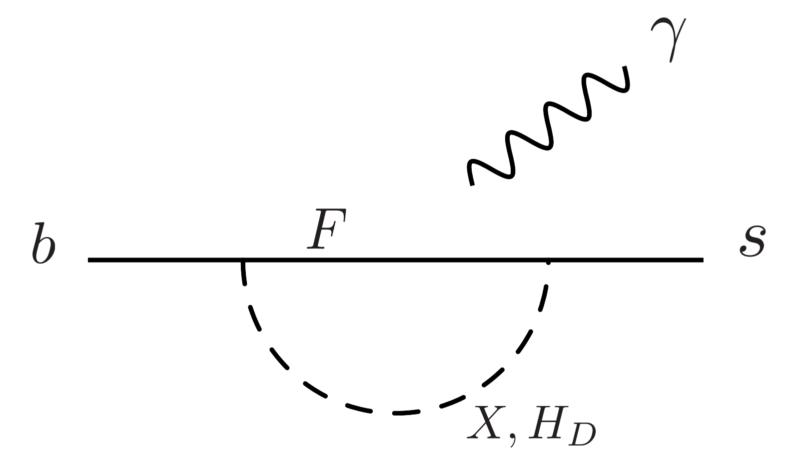
|δ(ΔMBs)| = O(10^{-2})

Other flavor and CP violating processes

B -> $X_s\gamma$

$$\mathcal{H}_{\rm eff}^{b\to s\gamma} = -g_{SM}\left\{C_7(\overline{s_L}\sigma^{\mu\nu}b_R)F_{\mu\nu} + C_7'(\overline{s_R}\sigma^{\mu\nu}b_L)F_{\mu\nu}\right\}$$

$$\left(g_{SM} = \frac{e m_b}{16\pi^2}\frac{4G_F}{\sqrt{2}}V_{ts}^* V_{tb} \right)$$



- ✓ ε_K bound: ◯ ⇒ B->$X_s\gamma$: ◯
- ✓ $C_7 = O(10^{-3})$ leads at most a few % correction

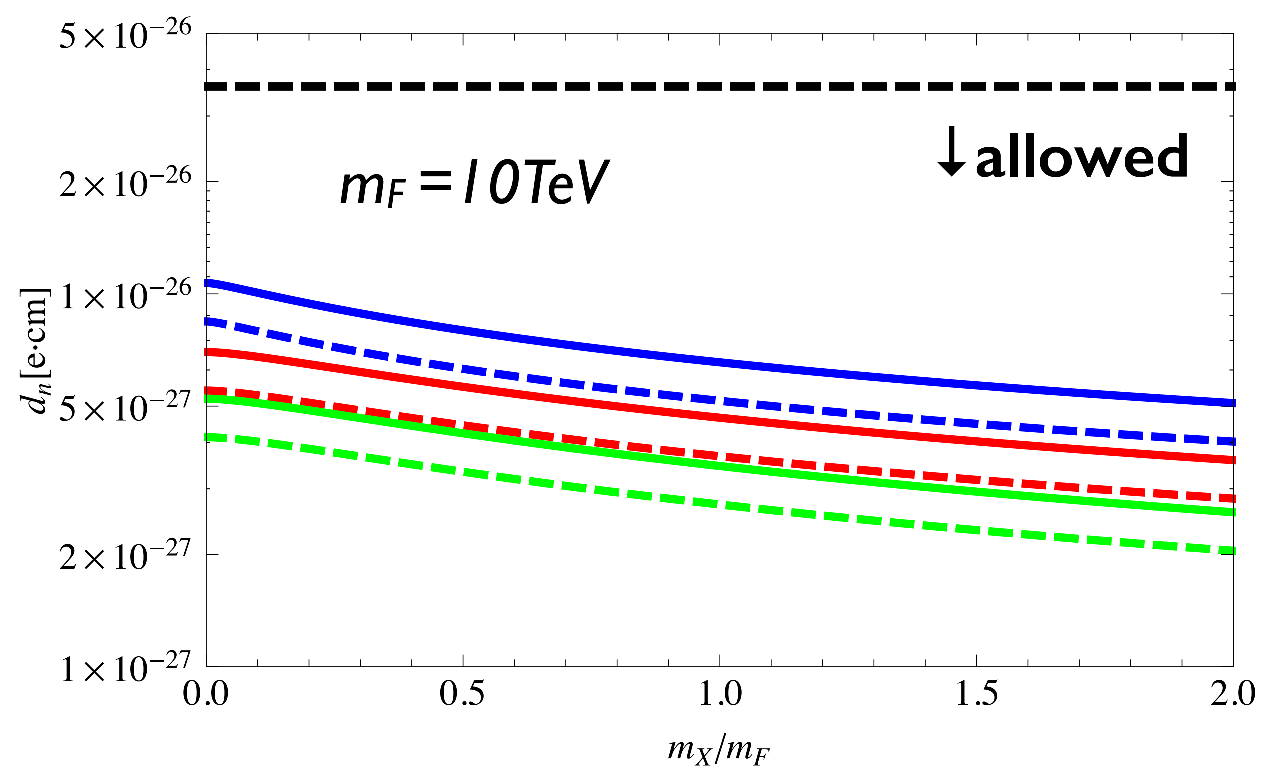
Electric dipole moment (EDM)

- ✓ neutron EDM bound:

  $|d_n| < 3.6\times 10^{-26}$ [e cm]

- ✓ our model (m_F =10TeV):

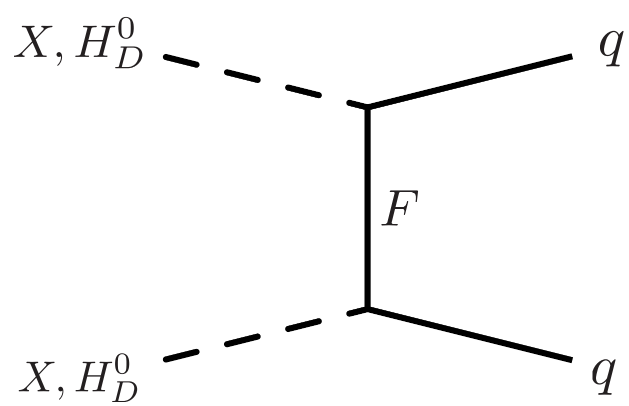
  $|d_n| = O(10^{-26})$-$O(10^{-27})$ [e cm]



DM candidates and interactions

We have two possible candidates: X or H_D^0

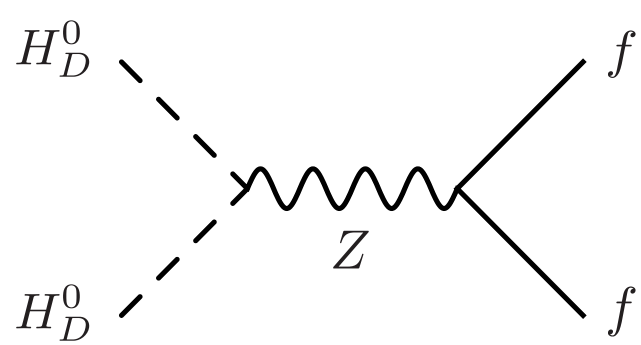
<u>VLQ exchange</u>



- ✓ p-wave dominant
- ✓ m_F > O(10TeV)

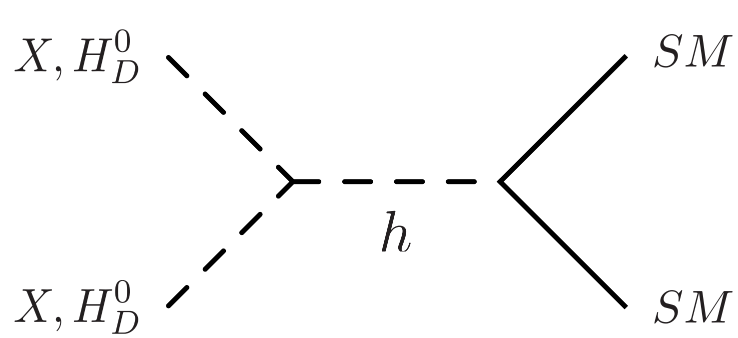
  ⇒ too small to achieve the observed density

<u>Z exchange</u>



- ✓ stringent direct detection bound
- ✓ need allow a term like $[(H_D^\dagger H)^2 + h.c.]$ to split CP even and odd scalars

<u>Higgs exchange</u>



- ✓ lower bound ~ several hundred GeV
- ✓ *XX, H_DH_D -> WW, ZZ, hh*
- ✓ dominant annihilation process

Constraints on DM

requirement from vacuum stability: $\frac{m_X m_H}{m_F^2} \gtrsim \mathcal{O}(0.01)$

singlet-like (DM~X)

✓ similar to minimal Higgs portal [V. Silveira and A. Zee (1985); J. McDonald (1994); etc.]

✓ mass ~ O(1TeV) - O(10TeV) ⇒ σ_{SI} ~ 1.7×10^{-9} [pb]

[Escudero, Berlin, Hooper, Lin, 1609.09079; etc.]

✓ XENON-1T can cover all mass region

[E. Aprile et al. (XENON collaboration), 1512.07501]

doublet-like (DM~H_D)

✓ DM is inert Higgs like

⇒ mass splitting b/w CP even and odd scalars of neutral H_D

⇒ a dark symmetry must be Z_2, not U(1)

✓ mass difference ~ O(10GeV) [Goudelis, Herrmann, Stal, 1303.3010; Arhrib, Tsai, Yuan, Yuan, 1310.0358; Ilnicka, Krawczyk, Robens, 1508.01671; Diaz, Koch, Quiroga, 1511.04429; Belyaev, Cacciapaglia, Rojas, Thomas, 1612.00511; etc.]

Summary

- We discuss a radiatively generating CKM model with complex scalars (*Xi*, *Hj*) and a vector-like quark *F*:
  - ✓ ε_K and EDMs cannot be made small at the same time
  - ✓ the lightest scalar can be DM candidate: DM mass ~ O(1TeV) - O(10TeV)
  - ✓ XENON-1T can cover almost DM mass region

- Future works:
  - ✓ Flavor violating sector?
  - ✓ other scalars' contributions
  - ✓ another setup?

Thanks for your attention!