CP Violating Dark Photon Kinetic Mixing and Type-III Seesaw

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Introduction

Dark photon

↓

Abelian/Non-Abelian kinetic mixing

↓

CP violating kinetic mixing

↓

Renormalizable CP violating kinetic mixing

Dark photon

Dark sectors — **portal** — **visible sectors**

↓

No charge under SM gauge groups

Portal

- **Spinor: Neutrino** $\bar{L}NH$
- **Scalar: Higgs** $SH^\dagger H,\ S^2H^\dagger H$
- **Pseudo-scalar: Axion** $(a/f_a)F\tilde{F}$
- **Vector: dark photon** $U(1)_Y \times U(1)_X$

$$L = -\frac{1}{4}Y_{\mu\nu}Y^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + j_Y^{\mu}Y_\mu + j_X^{\mu}X_\mu$$

No direct interaction with SM particle

Abelian kinetic mixing

$\epsilon X_{\mu\nu} F^{\mu\nu}$

1. **Renormalizable dimension 4 operator**
2. **Enlighten : dark photon interacts with SM particles**

Gauge group $SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_X$

$$L = -\frac{1}{4} Y_{\mu\nu} Y^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + j_Y^{\mu} Y_\mu + j_X^{\mu} X_\mu - \frac{\epsilon}{2} X_{\mu\nu} Y^{\mu\nu}$$

Rewrite in the canonical form to identify physical guage boson (remove mixing term)

Holdom 1986, Foot&He 1991

Non-Abelian kinetic mixing

$W^a_{\mu\nu} X^{\mu\nu}$ → **Not gauge invariant**

How to contract index a

1. triplet scalar Σ^a $\quad < \Sigma^a >= v_\Sigma/\sqrt{2}$

gauge singlet $W^a_{\mu\nu} X^{\mu\nu} \Sigma^a$

non-renormalizable dimension 5

2. Higher order $W^a_{\mu\nu} X^{\mu\nu} (H^\dagger \tau^a H)$

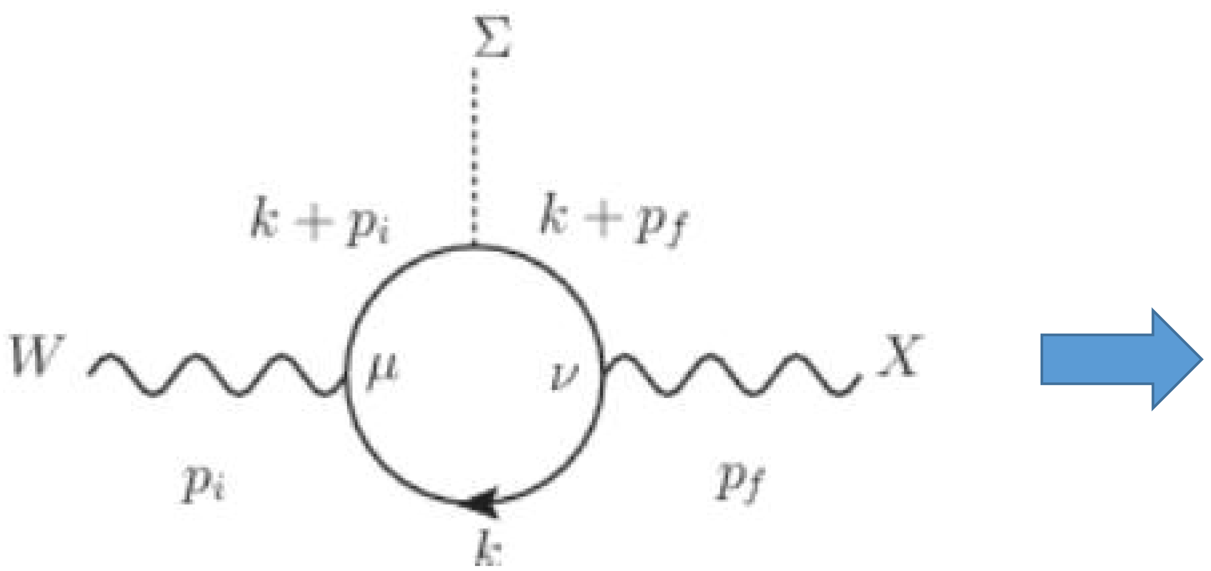
non-renormalizable dimension 6

Construct kinetic mixing between abelian and non-Abelian

arXiv: 1408.0233, PRD94(2016)055018, PLB770(2017)101

Non-Abelian kinetic mixing

Generate the kinetic mixing from renormalizable theory?



$$W^a_{\mu\nu} X^{\mu\nu} \Sigma^a$$

Generate the kinetic mixing at loop level

Non-abelian kinetic mixing $W^a_{\mu\nu} Y^{b\mu\nu} \Sigma^{ab}$

CP violation

1. Abelian

- **CP conserving** $X_{\mu\nu}Y^{\mu\nu}$
- **CP violating** $Y^{\mu\nu}\tilde{X}_{\mu\nu} = -\frac{\epsilon_{\mu\nu\alpha\beta}}{2}\partial^{\alpha}(Y^{\mu\nu}X^{\beta})$

2. Non-Abelian

$$\mathcal{L}_X = -\frac{\beta_X}{\Lambda}Tr(W_{\mu\nu}\Sigma)X^{\mu\nu} - \frac{\tilde{\beta}_X}{\Lambda}Tr(W_{\mu\nu}\Sigma)\tilde{X}^{\mu\nu}$$

$$-\frac{\beta_X}{2\Lambda}X^{\mu\nu}\left(s_W F_{\mu\nu} + c_W Z_{\mu\nu} + ig(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)\right)(v_\Sigma + \Sigma^0)$$

$$-\frac{\tilde{\beta}_X}{2\Lambda}\tilde{X}^{\mu\nu}\left[(s_W F_{\mu\nu} + c_W Z_{\mu\nu})\Sigma^0 + ig(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)(v_\Sigma + \Sigma^0)\right]$$

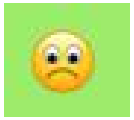
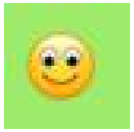
CP violating non-Abelian kinetic mixing

PRD101(2020)075016

Renormalizable CP violation

Renormalizable CPV non-Abelian kinetic mixing?

New fields generate the operator from loop order

- **Scalar: No generate CPV due to tensor** 
- **Fermion: SU(2)$_L$ multiplet** 

Type-III seesaw model

$$f = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} & \Sigma^+ \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} \end{pmatrix} \Rightarrow (\bar{\nu}_L, \bar{f}^c) \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ f \end{pmatrix}$$

Lepton triplet

Z.Phys.C 44 (1989) 441

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Renormalizable CPV kinetic mixing model

Gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$

1. SM particles has no $U(1)_X$ charge

2. Triplet scalar $\Sigma^a = (1,3,0)(0)$ → $\epsilon^{\alpha\beta\mu\nu} X_{\alpha\beta} W^a_{\mu\nu} \Sigma^a$

3. Triplet fermion (No scalar) → **Type-III seesaw model**

$$f_1 = (1,3,0)(x_f), \quad f_2 = (1,3,0)(-x_f), \quad f_3 = (1,3,0)(0)$$

Gauge anomaly free

4. Singlet scalar → **dark photon and heavy neutrino mass**

$$S_X = (1,1,0)(-2x_f),$$

5. Higgs scalar → **Neutrino mass matrix**

$$H'_{1,2} : (1,2,-1/2)(\mp x_f)$$

Component field

$$f_R = \frac{1}{2}\begin{pmatrix} f_R^0 & \sqrt{2}f_R^+ \\ \sqrt{2}f_R^- & -f_R^0 \end{pmatrix},\; f_L = f_R^c = \frac{1}{2}\begin{pmatrix} (f_R^0)^c & \sqrt{2}(f_R^-)^c \\ \sqrt{2}(f_R^+)^c & -(f_R^0)^c \end{pmatrix}$$

$$\Sigma = \frac{1}{2}\begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}, W_\mu = \frac{1}{2}\begin{pmatrix} W_\mu^0 & \sqrt{2}W_\mu^+ \\ \sqrt{2}W_\mu^- & -W_\mu^0 \end{pmatrix}$$

$$-(\beta_X/\Lambda)\mathrm{Tr}(W_{\mu\nu}\Sigma)X^{\mu\nu} \qquad -(\tilde{\beta}_X/\Lambda)\mathrm{Tr}(W_{\mu\nu}\Sigma)\tilde{X}^{\mu\nu}$$

$$-\frac{1}{2}\left[(s_W F_{\mu\nu} + c_W Z_{\mu\nu}) + ig(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)\right](v_\Sigma + \Sigma^0)$$

Coupling Lagrangian

Quark Yukawa coupling

$$\mathcal{L}_Y(q) = -\bar{Q}_L Y_u H U_R - \bar{Q}_L Y_d \tilde{H} D_R + \text{H.c.}$$

Lepton Yukawa coupling

$$\mathcal{L}_Y(l) = -\bar{L}_L Y_e \tilde{H} E_R - \bar{L}_L Y_{fL3} \tilde{H} f_{R\,3} - \bar{f}^c_{R\,1} Y_{fs1} S_X f_{R\,1} \\ -\bar{f}^c_{R\,2} Y_{fs2} S_X^\dagger f_{R\,2} - \bar{f}^c_{R\,1} m_{12} f_{R\,2} - \bar{f}^c_{R\,3} m_{33} f_{R\,3} + \text{H.c.}$$

New added term

$$-\bar{L}_L Y_{fL1} H'_1 f_{R\,1} - \bar{L}_L Y_{fL2} H'_2 f_{R\,2}$$

Interaction Lagrangian

$$W^0/X - f_R \;\; \text{coupling}$$

$$\begin{aligned}\mathcal{L}_{int} = X_\mu \big[&\bar{f}^+_{R\,1}\gamma^\mu f^+_{R\,1} + \bar{f}^0_{R\,1}\gamma^\mu f^0_{R\,1} + \bar{f}^-_{R\,1}\gamma^\mu f^-_{R\,1} \\ &-\bar{f}^+_{R\,2}\gamma^\mu f^+_{R\,2} - \bar{f}^0_{R\,2}\gamma^\mu f^0_{R\,2} - \bar{f}^-_{R\,2}\gamma^\mu f^-_{R\,2}\big] g_X x_f \\ +W^0_\mu \big[&\bar{f}^+_{R\,1}\gamma^\mu f^+_{R\,1} - \bar{f}^-_{R\,1}\gamma^\mu f^-_{R\,1} \\ &+\bar{f}^+_{R\,2}\gamma^\mu f^+_{R\,2} - \bar{f}^-_{R\,2}\gamma^\mu f^-_{R\,2}\big] g\end{aligned}$$

$$\Sigma - f \;\; \text{coupling}$$

$$\mathcal{L}_{Y_{f\sigma}} = Y_{f\sigma 12}\left(\overline{(f^+_{R\,1})^c} f^+_{R\,2} - \overline{(f^-_{R\,1})^c} f^-_{R\,2}\right)(v_\Sigma + \Sigma^0) + \text{H.c.}$$

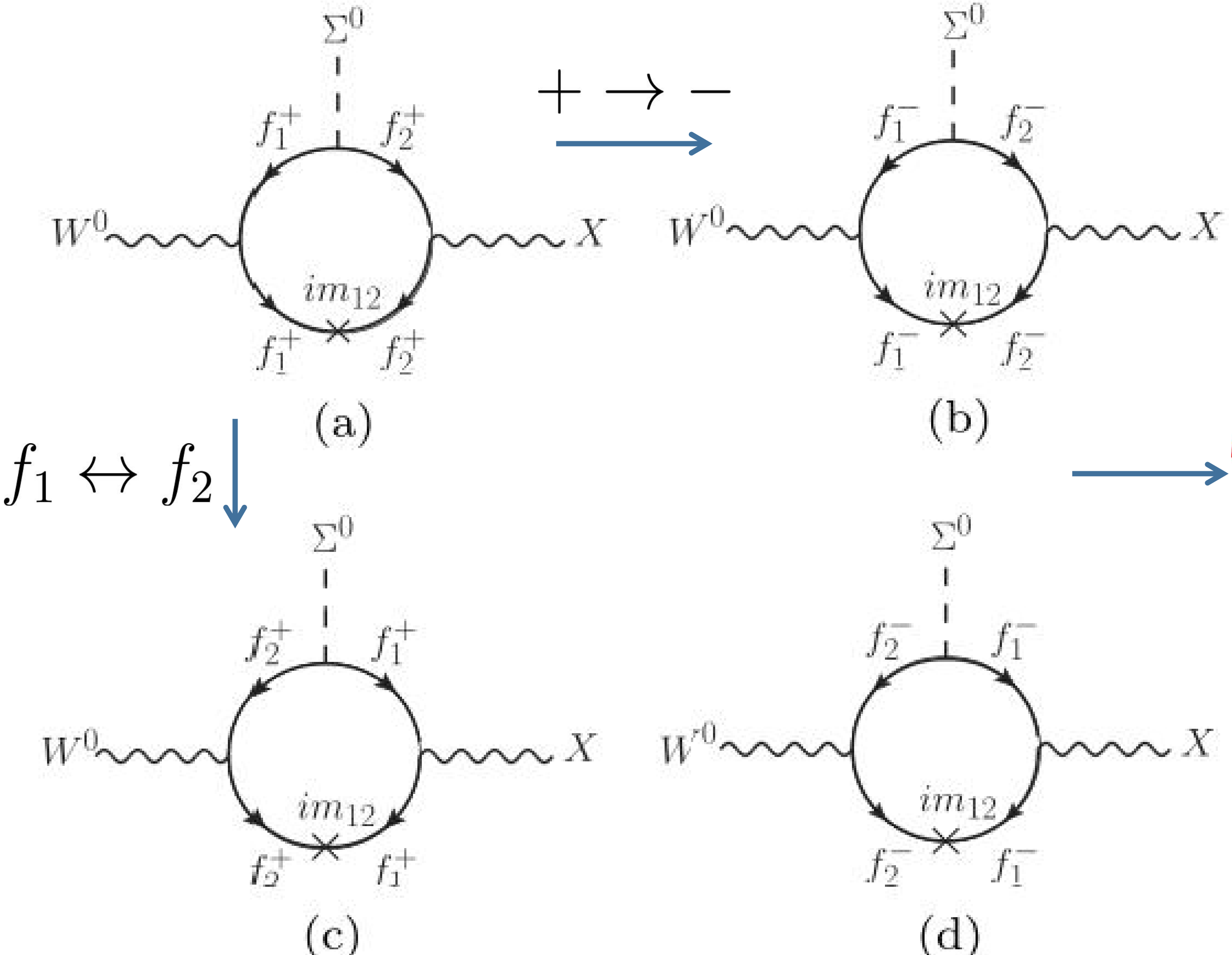
Lepton masses

$$\mathcal{L}_m = -\frac{1}{2}(\bar{\nu}_L, \bar{\nu}_R^c)\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

$$-(\bar{E}_L, \bar{f}_L)\begin{pmatrix} m_e & \sqrt{2}M_D \\ 0 & M_R \end{pmatrix}\begin{pmatrix} E_R \\ f_R \end{pmatrix}$$

$$M_D = \begin{pmatrix} \frac{Y_{fL11}v_1'}{\sqrt{2}} & \frac{Y_{fL12}v_2'}{\sqrt{2}} & \frac{Y_{fL13}v}{\sqrt{2}} \\ \frac{Y_{fL21}v_1'}{\sqrt{2}} & \frac{Y_{fL22}v_2'}{\sqrt{2}} & \frac{Y_{fL23}v}{\sqrt{2}} \\ \frac{Y_{fL31}v_1'}{\sqrt{2}} & \frac{Y_{fL32}v_2'}{\sqrt{2}} & \frac{Y_{fL33}v}{\sqrt{2}} \end{pmatrix} \quad M_R = \begin{pmatrix} \frac{Y_{fs1}v_s}{\sqrt{2}} & m_{12} & 0 \\ m_{12} & \frac{Y_{fs2}v_s}{\sqrt{2}} & 0 \\ 0 & 0 & m_{33} \end{pmatrix}$$

One loop kinetic mixing



$$\longrightarrow \mathrm{Tr}(W_{\mu\nu}\Sigma)\tilde{X}^{\mu\nu}$$

One loop kinetic mixing

$$M^{\mu\nu} = \frac{i}{4\pi^2} g g_X x_f m_{12} Y^*_{f\sigma} \epsilon^{\mu\nu\alpha\beta} p_{X\alpha} p_{W\beta}$$

No scalar

$$\times \left(f(m_1, m_2, p_W, p_X) + f(m_2, m_1, p_W, p_X)\right)$$

$$f(m_1, m_2, p_W, p_X) = \int_0^1 dx \int_0^{1-x} dy (1-x-y)$$

$$\times \left[D(m_1, m_2, p_W, p_X) + D(m_2, m_1, p_X, p_W)\right]$$

$$D(m_1, m_2, p_W, p_X) = \frac{m_1^2}{(m_1^2 - m_2^2)}$$

$$\times \frac{1}{(m_1^2 - y(m_1^2 - m_2^2) - x p_W^2 - y p_X^2 + (x p_W - y p_X)^2)}$$

CPC and CPV kinetic mixing

$$\mathcal{L}_X \to -\frac{\tilde{\beta}_X}{2\Lambda}\tilde{X}^{\mu\nu}\left[(s_W F_{\mu\nu} + c_W Z_{\mu\nu})\right](v_\Sigma + \Sigma^0)$$

$$\downarrow \quad 2\epsilon^{\mu\nu\alpha\beta} p_{X\alpha} p_{W\beta} \epsilon_{W\mu} \epsilon^*_{X\nu} \to -\tilde{X}^{\mu\nu} W^0_{\mu\nu}$$

CP conserving

$$\frac{\beta_X}{\Lambda} = \frac{1}{2\pi^2} g g_X x_f \mathrm{Re}(m_{12} Y^*_{f\sigma}) \times \left[f(m_1, m_2, p_W, p_X) + f(m_2, m_1, p_W, p_X)\right]$$

CP violating

$$\frac{\tilde{\beta}_X}{\Lambda} = \frac{1}{2\pi^2} g g_X x_f \mathrm{Im}(m_{12} Y^*_{f\sigma}) \times \left[f(m_1, m_2, p_W, p_X) + f(m_2, m_1, p_W, p_X)\right]$$

Gauge field Lagrangian

$$\mathcal{L}_{KM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu}$$ **kinetic term**

$$+\frac{1}{2}m_Z^2 Z_\mu Z^\mu + \frac{1}{2}m_X^2 X_\mu X^\mu$$ **mass term**

$$-\frac{1}{2}\epsilon_{AX} F_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\epsilon_{ZX} Z_{\mu\nu}X^{\mu\nu}$$ **kinetic mixing**

$$\epsilon_{AX} = \alpha_{XY} c_W + \beta_X s_W v_\Sigma / \Lambda$$

$$\epsilon_{ZX} = -\alpha_{XY} s_W + \beta_X c_W v_\Sigma / \Lambda$$

$$-(1/2)\alpha_{XY} X^{\mu\nu} B_{\mu\nu}$$

Mass eigen-state

leading order

$$\begin{pmatrix} A \\ Z \\ X \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\epsilon_{AX} \\ 0 & 1 & -\xi - \epsilon_{ZX} \\ 0 & \xi & 1 \end{pmatrix} \begin{pmatrix} A^m \\ Z^m \\ X^m \end{pmatrix}$$

$$\xi \approx -m_Z^2 \epsilon_{ZX} / (m_Z^2 - m_X^2)$$

$$\mathcal{L} = J^\mu_{em} A_\mu + J^\mu_Z Z_\mu + J^\mu_X X_\mu$$

$$\downarrow$$

$$\mathcal{L}^m$$

Numerical analysis

$$\frac{\tilde{\beta}_X}{\Lambda} = \frac{1}{2\pi^2} g g_X x_f \mathrm{Im}(m_{12} Y^*_{f\sigma}) \times \left[f(m_1, m_2, p_W, p_X) + f(m_2, m_1, p_W, p_X)\right]$$

degenerate $m_1 \approx m_2 \approx |m_{12}| \approx m$

$$\tilde{\beta}_X v_\Sigma/\Lambda \approx g g_X x_f |Y^*_{f\sigma}| v_\Sigma \sin\delta / 6\pi^2 m < 5 \sin\delta \times 10^{-4}$$

$\cos\delta$

$$\rho - 1 = \frac{4 v_\Sigma^2}{v^2} = 0.00038 \pm 0.00020 \longrightarrow v_\Sigma < 3\mathrm{GeV}$$

$$m > 790\mathrm{GeV(ATLAS)},\ 880\mathrm{GeV(CMS)}$$

$$g_X x_f \approx Y_{f\sigma} \approx \sqrt{4\pi}$$

EPJC81(2021)3,218, JHEP03(2020), 051

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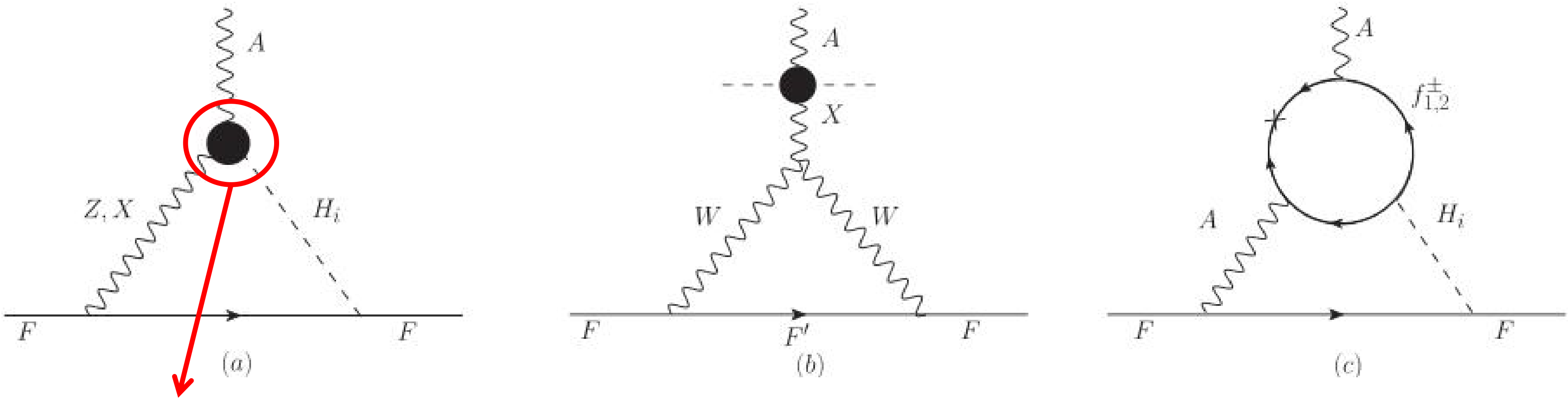
EDM

The EDM d_F for a SM fermion F



$\tilde{\beta}_X$ at one loop level → **Two loop(dominant)**

No A-X mixing → $d_q \approx 0$

Barr-Zee → **Cancel**

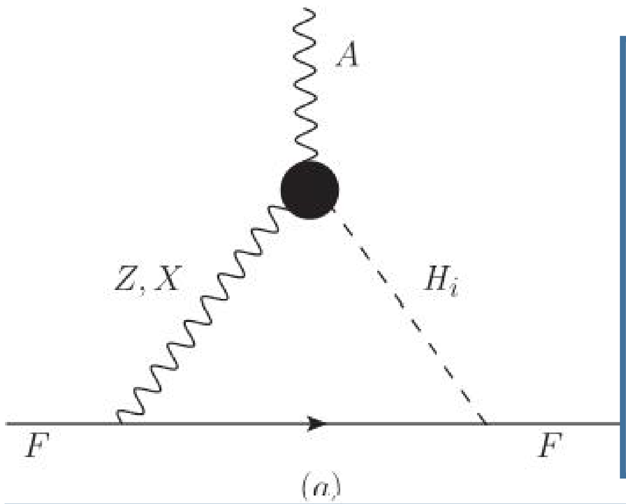
Phys.Rev.D101(2020)7,075016

EDM

$$L^{EDM} = -\frac{i}{2} d_F \bar{F} \sigma^{\mu\nu} \gamma_5 F F_{\mu\nu}$$

$$d_F = \frac{e}{8\pi^2} \frac{m_F}{v} \sum_{i=[1,N-1]} V_{\Sigma i} V_{hi} [C_Z V_Z^F f(m_Z^2/m_{H_i}^2, m_Z^2/m_{H_\Sigma}^2)$$
$$+ C_X V_X^F f(m_X^2/m_{H_i}^2, m_X^2/m_{H_\Sigma}^2)]$$

mixing



$$V_Z^F = (c_\xi - \epsilon_{ZX} s_\xi) \frac{g_Z^F}{c_W s_W} - Q_F \epsilon_{AX} s_\xi$$

$$V_X^F = -(s_\xi + \epsilon_{ZX} c_\xi) \frac{g_Z^F}{c_W s_W} - Q_F \epsilon_{AX} c_\xi$$

$$s_\xi \approx -\epsilon_{ZX} m_Z^2 / (m_Z^2 - m_X^2)$$

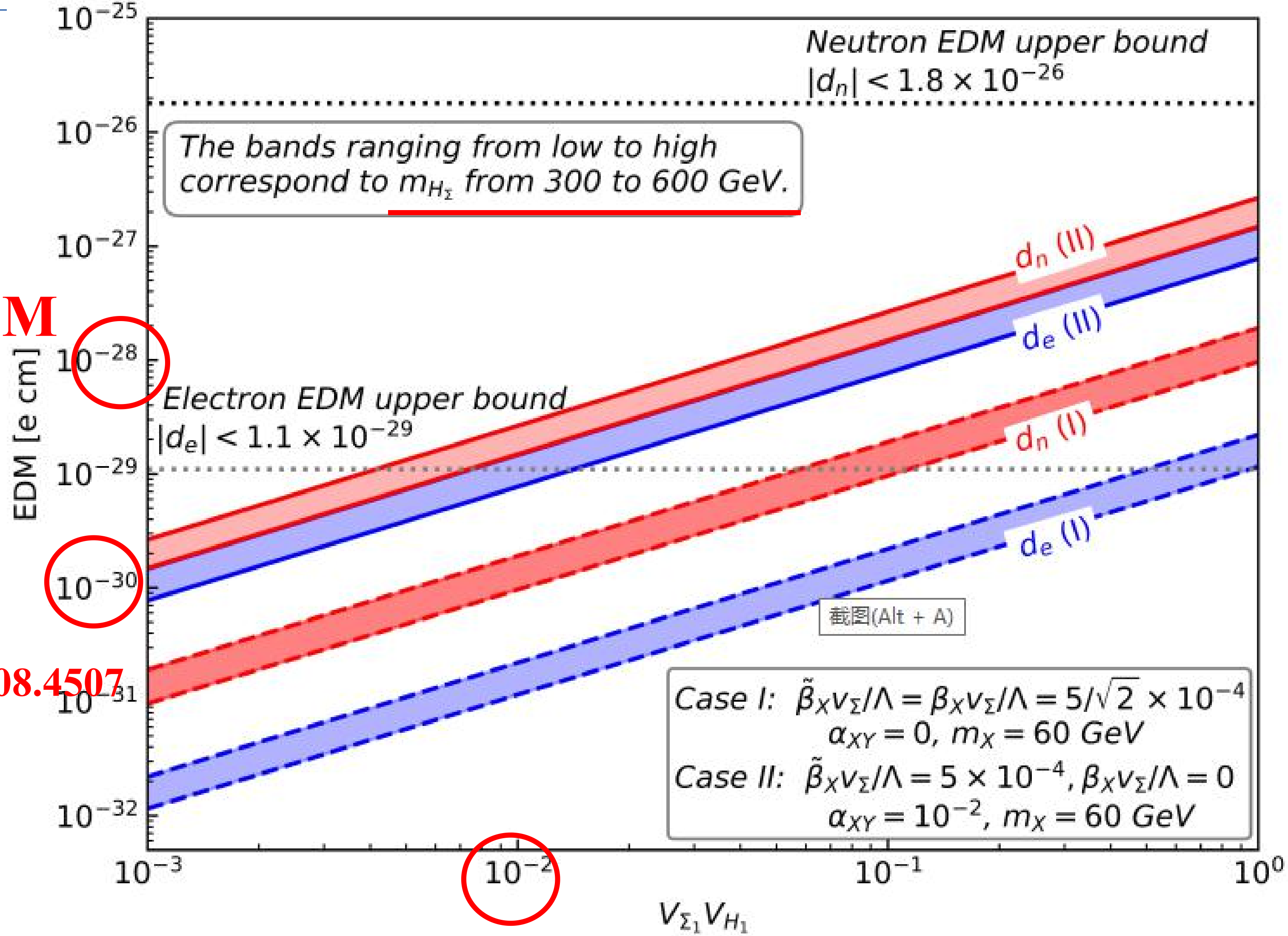
$$C_Z = \frac{\tilde{\beta}_X}{\Lambda} s_W s_\xi \,, \quad C_X = \frac{\tilde{\beta}_X}{\Lambda} s_W c_\xi \,, \quad g_Z^F = \frac{I_3^F}{2} - Q_F s_W^2$$

$$f(x,y) = (1/2)(\ln(y/x) - (x \ln x/(1-x) - y \ln y/(1-y)))$$

EDM

n2EDM

arXiv:1208.4507



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Conclusions

1. We construct for the first time a renormalizable dark photon model with CP violating kinetic mixing in combination with the type-III seesaw model.

2. We find that CP violating kinetic mixing induced interaction dominates the contribution to electron EDM which can be as large as experimental bound.

3. The model provides a bridge connecting dark photon, neutrino physics and also CP violation, and can be directly tested by near future EDM measurements.

https://indico-tdli.sjtu.edu.cn/event/769/

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Welcome!

Thanks!