Dark photon mixing effects and CP violation

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Based on arXiv: 2104.11563, 2204.10156, 2310.06526, 2503.21083

Work with Xiao-Gang He, Michael J. Ramsey-Musolf, Wei Liu, Zhi-Peng Xing, Fei Huang, Yu Cheng

CLHCP2025, Henan Normal University, 31/10/25

Research logic

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Dark photon

↓

Mixing effects

↙ ↘

Kinetic mixing | **Mass mixing**

Abelian | **Non-Abelian** | **New scalars**

↓

phenomenology

CP violation, EW bounds, DM,

Introduction

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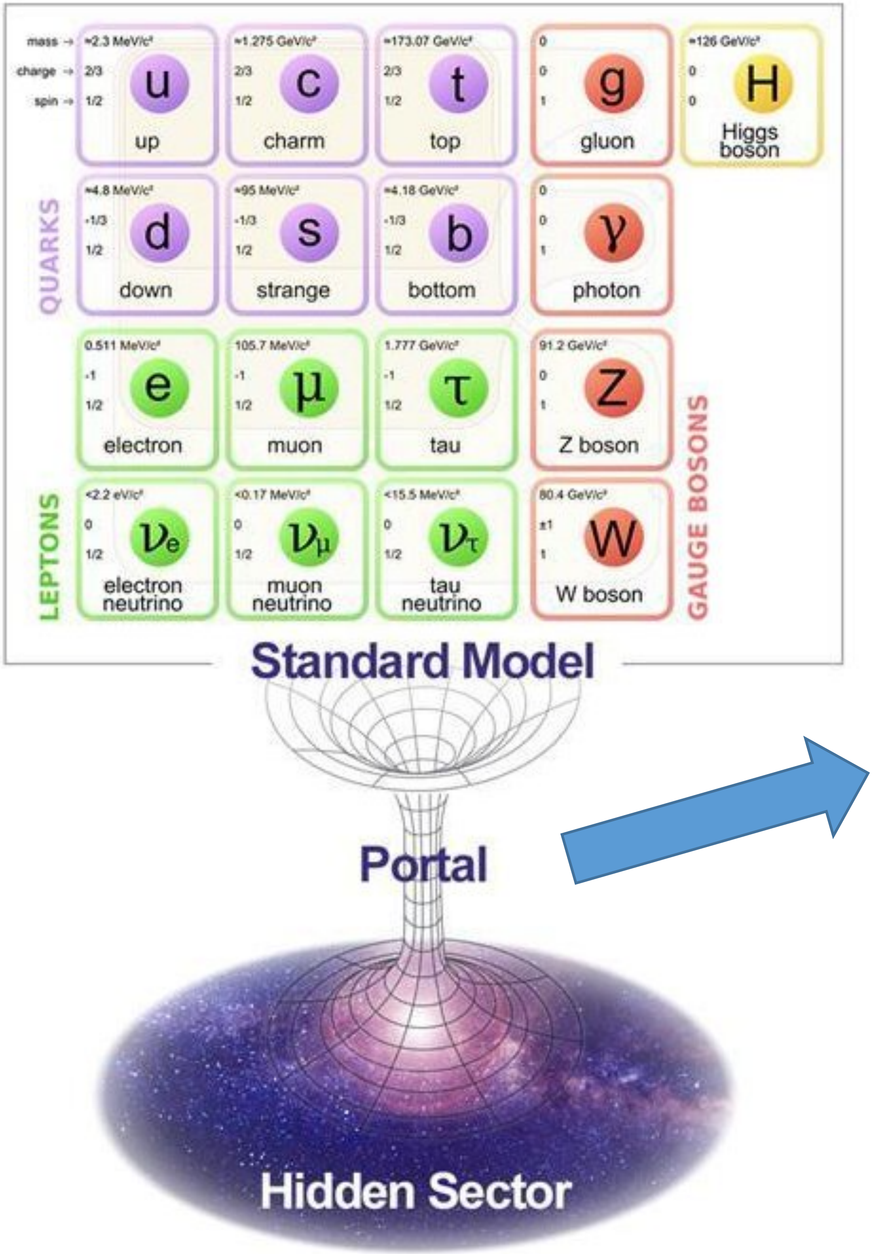

Portal

1. Spinor: Neutrino

$$\bar{L}NH$$

2. Scalar: Higgs

$$SH^\dagger H,\ S^2H^\dagger H$$

3. Pseudo-scalar: Axion

$$(a/f_a)F\tilde{F},\ (\partial_\mu a/f_a)j^\mu$$

4. Vector: dark photon

$$U(1)_X$$

Dark photon

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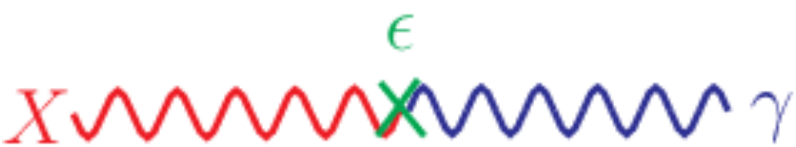
1. A new U(1) gauge boson acting like photon $Q_f A'_\mu \bar{f}\gamma^\mu f$
2. Dark: No charge under SM gauge groups
3. SM particle without charge under new U(1)

No direct interaction with SM particle $U(1)_Y \times U(1)_X$

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



Dark photon: massless or massive

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

Existing limits for Dark photon

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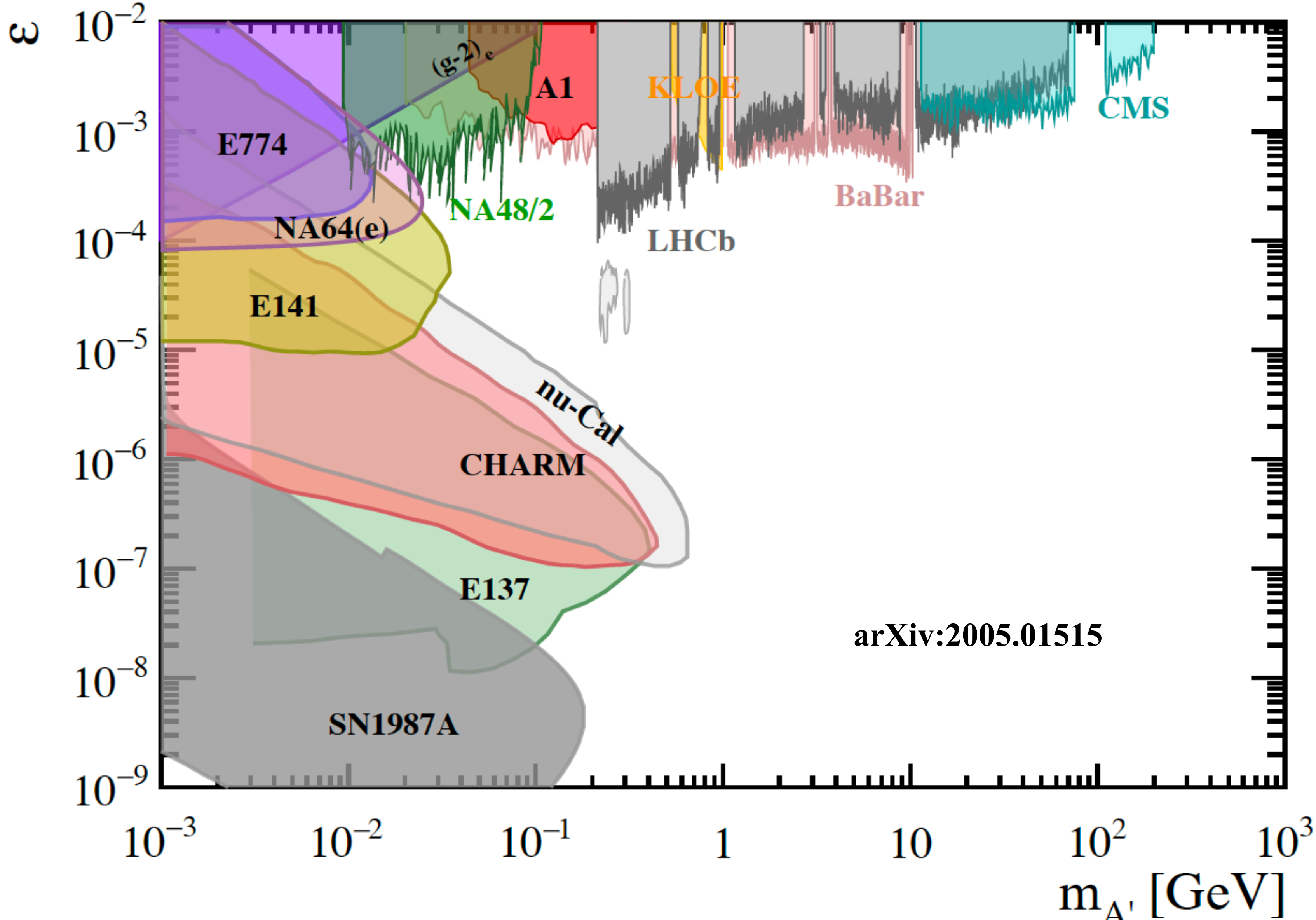

Abelian kinetic mixing

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

Holdom 1986, Foot&He 1991

a. Redefined X with no coupling to j^{μ}_{Y} ---dark

$$\hat{Y}_\mu = \sqrt{1-\epsilon^2}Y_\mu, \quad \hat{X}_\mu = \epsilon Y_\mu + X_\mu$$

$$\mathcal{L}_a = -\frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{4}\hat{Y}_{\mu\nu}\hat{Y}^{\mu\nu} + j^{\mu}_{Y}\frac{1}{\sqrt{1-\epsilon^2}}\hat{Y}_\mu + j^{\mu}_{X}\left(\hat{X}_\mu - \frac{\epsilon}{\sqrt{1-\epsilon^2}}\hat{Y}_\mu\right)$$

b. Redefined Y with no coupling to j^{μ}_{X} ---no dark

$$\hat{Y}'_\mu = Y_\mu + \epsilon X_\mu, \quad \hat{X}'_\mu = \sqrt{1-\epsilon^2}X_\mu$$

$$\mathcal{L}_b = -\frac{1}{4}\hat{X}'_{\mu\nu}\hat{X}'^{\mu\nu} - \frac{1}{4}\hat{Y}'_{\mu\nu}\hat{Y}'^{\mu\nu} + j^{\mu}_{Y}\left(\hat{Y}'_\mu - \frac{\epsilon}{\sqrt{1-\epsilon^2}}\hat{X}'_\mu\right) + j^{\mu}_{X}\frac{1}{\sqrt{1-\epsilon^2}}\hat{X}'_\mu$$

Which one is the correct one to choose?

Non-Abelian kinetic mixing

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

How to contract index a

1. triplet scalar Σ^a $<\Sigma> = v_\Sigma$

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

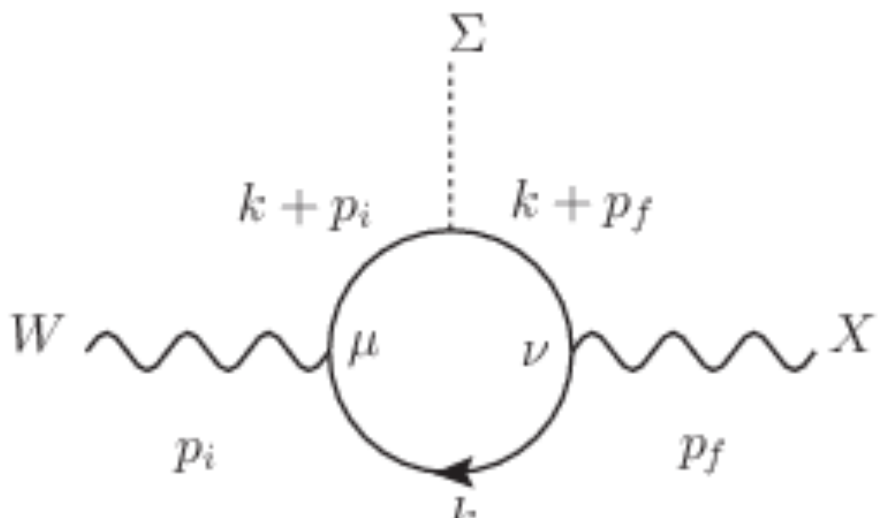
non-renormalizable dimension 5

2. Higher order

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

non-renormalizable dimen-6

Generate the kinetic mixing from renormalizable theory?



→ $W^a_{\mu\nu} X^{\mu\nu} \Sigma^a$

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New effect-mass mixing

1. Additional scalars: New doublet and singlet

2. New broken modes: EW and U(1) symmetry

$$\phi_1 : (1,2,1/2)(0),\ \phi_2 : (1,2,1/2)(1),\ \phi_d : (1,1,0)(1)$$

$$\mathscr{L}_{scalar} = \Sigma_i |D_\mu \phi_i|^2 \qquad D_\mu \phi_i = (\partial_\mu + igT_i \tilde{W}_{i\mu} + ig' Y \tilde{Y}'_\mu + ig_X Q_d \tilde{X}'_\mu)\phi_i$$

$$\mathcal{L}_{mass} = \frac{1}{2}(\tilde{Z}^\mu,\ \tilde{X}^\mu) M^2 \begin{pmatrix} \tilde{Z}_\mu \\ \tilde{X}_\mu \end{pmatrix}$$

$$\begin{pmatrix} m^2_{\tilde{Z}} & m^2_{\tilde{Z}} \frac{\sigma s_W (1-\epsilon)}{\sqrt{1-\sigma^2}} \\ m^2_{\tilde{Z}} \frac{\sigma s_W (1-\epsilon)}{\sqrt{1-\sigma^2}} & m^2_{\tilde{X}} + m^2_{\tilde{Z}} \sigma^2 s^2_W \frac{1-2\epsilon}{1-\sigma^2} \end{pmatrix}$$

Mass mixing

$$\epsilon = \frac{1}{\sigma} \frac{2g_X}{g'} \frac{v_2^2}{v^2}$$

New scalars introduces a new mass mixing pattern, which is clearly distinct from kinetic mixing

Dark photon interactions

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Transformation

$$\begin{pmatrix} \tilde{A}' \\ \tilde{Z}' \\ \tilde{X}' \end{pmatrix} = \begin{pmatrix} 1 & -s_\theta \frac{\sigma c_W}{\sqrt{1-\sigma^2}} & -c_\theta \frac{\sigma c_W}{\sqrt{1-\sigma^2}} \\ 0 & c_\theta + s_\theta \frac{\sigma s_W}{\sqrt{1-\sigma^2}} & -s_\theta + c_\theta \frac{\sigma s_W}{\sqrt{1-\sigma^2}} \\ 0 & s_\theta \frac{1}{\sqrt{1-\sigma^2}} & c_\theta \frac{1}{\sqrt{1-\sigma^2}} \end{pmatrix} \begin{pmatrix} A \\ Z \\ X \end{pmatrix}$$

$$\tan(2\theta) \approx \frac{2\sigma s_W(1-\epsilon)}{1-\tilde{r}^2}$$

Z interaction

X interaction

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} \\ & + j^\mu_{em}\left(A_\mu \boxed{- s_\theta \frac{\sigma c_W}{\sqrt{1-\sigma^2}} Z_\mu} - \boxed{c_\theta \frac{\sigma c_W}{\sqrt{1-\sigma^2}} X_\mu}\right) \\ & + j^\mu_Z \left(\boxed{\left(c_\theta + s_\theta \frac{\sigma s_W}{\sqrt{1-\sigma^2}}\right) Z_\mu} + \boxed{\left(-s_\theta + c_\theta \frac{\sigma s_W}{\sqrt{1-\sigma^2}}\right) X^\mu}\right) \\ & \boxed{+ j^\mu_X \left(s_\theta \frac{1}{\sqrt{1-\sigma^2}} Z_\mu + c_\theta \frac{1}{\sqrt{1-\sigma^2}} X_\mu\right)}. \qquad (13\end{aligned}$$

CP violation

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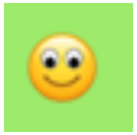
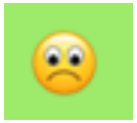
1. Abelian

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

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

$$\downarrow$$

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

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

CP violating non-Abelian kinetic mixing

Fuyuto, He, Li, Michael, 2019vfe,

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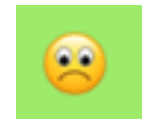
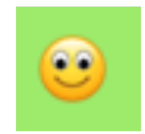
Renormalizable CPV non-Abelian kinetic mixing effect?

New fields generate the operator from loop order

- **Scalar: No generate CPV due to tensor**

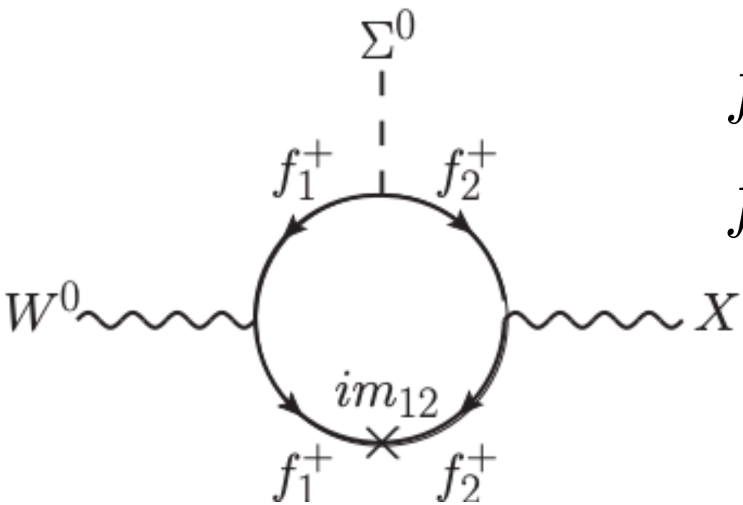


- **Fermion: SU(2)$_L$ multiplet**



Type-III seesaw model

$$f = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} & \Sigma^+ \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} \end{pmatrix}$$ **Lepton triplet**



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

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

EDM

EDM constraints

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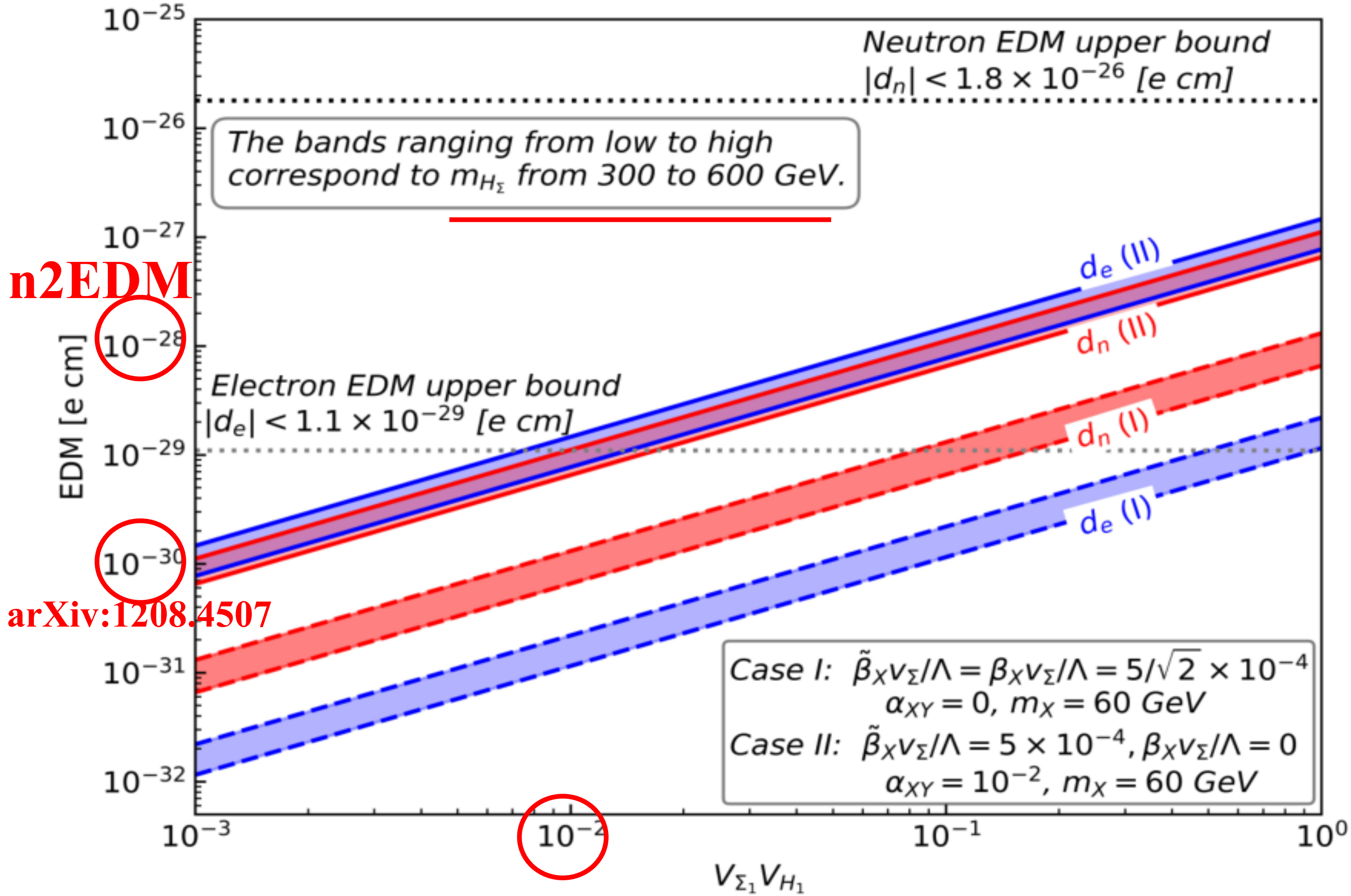

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Z couplings

$$j_Z^\mu = -\frac{e}{2s_W c_W}\bar{f}\gamma^\mu(\tilde{g}_V^f - \tilde{g}_A^f\gamma_5)f\,,\quad \tilde{g}_V^f = I_3^f - 2Q_f s_W^2\,,\qquad \tilde{g}_A^f = I_3^f$$

$$g_V^f = \tilde{g}_V^f\left(c_\theta + s_\theta\frac{\sigma s_W}{\sqrt{1-\sigma^2}}\right) + 2s_\theta\frac{\sigma s_W c_W^2}{\sqrt{1-\sigma^2}} \approx \tilde{g}_V^f\left[1+\sigma^2\tilde{s}_W^2\left(\frac{1-\epsilon}{1-\tilde{r}^2} - \frac{(1-\epsilon)^2}{2(1-\tilde{r}^2)^2}\right)\right]$$

$$g_A^f = \tilde{g}_A^f\left(c_\theta + s_\theta\frac{\sigma s_W}{\sqrt{1-\sigma^2}}\right) \approx \tilde{g}_A^f\left[1+\sigma^2 s_W^2\left(-\frac{(1-\epsilon)^2}{2(1-\tilde{r}^2)^2} + \frac{1-\epsilon}{1-\tilde{r}^2}\right)\right]$$

Special cases

No kinetic $\sigma = 0$

No mass $\epsilon = 0$

No mixing $\epsilon = 1$

General case

Z boson phenomenology

Global fits for all fermions

Observable	Experimental data	Our work $(m_X > m_Z)$
g_V^τ	-0.0366 ± 0.0010	-0.03814 ± 0.00022
g_V^μ	-0.0367 ± 0.0023	
g_V^e	-0.03817 ± 0.00047	
g_A^τ	-0.50204 ± 0.00064	-0.499784 ± 0.000084
g_A^μ	-0.50120 ± 0.00054	
g_A^e	-0.50111 ± 0.00035	
g_V^u	0.266 ± 0.034	0.19106 ± 0.00026
g_A^u	$0.519^{+0.028}_{-0.033}$	0.499784 ± 0.000084
g_V^d	$-0.38^{+0.04}_{-0.05}$	-0.34629 ± 0.00017
g_A^d	$-0.527^{+0.040}_{-0.028}$	-0.499784 ± 0.000084
$\mathrm{Br}_{\tau^+\tau^-}$	$(3.3658 \pm 0.0023)\%$	$(3.38080 \pm 0.00091)\%$
$Br_{\mu^+\mu^-}$	$(3.3662 \pm 0.0066)\%$	$(3.39090 \pm 0.00091)\%$
$Br_{e^+e^-}$	$(3.3632 \pm 0.0042)\%$	$(3.39094 \pm 0.00091)\%$
$Br_{c\bar{c}}$	$(12.03 \pm 0.21)\%$	$(11.5862 \pm 0.0074)\%$
$Br_{b\bar{b}}$	$(15.12 \pm 0.05)\%$	$(14.8783 \pm 0.0015)\%$
$Br_{(c\bar{c}+u\bar{u})/2}$	$(11.6 \pm 0.6)\%$	$(11.5891 \pm 0.0074)\%$
$Br_{(d\bar{d}+s\bar{s}+b\bar{b})/3}$	$(15.6 \pm 0.4)\%$	$(14.9390 \pm 0.0015)\%$
P_τ	-0.144 ± 0.015	-0.15176 ± 0.00090
P_μ	-0.142 ± 0.015	
P_e	-0.1515 ± 0.0019	
P_s	-0.90 ± 0.09	-0.93627 ± 0.00022
P_b	-0.923 ± 0.020	
P_c	-0.670 ± 0.027	-0.66708 ± 0.00059
$m_W(\mathrm{GeV})$	80.4028 ± 0.0067	80.408 ± 0.019
ρ	1.00038 ± 0.00020	1.00003 ± 0.00015

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$$\Delta m_W^2 = -\, m_Z^2 c_W^2 \frac{\sigma^2 s_W^2}{(1-\tilde{r}^2)(1-t_W^2)}(1-\epsilon)^2$$

Fit results

ϵ	σ	m_X
-1.37 ± 0.46	0.074 ± 0.021	275 ± 39
1	0.583	-0.045
	1	0.488
		1

$\chi^2/\mathrm{d.o.f} = 19.75/16 = 1.23$

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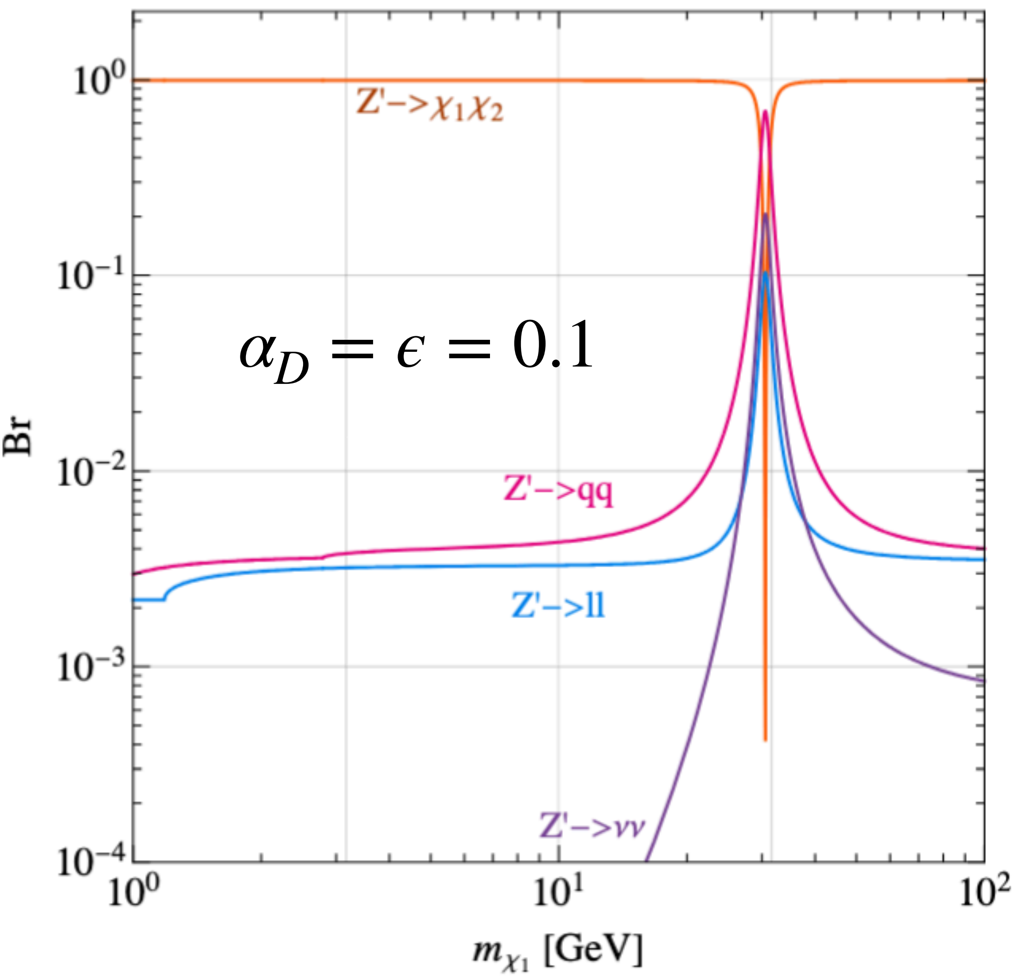
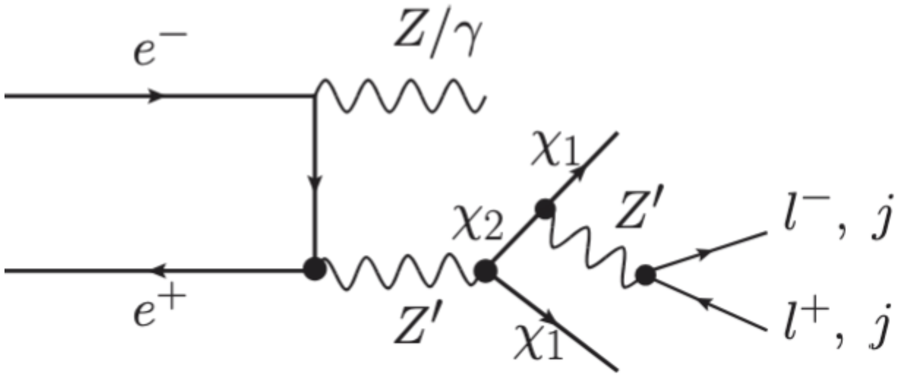
inelastic dark model

$$j^{\mu}_{Z'} = -i\frac{g_D}{2}(\overline{\chi_2}\gamma^{\mu}\chi_1 - \overline{\chi_1}\gamma^{\mu}\chi_2)$$



Lepton collider searches



Dark matter

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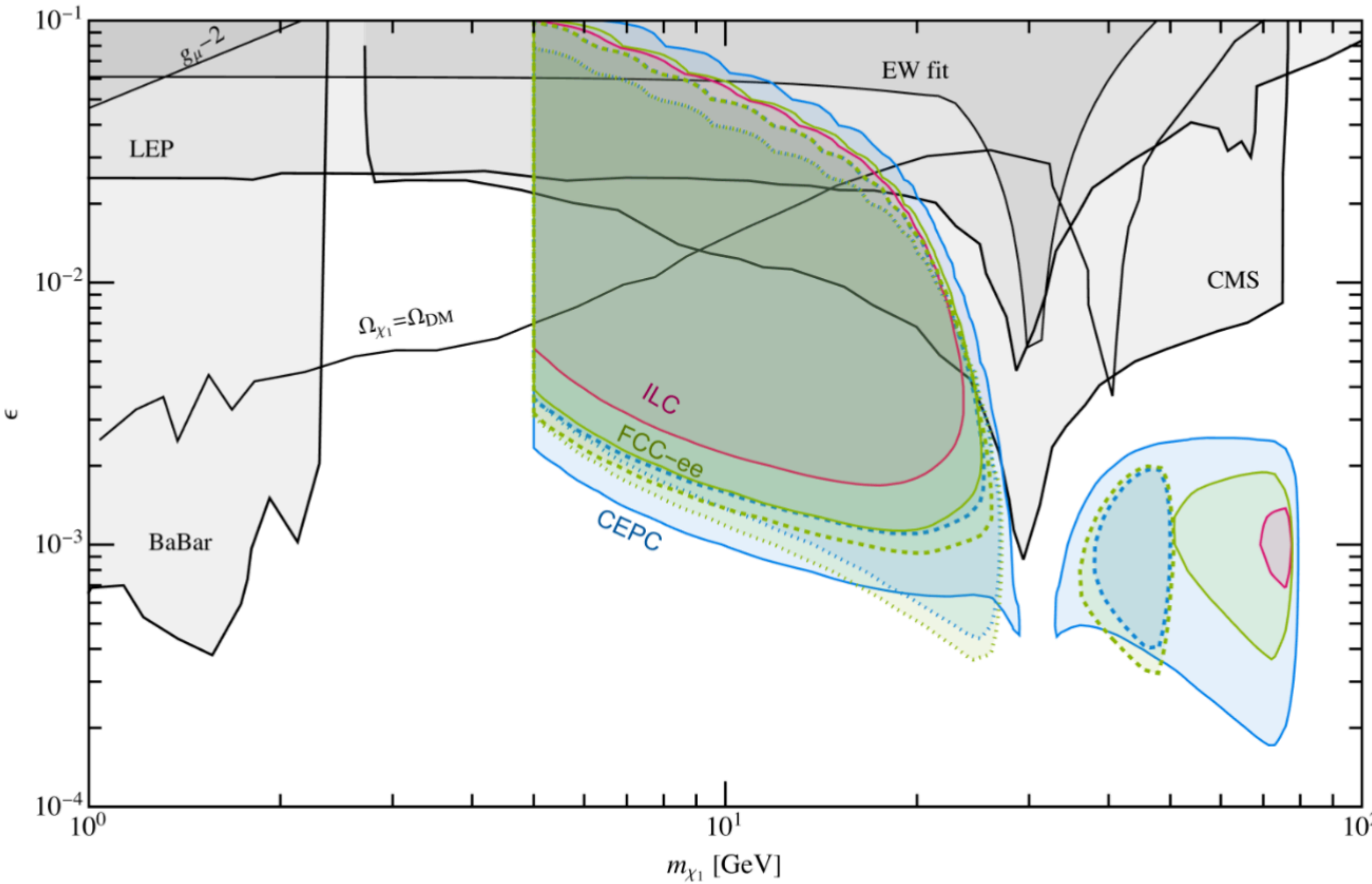

Summary

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1. **The dark photon provides a compelling portal between the visible and dark sectors.**

2. **Various mixing mechanisms—such as kinetic, non-Abelian, and mass mixing—can occur in dark photon models.**

3. **CP violation is explored in conjunction with relevant phenomenological implications.**

Thanks!
谢谢

Type-III seesaw

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

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

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

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

$$M_D = \begin{pmatrix} \frac{Y_{fL11} v'_1}{\sqrt{2}} & \frac{Y_{fL12} v'_2}{\sqrt{2}} & \frac{Y_{fL13} v}{\sqrt{2}} \\ \frac{Y_{fL21} v'_1}{\sqrt{2}} & \frac{Y_{fL22} v'_2}{\sqrt{2}} & \frac{Y_{fL23} v}{\sqrt{2}} \\ \frac{Y_{fL31} v'_1}{\sqrt{2}} & \frac{Y_{fL32} v'_2}{\sqrt{2}} & \frac{Y_{fL33} v}{\sqrt{2}} \end{pmatrix} \quad M_R = \begin{pmatrix} \frac{Y_{fs1} v_s}{\sqrt{2}} & m_{12} & 0 \\ m_{12} & \frac{Y_{fs2} v_s}{\sqrt{2}} & 0 \\ 0 & 0 & m_{33} \end{pmatrix}$$

Renormalizable CP violation

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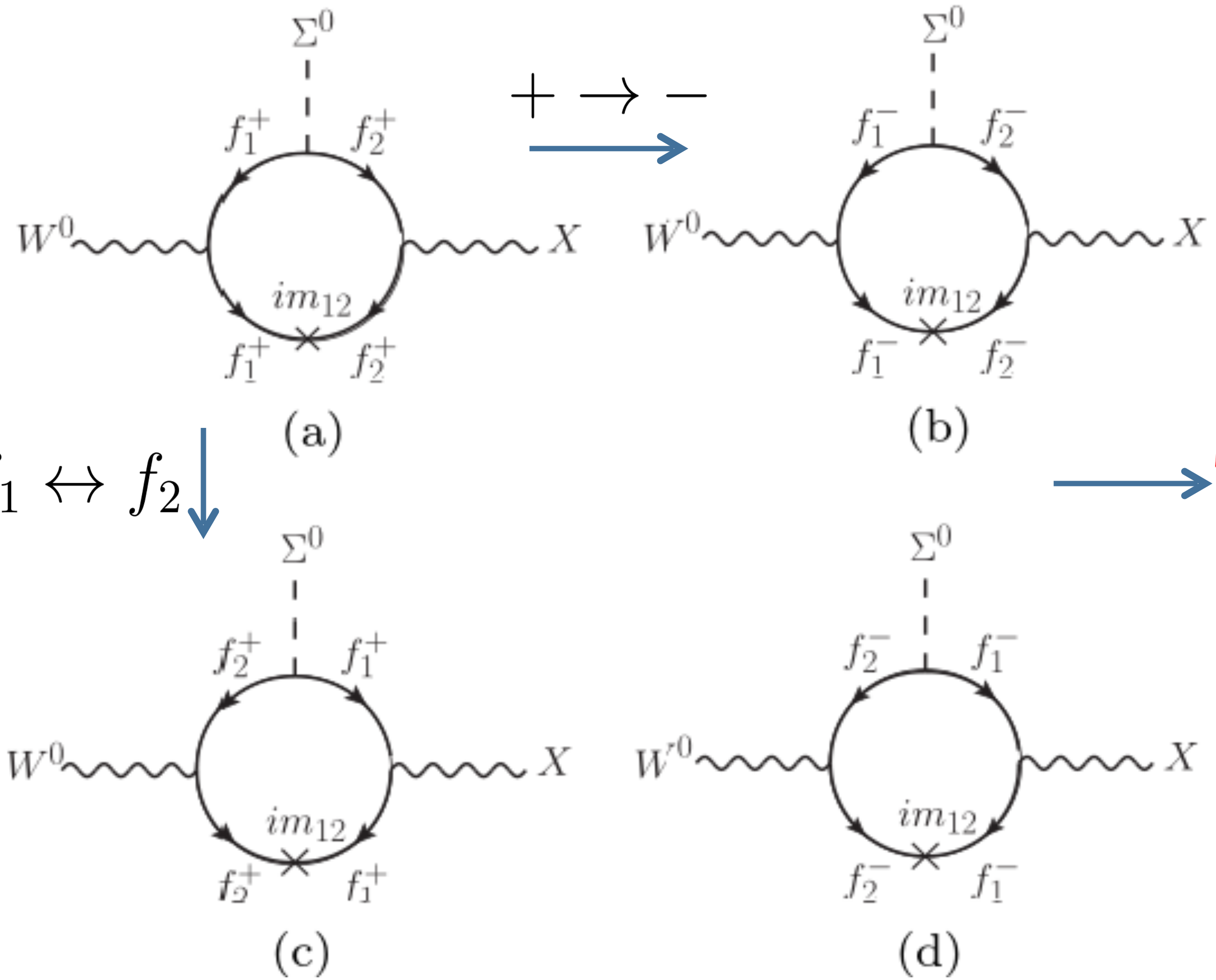
$$f_1 = (1,3,0)(x_f), \quad f_2 = (1,3,0)(-x_f),$$

$+ \to -$

$f_1 \leftrightarrow f_2$



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

SM fermion EDM

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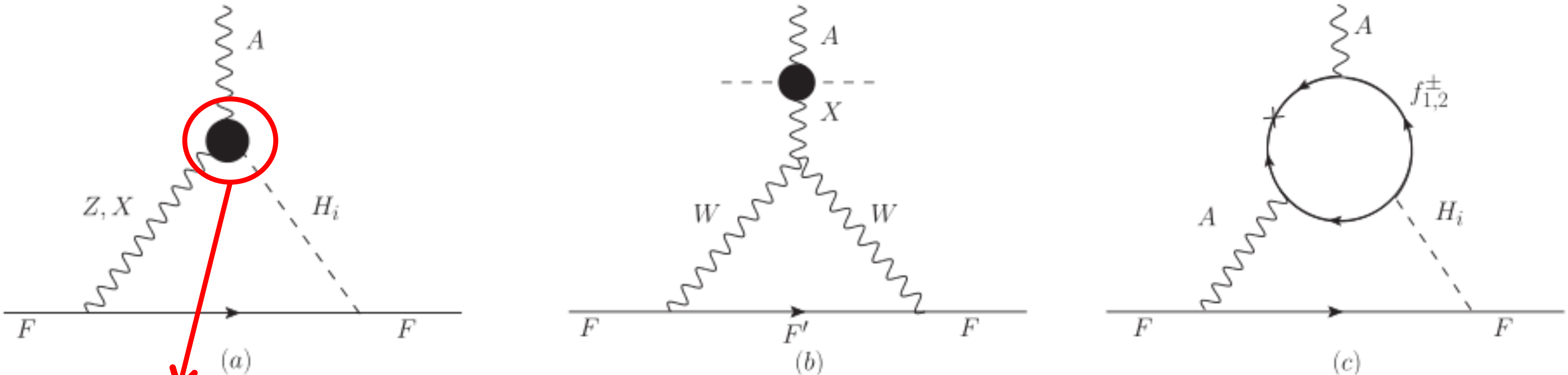

$\tilde{\beta}_X$ at one loop level **No Z-X mixing** **Barr-Zee**

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

Two loop(dominant)

$$d_q \approx 0$$

Cancel

CPC and CPV kinetic mixing

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

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

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

$$\frac{\tilde{\beta}_X}{\Lambda} = \frac{1}{2\pi^2} g g_X x_f \mathrm{Im}(m_{12} Y^*_{f\sigma})$$

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

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

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

Common regions

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Z boson physical processes

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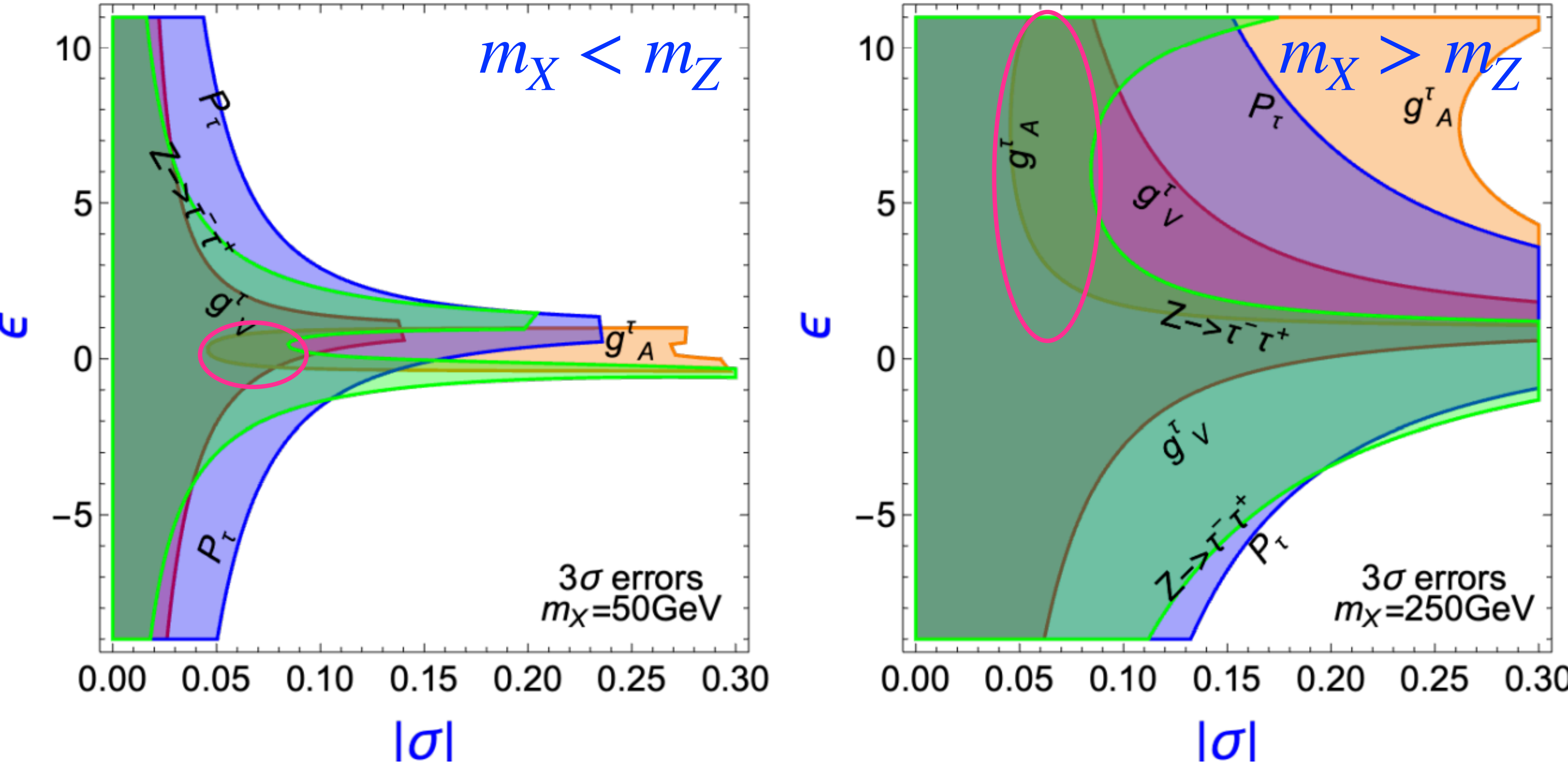

Common region to satisfy the constraints simultaneously

STU and W mass

YC, XGH, FH,ZPX, **JS**, 2204.10156
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$$\alpha S = \frac{4 s_W^2 c_W^2 \sigma^2}{1 - m_X^2/m_Z^2}\left(1 - \frac{s_W^2}{1 - m_X^2/m_Z^2}\right),$$

$$\alpha U = 4 s_W^4 c_W^2 \sigma^2 \left(-\frac{1 - 2m_X^2/m_Z^2}{(1 - m_X^2/m_Z^2)^2} + \frac{2}{1 - m_X^2/m_Z^2}\right)$$

$$\alpha T = -\sigma^2 s_W^2 \frac{m_X^2/m_Z^2}{(1 - m_X^2/m_Z^2)^2},$$

$$\rho = 1 + \frac{4 v_\Sigma^2}{v^2} = 1 + \alpha T_\Sigma,$$

Non-Abelian

$$\Delta m_W^2 = m_Z^2 c_W^2 \left(-\frac{\alpha S}{2(c_W^2 - s_W^2)} + \frac{c_W^2 \alpha T}{(c_W^2 - s_W^2)} + \frac{\alpha U}{4 s_W^2}\right)$$

$$= -m_Z^2 c_W^2 \frac{m_Z^2 (1 - s_W^2)\sigma^2 s_W^2}{(m_X^2 - m_Z^2)(-1 + 2 s_W^2)} + m_Z^2 c_W^2 \frac{c_W^2}{c_W^2 - s_W^2}\frac{4 v_\Sigma^2}{v^2}.$$

1. Only abelian $\Rightarrow$ $m_X > m_Z$

2. Non-abelian $\Rightarrow$ **Positive contribution**