Dark photon effects with the kinetic and Mass mixing in Z decay

Zhi-Peng Xing work with Jin Sun

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TDLI&NJNU

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- **Introduction**
- **Dark photon mixing model**
- **Phenomenology**
- **Conclusion**

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Portal:

1.Spinor: **Neutrino**

$$\bar{L}NH$$

2.Scalar: **Higgs**

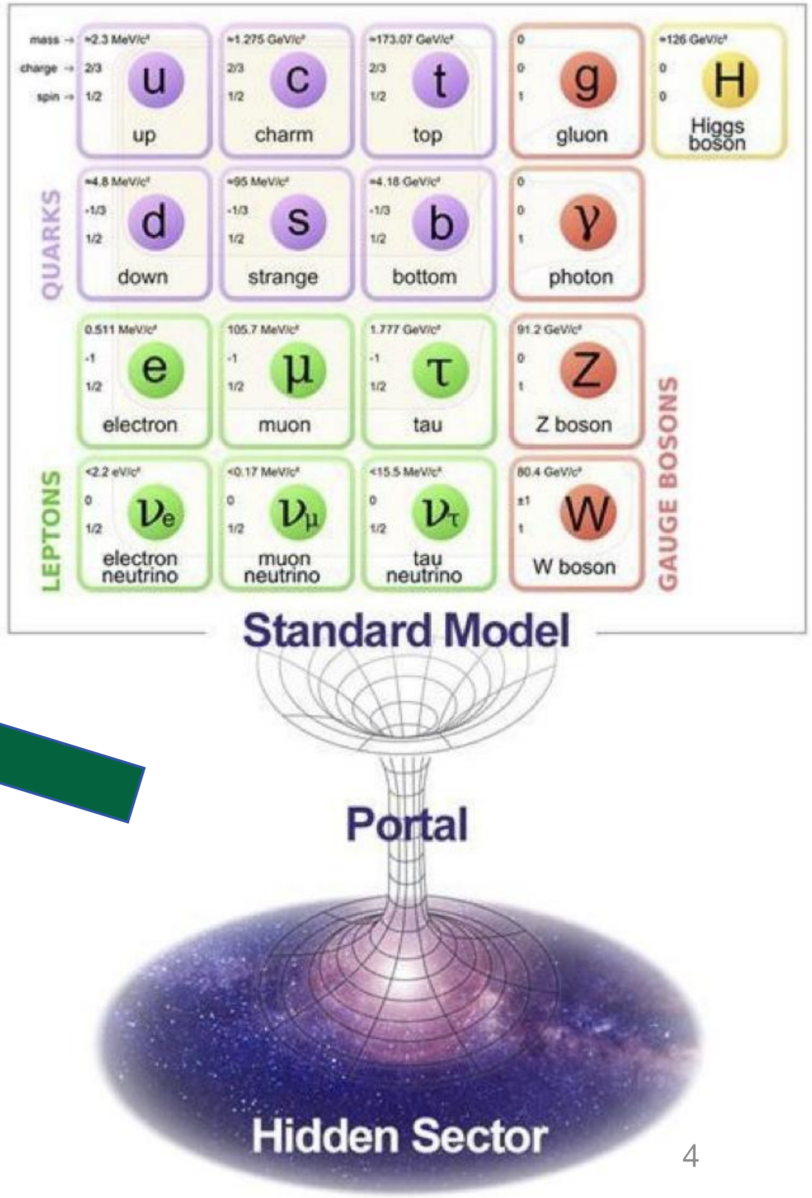
$$SH^\dagger H,\ S^2H^\dagger H$$

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:

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

No direct interaction with SM particle

$$U(1)_Y \times U(1)_X \qquad L = -\frac{1}{4}Y_{\mu\nu}Y^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + j_Y^\mu Y_\mu + j_X^\mu X_\mu$$

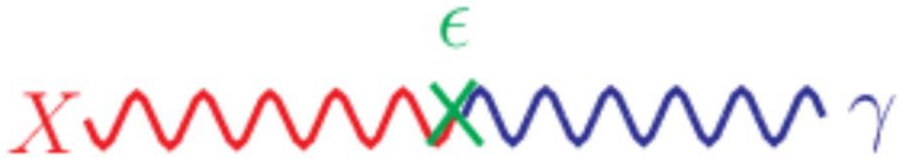
Dark photon
- Massless
- Massive

Introduction

Kinetic mixing:

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

- Renormalizable: dimension 4 operator
- 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)

Remove mixing scheme:

X does not coupling to SM current j_Y^μ

$$\hat{Y}_\mu = \sqrt{1-\epsilon^2} Y_\mu$$

$$\hat{X}_\mu = \epsilon Y_\mu + X_\mu$$

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

Y does not coupling to dark current j_X^μ

$$\hat{Y}'_\mu = Y_\mu + \epsilon X_\mu$$

$$\hat{X}'_\mu = \sqrt{1-\epsilon^2} X_\mu$$

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

case a: Massless

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case b: Massive

Remove mixing scheme:

X does not coupling to SM current j_Y^μ

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

$$\frac{1}{2} m_X^2 \left(\frac{-\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}} \tilde{A}_\mu + \frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}} \tilde{Z}_\mu + \tilde{X}_\mu \right)^2$$

need remove the mass term of A

Y does not coupling to dark current j_X^μ

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

mass term after redefiniation

$$\frac{1}{2} m_X^2 \left(\frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}} \tilde{Z}'_\mu + \frac{1}{\sqrt{1-\sigma^2 c_W^2}} \tilde{X}'_\mu \right)^2$$

massless dark photon need to identify with physical photon

case a: Massless

case b: Massive

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The simplest kinetic mixing:

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

$$\mathscr{L} = -\frac{1}{4}\tilde{X}'_{\mu\nu}\tilde{X}'^{\mu\nu} - \frac{\sigma}{2}\tilde{X}'_{\mu\nu}\tilde{Y}'^{\mu\nu} - \frac{1}{4}\tilde{Y}'_{\mu\nu}\tilde{Y}'^{\mu\nu} + j^\mu_Y\tilde{Y}'_\mu + j^\mu_X\tilde{X}'_\mu$$

$$\begin{pmatrix}\tilde{Y}' \\ \tilde{X}'\end{pmatrix} = \begin{pmatrix}1 & -\frac{\sigma}{\sqrt{1-\sigma^2}} \\ 0 & \frac{1}{\sqrt{1-\sigma^2}}\end{pmatrix}\begin{pmatrix}\tilde{Y} \\ \tilde{X}\end{pmatrix}$$

$$\mathscr{L} = -\frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{1}{4}\tilde{Y}_{\mu\nu}\tilde{Y}^{\mu\nu} + j^\mu_Y\left(\tilde{Y}_\mu - \frac{\sigma}{\sqrt{1-\sigma^2}}\tilde{X}_\mu\right) + j^\mu_X\frac{1}{\sqrt{1-\sigma^2}}\tilde{X}_\mu$$

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Mass mixing:

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

EW symmetry breaking (ϕ_1)

U(1) symmetry breaking (ϕ_2, ϕ_d)

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

SSB

$$\tilde{Y}_\mu = c_W \tilde{A}_\mu - s_W \tilde{Z}_\mu,\quad W^3_\mu = s_W \tilde{A}_\mu + c_W \tilde{Z}_\mu$$

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

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

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

Dark photon mixing model

Mass mixing:

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

EW symmetry breaking | **U(1) symmetry breaking**

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

SSB

$$\tilde{Y}_\mu = c_W \tilde{A}_\mu - s_W \tilde{Z}_\mu \,, \quad W^3_\mu = s_W \tilde{A}_\mu + c_W \tilde{Z}_\mu$$

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

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

$$\tan(2\theta) = \frac{2M_{12}^2}{M_{11}^2 - M_{22}^2} \approx \frac{2\sigma s_W (1-\epsilon)}{1-\tilde{r}^2}$$

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Mass mixing:

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

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

Z Interaction

Dark photon mixing model

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

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

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

only kinetic mixing $\epsilon = 0$

Z boson phenomenology

Dark photon mixing model

Z couplings:

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

$\epsilon = 1$ **case**

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

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

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

no mixing with Z

The effect of kinetic mixing in Z coupling are fully cancled by mass mixing.

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Z-tau coupling modification:

$$g_V^f = \left(-\frac{1}{2} + 2s_W^2\right)\left[1 + \sigma^2 s_W^2\left(\frac{1-\epsilon}{1-\tilde{r}^2} - \frac{(1-\epsilon)^2}{2(1-\tilde{r}^2)^2}\right)\right] + 2\sigma^2 s_W^2(1-s_W^2)\frac{1-\epsilon}{1-\tilde{r}^2}$$

$$g_A^f = -\frac{1}{2}\left[1 + \sigma^2 s_W^2\left(\frac{1-\epsilon}{1-\tilde{r}^2} - \frac{(1-\epsilon)^2}{2(1-\tilde{r}^2)^2}\right)\right]$$

Experiment data:

Vector and axial-vector

$$g_V^\tau = -0.0366 \pm 0.0010$$

$$g_A^\tau = -0.50204 \pm 0.00064$$

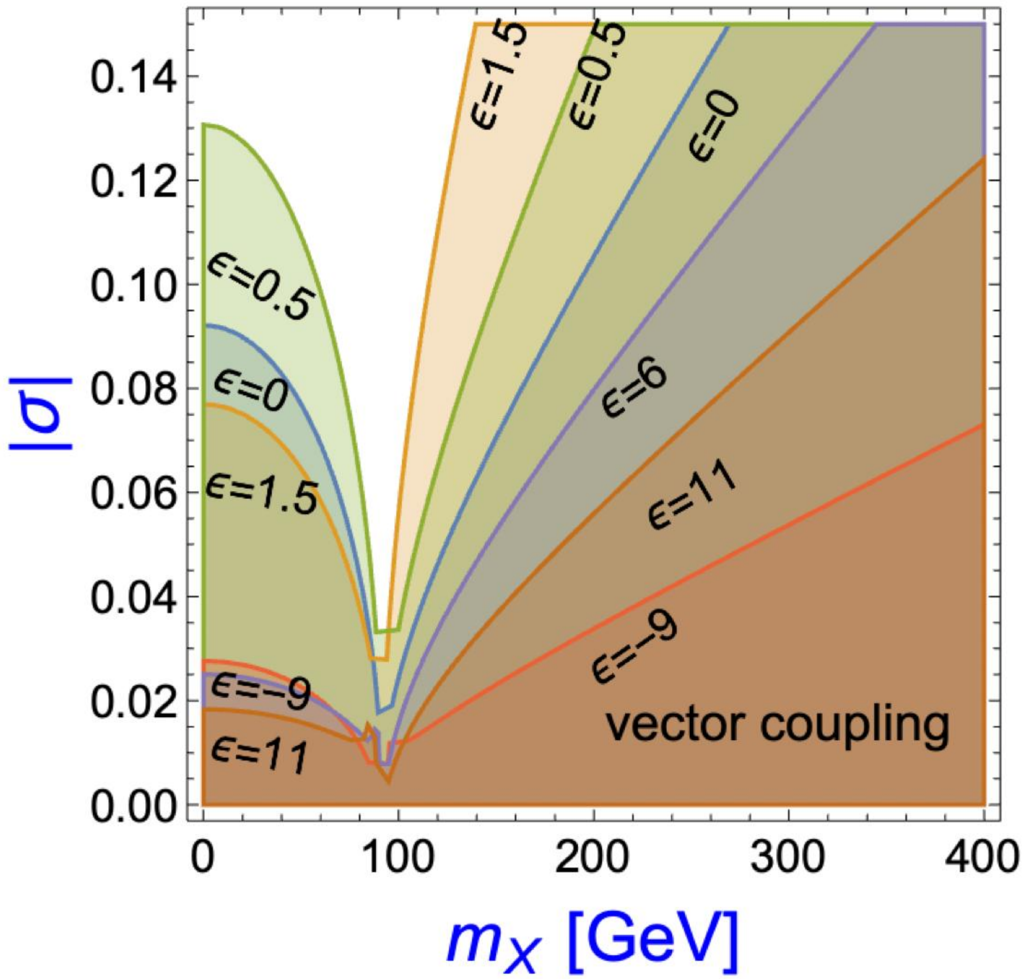
Z decay to tau tau

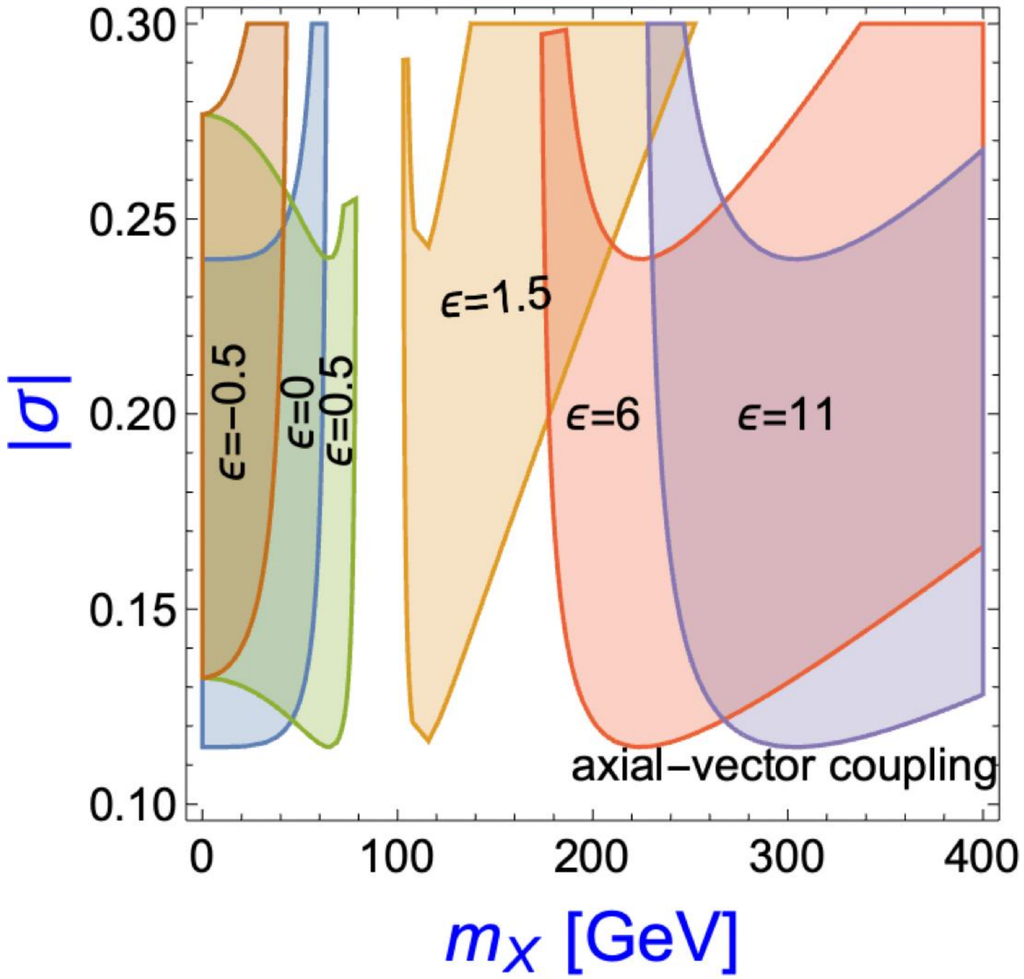
$$Br(Z \to \tau^+\tau^-) = (3.3696 \pm 0.0083)\,\%$$

$$P_\tau(Z) = -0.144 \pm 0.015$$

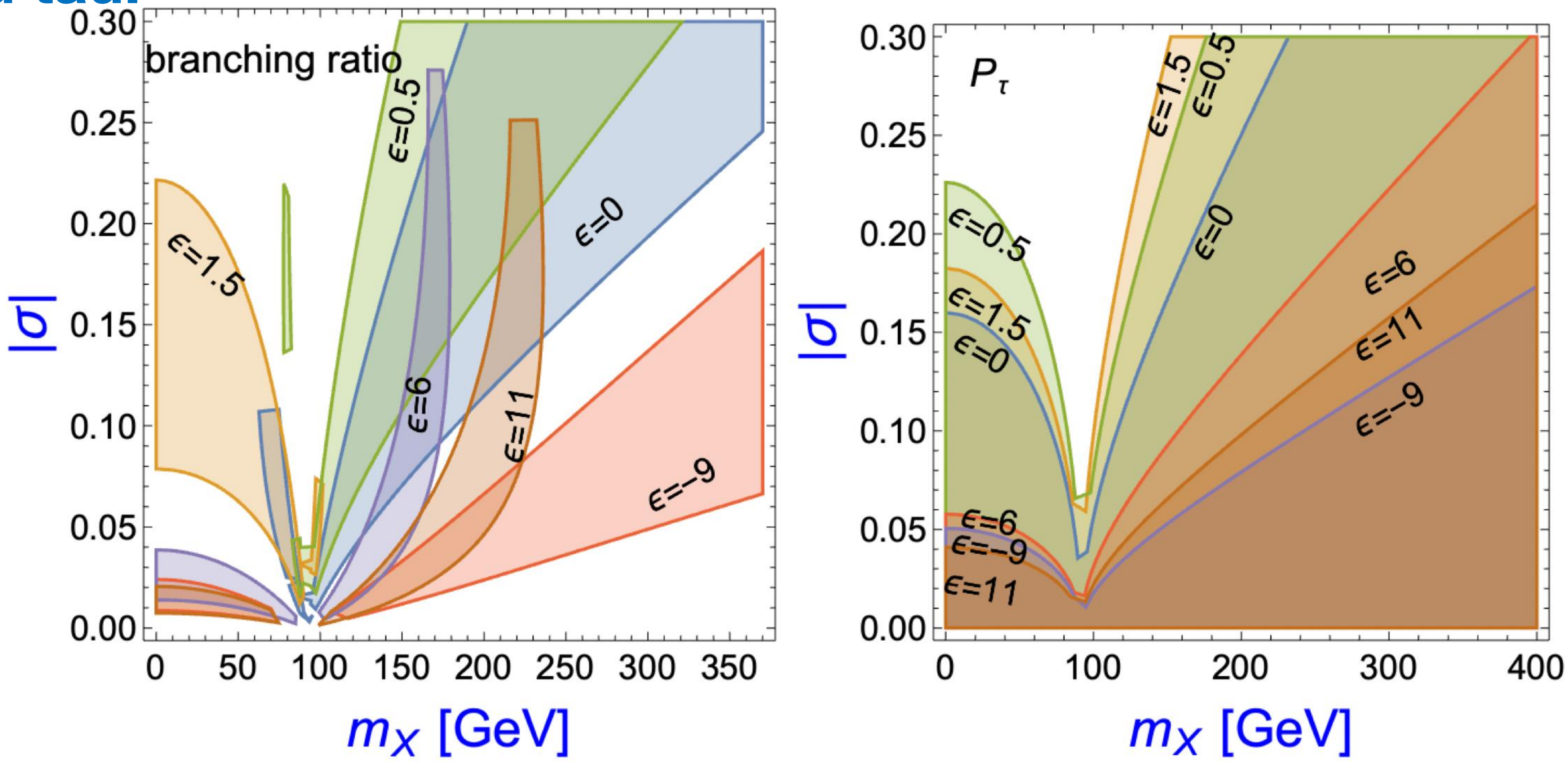
A. Hayrapetyan[CMS], 2023

Z-tau coupling:





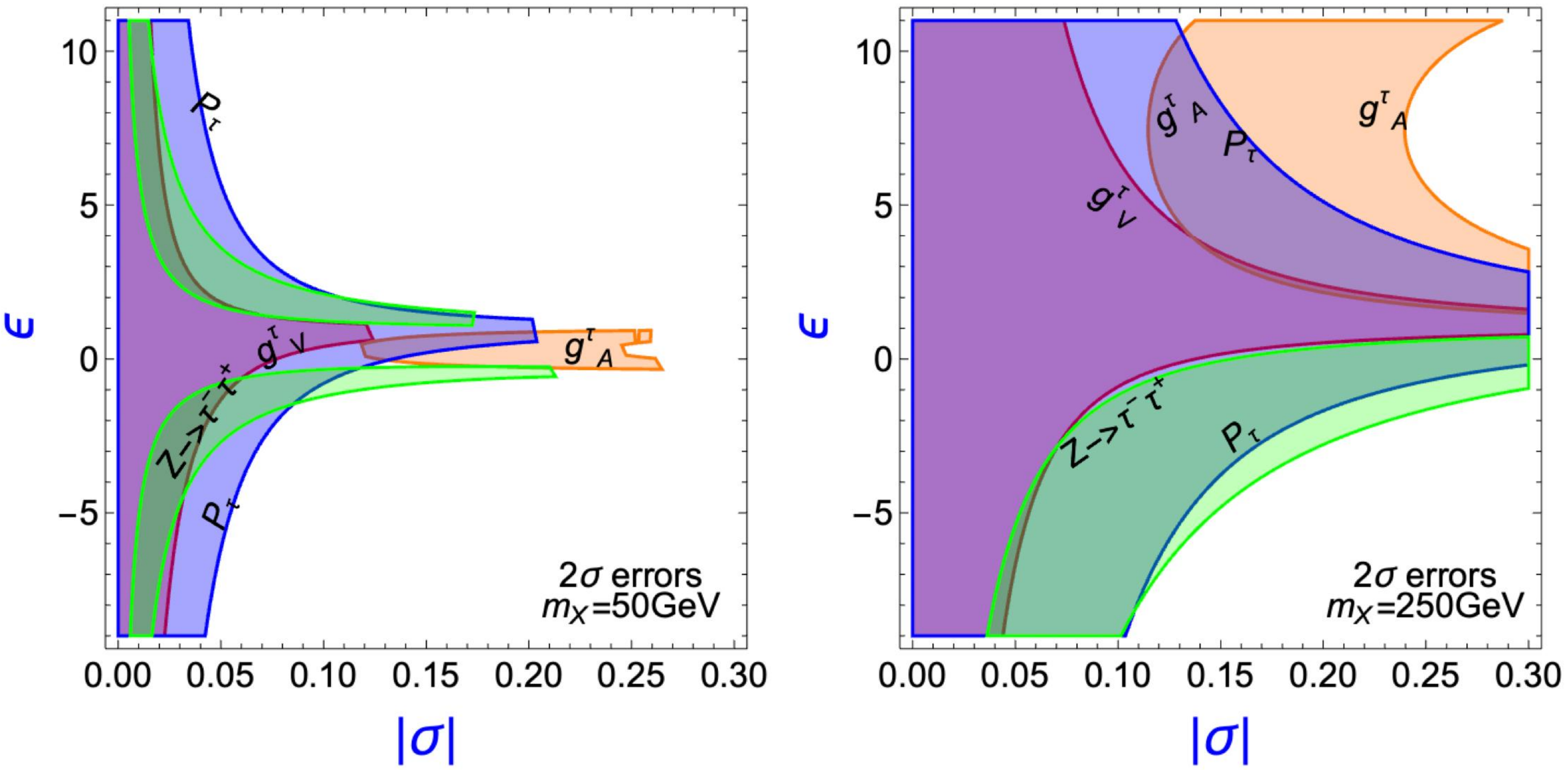
Z to tau tau:



$$Br(Z \to \tau^+\tau^-) = \frac{G_F m_Z^3}{6\sqrt{2}\pi\Gamma_Z}\sqrt{1-\frac{4m_\tau^2}{m_Z^2}}\left((g_V^\tau)^2+(g_A^\tau)^2\right)$$

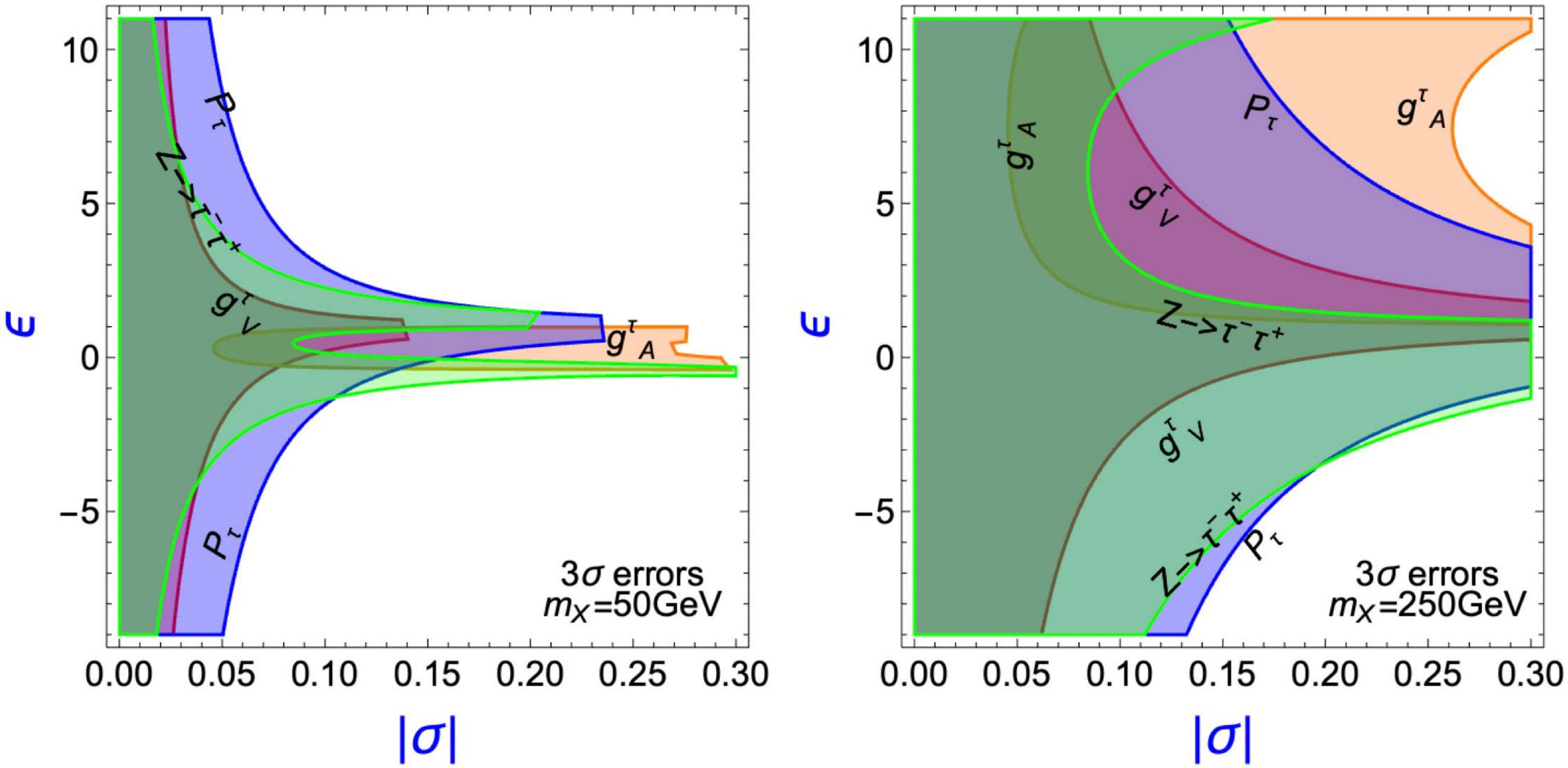
$$P_\tau = -2\frac{g_V^\tau g_A^\tau}{((g_V^\tau)^2+(g_A^\tau)^2)}$$

Common regions with 2 sigma error margin:



No common region to satisfy the constraints simultaneously

Common regions with 3 sigma error margin:



Common region to satisfy the constraints simultaneously

- Introduction
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- **Conclusion**

- The dark photon model with kinetic and mass mixing is constructed by introducing additional Higgs doublet with vev and U(1)x charge.
- The mixing ratio parameter modifies Z coupling to further affect its phenomenology.
- The relevant constraints can be satisfied within 3sigma error simultaneously.

Thanks!