CP-violating dark photon interaction

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New Physics with Exotic and Long-Lived Particles

ICISE, Quy Nhon, Vietnam
Dark photon as portal to DM

- We have plenty of evidences for dark matter from observations: galactic rotation curves, merging clusters of galaxies, CMB anisotropies

- In particle physics, we want to explore the candidates and interactions of DM

Dark sector can have lighter particles and weaker interactions and still have the right abundance. See Jonathan Feng's talk

= vector/dark photon, scalar, neutrino, axion portals

J. L. Feng, H. Tu, H.-B. Yu, 0808.2318 (JCAP)
Suppose that dark sector has an extra $U(1)$ gauge symmetry and can interact with the SM through the kinetic mixing

\begin{align*}
\begin{array}{c}
\mathcal{B} \quad \mathcal{X} \\
\hline
\hline
\end{array}
\end{align*}

\text{Abelian kinetic mixing}

\begin{align*}
\begin{array}{c}
\mathcal{W}^3 \quad \mathcal{X} \\
\hline
\hline
\end{array}
\end{align*}

\text{non-Abelian kinetic mixing}


renormalizable and non-decoupled kinetic mixing parameter insensitive to NP scale

non-renormalizable and decoupled kinetic mixing parameter suppressed by NP scale
Non-Abelian kinetic mixing

- A real triplet Higgs field \( \sim (3,0) \)

\[
\frac{\beta}{\Lambda} \text{Tr}(W_{\mu\nu} \Sigma) X^{\mu\nu}
\]

\[
W_{\mu\nu} = W^{a}_{\mu\nu} \tau^a / 2
\]

\[
\Sigma = \frac{1}{2} \begin{pmatrix} \Sigma^0 & \sqrt{2} \Sigma^+ \\ \sqrt{2} \Sigma^- & -\Sigma^0 \end{pmatrix}
\]

\[
\epsilon = \frac{\beta x_0 s_W}{\Lambda}
\]

\[
\rho = 1 + \frac{4x_0^2}{v_H^2}
\]

- In this paradigm:
  - kinetic mixing parameter is naturally small

- \( \gamma \) experimentaly, \( \epsilon < \mathcal{O}(10^{-3}) \)

- CP-violating dark photon interaction arises

- Long-lived dark photon can be tested

See talks by Igal Jaegle, Leandro de Paula, Albert De Roeck, ...
CPV dark photon interaction

- New source of CP violation is needed for baryogenesis (Sakharov, 1967)
  - CP-violating interaction is absent in the paradigm of Abelian kinetic mixing
    \[ B_{\mu\nu} \tilde{X}_{\mu\nu} = 0 + \text{total derivative} \]
  - CP-violating interaction arises in the paradigm of non-Abelian kinetic mixing

\[ \Sigma^0 = x_0 + \sigma \]
\[ W^{3}_{\mu\nu} = \partial_\mu W^3_\nu - \partial_\nu W^3_\mu + g \epsilon^{3bc} W^b_\mu W^c_\nu \]
\[ W_{\mu\nu} = W^a_{\mu\nu} \tau^a / 2 \]
\[ \Sigma = \frac{1}{2} \left( \frac{\Sigma^0}{\sqrt{2}} \begin{array}{c} \Sigma^- \\ \Sigma^+ \end{array} \right) \]

\[ \text{X-W}^3 \text{ mixing} \quad \text{CPV } \sigma W^3 X \text{ int.} \quad \text{CPV } X W^+ W^- \text{ int.} \]

in canonical form, then mass diagonalization

CPV interactions in the mass eigenstate basis
CPV dark photon interaction

- From the weak eigenstates to mass eigenstates

\[ A_0^\mu = A^\mu + e_{WX} s_W s_\xi Z^\mu - e_{WX} s_W c_\xi X^\mu + \mathcal{O}(e_{WX}^3), \]
\[ Z_0^\mu = (c_\xi + e_{WX} c_W s_\xi) Z^\mu + (s_\xi - e_{WX} c_W c_\xi) X^\mu + \mathcal{O}(e_{WX}^3), \]
\[ X_0^\mu = -s_\xi Z^\mu + c_\xi X^\mu + \mathcal{O}(e_{WX}^3), \]

- CP-even and non-universal couplings to SM fermions

\[ \tan 2\xi = \frac{2c_W e_{WX} m_Z^2}{m_Z^2 - m_X^2} + \mathcal{O}(e_{WX}^2) \]
\[ e_{WX} = \frac{\beta x_0}{\Lambda} \]
\[ \alpha_{AX} = s_W e_{WX} \]
\[ \alpha_{ZX} = c_W e_{WX} \]

\[ \mathcal{L}_{f\bar{f}X} = -\frac{g}{c_W} \bar{f} \gamma^\mu (V_X - A_X \gamma^5) f X^\mu \]

\[ V_X = (c_\xi \alpha_{ZX} - s_\xi) v_Z + Q_f \alpha_{AX} c_\xi s_W c_W, \]
\[ A_X = (c_\xi \alpha_{ZX} - s_\xi) a_Z, \]

LHCb 1710.02867 (PRL)
See Leandro de Paula's talk

- prompt muon pair
- fractions of each flavor quarks in dark photon production separated out
CPV dark photon interaction

- CPV couplings to Higgs bosons
  
  - through $X-W^3$ mixing
    \[
    \mathcal{L}_{\text{higgs}} = \frac{\chi g m_Z}{c_W} H_1 X_\mu Z^\mu
    \]
  
  - through $\sigma W^3 X$ interaction
    \[
    \chi = c_\theta (c_\xi + e_{WX} c_W s_W) (s_\xi - e_{WX} c_W c_\xi)
    \]
    \[
    \begin{pmatrix}
    h \\
    \sigma
    \end{pmatrix}
    = \begin{pmatrix}
    \cos \theta & -\sin \theta \\
    \sin \theta & \cos \theta
    \end{pmatrix}
    \begin{pmatrix}
    H_1 \\
    H_2
    \end{pmatrix}
    \]

- CP-even:
  \[
  - \frac{\beta}{2\Lambda} (c_W c_\xi + e_{WX} s_\xi) Z_{\mu\nu} (c_\theta H_2 + s_\theta H_1) c_\xi X^{\mu\nu}
  \]

- prompt leptons
  ATLAS 1802.03388 (JHEP)

\[e_{WX} = \frac{\beta x_0}{\Lambda}\]
CPV dark photon interaction

• CPV couplings to Higgs bosons
  
  • through $X-W^3$ mixing
    \[
    \mathcal{L}_{\text{higgs}} = \frac{\chi g m_Z}{c_W} H_1 X_\mu Z^\mu
    \]

  • through $\sigma W^3 X$ interaction

  CP-even:
  
  \[-\frac{\beta}{2\Lambda} (c_W c_\xi + e_W s_\xi) Z_{\mu\nu} (c_\theta H_2 + s_\theta H_1) c_\xi X^{\mu\nu} \]

  CP-odd:
  
  \[-\frac{\tilde{\beta}}{2\Lambda} s_W A_{\mu\nu} (c_\theta H_2 + s_\theta H_1) (c_\xi \tilde{X}^{\mu\nu} - s_\xi \tilde{Z}^{\mu\nu}) \]

  \[-\frac{\tilde{\beta}}{2\Lambda} (c_W c_\xi + e_W s_\xi) Z_{\mu\nu} (c_\theta H_2 + s_\theta H_1) c_\xi \tilde{X}^{\mu\nu} \]

  prompt leptons

ATLAS 1802.03388 (JHEP)
CPV dark photon interaction

- CPV couplings to W bosons

\[
\mathcal{L}_{\text{gauge}} = -ig(c_W s_\xi - e_W c_\xi) \left[ -\partial_\mu X^\nu (W^+_{\mu} W^-_\nu - W^+_{\nu} W^-_\mu) \\
+ X^\nu (-W^+_{\mu} \partial_\nu W^-_\mu + W^-_{\mu} \partial_\nu W^+_{\mu} + W^+_{\mu} \partial_\mu W^-_\nu - W^-_{\mu} \partial_\mu W^+_{\nu}) \right]
\]

- \( X-W^3 \) mixing

- CPV \( XW^+W^- \) interactions
CPV dark photon interaction

• CPV couplings to W bosons

\[ \mathcal{L}_{\text{gauge}} = -i g (c_\nu s_\xi - e W x c_\xi) \left[ -\partial^\mu X^\nu (W^+_{\mu} W^-_\nu - W^+_{\nu} W^-_\mu) \\
+ X^\nu (-W^+_{\mu} \partial_\nu W^-_\mu + W^-_{\mu} \partial_\nu W^+_- + W^+_{\mu} \partial_\mu W^-_\nu - W^-_{\mu} \partial_\mu W^+_-) \right] \\
- i g e W x c_\xi \partial^\mu X^\nu (W^+_{\mu} W^-_\nu - W^+_{\nu} W^-_\mu) \\
- i g \tilde{e} W x c_\xi \partial^\mu \tilde{X}^\nu (W^+_{\mu} W^-_\nu - W^+_{\nu} W^-_\mu) \]

X-W^3 mixing

CPV XW^+W^- interactions

How to test CPV dark photon interaction?
Tests of CPV dark photon interaction

- Azimuthal angle distribution

spin-0: $X=H$, differentiate CP structure

$X=$gluino, suppress background

Figy, Hankele, Klamke, Zeppenfeld, PRD74 (2006) 095001

Mukhopadhyay, Nojiri, Yanagida, JHEP 1410 (2014) 12
Tests of CPV dark photon interaction

- Azimuthal angle distribution
  - Process $pp \rightarrow jjX, X \rightarrow \ell^+\ell^-$
  - Asymmetry
    \[
    A = \frac{\sigma_{\Delta \phi_{jj}>0} - \sigma_{\Delta \phi_{jj}<0}}{\sigma_{\Delta \phi_{jj}>0} + \sigma_{\Delta \phi_{jj}<0}}
    \]
  - Benchmark values
    \[
    m_X = 20 \text{ GeV} \quad \frac{\beta x_0}{\Lambda} = \bar{\beta} \frac{x_0}{\Lambda} = 2 \times 10^{-3}
    \]
  - Asymmetry after cuts is around 20%
  - Cross section after cuts is $O(10^{-5})$ pb and about 30 events will accumulate at the HL-LHC with statistical uncertainties of 18% even with zero background
  - It is very challenging even at the HL-LHC

VBF cuts:

- $p_T^j > 20 \text{ GeV}$,
- $\Delta R_{jj} > 0.4$,
- $|y_j| < 5$,
- $|\Delta y_{jj}| > 4.2$,
- $y_1 \cdot y_2 < 0$,
- $m_{jj} > 600 \text{ GeV}$.
Tests of CPV dark photon interaction

• Fermion electric dipole moment

\[ \mathcal{L}^{\text{EDM}} = -\frac{i}{2} d_f \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu}. \]

\[ -\frac{\tilde{\beta}}{2\Lambda} s_W A_{\mu\nu} (c_\theta H_2 + s_\theta H_1) (c_\xi \tilde{X}^{\mu\nu} - s_\xi \tilde{Z}^{\mu\nu}) \]

1-loop contribution proportional to \( s_\theta e_{WX} \)

\[ \tilde{\mathcal{O}}_{WX} = -\frac{\tilde{\beta}}{\Lambda} \text{Tr}(W_{0\mu\nu} \Sigma) \tilde{X}_0^{\mu\nu}. \]

\[ \tilde{\mathcal{O}}_{WX} \supset \frac{i\tilde{\beta} x_0 s_\xi}{\Lambda} g W_\mu^+ W_\nu^- \tilde{Z}^{\mu\nu} \]

2-loop contribution proportional to \( (e_{WX})^2 \) and negligible

\[ \tan 2\xi = \frac{2 c_W e_{WX} m_Z^2}{m_Z^2 - m_X^2} + \mathcal{O}(e_{WX}^2) \]
Tests of CPV dark photon interaction

- Fermion electric dipole moment

\[ \mathcal{L}^{\text{EDM}} = -i \frac{2}{d_f} \bar{f} \gamma_5 f F_{\mu \nu}. \]

\[ -\frac{\tilde{\beta}}{2\Lambda} s_W A_{\mu \nu} (c_\theta H_2 + s_\theta H_1) (c_\xi \tilde{X}^{\mu \nu} - s_\xi \tilde{Z}^{\mu \nu}) \]

1-loop contribution proportional to $s_\theta e^{WX}$

EDMs are insensitive to dark photon mass

EDM searches provide the most promising avenue for probing the CPV dark photon interaction
Long-lived dark photon

- Production of dark photons

Long-lived dark photon

- Recast long-lived dark photon search in Higgs decaying into lepton jets

Two reconstructed displaced lepton-jets are selected and no invariant mass cut on the Higgs boson and missing energy are applied 1409.0746 (JHEP), ATLAS-CONF-2016-042

Summary

- Dark photon from additional U(1) gauge symmetry can interact with SM through non-Abelian kinetic mixing by introducing a real triplet Higgs
- The interaction can be CP violating in the paradigm of non-Abelian kinetic mixing
- CP-violating dark photon can be tested in EDMs but very challenging at colliders
- Long-lived dark photon in the paradigm of non-Abelian kinetic mixing can be produced with enough rate and tested at current LHC
Summary

• Dark photon from additional U(1) gauge symmetry can interact with SM through non-Abelian kinetic mixing by introducing a real triplet Higgs

• The interaction can be CP violating in the paradigm of non-Abelian kinetic mixing

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Thank you for your attention!