Abelian and non-Abelian kinetic mixing
dark photons

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Based on
M. He, X.-G. He, C.-K. Huang and GL, JHEP 1803 (2018) 139

IPMU Seminar, Oct. 10, 2018
Motivation

- Evidences for dark matter:
  - galactic rotation curves
  - merging clusters of galaxies
  - CMB anisotropies


The SM is incomplete...
Motivation

• Interactions of dark matter with the SM through mediator(s)

Higgs portal, vector portal, neutrino portal, axion portal,...

dark photon: New U(1) gauge boson

Motivation

- We assume that
  - SM particles are not charged under the new U(1) gauge symmetry
  - interactions with SM are generated from kinetic mixing

\[ L_{\text{kinetic}} = -\frac{1}{4} B^{\mu \nu} B_{\mu \nu} - \frac{1}{4} F'^{\mu \nu} F'^{\mu \nu} \]

SM part:

Abelian: U(1)_Y \times U(1)_X

\[ -\frac{1}{2} \sigma F'^{\mu \nu} B_{\mu \nu} \]

dim-4 operator
gauge invariant and renormalizable

After EWSB:

\[ \sigma \]

\[ A' \]

\[ \psi \]

\[ \gamma \]

\[ A' \]

\[ \epsilon \sim \frac{e g_D}{16 \pi^2} \log \frac{m_\psi}{M_*} \]

\( g_D \): dark gauge coupling

M_*: EW scale

\( \epsilon \) is order of \( 10^{-3} \) if \( m_\psi \approx M_* \)

NP may occur at arbitrary scale
Motivation

- We assume that
  - SM particles are not charged under the new U(1) gauge symmetry
  - interactions with SM are generated from kinetic mixing

Non-Abelian: $SU(2)_L \times U(1)_X$

\[
\mathcal{L} = \frac{C}{\Lambda^2} H^\dagger T^a H \mathcal{W}^a_{\mu\nu} X^{\mu\nu}
\]

dim-6 operator

After EWSB:

\[
\epsilon = \frac{C' v^2 s_W}{2 \Lambda^2}
\]

\[
\Lambda = \sqrt{\frac{C' v^2 s_W}{2\epsilon}} = \sqrt{\frac{C'}{\epsilon/10^{-4}}} \times 10 \text{ TeV}
\]


Toy model

$\Phi$ is triplet scalar with unit dark charge

\[
\lambda_{\text{mix}}(\phi^\dagger T^a \phi)(H^\dagger \tau^a H)
\]

\[
\epsilon = \frac{g g_D \lambda_{\text{mix}}}{96 \pi^2} \frac{v^2}{m_\phi^2} s_W \approx 10^{-4} g_D \lambda_{\text{mix}} \left(\frac{400 \text{ GeV}}{m_\phi}\right)^2
\]

$g_D$: dark gauge coupling
Motivation

- We assume that
  - SM particles are not charged under the new U(1) gauge symmetry
  - interactions with SM are generated from kinetic mixing

Non-Abelian: $\text{SU}(2)_L \times \text{U}(1)_X$

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

$W_{\mu\nu} = W^a_{\mu\nu} T^a$, $\Sigma = \Sigma^b T^b$

EWSB

real triplet scalar,

the only low-energy remnant of NP
beyond the SM

providing DM candidate...

M. Cirelli, N. Fornengo, A. Strumia,

$$\langle \Sigma^3 \rangle = x_0$$

$$\epsilon = \frac{\beta x_0 s_W}{\Lambda}$$

naturally suppressed by
small triplet vev

Motivation

• We assume that
  • SM particles are not charged under the new U(1) gauge symmetry
  • interactions with SM are generated from kinetic mixing

Non-Abelian: $SU(2)_L \times U(1)_X$

\[ W^3 \quad X=A' \]

dim-5 operator

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


1st term: CP-even, 2nd term: CP-odd (NEW)

New CP violation is necessary for baryogenesis

A. Sakharov, JETP Lett. 5 (1967) 24-27
In this talk, I will concentrate on the current constraints and future sensitivities of dark photon at colliders as well as test of CP violation

SM +

Abelian KM

\[ -\frac{1}{2}\sigma F'_{\mu \nu} B^{\mu \nu} \]

Non-Abelian KM

\[ -\frac{\beta}{\Lambda} \text{Tr}[W_{\mu \nu} \Sigma] X^{\mu \nu} - \frac{\tilde{\beta}}{\Lambda} \text{Tr}[W_{\mu \nu} \Sigma] \tilde{X}^{\mu \nu} \]
Parameters

• Dark photon mass can be generated by introducing a dark Higgs boson

\[
(D_\mu S)^\dagger (D^\mu S) \quad \Rightarrow \quad m_{A'} = g_{A'} s_{A'} v_s / \sqrt{2}
\]

Higgs portal:

\[
H \quad \rightarrow \quad S \quad \kappa |S|^2 |H|^2
\]

In Stueckelberg mechanism, no Higgs portal involved


• Free parameters considered: kinetic mixing parameter(s) and dark photon mass

• There are two steps to achieve couplings of physical dark photon to SM particles:
  • write the Lagrangian in the canonical form (kinetic mixing term is removed)
  • diagonalize the mass matrix

\[
B (W^3) \quad A' (X) \quad \text{EWSB} \quad \gamma, Z \quad A' (X) \quad \text{Two steps} \quad \text{physical couplings}
\]
Field redefinition

• In the Abelian KM case,

\[
\begin{pmatrix}
A_0 \\
Z_0 \\
A'_0
\end{pmatrix}
= V
\begin{pmatrix}
A \\
Z \\
A'
\end{pmatrix}
\]

\[ V = \begin{pmatrix}
1 & 0 & -c_W \sigma \\
0 & 1 & \frac{s_W \sigma m_{A'}^2}{m_{A'}^2 - m_Z^2} \\
0 & -\frac{s_W \sigma m_Z^2}{m_{A'}^2 - m_Z^2} & 1
\end{pmatrix} + O(\sigma^2) \]

\[
\epsilon = -c_W \sigma \]
\[
\tau = \frac{s_W \sigma m_{A'}^2}{m_{A'}^2 - m_Z^2}
\]

• In the non-Abelian KM case,

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

CP-odd term is not involved in field redefinition

\[
\langle \Sigma^3 \rangle = x_0
\]

\[
-\frac{\tilde{\beta}}{\Lambda} \text{Tr}(W_{0\mu\nu} \Sigma) \tilde{X}_0^{\mu\nu} \]

Levi-Civita tensor

\[
W_{0}^{3,\mu\nu} = \partial^\mu W_{0}^{3,\nu} - \partial^\nu W_{0}^{3,\mu} + g \epsilon^{3bc} W_{0}^{b,\mu} W_{0}^{c,\nu}
\]

\[
(\partial^\mu W_{0}^{3,\nu} - \partial^\nu W_{0}^{3,\mu}) \tilde{X}_0,\mu\nu = 0
\]

\[
(\partial^\mu W_{0}^{3,\nu} - \partial^\nu W_{0}^{3,\mu}) X_0,\mu\nu \neq 0
\]

\[
eq \frac{\beta x_0}{\Lambda}
\]

\[
eq \frac{2 c_W e_{WX} m_Z^2}{m_Z^2 - m_X^2} + O(e_{WX}^2)
\]
**Dark photon couplings**

- Couplings of dark photon to fermions

  **In the Abelian KM case,** the couplings of $X$ to fermions are universally rescaled by $\varepsilon$ for small $m_{A'}$.

  
  \[ \mathcal{L}_{f\bar{f}A'} = [\varepsilon e Q_f \bar{f} \gamma^\mu f + \tau \frac{g}{c_W} (v_Z - a_Z \gamma^5) f] A'_\mu \]

- **In the non-Abelian KM case,**

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

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

  \[ A_X = (c_\xi \alpha_{ZX} - s_\xi) a_Z, \]

  The couplings of $X$ to fermions are non-universally modified.

---

\[ \tau = -\frac{s_W m_{A'}^2 \varepsilon}{c_W (m_{A'}^2 - m_Z^2)} \]

\[ \alpha_{AX} = s_W e_W X \]

\[ \alpha_{ZX} = c_W e_W X \]
Dark photon couplings

- Couplings of dark photon to $Zh$

In the Abelian KM case,

$$\mathcal{L}_{\text{higgs}} = \frac{\tau g m_Z}{c_W} h A'_\mu Z^\mu$$

In the non-Abelian KM case,

$$\mathcal{L}_{\text{higgs}} = \frac{\chi g m_Z}{c_W} H_1 X_\mu Z^\mu$$

$$\tau = -\frac{s_W m^2_{A'} \epsilon}{c_W (m^2_{A'} - m^2_Z)}$$

$$\chi = c_\theta (c_\xi + e_{WX} c_W s_W) (s_\xi - e_{WX} c_W c_\xi)$$

After EWSB:

$$\Sigma^3 = x_0 + \sigma$$

$$\begin{pmatrix} h \\ \sigma \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \rightarrow 125 \text{ GeV}$$

$\Sigma$ acquires vev

$Z$ $X$
Dark photon couplings

- Couplings of dark photon to \( Zh \) (and \( Ah \))

In the non-Abelian KM case,

\[
\mathcal{O}_{WX} = -\frac{\beta}{\Lambda} \text{Tr}(W_{0\mu\nu}\Sigma)X_0^{\mu\nu},
\]

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

\[
W_0^{3,\mu\nu} = \partial^\mu W_0^{3,\nu} - \partial^\nu W_0^{3,\mu} + g\epsilon^{abc}W_0^{b,\mu}W_0^{c,\nu}
\]

\[
\begin{pmatrix} h \\ \sigma \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \rightarrow 125 \text{ GeV}
\]

\( \Sigma \) does not acquire vev, but neutral component

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

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

new \( H_1ZX \) couplings suppressed by \( s_\theta \)

important for EDMs (later)
Dark photon couplings

- Couplings of dark photon to $W^+W^-$

In the Abelian KM case,

$$\mathcal{L}_{\text{gauge}} = -ie(\epsilon + \tau \cot \theta_W) \left[ -\partial^\mu A^{\mu \nu}(W_{\mu}^+ W_{\nu}^- - W_{\nu}^+ W_{\mu}^-) 
+ A^{\mu \nu}(-W_{+\mu} \partial_{\nu} W_{-\mu}^- + W_{-\mu} \partial_{\nu} W_{+\mu}^- + W_{+\mu} \partial_{\nu} W_{-\nu}^- - W_{-\mu} \partial_{\nu} W_{+\nu}^-) \right]$$

In the non-Abelian KM case,

$$\mathcal{O}_{WX} = -\frac{\beta}{\Lambda} \text{Tr}(W_{0\mu}\Sigma) X_{0}^{\mu\nu},$$

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

$$W_{0}^{3,\mu\nu} = \partial_{\mu} W_{0}^{3,\nu} - \partial_{\nu} W_{0}^{3,\mu} + g \epsilon^{3bc} W_{0}^{b,\mu} W_{0}^{c,\nu}$$

$\Sigma$ acquires vev
Dark photon couplings

- Couplings of dark photon to $W^+W^-$

In the Abelian KM case,

$$
\mathcal{L}_{\text{gauge}} = -ie(\epsilon + \tau \cot \theta_W) \left[ -\partial^\mu A^{\nu}(W^\mu_W W^-_\nu - W^+_\nu W^-_\mu) \\
+ A^{\nu}(W^+\mu \partial_\nu W^-_\mu + W^-\mu \partial_\nu W^+_\mu + W^+\mu \partial_\mu W^-_\nu - W^-\mu \partial_\mu W^+_\nu) \right]
$$

In the non-Abelian KM case,

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

CP-violating $W^+W^-X$ coupling (later)
Constraints

- Lots of efforts to search for dark photons which kinetically mixes with photon
  - beam-dump, fixed-target, low energy $e^+e^-$ collider, rare-meson-decay experiments and LHC

Shaded: Existing bounds
Lines: Proposed experiments

We are interested in Abelian and non-Abelian KM dark photons accessible at the LHC and future $e^+e^-$ colliders

Both kinetic mixing parameter and dark photon mass are required not too small
Constraints

- Collider search strategies at the LHC (ATLAS/CMS, LHCb)
  
  M. Diamond, LHC DMWG 2017

  \[ pp \rightarrow Z_D \rightarrow l^+l^\prime \]
  - only requires vector portal

  \[ pp \rightarrow h \rightarrow Z \ Z_D \rightarrow 2l^+ 2l^\prime \]
  - only requires vector portal

  \[ pp \rightarrow h \rightarrow Z \ Z_D \rightarrow 2l^+ 2l^\prime \]
  - suppressed in vector portal
  - significant if Higgs portal added
Constraints

• Recast constraints from benchmark model to alternative model

\[ \sigma_A(m, g_A) B_A(m) \varepsilon(\tau_A(m, g_A)) = \sigma_B(m, g_B) B_B(m) \varepsilon(\tau_B(m, g_B)) \]

• given a limit for at point \((m, g_A)\) for model \(A\), solve above to find limit point \((m, g_B)\) for model \(B\)
• absolute cross-section can be tricky, ratios are easier

\[ \frac{\sigma_A(m, g_A) \varepsilon(\tau_A(m, g_A))}{\sigma_B(m, g_B) \varepsilon(\tau_B(m, g_B))} \frac{B_A(m)}{B_B(m)} = 1 \]

1. branching fraction ratio, \(\frac{B_A(m)}{B_B(m)}\)
2. cross-section ratio, \(\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)}\)
3. efficiency ratio, \(\frac{\varepsilon(\tau_A(m, g_A))}{\varepsilon(\tau_B(m, g_B))}\)

detector efficiency

P. Ilten, LHC DMWG 2018
Constraints

- Dark photon searches at the LHCb
  - interpreted as Abelian KM dark photon

\[ \frac{d\sigma_{pp \rightarrow X A' \rightarrow X \mu^+ \mu^-}}{d\sigma_{pp \rightarrow X \gamma^* \rightarrow X \mu^+ \mu^-}} = \epsilon^4 \frac{m_{\mu\mu}^4}{(m_{\mu\mu}^2 - m_{A'}^2)^2 + \Gamma_{A'}^2 m_{A'}^2} \]

for any multiparticle final state X and data-driven analysis is performed since efficiency and acceptance for the measured SM process are the same as for the inferred signal process.

Constraints

- Dark photon searches at the LHCb
  - interpreted as Abelian KM dark photon

proper decay length:

\[ c \tau_{\gamma' \rightarrow e^+e^-} \simeq \left( \frac{\epsilon^2 \alpha_{\text{EM}} m_{\gamma'}}{3} \right)^{-1} \]

\[ = 8 \times 10^{-3} \text{ cm} \left( \frac{10^{-4}}{\epsilon} \right)^2 \left( \frac{100 \text{ MeV}}{m_{\gamma'}} \right) \]

Y. Tsai, L.-T. Wang, Y. Zhao, Phys.Rev. D95 (2017) 015027

Phys.Rev.Lett. 120 (2018), 061801

prompt searches for

10 GeV < m_{A'} < 70 GeV
Constraints

• Dark photon searches at the LHCb
  • re-interpreted as non-Abelian KM dark photon

The couplings of X to fermions are non-universally modified, so one needs fractions of each flavor of quarks in dark photon production

\[
\frac{\sigma_X}{\sigma_{A'}} = \sum_{i=u,d,s,c,b} \left[ \frac{\sigma^{i}_{A'}}{\sigma^{i}_{A'}} \right] \left[ \frac{\sigma^{i}_{X}}{\sigma^{i}_{A'}} \right]
\]

\[
\frac{\sigma^{i}_{X}}{\sigma^{i}_{A'}} = \frac{\Gamma(X \to q_i \bar{q}_i)}{\Gamma(A' \to q_i \bar{q}_i)}
\]

\[
\frac{\sigma_X}{\sigma_{A'}} \frac{\text{Br}(X \to \mu^+ \mu^-) \epsilon(\tau_X)}{\sigma_{A'} \text{Br}(A' \to \mu^+ \mu^-) \epsilon(\tau'_{A'})} = 1
\]

Constraints

• Dark photon searches at the LHCb
  • re-interpreted as non-Abelian KM dark photon

\[
\frac{\sigma_X \, \text{Br}(X \rightarrow \mu^+ \mu^-) \, \epsilon(\tau_X)}{\sigma_{A'} \, \text{Br}(A' \rightarrow \mu^+ \mu^-) \, \epsilon(\tau_{A'})} = 1
\]

\[e_{WX} < 5 \times 10^{-3} \text{ for } 10 \text{ GeV} < m_X < 70 \text{ GeV}\]

Constraints

- Dark photon searches at the ATLAS/CMS
  - interpreted as $Z'$ in terms of $\sigma \text{ Br}$
  - re-interpreted as Abelian KM dark photon in terms of $\epsilon$

\[
\epsilon^{95\%\text{ C.L.}} = \left( \frac{[\sigma(A') \text{ Br}(\mu^+\mu^-)]^{95\%\text{ C.L.}}}{K_{\text{NLO}} \sigma_{\text{LO}}(A') \text{ Br}(\mu^+\mu^-)/\left(10^{-4} \epsilon^2\right)} \right)^{1/2} \sqrt{\frac{36.1 \text{ fb}^{-1}}{L}}
\]

\[\tau \text{ is included}\]

(non-Abelian dark photon with $m_\chi < 150$ GeV is considered)

we project the sensitivities to $300 \text{ fb}^{-1}$, $3000 \text{ fb}^{-1}$
Constraints

- Dark photon searches at the ATLAS/CMS
  - interpreted as Abelian KM dark photon in terms of $\sigma \, Br$

$Z$ can be on-shell or off-shell
$Z_d$ is always on-shell

$\tau = -\frac{s_W m_{A'}^2 \epsilon}{c_W (m_{A'}^2 - m_Z^2)}$ (small)

Constraints on $\epsilon$ in Abelian KM case are weak
Constraints

- Dark photon searches at the ATLAS/CMS
  - re-interpreted as non-Abelian KM dark photon

\[ \frac{\sigma_H^X \text{Br}(H \to Z(*) X \to 4\ell)}{\sigma_H^{A'} \text{Br}(H \to Z(*) A' \to 4\ell)} = 1 \]

Z can be on-shell or off-shell
Z\(d\) is always on-shell

\[ \chi = c_\theta (c_\xi + e_W x_c W s_W) (s_\xi - e_W x_c W c_\xi) \]

\[ \text{Br}(H \to Z(*) A') \text{Br}(Z \to \ell^+ \ell^-) = \frac{\sigma_H^X \Gamma(H \to Z(*) X \to \ell^+ \ell^- \ X) \text{Br}(X \to \ell^+ \ell^-)}{\sigma_H^{A'} \Gamma_H^{H \text{tot}} \text{Br}(A' \to \ell^+ \ell^-)} \]

(exp. upper limits)

\[ R_X = \frac{c_\theta^2 \Gamma(H \to Z(*) A' \to \ell^+ \ell^- A')}{\Gamma_H^{H \text{tot}} \text{Br}(H \to Z(*) A')^{\text{upper limit}} \text{Br}(Z \to \ell^+ \ell^-) \chi^2 \text{Br}(X \to \ell^+ \ell^-)} \]

\[ \frac{\tau^2 \text{Br}(A' \to \ell^+ \ell^-)}{} \]
Constraints

- Dark photon searches at the ATLAS/CMS
  - re-interpreted as non-Abelian KM dark photon

\[
\frac{\sigma_H \text{Br}(H \rightarrow Z(\ast) X \rightarrow 4\ell)}{\sigma_{H'} \text{Br}(H \rightarrow Z(\ast) A' \rightarrow 4\ell)} = 1
\]

\[
\begin{align*}
\epsilon_{WX} &< 2.6 \times 10^{-2} \text{ for } \\
10 \text{ GeV} &< m_X < 55 \text{ GeV}
\end{align*}
\]

R_X > 1 region is excluded

Constraints

• Constraints from SM measurements
  • In the Abelian KM case,

\[
\begin{pmatrix}
A_0 \\
Z_0 \\
A'_0
\end{pmatrix} = V \begin{pmatrix}
A \\
Z \\
A'
\end{pmatrix}
\]

\[
V = \begin{pmatrix}
1 & 0 & -c_W \sigma \\
0 & 1 & s_W \sigma \frac{m_{A'}^2}{m_{A'}^2 - m_Z^2}
\end{pmatrix}
\]

\[
(m_Z)^2 = m_Z^2 + \frac{m_Z^2 s_W^2 \sigma^2}{m_{A'}^2 - m_Z^2} + \mathcal{O}(\sigma^3)
\]


• In the non-Abelian KM case,

at order of \(e_{WX}\)

\[
A_0^\mu = A^\mu + e_{WX} s_W s_\xi Z^\mu - e_{WX} s_W c_\xi X^\mu + \mathcal{O}(e_{WX}^2),
\]

\[
Z_0^\mu = (c_\xi + e_{WX} c_W s_\xi) Z^\mu + (s_\xi - e_{WX} c_W c_\xi) X^\mu + \mathcal{O}(e_{WX}^2),
\]

\[
X_0^\mu = -s_\xi Z^\mu + c_\xi X^\mu + \mathcal{O}(e_{WX}^2),
\]

Z boson mass is also shifted

EWPT (in progress)
Proposed searches and sensitivities

- Abelian KM dark photon searches at future e^+e^- colliders (CEPC/ILC, FCC-ee)

radiative return process:

- Previously used for low mass dark photon searches at BaBar
  
  Phys.Rev.Lett. 113 (2014) 201801

- We proposed to search for dark photon with mass as large as kinematically allowed at future e^+e^- colliders

lepton momentum resolution:

\[ \frac{\Delta p_T}{p_T} = 0.1\% \oplus \frac{p_T}{10^5 \text{ GeV}} \]

Total width of A' is small

M. He, X.-G. He, C.-K. Huang and GL, JHEP 1803 (2018) 139
Proposed searches and sensitivities

- Abelian KM dark photon searches at future $e^+e^-$ colliders (CEPC/ILC, FCC-ee)
  - In the low-mass region, better sensitivities at the CEPC and FCC-ee (160 GeV) than at the LHCb
  - In the high-mass region, better sensitivities at the FCC-ee (160 GeV) and FCC-ee (350 GeV) than at the HL-LHC

LHC8,13/14=ATLAS/CMS

take CEPC as a benchmark machine at 240~250 GeV

lack of dark photon searches close to $Z$ mass region at the LHC

LHC8 result is from recast SM dilepton differential distribution measurements

$m_{A'} > 20$ GeV

M. He, X.-G. He, C.-K. Huang and GL,
JHEP 1803 (2018) 139
Test CP violation in non-Abelian KM dark photon model...
Proposed searches and sensitivities

- Non-Abelian KM dark photon constraints from electric dipole moments (EDMs)

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

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

\[ W_0^{3,\mu\nu} = \partial^\mu W_0^{3,\nu} - \partial^\nu W_0^{3,\mu} + g e^{3bc} W_0^{b,\mu} W_0^{c,\nu} \]

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

**Current limits:**

\[ |d_e| < 8.7 \times 10^{-29} \text{ e cm} \quad |d_n| < 3.0 \times 10^{-26} \text{ e cm} \]

Future sensitivities to \( d_e \) and \( d_p \) can be \( 1.0 \times 10^{-29} \text{ e cm} \)


Proposed searches and sensitivities

- Non-Abelian KM dark photon constraints from electric dipole moments (EDMs)

EDMs are proportional to $s_\theta c_\theta$

$e_{WX} \times \tilde{e}_{WX} \leq 4$ with $c_\theta = 0.95$
Proposed searches and sensitivities

• Non-Abelian KM dark photon constraints from electric dipole moments (EDMs)

Barr-Zee diagram:

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

\[ \tilde{\mathcal{O}}_{WX} \supset \frac{i\tilde{\beta}x_0s_\xi}{\Lambda} gW^{+}_\mu W^-_{\nu} \tilde{Z}^{\mu\nu} \]

\[ \tan 2\xi = \frac{2c_W e_{WX} m_Z^2}{m_Z^2 - m_X^2} + \mathcal{O}(e_{WX}^2) \]

double-suppressed by $e_{WX}$

negligible contribution to EDMs
Proposed searches and sensitivities

- Collider signature of CPV non-Abelian KM dark photon

\[ -i g \tilde{e}_W X c_\eta \partial^\mu \tilde{X}^\nu (W^+_{\mu} W^-_{\nu} - W^+_{\nu} W^-_{\mu}) \]

azimuthal angle distribution

- CPV HWW and HZZ couplings

- SUSY particles searches

- has not been applied to a spin-1 particle


Proposed searches and sensitivities

- Collider signature of CPV non-Abelian KM dark photon

For VBF $p p \rightarrow j j X$,

\[ \Delta \phi_{jj} = \phi_{j1} - \phi_{j2} \]

$\Phi_1 (\Phi_2)$ is the azimuthal angle of jet in the forward (backward) hemisphere

\[
\frac{d\sigma}{d\Delta \phi_{jj}} = A_0 + A_1 \cos(\Delta \phi_{jj}) + A_2 \cos(2\Delta \phi_{jj}) + B_1 \sin(\Delta \phi_{jj}) + B_2 \sin(2\Delta \phi_{jj})
\]


exist only if CP is violated

After integrating $\Delta \Phi_{jj}$ over $(0, \pi)$ and $(\pi, 2\pi)$, the asymmetry is

\[ \mathcal{A} = \frac{\sigma_{\Delta \phi_{jj}>0} - \sigma_{\Delta \phi_{jj}<0}}{\sigma_{\Delta \phi_{jj}>0} + \sigma_{\Delta \phi_{jj}<0}}. \]

$\mathcal{A} \neq 0$ with CP violation

$e_W^X \times \tilde{e}_W^X \leq 4$ with $c_\theta=0.95$

For $m_X=100$ GeV, $A=0.135$ (preliminary)

Summary and Outlook

- Current constraints and future sensitivities of dark photons in the Abelian and non-Abelian cases are discussed.
- EDMs and azimuthal angle distribution are used to test CP violation in the non-Abelian dark photon model.
- Long-lived dark photon with small kinetic mixing parameter may be considered in the future.

Thanks for your attention!

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