Abelian and non-Abelian kinetic mixing dark photons

Gang Li

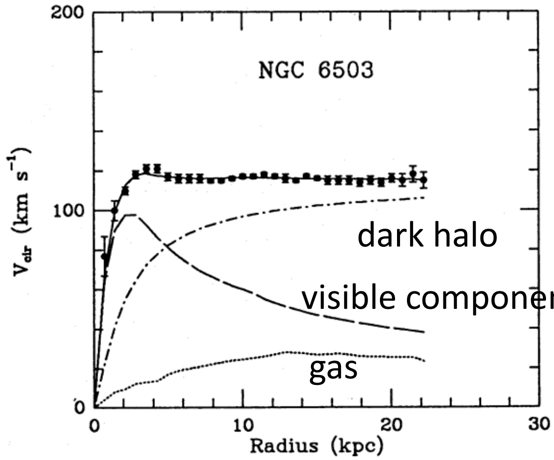
National Taiwan University

Based on
M. He, X.-G. He, C.-K. Huang and GL, JHEP 1803 (2018) 139
K. Fuyuto, X.-G. He, GL and M. J. Ramsey-Musolf, in preparation

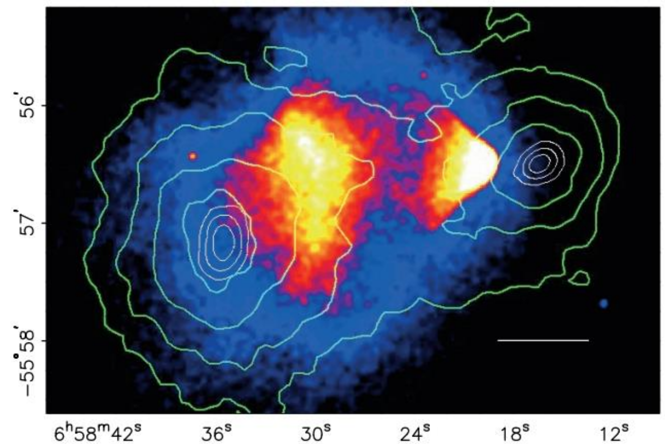
IPMU Seminar, Oct. 10, 2018

Motivation

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

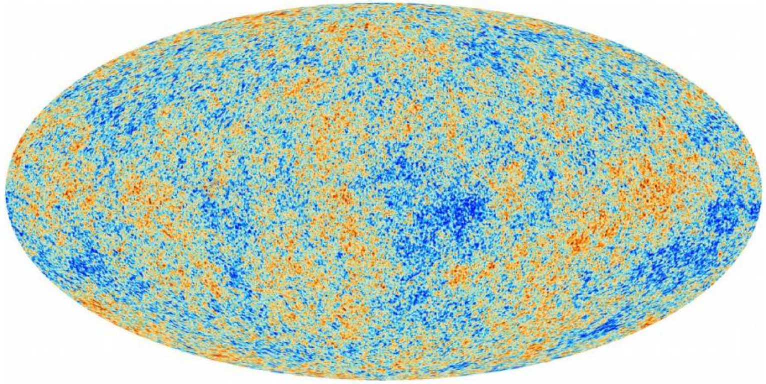


K.G. Begeman, A.H. Broeils, R.H. Sanders, MNRAS 249(1991) 523



gravitational lensing

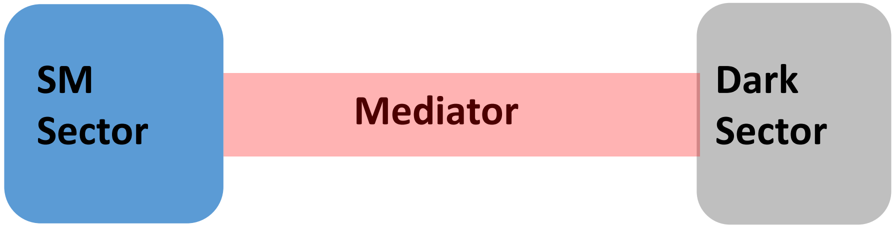
D. Clowe, et al, Astrophys. J. 648 (2006) L109



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

P. Fayet, Phys. Lett. B 95, 285 (1980)
P. Fayet, Nucl. Phys. B 187, 184 (1981)

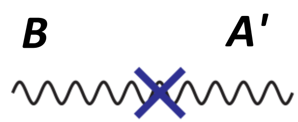
Motivation

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

SM part: $$L_{\text{kinetic}} = -\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu}$$

B. Holdom, Phys. Lett. B166, 196 (1986)
R. Foot, X-G He Phys.Lett. B267 (1991) 509

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

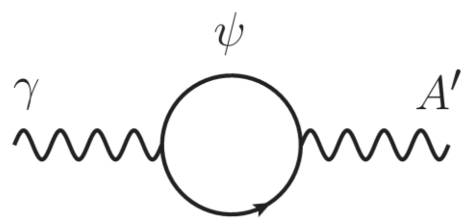


dim-4 operator $$-\frac{1}{2}\sigma F'_{\mu\nu}B^{\mu\nu}$$ gauge invariant and renormalizable

After EWSB:

$$\epsilon = -c_W \sigma$$

NP may occur at arbitrary scale



ψ has both DM and SM charges

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

g_D: dark gauge coupling
M_*:EW scale

ε is order of 10^{-3} if $m_\psi \sim M_*$

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

dim-6 operator

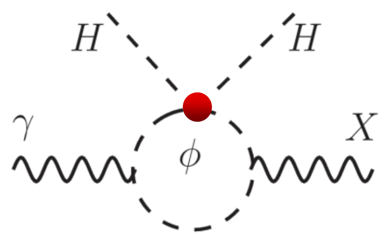
$$\frac{C}{\Lambda^2} H^\dagger T^a H W^a_{\mu\nu} X^{\mu\nu}$$

G. Barello, S. Chang, C.A. Newby, Phys.Rev. D94 (2016), 055018

After EWSB:

$$\epsilon = \frac{Cv^2 s_W}{2\Lambda^2}$$

toy model



Φ is triplet scalar with unit dark charge

$$\lambda_{\rm mix}(\phi^\dagger T^a \phi)(H^\dagger \tau^a H)$$

$$\Lambda = \sqrt{\frac{Cv^2 s_W}{2\epsilon}} = \sqrt{\frac{C}{\epsilon/10^{-4}}} \times \ 10 \text{ TeV}$$

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

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

dim-5 operator

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

C. A. Argüelles, X.-G. He, G. Ovanesyan, T. Peng, M. J. Ramsey-Musolf, Phys.Lett. B770 (2017) 101

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

real triplet scalar, $\langle \Sigma^3 \rangle = x_0$

EWSB

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

naturally suppressed by small triplet vev

the only low-energy remnant of NP beyond the SM

providing DM candidate...

M. Cirelli, N. Fornengo, A. Strumia, Nucl.Phys. B753 (2006) 178

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

dim-5 operator

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

K. Fuyuto, X.-G. He, GL, M. J. Ramsey-Musolf, in preparation

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

Parameters

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

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

Higgs portal: 

$\kappa |S|^2 |H|^2$

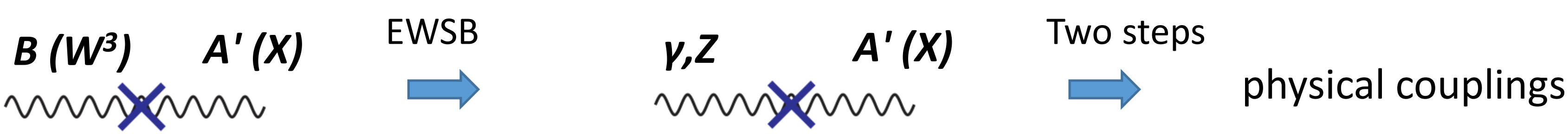
D. Curtin, R. Essig, S. Gori, J. Shelton, JHEP 1502 (2015) 157

In Stueckelberg mechanism, no Higgs portal involved

B. Kors, P. Nath, Phys.Lett. B586 (2004) 366

- Free parameters considered: kinetic mixing parameter(s) and dark photon masss

- 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



Field redefinition

- In the Abelian KM case,

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

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

$$\epsilon = -c_W\sigma$$

$$\tau = \frac{s_W\sigma m_{A'}^2}{m_{A'}^2 - m_Z^2}$$

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

- In the non-Abelian KM case,

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

$$Z_0^\mu = (c_\xi + e_{WX}c_W s_\xi)Z^\mu + (s_\xi - e_{WX}c_W c_\xi)X^\mu + \mathcal{O}(e_{WX}^3),$$

$$X_0^\mu = -s_\xi Z^\mu + c_\xi X^\mu + \mathcal{O}(e_{WX}^3),$$

$$e_{WX} = \frac{\beta x_0}{\Lambda}$$

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

CP-odd term is not involved in field redfinition

$$-\frac{\tilde\beta}{\Lambda}\mathrm{Tr}(W_{0\mu\nu}\Sigma)\tilde X_0^{\mu\nu}$$

Levi-Civita tensor →

$$(\partial^\mu W_0^{3,\nu} - \partial^\nu W_0^{3,\mu})\tilde X_{0,\mu\nu} = 0$$

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

$$W_0^{3,\mu\nu} = \partial^\mu W_0^{3,\nu} - \partial^\nu W_0^{3,\mu} + g\epsilon^{3bc}W_0^{b,\mu}W_0^{c,\nu}$$

$$(\partial^\mu W_0^{3,\nu} - \partial^\nu W_0^{3,\mu})X_{0,\mu\nu} \neq 0$$

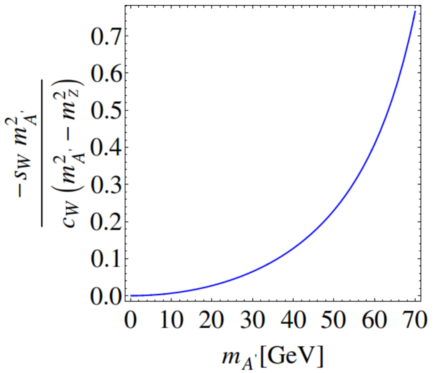
Dark photon couplings

- Couplings of dark photon to fermions

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

In the Abelian KM case, universally rescaled by ε for small $m_{A'}$

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



In the non-Abelian KM case,

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

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

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

$$\alpha_{AX} = s_W e_{WX}$$

$$\alpha_{ZX} = c_W e_{WX}$$

The couplings of X to fermions are non-universally modified

Dark photon couplings

- Couplings of dark photon to *Zh*

In the Abelian KM case,

$$\mathcal{L}_{\rm higgs} = \frac{\tau g m_Z}{c_W} h A'_\mu Z^\mu \qquad \tau = -\frac{s_W m_{A'}^2 \epsilon}{c_W (m_{A'}^2 - m_Z^2)}$$

In the non-Abelian KM case,

$$\mathcal{L}_{\rm higgs} = \frac{\chi g m_Z}{c_W} H_1 X_\mu Z^\mu \qquad \chi = c_\theta (c_\xi + e_{WX} c_W s_W)(s_\xi - e_{WX} c_W c_\xi)$$

$$\mathcal{O}_{WX} = -\frac{\beta}{\Lambda} {\rm Tr}(W_{0\mu\nu}\Sigma) X_0^{\mu\nu}$$

$$W_0^{3,\mu\nu} = \partial^\mu W_0^{3,\nu} - \partial^\nu W_0^{3,\mu} + g\epsilon^{3bc} W_0^{b,\mu} W_0^{c,\nu}$$

After EWSB: $\Sigma^3 = x_0 + \sigma$

Σ acquires vev

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

H_1 → 125 GeV

Dark photon couplings

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

In the non-Abelian KM case,

$$\mathcal{O}_{WX} = -\frac{\beta}{\Lambda}\mathrm{Tr}(W_{0\mu\nu}\Sigma)X_0^{\mu\nu},$$
$$\tilde{\mathcal{O}}_{WX} = -\frac{\tilde{\beta}}{\Lambda}\mathrm{Tr}(W_{0\mu\nu}\Sigma)\tilde{X}_0^{\mu\nu}.$$

$$W_0^{3,\mu\nu} = \partial^\mu W_0^{3,\nu} - \partial^\nu W_0^{3,\mu} + g\epsilon^{3bc}W_0^{b,\mu}W_0^{c,\nu}$$

After EWSB: $\Sigma^3 = x_0 + \sigma$

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

H_1 → 125 GeV

Σ does not acquires vev,
but neutral component

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

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

important for EDMs (later)

new H_1ZX couplings suppressed by s_θ

Dark photon couplings

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

In the Abelian KM case,

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

In the non-Abelian KM case,

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

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

$$W_0^{3,\mu\nu} = \partial^\mu W_0^{3,\nu} - \partial^\nu W_0^{3,\mu} + g\epsilon^{3bc}W_0^{b,\mu}W_0^{c,\nu}$$

$\Rightarrow$

$$\mathcal{O}_{WX} \supset -\frac{i\beta x_0}{2\Lambda}g(W_{0\mu}^+ W_{0\nu}^- - W_{0\mu}^- W_{0\nu}^+)X_0^{\mu\nu}$$

$$\tilde{\mathcal{O}}_{WX} \supset -\frac{i\tilde{\beta} x_0}{2\Lambda}g(W_{0\mu}^+ W_{0\nu}^- - W_{0\mu}^- W_{0\nu}^+)\tilde{X}_0^{\mu\nu}$$

Σ acquires vev

W^+, W^- fields do not change

Dark photon couplings

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

In the Abelian KM case,

$$\mathcal{L}_{\rm gauge} = -ie(\epsilon + \tau \cot\theta_W)\big[-\partial^\mu A'^\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) + A'^\nu(-W^{+\mu}\partial_\nu W^-_\mu + W^{-\mu}\partial_\nu W^+_\mu + W^{+\mu}\partial_\mu W^-_\nu - W^{-\mu}\partial_\mu W^+_\nu)\big]$$

In the non-Abelian KM case,

$$\begin{aligned}\mathcal{L}_{\rm gauge} =& -ig(c_W s_\xi - e_{WX} c_\xi)\big[-\partial^\mu X^\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) \\ &+ X^\nu(-W^{+\mu}\partial_\nu W^-_\mu + W^{-\mu}\partial_\nu W^+_\mu + W^{+\mu}\partial_\mu W^-_\nu - W^{-\mu}\partial_\mu W^+_\nu)\big] \\ &- ig e_{WX} c_\xi \partial^\mu X^\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) \\ &- ig \tilde{e}_{WX} c_\xi \partial^\mu \tilde{X}^\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu)\end{aligned}$$

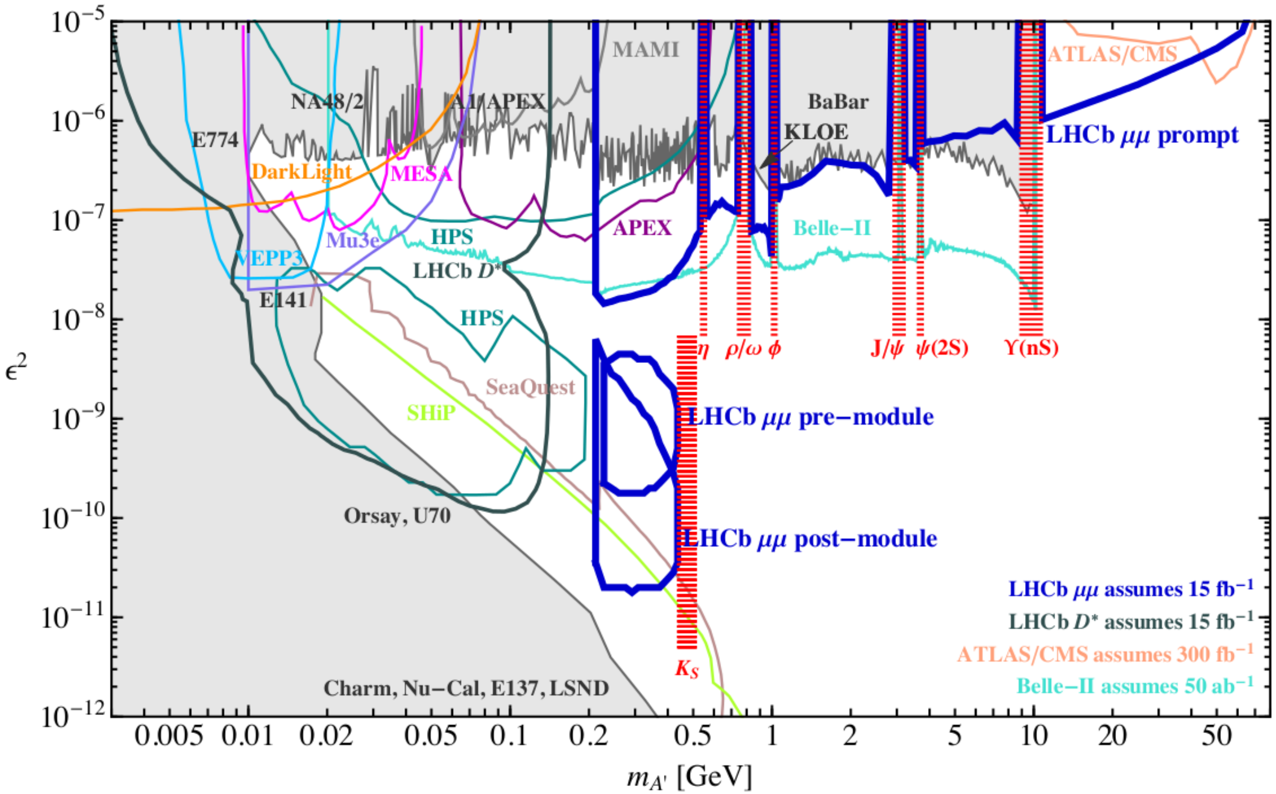
CP-even (first three lines)

CP-odd (last line)

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

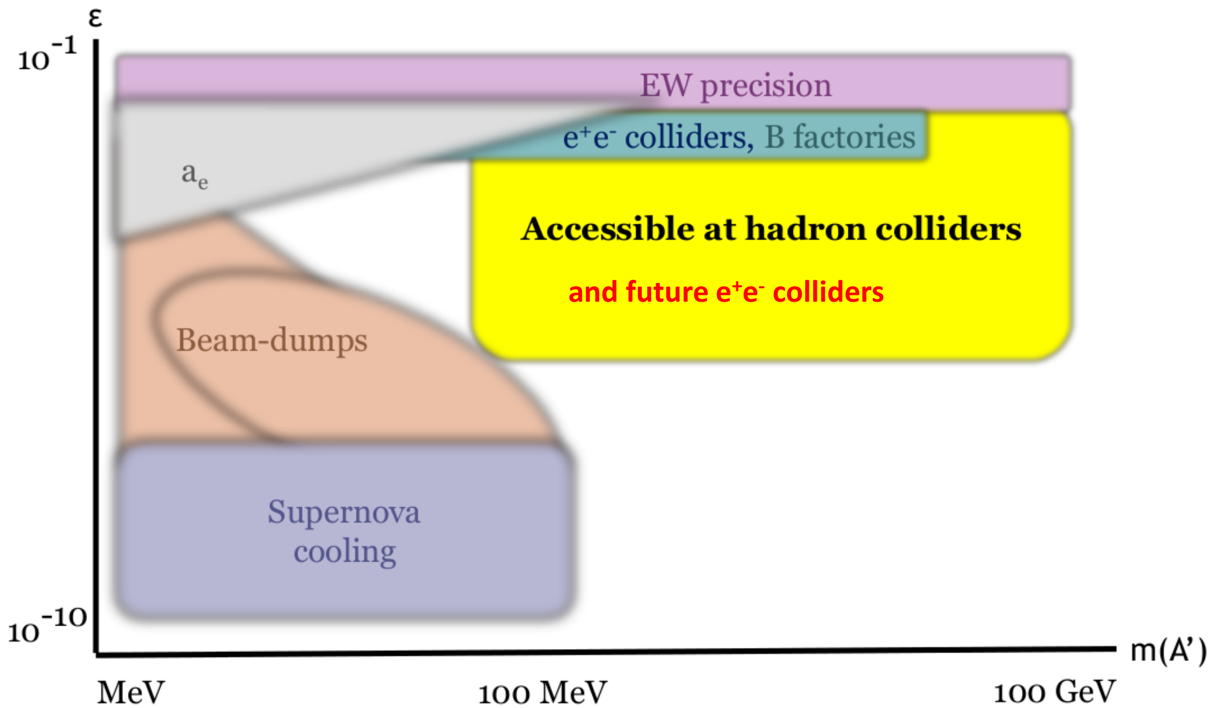


$$\varepsilon \equiv \frac{g'_e}{g_e}$$

Shaded: Existing bounds
Lines: Proposed experiments

P. Ilten, Y. Soreq, J. Thaler, M. Williams and W. Xue, Phys. Rev. Lett. 116, no. 25, 251803 (2016)

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



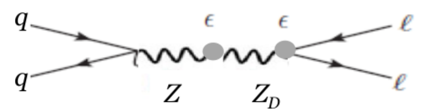
Both kinetic mixing paramter and dark photon mass are required not too small

Constraints

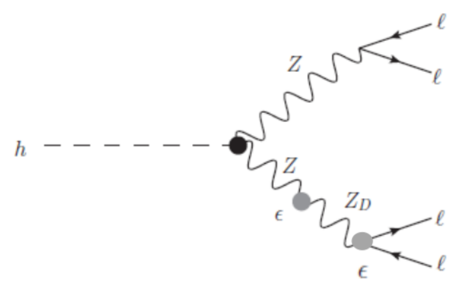
- Collider search strategies at the LHC (ATLAS/CMS, LHCb)

M. Diamond, LHC DMWG 2017

$pp \rightarrow Z_D \rightarrow l^+l^-$
- only requires vector portal



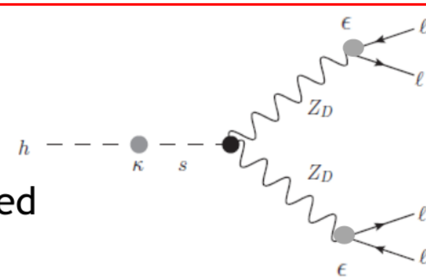
$pp \rightarrow h \rightarrow Z\, Z_D \rightarrow 2l^+ 2l^-$
- only requires vector portal



benchmark model

alternative model

$pp \rightarrow h \rightarrow Z_D\, Z_D \rightarrow 2l^+ 2l^-$
- suppressed in vector portal
- significant if Higgs portal added



DMWG's newest focus

LHC DMWG public meeting on dark photons

Friday 22 Jun 2018, 09:00 → 18:30 Europe/Zurich

4-S-030 (CERN)

Constraints

- Recast contraints from benchmark model to alternative model

$$\sigma_A(m, g_A)\mathcal{B}_A(m)\varepsilon(\tau_A(m, g_A)) = \sigma_B(m, g_B)\mathcal{B}_B(m)\varepsilon(\tau_B(m, g_B))$$

- 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

$$\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)} \frac{\varepsilon(\tau_A(m, g_A))}{\varepsilon(\tau_B(m, g_B))} \frac{\mathcal{B}_A(m)}{\mathcal{B}_B(m)} = 1$$

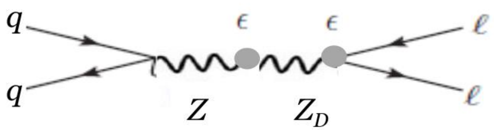
1. branching fraction ratio, $\frac{\mathcal{B}_A(m)}{\mathcal{B}_B(m)}$
2. cross-section ratio, $\frac{\sigma_A(m,g_A)}{\sigma_B(m,g_B)}$
3. efficiency ratio, $\frac{\varepsilon(\tau_A(m,g_A))}{\varepsilon(\tau_B(m,g_B))}$

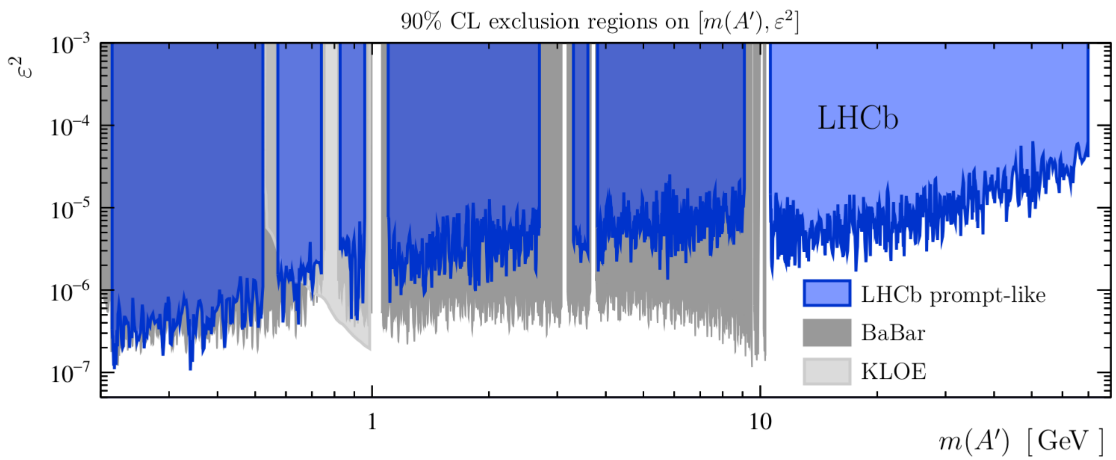
P. Ilten, LHC DMWG 2018

↑ detector efficiency

Constraints

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





τ term is neglected

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

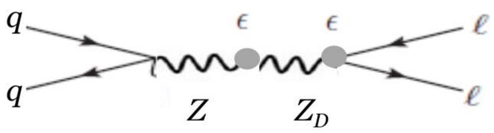
$$\frac{d\sigma_{pp\to XA'\to X\mu^+\mu^-}}{d\sigma_{pp\to X\gamma^*\to X\mu^+\mu^-}} = \epsilon^4 \frac{m_{\mu\mu}^4}{(m_{\mu\mu}^2 - m_{A'}^2)^2 + \Gamma_{A'}^2 m_{A'}^2}$$

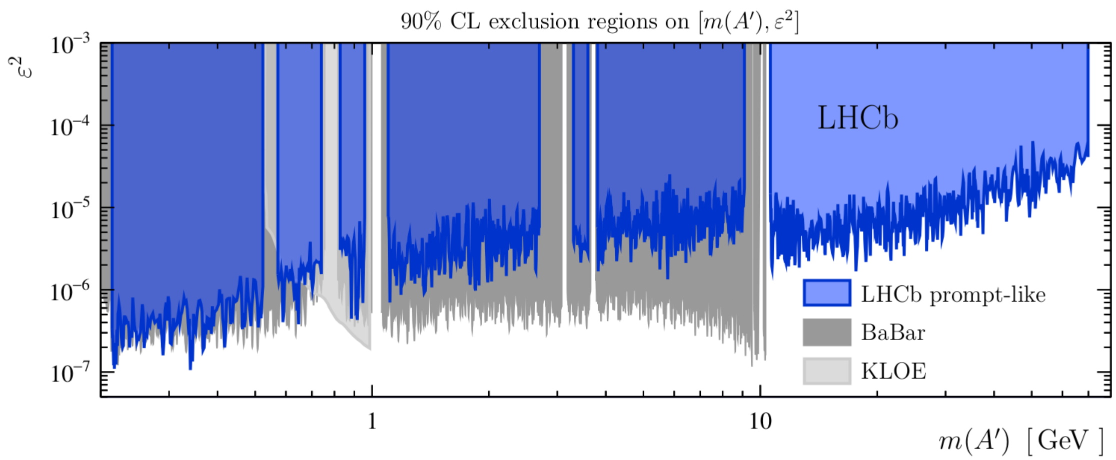
for any multiparticle final state *X and* data-driven analysis is performed since efficiency and acceptance for the measured SM process are the same as for the inferred signal process

P. Ilten, Y. Soreq, J. Thaler, M. Williams, W. Xue, Phys.Rev.Lett. 116 (2016) 251803

Constraints

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





proper decay length:

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

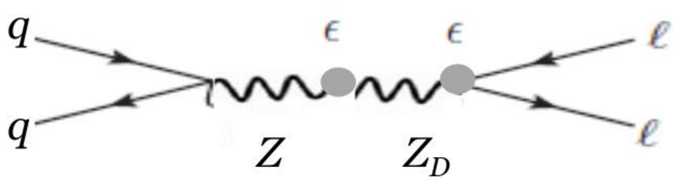
$$c\tau_{\gamma' \to e^+e^-} \simeq \left(\frac{\epsilon^2 \alpha_{\rm EM}\, m_{\gamma'}}{3}\right)^{-1}$$
$$= 8 \times 10^{-3}\,\text{cm} \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\,\text{MeV}}{m_{\gamma'}}\right)$$

→ prompt searches for 10 GeV < $m_{A'}$ < 70 GeV

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

Constraints

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



equal to 1 (prompt)

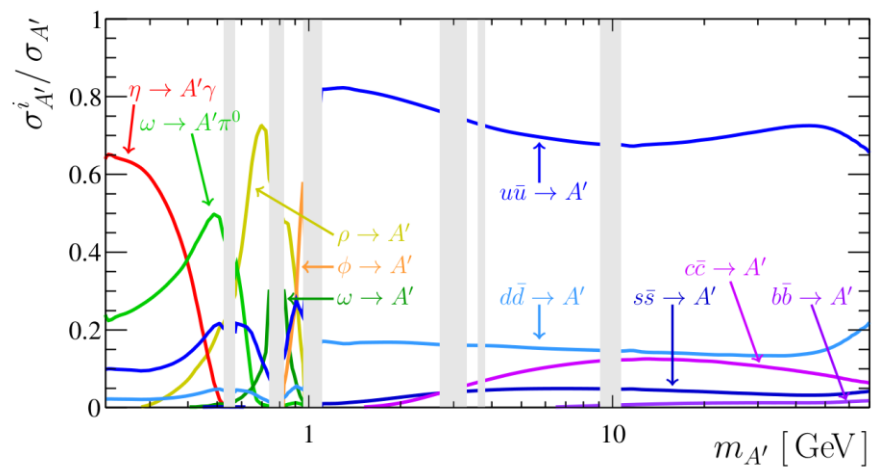
$$\frac{\sigma_X}{\sigma_{A'}} \frac{\mathrm{Br}(X \to \mu^+\mu^-)}{\mathrm{Br}(A' \to \mu^+\mu^-)} \frac{\epsilon(\tau_X)}{\epsilon(\tau'_A)} = 1$$

The couplings of X to fermions are non-universally modified, so one needs

fractions of each flavor of quarks in dark photon production

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

$$\frac{\sigma^i_X}{\sigma^i_{A'}} = \frac{\Gamma(X \to q_i \bar{q}_i)}{\Gamma(A' \to q_i \bar{q}_i)}$$



P. Ilten, Y. Soreq, M. Williams, W. Xue, JHEP 1806 (2018) 004

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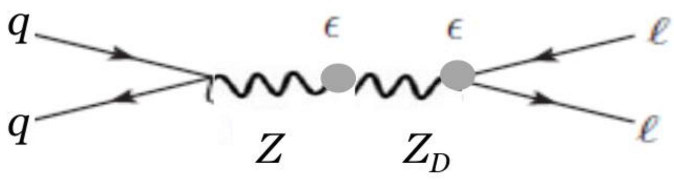
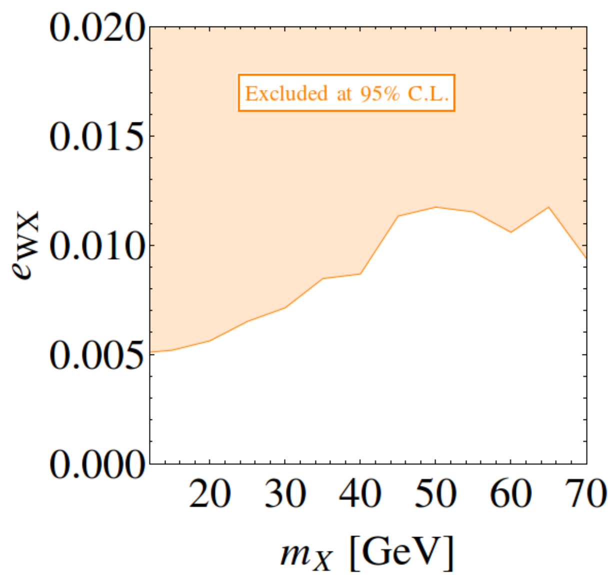
  - re-interpreted as non-Abelian KM dark photon



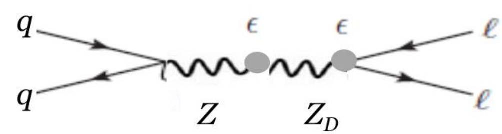
$$\frac{\sigma_X}{\sigma_{A'}} \frac{\mathrm{Br}(X \to \mu^+\mu^-)}{\mathrm{Br}(A' \to \mu^+\mu^-)} \frac{\epsilon(\tau_X)}{\epsilon(\tau'_A)} = 1$$



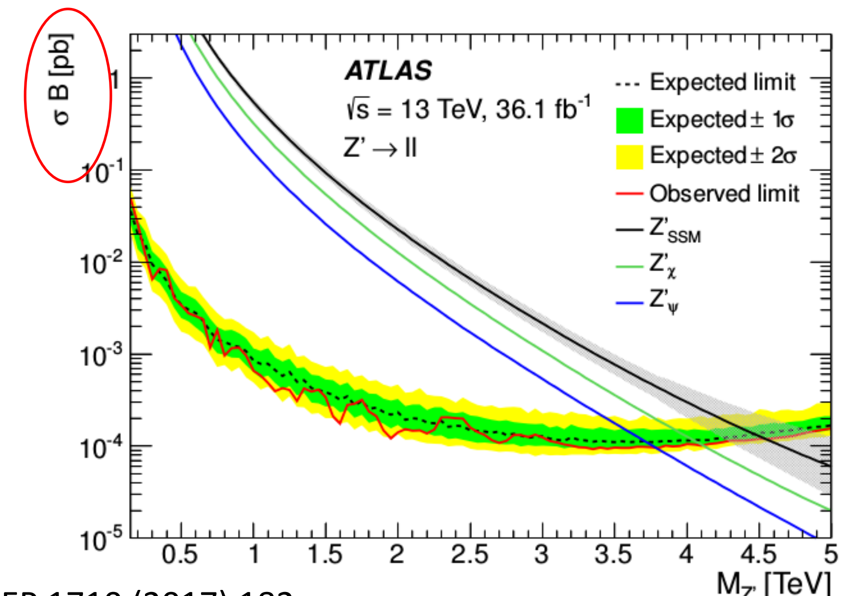
$e_{WX} < 5\times10^{-3}$ for 10 GeV $< m_X <$ 70 GeV

K. Fuyuto, X.-G. He, GL, M. J. Ramsey-Musolf, in preparation

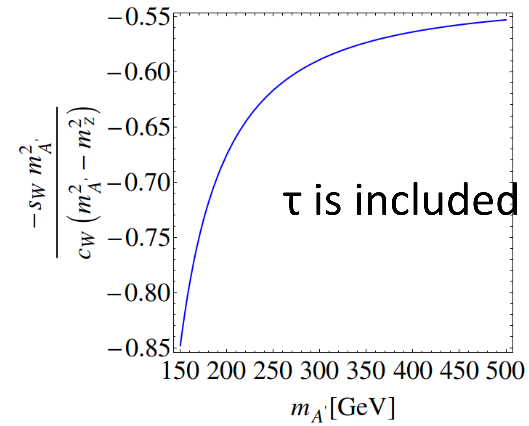
Constraints



- Dark photon searches at the ATLAS/CMS
  - interpreted as Z' in terms of σ Br



JHEP 1710 (2017) 182



(non-Abelian dark photon with m_X < 150 GeV is considered)

- re-interpreted as Abelian KM dark photon in terms of ε

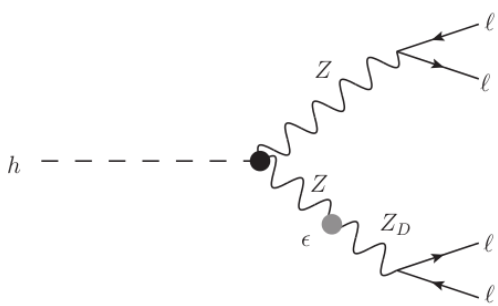
generate LO $pp \to A' \to \mu^+\mu^-$ $\epsilon/c_W = 10^{-2}$

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

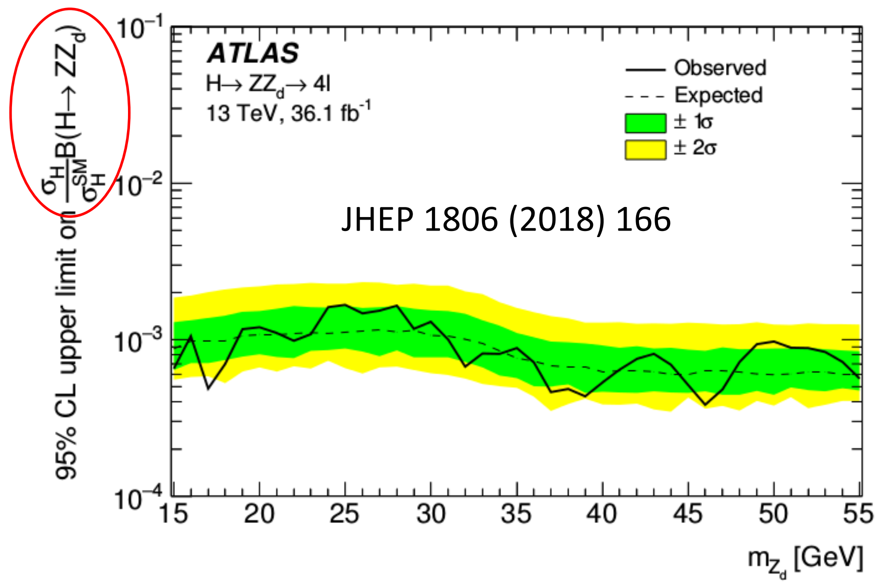
we project the sensitivities to 300 fb^{-1}, 3000 fb^{-1}

Constraints

- Dark photon searches at the ATLAS/CMS
  - interpreted as Abelian KM dark photon in terms of σ Br



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



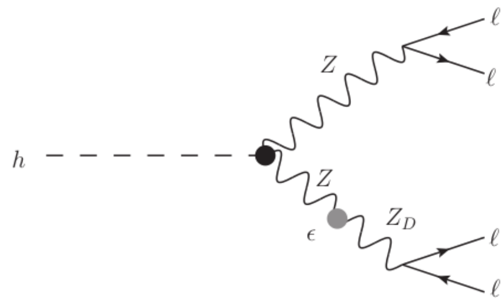
JHEP 1806 (2018) 166

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

constraints on ε in Abelian KM case are weak

Constraints

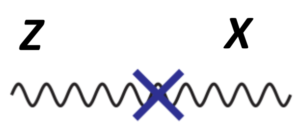
- Dark photon searches at the ATLAS/CMS
  - re-interpreted as non-Abelian KM dark photon



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

Z can be on-shell or off-shell

Z_d is always on-shell



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

$$\mathrm{Br}(H \to Z^{(*)} A')\mathrm{Br}(Z \to \ell^+\ell^-) = \frac{\sigma_H^X}{\sigma_H^{A'}} \frac{\Gamma(H \to Z^{(*)} X \to \ell^+\ell^- X)}{\Gamma_{\mathrm{tot}}^H} \frac{\mathrm{Br}(X \to \ell^+\ell^-)}{\mathrm{Br}(A' \to \ell^+\ell^-)},$$

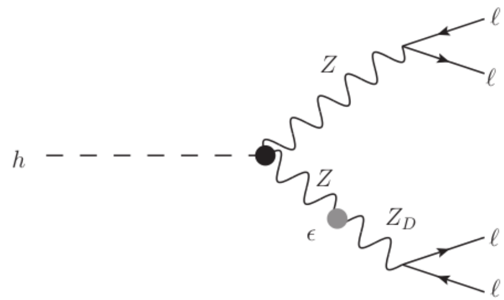
$$= c_\theta^2 \frac{\Gamma(H \to Z^{(*)} A' \to \ell^+\ell^- A')}{\Gamma_{\mathrm{tot}}^H} \frac{\chi^2}{\tau^2} \frac{\mathrm{Br}(X \to \ell^+\ell^-)}{\mathrm{Br}(A' \to \ell^+\ell^-)},$$

(exp. upper limits)

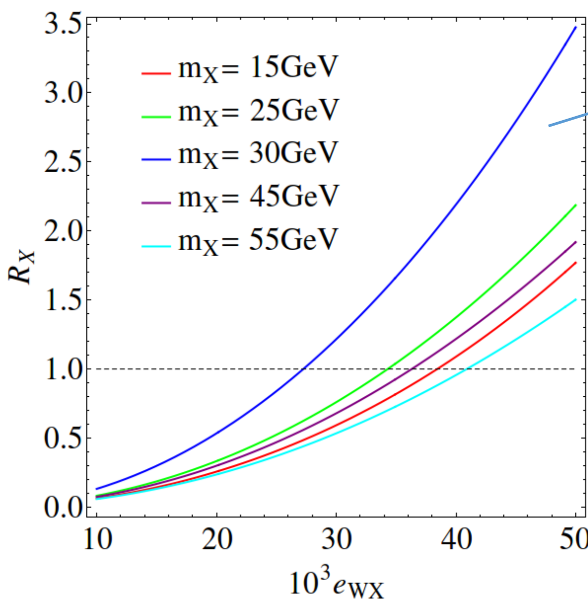
$$R_X = \frac{c_\theta^2 \Gamma(H \to Z^{(*)} A' \to \ell^+\ell^- A')}{\Gamma_{\mathrm{tot}}^H \mathrm{Br}(H \to Z^{(*)} A')^{\text{upper limit}} \mathrm{Br}(Z \to \ell^+\ell^-)} \frac{\chi^2}{\tau^2} \frac{\mathrm{Br}(X \to \ell^+\ell^-)}{\mathrm{Br}(A' \to \ell^+\ell^-)}$$

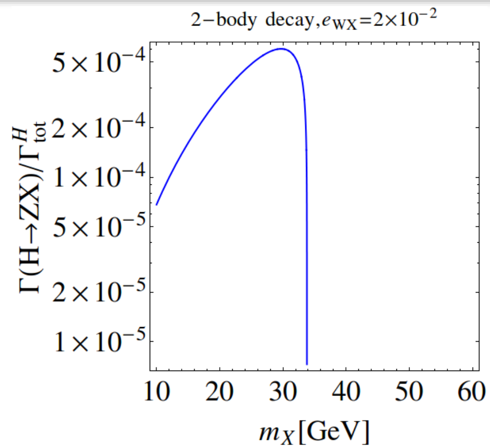
Constraints

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



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





R_X>1 region is excluded

$e_{WX} < 2.6\times10^{-2}$ for
10 GeV < m_X < 55 GeV

K. Fuyuto, X.-G. He, GL, M. J. Ramsey-Musolf, in preparation

Constraints

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

at order of σ

$$\begin{pmatrix} A_0 \\ Z_0 \\ A'_0 \end{pmatrix} = V \begin{pmatrix} A \\ Z \\ A' \end{pmatrix} \qquad V = \begin{pmatrix} 1 & 0 & -c_W\sigma \\ 0 & 1 & \dfrac{s_W\sigma m_{A'}^2}{m_{A'}^2 - m_Z^2} \\ 0 & -\dfrac{s_W\sigma m_Z^2}{m_{A'}^2 - m_Z^2} & 1 \end{pmatrix} + \mathcal{O}(\sigma^2)$$

A. Hook, E. Izaguirre and J. G. Wacker, Adv.High Energy Phys. 2011 (2011) 859762

$$(m_Z^{\text{phys.}})^2 = m_Z^2 + \frac{m_Z^4 s_W^2 \sigma^2}{m_Z^2 - m_{A'}^2} + \mathcal{O}(\sigma^3)$$

EWPT

  - In the non-Abelian KM case,

at order of e_{WX}

$$A_0^\mu = A^\mu + e_{WX} s_W s_\xi Z^\mu - e_{WX} s_W c_\xi X^\mu + \mathcal{O}(e_{WX}^2),$$
$$Z_0^\mu = (c_\xi + e_{WX} c_W s_\xi) Z^\mu + (s_\xi - e_{WX} c_W c_\xi) X^\mu + \mathcal{O}(e_{WX}^2),$$
$$X_0^\mu = -s_\xi Z^\mu + c_\xi X^\mu + \mathcal{O}(e_{WX}^2),$$

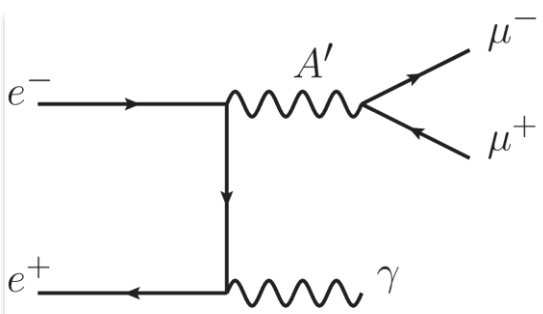
EWPT (in progress)

Z boson mass is also shifted

Proposed searches and sensitivities

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

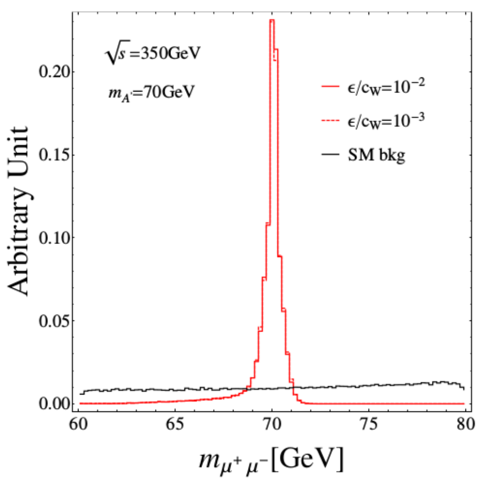
radiative return process:



- 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:

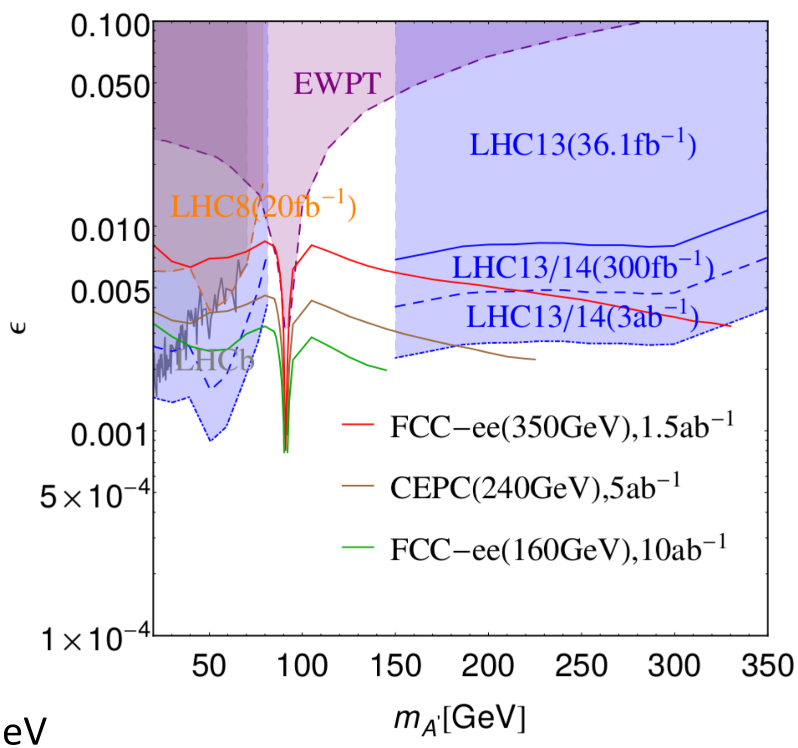
$$\frac{\Delta p_T}{p_T} = 0.1\% \oplus \frac{p_T}{10^5\ \mathrm{GeV}}$$

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



$m_{A'}$>20 GeV

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. 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

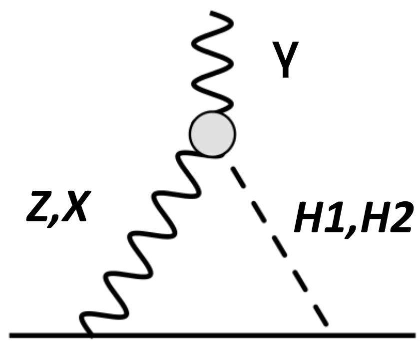
- Non-Abelian KM dark photon constriants from electric dipole moments (EDMs)

Fermion EDM $$\mathcal{L}^{\mathrm{EDM}} = -\frac{i}{2} d_f \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu}.$$

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

$$W_0^{3,\mu\nu} = \partial^\mu W_0^{3,\nu} - \partial^\nu W_0^{3,\mu} + g\epsilon^{3bc} W_0^{b,\mu} W_0^{c,\nu}$$

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



K. Fuyuto, X.-G. He, GL, M. J. Ramsey-Musolf, in preparation

current limits:

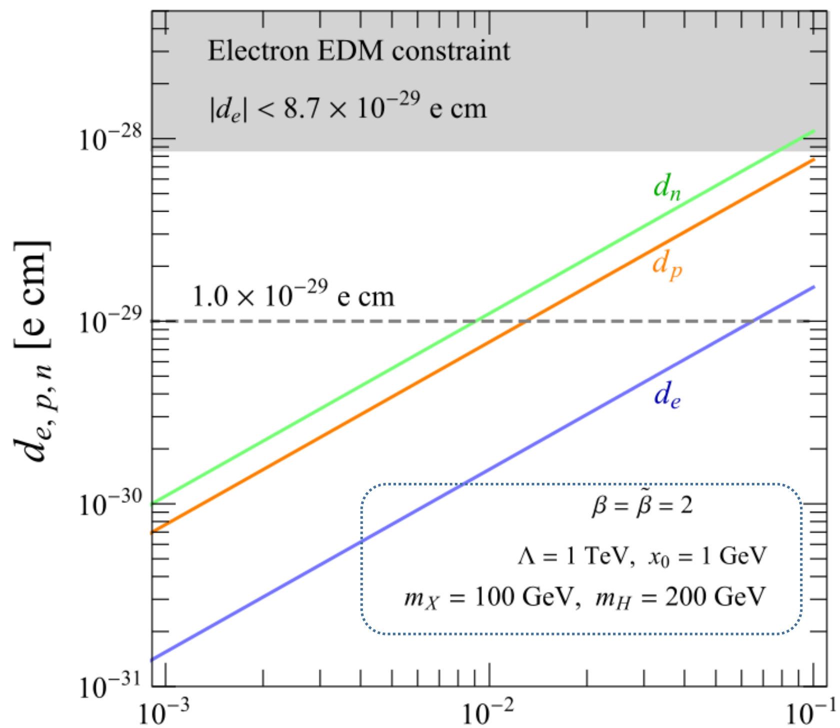
$$|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm} \qquad |d_n| < 3.0 \times 10^{-26}\ e\ \mathrm{cm}$$

future sensitivities to d_e and d_p can be 1.0×10^{-29} e cm

T. Chupp, P. Fierlinger, M. Ramsey-Musolf, J. Singh, arXiv:1710.02504

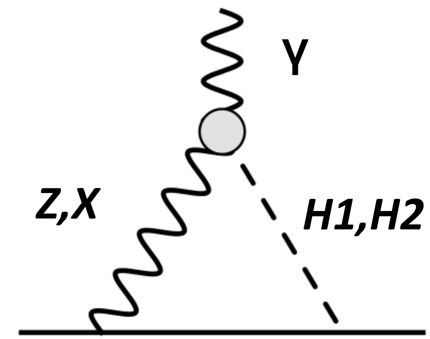
Proposed searches and sensitivities

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



Mixing between neutral scalars

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



K. Fuyuto, X.-G. He, GL, M. J. Ramsey-Musolf, in preparation

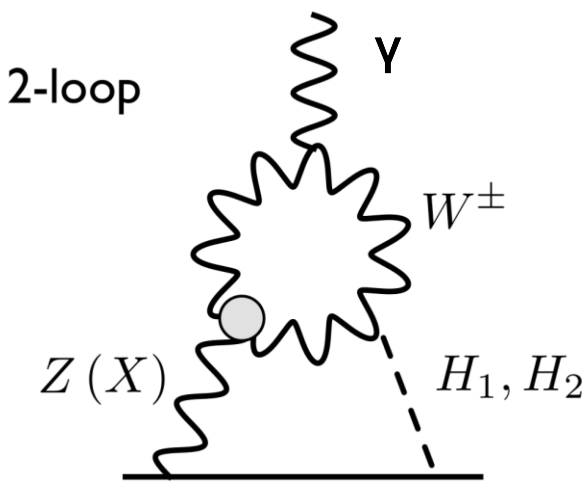
$$-\frac{\tilde{\beta}}{2\Lambda} s_W A_{\mu\nu}(c_\theta H_2 + s_\theta H_1)(c_\xi \tilde{X}^{\mu\nu} - s_\xi \tilde{Z}^{\mu\nu})$$

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

Proposed searches and sensitivities

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

Barr-Zee diagram:



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

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

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

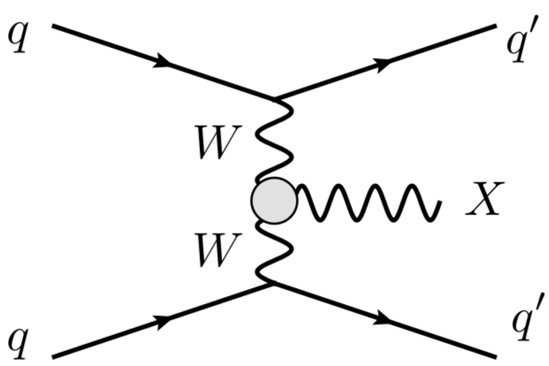
negligible contribution to EDMs

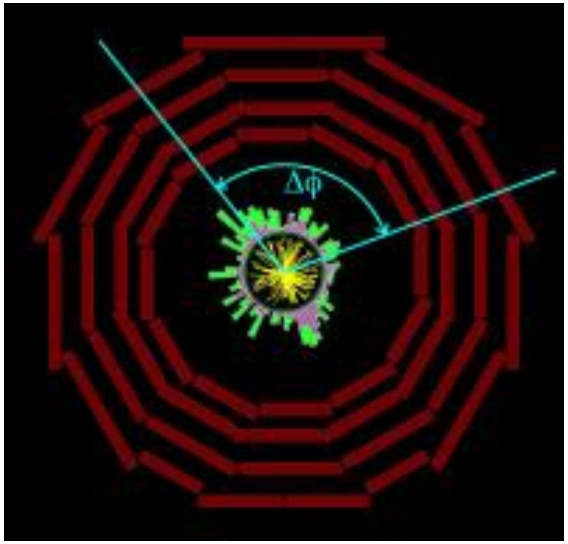
double-suppressed by e_{WX}

Proposed searches and sensitivities

- Collider signature of CPV non-Abelian KM dark photon

$$-ig\tilde{e}_{WX}c_\xi\partial^\mu\tilde{X}^\nu(W_\mu^+W_\nu^- - W_\nu^+W_\mu^-)$$





azimuthal angle distribution

- CPV HWW and HZZ couplings — T. Figy, V. Hankele, G. Klamke, D. Zeppenfeld, Phys.Rev. D74 (2006) 095001
- SUSY particles searches — S. Mukhopadhyay, M. M. Nojiri, T. T. Yanagida, JHEP 1410 (2014) 12
- 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 > j j X,

$$\Delta\phi_{jj} = \phi_{j_1} - \phi_{j_2}$$

Φ_1 (Φ_2) is the azimuthal angle of jet in the forward (backward) hemisphere

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

K. Hagiwara, Q. Li, K. Mawatari, JHEP 0907 (2009) 101

exist only if CP is violated

After integrating $\Delta\Phi_{jj}$ over (0, π) and (π, 2π), 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

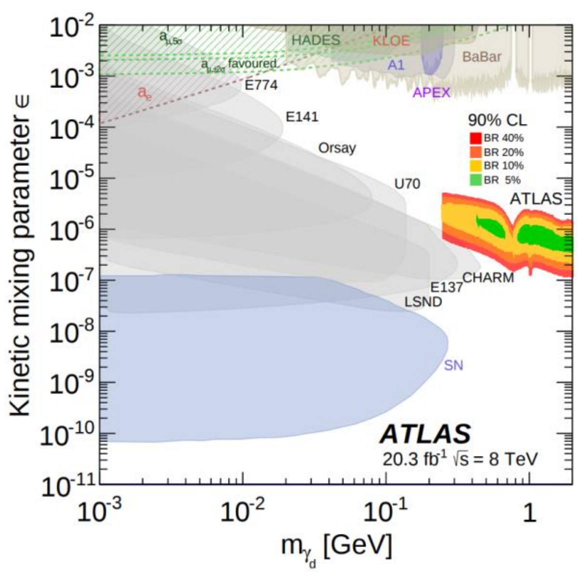
$e_{WX} \times \tilde{e}_{WX} \leq 4$ with c_θ=0.95

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

K. Fuyuto, X.-G. He, GL, M. J. Ramsey-Musolf, in preparation

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



JHEP 1411 (2014) 088

Thanks for your attention!