Abelian and non-Abelian kinetic mixing dark photons

Gang Li

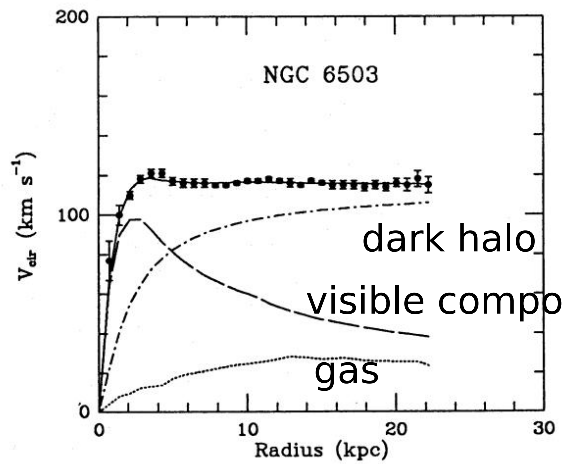
National Taiwan University

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

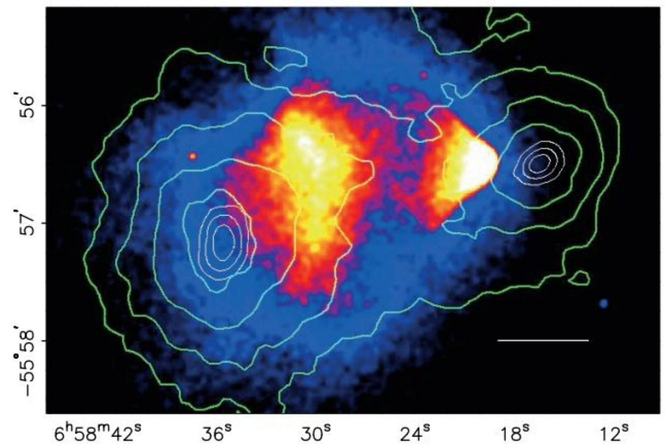
CYCU, HEP Seminar, Oct. 30, 2018

Motivation

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

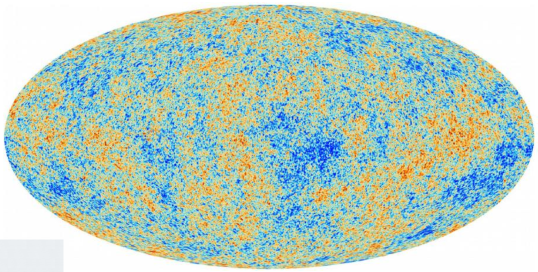


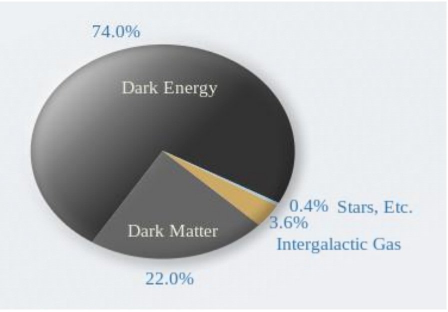
K.G. Begeman, A.H. Broeils, R.H. Sanders, MNRAS 249(1991) 523



gravitational lensing

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





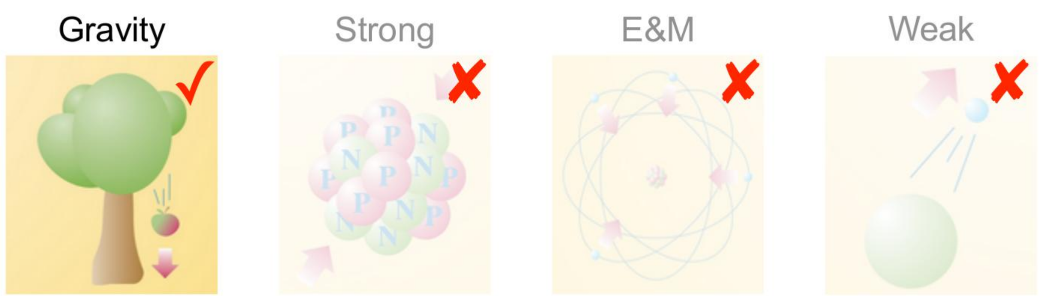
DM does exist

Motivation

- Curious questions:
  - Is dark matter a particle? How does it interact?

- (1) Weakly Interacting Massive Particle (WIMP) as the most popular dark matter candidate has been widely explored

- (2)



only gravitational interaction of DM is verified

dark sector beyond DM? (dark forces? dark particles?)

further motivations for dark sector: experimental anomalies

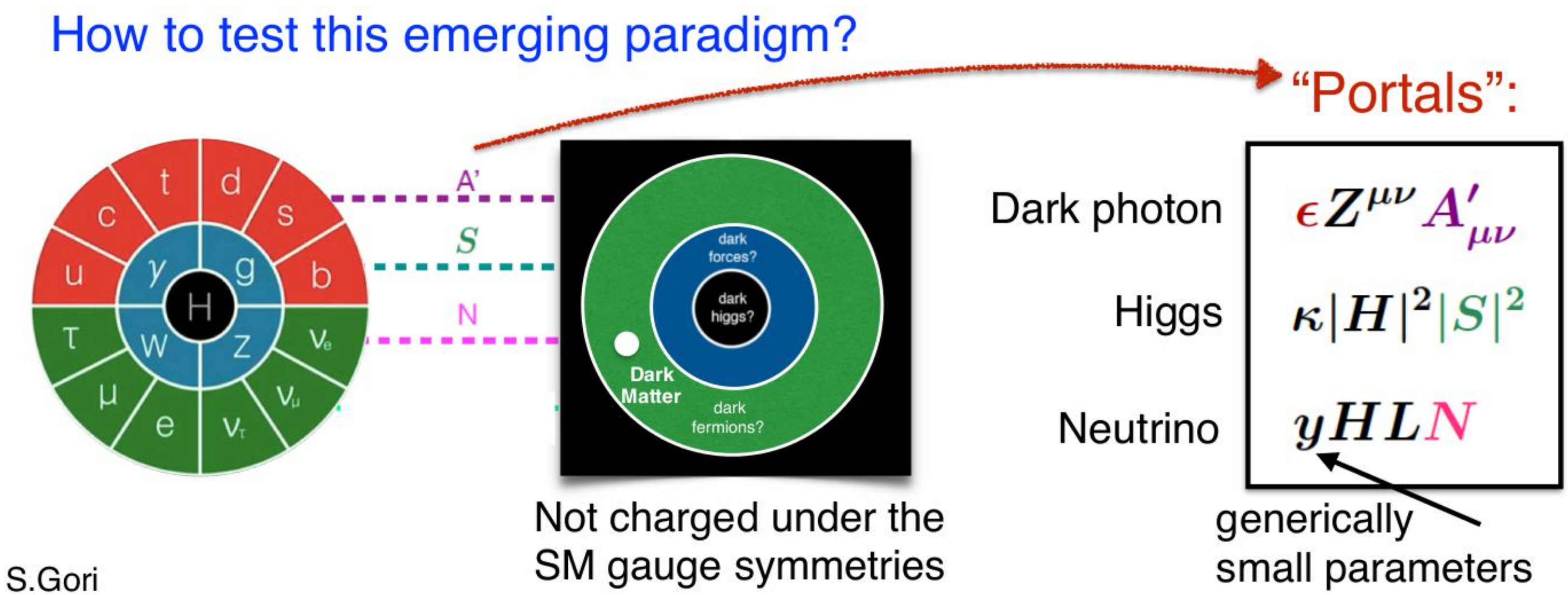
eg. $(g\text{-}2)_{\mu}$, B-physics anomalies, DM anomalies

can be addressed by dark sector

Motivation

- Curious questions:
  - Is dark matter a particle? How does it interact?

- (2) Dark sector

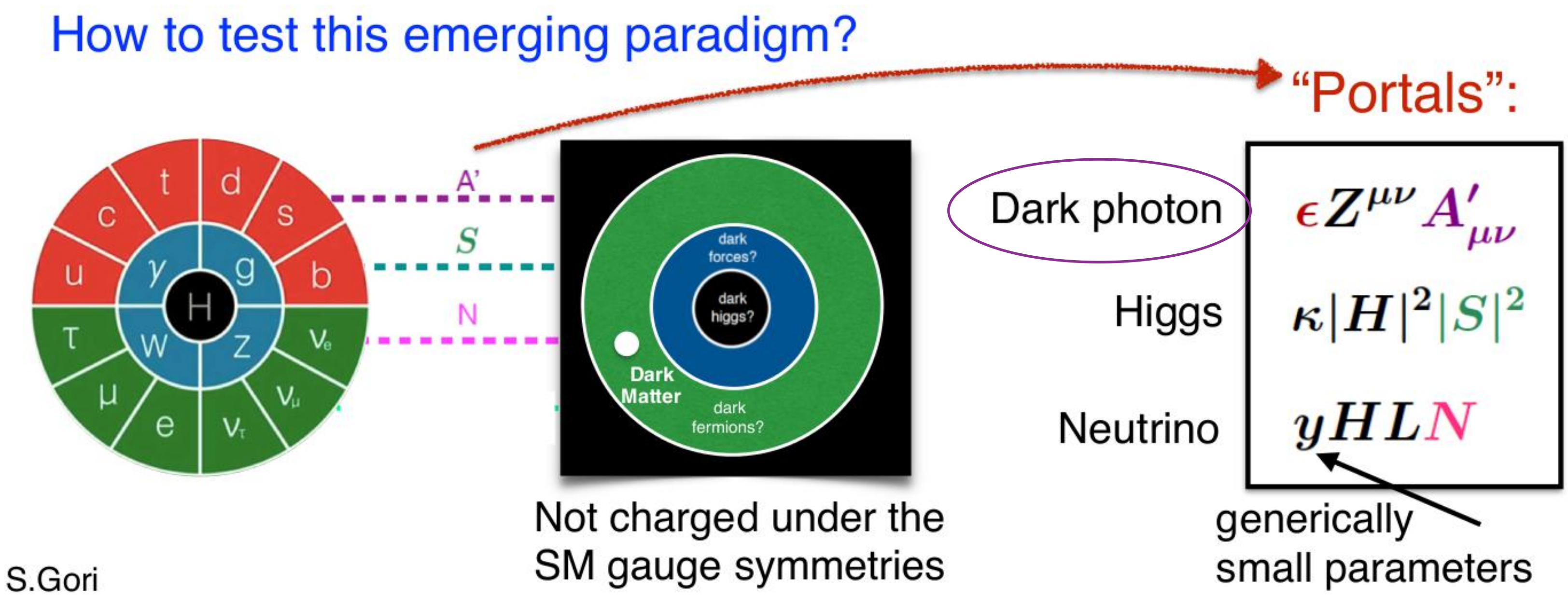


axion...

Motivation

- Curious questions:
  - Is dark matter a particle? How does it interact?

- (2) Dark sector

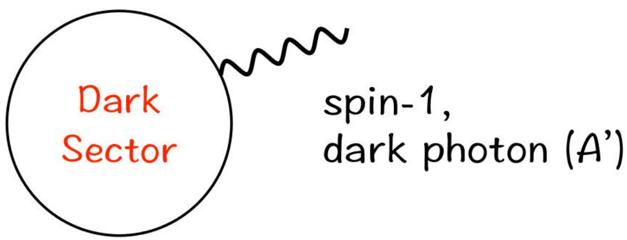


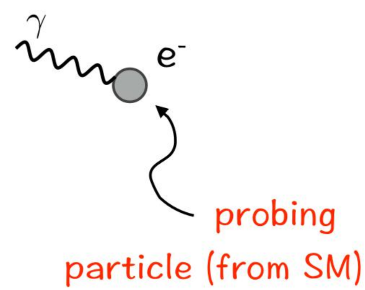
axion...

Motivation

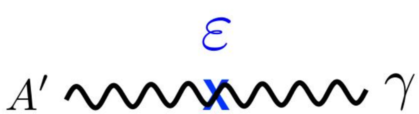
- Dark photon as a hair of dark sector
  - We need to check the assumption of the $SU(3) \times SU(2)_L \times U(1)_Y$ gauge symmetry. $U(1)_X$?
  - Extra U(1) symmetries exist in left-right symmetric or grand-unified theories

P. Fayet, Phys. Lett. B 95, 285 (1980)
P. Fayet, Nucl. Phys. B 187, 184 (1981)
P. Fayet, Nucl.Phys. B347, 743 (1990)





Gauge kinetic mixing $\varepsilon F'_{\mu\nu} F^{\mu\nu}$ supposing SM particles are uncharged under $U(1)_X$

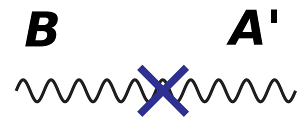


so that dark photon can couple to SM particles

B. Holdom, Phys. Lett. B166, 196 (1986)

Motivation

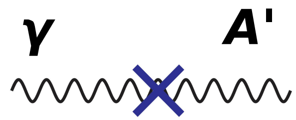
- Abelian kinetic mixing: $U(1)_Y \times U(1)_X$



$$L_{\text{kinetic}} = -\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} \boxed{-\frac{1}{2}\sigma F'_{\mu\nu}B^{\mu\nu}}$$

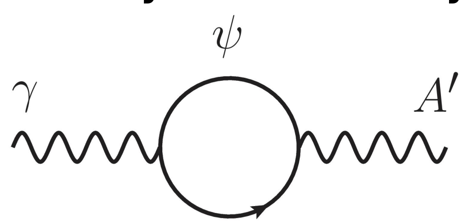
B. Holdom, Phys. Lett. B166, 196 (1986) R. Foot, X-G He Phys.Lett. B267 (1991) 509

After EWSB:



$$\epsilon = -c_W \sigma$$

- Origion of kinetic mixing:
  - at tree-level, ε is arbitrary and NP may occur at any scale
  - at loop-level



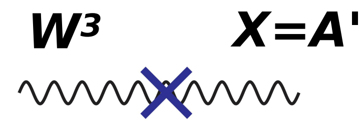
ψ has both SM and dark charges

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

g_D: dark gauge coupling
M_*:EW scale

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

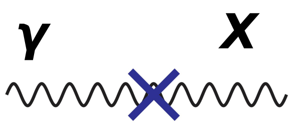
- Non-Abelian kinetic mixing: $SU(2)_L \times U(1)_X$



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:



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

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

Supposing that the dim-6 operator is generated at 1-loop level

$$\frac{c}{16\pi^2 m_\phi^2}\left(H^\dagger \tau^a H\right) W^a_{\mu\nu} F_D^{\mu\nu}$$

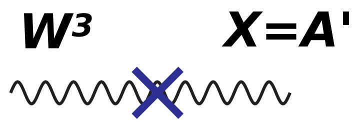
$$\frac{\epsilon}{2} F_{\mu\nu} F_D^{\mu\nu}; \qquad \epsilon = \frac{c\,v^2 s_W}{32\pi^2 m_\phi^2}$$

$$m_\phi = \sqrt{\frac{c\,v^2 s_W}{32\pi^2 \epsilon}} \sim \sqrt{\frac{c}{\epsilon/10^{-4}}} \times 1\,\mathrm{TeV}.$$

intensity frontier (dark photon) ⟷ non-Abelian KM ⟷ energy frontier (messager particle)

Motivation

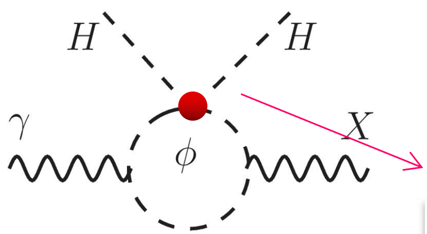
- Non-Abelian kinetic mixing: $SU(2)_L \times U(1)_X$



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

toy model:



Φ is a complex triplet scalar with dark charge

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

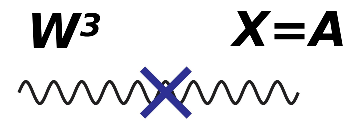
$$\epsilon = \frac{g g_D \lambda_{\rm mix}}{96\pi^2} \frac{v^2}{m_\phi^2} s_W \sim 10^{-4} g_D \lambda_{\rm mix} \left(\frac{400 \text{ GeV}}{m_\phi}\right)^2$$

g_D: dark gauge coupling

probed directly at the LHC

Motivation

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



dim-5 operator $$-\frac{\beta}{\Lambda}\mathrm{Tr}(W_{\mu\nu}\Sigma)X^{\mu\nu}$$

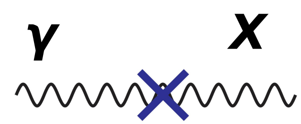
$$W_{\mu\nu} = W^a_{\mu\nu}T^a, \quad \Sigma = \Sigma^b T^b$$

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

After EWSB: $\langle \Sigma^3 \rangle = x_0$

Λ: integrating out unspecified heavy states with both SM and dark charges

SM with real triplet scalar Σ



$$\rho = 1 + \frac{4x_0^2}{v_H^2} = 1 + \Delta\rho \qquad x_0 \lesssim 3.2\ \mathrm{GeV}$$

H. E. Haber, H. E. Logan, Phys.Rev. D62 (2000) 015011

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

naturally suppressed by small triplet vev

strong 1st order phase transition

H. H. Patel, M. J. Ramsey-Musolf, Phys.Rev. D88 (2013) 035013

Motivation

- Observed baryon asymmetry of the universe, baryon to photon densiy ratio

$$\eta = \frac{n_B}{n_\gamma} = (5.54 \pm 0.06) \times 10^{-10}$$

- Three ingredients are needed for the baryogenesis:

A. Sakharov, JETP Lett. 5 (1967) 24-27

  - baryon number violation
  - C and CP violation
  - departure from thermal equilibrium (1st order phase transition)

SM CP violation is too small, new source of CP violation is needed

P. Huet, E. Sather, Phys.Rev. D51 (1995) 379

dim-5 operators $$-\frac{\beta}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]X^{\mu\nu} - \frac{\tilde{\beta}}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]\tilde{X}^{\mu\nu}$$

new CP violation

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

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

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

Non-Abelian KM

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

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

Parameters

- Dark photon mass generation
  - Higgs mechanism

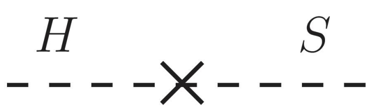
$$V_0(H,S) = -\mu^2|H|^2 + \lambda|H|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \kappa|S|^2|H|^2$$

S is SM singlet “dark Higgs” with $U(1)_X$ charge $s_{A'}$ and vev v_s

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

vector (dark photon) portal + Higgs portal:

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



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

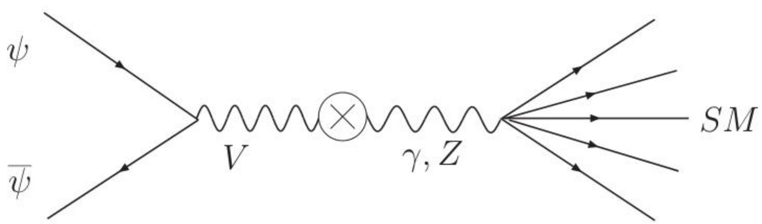
- Stueckelberg mechanism

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

Only dark photon portal is involved

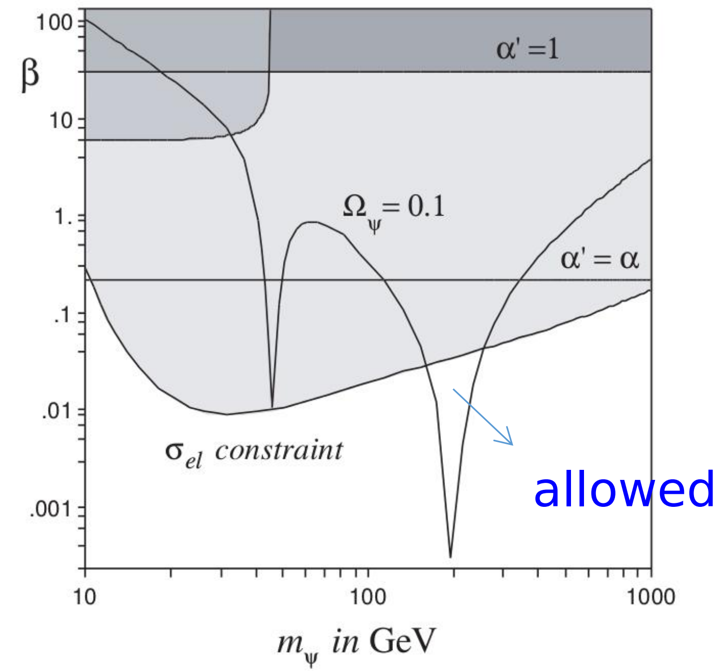
Parameters

- Dark photon interplay with dark matter
  - If $m_{A'} > 2m_\chi$, searches for $A' \to \chi\chi$ (invisible) also depend on m_χ and α_D χ: non-secluded WIMP dark matter



$$\langle \sigma_{\rm ann} v \rangle_{m_\psi \gg m_{\rm SM}} \approx 1.3 \text{ pbn} \times \beta \left(\frac{500 \text{ GeV}}{m_\psi} \right)^2 \times \left(\frac{4m_\psi^2}{4m_\psi^2 - m_V^2} \right)^2$$

resonantly enhanced for $m_\psi = m_V/2$

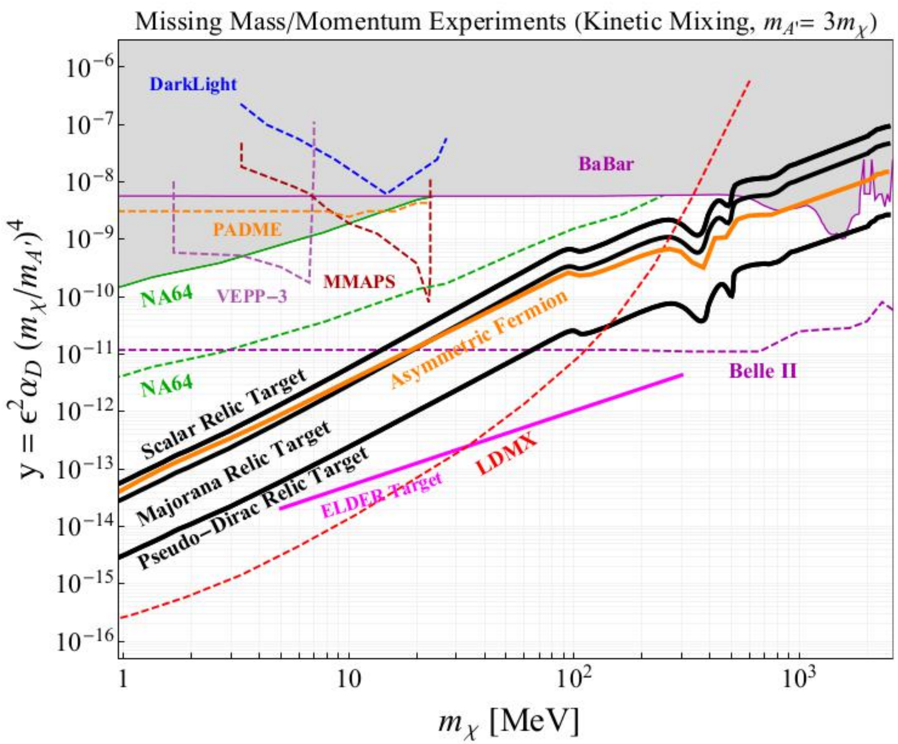


M. Pospelov, A. Ritz, M. B. Voloshin,
Phys.Lett. B662 (2008) 53

$$\beta \equiv \left(\frac{\kappa e'}{e \cos\theta_W} \right)^2$$

Parameters

- Dark photon interplay with dark matter
  - If $m_{A'} > 2m_\chi$, searches for $A' \rightarrow \chi\chi$ (invisible) also depend on m_χ and α_D χ: non-secluded WIMP dark matter

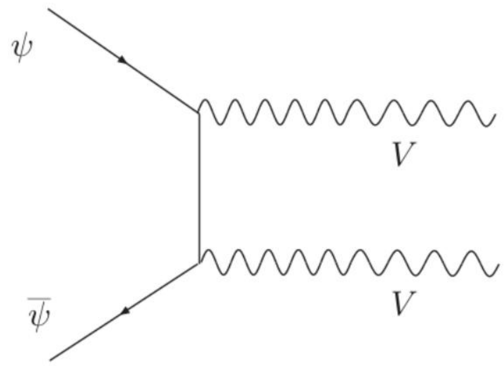


Battaglieri et al., 1707.04591

Parameters

- Dark photon interplay with dark matter
  - If $m_\chi > m_{A'}$, searches for A' → SM particles (visible) only depend on $m_{A'}$ and ε χ: secluded WIMP dark matter

M. Pospelov, A. Ritz, M. B. Voloshin, Phys.Lett. B662 (2008) 53



$$\sigma v = \frac{\pi(\alpha')^2}{m_\psi^2}\sqrt{1-\frac{m_V^2}{m_\psi^2}},$$

DM relic density is achieved if

$$\alpha' \times \left(1-\frac{m_V^2}{m_\psi^2}\right)^{1/4} \simeq 5\times 10^{-3} \times \left(\frac{m_\psi}{500\ \mathrm{GeV}}\right)$$

only constaint from thermal free-out

J. A. Evans, S. Gori, J. Shelton, JHEP 1802 (2018) 100

- Mininal dark photon signature with free parameters in the dark photon portal: kinetic mixing parameter(s) and dark photon mass

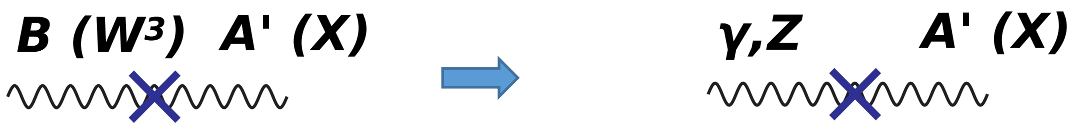
Field redefinition

- There are two steps to achieve couplings of physical dark photon to SM particles:

  R. Foot, X-G He Phys.Lett. B267 (1991) 509

  - write the Lagrangian in the canonical form (kinetic mixing term is removed)
  - diagonalize the mass matrix

- Massive dark photon can couple to the SM currents through the mixing with photon and *Z* boson



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,

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

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

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

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 →

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

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

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

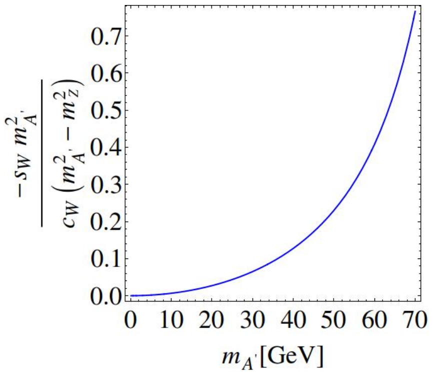
$$(\partial^\mu W_0^{3,\nu} - \partial^\nu W_0^{3,\mu}) X_{0,\mu\nu} \neq 0$$

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,

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

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

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

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

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

The couplings of X to fermions are non-universally modified

Dark photon couplings

- Couplings of dark photon to *Zh*

In the Abelian KM case,

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

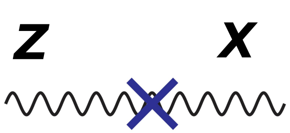
In the non-Abelian KM case,

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

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

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

Σ acquires vev



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

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

$H_1 \rightarrow$ 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,

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

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

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

Σ acquires vev

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

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

W^+,W^- fields do not change

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,

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

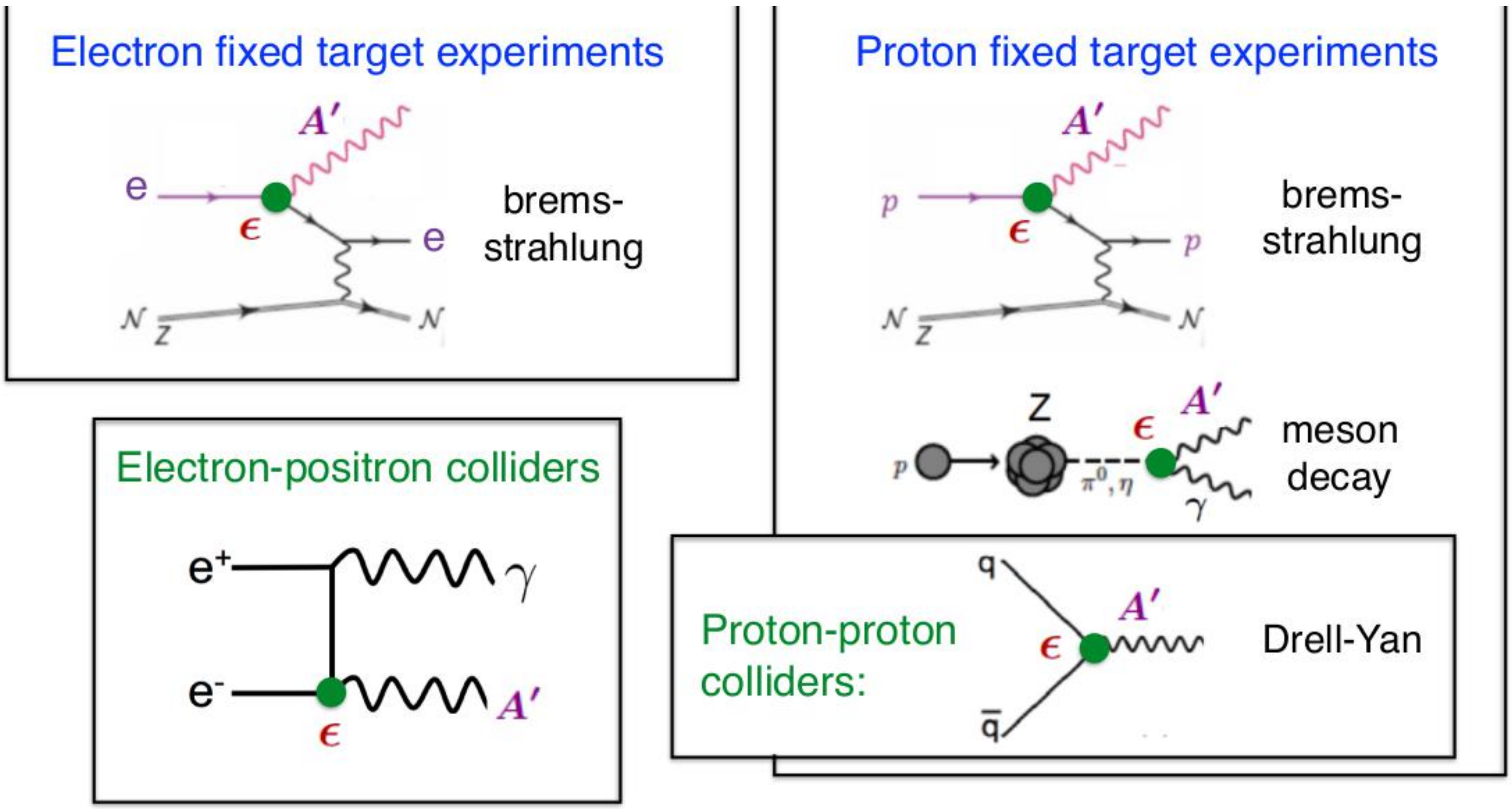
CP-even (first three lines)

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



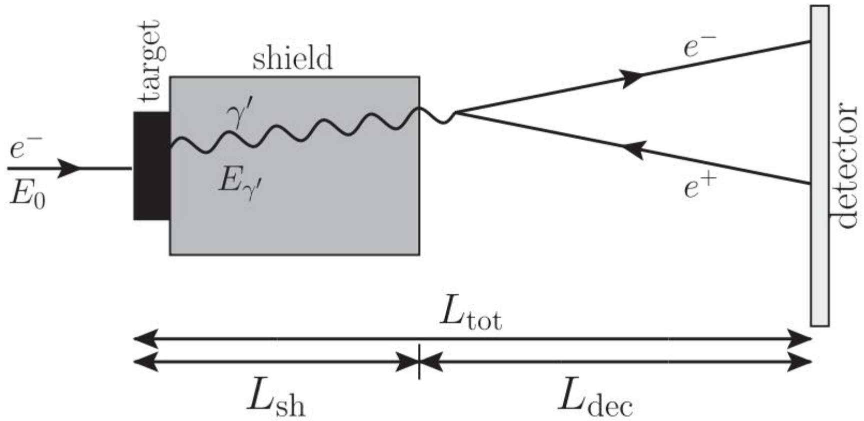
S. Gori, CIPANP 2018

High intensity High energy

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

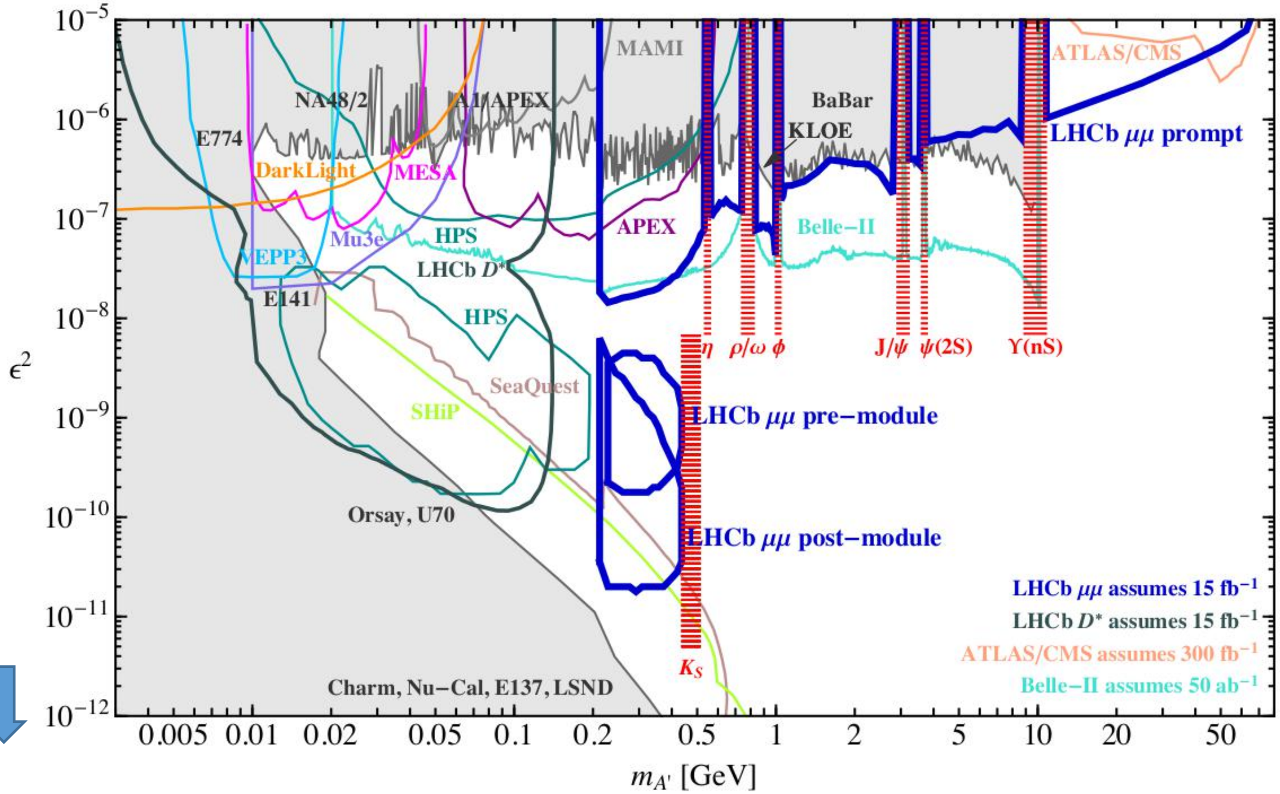
beam-dump experiments:



S. Andreas, C. Niebuhr, A. Ringwald, Phys.Rev. D86 (2012) 095019

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



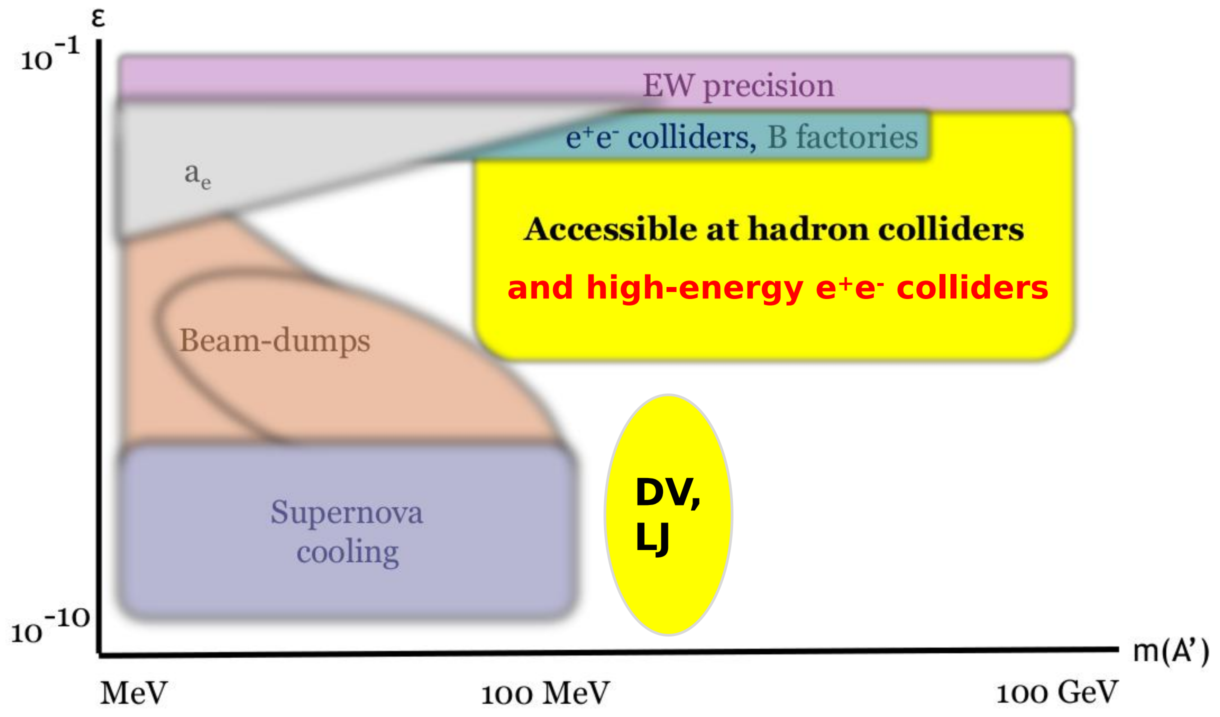
$$\varepsilon \equiv \frac{g'_e}{g_e}$$

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)

even smaller

I will concentrate on Abelian and non-Abelian KM dark photons that are accessible at the LHC and future high-energy e^+e^- colliders



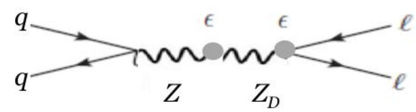
Kinetic mixing paramter(s) and dark photon mass are required not too small for prompt searches

Constraints

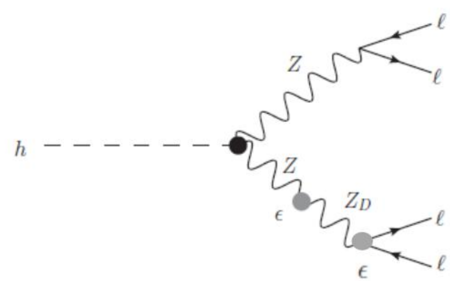
- Collider search strategies at the LHC (ATLAS/CMS, LHCb)

M. Diamond, LHC DMWG 2017

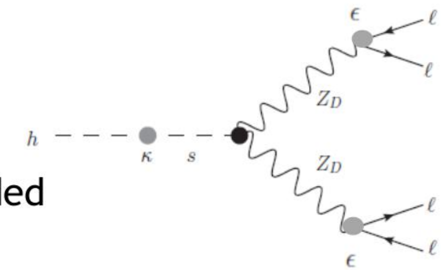
$pp \to Z_D \to l^+l^-$
- only requires vector portal



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



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



benchmark model

alternative model

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

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

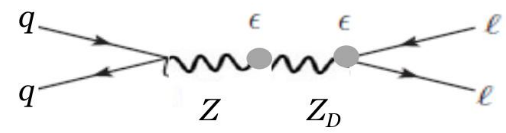
1. branching fraction ratio, $\frac{\mathcal{B}_A(m)}{\mathcal{B}_B(m)}$
2. cross-section ratio, $\frac{\sigma_A(m,g_A)}{\sigma_B(m,g_B)}$
3. efficiency ratio, $\frac{\varepsilon(\tau_A(m,g_A))}{\varepsilon(\tau_B(m,g_B))}$

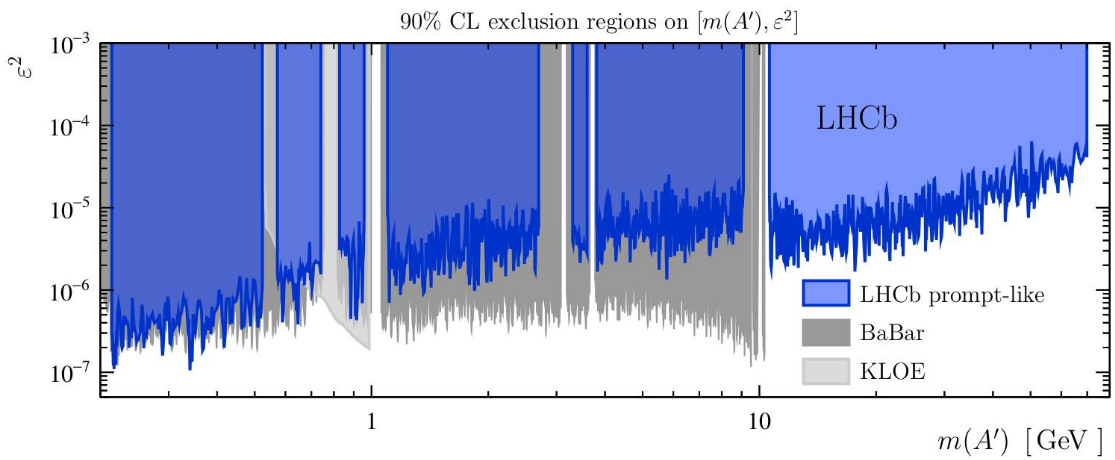
P. Ilten, LHC DMWG 2018

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

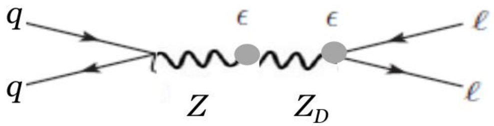
$$\frac{d\sigma_{pp\to XA'\to X\mu^+\mu^-}}{d\sigma_{pp\to X\gamma^*\to X\mu^+\mu^-}} = \epsilon^4 \frac{m_{\mu\mu}^4}{(m_{\mu\mu}^2 - m_{A'}^2)^2 + \Gamma_{A'}^2 m_{A'}^2}$$

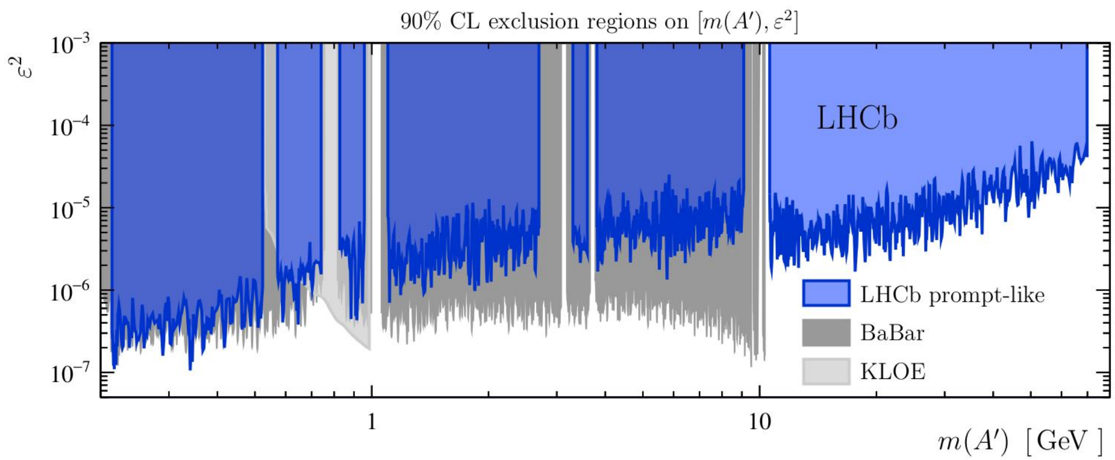
for any multiparticle final state *X and* data-driven analysis is performed since efficiency and acceptance for the measured SM process are the same as for the inferred signal process

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

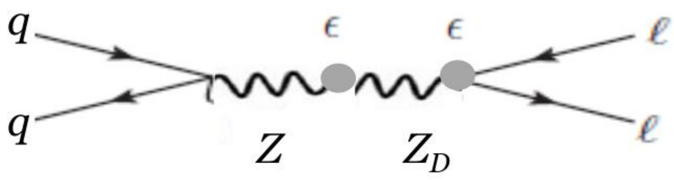
$$c\tau_{\gamma'\to e^+e^-} \simeq \left(\frac{\epsilon^2 \alpha_{\rm EM}\, m_{\gamma'}}{3}\right)^{-1} = 8\times 10^{-3}\,\text{cm}\left(\frac{10^{-4}}{\epsilon}\right)^2\left(\frac{100\,\text{MeV}}{m_{\gamma'}}\right)$$

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)

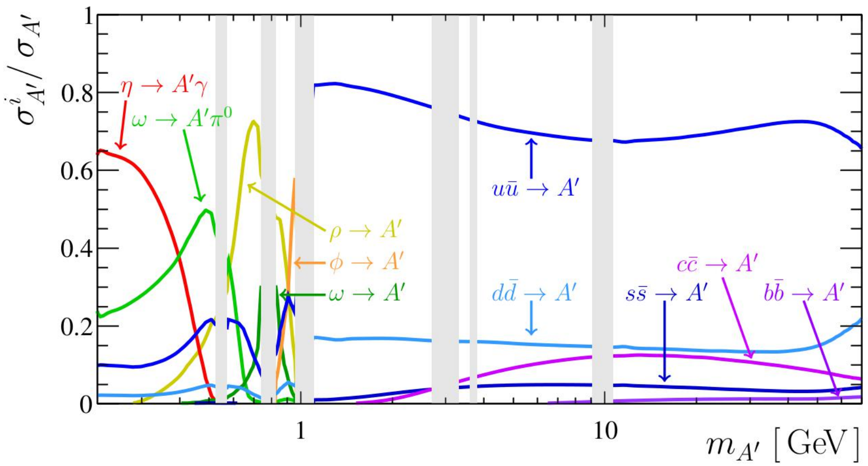
$$\frac{\sigma_X}{\sigma_{A'}}\frac{\mathrm{Br}(X\to\mu^+\mu^-)}{\mathrm{Br}(A'\to\mu^+\mu^-)}\frac{\epsilon(\tau_X)}{\epsilon(\tau'_A)}=1$$

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

fractions of each flavor of quarks in dark photon production

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

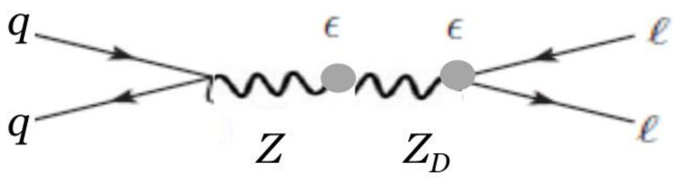
$$\frac{\sigma^i_X}{\sigma^i_{A'}}=\frac{\Gamma(X\to q_i\bar{q}_i)}{\Gamma(A'\to q_i\bar{q}_i)}$$



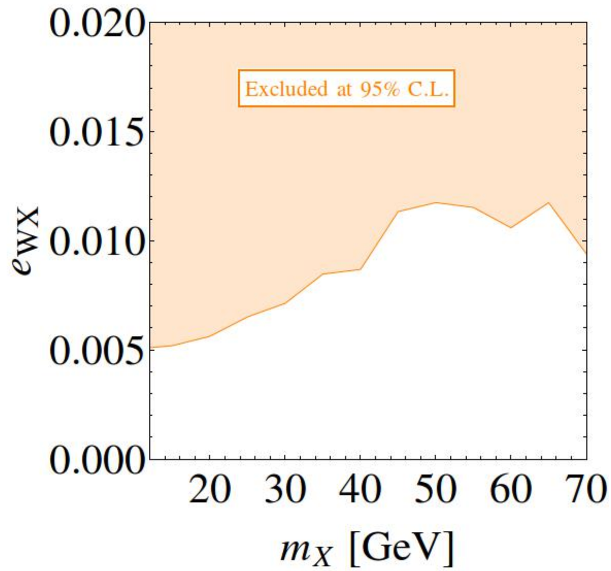
P. Ilten, Y. Soreq, M. Williams, W. Xue, JHEP 1806 (2018) 004

Constraints

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



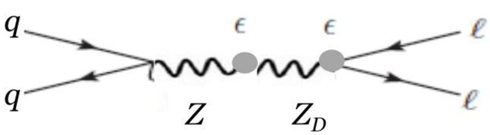
$$\frac{\sigma_X}{\sigma_{A'}}\frac{\mathrm{Br}(X\to\mu^+\mu^-)}{\mathrm{Br}(A'\to\mu^+\mu^-)}\frac{\epsilon(\tau_X)}{\epsilon(\tau'_A)}=1$$



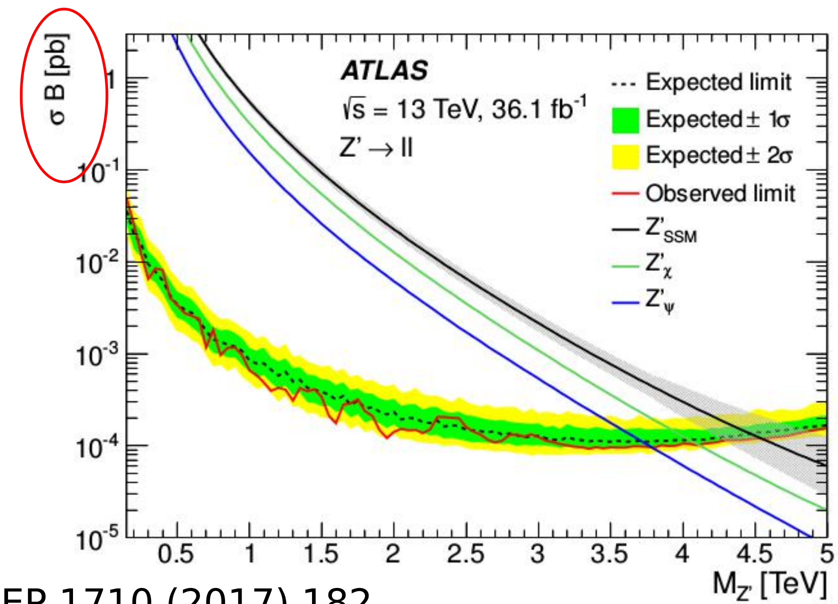
$e_{WX} < 5\times10^{-3}$ for 10 GeV $< m_X <$ 70 GeV

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

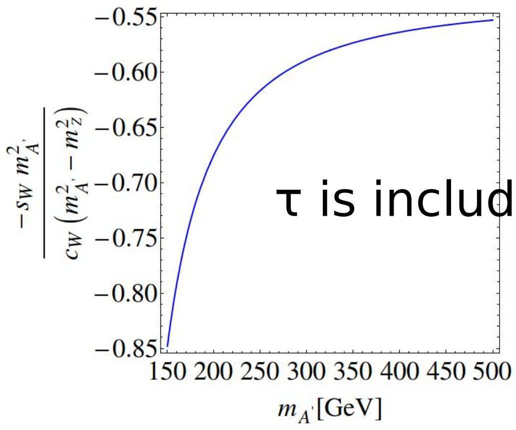
Constraints



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



JHEP 1710 (2017) 182



τ is included

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

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

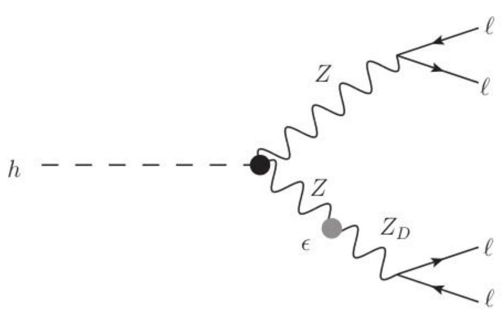
generate LO $pp \to A' \to \mu^+\mu^-$ with $\epsilon/c_W = 10^{-2}$

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

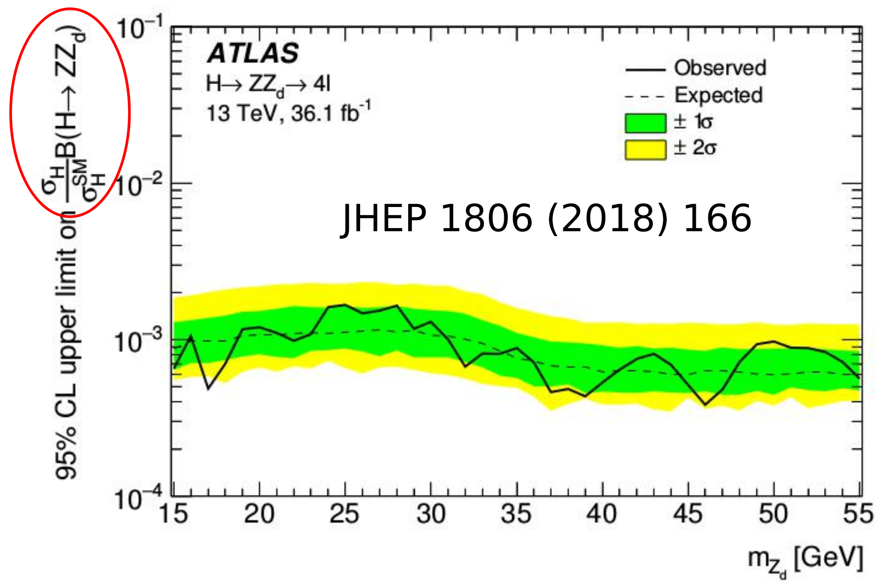
we project the sensitivities to 300 fb^{-1}, 3000 fb^{-1}

Constraints

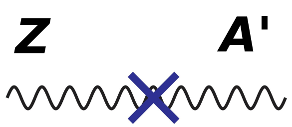
- Dark photon searches at the ATLAS/CMS
  - interpreted as Abelian KM dark photon in terms of σ Br



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



JHEP 1806 (2018) 166

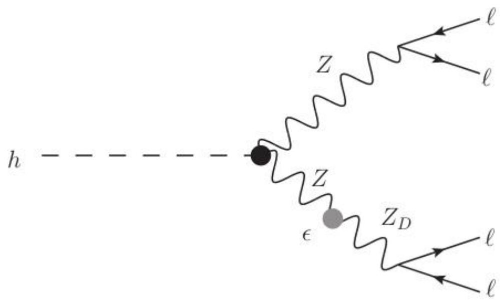


$$\tau = -\frac{s_W m_{A'}^2 \epsilon}{c_W (m_{A'}^2 - m_Z^2)}$$ (small)

constraints on ε in Abelian KM case are weak

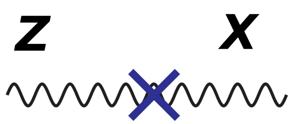
Constraints

- 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



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

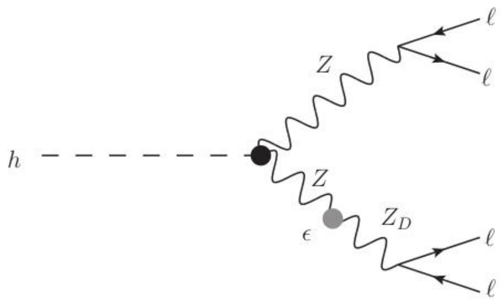
$$\mathrm{Br}(H \to Z^{(*)} A')\mathrm{Br}(Z \to \ell^+\ell^-) = \frac{\sigma_H^X}{\sigma_H^{A'}} \frac{\Gamma(H \to Z^{(*)} X \to \ell^+\ell^- X)}{\Gamma_{\mathrm{tot}}^H} \frac{\mathrm{Br}(X \to \ell^+\ell^-)}{\mathrm{Br}(A' \to \ell^+\ell^-)},$$
$$= c_\theta^2 \frac{\Gamma(H \to Z^{(*)} A' \to \ell^+\ell^-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

(exp. upper limits)

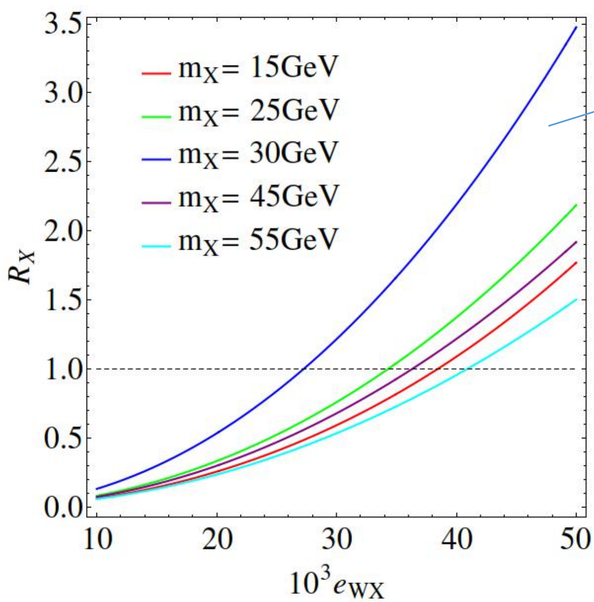
$$R_X = \frac{c_\theta^2 \Gamma(H \to Z^{(*)} A' \to \ell^+\ell^- A')}{\Gamma_{\mathrm{tot}}^H \mathrm{Br}(H \to Z^{(*)} A')^{\text{upper limit}} \mathrm{Br}(Z \to \ell^+\ell^-)} \frac{\chi^2}{\tau^2} \frac{\mathrm{Br}(X \to \ell^+\ell^-)}{\mathrm{Br}(A' \to \ell^+\ell^-)}$$

Constraints

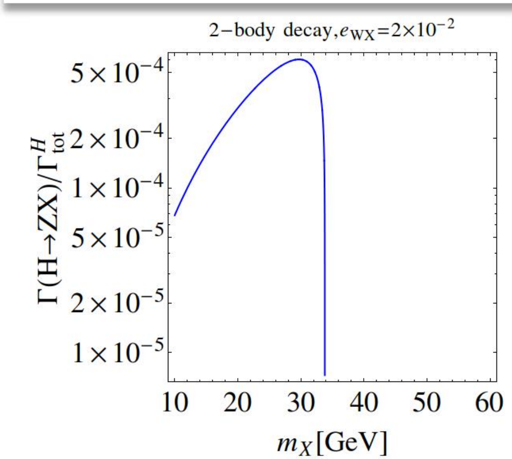
- Dark photon searches at the ATLAS/CMS
  - re-interpreted as non-Abelian KM dark photon



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



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,

deviation at order of σ^2

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

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

EWPT

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

  - In the non-Abelian KM case,

deviation at order of e_{WX}^2

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

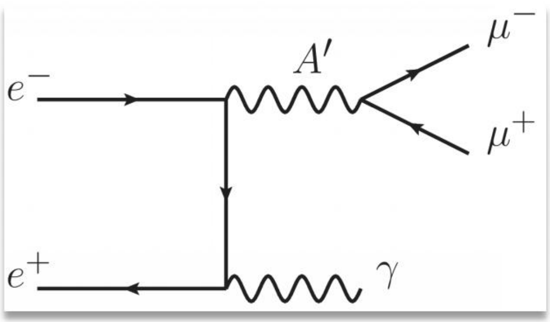
$$Z_0^\mu = (c_\xi + e_{WX} c_W s_\xi) Z^\mu + (s_\xi - e_{WX} c_W c_\xi) X^\mu + \mathcal{O}(e_{WX}^2),$$

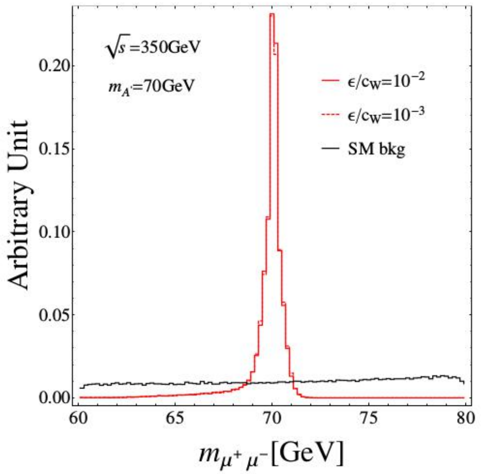
$$X_0^\mu = -s_\xi Z^\mu + c_\xi X^\mu + \mathcal{O}(e_{WX}^2),$$

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

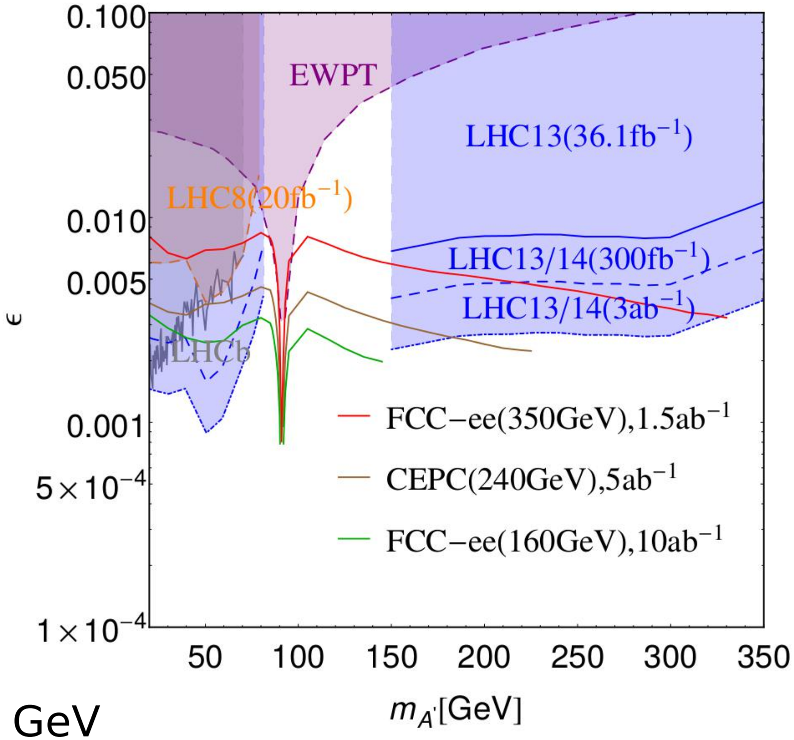
lepton momentum resolution:

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

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

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

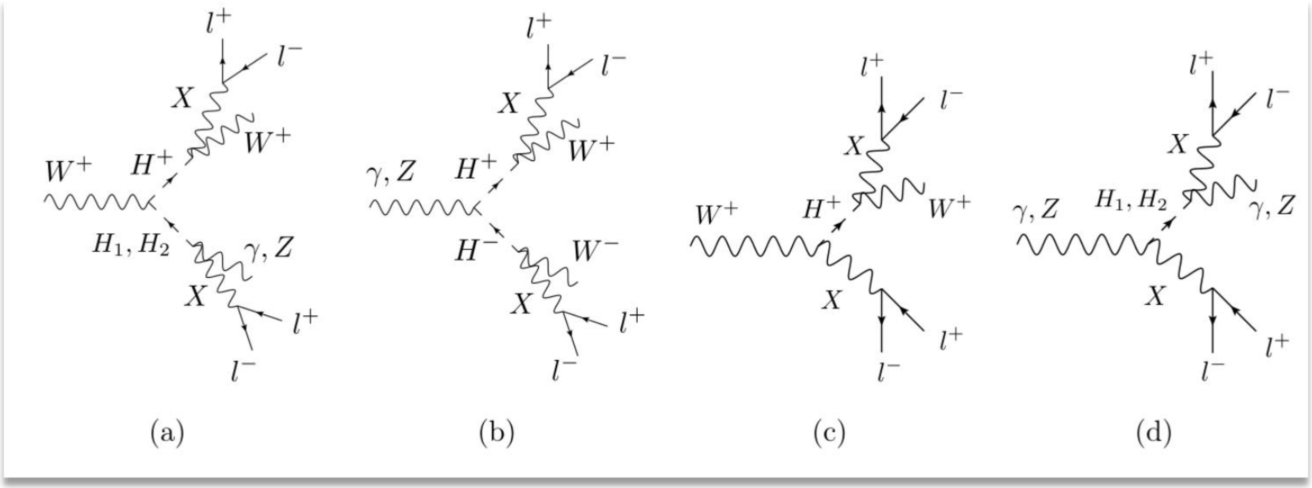
LHC8 result: I. Hoenig, G. Samach and D. Tucker-Smith, Phys. Rev. D 90, 075016 (2014)

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

Proposed searches and sensitivities

- Non-Abelian KM dark photon searches at the LHC *NEW*

$$H^{\pm} \to W^{\pm} X$$



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

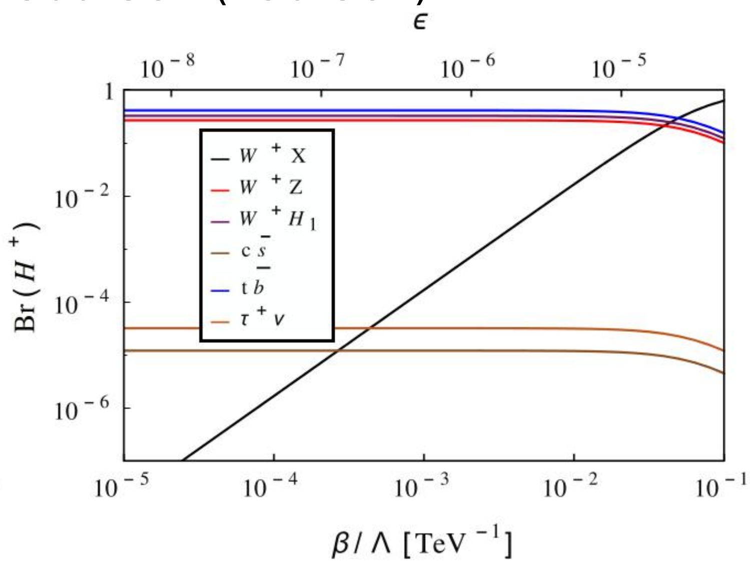
Proposed searches and sensitivities

- Non-Abelian KM dark photon searches at the LHC *NEW*

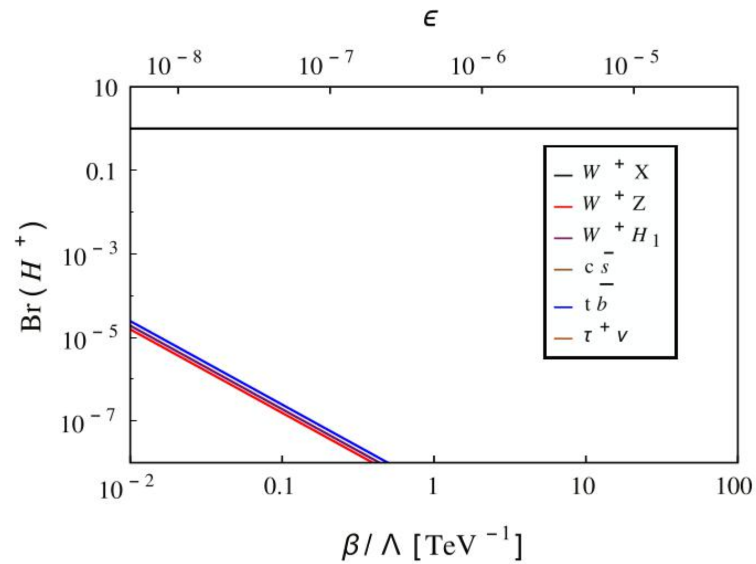
$H^{\pm} \to W^{\pm} X$

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

mx=300 GeV (130 GeV)



x_0=1 GeV



x_0=1 MeV

branching ratio for $H^+ \to W^+ X$ is essentially 100% for $\beta/\Lambda \gtrsim 0.1/\text{TeV}$

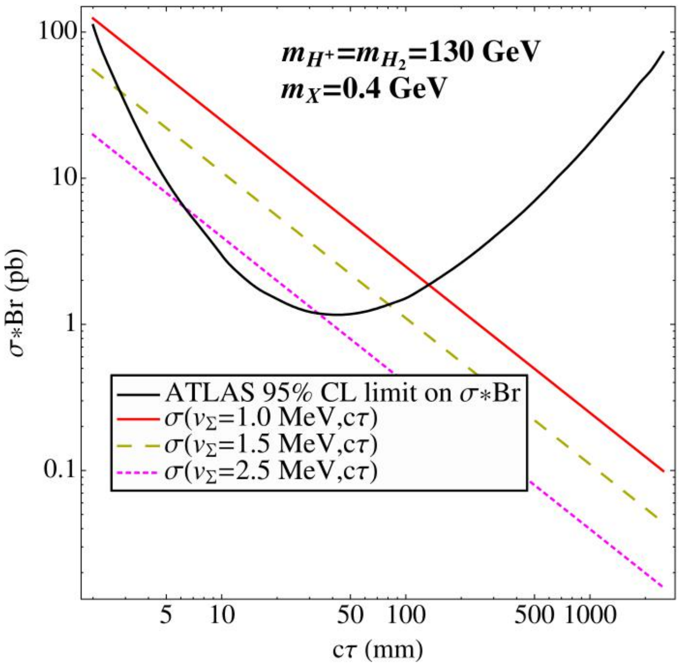
Proposed searches and sensitivities

- Non-Abelian KM dark photon searches at the LHC *NEW*

$$\Gamma(X \to f\bar{f}) = \kappa_X N_c^f \frac{g^2 m_X}{12\pi c_W^2}(V_X^2 + A_X^2)\theta(m_X - 2m_f) \quad \kappa_X = (1 + 2\frac{m_f^2}{m_X^2})\sqrt{1 - 4\frac{m_f^2}{m_X^2}}$$

proper decay length

$$c\tau = \frac{\hbar c}{\Gamma_X} \simeq \frac{1.97 \times 10^{-16}\ \mathrm{GeV} \cdot \mathrm{m}}{\Gamma_X}$$



long-lived X decays into collimated jets of leptons, i.e, lepton jets

recast h -> XX -> LJs

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

Test CP violation in non-Abelian case

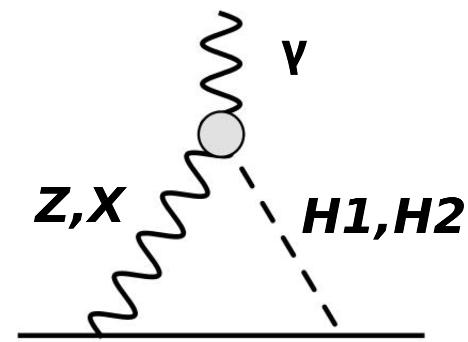
- Non-Abelian KM dark photon constriants from EDMs

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

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

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

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



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

current limits:

$$|d_e| < 1.1 \times 10^{-29} e\,{\rm cm} \qquad |d_n| < 3.0 \times 10^{-26}\ e\ {\rm cm}$$

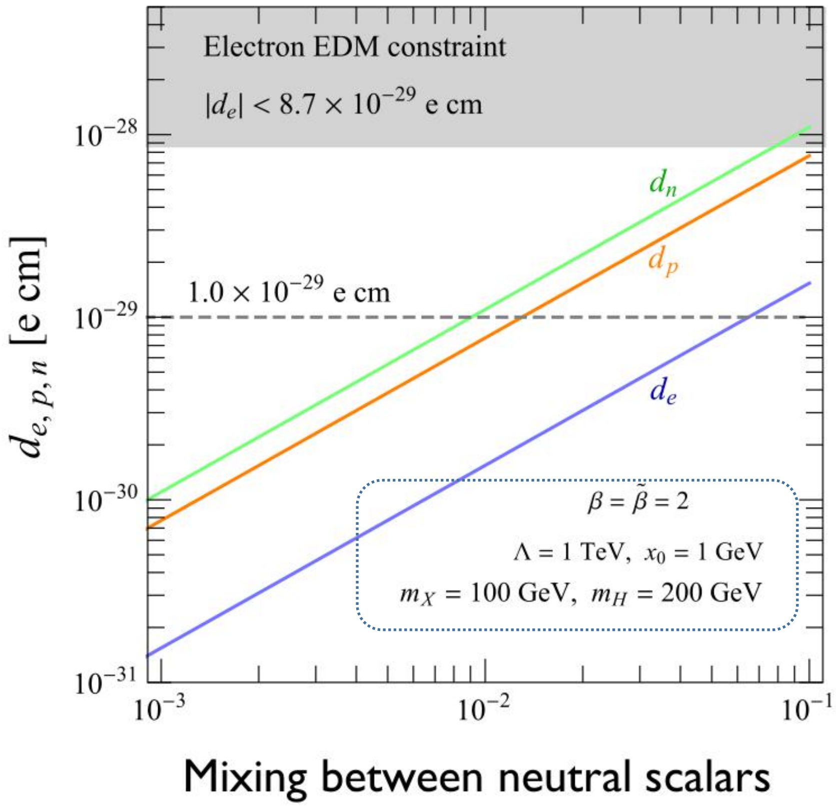
NEW

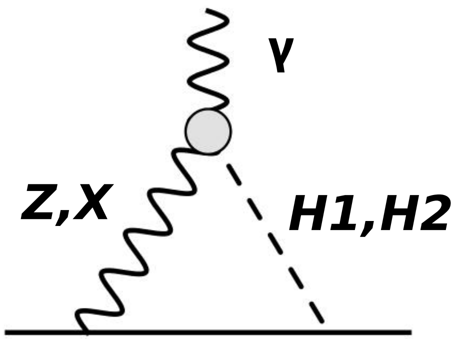
future sensitivities to d_p can be 1.0×10^{-29} e cm

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

Test CP violation in non-Abelian case

- Non-Abelian KM dark photon constriants from EDMs





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

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

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

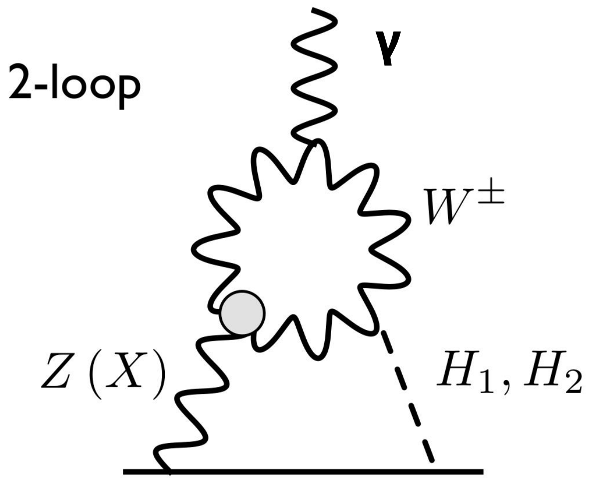
EDMs are proportional to $s_\theta c_\theta$

Test CP violation in non-Abelian case

- Non-Abelian KM dark photon constriants from EDMs

Barr-Zee diagram:

S. M. Barr, A. Zee,
Phys.Rev.Lett. 65 (1990) 21



negligible contribution to EDMs

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

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

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

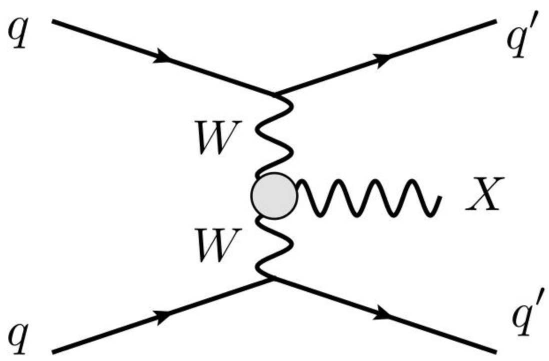
suppressed by $(e_{WX})^2$

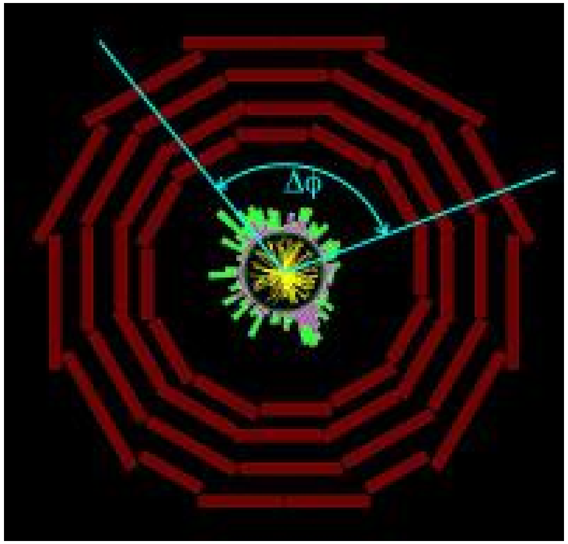
K. Fuyuto, X.-G. He, GL, M. J. Ramsey-Musolf, in preparation

Test CP violation in non-Abelian case

- 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

Test CP violation in non-Abelian case

- 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 (signal only)

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 photons and messager particles are of interest

Thanks for your attention!

CP-odd term

$$W^3_{\mu\nu}\hat{X}^{\mu\nu} = (\partial_\mu W^3_\nu - \partial_\nu W^3_\mu - g\epsilon^{3bc}W^b_\mu W^c_\nu)\,\epsilon^{\mu\nu\alpha\beta}(\partial_\alpha X_\beta - \partial_\beta X_\alpha)$$

$$= 0 - g\epsilon^{3bc}\epsilon^{\mu\nu\alpha\beta}W^b_\mu W^c_\nu(\partial_\alpha X_\beta - \partial_\beta X_\alpha)$$

since

$$(\partial_\mu W^3_\nu - \partial_\nu W^3_\mu)\,\epsilon^{\mu\nu\alpha\beta}(\partial_\alpha X_\beta - \partial_\beta X_\alpha)$$

$$= 4\,\partial_\mu W^3_\nu\,\epsilon^{\mu\nu\alpha\beta}\,\partial_\alpha X_\beta$$

$$= 4\,\partial_\mu(W^3_\nu\,\epsilon^{\mu\nu\alpha\beta}\partial_\alpha X_\beta) - 4W^3_\nu\,\epsilon^{\mu\nu\alpha\beta}\partial_\mu\partial_\alpha X_\beta$$

$$= 4\,\partial_\mu(W^3_\nu\,\epsilon^{\mu\nu\alpha\beta}\partial_\alpha X_\beta) - 4W^3_\nu\,\frac{1}{2}(\epsilon^{\mu\nu\alpha\beta}\partial_\mu\partial_\alpha X_\beta - \epsilon^{\mu'\nu\alpha'\beta}\partial_{\alpha'}\partial_{\mu'}X_\beta)$$

$$= 0$$

Test CP violation in non-Abelian case

- Non-Abelian KM dark photon constriants from EDMs

- Z boson contribution

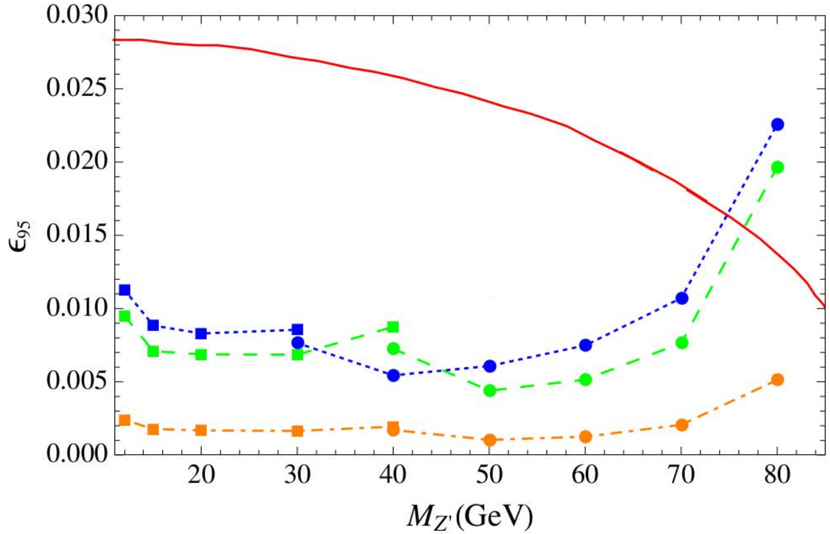
$$d_f^Z = \frac{e}{8\pi^2} C_Z V_Z c_\theta s_\theta \frac{m_f}{v} \left[\frac{1}{2} \log \left(\frac{m_{H_1}^2}{m_{H_2}^2} \right) - \frac{1}{2} \left\{ \frac{r_{ZH_1} \log r_{ZH_1}}{1 - r_{ZH_1}} - \frac{r_{ZH_2} \log r_{ZH_2}}{1 - r_{ZH_2}} \right\} \right], \tag{40}$$

- X boson contribution

$$d_f^X = \frac{e}{8\pi^2} C_X V_X c_\theta s_\theta \frac{m_f}{v} \left[\frac{1}{2} \log \left(\frac{m_{H_1}^2}{m_{H_2}^2} \right) - \frac{1}{2} \left\{ \frac{r_{XH_1} \log r_{XH_1}}{1 - r_{XH_1}} - \frac{r_{XH_2} \log r_{XH_2}}{1 - r_{XH_2}} \right\} \right], \tag{41}$$

where $r_{ZH} = m_Z^2/m_H^2$ and $r_{XH} = m_X^2/m_H^2$.

LHC low-mass region



EWPT 7 TeV, 4.5 fb^{-1} 8 TeV, 20 fb^{-1} 14 TeV, 3 ab^{-1}

$$\epsilon_{95} \sim 10^{-3}$$

I. Hoenig, G. Samach and D. Tucker-Smith, Phys. Rev. D 90, 075016 (2014)