CP-violating dark photon interaction

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K. Fuyuto, X.-G. He, GL and M. J. Ramsey-Musolf, arXiv: 1902.10340

New Physics with Exotic and Long-Lived Particles

ICISE, Quy Nhon, Vietnam

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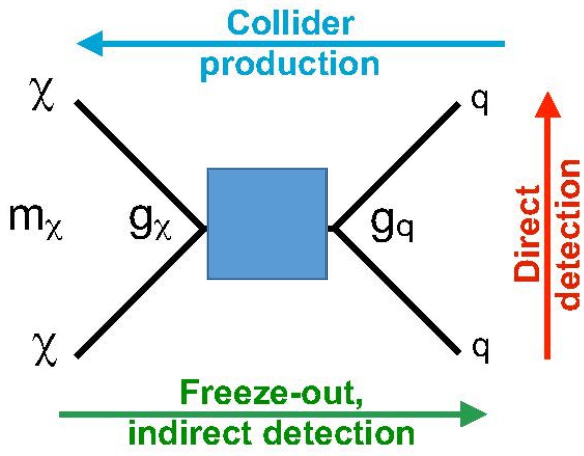
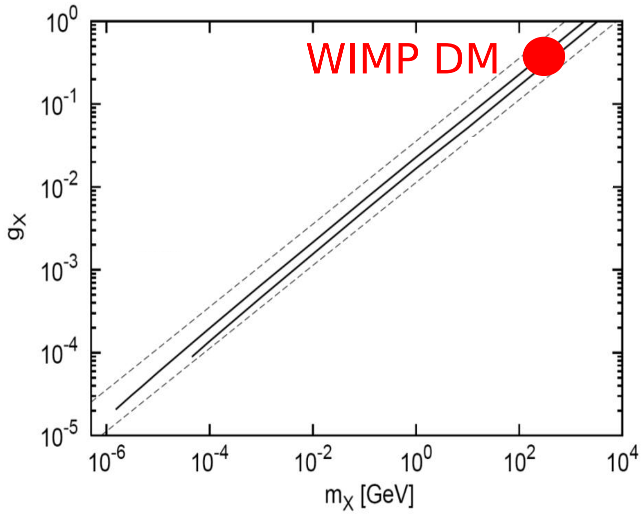
Dark photon as portal to DM

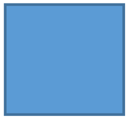
- We have plenty of evidences for dark matter from observations: galatic rotation curves, merging clusters of galaxies, CMB anisotropies
- In particle physics, we want to explore the candidates and interations of DM





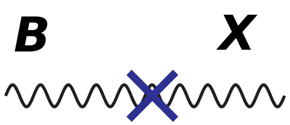
J. L. Feng, H. Tu, H.-B. Yu, 0808.2318 (JCAP)

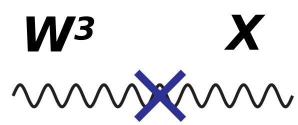
Dark sector can have lighter particles and weaker interactions and still have the right abundance. See Jonathan Feng's talk

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

Dark photon as portal to DM

- Suppose that dark sector has an extra U(1) gauge symmetry and can interact with the SM through the kinetic mixing





X is extra U(1) gauge field

Abelian kinetic mixing

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

non-Abelian kinetic mixing

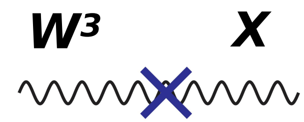
G. Barello, S. Chang, C.A. Newby, Phys.Rev. D94 (2016), 055018
C. A. Argüelles, X.-G. He, G. Ovanesyan, T. Peng, M. J. Ramsey-Musolf, Phys.Lett. B770 (2017) 101

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

non-renormalizble and decoupled kinetic mixing paramter suppressed by NP scale

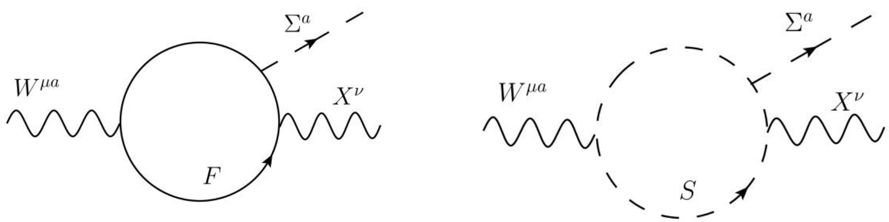
Non-Abelian kinetic mixing

- A real triplet Higgs field ~ (3,0)



$$W_{\mu\nu} = W^a_{\mu\nu}\tau^a/2$$

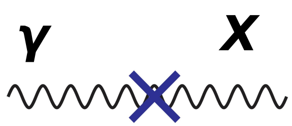
dim-5 operator $-\frac{\beta}{\Lambda}\mathrm{Tr}(W_{\mu\nu}\Sigma)X^{\mu\nu}$



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

$$\epsilon = \frac{\beta x_0 s_W}{\Lambda} \qquad \rho = 1 + \frac{4x_0^2}{v_H^2}$$

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



experimentally, $\epsilon < \mathcal{O}(10^{-3})$

See talks by Igal Jaegle, Leandro de Paula, Albert De Roeck, …

  - CP-violating dark photon interaction arises
  - Long-lived dark photon can be tested

CPV dark photon interaction

- New source of CP violation is needed for baryogenesis (Sakharov, 1967)
- CP-violating interaction is absent in the paradigm of Abelian kinetic mixing

$$B_{\mu\nu}\tilde{X}_{\mu\nu} = 0 + \text{total derivative}$$

- CP-violating interaction arises in the paradigm of non-Abelian kinetic mixing

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

$$W_{\mu\nu} = W^a_{\mu\nu}\tau^a/2$$

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

$$\Sigma^0 = x_0 + \sigma$$

$$W^3_{\mu\nu} = \partial_\mu W^3_\nu - \partial_\mu W^3_\nu + g\epsilon^{3bc}W^b_\mu W^c_\nu$$

vev → X-W^3 mixing

σ → CPV $\sigma W^3 X$ int.

vev → CPV XW^+W^- int.

in canonical form, then mass diagonalization

CPV interactions in the mass eigenstate basis

CPV dark photon interaction

X-W^3 mixing

- From the weak eigenstates to mass eigenstates

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

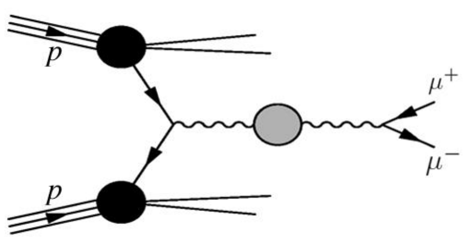
$$\tan 2\xi = \frac{2 c_W e_{WX} m_Z^2}{m_Z^2 - m_X^2} + \mathcal{O}(e_{WX}^2)$$
$$e_{WX} = \frac{\beta x_0}{\Lambda}$$

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

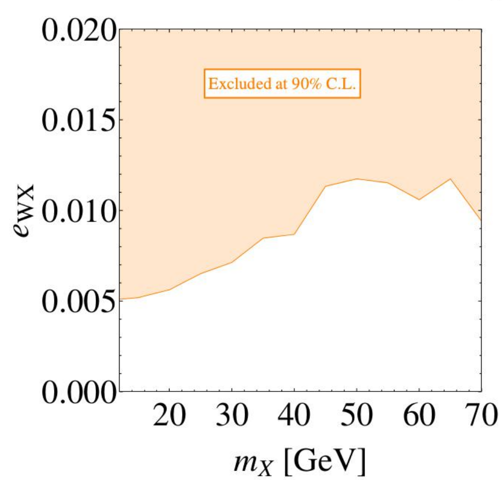
- CP-even and non-universal couplings to SM fermions

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

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



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



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

CPV dark photon interaction

- CPV couplings to Higgs bosons
  - through X-W³ mixing

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

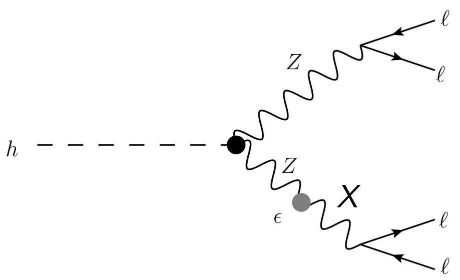
$$\chi = c_\theta (c_\xi + e_{WX} c_W s_W)(s_\xi - e_{WX} c_W c_\xi)$$

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

  - through σW³X interaction

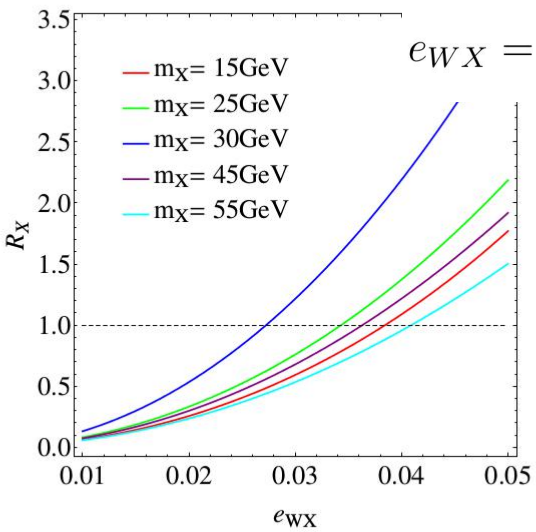
CP-even:

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



prompt leptons
ATLAS 1802.03388 (JHEP)

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



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  - through σW³X interaction

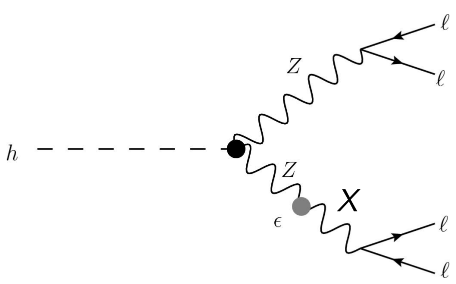
CP-even:

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

CP-odd:

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

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



prompt leptons
ATLAS 1802.03388 (JHEP)

CPV dark photon interaction

- CPV couplings to W bosons

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

X-W^3 mixing

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

CPV XW^+W^- interactions

CPV dark photon interaction

- CPV couplings to W bosons

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

X-W^3 mixing

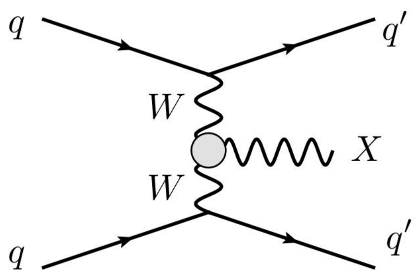
$$-ig e_{WX} c_\xi \partial^\mu X^\nu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-)$$
$$-ig \tilde{e}_{WX} c_\xi \partial^\mu \tilde{X}^\nu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-)$$

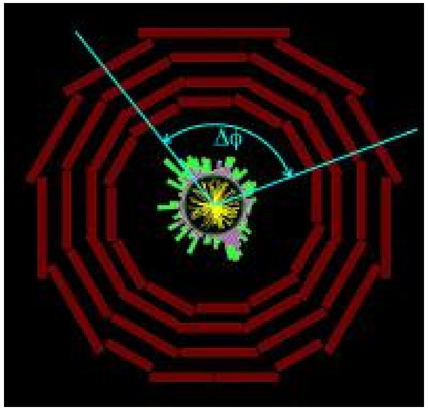
CPV XW^+W^- interactions

How to test CPV dark photon interaction?

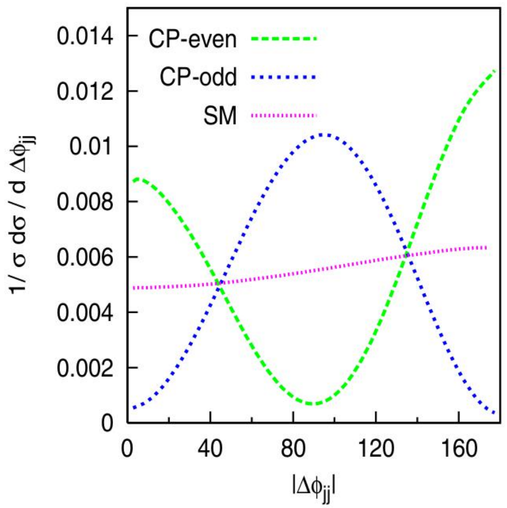
Tests of CPV dark photon interaction

- Azimuthal angle distribution



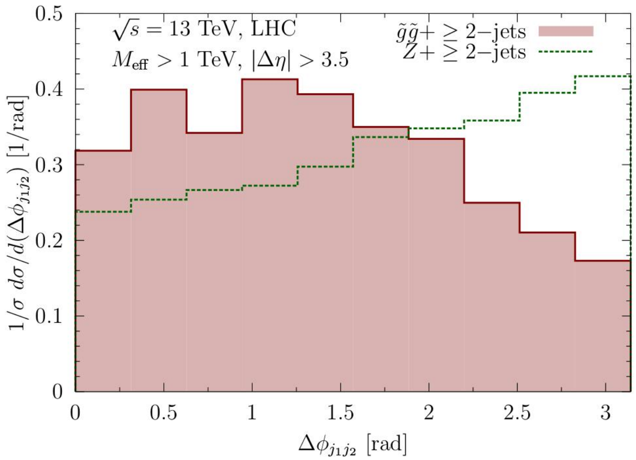


spin-0: X=H, differentiate CP structure



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

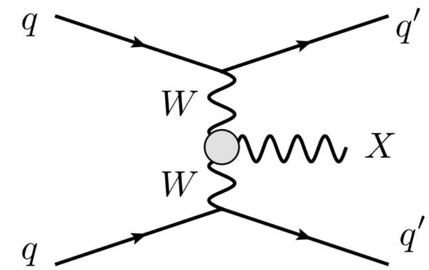
X=gluino, suppress background



Mukhopadhyay, Nojiri, Yanagida, JHEP 1410 (2014) 12

Tests of CPV dark photon interaction

- Azimuthal angle distribution



  - Process $pp \to jjX,\ X \to \ell^+\ell^-$
  - Asymmetry

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

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

  - Benchmark values

$$m_X = 20 \text{ GeV} \qquad \frac{\beta x_0}{\Lambda} = \frac{\tilde{\beta} x_0}{\Lambda} = 2 \times 10^{-3}$$

VBF cuts:

$$p_T^j > 20 \text{ GeV}, \quad \Delta R_{jj} > 0.4, \quad |y_j| < 5,$$
$$|\Delta y_{jj}| > 4.2, \quad y_1 \cdot y_2 < 0, \quad m_{jj} > 600 \text{ GeV}.$$

  - Asymmetry after cuts is around 20%
  - Cross section after cuts is $O(10^{-5})$ pb and about 30 events will accumulate at the HL-LHC with statistical uncertainties of 18% even with zero background

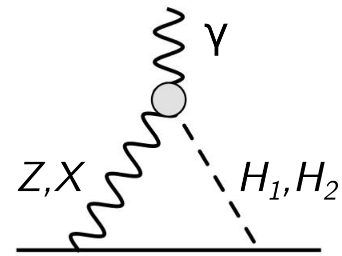
  - It is very challenging even at the HL-LHC

Tests of CPV dark photon interaction

- Fermion electric dipole moment

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

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

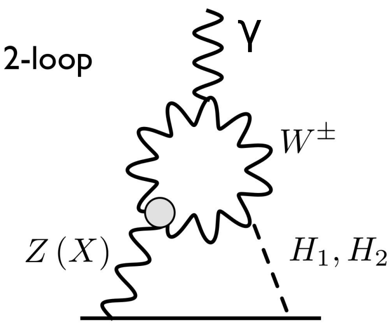


1-loop contribution proportional to $s_\theta e_{WX}$

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

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

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



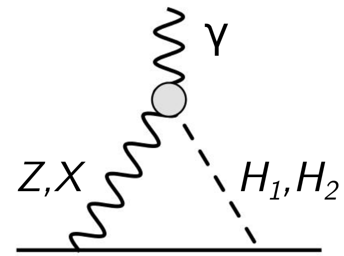
2-loop contribution proportional to $(e_{WX})^2$ and negligible

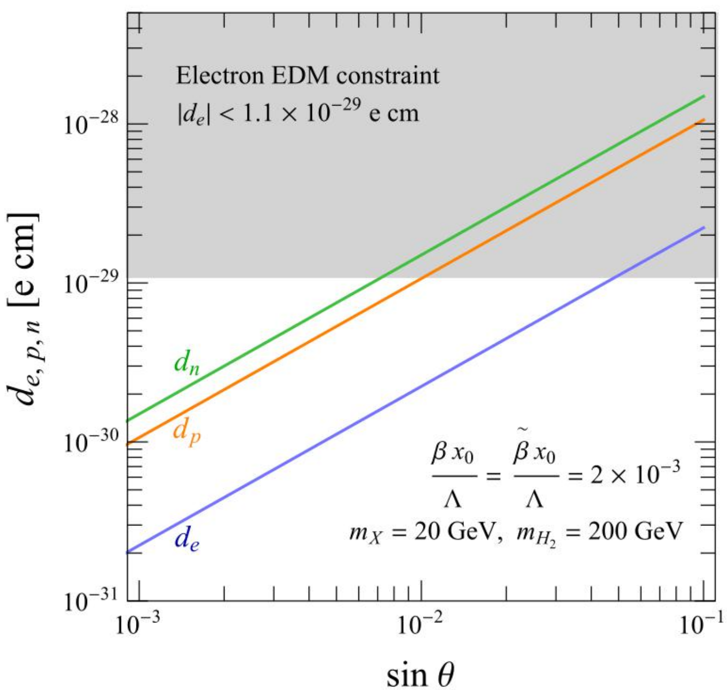
Tests of CPV dark photon interaction

- Fermion electric dipole moment

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

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





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

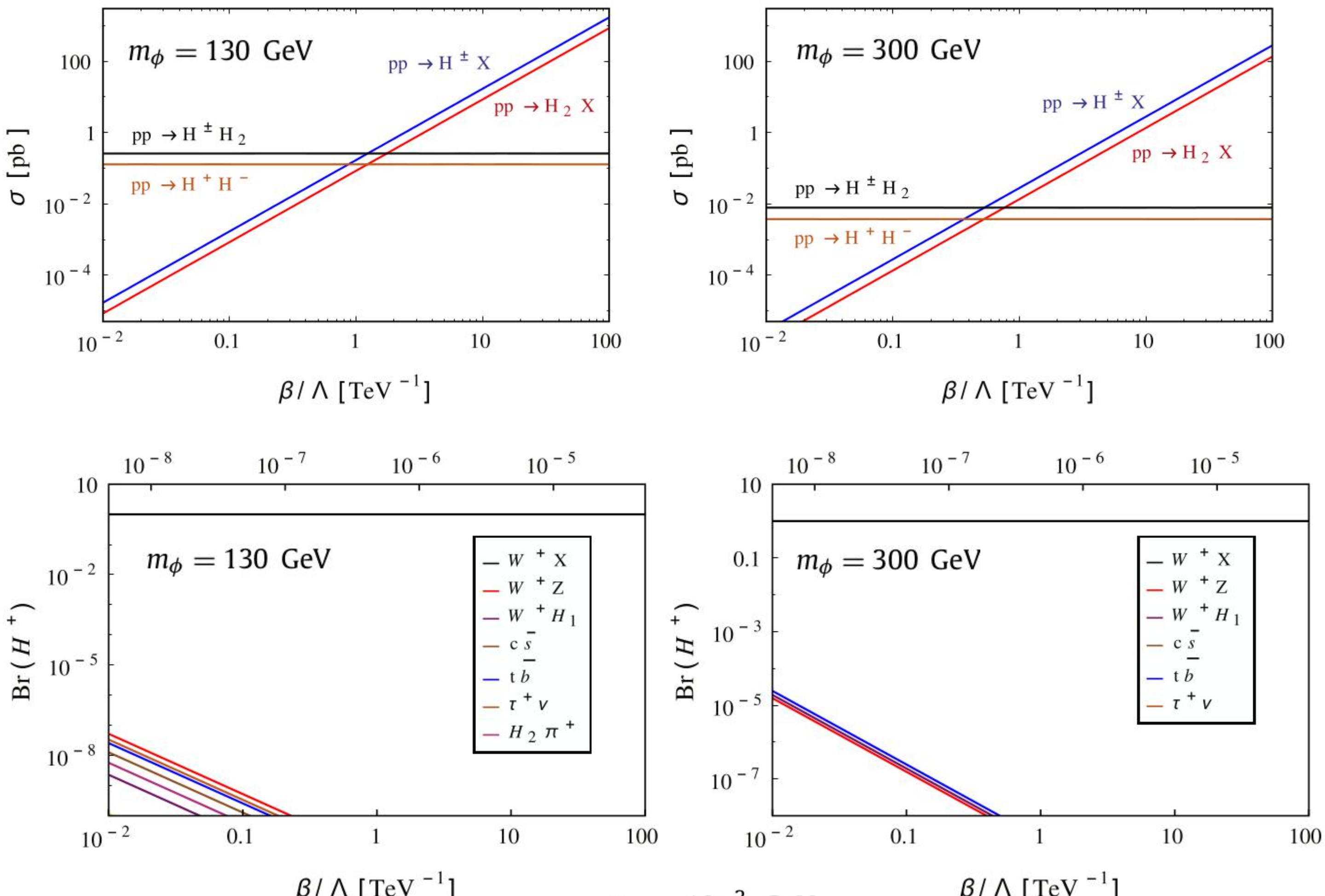
EDMs are insensitive to dark photon mass

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

Long-lived dark photon

- Production of dark photons

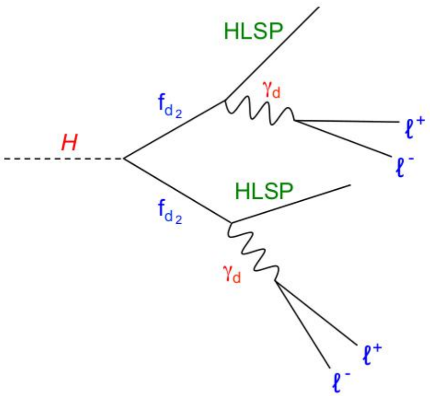
C. A. Argüelles, X.-G. He, G. Ovanesyan, T. Peng, M. J. Ramsey-Musolf, Phys.Lett. B770 (2017) 101

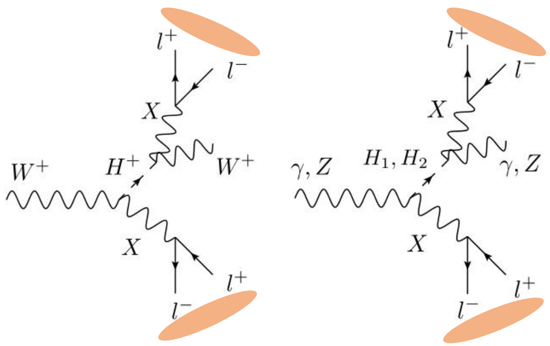


$v_\Sigma = 10^{-3}$ GeV

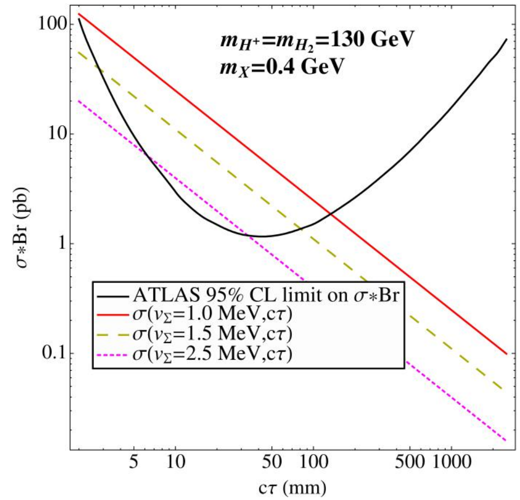
Long-lived dark photon

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



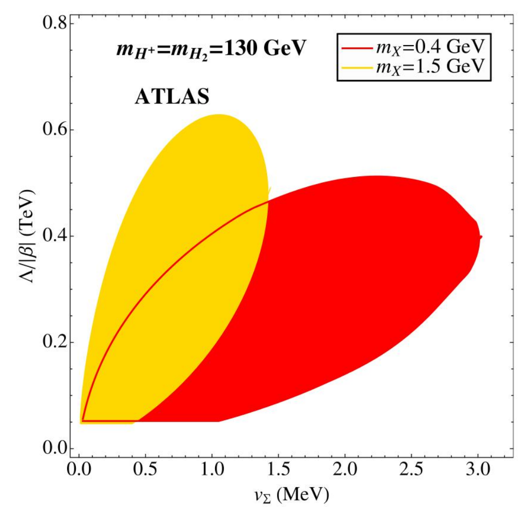


(c) (d)



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

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



Summary

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

Summary

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Thank you for your attention!