Enlighten Dark Photon With Kinetic Mixing

Xiao-Gang He

The 14th TeV Physics Workshop
April 19-22, 2019, Nanjing Normal University

1. Enlighten Dark Photon by Kinetic Mixing

2. e^+e^- Collider Detection of Dark Photon

3. Dark Photon From Non-Abelian Kinetic Mixing

4. CP Violating Kinetic Mixing

交大要闻

李政道研究所
Director：Frank Wilczek

因科学而生，以科学为路，向科学前行

李政道研究所入选2019年上海市重大建设项目

粒子与核物理部
Director： 何小刚

天文与天体物理部
Director： 赖东

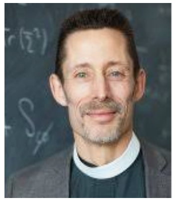
量子物理部
Director： 顾威

近日，2019年上海市重大建设项目清单公布，在清单中的10项科创中心项目中，李政道研究所位列其中。

李政道研究所粒子与核物理部成员

全职资深研究员






X-G He, T **X-D Ji, T&E** **M. Ramsey-Musolf** **T. Yanagida**


L. Maiani, **J. Ellis**

长访资深研究员

合聘研究员




H-J He, T **J-L Liu, E** **H-J Yang, E** **D Xiang, E**

研究员:



S Li, E **D-L Xu, E** **S-F Ge, T**

6 位研究员，5 博士后将近期加入

博士后:





Y-S Liu, T **C Kato, E** **G-J Choi, T** **P-W Xie, E** **Y-Z Liu, T**

Secretary: Zi Yang

1. Enlighten Dark Photon by Kinetic Mixing

A photon and a pure dark photon

A theory of $U(1)_{em} x U(1)_X$ gauge group

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

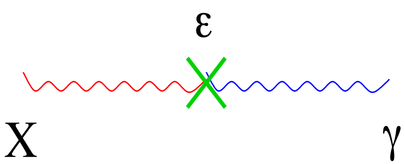
$$L = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} - \frac{1}{4} X_{\mu\nu}X^{\mu\nu} + A_\mu j^\mu_{em} + X_\mu j^\mu_X$$

$$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$$

A is the usual photon field and X is a new gauge field X and $j^\mu_{em,X}$ currents
X may have or not have a finite mass $m^2_A X^\mu X_\mu/2$

If j^μ_X does not involve with SM particle, X is a photon like particle which cannot be probed using laboratory probes – a **Dark Photon**

$$\epsilon X_{\mu\nu} F^{\mu\nu}$$



a  gauge invariant term.

This kinetic mixing term mixes photon and Dark Photon making dark photon to interact with SM particle, Dark Photon enlightened!

Holdom 1986, Foot and He 1991,….

Some basics for Dark Photon

Work with $SU(3)_C x SU(2)_L x U(1)_Y x U(1)_X$

Kinetic mixing can happen between $U(1)_Y$ and $U(1)_X$

$$\mathcal{L} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\sigma}{2} X_{\mu\nu} Y^{\mu\nu} - \frac{1}{4} Y_{\mu\nu} Y^{\mu\nu} + j_Y^\mu Y_\mu + j_X^\mu X_\mu$$

Need to re-write in the canonical form to identify physics gauge bosons. (mixing term removed!)

This may generate dark photon to interact with SM J^μ_Y

How to remove the mixing term?

M He, X-G He, G. Li,arXiv: 1807.00921

Not unique! Examples

$$Case\ \ a):\quad \mathcal{L}_a = -\frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{4}\hat{Y}_{\mu\nu}\hat{Y}^{\mu\nu} + j^\mu_Y \frac{1}{\sqrt{1-\sigma^2}}\hat{Y}_\mu + j^\mu_X(\hat{X}_\mu - \frac{\sigma}{\sqrt{1-\sigma^2}}\hat{Y}_\mu)\ ,$$

$$\hat{Y}_\mu = \sqrt{1-\sigma^2}Y_\mu\ ,\quad \hat{X}_\mu = \sigma Y_\mu + X_\mu\ ,$$

$$Case\ \ b):\quad \mathcal{L}_b = -\frac{1}{4}\hat{X}'_{\mu\nu}\hat{X}'^{\mu\nu} - \frac{1}{4}\hat{Y}'_{\mu\nu}\hat{Y}'^{\mu\nu} + j^\mu_Y(\hat{Y}'_\mu - \frac{\sigma}{\sqrt{1-\sigma^2}}\hat{X}'_\mu) + j^\mu_X \frac{1}{\sqrt{1-\sigma^2}}\hat{X}'_\mu\ ,$$

$$\hat{Y}'_\mu = Y_\mu + \sigma X_\mu\ ,\quad \hat{X}'_\mu = \sqrt{1-\sigma^2}X_\mu\ .$$

Case a), Redefined X does not couple to j^{μ}_{Y} is still “dark”

Case b), Redefined X does not couple to j^{μ}_{Y} is not dark any more, but Y does not couple to j^{μ}_{X} .

Which one is the correct one to choose?

Work with SM photon and dark photon

$$Y_\mu = c_W A_\mu - s_W Z_\mu \ , \quad W^3_\mu = s_W A_\mu + c_W Z_\mu \ ,$$

$$\mathcal{L}_0 = \ -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{2}\sigma c_W X_{\mu\nu}A^{\mu\nu} + \frac{1}{2}\sigma s_W X_{\mu\nu}Z^{\mu\nu}$$
$$+ j^\mu_{em}A_\mu + j^\mu_Z Z_\mu + j^\mu_X X_\mu + \frac{1}{2}m_Z^2 Z_\mu Z^\mu \ ,$$

Write the above into canonical form requires

$$Case \ \ a): \ \begin{pmatrix} A \\ Z \\ X \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{1-\sigma^2 c_W^2}} & \frac{-\sigma^2 s_W c_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}} & 0 \\ 0 & \frac{\sqrt{1-\sigma^2 c_W^2}}{\sqrt{1-\sigma^2}} & 0 \\ \frac{-\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}} & \frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}} & 1 \end{pmatrix} \begin{pmatrix} \tilde{A} \\ \tilde{Z} \\ \tilde{X} \end{pmatrix} \ ,$$

$$Case \ \ b): \ \begin{pmatrix} A \\ Z \\ X \end{pmatrix} = \begin{pmatrix} 1 & \frac{-\sigma^2 s_W c_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}} & \frac{-\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}} \\ 0 & \frac{\sqrt{1-\sigma^2 c_W^2}}{\sqrt{1-\sigma^2}} & 0 \\ 0 & \frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}} & \frac{1}{\sqrt{1-\sigma^2 c_W^2}} \end{pmatrix} \begin{pmatrix} \tilde{A}' \\ \tilde{Z}' \\ \tilde{X}' \end{pmatrix} \ ,$$

$$
\begin{aligned}
\mathcal{L}_a = \; & -\frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{1}{4}\tilde{A}_{\mu\nu}\tilde{A}^{\mu\nu} - \frac{1}{4}\tilde{Z}_{\mu\nu}\tilde{Z}^{\mu\nu} + \frac{1}{2}m_Z^2\frac{1-\sigma^2 c_W^2}{1-\sigma^2}\tilde{Z}_\mu\tilde{Z}^\mu \\
& + j_{em}^\mu\left(\frac{1}{\sqrt{1-\sigma^2 c_W^2}}\tilde{A}_\mu - \frac{\sigma^2 s_W c_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}\tilde{Z}_\mu\right) + j_Z^\mu\left(\frac{\sqrt{1-\sigma^2 c_W^2}}{\sqrt{1-\sigma^2}}\tilde{Z}_\mu\right) \\
& + j_X^\mu\left(\frac{-\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}}\tilde{A}_\mu + \frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}\tilde{Z}_\mu + \tilde{X}_\mu\right), \\
\mathcal{L}_b = \; & -\frac{1}{4}\tilde{X}'_{\mu\nu}\tilde{X}'^{\mu\nu} - \frac{1}{4}\tilde{A}'_{\mu\nu}\tilde{A}'^{\mu\nu} - \frac{1}{4}\tilde{Z}'_{\mu\nu}\tilde{Z}'^{\mu\nu} + \frac{1}{2}m_Z^2\frac{1-\sigma^2 c_W^2}{1-\sigma^2}\tilde{Z}'_\mu\tilde{Z}'^\mu \\
& + j_{em}^\mu\left(\tilde{A}'_\mu - \frac{\sigma^2 s_W c_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}\tilde{Z}'_\mu - \frac{\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}}\tilde{X}'_\mu\right) \\
& + j_Z^\mu\left(\frac{\sqrt{1-\sigma^2 c_W^2}}{\sqrt{1-\sigma^2}}\tilde{Z}'_\mu\right) + j_X^\mu\left(\frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}\tilde{Z}'_\mu + \frac{1}{\sqrt{1-\sigma^2 c_W^2}}\tilde{X}'_\mu\right).
\end{aligned}
$$

Which one to choose?

If dark photon is massive, easy to identify

X has a mass to start with: $(1/2)m_X^2 X^\mu X_\mu$

Example: get a mass from the vev of a scalar S with $U(1)_X$ charge but not charge with SM charges.

$$Case\ \ a):\quad \frac{1}{2}m_X^2\left(\frac{-\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}}\tilde{A}_\mu + \frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}\tilde{Z}_\mu + \tilde{X}_\mu\right)^2 ,$$

$$Case\ \ b):\quad \frac{1}{2}m_X^2\left(\frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}\tilde{Z}'_\mu + \frac{1}{\sqrt{1-\sigma^2 c_W^2}}\tilde{X}'_\mu\right)^2 .$$

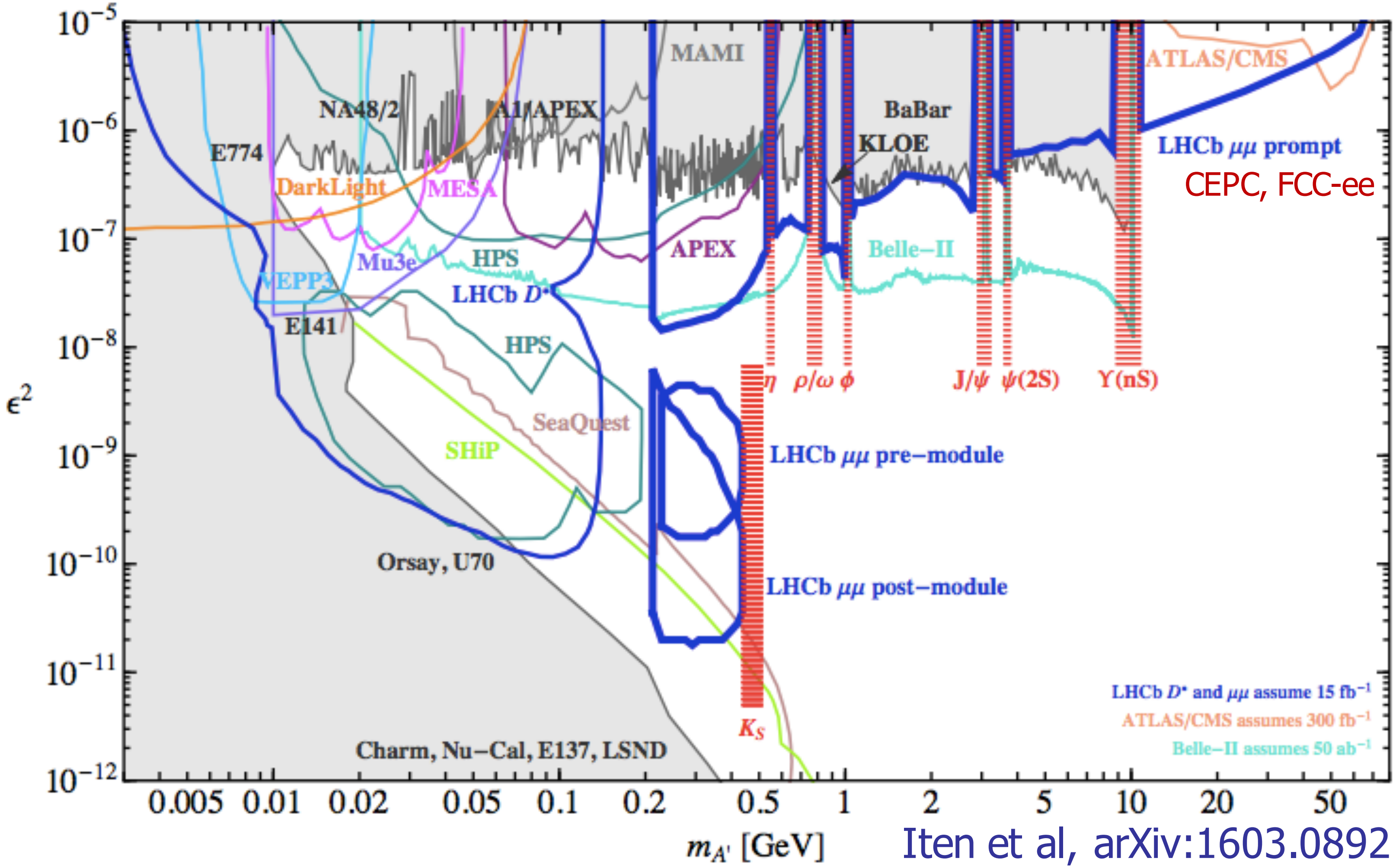
Case b) is more convenient to use, because tilde-A' already the physical massless photon, tilde-Z' and tilde X' mixing with each other

$$\begin{pmatrix} \frac{m_Z^2(1-\sigma^2 c_W^2)^2+m_X^2\sigma^2 s_W^2}{(1-\sigma^2)(1-\sigma^2 c_W^2)} & \frac{m_X^2\sigma s_W}{\sqrt{1-\sigma^2}(1-\sigma^2 c_W^2)} \\ \frac{m_X^2\sigma s_W}{\sqrt{1-\sigma^2}(1-\sigma^2 c_W^2)} & \frac{m_X^2}{1-\sigma^2 c_W^2} \end{pmatrix} , \qquad \begin{pmatrix} Z^m \\ X^m \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \tilde{Z}' \\ \tilde{X}' \end{pmatrix}$$

$$\tan(2\theta) = \frac{2m_X^2\sigma s_W\sqrt{1-\sigma^2}}{m_Z^2(1-\sigma^2 c_W^2)^2 - m_X^2[1-\sigma^2(1+s_W^2)]} .$$

Inconvenient to work with a) although finally one will reach the same interactions

Summary of constraints on the dark photon mass and coupling

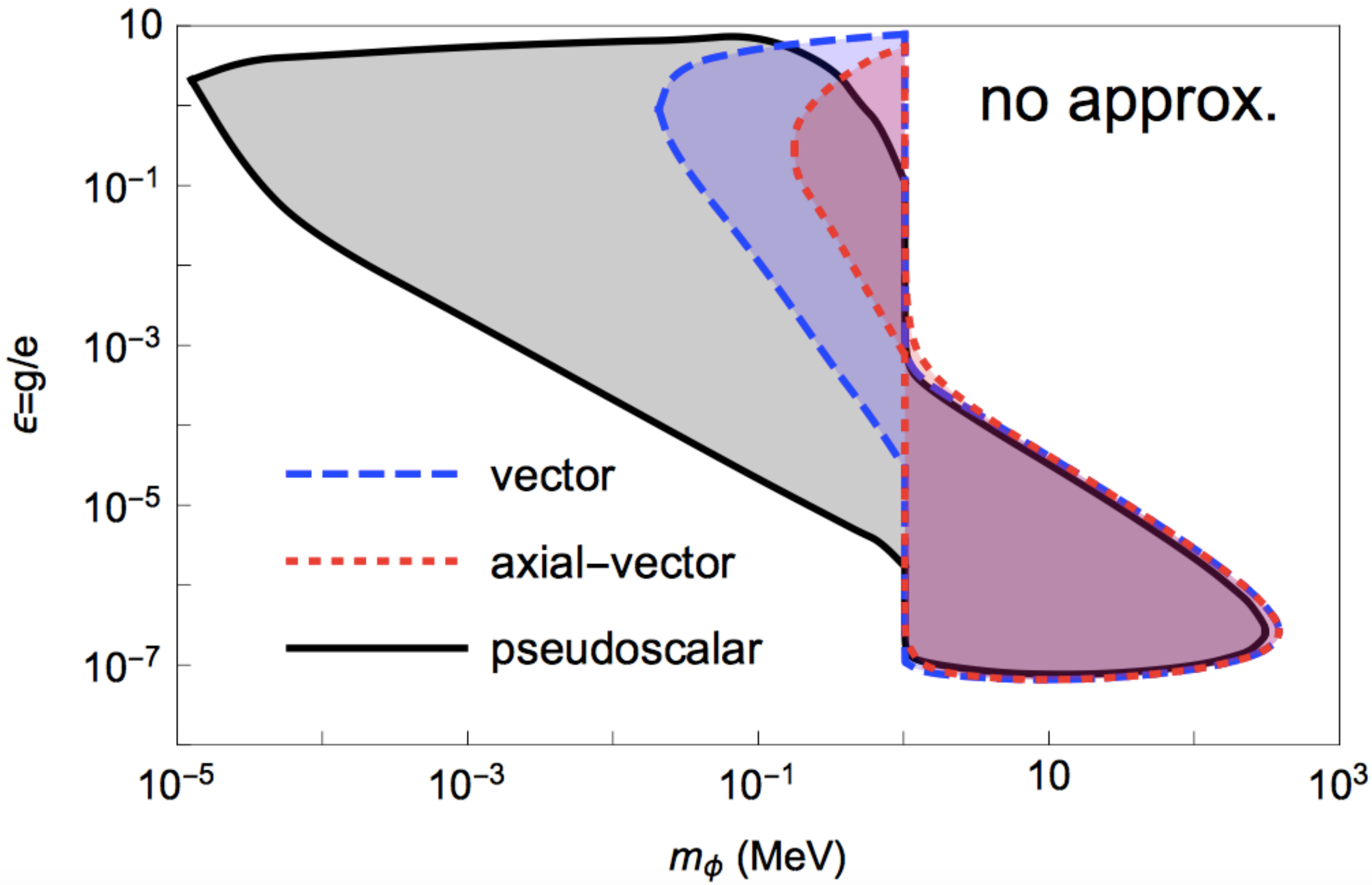


Iten et al, arXiv:1603.0892

For massless dark photon, much less stringent!

Very small mass or zero mass dark photon constraints (beam dump) very weak

Y-S Liu, G. Miller, PRD96(2017)016004



What above massless dark photon?

More complicated!

Photon and dark photon are both massless, degenerate!

They can be rotated into each other by an orthogonal transformation

$$\begin{pmatrix} \tilde{A}' \\ \tilde{X}' \end{pmatrix} = \begin{pmatrix} \sqrt{1-\sigma^2 c_W^2} & \sigma c_W \\ -\sigma c_W & \sqrt{1-\sigma^2 c_W^2} \end{pmatrix} \begin{pmatrix} \tilde{A} \\ \tilde{X} \end{pmatrix}$$

Which one is the photon and dark photon! Cannot be decided by looking at their masses.

In fact, any rotation from case b)

is as good as any other ones

$$\begin{pmatrix} \tilde{A}' \\ \tilde{X}' \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \bar{A}' \\ \bar{X}' \end{pmatrix} , \quad \tilde{Z}' = \bar{Z}'$$

$$\mathcal{L}_{\bar{b}} = -\frac{1}{4}\bar{X}'_{\mu\nu}\bar{X}'^{\mu\nu} - \frac{1}{4}\bar{A}'_{\mu\nu}\bar{A}'^{\mu\nu} - \frac{1}{4}\bar{Z}'_{\mu\nu}\bar{Z}'^{\mu\nu} + \frac{1}{2}m_Z^2\frac{1-\sigma^2 c_W^2}{1-\sigma^2}\bar{Z}'_\mu\bar{Z}'^\mu$$
$$+\left((c_\beta + \frac{\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}}s_\beta)j^\mu_{em} - s_\beta\frac{1}{\sqrt{1-\sigma^2 c_W^2}}j^\mu_X\right)\bar{A}'_\mu$$
$$+\left(\frac{\sqrt{1-\sigma^2 c_W^2}}{\sqrt{1-\sigma^2}}j^\mu_Z - \frac{\sigma^2 s_W c_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}j^\mu_{em} + \frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}j^\mu_X\right)\bar{Z}'_\mu$$
$$+\left(\frac{1}{\sqrt{1-\sigma^2 c_W^2}}c_\beta j^\mu_X + (s_\beta - \frac{\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}}c_\beta)j^\mu_{em}\right)\bar{X}'_\mu\,.$$

For case b), $\beta = 0$

For case a) $s_\beta = \sigma c_W,\ \bar{A}' = \tilde{A}$ and $\bar{X}' = \tilde{X}$

The final physical observable should be β independent!!!

Dark photon effects in electroweak interactions

Let us first look at the EM interactions alone.

A physical process include
how the process occur
how the results are detected
Photon or dark photon can affect observable involve EM interaction must be proportional to

j^{μ}_{em} X------ $g_{\mu\nu}$ (due to A, X exchange)------j^{υ}_{em}

Exchange A: $e^2 R_A$

$$R_A = \left(c_\beta + \frac{\sigma \bar{c}_W}{\sqrt{1-\sigma^2 c_W^2}} s_\beta \right)^2$$

Exchange X: $e^2 R_X$

$$R_X = \left(s_\beta - \frac{\sigma \bar{c}_W}{\sqrt{1-\sigma^2 c_W^2}} c_\beta \right)^2$$

Total: $e^2(R_A + R_X) = e^2/(1-\sigma^2 c_w^2)$

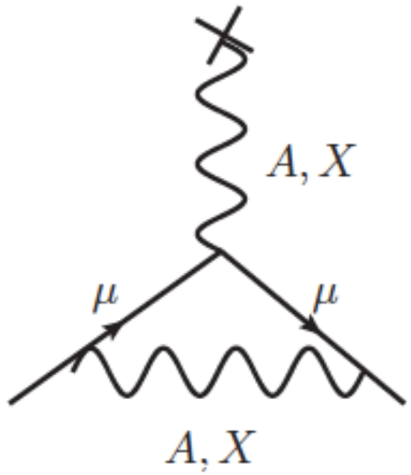
Normalize the electric charge: $\bar{e} = e/\sqrt{1-\sigma^2 c_W^2}$

No other observable effects!

Example: g-2 of leptons No observable effects!

$$a^{\gamma}_{\mu,X} = R_X \frac{\alpha}{2\pi}, \quad R_X = \left(s_\beta - \frac{\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}} c_\beta \right)^2,$$

$$a^{\gamma}_{\mu,A} = R_A \frac{\alpha}{2\pi}, \quad R_A = \left(c_\beta + \frac{\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}} s_\beta \right)^2.$$



$$a^{\gamma}_{\mu,\text{total}} = (R_X + R_A)\frac{\alpha}{2\pi} = \frac{1}{1-\sigma^2 c_W^2}\frac{\alpha}{2\pi} = \frac{\bar{\alpha}}{2\pi}, \quad \bar{\alpha} = \bar{e}^2/4\pi = \alpha/(1-\sigma^2 c_W^2)$$

This amounts to redefine $\bar{j}^{\mu}_{em} = (\bar{e}/e) j^{\mu}_{em}$.

EM interaction for an SM particle can all be absorbed into

$$\bar{e} = e/\sqrt{1-\sigma^2 c_W^2}.$$

$a^{\gamma_D}_{\mu,\text{total}} = -\sigma c_W \bar{\alpha}/2\pi$ under the influence of a non-zero $X_{\mu\nu}$.

What about weak interaction? No observable effects!

$$-\frac{1}{4}\bar{Z}'_{\mu\nu}\bar{Z}'^{\mu\nu}+\frac{1}{2}m_Z^2\frac{1-\sigma^2 c_W^2}{1-\sigma^2}\bar{Z}'_\mu\bar{Z}'^\mu$$

$$+\left(\frac{\sqrt{1-\sigma^2 c_W^2}}{\sqrt{1-\sigma^2}}j_Z^\mu-\frac{\sigma^2 s_W c_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}j_{em}^\mu+\frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}j_X^\mu\right)\bar{Z}'_\mu$$

No modifications on W interactions and W mass.

Modify Z mass: $\overline{m}_Z^2 = m_Z^2$ (1+z) $\qquad z = \sigma^2 s_W^2/(1-\sigma^2)$.

On-shell mass scheme $\qquad \bar{c}_W^2 \equiv \cos^2\bar{\theta}_W = c_W^2/(1+z)$

$$\overline{s}_f^2 = s_W^2[1+\sigma^2 c_W^2/(1-\sigma^2 c_W^2)] = \overline{s}_W^2$$

$$\bar{j}_{em}^\mu = \bar{e}Q_f\bar{f}\gamma^\mu f\ ,\quad \bar{j}_W^{+\mu} = \frac{g}{2\sqrt{2}}\bar{f}^u\gamma^\mu(1-\gamma_5)f^d\ ,\quad \bar{j}_Z^\mu = \frac{g_Z}{2}\bar{f}\gamma^\mu(\bar{g}_V^f-\bar{g}_A^f\gamma^5)f\ ,$$

$$g_Z = 2(\sqrt{2}G_F\bar{m}_Z^2)^{1/2}.$$

$$\bar{g}_A^f = I_f^3\ ,\quad \bar{g}_V^f = (I_f^3 - 2Q_f\bar{s}_f^2)$$

ρ parameter $\qquad \rho = \frac{g_Z^2/\bar{m}_Z^2}{g^2/\bar{m}_W^2} = 1\ .$

Where can massless dark photon be observed?

Minicharged particle

$$\mathcal{L}_a = -\frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{1}{4}\tilde{A}_{\mu\nu}\tilde{A}^{\mu\nu} - \frac{1}{4}\tilde{Z}_{\mu\nu}\tilde{Z}^{\mu\nu} + \frac{1}{2}m_Z^2\frac{1-\sigma^2 c_W^2}{1-\sigma^2}\tilde{Z}_\mu\tilde{Z}^\mu$$
$$+j^\mu_{em}\left(\frac{1}{\sqrt{1-\sigma^2 c_W^2}}\tilde{A}_\mu - \frac{\sigma^2 s_W c_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}\tilde{Z}_\mu\right) + j^\mu_Z\left(\frac{\sqrt{1-\sigma^2 c_W^2}}{\sqrt{1-\sigma^2}}\tilde{Z}_\mu\right)$$
$$+j^\mu_X\left(\frac{-\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}}\tilde{A}_\mu + \frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}\tilde{Z}_\mu + \tilde{X}_\mu\right),$$

Effective minicharged particle:

example $j^\mu_X = g_X \bar{f}_X \gamma^\mu f_X$

$$j^\mu_X(-\sigma c_W/\sqrt{1-\sigma^2 c_W^2})\bar{A}_\mu = (\bar{j}^\mu_X/\bar{g}_x)(\bar{e}Q_X)\bar{A}_\mu \text{ with } Q_X = -\sigma c_W \bar{g}_X/\bar{e}.$$

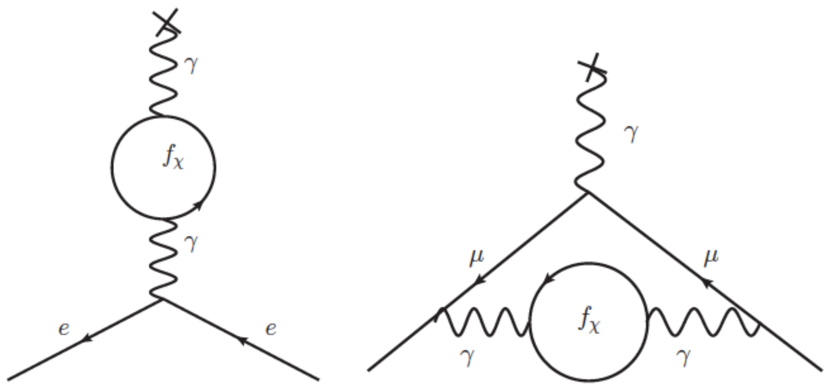
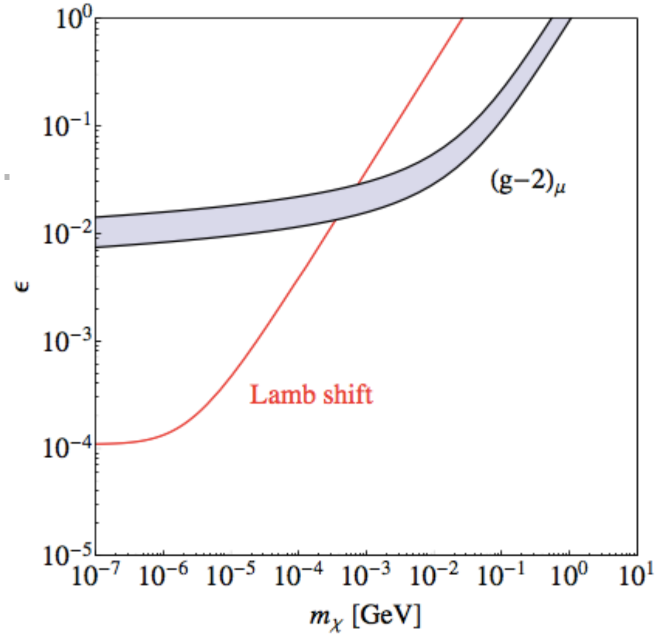


FIG. 2: Vacuum polarization diagrams contributing to and Lamb shift (left) and muon $g-2$ (right) in the presence of millicharged particles. The cross vertex denotes the external source.



Lamb shift between the levels of $2S_{1/2}$ and $2P_{1/2}$ of hydrogen atom

$$\delta E = -\epsilon^2 \frac{4\bar{\alpha}^3 m_e}{3\pi} \alpha^{*2} I(\alpha^*),$$

$$I(\alpha^*) = \int_1^\infty du \left(1 + \frac{1}{2u^2}\right) \frac{\sqrt{u^2-1}}{(\alpha^* + 2u)^4}$$

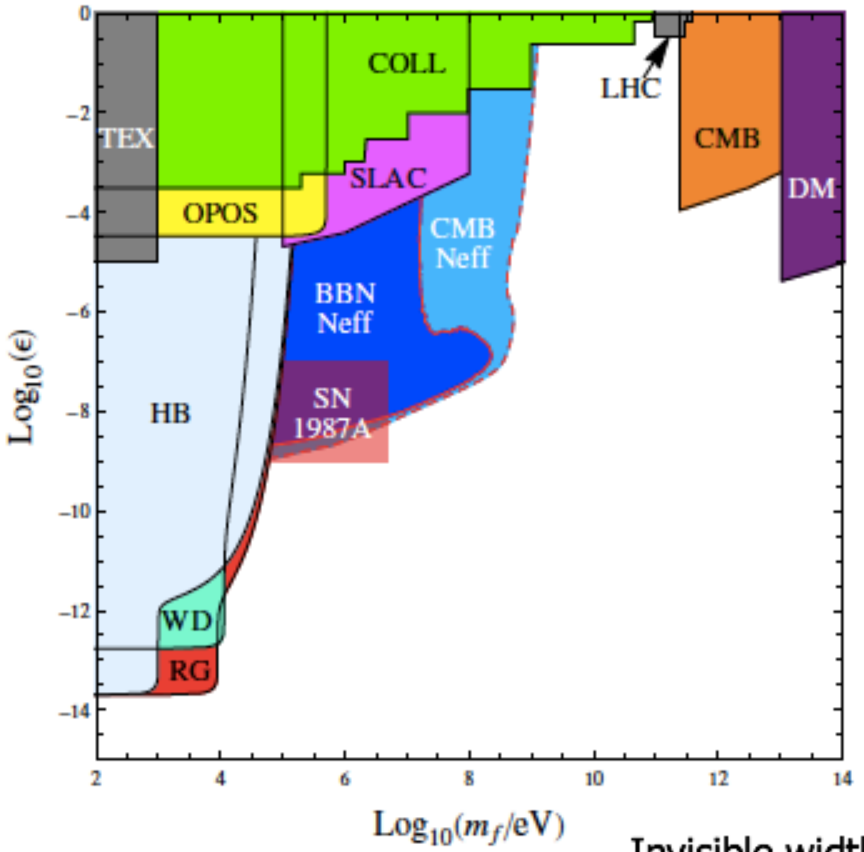
$$\alpha^* \equiv \bar{\alpha} m_e / m_{f_\chi}$$

$$a_\mu^{\textbf{2-loop}} = \epsilon^2 A_2\left(\frac{m_{f_\chi}}{m_\mu}\right)$$

$$A_2(x) = \frac{\alpha^2}{\pi^2} \int_0^1 du \int_0^1 dv \frac{u^2(1-u)v^2(1-v^2/3)}{u^2(1-v^2) + 4x^2(1-u)}$$

M. Gluck, S. Rakshit and E. Reya, arXiv:hep-ph/0703140
H.H. elend, Phys. Letts. 20, 682(1966)

Constraints from various other searches



arXiv:1311.2600

Invisible width of Z Z coupling to j_X: $(\sigma s_W/\sqrt{1-\sigma^2})\bar{j}^\mu_X \bar{Z}'_\mu$

Assuming $j^\mu_X = g_X \bar{f}_X \gamma^\mu f_X$ $Q_X = -\sigma c_W g_X$ $\epsilon \equiv |Q_X/\bar{e}|$

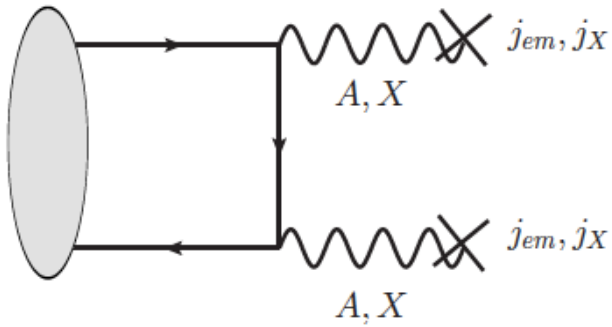
Effective neutrino number: $2.92 \pm 0.05.$ $\epsilon \lesssim 0.18$

Where can massless dark photon be observed?

- A process involve only SM particles, and detected by electroweak interactions, no observable!
- To feel effect massless dark photon effects, J_X information must be used. => missing energy $\not{E}_T$

Example: $h, pp \to \gamma\gamma,\ \gamma\gamma_D$ and $\gamma_D\gamma_D$.

- j_{em}^2: diphoton ($\gamma\gamma$);
- $j_{em}j_X$: mono-photon ($\gamma\not{E}_T$);
- j_X^2: $\not{E}_T$.



$$pp, h \to \gamma\gamma \quad e^4(2R_A \times R_X + R_A \times R_A + R_X \times R_X) = \left(\frac{e^2}{1 - \sigma^2 c_W^2}\right)^2$$

$\bar{e} = e/\sqrt{1 - \sigma^2 c_W^2}$ β independent. The same as SM!

$$\frac{B_{\gamma\gamma_D}}{B_{\gamma\gamma}} = 4\sigma^2 c_W^2 \ , \quad \frac{B_{\gamma_D\gamma_D}}{B_{\gamma\gamma}} = \sigma^4 c_W^4 \ .$$

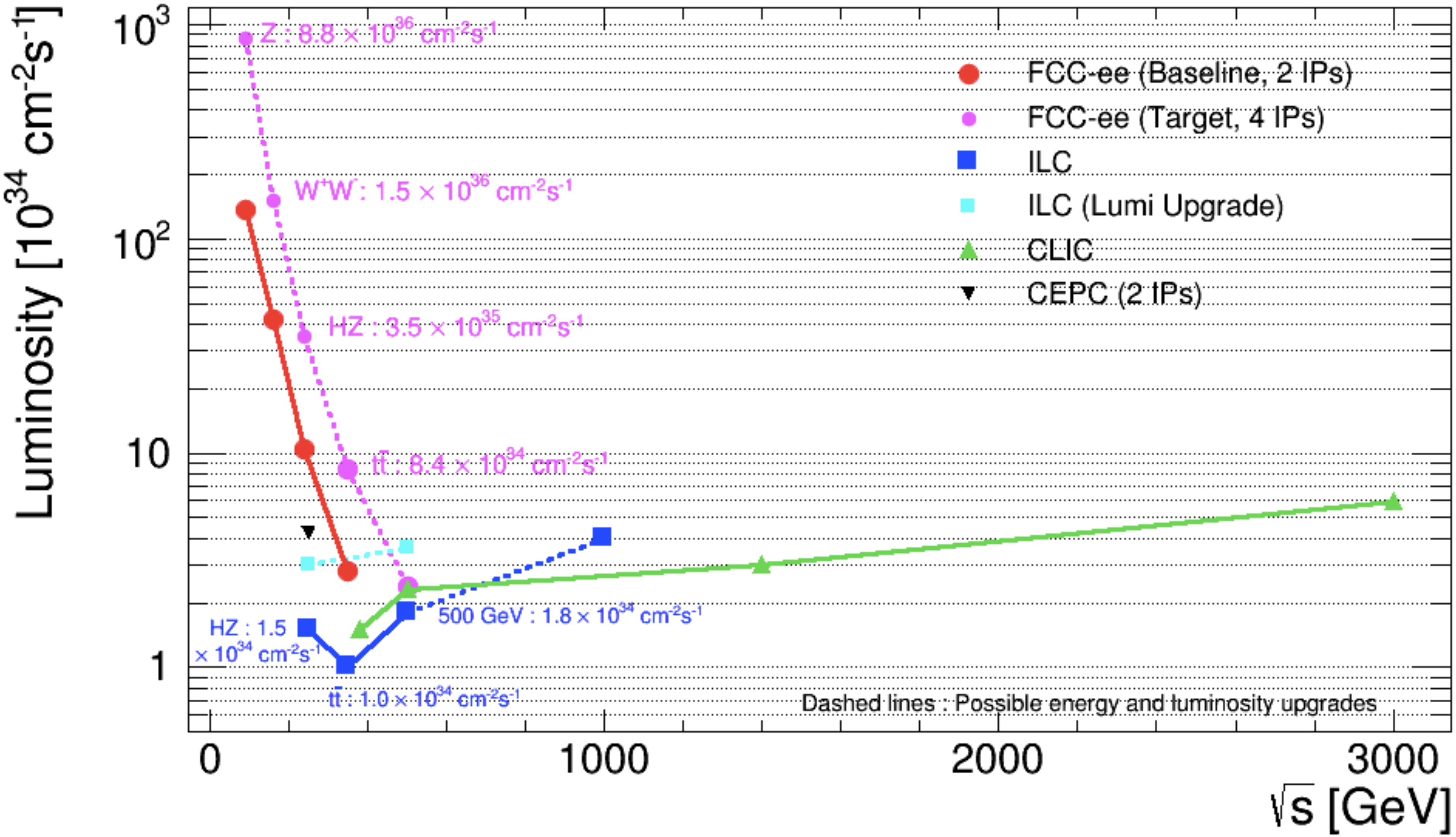
$$h \to \gamma \not{E}_T$$

Can reach 0.1% at HLLHC |σ| can be constrained to be less than 0.24 at 90% CL

- Dark photon can be enlightened by kinetic mixing and have interesting consequences.
- What is a dark photon, easily determined, by mass eigenstates, but for massless dark photon care should be taken to distinguish a dark photon and a photon
- Massless dark photon has no observable effect in processes involve only SM particles
- Massless dark photon needs to know how it interacts with visible world to know effect of kinetic mixing.

$h \to \gamma \gamma_D$ is a good process to search for such effects.

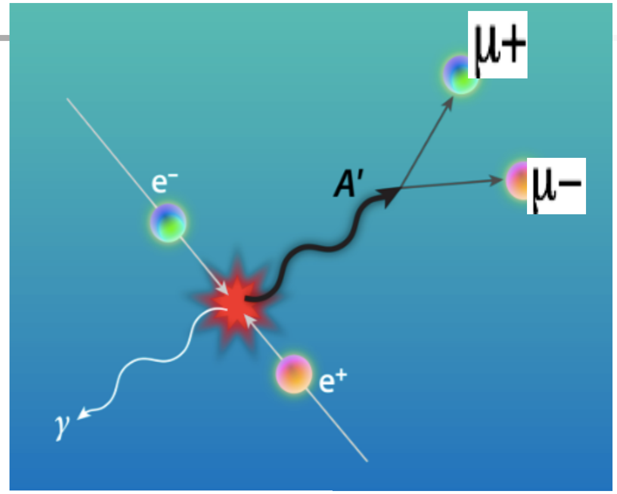
2. e^+e^- Collider Detection of Dark Photon



Luminosity [10^34 cm^-2s^-1]
Z : 8.8 × 10^36 cm^-2s^-1
W+W- : 1.5 × 10^36 cm^-2s^-1
HZ : 3.5 × 10^35 cm^-2s^-1
tt : 8.4 × 10^34 cm^-2s^-1
HZ : 1.5 × 10^34 cm^-2s^-1
tt : 1.0 × 10^34 cm^-2s^-1
500 GeV : 1.8 × 10^34 cm^-2s^-1
FCC-ee (Baseline, 2 IPs)
FCC-ee (Target, 4 IPs)
ILC
ILC (Lumi Upgrade)
CLIC
CEPC (2 IPs)
Dashed lines : Possible energy and luminosity upgrades
√s [GeV]

M. He, X-G He, C-K Huang,
Int. J. Mod. Phys. A32(2017)1750138

M He, X-G he, C-K Huang, G Li,
JHEP 1803(2018)139



$$\frac{d\sigma_{e^+e^-\to\gamma A'\to\gamma\mu^+\mu^-}}{d\sigma_{e^+e^-\to\gamma\gamma^*\to\gamma\mu^+\mu^-}}\Big|_{m_{\mu\mu}\sim m_{A'}} \sim \epsilon^4 \frac{m_{\mu\mu}^4}{(m_{\mu\mu}^2 - m_{A'}^2)^2+\Gamma_{A'}^2 m_{A'}^2} .$$

Naïve expectation

$$\frac{s}{B_{em-background}} \sim \epsilon^4 \frac{\pi}{8}\frac{m_{A'}^2}{\Gamma_{A'}\sigma_{\mu\mu}} ,$$

$$\Gamma_{A'->f\bar{f}} = \frac{\epsilon^2}{3} Q_f^2 \alpha_{em} m_{A'}(1+2\frac{m_f^2}{m_{A'}^2})\sqrt{1-\frac{4m_f^2}{m_{A'}^2}} .$$

Integrate dimuon energy range $|m_{\mu\mu} - m_{A'}| < 2\sigma_{\mu\mu}$

With some physical cuts

Basic cuts $|\eta_{\mu^\pm,\gamma}| < 3, \quad E_\gamma > 2\ \text{GeV}, \quad \Delta R_{ij} > 0.2, \quad \Delta m_{\mu^+\mu^-} < 10\ \text{GeV},$

CEPC

$$\frac{\Delta p_T}{p_T} = 0.1\% \oplus \frac{p_T}{10^5\ \text{GeV}} \text{ for } |\eta| < 1.0 \text{ and 10 times larger for } 1.0 < |\eta| < 3.0;$$

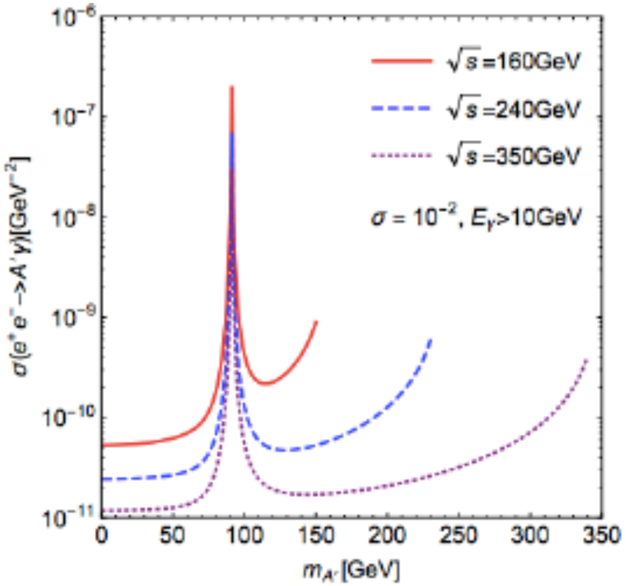
$$\frac{\Delta E}{E} = \frac{0.20}{\sqrt{E/\text{GeV}}} \oplus 0.5\%. \text{ for } |\eta| < 3.0.$$

FCC-ee

$$\frac{\Delta p_T}{p_T} = 0.1\% \oplus \frac{p_T}{10^5\ \text{GeV}} \text{ for } |\eta| < 1.0 \text{ and 10 times larger for } 1.0 < |\eta| < 2.4;$$

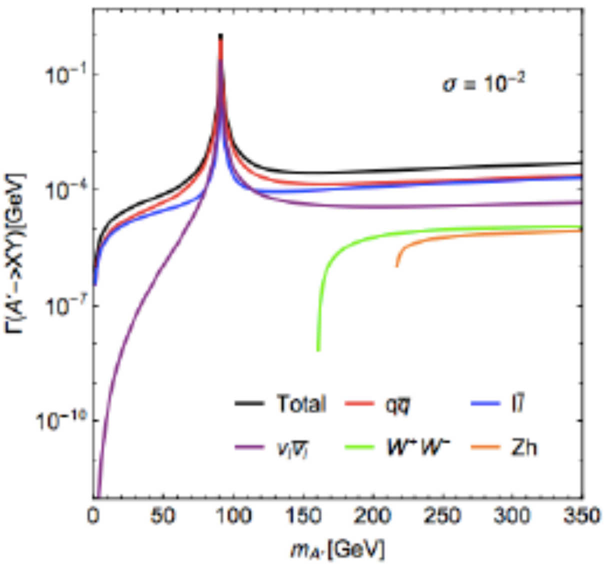
$$\frac{\Delta E}{E} = \frac{0.15}{\sqrt{E/\text{GeV}}} \oplus 1\%. \text{ for } |\eta| < 3.0.$$

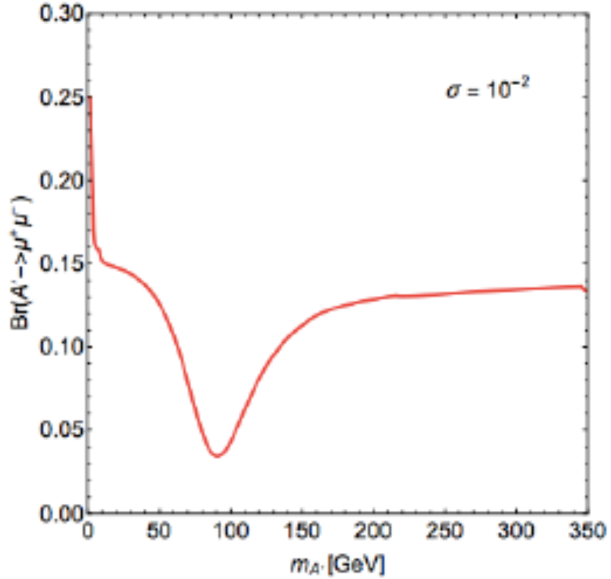
With Some Physical Cuts



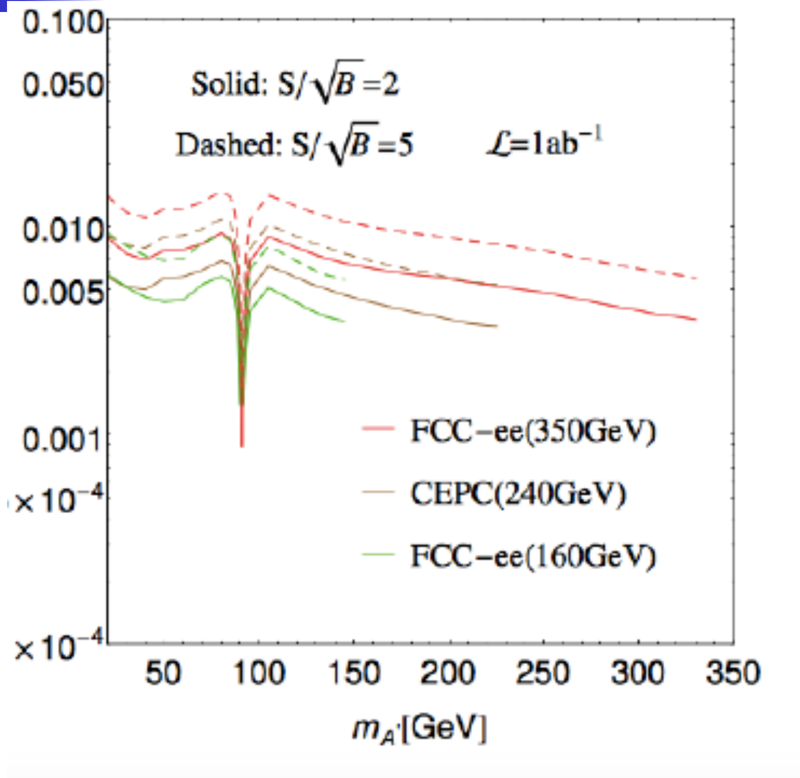
σ= 10-2, Eγ > 10GeV

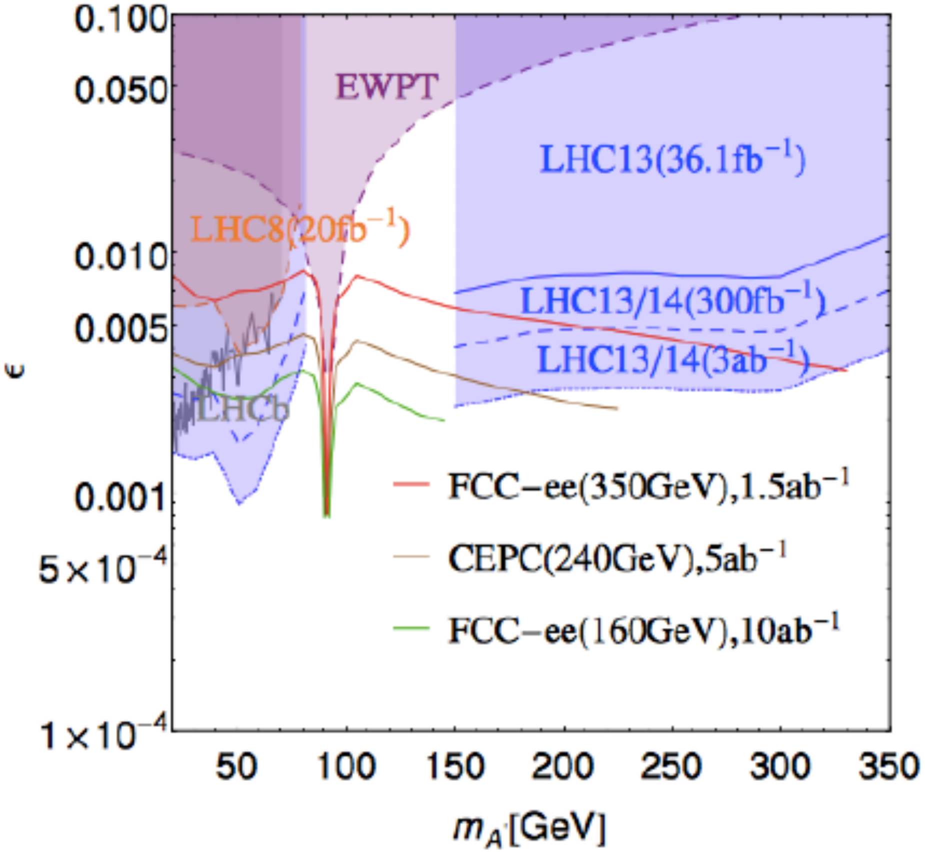
Dark photon decays



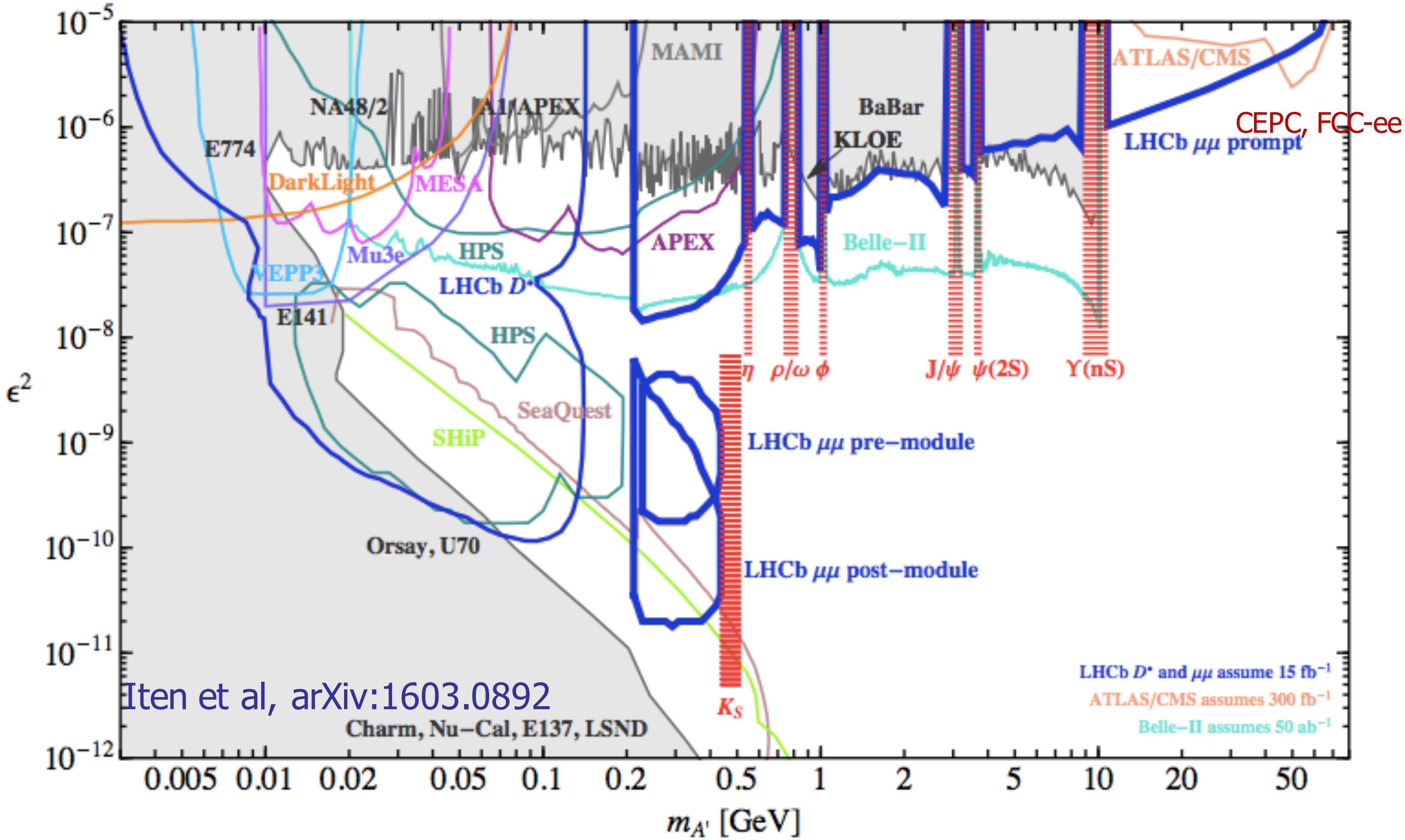


Sensitivities at various e⁺e⁻ colliders





CEPC may have advantage probing dark photon at 10 to a few 10s ($<<m_Z$) GeV mass range.



Iten et al, arXiv:1603.0892

3. Dark Photon From Non-Abelian Kinetic Mixing

Naively, not possible to have Abelian-No-Abelian Kinetic mixing, $W^a_{\mu\nu} X^{\mu\nu}$, is not gauge invariant!

Assuming that there is a field Δ^a transforming as 3 under $SU(2)_W$, then one can make gauge singlet: $W^a_{\mu\nu} X^{\mu\nu} \Delta^a$

If the VEV of $<\Delta^a> = v_3/\text{sqrt}(2)$ along a particular direction in group space is not zero, one can generate kinetic mixing term

$$W^3_{\mu\nu} X^{\mu\nu} v_3/\text{sqrt}(2)$$

Problem: not renormalizable.

If one gives up renormalizability one can write higher order operators to generate abelian and non-abelian gauge fields mixing!

In fact in the SM, one can generate such a mixing between $SU(2)_L$ and $U(1)_Y$

$$W^a_{\mu\nu} X^{\mu\nu} (H^+ \tau^a H)$$

Here H is the usual SM doublet!

Possible to have kinetic mixing between ablian and non-abelian gauge fields.

J. Cline and A. Frey, arXiv: 1408.0233; G. Barello abd s. Chang, PRD94(2016)055018

C. Arguelles, X-G He, G. Ovanesyan, T Peng, M Ramsey-Musolf, PLB770(2017)101

UV completion of kinetic mixing of Abeliand-NonAbelian gauge field?

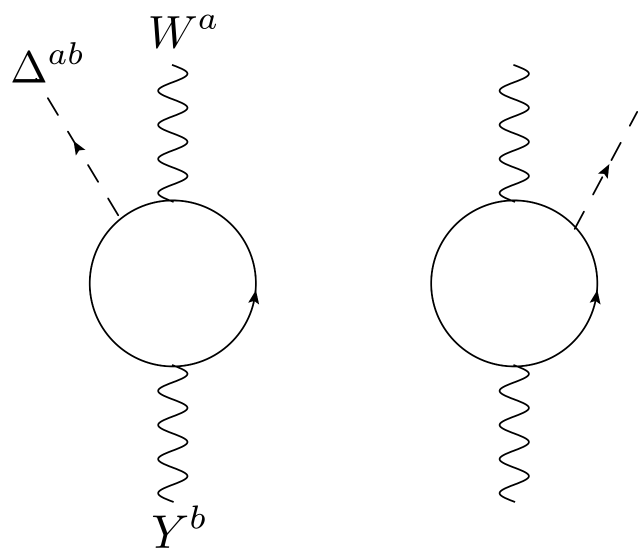
Yes, they can be generated at loop level starting from a renormalizable theory.

The particle in the loop carry both abelian and non-abelian charges.

One can even talking about

SU(N) and SU(m) kinetic mixing

$$W^a_{\mu\nu} Y^{b\mu\nu} \Delta_{ab}$$



Kinetic mixing between an Abelian and a non-Abelian fields should be very common when going beyond SM.

A triplet Δ^a (0,3,0) and W-B mixing

C. Arguelles, X-G He, G. Ovanesyan, T Peng, M Ramsey-Musolf, PLB770(2017)101

$SU(2)_W = SU(2)_L$, $U(1)_X = U(1)_Y$

$$L_{k-mixing} = -\frac{1}{2}\alpha\frac{v_\Delta/\sqrt{2}}{\Lambda}B^{0,\mu\nu}W^{3,0}_{\mu\nu}$$
$$= -\frac{1}{2}\epsilon\left(s_W c_W A^0_{\mu\nu}A^{0,\mu\nu} - s_W c_W Z^0_{\mu\nu}Z^{0,\mu\nu} + (c_W^2 - s_W^2)A^0_{\mu\nu}Z^{0,\mu\nu}\right)$$

$$m_W^2 = (m_W^0)^2\left(1 + 4\frac{v_\Delta^2}{v^2}\right)$$

Analysis the effects through S,T, U parameters

$$\Delta L_{eff} = -\frac{A}{4}A^0_{\mu\nu}A^{0,\mu\nu} - \frac{B}{2}W^{+0}_{\mu\nu}W^{-0,\mu\nu} - \frac{C}{4}Z^0_{\mu\nu}Z^{0,\mu\nu} + \frac{G}{2}A^0_{\mu\nu}Z^{0,\mu\nu}$$
$$+\ w(m_W^0)^2W^{+,0}_\mu W^{-,0,\mu} + \frac{z}{2}(m_Z^0)^2Z^0_\mu Z^{0\mu}\ ,$$

$$A = 2s_W c_W\epsilon\ ,\quad B = 0\ ,\quad C = -2s_W c_W\epsilon\ ,\quad G = -(c_W^2 - s_W^2)\epsilon\ ,\quad w = 4\frac{v_\Delta^2}{v^2}\ ,\quad z = 0.$$

$$\alpha S = 4s_W^2c_W^2\left(A - C - \frac{c_W^2 - s_W^2}{s_W c_W}G\right) = 4s_W^2c_W^2\left(4s_W c_W + \frac{(c_W^2 - s_W^2)^2}{s_W c_W}\right)\epsilon\ ,$$
$$\alpha T = w - z = 4\frac{v_\Delta^2}{v^2}\ ,$$
$$\alpha U = 4s_W^4\left(A - \frac{1}{s_W^2}B + \frac{c_W^2}{s_W^2}C - 2\frac{c_W}{s_W}G\right) = 0\ .$$

Some phenomenological implications

$$\mathcal{O}^{(5)}_{WX} = -\frac{\beta}{\Lambda}\,\mathrm{Tr}\,(W_{\mu\nu}\Sigma)\,X^{\mu\nu} \qquad \epsilon = \beta\sin\theta_W\,\left(\frac{v_\Sigma}{\Lambda}\right)$$

ε is naturally small!

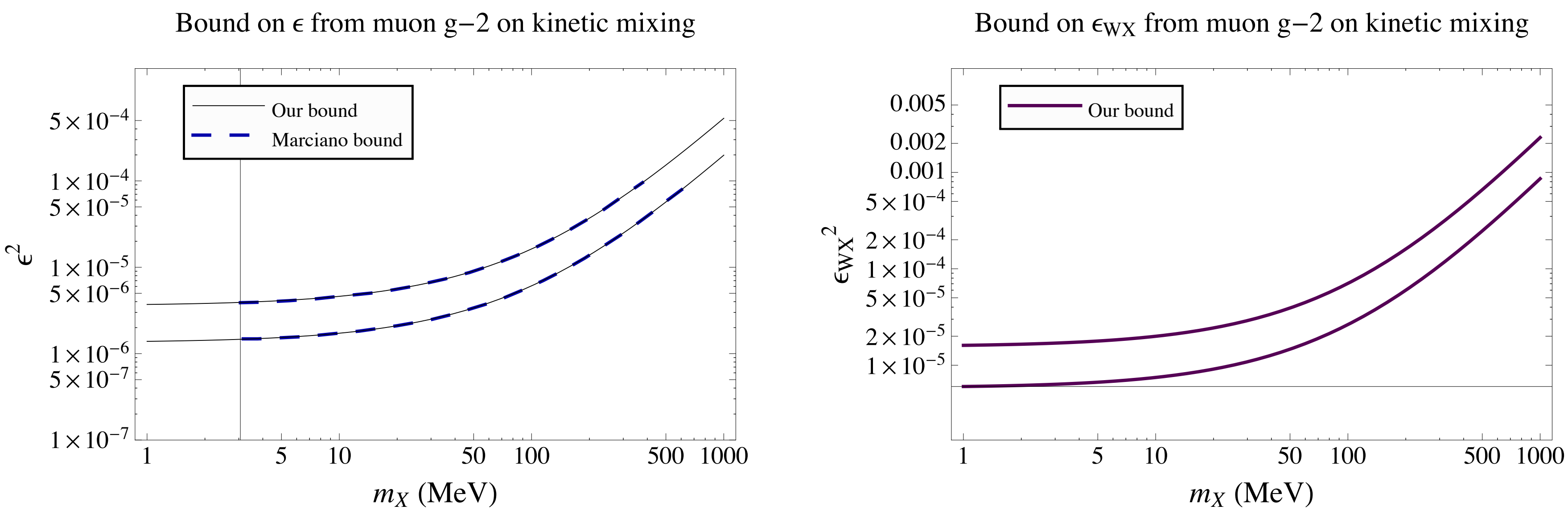
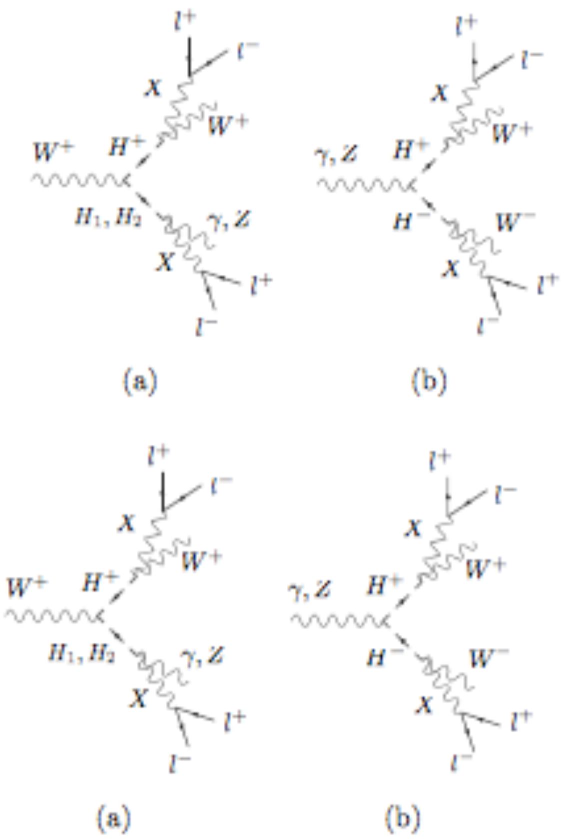


FIG. 1: Bound on abelian mixing parameter ϵ (left) and non-abelian mixing parameter ϵ_{WX} (right).



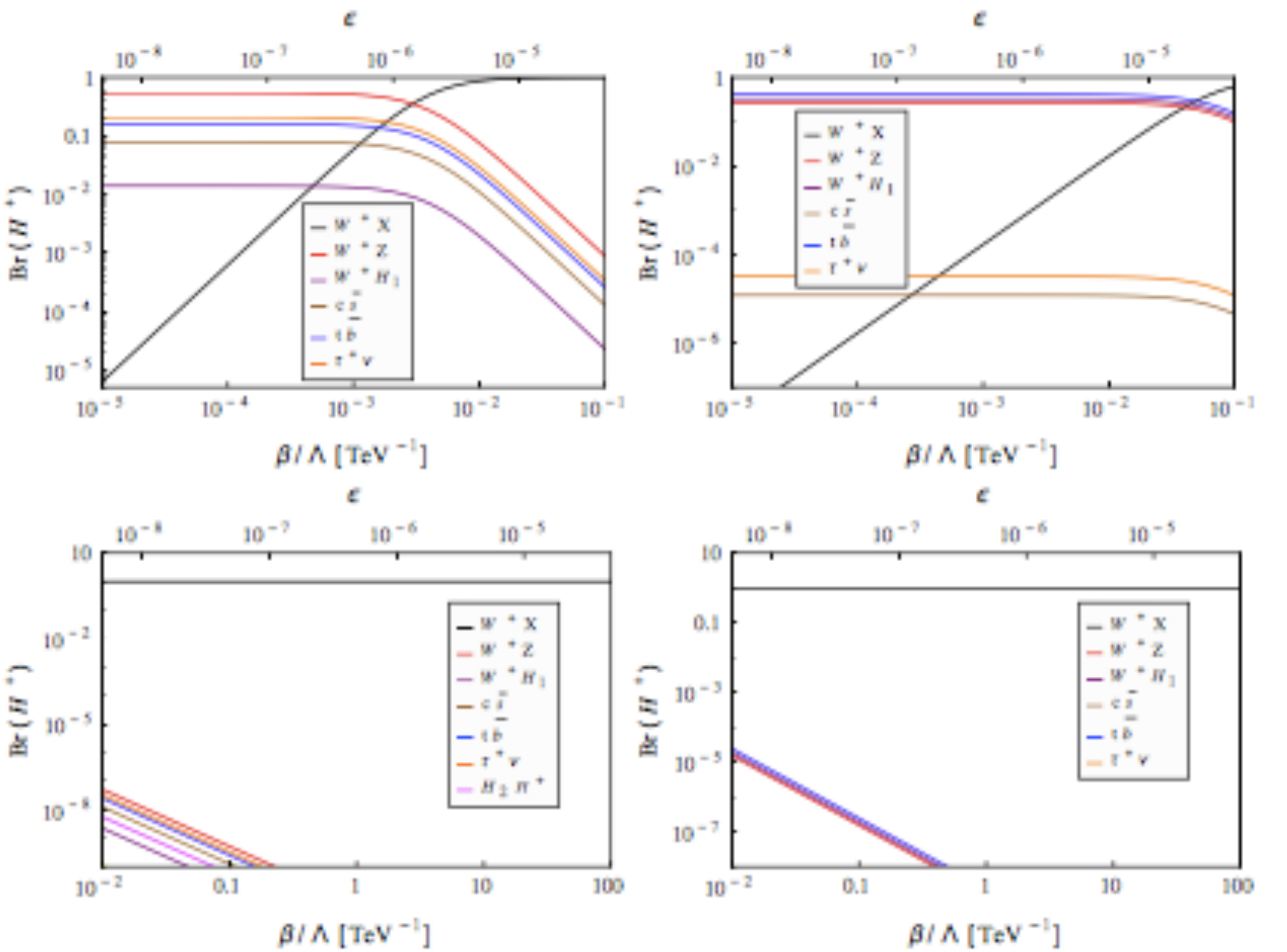


Figure 4. Branching ratios for H^+ decays as a function of β/Λ (bottom horizontal axis) and ϵ (upper horizontal axis) for $m_X = 0.4$ GeV. The top (bottom) row corresponds to $v_\Sigma = 1$ GeV ($v_\Sigma = 10^{-3}$ GeV), while the left (right) column corresponds to $m_{H^+} = 130$ GeV ($m_{H^+} = 130$ GeV). The solid black line indicates the branching ratio for $H^+ \to W^+X$. Branching ratios for other final states are as indicated by the legend insert.

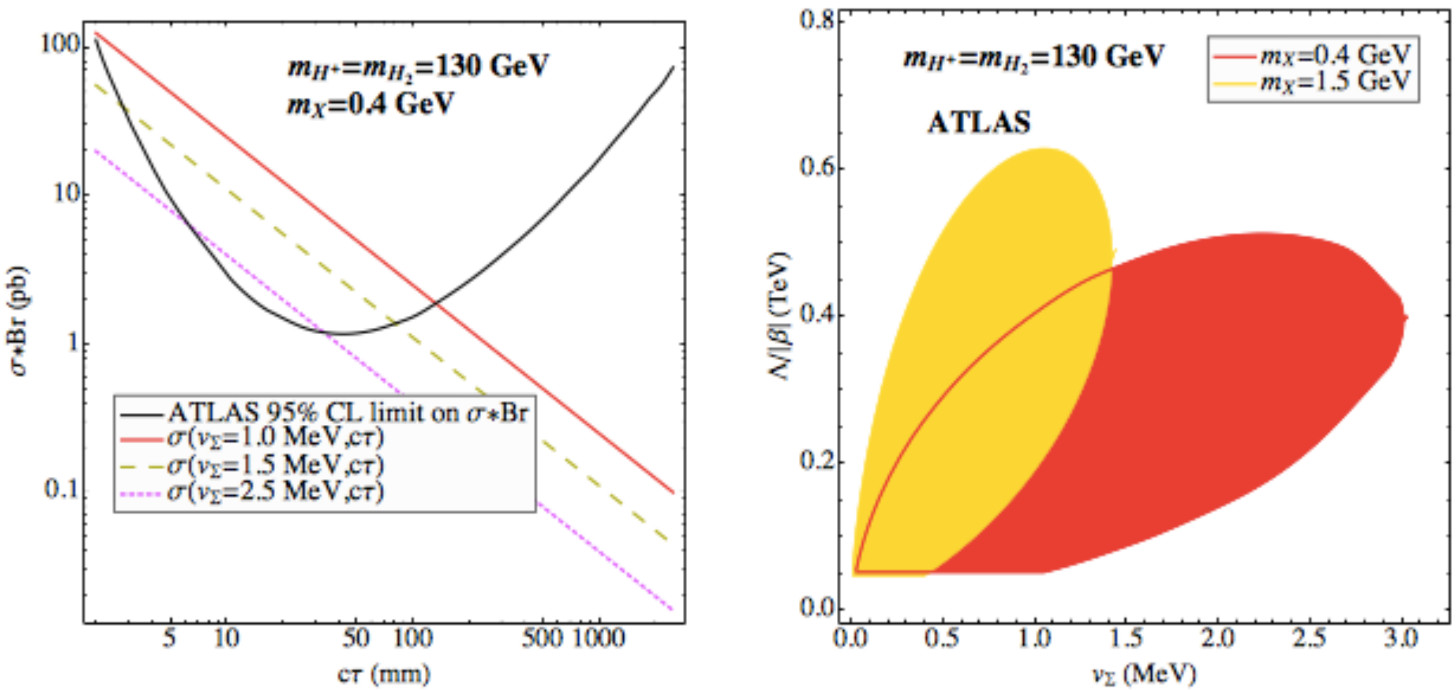


Figure 5. Constrains on triplet-assisted non-abelian kinetic mixing, recast from the ATLAS search reported Ref. [12]. The left panel gives the exclusion in the ($c\tau$, $\sigma \times$ BR) plane, where the region above the parabola is excluded. The diagonal lines indicate the dependence of $\sigma \times$ BR on $c\tau$ for different representative choices of v_Σ. The right panel gives the exclusion region in the(v_Σ, Λ/β) plane for $m_X = 0.4$ GeV (red region) and $m_X = 1.5$ GeV (yellow region).

- Kinetic mixing can also be induced for abelian and non-abelian gauge particles

- Effects can be searched at colliders

4. CP Violating Kinetic Mixing

CP violating kinetic mixing allowed?

K Fuyuto, X-G He, G. Li, M Ramsey-Musolf arXiv:1902.10340

For Abelian kinetic mixing

$Y^{\mu\nu}X_{\mu\nu}$, CP conserving

$Y^{\mu\nu}\tilde{X}_{\mu\nu}$, with $\tilde{X}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}X^{\alpha\beta}$, CP violating

But

$$Y^{\mu\nu}\tilde{X}_{\mu\nu} = -\epsilon_{\mu\nu\alpha\beta}\partial^{\alpha}(Y^{\mu\nu}X^{\beta})$$

It is a total derivative, can be dropped off. No physical effects.

For Non-Abelian kinetic mixing

$$\mathrm{Tr}(W_{\mu\nu}\Sigma)\tilde{X}^{\mu\nu}/\Lambda \qquad \Sigma = \frac{1}{2}\begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}$$

$$(x_0 + \Sigma^0)\tilde{X}^{\mu\nu}W^+_{\mu}W^-_{\nu}$$

x_0 vev of Σ_0

Allowed! There are physical effects.

A model study

$$\mathcal{L}^{(d=5)} = -\frac{\beta}{\Lambda}\mathrm{Tr}\left[W_{\mu\nu}\Sigma\right] X^{\mu\nu} - \frac{\tilde{\beta}}{\Lambda}\mathrm{Tr}\left[W_{\mu\nu}\Sigma\right] \tilde{X}^{\mu\nu}$$

$$\mathcal{L}^{(d=5)} \supset -\frac{1}{2}\left(\alpha_{ZX} Z_{\mu\nu} X^{\mu\nu} + \alpha_{AX} F_{\mu\nu} X^{\mu\nu}\right)$$

$$-\frac{\tilde{\beta}}{2\Lambda}\tilde{X}^{\mu\nu}\left[s_W F_{\mu\nu}\Sigma^0 - i g_2 (x_0 + \Sigma^0)\left(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-\right)\right]$$

$$V(H,\Sigma) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 - \frac{M_\Sigma^2}{2} F + \frac{b_4}{4} F^2 + a_1 H^\dagger \Sigma H + \frac{a_2}{2} H^\dagger H F,$$

$$\alpha_{ZX(AX)} = \beta x_0 c_W (s_W)/\Lambda$$

$F = \mathrm{Tr}(\Sigma^+\Sigma)$.

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \Sigma^0 \end{pmatrix}$$

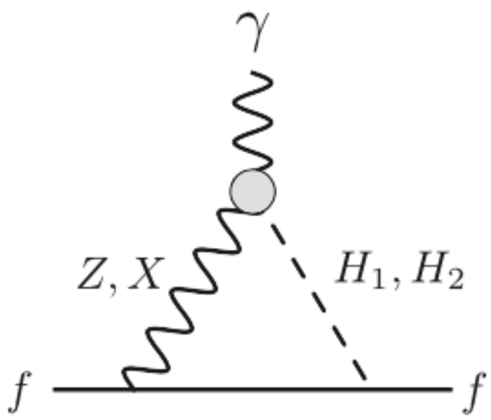
$$H = (\phi^+,\ (h + i\phi^0)/\sqrt{2})$$

a_1 breaks CP explicitly, x_0 breaks CP spontaneously

Physical effects

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

$$d_f = \frac{e}{8\pi^2} \frac{m_f}{v} c_\theta s_\theta \Big[C_Z V_Z^f f\left(r_{ZH_1},\ r_{ZH_2}\right) + C_X V_X^f f\left(r_{XH_1},\ r_{XH_2}\right) \Big]$$



$$C_Z = \frac{\tilde{\beta}}{\Lambda} s_W s_\xi, \qquad C_X = \frac{\tilde{\beta}}{\Lambda} s_W c_\xi, \qquad r_{Z(X)H} = m_{Z(X)}^2 / m_H^2,$$

$$V_Z^f = \left(c_\xi - s_\xi \alpha_{ZX}\right) \frac{g_Z^f}{c_W s_W} - Q_f \alpha_{AX} s_\xi, \qquad g_Z^f = \ I/2 - s_W^2 Q_f$$

$$V_X^f = -\left(s_\xi + c_\xi \alpha_{ZX}\right) \frac{g_Z^f}{c_W s_W} - Q_f \alpha_{AX} c_\xi, \qquad \tan 2\xi = -\frac{2 m_Z^2 \alpha_{ZX}}{m_Z^2 - m_X^2}$$

$$f(x,y) = \frac{1}{2} \log\left(\frac{m_{H_1}^2}{m_{H_2}^2}\right) - \frac{1}{2}\left(\frac{x \log x}{1-x} - \frac{y \log y}{1-y}\right)$$

$$|d_n| < 3.0 \times 10^{-26}\ e\ \text{cm},$$

$$|d_e| < 1.1 \times 10^{-29}\ e\ \text{cm (ThO [30])},$$
$$|d_e| < 1.3 \times 10^{-28}\ e\ \text{cm (HfF}^+\ \text{[31])}.$$

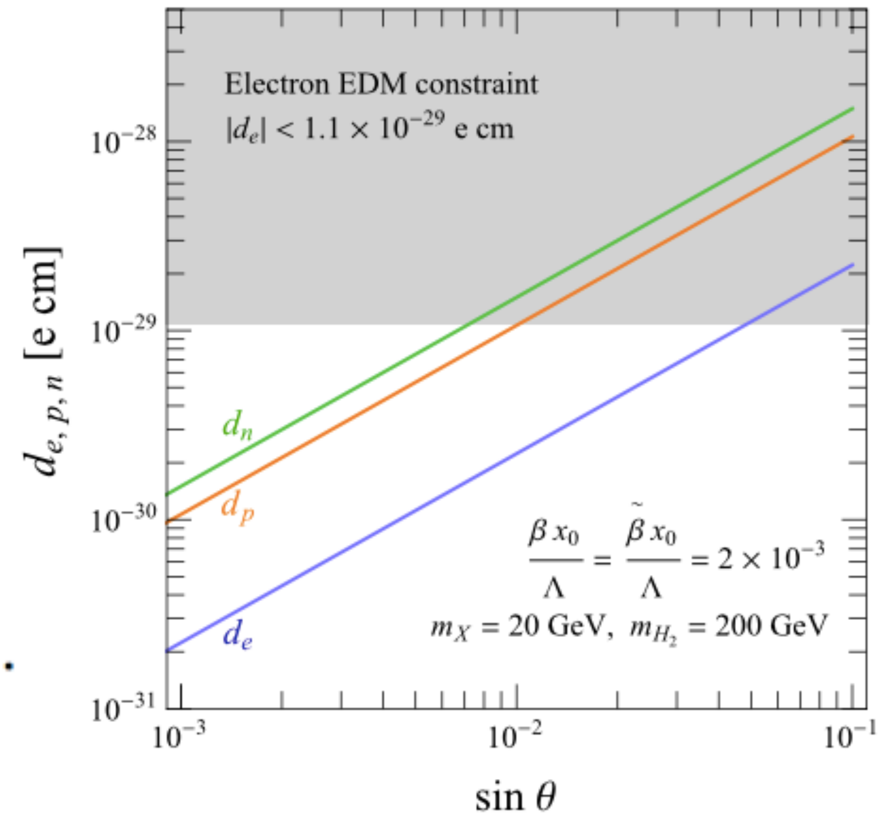
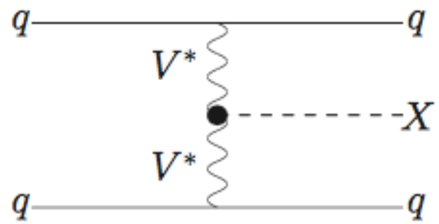


FIG. 2: The electron, proton and neutron EDMs against the mixing parameter $\sin\theta$. It is taken that $\beta x_0 \Lambda = \tilde{\beta} x_0 \Lambda = 2 \times 10^{-3}$, $m_X = 20$ GeV and $m_H = 200$ GeV.

We also tried to study collider signature:
Jet correlations probe effects of $(x_0/\Lambda)\tilde{X}^{\mu\nu}W^+_\mu W^-_\nu$

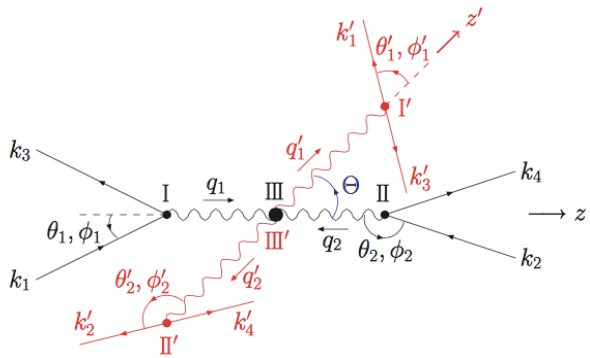


$$\mathcal{A} = \frac{\sigma(\sin\Delta\phi_{jj} > 0) - \sigma(\sin\Delta\phi_{jj} < 0)}{\sigma(\sin\Delta\phi_{jj} > 0) + \sigma(\sin\Delta\phi_{jj} < 0)}$$

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

ϕ_{j_1} and ϕ_{j_2} are the azimuthal angles of the jets in the forward and backward regions of the detector,

$$0 \leq \Delta\phi_{jj} \leq \pi \text{ and } -\pi \leq \Delta\phi_{jj} \leq 0$$



Unfortunately, although at parton level, the asymmetry can be large, but the back ground is to large, very chllenging to observe it experimentally.

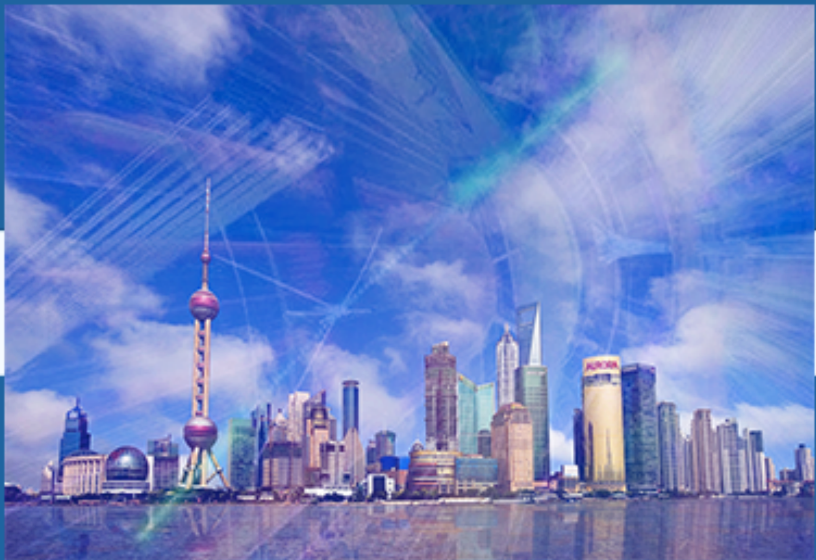
- CP violating kinetic mixing can be induced for abelian and non-abelian gauge particles.

- Effects can be searched by studying EDM of fundamental particles.

- Study of the CP violation effects are challenging at colliders.

Dark Photon can be enlightened by kinetic mixing

Yet to find any signal !



Workshop on Fractional Charge Particles, Monopoles, and Dark Photon

from 31 May 2019 to 1 June 2019
Tsung-Dao Lee Institute
Asia/Shanghai timezone

https://indico.leeinst.sjtu.edu.cn/event/54/overview