Dark Photon Search at future e^+e^- Colliders

Min He

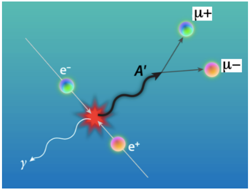
Shanghai Jiao Tong University, Shanghai, China

1701.08614(Int. J. Mod. Phys. A), 1712.09095(JHEP), 1807.11363

Collaborators: Xiao-Gang He, Cheng-Kai Huang, Gang Li and Jin-Jun Zhang

October 27, 2018

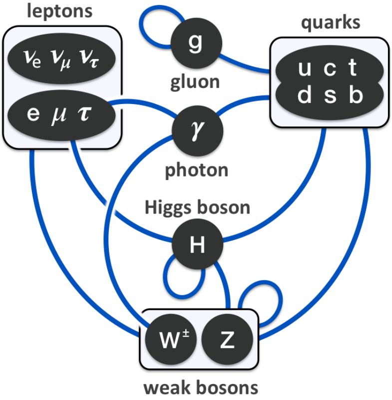
HFCPV-2018, Zhengzhou



Outline

Motivation

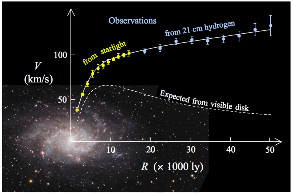
- The Standard Model has demonstrated huge successes in providing experimental predictions!



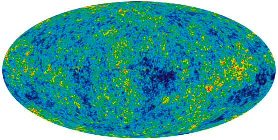
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

Motivation

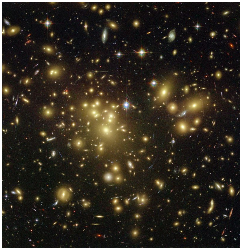
- But it leaves some phenomena unexplained. Evidences for DM.



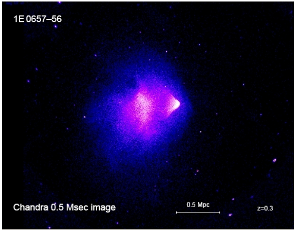
(a) Galaxy rotation curves



(b) CMB



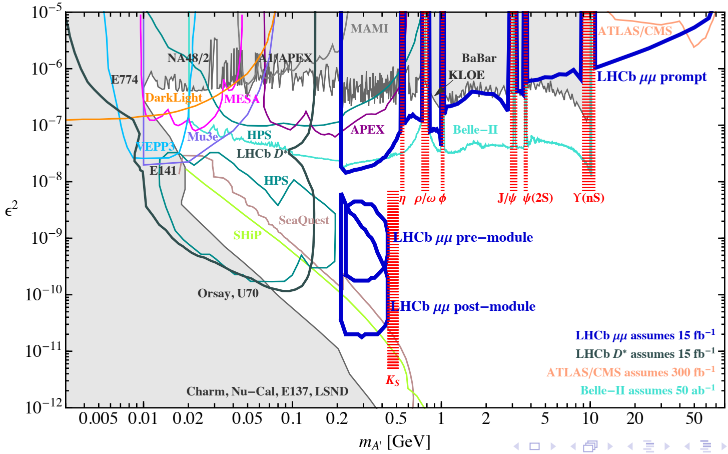
(c) Gravitational lens



(d) Bullet cluster

Motivation

- Dark matter candidates: axions, sterile neutrinos, weakly interacting massive particles(WIMPs), etc. [PDG review of dark matter].
- Search for dark photon. [Ilten, Soreq, Xue, PRL116.251803]



The dark photon model

- $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{A'}$ a new gauge group added.[Holdom, 1986]
- Lagrangian with kinetic mixing of $U(1)_Y$ and $U(1)_{A'}$

$$L_{\text{kinetic}} = -\frac{1}{4} B_0^{\mu\nu} B_{0,\mu\nu} - \frac{1}{2} \sigma F'_{0,\mu\nu} B_0^{\mu\nu} - \frac{1}{4} F'_{0,\mu\nu} F_0'^{\mu\nu} \,. \tag{1}$$

  - $B_0 = c_W A_0 - s_W Z_0$: $U(1)_Y$ gauge field
  - $B_{0,\mu\nu} = \partial_\mu B_{0,\nu} - \partial_\nu B_{0,\mu}$: $U(1)_Y$ gauge field strength tensor
  - A'_0: dark photon field
  - $F'_{0,\mu\nu} = \partial_\mu A'_{0,\nu} - \partial_\nu A'_{0,\mu}$: dark photon field strength tensor
  - σ: mixing parameter
  - $c_W = \cos\theta_W$, $s_W = \sin\theta_W$

- After $U(1)_{A'}$ symmetry breaking, A'_0 receives a mass $m_{A'}$.
- Stueckelberg mechanism.

The dark photon model

- Redefine the fields to get rid of mixing terms.

$$\begin{pmatrix} A_0 \\ Z_0 \\ A'_0 \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\frac{c_W \sigma}{\sqrt{1-\sigma^2}} \\ 0 & 1 & \frac{s_W \sigma}{\sqrt{1-\sigma^2}} \\ 0 & 0 & \frac{1}{\sqrt{1-\sigma^2}} \end{pmatrix} \begin{pmatrix} \tilde{A} \\ \tilde{Z} \\ \tilde{A}' \end{pmatrix} . \quad (2)$$

- The mass matrix for the redefined fields $\tilde{A}, \tilde{Z}, \tilde{A}'$ is in the form

$$M = \begin{pmatrix} 0 & 0 & 0 \\ 0 & m_Z^2 & \frac{\sigma s_W}{\sqrt{1-\sigma^2}} m_Z^2 \\ 0 & \frac{\sigma s_W}{\sqrt{1-\sigma^2}} m_Z^2 & \frac{1}{1-\sigma^2} m_{A'}^2 + \frac{\sigma^2 s_W^2}{1-\sigma^2} m_Z^2 \end{pmatrix} . \quad (3)$$

- We need to further diagonalize this mass matrix.

The dark photon model

- The final transformation matrix $V \equiv V_-(V_+)$ for $m_{A'} < m_Z (m_{A'} > m_Z)$ are given by

$$V_- = \begin{pmatrix} 1 & \frac{-c_W \sigma (\lambda_1 - m_Z^2)}{\mathbf{M}\sqrt{1-\sigma^2}} & \frac{-\sigma^2 s_W c_W m_Z^2}{\mathbf{M}(1-\sigma^2)} \\ 0 & \frac{s_W \sigma \lambda_1}{\mathbf{M}\sqrt{1-\sigma^2}} & \frac{1}{\mathbf{M}}\left(m_Z^2 - \lambda_1 + \frac{\sigma^2 s_W^2 m_Z^2}{1-\sigma^2}\right) \\ 0 & \frac{\lambda_1 - m_Z^2}{\mathbf{M}\sqrt{1-\sigma^2}} & \frac{\sigma s_W m_Z^2}{\mathbf{M}(1-\sigma^2)} \end{pmatrix}, \tag{4}$$

$$V_+ = V_- \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{pmatrix}, \quad \mathbf{M} = \sqrt{(\lambda_1 - m_Z^2)^2 + \frac{\sigma^2 s_W^2}{1-\sigma^2} m_Z^4}, \tag{5}$$

$$\lambda_{1,2} = \frac{1}{2}\left(m_Z^2 + \frac{1}{1-\sigma^2} m_{A'}^2 + \frac{\sigma^2 s_W^2}{1-\sigma^2} m_Z^2 \pm \Delta\right), \quad \lambda_1 \geq \lambda_2, \tag{6}$$

$$\Delta \equiv \sqrt{\left(m_Z^2 - \frac{1}{1-\sigma^2} m_{A'}^2 - \frac{\sigma^2 s_W^2}{1-\sigma^2} m_Z^2\right)^2 + \frac{4\sigma^2 s_W^2}{1-\sigma^2} m_Z^4}. \tag{7}$$

The dark photon model

- The intertaction Hamiltonian

$$L_{\text{int}} = J^{\mu}_{em}(V_{11}A_{\mu} + V_{12}Z_{\mu} + V_{13}A'_{\mu}) + J^{\mu}_{Z}(V_{22}Z_{\mu} + V_{23}A'_{\mu}) \,, \tag{8}$$

- We find that if $|m_Z - m_{A'}| \gg s_W m_Z \sigma$, we will have

$$V_{+} = V_{-} = \begin{pmatrix} 1 & 0 & -c_W\sigma \\ 0 & 1 & \dfrac{s_W\sigma m^2_{A'}}{m^2_{A'} - m^2_Z} \\ 0 & -\dfrac{s_W\sigma m^2_Z}{m^2_{A'} - m^2_Z} & 1 \end{pmatrix} + \mathcal{O}(\sigma^2), \tag{9}$$

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

$$L_{\text{int}} = J^{\mu}_{em}A_{1\mu} + J^{\mu}_{Z}Z_{1\mu} + \epsilon J^{\mu}_{em}A'_{1\mu} + \tau J^{\mu}_{Z}A'_{1\mu} \tag{10}$$

The dark photon model

- After diagonalizing the mass matrix, we get the mass for the eigenstates A, Z and A'

$$(m_A^{phys.})^2 = 0, \tag{11}$$

$$(m_Z^{phys.})^2 \approx m_Z^2 + \frac{m_Z^4 s_W^2 \sigma^2}{m_Z^2 - m_{A'}^2}, \tag{12}$$

$$(m_{A'}^{phys.})^2 \approx m_{A'}^2 + \frac{(c_W^2 m_Z^2 - m_{A'}^2) m_{A'}^2 \sigma^2}{m_Z^2 - m_{A'}^2} \tag{13}$$

- For $\sigma \sim 10^{-3} - 10^{-2}$, the relative mass shift is at most 0.3%. In later discussions, we will use m_Z and $m_{A'}$ as the physical Z boson mass and dark photon mass, respectively.

The dark photon model

- $m_{A'} < 1\text{MeV}$, $A' \to 3\gamma$, Landau-Yang theorem. The dark photon can be cosmologically stable, and can be the candidate of dark matter.

$$\Gamma_{V\to 3\gamma} = \frac{17\kappa^2\alpha^4}{2^7 3^6 5^3 \pi^3}\frac{m_V^9}{m_e^8}$$

Pospelov, Ritz, Voloshin 2008

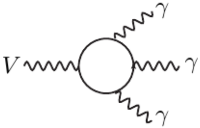
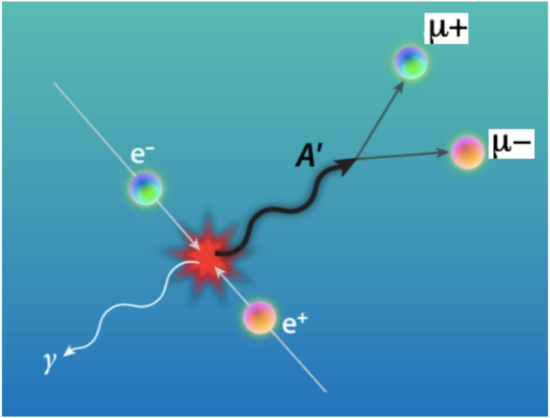


Figure: $V \sim A'$ and $\kappa \sim \sigma$

- $m_{A'} > 1\text{MeV}$, $A' \to e^+e^-$. The dark photon decays fast and can be the mediator of the dark force.

Production and decay of dark photon

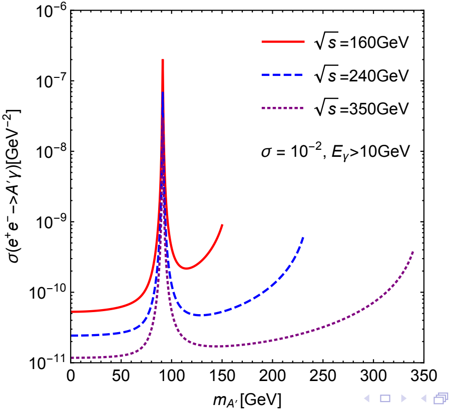
- What a circular e^+e^- collider can do for the dark photon?
- We study the prodcution and search for dark photon using porcess $e^+e^- \to \gamma A'^* \to \gamma\mu^+\mu^-$



Production and decay of dark photon

- Cross section of $e^+e^- \to A'\gamma$. Here $g_V^e = -1/2 + 2s_W^2$, $g_A^e = -1/2$.

$$\sigma_{A'\gamma} = -\frac{e^2(m_{A'}^4 + s^2)(1 - \ln\frac{s}{m_e^2})}{4\pi s^2(s - m_{A'}^2)}\left\{e^2\epsilon^2 + \frac{g^2\tau^2\left[(g_V^e)^2 + (g_A^e)^2\right]}{4c_W^2} - \frac{egg_V^e\epsilon\tau}{c_W}\right\},$$



Production and decay of dark photon

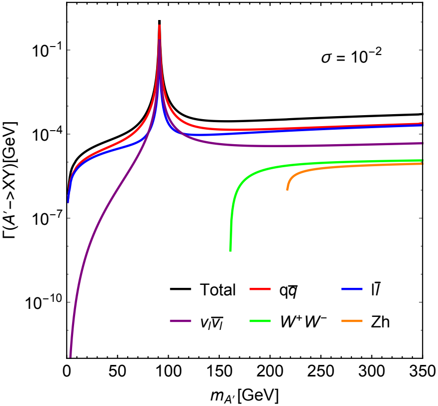
Assuming that the dark photon A' decays exclusively to the SM particles, the partial widths of A' are

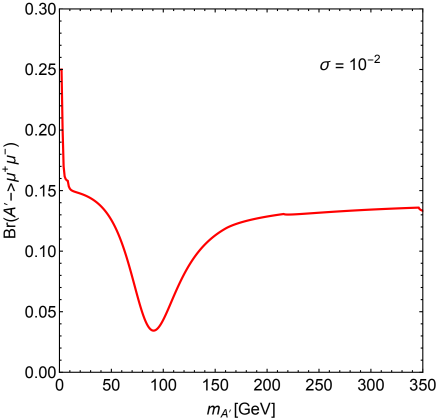
$$
\begin{aligned}
\Gamma(A' \to \bar{f}f) =& \frac{g^2 m_{A'}}{12\pi c_W^2} N_c^f \{\epsilon^2 Q_f^2 c_W^2 s_W^2 + \epsilon\tau Q_f c_W s_W g_V^f \\
&+ \frac{1}{4}\tau^2[(g_V^f)^2 + (g_A^f)^2]\}, \\
\Gamma(A' \to Zh) =& \frac{g^2\tau^2 m_{A'}}{192\pi c_W^2} \lambda^{1/2}(1, x_Z, x_h)\{\lambda(1, x_Z, x_h) + 12x_Z\}, \\
\Gamma(A' \to W^+W^-) =& \frac{g^2 s_W^2(\epsilon + \tau\cot\theta_W)^2 m_{A'}}{192\pi} x_W^{-2}(1 - 4x_W)^{3/2} \\
&\times (1 + 20x_W + 12x_W^2),
\end{aligned}
\tag{14}
$$

where $N_c^f = 3$ for quarks and 1 for leptons, $x_{W,Z,h} = (m_{W,Z,h}/m_{A'})^2$ and $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$.

Production and decay of dark photon

- Total and partial widths of A' (left) and the braching ratio of $A' \to \mu^+\mu^-$ (right) with $\sigma = 10^{-2}$.





Sensitivities at future e^+e^- colliders

- The projected/updated integrated luminosities at the CEPC, FCC-ee and ILC.

Integrated luminosity (ab^{-1})	CEPC	FCC-ee	ILC
$\sqrt{s} = 160$ GeV	-	10	0.5
$\sqrt{s} = 240 \sim 250$ GeV	5	5	1.5
$\sqrt{s} = 350$ GeV	-	1.5	0.2

For event generation, we use `MG5_aMC_v2_4_3`. The following *basic cuts* are imposed at the parton-level:

$$|\eta_{\mu^\pm,\gamma}| < 3, \quad E_\gamma > 2 \text{ GeV}, \quad \Delta R_{ij} > 0.2, \quad \Delta m_{\mu^+\mu^-} < 10 \text{ GeV}, \quad (15)$$

where $\Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$ with $i, j = \mu^\pm, \gamma$ and $\Delta m_{\mu^+\mu^-} \equiv |m_{\mu^+\mu^-} - m_{A'}|$.

- `Pythia6`: parton shower and hadronization
- `Delphes-3.4.1`: detector effects

Sensitivities at future e^+e^- colliders

The detector parametrization for muon momentum resolution and electromagnetic calorimeter (ECAL) energy resolution are

- $\frac{\Delta p_T}{p_T} = 0.1\% \oplus \frac{p_T}{10^5\ \text{GeV}}$ for $|\eta| < 1.0$ and 10 times larger for $1.0 < |\eta| < 3.0$;
- $\frac{\Delta E}{E} = \frac{0.20}{\sqrt{E/\text{GeV}}} \oplus 0.5\%$. for $|\eta| < 3.0$.

for the CEPC and

- $\frac{\Delta p_T}{p_T} = 0.1\% \oplus \frac{p_T}{10^5\ \text{GeV}}$ for $|\eta| < 1.0$ and 10 times larger for $1.0 < |\eta| < 2.4$;
- $\frac{\Delta E}{E} = \frac{0.15}{\sqrt{E/\text{GeV}}} \oplus 1\%$. for $|\eta| < 3.0$.

for the FCC-ee.

Sensitivities at future e^+e^- colliders

In order to identify objects in the final state, we impose the following *pre-selection criteria*:

- A pair of opposite-sign muons are selected with $E_{\mu^\pm} > 2$ GeV, $|\eta_{\mu^\pm}| < 2.5$ for the CEPC with a better muon identification than the ILD-like detector performance: $p_{T\mu^\pm} > 10$ GeV, $|\eta_{\mu^\pm}| < 2.5$, which is used for the simulation at the FCC-ee;
- Exactly one photon with $p_T^\gamma \geq 10$ GeV and $|\eta_\gamma| < 2.5$ is selected;
- $\Delta R_{ij} > 0.4$ for $i, j = \mu^\pm, \gamma$.

Sensitivities at future e^+e^- colliders

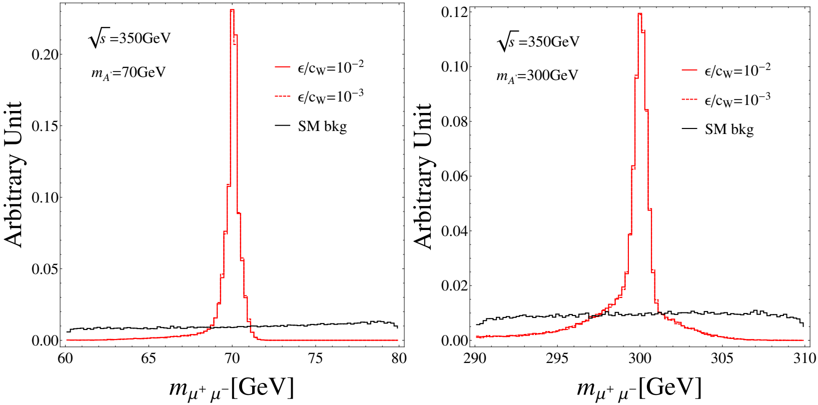


Figure: The normalized $m_{\mu^+\mu^-}$ distributions for $m_{A'} = 70$ GeV, 300 GeV with $\epsilon/c_W = 10^{-2}$ and $\epsilon/c_W = 10^{-3}$ at $\sqrt{s} = 350$ GeV. The distributions are not sensitive to the total width and thus ϵ for $\epsilon/c_W \sim 10^{-3} - 10^{-2}$.

Sensitivities at future e^+e^- colliders

Based on the kinematical distributions, we further impose the *selection cuts*:

$$\Delta m_{\mu^+\mu^-} < 0.5 \sim 1.5 \text{ GeV}, \quad E_T^{\text{miss}} < 5 \text{ GeV}, \tag{16}$$

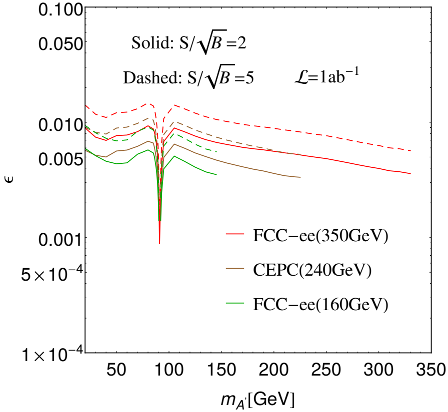
where the $\Delta m_{\mu^+\mu^-}$ cut is explicitly shown in the table below. The missing transverse momentum (E_T^{miss}) cut is used to remove the SM backgrounds $\tau^+\tau^-\gamma$ and $W^+W^-\gamma$, which have larger E_T^{miss}.

$m_{A'}$	FCC-ee (160 GeV)	CEPC (240 GeV)	FCC-ee (350 GeV)
$[20, 40]$	0.5	0.5	0.5
$[50, 60]$	0.5	1.0	1.0
$[70, 94]$	1.0	1.0	1.0
≥ 95	1.5	1.5	1.5

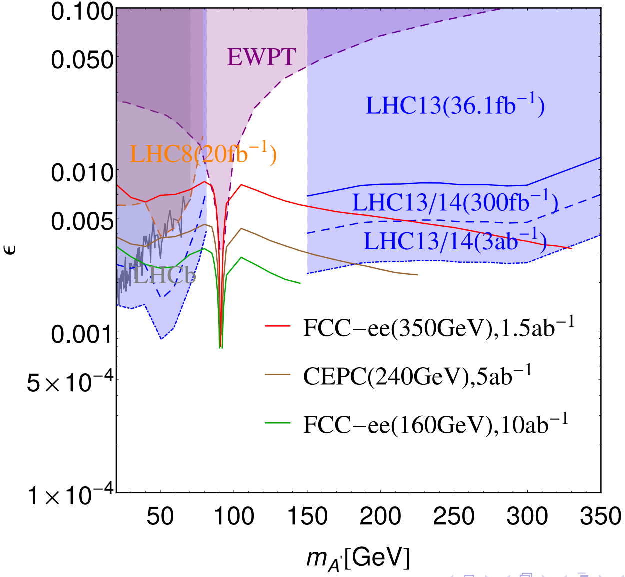
Sensitivities at future e^+e^- colliders

The signal significance is evaluated using

$$\frac{S}{\sqrt{B}} = (\frac{S}{\sqrt{B}})_0 \frac{\epsilon^2}{10^{-4}} \sqrt{\frac{\mathcal{L}}{1\ \mathrm{ab}^{-1}}}, \tag{17}$$



Sensitivities at future e^+e^- colliders



massless dark photon

The Lagrangian which discribles the photon, Z boson and massless dark photon fields kinetic energy and their interaction with corresponding currents is in the form of

$$\mathcal{L}_0 = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{2}\sigma c_W X_{\mu\nu}A^{\mu\nu} + \frac{1}{2}\sigma s_W X_{\mu\nu}Z^{\mu\nu} + j^{\mu}_{em}A_{\mu} + j^{\mu}_{Z}Z_{\mu} + j^{\mu}_{X}X_{\mu} + \frac{1}{2}m_Z^2 Z_{\mu}Z^{\mu}. \quad (18)$$

massless dark photon

There are two ways which have been used to remove the kinetic mixing term.

- Case a): Holdom, 1986. Dobrescu, 2005.
- Case b): Foot, He, 1991. Babu, Kolda, March-Russell, 1998.

$$Case\ \ a): \quad \begin{pmatrix} A \\ Z \\ X \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{1-\sigma^2 c_W^2}} & \frac{-\sigma^2 s_W c_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}} & 0 \\ 0 & \frac{\sqrt{1-\sigma^2 c_W^2}}{\sqrt{1-\sigma^2}} & 0 \\ \frac{-\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}} & \frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}} & 1 \end{pmatrix} \begin{pmatrix} \tilde{A} \\ \tilde{Z} \\ \tilde{X} \end{pmatrix}, \tag{19}$$

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

The corresponding Lagrangians are

$$\mathcal{L}_a = -\frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{1}{4}\tilde{A}_{\mu\nu}\tilde{A}^{\mu\nu} - \frac{1}{4}\tilde{Z}_{\mu\nu}\tilde{Z}^{\mu\nu} + \frac{1}{2}m_Z^2\frac{1-\sigma^2 c_W^2}{1-\sigma^2}\tilde{Z}_\mu\tilde{Z}^\mu$$
$$+ j_{em}^\mu\left(\frac{1}{\sqrt{1-\sigma^2 c_W^2}}\tilde{A}_\mu - \frac{\sigma^2 s_W c_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}\tilde{Z}_\mu\right) + j_Z^\mu\left(\frac{\sqrt{1-\sigma^2 c_W^2}}{\sqrt{1-\sigma^2}}\tilde{Z}_\mu\right)$$
$$+ j_X^\mu\left(\frac{-\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}}\tilde{A}_\mu + \frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}\tilde{Z}_\mu + \tilde{X}_\mu\right), \quad (20)$$

massless dark photon

$$\mathcal{L}_b = -\frac{1}{4}\tilde{X}'_{\mu\nu}\tilde{X}'^{\mu\nu} - \frac{1}{4}\tilde{A}'_{\mu\nu}\tilde{A}'^{\mu\nu} - \frac{1}{4}\tilde{Z}'_{\mu\nu}\tilde{Z}'^{\mu\nu} + \frac{1}{2}m_Z^2\frac{1-\sigma^2 c_W^2}{1-\sigma^2}\tilde{Z}'_\mu\tilde{Z}'^\mu$$
$$+ j^\mu_{em}(\tilde{A}'_\mu - \frac{\sigma^2 s_W c_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}\tilde{Z}'_\mu - \frac{\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}}\tilde{X}'_\mu)$$
$$+ j^\mu_Z(\frac{\sqrt{1-\sigma^2 c_W^2}}{\sqrt{1-\sigma^2}}\tilde{Z}'_\mu) + j^\mu_X(\frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}}\tilde{Z}'_\mu + \frac{1}{\sqrt{1-\sigma^2 c_W^2}}\tilde{X}'_\mu)\ . \quad (21)$$

Actually above two bases are related by

$$\begin{pmatrix} \tilde{A}' \\ \tilde{X}' \end{pmatrix} = \begin{pmatrix} \sqrt{1-\sigma^2 c_W^2} & \sigma c_W \\ -\sigma c_W & \sqrt{1-\sigma^2 c_W^2} \end{pmatrix} \begin{pmatrix} \tilde{A} \\ \tilde{X} \end{pmatrix} . \qquad (22)$$

In gerneral we could have a rotation

$$\begin{pmatrix} \tilde{A}' \\ \tilde{X}' \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \bar{A}' \\ \bar{X}' \end{pmatrix} , \quad \tilde{Z}' = \bar{Z}' . \qquad (23)$$

massless dark photon

The Lagrangian in the most general form can be written as

$$
\begin{aligned}
\mathcal{L}_{\bar{b}} = & \\
& -\frac{1}{4}\bar{X}'_{\mu\nu}\bar{X}'^{\mu\nu} - \frac{1}{4}\bar{A}'_{\mu\nu}\bar{A}'^{\mu\nu} - \frac{1}{4}\bar{Z}'_{\mu\nu}\bar{Z}'^{\mu\nu} + \frac{1}{2}m_Z^2\frac{1-\sigma^2 c_W^2}{1-\sigma^2}\bar{Z}'_\mu\bar{Z}'^\mu \\
& + \left((c_\beta + \frac{\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}} s_\beta) j^\mu_{em} - s_\beta \frac{1}{\sqrt{1-\sigma^2 c_W^2}} j^\mu_X \right) \bar{A}'_\mu \\
& + \left(\frac{\sqrt{1-\sigma^2 c_W^2}}{\sqrt{1-\sigma^2}} j^\mu_Z - \frac{\sigma^2 s_W c_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}} j^\mu_{em} + \frac{\sigma s_W}{\sqrt{1-\sigma^2}\sqrt{1-\sigma^2 c_W^2}} j^\mu_X \right) \bar{Z}'_\mu \\
& + \left(\frac{1}{\sqrt{1-\sigma^2 c_W^2}} c_\beta j^\mu_X + (s_\beta - \frac{\sigma c_W}{\sqrt{1-\sigma^2 c_W^2}} c_\beta) j^\mu_{em} \right) \bar{X}'_\mu \ . \qquad (24)
\end{aligned}
$$

Redefine some parameters.

$$
\begin{aligned}
\overline{m}_Z^2 &= m_Z^2(1+z), \\
z &= \sigma^2 s_W^2/(1-\sigma^2), \\
\bar{c}_W^2 &= \cos^2\bar{\theta}_W = c_W^2/(1+z), \\
c_W^2 &= m_W^2/m_Z^2, \\
\bar{e} &= \sqrt{4\pi\alpha} = e(c_\beta + \sigma c_W s_\beta/\sqrt{1-\sigma^2 c_W^2}), \\
\bar{j}_{em}^\mu &= \bar{e} Q_f \bar{f}\gamma^\mu f, \\
\bar{j}_Z^\mu &= (\sqrt{2} G_F \bar{m}_Z^2)^{\frac{1}{2}} \bar{f}\gamma^\mu(\bar{g}_V^f - \bar{g}_A^f\gamma^5) f, \\
\bar{g}_A^f &= \sqrt{\rho_f} I_f^3, \\
\bar{g}_V^f &= \sqrt{\rho_f}(I_f^3 - 2Q_f\bar{s}_f^2), \\
\sqrt{\rho_f} &= \frac{\sqrt{1-\sigma^2\bar{s}_W^2}}{\sqrt{1-\sigma^2}c_\beta + \sigma\bar{c}_W s_\beta}.
\end{aligned} \tag{25}
$$

Then the interaction Lagrangian (without dark current) can be written as

$$L_{int} = \bar{j}^{\mu}_{em}\bar{A}'_{\mu} + \bar{j}^{\mu}_{Z}\bar{Z}'_{\mu} + R\bar{j}^{\mu}_{em}\bar{X}'_{\mu},$$
$$R = \left(\frac{s_\beta\sqrt{1-\sigma^2} - \sigma\bar{c}_W c_\beta}{c_\beta\sqrt{1-\sigma^2} + \sigma\bar{c}_W s_\beta}\right)^2 . \quad (26)$$

Then the ρ_0 parameter, dark phton contribution to $g-2$ and the $h \to \gamma\bar{X}'$ decay to $h \to \gamma\gamma$ decay ratio can be written as ($\tan\delta = \sigma\bar{c}_W/\sqrt{1-\sigma^2}$)

$$\rho_0 = \frac{1}{(1+z)^2\rho_f} = (1-\sigma^2\bar{s}_W^2)^2\cos^2(\delta-\beta)$$
$$a_{\mu,e}^{\text{dark photon}} = R\frac{\alpha}{2\pi},$$
$$\mathcal{R}_{\gamma\bar{X}'} = \frac{\text{Br}(h\to\gamma\bar{X}')}{\text{Br}(h\to\gamma\gamma)} = 2R. \quad (27)$$

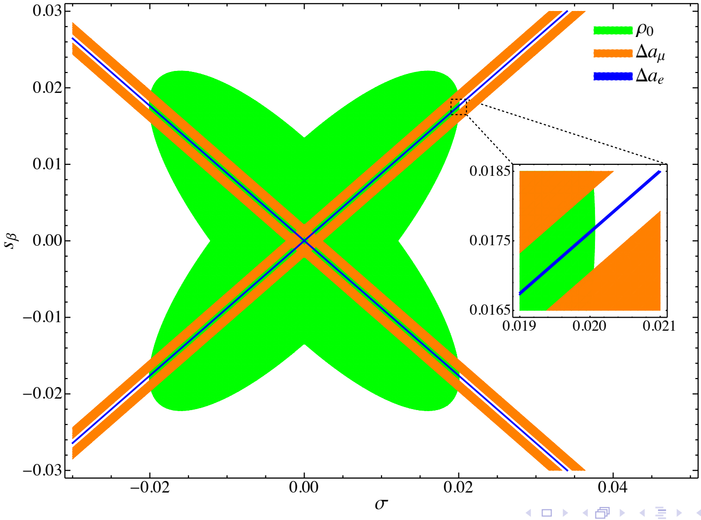
Using below experimental results, we get constraints on next page.

$$\begin{aligned}\Delta a_\mu &= a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 268(63)(43) \times 10^{-11},\\ \Delta a_e &= a_e^{\text{exp}} - a_e^{\text{SM}} = -87(36) \times 10^{-14},\\ \rho_0 &= 1.00039 \pm 0.00019.\end{aligned} \tag{28}$$

We have $\mathcal{R}_{\gamma\bar{X}'} \leq 3.62 \times 10^{-10}$ in order to satisfy data on electron $g-2$.
For a special case: $R = 0$, we have

$$\sigma^2 = \frac{1-\sqrt{\rho_0}}{\bar{s}_W^2}\,, \quad c_\beta^2 = \frac{\sqrt{\rho_0} - \bar{c}_W^2}{\bar{s}_W^2\sqrt{\rho_0}}\,. \tag{29}$$

massless dark photon



Summary

- we study dark photon search using $e^+e^- \to \gamma A' \to \gamma\mu^+\mu^-$ for a dark photon mass $m_{A'}$ as large as kinematically allowed at future e^+e^- colliders.
- We perform a detailed detector simulation with selection cuts based on a realistic muon momentum resolution.
- We show that stringent constraints on the parameter ϵ for a wide range of dark photon mass can be obtained at planed e^+ e^- colliders, such as CEPC, ILC and FCC-ee.
- For a massless dark photon, we need a new parameter β to define the physical photon and dark photon. This parameter together with kinetic mixing parameter σ could explan both the tightly constrained $g-2$ and the relative loosely constrained ρ_0 parameter.

Backup

- $\sigma_{NLO}/\sigma_{\gamma(\gamma,Z)} = 5 \times 10^{-5}$

Table: ratio of interference term to dark photon contribution at $\epsilon = 10^{-2}$

$m_{A'}$(GeV) \ $\frac{\sigma_{int}}{\sigma_{\gamma A'}}(10^{-5})$ \ $\sqrt{s}$(GeV)	160	240	350
1	3.1	3.1	3.1
30	6.0	5.4	5.2
60	12	9.3	8.1

Sensitivities for CEPC and FCC-ee circular colliders