Search for a heavy dark photon at future e^+e^- colliders

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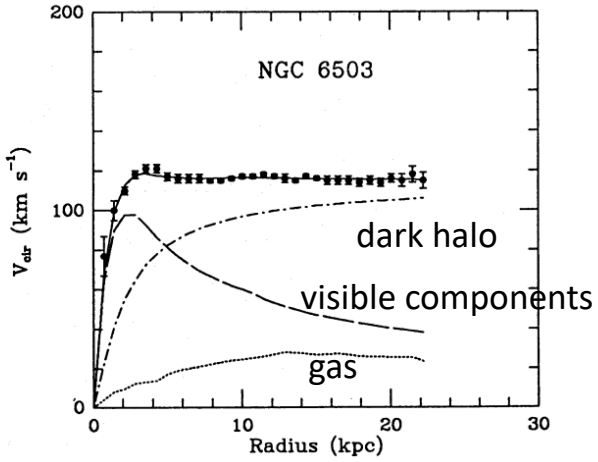
JHEP 1803 (2018) 139 (arXiv:1712.09095)

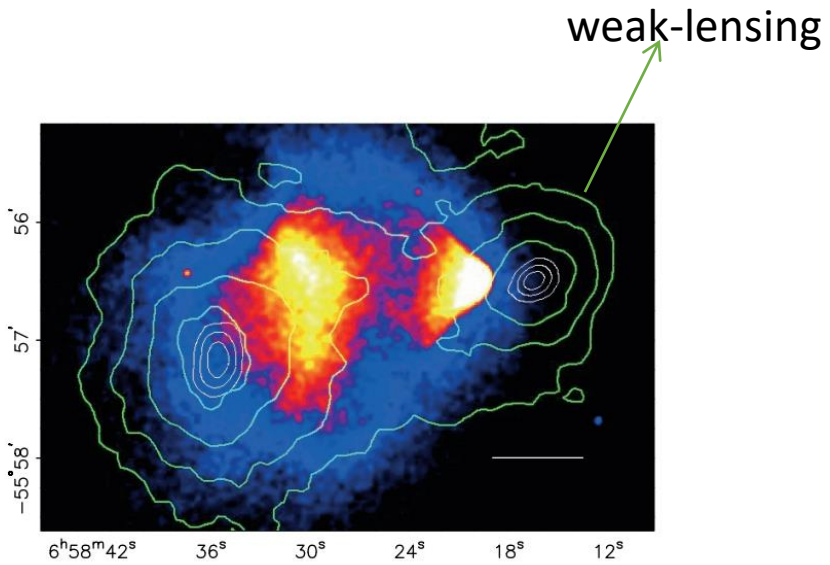
ICHEP 2018, July 7, 2018

Why we need dark photon?

- Evidences of dark matter:
  - spiral galaxy rotation curves
  - merging clusters and galaxies
  - cosmic microwave background



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

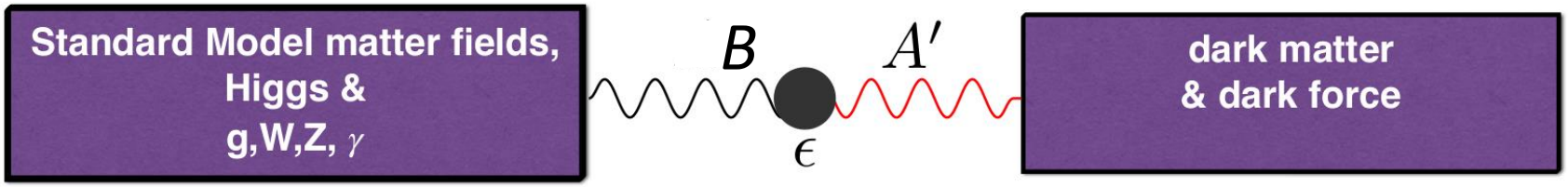


D. Clowe, et al, Astrophys. J. 648 (2006) L109

- But there is no dark matter candidate in the SM
- Dark matter may not interact with the SM directly, but through some mediator

Why we need dark photon?

- Dark photon provides such connection between the SM and the dark sector

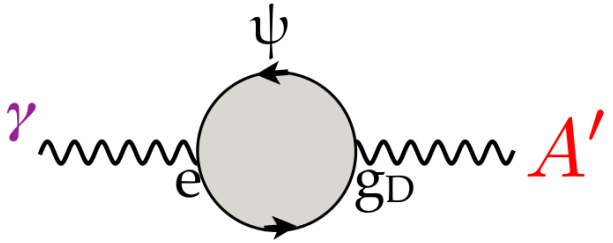


through a kinetic mixing between $U(1)_{A'}$ field with $U(1)_Y$ field

W. Xue, 2016

– Simplest case: one heavy particle ψ with both EM charge & dark charge

B. Holdom, Phys. Lett. 166B, 196 (1986)



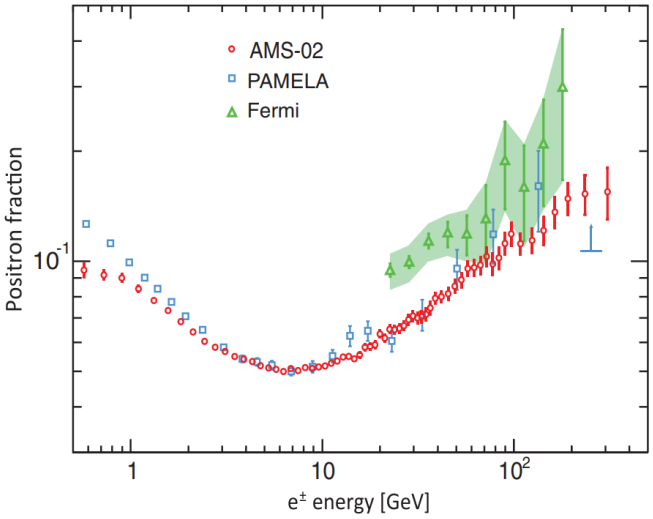
generates $\epsilon \sim \frac{e\, g_D}{16\pi^2} \log \frac{m_\psi}{M_*} \sim 10^{-2} - 10^{-4}$

N. Toro, Dark Sectors 2016

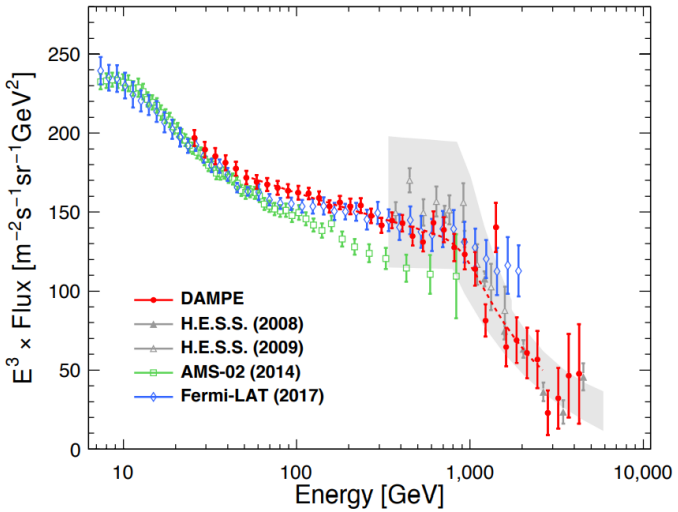
Why we need dark photon?

- Dark photon provides such connection between the SM and the dark sector through a kinetic mixing between $U(1)_{A'}$ field with $U(1)_Y$ field
  - excess in positron fraction
  - peak-like spectrum of cosmic-ray electrons and positrons

P.-H. Gu, X.-G. He, Phys.Lett. B778 (2018) 292



AMS, Phys.Rev.Lett. 110 (2013) 141102

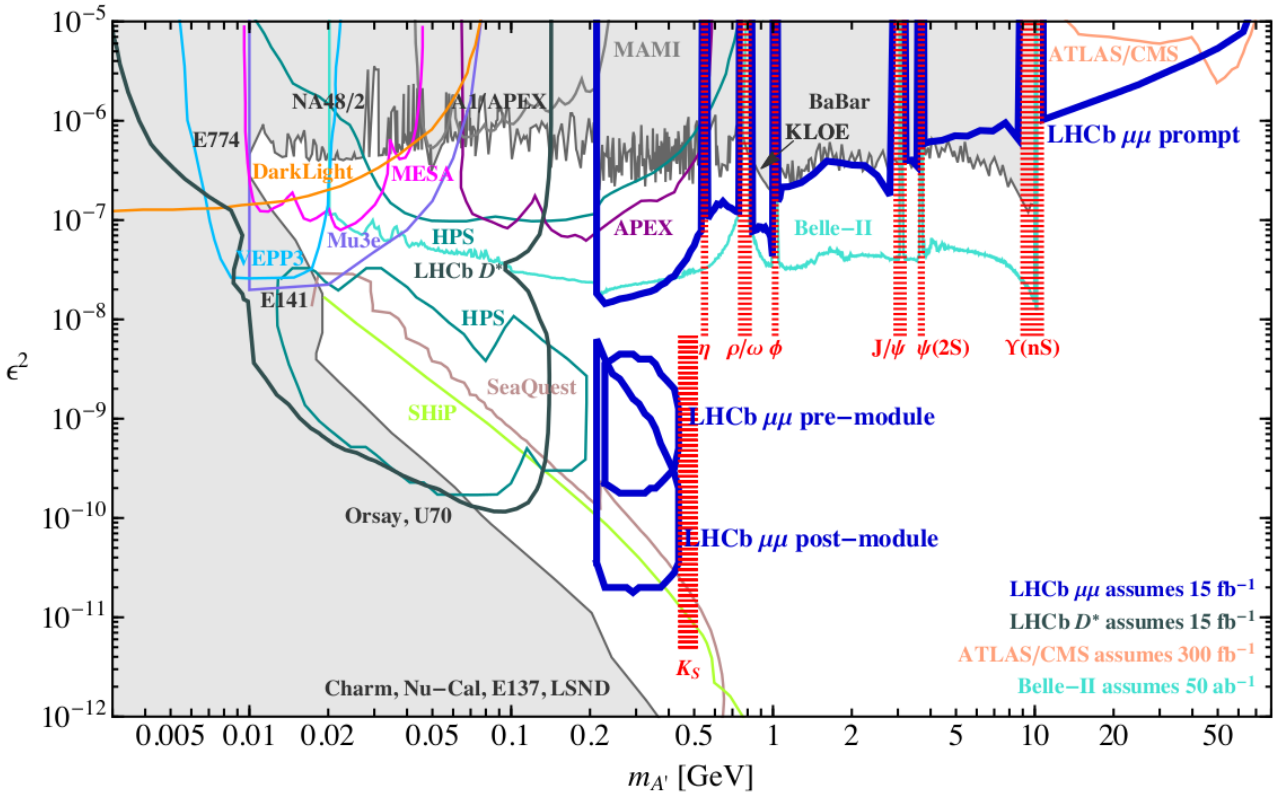


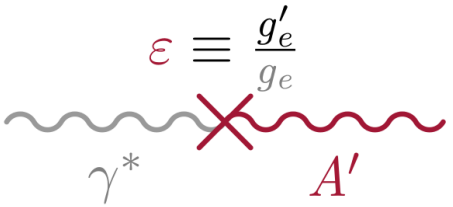
DAMPE, Nature 552 (2017) 63-66

~1.4 TeV

Light dark photon searches

- Many efforts have been made to constrain the mixing parameter for a dark photon mass below m_Z
- Beam damp expeiments, fixed target experiments, low energy e^+e^- colliders, rare meson decays...





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

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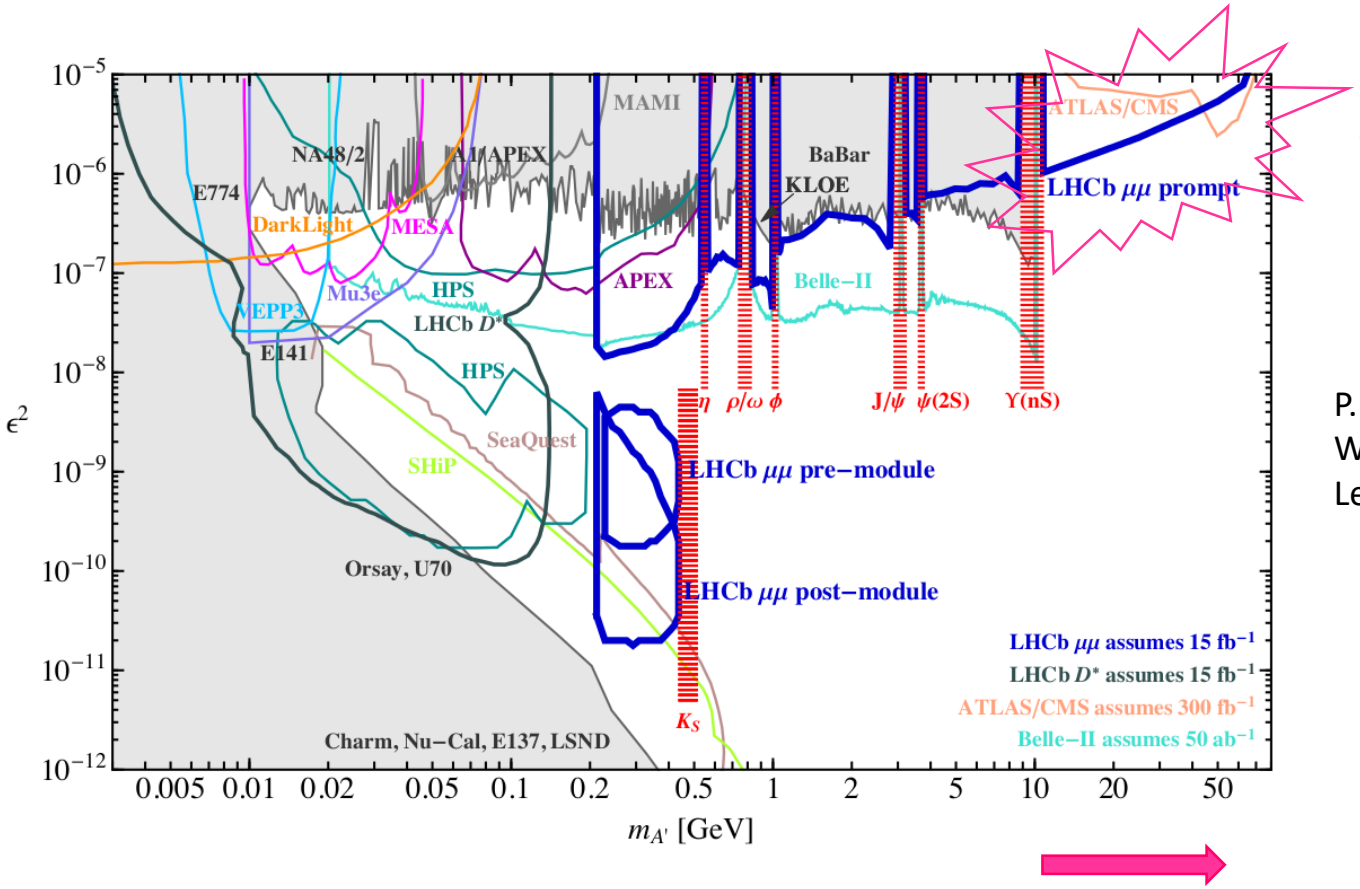
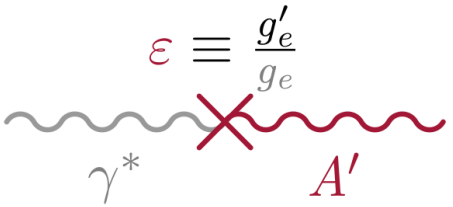


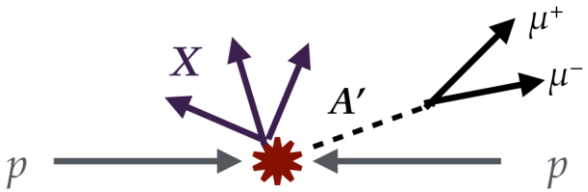


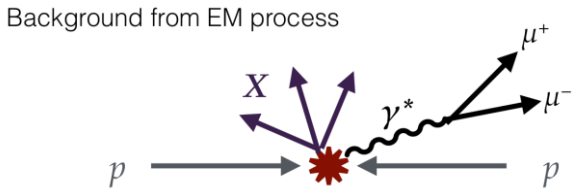
P. Ilten, Y. Soreq, J. Thaler, M. Williams and W. Xue, Phys. Rev. Lett. 116, no. 25, 251803 (2016)

Light dark photon searches

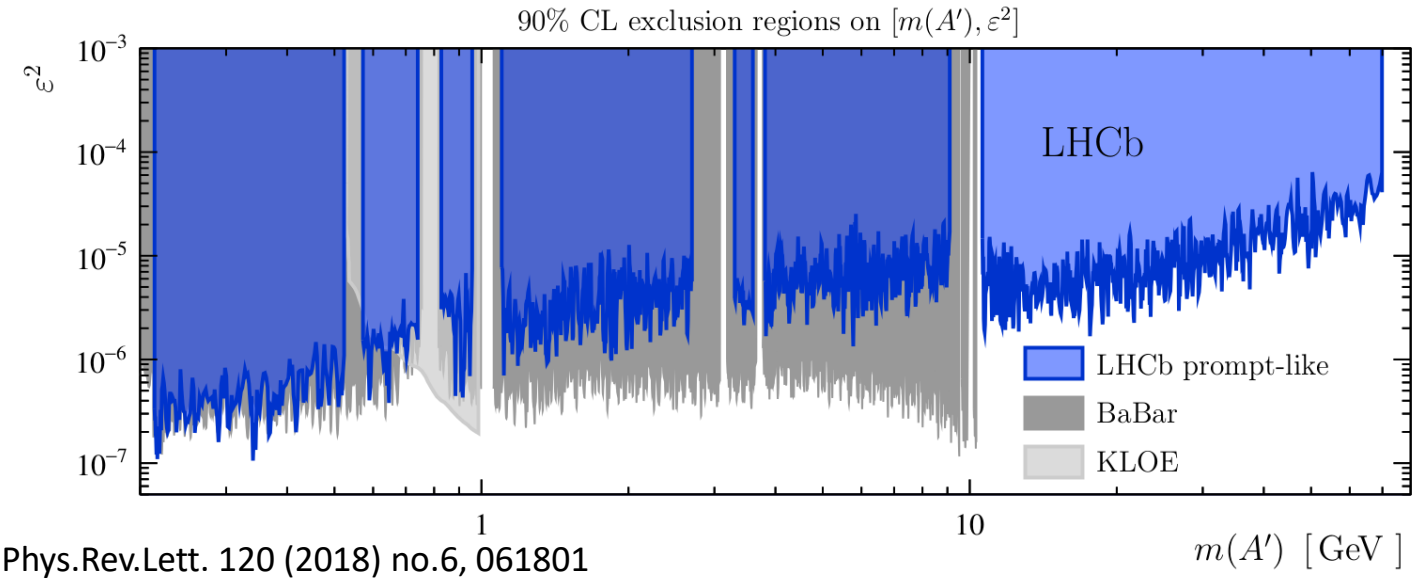
Prompt $\mu^+\mu^-$ @ LHCb

W. Xue, 2016





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



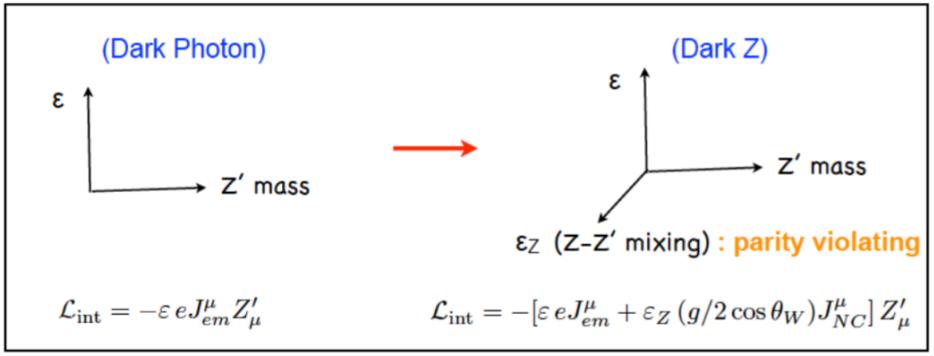
Phys.Rev.Lett. 120 (2018) no.6, 061801

Dark photon searches: from light to heavy

- There is no special reason why dark photon mass should be small
- Introducing a singlet S with a non-trival $U(1)_{A'}$ quantun number $s_{A'}$

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

- Mixing of $U(1)_{A'}$ and $U(1)_Y$ can induce mixing between
  - photon and dark photon
  - Z boson and dark photon



H.-S. Lee, 1410.8435

Figure 2. Dark Photon vs. Dark Z. The dark Z is a dark photon with more general couplings.

Formalism

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

renormalizable

In the canonical form $A'_0 = \frac{1}{\sqrt{1-\sigma^2}}\tilde{A}', \quad B_0 = \tilde{B} - \frac{\sigma}{\sqrt{1-\sigma^2}}\tilde{A}'$

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

Interactions with the SM currents

$$J^\mu_{em}(\tilde{A}_\mu - \frac{c_W\sigma}{\sqrt{1-\sigma^2}}\tilde{A}'_\mu) + J^\mu_Z(\tilde{Z}_\mu + \frac{s_W\sigma}{\sqrt{1-\sigma^2}}\tilde{A}'_\mu) + \frac{1}{\sqrt{1-\sigma^2}}J^\mu_D\tilde{A}'_\mu$$

In the $\tilde{Z}$ and $\tilde{A}'$ basis, the mass matrix

$$\begin{pmatrix} m_Z^2 & \frac{\sigma s_W}{\sqrt{1-\sigma^2}}m_Z^2 \\ \frac{\sigma s_W}{\sqrt{1-\sigma^2}}m_Z^2 & \frac{1}{1-\sigma^2}m_{A'}^2 + \frac{s_W^2\sigma^2}{1-\sigma^2}m_Z^2 \end{pmatrix}$$

Formalism

Diagonalizing it by an unitary transformation U

$$\begin{pmatrix} \tilde{A} \\ \tilde{Z} \\ \tilde{A}' \end{pmatrix} = U \begin{pmatrix} A \\ Z \\ A' \end{pmatrix}, \quad \begin{pmatrix} A_0 \\ Z_0 \\ A_0' \end{pmatrix} = SU \begin{pmatrix} A \\ Z \\ A' \end{pmatrix}, \quad V \equiv SU$$

$V = V_-(V_+)$ for $m_{A'} < m_Z (m_{A'} > m_Z)$ are given by

$$\mathbf{M} = \sqrt{(\lambda_1 - m_Z^2)^2 + \frac{\sigma^2 s_W^2}{1-\sigma^2} m_Z^4}$$

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

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

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

$$m_{A'}^{\text{phys.}} = \begin{cases} \lambda_2, & \text{for } m_{A'} < m_Z, \\ \lambda_1, & \text{for } m_{A'} > m_Z. \end{cases}$$

Formalism

$$J^{\mu}_{em}(V_{11}A_{\mu} + V_{12}Z_{\mu} + \epsilon A'_{\mu}) + J^{\mu}_{Z}(V_{22}Z_{\mu} + \tau A'_{\mu})$$

if $|m_Z - m_{A'}| \gg s_W m_Z \sigma$,

$$\Delta = |m_Z^2 - m_{A'}^2| + \frac{(m_{A'}^4 + s_W^2 m_Z^4 - c_W^2 m_Z^2 m_{A'}^2)\sigma^2}{|m_Z^2 - m_{A'}^2|} + \mathcal{O}(\sigma^3)$$

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

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

τ is very small if $m_{A'} \ll m_Z$

Z boson and dark photon physical mass

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

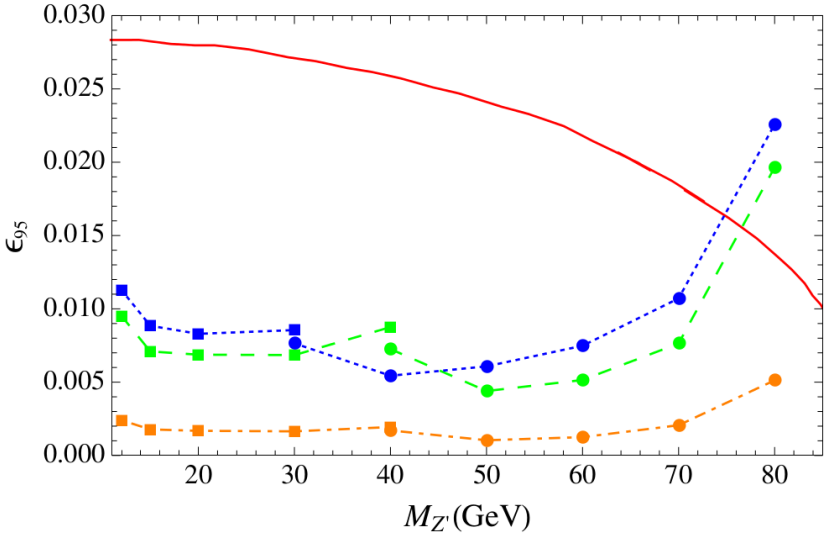
$$(m_{A'}^{\text{phys.}})^2 = m_{A'}^2 + \frac{(c_W^2 m_Z^2 - m_{A'}^2) m_{A'}^2 \sigma^2}{m_Z^2 - m_{A'}^2} + \mathcal{O}(\sigma^3)$$

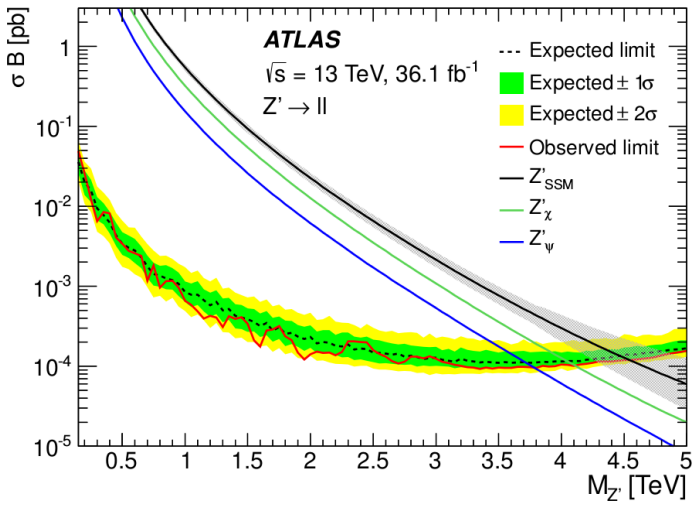
$m_{A'}, \epsilon$

Dark photon searches @ ATLAS & CMS

$$J^{\mu}_{em}(V_{11}A_{\mu} + V_{12}Z_{\mu} + \epsilon A'_{\mu}) + J^{\mu}_{Z}(V_{22}Z_{\mu} + \tau A'_{\mu})$$

Direct searches via Drell-Yan process @ ATLAS and CMS (Z' searches)





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

ATLAS, JHEP 1710 (2017) 182

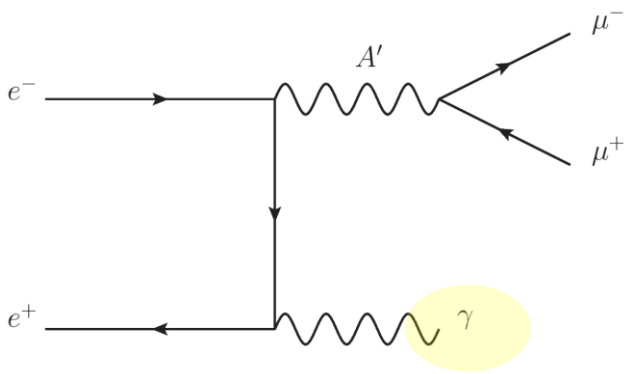
$\epsilon_{95} \sim 10^{-3}$

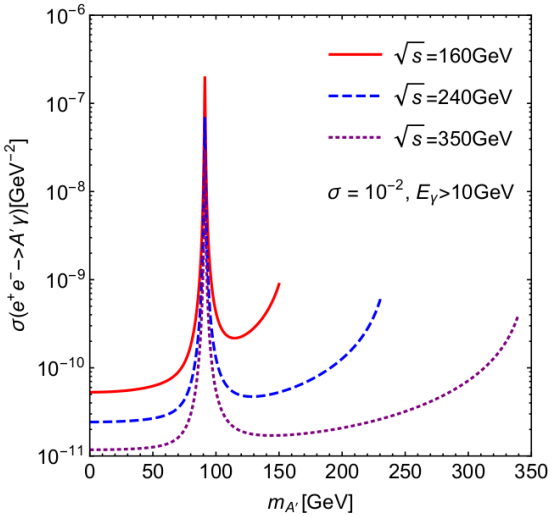
$$\epsilon^{95\%\text{C.L.}} = \left(\frac{[\sigma(A')\text{Br}(\mu^+\mu^-)]^{95\%\text{C.L.}}}{K_{\text{NLO}}\sigma_{\text{LO}}(A')\text{Br}(\mu^+\mu^-)/(10^{-4}c_W^2)} \sqrt{\frac{36.1\ \text{fb}^{-1}}{\mathcal{L}}} \right)^{1/2}$$

I. Hoenig, G. Samach and D. Tucker-Smith,
Phys. Rev. D 90, no. 7, 075016 (2014)

Dark photon searches @ future e^+e^- colliders

We studied a dark photon with mass as large as kinematically allowed through $e^+e^- \to A'X, A' \to \mu^+\mu^-$





$$J^\mu_{em}(V_{11}A_\mu + V_{12}Z_\mu + \epsilon A'_\mu) + J^\mu_Z(V_{22}Z_\mu + \tau A'_\mu)$$

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

Dark photon searches @ future e^+e^- colliders

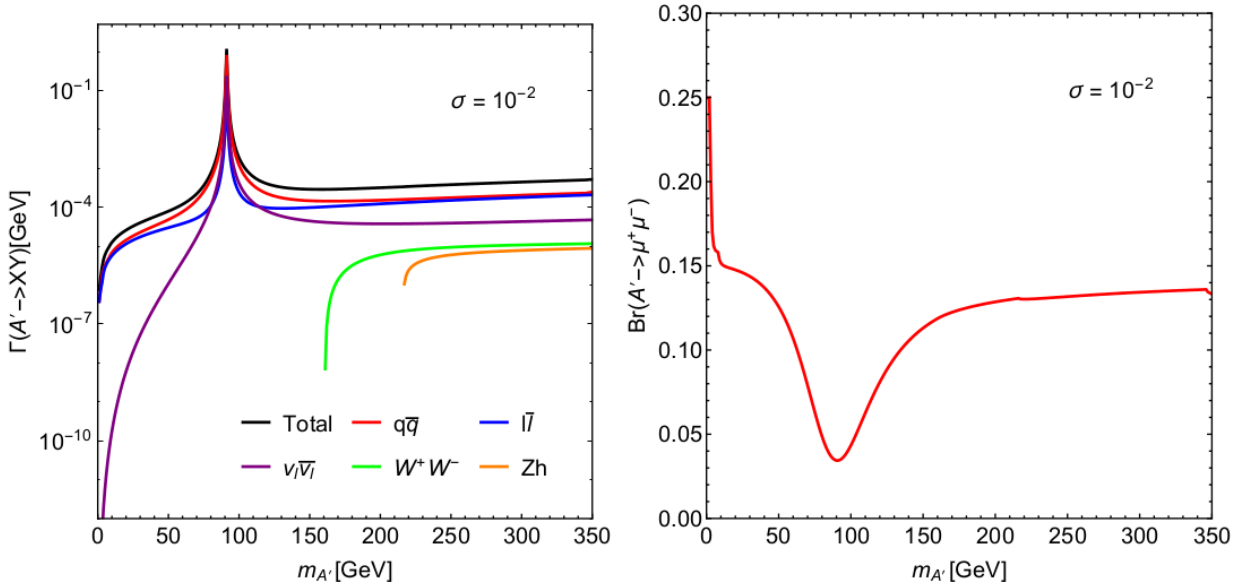
$$J^\mu_{em}(V_{11}A_\mu + V_{12}Z_\mu + \epsilon A'_\mu) + J^\mu_Z(V_{22}Z_\mu + \tau A'_\mu)$$

$$\Gamma(A' \to f\bar{f}) = \frac{g^2 m_{A'}}{12\pi c_W^2} N_c^f \left\{\epsilon^2 Q_f^2 c_W^2 s_W^2 + \epsilon\tau Q_f c_W s_W g_V^f + \frac{1}{4}\tau^2[(g_V^f)^2 + (g_A^f)^2]\right\},$$

$$\Gamma(A' \to Zh) = \frac{g^2\tau^2 m_{A'}}{192\pi c_W^2}\lambda^{1/2}(1, x_Z, x_h)\left\{\lambda(1, x_Z, x_h) + 12x_Z\right\},$$

$$\Gamma(A' \to W^+W^-) = \frac{g^2 s_W^2(\epsilon + \tau\cot\theta_W)^2 m_{A'}}{192\pi} x_W^{-2}(1 - 4x_W)^{3/2}(1 + 20x_W + 12x_W^2),$$

$$x_{W,Z,h} = (m_{W,Z,h}/m_{A'})^2$$



Dark photon searches @ future e^+e^- colliders

signal: $e^+e^- \to \gamma A' \to \gamma\mu^+\mu^-$ main background: $e^+e^- \to \gamma\mu^+\mu^-$

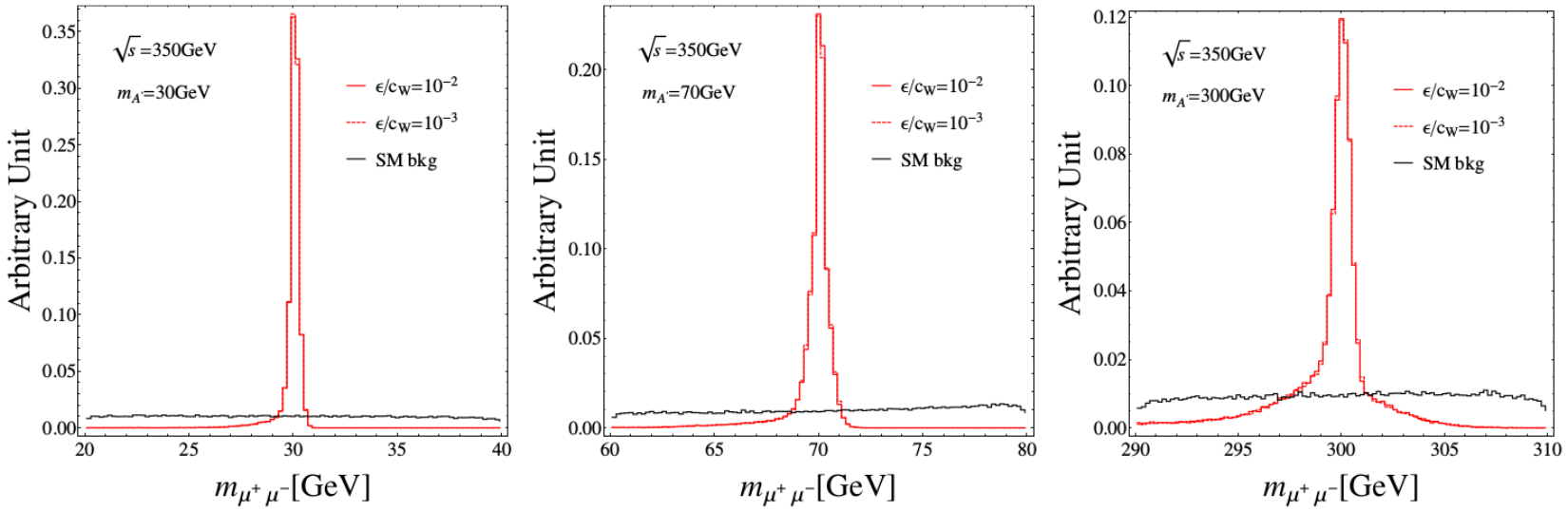
- Interference and off-shell A' contributions are negligible for a narrow A' resonance
- At CEPC: `delphes_card_CEPC.tcl`
  - $\frac{\Delta p_T}{p_T} = 0.1\% \oplus \frac{p_T}{10^5\ \mathrm{GeV}}$ for $|\eta| < 1.0$ and 10 times larger for $1.0 < |\eta| < 3.0$;
  - $\frac{\Delta E}{E} = \frac{0.20}{\sqrt{E/\mathrm{GeV}}} \oplus 0.5\%$. for $|\eta| < 3.0$.
- At FCC-ee: `delphes_card_ILD.tcl`
  - $\frac{\Delta p_T}{p_T} = 0.1\% \oplus \frac{p_T}{10^5\ \mathrm{GeV}}$ for $|\eta| < 1.0$ and 10 times larger for $1.0 < |\eta| < 2.4$;
  - $\frac{\Delta E}{E} = \frac{0.15}{\sqrt{E/\mathrm{GeV}}} \oplus 1\%$. for $|\eta| < 3.0$.

Dark photon searches @ future e^+e^- colliders

signal: $e^+e^- \to \gamma A' \to \gamma\mu^+\mu^-$ main background: $e^+e^- \to \gamma\mu^+\mu^-$

normalized $m_{\mu^+\mu^-}$ distributions

- Total width
- Momentum resolution

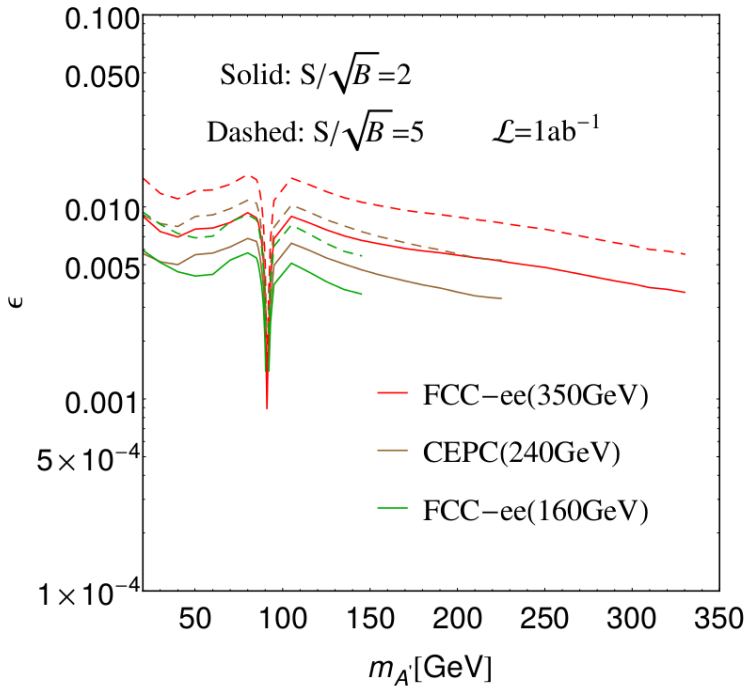


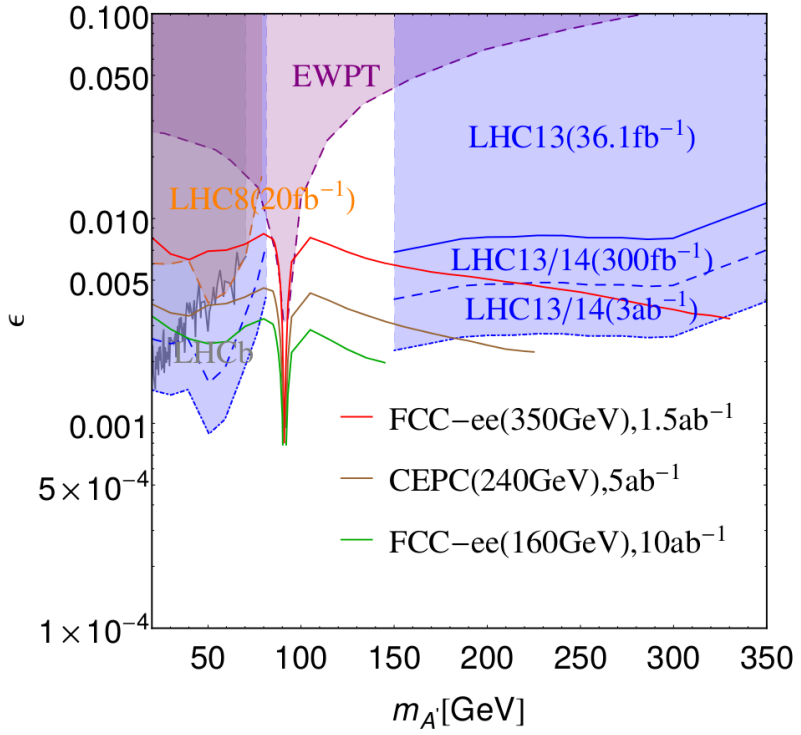
$$\Delta m_{\mu^+\mu^-} < 0.5 \sim 1.5 \text{ GeV}, \quad E_T^{\text{miss}} < 5 \text{ GeV}$$

Dark photon searches @ future e^+e^- colliders

signal significance:

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





Dark photon searches @ future e^+e^- colliders

TABLE IV: The values of ϵ corresponding to $S/\sqrt{B} = 2$ for $m_{A'} = 30$ GeV, 115 GeV, 230 GeV and 320 GeV in different channels at the 350 GeV FCC-ee with the integrated luminosity of 1.5 ab^{-1}. The notation of "aE-b" stands for $a \times 10^{-b}$.

FCC-ee (350 GeV)	30 GeV	115 GeV	230 GeV	320 GeV
$\mu^+\mu^-\gamma$	7.62E-3	8.47E-3	5.26E-3	3.81E-3
$e^+e^-\gamma$	1.06E-2	1.62E-2	3.28E-2	7.74E-3
$\tau^+\tau^-\gamma$	3.40E-2	3.55E-2	1.22E-2	7.27E-3
$q\bar{q}\gamma$	9.40E-3	8.18E-3	3.92E-3	2.48E-3
$Zh\gamma$	–	–	3.90E-2	2.10E-2
$W^+W^-\gamma$	–	–	4.05E-2	2.21E-2

Also promising in jet final state

Summary

- A coupling of dark photon to the SM can be generated through kinetic mixing
- A non-zero mixing parameter ϵ induces a mixing between A' and Z if dark photon mass is not zero, which can be large when $m_{A'}$ close to m_Z even if ϵ is small
- Many efforts have been made to constrain the mixing parameter for a dark photon mass below m_Z
- We studied the search for dark photon in $e^+e^- \to \gamma A' \to \gamma\mu^+\mu^-$ for a dark photon mass as large as kinematically allowed at future e^+e^- colliders