

Searching for dark photons from dark-scalar decays at CEPC and FCC-ee

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Motivation

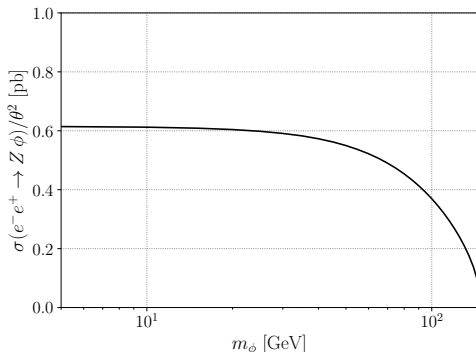
- **Portal-physics** models – connecting the visible and dark sectors
 - fermion portal – heavy neutral leptons
 - vector portal – **dark photon γ'**
 - scalar portal – **dark scalar ϕ**
 - pseudoscalar portal – axionlike particle
- **Hidden Abelian Higgs Model**: both γ' and ϕ with ϕ giving mass to γ'
- These mediators can be long-lived if light or feebly coupled to the SM
- Related to DM, $g-2$, strong first-order phase transition, or gravitational waves...
- CEPC and FCC-ee – Higgs factories: $e^+e^- \rightarrow Z\phi, \phi \rightarrow \gamma'\gamma'$
- To our knowledge: **first study** on searches for long-lived dark photons in this signal process
- **No published experimental search** for the scenario involving both the dark scalar and the dark photon in the mass ranges of interest

Theoretical model

$$L_{\text{int}} = g' m_{\gamma'} \phi \gamma'_\mu \gamma'^\mu + e \gamma'_\mu J_{\text{EM}}^\mu + \sum_f \frac{m_f \theta}{v} \phi \bar{f} f$$

$$\sigma(e^+ e^- \rightarrow Z \phi) = \frac{G_F^2 m_Z^4}{96 \pi s} (v_e^2 + a_e^2) \sqrt{\lambda} \frac{\lambda + 12 m_Z^2 / s}{(1 - m_Z^2 / s)^2} \cdot \theta^2$$

$$\lambda = \left(1 - \frac{(m_\phi + m_Z)^2}{s}\right) \left(1 - \frac{(m_\phi - m_Z)^2}{s}\right)$$



For 1 ab^{-1} and $\theta = 10^{-2}$,
 $N_{e^- e^+ \rightarrow Z \phi} \sim \mathcal{O}(10^9)$

Mass ranges and decay widths

- $m_\phi \in [25 \text{ GeV}, 140 \text{ GeV}]$ and $m_{\gamma'} \in [2 \text{ GeV}, m_\phi/2]$
- **Existing bounds** on ϵ and θ from collider searches:
 - ϵ : CMS, LHCb, BaBar – all of order 10^{-3}
 - θ : CMS, ATLAS, LEP2, L3 – $\theta \lesssim 10^{-2} - 10^{-1}$

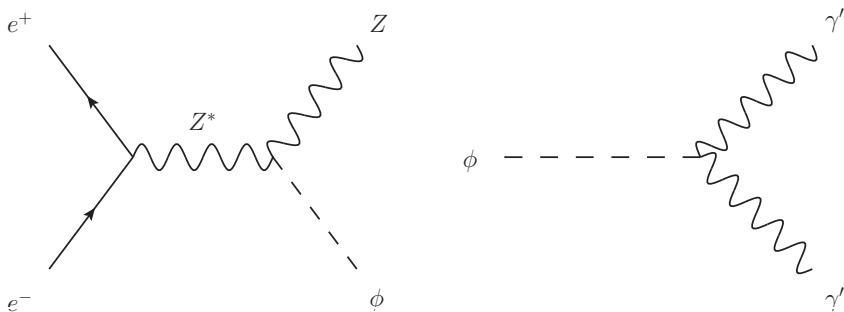
$$\Gamma_{\phi \rightarrow \gamma' \gamma'} = \frac{g'^2}{8\pi} \frac{m_{\gamma'}^2}{m_\phi} \left(2 + \frac{m_\phi^4}{4m_{\gamma'}^4} \left(1 - \frac{2m_{\gamma'}^2}{m_\phi^2} \right)^2 \right) \sqrt{1 - \frac{4m_{\gamma'}^2}{m_\phi^2}}$$

$$\Gamma_{\phi \rightarrow f \bar{f}} = N_c \frac{m_\phi}{8\pi} \left(\frac{m_f}{v} \right)^2 \theta^2 \left(1 - \frac{4m_f^2}{m_\phi^2} \right) \sqrt{1 - \frac{4m_f^2}{m_\phi^2}}$$

- We fix $\theta = 10^{-2}$ and $g' = 10^{-2} \Rightarrow \text{BR}(\phi \rightarrow \gamma' \gamma') \simeq 100\%$
- ϕ promptly decays
- Perturbative γ' decay widths:

$$\Gamma_{\gamma' \rightarrow f \bar{f}} = \frac{1}{3} N_c Q_f^2 \alpha \epsilon^2 m_{\gamma'} \left(1 + \frac{2m_f^2}{m_{\gamma'}^2} \right) \sqrt{1 - \frac{4m_f^2}{m_{\gamma'}^2}}$$

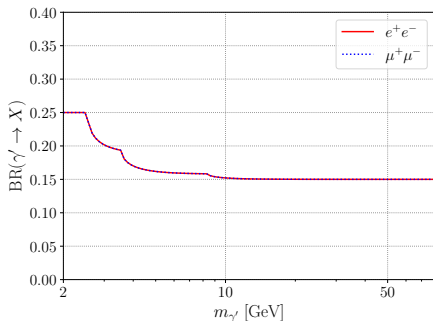
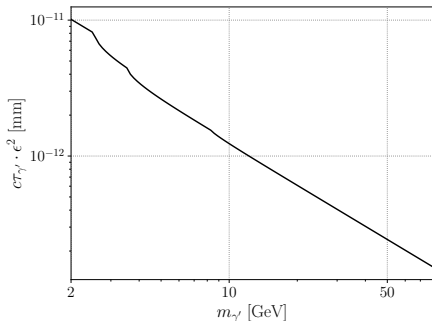
Production and decay of ϕ



- ϕ is **produced** via mixing with the SM Higgs boson (θ)
- ϕ **decays** promptly into a pair of dark photons (g')

Dark-photon decays

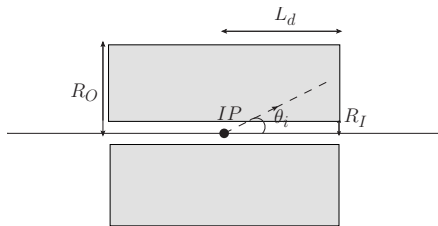
- $$\Gamma_{\gamma'} = \sum_f \Gamma_{\gamma' \rightarrow f\bar{f}} \quad c\tau_{\gamma'} = c\hbar/\Gamma_{\gamma'}$$



- The kinks at $m_{\gamma'} \sim 2.5$ GeV, 3.5 GeV, and 8.3 GeV, arise from the opening of the dark-photon decay channels into a pair of charm quarks, τ -leptons, and bottom quarks, respectively

Search strategies

- Short-lived ϕ and long-lived γ'
- Focus on the inner tracker of the main detectors
 - ① At least one DV consisting of an electron pair or a muon pair should be reconstructed.
 - ② Exactly two DVs should be reconstructed, composed of any final states of the dark-photon decays.



- Extracted from [PRD101\(2020\)035003](#)

- Two DVs both of a muon pair reconstructed in the muon chamber

⇒ no sensitivity

Acceptance formulas

$$\mathcal{A}_1 = \frac{1}{N_{\text{MC}}} \sum_{i=1}^{N_{\text{MC}}} \left\{ P(\gamma'_1 \text{ in IT}) \cdot \left(1 - P(\gamma'_2 \text{ in IT})\right) \cdot \mathcal{B} \right. \\ \left. + P(\gamma'_2 \text{ in IT}) \cdot \left(1 - P(\gamma'_1 \text{ in IT})\right) \cdot \mathcal{B} \right. \\ \left. + P(\gamma'_1 \text{ in IT}) \cdot P(\gamma'_2 \text{ in IT}) \cdot \mathcal{B}^2 \right\}$$

$$\mathcal{B} \equiv \text{BR}(\gamma' \rightarrow e^+ e^-) + \text{BR}(\gamma' \rightarrow \mu^+ \mu^-)$$

$$\mathcal{A}_2 = \frac{1}{N_{\text{MC}}} \sum_{i=1}^{N_{\text{MC}}} \left\{ P(\gamma'_1 \text{ in IT}) \cdot P(\gamma'_2 \text{ in IT}) \right\}$$

$$P(\gamma' \text{ in IT}) = \begin{cases} e^{-L_1/\lambda_{\text{lab}}} - e^{-L_2/\lambda_{\text{lab}}}, & \text{if } |L_d \tan \theta| > R_I \\ 0, & \text{else,} \end{cases}$$

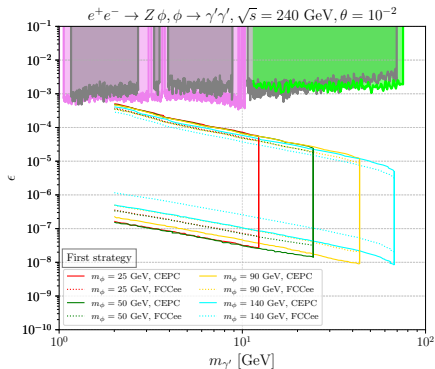
$$L_1 \equiv R_I, \quad L_2 \equiv \min(|L_d \tan \theta|, R_O), \quad \lambda_{\text{lab}} \equiv \beta_T \gamma c \tau_{\gamma'}.$$

Background discussion

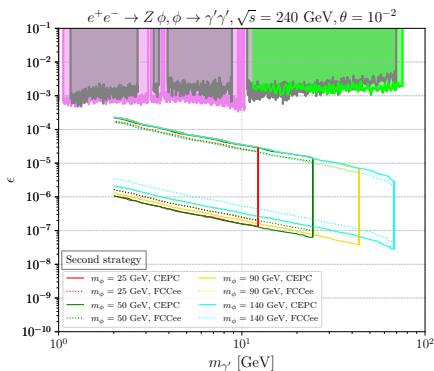
- **One DV**: dominant background from photon conversion – strongly suppressed by our choice of fiducial volume and can be further reduced by using a detailed material map and by requiring that the DV direction should not be collinear with any reconstructed prompt photon
- **Other backgrounds for one DV**: hadronic secondary interactions (tending to produce multi-track vertices), $K_S \rightarrow \pi^+ \pi^-$ or heavy-flavor decays with pion-to-lepton misidentification, and random track combinatorics – Cuts on track multiplicity, lepton identification, invariant mass of the dilepton, and DV pointing reduce these sources to a negligible level, without decreasing signal largely
- **Two DVs**: expect that the requirement of two spatially separated DVs eliminates all SM backgrounds to a negligible level, independently of the final state of the dark photons
- $\Rightarrow$ we assume a background-free environment

Sensitivity reach

- $N_{S,i} = \mathcal{L}_{\text{int.}} \cdot \sigma(e^+e^- \rightarrow Z\phi) \cdot \mathcal{A}_i$ with $i = 1, 2$
- $\mathcal{L}_{\text{int.}}^{\text{CEPC}} = 22 \text{ ab}^{-1}$ & $\mathcal{L}_{\text{int.}}^{\text{FCC-ee}} = 5.6 \text{ ab}^{-1}$
- Assume 100% detector efficiency and 100% DV-reconstruction efficiency
- 0 backgrounds



▪ $\geq 1 \text{ DV}$



▪ 2 DV

- Gray, green, pink: [LHCb](#), [CMS](#), [BaBar](#) existing bounds

Summary

- Proposed to search for **long-lived γ'** from prompt ϕ decays at CEPC and FCC-ee
- Employed **two DV-based search strategies** with different requirements on the decay-product types and the number of DVs inside the IT of the main detectors of CEPC and FCC-ee
- $\sqrt{s} = 240$ GeV and $\mathcal{L}_{\text{int.}}^{\text{CEPC}} = 22 \text{ ab}^{-1}$ & $\mathcal{L}_{\text{int.}}^{\text{FCC-ee}} = 5.6 \text{ ab}^{-1}$
- Zero backgrounds** and the numerical results indicate that these search strategies can probe values of ϵ **several orders of magnitude below the existing bounds**, for $m_\phi \sim 10 - 100$ GeV and $m_{\gamma'}$ between 2 GeV and $m_\phi/2$
- Expect mild effects when more realistic factors are taken into account, unless dark photons are close to the kinematic threshold $\phi \rightarrow \gamma'\gamma'$

Thank You! 谢谢!

Back-up slides

CEPC and FCC-ee IT parameters

Detector	R_I [mm]	R_O [m]	L_d [m]	V [m ³]
CEPC	16	1.8	2.35	47.8
FCC-ee	17	2.0	2.0	50.3

- Extracted from CEPC CDR vol. 2 and FCC-ee CDR vol. 2

Simulation procedures

- Pythia 8.3 with HiggsSM:ffbar2HZ at $\sqrt{s} = 240$ GeV with back-to-back e^+e^- collisions
- Tuning the mass of the SM Higgs boson to that of ϕ we mimic the kinematics of the signal process
- $\sigma(e^+e^- \rightarrow Z\phi)$ is computed with MadGraph5
- Fix $m_\phi = 25, 50, 90$, and 140 GeV
- Scan $m_{\gamma'}$ between 2 GeV and $m_\phi/2$

Smaller values of θ

- For $\theta < 10^{-2}$, worse sensitivity reach is expected, because fewer dark scalars and thus fewer dark photons would be produced
- If θ is reduced by a factor of 10 the total dark-photon production rates would decrease by 100. For the first search strategy, the lower sensitivity reach to ϵ would be weakened by a factor of 10 while that for the second search would be impaired by about a factor of $\sqrt{10}$.
- Smaller ratio g'/θ can lead to $\text{BR}(\phi \rightarrow \gamma'\gamma') < 100\%$ and thus weaker sensitivities
- Much smaller g' and θ can make ϕ also long-lived and thus weaker sensitivities