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

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Motivation

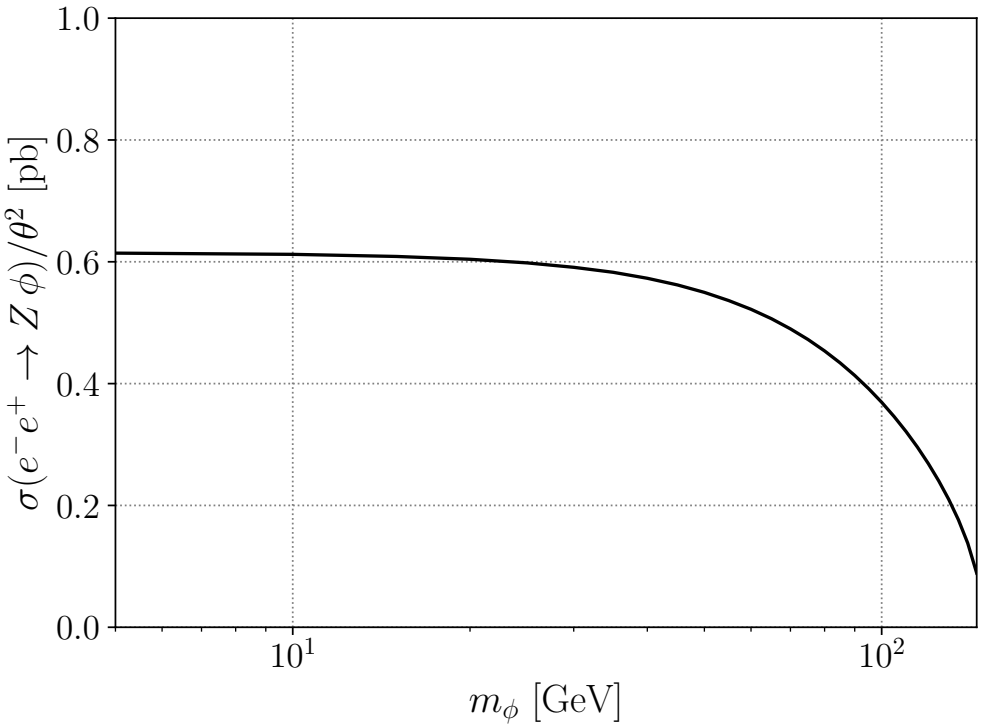
- Portal-physics models – connecting the visible and dark sectors
  - fermion portal – heavy neutral leptons
  - vector portal – dark photon γ'
  - scalar portal – dark scalar ϕ
  - pseudoscalar portal – axionlike particle
- Hidden Abelian Higgs Model: both γ' and ϕ with ϕ giving mass to γ'
- These mediators 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: $e^+e^- \to Z\phi, \phi \to \gamma'\gamma'$
- 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

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

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

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



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

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}

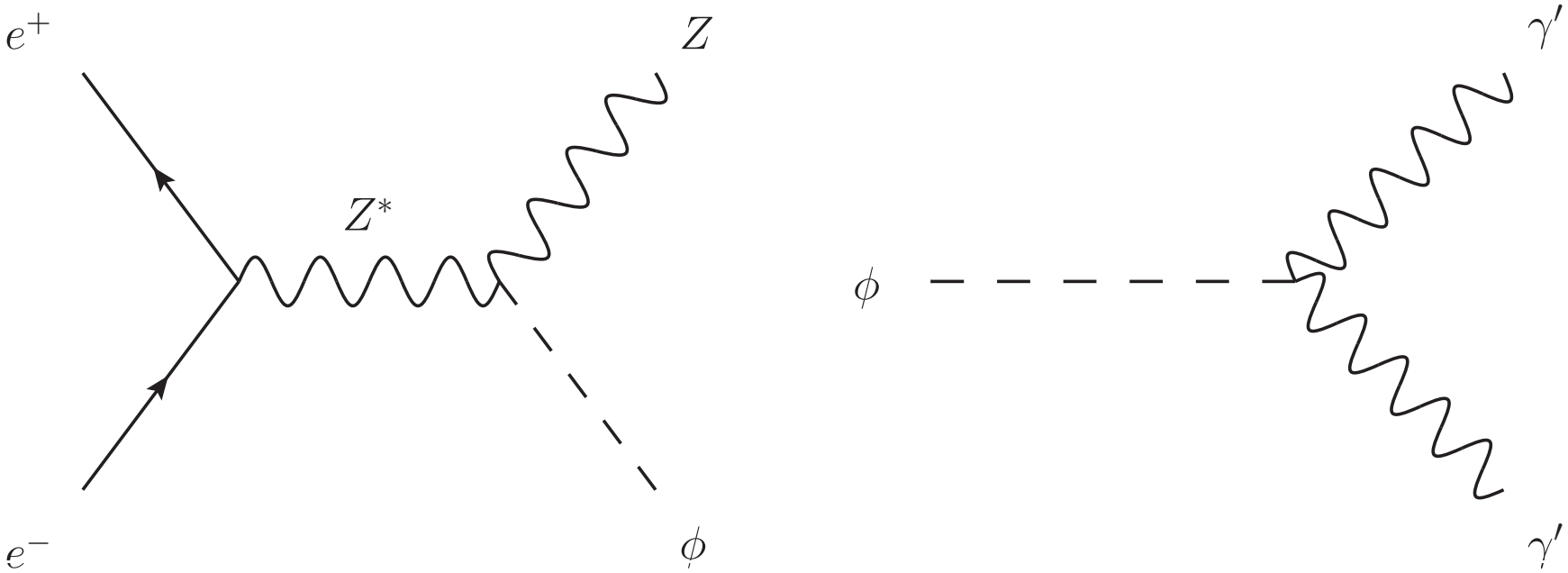
$$\Gamma_{\phi\to\gamma'\gamma'} = \frac{g'^2}{8\pi}\frac{m_{\gamma'}^2}{m_\phi}\left(2+\frac{m_\phi^4}{4m_{\gamma'}^4}\left(1-\frac{2m_{\gamma'}^2}{m_\phi^2}\right)^2\right)\sqrt{1-\frac{4m_{\gamma'}^2}{m_\phi^2}}$$

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

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

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

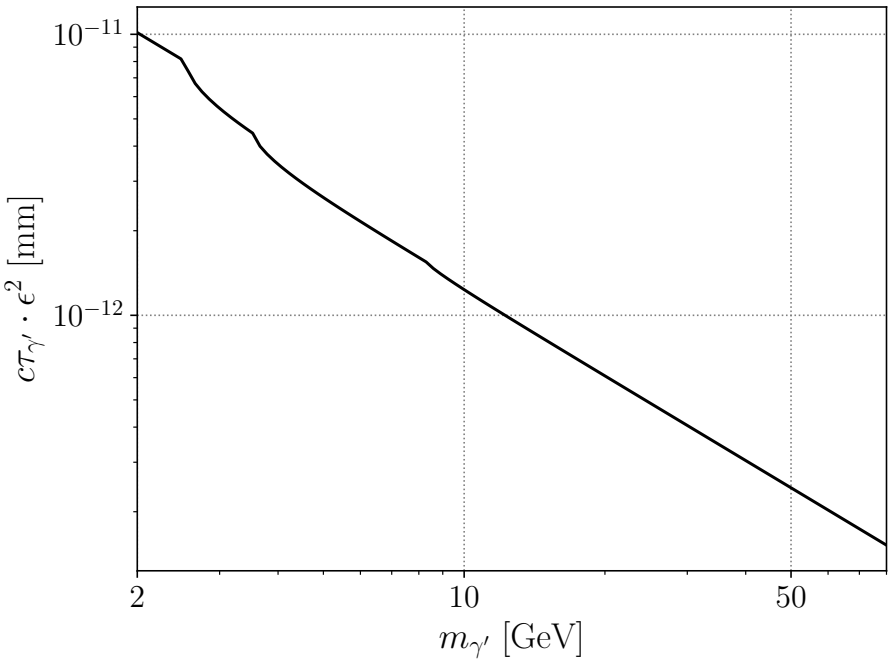
Production and decay of ϕ

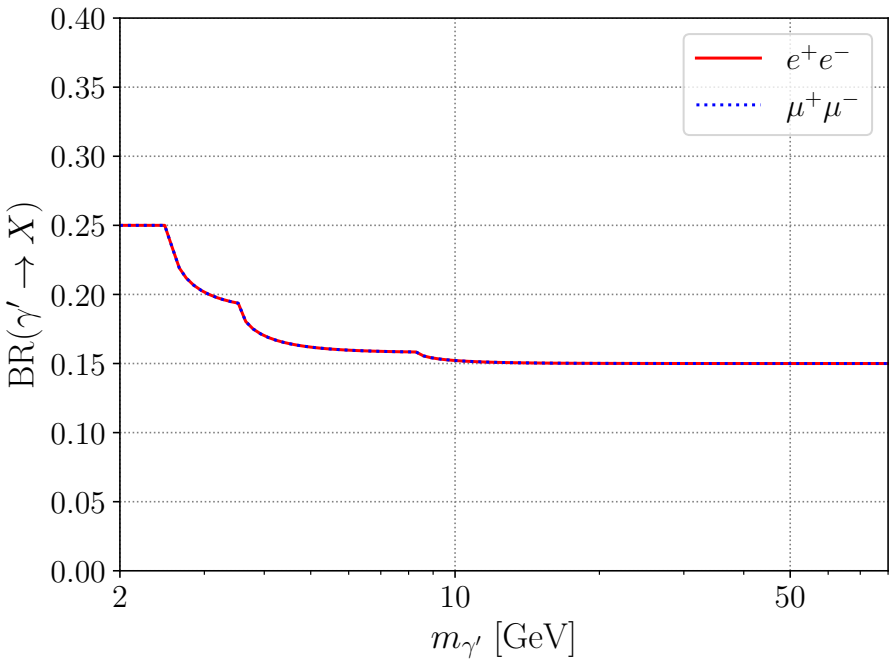


- ϕ is produced via mixing with the SM Higgs boson (θ)
- ϕ decays promptly into a pair of dark photons (g')

Dark-photon decays

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



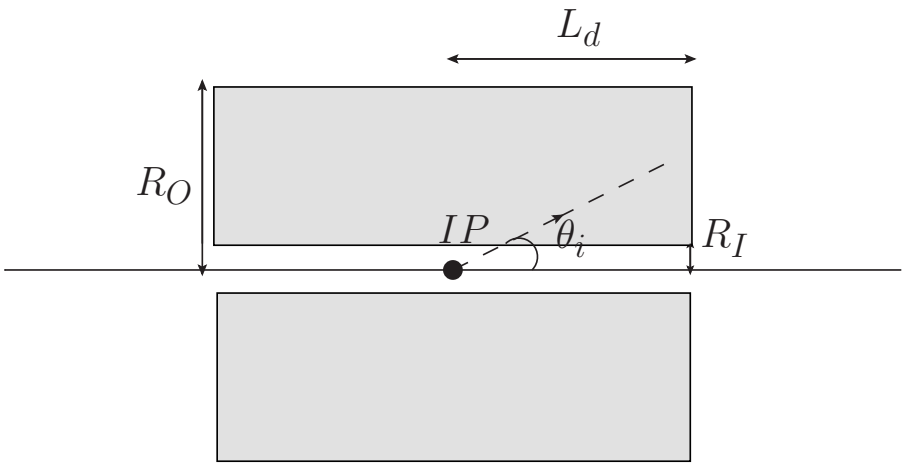


- The kinks at $m_{\gamma'} \sim 2.5$ GeV, 3.5 GeV, and 8.3 GeV, arise from the opening of the dark-photon decay channels into a pair of charm quarks, τ-leptons, and bottom quarks, respectively

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

$\Rightarrow$ no sensitivity

Acceptance formulas

$$\mathcal{A}_1 = \frac{1}{N_{\rm MC}} \sum_{i=1}^{N_{\rm MC}} \Big\{ P(\gamma_1' \text{ in IT}) \cdot \Big(1 - P(\gamma_2' \text{ in IT})\Big) \cdot \mathcal{B} + P(\gamma_2' \text{ in IT}) \cdot \Big(1 - P(\gamma_1' \text{ in IT})\Big) \cdot \mathcal{B} + P(\gamma_1' \text{ in IT}) \cdot P(\gamma_2' \text{ in IT}) \cdot \mathcal{B}^2 \Big\}$$

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

$$\mathcal{A}_2 = \frac{1}{N_{\rm MC}} \sum_{i=1}^{N_{\rm MC}} \Big\{ P(\gamma_1' \text{ in IT}) \cdot P(\gamma_2' \text{ in IT}) \Big\}$$

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

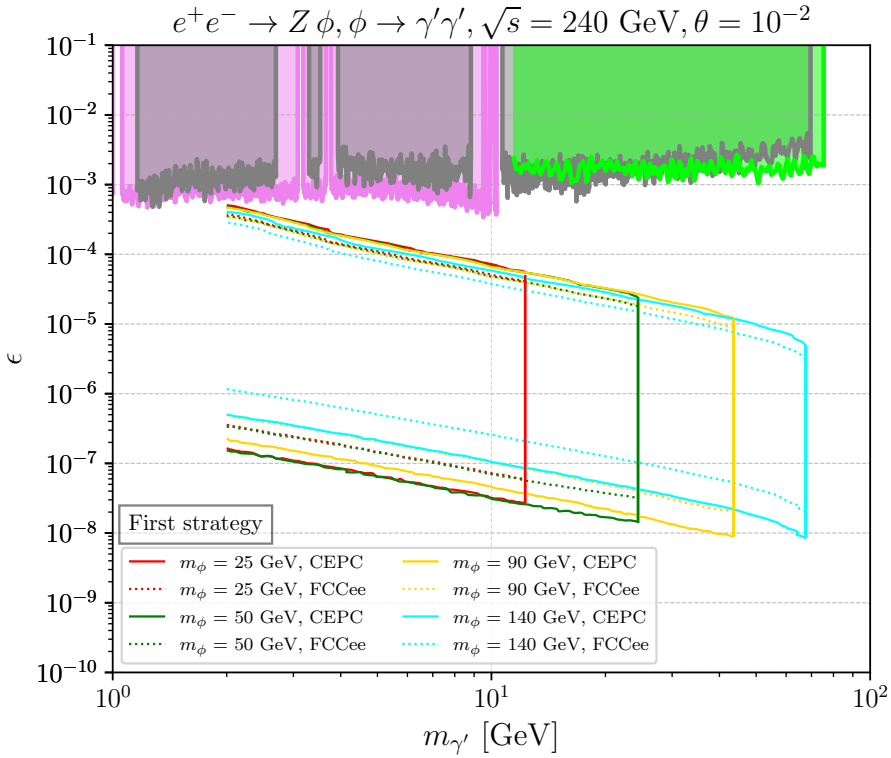
$L_1 \equiv R_I$, $\quad L_2 \equiv \min(|L_d \tan\theta|, R_O)$, $\quad \lambda_{\rm lab} \equiv \beta_T \gamma \, c \tau_{\gamma'}$.

Background discussion

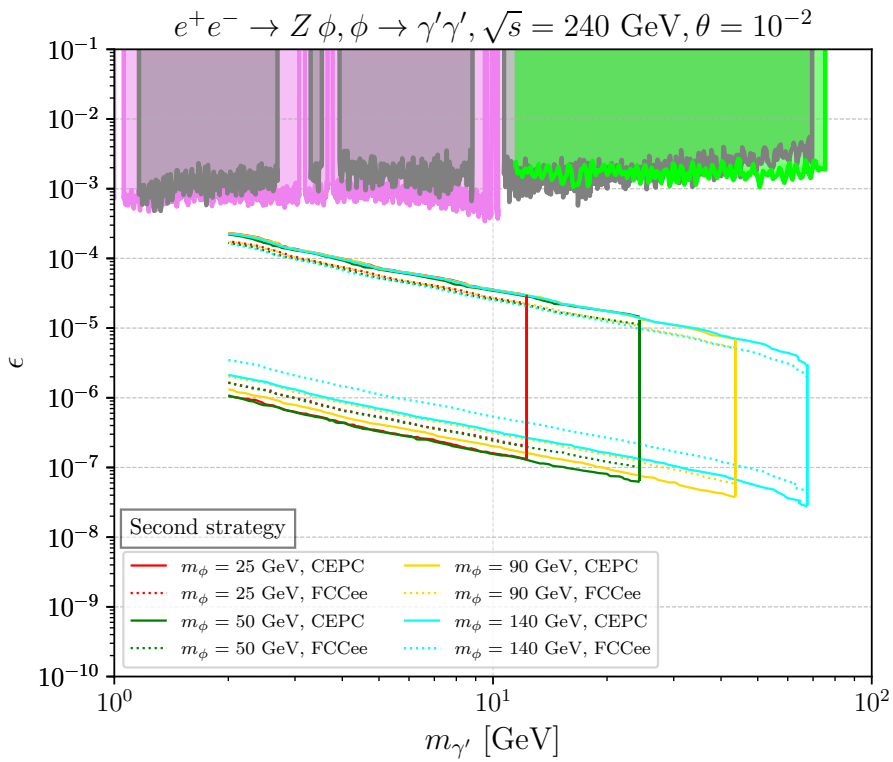
- One DV: dominant background from photon conversion – strongly suppressed by our choice of fiducial volume and can be further reduced by using a detailed material map and by requiring that the DV direction should not be collinear with any reconstructed prompt photon
- Other backgrounds for one DV: hadronic secondary interactions (tending to produce multi-track vertices), $K_S \to \pi^+\pi^-$ 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

- $N_{S,i} = \mathcal{L}_{\text{int.}} \cdot \sigma(e^+e^- \to Z\phi) \cdot \mathcal{A}_i$ with $i = 1, 2$
- $\sqrt{s} = 240$ GeV & $\mathcal{L}_{\text{int.}}^{\text{CEPC}} = 22$ ab^{-1} & $\mathcal{L}_{\text{int.}}^{\text{FCC-ee}} = 5.6$ ab^{-1}
- Assume 100% detector efficiency and 100% DV-reconstruction efficiency
- 0 backgrounds



- ≥ 1 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 $\mathcal{L}_{\text{int.}}^{\text{CEPC}} = 22$ ab^{-1} & $\mathcal{L}_{\text{int.}}^{\text{FCC-ee}} = 5.6$ 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 $\phi \to \gamma'\gamma'$

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
- $\sigma(e^+e^- \to Z\phi)$ 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 BR$(\phi \to \gamma'\gamma') < 100\%$ and thus weaker sensitivities
- Much smaller g' and θ can make ϕ also long-lived and thus weaker sensitivities