The impact of dark Higgs mechanism on the detection of invisible dark photon

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Based on:

- **Unraveling dark Higgs mechanism via dark photon production at an e+ e- collider**, 2506.20208. S. Li, J. M. Yang, M. Zhang, Y. Zhang, R. Zhu.

- **Theoretical bounds on dark Higgs mass in a self-interacting dark matter model with U(1)'**, 2405.18226. S. Li, J. M. Yang, M. Zhang, R. Zhu.

Contents

Introduction

The secluded dark matter models

- The dark sector couples to SM particles through a mediator.
- Easy to escape the strong constraints from the DM direct detection experiments.
- Common dark sector portals include dark photon, axion, scalar, sterile neutrino …

Dark photon (A′)

- A dark U(1)′ gauge interaction is introduced to stabilize DM and it provides a vector mediator — dark photon.

A′ couples to the SM electromagnetic current via kinetic mixing ε

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} \boxed{- \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu} \boxed{- \varepsilon e J_\mu^{\mathrm{EM}} A'^\mu}$$

To escape limits from BBN, the dark photon generally needs to be massive

Introduction

The mass origin of dark photon

Two parameters $\{m_{A'}, \varepsilon\}$ are introduced

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \varepsilon e J_\mu^{\rm EM} A'^\mu$$

But what is the mass origin of dark photon?

- Usually assume it is generated via the Stueckelberg mechanism.
- The Stueckelberg mechanism is actually the Higgs mechanism in Abelian gauge theory with the Higgs boson is decoupled.

Is the heavy Higgs assumption in the Stueckelberg mechanism valid?

Let's check it!

Introduction

The mass origin of dark photon

Consider a dark $U(1)'$ Higgs mechanism.

The complete Lagrangian for the dark sector before symmetry breaking is

$$\mathcal{L}_{\text{dark}} = (D_\mu S)^\dagger D^\mu S - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \mu^2 S^\dagger S - \frac{1}{4}\lambda(S^\dagger S)^2 + \bar{\chi}(i\not{D} - m_\chi)\chi - \varepsilon e J_\mu^{\text{EM}} A'^\mu$$

Spontaneous $U(1)'$ symmetry breaking

$$S = \frac{1}{\sqrt{2}}(v + s + ia)$$

$$v = 2\mu/\sqrt{\lambda}$$

$$m_s^2 = \frac{1}{2}\lambda v^2 \ , \ m_{A'}^2 = g'^2 v^2.$$

$$\frac{m_s^2}{m_{A'}^2} = \frac{\lambda}{2g'^2}$$

$D_\mu = \partial_\mu - ig'A'_\mu$

S: dark Higgs field

$F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$

χ: dark fermion

s: dark Higgs

a: Goldstone

Only if $\lambda \gg g'^2$, the Stueckelberg mechanism is valid.

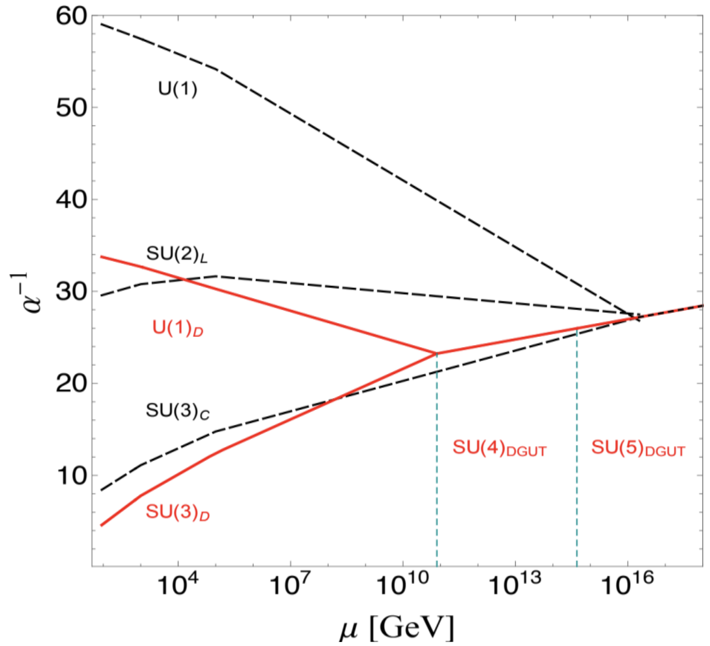
Introduction

The mass origin of dark photon

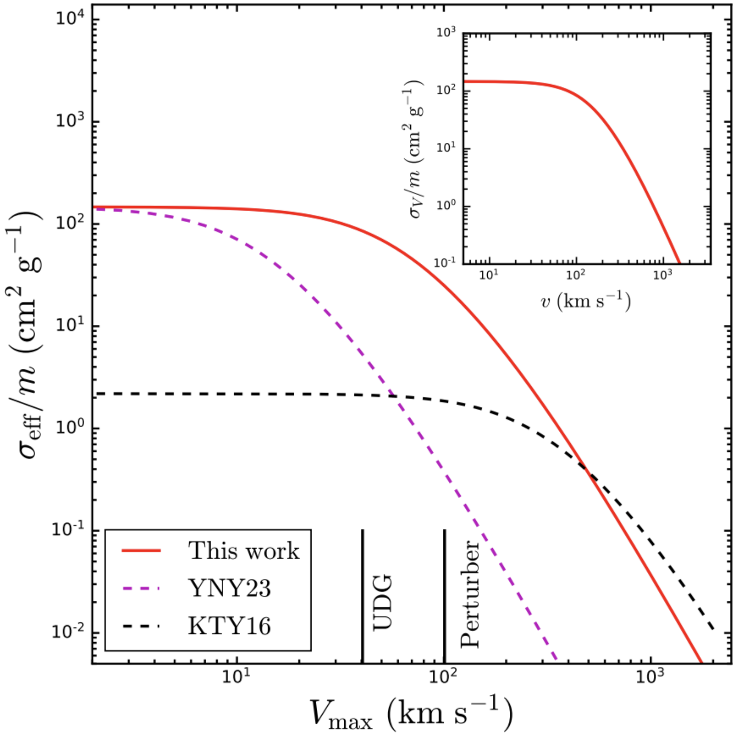
Is the condition $\lambda \gg g'^2$, met?

Not always.

- The perturbative unitarity gives λ an upper bound 4π, so λ is not too large.
- Embed the dark $U(1)'$ into GUT, then g' can not be too smaller than the SM gauge coupling.
- To solve the “diversity problem” of dark matter, the gauge coupling in the dark sector can not be small.



1907.03404. M.Ibe, A.Kamada, S.Kobayashi, T.Kuwahara, W.Nakano



2306.01830. E.Nadler, D.Yang, H.Yu

Introduction

Some assumptions in our work

- In the following, we take the dark Higgs mechanism into account. The number of parameters increases:

$$\{m_{A'}, \varepsilon\} \longrightarrow \{m_{A'}, \varepsilon, m_s, \alpha'\} \qquad \alpha' \equiv \frac{g'^2}{4\pi}$$

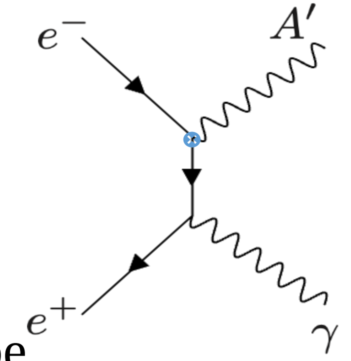
- To simplify the scenario, we take $m = m_{A'} = m_s$.

  So our model has 3 free parameters $\{m, \varepsilon, \alpha'\}$.

- Assuming the dark Higgs decays invisibly, discuss its impact on the detection of invisible dark photon on an e^+e^- collider.

Dark final-state radiation and its effects

The detection of invisible dark photon

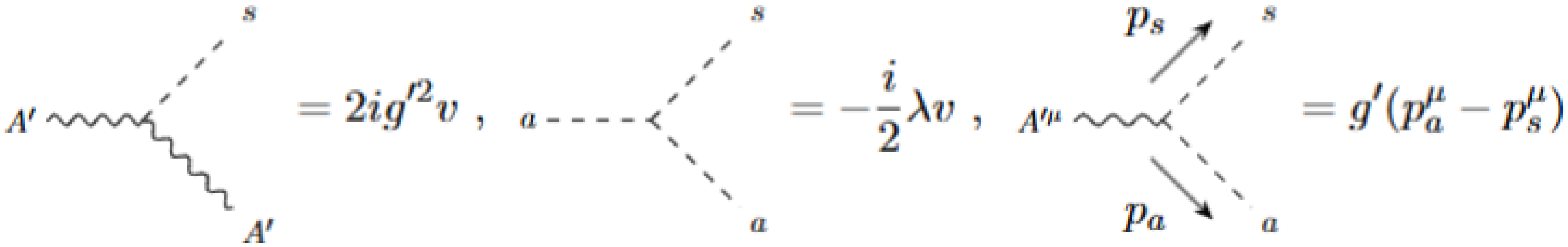


- ✓ **Production**: Since the dark photon couples to the SM electromagnetic current, it can be produced like ordinary photon. On an e^+e^- collider, the main production mechanism is $e^+e^- \to \gamma A'$.
- ✓ **Decay**: If $m_{A'} > 2m_\chi$, dark photons can decay to dark fermion pairs invisibly. And when $\alpha' \gg \alpha\varepsilon^2$, this channel is dominant.
- ✓ **Detection**:
  - The missing mass technique is frequently-used in the detection of invisible particles.
  - Characteristic signature is a narrow resonance emerging over a smooth background in the distribution of the missing mass.
  - For the process $e^+e^- \to \gamma A'$, the square of missing mass is $M_X^2 = s - 2E_\gamma\sqrt{s}$
  - For low mass region, considering the detector resolution, M_X^2 may be negative.

Dark final-state radiation and its effects

The dark final-state radiation

Considering the dark Higgs mechanism, there are couplings between dark photon and dark Higgs:



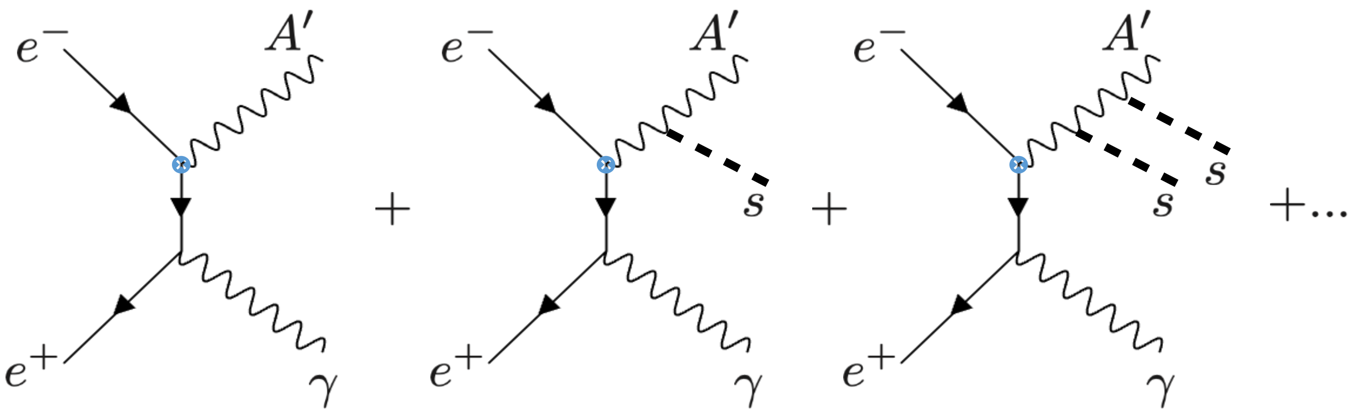
Here, a is the Goldstone absorbed by dark photon.

Dark photon with high energy may emit dark Higgs $A' \to A's$ (called the dark final-state radiation (dark FSR) in the following).

Dark final-state radiation and its effects

The dark final-state radiation

If dark Higgs is also invisible, the dark FSR does not change the signature of $e^+e^- \to \gamma A'$, i.e. mono-photon plus missing energy.



Dark final-state radiation and its effects

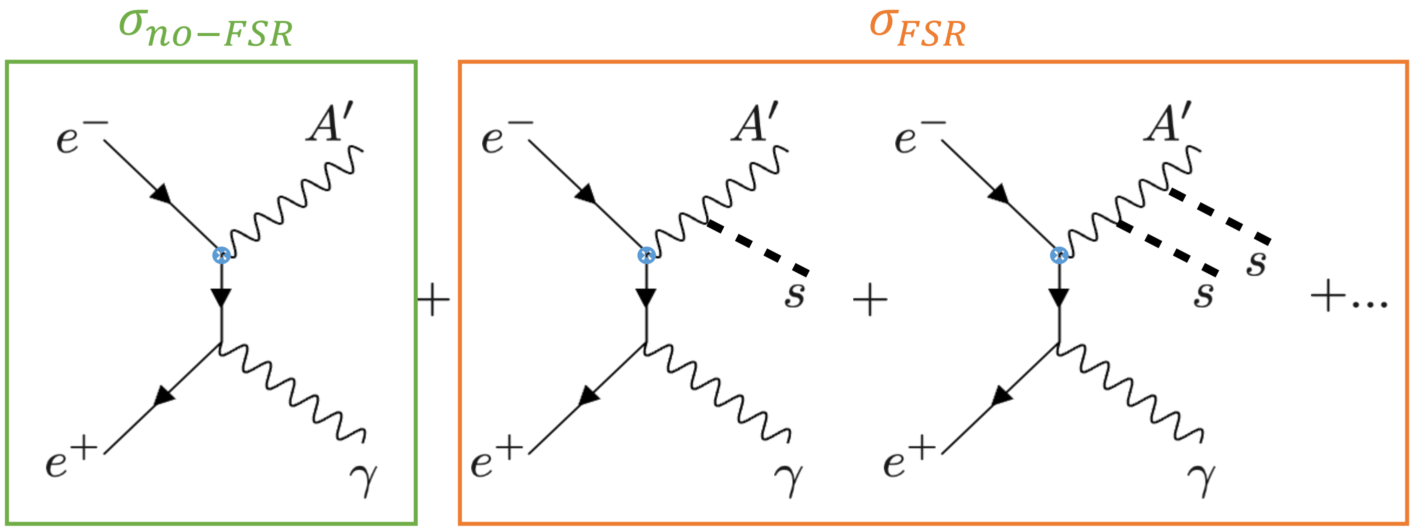
The impact of the dark FSR

Due to the emergence of the processes with dark Higgs in final-state, the search for invisible dark photon would be affected in two aspects:

✓ **The total signal cross section increases**

$\sigma_{\text{no-FSR}}$

$$\sigma_{\text{tot}} = \sigma_{\text{no-FSR}} + \sigma_{\text{FSR}}$$



Dark final-state radiation and its effects

The impact of the dark FSR

✓ **Flattening of the squared missing mass distribution**

- With out FSR, the theoretical distribution (if the decay width of A' is very small) :

$$f^{\rm th}_{\text{no-FSR}}(M_X^2) = \delta(M_X^2 - m_{A'}^2)$$

- When dark FSR is included, the total theoretical distribution is a weighted summation:

$$f^{\rm th}_{\rm tot}(M_X^2) = \lambda f^{\rm th}_{\text{no-FSR}}(M_X^2) + (1-\lambda) f^{\rm th}_{\rm FSR}(M_X^2)$$

in which

$$\lambda = \frac{\sigma_{\text{no-FSR}}}{\sigma_{\text{no-FSR}} + \sigma_{\rm FSR}}.$$

- The experimentally observed signal distribution results from the convolution of this theoretical distribution with the detector resolution function.

$$f^{\rm ex}_{\rm tot}(M_X^2) = f^{\rm th}_{\rm tot}(M_X^2) \otimes f^{\rm re}(M_X^2)$$

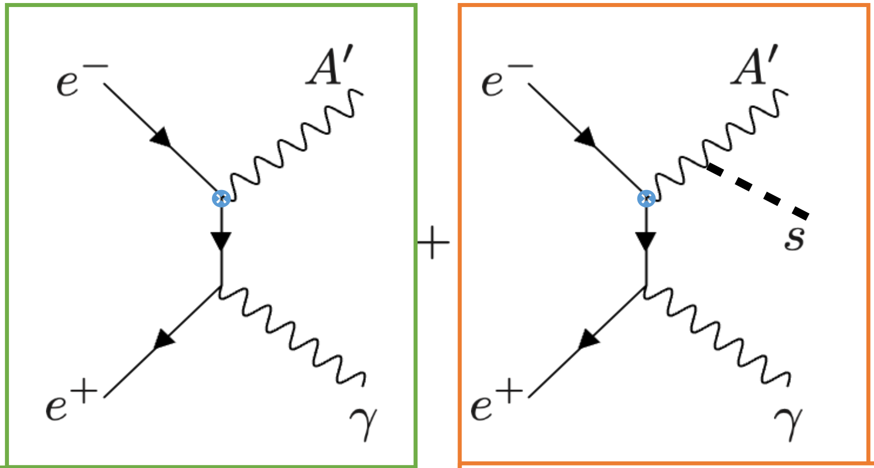
- Due to the presence of $f^{\rm th}_{\rm FSR}(M_X^2)$, both $f^{\rm th}_{\rm tot}(M_X^2)$ and $f^{\rm ex}_{\rm tot}(M_X^2)$ are flattened.

How to deal with the dark FSR

✓ **For a large $m = m_{A'} = m_s$**

For a large m, the process $e^+e^- \to \gamma A's$ is considered as the next-to-leading-order contribution.

LO NLO



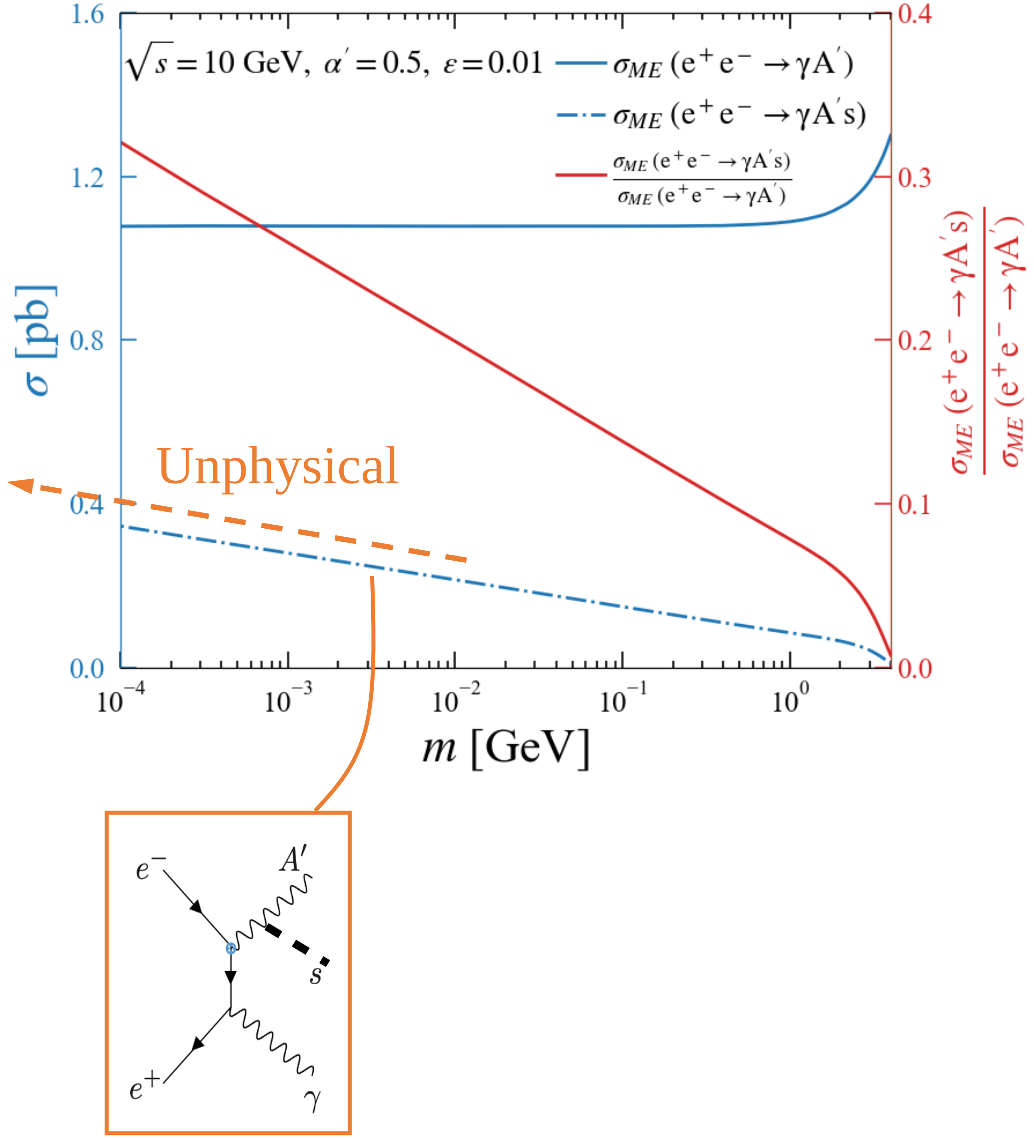
$\sigma_{\text{no-FSR}} = \sigma_{\text{ME}}(e^+e^- \to \gamma A')$ $\sigma_{\text{FSR}} = \sigma_{\text{ME}}(e^+e^- \to \gamma A's)$ (for large m)

And it is reasonable to estimate with the fixed-order matrix element (ME) calculation.

How to deal with the dark FSR

✓ **For a small $m = m_{A'} = m_s$**

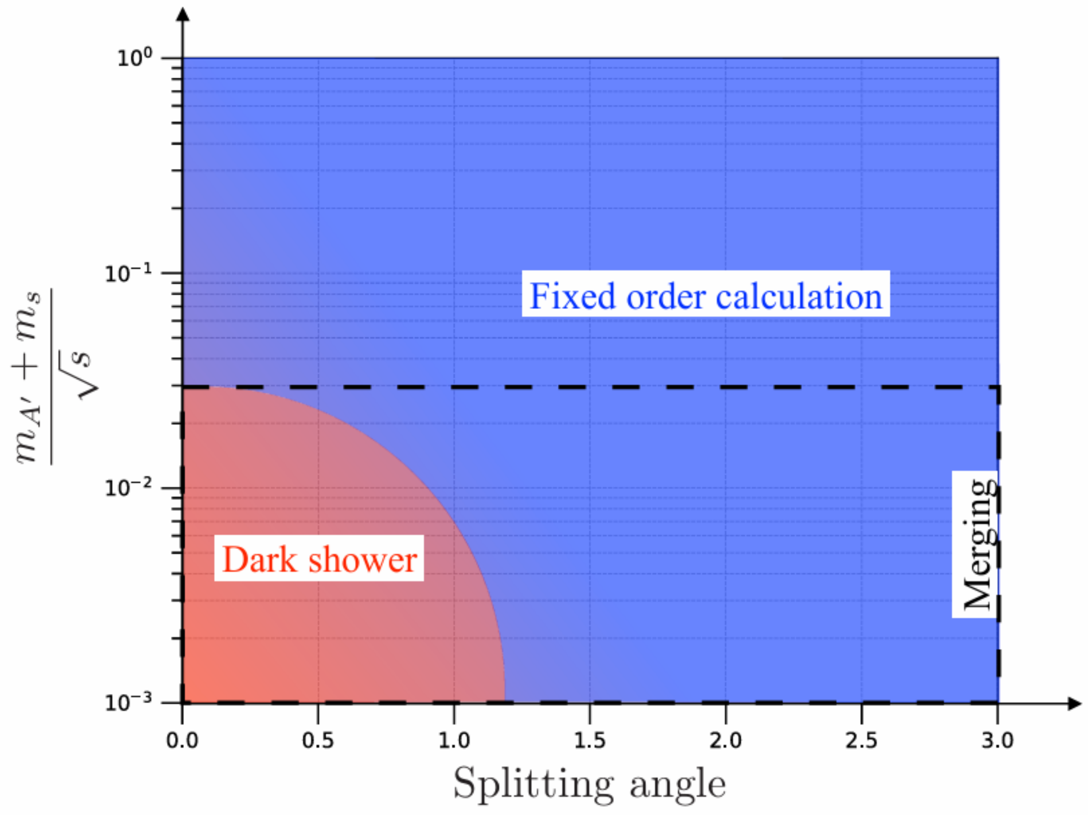
- $\sigma_{\mathrm{ME}}(e^+e^- \to \gamma A's)$ shows unphysical enhancement as $m \to 0$.
- This IR divergence can be canceled by virtual correction, as promised by Kinoshita-Lee-Nauenberg theorem.
- But it is difficult to get the physical final-state distribution and cross section after cut by considering virtual correction.



How to deal with the dark FSR

✓ **For a small $\boldsymbol{m = m_{A'} = m_s}$**

- For $m \ll \sqrt{s}$, similar to parton shower in the SM, we use dark shower to describe the soft collinear radiation.
- Then the result of dark shower should be merged with the fixed-order result, which describes the non-collinear phase space.



The diagrammatic sketch of the method to deal with the dark FSR.

How to deal with the dark FSR

Dark shower

✓ **Splitting function**

- The differential splitting function $d\mathcal{P}(A' \to s + A')$ quantifies the probability of "finding" a dark Higgs within a dark photon.
- If a final-state dark photon emits a soft collinear dark Higgs, since the propagator A' remains approximately on-shell, the differential cross section with dark FSR can be factorized as:

$$d\sigma(X \to Y + A' + s) \simeq d\sigma(X \to Y + A') \times d\mathcal{P}(A' \to s + A')$$

How to deal with the dark FSR

Dark shower

z: the energy fraction of s relative to mother particle A', $\bar{z} \equiv 1 - z$

p_T: the transverse momentum of s perpendicular to the mother A'

$\tilde{p}_T^2 \equiv p_T^2 + \bar{z} m_s^2 + z m_{A'}^2 - z\bar{z} m_{A'}^2$

✓ **Splitting function**

- Leading power : $(\propto \frac{p_T^2}{\tilde{p}_T^4})$

polarization is altered   splitting kernel

$$\frac{d\mathcal{P}}{dzdk_T^2}(A'_T \to s + A'_L) = \frac{\alpha'}{2\pi} z\bar{z} \frac{p_T^2}{\tilde{p}_T^4},$$

$$\frac{d\mathcal{P}}{dzdk_T^2}(A'_L \to s + A'_T) = \frac{\alpha'}{2\pi} \frac{2z}{\bar{z}} \frac{p_T^2}{\tilde{p}_T^4}.$$

- Next-to-leading power : $(\propto \frac{m_{A'}^2}{\tilde{p}_T^4})$

$$\frac{d\mathcal{P}}{dzdk_T^2}(A'_T \to s + A'_T) = \frac{\alpha'}{2\pi} 2z\bar{z} \frac{m_{A'}^2}{\tilde{p}_T^4},$$

$$\frac{d\mathcal{P}}{dzdk_T^2}(A'_L \to s + A'_L) = \frac{\alpha'}{2\pi} \frac{z\bar{z}}{2} \left(\frac{m_s^2}{m_{A'}^2} + \frac{2(1 - z\bar{z})}{\bar{z}} \right)^2 \frac{m_{A'}^2}{\tilde{p}_T^4}.$$

The following analysis focuses on the leading-power contribution.

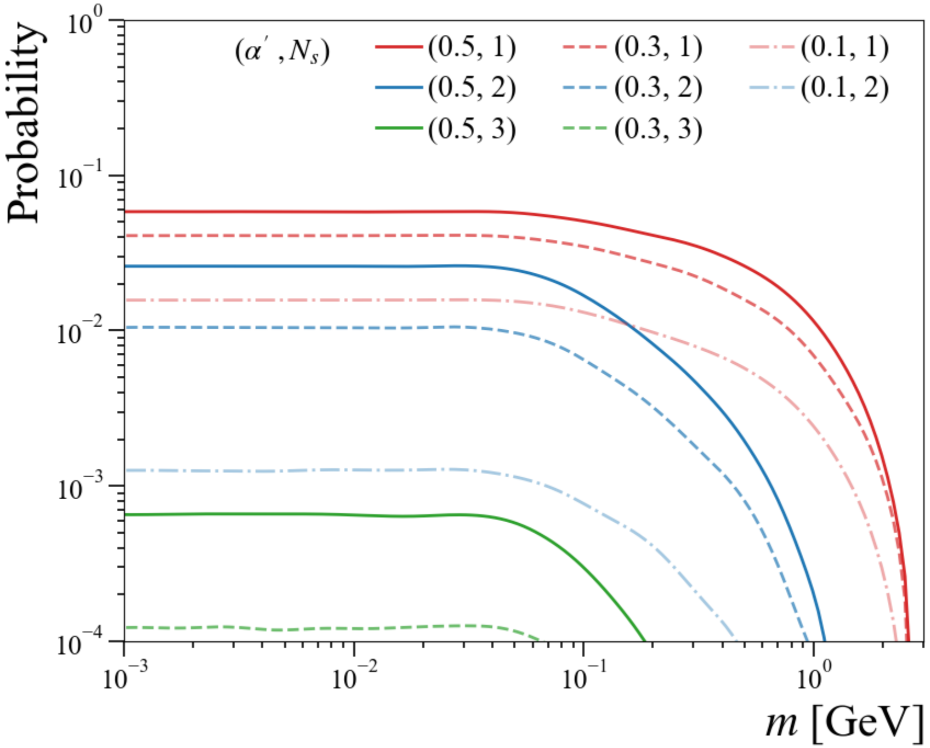
How to deal with the dark FSR

Dark shower

$$P_{A'_T \to s + A'_L}(z) = z\bar{z}$$
$$P_{A'_L \to s + A'_T}(z) = \frac{2z}{\bar{z}}$$

✓ **Dark shower simulation**

- With these splitting kernels, the dark shower can be realized numerically by the veto algorithm implemented in Pythia8.3.
- The dark shower simulation gives the probability to radiate at least one dark Higgs (sh-wiDH), denoted as β.
- The ratio of containing dark Higgs in the final-state to not containing is $\frac{\beta}{1-\beta}$



The probability for a final-state dark photon to radiate N_s dark Higgs bosons given by the parton shower simulation.

- The cross section contributed by dark FSR given by shower is $\sigma_{\text{sh-wiDH}} = \frac{\beta}{1-\beta} \times \sigma_{\text{ME}}(e^+e^- \to \gamma A')$

How to deal with the dark FSR

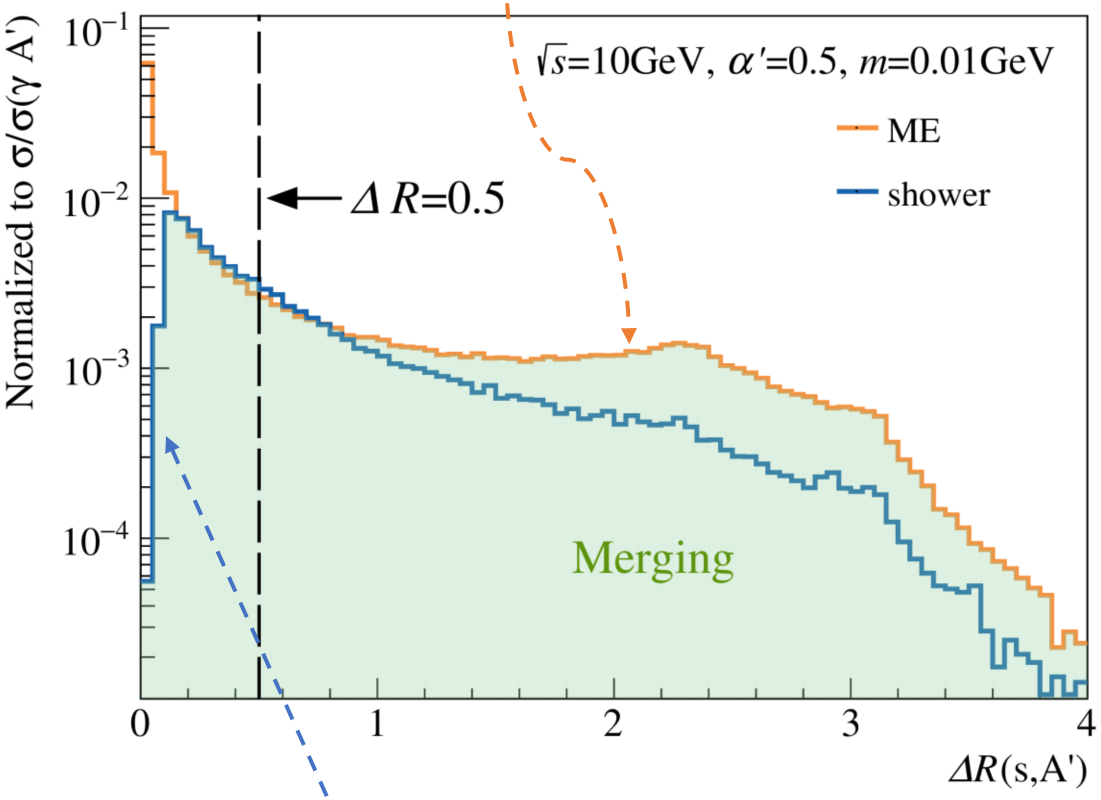
Merging in the dark sector

- Partition the phase space using
  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ between A′ and s.
- Using $\Delta R_{cut} = 0.5$ as the separatrix, and combine the results of shower and the fixed-order calculation of $e^+e^- \to \gamma A's$.
- The cross section contributed by the dark FSR process is

$$\begin{aligned}\sigma_{\rm FSR} \;=\;& P_{\text{sh-wiDH}}(\Delta R < \Delta R_{\rm cut})\sigma_{\text{sh-wiDH}} \\ & + P_{\rm ME}(\Delta R > \Delta R_{\rm cut})\sigma_{\rm ME}(e^+e^- \to \gamma A's)\end{aligned}$$

- The distributions can be given by MC events considering the different weights for the two parts.

MadGraph-generated fixed-order events ($e^+e^- \to \gamma A's$).



PYTHIA-simulated shower events (acquiring at least one dark Higgs in the final-state)

Recast BaBar analysis with dark FSR effects

Search for invisible dark photon at BaBar

- The BaBar collaboration collected data at the PEP-II B-Factory near the $\Upsilon(2S)$, $\Upsilon(3S)$ and $\Upsilon(4S)$ resonance peaks ($\sqrt{s}\sim 10$ GeV), with an integrated luminosity of 53 fb $^{-1}$.
- They derived the exclusion limit on the mixing parameter ε via a maximum likelihood fit to the distribution of M_X^2.
- We quantify the specific impact of the dark FSR on BaBar's exclusion limit under the assumption $\alpha' = 0.5$ and for m in the range [0.001, 2] GeV.

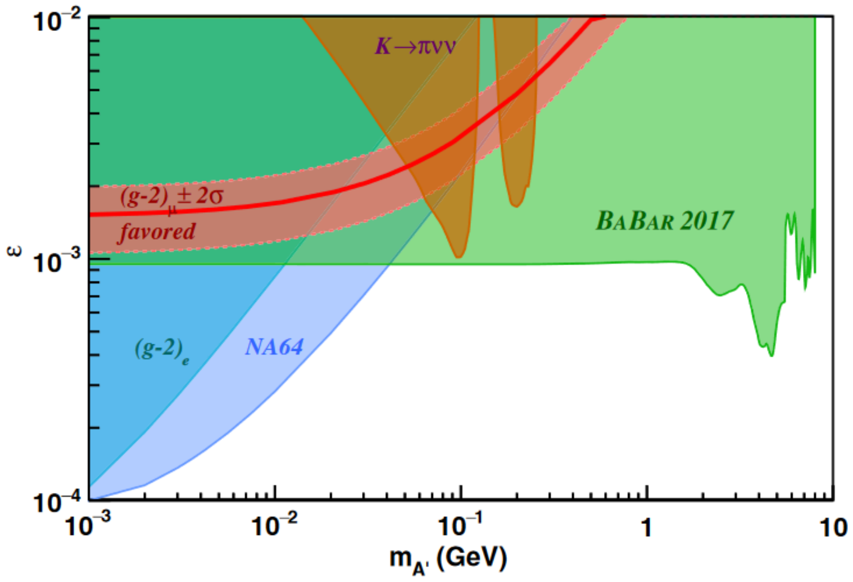


FIG. 5. Regions of the A' parameter space (ε vs $m_{A'}$) excluded by this work (green area) compared to the previous constraints [7,18–20] as well as the region preferred by the $(g-2)_\mu$ anomaly [5].

1702.03327. BaBar collaboration

Recast BaBar analysis with dark FSR effects

Decompose the impact

Since signal count $\propto$ cross section $\propto \varepsilon^2$,

$$N_0 \propto \sigma_{\text{no-FSR}}(\varepsilon = \varepsilon_0) = \varepsilon_0^2 \sigma_{\text{no-FSR}}(\varepsilon = 1)$$

$$N' \propto \sigma_{\text{tot}}(\varepsilon = \varepsilon') = \varepsilon'^2 \sigma_{\text{tot}}(\varepsilon = 1)$$

Upper limit	Without dark FSR	With dark FSR
Signal count	N_0	N'
Mixing parameter	ε_0	ε'

We can separate the impact of the dark FSR into two parts:

- S_{fit}: the correction factor due to the altered signal distribution affecting the fit.
- S_{cxs}: the correction factor from the cross section increase.

$$\frac{\varepsilon'^2}{\varepsilon_0^2} = \underbrace{\boxed{\frac{N'}{N_0}}}_{S_{\text{fit}}} \underbrace{\frac{\sigma_{\text{no-FSR}}(\varepsilon = 1)}{\sigma_{\text{tot}}(\varepsilon = 1)}}_{S_{\text{cxs}}} = S_{\text{fit}} \cdot S_{\text{cxs}}.$$

Recast BaBar analysis with dark FSR effects

Effect of signal distribution

✓ **Probability density function (PDF) of M_X^2 for signal**

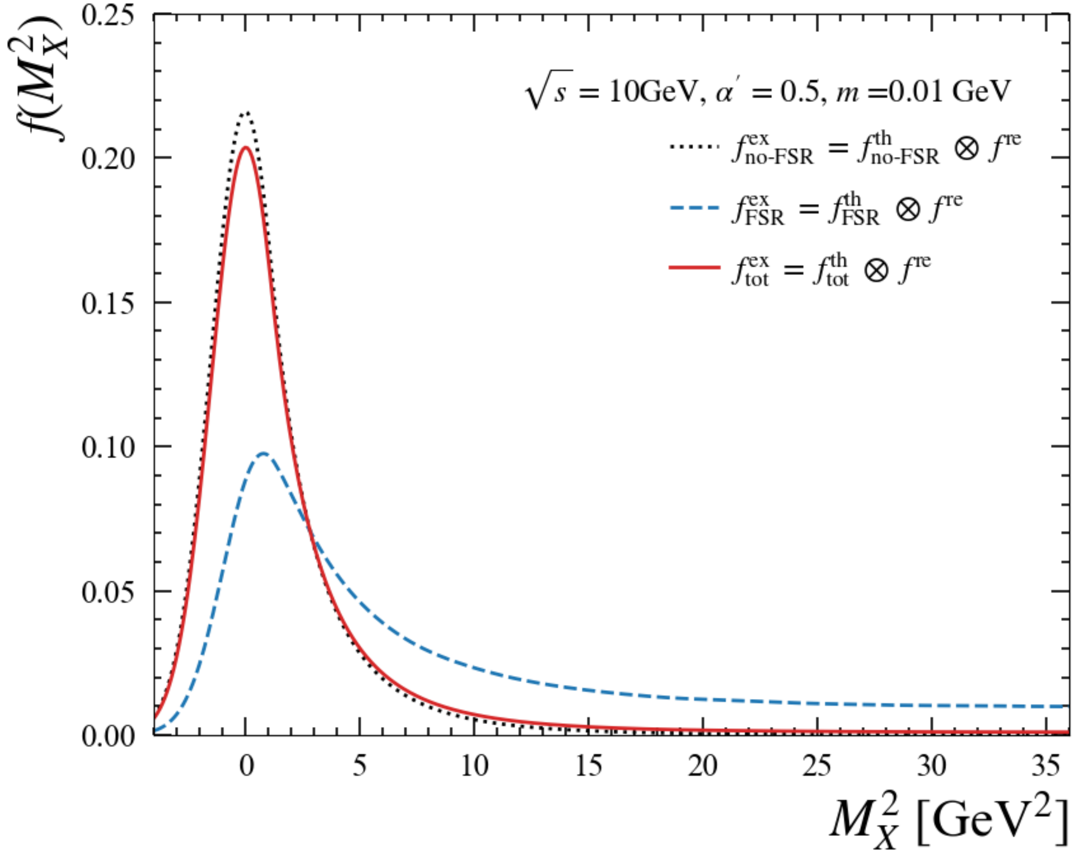
Take $m = 0.01\text{GeV}$ as an example,

Delta function MC simulation

$$f_{\text{tot}}^{\text{th}}(M_X^2) = \lambda f_{\text{no-FSR}}^{\text{th}}(M_X^2) + (1-\lambda) f_{\text{FSR}}^{\text{th}}(M_X^2)$$

$\otimes f^{\text{re}}(M_X^2)$ Crystal Ball function

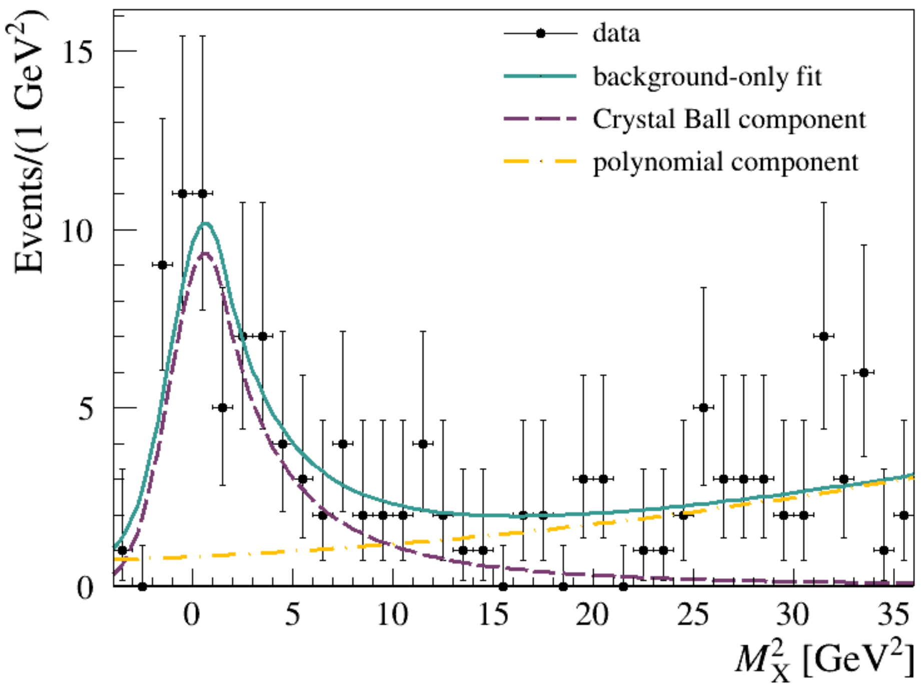
$$f_{\text{tot}}^{\text{ex}}(M_X^2) = \lambda f_{\text{no-FSR}}^{\text{ex}}(M_X^2) + (1-\lambda) f_{\text{FSR}}^{\text{ex}}(M_X^2). \qquad \lambda = \frac{\sigma_{\text{no-FSR}}}{\sigma_{\text{no-FSR}} + \sigma_{\text{FSR}}}.$$



For the Crystal Ball function, the resolution $\sigma(M_X^2) = 1.5\ \text{GeV}^2$, and other parameters are determined by fitting the signal peak in Fig.3 of BaBar.

Recast BaBar analysis with dark FSR effects

Effect of signal distribution



✓ **Data**

For simplicity, we only focus on the region near the $\Upsilon(3S)$ resonance satisfying the $\mathcal{R}'_L$ selection criteria, which contains the most events.

✓ **PDF of M_X^2 for background**

Decompose the background-only fit into

(1) A Crystal Ball function describing the peaking background from $e^+e^- \to \gamma\gamma$;

(2) A second-order polynomial which primarily comes from Bhabha scattering $e^+e^- \to \gamma e^+e^-$.

✓ **The S_{fit} factor**

Perform hypothesis test inversion to obtain the 90% C.L. upper limits on the signal yield.

Then get the value of S_{fit} which is always in the range of 1.03 to 1.04.

Recast BaBar analysis with dark FSR effects

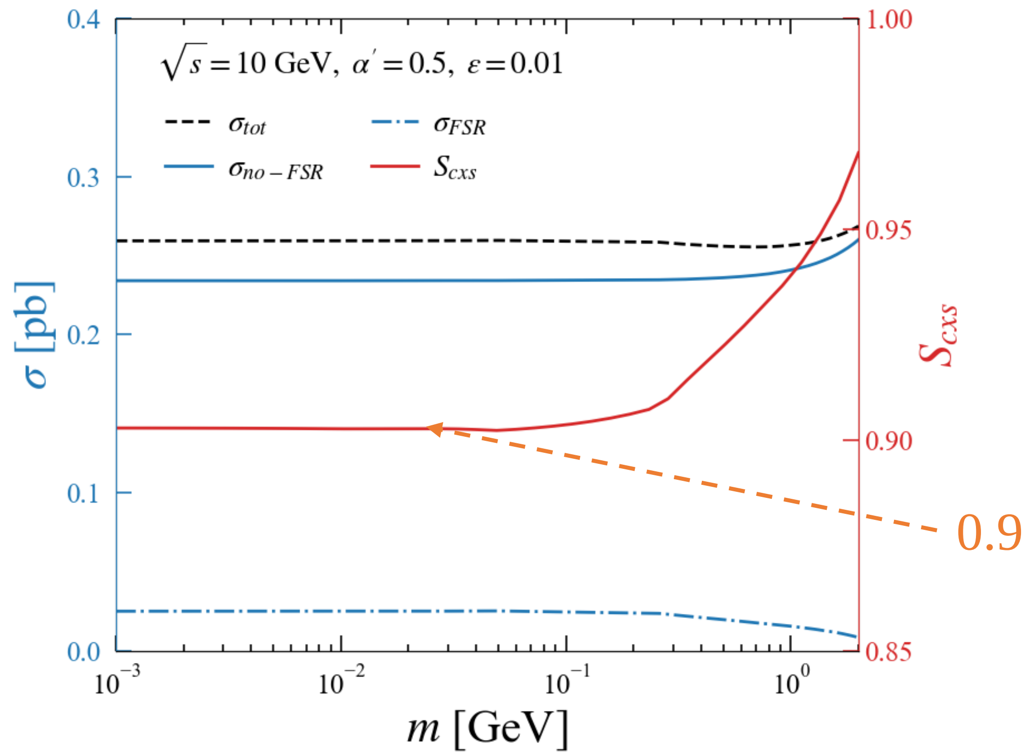
Effect of cross section

$\sigma_{\text{no-FSR}}$

$\downarrow$

$\sigma_{\text{tot}} = \sigma_{\text{no-FSR}} + \sigma_{\text{FSR}}$

$$S_{\text{cxs}} = \frac{\sigma_{\text{no-FSR}}}{\sigma_{\text{tot}}}$$

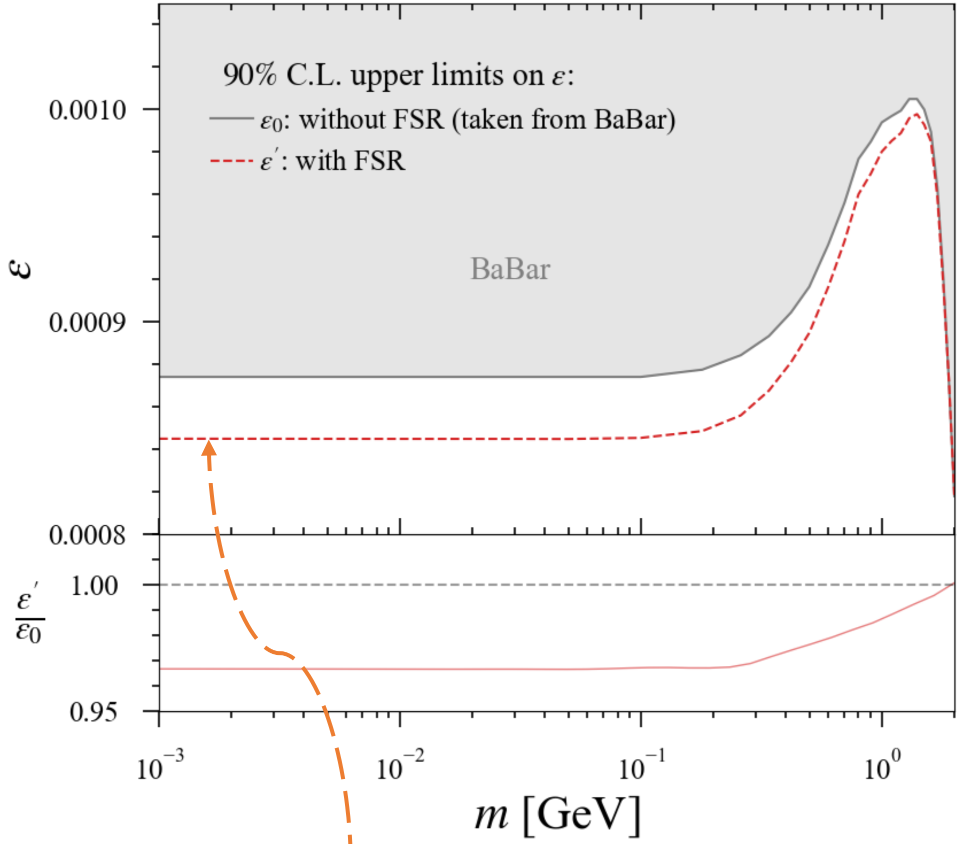


The cross section requiring $E_\gamma > 3$GeV, $|\cos\theta_\gamma| < 0.6$ and $-4 < M_X^2 < 36\ \text{GeV}^2$.

Recast BaBar analysis with dark FSR effects

Limit with dark FSR

$$\frac{\varepsilon'^2}{\varepsilon_0^2} = S_{\text{fit}} \cdot S_{\text{cxs}}.$$



The upper limit is lowered by approximately 3%

Summary

- ✓ For a dark sector model with a spontaneously broken U $(1)'$, it is possible for a high energy dark photon to emit a dark Higgs via dark FSR $A' \rightarrow A's$.
- ✓ For the $e^+e^- \rightarrow \gamma A'$ channel searching for invisible dark photons, we analyzed the impact of the dark FSR from two aspects:
  - The increase of cross section would strengthen the exclusion limit (lowering the upper bound on ε);
  - The broadening of the signal's distribution reduces detection sensitivity, thereby relaxing the constraint.
- ✓ Through a recast of the BaBar experiment, we derived a new exclusion limit with dark FSR on the kinetic parameter ε. Since the cross-section enhancement effect dominates, the new limit is moderately stronger than the original result.

Thanks!