Dark Photon from Light Scalar Boson Decays at FASER

Takashi Shimomura
(Miyazaki U.)

based on

"Dark Photon from Light Scalar Boson Decays at FASER"
JHEP03 (2021), arXiv:2008.12765

in collaboration with

Takeshi Araki (Ohu U.)
Kento Asai (Tokyo U.)
Hidetoshi Otono (Kyushu U.)
Yosuke Takubo (KEK)

March 26th, 2021 @ Higgs as a Probe of New Physics

Introduction

- Non-observation of Dark Matter/BSM leads to the idea of “**dark sector**”.

- No direct interactions between the SM and dark particles.
- Messenger particle (portal) connects two sectors.

Portals

<u>Vector portal</u>, <u>Scalar portal</u>, Heavy neutral lepton portal, Axion portal

dark photon   dark higgs

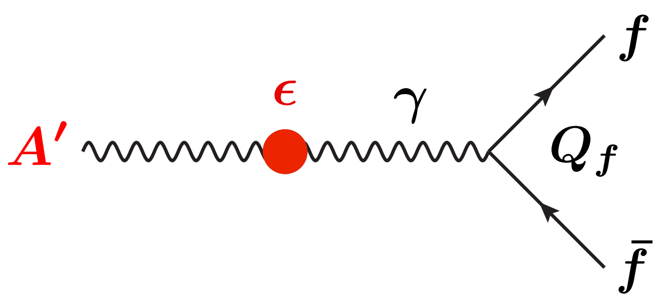
Dark Photon

- Gauge boson of a new U(1)$_{\text{dark}}$ symmetry.
- Mixing with U(1)$_Y$ or U(1)$_{\text{EM}}$ gauge boson

$$\mathcal{L} = -\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

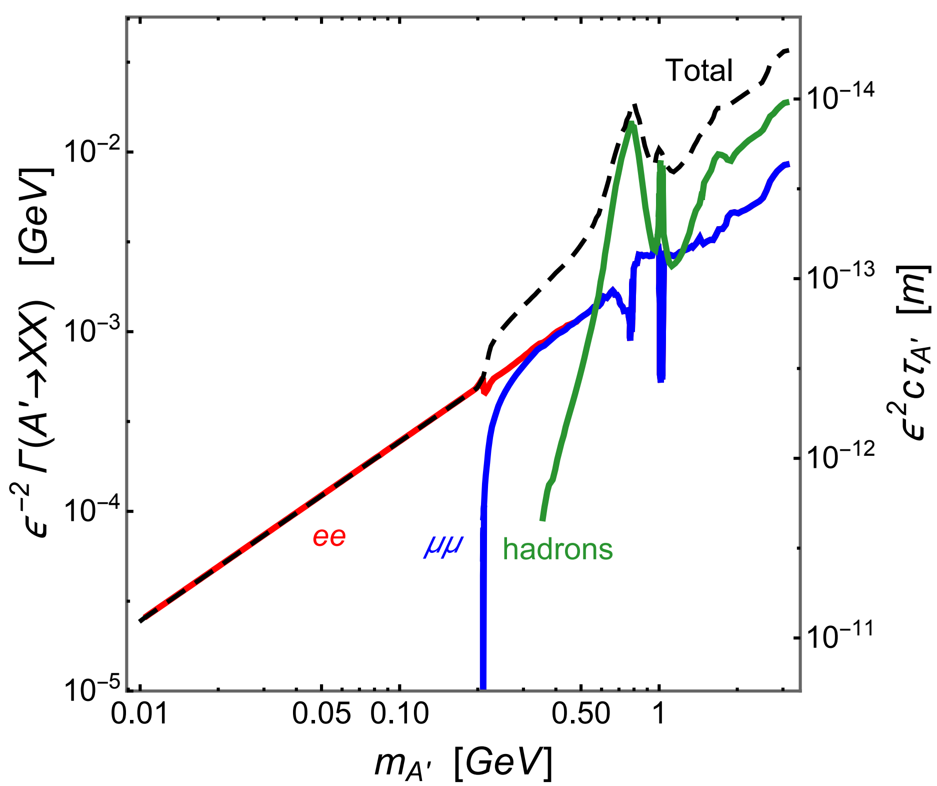
ϵ :gauge kinetic mixing

- Dark Photon (DP, *A'*) can interact with the SM particles via ε.



$$\mathcal{L}_{\text{int}} \supset \epsilon e A'_\mu J^\mu_{\text{EM}}$$

(couple to the EM current)



Dark photon can be long-lived

$\varepsilon \sim 10^{-7}$

↓

$c\tau \sim O(100)$ m

Origin of DP mass

- One of the dynamical origins of the mass is spontaneous breaking.
  - A new scalar boson should be introduced to give a mass.

Dark Higgs kinetic term

$$\mathcal{L} \supset g'^2 \phi^\dagger \phi A'_\mu A'^\mu \xrightarrow[\langle\phi\rangle = v_\phi/\sqrt{2}]{\text{U(1)}_{\text{dark}}\text{ br.}} \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu + g' m_{A'} \phi A'_\mu A'^\mu$$

Direct consequence of the mass generation.

- Dark Higgs decays into *A'A'*
  - Controlled by *g'*, not *ε*.
  - Enhanced when $m_{A'} << m_\phi$.

$$\Gamma(\phi \to A'A') = \frac{g'^2}{8\pi} \frac{m_{A'}^2}{m_\phi} \beta_\phi(A') \left[2 + \frac{m_\phi^4}{4m_{A'}^4} \left(1 - \frac{2m_{A'}^2}{m_\phi^2} \right)^2 \right]$$

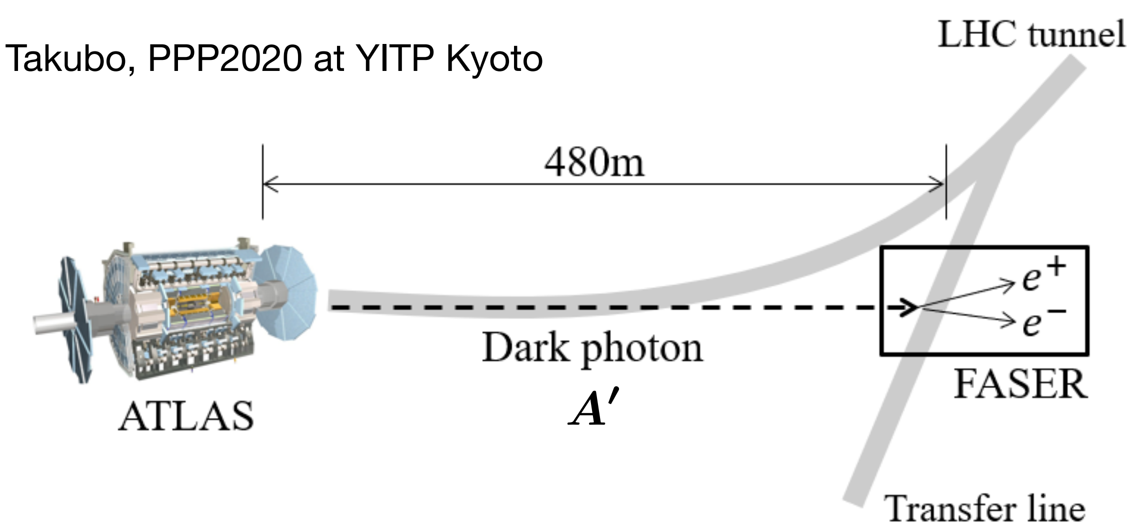
where $\beta_\phi(A') = \sqrt{1 - 4m_{A'}^2/m_\phi^2}$

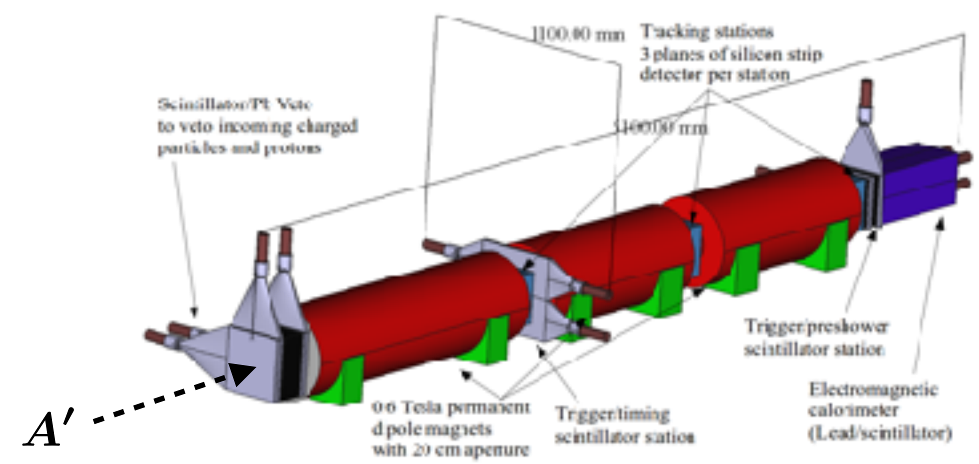
FASER experiment

Feng, Galon, Kling, Trojanowski, PRD97 (2018)
FASER collaboration, arXiv:1708.09389

- ForwArd Search ExpeRiment (FASER) at LHC, starting from 2022.
- Detector is placed 480m downstream from the ATLAS interaction point.
- Search for dark photon, dark Higgs, Axion-like particle, etc.

Takubo, PPP2020 at YITP Kyoto





New light and weakly int. particles preferentially go in forward direction

	$L_{\min}$ (m)	$L_{\max}$ (m)	R (m)	$\mathcal{L}$ (ab^{-1})
FASER	478.5	480	0.1	0.15
FASER 2	475	480	1.0	3.0

DP search at FASER

- Production of dark photon

  meson decays : $\pi^0 \to \gamma A', \ \eta \to \gamma A'$

  proton bremss. : $pp \to pXA'$

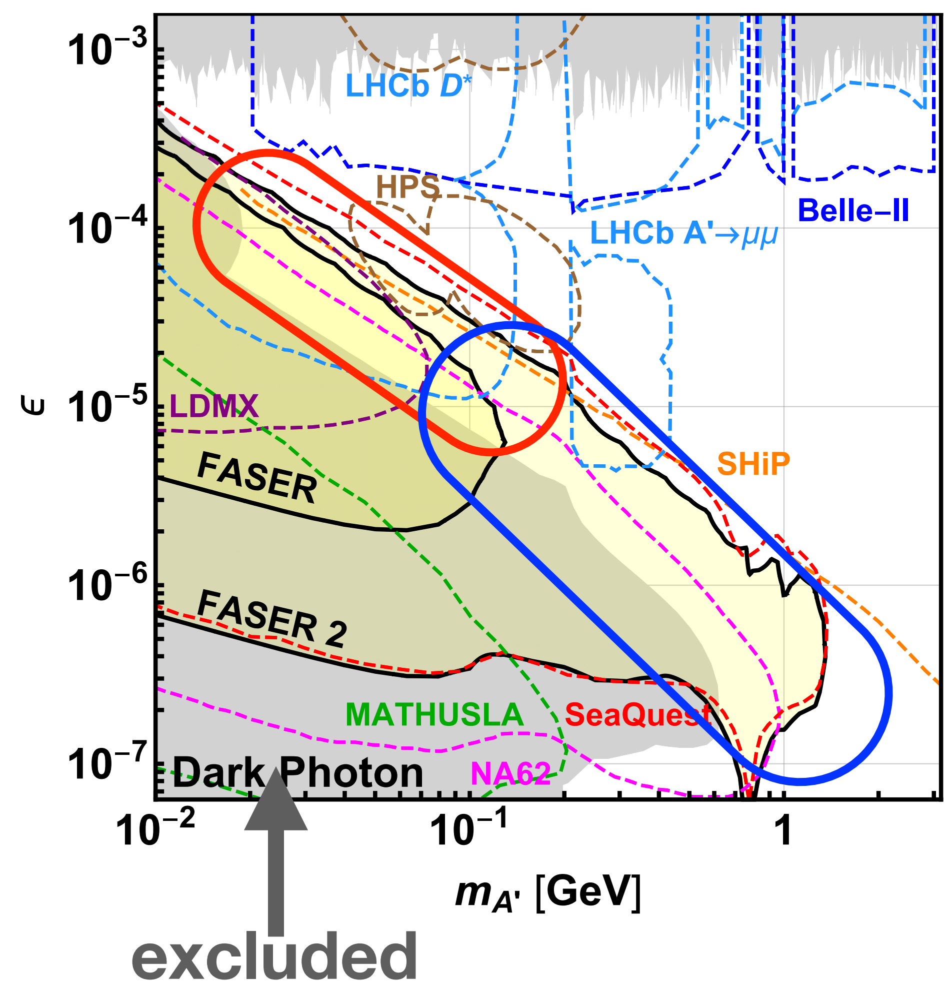
  QCD processes : $q\bar{q} \to gA', \ qg \to qA'$

- Detection

  $A' \to e\bar{e}, \ \mu\bar{\mu}, \ \mathrm{hadrons}$

FASER/FASER 2 can explore parameter region between collider and beam dump exp.

(FASER, PRD99,9, (2019))



95% C.L.

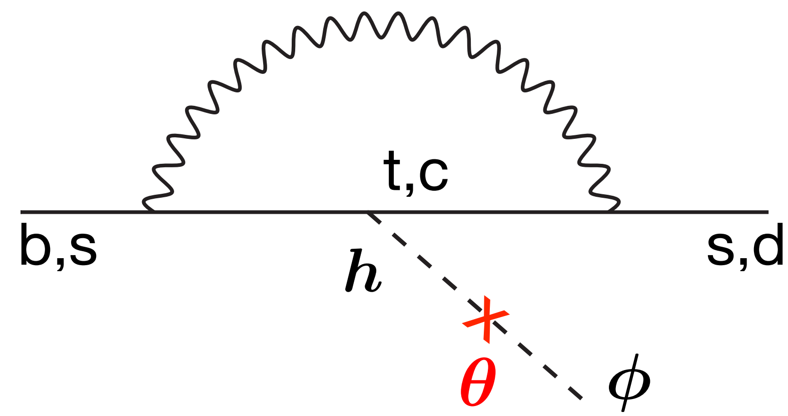
Dark Higgs Production

Feng, Galon, Kling, Trojanowski, PRD97 (2018)

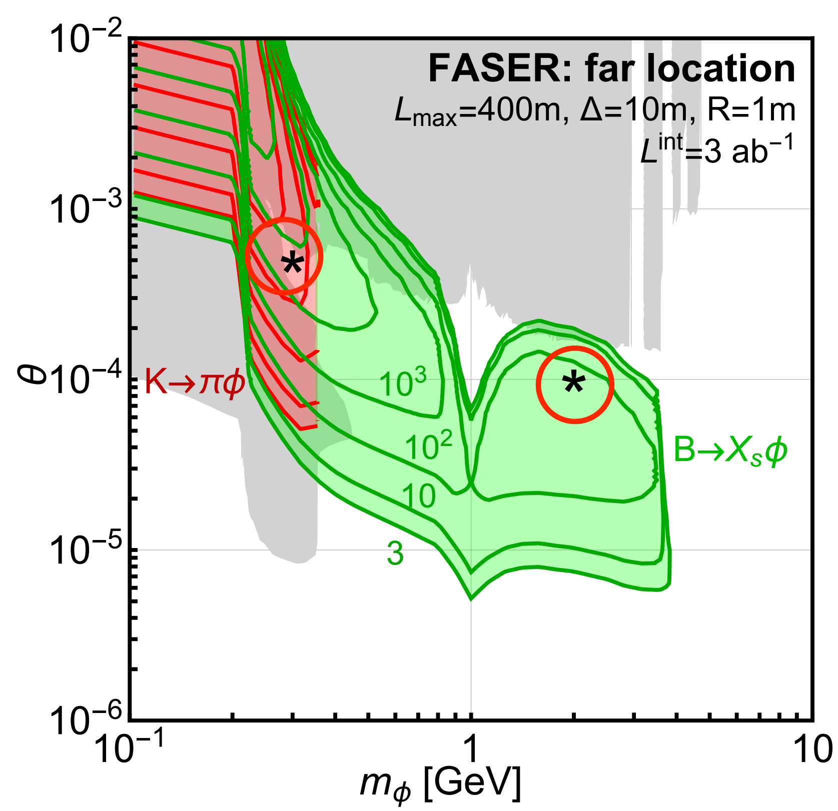
- Dark Higgs is produced from meson decays through the ϕ-h mixing.

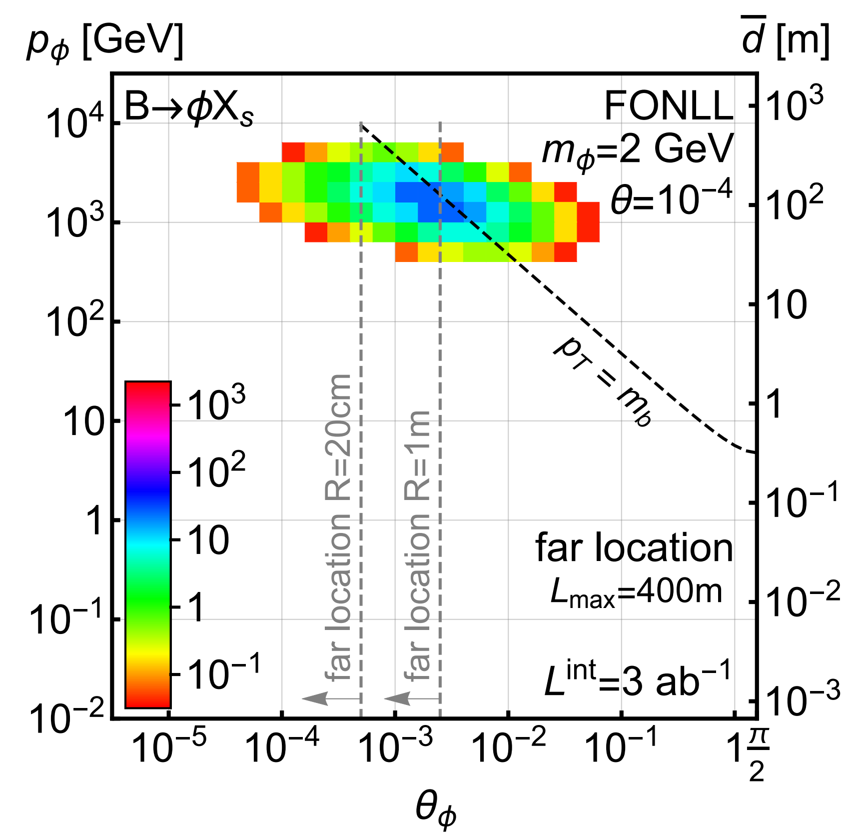
meson decays :

$$B \to X_s \phi$$
$$K \to \pi \phi$$
$$\eta' \to \eta \phi$$



more than 100-1000 DH can be produced



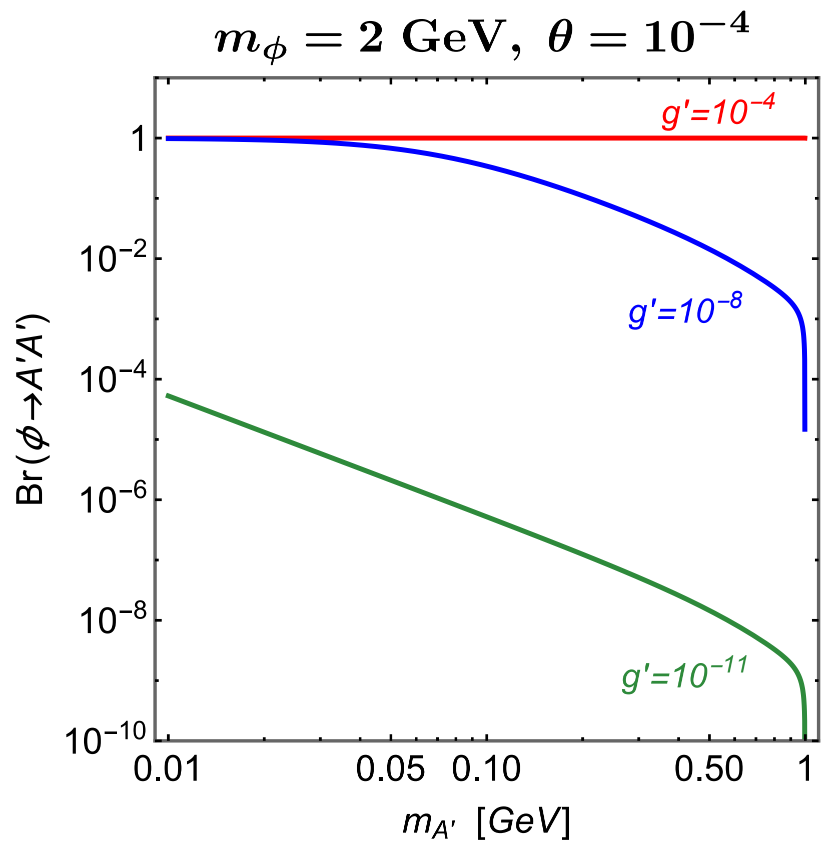


Dark Higgs Decay

Assuming $m_\phi >> m_{A'}, m_f$,

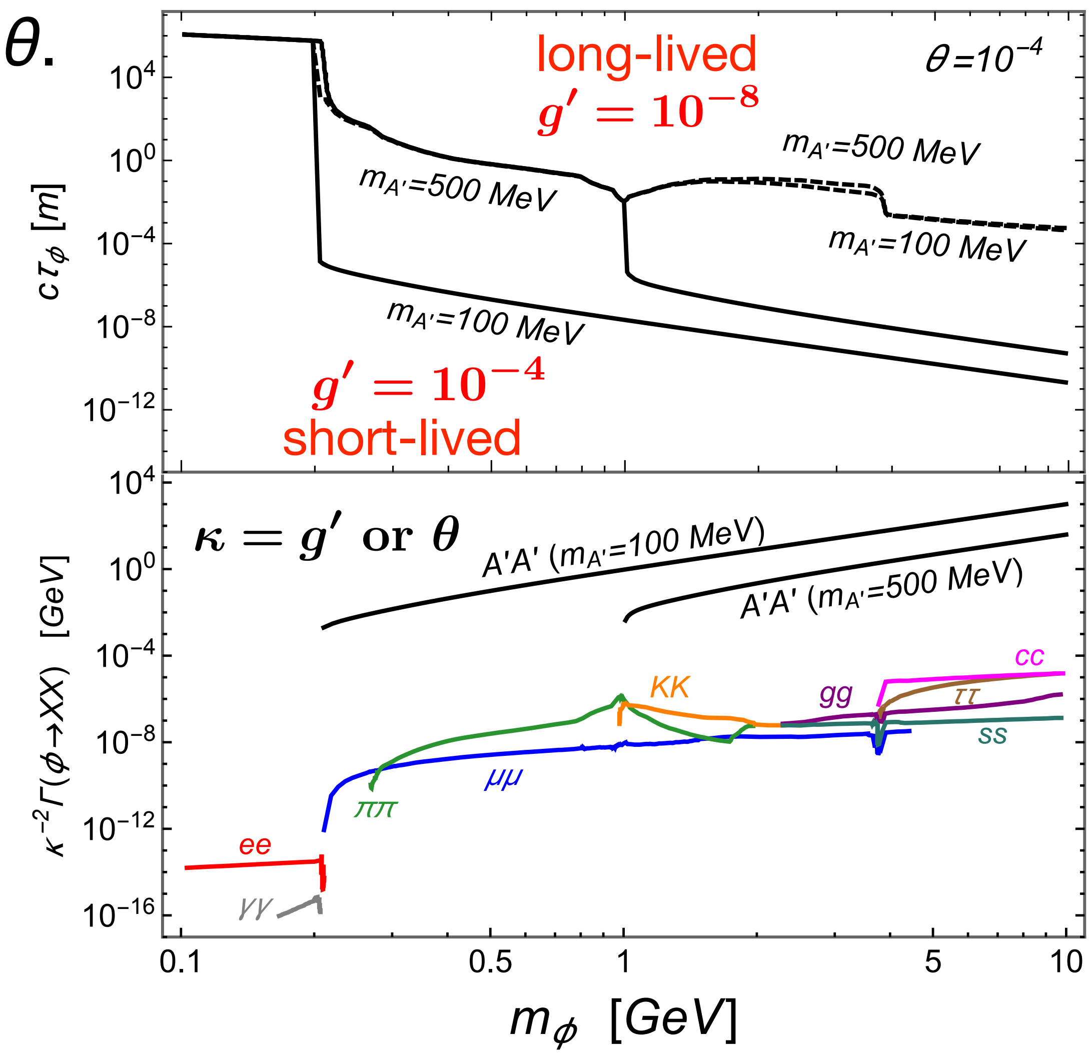
$$\Gamma(\phi \to A'A') \simeq \frac{g'^2}{32\pi}\left(\frac{m_\phi}{m_{A'}}\right)^2 m_\phi$$

$$\Gamma(\phi \to f\bar{f}) \simeq \frac{\theta^2}{8\pi}\left(\frac{m_f}{v}\right)^2 m_\phi$$

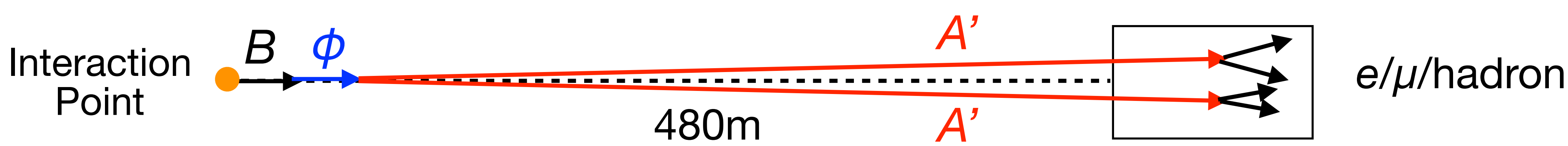


- The scalar mainly decays into DPs for $g' > \theta$.
  New source of DPs
  ⟶ smaller ε can be searched

- The scalar can be long-lived for $g' << \theta$.
  Carrier of dark photon
  ⟶ larger ε can be searched



Short-lived DH at FASER2

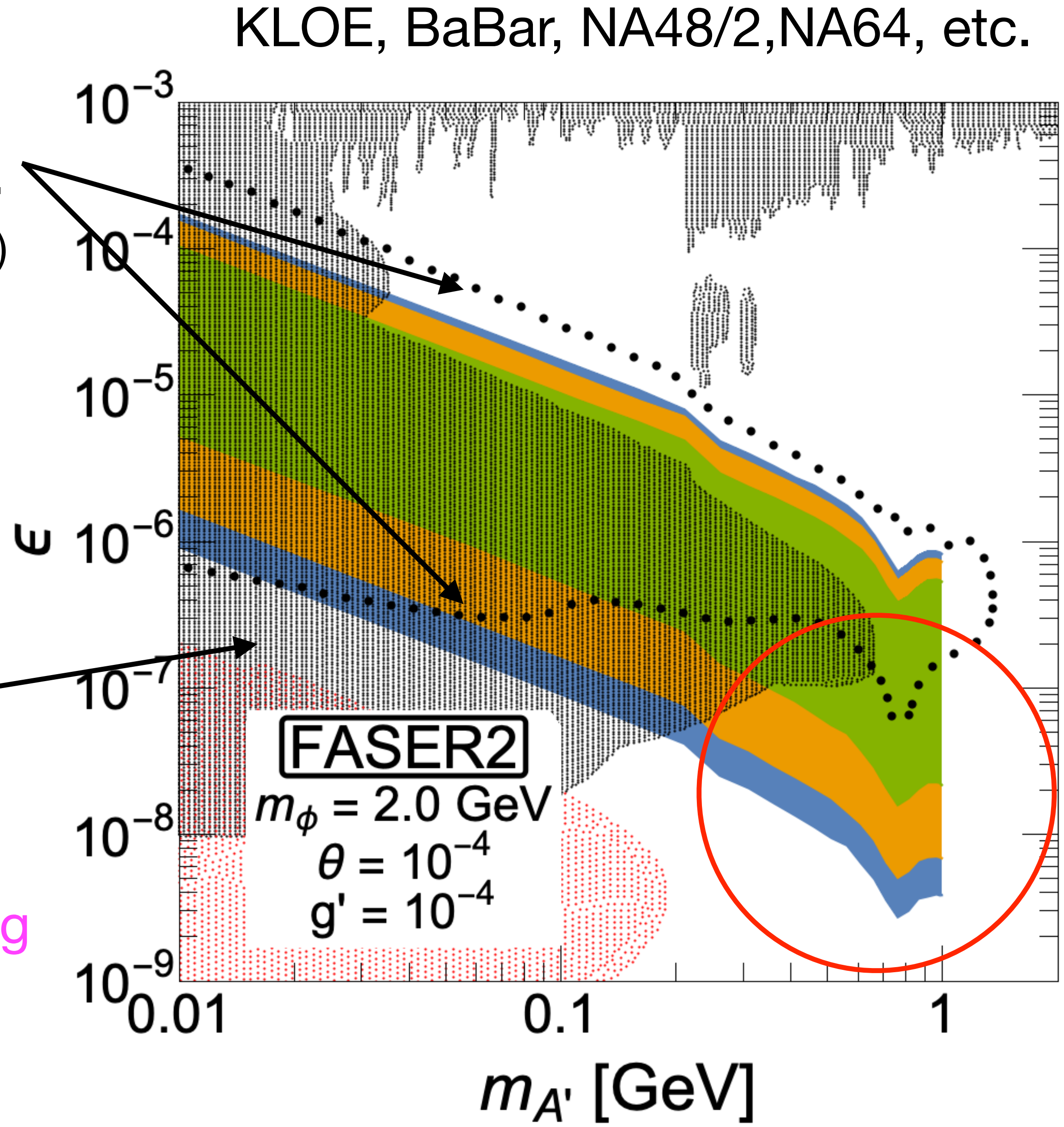


95% C.L. (>3) projected sensitivity only from direct prod.
(FASER, PRD99,9, (2019))

$\pi^0 \to \gamma A',\ \eta \to \gamma A'$
$pp \to pXA'$
$q\bar{q} \to gA',\ qg \to qA'$

NuCal, CHARM, LSND, etc.

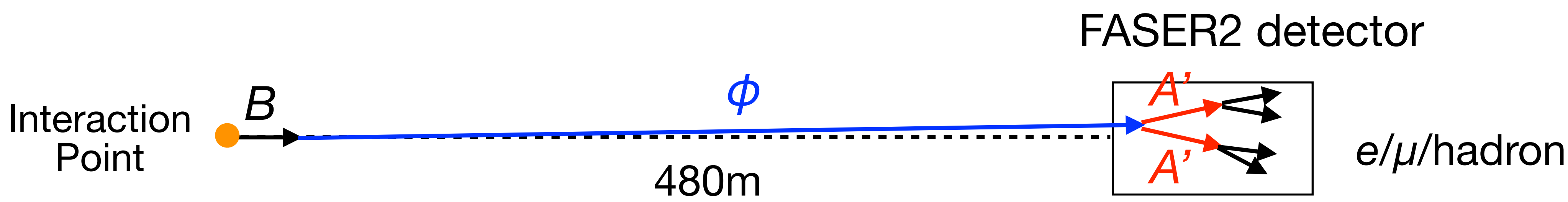
Supernova cooling



Number of A' decays produced from ϕ
- >100
- 10-99
- 3-9

Signal of DP production from ϕ decay

Long-lived DH at FASER2



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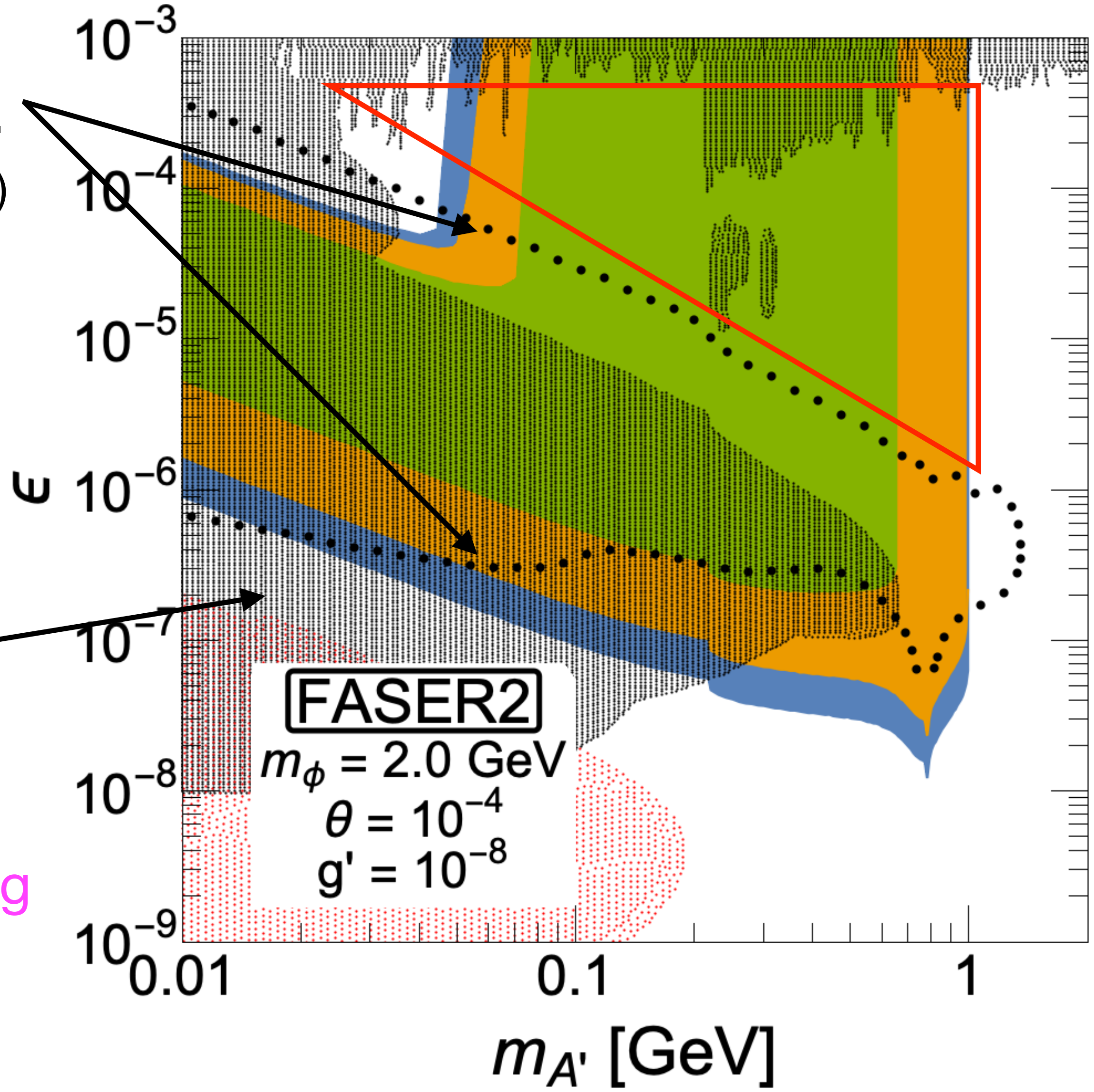
NuCal, CHARM, LSND, etc.

Supernova cooling

KLOE, BaBar, NA48/2,NA64, etc.



Signal of DP production from long-lived ϕ decay

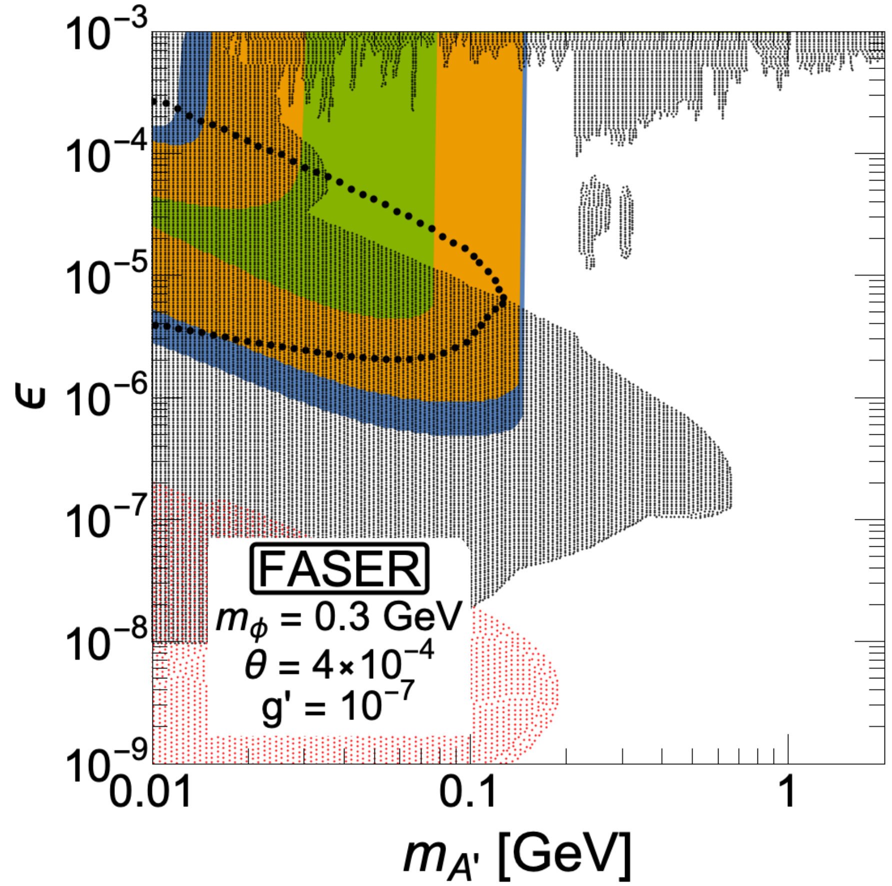
Number of A' decays produced from ϕ

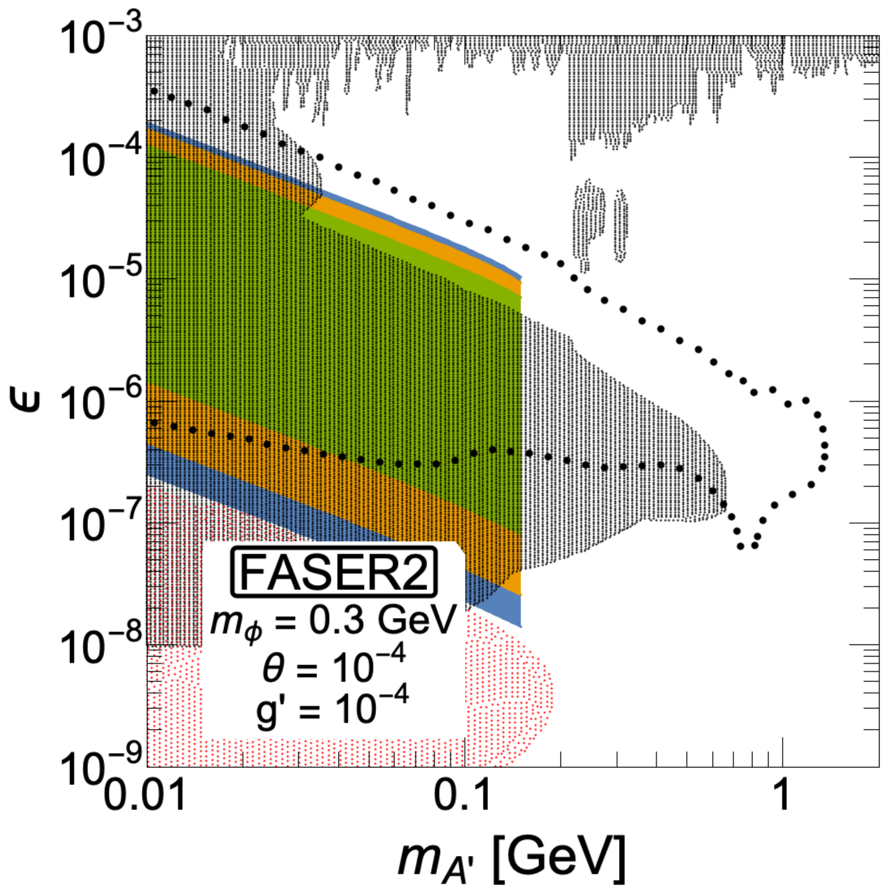
>100

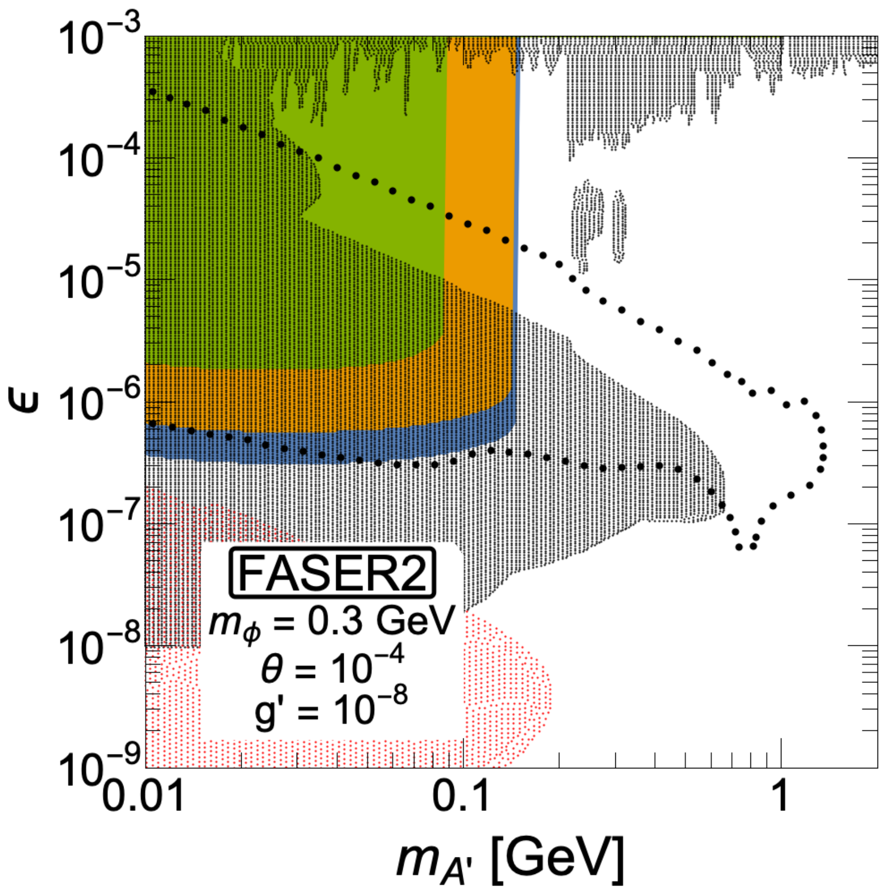
10-99

3-9

Lighter Dark Higgs







Summary

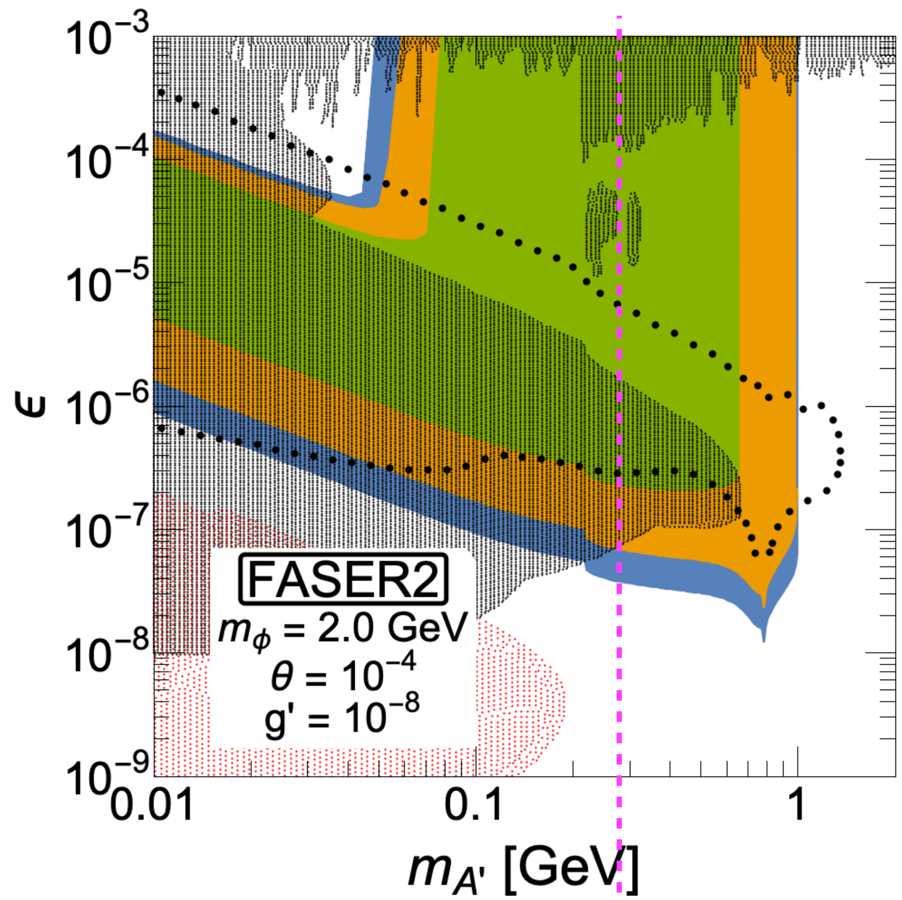
- When dark photon acquires mass from the vev of dark higgs,
  - The DH-DP-DP interaction appears as the consequence of symmetry breaking.
  - The signal can be found in different region for directly produced DPs both in short-lived or long-lived dark Higgs cases.

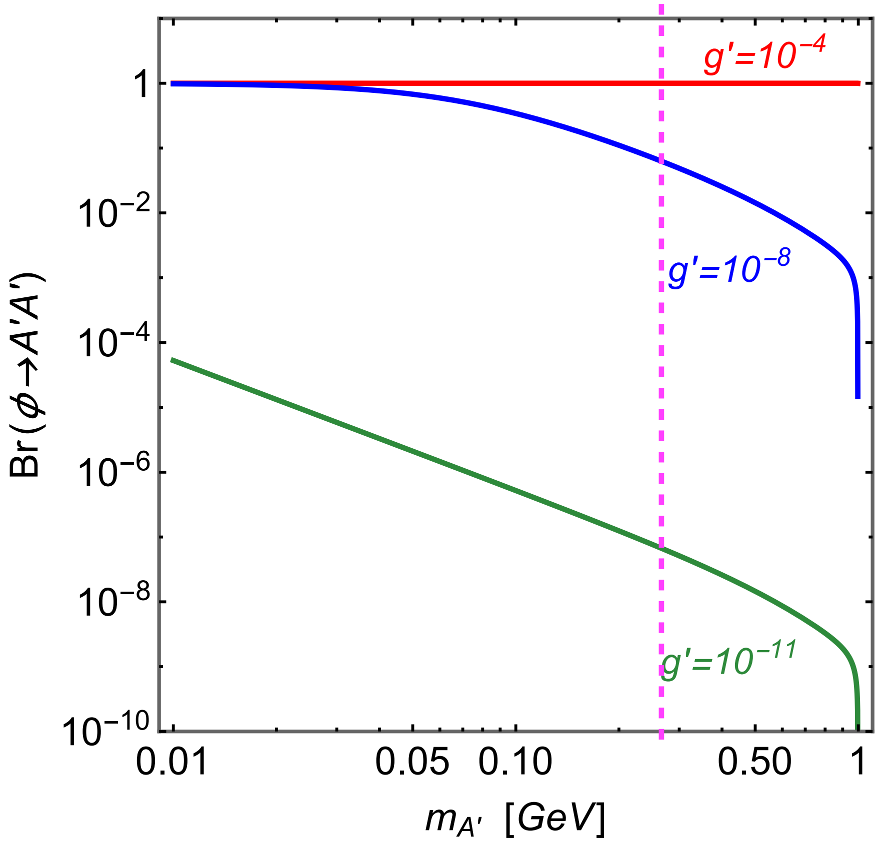
  - The origin of DP mass will be investigated at FASER(2).

Thank you for your attension !

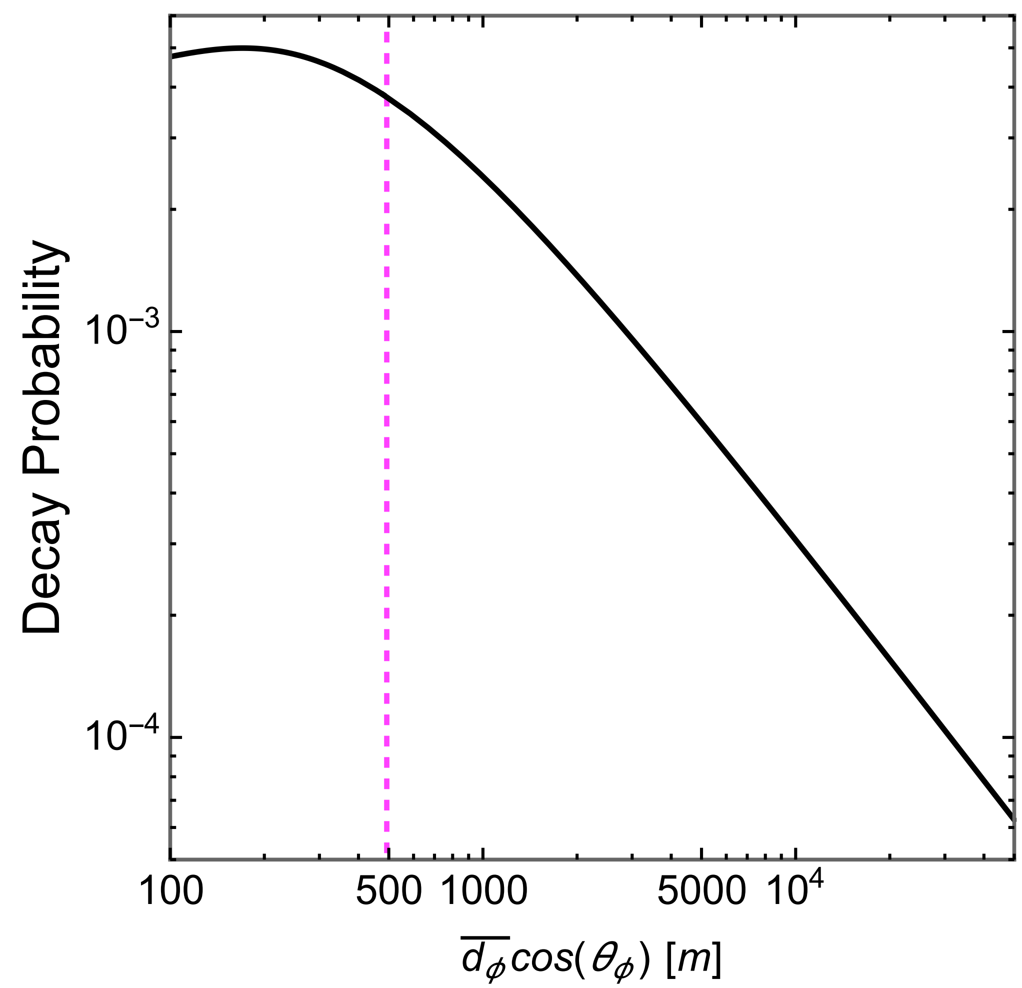
Back-Up Slides

Long-lived at FASER2





decay probability :



Some DP decay inside the detector even it is long-lived.

Signal Calculation

- The ϕ production from mesons is only considered.
- We have calculated the signal of DP decays.
  (using data of B meson production provided by Felix Kling, thanks!)

$$
\begin{aligned}
N &= \mathcal{L} \int d\boldsymbol{p}_{A'} \frac{d\sigma_{pp\to A'X}}{dp_{A'}d\theta_{A'}} \mathcal{P}^{\rm det}_{A'}(\boldsymbol{p}_{A'}, \boldsymbol{p}_\phi) \\
&= \mathcal{L} \sum_{i:\text{meson}} \sum_{j=1,2} \int dp_i d\theta_i \int d\boldsymbol{p}_{A'} \int d\boldsymbol{p}_\phi \frac{d\sigma_{pp\to iX}}{dp_i d\theta_i} \text{Br}(i \to \tilde{X}\phi)\text{Br}(\phi \to A'_1 A'_2) \\
&\quad \times \mathcal{P}^{\rm det}_{A'_j}(\boldsymbol{p}_{A'}, \boldsymbol{p}_\phi) \ ,
\end{aligned}
$$

with

decay probability : $\mathcal{P}^{\rm det}_{A'}(\boldsymbol{p}_{A'}, \boldsymbol{p}_\phi) = \dfrac{1}{\bar{d}_\phi \cos\theta_\phi} \displaystyle\int_{z_{\phi,\min}}^{z_{\phi,\max}} dz_\phi e^{-\frac{z_\phi}{\bar{d}_\phi \cos\theta_\phi}} \dfrac{1}{\bar{d}_{A'} \cos\theta_{A'}} \int_{z_{A',\min}}^{L_{\max}} dz_{A'} e^{-\frac{z_{A'}-z_\phi}{\bar{d}_{A'}\cos\theta_{A'}}}$

$$
\times \Theta(R - r_{A',R})\Theta(R - r_{A',F}),
$$

- Cut $p_{A'} > 100$ GeV is imposed.

Beam Dump Exp.

Special thanks Felix and Sebastian

For m_ϕ = 2 GeV, θ=10^{-4}

- CHARM experiment
  - proton beam energy : 400 GeV

    $N_{pot} = 2\times10^{18} \longrightarrow N_{\phi\ total} = 3.0\times10^{4}$ ($N_B = 6.4\times10^{11}$)

    Alekhin et al, 1504.04855
  - The detection probability

    P ~10^{-4} for $0.068 < \theta_{det} < 0.0126$

    Dobrich et al, 1512.03069

    $\longrightarrow N_{A'} = 6.0\times10^{4}\times10^{-4} = 6$

- NuCal experiment
  - proton beam energy : 70 GeV

    $N_{pot} = 1.7\times10^{18} \longrightarrow N_{\phi\ total} = O(10)$ (Bremsstrahlung)
  - The detection probability

    Batell et al, 2008.08108

    P ~10^{-1} for $\theta_{det} < 0.015$

    $\longrightarrow N_{A'} = O(1)$

might not be significant, but need more detailed analyses