Dark photon pair production via off-shell dark Higgs at FASER

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arXiv:2406.17760

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14th workshop of the Long-Lived Particle Community

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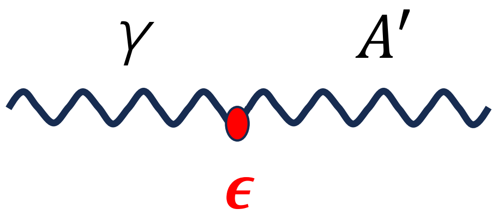
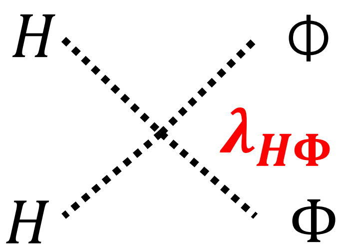
Introduction

- Non-observation of dark matter implies dark sector idea.
- Portal mediates Standard Model sector and dark sector.

portal to dark sector from Standard Model sector

example : kinetic mixing between photon and dark photon,
mixing between Higgs and dark Higgs





etc.

mediator particles are long-lived

origin of dark photon mass

origin of dark photon mass

・**spontaneously symmetry breaking of dark Higgs(our case)**

・Stuckelberg mechanism　etc

dark sector Lagrangian

$$L_{DS} = -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \left| \mathrm{D}_\mu \Phi \right|^2 - V(\Phi), \ \ F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu,$$

$$D_\mu = \partial_\mu - i g' A'_\mu \ , \quad \Phi = \langle \Phi \rangle + \phi/\sqrt{2}$$

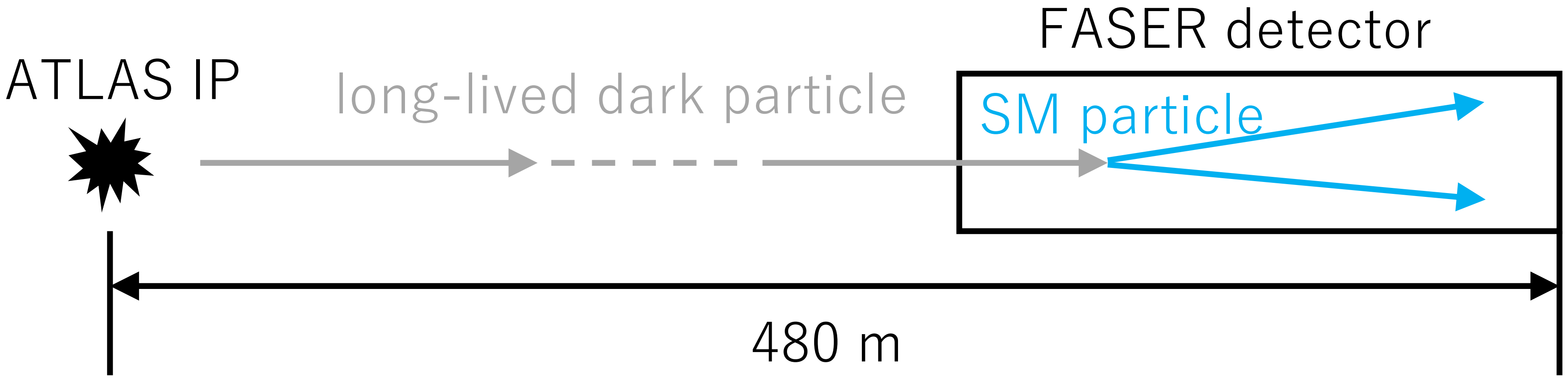
g' : extra U(1) gauge coupling,　A' : dark photon,

ϕ : dark Higgs as origin of dark photon mass

FASER(started from 2022)

FASER detector is 480 meters away from ATLAS interacrion point(IP) along with proton beam axis.

→ **FASER is suitable for long-lived particle search**.



FASER is planned to upgrade to FASER2 at HL-LHC.

Dark photon and dark Higgs have been well studied at FASER.

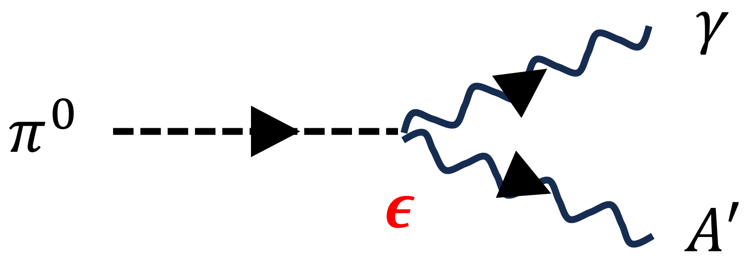
Felix Kling et al. Phys. Rev. D 97 (2018) 5, 055034, A. Ariga et al. Phys. Rev. D 99 (2019) 9, 095011

Main dark photon production process at FASER

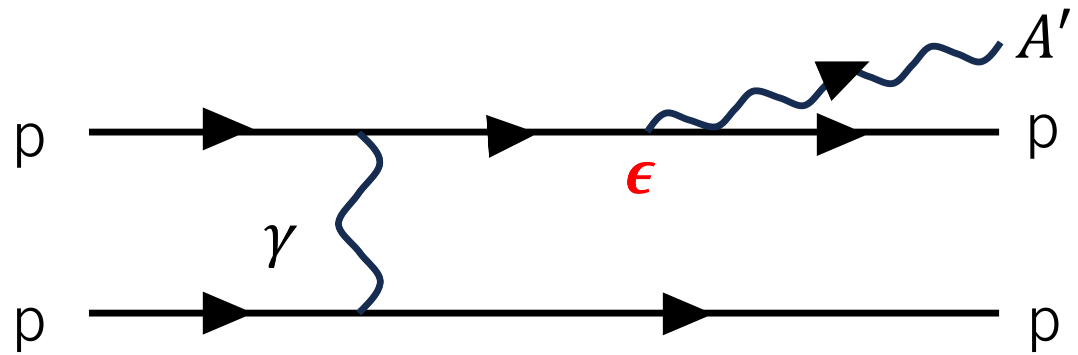
① meson decay(mainly π^0)

pp collision → meson,

meson decay → dark photon



② dark bremsstrahlung



③ **dark Higgs decay**

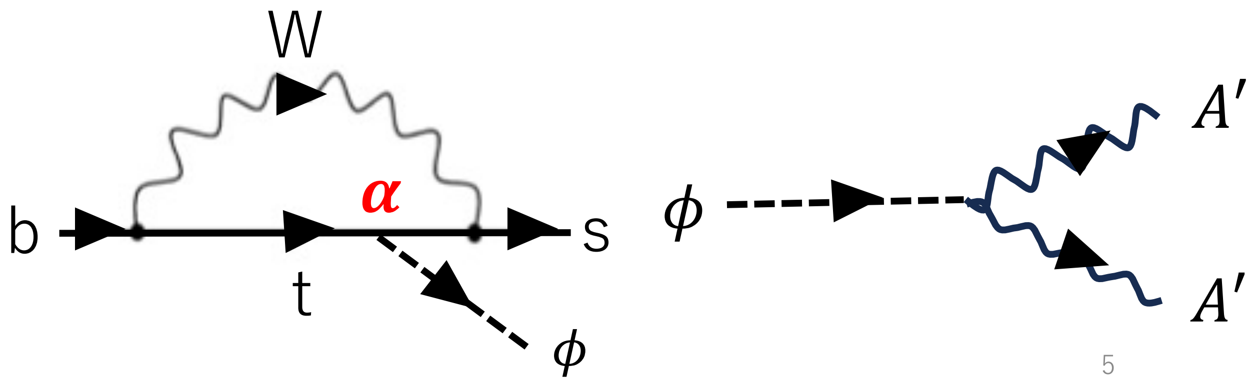
pp collision → meson,

meson decay(mainly B)

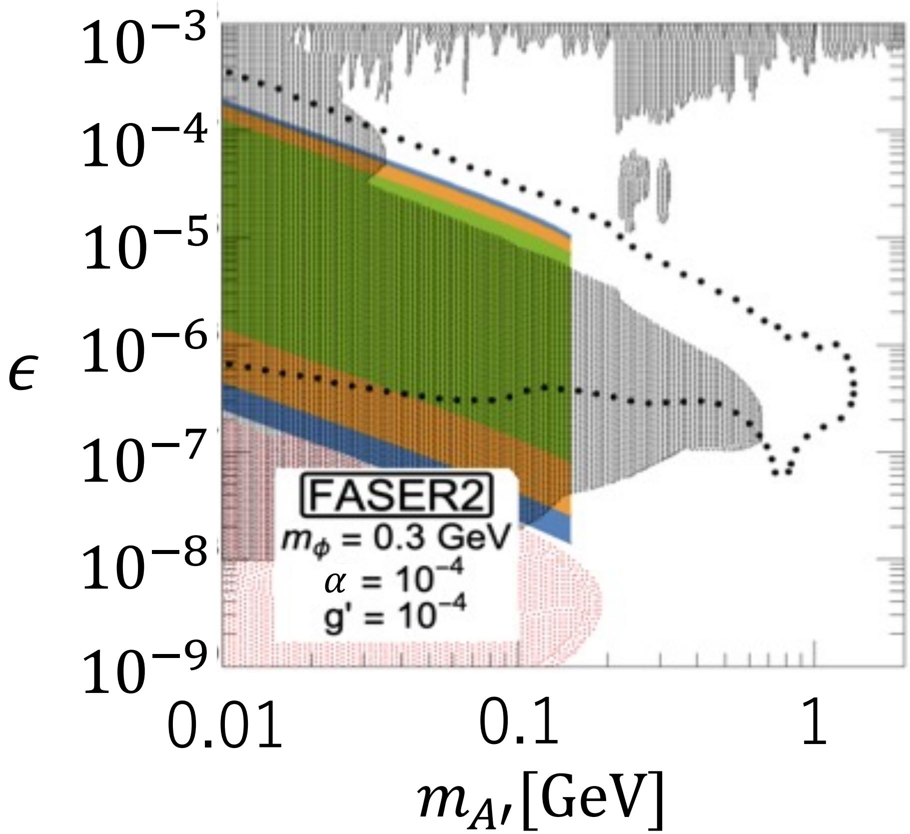
→ dark Higgs,

dark Higgs decay

→ dark photon



Dark photon sensitivity at FASER2



dotted line ....

from meson decay and dark bremsstrahlung(①, ②)

A. Ariga et al. Phys. Rev. D 99, 095011 (2019)

colored region

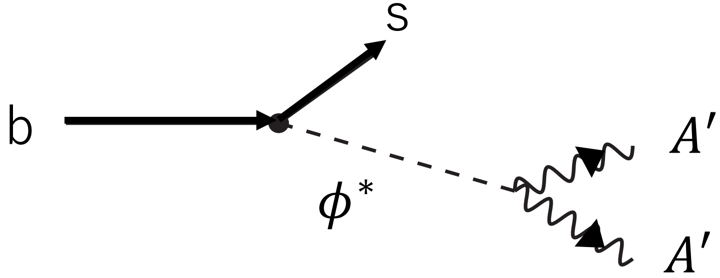
from dark Higgs decay(③)

T. Araki et al. JHEP03(2021)072

Sensitivity region closes at $m'_A = m_\phi/2$.

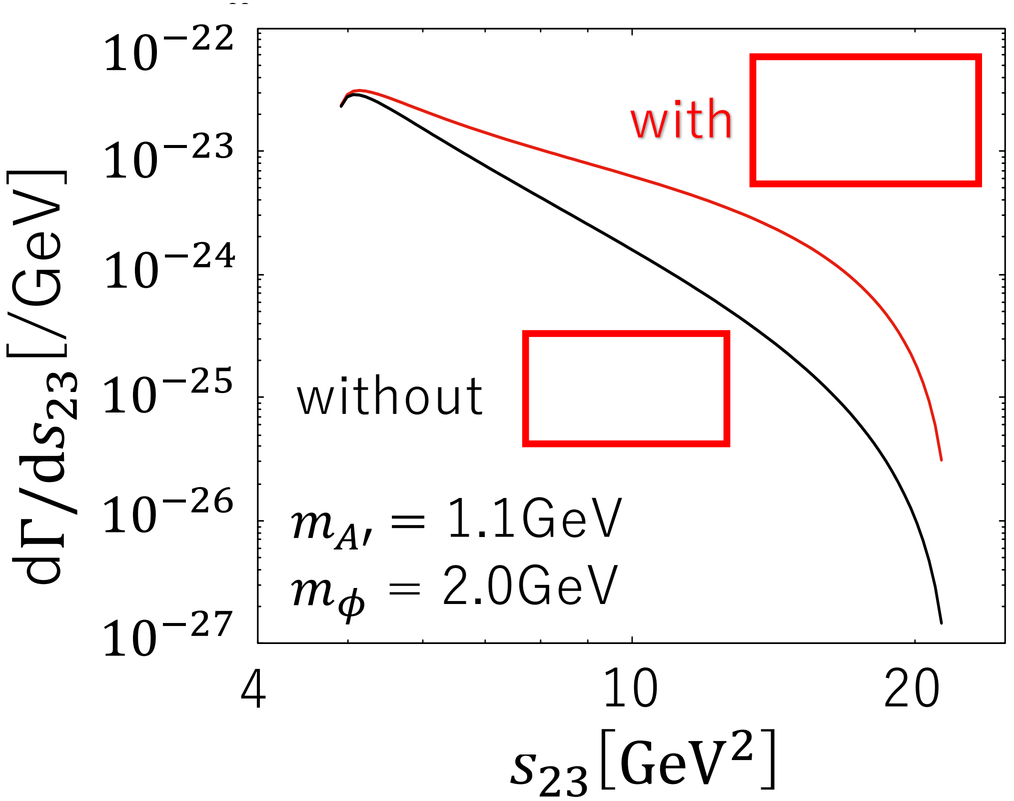
→ contribution of off-shell dark Higgs?

Dark photon production from **off-shell** dark Higgs decay



$$k^\mu = (E, 0, 0, k),$$

$$\epsilon_L^\mu(k) = \left(\frac{k}{m_{A'}}, 0, 0, \frac{E}{m_{A'}}\right)$$



$$\frac{\mathrm{d}\Gamma}{\mathrm{d}s_{23}}(b \to sA'A') \propto \frac{1}{(s_{23} - m_\phi^2)^2 + m_\phi^2\Gamma_\phi^2}\left[2 + \left(\frac{s_{23}}{2m_{A'}^2} - 1\right)^2\right]$$

R .S. Chivukula and A. V. Manohar

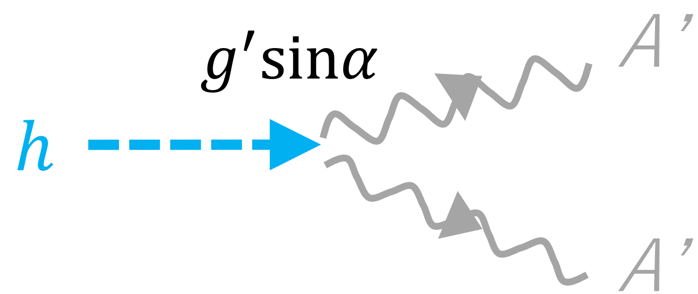
longitudinal enhancement

s_{23} : square of dark Higgs momentum

$$4m_{A'}^2 < s_{23} < (m_b - m_s)^2$$

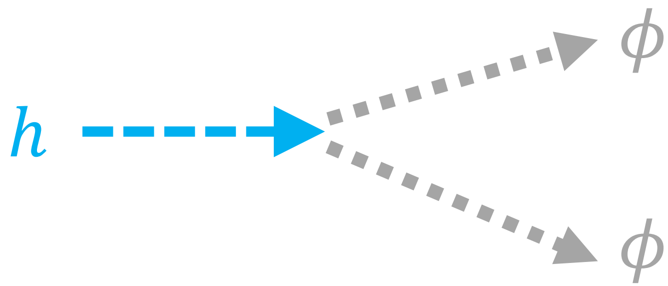
Constraints from Higgs → invisible ①

- SM Higgs can decay into dark photons or dark Higgs.
- **Dark Higgs and dark photon are invisible at ATLAS and so on due to their long lifetime.**



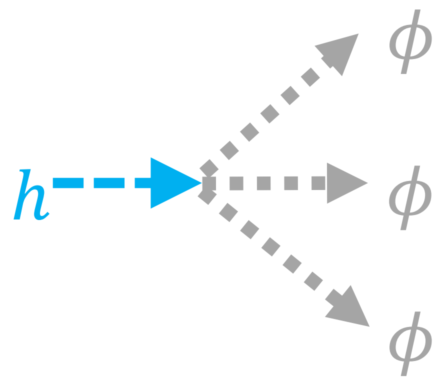
$\Gamma(h \to A'A') \propto \frac{m_h^3}{m_{A'}^2} g'^2 \sin^2\alpha$

longitudinal enhancement



$\Gamma(h \to \phi\phi) \propto \frac{m_h^3}{m_{A'}^2} g'^2 \sin^2\alpha$

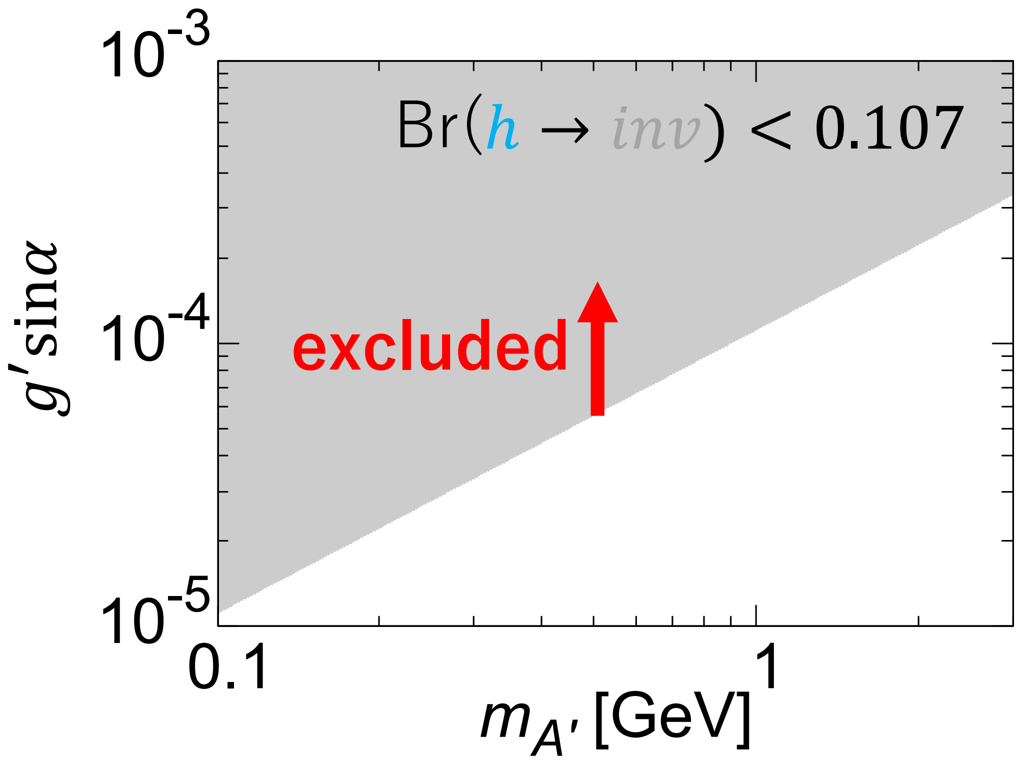
$h\phi\phi$ coupling $\propto \frac{m_h^2}{m_{A'}} g'\sin\alpha$

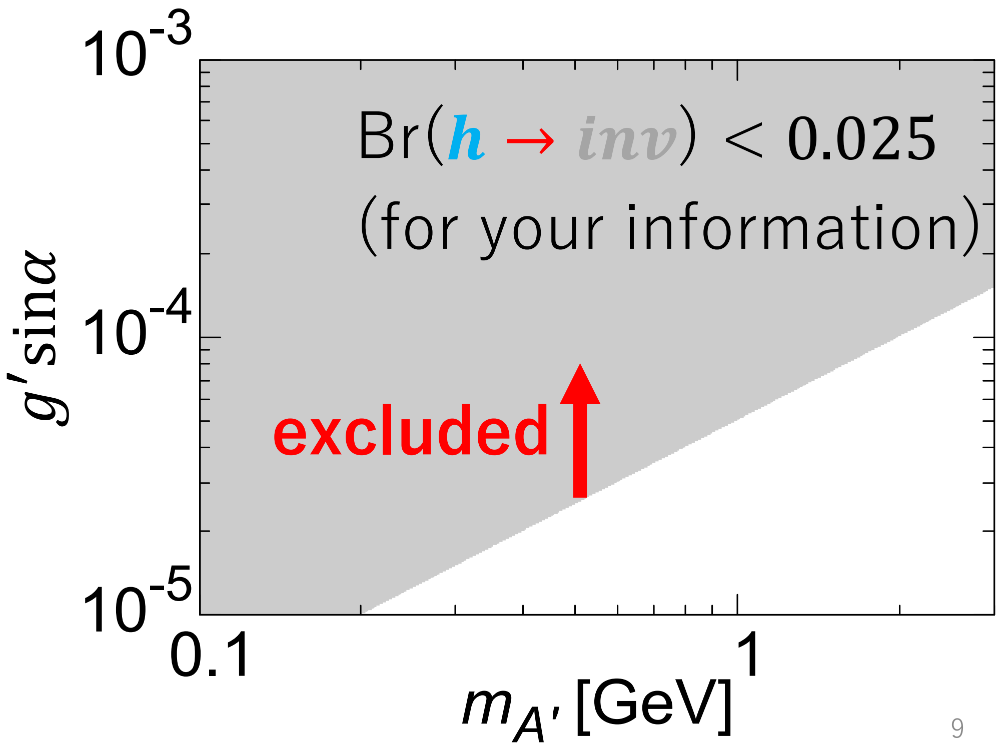


phase space suppression

Constraints from Higgs → invisible ②

- **From Br$(h \to inv) < 0.107$ (PDG) , $g' \sin\alpha$ is constrained.**
- Upper bound on Br$(h \to inv)$ is expected to be Br$(h \to inv) < 0.025$ at HL-LHC. “Snowmass White Paper Contribution: Physics with the Phase-2 ATLAS and CMS Detectors”, (2022)





Constraints from perturbative unitarity①

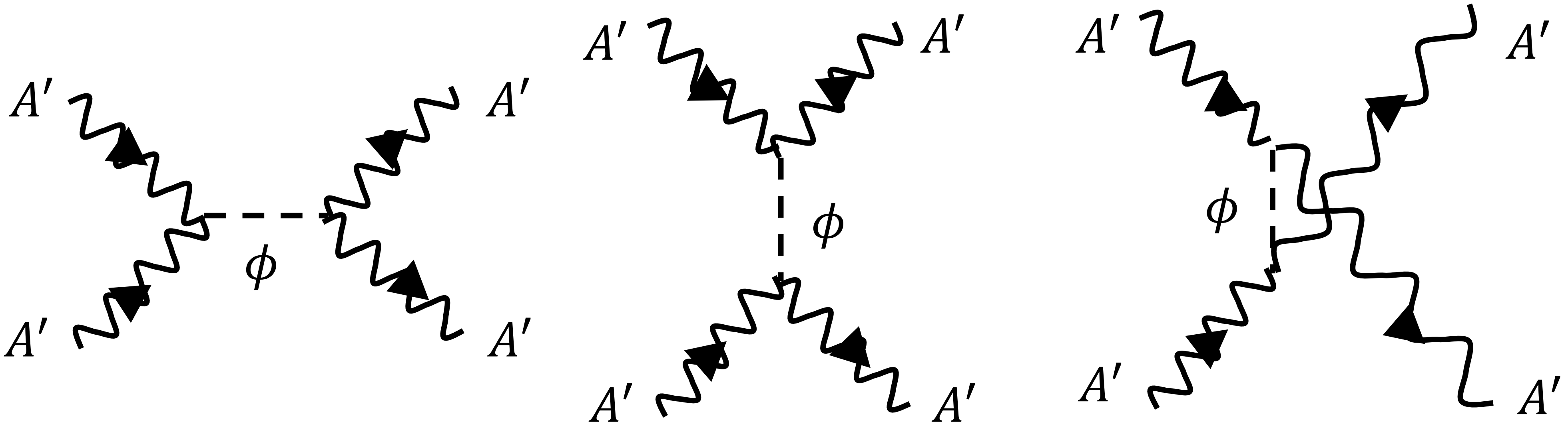
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}s_{23}}(b \to sA'A') \propto \frac{s_{23}^2}{m_{A'}^4}$$

For too light $m_{A'}$, is decay width too enhanced ?

→ check by considering perturbative unitarity B, Lee et al. Phys. Rev. D40, 1145, (1977)

calculate two-body scattering amplitude in dark sector at tree level

example : $A'A' \to A'A'$ diagrams(unitary gauge)

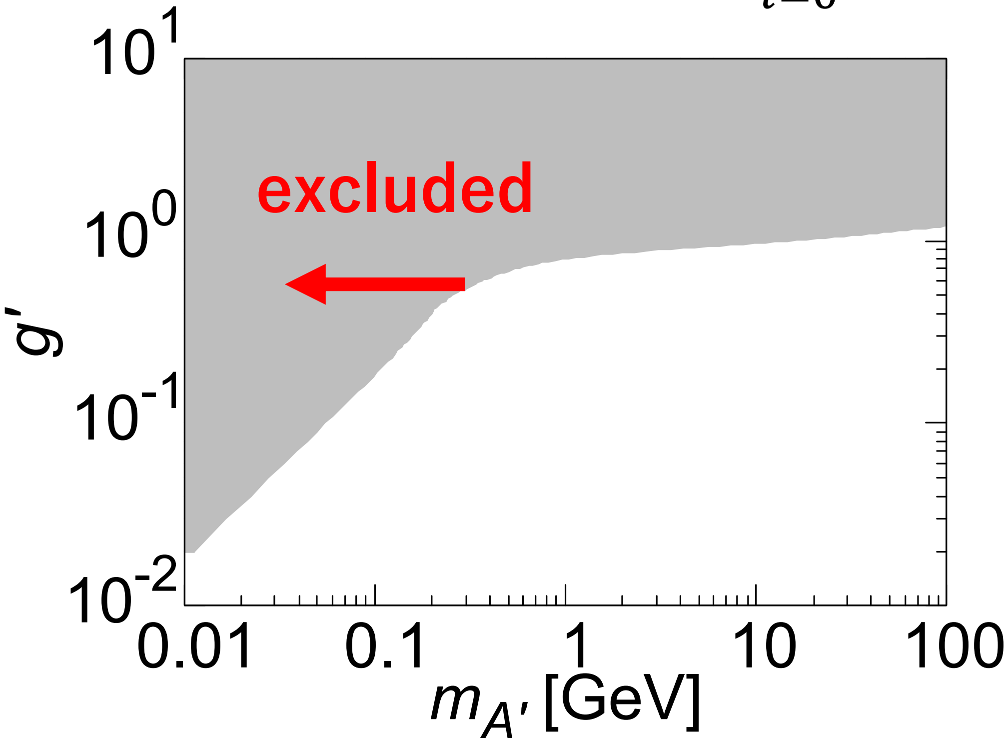


Constraints from perturbative unitarity②

$$\frac{d\Gamma}{ds_{23}}(b \to sA'A') \propto \frac{s_{23}^2}{m_{A'}^4}$$

expand $M(A'A' \to A'A')$ and so on by Legendre polynomial

$$M = 16\pi \sum_{l=0}^{\infty} (2l+1) a_l(|\vec{p}\,|) P_l(\cos_\theta)$$



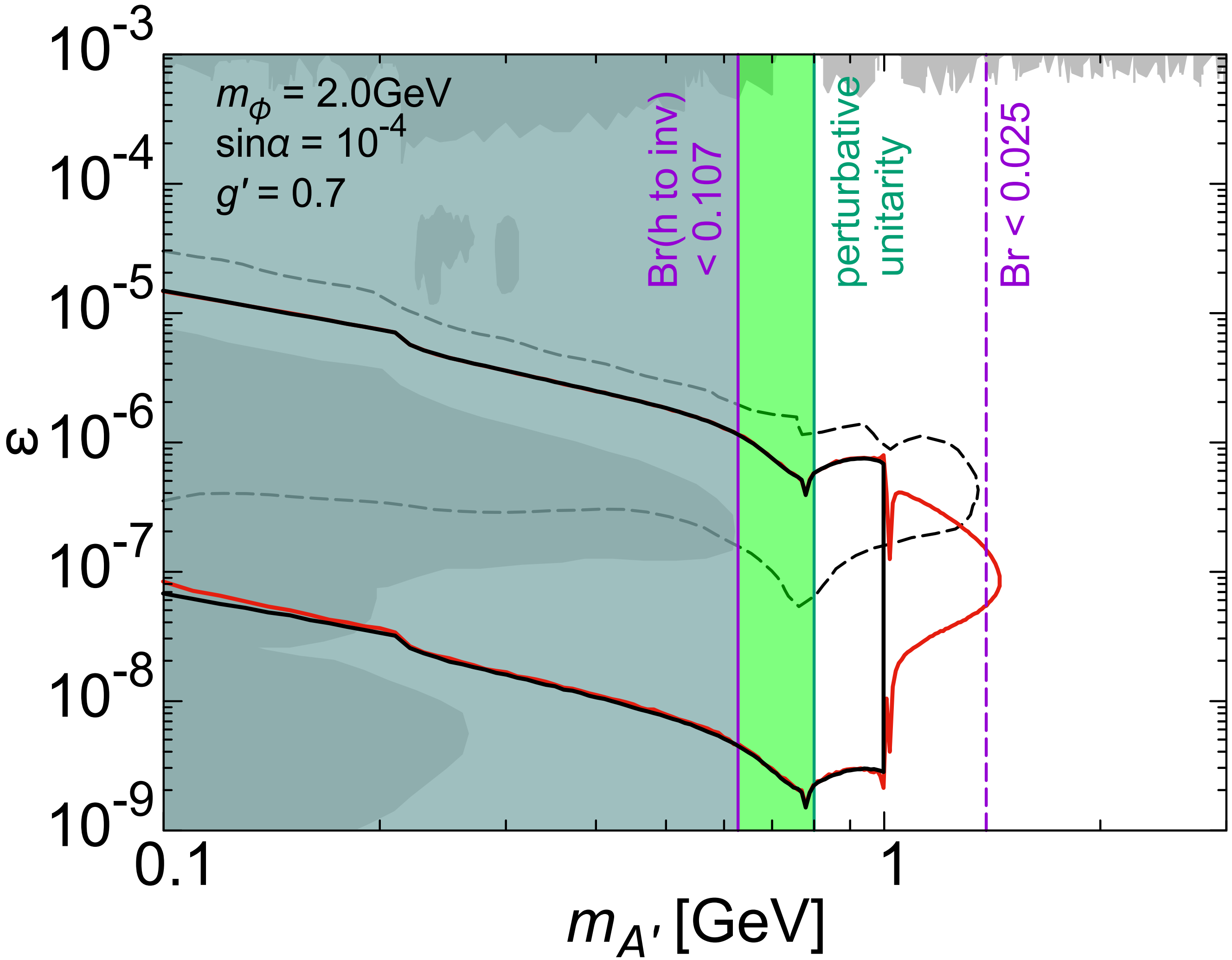
perturbative unitarity bound

$$|\mathrm{Re}\ a_0| < 1/2$$

$$1 - \frac{2m_\phi^2}{m_{A'}^2} - 2\log\left(\frac{s}{m_{A'}^2}\right) \leq \frac{8\pi}{g'^2} \quad \text{etc}$$

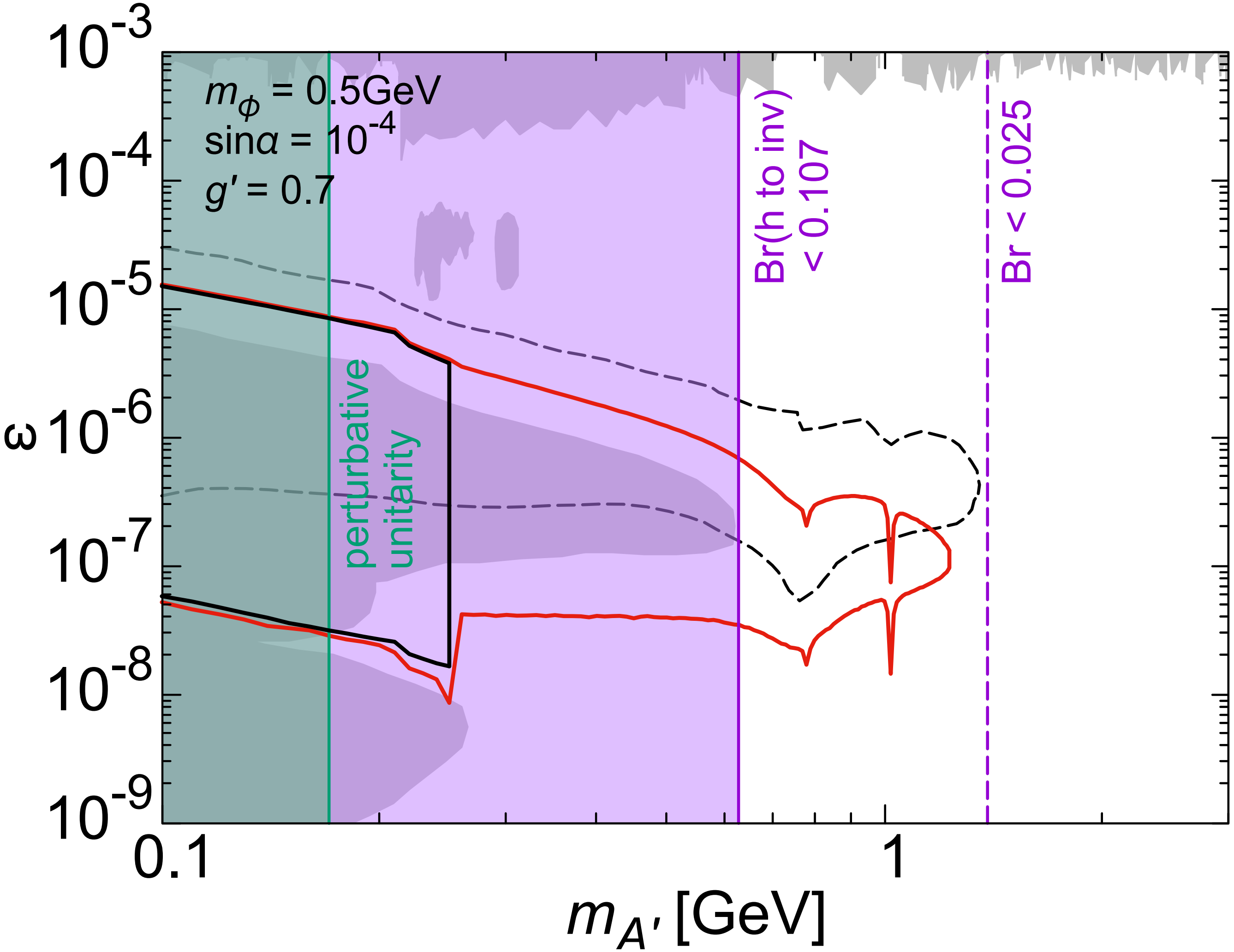
There is lower bound on $m_{A'}$.

Results of **off-shell** dark Higgs contribution①



Sensitivity region is extended!

Results of **off-shell** dark Higgs contribution②



Sensitivity region is extended!

Summary

- We have studied the possibility of dark photon production from off-shell dark higgs decay at FASER2.
- Dark photon production process is enhanced by its longitudinal component.
- The scalar mixing and extra U(1) gauge coupling constant are constrained by $h \to inv$.
- We can not use perturbative calculation for too light dark photon and large gauge coupling.
- **Sensitivity region is extended by contribution of off-shell dark higgs.**

appendix

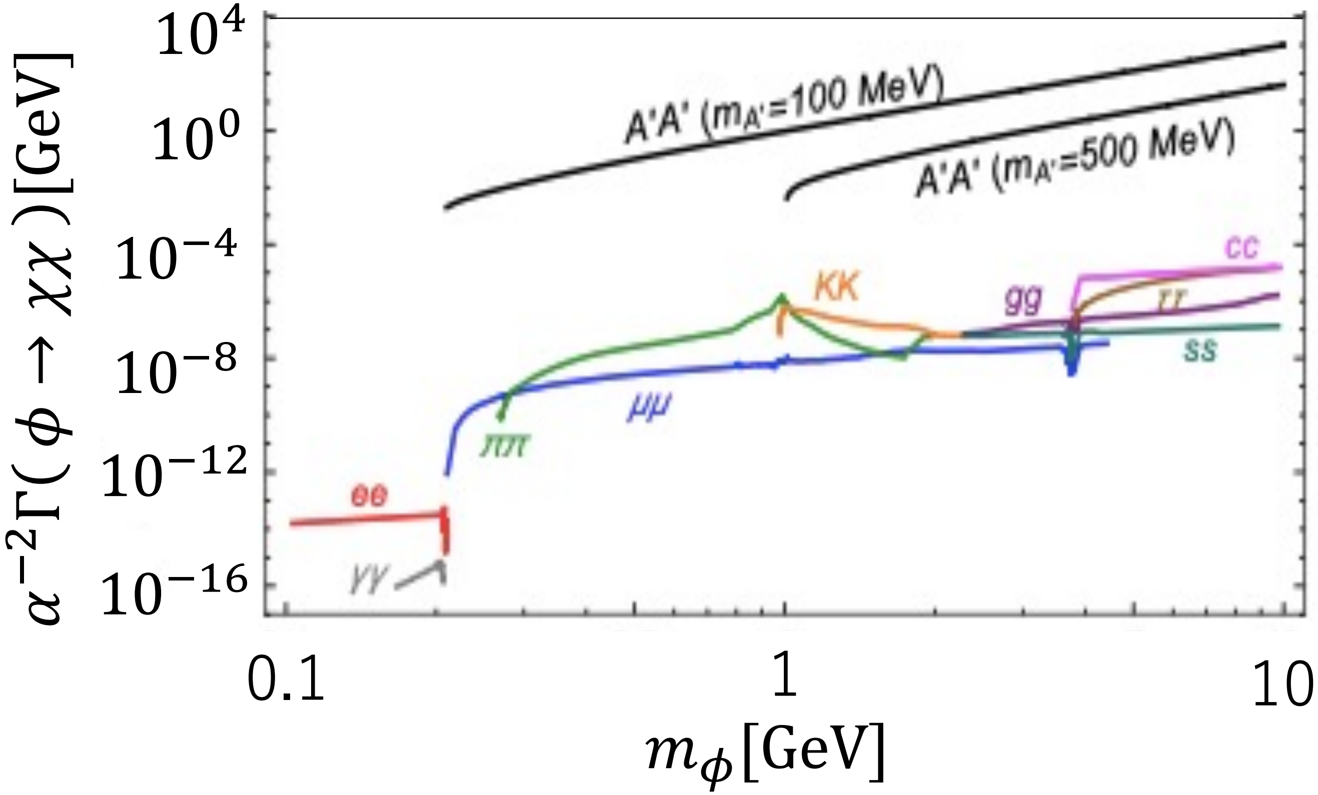
FASER2

	Lmin(m)	Lmax(m)	R(m)	$\mathbf{L\ (ab^{-1})}$
FASER	478.5	480	0.1	0.15
FASER2	475	480	1.0	3.0

Decay width of dark Higgs

decay width of dark Higgs to dark photon

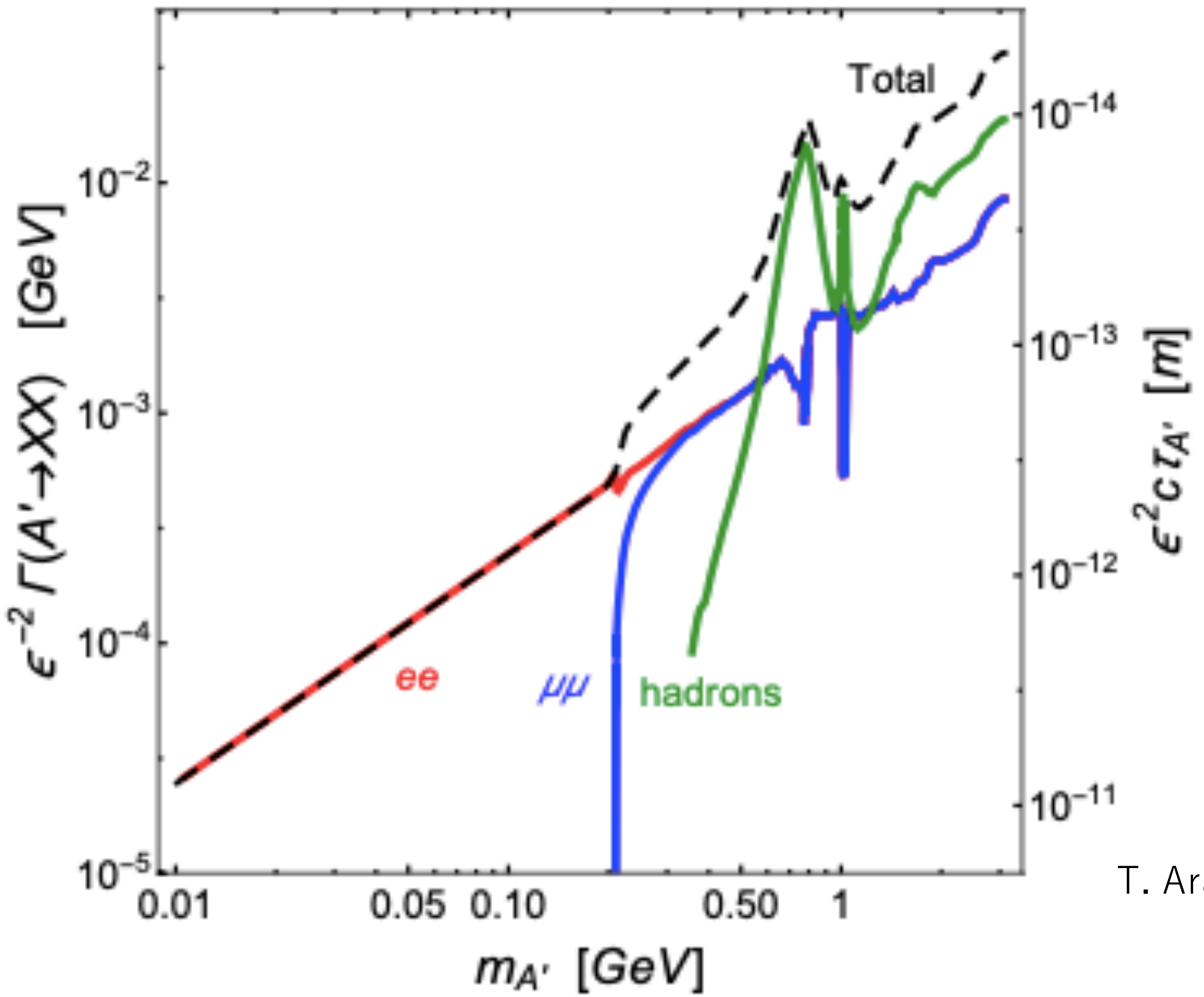
$$\Gamma(\phi \to A'A') = \frac{g'}{8\pi}\frac{{m'_A}^2}{m_\phi}\,\beta_\phi(A')\left(2 + \frac{m_\phi^4}{4{m'_A}^4}\left(1 - \frac{2{m'_A}^2}{m_\phi^2}\right)^2\right)$$ (enhanced by $\frac{m_\phi^4}{{m'_A}^4}$)



The Decay to dark photon is dominant.

T. Araki et al. JHEP03(2021)072

Decay width of dark photon



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Full $\frac{\mathrm{d}}{\mathrm{d}s_{23}}\Gamma(\, b \to s + A'A')$

$$\frac{d}{ds_{23}}\Gamma\left(b \to s + A'A'\right) = \frac{1}{2m_b}\frac{1}{256\pi^3}\left(1 - \frac{s_{23}}{m_b^2}\right)\sqrt{1 - \frac{4m_A'^2}{s_{23}}}$$
$$\times \frac{9\alpha^2}{32^2\pi^2 \sin{\theta_W}^4}\left|V_{tb}\right|^2 \frac{m_t^4}{m_W^4}\left|V_{ts}\right|^2 \frac{s^2}{v^2} m_b^2 {g'}^2 m_{A'}^2 c^2$$
$$\times 2\left(m_b^2 - s_{23}\right)\frac{1}{\left(s_{23} - m_\phi^2\right)^2 + m_\phi^2\Gamma_\phi^2}\left[2 + \left(\frac{s_{23}}{2m_{A'}^2} - 1\right)^2\right]$$

Event number of $B \to X_s, \phi^* \to X_s, A', A'$

$$N = L \times \int dp_B d\theta_B ds_{23} d\widehat{\theta_{A'}} d\widehat{\phi_{A'}} d\theta'_s d\phi'_s \frac{d\sigma(pp \to X, B)}{dp_B d\theta_B}$$

$$\times \frac{dB(B \to X_s, A', A')}{ds_{23} d\widehat{\theta_{A'}} d\widehat{\phi_{A'}} d\theta'_s d\phi'_s} \times (P_{A'_1} + P_{A'_2} + P_{A'_1} P_{A'_2})$$

$$P_{A_i} = \left(\mathrm{e}^{-\frac{L_{\min}}{d_{A_i}}} - \mathrm{e}^{-\frac{L_{\max}}{d_{A_i}}} \right) \times \Theta(R - L_{\max} \tan\theta_{A_i})$$

^ is the value of dark Higgs rest frame, ‘ is the value of B meson rest frame. This is calculated by Monte Carlo method.

Constrain for light dark Higgs A. Fradette, Phys.RevD99(2019)7, 075004