Sensitivity to Decays of Long-Lived Dark Photons at the ILC

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Link to our Snowmass paper

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Introduction

We present a study on the sensitivity to detecting long-lived dark photons at the proposed International Linear Collider (ILC) to set a benchmark for long-lived particle studies at the ILC and motivate searches for long-lived particles at future electron-positron colliders.

Motivation

Many theories predict that new particles could have relatively long lifetimes. While well theoretically motivated, long-lived signatures are often left out of the scope of traditional searches for promptly decaying particles; as a result, dedicated studies of the sensitivity to different long-lived signals are required to gain a fuller picture of a detector's ability to discover new physics. Dark photons (γ_D), mediators of a broken dark U(1) gauge theory that mixes kinematically with the standard model hypercharge with coupling strength ϵ, are a common benchmark for establishing a detector's baseline sensitivity to long-lived particles because of their mid-range mass and potential production via interactions between the Standard Model Higgs and the dark sector Higgs (h_D) as shown in the Feynman diagram in Figure 1. The lifetime of dark photons is a function of their mass and the coupling ϵ, as shown in Figure 2 below; by varying these parameters, we can gain access to a range of lifetimes to study. In our study, we look at the sensitivity to detecting long-lived dark photons produced by exotic Higgs decay with masses between 0.1 and 10 GeV and with coupling strengths of either $\epsilon = 10^{-6}$ or $\epsilon = 10^{-7}$; both hadronic and leptonic decay modes are separately considered to gain a fuller picture of the detector's sensitivity to different types of signals. To demonstrate the displaced vertices found in our event samples, the decay distances from the primary vertex of a selection of dark photon decay distances and mixings are shown below in Figure 3.

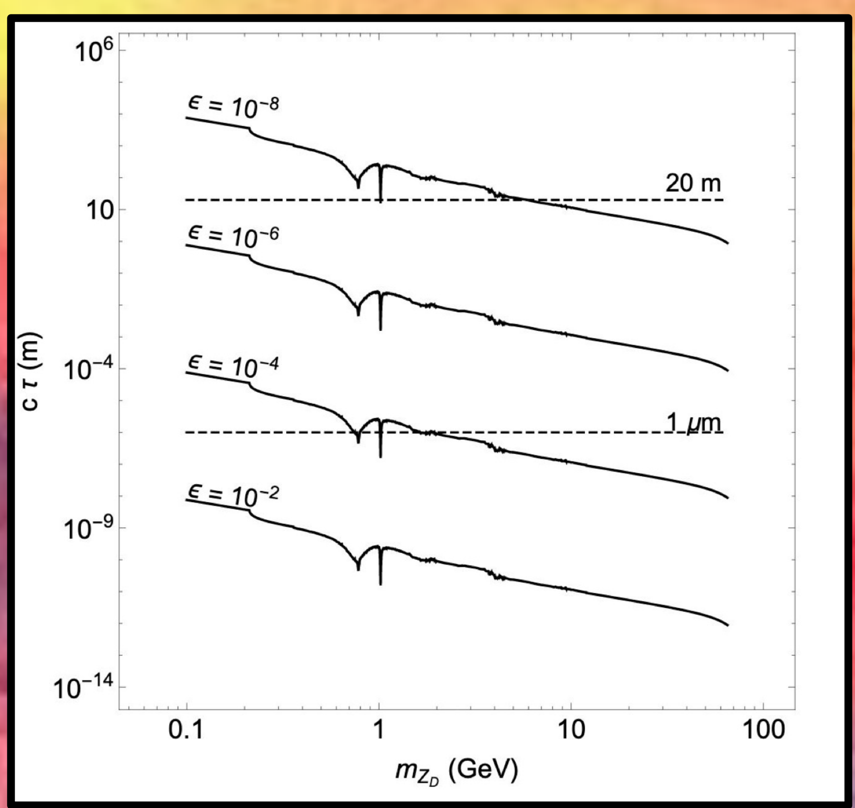
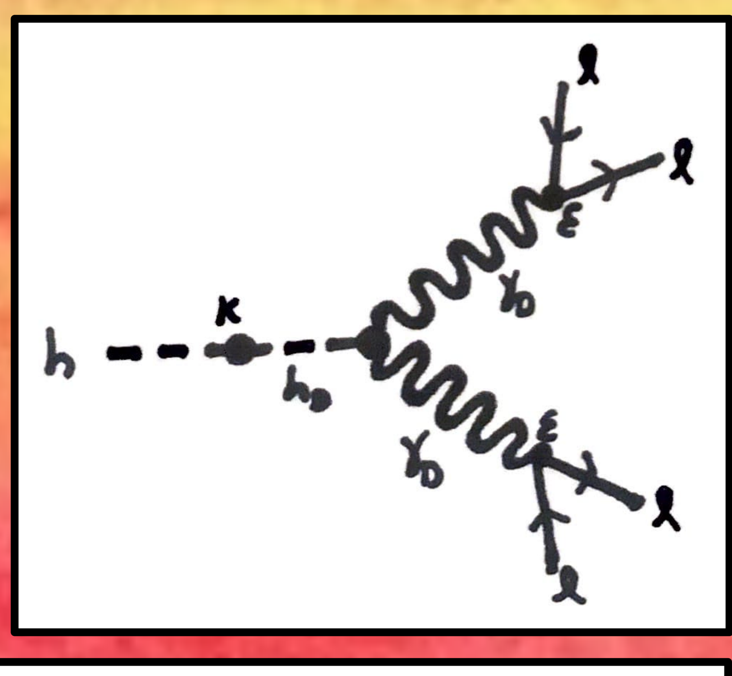


Figure 2 (above): Relationship between dark photon mass, mixing, and lifetime [1]

Figure 1 (right): Feynman diagram showing dark photon production via exotic Higgs decay. In our model, the dark photons can decay to either two leptons or hadronically



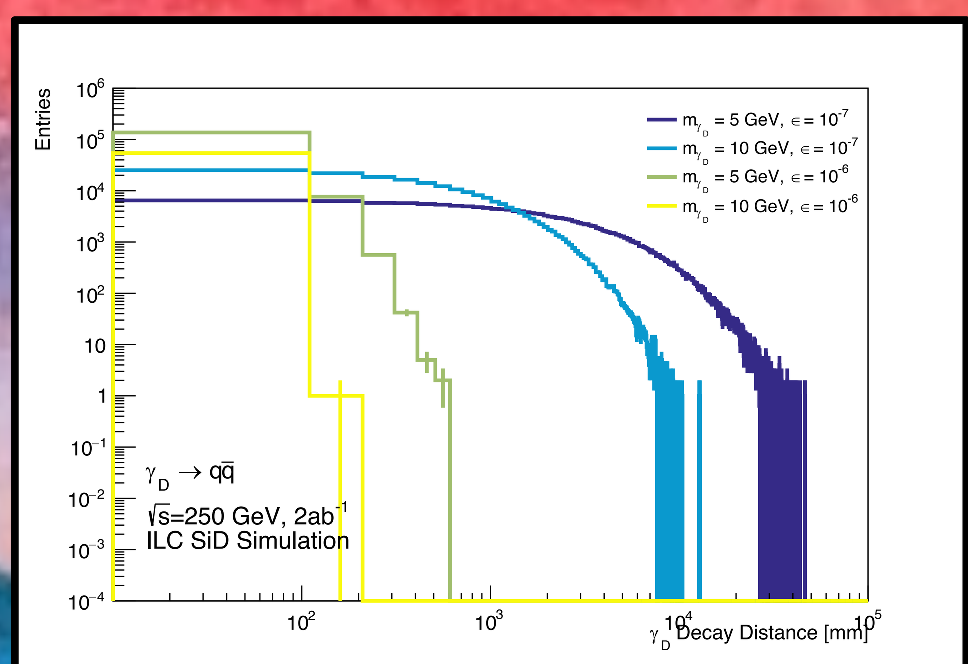
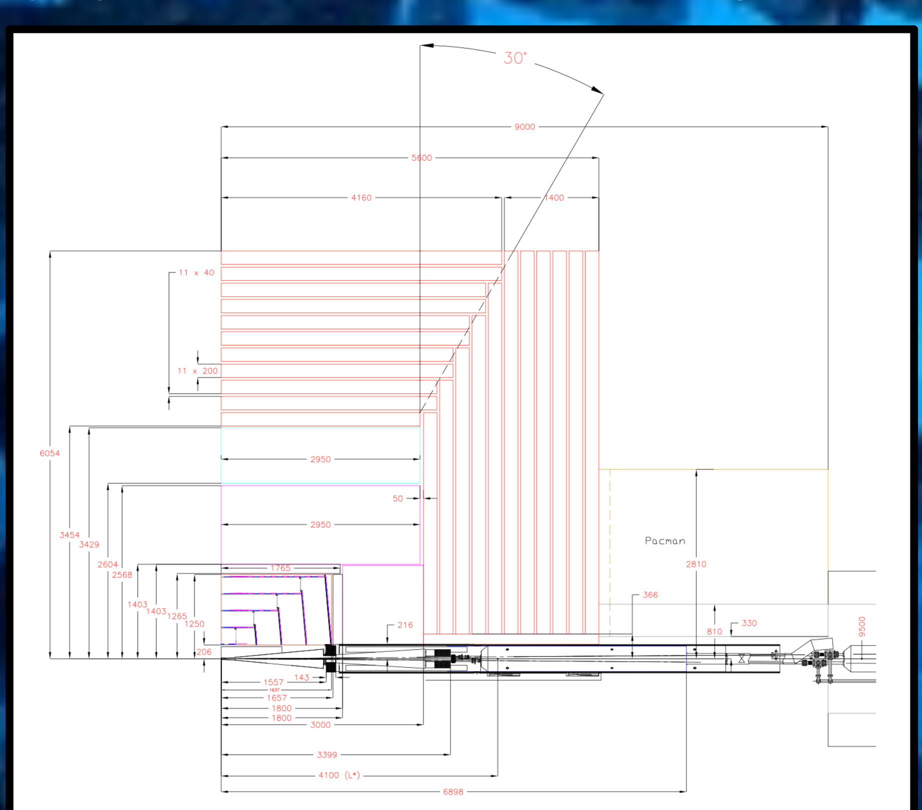


Figure 3 (right): Distance from primary vertex to dark photon decay vertex for several dark photon masses and coupling strengths. By varying the mass and mixing, we can access a large range of decay distances

ILC and SiD

The ILC is predicted to generate a large number of events containing Higgs Bosons in a clean environment compared with hadron colliders, providing an opportunity to study weakly-interacting, low mass displaced vertices. As a result, the ILC should be ideal for studying signals such as the one used in this study, with a Higgs decaying to a low-to-medium mass long-lived particle. We studied the sensitivity to displaced vertices in one of two proposed ILC detectors, the Silicon Detector (SiD), which is designed to provide all-silicon vertexing, tracking, and calorimetry, in addition to particle flow reconstruction, aided by a 5T magnetic field generated by a solenoid located between the hadronic calorimeter and muon systems. Diagrams of the proposed SiD are shown below in Figures 4 (a) and (b).



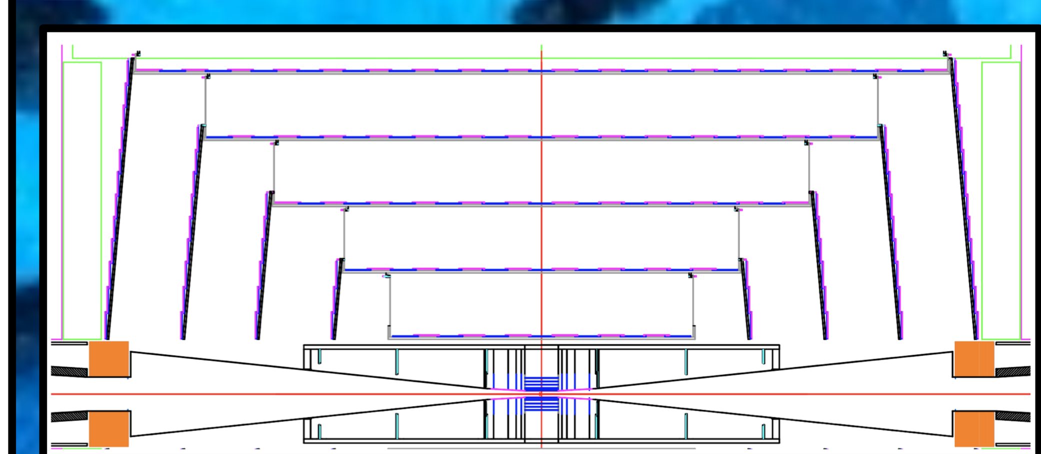


Figure 4 (a, left): Diagram of proposed Silicon detector showing distances to different subsections from beamline [2], (b, right): Diagram showing SiD Vertex detector and tracker systems [3]

Simulation

Using the model provided by Curtin et. al [1], event samples were generated using MadGraph MG5@NLO with Pythia 8 at a luminosity of 2 ab^{-1} and with $\sqrt{s} = 250$ GeV. The following samples were generated to study a range of lifetimes

- Leptonic decays ($\gamma_D \to l^+l^-$) : $\epsilon = 10^{-6}, 10^{-7}, m_{\gamma_D} = 0.1,1,2,3,4,5,6,7,8,9,10$
- Hadronic decays ($\gamma_D \to q\bar{q}$) : $\epsilon = 10^{-6}, 10^{-7}, m_{\gamma_D} = 1,2,3,4,5,6,7,8,9,10$

Projection

Two signal regions, R1 and R2, were defined to study the detector acceptance and look at the performance of different subsections. The first signal region, R1, selected events where the dark photon decayed within the vertex detector, while the second selected events where the dark photon decayed before the calorimeters to study calorimeter performance. For an event to pass the definitions of the signal regions (outlined in Table 1 below), at least one dark photon was required to decay within the specified area, and the dark photon's decay products were required to pass certain cuts at generator level designed for the signature of a displaced vertex. For leptonic decays, both decay products were required to pass the cuts, and for hadronic, at least four charged decay products in the final state were required to pass all cuts. Finally, to determine the baseline acceptance in each region, it was assumed that there would be 100% reconstruction efficiency within the fiducial acceptance with zero background. The acceptance for the leptonic (Figure 5(a)) and hadronic (Figure 5(b)) samples are shown below. From these acceptances, the minimum branching ratio of the Standard Model Higgs to dark photons that could be detected was calculated and is shown below in Figure 6 (a) and (b), providing the baseline projection for the detector's sensitivity to displaced decays from $h_D \to \gamma_D\gamma_D$.

	Signal Region 1 (R1)	Signal Region 2 (R2)
γ_D Decay Position	Within vertex detector {2 mm < r < 60 mm}	Before calorimeters {2 mm < r < 1250 mm}
Decay Product Min. Momentum	0.3 MeV	1 GeV
Decay Product Min. Theta	20°	20°
Decay Product Min. d0	2 mm	2 mm

Table 1: Definitions of two signal regions defined in our study, R1 and R2

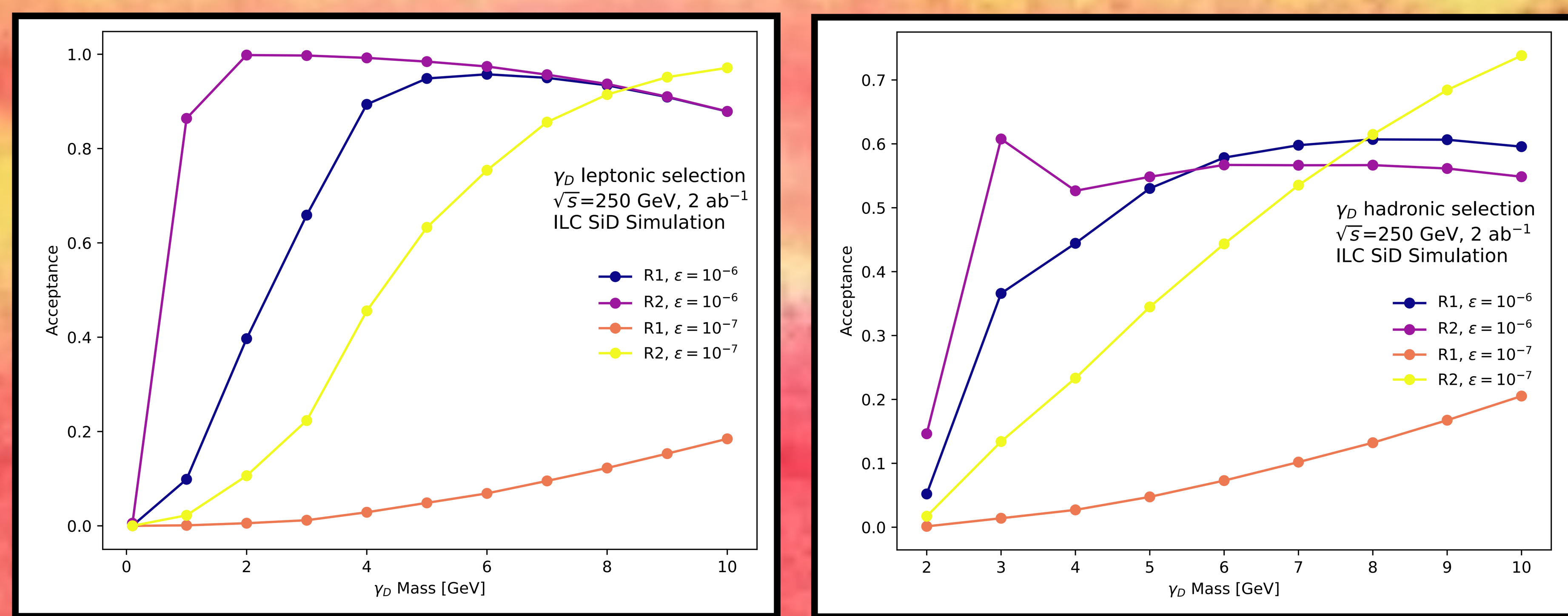


Figure 5 (a, above left and b, above right): Acceptance of finding an event with at least one dark photon decaying leptonically (a) or hadronically (b) and fitting the requirements of the two signal regions R1 and R2 as outlined in the table above for a range of dark photon masses and mixing strengths

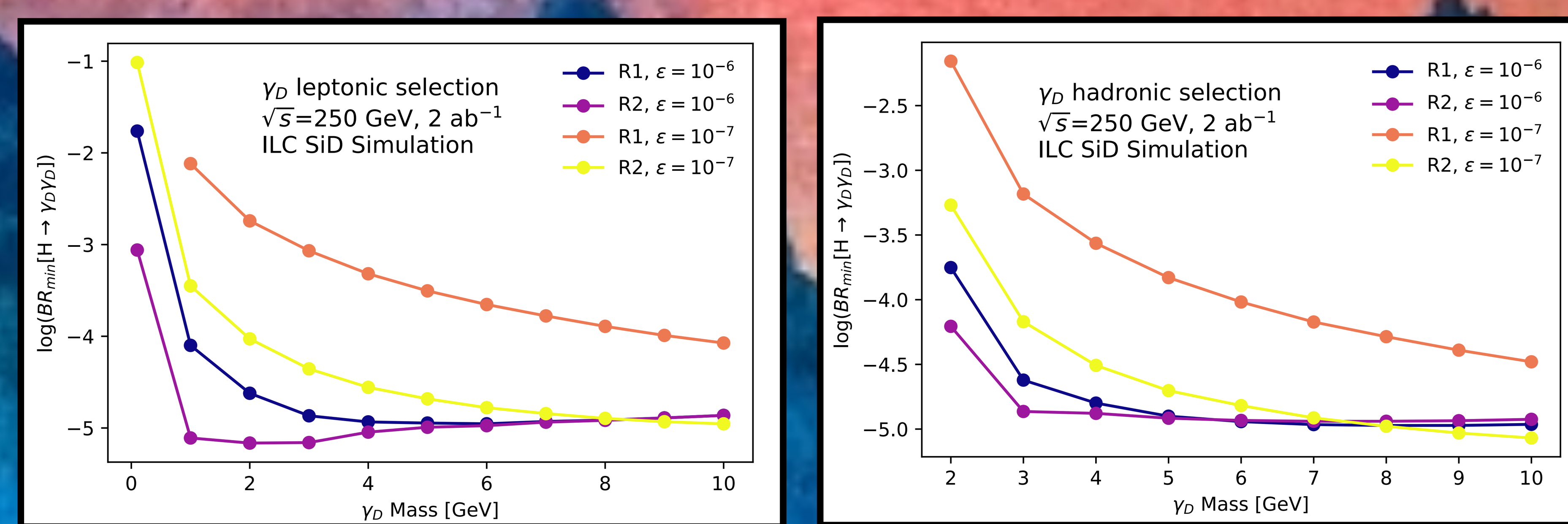


Figure 6 (a, left and b, right): Minimum branching ratio of Higgs to dark photons detectable by the ILC SiD for a range of dark photon lifetimes and masses, assuming 100% efficiency and no background

Conclusion

Our study provides the first look at the sensitivity to discovering long-lived particles at the ILC, using dark photons as a benchmark model. Our results provide sensitivity down to just below order 10^{-5} for the minimum branching ratio of Higgs to dark photons, competitive with other prospective experiments as shown below in Figure 7.

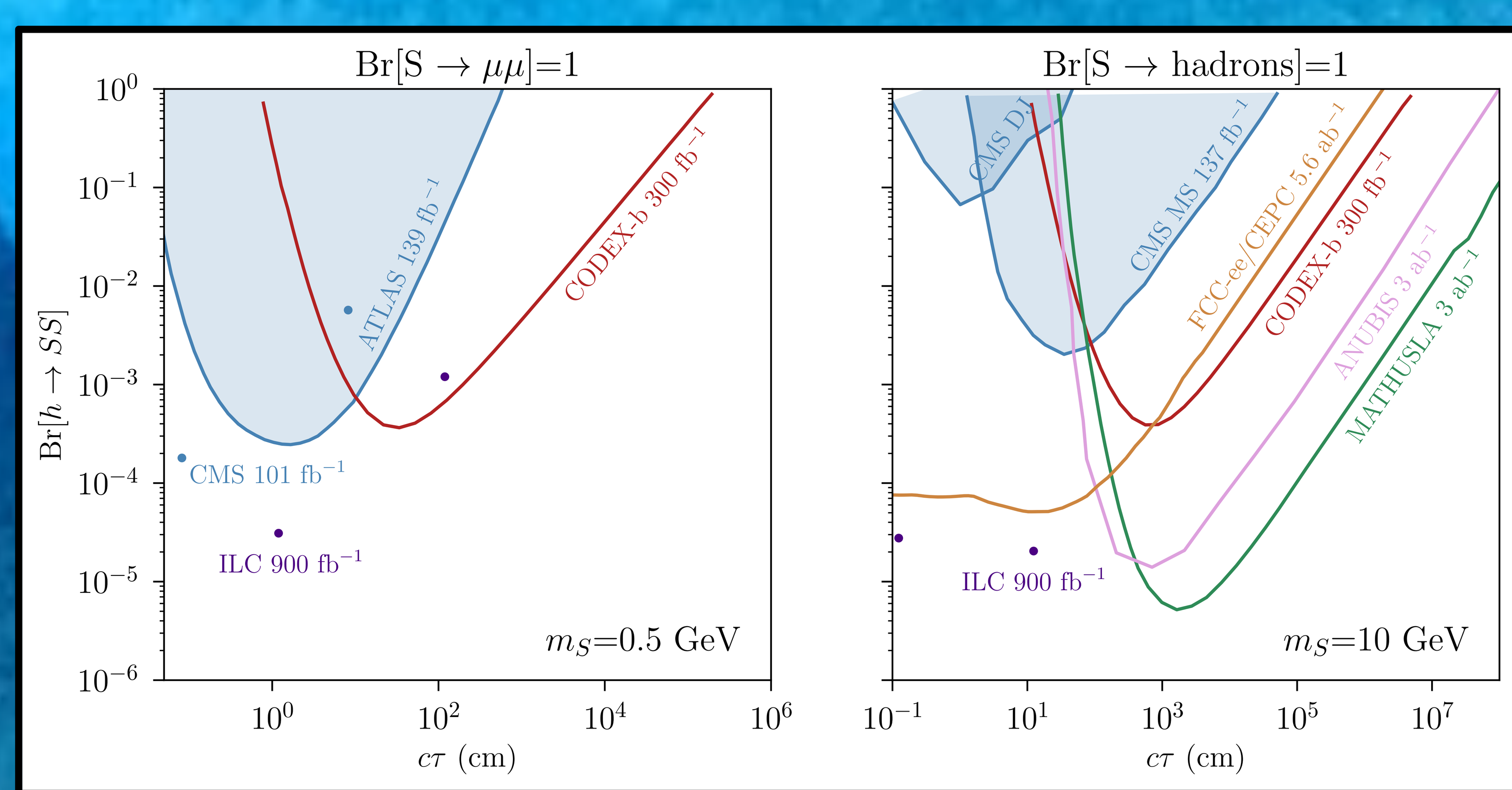


Figure 7: Comparison of our results with sensitivities of Higgs to displaced particle decays for different detectors, showing the ILC provides competitive sensitivities at the lifetimes shown [4]

References: [1] Illuminating Dark Photons with High-Energy Colliders, Curtin, Essig, Gori, & Shelton, arXiv:1412.0018 , [2] Primer on ILC Physics and SiD Software Tools, Potter, arXiv:2002.02399, [3] International Linear Collider Technical Design Report – Volume 4: Detectors, arXiv:1306.6329, [4] Plot provided by Simon Knapen; Background watercolor painting by Laura Nosler

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