Long-lived dark photons at the ILC

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Introduction

Interest in studying ILC sensitivity to long-lived particles as part of the US Snowmass process

Work in progress -- today, highlight motivation, plans and status so far

Sensitivity to decays of long-lived dark photons at the ILC

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I. INTRODUCTION

Searches for light, weakly coupled particles are an important component of the physics program at present and future colliders. New hidden or dark sectors around the electroweak scale which are weakly coupled to the Standard Model (SM) through mediators are well motivated by numerous theoretical and observational considerations, including naturalness, dark matter, and electroweak baryogenesis. A classic benchmark for a potential vector-boson mediator between the SM and dark sector is the hypothetical dark photon, γ_D, which interacts with the SM through kinematic mixing with the weak hypercharge field B with coupling strength ϵ. The dark sector could also have a dark Higgs boson, h_D, which in the general case will mix with the SM Higgs Boson [1]. This opens up a Higgs portal production mode for dark photons.

Prospects for sensitivity to γ_D and h_D production have mainly focused on prompt, leptonic decays of the γ_D for vector portal γ_D production when the mass of the dark photon is greater than about 1 GeV. For small enough ϵ ($\epsilon \lesssim 10^{-5}$), the γ_D becomes long-lived, a mode which is accessible if Higgs portal production is also considered [1, 2]. The prospects for detection of long-lived particles produced via the Higgs portal at future linear colliders has been studied for displaced hadronic decays, focusing on CEPC and FCC-ee [3].

In this project, we aim to study the sensitivity for detection of long-lived dark photons at the ILC. Existing work on γ_D and h_D production at the ILC has focused on prompt di-muon decays of γ_D production and indirect constraints from measurements of the Higgs to invisible branching ratio [2, 4]. We aim to add the Higgs portal production mode and use the displaced decays of long-lived γ_D as a benchmark to study the detector performance for detection of displaced decays.

II. QUESTIONS TO STUDY

We plan to focus on the proposed ILC dataset of 2 ab^{-1} at $\sqrt{s} = 250$ GeV. We are interested to use truth-level signal simulation samples to explore the full acceptance available to the ILC detectors. To explore the expected detector performance, we aim to use a benchmark signal sample reconstructed with full simulation of the SiD detector. The nominal SiD vertex detector [5] comprises five barrels closed by four disks one each side, together with three more forward disks further along the beamline on each side. Barrels and disks are instrumented with Silicon pixels with 5 μm or better hit resolution [5]. Comparisons of truth-level acceptance and full simulation with the standard reconstruction will provide a benchmark for the efficiency of the default reconstruction, and potentially identify areas of reconstruction which could be improved for the identification of displaced decays. To complement the expected coverage of the HL-LHC and take advantage of the excellent vertexing of SiD and clean background environment, we will focus on signal scenarios with shorter lifetimes and/or lighter masses [3].

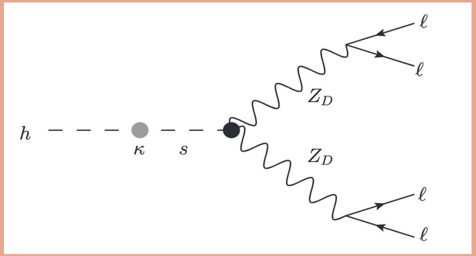
In addition to the potential acceptance and performance of the default reconstruction, it is interesting to study whether the timing constraints of the ILC detectors impose limitations on the detection of long-lived particles with moderate mass [6]. If time permits, we would like to explore potential backgrounds to the identification of a displaced vertex arising from the decay of a long-lived neutral particle, potentially including both physics and machine-induced sources, and analyze handles for the separation of signal and background.

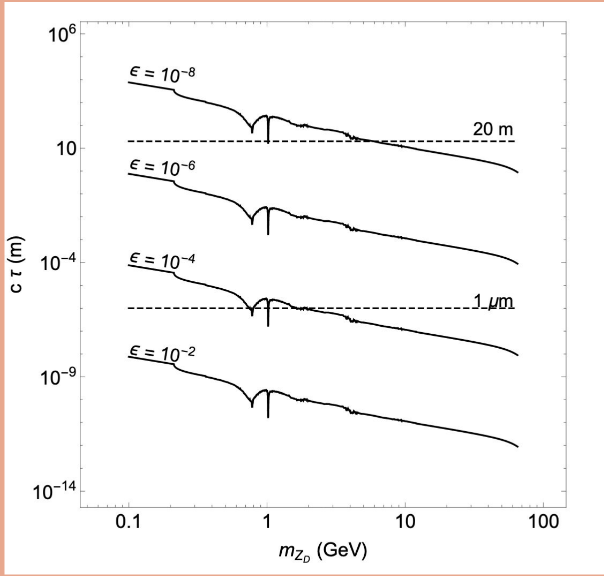
[1] D. Curtin, R. Essig, S. Gori, and J. Shelton, Illuminating Dark Photons with High-Energy Colliders, JHEP **02**, 157, arXiv:1412.0018 [hep-ph].
[2] R. K. e. a. Ellis, *Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020*, Tech. Rep. arXiv:1910.11775 (Geneva, 2019) 254 p.
[3] S. Alipour-fard, N. Craig, M. Jiang, and S. Koren, Long live the higgs factory: Higgs decays to long-lived particles at future lepton colliders, Chinese Physics C **43**, 053101 (2019).
[4] J. de Blas, , *et al.*, Higgs boson studies at future particle colliders, Journal of High Energy Physics **2020**, 10.1007/jhep01(2020)139 (2020).
[5] H. Abramowicz *et al.*, The International Linear Collider Technical Design Report - Volume 4: Detectors, (2013), arXiv:1306.6329 [physics.ins-det].
[6] K. F. et al, Ilc study questions for snowmass 2021 (2020), arXiv:2007.03650 [hep-ph].

Link to LOI in Snowmass EF08 and EF09

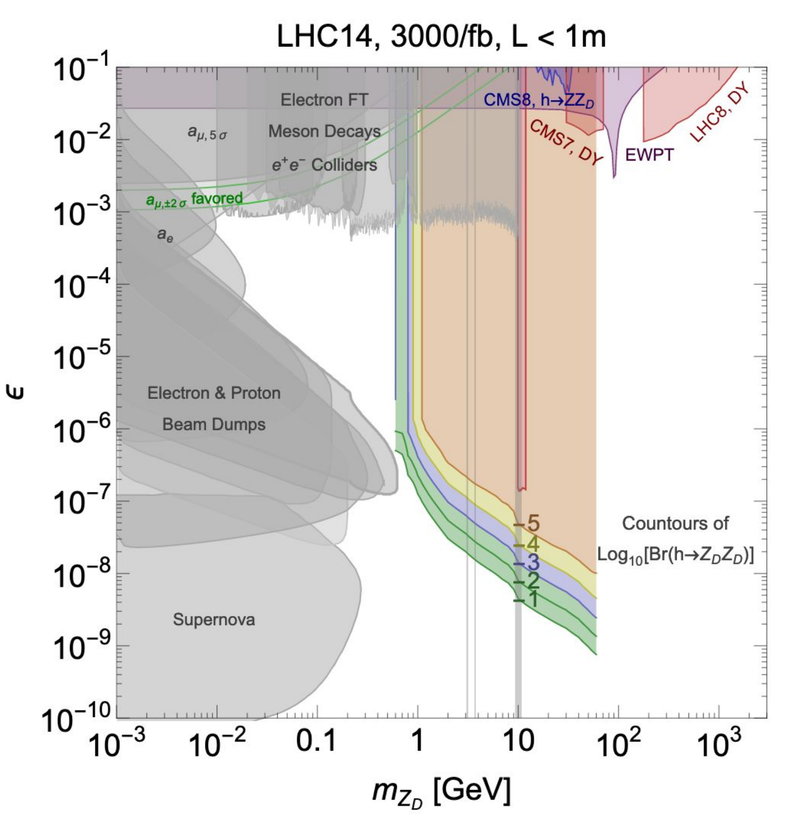
Dark photons

- Searches for new, light, weakly coupled particles an important component of current and future colliders
- Dark photons (Z_D) are a classic benchmark for a potential vector-boson mediator between the Standard Model and the dark sector
- If dark sector also contains a dark Higgs (s), production via mixing via Standard Model Higgs Boson opens up
    - production occurs via κ (Higgs mixing)
    - decay occurs via ε (dark photon mixing)
- For small ε ($<10^{-4}$ - 10^{-5}), dark photons acquire measurable lifetime





Curtin, Essig, Gori & Shelton, arXiv:1412.0018



Context

HL-LHC sensitivity to this model

Curtin et al

Sensitivity at CEPC and FCC-ee

Alipour-fard et al

Sensitivity via H→ inv

J. de Blas et al

Sensitivity of dark Higgs via direct decay

R. K. Ellis et al

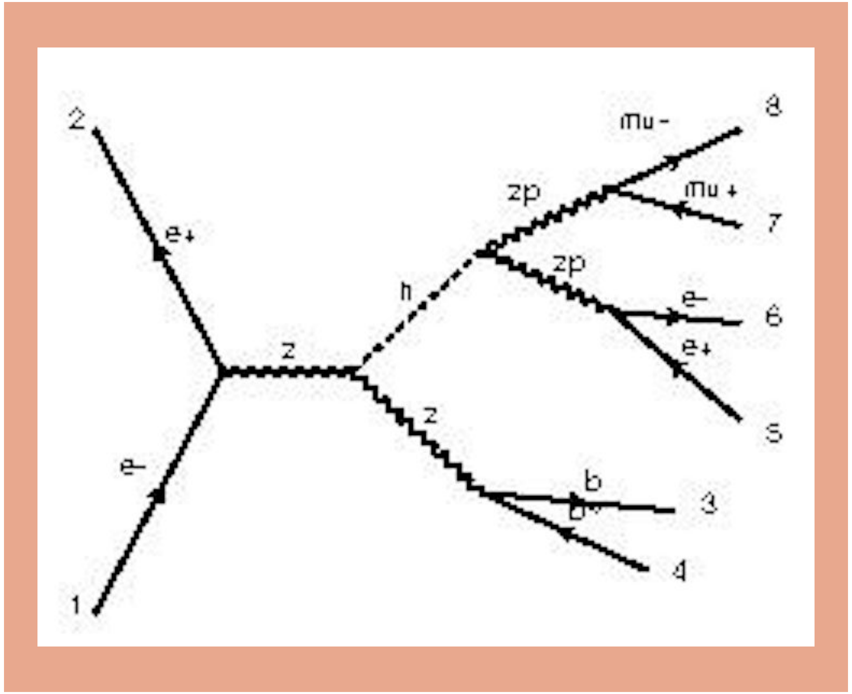
European Strategy Report 2020

Goals of the study

- Provide a rough estimate of ILC sensitivity to long-lived Z_D production
    - via Higgs portal production, for Z_D in the mass ranges of 1 -- tens of GeV
- Provide first studies of SiD performance for long-lived particle detection
    - via displaced decays, using dark photons as a benchmark
- Contribute to exchange of expertise between LLP and ILC communities

Roadmap

- Target proposed ILC dataset of 2 ab^{-1} at sqrt(s) = 250 GeV
- Focus on SiD detector
- Production mechanism
    - $e^+e^- \to ZH \to Z\, Z_D\, Z_D$
- Signature: displaced vertex from Z_D decay
- Displaced vertex provides very clean experimental signature
    - Explore both leptonic and hadronic decays of Z_D
- Study acceptance at truth level
- Explore reconstruction efficiency, backgrounds from full simulation



Sample production

- Produced benchmark $e^+e^- \rightarrow ZH \rightarrow Z\, Z_D\, Z_D$ events
    - Using MG5@NLO + Pythia8
    - Using model provided here by arXiv:1412.0018
    - 80/30 e^-/e^+ polarization
- Model parameters
    - Z_D mass
    - ε and Z_D width
    - Dark higgs mass
    - Higgs / Dark higgs mixing

    } ratio proportional to κ’, determines $BR(h \rightarrow Z_D)$
- Simulation
    - Fast sim w/ Delphes (only for prompt decays, and truth level -- and turn off isolation)
    - Full sim w/ ILCSoft (note: difficult to convert HepMC from Pythia to std::hep for ILCSoft)

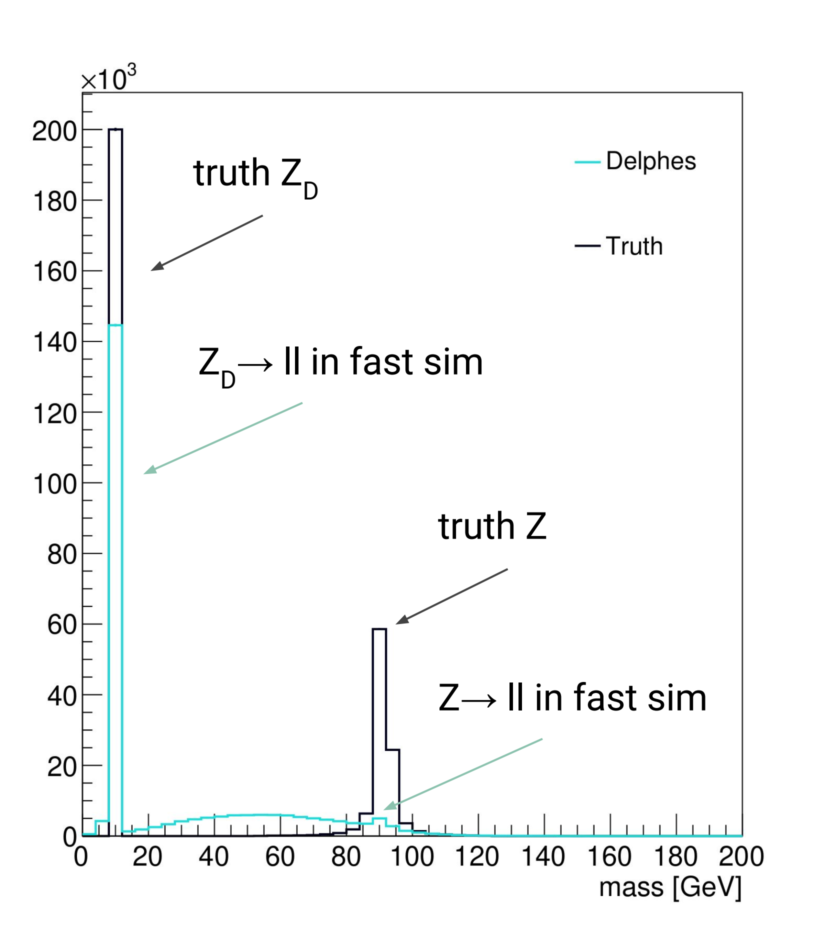
First benchmark sample

$c\tau$ = 10 μm

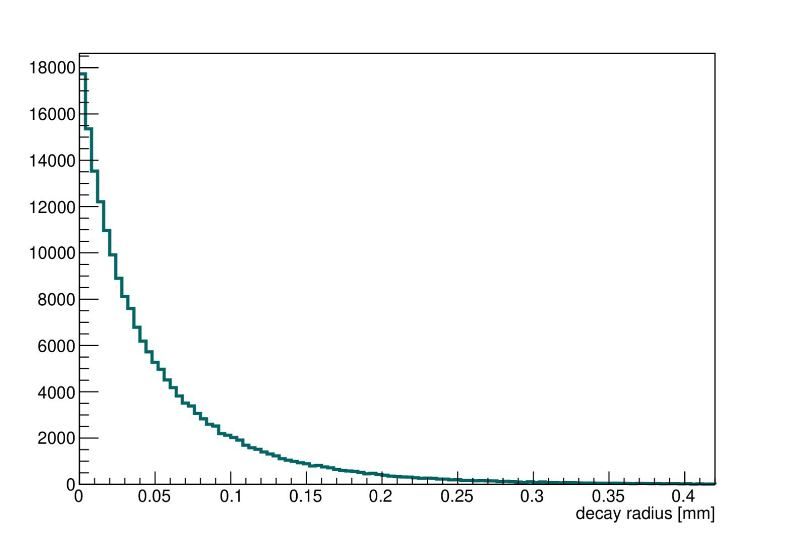
mass Z_D = 10 GeV

only e, μ decays of Z_D

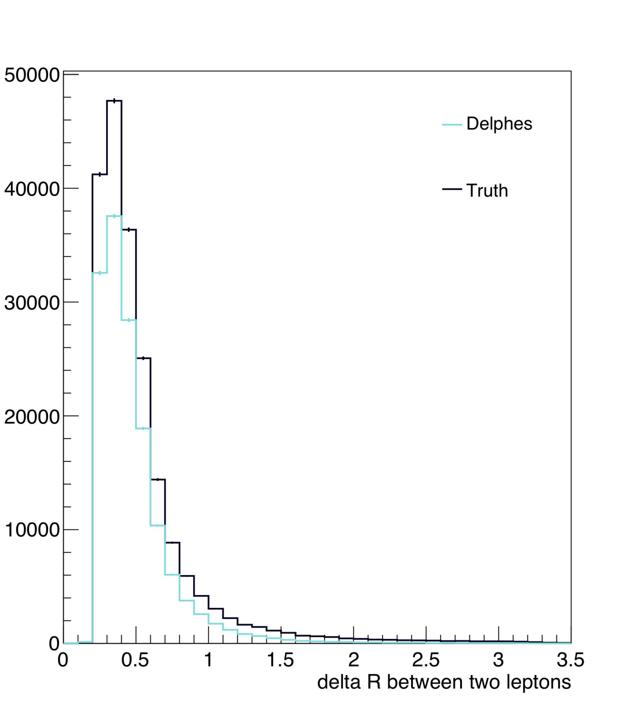
Invariant mass of truth particles and l^+l^- pairs



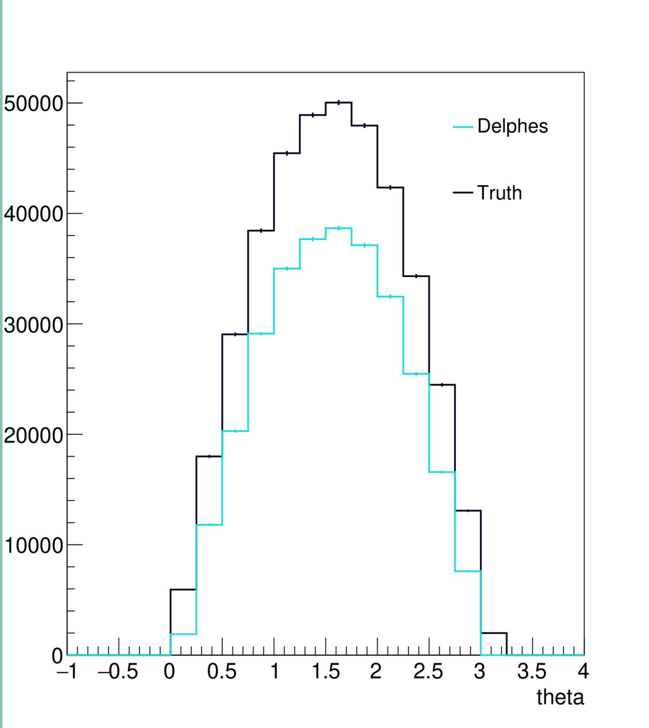
Z_D decay radius at truth



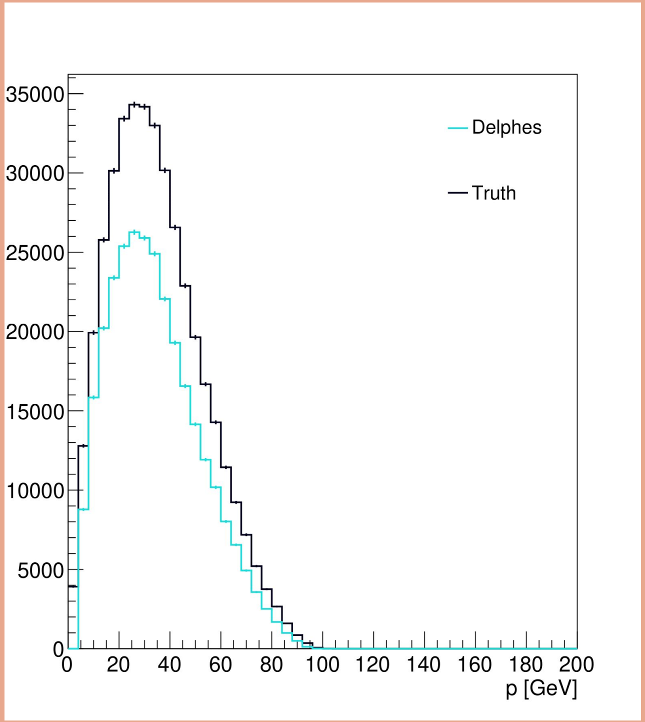
ΔR between two leptons from Z_D



$Z_D \rightarrow l^+l^-$ theta at truth and fast sim



$Z_D \rightarrow l^+l^-$ p at truth and fast sim



Acceptance considerations

- Calculate truth-level acceptance of single Z_D decay as a function of
  - Lifetime, mass, relativistic β
  - Under a series of various assumptions about requirements to eliminate background:
    - Minimum d0, p, theta
    - Minimum decay radius (to reject prompt decays, eliminate background from Z → bb)
    - Maximum decay radius (reconstruct displaced tracks in vertex / tracker, or look for displaced leptons / hadrons in calo, MS)
- Calculate max sensitivity as a function of Z_D mass, Z_D lifetime, mixing (κ), and ε assuming zero background, under different fiducial requirements
- Timing constraints

- After studying acceptance, examine default reconstruction in full simulation

Background considerations

- Backgrounds come mostly from instrumental effects at LHC, likely similar at ILC
  - Photon conversions
  - Hadronic interactions with detector material
  - ~~Accidental crossings of two (or more) tracks~~
  - b-hadron production for low lifetimes (small ε)
  - $K^0_S \rightarrow \pi^+\pi^-$, or other long lived hadrons

} reject by vetoing displaced vertices consistent with material

- Plan to study ZH, ZZ, Ze^+e^- ($Z \rightarrow bb$, $Z \rightarrow ss$, etc..) backgrounds in full simulation after looking at signal in full simulation

Outlook

Plans for sensitivity study of long-lived dark photons at SiD

use Z_D as benchmark for weakly-coupled new particles

First simulation samples validated at truth level

Delphes looks reasonable for prompt decays

Full simulation produced, validation ongoing

Work ongoing on acceptance calculations, detector considerations

Early days of the study

Please feel free to reach out with ideas or suggestions

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