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Long-lived particle searches with the ILD

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This note presents results of the first full simulation study addressing prospects for observation of long-lived particles (LLPs) with the International Large Detector (ILD). Neutral LLP production, resulting in a displaced vertex signature inside the ILD's time projection chamber (TPC), is considered. We focus on scenarios interesting from the experimental perspective and perform a search based on displaced vertex finding inside the TPC volume. Two experimentally very challenging types of scenarios are explored: first, involving very soft final states due to a small mass splitting between heavy LLP and a dark matter candidate to which the LLP decays, and the second one, with a light LLP production resulting in almost colinear vertex tracks because of a large boost of the LLP. The expected limits on the signal production cross section are presented for a wide range of the LLP proper lifetimes corresponding to $c\tau$ from $0.1\,\mathrm{mm}$ to $10\,\mathrm{km}$. The analysis was extended to consider also Higgs boson decays to LLPs, using additional assumptions on the final state to improve the expected sensitivity.

This work was carried out in the framework of the ILD Concept Group

1 Introduction

The ILD [1] is one of the experiments proposed for operation at a future Higgs factory. Its tracking systems include a pixel vertex detector and a silicon inner tracker, surrounded by a time projection chamber (TPC), which is beneficial for searches for delayed decays. This note, to a large extent based on Ref. [2], presents prospects for the detection of neutral LLPs with the ILD, using the International Linear Collider (ILC) [3] operating at $\sqrt{s} = 250\,\mathrm{GeV}$ (ILC250) as a reference collider.

2 Analysis strategy and benchmark scenarios

Benchmark scenarios considered were not selected based on existing constraints on BSM models, but for signatures challenging from experimental perspective. Two opposite classes of benchmarks were chosen, with the first one involving a very soft displaced track pair in the final state. We used pair-production of heavy neutral scalars, A and H, where the former is the LLP and the latter is stable (and escapes undetected). The LLP decay channel is A $\rightarrow$ Z*H, and its mass and proper decay length were fixed to $m_A = 75\,\mathrm{GeV}$ and $c\tau = 1\,\mathrm{m}$. Four mass splitting values between A and H were considered: $m_A - m_H = 1, 2, 3, 5\,\mathrm{GeV}$. The second class features production of a very light and highly boosted LLP with strongly collimated final-state tracks. It was generated using the associated production of a pseudoscalar LLP, a, with a hard photon. LLPs of four different masses were considered, $m_a = 0.3, 1, 3, 10\,\mathrm{GeV}$, with $c\tau = m_a \cdot 10\,\mathrm{mm/GeV}$. Only decays of Z* and a to muons were simulated. The analysis relied on vertex-finding algorithm designed for this study and was performed in a model-independent way, considering only the displaced vertex signature in the TPC, ignoring any other activity in the detector. The study was carried out using full detector response simulation.

3 Background reduction

Two types of background have been taken into account – soft, beam-induced (low-p_T) processes and hard (high-p_T) processes. The beam-induced processes occurring in each bunch-crossing constitute a significant standalone background if one wants to consider soft signals. To reject fake vertices, a set of quality cuts was applied on the variables describing kinematic properties of tracks. The main background sources that remain include V^0 particles (long-lived neutral hadron decays and photon conversions) and secondary interactions of particles with the detector material. In addition to rejection based on a dedicated ILD software for V^0 identification, cuts corresponding to masses of different V^{0}s are applied. Further cuts on the total p_T^{vtx} of tracks forming the vertex, and on variables describing track-pair geometry, provide the total reduction factor of $1.26 \cdot 10^{-10}$ for beam-induced backgrounds. Two- and four-fermion production with hadronic jets in the final state was considered as the high-p_T background. To improve the high-p_T background rejection, in addition to the *standard* selection described above, we also consider the *tight* selection, where track pairs with an invariant mass below $700\,\mathrm{MeV}$ are rejected. An isolation criterion is also included in the tight selection.

4 Results of the model-independent analysis

Vertex finding rates for the signal and the background were used to obtain the expected 95% C.L. upper limits on the signal production cross section, $\sigma_{95\%\mathrm{C.L.}}$, assuming integrated luminosity of $2\,\mathrm{ab}^{-1}$. An event re-weighting was also performed to obtain the limits for a range of LLP lifetimes without generating and processing a large number of event samples. The limits are presented in Figure 1 as a function of LLP proper decay length $c\tau$. The tight selection allows to strongly enhance the reach, but results in a loss of sensitivity to the $m_a = 300\,\mathrm{MeV}$ scenario.

5 Higgs decays to long-lived particles

We also consider a set of benchmarks with the SM-like Higgs boson decays to long-lived scalars. The Higgs production channel used was e$^+$e$^-$ $\rightarrow$ hZ at ILC250, with Z $\rightarrow$ $\nu\bar{\nu}$ and h $\rightarrow$ SS, where S is long-lived. We

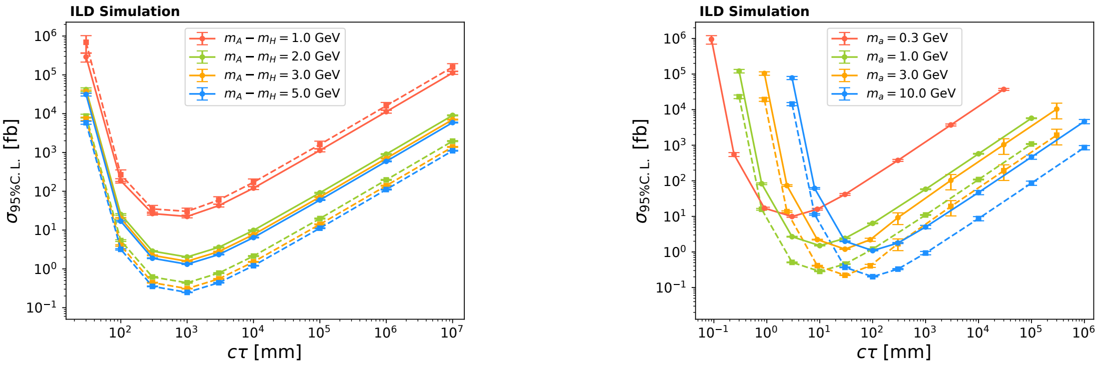

Figure 1: Expected 95% C.L. upper limits on the signal production cross-section for the considered benchmarks and different LLP mean decay lengths, for the scalar pair-production (left) and the light pseudoscalar production (right) at $\sqrt{s} = 250\,\mathrm{GeV}$. Solid lines corresponds to the standard selection and dashed lines to the tight set of cuts. The uncertainties are statistical.

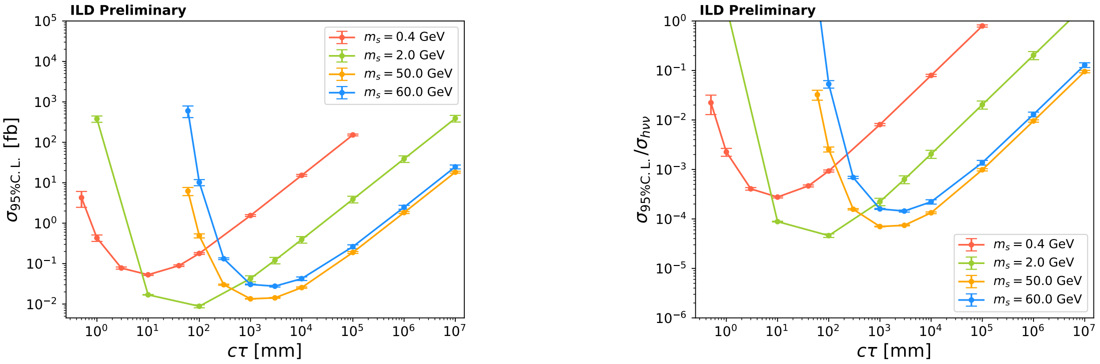

Figure 2: Expected 95% C.L. upper limits on the signal production cross-section (left) and the branching ratio (right) for the considered benchmarks and different LLP mean decay lengths, for the Higgs decays to long-lived scalars at $\sqrt{s} = 250\,\mathrm{GeV}$. The uncertainties are statistical.

selected four benchmarks, two low-mass ($m_S = 0.4\,\mathrm{GeV}$ and $2\,\mathrm{GeV}$, with $c\tau = 10\,\mathrm{mm}$) and two high-mass ($m_S = 50\,\mathrm{GeV}$ and $60\,\mathrm{GeV}$, with $c\tau = 1\,\mathrm{m}$) scenarios. Because Z decays to neutrinos, and one of the LLPs can escape the acceptance, the expected signature is just at least one displaced vertex. Therefore, in addition to the selection described so far, events containing prompt tracks with $p_T > 2\,\mathrm{GeV}$ are rejected. Now also the $p_T^{vtx} > 10\,\mathrm{GeV}$ requirement was applied to allow us to fully neglect low-p_T beam-induced backgrounds. The expected number of background events is approximately 0.64 after the standard selection and the additional cuts. The corresponding 95% C.L. limits on the signal production cross section (left) and the branching ratio $\mathrm{BR}(\mathrm{h} \to \mathrm{SS}) = \sigma_{95\%\,\mathrm{C.L.}}/\sigma_{h\nu\nu}$ (right) are presented in Figure 2, conservatively assuming that the observed number of events is one. ILD could improve the current limits [4] in the most extreme scenarios by an order of magnitude, or investigate longer lifetimes. Smaller decay lengths could be tested by a dedicated search using a vertex detector, while more data collected at higher energy stages of ILC could further enhance the reach.

6 References

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[4] A. Hayrapetyan et al., CMS, *Dark sector searches with the CMS experiment* (2024), arXiv: `2405.13778 [hep-ex]`.