Searches for Dark Photons and Doubly-Charged Higgs in 4-Lepton Final States

Letter of Interest for the Snowmass 2021 Study, August 30, 2020

Lenny Spiegel, Fermi National Accelerator Laboratory
Peter Dong, Illinois Mathematics and Science Academy
Paul Karchin, Wayne State University (contact: karchin@wayne.edu)

Abstract

This is an investigation of exotic searches with 4 leptons (electrons or muons) in the final state, produced in pp collisions at HL-LHC, HE-LHC, or FCC. We consider dark photons produced in the SUSY Portal or Higgs Portal models, and doubly-charged Higgs produced in a left-right symmetric model. Our goal is to estimate the cross section sensitivity and to optimize the trigger strategy. We will evaluate the benefits of employing track information in the trigger and timing information in reconstruction. The utility of event scouting (recording only reconstructed objects from the high-level trigger) will also be evaluated.

Introduction

The four-lepton final state is attractive for new physics searches for a number of reasons. A variety of theoretical models predict such final states and the experimental signatures have several desirable features. An event with four distinctive leptons (electrons or muons) provides a clearly-identified signal. Standard model processes rarely produce such a a state. Experiment triggers requiring multiple leptons and same-sign leptons can be powerful in reducing the trigger rate. Triggers may profit from new, advanced trigger capabilities such as track finding and event scouting (recording of reduced event data). High-level trigger and off-line analysis can take advantage of advanced detector features such as intra-bunch timing resolution and expanded coverage in pseudo-rapidity.

SUSY Portal Model for Dark Photon Production

Models in which dark photons couple to SUSY particles are referred to as "SUSY Portal" models. Our benchmark model is that of Cheung, Ruderman, Wang, and Yavin [1]. Quark scattering produces a pair of s-quarks each of which decays to a quark and neutralino. Each neutralino decays to a pair of dark particles, one of which is a dark photon. In the simplest case, each dark photon decays, through kinetic mixing, to a lepton jet consisting of a highly collimated opposite-sign pair of leptons. Depending on its lifetime, the dark photon can be promptly produced at the primary interaction vertex, or have a measurable decay length. A search for dark photons was reported by the ATLAS experiment [2] at 8 GeV collision energy.

A SUSY Portal model is implemented in Pythia. Our initial studies were for HL-LHC with a 1 GeV mass dark photon decaying into a single lepton pair. The leading p_T distribution peaks at about 12 GeV and extends well over 100 GeV because the dark photons are highly boosted. Triggering and detecting electrons and muons below about 10 GeV is experimentally challenging. However, the presence of multiple GeV-scale leptons of both signs are possible trigger signatures that could help reduce the trigger rate allowing for lower lepton p_T thresholds. The distribution of separation of lepton pairs in η-ϕ space is largely below 0.1 illustrating the collimated nature of the lepton jet. It is important to study the efficiency for triggering and reconstructing closely spaced electrons and muons for HL-LHC, HE-LHC, and FCC detectors. If charged track information is available at the trigger level, merged electron showers could be identified as originating from electron pairs. Similarly, track information could identify closely spaced muon pairs that, because of multiple Coulomb scattering, are difficult to identify in the muon detector. It is also important to study the backgrounds to lepton jets from SM processes and from mis-identified hadrons.

Higgs Portal Model for Dark Photon Production

Models in which dark photons couple to Higgs bosons are referred to as Higgs Portal models. Our benchmark model is that of Falkowski, Ruderman, Volansky and Zupan [3]. The Higgs boson decays to a pair of dark fermions, each of which decays to a Hidden Lightest Stable Particle (HLSP) and a dark photon. The dark photon decays to a lepton jet, as in the SUSY Portal model. Higgs Portal models are implemented in Pythia and under current evaluation by our group. Initial studies for HL-LHC indicate that the kinematic distributions are similar to those for the SUSY portal. Thus, the same considerations for triggering and reconstruction efficiency apply for both dark photon models.

Pair Production of Doubly-Charged Higgs

An exotic doubly-charged Higgs could decay to same-sign lepton pairs (electron or muon pairs) resulting in a four-lepton final state with much different kinematic properties compared to those in the dark photon models. Our benchmark model is the left-right symmetric model of Huitu, Maalampi, Pietila, and Raidal [4]. The production process is similar to that in Drell-Yan production: quark anti-quark scattering produces a virtual Z/γ state which decays to a pair of oppositely-charged doubly-charged Higgs. Each Higgs can decay to same-sign electrons or muons. A search in this channel was published by ATLAS [5] at 13 TeV collision energy.

This doubly-charged Higgs production is implemented in Pythia. Our first studies have been for HL-LHC with a 200 GeV Higgs. The leading lepton p_T distribution peaks just below 200 GeV and only a small fraction of events have p_T less than 100 GeV. Future searches will explore the 1 TeV and greater mass range. A single lepton p_T trigger will be highly efficient.

Plans for the Snowmass Study

For the HL-LHC, HE-LHC, and FCC our goal is to estimate the sensitivity in cross-section for dark photons and doubly-charged Higgs as a function of mass for the models presented. We will optimize the trigger strategies and evaluate the benefits of employing track information in the trigger and timing information in reconstruction. The utility of event scouting will also be evaluated. We will consider several values of collision energy for each accelerator.

Our initial goal is to make these studies using only Pythia, with estimates of the detector acceptance and efficiency for electrons and muons as a function of lepton η and p_T. Subsequently we will employ a full detector simulation for the HL-LHC for the CMS detector. This is a crucial step to determine the effect of pile-up on signal efficiency and suppression of standard model backgrounds. This full simulation is also important for studying complex lepton jets from dark photon decays with multiple lepton pairs and multiple pions. The full simulation can be used to obtain realistic parameterizations of lepton efficiency that can be used for Pythia-only simulations.

References

[1] C. Cheung, J.T. Ruderman, L.-T. Wang and I. Yavin, "Lepton Jets in (Supersymmetric Electroweak Processes," JHEP 04 (2010) 116 [arXiv:0909.0290].

[2] ATLAS Collaboration, "A search for prompt lepton-jets in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," JHEP 02 (2016) 062.

[3] A. Falkowski, J.T. Ruderman, T. Volansky and J. Zupan, "Discovering Higgs Decays to Lepton Jets at Hadron Colliders," Phys. Rev. Lett. 105 (2010) 241801 [arXiv:1007.3496].

[4] K. Huitu, J. Maalampi, A. Pietila, M. Raidal, "Doubly charged Higgs at LHC," Nucl. Phys. B 487, 27 (1997) [arXiv:hep-ph/9606311].

[5] ATLAS Collaboration, "Search for doubly charged Higgs boson production in multi-lepton final states with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV," Eur. Phys. J. C (2018) 78:199.