Dark sector searches using the Higgs boson in ATLAS

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Observational and experimental data from astrophysics, cosmology, and particle physics strongly support the possible existence of new phenomena that are beyond the standard model of particle physics. The Higgs boson may provide sensitivity to this new sector which has remained inaccessible up to now. We provide an overview of an analysis strategy to determine the ATLAS detector sensitivity to couplings of the Higgs boson to dark or hidden sector vector bosons, Z_d, that decay to leptons (muons and electrons).

Theories of fundamental interactions that are beyond the standard model (BSM) of particle physics are believed to be necessary in order to explain much natural phenomena. The standard model (SM), while extremely powerful as a theory of the strong, electromagnetic and weak interactions [1, 2, 3], does not appear to provide a natural candidate to explain Dark Matter (DM), Dark Energy, the θ term in the QCD Lagrangian, or the reason for so many free parameters in the theory. The SM may be part of or embedded in a more fundamental structure of particles and interactions at a new mass scale or with couplings that have not been previously accessible experimentally. In this case, new particles, dynamics, and symmetries that are beyond the SM could appear and signal the new physics associated with it. When the SM is embedded in a larger unified theory based, for example, on superstrings or supergravity, a hidden or “dark” sector of particles and interactions usually results [4]. Much recent attention in the theoretical community on this “dark sector” physics has been focussed on massive particles with MeV to TeV mass scales [5, 6, 7]. In astro-particle physics, the most recent satellite data from Fermi-LAT [8] and AMS-02 [9] indicate a stiffening of the positron spectra with energy from about 10 GeV up to a few hundred GeV (AMS-02: 8-275 GeV) where a behavior that decreases with energy is expected. Possible explanations for this excess are that it is attributed to more mundane phenomena such as radiation from nearby pulsars, or molecular cloud ionization. However, a strong possibility is that this excess is due to DM annihilation that proceeds through the exchange of a dark force or dark matter particle. These ideas are thus suitable for testing at the Large Hadron Collider (LHC) [10]. The bosons of the dark sector would couple only very feebly to SM fields that were used previously, in order to be consistent with observations. There could be several types of dark sector particles, with scalar, pseudoscalar, and vector intrinsic spin assignments [11].

A new probe of this hypothetical hidden or dark sector may have become available at the energy frontier opened up by the LHC. The experimental search for a Higgs boson has resulted in a new discovery at the LHC, a boson with a mass in the vicinity of 125 GeV [12, 13]. This was interpreted as a clear evidence for the production of a neutral particle and found to be compatible with the production and decay of the SM Higgs boson. If there is a family of dark sector particles and interactions, they may couple to this Higgs boson in a unique manner that is not possible with other SM fields. This physics may therefore be accessible experimentally in a way that did not exist previously [14, 15, 4, 16, 17]. In this work, we consider the effect of the Higgs boson (H) couplings to both a dark sector (Z_d) and a SM weak vector (Z), $H \to ZZ_d \to 4l$, as well as the SM process, $H \to ZZ^* \to 4l$, where $l = e, \mu$ in both cases. Only four lepton events resulting in the new Higgs boson at approximately 125 GeV are used in the study. The search is for a narrow peak or excess above background in the Z^* spectrum (the Z^* can propagate off-shell), resulting from decays to di-leptons. An example of the process described in this work can be seen in the top process of Figure 1. The Higgs boson is produced via gluon-gluon fusion, the dominant production mechanism at the LHC. The Higgs boson would then decay into a SM Z^0 boson and a hidden sector gauge boson Z_d that subsequently decays directly into two leptons, in this case either a di-muon or di-electron pair. It is possible that the dark sector gauge boson would kinetically mix with the SM Z^* boson (if it is itself a vector boson) that then decays into di-leptons as shown in the top process of Figure 1.

Several groups in ATLAS [18] have or are presently engaged in related searches, but with very different strategies and signatures than those used in the analysis described here. Invisible Higgs searches may be used to set limits on its couplings to hidden sector particles and interactions. Analyses that attempt a search for Higgs invisible decays to a hidden sector will include an incoming gluon or quark in the production channel that radiate a single gluon or photon (mono-X events), for instance [19, 20]. The mono-X events include large amounts of missing transverse energy, and a high energy jet or photon, unlike this present study. Invisible decays of the Higgs boson may also be studied in events that include associated production with or without vector bosons, such as $q\bar{q} \to q\bar{q}H$, $gg \to ZH$ [21]. SM fields may couple to a supersymmetric hidden valley of BSM particles via a mediator messenger dark boson that itself decays to pairs of highly collimated leptons (lepton jets) [22]. The final states in those processes are similar to those of the present study, except that the former are highly collimated. Several new BSM vector bosons are predicted in models that are tested in the analysis of di-lepton decays [23]. These studies focus on high invariant mass di-lepton events so as to be consistent with LEP constraints. The direct production and decays of these predicted resonances are considered, unlike in the present study where the new hypothetical resonance couples directly to the Higgs boson and decays to

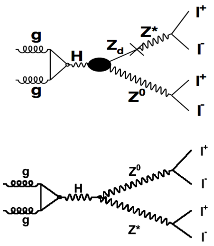

Figure 1: The Higgs boson (H) may decay into an on-shell SM Z^0 boson plus a dark sector vector boson Z_d, with kinetic mixing, as indicated in the top diagram. The bottom diagram shows the SM process where the Higgs boson decays into a Z^0 boson as well as an off-shell Z^* boson.

two leptons in the process shown at the top of Figure 1.

The process $H \to 4l$ was one of the two "discovery modes" in the search for the Higgs boson (the other being $H \to \gamma\gamma$) [12, 13, 24]. The present analysis makes use of this clear discovery channel in the search for a new dark vector boson. The search strategy is as follows:

1. The $H \to ZZ^* \to 4l$ events are the starting point for the analysis. Only those $4l$ final state events that reconstruct the resonance near 125 GeV are used in the subsequent analysis to search for Z_d.

2. The Z^0 boson invariant mass is fully reconstructed in the intermediate state and this selection is shown to agree with the Particle Data Group value.

3. Decays of the Z^* boson that propagates off the mass shell are then considered. These invariant mass events are not expected to exhibit a peak for SM events. Thus, a narrow peak or excess of events above background in this spectrum signals the new particle state, Z_d.

4. The Profile Likelihood ratio based on the the frequentist ATLAS statistical procedure [25] is used to quantify any narrow peak or excess of events above background in the subleading di-lepton invariant mass spectrum. In the absence of a signal, the search results are presented as a limit of the ratio

$$\frac{BR(H \to ZZ_d \to 4l)}{BR(H \to 4l)} \tag{1}$$

in the mass range considered.

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