Higgs boson decays to 4l+MET via dark vector bosons

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Abstract. Physics beyond the Standard Model (BSM) is well motivated and one important search area is to use the Higgs as a discovery portal for dark matter (DM). One specialisation of this search is to the exotic decay of the Higgs via two dark vector bosons, Z_d, each of which promptly decay to two leptons, giving a clean four lepton final state. In this search, the SM Higgs fluctuates to the dark Higgs via Higgs mixing at the SM Higgs mass. The decay then proceeds via the virtual dark Higgs. A variation is that the Higgs is produced rather at the dark Higgs mass, with the same production mechanism and decay topology. In this case, the search includes S, the dark Higgs, in addition to the dark vector boson, Z_d. Previous studies of these channels have shown a search for Higgs decays to a 4l+MET final state could be another promising avenue. Here MET refers to missing transverse momentum, meaning there is also an additional dark particle in the modelling. Currently there are no constraints on the dark Higgs mass. We introduce this new search, which is still in the initial stages.

1. Introduction

The Large Hadron Collider at CERN (LHC), Switzerland, is able to detect billions of high energy events in proton-proton collisions. This allows us to probe exciting new areas of physics. One of these areas is dark matter: there are many theories for what constitutes dark matter but little positive evidence for what it could be [1]. Investigating potential candidates for dark matter and how they interact with normal matter is a crucial part of advancing our understanding of fundamental physics.

2. Background

2.1. Dark Matter

There is extensive astrophysical evidence for dark matter, including: rotational curve of many galaxies which indicate that normal matter cannot account for the gravitational strength observed, another phenomenon is gravitational lensing by clusters of galaxies, which also requires additional gravitating mass and also mentioned is the observed large scale structure of the cosmos and the microwave background, the modelling of which requires the existence of cold dark matter [2]. Thus, we must search for matter which interacts predominantly via gravity and potentially only very weakly via a residual interaction.

2.2. Higgs Portal

The discovery of the Higgs boson in 2012 by the ATLAS and CMS experiments [3, 4] opened up a promising new avenue in the search for dark matter. Because of both the Higgs' high mass and its role as the excitation of the Higgs field, which gives particles mass, it may preferentially couple to exotic, high-mass particles. If this is the case then decays of the Higgs boson could be rich sources of information for production and behaviour of exotic particles, such as dark matter particles [5–8].

2.3. Dark Vector Bosons

One branch of exotic Higgs decays that has already been investigated is Higgs decays via dark vector bosons [9–12]. These studies used the Hidden Abelian Higgs Model (HAHM) [13–18]. This model allows coupling of dark matter to normal matter. This can be represented by the introduction of a kinetic mixing term, ϵ, between normal bosons and dark bosons would allow for such a residual weak interaction [14]. The mixing between the SM and dark Higgs is also accommodated within this model. In the searches discussed above, a Higgs is produced by gluon-gluon fusion (ggF) which subsequently mixes to the dark Higgs and then decays to two dark vector bosons, Z_d, each of which themselves decay into two leptons of opposite sign and opposite flavour, giving a four lepton final state.

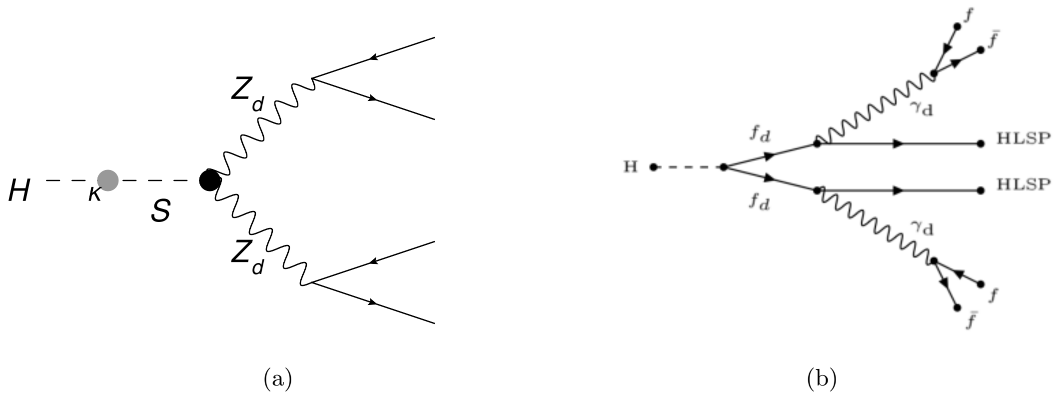

Figure 1: Feynman Diagrams (a) where a Higgs boson is produced by ggF, fluctuating to the dark Higgs, S, which decays via two Z_d to 4-leptons and (b) an example where there is also missing transverse momentum in the final state [19].

This scenario is shown in figure 1(a). Depending on whether the ggF Higgs production is on shell for the Higgs or the dark Higgs (sometimes called more generally the additional scalar), then the invariant mass of either the Higgs or the dark Higgs can be reconstructed from the kinematics of the four leptons. Higgs to Z_d to four leptons studies allow us to search for possible dark vector bosons and possibly also the dark Higgs and then study the coupling constants.

The previous studies have shown Z_d candidates, which are still however consistent with the SM, yet they remain of interest to follow up, shown in figure 2. The region of interest for a possible Z_d from these studies is 20-30 GeV.

2.4. 4l and MET

The final state event displays for the previous Z_dZ_d analysis indicated the presence of MET in the range 20-80GeV , which was not accounted for in these studies.A typical event display in the additional scalar search as mentioned above but not yet published is shown in figure 3. A natural progression of the previous searches is to conduct a search that includes MET in the 4-lepton final state and investigate the bumps further. Accordingly we have chosen a model which can generate events in this scenario, as shown in figure 1(b). The previous studies used the Hidden Abelian Higgs Model (HAHM), which does not include any MET. This particular model uses

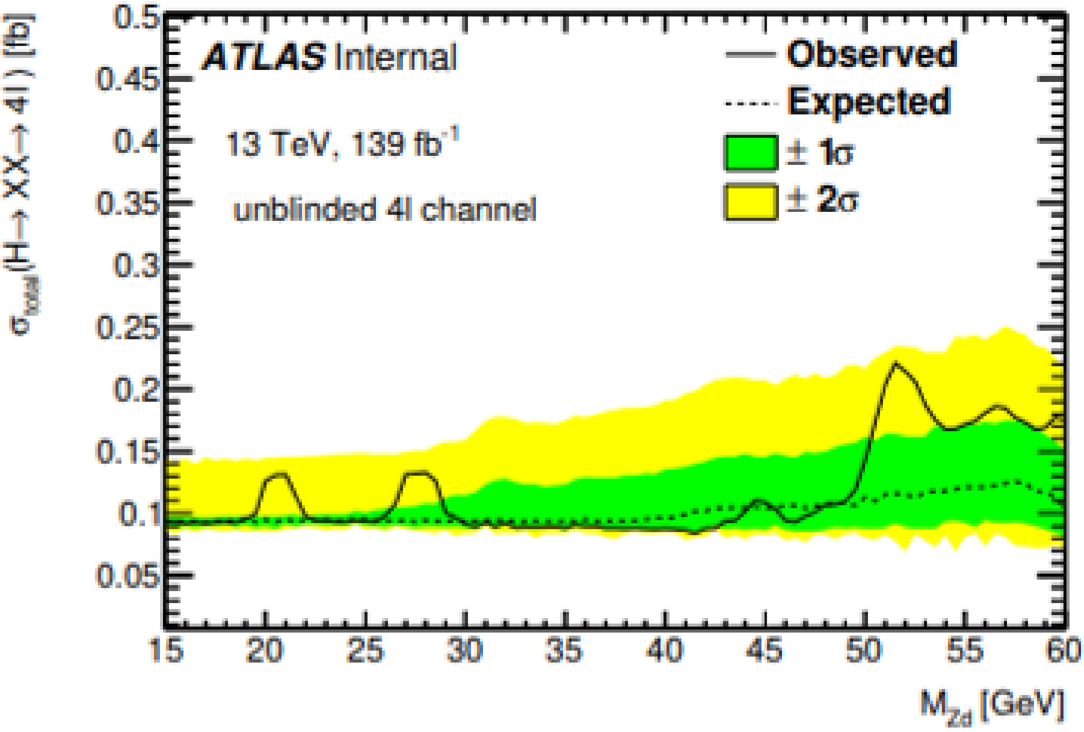

Figure 2: Cross section of the Higgs to $Z_d Z_d$ decay for different Z_d masses. Future regions to follow up are the regions (still consistent with the SM) at 20Gev, 25-30Gev and 50-55GeV [9–12]

the the Falkowski–Ruderman–Volansky–Zupan (FRVZ) model, which introduces lepton jets - events which produce between 4 and 8 collimated leptons in the final [20, 21]. Lepton jets are predicted by models which predict a massive hidden vector particle in the MeV to GeV range, in this case a dark photon. This dark photon has a small kinetic mixing with the SM photon, which allows it to decay to lighter particles with electric charge

Including MET in the kinematics for the signal Monte Carlo event generation via the above model is not considered a model dependent analysis. This allows one to have signal events, to be added to the Monte Carlo background events, to facilitate the development of the search algorithm. The actual search will look for excesses which could come from a more general class of models that still conform somewhat to these kinematics.

3. Methodology

We will conduct a resonance search where the mass of each Z_d boson can be reconstructed from the combined invariant mass of the resulting lepton pairs. The search will look specifically in the mass ranges of 20-30 GeV for the Z_d. Currently the analysis is still in the early stages of signal generation.

3.1. Signal Generation

The first step in the analysis is signal generation. A suitable model must be found to produce the signal for the $H- > 4l + MET$ decay. This is done using Monte-Carlo (MC) programs, such as MadGraph [22] and Pythia [23], which can generate chains of particle interactions starting from a proton-proton collision. These programs allow you to simulate the decay of a particle via a specific path and record statistics, such as particle kinematics, for every step along the way. The model used for signal generation must be validated by producing kinematic plots for final

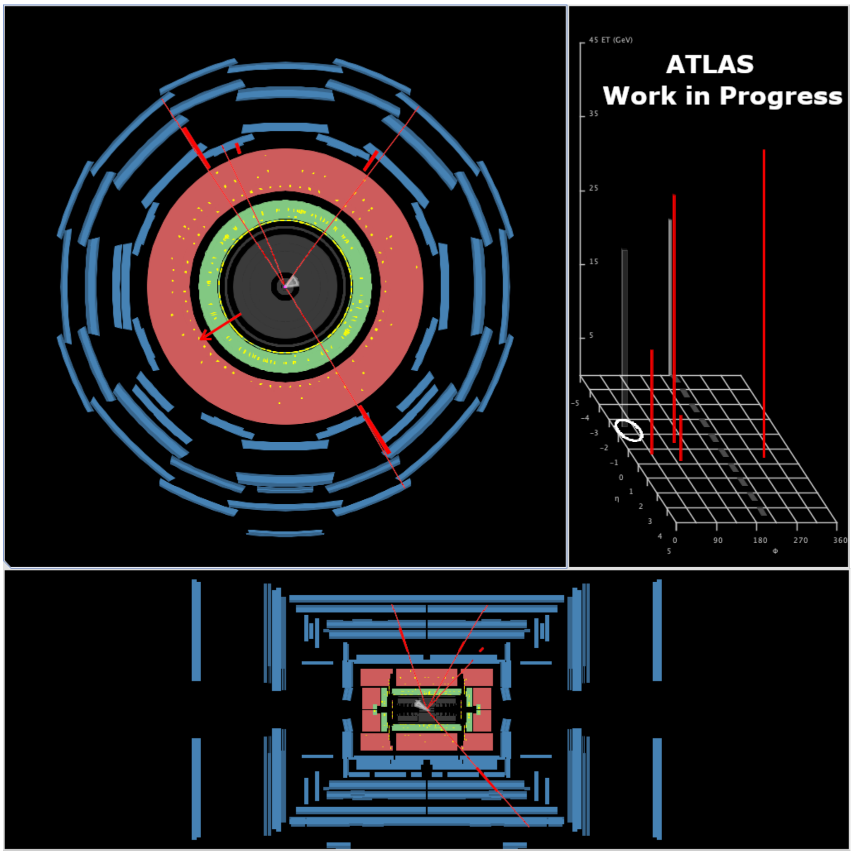

Figure 3: Event display for one candidate event. Electrons are indicated by green segments/towers, and muons by red segments/towers. The ovals in the η–ϕ plane represent jets ($p_T > 15\,\mathrm{GeV}$) and the red arrow represents the $E_{\mathrm{T}}^{\mathrm{miss}}$. For this 4μ event, $m_{4\ell} = 107.4\,\mathrm{GeV}$, $\langle m_{\ell\ell}\rangle = 30.8\,\mathrm{GeV}$, and $E_{\mathrm{T}}^{\mathrm{miss}} = 21.0\,\mathrm{GeV}$

state particles in the mass region of interest. Constructing a program to simulate your decay from scratch can be very complex and time-consuming. Thus the best approach is to reuse code from another analysis with a similar decay and final state, by adapting it to be as close as possible to the decay and final state you desire. Because the previous Z_dZ_d studies used the HAHM, they could not be adapted to include MET in the final state, so a new model had to be found and adapted. A similar model to our decay can be seen in an analysis investigating light long-lived particle that decay to lepton jets [19].

A decay for the this model can be seen in figure 1(b). For the purpose of the 4l+MET, the model can be adapted such that the Hidden Lightest Supersymmetric Particle (HLSP) would constitute the MET and the dark photons would become the dark bosons. The fermions would be leptons and the f_d would be further intermediate dark particles.

One issue with this model is that the particles labelled f_d are produced back-to-back: their transverse momentum, p_T, must cancel each other out. This means their subsequent decay products must have a p_T that also adds up to being effectively back-to-back, which limits the MET p_T distribution to being quite low - to have a high p_T MET you would also have to have the other decay products by high p_T, which is less likely. This limits the MET to being almost entirely below 50GeV, which limits the maximum MET size we can analyse from this model. However, it is still worth using this model for validation plots as there could still be interesting information for MET in this region.

Figure 4 shows typical kinematical distributions as produced by this model. The examples selected are the leading and subleading electron and muon pairs transverse momenta.

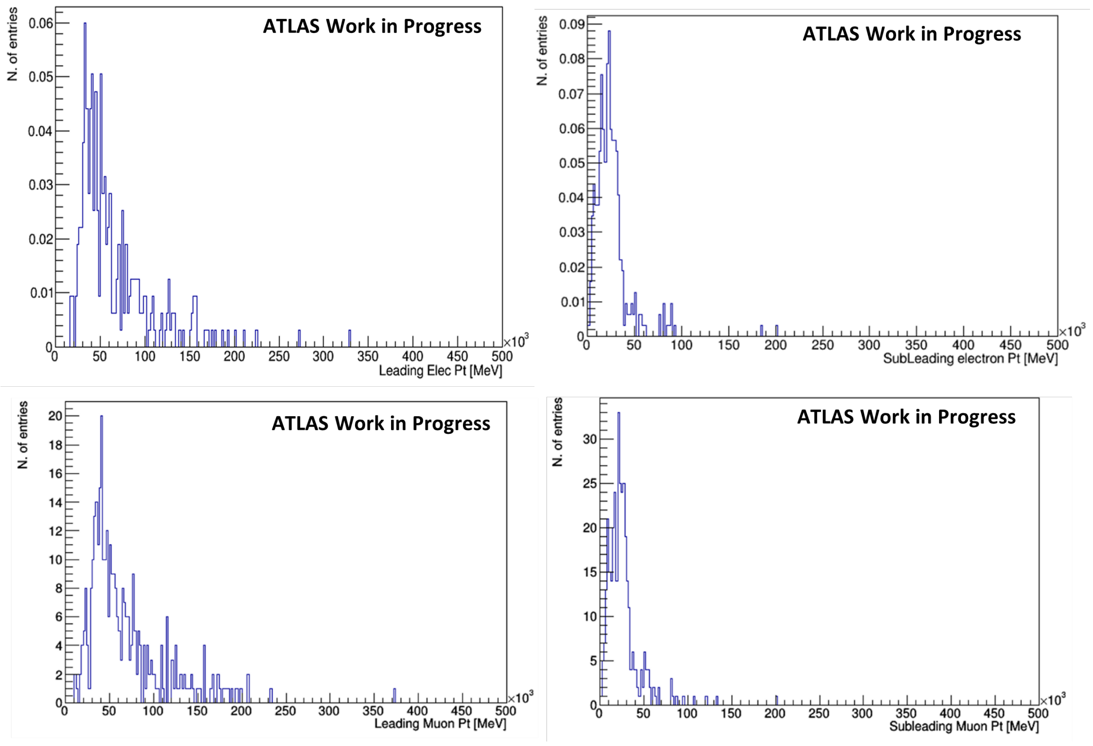

Figure 4: Kinematic plots of leading and subleading electron pair and muon pair transverse momenta produced using the Lepton Jets model [19].

3.2. Background

It is expected that most backgrounds for this analysis will be due to incorrect identification of leptons. Events with more than 4-lepton final states where some leptons go undetected or are mislabelled could be mistaken as candidate events. Similarly events with leptons plus jets/ photons in the final state where the jets/ photons fake leptons could be mistaken as a 4-lepton final state. In the SM, MET always represents neutrinos so events with four charged leptons plus some neutrinos could be mistaken as candidate events. Jets can also be misidentified as MET.

4. Conclusions

The aim of the analysis is to investigate a Higgs decay via dark bosons to a 4l+MET final state, which is motivated by previous studies into a 4l final state that revealed excesses at certain masses. The analysis is still in the early stages: progress has been made in signal generation and a potential model for the signal has been discovered but still needs to be validated. Once signal generation has been completed then the relevant backgrounds will have to be determined and modelled as well. The general statistical analysis must be developed in order to be able to determine signal from background. Novel machine learning methods for reducing background will also be investigated and compared to standard cut-based methods.

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