Hypothesising Dark Matter Models in pp Collisions

Stefan von Buddenbrock[1], **Alan S. Cornell**[2] **and Bruce Mellado**[3]
School of Physics, University of the Witwatersrand, Wits 2050, South Africa
E-mail: [1]stef.von.b@cern.ch, [2]alan.cornell@wits.ac.za, [3]bmellado@mail.cern.ch

Abstract. Recent LHC Run 1 analyses have shown an apparent mismodelling is Higgs p_T from ATLAS $\gamma\gamma$ and 4ℓ decay channels, as well as the CMS 4ℓ decay channel. We refer to this as the p_T crisis, and postulate that it can be explained by the Higgs being produced in combination with a dark matter particle. A minimal Z' is modelled as a dark matter mediator and shown to have cross sections too low to satisfy current experimental constraints. The viability of a 2HDM being modelled as a form of dark matter is then argued to be a viable solution to an excess of double Higgs production events from Run 1 LHC data, and an experimental analysis done by ATLAS is given as motivation. We conclude by noting that these analyses will be enhanced by data from Run 2 of the LHC.

1. Apparent Mismodelling in the Standard Model

1.1. The p_T Crisis

It goes without saying that the discovery of the Standard Model (SM) Higgs boson in 2012 [1, 2] has sparked the interest of the global particle physics community. With a large amount of confidence that the discovered particle is indeed the Higgs boson predicted by the SM, physicists are now asking questions about whether the Higgs boson carries with it some signature of physics beyond the Standard Model (BSM).

Experimental observations are, at the moment, the only resource by which we can infer the existence of BSM physics. By measuring the properties of Higgs production and comparing the data to what we would expect from the SM, we can look for instances of what we call *mismodelling* – that is, the SM may not reproduce what we observe in experiment. It has become apparent that the ATLAS and CMS pp collision results from Run 1 of the LHC are indeed exhibiting a sort of mismodelling.

In particular, we consider the so-called p_T crisis. Recent analysis of LHC Run 1 data has shown that there is a mismodelling of Higgs transverse momentum (p_T) spectra. Experimentally obtained p_T spectra indicate that the data is assuming a different structure from what we expect in the SM. This can be seen from the ATLAS $h \to \gamma\gamma$ decay results [3] (shown in figure 1), the ATLAS $h \to ZZ \to 4\ell$ decay results [4], and the CMS $h \to ZZ \to 4\ell$ decay results [5]. Our interest is the apparent excess of p_T in these spectra. An excess of p_T might imply that the Higgs boson produced in the LHC is recoiling off of a particle which, along with its decay products, does not interact with the detector at all. We will refer to this type of particle as a *dark matter* particle. The purpose of this study is to test the viability of dark matter production at the LHC being responsible for the p_T crisis.

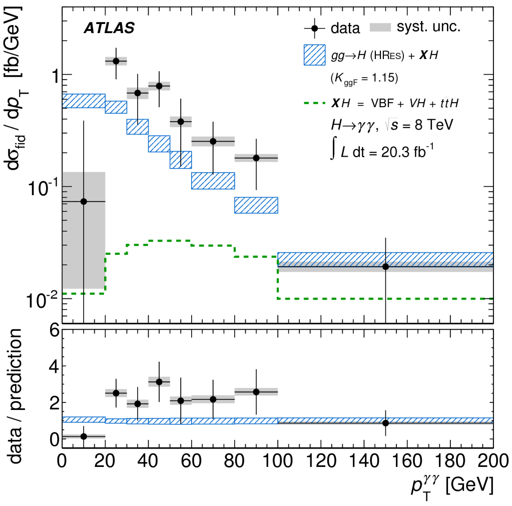

Figure 1. The p_T spectra arising from performing analysis on the ATLAS Run 1 diphoton decay channel data and extracting fiducial cross sections of the processes [3].

1.2. Dark Matter

The existence of dark matter was first postulated by astrophysical measurements. Nowadays, we regard dark matter as making up about 24% of the universe's energy content. As a particle physicist, however, one can think of dark matter merely as a massive particle which does not interact electromagnetically. Therefore, any model which may be proposed for the existence of dark matter is currently believed to satisfy a set of two experimental constraints. The first set of constraints is one which we can attribute to its particle nature, and these constraints are set by the fundamental principles of quantum field theory as well as particle detector data. The second set of constraints comes from astrophysical observations. For instance, a dark matter candidate (or candidates) must be able to explain the dark matter density in the universe [6]

$$\Omega_{\mathrm{DM},0}h^2 = \frac{\rho h^2}{\rho_0} = 0.1196 \pm 0.0031,$$

where h here is the scale factor of the universe and $\Omega_{\mathrm{DM},0}$ is the energy density of dark matter in universe. Thus, the study of dark matter is inherently interesting and difficult due to the fact that it links particle physics with cosmology.

2. Z' Dark Matter

2.1. Theoretical Construction

By Occam's Razor, we note that it is often wisest to consider the simplest hypothesis when attempting to explain phenomena. In the case of dark matter, the simplest model is one which extends the gauge symmetry of the SM by including an extra $U(1)$ symmetry. An extra $U(1)$ predicts the addition of an extra particle, which is usually denoted by Z'. The model which I have considered is the *minimal* Z' model, which has a corresponding conserved *baryon minus lepton* charge, denoted by $B - L$ for short [7].

In pp collisions, we would expect the leading order of Z' production come from tree level reactions of which the diagram is shown in figure 2. This is where the virtue of the Higgs boson can be seen in detecting dark matter. Since the Z' is considered an *invisible* particle and will not interact electromagnetically, the best chance of detecting such a particle will come by virtue of its mass. Since the Z' is considered to be a massive particle, it will couple to the Higgs, and we can therefore use the Higgs boson as a *portal* in studying possible dark matter candidates.

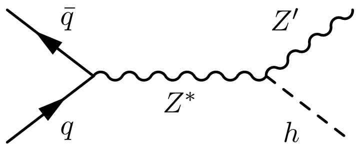

Figure 2. Leading order Z' production from pp collisions.

2.2. Simulation Results

A `MadGraph` [8] model was generated from a `FeynRules` package implemented by Lorenzo Basso [7]. This computational model was created using the minimal Z' physical model described above. The model allows for the variation of the Z' mass as well as its associated gauge couplings. In this work, we determined the effect of varying the mass of the Z', while the couplings at their default values.

The process which was modelled has the form

$$q\bar{q} \to Z \to Z'H,$$

the Feynman diagram of which can be seen in figure 2. For all simulations, we used a center of mass energy of $\sqrt{s} = 14\text{TeV}$. By varying the mass of the Z' between values of 0.05TeV and 1.5TeV, we were able to plot the cross section as a function of $M_{Z'}$ which is shown in figure 3.

We can note that in figure 3, there is a clear constraint on the mass of the Z' which can be deduced, should we seek to detect the particle. The production cross section is only substantial at masses smaller than $\sim$ 100GeV. This implies that if we are to detect a Z', there is a very little chance that we could detect a Z' with a mass in the TeV scale. This puts the idea of Z' dark matter in a rather unconvincing light, since it can be argued that dark matter mediated by a Z' could only be plausible if the Z' mass is in the TeV scale [9].

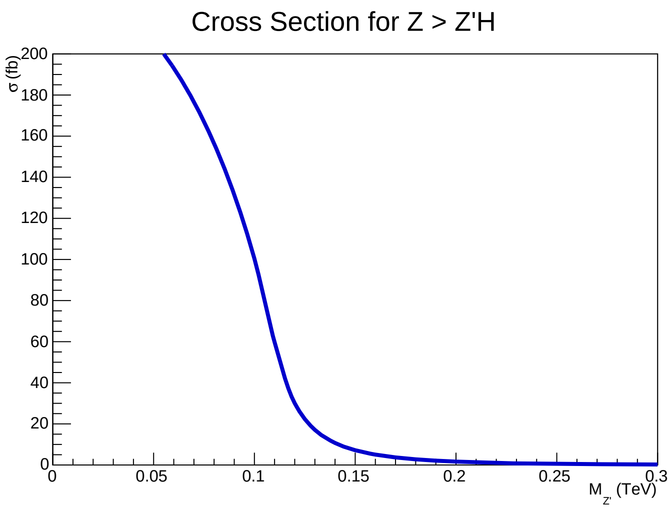

Figure 3. The cross section for tree level Z' production reactions in association with a Higgs boson, as shown in figure 2. The mass of the Z' was varied, while keeping its associated couplings constant.

3. Two-Higgs-Doublet Models

3.1. Theoretical Construction

The SM of particle physics is built by incorporating and studying electroweak symmetry breaking (EWSB) – that is, the spontaneous breaking of the $SU(2)_L \times U(1)_Y$ gauge symmetry . After EWSB, we are left with four massive bosonic states: the Z boson, the W^+ and W^- bosons, and the Higgs boson h. This is because we impose the existence of a complex scalar doublet (which has four degrees of freedom), the Higgs doublet ϕ. The SM Higgs potential has the form

$$V_H(\phi) = \mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2.$$

The experimental discovery of the Higgs boson is well explained by this structure of the SM.

However, what has been observed experimentally could be explained equally as well by imposing two Higgs doublets in the construction of the SM. If we call these doublets ϕ_1 and ϕ_2, then the general renormalisable Higgs potential can be written down as [10]

$$V_H(\phi_1,\phi_2) = m_{11}^2|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2\phi_1^\dagger\phi_2 - \left(m_{12}^2\right)^*\phi_2^\dagger\phi_1 + \frac{1}{2}\lambda_1|\phi_1|^4$$
$$+\frac{1}{2}\lambda_2|\phi_2|^4 + \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right) + \frac{1}{2}\lambda_5\left(\phi_1^\dagger\phi_2\right)^2 + \frac{1}{2}\lambda_5^*\left(\phi_2^\dagger\phi_1\right)^2.$$

Any model which incorporates two Higgs doublets in this way is called a Two-Higgs-Doublet Model (2HDM). The spontaneous symmetry breaking of a 2HDM requires us to introduce a different vacuum expectation value (VEV) for the second Higgs doublet, v_2, in addition to the normal VEV we are familiar with, v_1. The physical VEV is then given by

$$v^2 = {v_1}^2 + {v_2}^2,$$

and the two VEVs are related by an angle β such that

$$\tan\beta = \frac{v_2}{v_1}.$$

The physical implication of introducing a second Higgs doublet is that four new massive physical states are introduced. These are a heavy CP even Higgs boson H (which is heavier than the SM Higgs boson by convention), a CP odd Higgs boson A, and two charged Higgs boson H^+ and H^-. The two neutral CP even Higgs bosons are related by a mixing angle α. One might treat These new states (or at least their potential decay products) as dark matter particles.

3.2. Experimental Work

While we have done no work on modelling a 2HDM states as dark matter particles, it should be noted that the existence of these states is currently being taken very seriously in certain ATLAS analyses. One such analysis is, which we will consider, is that of an excess of double Higgs production from Run 1 LHC data.

Using the SM, one shouldn't expect to find a significant contribution resulting from pp collisions resulting in a final state of two Higgs bosons. However, Run 1 LHC data seems to indicate an excess of double Higgs production events. One explanation for this is that a heavy resonance X is decaying into a Higgs pair.

Figure 4 shows the 95% CL limit while modelling a resonance decay with the variation of the its mass. This analysis was conducted by studying the $\gamma\gamma b\bar{b}$ decay channel of the Higgs pair [11]. It seems evident that Run 1 data seems to favour a resonance mass of about 300GeV. We could model this resonance as being the heavy Higgs state predicted by a 2HDM, since a heavy

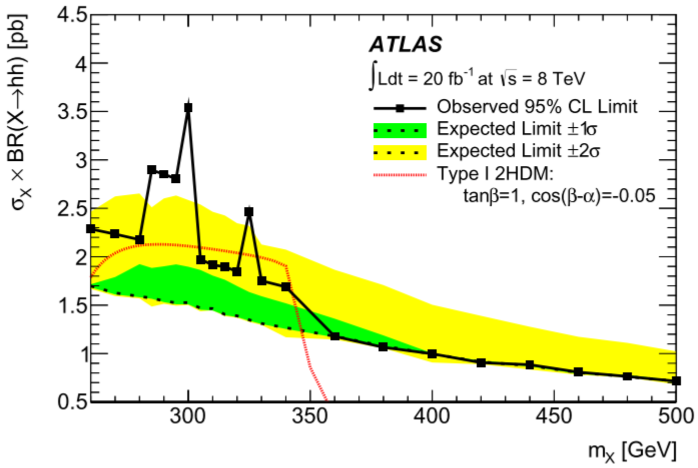

Figure 4. A 95% CL upper limit on the cross section times branching ratio of a resonance X decaying to a Higgs pair as a function of the resonance mass [11].

Higgs could decay into two SM Higgs bosons. If we use a 2HDM to study the process, we would expect contributions from the diagrams shown in figure 5.

Although it seems that this excess is due to a resonance decaying, it should be noted that there is a possibility of it being due to a non-resonance effect as well. There is also, of course, the possibility that the excess is merely a statistical fluctuation, but only more data will shed light on this possibility.

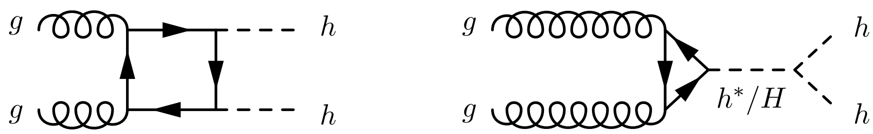

Figure 5. The leading order diagrams for double Higgs production from pp collisions. The diagram to the right shows the possibility of a heavy Higgs decaying into a pair of lighter SM Higgs bosons.

4. Concluding Remarks

The p_T crisis resulting from Run 1 LHC data presents us with the possibility to explore BSM physics. The fact that we see an excess in Higgs p_T alludes to the idea that the Higgs boson is being produced in combination with a massive and invisible particle which we might think of as a dark matter particle. While the possibility of a Z' mediating dark matter seems to be far from feasible with current constraints, we do recognise the possibility of finding a state predicted by a 2HDM, although more data is needed to start work on classifying whether or not it could count as a discovery. The p_T crisis itself could merely be a statistical fluctuation. We can conclude by saying that many of the results and ideas presented are in need of clarification which only more experimental data could provide, and these analyses will benefit from the data accrued by Run 2 of the LHC.

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