Phenomenology for a dark matter model with two mediators

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September 6, 2017

Abstract

We discuss the expected signal at the LHC from a dark matter model with two mediators. The model extends the Standard Model by one dark Majorana fermion χ, a heavy Z' gauge boson and a dark Higgs s. We discuss the number of events we can expect for the current LHC run with $\sqrt{s} = 13\text{TeV}$ and a luminosity of 40fb^{-1} for different masses. The characteristic signature is missing energy from the production of $\chi\chi$ and the decay of a dark Higgs via mixing with the Standard Model Higgs. This decay can be $s \to b\bar{b}$, where we find many events, but we expect a large background. A much lower background is expected for the dark Higgs decay to $\gamma\gamma$. However, the number of events depends on the branching ratio $s \to \gamma\gamma$, which might be as small as the SM Higgs branching ratio $H \to \gamma\gamma$. In this case the mass parameter range where a detection is possible is small. With the upcoming Run 3 at the LHC, where $\sqrt{s} = 14\text{TeV}$ and the luminosity is 300fb^{-1}, the sensitivity of the LHC is much higher and the possibility to detect the decay $s \to \gamma\gamma$ is increased.

Contents

1 Introduction

The only evidence for the existence of dark matter (DM) is it's gravitational interactions. The structure of the dark sector, assuming it exists, is therefore unknown. But because DM is not seen in any experiments so far, there are restrictions on DM models. For example, DM has to be electrically neutral and non-relativistic [1]. A common way to use all the experimental knowledge we have on what DM cannot be is to use Effective Field Theories (EFTs). In EFTs, we can integrate out degrees of freedom because the energy that can be accessed in the experiment is much lower than the energy of the underlying dynamics. Therefore, one only considers one DM particle, which directly couples to the Standard Model (SM). This results in a very simple model with few parameters and an easy possibility to compare different experimental results.

However, EFTs have some drawbacks: they have strong boundaries from experiments because nothing has been observed so far, and their validity for collider searches at the Large Hadron Collider (LHC) has been questioned [2]. The easiest way to build models that still have a promising parameter range is to use simplified models. In simplified models, the EFT is expanded by including a dark mediator. The dark mediator is heavy, but can be produced at the LHC, and couples to a DM fermion as well as to the SM. Searching for signals from a simplified model assumes that the collider energy is high enough to resolve some of the underlying process, but not all of it. In the limit of a high mediator mass, the EFT is recovered.

The simplified model we consider consists of a DM fermion χ and two mediators, one carrying spin 1 (a new dark Z' gauge boson) and the other carrying spin 0 (an additional Higgs boson s in the dark sector). We assume that the mediators interact with the Standard Model particles. This model has already been discussed in [3] and [4]. In this report, we will discuss the possibility of detecting the interaction between DM and SM particles at the LHC, assuming the model we will discuss in detail in Section 2. We will redo part of the analysis that was done in [4]; namely $pp \to \chi\chi s; s \to b\bar{b}$ in Section 3.1. Then, we will discuss the process $pp \to \chi\chi s; s \to \gamma\gamma$, where $s \to \gamma\gamma$ is a loop process, in Section 3.2.

2 Theory

Introducing two mediators in the dark sector has several advantages [4]: A large parameter space is already ruled out by experiment for DM models with one mediator. Those limitations on masses and coupling constants often lead to cross sections that are too small. And if the cross section is too small, DM is overproduced, meaning that not enough annihilations of DM to SM particles could have happened before the freeze-out. The introduction of a mediator which is lighter than the DM fermion brings new annihilation channels which help setting the observed relic abundance. Furthermore, it is possible to establish thermal equilibrium with a simplified model.

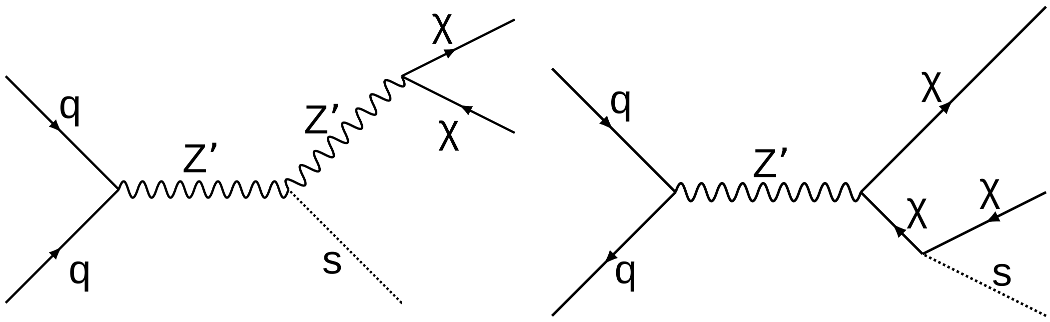

Figure 1: Example Feynman diagrams for the production and decay of a dark mediator Z' as proposed by the model in Eq. 1.

The full Lagrangian of this model is the following:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_\chi + \mathcal{L}_S + \mathcal{L}'_{\rm gauge}, \tag{1}$$

where $\mathcal{L}_{\rm SM}$ is the Standard Model Lagrangian and $\mathcal{L}_\chi$ describes the DM fermion χ:

$$\mathcal{L}_\chi = \frac{i}{2}\bar{\chi}\partial\!\!\!/\chi - \frac{1}{2}g_\chi Z'^\mu \bar{\chi}\gamma^5\gamma_\mu\chi - \frac{1}{2}m_\chi\bar{\chi}\chi - \frac{m_\chi g_\chi}{m_{Z'}}s\bar{\chi}\chi. \tag{2}$$

The first term is the kinetic term, the second term describes the interaction of the DM fermion with the spin 1 mediator Z' via an axial vector coupling, where the coupling strength is given by g_χ. The third term is the mass term and the last term describes the interaction between the spin 0 mediator s and the fermion. Note that the dark fermion χ does not couple to any SM particles directly.

Interactions of the gauge boson Z' and the dark Higgs s are described by $\mathcal{L}_S$:

$$\begin{aligned}\mathcal{L}_S =& \frac{1}{2}m_{Z'}^2 Z'^\mu Z'_\mu + \frac{1}{2}\partial^\mu s \partial_\mu s + 2g_\chi^2 Z'^\mu Z'_\mu \left(s^2 + \frac{m_{Z'}}{g_\chi}s\right) + \frac{\mu_s^2}{2}\left(s + \frac{m_{Z'}}{2g_\chi}\right)^2 \\ &- \frac{\lambda_s}{4}\left(s + \frac{m_{Z'}}{2g_\chi}\right)^4 + \frac{\lambda_{hs}}{4}\left(s + \frac{m_{Z'}}{2g_\chi}\right)^2 (h+v)^2.\end{aligned} \tag{3}$$

The first term is the Z' gauge boson mass term and the second term is the kinetic term of the dark Higgs. The third term describes the three- or four mediator vertex between two Z' gauge bosons and one or two dark Higgs bosons. The remaining terms originate from the dark Higgs potential and the dark Higgs coupling to the Standard Model Higgs after electroweak and $U(1)'$ spontaneous symmetry breaking. μ_s and λ_s model the dark Higgs potential and λ_{hs} models the coupling strength between the dark Higgs boson and the Standard Model Higgs boson. μ_s, λ_s and λ_{hs} are no free parameters of the model but can be related to couplings, masses and the mixing angle between the dark Higgs and the Standard Model Higgs.

We also need $\mathcal{L}'_{\text{gauge}}$:

$$\mathcal{L}'_{\text{gauge}} = -Z'^{\mu} \sum_{f=q} g_f \bar{f} \gamma_\mu f - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} \sin \epsilon F'^{\mu\nu} B_{\mu\nu}. \tag{4}$$

Here, the first term describes the interaction between the mediator Z' and Standard Model quarks. The second term is the field strength tensor for the Z' and the third term describes the mixing between the Z' field and the Standard Model $U(1)_Y$, where ϵ is the mixing angle. This angle is assumed to be very small, which is why we neglected this term for our analysis.
This model proposes interactions between Standard model quarks and the new dark mediator Z'. Z' then decays into two dark fermions χ and a dark Higgs s. Feynman diagrams of such processes are given in Fig. 1.

3 Phenomenology

The goal of this work was to determine whether it would be possible to detect decays of heavy Z' mediators at the LHC. In our model, the Z' couples to the quarks and thus it is possible to produce Z' via $qq \to Z'$. The Z' then decays to two DM fermions and a dark Higgs. The DM fermions don't interact with the detector, and therefore we expect missing transverse energy $\not{E}_T$ as the characteristic signature of the decay. Since the dark Higgs is the lightest particle in the dark sector, it decays into Standard Model particles. If we assume that the dark Higgs decays via mixing with the SM Higgs, then the highest branching ratio for the dark Higgs is $s \to b\bar{b}$, similar to the SM Higgs. An analysis for this process is discussed in Section 3.1. The decay $s \to \gamma\gamma$ is a loop process and much less likely. But the unique signature of this decay makes it easier to discriminate background processes. The process $s \to \gamma\gamma$ is discussed in Section 3.2.

3.1 $s \to b\bar{b}$

This process has already been discussed in [4]. We reproduce some of the results. We calculated the cross section of $pp \to \chi\chi s$, $s \to b\bar{b}$ for different Z' masses. The coupling constants were chosen as $g_q = 0.25$ and $g_\chi = 1$. The events were produced in MadGraph5 [5] with an UFO model file created in FeynRules [6], showered with PYTHIA8 [7] and analyzed with MadAnalysis5 [8]. In the analysis, we made the same cuts as the ATLAS mono-jet search [9]:

- The transverse energy must be large, $\not{E}_T > 500$GeV.
- We require the most energetic jet j_1 to have a large transverse momentum $p_T(j_1) >$ 250GeV.
- If there are more than 4 jets with more than 30 GeV transverse momentum, we reject the event.

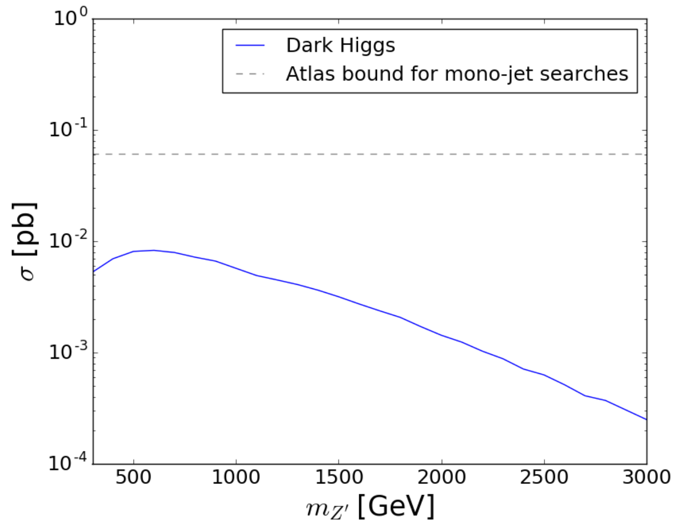

Figure 2: Cross section σ of the process $pp \to \chi\chi s; s \to b\bar{b}$ for different $m_{Z'}$. We require $\not{E}_T > 500\text{GeV}$. The DM fermion mass m_χ was assumed to be 100 GeV, the mass of the dark Higgs m_s was assumed to be 70 GeV. The coupling constants were chosen as $g_q = 0.25$ and $g_\chi = 1$.

- We reject the event if $|\eta| > 2.8$ for any jet with $p_T > 30\text{GeV}$.
- We reject the event if there is an electron with $p_T > 20\text{GeV}$ and $|\eta| < 2.47$ or if there is a muon with $p_T > 10$ and $|\eta| < 2.5$.
- We reject the event if the angle ϕ between the missing energy vector and the most energetic jet is smaller than 0.4.

The result can be seen in Fig. 2. The ATLAS bound from [9] for mono-jet searches is an order of magnitude higher than the maximal cross section we can expect. However, we can expect a better sensitivity for the dark Higgs search because we expect the jet to be a dark Higgs mixing with the SM Higgs, which then decays into $b\bar{b}$.
The analysis for mono-jets can therefore be improved for the dark Higgs search with b-tagging. This was done with Rivet [10] and FastJet [11]. For the more detailed analysis, we did the following:

- Again, we require that the transverse energy must be large, $\not{E}_T > 500\text{GeV}$.
- We use FastJet to find anti-k_T fat jets with $R = 1.0$.
- We apply a trimming algorithm to the fat jets which reclusters the fat jet constituents to k_T jets with $R = 0.2$ and rejects k_T jets which carry less than 5% of the total transverse momentum of the fat jet.
- After the trimming procedure, we require at least one fat jet with $p_T > 250\text{GeV}$ and $|\eta| < 2.0$.

- Then, we use a b-tagging procedure. We cluster the event into antk-k_T jets with $R = 0.2$. Then, we assume an efficiency of 70% and a mistagging probability of 1%. We require at least 2 b-tagged jets.

- To find our final fat jet, we consider the geometry of the event: we only accept the event if there is exactly one fat jet which has exactly two b-jets closer then $\Delta R = 1.1$. The mass of this fat jet is then approximately the mass of the dark Higgs.

The result for different dark Higgs masses and for different Z' masses can be seen in Fig. 3. One can clearly see the peak in the mass distribution in all masses. For increasing m_s or increasing $m_{Z'}$, the number of expected events increases. The plots agree well with the corresponding results in [4]. The challenge for a detection in the $b\bar{b}$ channel is the successful discrimination between event and background, which is discussed in [4].

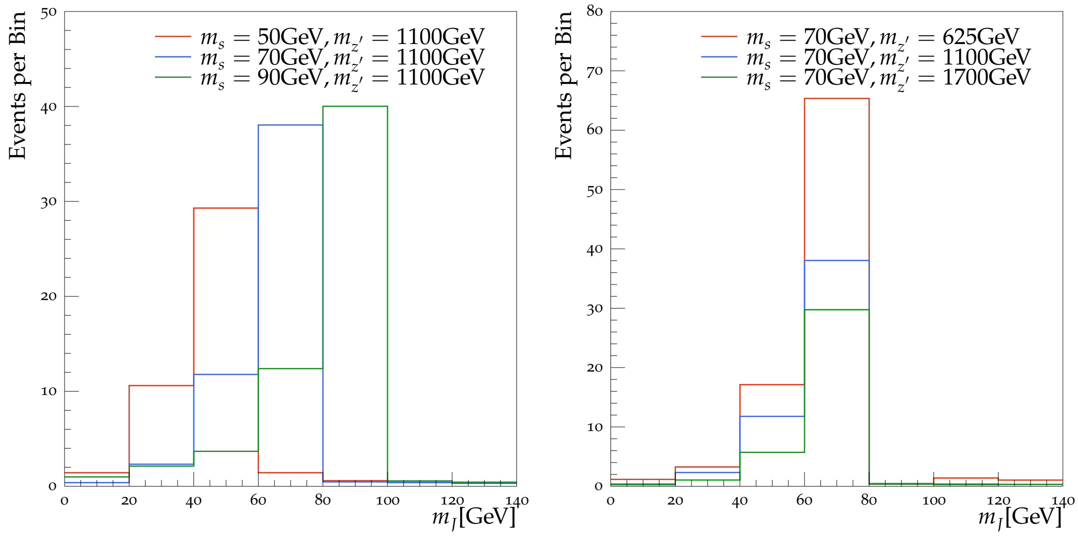

Figure 3: Number of events expected for different dark Higgs masses (left) and for different Z' masses (right). For both plots we assumed $\sqrt{s}$ =13 TeV and a luminosity of 40fb^{-1}.

3.2 $s \to \gamma\gamma$

To calculate the events for $pp \to \chi\chi s$ with $s \to \gamma\gamma$ via coupling to the SM Higgs and loop processes (Fig. 4), we used FeynRules and MadGraph5 again. The decay $s \to \gamma\gamma$ and the showering was done with PYTHIA8 and the analysis with Rivet. The couplings were again chosen as $g_q = 0.25$ and $g_\chi = 1$. Since the branching ratio for $H \to \gamma\gamma$ is very small ($2.28 \cdot 10^{-3}$) [12], we set the branching ratio of $s \to \gamma\gamma$ by hand to 1. This has two reasons: it is convenient because we are not generating a large amount of events that we don't need, but it can also be justified if we extend our model:

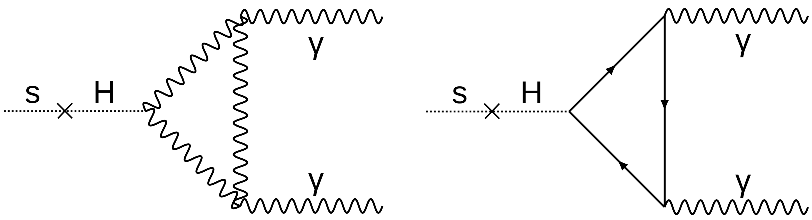

Figure 4: Example Feynman diagrams for the loop process of a dark Higgs decaying to two photons. The left process is via an mediator loop, and the right process is a quark loop.

If we assume new heavy dark fermions Q in the model, then the dark Higgs can not only decay via it's mixing with the SM Higgs, but also via a dark quark loop. This is under the assumptions that $m_s < 2m_Q$, because otherwise the dark Higgs could decay to two dark heavy fermion and we would not detect it, and that Q carries electroweak quantum numbers and therefore interacts with the photon. Furthermore, we also require $m_s < m_Z$ and $m_s < m_W$ to forbid the decay of a dark Higgs into a SM boson $s \to WW$, $s \to ZZ$, $s \to Z\gamma$. Then the branching ratio for $s \to \gamma\gamma$ can be much larger than the SM branching ratio $H \to \gamma\gamma$.
The analysis is not as complicated as the $b\bar{b}$ analysis, because we expect less background and a clear signal from two leading photons. Therefore, we do the following steps in the analysis:

- We require a missing transverse energy $\not{E}_T > 200\text{GeV}$.
- We assume that the two photons with the hightest transverse momentum originate from the dark Higgs and recombine them to the mass of the dark Higgs.

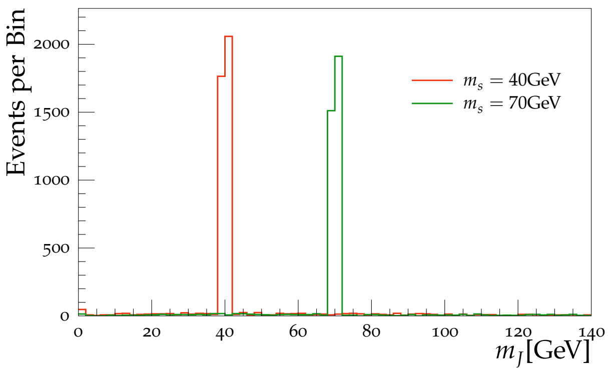

Figure 5: Dark Higgs mass distribution. We assumed that the branching ratio for $s \to \gamma\gamma$ is 1, $m_{Z'} = 1000\text{GeV}$, $m_\chi = 300\text{GeV}$, $\sqrt{s} = 13\text{TeV}$ and a luminosity of 40fb^{-1}. The distribution is very narrow compared to the $b\bar{b}$ mass peak.

In Fig. 5, we plotted the reconstructed dark Higgs mass for $m_s = 40\text{GeV}$ and for $m_s = 70\text{GeV}$. As expected, the peak of the reconstructed mass of the two most energetic photons is very narrow. For a branching ratio $s \to \gamma\gamma$, we expect many events. However, the branching ratio is most likely much smaller than 1, and therefore we expect fewer events.
In order to get a better idea of how many $s \to \gamma\gamma$ events we can expect to detect at the LHC, we did a mass scan for different $m_{Z'}$ and m_χ. We again assumed $\sqrt{s} = 13\text{Tev}$ and a luminosity of 40fb^{-1}. We did this scan for a dark Higgs mass of $m_s = 40\text{GeV}$ and for $m_s = 70\text{GeV}$. The results can be seen in Fig. 6. It shows the mass parameter space in which we expect more than 50 events for different $s \to \gamma\gamma$ branching ratios.

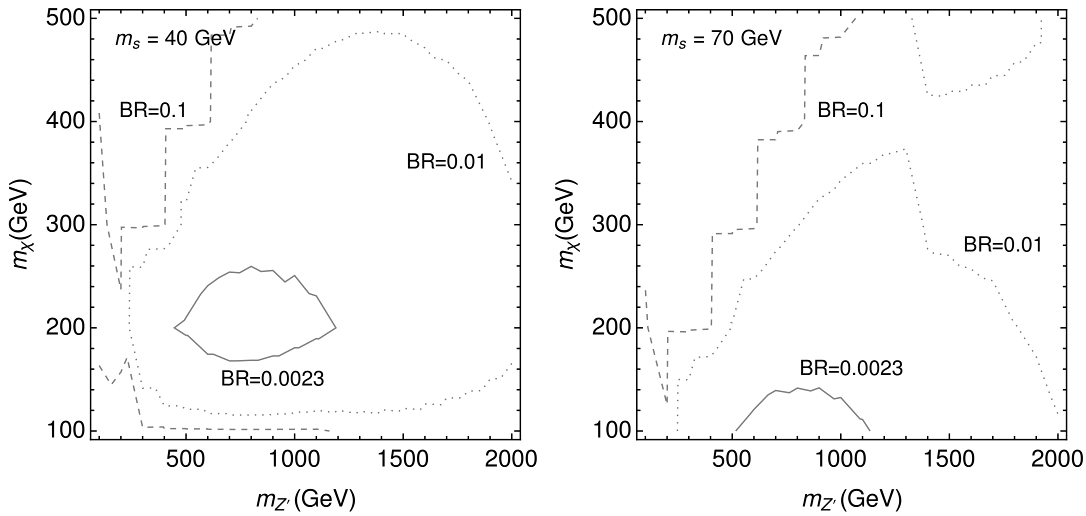

Figure 6: Parameter space with more than 50 events expected for $m_s = 40\text{GeV}$ (left) and $m_s = 70\text{GeV}$ (right) for branching ratios $s \to \gamma\gamma$ of $2.28 \cdot 10^{-3}$ (SM Higgs branching ratio), 0.01 and 0.1 for the LHC Run 2 ($\sqrt{s} = 13\text{TeV}$ and luminosity of 40fb^{-1}).

In Run 3 of LHC, the expected beam energy is $\sqrt{s} = 14\text{TeV}$ and the luminosity is increased to 300fb^{-1}. In this case, assuming $m_s = 40\text{GeV}$, we find Fig. 7. This is as expected: due to the increase center of mass energy and the increase in luminosity, more decays happen and the possibility to detect the decay of a dark Higgs increases a lot, even if we assume the SM Higgs branching ratio. For $m_\chi \lesssim 200\text{GeV}$, we find more than 200 events for almost all $m_{Z'}$ we considered. If we assume a higher branching ratio, then we expect more than 200 events for a large parameter space.

4 Conclusion

In conclusion, we can say that the LHC at the current Run 2 and even more at the upcoming Run 3 is sensitive to the decay of a dark Higgs for a large parameter range.

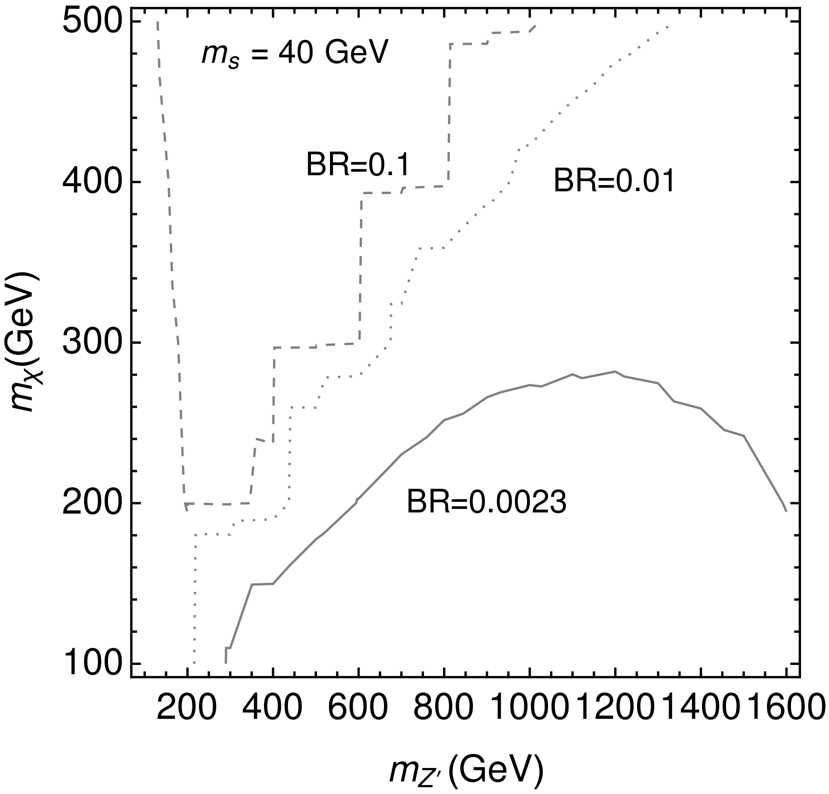

Figure 7: Parameter space with more than 200 events expected for $m_s = 40\text{GeV}$ for branching ratios $s \to \gamma\gamma$ of $2.28 \cdot 10^{-3}$ (SM Higgs branching ratio), 0.01 and 0.1 for the LHC Run 3 ($\sqrt{s} = 14\text{TeV}$ and luminosity of 300fb^{-1}).

Assuming the model in Eq. 1, we find a peak for the decay $s \to b\bar{b}$ and a large number of events. The problem for this decay channel is it's large background, which was not discussed in this work.

For the loop process $s \to \gamma\gamma$, we conclude that this process could be detected at the LHC as well. If we only assume SM Higgs branching ratio for the decay of the dark Higgs, then the parameter space in which we find sufficiently many events is relatively small. But if either the branching ratio is enhanced due to an extra dark fermion Q that couples to the photon or if we discuss the upcoming Run 3, the expected number of events is high in a large parameter space.

Thus it would be possible to detect the decay of a Z' into two dark fermions χ and a dark Higgs s, which then decays into SM particles.

Acknowledgements

I would like to thank my supervisors Kai Schmidt-Hoberg and Michael Duerr for their advice, help and feedback during my stay, as well as the organization team for giving me the opportunity to participate in the DESY summer student program.

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