Reply to SciPost Referee Reports

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We thank the referees for their careful revision of our manuscript. Here, we address the various points raised in their reports and we explain how the manuscript has been modified.

REPORT 1

(1) In our work we have not considered modifications of cosmic ray propagation or similar constraints from cosmology since these generally require very large cross sections $\sigma_{p\chi}$. Therefore, in the following we give a brief estimate of the typical couplings required to observe proton-DM scattering of cosmic rays as e.g. considered in [1].

Assuming a 10 GeV proton scatters off a DM particle in the galactic halo (at rest), the corresponding process will be best described by elastic nucleon-DM scattering. In a sense, this corresponds exactly to the scattering described in Appendix A.5 of our paper, but happening at relativistic energies. Starting from the relativistic matrix element in Eq. (110) for the Higgs portal interaction we find after summing and averaging over proton spin states the squared matrix element

$$|\overline{\mathcal{M}}|^2 = \left(\frac{\lambda_{hs}\, m_p}{m_h^2}\right)^2 \left(f^p_{T,u} + f^p_{T,d} + f^p_{T,s} + \frac{2}{9}\, f^p_{T,g}\right)^2 \left(4\, m_p^2 - t\right) . \tag{1}$$

Plugging this into the cross section formula yields

$$\frac{d\sigma}{dt} = \frac{\lambda_{hs}^2\, m_p^2}{64\,\pi\, |\vec{p}_{1,\text{lab}}|^2\, m_s^2\, m_h^4} \left(f^p_{T,u} + f^p_{T,d} + f^p_{T,s} + \frac{2}{9}\, f^p_{T,g}\right)^2 \left(4\, m_p^2 - t\right) , \tag{2}$$

where we have used $p_{1,\text{CM}} = p_{1,\text{lab}}\, m_s/\sqrt{s}$. Integrating the cross section over t with integration limits $t_0 = 0$ and $t_1 = -4\, p_{1,\text{CM}}^2$ yields

$$\sigma = \frac{\lambda_{hs}^2\, m_p^2}{64\,\pi\, |\vec{p}_{1,\text{lab}}|^2\, m_s^2\, m_h^4} \left(f^p_{T,u} + f^p_{T,d} + f^p_{T,s} + \frac{2}{9}\, f^p_{T,g}\right)^2 \left(16\, m_p^2\, p_{1,\text{CM}}^2 - 8\, p_{1,\text{CM}}^4\right) . \tag{3}$$

For $m_s \ll p_{1,\text{lab}}$ and $m_s \ll m_p$ the CM energy is to good approximation $\sqrt{s} \approx m_p$ and hence $p_{1,\text{CM}} = p_{1,\text{lab}}\, m_s/m_p$. Plugging this into the cross section for proton-DM scasttering finally leaves us with the expression

$$\sigma_{p\text{DM}} \approx \frac{\lambda_{hs}^2\, m_p^2}{4\,\pi\, m_h^4} \left(f^p_{T,u} + f^p_{T,d} + f^p_{T,s} + \frac{2}{9}\, f^p_{T,g}\right)^2 . \tag{4}$$

As an order of magnitude estimate we can approximate this as

$$\sigma_{p\text{DM}} \approx \lambda_{hs}^2 \times \frac{10^{-10}}{\text{GeV}^2} \sim \lambda_{hs}^2 \times 10^{-38}\,\text{cm}^2 . \tag{5}$$

As a consequence, even for relatively small DM masses of $m_s \sim 10^{-6}$ GeV the constraint of $\sigma_{p\chi} \sim 10^{-27}$ cm^2 of [1] translates only into a limit on the portal coupling of $\lambda_{hs} > 10^5$. Hence, these constraints might only be relevant for the very large coupling regime, which is not the focus of this work.

To account for these constraints we have hence added a sentence at the bottom of page 11: *"It is worth pointing out that further bounds exist from cosmic ray propagation [1, 2] and cosmology [3–6], which constrain very large DM-nucleus cross sections."*

(2) Indeed, DM-electron scattering does not play any role in these models since the DM-electron couplings are heavily suppressed, either via the Higgs Yukawa coupling or via loops in the case of an effective DM-gluon coupling.

(3) Since the DM background density at the earth is assumed to be approximately constant it is not expected to change in different areas of the LHC. Either way, as the referee pointed out, this process is unobservable since the mean free path for DM-background scattering is orders of magnitudes larger than the size of the universe.

(4) The DIS-like collider signature studied in this paper has the potential to cover a blind spot in searches for light DM coupled to a weak-scale mediator, either the SM Higgs or a new singlet scalar. The key for being able to discriminate this signature from soft hadronic SM background is the production of a high-p_T displaced recoil jet in the DM-nucleus scattering. In order for this to happen, the incident DM particle has to carry large momentum. In the mediator models discussed in this paper, this is achieved from pair producing the light DM in decays of the heavy mediator, such that the DM carries away the momentum $p_{\text{DM}} \sim M/2$, with M denoting the mediator mass.

   (a) Hence, in order for the DIS signature to be detectable, it is crucial to produce the heavy mediator on-shell. If the mediator is virtual this will not only lead to a suppression of the DM production cross section, but also to low DM momenta resulting in soft jets, if any. Therefore, although fixed target experiments boast very large luminosities, they do not have high enough energies to produce a Higgs-like mediator on-shell. As a consequence, the resulting soft recoil jets would be indistinguishable from the soft QCD background. Similarly, exchanging the heavy mediator for a light one would circumvent the issue of a reduced DM production cross section, but would equally result only in soft recoil jets.

   (b) On the other hand side, if the mediator mass is chosen to be much heavier than Higgs mass mono-jet searches are the most promising way to search for these mediators directly. At around ∼100 GeV, SM backgrounds such as $Z(\to \nu\nu)$+jets and $W(\to l\nu)$+jets make mono-jet searches very challenging. Consequently, the chosen mass of 100 GeV represents a natural mass scale to employ searches for DIS-like recoil jets in an otherwise very challenging range for LHC searches.

   (c) Finally, the referee raises a good point in asking about the impact of different target materials. We have studied this effect by taking into account different gluon PDFs sets. For example, taking pure proton PDFs (which would constitute a very extreme choice of material) instead of lead or iron results in having roughly 40% more events. We have described this in some detail below Eq. (57).

REPORT 2

(1) It is correct that the transition of the Eot-Wash exclusion limits from the left to the right plot is not smooth. The reason for that is that the limits in both ranges are based on different interpretations of the Eot-Wash data.

In the mass region between $10^{-6} - 10^{9}$ eV, we take into account the constraints on effective (pseudo-) scalar-nucleon operators as in Ref. [7]. These interactions can induce a Casimir-Polder force between nucleons via a two scalar exchange that finally sets constraints on the effective suppression scale of the operator. This can be translated to our model parameters via eq. (9) in our paper.

In the mass range between $10^{-24} - 10^{-6}$ eV, the limits are based on Ref. [8]. The paper studies the observational consequences of a violation of the Einstein Equivalence Principle induced by light scalar DM. In particular, in the case of the Eot-Wash experiment the violation of the Universality of Free Fall is studied by looking at the motion of a test mass. The test mass term and consequently the differential acceleration can be expressed in terms of an oscillating DM background field through its fundamental couplings to the SM. Limits coming from this effect are assuming that the new scalar has DM nature. This is indicated by a dotted line in the left plot of Fig.2 and described in the corresponding caption.

The observation of the referee is right that there is a gap in the exclusion limits for Eot-Wash between $10^{-8} - 10^{-6}$ eV. Unfortunately both analyses do not report the mass range between $10^{-8} - 10^{-6}$ eV and hence, we conservatively leave that mass range open.

(2) The ultralight scalar or pseudo-scalar DM particles must most likely be produced in a non-thermal mechanism (like the misalignment mechanism) in order not to spoil early universe cosmology, like BBN or CMB. They are themselves therefore very cold and due to their tiny masses will not scatter with any nuclear material. In order to produce energetic ultralight DM particles, one would require some astrophysical source like e.g. the centre of the galaxy or supernovae. However, the study of such processes is beyond the scope of this analysis, which focuses on ways to produce DM in the laboratory.

(3) To answer the question in which way the mediator mass value impacts the plots 8-9 in our paper, we would like to refer to the answer to point (4) of Report 1. Therein we explain the mediator mass dependence on the proposed DIS-like collider signature and in which phase-space regions the signature will be most powerful.

(4) We want to thank the referee for pointing out this typo in the conclusion. We have fixed it and the sentence now reads: *"[...] over the full range of dark matter masses below the GeV scale."*

NUMBER OF EFFECTIVE DEGREES OF FREEDOM

During the process of addressing the issues raised by the referees we were made aware of the fact that in general large mediator-gluon couplings can keep the DM in equilibrium with the SM bath past the QCD phase transition in the early universe. The resulting contribution from a scalar DM candidate decoupling after the QCD phase transition to the number of effective degrees of freedom, $\Delta N_{\rm eff}$, could be in tension with the Planck observations [9]. However, since in our effective field theory approach we only assume gluon couplings at the tree-level, the DM will most likely decouple very quickly once the temperature of the universe drops below $T \lesssim m_\pi$ leading to an increase of $\Delta N_{\rm eff} \sim 0.05 - 0.5$. This is unfavoured by current Planck data, but not yet excluded given the uncertainty of the input parameters of the fit.

We have added a brief discussion of this issue in a separate paragraph in Section 2 on pages 5-6.

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