Reply to reports on scipost_202203_00007v1

Spyros Argyropoulos and Ulrich Haisch,
Benchmarking LHC searches for light 2HDM+a pseudoscalars, 2202.12631.

We thank the referees for their careful reading of the manuscript and for their valuable comments. We try to address all the comments and suggestions in this reply and by changing the manuscript accordingly. We enclose to the new submission a version of the draft, where all modifications and additions are coloured in red.

Report of referee 1

(Q1) *The paper seems to very much built around the idea that eq. (4) makes a significant difference in the interpretation of the results of the searches. So my question is: had you included all constraints and all searches but not (4) would you get a sizeable difference in Figs. 1 and 2, left? [...] Related to the previous comment, a short discussion about what happens to Figs. 1 and 2 left, if we move away from the benchmark points, is needed. I see that most of the light masses are excluded (except in regions where searches were not performed). Is this result robust against variation of the parameters?*

(A1) Notice that the bound (4) is not imposed directly as a constraint in our work, but the inequality (4) is fulfilled by choosing suitable 2HDM+a model parameters. In practice, this is done by first fixing values for $\tan\beta$, $\sin\theta$, $\lambda_3 = \lambda_{P1} = \lambda_{P2}$ and y_χ and then adjusting $m_A = m_H = m_{H^\pm}$ such that $|g_{haa}| < 0.94$ holds. The first part of the question of the referee can therefore not be answered in a meaningful way.

On the other hand, we agree with referee 1 that a discussion of the robustness of our results against variations of parameters was missing in the first version of our manuscript. We have tried to improve on this point in the revised version of scipost_202203_00007v1. See the extended discussion in Section 3.3.

(Q2) *Do the plots presented complete in any way what was presented in 1802.02156 by extending the mass region and by including new searches?*

(A2) In this context it is crucial to realise that the 2HDM+S model studied in 1802.02156 and the 2HDM+a model discussed in our manuscript are not the same model. The two most important differences are: *i*) the 2HDM+S model does, in contrast to the 2HDM+a model, not involve a dark matter (DM) candidate χ and therefore does also not contain a coupling between the light pseudoscalar and DM. As a result the pseudoscalar decay can only decay in the 2HDM+a model via $a \to \chi\bar{\chi}$, which in turn leads to Higgs invisible decays of the form $h \to aa \to \chi\bar{\chi} + X$ where $X = \chi\bar{\chi}, f\bar{f}$ with f denoting all kinematically accessible Standard Model (SM) fermions. *ii*) in the 2HDM+S model the triple Higgs coupling g_{haa} or equivalently the branching ratio $\mathrm{BR}(h \to aa)$ is treated as a free parameter, while in the 2HDM+a model the coupling g_{haa} is related to the physical Higgs masses, mixing angles and some of the trilinear couplings that appear in the full scalar potential (see (2) of scipost_202203_00007v1).

The plots in our work therefore do not present simple extensions of the results given in 1802.02156. In fact, scipost_202203_00007v1 is the first study of the existing constraints on light pseudoscalars with masses $m_a \lesssim 100\,\text{GeV}$. Other works like 1701.07427, 1810.09420, 2106.02962 and 2109.13597 that discuss the 2HDM+a model in detail do not consider this mass region. We have modified the abstract and some parts of the text accordingly to stress this point.

(Q3) *The authors state in the end of page 2 "For values of $|g_{haa}|$ that are not fine-tuned"; what does this sentence mean?*

(A3) The sentence is meant to say that if DM is kinematically accessible, i.e. $m_\chi < m_a/2$, invisible decays of the Higgs boson set very strong constraints on m_a unless the coupling g_{haa} obeys $|g_{haa}| \lesssim 0.02$. We have rewritten the sentence accordingly.

(Q4) *And in the same paragraph can the authors please explain how the invisible Higgs decay width sets a lower bound of 100 GeV in the a mass? Or did I misunderstand the sentence?*

(A4) The quoted bound of $m_a \gtrsim 100\,\text{GeV}$ arising from invisible decays of the Higgs boson is correct. Naively, one would expect that invisible decays of the Higgs boson can only probe values $m_a < m_h/2 \simeq 62.5\,\text{GeV}$. Since the SM Higgs boson however has a very small relative decay width of $\Gamma_h^{\text{SM}}/m_h \simeq 3 \cdot 10^{-5}$ also off-shell contributions to multi-body Higgs decays can lead to relevant constraints. In fact, in the case of the 2HDM+a model it has been shown in 1701.07427 that the constraints arising from $h \to aa \to \chi\bar{\chi}f\bar{f}$ with f denoting all kinematically accessible SM fermions allow to test and to exclude pseudoscalar masses m_a in excess of 62.5 GeV. To clarify this point we have added some explanations to the paragraph before (3).

(Q5) *When the authors start discussing benchmark I, they write "This corresponds to a parameter tuning of around 5%". Can the authors explain the meaning of this sentence? Same question for benchmark 2.*

(A5) In the case of benchmark I, the parameter tuning of around 5% refers to the fact that to satisfy the bound (4) the heavy scalar masses have to lie in the mass range $m_A = m_H = m_{H^\pm} = [1160, 1270]\,\text{GeV}$. Similar statements apply in the case of benchmark II. To clarify this point we have changed the corresponding parts of the text.

Report of referee 2

(Q1) *The authors look at constraints from Higgs decays, how about the 4 lepton final states that would be relevant for larger masses of a (c.f. arXiv: 2107.00404).*

(A1) As a result of CP conservation the field a has no couplings of the form aW^+W^- and aZZ. In the case of the CP-conserving 2HDM+a model studied in our work there

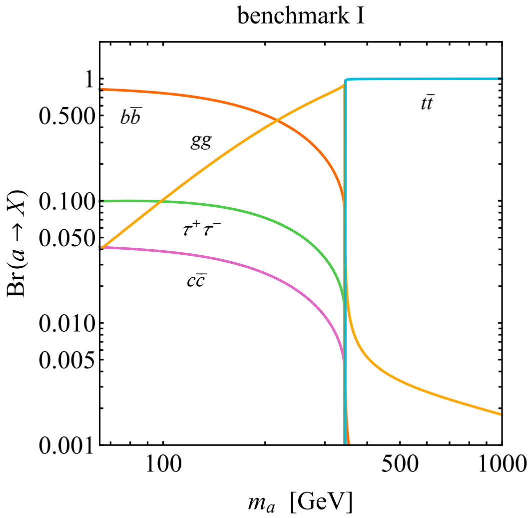

Figure 1: Branching ratios of the pseudoscalar a as a function of its mass in the benchmark I model assuming that the decays $a \to \chi\bar{\chi}$ is kinematically forbidden.

are therefore no three- or four-lepton signals associated to $pp \to a \to ZW \to 3\ell$ and $pp \to a \to ZZ \to 4\ell$ production. Since searches for multi-lepton final states provide no constraint, we would prefer to not comment on this in a revised version of scipost_202203_00007v1.

(Q2) *Given the large branching ratio to b-quarks, there should be some comments regarding the low and high mass dijet searches. (c.f. arXiv: 1802.06149 (Fig. 4) and arXiv: 1801.08769).*

(A2) In benchmark scenario I the dominant SM decay mode of the pseudoscalar a in the mass range studied by 1802.06149 is not $a \to b\bar{b}$ but $a \to t\bar{t}$. This is illustrated in Figure 1 assuming that the decay channel $a \to \chi\bar{\chi}$ is not open. The search 1802.06149 therefore does not provide any constraint on the 2HDM+a benchmark I. While we believe that a detailed recast of 1801.08769 is beyond the scope of our work, it is again straightforward to see that the latter dijet search does not lead to relevant constraints. For $m_a = 150\,\text{GeV}$ one has $\sigma\left(pp \to a\right) \simeq 3\,\text{pb}$ at $\sqrt{s} = 13\,\text{TeV}$ and $\text{BR}\left(a \to jj\right) \simeq 90\%$ where jj includes the $b\bar{b}, c\bar{c}$ and gg final states (we have again assumed that $m_\chi \gg m_a$). Taking into account that the search 1801.08769 has an acceptance of $A \simeq 0.1\%$ in the initial-state radiation jet channel, one finds $\sigma\left(pp \to a \to jj\right) \cdot A \simeq 3 \cdot 10^{-3}\,\text{pb}$. As can be seen from left plot in Figure 5 of 1801.08769 this effective cross section is around two orders of magnitude smaller than the sensitivity of the dijet search in question. This implies that the results of 1801.08769 have no impact on our benchmark I analysis.

In benchmark scenario II the dominant SM decay mode of the pseudoscalar a is indeed $a \to b\bar{b}$ with a branching ratio of $\text{BR}\left(a \to b\bar{b}\right) \simeq 85\%$ largely independent of m_a as long as the decay channel $a \to \chi\bar{\chi}$ is closed. The searches 1802.06149 and 1801.08769 are however again not sensitive enough to constrain the 2HDM+a benchmark II. For $m_a = 400\,\text{GeV}$ one finds $\sigma\left(pp \to a\right) \cdot \text{BR}\left(a \to b\bar{b}\right) \simeq 2 \cdot 10^{-1}\,\text{pb}$ while 1802.06149 only excludes cross sections in excess of around $7\,\text{pb}$. See the left panel in Figure 3 of 1802.06149. For $m_a = 150\,\text{GeV}$ one has $\sigma\left(pp \to a \to b\bar{b}\right) \cdot A \simeq 5 \cdot 10^{-2}\,\text{pb}$ which is a factor of $\mathcal{O}(5)$ below the sensitivity of 1801.08769. See the left plot in Figure 5 of 1801.08769.

From the above discussion it should be clear that dijet searches do not provide relevant constraints on the two 2HDM+a benchmark scenarios studied in our work. In fact, this is a rather generic finding in 2HDM+a models. Since we were aware of this feature before writing our article, we did no mention dijet searches in scipost_202203_00007v1. We would prefer to keep it this way in the updated manuscript.

(Q3) *Typo on page 3 below equation 5 "... on $|g_{ahh}|$ assuming a light pseudoscalars a." should be "... on $|g_{haa}|$ assuming a light pseudoscalars a.".*

(A3) We have corrected this misprint.

(Q4) *Orange and red are not the best colours to choose especially when there are overlapping regions - Could you possibly change or improve this presentation in the two Figures (1 and 2 right).*

(A4) We have tried to improve the presentation of the plots that summaries the constraints in the two benchmark scenarios.

Report of referee 3

(Q1) *In general the analysis in Section 3 appears to be comprehensive while providing useful benchmarks for future LHC studies. I would have preferred a slightly more detailed presentation in Section 2 to make the paper more self-contained. The authors should at least provide a little more information on the relevant model parameters. For example, eq. (2) depends on a number of scalar potential parameters whose definitions are provided in a previously published paper. It would not have taken much space to present the relevant scalar potential prior to exhibiting eq. (2), so that the reader can immediately see the origin of the relevant parameters. The parameter θ is also introduces as a mixing angle, which again is related to the scalar potential parameters. To summarize, the relevant parameters (especially those used to define the benchmark scenarios) should be more explicitly defined in Section 2.*

(A1) Following the suggestion of the referee we have added a comprehensive discussion of the structure of the 2HDM+a model at the beginning of Section 2.

(Q2) *I also note that the authors denote the fermionic dark matter by χ, although this symbol does not show up until the bottom of page 2. For clarity, this symbol should be introduced earlier.*

(A2) The symbol χ is now introduced already at the beginning of Section 1.

(Q3) *Finally, the statement at the top of page 3 on the lower limit of 100 GeV for* m_a *is quite mysterious, as the authors associate this with the latest searches for invisible Higgs decay. However, for a masses above half the Higgs boson mass (62.5 GeV), the invisible Higgs decay limits are irrelevant. Thus, it is hard to understand where the 100 GeV limit is coming from. (This point has also been echoed by one of the other referees.)*

(A3) As already explained above, since the SM Higgs boson has a tiny total decay width, multi-body decay channels of the 125 GeV Higgs boson can be phenomenologically relevant. In fact, in the case of the 2HDM+a model contributions to the $h \to aa \to \chi\bar{\chi}f\bar{f}$ modes from off-shell pseudoscalar exchange lead to a correction to $h \to \text{inv}$ that violates existing LHC bounds for $m_a \lesssim 100\,\text{GeV}$ in the case that DM is not too heavy. In contrast to the assertion of referee 3, the limits from Higgs physics are therefore even relevant for pseudoscalar masses larger than $m_a = m_h/2 \simeq 62.5\,\text{GeV}$.

(Q4) *Finally, above eq. (3), the authors state that the total Higgs decay width predicted by the SM is 4.07 GeV, which is much smaller than the LHC sensitivity on* Γ_h*. The authors then impose* $\Gamma_h < 1.1$ *GeV. However, an indirect determination of the Higgs width at the LHC using off-shell Higgs production (admittedly with some caveats), concludes that the observed Higgs width is quite close to its Standard Model value. See arXiv:2202.06923 for further details. Presumably, this would lead to a significant reduction of the bound quoted in eq. (4). The authors should comment on this and indicate how the results of Section 3 would be affected by imposing the stricter bound.*

(A4) The existing LHC determinations of Γ_h using $pp \to h^* \to ZZ \to 4\ell$ production are rather model dependent since they all assume a certain connection between the on- and off-shell Higgs production rates. This connection is established by noting that a rescaling of the form $g_{hXX}^{\text{SM}} \to \xi^{1/4}\, g_{hXX}^{\text{SM}}$ and $\Gamma_h^{\text{SM}} \to \xi\, \Gamma_h^{\text{SM}}$ with g_{hXX}^{SM} and Γ_h^{SM} denoting the couplings and total decay width of the SM Higgs boson, respectively, modifies the kinematic distributions in off-shell Higgs production, while leaving the on-shell rate unchanged (see for instance 1307.4935 for details). The stringent limit on Γ_h derived in 2202.06923 only applies in models in which the modifications of g_{hXX} and Γ_h are at least approximately compatible with the above rescaling relations. Clearly, this is not the case in the 2HDM+a model where the SM Higgs couplings g_{hXX} are unmodified in the alignment limit, but Γ_h is altered because of the presence of additional decay channels such as $h \to aa$ with $a \to \chi\bar{\chi}, f\bar{f}$. To clarify this point we have added a new paragraph after (4).

We again thank the referees for the very useful feedback and hope that with the above explanations and the made changes the manuscript can be published in SciPost Physics in its revised form.