Motivations for benchmark points to study of $h_{1,2} \to a_1 a_1$ and $h_3 \to Z a_1$ in the NMSSM

RC Aggleton, D Barducci, N-E Bomark, S Moretti,
A. Nikitenko and CH Shepherd-Themistocleous

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One very interesting possibility in the NMSSM is a light singlet-like pseudoscalar a_1. We propose here some benchmark points designed to study possible detection channels of such pseudoscalars.

The NMSSMTools cards are attached, both input SLHA files (ending with `inp.slha`) and output spectrum from NMSSMTools version 4.6.0 (ending with `spectr.slha`).

1 $h_{1,2} \to a_1 a_1$

The final states to look for are 4τ, $4b$, $2b2\tau$ and possibly $2\tau 2\mu$ plus $2b2\mu$ (the study of the latter is on-going). Since the final state objects here will be rather soft, collaboration between theorists and experimentalists (both are represented in the proposer list) is vital to properly assess the viability of the channels.

One important possibility is to look for heavier scalars that decay to pairs of pseudoscalars. This was shown in [1] to be viable for Gluon Fusion (GF) production of $h_{1,2}$ and consequent decay $a_1 a_1$. In [2] it was shown that also Vector Boson Fusion (VBF) and HiggsStrahlung (HS) production of the initial scalar may at least serve as a complement to the GF production. Here one also defined three benchmark points (given in table 3 of [2]) that cover most of the interesting parameter space with $m_{a_1} > 2m_b$. Two points have h_2 being the Standard Model (SM) like Higgs boson, one point with low m_{a_1} at 26 GeV, so that jet substructure methods may be studied, and one, which we propose here, with $m_{a_1} = 55$ GeV (`h2_a1_55`), to cover the higher mass range. The third point has h_1 SM-like and $m_{a_1} = 66$ GeV just above the $h_1 \to a_1 a_1$ threshold as it is very hard to get lighter pseudoscalars in this scenario. Though these points were defined for the study of VBF and HS production of the heavy scalar, they can serve just as well as benchmarks for the GF channels. Note that we do not mention $h_3 \to a_1 a_1$ here as it was shown in [1] that this channel is not viable.

If the case that the mass of the a_1 is below the $b\bar{b}$ threshold, $m_{a_1} < 2m_b$, the phenomenology changes dramatically as now the decay channel of the pseudoscalar to two b-quarks is closed and 4τ [5] and $2\tau 2\mu$ [6] final states become the most relevant ones. To capture also these possibilities we provide one additional point with $m_{a_1} = 8$ GeV and h_1 SM-like (h1_a1_8), where the benchmark point has been chosen so as to avoid the Υ resonances and with a $\sigma(gg \to h_1)Br(h_1 \to a_1 a_1)Br(a_1 \to \tau\tau)^2 \sim 2$ pb.

2 $h_3 \to Za_1$

One other channel that may complement the above for somewhat heavier pseudoscalars is $h_3 \to Za_1$ where h_3 is produced through GF. It was shown in [1] that neither $h_{1,2} \to Za_1$ (for any production mechanism of the $h_{1,2}$) nor VBF nor HS production of h_3 carry promise, but $gg \to h_3 \to Za_1$ may be feasible.

For further study of this channel we provided in [1] some benchmark points (summarised in table 3). There are three points using h_2 SM-like with m_{a_1} being 64, 74 and 106 GeV respectively and one point with h_1 SM-like. All points have a high rate for the channel in discussion.

3 Experimental perspective

Within the benchmarks proposed, there are a variety of factors which can affect experimental searches. A light a_1 ($\mathcal{O}(10)$ GeV) will be produced with a large boost, which in turns collimates its decay products. This renders standard object reconstruction inefficient.

For h1_a1_8: If the a_1 is very light ($m_{a_1} < 2m_b$), then within the NMSSM the 4τ final state will dominate. For each pair of taus, the separation between the 2 taus will be approximately $\Delta R \sim 4m_{a_1}/m_h \sim 0.3$ for $m_{a_1} = 9$ GeV [3]. One option is to require one tau in each pair to decay muonically, whilst requiring a decay to 1 charged object from the other tau in the pair. Then one searches for a non-isolated muon with a track nearby, or modifies the tau algorithm to first remove the nearby muon object and then perform the tau clustering. One could also potentially try to utilise jet substructure techniques to identify 2 overlapping tau decays.

An alternate search strategy would be to search for the $\mu\mu\tau\tau$ decay mode, where one a_1 decays to a muon pair, such as in [4]. Due to the naturally small width of the a_1 ($\Gamma_{a_1} \sim$ MeV), the measured width will be determined by the experimental resolution. Such a resonance would appear as a sharp peak against a relatively smooth background in the dimuon invariant spectrum (with the caveat that $J/\Psi, \Upsilon$ and other resonances can complicate matters). Whilst $a_1 \to \mu\mu$ has a much smaller branching ratio than $a_1 \to \tau\tau$, the dimuon invariant mass can be used as a powerful discriminator between signal and background. The ATLAS search referenced above was able to probe $\sigma \times BR(h \to aa) \times BR(a \to \tau\tau)^2 \sim 2$ pb, but under the assumption that $BR(a_1 \to \tau\tau) = 1 - BR(a_1 \to \mu\mu)$. Thus, the benchmark point could be reachable at LHC14. Unfortunately, a complementary 4τ search has not been published yet to allow a full comparison between the two final states although two are underway at CMS.

For `h2_a1_55`: For heavier a_1 bosons ($m_{a_1} > 2m_b$), the $a_1 \to bb$ decay mode is kinematically available and thus one can tag the a_1 decay via a pair of b-jets. However, due to the the larger a_1 mass, there is potential for overlapping or 'fat' b-jets. To tackle this, jet substructure techniques have been studied [1], which show a significant improvement in sensitivity. Whilst a $4b$ search has been performed at CMS, it was in the context of a heavy Higgs search. One should note that there is potentially a large QCD background in this final state, impacting the search sensitivity.

Alternatively, one could consider then the $2b2\tau$ final state to try and suppress the large QCD backgrounds. Whilst $BR(a_1 \to bb) \gg BR(a_1 \to \tau\tau)$, it allows one to combine search strategies, such as tagging one or both taus via their leptonic decays. This final state has not been explored at ATLAS or CMS.

The above statements make no assumptions about the Higgs production mechanism. If one considers the VBF and Higgstrahlung production mechanisms, then there are additional opportunities to tag the event, which could improve $S : B$ despite the lower production σ, especially in scenarios such as the $4b$ final state.

On pages 9 & 10 of [2], a suggestion is made for the selection of such events. On page 20 of the same reference, an investigation is provided into the relevant backgrounds and the luminosity required for $S/\sqrt{B} > 5$ at LHC14.

For what concerns the non scalar sector of two benchmark points we summarise here the main characteristic.

In `h1_a1_8` the lightest stop has a mass of $\sim$ 850 GeV with however, suppressed decay rate into $\chi_1^+ b$ and $\chi_1^0 t$, which will make the standard stop searches less efficient. An interesting decay pattern that is realised is $\tilde{t}_1 \to \chi_{2,3}^0 t, \chi_{2,3}^0 \to \chi_1^0 a_1$ which can have a substantial combined decay rate ($\sim$ 10% and $\sim$ 20% respectively). For this reason standard EWinos searches involving $\chi^\pm \chi_2^0$ production might lose sensitivity and analogous decay of $\chi_{2,3}^0$ might be interesting to consider. It is also worth noting that this point survives the exclusion limits on EWino production from [7], due to the lower than expected exclusion in the region of small mass differences between $\chi^\pm, \chi_2^0$ and χ_1^0. This means that this scenario will be among the first to be tested at future LHC runs.

In `h2_a1_55` the stop mass is around 1 TeV and in this case the main decay rates are the ones into $\chi_1^+ b$ and $\chi_1^0 t$, which will be tested by the upgrades of the standard stop searches. Also in this case χ_2^0 decay modes are different from the standard simplified model assumptions, being again $\chi_2^0 \to \chi_1^0 a_1$ the main decay rate and similar consideration to the first benchmark point can be made.

References

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