Discovering Nonstandard Higgs bosons in the $H \rightarrow ZA$ Channel Decay to Multileptons

Spencer Chang and Arjun Menon
_Institute of Theoretical Science, University of Oregon, Eugene, OR 97403, USA_

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Abstract

In this article we consider the possibility of observing nonstandard Higgs bosons in the $H \rightarrow ZA \rightarrow Z\tau^+\tau^-$ channel. We present three benchmark scenarios in the NMSSM where $H \rightarrow ZA$ is the dominant decay mode for one of the nonstandard Higgs bosons while the lightest CP-even Higgs is Standard Model like. Using the latest CMS multilepton analysis based on 7 TeV LHC data, we put limits on the signal cross-section, which constrain leptophilic scenarios. Projecting to future LHC analyses with improvements in background modeling, we show that with $O(30) \text{ fb}^{-1}$ of data, such a multilepton analysis is very close to constraining our NMSSM benchmarks. As we illustrate with a toy model, for light $A$ masses, the large boost of the $A$ makes it inefficient to select two hadronic taus, since isolation and the transverse momenta are in tension. This efficiency could be improved by including boosted di-tau jets as an object in future multilepton analyses. We also discuss different methods to confirm this scenario by reconstruction of the $m_H$ and $m_A$ masses. In particular we consider the transverse mass distribution, collinear mass distribution and an analytical solution using trial masses.
1 Introduction

Recently, ATLAS and CMS announced the discovery of a particle consistent with the Standard Model Higgs [1,2]. If the properties of this particle are confirmed to be that of a Higgs boson, this will be a major revolution in particle physics, as it would be the first fundamental scalar field proven to exist. This discovery opens up the possibility for other fundamental scalars and thus motivates searches at the LHC for additional spin zero particles. Moreover, in many theories beyond the Standard Model, e.g. supersymmetry or two Higgs doublet models, such additional Higgs bosons are required and thus their discovery would be an important first step towards uncovering this new physics.

The phenomenology of such scalars has so far been incompletely explored. In the minimal supersymmetric Standard Model, there is a well explored phenomenology of the heavy Higgs states $H,A$ with ongoing searches in $\tau^+\tau^-$ [3,4] and potentially observable $b\bar{b}$ decays [5]. However, scalars can also have extremely challenging signals, many of which were explored in the nonstandard Higgs scenario [6]. Thus, it is fruitful to continue to explore promising signals for new bosons.

In this note, we point out an interesting signal with the potential to discover two new scalars. The signal process is $H \rightarrow Z,A \rightarrow \ell^+\ell^-,\tau^+\tau^-$ which has been studied in the context of explaining LEP anomalies [7,8]. Such a signal is motivated by the recent CMS multilepton search [9] in particular its channels with an onshell leptonic $Z$. Recently, the multilepton search has also been shown to be sensitive to Standard Model Higgs modes [10], flavor violating top decays into a Higgs ($t \rightarrow ch$) [11], and two Higgs doublet models [12]. These previous analyses did not consider reconstructing hadronic taus and focused on an inclusive search using all the CMS multilepton channels. Considering our signal’s exclusive channels into hadronic taus provides an important additional probe which is sensitive to a substantial branching fraction of the signal and also allows a variety of mass reconstruction techniques given the limited number of neutrinos. Admittedly, the substantial excess in the original CMS multilepton search [13] in these channels went down in [9], but this signal still remains promising in future updates.

In this paper, we analyze the prospects a CMS-like multilepton analysis has in discovering such a signal. The outline of the rest of the paper is as follows. In Sec. [2] we explore simple benchmarks to realize such a signal in the Next-to-Minimal Supersymmetric Standard Model. This provides an important existence proof in a motivated theory. More optimistic scenarios exist as well in leptophilic two Higgs doublet models. Those interested in the phenomenology can skip to Sec. [3] where we estimate the efficiency the CMS multilepton search has on such a signal and use them to derive model-independent bounds on the signal rate. In Sec. [4] we compare the utility of a variety of mass reconstruction techniques for determining the $H,A$ masses. In Sec. [5] we conclude and look at future directions. In Appendix [B] we give details for solving the neutrino momenta given trial masses for the two bosons.
2 A simple model for $H \to ZA$ signals

In this section we discuss the possibility of enhancing the coupling of a CP-even Higgs boson ($H$) to the $Z$ gauge boson and a pseudo-scalar ($A$). We would like to develop a model where the $H$ decays predominantly to $ZA$ and the $A$ in turn decays into $\tau^+\tau^-$. This model has the possibility of explaining the slight excesses observed by the CMS collaboration [9] in the $4\ell+0\tau_h$, $3\ell+1\tau_h$ and $2\ell+2\tau_h$ channels with a reconstructed leptonic $Z$. In these channels, the $\tau_h$’s indicate reconstructed one-prong hadronic decays. Therefore, to realize this scenario in a model we need the $A$ to be reasonably light and the branching ratios of $H \to ZA$ and $A \to \tau^+\tau^-$ to be significant. In particular, we are interested in benchmarks where $m_H \sim 200$ GeV and $m_A \sim 10 – 100$ GeV, ensuring that the $Z$ decay is open and the $H$ can be produced with reasonable rates. Such a decay is particularly difficult to realize in the Minimal Supersymmetric Standard Model due to the decoupling limit constraining both the mass of $A$ and the decay of $H \to ZA$ and thus, we have to turn to other theories.

To demonstrate a realization of such a model we consider the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [14]. The superpotential has the form

$$W = W_{\text{Yuk}} + \lambda \hat{H}_u \hat{H}_d \hat{S} + \frac{\kappa}{3} \hat{S}^3$$

where $W_{\text{Yuk}}$ are the usual Yukawa interactions and the hatted fields denote the chiral superfields. The corresponding soft supersymmetry breaking terms are

$$V_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + \sqrt{2} \left( m_\lambda S H_u H_d - m_\kappa S^3 \right).$$

Here, we will follow the discussion and notation of Ref. [15]. The relationships to the standard NMSSM notation of Ref. [16] are $m_\kappa \equiv -\kappa A_\kappa/\sqrt{2}$ and $m_\lambda \equiv \lambda A_\lambda/\sqrt{2}$. We will work in the CP-even Higgs basis ($h_0^v, H_0^v, h_0^s$) and CP-odd basis ($A_0^v, A_0^s$), where

$$H_0^d = \frac{1}{\sqrt{2}} [(v + h_0^v - iG^0) c_\beta - (H_0^v - iA_0^v) s_\beta]$$

$$H_0^u = \frac{1}{\sqrt{2}} [(v + h_0^v + iG^0) s_\beta - (H_0^v + iA_0^v) c_\beta]$$

$$S = \frac{1}{\sqrt{2}} (s + h_0^s + iA_0^s),$$

$v \sim 246$ GeV is the Higgs vacuum expectation value (VEV), $\tan \beta = (v_u/v_d)$, $G^0$ is the goldstone mode, $s$ is the $S$ VEV. An effective $\mu$ parameter can be defined $\mu_{\text{eff}} \equiv \lambda s/\sqrt{2}$. As $h_0^v$ is rotated in the same way as $v$, it is the linear combination that gives mass to the $W$ and $Z$ and hence is the one that has trilinear couplings to these gauge bosons. Therefore the Standard Model-like Higgs boson is the one which has the largest component in the $h_0^v$ direction, while the nonstandard Higgs boson is the one that is mostly in the $H_0^v$ direction.

We consider benchmark points in which the pseudo-scalar is an R-axion and use NMSSM-tools 3.2.3 [16] to find the benchmark scenarios with NMSSM parameters shown in Tab. 1 and physical Higgs boson masses in Tab. 2. In Appendix A we provide a phenomenological
Table 1: Model parameters of benchmark scenarios for enhanced $H_2^0 \to Z A_1^0$ signals.

| Model | $\lambda$ | $\kappa$ | $t_\beta$ | $A_\lambda$ (GeV) | $A_\kappa$ (GeV) | $A_t$ (TeV) | $\mu_{\text{eff}}$ (GeV) | $M_{\tilde{q}}$ (TeV) |
|-------|----------|---------|---------|---------------|---------------|------|----------------|-----------|
| BM1   | 0.71     | 1.10    | 1.5     | -11.0         | -8.0          | 0.0  | 160            | 0.5       |
| BM2   | 0.71     | 1.10    | 1.5     | -9.1          | -7.0          | 0.0  | 166            | 0.5       |
| BM3   | 0.67     | 0.78    | 1.5     | -4.2          | -40.6         | 0.0  | 170            | 0.5       |

Table 2: Higgs mass spectra and normalized coupling to top quark in the benchmark scenarios.

| Model | $m_{H_1^0}$ (GeV) | $m_{H_2^0}$ (GeV) | $m_{A_1^0}$ (GeV) | $m_{A_2^0}$ (GeV) | $m_{H^\pm}$ (GeV) | $g_{H_1^0}^{\text{rel.}}$ | $g_{H_2^0}^{\text{rel.}}$ |
|-------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| BM1   | 125.2           | 270             | 495             | 8.9             | 357             | 0.982           | -0.691          |
| BM2   | 125.1           | 283             | 513             | 19.7            | 365             | 0.984           | -0.690          |
| BM3   | 124.5           | 252             | 391             | 117             | 328             | 0.992           | -0.668          |

Table 3: Relevant branching ratios of the Standard Model-like Higgs boson in the benchmark scenarios.

| $BR$ of $H_1^0$ | $bb$ | $\gamma\gamma$ | $WW^*$ | $ZZ^*$ | $A_1^0 A_1^0$ |
|-----------------|------|----------------|--------|--------|---------------|
| BM1             | 0.63 | $2.6 \times 10^{-3}$ | 0.19   | $2.1 \times 10^{-2}$ | $2.9 \times 10^{-3}$ |
| BM2             | 0.61 | $2.5 \times 10^{-3}$ | 0.18   | $2.0 \times 10^{-2}$ | $4.3 \times 10^{-2}$ |
| BM3             | 0.64 | $2.7 \times 10^{-3}$ | 0.18   | $2.0 \times 10^{-2}$ | 0.0           |

Table 4: Relevant branching ratios of the lightest non-Standard CP even Higgs boson in the benchmark scenarios.

| $BR$ of $H_2^0$ | $bb$ | $WW$ | $ZZ$ | $H_1^0 H_1^0$ | $Z A_1^0$ | $A_1^0 A_1^0$ |
|-----------------|------|------|------|---------------|-----------|---------------|
| BM1             | $4.5 \times 10^{-3}$ | $1.7 \times 10^{-3}$ | $7.3 \times 10^{-3}$ | $5.6 \times 10^{-4}$ | 0.78       | 0.17          |
| BM2             | $4.3 \times 10^{-3}$ | $1.6 \times 10^{-3}$ | $7.0 \times 10^{-4}$ | $4.9 \times 10^{-4}$ | 0.70       | 0.16          |
| BM3             | $1.9 \times 10^{-2}$ | $1.2 \times 10^{-3}$ | $5.0 \times 10^{-4}$ | $1.7 \times 10^{-6}$ | 0.78       | 0.19          |

Table 5: Relevant branching ratios of the lightest CP-odd Higgs boson in the benchmark scenarios and the signal rate $\mu = \frac{\sigma(pp\to H_2^0\to ZA\to Z\tau^+\tau^-)}{\sigma(pp\to H_{SM})}$ normalized to the Standard Model Higgs cross section.

| $BR$ of $A_1^0$ | $\tau\tau$ | $bb$ | $gg$ | Signal Rate ($\mu$) |
|-----------------|------------|-----|-----|---------------------|
| BM1             | 0.74       | 0.0 | 0.12| 0.28                |
| BM2             | $5.9 \times 10^{-2}$ | 0.92| $1.1 \times 10^{-2}$ | $3.7 \times 10^{-3}$ |
| BM3             | $9.1 \times 10^{-2}$ | 0.87| $2.9 \times 10^{-2}$ | 0.01                |
explanation of how such a region of parameter space arises in the NMSSM. As can be seen in the last column of Tab. 2, the $H_1 (H_2)$ has production cross sections through gluon fusion $\sim 1 (1 / 2)$ times the cross section for a Standard Model Higgs at that mass. The branching ratios are shown in Tab. 3, Tab. 4 and Tab. 5. Tab. 2 and Tab. 3 show that the $H_0$ has Standard Model-like production cross-sections and branching ratios (with deviations ranging 10-30%) which are consistent with the current sensitivities of the LHC Higgs analyses [1, 2]. To suppress $H_2$ couplings to down-type fermions we have chosen to only consider $\tan \beta = 1.5$. Scenarios, which also leads to an enhancement in the top quark coupling. The values of $\lambda$ and $\kappa$ are large in order to generate a significant mass splitting between the two pseudo-scalar states. Some of these couplings are large enough to develop a Landau-pole before the GUT-scale. Hence the UV-completion of such scenarios may require Fat-Higgs like models discussed in Ref. [17]. For these regions of parameter space, the Standard Model-like Higgs boson is the $H_1$ state and for $\lambda \lesssim 1$, its tree-level mass $m_{H_1}^{\text{tree}} \lesssim 100$ GeV. Hence a small amount of stop radiative contributions is needed to raise the physical SM-like Higgs to the observed Higgs boson mass [18, 19, 20, 21].

Benchmark point BM1 was chosen so that $A_1$ decays mostly to $\tau$'s due to the phase space suppression of $A_1$ decays to bottom quarks. In the R-axion limit $m_{A_1} \propto \sqrt{s}$, so we raised the mass of $A_1$ by increasing $s$ which leads to BM2. In BM2, $A_1$ the branching ratio to bottom quarks is 0.9 while that to $\tau$-leptons is 0.06 because $m_{A_1} \gg 2m_b$. Finally, the benchmark point BM3 was chosen so to illustrate that regions of NMSSM parameter space exist where $A_1$ need not be light and the branching ratio of $H_2 \to Z A_1$ can still be enhanced. These three specific benchmark scenarios serve as an important existence proof that it is possible to have significantly enhanced decay rates of $H_2 \to Z A_1$ compared to the $H_2 \to b \bar{b}$ and still have a $H_1$ state with similar branching ratios as a Standard Model Higgs. However, it is important to keep in mind that even more optimistic scenarios are possible for the signal rate. For example, the $A$ decays into taus could be enhanced in all parts of parameter space in a leptophilic two Higgs doublet model.

3 Limits on the simplified model from current searches

In this section we take the benchmark points shown in Sec. 2 to be indicative of a generalized model where a nonstandard Higgs boson $H$ dominantly decays into the $Z$ boson and a lighter pseudo-scalar $A$. From now on, we proceed model-independently and analyze the phenomenology of the signal process $H \to Z A \to Z \tau^+ \tau^−$ in the multilepton decay channel for a broad range of $H, A$ masses. We start by finding the efficiency of observing this model in the CMS multilepton analyses under the selection cuts in Ref. [9].

Event simulation

We generate samples of signal events for a broad range of $H, A$ masses using Pythia8.170 [22] including the effects of initial state radiation, final state radiation, multiple interactions and fragmentation. These events samples were generated for $pp$ collisions at $\sqrt{s} = 7$ TeV using
The CTEQ5L parton distribution functions \cite{23} events we only consider the leptonic decay of the Z-boson (including \( \tau \)'s) and assume that the \( A \) decays only into \( \tau \)-leptons. We do not apply any detector simulation on the events, in order to apply our own tau reconstruction.

Figure 1: Our \( \tau \) reconstruction efficiency for a sample of Drell-Yan \( Z \to \tau \tau \) events where one tau decays in a one-prong hadronic decay as a function of the tau’s generated \( p_T \). The efficiency asymptotes to \( \sim 60\% \) at high \( p_T \) and we have plotted an analytic function to guide the eye.

Ref. \cite{9} uses the CMS particle flow algorithm to identify the neutral pions and \( p_T \) of the \( \tau_h \) candidate, which may lead to a difference between our simulation and the CMS data. As a check of our tau reconstruction, we simulated one-prong tau decays in Drell-Yan \( Z \to \tau \tau \) and found reconstruction efficiencies as shown in Fig. 1 as a function of the generated tau \( p_T \). Our asymptotic efficiency is about 60\% at high \( p_T \). This can be compared with the published CMS tau efficiencies in figure 3 of Ref. \cite{24}. There is a difference in presentation since the CMS figures are plotted with respect to the generated visible tau \( p_T \) which is
Figure 2: Contours of the efficiencies in the 0 one-prong hadronically decay $\tau$ channel, 1 one-prong hadronically decay $\tau$ channel and 2 one-prong hadronically decay $\tau$ channel. In these channels, there is an electron or muon pair with mass consistent with the $Z$ and a total of four leptons (electrons, muons, and one-prong taus). The brown hatched regions in the upper left are plotted to avoid the kinematically squeezed region where $m_H - m_A < 100$ GeV.

approximately $1/2 - 1/3$ of the generated tau $p_T$. However, taking this into account, the behavior is similar to the TANC medium tau algorithm and systematically higher than the efficiencies of the HPS algorithms (which peak at 50%). This gives us confidence that our tau reconstruction is realistic and maybe just a bit more optimistic than the true CMS algorithms.

As the $Z$-boson can also decay to $\tau$-leptons which can further decay into $e$ or $\mu$, there is also a possibility of this process also contributing to the multilepton events in Ref. [13] and Ref. [9] where the invariant mass of no two leptons are within the $Z$ mass window $75\text{ GeV} \leq m_{\ell^+\ell^-} \leq 105\text{ GeV}$. However these electrons and muons are typically soft and therefore such events have more difficulty with the triggering requirement.

In Fig. 2 we show the contours of the efficiencies for each channel,

$$
\epsilon_i \equiv \frac{N(\text{selected})_i}{N(Z \rightarrow (e^+e^-, \mu^+\mu^-, \tau^+\tau^-), A \rightarrow \tau^+\tau^-)}
$$

where the channels are the $4\ell + 0\tau_h$, $3\ell + 1\tau_h$ and $2\ell + 2\tau_h$ channels with a reconstructed leptonic $Z$. Thus, our convention takes out the $Z$ branching ratio into the three generations of leptons and the $A$ branching ratio into $\tau$ pairs, but includes the $\tau$ branching ratios into the efficiency. The brown hatched regions in the upper left are plotted to avoid the kinematically squeezed region where $m_H - m_A < 100$ GeV. In the $0\tau_h$ channel, each of the $\tau$-leptons from the $A$ decay have decayed leptonically via the three-body decay. Thus, the resulting leptons from the decay of the $\tau$’s are relatively soft. This explains the efficiency improvement as $m_A$ increases, since the $\tau$’s have larger average $p_T$ and are more geometrically leading to better isolation. The $1\tau_h$ and $2\tau_h$ efficiency curves have a similar structure to the $0\tau_h$ events because of the similar effects of boosting the $A$ and $\tau$-leptons. However, the value of $m_H$
with optimal efficiency for the $1\tau_h$ and $2\tau_h$ channels is different because of the different isolation requirements for 1-pronged hadronic $\tau$'s and the greater visible $p_T$ in such decays as compared to the leptonic case. This helps to explain the slope of the contours, as a smaller boost to the $A$ is required for hadronic taus to pass the $p_T$ selection.

Using a toy model, we can get further insight into the inefficiency of the searches at low $m_A$. In our toy model, we assume that $H$ is produced at rest, with the $A$ particle being produced in the transverse direction. This $A$ is taken to decay into two single prong $\tau$'s where the $\tau$’s decay $\tau^+ \to \pi^+, \bar{\nu}_\tau$, assuming $p_{\pi^+} = p_{\tau^+}/2$. In this case, we can very simply predict the visible pion kinematics as a function of the $\tau^+$ decay angle in the $A$ rest frame. The $p_T$ and $\Delta R$ of the charged pions are shown in Fig. 3 for the case of $m_H, m_A = 200, 10$ GeV. Here, we see that the tau reconstruction requirement of a track with $p_T > 8$ GeV restricts us to $|\cos \theta_{CM}| \lesssim .6$ in order to select both hadronic $\tau$’s. However, as the $\Delta R$ figure shows, the isolation condition is in direct conflict, requiring $|\cos \theta_{CM}| \gtrsim .6$. Thus, these two conditions are in tension. Due to the softness of the pions, the configuration that works best for getting substantial $p_T$ is where the two taus decay in the longitudinal direction, so that the boost enhances both of their transverse momenta. However, at the same time this pushes the pions on top of each other, worsening isolation. This tension is exacerbated with larger boosts. For example, as the $H$ mass is increased, the slope of the $p_T$ plots increases whereas the dip of the $\Delta R$ plot decreases. Thus, we see that the standard tau selection and reconstruction is inefficient for the boosted regime. For such decays, searches for boosted taus has been show to be efficient [25, 26], in particular using $N$-subjettiness [27]. Thus, multilepton analyses should consider a boosted tau pair object as a way to recover such regions of parameter space.

Figure 3: Toy model kinematics of the charged pions as a function of the decay angle of the $\tau^+$ in the rest frame of $A$. The $p_T$ selection cut is shaded on the left plot and the isolation annulus is shaded on the right plot. The masses for these plots are $m_H, m_A = 200, 10$ GeV.
Table 6: The observed number of events and expected backgrounds for the three channels as given in Ref. [9]. In the second to last column is our derived 95% C.L. limit on the number of signal events in each channel and the last column is the projected limit a 30 fb$^{-1}$ analysis would have given only statistical background errors.

**Signal limits using the CMS analysis**

The multilepton analysis Ref. [9] observed number of events and expected background is tabulated in Tab. 6. There is a slight excess, predominantly in the $2\tau_h$ channel, which unfortunately is not fit well by our signal. This is due to the fact that the efficiencies for the $1\tau_h, 2\tau_h$ channels are similar (see Fig. 2), which limits the amount of the excess that can be explained. In order to set limits on our model, we use this data to calculate the maximum number of signal events at 95% C.L. in each channel. Due to the low statistics we assume a Poisson distribution for the number of events and therefore the probability of observing at least $N_{obs}$ events due to signal and background is $P(N_{obs}|S + B) = \Gamma(N_{obs} + 1, S + B)/N_{obs}!$, where $\Gamma(A, B)$ is the incomplete gamma function. We assume the background has a gaussian distribution with mean $\mu_B$ and variance $\sigma_B^2$ and find the maximum allowed number of signal events at 95% C.L. ($S_{95}^{\text{Max}}$) by solving the equation

$$
\int_0^\infty dB \frac{\Gamma(N_{obs} + 1, S_{95}^{\text{Max}} + B)}{N_{obs}!} \frac{1}{N_B} \exp \left[ -\frac{(B - \mu_B)^2}{2\sigma_B^2} \right] = 0.05
$$

where $N_B$ normalizes the background’s gaussian distribution over the interval $[0, \infty)$. Using these limits on the number of signal events in each channel for each selection, we can put bounds on the cross-section for this process, normalized to the Standard Model Higgs production cross-section by defining a signal strength parameter

$$
\mu_{95}^i \equiv \frac{S_{95}^{\text{Max}}}{\sigma_{H_{SM}}^i} \frac{\mathcal{BR}(Z \rightarrow l^+l^-) \times e_i \times \mathcal{L}}{\sigma_{A^0} \times \mathcal{BR}(A^0 \rightarrow \tau\tau)}
$$

where $l = e, \mu, \tau$ and $e_i$ is the efficiency for $i^{th}$ channel and $\mathcal{L}$ is the integrated luminosity.

In Fig. 4 we present contours of the minimum value of $\mu_{95}$ for the $\mathcal{L} = 4.8$ fb$^{-1}$ of data. The limits are weaker for small values of $m_A$ because of the lower efficiencies and they are stronger for small values of $m_H$ because of the larger production cross-section. Using the couplings in Tab. 2 and the branching ratios in Tab. ?? we see that these benchmarks have $\mu \sim 0.25$ for $m_A = 10$ GeV and $\mu \sim 0.023$ for $m_A \gtrsim 10$ GeV. Therefore the benchmark points considered in Tab. 1 are not constrained by the present experimental data. However, in more optimistic scenarios where the $A$ is leptophilic (i.e. $\mathcal{BR}(A^0 \rightarrow \tau\tau) \sim 1$), we see that the Standard Model cross section is already strongly constrained for $A$ masses above about 15-20 GeV.
Figure 4: In the left figure, the contours of the 95% CL limit on the signal parameter $\mu_{95}$ is displayed, while in the right figure, the projected limit a 30 fb$^{-1}$ CMS-like analysis would have.

With improvements in statistics and in the background modeling, a future multilepton analysis would have improved sensitivities to this signal and start to constrain more interesting signal rates. To estimate this improvement, in Tab. 6 we have projected the signal events allowed in a 30 fb$^{-1}$ CMS-like analysis. In making this estimate, we have ignored the background and signal cross section changes with $\sqrt{s} = 8$ TeV running and further assumed that the background uncertainty can be reduced to being purely statistical. As shown in the right figure of Fig. 4 this gives a projected limit at 30 fb$^{-1}$ that is roughly 4 – 5 times stronger than the current analysis. This is very close to being sensitive to our benchmark signal rates and would place stringent constraints on scenarios where the $A$ branching ratio to taus is enhanced. Hence, a multilepton analysis using the full LHC data set of 2012 could have an interesting reach for for this nonstandard Higgs signal.

4 Comparison of methods of mass reconstruction $H \rightarrow ZA$

If an excess in these channels is seen in future multilepton analyses, it will be important to reconstruct the signal in order to determine the underlying theory. As a step in this direction, in this section we consider reconstructing this signal by measuring the masses $m_H$ and $m_A$ through a variety of techniques. In particular we consider three possibilities: $i$) transverse mass, $ii$) collinear mass and $iii$) an analytic solution based on trial masses for $H, A$. In this section we will be concentrating purely on the $2\tau_h$ channel because there are more neutrino final states in the $0\tau_h$ and $1\tau_h$ channels, complicating the reconstruction. We summarize these mass reconstruction methods below.
Transverse Mass Variables: Using the visible components of the \( \tau \)'s \( p_{V1,2} \), the reconstructed \( Z \) momentum \( p_Z \) and the total MET components \( p_T^+ \) we can define the transverse masses \[28\]

\[
m_T^A = \sqrt{p_V^2 + 2(E_V E_T^+ - p_V^T \cdot p_T^+)} \tag{9}
\]

\[
m_T^H = \sqrt{(p_V + p_Z)^2 + 2((E_V + E_Z)E_T^+ - (p_V^T + p_Z^T) \cdot p_T^+)} \tag{10}
\]

where \( p_V = p_{V1} + p_{V2} \). These variables have the property that \( m_T^X \leq m_X \), so measuring the endpoints gives a determination of the masses.

Collinear Approximation: Since the pseudo-scalar \( A \) typically has a large boost, it is a good approximation to assume that the final state neutrinos are collinear with the visible final state hadrons of the taus. In this approximation, the neutrino momenta are proportional to the visible components of the \( \tau \)-leptons and we need to solve the linear equation \[29\]

\[
\lambda_1 p_{V1}^T + \lambda_2 p_{V2}^T = p_T^+ \tag{11}
\]

Physical solutions require the coefficients \( \lambda_{1,2} \) to be positive. From these, one approximates the \( \tau \) momenta as \((1 + \lambda_i)p_{Vi}^T\) to determine the \( A, H \) masses.

Analytic Solution: Finally, as shown in Appendix [3] for trial masses \( m_H \) and \( m_A \) we can solve the neutrino momenta exactly. Similar to Ref. [30], for each event, there is an allowed region of masses where there are consistent neutrino solutions. For each such event, our estimator for the masses is the center of mass of the allowed \((m_H, m_A)\) region. See Appendix [3] for more details on this method.

In Fig. 5 we show the histograms for each of these different mass variables for signal events generated with \((m_H, m_A) = (200 \text{ GeV}, 10 \text{ GeV}), (200 \text{ GeV}, 100 \text{ GeV})\) and \((300 \text{ GeV}, 100 \text{ GeV})\). The blue (darker grey) histograms correspond to method \(iii\), the average values of \( m_H \) and \( m_A \) that provide analytic neutrino solutions for each event. The yellow (lighter grey) histograms correspond to the transverse masses for each event as defined in Eq. (9) and Eq. (10). The purple (grey) histograms are the \( m_H \) and \( m_A \) masses calculated in the collinear approximation. The peaks of the blue and purple histograms determine the reconstructed mass of \( m_H \) and \( m_A \), while the transverse masses (shown in yellow) give another estimate of the masses as the transverse mass should drop above the physical mass. Hence the peaks for blue and purple histograms are to be compared with the value of the mass where the yellow histograms drops down. As can be seen by the plots, this drop off is not always sharp, so an accurate extraction of the mass from the transverse mass distribution can require a good understanding of its shape.

The average solutions shown by the blue histogram typically reconstruct an \( m_H \) that agrees well with the true value in the signal, although the value of \( m_A \) is slightly higher than its true value for low values of \( m_A \). This slight bias of reconstructed \( A \) masses, at low values of \( m_A \), is due to the selection requirements preferring taus with a higher \( p_T \). Furthermore about 90% of the \( 2\tau_h \) events that pass the isolation and trigger cuts, reconstruct to a physical solution. This is to be compared to the collinear solution where less than 50% of the \( 2\tau_h \) events lead to physical solutions with positive \( \lambda_{1,2} \). The plotted event counts reflects this
Figure 5: Comparison of the reconstruction of mass variables for a \((m_H, m_A) = (200 \text{ GeV}, 10 \text{ GeV}), (200 \text{ GeV},100 \text{ GeV})\) and \((300 \text{ GeV},100 \text{ GeV})\). The left panels are the reconstruction of the \(H\) mass while the right panels correspond to those of the \(A\) mass. The yellow (light grey) histogram corresponds to the transverse masses of \(H\) and \(A\) method \(i\) and its drop off determines the mass, the purple (grey) histograms correspond to the mass reconstructed by using the collinear solution to the neutrino momenta method \(ii\) and the blue (dark grey) histograms corresponds to the reconstructed mass using the analytic method \(iii\).
difference in solution efficiency, giving a visual indication of the increase in reconstructible
events. Thus, for a given set of events, the analytic method can provide a more accurate and
efficient measurement of the $H$ and $A$ masses. The reconstructed masses using the collinear
method are typically slightly lower than physical masses because that angles between the
neutrinos and visible hadrons are neglected. From Fig. 5 we see that the widths of the
distributions using methods $ii$) and $iii$) are comparable. Comparing the transverse mass
distributions for $m_H = 200$ GeV and $m_H = 300$ GeV, we see that the mass resolution of $H$
and $A$ using the end points of the distributions is better for lower masses than for higher
masses. Therefore, the mass determination using the transverse mass distribution is more
complicated for these higher mass points.

To summarize, we have compared three different mass variables as a means to reconstruct
this signal process. These mass reconstruction methods all work reasonably well, displaying
different advantages and disadvantages depending on the situation. We focused on the $2\tau_h$
channel, since there the kinematics can be solved once trial masses for $A, H$ are given.
Even though the analytic method can be quite sensitive to the measured visible momenta,
most of the $2\tau_h$ solutions lead to a physical solution. This result is to be compared to the
collinear method where a majority of the events do not have a physical solution and
the transverse mass distribution whose endpoint may be uncertain. In our reconstruction,
the only uncertainty was the decay widths of the heavy particles, thus our analysis gives an
idea of the irreducible uncertainties without considering detector effects. To improve further,
there are more advanced techniques being developed which could yield further improvements.
Likelihood methods taking into account the $\tau$ decay kinematics, such as $[31]$, would be worth
applying to this process.

5 Conclusion

In this article we have shown that it is possible for nonstandard CP-even Higgs bosons to
have large branching fraction into $ZA$ where $m_A \lesssim 100$ GeV and $A$ has a sizeable branching
fraction into $\tau$-leptons. In particular, in the NMSSM we have presented three benchmark
scenarios where the $H^0_2 \rightarrow ZA_1^0$ decay mode has the largest branching fraction while $H^0_1$
phenomenology is SM-like. In these scenarios, low $\tan \beta$ and large mixing in the pseudo-
scalar sector are preferred. These rates can be further enhanced in more optimistic scenarios
like in leptophilic two Higgs doublet models.

In the collider study of the $H \rightarrow ZA \rightarrow Z\tau^+\tau^-$ scenario we found the efficiencies for
passing the selection cuts in the $0\tau_h$, $1\tau_h$ and $2\tau_h$ channels that included a leptonic $Z$ in the
latest CMS multilepton analysis $[9]$. The shape of the efficiencies contours for each channel
are due an interplay between the selection cuts, the isolation requirements and the kinematics
of the events. Using a toy model, we demonstrated that the low $m_A$ parameter space is
inefficiently picked up by the multilepton selection. In particular, the transverse momenta
and isolation requirements for the taus are in direct tension with each other. This motivates
including boosted di-tau jets, as explored in $[25]$, as a physics object in future multilepton
analyses. Using the observed and expected background events we constructed the 95\% C.L.
limits on the number of signal events in each channel. We found that the strongest limit on such a scenario was due to the $1\tau_h$ channel because of a high signal efficiency and the consistency between expected and observed events. In addition, we made a projection of the reach of a 30 $fb^{-1}$ CMS-like study would have on this scenario. If the background uncertainties can be reduced to purely statistical, we estimate that a large portion of the interesting parameter space can be covered.

Finally we considered the possibility of observing this scenario by measuring the $m_H$ and $m_A$ masses in the transverse mass, the collinear mass and an analytical solution based on the trial masses in the $2\tau_h$ channel. We found that this analytical solution allows for a greater number of events with physical solutions than the collinear method, while maintaining a similar resolution. The analytical method can also reconstruct larger values of the $H$ mass, which may be problematic using the transverse mass distribution, as the fall off of the transverse mass distribution is much softer for heavier masses.

Note Added: A new CMS multilepton analysis was recently presented at the HCP 2012 conference using 9.2 $fb^{-1}$ of 8 TeV data [32]. Due to an increase in the $p_T$ thresholds of taus, the observed number of events has decreased, which will have a strong impact on the efficiency of our signal.

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A NMSSM Realization of a large $H \to ZA$

In this section we provide an analytic explanation for the enhanced $H \to ZA$ branching ratio in the benchmark points in Tab. 1, 2, 3 and 4. The minimization conditions for the super potential in Eq. (1) and the soft terms in Eq. (2) can be used to eliminate some of the soft SUSY breaking parameters:

$$m_{H_d}^2 = -\frac{\lambda}{2}(s^2 + v^2 \cot^2 \beta) + \frac{\lambda \kappa}{2} t_\beta - \frac{m_Z^2}{2} c_{2\beta} + m_\lambda s t_\beta$$  \hspace{1cm} (12)

$$m_{H_u}^2 = -\frac{\lambda}{2}(s^2 + v^2 \cot^2 \beta) + \frac{\lambda \kappa}{2} t_\beta^{-1} - \frac{m_Z^2}{2} c_{2\beta} + m_\lambda t_\beta^{-1}$$  \hspace{1cm} (13)

$$m_S^2 = -\frac{\lambda}{2} v^2 + \frac{\lambda \kappa}{2} v^2 s_{2\beta} - \kappa^2 s^2 + \frac{m_\lambda v^2}{2s} + m_\kappa s$$  \hspace{1cm} (14)

After substituting these solutions into the scalar potential, there are six remaining free parameters $\lambda, \kappa, \beta, m_\lambda, m_\kappa$ and $s$. In terms of them, the tree-level CP-even mass matrix in the $(h_v^0, H_v^0, h_u^0)$ basis is

$$\mathcal{M}_{h_v^0}^2 = v^2 \begin{pmatrix} r + \frac{M_3^2}{v^2} & r \cot 2\beta & \lambda^2 \frac{s}{v} - R \\ r \cot 2\beta & -r + \frac{\lambda \kappa s^2 + 2 m_\lambda s}{v^2 \sin 2\beta} & -R \cot 2\beta \\ \lambda^2 \frac{s}{v} - R & -R \cot 2\beta & \frac{m_\kappa}{s} + s \left( \frac{m_\lambda}{2s^2} - \frac{m_\kappa}{v^2} \right) \end{pmatrix}$$  \hspace{1cm} (15)
where
\[
\begin{align*}
  r &
  \equiv \left( \frac{\lambda^2}{2} - \frac{M^2}{v^2} \right) \sin^2 2\beta, \\
  R &
  \equiv \frac{1}{v} (2\lambda\kappa s + m_\lambda) \sin 2\beta.
\end{align*}
\]

Similarly, the CP-odd states \((A^0_v, A^0_s)\) have a tree-level mass matrix
\[
\mathcal{M}_A^2 = \begin{pmatrix}
  (\lambda\kappa s^2 + 2m_\lambda s) s_{2\beta}^{-1} & -v(\lambda\kappa s - m_\lambda) \\
  -v(\lambda\kappa s - m_\lambda) & (\lambda\kappa + \frac{m_\lambda}{s^2}) v^2 s_{2\beta} + 3m_\kappa
\end{pmatrix}
\]
where the rotation angle \(\theta_A\) satisfies
\[
\tan 2\theta_A = \frac{4vs(\lambda\kappa s - m_\lambda) \sin 2\beta}{v^2 \sin^2 2\beta(2\lambda\kappa s + m_\lambda) - 2s^2(\lambda\kappa s + 2m_\lambda - 3m_\kappa \sin 2\beta)}.
\]

In this basis the \(ZA\) couplings to the CP-even states have the form
\[
\mathcal{L}_{\text{Higgs}}^{\text{Kin}} = D^\mu H_u^\dagger D_{\mu} H_u + D^\mu H_d^\dagger D_{\mu} H_d 
\]
\[
\subset - \frac{g_2}{2c_{\theta_W}} Z^\mu (A^0_v \leftrightarrow \partial_{\mu} (s_{2\beta} h_v^0 + c_{2\beta} H_v^0)) 
\]
\[
= - \frac{g_2}{2c_{\theta_W}} Z^\mu (c_{\theta_A} A^0_1 - s_{\theta_A} A^0_2) \leftrightarrow \partial_{\mu} (s_{2\beta} h_v^0 + c_{2\beta} H_v^0)
\]
where \(a \leftrightarrow \partial_{\mu} b = a\partial_{\mu} b - b\partial_{\mu} a\) and in the last line we have rotated into the CP-odd Higgs mass basis.

Within the NMSSM, a light pseudo-scalar can exist either in the Peccei-Quinn (PQ) or the \(U(1)_R\) limit. If we take the \(U(1)_R\) axion limit discussed in Ref. \[15\], where \(O(10^{-3}) \lesssim \frac{m_{\lambda,\kappa}}{v} \ll 1\), the mass of the lightest CP-odd scalar is
\[
m_{A^0_1} \simeq \sqrt{3s} \left( m_\kappa \sin^2 \theta_A + \frac{3m_\lambda \cos^2 \theta_A}{2\sin 2\beta} \right)^{1/2} + O \left( \frac{m_{\lambda,\kappa}}{v} \right)
\]
and the rotation angle is
\[
\tan \theta_A \simeq \frac{s}{v \sin 2\beta} + O \left( \frac{m_{\lambda,\kappa}}{v} \right).
\]

In order to have a light \(A^0_1\) with a large \(g_{H^0_2 A^0_1}\) coupling we require large mixing in the CP-odd Higgs sector, \(\theta_A \simeq \frac{\pi}{4}\). Also, to satisfy charged Higgs limits from top decays \[33, 34\], we have to raise the \(A_2\) mass since it is correlated with the charged Higgs. \[1\] In the R-axion limit, the magnitude of \(m_{A^0_2}\) is set by \(\lambda\kappa (v^2 s_{2\beta} + s^2 s_{2\beta}^{-1})\), so the mass constraint implies that \(\lambda\) and \(\kappa\) are both order one. To suppress the \(g_{H^0_2 A^0_2}\) coupling relative to \(g_{H^0_2 A^0_1}\) we need
\[1\] It is possible to avoid this constraint if the \(H^\pm \to W^\pm A\) is kinematically allowed \[8\]. For that top quark cascade decay, the relevant limit is the following CDF study \[35\], which applies only for \(m_A < 10\ \text{GeV}\) and has weaker limits. We thank R. Dermisek for emphasizing this point to us.
to be at low tan $\beta$. Additionally, maximal mixing in the pseudo-scalar sector along with Eq. (24) suggests that $s \approx v \sin 2\beta \approx v$. Large $g_{H^0 Z A_1}$ couplings also typically lead to an enhancement of the $g_{H^0 A_1 A_1}$ which reduces the $H_1$'s branching ratio into Standard Model decays, which is constrained by the present Higgs boson measurements at the LHC [1, 2]. Hence, when $m_{A_1} < m_{H_1}/2$, viable benchmark points need a tuning so that the $g_{H^0 A_1 A_1}$ coupling is suppressed, such that the branching ratios of $H_1$ remain SM-like.

We note in passing that the PQ-axion is not a useful limit for our benchmarks. In the PQ limit with $\kappa, m_\kappa$ small, we can neglect the $\kappa$ and $m_\kappa$ terms in Eq. (18) and find that $\theta_A \approx \pi/4$ implies $s \approx vs_{2\beta}/2$. Since the VEV $s \sim v/2 \sim 125$ GeV is smaller than in the PQ limit, the results small $\mu_{\text{eff}}$ often leads to chargino masses in violation of LEP2 bounds.

**B Neutrino Solution Using Trial Values of $m_H$ and $m_A$**

In this appendix, we show how to solve for the two neutrino four vectors $p_{\nu_1,2}$, knowing the momenta of the visible decay products of the $\tau$’s $p_{V_1,2}$ and the reconstructed $Z$ vector $p_Z$. There are eight kinematic constraints

$$ p_{\nu_1}^2 = 0 = p_{\nu_2}^2 \quad (25) $$

$$ (p_{\nu_1} + p_{\nu_1})^2 = m_\tau^2 = (p_{\nu_2} + p_{\nu_2})^2 \quad (26) $$

$$ m_A^2 = (p_{\nu_1} + p_{\nu_2} + p_{\nu_2})^2 \quad (27) $$

$$ m_H^2 = (p_Z + p_{\nu_1} + p_{\nu_1} + p_{\nu_2} + p_{\nu_2})^2 \quad (28) $$

$$ p_{\nu_1}^2 + p_{\nu_2}^2 = p_+^2 \quad (29) $$

$$ p_{\nu_1}^2 + p_{\nu_2}^2 = p_-^2 \quad (30) $$

where $m_{H,A}$ are the trial masses and for simplicity we have defined

$$ p_\pm = p_{\nu_1} \pm p_{\nu_2}. \quad (31) $$

In particular, the $x, y$ components of $p_\pm$ are the missing transverse energy components.

The undetermined components of $p_\pm$ satisfy

$$ p_+^x = \frac{E_Z E_+ - \Delta_H}{p_Z^x} \quad (32) $$

$$ E_+^2 - \left( \frac{E_Z E_+ - \Delta_H}{p_Z^x} \right)^2 + 2 \left( E_+ E_V - \frac{E_Z E_+ - \Delta_H}{p_Z^x} p_V^x \right) = \Delta_A \quad (33) $$

where

$$ p_V = p_{\nu_1} + p_{\nu_2} \quad (34) $$

$$ \Delta_H = \frac{1}{2} (m_H^2 - m_Z^2 - m_A^2) - p_Z \cdot p_V + p_T^V \cdot p_T^V \quad (35) $$

$$ \Delta_A = m_A^2 - p_V^2 + (p_T^V)^2 + 2p_T^V \cdot p_V. \quad (36) $$

15
Therefore for a particular \((m_H, m_A)\), a physical solution is possible only if a real positive root to Eq. \([33]\) exists.

The \(p_-\) equations are

\[
\begin{align*}
p_- \cdot p_{V_1} &= \Delta_1 \quad (37) \\
p_- \cdot p_{V_2} &= -\Delta_2 \quad (38) \\
p_- \cdot p_+ &= 0 \quad (39) \\
p_-^2 &= -p_+^2 \quad (40)
\end{align*}
\]

where the terms on the right hand side are

\[
\Delta_i = m_r^2 - p_{V_i}^2 - p_+ \cdot p_{V_i} \quad (41)
\]

We can solve for the spatial components in terms of \(E_-\)

\[
\vec{p}_- = E_- \vec{A} + \vec{B} \quad (42)
\]

where

\[
\vec{A} = X \begin{pmatrix} E_{V_1} \\ E_{V_2} \\ E_+ \end{pmatrix} \quad (43)
\]

\[
\vec{B} = X \begin{pmatrix} -\Delta_1 \\ \Delta_2 \\ 0 \end{pmatrix} \quad (44)
\]

\[
X = \begin{pmatrix} p_{V_1}^x & p_{V_1}^y & p_{V_1}^z \\ p_{V_2}^x & p_{V_2}^y & p_{V_2}^z \\ p_+^x & p_+^y & p_+^z \end{pmatrix}^{-1} \quad (45)
\]

Plugging this solution back into Eq. \([40]\) we see that a solution for the trial \(m_H\) and \(m_A\) values exists only if \(E_-\) is real. Hence the conditions for a particular event arising from a trial \((m_H, m_A)\) are that at least one of the roots of Eq. \([33]\) is positive and real and the \(p_+\) corresponding to that root also satisfies the condition

\[
(\vec{A}(p_+) \cdot \vec{B}(p_+))^2 - (1 - |\vec{A}(p_+)|^2)(p_+^2 - |\vec{B}(p_+)|^2) \geq 0
\]

which ensures that \(E_-\) is real.

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