LHC discovery potential of the lightest NMSSM Higgs in $h \to a_1 a_1 \to \mu\mu\mu\mu$ channel

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We explore the potential of Large Hadron Collider to observe $h_1 \to a_1 a_1 \to 4\mu$ signal from the lightest lightest scalar Higgs boson (h_1) decaying into two lightest pseudoscalar Higgs bosons(a_1) followed by their decays into 4 muons within the Next-to-Minimal Supersymmetric Standard Model (NMSSM). The signature under study allows to cover the NMSSM parameter space with M_{a_1} below 3.5 GeV and large $Br(h_1 \to a_1 a_1)$ which has not been studied previously. In case of such a scenario, the suggested strategy of the observation of 4μ signal with the respective background suppression would provide a unique way to discover the lightest scalar NMSSM Higgs boson.

INTRODUCTION

The next-to-minimal supersymmetric standard model (NMSSM) [1–13] is extended by one singlet superfield in addition to the particle content of the Minimal Supersymmetric Standard Model (MSSM). NMSSM has several new attractive features as compared to MSSM. First of all, NMSSM elegantly solves the so called μ-problem [14]: the scale of the μ-parameter is automatically generated at the electroweak or SUSY scale when the singlet Higgs acquires a vacuum expectation value. Second, the severeness of the fine-tuning and little hierarchy problems in NMSSM is greatly diminished as compared to MSSM [15]. In NMSSM, the upper mass limit on the lightest CP-even Higgs boson is higher than in the MSSM case making it less constrained experimentally. Another reason effect is that in the NMSSM the lightest CP-even higgs can have a significant branching fraction for the new $h_1 \to a_1 a_1$ decay (h_1 and a_1 stands for the lightest CP-even and CP-odd Higgs bosons respectively). That substantially weakens the constraining power of the LEP-II higgs searches on the allowed parameter space of the model as this new decay channel diminishes the branching fractions of h_1 for the conventional modes used in direct Higgs searches and largely softens direct Higgs boson mass limits from LEP. Apart from the Higgs angle, there are interesting implications in the cosmological Dark Matter sector of the model due to the appearance of the fifth neutralino, "singlino". It was shown [25] that NMSSM is consistent with the experimentally measured relic density, and the data provides important constraints on the allowed NMSSM parameters.

Richer phenomenology offered by NMSSM and stemming from the extension of the scalar sector has been the focus of a number of studies [16–24]. In [17] the first attempt to establish 'no-lose' theorem for NMSSM has been presented. This theorem states that LHC has a potential to discover at least one NMSSM Higgs boson in the conventional mode given that Higgs-to-Higgs decay modes are not important. However the point is that Higgs-to-Higgs decay modes can be important as has been shown and studied later on in analysis devoted to re-establishing of 'no-lose' theorem [18–24] for the case when $h_1 \to a_1 a_1$ decay is significant and a_1 is light. The NMSSM scenarios with m_{a_1} between the $2m_\tau$ and $2m_b$-quark $2m_\tau < m_{a_1} < 2m_b$ have been considered focusing on the 4τ [24] and the 4μ [**?**] channels in Higgs-strahlung and Vector Boson Fusion and establishing the NMSSM No-Lose Theorem at the LHC [24]. Potential future analysis at in the 4τ channels is likely to be very challenging technically and both analyses can only be performed with large datasets (typical intergrated luminosity of 10-100 fb^{-1}).

In this paper we explore the mass region of a_1 with the mass below 2τ threshold: $m_{a_1} < 2m_\tau$. In this case, which has not been studied previously, we explore the potential of $h_1 \to a_1 a_1 \to \mu\mu\mu\mu$ signature at the LHC. Unlike searches for 4τ signature, the measurement of invariant mass of muon pair provides a direct estimate of m_{a_1} which defines a clear set of the kinematical cuts for the background suppression. Further, this channel is essentially free of backgrounds and therefore allows to use direct gluon fusion production combined with $b\bar{b}$ fusion production instead of subdominant vector boson fusion or associate Higgs production processes used in case of 4τ signature to to suppress large QCD backgrounds.

We demonstrate that the analysis in the four muon mode has excellent sensitivity for Lightest CP-even NMSSM Higgs boson and can be performed with just a handful of first LHC data and requires very little in terms of detector performance except reasonably robust tracking for muons and well functioning muon system. To make this a realistic analysis, we use parameters of the CMS experiment in designing selections and estimating background contributions.

The rest of the paper is organized as follows. In Section II we study the NMSSM parameters space for which $m_{a_1} < 2m_\mu$ case of our study is realized. In Section III we perform signal versus background analysis and present our final results in Section IV. In Section V we draw our conclusions.

FIG. 1: (a): Lightest (h_1) and second-lightest (h_2) CP-even Higgs masses as a function of $\mu\kappa/\lambda$ and λ. The density of generated points surviving constraints is shown in the blue color scale, and the red line presents the single-valued $\lambda \ll 1$ limit. (b): mass of the CP-odd Higgs (m_a) as a function of A_κ and λ. The color scale is the average mass in each bin, and filled circles are models with $m_a < 2m_\tau$. Low m_a region follows the parabolic curve, (30 GeV)$\lambda^2 - A_\kappa \geq 0$.

NMSSM PARAMETER SPACE

In our study we consider the simplest version of the NMSSM [1–12], in which the $\mu\widehat{H_1}\widehat{H_2}$ term of the MSSM superpotential is replaced by

$$\lambda\widehat{S}\widehat{H}_1\widehat{H}_2 + \frac{\kappa}{3}\widehat{S}^3, \tag{1}$$

which makes the superpotential scale invariant. In general, there are five soft braking terms; in the "non-universal" case,

$$m_{H_1}^2 H_1^2 + m_{H_2}^2 H_2^2 + m_S^2 S^2 + \lambda A_\lambda H_1 H_2 S + \frac{\kappa}{3} A_\kappa S^3. \tag{2}$$

In the above equations, capital letters with tildes denote superfields while symbols without tildes denote the scalar component of the respective superfield.

Soft breaking parameters in Eq.(2), $m_{H_1}^2$, $m_{H_2}^2$ and m_S^2, can be expressed in terms of M_Z, the ratio of the doublet Higgs vacuum expectation values (VEVs) $\tan\beta$, and $\mu = \lambda s$ (where $s = \langle S\rangle$, the VEV of the singlet Higgs field) through the three minimization equations of the Higgs potential. Assuming that the Higgs sector is CP conserving, the NMSSM Higgs sector at the Electro-Weak (EW) scale is uniquely defined by 14 parameters: $\tan\beta$, the trilinear couplings in the superpotential λ and κ, the corresponding soft SUSY breaking parameters A_λ and A_κ, the effective μ parameter $\mu = \lambda s$, the gaugino mass parameters M_1, M_2 and M_3, the squark and slepton trilinear couplings A_t, A_b and A_τ, and the squark and slepton mass parameters M_{f_L} and M_{f_R}. For simplicity, we assume here the universality within 3 generations for the last two parameters, leaving only 6 parameters for sfermion masses.

In particular, the above parameters define $\mathcal{M}_S$ and $\mathcal{M}_P$, the CP-even and CP-odd Higgs mass matrices, respectively [26]:

$$\begin{aligned}
\mathcal{M}^2_{S11} &= g^2 v^2 \sin\beta^2 + \mu \cot\beta (A_\lambda + \kappa s) \\
\mathcal{M}^2_{S22} &= g^2 v^2 \cos\beta^2 + \mu \tan\beta (A_\lambda + \kappa s) \\
\mathcal{M}^2_{S33} &= \lambda A_\lambda \frac{v^2 \sin 2\beta}{2s} + \kappa s (A_\kappa + 4\kappa s) \\
\mathcal{M}^2_{S12} &= (\lambda^2 - g^2/2) v^2 \sin 2\beta - \lambda s (A_\lambda + \kappa s) \\
\mathcal{M}^2_{S13} &= \lambda v (2\lambda s \sin\beta - \cos\beta (A_\lambda + 2\kappa s)) \\
\mathcal{M}^2_{S23} &= \lambda v (2\lambda s \cos\beta - \sin\beta (A_\lambda + 2\kappa s))
\end{aligned} \tag{3}$$

$$\begin{aligned}
\mathcal{M}^2_{P11} &= \frac{2\lambda s}{\sin 2\beta}(A_\lambda + \kappa s) \\
\mathcal{M}^2_{P22} &= 2\lambda\kappa v^2 \sin 2\beta + \lambda A_\lambda \frac{v^2 \sin 2\beta}{2s} - 3\kappa A_\kappa s \\
\mathcal{M}^2_{P12} &= \lambda v (A_\lambda - 2\kappa s)
\end{aligned} \tag{4}$$

Parameter Scan of the NMSSM Low-m_a Region

To find the parameter space for our region of interest, $m_a < 2m_\tau$, we scan the NMSSM parameter space using the NMSSMTools package [26–28], applying all known phenomenological and experimental constraints except the following: the cosmological dark matter relic density measured by WMAP [29], direct $p\bar{p} \to h_1 \to aa \to 4\mu$ and 2μ, 2τ searches by the Tevatron [30], direct $e^+e^- \to Zh_1$, $h_1 \to aa$ searches by LEP [31, 32], and direct $\Upsilon \to \gamma a$ searches by CLEO [33] and BaBar [34]. These important constraints will be applied explicitly to our region of interest in a later section.

FIG. 2: (a): Non-singlet fraction of a_1 on a logarithmic scale: a_1 is nearly a pure singlet **for the entire parameter space**; (b): Singlet fraction of h_1 as a function of $\mu\kappa/\lambda$.

The scan was performed by sampling NMSSM model points uniformly in a six dimensional space determined by the following variables and ranges:

- 100 GeV $< \mu < 1000$ GeV
- $0 < \lambda < 1$
- $1.5 < \tan\beta < 50$
- -1 TeV $< A_\lambda < 5$ TeV
- $0 < \mu\kappa/\lambda < 120$ GeV
- -0.1 GeV $< (30$ GeV$)\lambda^2 - A_\kappa < 3$ GeV.

while the remaining parameters (entering the Higgs sector at loop-level) were fixed at $M_1/M_2/M_3 = 150/300/1000$ GeV, $A_t = A_b = A_\tau = 2.5$ TeV, $M_{f_L} = M_{f_L} = 1$ TeV. The first four scan parameters are conventional, broad ranges over the probable values of μ, λ, $\tan\beta$, and A_λ. We chose the fifth parameter of the scan equal to $\mu\kappa/\lambda = \kappa s$ since it is correlated with the mass of the CP-even higgs bosons as one can see in Fig. 1(a).

Generally, a_1 is light if the parameters of the model are near Peccei-Quinn (PQ) symmetry limit ($\kappa \to 0$) or/and near the R-symmetry (RS) limit ($A_\kappa, A_\lambda \to 0$). In both limits, a_1 is a massless axion, as it directly follows from Eq.(4). It can be decomposed in terms of the weak eigenstates H_{uI}, H_{dI} and S_I as (see e.g. [35]):

$$a_1 = c_{\theta_P} A + s_{\theta_P} S_I \tag{5}$$

where $A = \cos\beta H_{uI} + \sin\beta H_{dI}$. In the case of PQ limit mixing parameters $c_{\theta P}$, $s_{\theta P}$ are:

$$c_{\theta_P} = \frac{v \sin 2\beta}{\sqrt{v^2 \sin^2 2\beta + 4s^2}}, s_{\theta_P} = -\frac{2s}{\sqrt{v^2 \sin^2 2\beta + 4s^2}}. \tag{6}$$

In the case of RS limit, the same parameters are:

$$c_{\theta_P} = \frac{v \sin 2\beta}{\sqrt{v^2 \sin^2 2\beta + s^2}}, s_{\theta_P} = \frac{s}{\sqrt{v^2 \sin^2 2\beta + s^2}}. \tag{7}$$

Mass of a_1 is driven by $\mathcal{M}_{P22}$ element in Eq. (4). Using $m_{h1} \simeq 2\mu\kappa/\lambda$, that expression can be re-written as

$$\frac{2}{3}\frac{m_{a_1}^2}{m_{h_1}} \simeq \zeta\lambda^2 - A_\kappa, \text{ where } \zeta = \frac{v^2 \sin 2\beta}{3\mu}(2 + \frac{A_\lambda}{m_{h_1}}).$$

Therefore, a_1 is light if $(\zeta\lambda^2 - A_\kappa)$ is low, motivating the choice of the empirical parameter (30 GeV)$\lambda^2 - A_\kappa$ used in the scan. The range used in the scan for this parameter selects a region with a roughly uniform distribution of m_{a_1} between 0 and 30 GeV and avoids most of the theoretically inaccessible region with $\zeta\lambda^2 - A_\kappa < 0$ where $m_a^2 < 0$. **In this region A_κ is limited to be small which is motivated by RS limit, pushing a_1 to be light. (is this right and relevant? - Alexei)**

In the region of interest (small λ (???), A_λ (???) and A_κ), the mass of the lightest CP-even Higgs mass is determined by $\mathcal{M}_{S33} \simeq 2\kappa s = 2\mu\kappa/\lambda$, see Eq. 4. For $\mu\kappa/\lambda < 60$ GeV, h_1 is light with the mass $m_{h1} \simeq 2\mu\kappa/\lambda$ as illustrated in Fig. 1(a), and has a significant singlet component, particularly for smaller values of λ (and A_λ), which suppresses the doublet-singlet mixing. For $\mu\kappa/\lambda > 60$ GeV, $\mathcal{M}_{S33}$ defines the mass of the h_2 Higgs boson, which aquires a large singlet component, while h_1 becomes the SM-like Higgs with $m_{h_1} \simeq 120$ GeV. The upper bound on the scan parameter $\mu\kappa/\lambda < 120$ GeV was therefore chosen to create two equal size but phenomeologically distinct sub-regions.

FIG. 3: Reduced couplings of h_1 to up-type quarks (left), down-type quarks (middle), and vector bosons (right) as a function of $\mu\kappa/\lambda$, with the requirement that $m_a < 2m_\tau$. The red line presents the single-valued $\lambda \ll 1$ limit.

The couplings of h_1 and a to each other and to Standard Model particles, are determined by their singlet and non-singlet componets. The CP-odd a_1 is nearly a pure singlet in both PQ and RS limits because $s = \mu/\lambda \gg v \sin 2\beta$ so that $s_{\theta_P} \simeq 1$, see Eq.(6, 7). In fact, as shown in Fig.2(a), the non-singlet fraction $1 - s_{\theta_P}^2 \lesssim 10^{-4}$ for the entire region of interest. **Following bold text seems incomplete or out of context: Here we denote $\mathcal{S}_{13}$ as a**

mixing between the first (H_{dR}) and the third (S_R) CP-even Higgs boson weak eigensttaes. Increase of λ enhances the mixing of singlet and nonsinglet Higgs boson eigenstates for both, CP-odd and CP-even Higgses. (let us plot $\log(1 - s_{\theta_P})$ versus $log(v \sin 2\beta\lambda/\mu)$, where v =174 GeV) - SASHA

The singlet fraction of h_1 (parameter $\mathcal{S}_{13}^2$ in NMSSMTools) is primarily driven by $\mu\kappa/\lambda$ and λ, as illustrated in Fig. 2(b). In the small λ limit, h_1 is nearly a pure singlet in the $\mu\kappa/\lambda \lesssim 60$ GeV sub-region, while in the $\mu\kappa/\lambda \gtrsim 60$ GeV domain h_1 has negligible singlet component and is essentially the SM Higgs. Figure 3 shows strong suppression of reduced couplings of h_1 to up- and down-type quarks as well as vector bosons in the $\mu\kappa/\lambda \lesssim 60$ GeV domain. This suppression leads to a severe reduction in the production rates of h_1 at colliders making this scenario challenging for experimental exploration.

Experimentally important branching fractions of h_1 are determined by relative strength of the h_1 couplings to SM particles and the new, specific to MSSM, $h_1a_1a_1$ coupling. Because a_1 has a very high singlet fraction, the singlet/doublet content of h_1 has a strong effect on the strength of the $h_1h_1a_1$ coupling. If this was the only effect, $B(h_1 \to a_1a_1)$ would have been close to 100% in the lower half of the $\mu\kappa/\lambda$ domain and negligible in the upper half. However, this coupling is also proportional to λ (see Eq. 2), which creates a competing effect as larger values of λ smear the nearly perfect separation of singlet- and doublet-type h_1 in the lower and upper halfs of the $\mu\kappa/\lambda$ domain. The end result is illustrated in Fig. 4 showing average $B(h_1 \to a_1a_1)$ for NMSSM models with $m_a < 2m_\tau$ as a function of $\mu\kappa/\lambda$ and λ. It is evident that the suppression of h_1 SM couplings for $\mu\kappa/\lambda < 60$ GeV makes $B(h_1 \to a_1a_1)$ substantial as long as λ is not too small. For the upper part of the $\mu\kappa/\lambda$ domain, $B(h_1 \to a_1a_1)$ is small except only for large values of λ where the h_1 singlet fraction is enhanced.

FIG. 4: Branching fraction of $h_1 \to a_1a_1$ in the λ, $\mu\kappa/\lambda$ plane, with the requirement that $m_a < 2m_\tau$.

As the lightest Higgs boson, a_1 can only decay to SM particles. Coupling of nearly-singlet a_1 to all SM particles is strongly suppressed. This suppression is not universal in that the ratio of couplings of to up- and down-type quarks is about $1 - 3 \times 10^{-3}$ for the region of parameter space applicable to this study. As a result, a_1 branching fractions follow the standard mass hierarchy throughout our region of interest, except for a strong suppression of decays to the up-type quarks. **(I think we need to say if the lifetime is affected or not, this seems as an obvious question. Do we have partial widths for a_1? We just need any one channel).** Figure 5 shows the the branching fraction for $a \rightarrow \mu\mu$ as obtained using NMSSMTools package. For $m_a < 2m_\tau$ the $a \rightarrow \mu\mu$ channel becomes significant, making an analysis in the four muon mode viable for experimental searches.

FIG. 5: Branching fraction of $a_1 \rightarrow \mu\mu$ for generated models as a function of m_a. The red line is the average as a function of m_a, demonstrating that the branching fraction is nearly a strict function of mass. The threshold at 3.55 GeV is $2m_\tau$. When $m_a < 3m_\pi$ (the grey box), the branching fraction to $\mu\mu$ becomes nearly 100%.

It is important to note that the NMSSMTools calculation of $B(a \rightarrow \mu\mu)$ shown in Fig. 5 does not include hadronization effects important in the region $m_a < 1$ GeV/c^2, and therefore requires certain corrections. First, for $m_a < 3m_\pi$, $B(a \rightarrow \mu\mu)$ is expected to be very high because $q\bar{q}$ and gg decays are prohibited by hadronization and spin effects **need a reference?** and $\gamma\gamma$ is small **(the preprint with BR's says that in LH η does not couple to vector bosons, which makes $\gamma\gamma$ smaller, which may not be the case for us, it can explain the difference in BR below)**. As for the NMSSMTools prediction for $m_a > 0.5$ GeV/c^2, we compared it with another calculation [44] performed in the context of the Little Higgs model. The two calculations cannot be compared directly because the $c\bar{c}$ decay becomes dominant for $m_\eta >$2.5 GeV/c^2 in the Little Higgs case, while it is strongly suppressed in NMSSM. If corrected for this difference, calculation in [44] seems to predict $B(a_1 \rightarrow \mu\mu)$ of the order of 27% instead of slightly under 20% by NMSSMTools and have a similar shape. **(We should explain what was wrong in the recent paper by DZero in using an incorrect $B(a \rightarrow \mu\mu)$. I am not sure here, Jim, could you draft the text?)**. For our numeric estimations, we choose to follow the NMSSMTools calculations shown in Fig. 5, but all results can be easily corrected if a different calculation becomes available.

Cosmological Constraints

Lighest NMSSM neutralino becomes the candidate for the Cold Dark Matter (CDM). WMAP measurement of the CDM relic density therefore serves as an important constraint on the allowed NMSSM parameter space. In our scan, we used the MicrOmegas package [43] linked to the NMSSMTools to calculate Ω_{NMSSM} to determine if a particular model is consistent with the experimental data. We considered a model to be consistent with the CDM measurement

FIG. 6: Sampled points with $m_a < 2m_\tau$ and experimental constraints successively applied in λ vs. $\mu\kappa/\lambda$ space. Note that the low energy e^+e^- data (CLEO and BaBar) have essentially no impact on the allowed parameter space. Color scale is number density and filled points are 100 models (before application of experimental constraints).

FIG. 7: Sampled points with $m_a < 2m_\tau$ and experimental constraints successively applied similar to Fig. 6 but in m_a vs. m_h space. Note that the low energy e^+e^- data (CLEO and BaBar) have essentially no impact on the allowed parameter space. Color scale is number density and filled points are 100 models (before application of experimental constraints).

if $\Omega_{NMSSM} \leq 0.1099 + 2 \times 0.0062$, which corresponds to the 95% upper limit obtained using the latest WMAP 5-year dataset [**ref**].

To illustrate the effect of WMAP constraints, Fig 6(a) shows the density of generated NMSSM models in the λ versus $\mu\kappa/\lambda$ space under the constraint $m_{a_1} < 2m_\tau$. Models that were determined to be consistent with the WMAP data are shown in Fig. 6(b). The comparison shows that the WMAP bound excludes the region of small $\mu\kappa/\lambda$ and λ. In that region, the lightest neutralino is light and weakly interacts with SM particles. That suppresses neutralino annihilation rate enhancing the neutralino relic density to unacceptably large values. Figures 7(a) and (b) make the same comparison but in the m_{a_1} versus m_{h_1} plane.

Constraints from Direct Searches at Colliders

Several searches for NMSSM have been performed at collider experiments. The strongest impact on the allowed NMSSM models comes from the LEP data. Although the large singlet component of h_1 at low $\mu\kappa/\lambda$ (and correspondingly low m_{h_1}) strongly suppresses h_1 production at LEP, relevant scenarios surviving WMAP constraints typically have sufficiently large λ, which enhances the doublet component of h_1 to the level sufficient to exclude $h_1 \rightarrow aa$ within the kinematic limits of $e^+e^- \rightarrow Zh_1$, $45 < m_{h_1} < 86$ GeV, and the detector efficiency for light CP-odd Higgs bosons, $m_a > 2$ GeV [ref]. In addition to LEP data, there have been several recent attempts aimed at direct searches at colliders. Searches at lower energy e^+e^- colliders [40, 41] have been focusing on searching for the CP-odd Higgs via $\Upsilon \rightarrow \gamma a_1$ followed by the decay of a_1 to muons. Neither of these searches constrain the NMSSM models with low m_a because the high singlet component of a_1 (see Fig. 2(a)) leads to negligible bba_1 coupling thus precluding production of a_1 at the low energy e^+e^- colliders. Because CLEO and BaBar results have no effect on the allowed parameter space, Figs. 6(c) and 7(c) show combined LEP+CLEO+BaBar constraints, but the reader is reminded that only LEP constraints are important.

Results of a search [42] for NMSSM with a low mass a_1 at the Tevatron was recently published by the $D\O$ experiment in the channel $h_1{\to}a_1a_1{\to}\mu\mu\mu\mu$. With no excess of data over the SM expectations, the paper quotes 95% C.L. upper limits for the cross-section of this process. To interpret the $D\O$ result in terms of constraints on allowed NMSSM models in our scan, we calculate the NLO production cross-section for $p\bar{p}{\to}h_1$ in NMSSM using the SM NLO calculations for $gg{\to}H_{SM}$ [36] and $b\bar{b}{\to}H_{SM}$ with QCD-improved (running) Yukawa couplings [38] corrected for differences in coupling between SM and NMSSM using the NMSSMTools:

$$\begin{aligned}\sigma(gg{\to}h_1) &= \sigma(gg{\to}H_{SM})\frac{\Gamma(h_1{\to}gg)}{\Gamma(H_{SM}{\to}gg)} \qquad (8)\\ &= \sigma(gg{\to}H_{SM})\frac{Br(h_1{\to}gg)\Gamma^{tot}(h_1)}{\Gamma(H_{SM}{\to}gg)}\\ \sigma(b\bar{b}{\to}h_1) &= \sigma(b\bar{b}{\to}H_{SM})\left(\frac{Y_{bbh_1}}{Y_{bbH_{SM}}}\right)^2 \qquad (9)\end{aligned}$$

where $\sigma(gg{\to}H_{SM})$ and $\Gamma(H_{SM}{\to}gg)$ is calculated using HIGLU, while $Br(h_1{\to}gg)$, $\Gamma^{tot}(h_1)$, and the ratio of Yukawa couplings $Y_{bbh_1}/Y_{bbH_{SM}}$ are obtained using NMSSMTools. It turns out that for $\mu\kappa/\lambda < 60$ (non-SM h_1 lighter than 120 GeV), the cross-section is strongly suppressed even compared to SM for low m_a because h_1 has a large singlet fraction and weakly couples to SM partciles (see Fig. 3). For larger $\mu\kappa/\lambda$ the lighest CP-even higgs h_1 becomes the SM-like Higgs and has small $h_1{\to}aa$ branching.

The paper [42] quotes the 95% C.L. limits on $\sigma(p\bar{p}{\to}h_1) \times B_{h_1\to aa\to\mu\mu\mu\mu}$ for several choices of m_{a_1} calculated for m_{h_1} = 100 GeV/c^2. To determine if a particular model in our scan is excluded by data, we linearly interpolate the published cross-section limits for values of m_{a_1} between the points in [42]. To obtain the experimental cross-section limits as a function of m_{h_1}, we need to correct for the variations in experimental acceptance. We obtain those limits by taking the analysis acceptance to be linear versus m_{h_1} "increasing by ∼10% when m_{h_1} increases from 80 to 150 GeV" [42] and matching it to the full analysis acceptance given at m_{h_1} = 100 GeV/c^2. We then calculate the production cross-section and branching ratios for the model points and compare it to the value we derived from [42]. Figures 6(d) and 7(d) show the density of NMSSM models surviving WMAP, LEP and Tevatron constraints. Because

FIG. 8: 14 TeV production cross-section of h_1 as a function of $\mu\kappa/\lambda$ and λ, from gg (left) and $b\bar{b}$ (right), with the requirement that $m_a < 2m_\tau$. The red line represents the single-valued $\lambda \ll 1$ limit.

of the suppression in the production rate at lower $\mu\kappa/\lambda$ and small $B(h_1 \to a_1 a_1)$ at high $\mu\kappa/\lambda$, the Tevatron search has only a limited impact on the allowed NMSSM parameter space, mainly constraining models with high λ. A significant improvement in Tevatron reach for NMSSM would require a large increase in integrated luminosity likely leaving it up to the LHC to make a definitive discovery or exclusion of NMSSM models with low m_a.

Summary

Existing experimental data provides important constraints on the NMSSM parameter space for models with low m_{a_1}. Particularly, WMAP data excludes many models with very low λ, particularly in the lower part of the $\mu\kappa/\lambda$ range. These scenarios are difficult for collider searches due to a large suprpession in cross-section production in the low $\mu\kappa/\lambda$ domain and and small brnaching fraction $B(h_1 \to a_1 a_1$ for larger $\mu\kappa/\lambda$. Nevertheless, LEP data allows nearly complete exclusion of models with low $\mu\kappa/\lambda$ (light m_{h_1}) and $m_{a_1} > 2$ GeV/c^2. Tevatron data further excludes a fraction of models with large λ. CLEO and BaBar data have little if any effect on these NMSSM models as direct production for a_1 is extremely suppressed due to its high singlet component. A large fraction of the parameter space still survives all these constraints leaving it up to the LHC to either discover or exclude these models. Conclusive exclusion or discovery of new physics in this scenario would require a dedicated analysis performed at LHC. In the following, we propose the outline of such analysis and estimate its sensitivity.

A DEDICATED SEARCH FOR THE LOW m_{a_1} NMSSM AT THE LHC

Because a_1 is dominated by the singlet component, it can only be produced at the LHC via decays of light Higgs $h_1 \to a_1 a_1$. The main characteristic of such signal at the LHC is two back-to-back (in ϕ) di-muon pairs with pairs consisting of spatially close muons. The di-muon pairs, if reconstructed, should have invariant masses consistent with each other and also serves as a direct measurement of m_a. Additionally, the four muon invariant mass distribution should have a narrow spike corresponding to the m_h mass. We use these striking features of signal events in designing the analysis suitable for early LHC running.

Experimentally, the four muon final state considered in this analysis is a very clean signature with relatively low backgrounds. Therefore, instead of using the Vector Boson Fusion (VBF) chosen in earlier NMSSM searches targeting the $m_a > 2m_\tau$ region **[ref]**, we focus on the largest Higgs production modes at the LHC, $gg \to h_1$ and $b\bar{b} \to h_1$. We calculate the NLO cross-section for $pp \to h_1$ for NMSSM by rescaling the LHC SM NLO calculations [36, 38] to correct for differences in couplings between SM and NMSSM (Eqs. 9 and 9). Similar to the Tevatron case, the cross-section is strongly suppressed compared to SM if h_1 has a large singlet fraction. Figure 8 shows the production cross-section for 14 TeV $pp \to h_1 + X$ as a function of $\mu\kappa/\lambda$. While this large suppression makes this analysis challenging even at the LHC, the constraints arising from the WMAP relic density measurement exclude models with very low values of λ, so that the allowed models have small but not negligible production cross-section.

Analysis Selections

We use Pythia to generate signal event templates with m_h in the range from 70 to 140 GeV/c^2 and m_a in the range from 0.5 to 4 GeV/c^2. We chose the CMS detector as a benchmark for modeling a realistic experimental environment and use parameters described in **[ref CMS TDR**. The key parameters important for this analysis are muon momentum resolution, low threshold on muons to reach the muon system, acceptance and the average muon reconstruction efficiencies. Because of the large number of reconstructed muons in the event, we take the trigger efficiency to be 100%.

FIG. 9: Acceptance as a function of m_a for fixed m_h. Acceptance as a function of m_h for fixed m_a.

The analysis starts by requiring at least four muon candidates with $p_T > 5$ GeV/c in the fiducial volume of the detector $|\eta| < 2.4$, of which at least one has to have $p_T > 20$ GeV/c to suppress major backgrounds and to satisfy trigger requirements. Each event must have at least two muon candidates of positive and negative charge each. For surviving events, we define quadruplets of candidates consisting of two positive and two negatively charged muon candidates. Next, we sort the four muon candidates in quadruplet into two di-muon pairs by minimizing the quantity

$(\Delta R(\mu_i, \mu_j)^2 + \Delta R(\mu_k, \mu_l)^2)$, where $\Delta R^2 = \Delta\eta^2 + \Delta\phi^2$, under the constarint that each di-muon pair consists of two muon candidates of opposite charge. Muon quadruplets, for which ΔR between muons in any of the two pair exceeds 0.5, are discarded as inconsistent with signal topology. Acceptance for the selections listed above is shown in Fig. 9 for several representative choices of values for m_h and m_a.

The requirement of four sufficiently energetic muons in the event drastically reduces contributions of potential backgrounds for this analysis. After acceptance selections, the dominant background is due to the QCD multijet production where muons originate from either heavy flavor quark decays or from K/π decays in flight. We use Pythia to estimate the QCD multijet background and we estimate it at this stage to be approximately 2.6 events/pb^{-1} (approximately half due to true muons and the rest from events with both prompt muons and muons from decays in flight). We also considered electroweak backgrounds estimated using CompHEP **[ref]** $pp \to 4l + X$ process to be 0.04 events/pb^{-1} and direct J/psi production (Pythia), which was found to be completely negligible. Other SM backgrounds (top, W+jets) are negligible in the region of interest of this analysis.

The backgrounds are further reduced by applying kinematics requirements consistent with the expected signal siganture. We calculate invariant mass of each of the di-muon pair, m_{12} and m_{34}, as well as the invariant mass of all four muons denoted as M. Figure 10a) shows the invariant mass of the muon pairs passing all selections in signal events for two choices of m_h and m_a. Figure 10b) shows the distribution of the invariant mass M of the four muon system for two benchmark points. To focus on the region of interest, we require $M > 60$ GeV/c^2, $m_{12}, m_{34} < 4$ GeV/c^2, which reduces the QCD background to 0.4 events/pb^{-1}.

FIG. 10: Left: Reconstructed invariant mass of reconstructed muon pairs for $m_a = 0.5$ and 3 GeV/c^2 (in both cases $m_H = 100$ GeV/c^2). Right: Reconstructed invariant of four muons for $m_H = 80$ and $m_H = 120$ GeV/c^2 (in both cases $m_a = 3.0$ GeV).

To ensure the compatibility of the measured invariant masses of the two di-muon pairs, one could require $|m_{12} - m_{34}| < 0.08 + 0.005 * (m_{12} + m_{34})$. Such cut would enforce the requirement that the two pair masses are consistent with each other and takes into account widening of the absolute resolution in the reconstructed di-muon mass as a function of mass. If applied, the only background that still may be not completely negligible is the QCD multi-jet production,

TABLE I: Expected rate of background events per 100 pb^{-1} of luminosity after the selection cuts.

for which we conservatively estimate the upper bound to be 0.02 events/pb^{-1}. However, instead of applying this selection explicitly, a better approach would be to fit the data in the 3D space of measured values of $(m_{12}, m_{34}, m_{1234})$ taking into account kinematical properties of signal events. This approach allows maximizing signal acceptance and therefore statistical power of the analysis. It is also convenient from experimental standpoint as the background events are distributed in a smooth fashion over the 3D space allowing fitting the 3D distribution to estimate backgrounds directly from the data. Potential signal would appear as a concentration of events in one specific region in the 3D space (a 3D "bump"). We use a binned likelihood defined as a function of parameters m_a, m_h and effective signal cross section $\sigma \times B(h \rightarrow aa) B^2(a \rightarrow \mu\mu)$. Thus defined likelihood is used to fit pseudodata generated using either background or signal+background templates. We estimate sensitivity of the proposed analysis and present it in terms of the 95% C.L. exclusion levels for signal cross-section using Bayesian technique.

Our estimations show that for an early data search ($L \simeq 100$ pb^{-1}), the backgrounds are negligibe. For analysis with higher luminosity, one can return back to the zero background situation by adding the isolation requirement to one or both of the di-muon pairs in the event. Isolation can be defined by either setting the upper bound on the sum of transverse momenta of all tracks in a cone around the reconstructed direction of the di-muon pair excluding momenta of the two muon tracks, or by rejecting pairs with additional tracks above a certain threshold. For our projections for an analysis with $L = 1$ fb^{-1}, we required no charged tracks with momentum $p_T > 1$ GeV in the cone of $\Delta R = \sqrt{(\Delta\eta)^2 + \Delta\phi)^2} = 0.3$ around the direction of at least one of the two muon pairs. This requirement is 96% efficient for signal and reduces QCD multijet background, dominated by events with muons originating from heavy flavor jets, by a factor of 6-7. For high luminosity datasets, isolation can be further tightened to increase background suppression with only a moderate loss in signal efficiency.

Results

We calculate the 95% C.L. upper limit on the product $\sigma(pp \to h) B_{h\to aa} B^2_{a\to\mu\mu}\,\alpha$, using Bayesian technique. Because this is a zero background case, the upper limit on signal corresponds to approximately three reconstructed signal events. The limit is 0.0293 pb for $L = 100$ pb^{-1}, and scales linearly with the luminosity as long as the number of observed background events remains zero. In the vast majority of pseudoexperiments, this limit is independent of m_h and m_a because the effective signal region that dominates signal significance in the fitter is essentially background free and probability to observe any pseudodata event is very small. Note that the corresponding projection for $L = 1$ fb^{-1} includes the isolation cut, slightly reducing signal efficiency and correspondingly loosening the limit. The upper limit on $\sigma(pp \to h) B_{h\to aa}$ is shown as a function of m_h and m_a in Table II. **Note that $B_{h\to aa}$ is close to 100% in much of the selected region of NMSSM parameter space.???**

TABLE II: Top: 95% C.L. upper limit on $\sigma(pp \to h) \times B_{h\to aa\to 4\mu}$ (fb) at the LHC with $L = 100$ pb^{-1} (no isolation used); Bottom: the same limit assuming $L = 1$ fb^{-1} of data (includes isolation). Tightening of the limit towards higher m_h is due to increase in acceptance with m_h.

FIG. 11: Sampled models excluded by the Tevatron and LHC (with $m_a < 2m_\tau$, WMAP, and LEP constraints applied in all cases). With only 100 pb^{-1}, the LHC's reach extends beyond that of the Tevatron.

RESULTS

TO BE WRITTEN

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