Dilepton Mass Endpoint in the NMSSM

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NMSSM scenarios are investigated to explain an excess in the opposite-sign dilepton mass distribution in events with dilepton, jets and missing transverse energy reported by the CMS experiment. We show that the NMSSM scenarios can possess unique features to explain this excess, and can be distinguished from the MSSM scenarios in the ongoing LHC runs as well as direct detection experiments.

I. INTRODUCTION

Recently, CMS reported of an excess of lepton pairs \cite{1} with energy below the $Z$ mass, in a final state of $l^+l^−jj + \not{E}_T$ where $\not{E}_T$ denotes the missing transverse energy. Beyond the the Standard Model (BSM) theoretical attempts have been made to account for such an excess in the context of the Minimal Supersymmetric Standard Model (MSSM) \cite{2,3} using cascade decays from the sbottom pair production at the LHC, a leptoquark scenario \cite{4} and superstring inspired models \cite{5}, where the cascade decay of new particle states give rise to a pair of leptons, two associated jets, and new invisible particles that escape the detector as $\not{E}_T$.

Two same-flavor, opposite-sign leptons can be produced from a cascade decay that has particles decay into leptons in the intermediate state during the process. Such lepton partners and heavier states, which give rise to the cascades, are readily available in supersymmetric models. The sbottom pair production and its cascade decays into the next to lightest neutralino which subsequently decays into two leptons and the lightest neutralino via an intermediate slepton state is a very interesting option to explain the excess. Two $b$ jets are also produced along with $l^+l^− + \not{E}_T$ in the final states. The existence of two $b$ jets in the signal provides an interesting prediction arising from this scenario which will be checked in Run II. Prior to this new result, $l^+l^−jj + \not{E}_T$ was considered as a possible final state from the stop decay \cite{6}. Since we have $\tilde{t} \rightarrow t + \tilde{\chi}^0_2$, we expect lepton(s) from top decay in addition to $\tilde{\chi}^0_2 \rightarrow l^+l^-\tilde{\chi}^0_1$. This doesn’t support the CMS edge paper. In this paper we focus on a well motivated Next-to Minimal Supersymmetric Standard Model \cite{7} (NMSSM), which introduces an additional singlet superfield into the MSSM. The observed Higgs mass at the LHC \cite{8} can be accommodated naturally if the coupling $\lambda$ between the singlet and the supersymmetric Higgs fields is large and this new term also provides a solution to the $\mu$ problem of the MSSM (see \cite{9} and references therein). Recently, signals of such a scenario at the LHC were investigated and possible ways to distinguish from the MSSM were also discussed \cite{10}.

The singlet superfield in the NMSSM gives rise to a new neutralino (singlino) to the gaugino sector, besides other modification on the MSSM particle spectrum. This paper investigates the effect of the singlino that creates more freedom to realize the aforementioned cascade decays of sbottom, which alleviates a relatively tight requirement on the MSSM gaugino mixings. Further, since the neutralino sector is modified the NMSSM explanation will be associated with distinguishable predictions. The cascade process to explain the endpoint in the context of the NMSSM is discussed in Section III. A collider analysis is carried out in Section IV that examines the NMSSM’s explanation of the CMS dilepton excess. We discuss our results and conclude in Section V.

II. SQUARK-NEUTRALINO CASCADES

The CMS excess in the relatively low energy ‘endpoint’ in opposite sign dileptons can rise from the cascade decays of one or more next-to-lightest supersymmetric particles (NLSPs) in the supersymmetric neutralino sector, where the second lightest neutralino can decay via a two-step process,

$$\tilde{\chi}^0_2 \rightarrow l^+l^−, \quad l^- \rightarrow l^−\tilde{\chi}^0_1. \quad (1)$$

that yields a pair of leptons of the same flavor, whose total energy distribution is limited by the mass difference
$M_{\chi_2^0} - M_{\chi_1^0}$ ($\tilde{t}$ denotes both left and right sleptons of the first two lepton flavors). Thus a neutralino spectrum with $M_{\chi_2^0} \sim M_{\chi_1^0} + 70$ GeV can lead to such a dilepton excess if the slepton masses lie between the two neutralino masses and if the second neutralino can be produced at adequate rates.

The QCD-dominated production of sbottom\(^1\) can lead to the correct pair-production rates for the CMS experiment. A mostly right-handed sbottom (denoted by $\tilde{b}_1$ here) can be a perfect candidate [1] that decays into the required neutralinos. The Feynman diagram for the production process is illustrated in Fig. [1]. The sbottom is preferably right-handed as it does not require a left-handed stop to be equally light in mass. Moreover, the CMS non-observation of more than two leptons in this channel puts a constraint on the decay of such a sbottom, i.e., the branching fraction, $BF(\tilde{b}_1 \to \chi_1^0 b)$, should dominate over $BF(\tilde{b}_1 \to \chi_1^0 \bar{b})$ unless the latter produces many lepton pairs in a final state from the pair of sleptons. This requirement, however, may force certain relations among the neutralino mixings.

In the MSSM, a sbottom can decay into a $b$ quark and a neutralino via either the $U(1)_Y$ gauge coupling or the Yukawa coupling. The $U(1)_Y$ gauge coupling depends on the Bino ($\tilde{B}$) component of the daughter neutralino, while the Yukawa coupling depends on the down-type Higgsino ($\tilde{H}_d$) component and the size of the coupling $y_d$. Since the MSSM’s LSP needs to be dominantly Bino to avoid increasingly severe experimental constraints (from indirect [11, 12] and direct [13] detections). However, the Bino content of the LSP would dictate the sbottom decay (by a few orders of magnitude) and leaves with small $B$ for $\chi_2^0$ for the $\tilde{b}_1 \to \chi_2^0 b$ decay when $M_{\chi_2^0} - M_{\chi_1^0} \approx 70$ GeV.

The BF to $\tilde{b}_1 \to \chi_2^0 b$ can be increased when $\tan \beta$ is large which causes larger Yukawa coupling contribution [2].

In the NMSSM, however, the option of a singlino LSP opens up alternative gaugino mixing scenarios to realize sbottom decays into both $\chi_1^0$ and $\chi_2^0$ in a suitable way, which differ from the MSSM. Consequently, the collider signals arising from the direct production of gauginos will be helpful to discern MSSM from NMSSM.

(A) We can satisfy the CMS excess for mostly singlino LSP and a heavy Bino. The components of $\tilde{B}$ in both $\chi_1^0, \chi_2^0$ are small but comparable in magnitude for heavier $\tilde{B}$. This allows a small $\tan \beta$ scheme where both $\tilde{b}_1 \to \chi_1^0 b, \chi_2^0 b$ decays occur via the $U(1)_Y$ coupling, while the down-type Yukawa contribution to the decays is small.

The NLSP can be wino and/or Higgsino. A wino-NLSP case is shown in Table I. In comparison, when the NLSP is mainly Higgsino, $\chi_3^0$ would be relatively light and the sbottom may decay into two NLSPs. However, the Higgsino-NLSP case tends to allow the LSP to have a larger Higgsino mixing which faces constraint from the direct detection result unless we chose the correct sign of gaugino, Higgsino mass parameters to cancel the Higgs contribution in the direct detection amplitude [14].

| Point | $M_1$ | $M_2$ | $\tan \beta$ | $\lambda$ | $\kappa$ | $\mu_{\text{eff}}$ | $M_{\chi_1^0}$ | $M_{\chi_2^0}$ | $M_{\chi_3^0}$ | $M_{\chi_1^+} + M_{\chi_1^0}$ |
|-------|-------|-------|---------------|--------|--------|-------------------|--------------|--------------|-------------|----------------------|
| A     | 600   | 10    | 4.0           | 0.7    | 0.11   | 0.44              | 250          | 320          | 373         | 315 + 285           |
| B     | 248   | 15    | 0.5           | 0.57   | 0.12   | 0.36              | 230          | 300          | 357         | 333 + 265           |
| C     | 310   | 10    | 0.6           | 0.14   | 0.13   | 0.44              | 229          | 305          | 357         | 500 + 850           |

TABLE I: The NMSSM benchmark points that yield same-flavor opposite-sign lepton pairs in sbottom cascade decays. The mass spectrum is evaluated using NMSSMTools [13] and its values are given in GeV. $\tilde{t}$ denotes both both left and right sleptons of the first two lepton flavors.

(B) We can satisfy the CMS excess for mostly Bino type $\chi_2^0$, where $\chi_2^0$ is mostly singlino and $\chi_3^0, \chi_4^0$ consist of mostly Higgsinos and Wino. Just like the MSSM, a large $\tan \beta$ is required to boost the decay via down-type Yukawa coupling to the $H_d$ component in $\chi_2^0$, which is closer in mass to the Higgsinos in comparison to the much lighter $\chi_1^0$. The major difference of this scenario from the MSSM is that the lightest chargino $\chi_1^+$ mass is close to $\chi_2^0$ rather than $\chi_2^0$, and consequently can be heavier than that of the MSSM. This allows a wider mass range of the sbottom after satisfying $M_{\chi_1^0} - M_{\chi_1^+} < M_1$ so that $\tilde{b}_1$ does not decay into top quarks.

(C) We can also satisfy the CMS excess for a mostly singlino type $\chi_1^0$ where $\chi_2^0$ is mostly Bino. Since $\chi_2^0$ is mostly Bino, $BF(\tilde{b}_1 \to \chi_2^0 b)$ is large and yields a large number of final state leptons via sleptons situated in between the two neutralinos which may not be a suitable option. A virtual slepton mediated three-body decay $\{\chi_2^0 \to l^+_l l^- \chi_3^0, l^+_l l^- \to l^- \chi_3^0\}$, however, can give the correct $2l + E_T$ rate. This parameter space is represented by point C which shows that the slepton masses are much higher than the $\chi_1^0, \chi_2^0$ mass range, e.g., the slepton masses are almost at TeV scale for point C. It is interesting to note that even if we imagine a scenario where the slepton masses are very close to each other $\chi_2^0$ or $\chi_3^0$, and only one of the leptons from each sbottom cascade is visible, the invariant mass of the two leptons from different cascades can easily be more than 70 GeV and contradicts with observation.

III. COLLIDER SIGNAL

Here we discuss the dilepton yield from the NMSSM benchmark points at the 8 TeV LHC. At each point, a mass gap is kept at 70 GeV between the two lightest neutralinos that limits the energy of the lepton pair. $\chi_3^0$ is above $\tilde{b}_1$ and all sfermions other than $\tilde{l}$ and $\tilde{b}_1$ have multi-

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1 The dilepton mass endpoint can also be produced from the decay of a light stop, but when stop is pair produced we also expect to see multilepton final state and the non-observation of more than two leptons along with 2 jet and $E_T$ makes this scenario not preferred.
We generate inclusive sbottom pair production events with 0-2 associated jets at 8 TeV in MadGraph5 v2.2.2 [16] with CTEQ6.6 [17] parton distribution functions. Pythia v6.426 [18] is used for showering and hadronization and PGS4 [19] is used for detector simulation in which the electron and muon detection efficiencies are assumed to be 92% and 98%, respectively. To avoid double-counting of jets the MLM jet matching scheme [20] is implemented.

The LO production cross section $\sigma_{\text{LO}} \approx 500$ fb for sbottom with approximately 360 GeV mass. This is scaled up by a K-factor of 1.7 to the NLO value that is obtained from the package Prospino [21]. The dilepton signal rate is then,

$$ (20 \text{ fb}^{-1}) \cdot \sigma_{\text{NLO}} \cdot A_{\text{eff}}, $$

where $A_{\text{eff}}$ denotes the total event selection acceptance. The selection criteria for the jet and lepton objects are as follows: $p_T(\text{jet}) > 40$ GeV with $|\eta| < 3$, $p_T(\text{lepton}) > 20$ GeV with $|\eta| < 2.4$, excluding $1.4 < |\eta| < 1.6$; the central region is defined as $|\eta| < 1.4$.

\[ \begin{array}{c|c|c|c|c} \hline \text{BF}_{\tilde{b} \to \tilde{\chi}_1^0 b}, \text{BF}_{\tilde{b} \to \tilde{\chi}_2^0 b}, \text{BF}_{\tilde{b} \to \tilde{\chi}_1^0 t \tilde{\chi}_1^0}, \epsilon_{ll} \tabularnewline \hline A & 69\% & 31\% & 25\% & 38\% \\
B & 90\% & 10\% & 57\% & 38\% \\
C & 10\% & 89\% & 11\% & 26\% \\
\hline \end{array} \]

TABLE II: $\tilde{b}$ decay branching fractions and the dilepton selection efficiencies for the benchmark points. $\epsilon_{ll}$ is given in Eq. (2) $\text{BF}_{\tilde{b} \to \tilde{\chi}_2^0 t \tilde{\chi}_1^0}$ for point C in column 4 should read as $\text{BF}_{\tilde{b} \to \tilde{\chi}_2^0 t \tilde{\chi}_1^0}$.  

We find that point C shows lower efficiency at this stage compared to points A and B. This is due to the fact that $\tilde{b}$ has a larger branching ratio into $\tilde{b} \rightarrow b + \tilde{\chi}_1^0$ for points A and B where $\tilde{\chi}_1^0$ is mostly Bino compared to the point C where $\chi_1^0$ is mostly singlino. A large mass gap ($\sim 120$ GeV) between $\tilde{b}$ and $\chi_1^0$ causes the existence of more higher $p_T$ jets for points A and B. On the other hand, for point C, $\tilde{b}$ has larger branching ratio into $b + \tilde{\chi}_2^0$ and a smaller mass gap ($\sim 50$ GeV) between $\tilde{b}$ and $\chi_2^0$. The fraction of isolated leptons is a combination of the $b, \chi_2^0$ decay branching fractions and dilepton selection efficiency $\epsilon_{ll}$.

$$ 2 \cdot x(1-x) \epsilon_{ll}, $$

$$ x \equiv \text{BF}(\tilde{b} \rightarrow \tilde{\chi}_1^0 b) \cdot \text{BF}(\tilde{\chi}_2^0 \rightarrow ll). \quad (3) $$

$\epsilon_{ll}$ is a fraction of events with at least two reconstructed OSSF leptons passing the lepton selection criteria out of the events with two OSSF leptons from the $\chi_2^0$ decays. In principle, $\epsilon_{ll}$ can vary with the lepton energy that is determined by the mass difference between the sleptons and neutralinos. At points A and B, when $M_T \sim (M_{\chi_1^0} + M_{\chi_2^0})/2$ with both leptons at $E_l = 35$ GeV, we get maximal acceptance of $\epsilon_{ll} \approx 38\%$. At point C the leptons arise from a three body decay and the energy partition becomes uneven, and the acceptance can suffer if one of the leptons is too soft. The lepton pairs are further required to be in the central region with pseudorapidity $|\eta| < 1.4$, and finally the overall acceptance gives the accumulated selection efficiency.

At all three benchmark points, a dilepton signal of around 120 events are obtained. The dilepton mass distributions for points A and B are similar, and they both show a clear dilepton invariant mass endpoint at $M_{\tilde{\chi}_1^0} - M_{\tilde{\chi}_2^0}$ as each of two leptons has a fixed 35 GeV energy, where the invariant mass of the dilepton maximizes. The endpoint for point C is less pronounced due to the possible unequal energy between the two leptons in the three body decay of $\tilde{\chi}_1^0$. In Fig. 2 we show the dis-

| Event selection | Relative Efficiency |
|-----------------|---------------------|
| $N_T \geq 2(3) + E_T > 150(100)$ GeV | 32% 37% 25% |
| Two isolated OSSF leptons | 3.2% 2.3% 3.2% |
| Dileptons in the central region | 85% 85% 84% |
| Overall acceptance | 0.85% 0.72% 0.66% |

TABLE III: The selection efficiencies for the $l^+l^-jj + E_T$ signal at benchmark points A, B and C.
In conclusion, if the CMS excess is proved to be correct at the ongoing run of the LHC, it will be possible to find an explanation in the context of NMSSM, which
is not ruled out by the direct detection experiments and with unique features in the neutralino sector compared to the MSSM. It will be feasible to establish these NMSSM scenarios by investigating the direct productions of neutralinos, charginos and sleptons.

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