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CMS kinematic edge from sbottoms

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We present two scenarios in the Minimal Supersymmetric Extension of the Standard Model (MSSM) that can lead to an explanation of the excess in the invariant mass distribution of two opposite charged, same flavor leptons, and the corresponding edge at an energy of about 78 GeV, recently reported by the CMS Collaboration. In both scenarios, sbottoms are pair produced, and decay to neutralinos and a b-jet. The heavier neutralinos further decay to a pair of leptons and the lightest neutralino through on-shell sleptons or off-shell neutral gauge bosons. These scenarios are consistent with the current limits on the sbottoms, neutralinos, and sleptons. Assuming that the lightest neutralino is stable we discuss the predicted relic density as well as the implications for dark matter direct detection. We show that consistency between the predicted and the measured value of the muon anomalous magnetic moment may be obtained in both scenarios. Finally, we define the signatures of these models that may be tested at the 13 TeV run of the LHC.

I. INTRODUCTION

After the Higgs discovery [1,2], the main goal of the LHC experiments is the search for new physics at the TeV scale. Current searches at the 8 TeV LHC have provided no evidence of new physics beyond the Standard Model (SM). There are, however, some intriguing signatures that may hint at the presence of new physics. For instance, in a recent analysis of the invariant mass distribution of two opposite charged, same flavor (SFOS) leptons [3], CMS has reported an intriguing excess of events with respect to the ones expected in the SM. In this search CMS looks for two isolated lepton final states using the 8 TeV data set with an integrated luminosity of 19.4 fb^{-1}. Events with SFOS leptons are selected (e^+e^- or $\mu^+\mu^-$) with both leptons having transverse momentum $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.4$. CMS sets additional requirements on jets and missing energy, and selects events with a number of jets $N_{\text{jets}} \geq 2$ and missing transverse energy $E_T^{\text{miss}} > 150$ GeV or $N_{\text{jets}} \geq 3$ and $E_T^{\text{miss}} > 100$ GeV. The jets are required to have $p_T > 40$ GeV and $|\eta| < 3.0$. The selected events are separated into a central signal region, where both leptons satisfy $|\eta| < 1.4$, and a forward region, where at least one lepton satisfies $1.6 < |\eta| < 2.4$. Then CMS performs a search for an edge in the invariant mass (m_{ll}) distributions by fitting the signal and background hypothesis to data in the range of 20 GeV $< m_{ll} < 300$ GeV. The best fit to the SFOS event distribution is obtained for an edge at an energy of 78.7 ± 1.4 GeV. An alternative search is done by a counting experiment, without any assumption of the signal and background shape. The counting experiment is performed in the mass range of $20 < m_{ll} < 70$ GeV, and an excess of 130^{+48}_{-49} events are seen in the central region, corresponding to a local significance of 2.6σ.

In this article, we shall interpret the presence of this edge as a signature of the production of third generation supersymmetric particles at the LHC.[1] Supersymmetry is an attractive framework [5–7] that leads to the unification of couplings at high scales and provides dark matter candidates in terms of the superpartners of the neutral Higgs and gauge bosons. Moreover, for supersymmetric particle masses of the order of the TeV scale, low energy supersymmetry leads to the radiative breaking of the electroweak symmetry with a light, mostly SM-like Higgs boson with a mass which may be consistent with the value observed at the LHC [8–13]. It has been pointed out that the study of kinematic edges can be important for the detection of light supersymmetric particles (for recent work, see [14,15]), and several kinematic variables have been proposed to distinguish new physics from background. In this article, we shall focus on the edge in the m_{ll} distribution.

The kinematic edge can be explained by the presence of a light sbottom.[2] The sbottoms are pair produced in the detector, and one of the sbottoms decays to a b-jet and the lightest supersymmetric particle (LSP). The other one decays to a heavier neutralino and a b-jet, and the heavier neutralino subsequently decays to the lightest neutralino and a pair of SFOS leptons through a slepton or an off-shell Z, depending on the mass of the sleptons and the composition

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[1]During the completion of this work, an alternative explanation of this kinematic edge in terms of first and second generation squarks together with light sleptons was presented [4].

[2]The explanation of the edge events via the decay of sbottoms is consistent with the benchmarks proposed by CMS in Ref. [3]. However, the CMS benchmarks, based on the heavier neutralino's decay to an off-shell Z and the lightest neutralino, are in tension with the ATLAS limits on the b-jet $+ E_T^{\text{miss}}$ channel.

of the neutralinos. We therefore defined two scenarios. In scenario A, the sbottom decays through the decay chain of $\tilde{b}_1 \to b\tilde{\chi}_2^0 \to b\tilde{l}l \to bl^+l^-\tilde{\chi}_1^0$. In scenario B, instead, the sbottom decay features the cascade decay of $\tilde{b}_1 \to b\tilde{\chi}_{2,3}^0 \to bZ^*\tilde{\chi}_1^0 \to bl^+l^-\tilde{\chi}_1^0$. Thus, the two sbottoms together give 2 b-jets, a pair of SFOS leptons and missing energy. Under these conditions, the m_{ll} distribution will feature a kinematic edge.

This article is organized as follows: In Sec. II, we will analyze the two possible scenarios in more detail, and study the resultant contributions to the kinematic edge. We also discuss the implications of these scenarios for dark matter and the muon anomalous magnetic moment. In Sec. III we consider possible constraints on both scenarios from the LHC. We reserve Sec. IV for our conclusions.

II. SBOTTOM CONTRIBUTIONS TO THE DILEPTON KINEMATIC EDGE

Scenarios with pair produced sbottoms are able to explain the kinematic edge. The spectra in Figs. 1 and 3 are examples of possible scenarios, and the particle masses necessary to explain the data in each of these scenarios are presented in Table I.

A. Scenario A

The spectrum in Fig. 1 features a sbottom with a mass around 390 GeV and a light slepton. The sbottom can decay to a $\tilde{\chi}_2^0$ and a b-jet. The $\tilde{\chi}_2^0$, with a mass around 340 GeV, can decay to two leptons and a $\tilde{\chi}_1^0$ through a right-handed selectron or a smuon with masses $m_{\tilde{e}_R} = m_{\tilde{\mu}_R} = m_{\tilde{l}}$ around 300 GeV. The mass of the LSP is chosen to be 260 GeV. Those two leptons will have the same flavor and opposite signs, and the edge of the invariant mass of the dilepton will be at

$$m_{ll}^{\text{edge}} = \sqrt{\frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}}^2}}, \qquad (1)$$
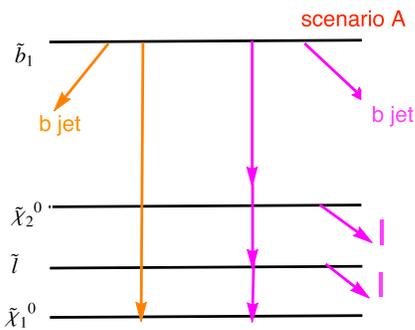

FIG. 1 (color online). A spectrum that could account for the dilepton kinematic edge. $\tilde{\chi}_2^0$ decays to the LSP and a pair of same flavor, opposite sign dileptons through a light slepton.

TABLE I. Parameters for the two scenarios described in the text.

Parameter	Scenario A	Scenario B
$m_{\tilde{b}_1}$ (GeV)	390	330
$m_{\tilde{\chi}_1^0}$ (GeV)	260	212
$m_{\tilde{\chi}_2^0}$ (GeV)	340	288
$m_{\tilde{\chi}_3^0}$ (GeV)	∼500	290
$m_{\tilde{l}}$ (GeV)	297	500
$\tan\beta$	25	50
$\sigma(pp \to \tilde{b}_1\tilde{b}_1)$ (pb)	0.42	1.14
BF($\tilde{b}_1 \to b\tilde{\chi}_1^0$)	0.93	0.56
BF($\tilde{b}_1 \to b\tilde{\chi}_2^0$)	0.07	0.25
BF($\tilde{b}_1 \to b\tilde{\chi}_3^0$)	0	019
Δa_μ	2.0×10^{-9}	2.7×10^{-9}
Ωh^2	0.11	0.11
σ_{SI}^p in cm^2	4×10^{-45}	2.7×10^{-44}

which is about 80 GeV in this spectrum. In Eq. (1) $m_{\tilde{l}}$ is the slepton mass and $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_2^0}$ are the lightest and second lightest neutralino masses, respectively. The competing decay channel of the sbottom is a b-jet and the LSP. Therefore, the pair produced sbottoms, with one sbottom decaying to a b-jet and the LSP, and the other decaying through the decay chain discussed above, will contribute to the SFOS dilepton$+ \geq 2$ jets $+$ missing energy channel with a kinematic edge around 80 GeV. Also, since the sbottom decays to either a b-jet and missing energy, or a b-jet, two leptons and missing energy, there will be no significant contributions to the 2b-jets plus 2 jets channel from sbottom pair production.

The mass parameters in scenario A were chosen in order to give a sufficiently large cross section without being in conflict with other experimental constraints, which will be discussed in more detail in Sec. III. We choose $m_{\tilde{b}_1}$ around 390 GeV so that it has a sizable production cross section. The mass of the lightest neutralino is chosen to be sufficiently low to allow the existence of an edge, but not low enough to lead to a conflict with searches for pair production of $\tilde{b}_1$ in the 2 b-jets plus E_T^{miss} channel. The mass of the second lightest neutralino is chosen to lead to the required edge while avoiding a degenerate spectrum which will give too soft b-jets. For a $\tilde{b}_1$ of 390 GeV and a decay branching ratio BF($\tilde{b}_1 \to b\tilde{\chi}_1^0$) = 1, the bound on the LSP mass is 260 GeV, and in order satisfy the above requirements we chose the $\tilde{\chi}_1^0$ mass to be close to this value, which is consistent with the ATLAS experimental bounds due to the fact that in scenario A BF($\tilde{b}_1 \to \tilde{\chi}_1^0$) < 1. In order to induce a large excess of events in the 2 b-jets plus SFOS leptons channel without generating a similarly large number of events in the 2-b-jets plus four leptons channel, we require that BF($\tilde{b}_1 \to b\tilde{\chi}_2^0$) $\ll$ BF($\tilde{b}_1 \to b\tilde{\chi}_1^0$). A simple way of satisfying this requirement is to assume that $\tilde{b}_1$ is

mostly right handed, $\tilde{\chi}_2^0$ is mostly a wino and $\tilde{\chi}_1^0$ is mostly a bino. $\tilde{\chi}_1^\pm$ is winolike. Observe that the chargino contribution to the sbottom decay branching fraction, $\mathrm{BF}(\tilde{b}_1 \to t^*\tilde{\chi}_1^\pm)$, is highly suppressed due to phase space factors.

The parameters are further constrained by the requirement of obtaining a proper dark matter relic density and a value of the anomalous magnetic moment of the muon consistent with experiment. To obtain the right relic density, we can either mix the binolike LSP with Higgsinos, so that the LSP can annihilate more efficiently through the Higgsino components, or approach the so-called A-funnel region, where $m_{\tilde{\chi}_1^0} \simeq m_A/2$, with m_A being the CP-odd Higgs mass, so the LSP can annihilate efficiently through the resonant mediation of the heavy Higgs bosons. For a neutralino mass $m_{\tilde{\chi}_1^0} \simeq 260$ GeV, the A-funnel region is excluded by the CMS Higgs to $\tau\tau$ searches [16] for $\tan\beta > 20$. Then, for large $\tan\beta$ the right relic density requires a small Higgsino mass parameter μ to get a large enough Higgsino component. A small μ and a large $\tan\beta$ make the Higgsino components in $\tilde{\chi}_2^0$ too large to give a $\mathrm{BF}(\tilde{b}_1 \to \tilde{\chi}_2^0 b)$ small enough to be consistent with the 4 lepton + missing energy searches. That means that the right relic density and a small $\mathrm{BF}(\tilde{b}_1 \to \tilde{\chi}_1^0 b)$ together favor moderate values of $\tan\beta$.

At the same time, to get the right muon anomalous magnetic moment, a larger $\tan\beta$ is favored. So if we put the restriction on the relic density, $\mathrm{BF}(\tilde{b}_1 \to \tilde{\chi}_1^0 b)$ and muon g-2 together, a sizable, but not very large value of $\tan\beta$ is favored. When $\tan\beta = 25$, as in scenario A, the bound on m_A from the CMS Higgs to $\tau\tau$ searches is about 600 GeV. Then, values of μ around 500 GeV are necessary to give the right relic density. Also, $\mathrm{BF}(\tilde{b}_1 \to \tilde{\chi}_1^0 b)$ is 7.4% for $\tan\beta = 25$ and $\mu = 500$ GeV, which is consistent with the constraints coming from 4 lepton searches, which we are going to discuss in detail in Sec. III. Then we choose the mass of the right-handed sleptons to be 320 GeV to give the m_{ll} edge at 80 GeV according to Eq. (1). In addition, we choose the mass of the left-handed sleptons to be around 400 GeV to give a larger contribution to the muon anomalous magnetic moment, which in this scenario is about $\Delta a_\mu = 2 \times 10^{-9}$. This is consistent with the experiment value $\Delta a_\mu = (2.87 \pm 0.8) \times 10^{-9}$ [17–25]. Smaller values of μ would further enhance the value of Δa_μ, but they will also lead to an enhancement of the $\mathrm{BF}(\tilde{b}_1 \to b\tilde{\chi}_2^0)$ and therefore we will not consider them in this analysis.

We performed a collider study of sbottom pair production using the spectra shown in Fig. 1. We generated the events with Isajet [26], and pass the event to Pythia [27] and PGS [28] for showering and the detector simulation and follow the CMS event selection described in Sec. I. The production cross section was scaled to the Prospino next to leading order results [29]. In the scenario A under analysis, $\tilde{\chi}_2^0$ is winolike and $\tilde{\chi}_1^0$ is binolike, $\mathrm{BF}(\tilde{b}_1 \to \tilde{\chi}_2^0 b)$ is 7.4%,
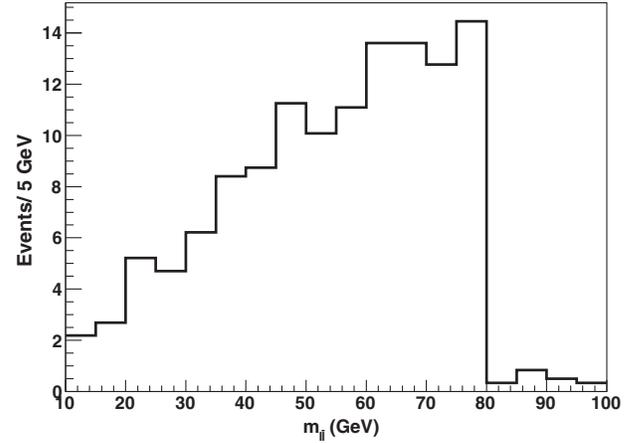

FIG. 2.   Invariant mass distribution of the same flavor, opposite sign dileptons. See the spectrum in Fig. 1 and Table I.

$\mathrm{BF}(\tilde{b}_1 \to \tilde{\chi}_1^0 b)$ is 92.6% and $\sigma(pp \to \tilde{b}_1\bar{\tilde{b}}_1) = 0.42$ pb. We found out that at the 8 TeV LHC, with a total integrated luminosity of 19.4 fb^{-1}, 110 SFOS dilepton events are expected in the central signal region and 13.4 events in the forward signal region. As stressed before, there are no significant contributions to the $\geq 2\mathrm{bjets} + \geq 2$ jets channel. The invariant mass distribution of the dilepton system shows an edge at about 80 GeV, as predicted by Eq. (1), and shown in Fig. 2.

Although we have not attempted to find the optimal values of the supersymmetric particle masses consistent with the observed signal, we have analyzed the effects of possible variations of these parameters. A sbottom lighter than 390 GeV will have a larger production rate, but the generation of the kinematic edge becomes more difficult due to the fact that for a $\mathrm{BF}(\tilde{b}_1 \to \tilde{\chi}_1^0 b) \simeq 1$ the experimental bounds on the LSP mass for sbottoms with masses between 300 and 400 GeV (which will be discussed in more detail in the next section) do not change much with the mass of sbottoms. That means, for a lighter sbottom, the allowed mass for the LSP would only be slightly smaller than 260 GeV. Therefore, in order to reproduce the edge the heavier neutralino mass should be kept at approximately the same value and the $\mathrm{BF}(\tilde{b}_1 \to b\tilde{\chi}_2^0)$ would be smaller than in the example we discussed above. For instance, for a sbottom around 385 GeV, the cross section is increased to 0.45 pb while $\mathrm{BF}(\tilde{b}_1 \to b\tilde{\chi}_2^0)$ is reduced to 0.064. Assuming the kinematic properties do not change in a significant way, the number of events expected would be rescaled by the ratios of the corresponding cross sections and branching ratios, implying about 103 events in the central region. Hence, a small reduction of the signal would be obtained.

If the mass of the sbottom is larger than what we discussed in the scenario A example, the sbottom pairs will be produced at a lower rate. For a 400 GeV sbottom, for instance, the production cross section drops to 0.36 pb. The number of SFOS events may be recovered by

increasing $\mathrm{BF}(\tilde{b}_1 \to b\tilde{\chi}_2^0)$ (for instance increasing slightly the Higgsino composition of $\tilde{\chi}_2^0$ or changing the masses of $\tilde{\chi}_2^0$ and of the LSP), a possibility which is however constrained by the searches in the 4 lepton channel. A more detailed collider study would be needed to estimate the largest $\mathrm{BF}(\tilde{b}_1 \to b\tilde{\chi}_2^0)$ allowed by the 4 lepton searches, which is beyond the discussion of this article, but $\tilde{b}_1$ masses above 400 GeV are significantly constrained by this requirement.

As we explained above, the value of $\tan\beta$ was fixed from the requirement of consistency with dark matter and muon anomalous magnetic moment constraints. The predicted dark matter relic density in scenario A, for $m_A \simeq 600$ GeV, is $\Omega h^2 \simeq 0.11$, which is consistent with the cosmological observations $\Omega h^2 = 0.1198 \pm 0.0026$ [30]. The value of $\tan\beta$ may be lower, implying a lower bound on the CP-odd Higgs mass m_A. Therefore, we can go to the A-funnel region (resonant annihilation through the CP-odd Higgs) to get the right relic density and μ can be chosen to the value that gives a $\mathrm{BF}(\tilde{b}_1 \to \tilde{\chi}_1^0 + b)$ large enough to contribute about 130 events in the edge and small enough to be consistent with the 4-lepton searches. However, since the main contribution to the muon $g-2$ in the MSSM is amplified by $\tan\beta$, the value of Δa_μ would be smaller than the one obtained in scenario A. In the region where $\tan\beta$ is large, instead, the Higgs to $\tau\tau$ searches prevent m_A from approaching the A-funnel region. At the same time, a large $\tan\beta$ means $\tilde{\chi}_2^0$ must be very winolike so that the $\mathrm{BF}(\tilde{b}_1 \to b\tilde{\chi}_2^0)$ can be small enough to not let the sbottom signals show up in the 4 lepton channel. That means μ is also required to be large in this region. Then the LSP is binolike, and away from the A-funnel region, so the relic density is larger than the observed value. For instance, for $\tan\beta = 50$, and $m_A = 1$ TeV, the predicted dark matter relic density in scenario A is $\Omega h^2 \simeq 0.8$, which is higher than the cosmological observations.[3] In general, for values of $\tan\beta$ significantly larger or smaller than the one chosen in scenario A there will be tension between the requirement of obtaining a value Δa_μ consistent with the observed experimental value and the obtention of the proper relic density.

The spin-independent cross section of the LSP scattering off a proton for scenario A is $\sigma_{\mathrm{SI}}^p = 3.6 \times 10^{-45}$ cm^2, which is consistent with LUX [32] and will be probed by Xenon1T and other future experiments [33]. If the sign of $\mu \times M_1$ is flipped, but the rest of the parameters are kept as defined in scenario A (with only small variations to obtain the proper relic density) then σ_{SI}^p is reduced to about

3×10^{-47} cm^2 due to the destructive interference between the contribution from the SM-like Higgs and the heavy CP-even Higgs [34–37]. Xenon1T might be able to probe this scenario. In order to keep a positive contribution to Δa_μ, however, $\mu \times M_2$ should be kept positive. For negative values of $\mu \times M_1$ and positive values of $\mu \times M_2$, the contribution to Δa_μ is reduced by about 20% because the sign of the right-handed slepton and neutralino loop contribution turns negative, but the dominant contributions from the left-handed slepton and neutralino as well as the sneutrino and chargino loop contributions remain approximately the same.

B. Scenario B

An alternative scenario will be that the heavier neutralino decays to a $\tilde{\chi}_1^0$ and an off-shell Z, and then the $Z*$ decays to a l^+l^- pair. A spectrum that could be responsible for the CMS kinematic edge is shown in Fig. 3. Contrary to what happens in scenario A, since the branching fraction of a $Z* \to l^+l^-$ is about 6%, (summed over electrons and muons), a sizable $\mathrm{BF}(\tilde{b}_1 \to \tilde{\chi}_2^0 b)$ is needed to get the number of events around 100 without lowering the $\tilde{b}_1$ mass to the current excluded region. To fulfill that requirement, we have $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ Higgsino-like, and $\tan\beta$ large to enhance the $\tilde{b}_1 \tilde{H} b$ coupling. Since the $\mathrm{BF}(\tilde{b}_1 \to b\tilde{\chi}_1^0)$ is significantly lower than 1, the mass of the $\tilde{b}_1$ could be lower without leading to a conflict with the 2 b-jets $+ E_T^{\mathrm{miss}}$ data.

In the spectrum shown in Fig. 3, we choose the $\tilde{b}_1$ mass around 330 GeV, the Higgsino mass parameter μ to be around 290 GeV and the LSP mass at 212 GeV. Then for these values of the mass parameters, $\mathrm{BF}(\tilde{b}_1 \to \tilde{\chi}_2^0 b) = 0.25$ and $\mathrm{BF}(\tilde{b}_1 \to \tilde{\chi}_3^0 b) = 0.19$. In this case, $\mathrm{BF}(\tilde{b}_1 \to \tilde{\chi}_1^0 l^+l^- b)$ is around $0.44 \times 0.06 \simeq 0.03$, which is small enough to suppress the 4 lepton mode and large enough to contribute about 100 events to the dilepton edge. In this scenario, the sbottom pair production will also contribute to the ≥ 2 jets $+ \geq 2$ b-jet channel. There is a potentially large signal in this channel coming from sbottom pair production, and in the next section we shall discuss the constraints
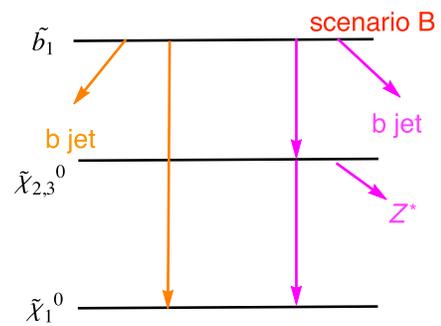

FIG. 3 (color online). A spectrum that could account for the dilepton kinematic edge. $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ decay to the LSP and a pair of same flavor, opposite sign leptons through an off-shell Z.

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[3]The overabundance problem can be solved, for instance, by introducing a scalar field ϕ, which dominates the energy density of the early Universe before the nucleosynthesis era [31]. For example, for a number of neutralinos produced per ϕ decay and per 100 TeV mass of ϕ, $\eta \leq 10^{-6}$, and a reheating temperate of about 1 GeV an observable relic density consistent with experiment may be obtained.

coming from it. Let us only emphasize here that the jets coming from the heavier neutralino decays tend to be soft and there are overwhelming backgrounds associated, for instance, with $t\bar{t}$ production, so that the scenario B is still consistent with this constraint.

In scenario B, the production cross section is $\sigma(pp \to \tilde{b}_1\overline{\tilde{b}_1}) = 1.14$ pb. At the 8 TeV LHC, with a luminosity of 19.4 fb^{-1}, there are 80 events in the central signal region and 9.0 events in the forward signal region. In this case, the predicted edges are located at the mass difference between the heavier and the lightest neutralino,

$$m_{ll}^{\text{edge}} = m_{\tilde{\chi}_2^0,\tilde{\chi}_3^0} - m_{\tilde{\chi}_1^0}, \qquad (2)$$

that was chosen to be 78 and 76 GeV for the third and second lightest neutralino in this scenario, respectively.

These edges can be seen in the invariant mass distribution presented in Fig. 4. At the current luminosity, the mass splitting between the two Higgsinos $m_{\tilde{\chi}_3^0} - m_{\tilde{\chi}_2^0} \sim 2$ GeV is sufficiently small to not be distinguishable in this distribution, and a single edge appears at about 78 GeV, consistent with the CMS data.

The number of events obtained in the central region in this scenario is lower by about 1 standard deviation than the central value reported by CMS. This amount may be increased by selecting a larger value of BF$(\tilde{b}_1 \to b\tilde{\chi}_2^0, \tilde{\chi}_3^0)$ or a larger $\tilde{b}_1$ production cross section, associated with a lower $\tilde{b}_1$ mass. However, any increase on these quantities will also lead to an increase of the number of events in the ≥ 2 jets, ≥ 2 b-jets $+ E_T^{\text{miss}}$ channel (as well as more events in the four lepton $+ E_T^{\text{miss}}$ channel). As we shall discuss in Sec. III, there is already a slight tension between the predicted number of events in scenario B and the ones observed by the LHC experiments. Hence, it is in general
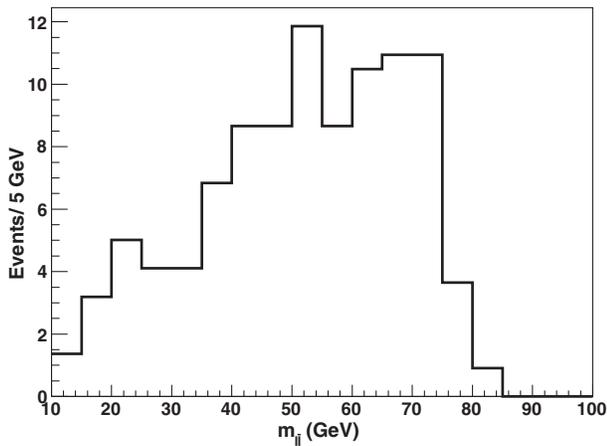

FIG. 4.   Invariant mass distribution of the same flavor, opposite sign dileptons. The edge is located at the mass difference between the Higgsinos and $\tilde{\chi}_1^0$. See the spectra in Fig. 3 and Table I.

difficult to obtain a significantly larger number of SFOS dileptons in this scenario.

Moreover, for a lighter sbottom, the production cross section increases but BF$(\tilde{b}_1 \to b\tilde{\chi}_{2,3}^0)$ decreases. For instance, for $m_{\tilde{b}_1} = 320$ GeV, BF$(\tilde{b}_1 \to b\tilde{\chi}_{2,3}^0) \sim 0.35$ and the cross section is 1.37 pb, which rescaling the previous result by the ratio of the corresponding production cross sections and branching ratios leads to about 88 events. However, the bottom quarks coming from the $\tilde{b}_1$ decay are softer implying that the actual number of events in the edge remains approximately the same as for $m_{\tilde{b}_1} = 330$ GeV. This could be improved by lowering the overall neutralino mass scale, but then the constraints from sbottom direct detection in the 2 b-jets $+ E_T^{\text{miss}}$ channel become stronger, making an increase of events difficult (beyond the problems in the ≥ 2jets, ≥ 2 b-jets $+ E_T^{\text{miss}}$ channel mentioned above). Similar considerations apply for a heavier sbottom. Although in such a case the production cross section decreases, a larger BF$(\tilde{b}_1 \to b\tilde{\chi}_{2,3}^0)$ is expected, together with harder b-jets and missing energy. Therefore, there may be some space with a heavier sbottom to obtain roughly 100 events in the central region, despite the production cross section being smaller. Again, one of the main constraints in the region with a heavier sbottom is from the ≥ 2-jet ≥ 2 b-jet channel, with the number of events in this channel scaled up by a factor of BF$(\tilde{b}_1 \to b\tilde{\chi}_{2,3}^0)^2$. We will come back to these issues in the next section.

This scenario leads to a proper anomalous magnetic moment of the muon for natural values of the slepton and wino masses. In order to accommodate the muon $g-2$ result, the sleptons should not be too heavy. For instance, for $m_{\tilde{l}_R} = m_{\tilde{l}_L} = 500$ GeV, $M_2 \simeq 600$ GeV and heavy left-handed sleptons $\Delta a_\mu = 2.7 \times 10^{-9}$, which is consistent with the experiment value $\Delta a_\mu = (2.87 \pm 0.8) \times 10^{-9}$.

Contrary to what happens in scenario A, the presence of light Higgsinos and binos in the spectrum makes it possible to obtain a large enough dark matter annihilation cross section to ensure consistency with the observed relic density without the need for any fine-tuning of parameters. The predicted dark matter relic density for scenario B is $\Omega h^2 \simeq 0.11$, assuming the CP-odd Higgs is heavy, $m_A \simeq 1.5$ TeV, which is consistent with experiments. The spin-independent cross section of the LSP scattering off a proton is $\sigma_{\text{SI}}^p = 2.7 \times 10^{-44}$ cm^2, which is consistent with LUX [32] and will be probed by Xenon1T and other future experiments [33]. As discussed above, if the sign of $\mu \times M_1$ is flipped, then due to the destructive interference between the light and heavy CP-even Higgs bosons, σ_{SI}^p is reduced to $\sim 1 \times 10^{-46}$ cm^2 and Xenon1T may be able to probe this scenario. Provided the sign of $\mu \times M_2$ remains positive, the contribution to Δa_μ is reduced by about 10% in this case.

III. CONSTRAINTS FROM LHC SEARCHES AND POSSIBLE FUTURE SEARCHES

As we discussed in the previous section, there are several constraints on the presence of light sbottoms and neutralinos coming from both ATLAS and CMS. The constraints from direct searches for sbottoms decaying into bottom quarks and missing energy [38,39] apply here. For scenario A, the direct limit for sbottoms shows that, for a mass of the LSP of about 260 GeV, and a $\mathrm{BF}(\tilde{b}_1 \to b\tilde{\chi}_1^0) = 1$, sbottoms with masses from 390 to 620 GeV are excluded by ATLAS, while CMS has a weaker limit. Due to the smaller $\mathrm{BF}(\tilde{b} \to b\tilde{\chi}_1^0)$, these bounds are weakened for this scenario. In particular, as we stressed in the previous section, since we chose masses close to the ATLAS limit for a $\mathrm{BF}(\tilde{b}_1 \to b\tilde{\chi}_1^0) = 1$, the mass parameters in scenario A are beyond the current ATLAS limit.

For scenario B, the direct limit for sbottoms in the $2\,\mathrm{b\text{-}jet} + E_T^{\mathrm{miss}}$ channel shows that for a LSP mass about 210 GeV, sbottoms with masses from 240 to 655 GeV are excluded if $\mathrm{BF}(\tilde{b}_1 \to \tilde{\chi}_1^0 b) = 1$. In scenario B, $\mathrm{BF}(\tilde{b}_1 \to \tilde{\chi}_1^0 b)$ is about 0.56, so the limits are weakened. We studied the number of events expected in this scenario to compare with the ATLAS result [39]. In the ATLAS analysis, events are separated into two signal regions. In signal region A (SRA), a large mass splitting between $\tilde{b}_1$ and $\tilde{\chi}_1^0$ is expected, identifying two b-tagged high p_T jets as products of the two sbottom decays. Any other central jets or leptons are vetoed. Signal region B (SRB), instead, targets signal events with small mass splitting, by selecting events with a high p_T jet, which are likely to be produced as initial state radiation, recoiling against the sbottom pairs. The two additional jets are required to be b-tagged and large missing energy $E_T^{\mathrm{miss}} > 250$ is imposed. We expect 23.4 events in SRA, which is consistent with ATLAS results—ATLAS expected 157.2 ± 14.6 and observed 174 events. The number of events in separate bins is also consistent with ATLAS analysis. We expect < 0.46 events, while ATLAS observed 1 event in SRB. With more integrated luminosity, we expect to see an excess in the $2\,\mathrm{b\text{-}jet} + E_T^{\mathrm{miss}}$ channel.

Both scenarios contribute to the 4-lepton, ≥ 1 jets plus missing energy channel. CMS studied this channel [40]. CMS does not observe any events in the region $H_T > 200$ GeV and $E_T^{\mathrm{miss}} < 50$ GeV, while 0.08 events were expected in the SM. In the region of $H_T < 200$ GeV and $E_T^{\mathrm{miss}} < 50$ GeV, 1 event is observed while 0.23 events are expected in the SM.

We studied the expected number of four lepton events in our scenarios. In scenario A, 0.3 events are expected in the $H_T > 200$ GeV and $E_T^{\mathrm{miss}} < 50$ GeV region and 1.6 events are expected in the $H_T < 200$ GeV and $E_T^{\mathrm{miss}} < 50$ GeV region. For scenario B, the expected signals are 0.9 events and 1.4 events in the $H_T > 200$ GeV and $H_T < 200$ GeV

region, respectively. Both scenarios agree with the CMS results, and with more integrated luminosity, we expect to see an excess in the 4-lepton, ≥ 1jets plus missing energy channel.

A strong constraint to scenario B is associated with the searches in $\geq 2\,\mathrm{jets} + \geq 2\,\mathrm{b\text{-}jets}$ channel. About 200 events with $E_T^{\mathrm{miss}} > 150$ GeV are expected in this scenario. We compare the predicted number of events with the observations of the LHC experiments in the $\geq 4\text{-}\mathrm{jets} + E_T^{\mathrm{miss}}$ channel [41]. For loose cuts the number of observed events is consistent with the ones associated with sbottom production. For tight cuts, the number of observed events is small but it falls short of the ones expected in the SM. Therefore, there is a small tension with the numbers predicted from sbottom production in scenario B, which however are still much smaller than background. Therefore, if the edge is confirmed, we expect this channel to provide a relevant test of scenario B at the next run of the LHC.

Also, the limits from chargino and neutralino searches should be taken into consideration [42,43]. The limits are quite weak for a LSP as heavy as 200 GeV, and our choice of parameters in Sec. II is well allowed by both experiments. Both scenarios contribute to the single lepton channel, but both experiments require more than 3 hard jets in the single lepton search [44–47] and therefore do not set any constraints in our scenarios from this channel. Scenario A also gets constrained by direct slepton searches, but the current limits from direct slepton searches do not cover the LSP mass larger than 100 GeV [42,43] assuming the lighter slepton is right handed.

IV. CONCLUSIONS

To summarize, we have shown two possible scenarios with sbottoms with masses around 300 to 400 GeV to explain the recent CMS excess of events in the SFOS dilepton and missing energy channel, leading to an edge with a dilepton invariant mass $m_{ll} \simeq 78$ GeV. In both scenarios, one of the pair produced sbottoms decays to a b-jet and the LSP, and the other decays to a b-jet and a heavier neutralino, which further decays to the LSP and a pair of SFOS leptons through an on-shell slepton or an off-shell Z, respectively. Both scenarios feature an edge around 78 GeV and produce a number of events consistent with the observation of CMS. The sbottom, slepton and neutralino masses are within the current experimental limits.

We showed that the predicted value of the muon anomalous magnetic moment may be consistent with experiments in both scenarios, what defines additional constraints on the parameters of the model. Moreover, consistency of the predicted value of the dark matter relic density with observations may be obtained and the predicted values of the spin-independent direct dark matter cross section are beyond the current limits but may be probed by future searches.

For simplicity, we have assumed staus to be heavy in both scenarios. It would be natural to expect the presence of light staus in scenario A. In the presence of a light stau, we would expect 2b-jets + 2 taus + E_T^{miss} as well as a small amount of 2-bjets + 2 taus + SFOS leptons + E_T^{miss} and 2 b-jets, 4 taus and E_T^{miss} events at the LHC. While we do not expect that currently these channels set any additional constraints on this scenario, they must be studied and in the presence of light staus they may provide additional ways of testing this scenario at the LHC. A light stau would also induce a new dark matter annihilation channel and, depending on its mass, could change the discussion we had on this issue, but the discussion on muon anomalous magnetic moment would stay the same (for a recent study on light stau contributions to dark matter annihilation, see for instance Ref. [48]).

These scenarios should be probed in the near future by a similar analysis of the 8 TeV LHC data from ATLAS.

If the existence of the edge is confirmed, further analyses in the 2 b-jets plus E_T^{miss} channel, the 4 lepton plus E_T^{miss} channel, and the $\geq$ 2-bjets $\geq$ 2jets E_T^{miss} channel in the next run of the LHC will be able to further probe these scenarios.

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