Interpreting the CMS $\ell^+\ell^-jjE_T$ Excess with a Leptoquark Model

Ben Allanach$^{a}$, Alexandre Alves$^{a}$, Farinaldo S. Queiroz$^{c,d,e}$, Kuver Sinha$^{f}$, and Alessandro Strumia$^{g,h}$

$^a$ DAMTP, CMS, Wilberforce Road, University of Cambridge, Cambridge, CB3 0WA, United Kingdom
$^b$ Departamento de Ciências Exatas e da Terra, Universidade Federal de São Paulo, Diadema-SP, 09972-270, Brasil
$^c$ Department of Physics and Santa Cruz Institute for Particle Physics University of California, Santa Cruz, CA 95064, USA
$^d$ Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
$^e$ International Institute of Physics, UFRN, Av. Odilon Gomes de Lima, 1722 - Capim Macio - 59078-400 - Natal-RN, Brazil
$^f$ Department of Physics, Syracuse University, Syracuse, NY 13244, USA
$^g$ Dipartimento di Fisica dell’ Universita di Pisa and INFN, Italy
$^h$ National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

(Dated: January 16, 2015)

Motivated by excesses in $eejj$ and $e\nu jj$ channels observed by the CMS collaboration, in 8 TeV LHC data, a model of lepto-quarks with mass around 500 GeV was proposed in the literature. In order to reproduce the claimed event rate, lepto-quarks were assumed to have a significant partial branching ratio into an extra sector, taken to be Dark Matter, other than the canonical $e\nu$. We here show that the decay channel of lepto-quark into Dark Matter can fit another excess claimed by CMS, in $\ell^+\ell^-jjE_T$: the event rate, the distribution in di-lepton invariant mass and the rapidity range are compatible with the data. We provide predictions for the forthcoming Run II of the 14 TeV LHC and discuss aspects of dark matter detection.

INTRODUCTION

The CMS collaboration reported a 2.6$\sigma$ excess compared with Standard Model expectations in $\ell^+\ell^-jjE_T$ events, containing two opposite-sign same-flavor leptons $\ell = \{e, \mu\}$, at least two jets and missing transverse momentum $E_T$. No similar ATLAS analysis has been presented. The CMS analysis was performed with 19.4 fb$^{-1}$ of integrated luminosity at a center of mass energy of 8 TeV. The excess was found in the central region with di-lepton pseudo-rapidities $|\eta| \leq 1.4$, after various event selection and flavor subtraction cuts, and in the kinematical region with di-lepton invariant mass $m_{\ell\ell} < 80$ GeV, as shown in Fig. 1. No excess is seen in other regions nor in the trilepton channel.

The excess was found in the context of CMS searches for edges in $m_{\ell\ell}$. The triangular edge is a classic supersymmetry signal, and interpretations of the CMS excess in the context of the so-called golden cascade ($\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^\pm\tilde{\ell}^\mp \rightarrow \tilde{\chi}_1^0\tilde{\ell}^\pm\tilde{\ell}^\mp$) have been proposed ($\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, and $\tilde{\ell}$ are the lightest neutralino, the next-to-lightest neutralino and the slepton, respectively). Since direct electroweak production of $\tilde{\chi}_2^0$ has too small a cross section to provide a large enough rate whilst evading previous collider bounds from LEP, assistance from colored particle production is required. The decay chain could start with $\tilde{\ell} \rightarrow t\chi_2^0$ or $\tilde{q} \rightarrow q\chi_2^0$. The former interpretation is constrained by the fact that the CMS study did not observe a large excess in trilepton final states, which should be present from the leptonic top quark decay. The latter case will be increasingly constrained as the exclusion limits on first two generations squarks becomes stronger. The CMS study itself opted for an explanation in terms of light sbottoms $\tilde{b} \rightarrow b\chi_2^0$, and $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\ell}^\pm\tilde{\ell}^\mp$, although no $b$-jet requirement was made on the final states. Ref. 4 explored the parameter space in order to simultaneously satisfy bounds from 4 charged lepton production. The purpose of the present letter is to show that the CMS excess can be explained by a different, non-supersymmetric, class of models that were introduced for a different purpose. A CMS search for leptoquarks (LQs) 7-13 found a mild excess in the $eejj$ and $e\nu jj$ channels, giving hints for a first-generation scalar lepto-quark with mass $500-650$ GeV and branching ratio of the lepto-quark into leptons and quarks of $\approx 15\%$ 5. In the model presented in 14 a Dark Matter sector was added to account for the missing branching ratio. This extra decay channel of the LQ enables us to fit the CMS $\ell^+\ell^-jjE_T$ excess.

Fig. 1 exemplifies how the $\ell^+\ell^-jjE_T$ excess can be reproduced by lepto-quarks with $\approx 500$ GeV masses: the model predicts a peak in $m_{\ell\ell}$, which fits data roughly as well as the triangular edge searched for by CMS. The model also predicts small numbers of events in the forward region and for trilepton final states, also compatible with the CMS measurements.
The paper is structured as follows: we first describe our model, the spectrum and decays of the LQ, and the constraints on the spectrum from various experiments. After giving technical details about our estimates, we define five benchmark points, providing expected event numbers for them and the $E_T$ spectrum for one of them. Expected event numbers for Run II are also provided. We finish with a summary.

THE MODEL

Renormalizable LQ models were classified in the early literature [15] [16]. Given the quantum numbers of the SM quarks and leptons, some LQs could also couple to two first generation quarks, leading to proton decay. We consider lepto-quarks that do not lead to proton decay at renormalizable level: either a scalar $\tilde{R}_2$ in the $(3, 2, 7/6)$ representation of SU(3) $\otimes$ SU(2) $\otimes$ U(1) that can couple to $\tilde{Q}e$ and to $L\pi$; or a scalar $\tilde{R}_2$ in the $(3, 2, 1/6)$ representation (the same as the quark doublet $Q$) that can couple to $L\bar{L}$. We focus on $\tilde{R}_2$ because its quantum numbers are favorable from a dark matter perspective, as we will clarify later. Pair production of $\tilde{R}_2$ thus constitutes our main example. Its Lagrangian couplings are

$$- \lambda_d^{ij} \bar{d}_R \tilde{R}_2^i e_L^j + \text{h.c.}, \quad (1)$$

where $i, j$ denote flavor indices. In the above,

$$\tilde{R}_2 = \begin{pmatrix} V_a \\ Y_a \end{pmatrix}, \quad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, \quad L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}. \quad (2)$$

Expanding the SU(2) components yields

$$- \lambda_d^{ij} \bar{d}_R (V_a e_L^j - Y_a \nu_L^j) + \text{h.c.}. \quad (3)$$

In addition to the LQ, we introduce a dark sector with a scalar $S$ and a fermion $\chi$, with a $Z_2$ symmetry under which the dark sector is odd, whereas the SM and LQ sector is even. Thus, our new physics content is

$$\tilde{R}_2 = (3, 2, 1/6)_+$$

$$S = (1, 3, 0)_- = \begin{pmatrix} \frac{1}{\sqrt{2}} S^0 \\ \frac{1}{\sqrt{2}} S^- \\ -\frac{1}{\sqrt{2}} S^0 \end{pmatrix}, \quad (4)$$

$$\chi = (1, 1, 0)_-, \quad (5)$$

where we have also displayed the $Z_2$ quantum numbers as a subscript. Notice that there is almost no freedom in choosing the above particle content. The quantum charges of the dark sector are fixed by symmetries; either the scalar $S$ or the fermion $\chi$ has to be a triplet under SU(2)$_L$ (having both singlets will not give enough charged leptons in the final state to match the CMS study, as we will see). We have chosen a scalar triplet for convenience; the discussion and results would be analogous for a model with a triplet fermion $\chi$ and a singlet scalar $S$. The hypercharge of the dark sector is fixed to be zero to easily accommodate dark matter direct detection constraints.

The LQ decay into the dark sector can then be described by adding the following dimension-5 effective operators:

$$- \frac{h_i}{\lambda_1} S \bar{Q}_i \chi \tilde{R}_2 - \frac{h'}{\lambda_2} S \bar{L}_i \chi \tilde{H}, \quad (6)$$

where $\tilde{H}$ is the iso-spin transformation of the Higgs doublet. Constraints on the LQ couplings are discussed in [14].

The CMS study does not discuss the relative number of $e^+e^-$ and $\mu^+\mu^-$ events in the $\ell^+\ell^- jj E_T$ excess. We will assume them to be equal and introduce both a first generation LQ and a second generation LQ in order to obtain both $e^+e^-$ and $\mu^+\mu^-$ events. Moreover, while the CMS study does not specify the number of $b$-jets in the signal, we note that $\tilde{R}_2$ could decay to $b$-quarks and other down quarks democratically or preferentially across generations, depending on the choice of the Yukawa $h_i$ in Eq. (6).

Spectrum and Decays

Either the triplet component $S^0$ or the singlet $\chi$ can be the lightest DM particle. The two possibilities lead to different dark matter phenomenology. Here, we will mainly consider the case of a singlet $\chi$ as the dark matter candidate (the collider analysis of the other case can be performed analogously).

The two couplings of the LQ induce two decay modes:

$$\tilde{R}_2 \rightarrow \ell j \quad \text{and} \quad \tilde{R}_2 \rightarrow S j \chi \quad (7)$$

where $\ell$ can be a charged lepton or a neutrino.

The latter coupling in eq. (6) induces the $S \rightarrow \ell \chi$ decays of $S$. In components:

$$S^\pm \rightarrow \chi \ell^\pm, \quad S^0 \rightarrow \nu \chi \quad (8)$$

so that decays of charged scalars $S^\pm$ give charged leptons and $E_T$ in the final state. One loop electro-weak corrections induce a small mass splitting of $\approx 200$ MeV between the neutral and charged states in $S$. Combining all decays, one $\tilde{R}_2$ LQ can produce the following final states:

1. A lepton and a jet. The free couplings of the Lagrangian allow us to set the $\tilde{R}_2$ branching ratio to the level required by the CMS $\ell\ell jj$ anomaly: we will assume $15\%$

Consequently $\text{BR}(\tilde{R}_2 \rightarrow S j \chi) \sim 85\%$.

2. A jet and missing energy, with

$$\text{BR}(\tilde{R}_2 \rightarrow S^0 j \chi \rightarrow j E_T) \sim 25\%.$$ 

3. A charged lepton, a jet and missing energy, with

$$\text{BR}(\tilde{R}_2 \rightarrow S^\pm j \chi \rightarrow \ell^\pm j E_T) \sim 60\%.$$
for LQs in the mass range 450 – 650 GeV, we map the neutralino mass $m_{\tilde{\chi}}$ effectively escape undetected. To compare to the experimental BR case, the squark mass $m_{\tilde{S}}$ and escapes the detector. In our model, both $e\nu jj$ and $\mu\nu jj$ final states has resulted in the exclusion of scalar LQs with masses below 1070 (785) GeV for $BR_{\mu j} = 1(0.5)$ \cite{6}.

In our model, the second term in Eq. (6) provides a decay channel to $e\nu jj$ and $\mu\nu jj$. For first generation LQs, a branching $BR(\tilde{R}_2 \rightarrow ej) \sim 15\%$ agrees well with the observed excess in the 500 – 650 GeV mass range. For second generation LQs, the absence of an excess means that the corresponding branching $BR(\tilde{R}_2 \rightarrow \mu j)$ should be smaller. We note that a smaller value of $BR(\tilde{R}_2 \rightarrow \mu j)$ would increase $BR(\tilde{R}_2 \rightarrow \mu j E_T)$ and hence our signal for this study. We will thus set $BR(\tilde{R}_2 \rightarrow \mu j) \lesssim 15\%$ in the analogous second generation LQ study. We note that leptons coming from $\tilde{R}_2 \rightarrow \ell j$ decays are usually too hard to pass the upper dilepton mass cut for the signal we are studying. Thus, the branching ratio to $\ell j$ should not be too large in order to maintain a reasonable signal rate.

(ii) Constraints from CMS LQ searches: There are now constraints on first and second generation LQs from CMS. For first generation LQs, there is a mild evidence for $\sim 550 – 650$ GeV scalar LQs, using $19.6 \, fb^{-1}$ of integrated luminosity, at $2.4\sigma$ and $2.6\sigma$ in the $e\nu jj$ and $\mu\nu jj$ channels respectively \cite{5}. For second generation LQs, studies of the $\mu\nu jj$ and $\mu\nu jj$ final states has resulted in the exclusion of scalar LQs with masses below 1070 (785) GeV for $BR_{\mu j} = 1(0.5)$ \cite{6}.

In our model, the second term in Eq. (6) provides a decay channel to $e\nu jj$ and $\mu\nu jj$. For first generation LQs, a branching $BR(\tilde{R}_2 \rightarrow ej) \sim 15\%$ agrees well with the observed excess in the 500 – 650 GeV mass range. For second generation LQs, the absence of an excess means that the corresponding branching $BR(\tilde{R}_2 \rightarrow \mu j)$ should be smaller. We note that a smaller value of $BR(\tilde{R}_2 \rightarrow \mu j)$ would increase $BR(\tilde{R}_2 \rightarrow \mu j E_T)$ and hence our signal for this study. We will thus set $BR(\tilde{R}_2 \rightarrow \mu j) \lesssim 15\%$ in the analogous second generation LQ study. We note that leptons coming from $\tilde{R}_2 \rightarrow \ell j$ decays are usually too hard to pass the upper dilepton mass cut for the signal we are studying. Thus, the branching ratio to $\ell j$ should not be too large in order to maintain a reasonable signal rate.

Constrants on the masses of $\tilde{R}_2, S, \chi$

(i) Constraints from $jE_T$ searches. As described previously, LQ pairs have decays to jets and missing energy that must be compatible with $jE_T$ searches from ATLAS \cite{18} and CMS \cite{19}. The most relevant exclusion limits from these searches are phrased in the squark-neutralino ($m_{\tilde{q}}, m_{\tilde{\chi}}$) mass plane (Fig. 10 of \cite{18}), where the lightest neutralino is stable and escapes the detector. In our model, both $S^0$ and $\chi$ effectively escape undetected. To compare to the experimental studies, we map the neutralino mass $m_{\tilde{\chi}}$ to $m_S + m_{\chi}$ and the squark mass $m_{\tilde{q}}$ to $m_{\tilde{R}}$. Taking into account that, in our case, $BR(\tilde{R}_2 \rightarrow jE_T) \sim 25\%$, we conservatively estimate the bound

$$m_S + m_{\chi} > 300 \, \text{GeV} $$

for LQs in the mass range 450 – 650 GeV.

(ii) Constraints from CMS LQ searches: There are now constraints on first and second generation LQs from CMS. For first generation LQs, there is a mild evidence for $\sim 550 – 650$ GeV scalar LQs, using $19.6 \, fb^{-1}$ of integrated luminosity, at $2.4\sigma$ and $2.6\sigma$ in the $e\nu jj$ and $\mu\nu jj$ channels respectively \cite{5}. For second generation LQs, studies of the $\mu\nu jj$ and $\mu\nu jj$ final states has resulted in the exclusion of scalar LQs with masses below 1070 (785) GeV for $BR_{\mu j} = 1(0.5)$ \cite{6}.

In our model, the second term in Eq. (6) provides a decay channel to $e\nu jj$ and $\mu\nu jj$. For first generation LQs, a branching $BR(\tilde{R}_2 \rightarrow ej) \sim 15\%$ agrees well with the observed excess in the 500 – 650 GeV mass range. For second generation LQs, the absence of an excess means that the corresponding branching $BR(\tilde{R}_2 \rightarrow \mu j)$ should be smaller. We note that a smaller value of $BR(\tilde{R}_2 \rightarrow \mu j)$ would increase $BR(\tilde{R}_2 \rightarrow \mu j E_T)$ and hence our signal for this study. We will thus set $BR(\tilde{R}_2 \rightarrow \mu j) \lesssim 15\%$ in the analogous second generation LQ study. We note that leptons coming from $\tilde{R}_2 \rightarrow \ell j$ decays are usually too hard to pass the upper dilepton mass cut for the signal we are studying. Thus, the branching ratio to $\ell j$ should not be too large in order to maintain a reasonable signal rate.

(iii) Constraints from the dilepton invariant mass $m_{\ell\ell}$ distribution of the CMS $\ell^+\ell^- jj E_T$ excess, located mostly below $m_{\ell\ell} \approx 80$ GeV. The two leptons in our case come from the decay $S \rightarrow \ell \chi$. To get the excess in the required range the mass difference between $S$ and $\chi$ should be

$$m_S - m_{\chi} \sim 20 - 40 \, \text{GeV} \ .$$

Spectra where $m_S - m_{\chi} \gtrsim 40 \, \text{GeV}$ are disfavored since the dilepton invariant mass distributions would peak at a value of $m_{\ell\ell}$ that is too large compared to the excess. On the other hand, for $m_S - m_{\chi} \lesssim 20 \, \text{GeV}$, the leptons are too soft and do not survive the $p_T$ cuts for leptons, as we will see later.

RESULTS

We take our background estimates from \cite{1}. Opposite sign opposite-flavor (OSOF) leptons from $t\bar{t}$, which has equal rates for the same-flavor and opposite-flavor channels, are used to measure the backgrounds in the CMS study. Drell-Yan production of $\gamma^*/Z^0$ bosons is an irreducible background since it gives same-flavor events. This is estimated by a control region which does not overlap with the signal region.

We follow the CMS counting experiment analysis in \cite{11} for the signal. The final state is required to have at least two leptons and at least two jets. The cuts employed are:

Cut (i) Two OSSF leptons are required to be present, with $p_T > 20 \, \text{GeV}$ in $|\eta| < 1.4$ which is defined as the central region in the CMS study.

Cut (ii) At least two jets are required with $p_T > 40 \, \text{GeV}$ in $|\eta| < 3.0$. Jets are reconstructed by the anti-$k_T$ algorithm \cite{20} using \textsc{FastJet} \cite{21}, with a jet radius parameter

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{feynman_diagram.png}
\caption{Upper: an example Feynman diagram showing LQ decay that can produce the CMS $eejj$ excess. Lower: an example Feynman diagram showing LQ decay that can produce the CMS $\ell^+\ell^- jj E_T$ excess. Other diagrams exist for producing identical final states through LQ pair production.}
\end{figure}
of $R = 0.5$. An event is selected if it contains two jets and satisfies $E_T > 150$ GeV, or, if it contains three or more jets and satisfies $E_T > 100$ GeV. In the dilepton invariant mass range $20$ GeV < $m_{\ell\ell} < 70$ GeV, the total background estimate provided by the CMS study for central OSSF events is $730 \pm 40$. The observed number was 860, corresponding to an excess of $130^{+38}_{-29}$ events provided by new physics, we hypothesize. In our model, this excess number of events is produced by first and second generation LQs. We implement the model in FeynRules [22] and calculate the branching ratios and cross sections using MadGraph 5.11 [23]. The events are then passed onto Pythia [24] for parton showering and hadronization followed by the modelling of detector effects by Delphes 3.1.2 [25]. We took exactly the same electron/muon/jets isolation criteria adopted in [1].

We performed a scan over the masses ($m_{\tilde{R}}$, $m_S$, $m_{\chi}$) and over $h_i/\Lambda$ to adjust the coupling of the first term of Eq. 6 as well. We fixed the couplings $\lambda^2_d = 0.01$ and $h_i/\Lambda = 0.001$ GeV$^{-1}$. The cut flow is displayed in Table I for those spectra that best fit the number of events in the central region of the CMS search with BR($R_2 \rightarrow e\nu jj$) $\sim 15\%$, $m_S + m_{\chi} > 300$ GeV and $m_S - m_{\chi} < 40$ GeV. The $E_T$ distribution after the lepton and jet $p_T$ requirements (but prior to the dilepton mass requirement) is shown in Fig. 3. Clearly, a large number of events can survive the MET requirement.

The dilepton invariant mass distribution of the signal after all cuts is displayed in Fig. 4. In this figure we see that the majority of events of benchmark point $C$ are concentrated in the invariant mass window defined in the counting analysis of the CMS search. In fact, all of the points of Table I present this feature. While the CMS study showed a triangular shape with a sharp edge, for benchmark point $C$ around 19 events survive in the region $m_{\ell\ell} > 100$ GeV, which is well within the background uncertainty.

In Fig. 4 we show the comparison between the CMS data points and the predicted distribution for our model at benchmark point $C$. As we see, our model can fit the data very well. The other benchmark points of Table I compare favorably to the experimental points too. By performing a $\chi^2$ fit we find that all these solutions have comparable quality and are also comparable to the SUSY triangular-edge proposed by CMS.

We also checked that the number of events in the forward region defined in the experimental study, $1.6 < |\eta| < 2.4$ is small, around 7 events for benchmark $C$ and similar for the other points. This is consistent with the CMS reported number of $6 \pm 20$ events in the forward region. Moreover, the expected fraction of signal events with 3 or more leptons in those benchmark points is never beyond 0.5%, again consis-
The dark matter phenomenology of this model has been discussed thoroughly in [14]. Here, we recapitulate the main points. DM stability is guaranteed by the discrete $Z_2$ symmetry. The options are to have either triplet or singlet dark matter that could be the fermion $\chi$ or the scalar $S$.

After taking into account direct and indirect detection constraints, as well as constraints from the LHC, the following possibilities emerge:

1. A scalar singlet $S$ coupled to the Higgs portal. The portal is constrained by direct detection limits from LUX and Higgs invisible decay widths. After taking these into account, the mass range $m_S > 100$ GeV and $m_S \sim 60 - 65$ GeV emerge as allowed ranges, with the latter being in the Higgs resonance. This option will increasingly be probed by direct detection, with XENON1T poised to rule out much of the mass range up to a TeV [26].

2. A fermionic singlet with a significant pseudoscalar coupling to the Higgs portal, which results in a dominant (and less experimentally constrained) spin-dependent scattering cross section. Following [30], we write the portal Lagrangian as

$$L = L_{\text{SM}} + \overline{\chi}(i\ddot{\phi} - M_\chi)\chi + \frac{1}{\Lambda} \left( \Lambda h + \frac{1}{2} h^2 \right) \left[ \cos \xi \overline{\chi} \chi + \sin \xi \overline{\chi} 5\chi \right].$$

where $\Lambda$ sets the scale of the portal interaction, and $\sin \xi$ sets the pseudoscalar coupling. From Fig.7 of [30], it is clear that $m_\chi \gtrsim O(100)$ GeV is allowed by LUX results for $\sin^2 \xi \gtrsim 0.7$ with $\Lambda \sim 1 - 5$ TeV. The bounds do not depend much on whether $\chi$ is Majorana or Dirac.

3. A scalar or fermionic triplet; this is, however, highly constrained now. Fermi-LAT dwarf galaxy data [27] rule out triplet dark matter masses up to around 400 GeV. Galactic center data rule out a dark matter of either NFW or Einasto profiles [28]. The bounds become stronger (weaker) if one considers steeper (less steep) profiles, or Einasto profiles [28]. The bounds do not depend much on whether $\chi$ is Majorana or Dirac.

Thus, a singlet fermionic dark matter candidate with mass $m_\chi \sim 140$ GeV that we have taken in our collider analysis of this paper is currently a viable option.

**CONCLUSIONS**

In this paper, we have explored the possibility that the tentative excess observed by CMS in their $\ell^+ \ell^- jj E_T$ search comes...
from a LQ model. The model consists of scalar first generation and second generation LQs that decay dominantly to leptons, jets, and missing energy in the form of a stable dark matter candidate. The confluence of proton decay constraints and dark matter direct/indirect detection results in a highly predictive model of LQs that can satisfy the CMS $\ell^+\ell^-jj\not{E_T}$ search. Our model provides a proof of concept that a peak distribution in the required dilepton mass range can be obtained outside the purview of supersymmetry.

Benchmark point C consists of first and second generation LQs with masses of 500 GeV, and dark sector particle masses of $m_S=160$ GeV and $m_S=140$ GeV. The LQs dominantly decay to $\ell j\not{E_T}$ final states ($\sim 60\%$ branching), and subdominantly into the canonical LQ final states of $\ell j$ ($\sim 15\%$ branching) and also $j\not{E_T}$ ($\sim 25\%$ branching). The LQs could as easily decay to $\ell b$ final states instead (or as well), in which case it would be interesting to see $b$-tag rates in the data.

While CMS fit a triangular shape in the opposite-sign-same-flavor dilepton invariant mass distribution after event selection and flavor subtraction, it is too premature to settle definitively on a kinematic edge. In our model, the number of signal events in the window $20 < m_{\ell\ell} < 70$ GeV after event selection is 100 for the benchmark point. The dilepton mass distribution peaks in the window between $20 - 70$ GeV with the required event count, while the number of events in the region $m_{\ell\ell} > 100$ GeV is within the background uncertainty. In a simple $\chi^2$ fit, this point compares favorably with the CMS SUSY fit in [1]. The model is consistent with the non-observation of signal in the forward region, and in the trilepton final states. We have also provided a prediction of $\sim 4700$ events at LHC14 for the same mass point with 100 fb$^{-1}$ luminosity.

We have also considered a benchmark point with LQs of masses 550 GeV, and dark sector particle masses of $m_S=200$ GeV and $m_S=170$ GeV, that can simultaneously explain both CMS studies. The number of signal events in the window $20 < m_{\ell\ell} < 70$ GeV after event selection is 79, which is near the lower limit of the event count observed by CMS.

**ACKNOWLEDGEMENTS**

This work was supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) grant 2013/22079-8, STFC grant ST/L000385/1, US Department of Energy Award SC0010107 and the Brazilian National Counsel for Technological and Scientific Development (CNPq) and NASA Astrophysics Theory Grant NNH12ZDA001N, by ESF grant MTT8.

[a] aalves@unifesp.br

[1] CMS PAS SUS-12-019

---

[2] B. Dutta, T. Kamon, N. Kolev, K. Sinha, K. Wang and S. Wu, Phys. Rev. D 87, no. 9, 095007 (2013) [arXiv:1302.3231].

[3] B. Allanach, A. R. Raklev and A. Kvellestad, arXiv:1409.3532.

[4] P. Huang and C. E. M. Wagner, arXiv:1410.4998 [hep-ph].

[5] CMS PAS EXO-12-041, http://cds.cern.ch/record/1742179/files/

[6] CMS PAS EXO-12-042 ATLAS Collaboration, Eur. Phys. J. C 72, 2151 (2012) [arXiv:1203.3172]; CMS Collaboration, arXiv:1408.0806 [CMS PAS EXO13010].

[7] J. C. Pati and A. Salam, Phys. Rev. D 10, 275 (1974) [Erratum-ibid. D 11, 703 (1975)].

[8] H. Georgi and S. L. Glashow, Phys. Rev. Lett. 32, 438, (1974).

[9] E. Farhi and L. Susskind, Phys. Rept. 74, 277 (1981); S. Dimopoulos and L. Susskind, Nucl. Phys. B 155, 237 (1979);

[10] J. L. Hewett and T. G. Rizzo, Phys. Rev. D 56, 5709 (1997) [hep-ph/9703337].

[11] M. Leurer, Phys. Rev. D 49, 333 (1994) [hep-ph/9309266].

[12] S. Davidson, D. C. Bailey and B. A. Campbell, Z. Phys. C 61, 613 (1994) [hep-ph/9309310].

[13] S. S. Gershtein, A. A. Likhoded and A. I. Onishchenko, Nucl. Phys. Rept. 320 (1999) 159; I. Dorsner and P. Fileviez Perez, Nucl. Phys. B 723, 53 (2005) [arXiv:hep-ph/0504276]; B. Gripaios, JHEP 1002 (2010) 045 [arXiv:0910.1769]; P. Fileviez Perez, T. Han, T. Li and M. J. Ramsey-Musolf, Nucl. Phys. B 819 (2009) 139 [arXiv:0810.4138]; P. Y. Popov, A. V. Povarov and A. D. Smirnov, Mod. Phys. Lett. A 20 (2005) 3003 [arXiv:hep-ph/0511149]; K. S. Babu and J. Julio, Nucl. Phys. B 841, 130 (2010) [arXiv:1006.1092].

[14] F. S. Queiroz, K. Sinha and A. Strumia, arXiv:1409.6301.

[15] W. Buchmüller, R. Ruckl and D. Wyler, Phys. Lett. B 191, 442 (1987) [Erratum-ibid. B 448, 320 (1999)].

[16] A. J. Davies and X. G. He, Phys. Rev. D 43, 225 (1991).

[17] J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013) [arXiv:1304.6119].

[18] ATLAS Collaboration, JHEP 1409, 176 (2014) [arXiv:1405.7875].

[19] CMS Collaboration, JHEP 1406, 055 (2014) [arXiv:1402.4770].

[20] M. Cacciari, G. P. Salam and G. Soyez, JHEP 0804, 063 (2008) [arXiv:0802.1189].

[21] M. Cacciari, G. P. Salam and G. Soyez, Eur. Phys. J. C 72 (2012) 1896 [arXiv:1111.6097].

[22] N. D. Christensen and C. Duhr, Comput. Phys. Commun. 180, 1614 (2009) [arXiv:0806.4194].

[23] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, JHEP 1106, 128 (2011) [arXiv:1106.0522].

[24] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP 0605, 026 (2006) [hep-ph/0603175].

[25] DELPHES 3 Collaboration, JHEP 1402, 057 (2014) [arXiv:1307.6346].

[26] F. S. Queiroz and K. Sinha, Phys. Lett. B 735, 69 (2014) [arXiv:1404.1400]; J. M. Cline, K. Kainulainen, P. Scott and C. Weniger, Phys. Rev. D 88, 055025 (2013) [arXiv:1306.4710]; L. Feng, S. Profumo and L. Ubaldi, arXiv:1412.1105; C. Kouvaris, I. M. Shoemaker and K. Tuominen, arXiv:1411.3730.

[27] M. Ackermann et al., Phys. Rev. D 86, 022002 (2012).

[28] A. Hryczuk, I. Cholis, R. Iengo, M. Tavakoli and P. Ullio, JCAP 1407, 031 (2014) [arXiv:1401.6212].

[29] A. X. Gonzalez-Morales, S. Profumo and F. S. Queiroz, arXiv:1406.2424.

[30] M. A. Fedderke, J. Y. Chen, E. W. Kolb and L. T. Wang, JHEP 1408, 122 (2014) [arXiv:1404.2283 [hep-ph]].