Interpreting a CMS $lljjp_T$ Excess With the Golden Cascade of the MSSM

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CMS recently reported an excess consistent with an invariant mass edge in opposite-sign same flavor (OSSF) leptons, when produced in conjunction with at least two jets and missing transverse momentum. We provide an interpretation of the edge in terms of (anti-)squark pair production followed by the ‘golden cascade’ decay for one of the squarks: $\tilde{q} \rightarrow \tilde{\chi}^0_l \rightarrow l\tilde{l} \rightarrow \tilde{\chi}^0_l \mu l$ in the minimal supersymmetric standard model (MSSM). A simplified model involving binos, winos, an on-shell slepton, and the first two generations of squarks fits the event rate and the invariant mass edge while passing current collider constraints. We present the good-fit parameter space of the model, along with squark production predictions for LHC Run II conducted at 13 TeV centre of mass energy. Portions of the good-fit parameter space also predict a thermal relic density of neutralino dark matter ($\Omega h^2$) compatible with cosmological observations, and an anomalous magnetic moment of the muon ($g-2$)$_\mu$ compatible with measurements.

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A recent CMS search for beyond the standard model physics in a channel with at least two leptons, at least two jets and missing transverse momentum ($p_T$), reports a $2.6\sigma$ excess [1] for 19.4 fb$^{-1}$ of integrated luminosity at a centre of mass energy of 8 TeV. The signal consists of two isolated OSSF leptons $l$ (e or $\mu$). $e\mu$ opposite sign opposite-flavor (OSOF) leptons are used to measure the backgrounds accurately. These are dominated by $tt$, which gives equal rates for the same-flavor and opposite-flavor channels. Drell-Yan production of $\gamma^*/Z^0$ bosons is a secondary irreducible background, yielding same-flavor events, and is estimated by a control region in the event kinematics which does not overlap with the signal region. The other general purpose LHC experiment, ATLAS, has yet to provide a similar analysis of its 8 TeV LHC data.

The CMS excess over Standard Model expectation is depicted in Fig. 1 and shows an interesting kinematical feature: the invariant mass of the lepton pair $m_{ll}$ is consistent with a right triangular shaped kinematic edge at $m_{ll} = 78.7 \pm 1.4$ GeV [1]. Features such as edges are less likely to come from mis-modelling the detector response to backgrounds than smoother shapes, and so they are particularly welcome as indicators of a signal. This triangular edge is a classic signal of the production of supersymmetric (SUSY) particles which undergo two-body cascade decays through successively lighter on-shell SUSY particles, for example the chain $\tilde{\chi}^0_2 \rightarrow \tilde{l}^- l^+$ or $\tilde{\chi}^0_3 \rightarrow \tilde{\chi}^0_1 l^- l^+$. In the MSSM, the lightest neutralino $\tilde{\chi}^0_1$ is a stable, weakly interacting dark matter candidate and provides $p_T$ in LHC events, whereas $\tilde{l}$ are SUSY scalar copies of the leptons. In fact there are four neutralinos predicted by the MSSM, $\tilde{\chi}^0_i$, which in general are mixtures of the fermionic SUSY copies of higgs bosons, $Z^0$ bosons and photons $\gamma$. The jets in the event could either be the result of initial state radiation or of the $\tilde{\chi}^0_i$ being produced itself by the decay of a SUSY copy of a quark, the squark $\tilde{q} \rightarrow \tilde{\chi}^0_1 q$. This golden chain, starting from the squark, see Fig. 2, has been intensely studied for the possibilities it brings for determining the parameters of the particles involved, such as mass and spin. For a review see [2].

The MSSM predicts that the LHC produces pairs of SUSY particles, e.g. squarks and neutralinos, each with various possible decay chains. As an interpretation CMS gave three benchmark model points with a

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FIG. 1. Invariant mass distribution of OSSF in the CMS selection after cuts. The Standard Model background is shown, which is calculated from data by using OSOF events, as well as the observed data and an example signal point in our parameter space involving the golden cascade: $M_2 = 300$ GeV, $m_{\tilde{t}_R} = 200$ GeV, $m_{\tilde{q}} = 1050$ GeV. Error bars on the observed number of events show the expected statistical standard deviation.

FIG. 2. Feynman diagram for the golden cascade decay.
They solved it for the other 4 solutions coming from the central value inferred from CMS data in the decay. We show the edge constraint on the masses coming from the cascade decay chain \[ \tilde{\chi}^0_2 \] and edge inferences: \[ m_{ll}^{\text{max}} = 78.7 \text{ GeV} \].

They showed that the predicted \[ m_{ll}^{\text{max}} \] distribution was roughly in agreement with data for two of their benchmarks but provided no scan or other tests of them. Here, we shall instead interpret the excess in terms of squarks from the first two generations and provide a more comprehensive exploration of the interesting parameter space. Strong direct constraints on squarks from the first two generations come from LHC searches for jets and \( p_T \) and no leptons, since jets and \( p_T \) come from the production and subsequent decays of strongly interacting SUSY particles (squarks and gluinos), ultimately into the lightest neutralino. However, we shall show that it is possible to fit the CMS excess involving leptons while respecting these strong constraints.

The edge in \( m_{ll} \) predicted by the \( \tilde{\chi}^0_2 \) decay chain is due to kinematics: one finds [5], by energy-momentum conservation, that in the decay chain described above with an on-shell slepton \( \tilde{l} \), it has a maximum value

\[
m_{ll}^{\text{max}} = \sqrt{\frac{(m_{\tilde{\chi}^0_2}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\tilde{\chi}^0_2}^2)}{m_{\tilde{l}}^2}}.
\]

Thus, measurement of the edge leads to a constraint upon the masses of the three SUSY particles involved in the decay. We show the edge constraint on the masses coming from the central value inferred from CMS data in Fig. 3. From the endpoint constraint alone the hypersurface will extend to infinite masses, while from below it only bounds the mass of \( \tilde{\chi}^0_2 \). The errors on the CMS fit to the edge are so small that varying \( m_{ll}^{\text{max}} \) within them would produce no visible difference in the figure.

In our interpretation we follow the CMS counting experiment analysis where two OSSF leptons are required to have transverse momentum \( p_T > 20 \text{ GeV} \) and pseudorapidity \( |\eta| < 2.4 \), excluding the range \( 1.4 < |\eta| < 1.6 \) where electron and muon efficiencies differ greatly. Jets are reconstructed by the anti-\( k_T \) algorithm [6] using FastJet [7], with a jet radius parameter of \( R = 0.5 \), and are required to have \( p_T > 40 \text{ GeV} \) and lie within \( |\eta| < 3.0 \). A combination of two jets and missing transverse momentum \( \vec{p}_T > 150 \text{ GeV} \), or three or more jets and \( \vec{p}_T > 100 \text{ GeV} \), is required in the events. For di-lepton invariant masses in the range \( 20 \text{ GeV} < m_{ll} < 70 \text{ GeV} \) the total CMS background estimate is \( 730 \pm 40 \) events for central production (both leptons within \( |\eta| < 1.4 \)), whereas 860 OSSF, corresponding to a 2.6\( \sigma \) deviation. The deviation of \( 130^{+48}_{-49} \) events constrains the MSSM parameter space.

For given \( m_{\tilde{\chi}^0_1} \) and \( m_{\tilde{\chi}^0_2} \) masses and the measured \( m_{ll}^{\text{max}} \), there are at most two possible positive real solutions of Eq. (1) for \( m_{l} \). In the rest of this work we shall pick \( m_{l} \) and either \( m_{\tilde{\chi}^0_1} \) or \( m_{\tilde{\chi}^0_2} \) by changing an input parameter, then impose Eq. (1) by solving it for the other neutralino mass. Then, the overall interpreted signal rate gives the mass for the squarks: the heavier they are, the smaller the production cross section and the smaller the rate.

We shall use a bottom-up prescription in order to fit the CMS excess, setting MSSM particles that are irrelevant for the signal to be heavy. We use as free parameters the wino soft-mass \( M_2 \), a common first and second gen-

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1 In this chain, the \( \tilde{\chi}^0_2 \) decays through an off-shell Z, which does not predict an exact triangular di-lepton distribution [3, 4].
eration\textsuperscript{2} right-handed soft mass $m_{\tilde{t}_R}$, solving for the correct value of the bino soft-mass $M_1$,\textsuperscript{3} and a common first and second generation squark mass (both left- and right-handed) $m_{\tilde{q}}$. The SUSY copy of the left-handed lepton’s mass $m_{\tilde{\ell}_L}$ is fixed to be $2m_{\tilde{t}_R}$. Setting $m_{\tilde{\ell}_L} < m_{\tilde{t}_R}$ would introduce the $\tilde{t}_L$ into the decay chain, and light sneutrinos that steal branching ratio from the golden cascade, and thus lower the signal rate. All other soft masses are decoupled at\textsuperscript{4} 3500 GeV, and the trilinear soft SUSY breaking scalar couplings are set to zero. Decoupling the gluino mass makes it easier for the scenario to pass constraints from searches in the jets plus $p_T$ channel, however, an alternative interpretation could potentially be found by decoupling the squarks instead. We also set $\tan\beta = 10$. Although this is a parameter in the neutralino mass matrix we have checked that changing $\tan\beta$ has a negligible effect on our CMS fit. We show an example spectrum, along with prominent decays, in Fig. 4.

We calculate the resulting sparticle spectrum using \texttt{SOFTSUSY 3.5.1}\textsuperscript{10} and the sparticle branching ratios with \texttt{SUSYHIT 1.4}\textsuperscript{11}. Spectrum and decay information is communicated via the SUSY Les Houches Accord [9]. We then generate 40 000 SUSY Monte Carlo events per point using \texttt{Pythia 8.186}\textsuperscript{12, 13}. These are propagated through our implementation of the CMS analysis. For given values of $m_{\tilde{t}_R}$ and $M_2$, $M_1$ is calculated to solve Eq. 1. In all, 40 values of $m_{\tilde{q}}$ between 50 GeV and 2 TeV are scanned, and by interpolation, the number of predicted events is used to find points in the parameter space that give exactly the central value of the measured excess.

Both ATLAS and CMS have searched in the jets and $p_T$ channel. Neither experiment observed a significant excess, and the exclusions from each are rather similar. Here, we constrain our parameter space with an ATLAS search at 8 TeV in 20.3 fb\textsuperscript{-1} of integrated luminosity\textsuperscript{14}. They interpreted the lack of excess as a constraint in the $m_{\tilde{q}} - m_{\tilde{\chi}_1^0}$ plane, assuming a decoupled gluino and a 100% branching ratio for $\tilde{q} \rightarrow q\chi_1^0$. We reproduce the observed limit in Fig. 5. The similar CMS search is also shown on the figure\textsuperscript{15}. We will also apply bounds from an ATLAS search for sleptons\textsuperscript{16} in the di-leptons plus missing transverse momentum channel, where a 100% branching ratio for $\tilde{t}_R \rightarrow \chi_1^0\ell_R$ is assumed. For points lying in either shaded region, we shall consider them to be excluded.

This is a conservative approach, because in our good-fit parameter space, the branching ratios involved in the excluded regions may be less than 100%. A few parameter points are excluded by the jets plus $p_T$ constraint, whereas only one couple are excluded by the slepton search.

The result of our scan is shown in Fig. 6. We see that a significant portion of our parameter space fits the central value of the CMS excess rate. The predicted $m_{\tilde{\mu}}$ distribution of an example point that fits the rate and the inferred edge is shown in Fig. 1. It agrees well with data. Viable squark masses between 600 GeV and 2000 GeV are predicted, depending upon parameters. There is an upper bound on slepton masses $m_{\tilde{\mu}} < 800$ GeV implied by the fit. This is because in order to get a sizeable decay rate for the golden cascade, we require the mass ordering $m_{\tilde{q}} > m_{\chi_1^0} > m_{\tilde{t}_R} > m_{\tilde{\chi}_2^0}$ and for such high $m_{\tilde{q}}$, it is no longer possible to get a large enough signal event rate. $m_{\chi_1^0}$ is highly correlated with $m_{\tilde{t}_R}$ in order to get the central inferred $m_{\tilde{q}}^{\text{max}}$ value, and lies in the range 50 GeV to 800 GeV. We have checked that, with a lower signal rate that is just allowed at the 95% CL, slightly higher squark masses are predicted in order to lower the rate. In addition, a few more points in the $m_{\chi_2^0} - m_{\tilde{t}_R}$ plane become feasible.

It is possible that SUSY is responsible for the measurement of $(g - 2)_\mu$\textsuperscript{17}, which disagrees with Standard Model expectations at the 3.5$\sigma$ level. The dominant SUSY contribution involves one-loop diagrams with sleptons and the lightest neutralinos/charginos, all of which are quite light in our scenario. We show the predicted value of the SUSY contribution in the upper panel of Fig. 7 from \texttt{MicrOMEGAs 3.6.9.2}\textsuperscript{18, 19}, and it is clear that some of the good-fit parameter space is compatible with the inferred required additional contribution.

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\textsuperscript{2} CMS did not release a flavor decomposition of the events. Given more statistics, this can be used to infer a possible smuon-selectron mass splitting\textsuperscript{8}.

\textsuperscript{3} We consider both hierarchies: $M_2 > M_1$ (bino dominated LSP) and $M_2 < M_1$ (wino dominated LSP).

\textsuperscript{4} Instead of fixing the Lagrangian parameters for the soft SUSY breaking Higgs mass parameters, we calculate them by minimising the MSSM Higgs potential after fixing $M_A$ and the $\mu$ parameter to 3500 GeV\textsuperscript{9}.
FIG. 6. Constraints on parameter space. A coloured box indicates a point that fits the central inferred value of signal rate and is also consistent with CMS’s edge inference. The squark mass is given by reference to the scale on the right-hand side. A cross indicates that the point fails our simple implementation of an ATLAS search for jets plus $p_T$ [14], whereas a ‘+’ fails an ATLAS search for sleptons [16].

$\Delta(g − 2)_\mu/2 = (29.4 \pm 8.8) \times 10^{-10}$ for $^5 \tan \beta = 10$. We also show, in the bottom panel of Fig. 7, the predicted dark matter thermal relic density, which is compatible with the value inferred from cosmological observations $\Omega h^2 = 0.1198 \pm 0.0026$ [20]. In the early universe, (co-)annihilation processes involve sleptons, and tend to give leptons in the final state. The diagonal dark stripe on the upper edge of the figure is due to wino-dominated neutralinos, which have large annihilation cross-sections, and so they annihilate efficiently. It is striking that parameter space consistent with the LHC constraints, $\Omega h^2$ and the $(g − 2)_\mu$ measurement exists.

The squark masses as constrained in Fig. 6 predict particular squark production cross-sections for Run II of the LHC, which is expected to be conducted with 13 TeV centre of mass $pp$ collisions. In Fig. 8, using Prospino [21], we show that a NLO cross-section of several to thousands of femtobarns in the allowed parameter space is possible.

$^5$ Note that $\Delta(g − 2)_\mu$ is approximately proportional to $\tan^2 \beta$, and so different parts of the good-fit region would be preferred at different values of $\tan \beta$.

To summarize, we have shown that a golden cascade interpretation of the CMS excess in di-lepton $p_T$ events is viable, and fits data well, including the inferred dark matter relic density and anomalous magnetic moment of the muon. Squark masses below 2000 GeV are compatible with the number of events seen, and the prospects for sparticle production at LHC Run-II are good: in the good-fit region, one can produce squarks with cross-sections from 10 fb and up. The slepton mass ranges
from 150–800 GeV, and the lightest neutralino mass up to 800 GeV. The golden cascade also predicts kinematic edges in the \( m_{ql} \) and \( m_{qll} \) invariant masses \([5]\), so we encourage CMS to look for these in their current \( lljj/\not{p_T} \) sample. We eagerly await a similar ATLAS analysis in the \( lljj/\not{p_T} \) channel from 8 TeV LHC data, as well as a definitive verdict from LHC Run II.

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