Squark-mediated Higgs+jets production at the LHC

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We investigate possible scenarios of light-squark production at the LHC as a new mechanism to produce Higgs bosons in association with jets. The study is motivated by the SUSY search for H+jets events, performed by the CMS collaboration on $\sqrt{s} = 8,13\,\text{TeV}$ data using the razor variables. Two simplified models are proposed to interpret the observations in this search. The constraint from Run I and the implications for Run II and beyond are discussed.

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INTRODUCTION

The ATLAS and CMS collaborations has searched intensively for SUSY production in the data collected at a center-of-mass energy $\sqrt{s} = 8\,\text{TeV}$ in 2012. A large part of the searches focused on SUSY models with conserved R-parity, for which the lightest SUSY particle (LSP) is stable. The LHC is particularly sensitive to the production of SUSY partners charged under QCD (squarks and gluinos), given the dominant hadroproduction cross section in proton-proton collisions. Following the stringent bounds on generic SUSY models obtained with $\sqrt{s} = 7\,\text{TeV}$ data, ATLAS and CMS moved the focus of their SUSY searches to the so-called natural SUSY models [1]. In its minimal realization, a natural SUSY spectrum is composed of the minimum set of SUSY partners needed to protect the mass of the Higgs (H) boson from quantum corrections: a gluino, one bottom squark, two top squarks, and three higgsinos (two neutral and one charged). This SUSY scenario results in events with multiple top and bottom quarks, produced in association with missing transverse energy $E_T^{\text{miss}}$. No evidence for the production of such particles has been found, pushing the allowed mass range for gluinos and top squarks above $\sim 1600\,\text{GeV}$ and $\sim 700\,\text{GeV}$, respectively, for a low-mass neutralino LSP and largely independent of the top squark and gluino branching ratios (see for instance Ref. [2, 3]).

In a few cases, a data yield above the expected background was observed for certain signal regions, for example, in the case of the edge dilepton analysis by CMS [4] and the SUSY search in Z+jets events by ATLAS [5]. These excesses correspond to, respectively, $\sim 2.4\sigma$ and $\sim 3.0\sigma$ of local significance, which are reduced after accounting for the look-elsewhere effect (LEE). Several interpretations of these results were given in the literature [6–11], mainly related to the electroweak production of SUSY particles with long decay chains.

Here we discuss the re-interpretation of the search for electroweak SUSY partners in H($\gamma\gamma$)+ ≥ 1 jet events by the CMS collaboration performed at 8 TeV [12]. The analysis uses the diphoton invariant mass $m_{\gamma\gamma}$ to select events with a H-like candidate. The non-resonant (mostly QCD diphoton production) and resonant (standard model H($\gamma\gamma$) production) backgrounds are estimated using the $m_{\gamma\gamma}$ sidebands in data and the Monte Carlo simulation, respectively. The background prediction is performed as a function of the razor variables $M_R$ and $R^2$ in five mutually exclusive boxes, targeting different final states: high-$p_T$ H($\gamma\gamma$) (HighPt box), H($\gamma\gamma$) + H(b$\bar{b}$) (Hbb box), H($\gamma\gamma$) + Z(b$\bar{b}$) (Zbb box), and low-$p_T$ H($\gamma\gamma$) with high- and low-resolution photons (HighRes and LowRes boxes, respectively). Five events are observed in one ($M_R$, $R^2$) bin of the HighRes box, compared to less than one expected background event. This corresponds to a local significance of 2.9σ, reduced to 1.6σ after the LEE.

In this paper, we propose and study a new interpretation of this search in terms of SUSY models with light quarks. We emulate this CMS analysis to derive bounds on squark production. Since the analysis does not require or veto jets originating from b-quarks (b-jets), the results apply to bottom-squark production in natural SUSY models.

Recently, an updated search was performed with data collected at 13 TeV [13]. One of the models proposed during the studies presented in this paper (model B) was also used for the interpretation of the results.

BENCHMARK SIGNAL MODELS

We consider two simplified models with bottom squark pair production, both resulting in a H+jets final state.

In the first model, hereafter referred to as model A, we consider the asymmetric production of a $b_2\bar{b}_1$ pair, where $b_2$ and $b_1$ are the heaviest and the lightest bottom squarks, respectively. The $b_2$ decays to $b\chi^0_2$, with $m_{\chi^0_2} \rightarrow H\chi^0_1$. The lightest neutralino $\chi^0_1$ is assumed to be...
the LSP. The \( \tilde{b}_1 \), close in mass to the LSP, decays to \( b\tilde{\chi}^0_1 \). All the other SUSY partners are assumed to be too heavy to be produced at the LHC and are ignored in this analysis. This model represents a new mechanism for the production of H + 2b-jets + invisible, with one of the associated b-jets typically having low momentum.

In the second model, hereafter referred to as model B [14], two bottom squarks \( b_1b_1 \) are produced, each decaying as \( b_1 \rightarrow b\tilde{\chi}^0_2 \). The \( \tilde{\chi}^0_2 \) then decays to \( H\tilde{\chi}^0_1 \), the \( \tilde{\chi}^0_1 \) being the LSP. As for model A, the other SUSY partners are ignored. This simplified model corresponds to a final state consisting of 2H + 2b-jets + invisible.

The mass spectrum for each model is shown in Fig. 1. We fix the \( \tilde{\chi}^0_2 \) and \( \tilde{\chi}^0_1 \) masses to 230 GeV and 100 GeV, respectively. In model A, we fix the \( \tilde{b}_1 \) mass to 130 GeV as varying its mass in between the limits of the \( \tilde{\chi}^0_2 \) and \( \til\chi^0_1 \) masses has little effect. Finally, we scan the \( \tilde{b}_2 \) (\( \tilde{b}_1 \)) mass between 250 GeV and 800 GeV for model A (B). These assumptions do not limit the conclusions derived on the squark production cross section. In fact, the analysis is sensitive to mass differences and not to the absolute mass of SUSY partners. On the other hand, the chosen LSP and NLSP masses does play a role when the cross section limits are translated in terms of mass exclusion bounds.

![FIG. 1: Pictorial representation of the decay chains and event topologies associated with model A (left) and model B (right), as described in the text.](image)

**EVENT GENERATION AND DETECTOR SIMULATION**

The study is performed using samples of Monte Carlo events. The event generation is performed in PYTHIA 8.210 [15, 16]. The default parton density function set is NNPDF 2.3 QCD+QED LO (with \( \alpha_s(m_Z) = 0.130 \)) [17–19]. Fast simulation of the detector is performed in DELPHES 3.3.2 [20]. The default description of CMS as provided in the release is used, except for a modification to the photon isolation and efficiency, described in the next section. Jet clustering is performed using FASTJET 3.1.3 [21]. As in CMS, the anti-\( k_T \) jet clustering algorithm is used with jet-size parameter \( R = 0.5 \) [22].

**EMULATION OF THE CMS SEARCH**

The emulated event selection is summarized as follows,

- Events with two isolated photons with \( p_T > 25 \) GeV and \( |\eta| < 1.44 \) are selected. As in Ref. [23], the photon isolation variables, \( I_\gamma \), \( I_n \), and \( I_\pi \), are computed by summing the transverse momenta of photons, neutral hadrons, and charged hadrons, respectively, inside an isolation cone of radius \( \Delta R = 0.3 \) around the selected photon. The photon isolation requirements, as in Ref [23], are computed by summing the transverse momenta of photons, neutral hadrons, and charged hadrons, respectively, inside an isolation cone of radius \( \Delta R = 0.3 \) around the selected photon.

| \( I_\gamma \) & \( I_n \) & \( I_\pi \) |
| :---: | :---: | :---: |
| barred endcap 1.3 GeV + 0.005p_T | barred endcap 3.5 GeV + 0.04p_T | barred endcap 2.6 GeV |
| endcap 1.3 GeV + 0.005p_T | endcap 2.9 GeV + 0.04p_T | endcap 2.3 GeV |

- Events with one H candidate with \( p_T > 20 \) GeV are selected. A pair of selected photons is considered an H candidate if at least one photon has \( p_T > 40 \) GeV and the diphoton mass \( m_{\gamma\gamma} > 100 \) GeV. If the event contains more than one H candidate, the one with the highest scalar sum \( p_T \) of the two photons is selected.

- Jets are reconstructed using the FASTJET [21] implementation of the anti-\( k_T \) [22] algorithm with jet radius parameter \( R = 0.5 \).

- Events with at least one jet with \( p_T > 30 \) GeV and \( |\eta| < 3.0 \) are selected.

- An emulation of the “medium” requirement (mistag probability of 1% and b-tag efficiency of
A b\bar{b} candidate pair is identified if both jets satisfy the medium requirement of the b-tagging algorithm (note: the CMS analysis requires only one to satisfy the medium requirement, while both are required to satisfy the loose requirement).

- The b\bar{b} candidate pair with the mass closest to 125 GeV or 91.2 GeV is chosen as the H → b\bar{b} or Z → b\bar{b} candidate, respectively.

- The razor variable \textit{M}_R, calculated from two megajets \cite{25} is required to be greater than 150 GeV. All possible combinations of the reconstructed jets and the H(\gamma\gamma) candidate are clustered to form megajets. The pair of megajets that minimizes the sum in quadrature of the invariant masses of the two megajets is selected.

After this baseline selection, events are categorized according to the following requirements,

- \textit{HighPt}: all events with an H → \gamma\gamma candidate with \textit{p}_T > 110 GeV.

- \textit{Hbb}: remaining events with a H → b\bar{b} candidate with mass 110 \geq m_{b\bar{b}} \geq 140 GeV.

- \textit{Zbb}: remaining events with a Z → b\bar{b} candidate with mass 76 \geq m_{b\bar{b}} \geq 106 GeV.

- \textit{HighRes}: 70\% of remaining events after the Zbb selection (emulating the efficiency of the “high-resolution photon” selection).

- \textit{LowRes}: all remaining events.

We assume the breakdown of events between the \textit{HighRes} box and \textit{LowRes} box is 70\%-to-30\% after the Zbb selection. This is based on the following observations: (i) CMS categorizes events in the \textit{HighRes} box if both photons in the event satisfy \textit{\sigma}_E/E < 0.015, where \textit{\sigma}_E/E is the estimated relative energy resolution, and categorizes events in the \textit{LowRes} box otherwise, (ii) CMS observes a similar 70\%-to-30\% breakdown for both SM Higgs production and electroweak SUSY processes in Monte Carlo simulation \cite{12}, and (iii) we expect this breakdown to be model-independent assuming both photons are real and come from the decay of a Higgs boson, as it is based on the properties of such photons detected in CMS and not on the details of the model.

Finally, the search region selection is as follows,

- The search region in the \textit{m}_{\gamma\gamma} distribution is defined by (125 - 2\textit{\sigma}_{\text{eff}}, 126 + 2\textit{\sigma}_{\text{eff}}) in each event category, where \textit{\sigma}_{\text{eff}} is defined such that \sim 68\% of Higgs boson events fall in an interval of \pm \textit{\sigma}_{\text{eff}} around the nominal \textit{m}_H value. Following this procedure using our generated and simulated signal samples, we derive \textit{\sigma}_{\text{eff}} to be 3.8 GeV in the \textit{HighPt} box and 2.2 GeV in the \textit{HighRes} and \textit{LowRes} boxes. For the \textit{Hbb} and \textit{Zbb} boxes, due to the low number of selected signal events, we use the overall average value of 2.8 GeV.

We note that these \textit{\sigma}_{\text{eff}} values are larger than the corresponding ones in Ref. \cite{12}. This is due to the larger width observed for the diphoton mass distribution in Higgs boson events simulated and reconstructed with DELPHES, compared to official CMS software. This implies the effective diphoton mass resolution when using DELPHES is larger than in the real CMS detector. We attempt to account for this with a modification explained in Sec. .

**BAYESIAN STATISTICAL INTERPRETATION**

We model the likelihood according to a Poisson density, considering the expected background yield (with associated uncertainty), the expected signal yield (for a given signal cross section), and the observed yield. The background uncertainty is modeled with a gamma density. The background yields and the corresponding uncertainties are taken from the tables provided in Ref. \cite{12}. To take into account systematic uncertainties on the signal, we assign a 30\% uncertainty (assuming a log-normal density) on the signal strength, a multiplicative factor modifying the signal cross section. We then derive the posterior density for the signal cross section \sigma as:

\[
p(\sigma|\text{data}) \propto L(\text{data}|\sigma)p_0(\sigma)
\]  

where \textit{L(\text{data}|\sigma)} is the likelihood and \textit{p}_0(\sigma) is the prior density taken to be uniform. The likelihood is then

\[
L(\text{data}|\sigma) = \int_0^{\infty} d\mu \text{Ln}(\mu|\tilde{\mu}, \delta\mu) \\
\times \prod_{i=0}^{n_{\text{bins}}} \int_0^{\infty} db_i \text{Poisson}(n_i|L\mu \epsilon_i + b_i) \\
\times \Gamma(b_i|b_i, \delta b_i)
\]

where the product runs over the number of bins \textit{n}_{\text{bins}}: \textit{n}_i is the observed yield in the \textit{i}th bin, \textit{L} is the integrated luminosity, \textit{b}_i is the assumed value of the background yield in the \textit{i}th bin and \textit{b}_i \pm \delta \textit{b}_i is its expected value and the associated uncertainty; \epsilon_i is the nominal value of the signal efficiency times acceptance in the \textit{i}th bin; \mu is the signal strength, a nuisance parameter modifying the signal cross section (nominally equal to \tilde{\mu} = 1 with a \delta\mu = 30\% uncertainty); \text{Ln}(x|m, \delta) is the log-normal distribution for \textit{x}, parameterized such that \text{Log}(m) is the mean and \text{Log}(1 + m\delta) is the standard deviation of the log of the distribution; \Gamma(x|m, \delta) is the gamma distribution.
for $x$, parameterized such that $m$ is the mode and $\delta^2$ is the variance of the distribution. The 95% credibility level (CL) upper limit on the signal cross section $\sigma_{up}$ is obtained from the posterior, such that

$$ \frac{\int_0^{\sigma_{up}} d\sigma p(\sigma|\text{data})}{\int_0^{\infty} d\sigma p(\sigma|\text{data})} = 0.95. \quad (4) $$

We also utilize a signal significance measure defined by

$$ Z(\sigma) = \text{sign}[\log B_{10}(\text{data}, \sigma)] \sqrt{2|\log B_{10}(\text{data}, \sigma)|}, \quad (5) $$

where

$$ B_{10}(\text{data}, \sigma) = \frac{L(\text{data}|\sigma, H_1)}{L(\text{data}|H_0)} \quad (6) $$

is the local Bayes factor for the data for a given signal cross section $\sigma$, and $L(\text{data}|\sigma, H_1)$ and $L(\text{data}|H_0)$ are the likelihoods for the signal-plus-background ($H_1$) and background-only ($H_0$) hypotheses, respectively. As described in Ref. [26], this measured is a signed Bayesian analog of the frequentist “n-sigma.” For each signal model with specified masses, we scan the signal cross section $\sigma$ to find the maximum significance, which occurs at the mode of the posterior.

**CORRECTION AND VALIDATION**

As discussed above, we find differences in the performance of the emulated CMS detector and the real CMS detector, e.g. the larger diphoton mass resolution. To take into account this and other differences in the detector simulation and reconstruction performed by DELPHES and official CMS software, we conservatively double the background uncertainties in each bin reported by CMS in Ref. [12] when evaluating the likelihood in Eqn. 3. We find this conservative approach better reproduces the observed and expected limits on a benchmark simplified model.

To validate our emulation result, we produced 95% CL limits on the production cross section of an electroweak simplified model of $\tilde{\chi}^\pm_1 \tilde{\chi}^0_2$ production, followed by the decays $\tilde{\chi}^\pm_1 \rightarrow W^\pm \tilde{\chi}^0_1$, $\tilde{\chi}^0_2 \rightarrow H \tilde{\chi}^0_1$. For this model, CMS provides the 95% confidence level upper limits on the cross section assuming an LSP mass of $m_{\tilde{\chi}^0_1} = 1$ GeV and equal chargino and second neutralino masses, $m_{\tilde{\chi}^\pm_1} = m_{\tilde{\chi}^0_2}$. The comparison between our result and the CMS result for this model is shown in figure 2 as a function of $m_{\tilde{\chi}^1_1}$.

**RESULTS**

Figures 3-5 contain the results of the reinterpretation of the CMS data for both models. To show how well signal model A agrees with the excess observed by CMS, the 95% CL upper limit on the signal cross section $\sigma_{up}$ is obtained from the posterior, such that

$$ \frac{\int_0^{\sigma_{up}} d\sigma p(\sigma|\text{data})}{\int_0^{\infty} d\sigma p(\sigma|\text{data})} = 0.95. \quad (4) $$

We also utilize a signal significance measure defined by

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**RESULTS**

Figures 3-5 contain the results of the reinterpretation of the CMS data for both models. To show how well signal model A agrees with the excess observed by CMS,

![Figure 2: Comparison between the CMS result (red) and our emulation (black). Note, this scan assumes $m_{\tilde{\chi}^1_1} = 100$ GeV and $m_{\tilde{\chi}^0_1} = 100$ GeV. The limit and significance scans are taken from the CMS yield tables in Ref. [12] and are reproduced in Tab. II. The normalization for each signal model is taken from the mode (i.e. “best-fit”) signal cross section of the posterior density in the HighRes box. Fig. 4 (top), shows the 95% CL combined upper limit on the cross section for model A. Finally, Fig. 5 (top) shows the maximum significance $Z$ as well as the best fit signal cross section for model A as a function of $m_{\tilde{\chi}^0_2}$. The bottom of Fig. 3-5 are the analogous results for model B. The chosen model B mass points in Fig. 3 are $m_{\tilde{\chi}^0_1} = 500$ GeV or $m_{\tilde{\chi}^0_1} = 800$ GeV, $m_{\tilde{\chi}^0_2} = 230$ GeV, and $m_{\tilde{\chi}^0_1} = 100$ GeV. The limit and significance scans in Fig. 4 and 5 are performed as a function of the $b_1$ mass. For model B, we also compare both the excluded cross section at 95% CL and the best-fit cross section as a function of the $b_1$ mass to the NLO+NLL pre-
dicted cross section at $\sqrt{s} = 8\text{ TeV}$ [27–32]. We find the 8 TeV data excludes bottom squark pair production below $m_{\tilde{b}_1} = 330\text{ GeV}$ for the chosen neutralino masses of $m_{\tilde{\chi}^0_2} = 230\text{ GeV}$ and $m_{\tilde{\chi}^0_1} = 100\text{ GeV}$. More interestingly, the largest combined significance is $1.8\sigma$ for $m_{\tilde{b}_1} = 500\text{ GeV}$ and the best-fit cross section is $0.4\text{ pb}$, which is of the same order of magnitude as the predicted cross section.

FIG. 3: (Top) The expected background and uncertainty (multiplied by a factor of two as explained in the text) compared to the best-fit signal distribution in the HighRes box for two particular mass points, $m_{\tilde{\chi}^0_2} = 500\text{ GeV}$ and $m_{\tilde{\chi}^0_2} = 800\text{ GeV}$, in model A. (Bottom) The expected background and uncertainty (multiplied by a factor of two as explained in the text) compared to the best-fit signal distribution in the HighRes box for two particular mass points, $m_{\tilde{\chi}^0_1} = 500\text{ GeV}$ and $m_{\tilde{\chi}^0_1} = 800\text{ GeV}$, in model B. The bin numbers correspond to the order of the signal regions in the yield tables in Ref. [12] and are reproduced in Tab. II.

FIG. 4: (Top) The 95% CL upper limit on the cross section on $b_1b_2$ production in model A as a function of $m_{\tilde{b}_2}$ (black). (Bottom) The 95% CL upper limit on the cross section on $\tilde{b}_1\tilde{b}_1$ production in model B as a function of $m_{\tilde{b}_1}$ (black) compared to the NLO+NLL predicted cross section (yellow). Note, these scans assume $m_{\tilde{\chi}^0_1} = 100\text{ GeV}$, $m_{\tilde{\chi}^0_2} = 230\text{ GeV}$, and for model A $m_{\tilde{b}_1} = 130\text{ GeV}$.

DISCUSSION AND SUMMARY

In this paper, we proposed two simplified models of bottom squark pair production for use in the interpretation of an excess observed by CMS in a search for SUSY in $H+\text{jets}$ events using razor variables at $\sqrt{s} = 8\text{ TeV}$ [12]. In model A, we considered the asymmetric production of a $b_2b_1$ pair, with the $b_1 \rightarrow \tilde{\chi}_1^0$, $b_2 \rightarrow b\tilde{\chi}^0_2$, and $\tilde{\chi}^0_2 \rightarrow H\tilde{\chi}_1^0$, where $\tilde{\chi}_1^0$ is a neutralino LSP and we fix the mass splitting $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} = 130\text{ GeV}$. In model B, we considered the symmetric production of a $\tilde{b}_1\tilde{b}_1$ pair, with $\tilde{b}_1 \rightarrow b\tilde{\chi}^0_2$, $\tilde{\chi}^0_2 \rightarrow H\tilde{\chi}_1^0$, and $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} = 130\text{ GeV}$.

We scanned the bottom squark masses for a fixed LSP mass of $m_{\tilde{\chi}^0_1} = 100\text{ GeV}$ for both models and quantified the agreement with the data. We found the excess observed in data is broadly consistent with both models, with the largest signal significance being $1.8\sigma$ correspond-
The work is motivated by results obtained as part of the discovery of the Higgs boson at the LHC in 2012 and especially the SUSY searches group of the CMS collaboration. The work is motivated by results obtained as part of the CMS collaboration to interpret the results of the 13 TeV search for SUSY in the same channel [13], by the CMS collaboration to interpret the results of the 8 TeV search for SUSY in events with a Higgs decaying to two photons using the razor variables. Technical Report CMS-PAS-SUS-16-012, CERN, Geneva, 2016.

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