Search for supersymmetry using razor variables in events with b-tagged jets in pp collisions at $\sqrt{s} = 8$ TeV

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An inclusive search for supersymmetry in events with at least one b-tagged jet is performed using proton-proton collision data collected by the CMS experiment in 2012 at a center-of-mass energy of 8 TeV. The data set size corresponds to an integrated luminosity of 19.3 fb^{-1}. The two-dimensional distribution of the razor variables R^2 and M_R is studied in events with and without leptons. The data are found to be consistent with the expected background, which is modeled with an empirical function. Exclusion limits on supersymmetric particle masses at a 95% confidence level are derived in several simplified supersymmetric scenarios for several choices of the branching fractions. By combining the likelihoods of a search in events without leptons and a search that requires a single lepton (electron or muon), an improved bound on the top-squark mass is obtained. Assuming the lightest supersymmetric particle to be stable and weakly interacting, and to have a mass of 100 GeV, the branching-fraction-dependent (-independent) production of gluinos is excluded for gluino masses up to 1310 (1175) GeV. The corresponding limit for top-squark pair production is 730 (645) GeV.

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I. INTRODUCTION

Supersymmetry (SUSY) is a proposed symmetry of nature that introduces a bosonic (fermionic) partner for every standard model (SM) fermion (boson) [1–9]. Supersymmetric extensions of the SM that include a stable new particle at the electroweak scale are well motivated because they may explain the origin of dark matter. The discovery of the Higgs boson [10–12] at the CERN LHC has renewed interest in "natural" SUSY models, which minimize the fine-tuning associated with the observed value of the Higgs boson mass due to its radiative corrections. In the typical spectrum of these models, the lightest neutralino and chargino are the lightest (LSP) and next-to-lightest (NLSP) SUSY particles, respectively [13–18]. Charginos and neutralinos are fermions, corresponding to a quantum mixture of the SUSY partners of the electroweak and Higgs bosons. The bottom and top squarks are the lightest squarks. The gluino is heavier than these particles but potentially accessible at the LHC. Events are thus characterized by an abundance of jets originating from the hadronization of bottom quarks, a feature that we exploit in this study. Previous searches for natural SUSY by the CMS [19–23] and ATLAS Collaborations [24–28] at the LHC have probed gluino masses up to 1300 GeV and top squark masses up to 700 GeV under the assumptions of specific decay modes for the SUSY particles.

We present an inclusive search for gluinos and top squarks in the context of natural SUSY. Natural SUSY spectra include a gluino, the third-generation squarks, a chargino, and a neutralino, representing the minimum particle content needed in SUSY theories to stabilize the Higgs boson mass. Within the context of natural SUSY, several simplified models [29–34] are considered (Sec. II), defined by a specific production mechanism of SUSY particle pairs, with at most two decay channels for each production mode.

The search is performed using events with two or more jets, at least one of which is identified as originating from a bottom quark (jet b tagging). The study is based on the data collected by the CMS Collaboration in proton-proton collisions at $\sqrt{s} = 8$ TeV in 2012, corresponding to an integrated luminosity of 19.3 fb^{-1}. We distinguish the signal from the SM background through their different shapes in the razor variables M_R and R^2 [35,36]. This search extends the results we presented at 7 TeV [37,38] using the same analysis procedure. The razor variables have also been used by the ATLAS Collaboration to perform a multichannel search for SUSY at 7 TeV [39].

The razor variables M_R and R^2 are motivated by the generic process of the pair production of two heavy particles (e.g., squarks or gluinos), each decaying to an undetected particle (the stable, weakly interacting LSP $\tilde{\chi}_1^0$) plus visible particles. The LSP is assumed to escape without detection, leading to an imbalance $\vec{p}_\mathrm{T}^\mathrm{miss}$ in the momentum perpendicular to the beam axis. Each event is treated as a dijetlike event and the four-momenta of the two jets are used to compute M_R and M_T^R, defined as

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$$M_{\mathrm{R}} \equiv \sqrt{(|\vec{p}^{j_1}| + |\vec{p}^{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2}, \quad (1)$$

$$M_{\mathrm{T}}^{\mathrm{R}} \equiv \sqrt{\frac{E_{\mathrm{T}}^{\mathrm{miss}}(p_{\mathrm{T}}^{j_1} + p_{\mathrm{T}}^{j_2}) - \vec{p}_{\mathrm{T}}^{\mathrm{miss}} \cdot (\vec{p}_{\mathrm{T}}^{j_1} + \vec{p}_{\mathrm{T}}^{j_2})}{2}}, \quad (2)$$

where $\vec{p}_{j_i}$, $\vec{p}_{\mathrm{T}}{}^{j_i}$, and $p_z^{j_i}$ are the momentum of the ith jet, its transverse component with respect to the beam axis, and its longitudinal component, respectively, with $E_{\mathrm{T}}^{\mathrm{miss}}$ the magnitude of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$. While $M_{\mathrm{T}}^{\mathrm{R}}$ quantifies the transverse momentum imbalance, M_{R} estimates the mass scale of new-physics particle production in the event. The razor dimensionless ratio is defined as

$$\mathrm{R} \equiv \frac{M_{\mathrm{T}}^{\mathrm{R}}}{M_{\mathrm{R}}}. \quad (3)$$

In this search, each event is reduced to a two-jet topology by clustering the selected objects (jets and leptons) into two megajets [36–38]. All possible assignments of objects to the megajets are considered, with the requirement that a megajet consist of at least one object. The sum of the four-momenta of the objects assigned to a megajet defines the megajet four-momentum. When more than two objects are reconstructed, more than one megajet assignment is possible. We select the assignment that minimizes the sum of the invariant masses of the two megajets.

The analysis is performed on several exclusive data sets, referred to as razor boxes, differing in the lepton and jet multiplicity. Each box with fewer than two identified leptons (electrons or muons) is analyzed in exclusive b-tagged jet multiplicity bins in order to maximize the sensitivity to both direct and cascade production of third-generation squarks. For a given box and b-tagged jet multiplicity, the shape of the SM background distribution is evaluated in two rectangular regions of the $(M_{\mathrm{R}}, \mathrm{R}^2)$ plane (sidebands), selected so that potential bias due to contributions from signal events is negligible. The background shape is then extrapolated to the signal-sensitive region of the $(M_{\mathrm{R}}, \mathrm{R}^2)$ plane. The results are interpreted in the context of several SUSY simplified models by performing a hypothesis test. The test compares the background-only and signal-plus-background possibilities through simultaneous examination of the data in the two sidebands and the signal-sensitive region [40]. In addition, we combine the results from the razor boxes with those from our previous search [19] for top-squark production in the single-lepton (electron or muon) channel to obtain an improved bound on top-squark pair production with respect to previous CMS studies. For this combination, only the razor boxes without an identified lepton (hadronic boxes) are used, so the event samples from the two studies are mutually exclusive.

This paper is organized as follows. Section II presents the spectra of the simplified natural SUSY models examined in this analysis. The CMS detector is briefly described in Sec. III. The event selection and razor variables are defined in Secs. IV and V, respectively. The statistical model used to describe the SM backgrounds, as well as the comparisons between the predicted and observed event yields in the search regions, is shown in Sec. VI, followed by a summary of the limit-setting procedure in Sec. VII. The interpretation of the results and a summary are presented in Secs. VIII and IX, respectively.

II. SIMPLIFIED NATURAL SUSY MODELS

In this paper, natural simplified SUSY scenarios are used to interpret results. The LSP is the lightest neutralino $\tilde{\chi}_1^0$ while the NLSP is the lightest chargino $\tilde{\chi}_1^{\pm}$. They are both Higgsinos, and their mass splitting is taken to be 5 GeV. The NLSP decays to the LSP and a virtual W boson ($\tilde{\chi}_1^{\pm} \to W^* \tilde{\chi}_1^0$). The other SUSY particles accessible at the LHC are the gluino and the lightest top and bottom squarks. All other SUSY particles are assumed to be too heavy to participate in the interactions. The SUSY particles and their possible decay modes within this natural SUSY spectrum are summarized in Fig. 1.

In the context of this natural spectrum, five simplified models [29–34] are considered for gluino pair production, based on three-body gluino decays [41]:

(i) *T1bbbb*: pair-produced gluinos, each decaying with a 100% branching fraction to a bottom quark-antiquark ($b\bar{b}$) pair and the LSP.

(ii) *T1tbbb*: pair-produced gluinos, each decaying with a 50% branching fraction to a $b\bar{b}$ pair and the LSP or to a top quark (antiquark), a bottom antiquark (quark), and the NLSP.

(iii) *T1ttbb*: pair-produced gluinos, decaying with a 100% branching fraction to a top quark (antiquark), a bottom antiquark (quark), and the NLSP.

(iv) *T1tttb*: pair-produced gluinos, each decaying with a 50% branching fraction to a top-quark-antiquark ($t\bar{t}$) pair and the LSP or to a top quark (antiquark), a bottom antiquark (quark), and the NLSP.

(v) *T1tttt*: pair-produced gluinos, each decaying with a 100% branching fraction to a $t\bar{t}$ pair and the LSP.

The corresponding Feynman diagrams are shown in Fig. 2.

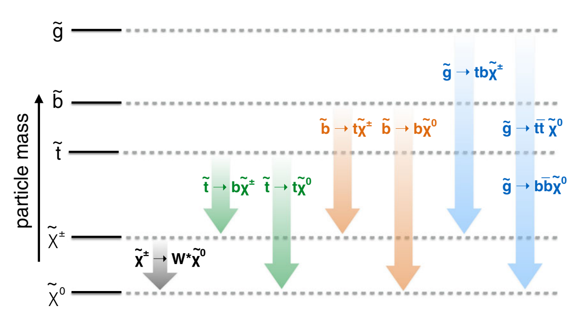

FIG. 1 (color online). The simplified natural SUSY spectrum considered in this paper, along with the assumed decay modes.

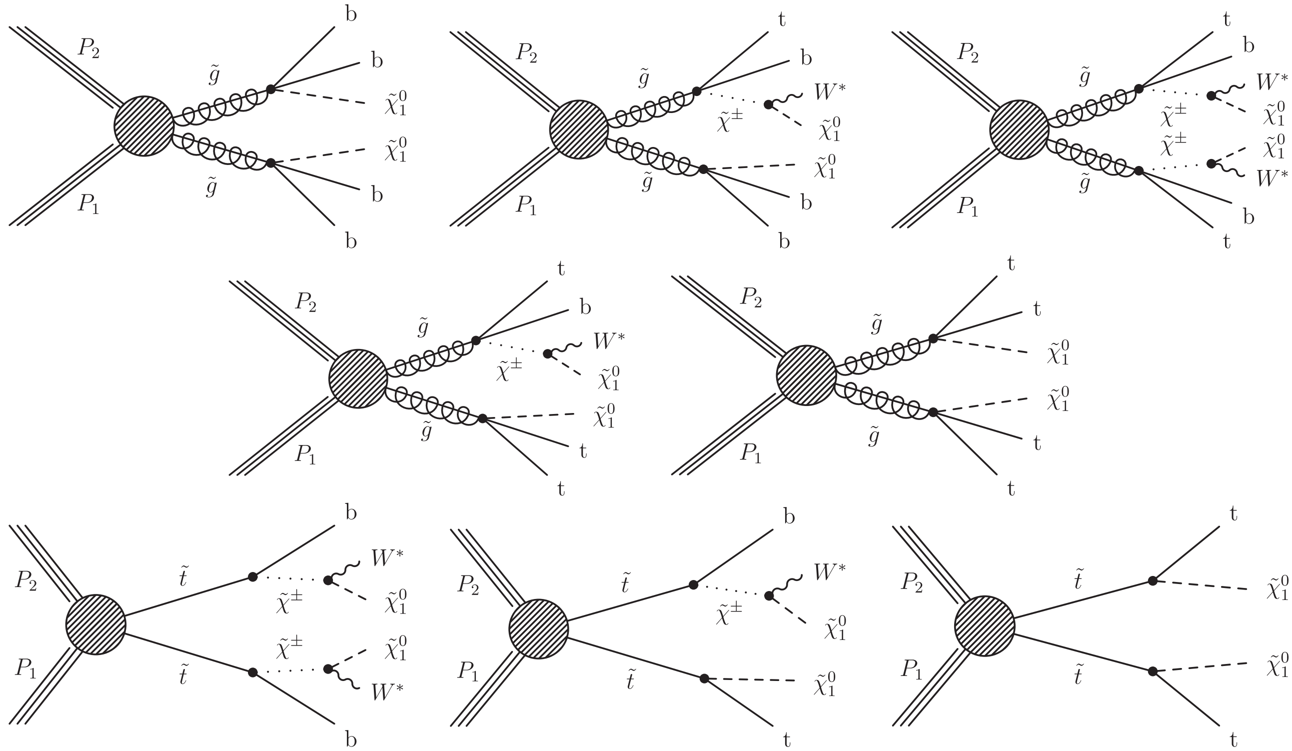

FIG. 2. Diagrams displaying the event topologies of gluino (upper 5 diagrams) and top-squark (lower 3 diagrams) pair production considered in this paper.

In addition, the following three simplified models are considered for the production of top-squark pairs:

(i) T2bW*: pair-produced top squarks, each decaying with a 100% branching fraction to a bottom quark and the NLSP.

(ii) *T2tb*: pair-produced top squarks, each decaying with a 50% branching fraction to a top quark and the LSP or to a bottom quark and the NLSP.

(iii) *T2tt*: pair-produced top squarks, each decaying with a 100% branching fraction to a top quark and the LSP.

The corresponding Feynman diagrams are shown in Fig. 2.

Events for the eight simplified models are generated with the MadGraph V5 generator [42,43], in association with up to two partons. The SUSY particle decays are treated with pythia V6.4.26 assuming a constant matrix element (phase space decay). The parton showering is described by pythia and matched to the matrix element kinematic configuration using the MLM algorithm [44], before being processed through a fast simulation of the CMS detector [45]. The SUSY particle production cross sections are calculated to next-to-leading order (NLO) plus next-to-leading-logarithm (NLL) accuracy [46–50], assuming all SUSY particles other than those in the relevant diagram to be too heavy to participate in the interaction. The NLO + NLL cross section and its associated uncertainty [51] are taken as a reference to derive the exclusion limit on the SUSY particle masses.

III. THE CMS DETECTOR

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and a silicon strip tracker, a lead-tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the magnet steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Jets and leptons are reconstructed within the pseudorapidity region $|\eta| < 3$, covered by the electromagnetic and hadron calorimeters. Muons are reconstructed with $|\eta| < 2.4$. Events are selected by a two-level trigger system. The first level (L1) is based on a hardware filter, followed by a software-based high level trigger (HLT). A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [52].

IV. EVENT SELECTION

Events are selected at the L1 trigger level by requiring at least two jets with $|\eta| < 3$. At the HLT level, events are selected using dedicated razor algorithms, consisting of a loose selection on M_R and R^2. Razor-specific triggers are

TABLE I. Kinematic and multiplicity requirements defining the nine razor boxes. Boxes are listed in order of event filling priority.

Box	Lepton	b-tag	Kinematic	Jet
		Two-lepton boxes		
MuEle	≥ 1 tight electron and ≥ 1 loose muon	≥ 1 b-tag	($M_R > 300$ GeV and $R^2 > 0.15$) and ($M_R > 350$ GeV or $R^2 > 0.2$)	≥ 2 jets
MuMu	≥ 1 tight muon and ≥ 1 loose muon			
EleEle	≥ 1 tight electron and ≥ 1 loose electron			
		Single-lepton boxes		
MuMultiJet	1 tight muon	≥ 1 b-tag	($M_R > 300$ GeV and $R^2 > 0.15$) and ($M_R > 350$ GeV or $R^2 > 0.2$)	≥ 4 jets
EleMultiJet	1 tight electron			
MuJet	1 tight muon			2 or 3 jets
EleJet	1 tight electron			
		Hadronic boxes		
MultiJet	none	≥ 1 b-tag	($M_R > 400$ GeV and $R^2 > 0.25$) and	≥ 4 jets
≥ 2 b-tagged jet	none	≥ 2 b-tag	($M_R > 450$ GeV or $R^2 > 0.3$)	2 or 3 jets

used in the HLT in order to avoid biases on the shapes of distributions from the SM background that are introduced by requirements on more traditional selection variables such as $E_T^{\rm miss}$. The razor triggers reject the majority of the SM background, which mostly appears at low R^2 and low M_R, while retaining events in the signal-sensitive regions of the (M_R, R^2) plane. Two types of triggers are used: (i) a hadronic razor trigger, which selects events that contain at least two jets with transverse momentum $p_T > 64$ GeV by applying threshold requirements on R^2, M_R, and their product; (ii) a muon and electron razor trigger, which selects events with at least one isolated electron or muon with $p_T > 12$ GeV in combination with looser requirements on R^2, M_R, and their product. The trigger efficiency, evaluated using a dedicated trigger, is measured to be $(95 \pm 5)\%$ and is independent of R^2 and M_R for the events selected with the baseline requirements described in Sec. V.

Following the trigger selection, events are required to contain at least one reconstructed interaction vertex. If more than one vertex is found, the one with the highest p_T^2 sum of associated tracks is chosen as the interaction point for event reconstruction. Algorithms are used to remove events with detector- and beam-related noise that can mimic event topologies with high energy and large p_T imbalance [53–55].

The analysis uses a global event description based on the CMS particle flow (PF) algorithm [56,57]. Individual particles (PF candidates) are reconstructed by combining the information from the inner tracker, the calorimeters, and the muon system. Five categories of PF candidates are defined: muons, electrons, photons (including their conversions to e^+e^- pairs), charged hadrons, and neutral hadrons. The contamination from other proton-proton collisions in the same or in neighboring bunch crossings is reduced by discarding the charged PF candidates that are not compatible with the interaction point. When computing lepton isolation and jet energy, the corresponding contamination from neutral particles is subtracted, on average, by applying an event-by-event correction based on the jet-area method [58–60].

A "tight" lepton identification is used for muons and electrons, consisting of requirements on isolation and track reconstruction quality. For electrons, the shape and position of the energy deposit in the electromagnetic calorimeter is used to further reduce the contamination from hadrons [61].

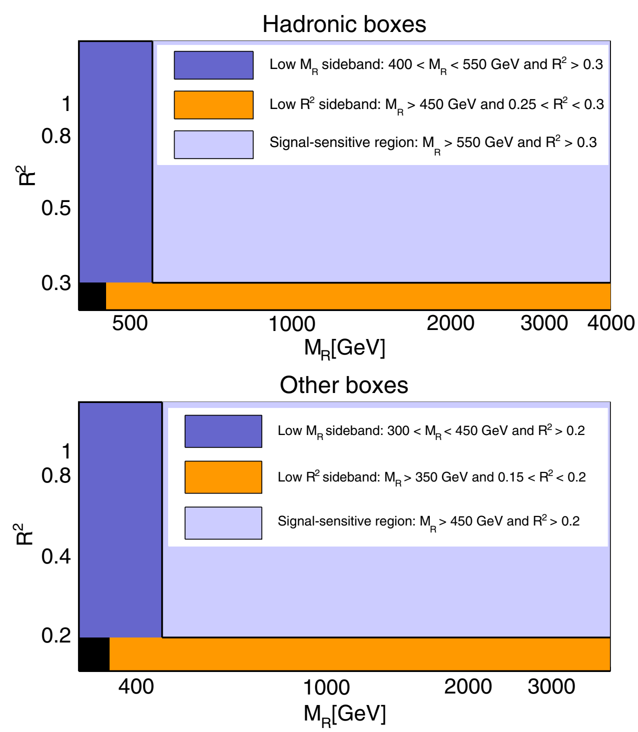

FIG. 3 (color online). Definition of the sideband and the signal-sensitive regions used in the analysis, for (top panel) the hadronic boxes and (bottom panel) the other boxes.

For events with one identified tight lepton, additional muons or electrons are identified through a "loose" lepton selection, characterized by a relaxed isolation requirement [62]. Tight leptons are required to have $p_T > 15$ GeV and loose leptons $p_T > 10$ GeV.

Jets are reconstructed by clustering the PF candidates with the FASTJET [63] implementation of the anti-k_T [64] algorithm with the distance parameter $R = 0.5$. We select events containing at least two jets with $p_T > 80$ GeV and $|\eta| < 2.4$, representing a tighter version of the L1 jet selection criterion. The p_T imbalance in the event, $\vec{p}_T^{\,\rm miss}$, is the negative of the sum of the $\vec{p}_T$ of the PF candidates in the event. Its magnitude is referred to as $E_T^{\rm miss}$. For each event, the $\vec{p}_T^{\,\rm miss}$ and the four-momenta of all the jets with $p_T > 40$ GeV and $|\eta| < 2.4$ are used to compute the razor variables, as described in Sec. V.

The medium working point of the combined secondary vertex algorithm [65] is used for b-jet tagging. The b-tagging efficiency and mistag probability are measured from data control samples as a function of the jet p_T and η. Correction factors are derived for Monte Carlo (MC) simulations through comparison of the measured and simulated b-tagging efficiencies and mistag rates found in these control samples [65].

Events with no b-tagged jets are discarded, a criterion motivated by the natural SUSY signatures described in Sec. II. A tighter requirement (≥ 2 b-tagged jets) is imposed on events without an identified tight lepton and fewer than four jets. This requirement reduces the expected background from SM production of $Z(\to \nu\bar{\nu})$ + jets events to a negligible level.

V. BOX DEFINITIONS

The selected events are categorized into the different razor boxes according to their event content as shown in Table I. In the table, the boxes are listed according to the filling order, from the first (at the top of the table) to the last (at the bottom). If an event satisfies the requirements of two or more boxes, the event is assigned to the first listed box to ensure the boxes correspond to disjoint samples.

The events in the single-lepton and two-lepton boxes are recorded using the electron and muon razor trigger. The remaining two boxes, generically referred to as "hadronic" boxes, contain events recorded using the hadronic razor trigger.

In the two-lepton boxes, the (M_R, R^2) distribution of events with at least one b-tagged jet is studied. For the other boxes, the data are binned according to the b-tagged jet multiplicity: 1 b-tag, 2 b-tags, and ≥ 3 b-tags.

A baseline kinematic requirement is applied to define the region in which we search for a signal:

(i) $M_R > 400$ GeV and $R^2 > 0.25$ for the hadronic boxes.

(ii) $M_R > 300$ GeV and $R^2 > 0.15$ for the other boxes.

The tighter baseline selection for the hadronic boxes is a consequence of the tighter threshold used for the hadronic razor trigger. The kinematic plane defined by the baseline selection is divided into three regions (see Fig. 3):

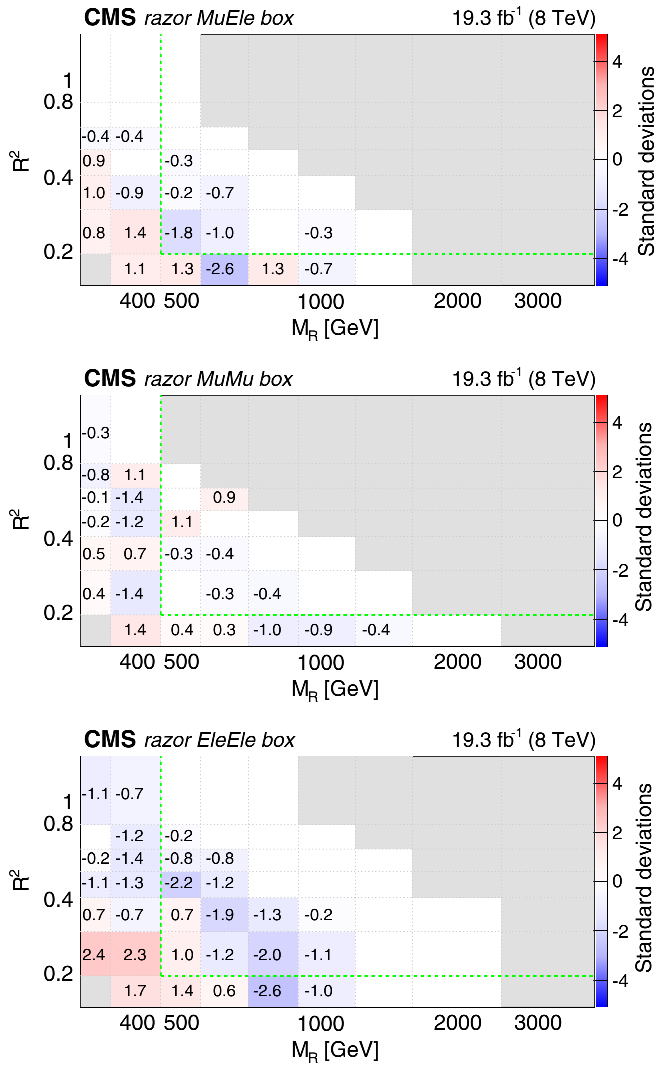

FIG. 4 (color online). Comparison of the expected background and the observed yield in the (top panel) MuEle, (middle panel) MuMu, and (bottom panel) EleEle boxes. A probability density function is derived for the bin-by-bin yield using pseudo-experiments, sampled from the output of the corresponding sideband fit. A two-sided p-value is computed comparing the observed yield to the distribution of background yield from pseudo-experiments. The p-value is translated into the corresponding number of standard deviations, quoted in each bin and represented by the bin-filling color. Positive and negative significance correspond to regions where the observed yield is respectively larger and smaller than the predicted one. The white areas correspond to bins in which a difference smaller than 0.1 standard deviations is observed. The gray areas correspond to empty bins with less than one background event expected on average. The dashed lines represent the boundaries between the sideband and the signal regions.

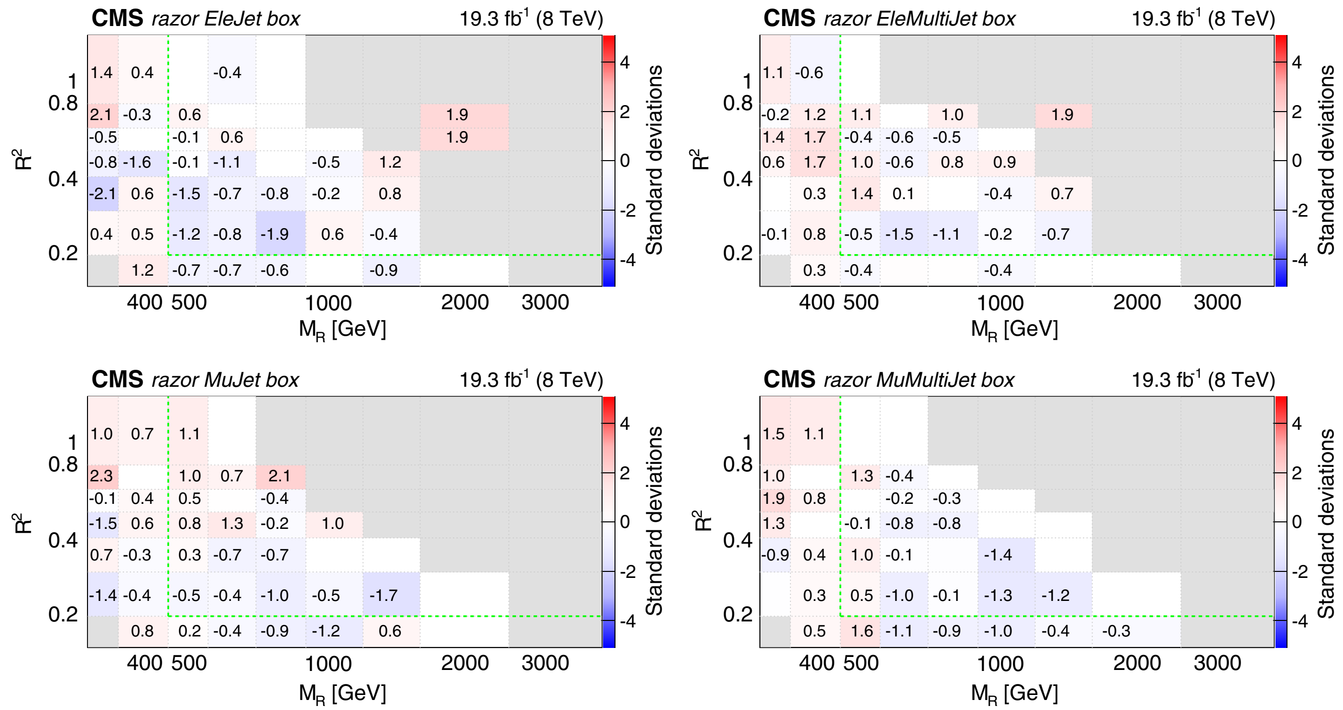

FIG. 5 (color online). Comparison of the expected background and the observed yield in (upper left panel) the EleJet, (upper right panel) the EleMultiJet, (lower left panel) the MuJet, and (lower right panel) the MuMultiJet boxes. A detailed explanation is given in the caption of Fig. 4.

(i) Low M_R sideband: $400 < M_R < 550$ GeV and $R^2 > 0.30$ for the hadronic boxes; $300 < M_R < 450$ GeV and $R^2 > 0.20$ for the other boxes.
(ii) Low R^2 sideband: $M_R > 450$ GeV and $0.25 < R^2 < 0.30$ for the hadronic boxes; $M_R > 350$ GeV and $0.15 < R^2 < 0.20$ for the other boxes.
(iii) Signal-sensitive region: $M_R > 550$ GeV and $R^2 > 0.30$ for the hadronic boxes; $M_R > 450$ GeV and $R^2 > 0.20$ for the other boxes.

The bottom left corner of the razor plane, not included in any of the three regions, is excluded from the analysis. Given this selection, the multijet background from quantum chromodynamics processes is reduced to a negligible level due to the fact that these processes typically peak at $R^2 \approx 0$ and fall exponentially for larger values of R^2 [37,38].

VI. MODELING OF THE STANDARD MODEL BACKGROUNDS

Under the hypothesis of no contribution from new-physics processes, the event distribution in the considered portion of the (M_R, R^2) plane can be described by the sum of the contributions from SM $V+$jets events (where V indicates a W or Z boson) and SM top quark-antiquark and single-top events, where the events with a top quark are generically referred to as the $t\bar{t}$ contribution. Based on MC

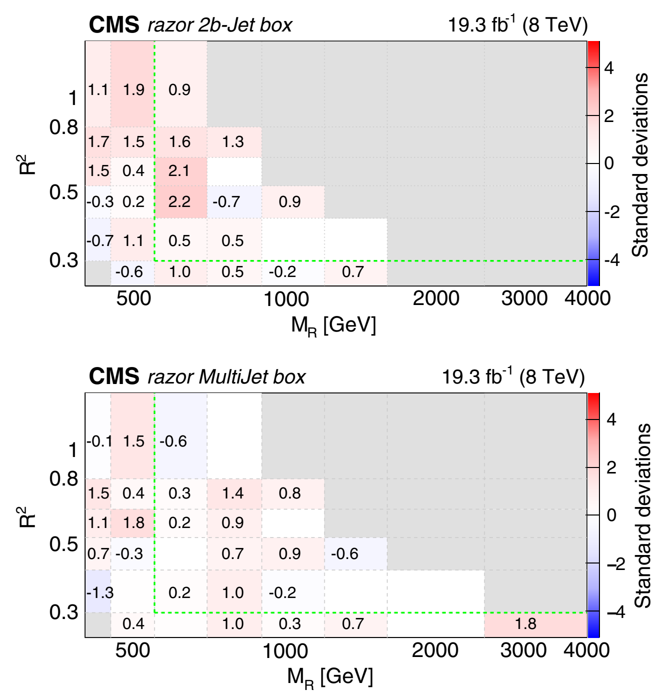

FIG. 6 (color online). Comparison of the expected background and the observed yield in the ≥ 2 b-tagged jet box (top panel) and the MultiJet box (bottom panel). A detailed explanation is given in the caption of Fig. 4.

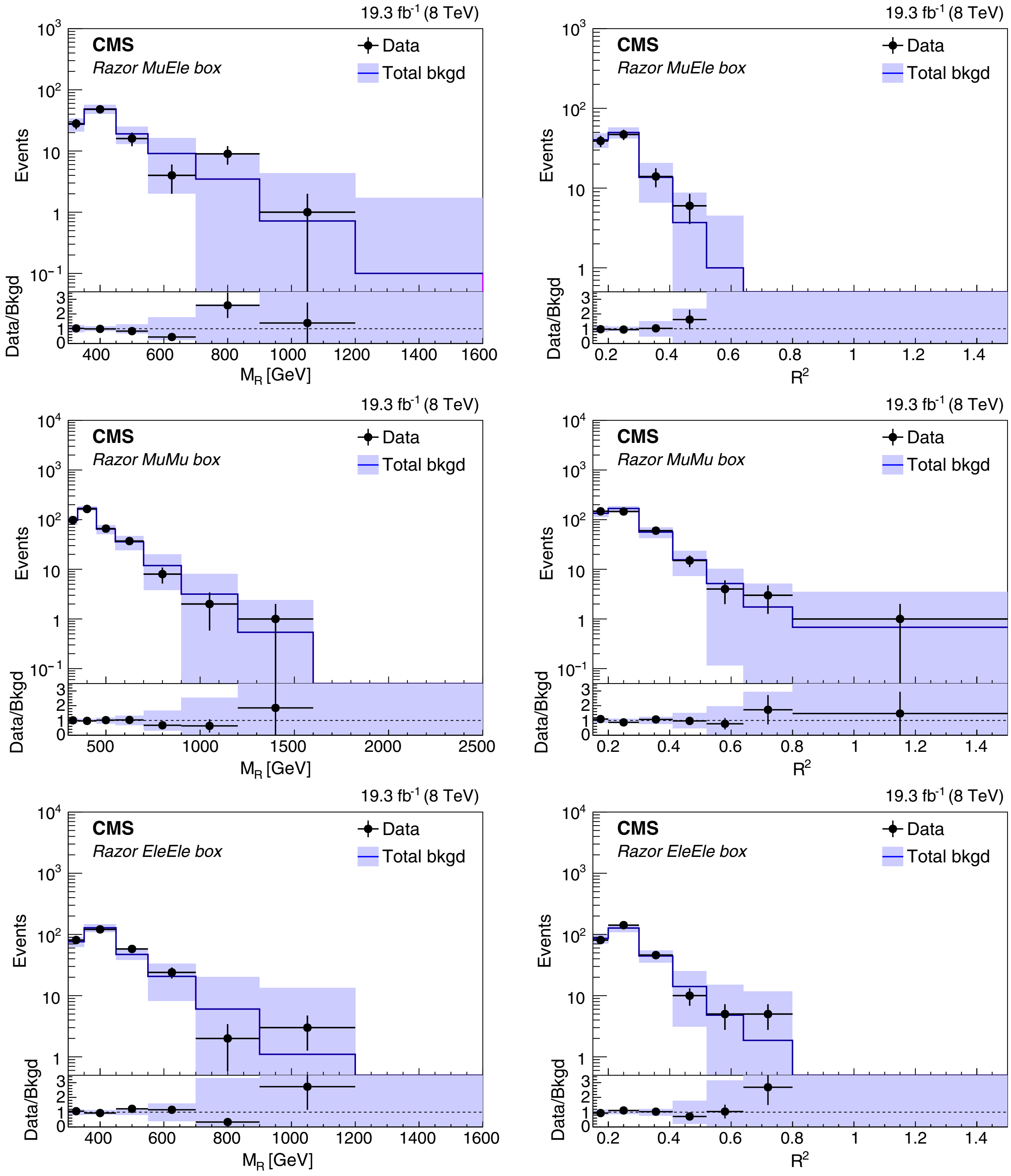

FIG. 7 (color online). Projection of the sideband fit result in the (upper row) MuEle, (middle row) MuMu, and (lower row) EleEle boxes on M_{R} (left) and R^2 (right), respectively. The fit is performed in the sideband regions and extrapolated to the signal-sensitive region. The solid line and the filled band represent the total background prediction and its uncertainty. The points and the band in the bottom panel represent the data-to-prediction ratio and the prediction uncertainty, respectively.

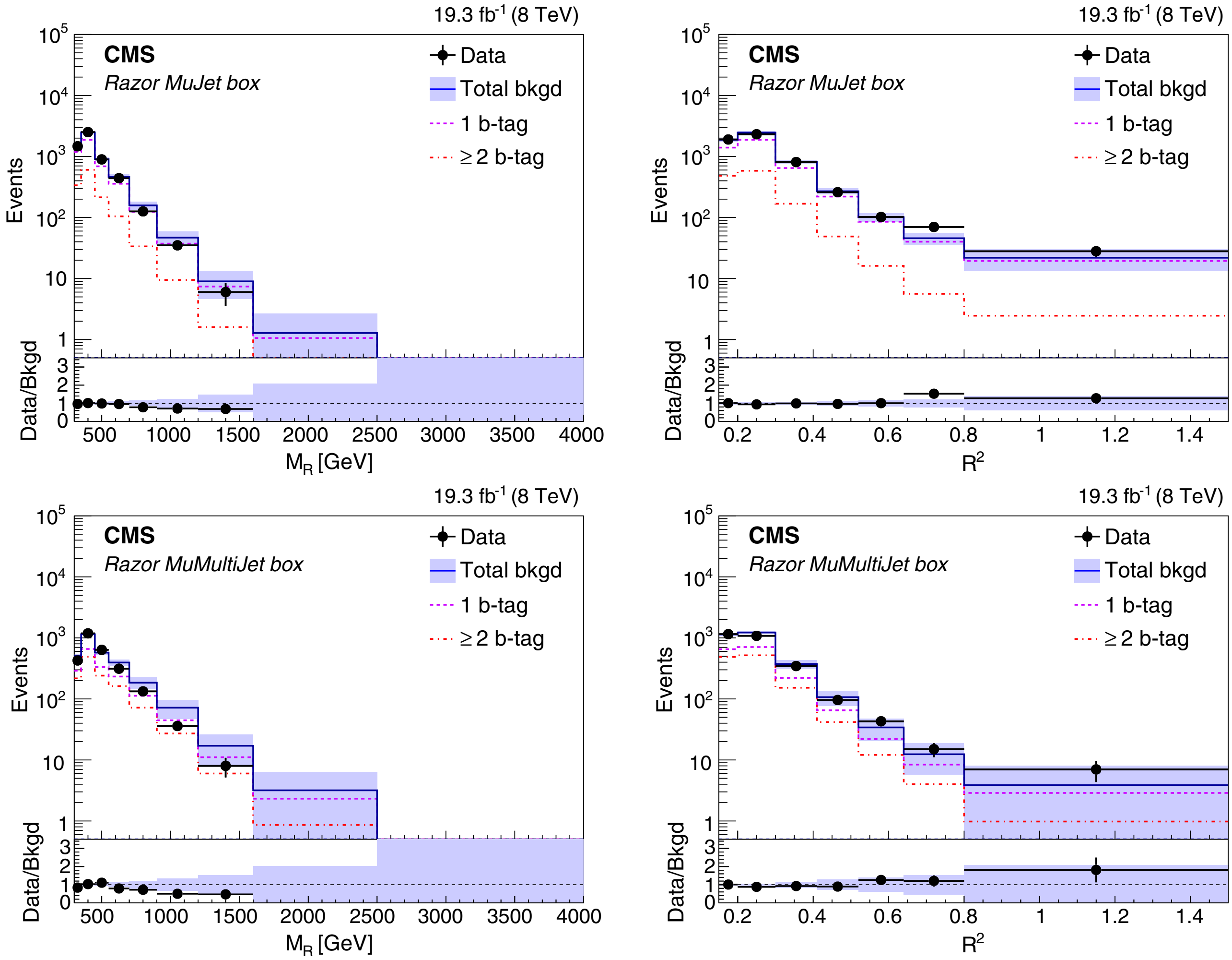

FIG. 8 (color online). Projection of the sideband fit result in the MuJet box on (upper left panel) M_R and (upper right panel) R^2, and of the sideband fit result in the MuMultiJet box on (lower left panel) M_R and (lower right panel) R^2. The fit is performed in the sideband regions and extrapolated to the signal-sensitive region. The solid line and the filled band represent the total background prediction and its uncertainty. The dashed and dot-dashed lines represent the background shape for 1 b-tag and ≥2 b-tag events, respectively. The points and the band in the bottom panel represent the data-to-prediction ratio and the prediction uncertainty, respectively.

studies, the contributions from other processes are determined to be negligible.

We study each of these processes using MC samples, generated with the MadGraph v5 simulation [42,43]. Parton shower and hadronization effects are included by matching events to the PYTHIA v6.4.26 simulation [66] using the MLM algorithm [44]. The events are processed by a GEANT-based [67] description of the CMS apparatus in order to account for the response of the detector.

Once normalized to the NLO inclusive cross section and the integrated luminosity, the absolute yield of the $V+$jets events contribution satisfying the event selection is found to be negligible in all of the two-lepton boxes. In the remaining boxes, its contribution to the total SM background is found to be approximately 25%. The contribution of $V+$jets events in the ≥2 b-tag and the ≥4 jet sample is found to be negligible. The remainder of the background in each box originates from $t\bar{t}$ events.

Based on the study of the data collected at $\sqrt{s} = 7$ TeV and the corresponding MC samples [37,38], the two-dimensional probability density function $P_{\mathrm{SM}}(M_R, \mathrm{R}^2)$ for each SM process is found to be well described by the empirical function

$$f(M_R, \mathrm{R}^2) = [b(M_R - M_R^0)^{1/n}(\mathrm{R}^2 - \mathrm{R}_0^2)^{1/n} - 1] \times e^{-bn(M_R - M_R^0)^{1/n}(\mathrm{R}^2 - \mathrm{R}_0^2)^{1/n}}, \quad (4)$$

where b, n, M_R^0, and R_0^2 are free parameters of the background model. For $n = 1$, this function recovers the two-dimensional exponential function used for previous studies [37,38]. The shape of the empirical function is determined through a RooFit-based extended and unbinned maximum likelihood fit to the data [68]. Two kinds of fit are performed: (i) a sideband-only fit, which is extrapolated to the signal region in order to test for the

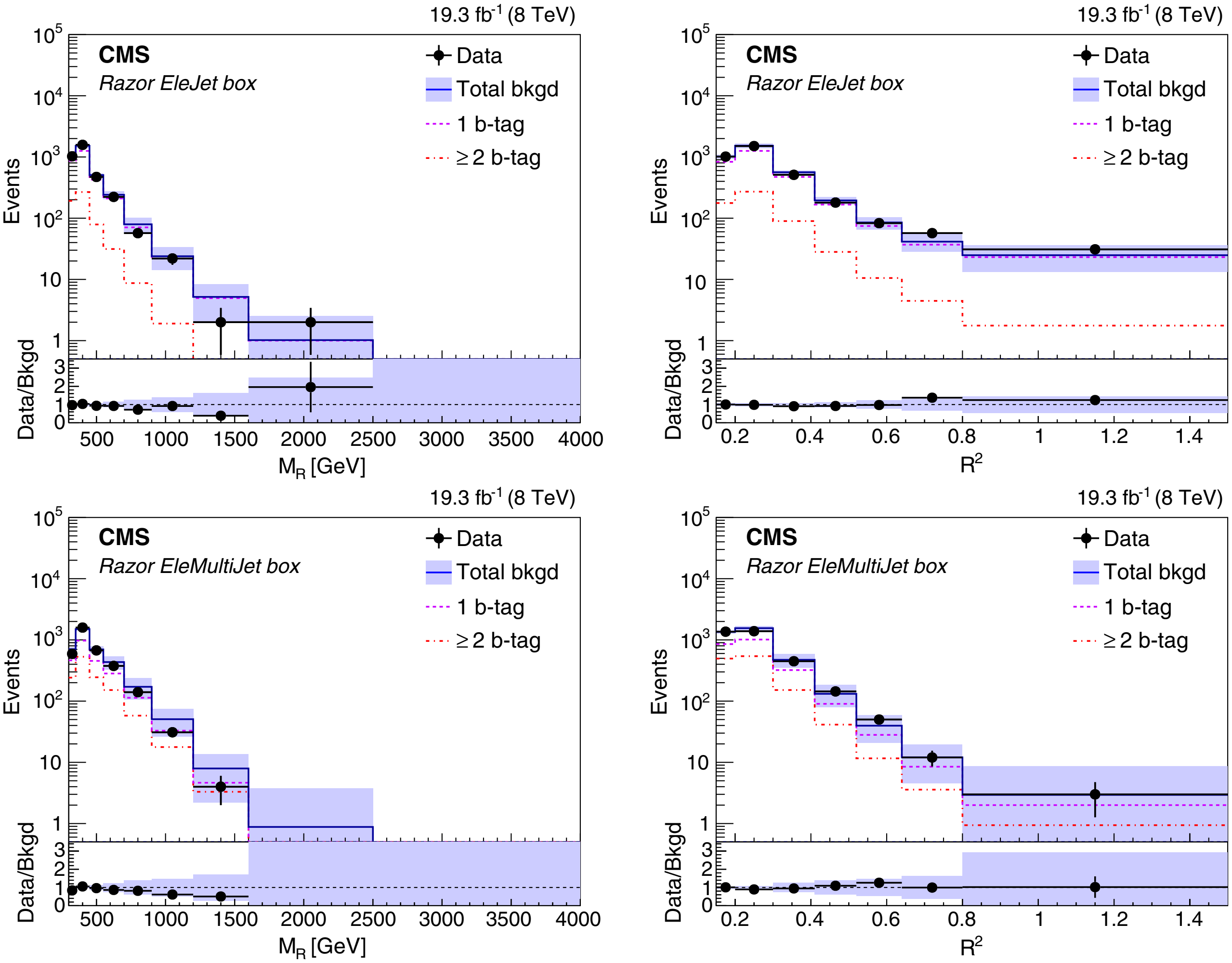

FIG. 9 (color online). Projection of the sideband fit result in the EleJet box on (upper left panel) M_R and (upper right panel) R^2, and projection of the sideband fit result in the EleMultiJet box on (lower left panel) M_R and (lower right panel) R^2. A detailed explanation is given in the caption of Fig. 8.

presence of a signal (discussed in the remainder of this section), and (ii) a simultaneous fit to the signal and sideband regions, performed both under the background-only and background-plus-signal hypotheses, which is used for the interpretation of the results (Sec. VII). In both cases, the empirical function is found to adequately describe the SM background in each of the boxes, for each b-tagged jet multiplicity value.

The SM background-only likelihood function for the two-lepton boxes is written as

$$\mathcal{L}(\mathrm{data}|\Theta) = \frac{e^{-N_{\mathrm{SM}}}}{N!}\prod_{i=1}^{N} N_{\mathrm{SM}} P_{\mathrm{SM}}(M_{\mathrm{R}(i)}), \mathrm{R}^2{}_{(i)}, \tag{5}$$

where $P_{\mathrm{SM}}(M_{\mathrm{R}}, \mathrm{R}^2)$ is the empirical function in Eq. (4) normalized to unity, N_{SM} is the corresponding normalization factor, Θ is the set of background shape and normalization parameters, and the product runs over the N events in the data set. The same form of the likelihood is used for the other boxes, for each b-tagged jet multiplicity. The total likelihood in these boxes is computed as the product of the likelihood functions for each b-tagged jet multiplicity.

The fits are performed independently for each box and simultaneously across the b-tagged jet multiplicity bins. Common background shape parameters (b, ${M_{\mathrm{R}}}^0$, R^2_0, and n) are used for the 2 b-tag and ≥ 3 b-tag bins, since no substantial difference between the two distributions is observed on large samples of $t\bar{t}$ and $V+$jets MC events. A difference is observed between 1 b-tag and ≥ 2 b-tag samples, due to the observed dependence of the b-tagging efficiency on the jet p_{T}. Consequently, the shape parameters for the 1 b-tag bins are allowed to differ from the corresponding parameters for the ≥ 2 b-tag bins. The background normalization parameters for each b-tagged jet multiplicity bin are also treated as independent parameters.

The background shape parameters are estimated from the events in the two sidebands (Sec. V). This shape is then

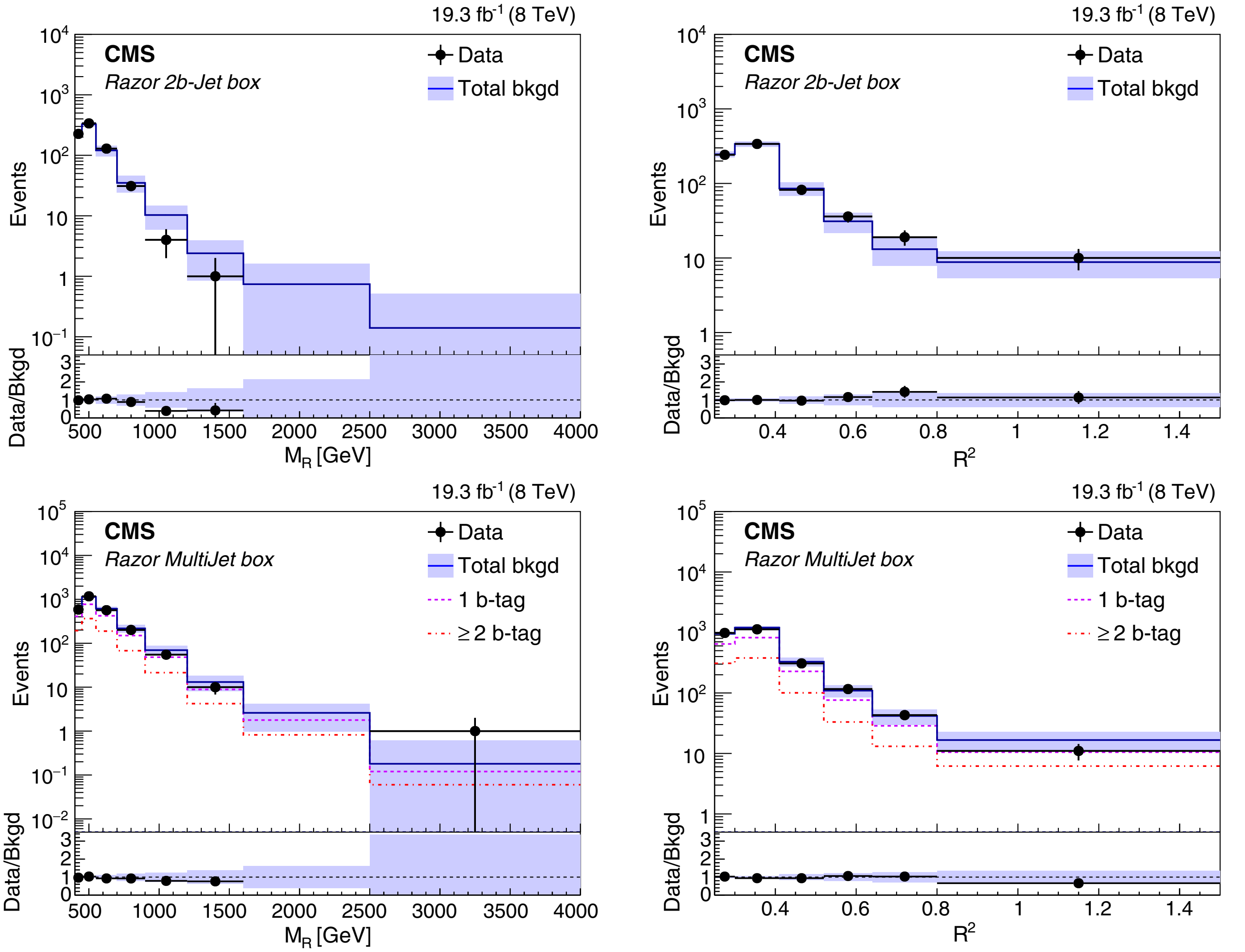

FIG. 10 (color online). Projection of the sideband fit result in the ≥ 2 b-tagged jet box on (upper left panel) M_R and (upper right panel) R^2, and projection of the sideband fit result in the MultiJet box on (lower left panel) M_R and (lower right panel) R^2. A detailed explanation is given in the caption of Fig. 8.

used to derive a background prediction in the signal-sensitive region: 30 000 alternative sets of background shape parameters are generated from the covariance matrix returned by the fit. An ensemble of pseudo-experiment data sets is created, generating random (M_R, R^2) pairs distributed according to each of these alternative shapes. For each bin of the signal-sensitive region, the distribution of the predicted yields in each pseudo-experiment is compared to the observed yield in data in order to quantify the agreement between the background model and the observation. The agreement, described as a two-sided p-value, is then translated into the corresponding number of standard deviations for a normal distribution. The p-value is computed using the probability density as the ordering principle. The observed numbers of standard deviations in the two-lepton boxes are shown in Fig. 4, as a function of M_R and R^2. Positive and negative significance correspond to regions where the observed yield is respectively larger and smaller than the predicted one. Light gray areas correspond to empty bins with less than one event expected on average. Similar results for the one-lepton and hadronic boxes are shown in Figs. 5 and 6. Figures 7–10 illustrate the extrapolation of the fit results to the full (M_R, R^2) plane, projected onto R^2 and M_R and summed over the b-tagged jet multiplicity bins. No significant deviation of data from the SM background predictions is observed.

To demonstrate the discovery potential of this analysis, we apply the background-prediction procedure to a simulated signal-plus-background MC sample. Figure 11 shows the M_R and R^2 distributions of SM background events and T1bbbb events (Sec. II). The gluino and LSP masses are set, respectively, to 1325 GeV and 50 GeV, representing a new-physics scenario near the expected sensitivity of the analysis. A signal-plus-background sample is obtained by adding the two distributions of Fig. 11, assuming an integrated luminosity of 19.3 fb^{-1} and a gluino-gluino production cross section of 0.02 pb, corresponding to 78 expected signal events in the signal-sensitive region. The

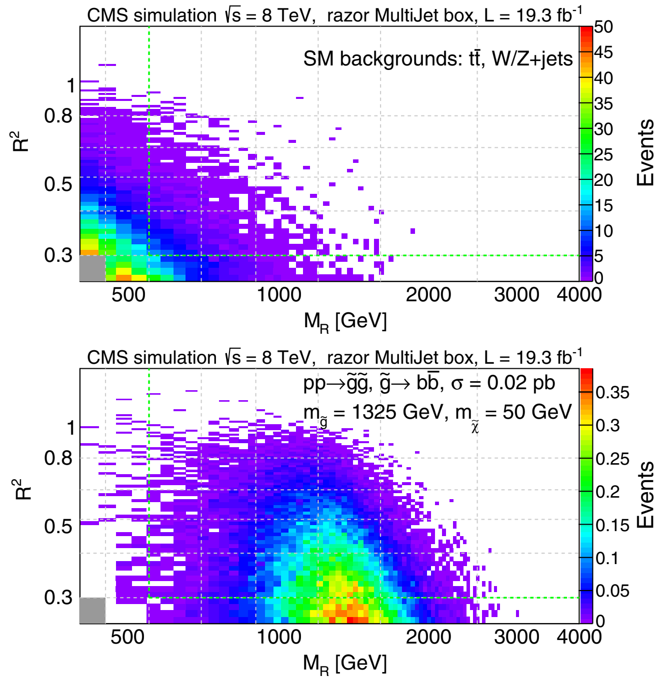

FIG. 11 (color online). Distribution of (top panel) simulated SM background events and (bottom panel) T1bbbb gluino-gluino events in the MultiJet box. Each $\tilde{g}$ is forced to decay to a $b\bar{b}$ pair and a $\tilde{\chi}_1^0$, assumed to be the stable LSP. The $\tilde{g}$ and $\tilde{\chi}_1^0$ masses are fixed to 1325 GeV and 50 GeV, respectively.

agreement between the background prediction from the sideband fit and the yield of the signal-plus-background pseudo-experiments is displayed in Fig. 12. The contribution of signal events to the sideband region has a negligible impact on the determination of the background shape, while a disagreement is observed in the signal-sensitive region, characterized as an excess of events clustered around $M_R \approx 1300$ GeV. The excess indicates the presence of a signal, and the position of the excess in the M_R variable provides information about the underlying SUSY mass spectrum.

VII. LIMIT-SETTING PROCEDURE

We interpret the results of the searches by determining the 95% confidence level (C.L.) upper limits on the production cross sections of the SUSY models presented in Sec. II, using the LHC $\mathrm{CL_s}$ procedure [40] and a global likelihood determined by combining the likelihoods of the different search boxes and sidebands. To reduce computational requirements, a binned likelihood is used.

For the razor search boxes, the signal contribution is modeled by a template function, for a given signal hypothesis in a specific box and a given b-tagged jet multiplicity. The template function, normalized to unit probability, is multiplied by the expected signal yield in each bin ($\sigma_{\mathrm{NLO+NLL}} L \epsilon_{b\text{-tag}}^{\mathrm{box}}$). Here $\sigma_{\mathrm{NLO+NLL}}$ is the SUSY signal cross section, L is the integrated luminosity

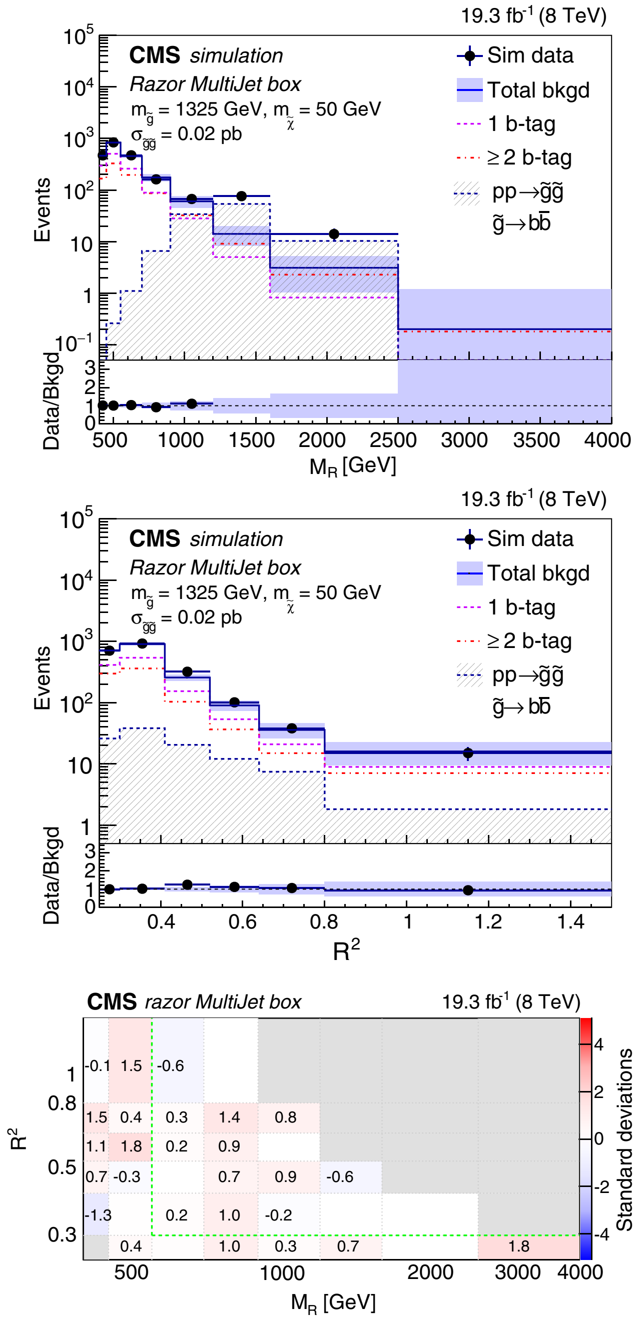

FIG. 12 (color online). Result of the fit to the sideband events of a signal-plus-background MC sample, corresponding to the gluino model whose distribution is shown in Fig. 11. A gluino-gluino production cross section of 0.02 pb is assumed. The one-dimensional projections on (top panel) M_R and (middle panel) R^2 are shown, together with (bottom) the agreement between the observed yield and the prediction from the sideband fit as a function of R^2 and M_R. This agreement is evaluated from a two-sided p-value using an ensemble of background-only pseudo-experiments as described in Sec. VI.

corresponding to the size of the data set, and $\epsilon_{b\text{-tag}}^{\mathrm{box}}$ is the signal selection efficiency for a given box and, in case of the single-lepton and hadronic boxes, for a given b-tagged jet multiplicity.

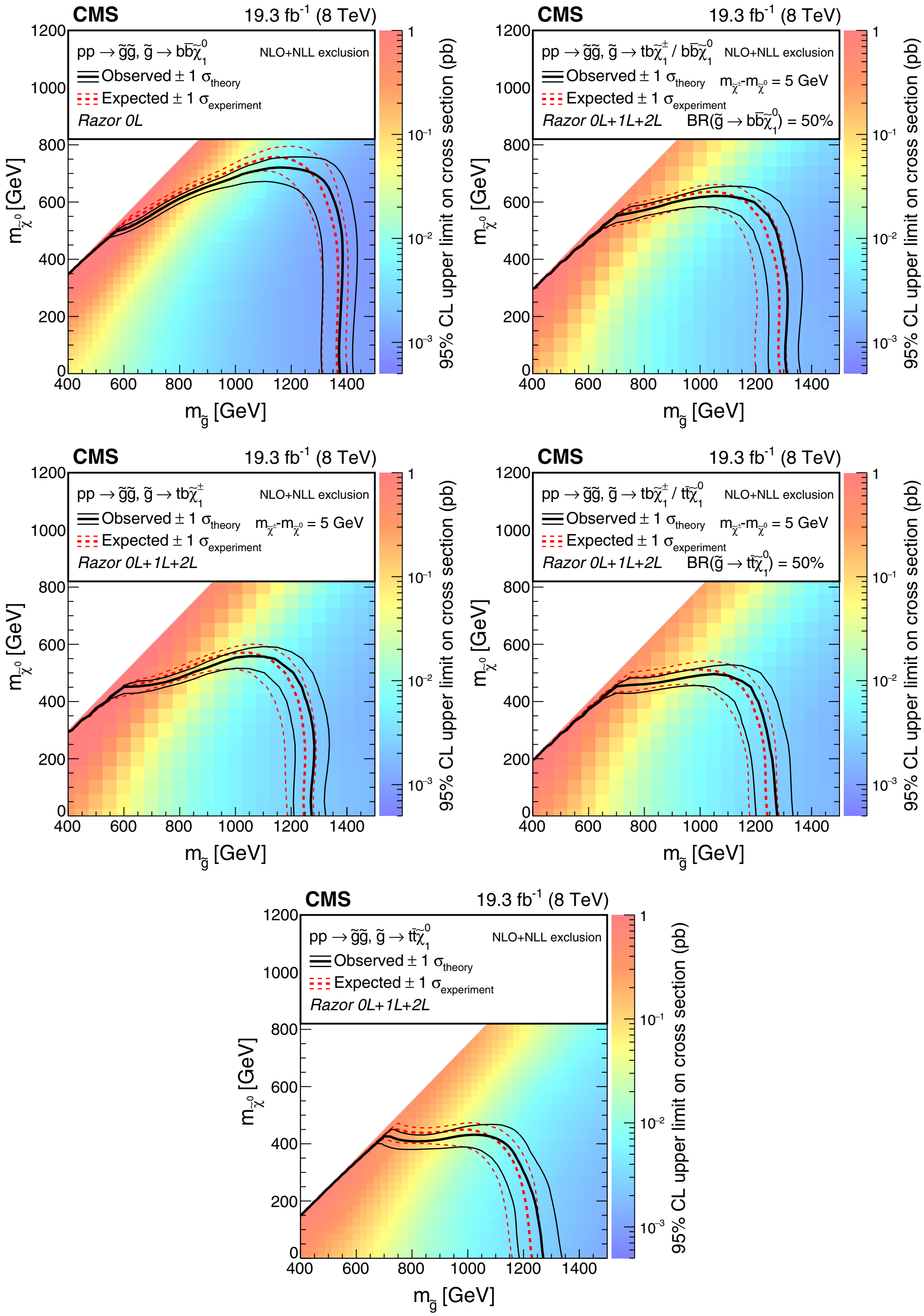

FIG. 13 (color online). Interpretation of the inclusive search with razor variables in the context of gluino pair production models: (upper left panel) T1bbbb, (upper right panel) T1tbbb, (middle left panel) T1ttbb, (middle right panel) T1tttb, and (bottom panel) T1tttt. The limit for T1bbbb is derived using only the hadronic boxes, while the limits for the remaining models are derived using all nine boxes. The color coding indicates the observed 95% CL. upper limit on the signal cross section. The dashed and solid lines represent the expected and observed exclusion contours at a 95% CL., respectively. The dashed contours around the expected limit and the solid contours around the observed one represent the 1 standard deviation theoretical uncertainties in the cross section and the combination of the statistical and experimental systematic uncertainties, respectively.

Each systematic uncertainty is incorporated in the likelihood with a dedicated nuisance parameter, whose value is not known *a priori* but rather must be estimated from the data. The set of nuisance parameters may be divided into three distinct classes (though their statistical treatment is the same): those related to the signal normalization, those related to the signal shape, and those related to the background normalization and shape.

We consider the following systematic uncertainties associated with the signal normalization, with the size of the uncertainty indicated in parentheses:

(i) integrated luminosity (2.6%) [69];
(ii) trigger efficiency (5%);
(iii) lepton reconstruction and identification efficiencies (3% per lepton), measured from an inclusive $Z \to \ell^+\ell^-$ event sample ($\ell = e, \mu$) as a function of the lepton p_T and η values [61,62].

In addition, four signal-shape systematic uncertainties are considered, whose sizes vary with R^2, M_R, and the b-tagged jet multiplicity:

(i) The uncertainty in the jet b-tagging and mistagging efficiencies (up to 20% depending on the signal model), evaluated for each (M_R, R^2) and b-tagged jet multiplicity bin. The uncertainty is evaluated by propagating the uncertainty in data-to-simulation scale factors [65].
(ii) The uncertainty in the modeling of the parton distribution functions (PDFs) (up to 10% depending on the signal model), evaluated for each bin in the (M_R, R^2) plane and for each box and b-tag multiplicity following the PDF4LHC [70–72] prescription, using the CTEQ-6.6 [73] and MRST-2006-NNLO [74] PDF sets.
(iii) The uncertainty in the jet energy scale and resolution (up to 5% depending on the signal model), evaluated from a set of data control samples and MC simulations [60].
(iv) The uncertainty in the modeling of the associated jet production by the MadGraph simulation (up to 20% depending on the signal model), studied using $Z +$ jets and $t\bar{t}$ data events and parametrized by an MC-to-data scale factor as a function of the magnitude of the vector sum of the p_T values of the two produced SUSY particles [19].

The impact of each of these uncertainties on the SUSY signal shape is taken into account by varying each effect up or down by 1 standard deviation.

The uncertainty in the knowledge of the background distributions is taken into account by maximizing the likelihood with respect to the background shape and normalization parameters using the data in the two sidebands and the signal-sensitive region. The background parametrization is able to accommodate several sources of systematic uncertainties defined below:

(i) dependence of the background shape on the b-tag multiplicity;
(ii) dependence of the background shape on the lepton and jet multiplicities;
(iii) deviation of the two-dimensional shape from an exponentially falling distribution, through the background empirical function parameter n, which modifies the tail in M_R and R^2;
(iv) shape bias induced by the dependence of the b-tagging efficiency and mistag rate on the jet p_T;
(v) deviation of the b-tagging and mistagging efficiencies from the MC prediction, through independent normalization factors in each b-tagged jet multiplicity bin.

The combination of razor and exclusive single-lepton [19] searches is performed using the same procedure, taking into account the systematic uncertainties associated with the following five effects:

(i) the PDFs;
(ii) the jet energy scale correction;
(iii) the integrated luminosity;
(iv) the b-jet tagging efficiency;
(v) the associated jet production.

The uncertainties in the background predictions are taken to be uncorrelated, being derived from independent data control samples with different techniques. We verified that the correlation model for the systematics has a negligible impact on the combination, since similar results are obtained when neglecting any correlation between the systematic uncertainties of the two searches.

VIII. INTERPRETATION

The results of this search are interpreted in the context of the natural SUSY simplified models presented in Sec. II.

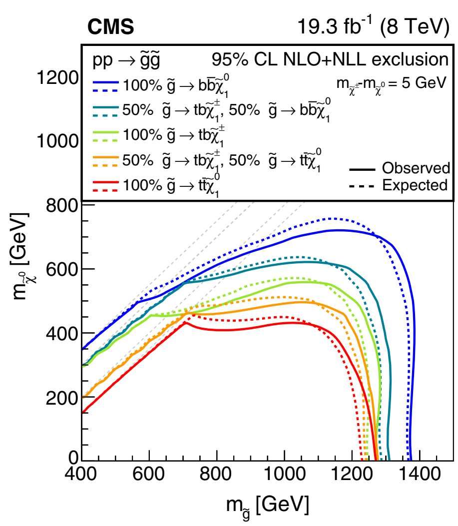

FIG. 14 (color online). Gluino mass limit at a 95% CL., obtained for different gluino pair production models with the inclusive razor analysis in the context of the natural SUSY spectrum of Fig. 1.

A. Limits on gluino pair production

Derived limits on gluino pair production in the T1bbbb, T1tbbb, T1ttbb, T1tttb, and T1tttt scenarios are presented in Fig. 13. A comparison of the simplified natural SUSY gluino-gluino exclusions, obtained for the different decay-mode combinations of third generation quarks, is shown in Fig. 14. The limits corresponding to gluino-gluino topologies with mixed branching fractions lie within the band defined by the T1bbbb and the T1tttt contours. As an example, gluino masses smaller than 1175 GeV for T1tttt and 1310 GeV for T1bbbb are excluded, for a LSP mass of 100 GeV. For any LSP mass value, a larger number of top quarks in the decay topology corresponds to a weaker limit, mainly due to a reduced total signal efficiency with respect to the four-bottom-quark final state and a worse M_{R} and R^2 resolution for events with higher jet multiplicity in the final state. Given this fact and the inclusive nature of the analysis, the T1tttt limit can be considered to represent a conservative estimate of a branching-fraction-independent limit, generically valid for gluino-gluino production within the context of the natural SUSY spectrum shown in Fig. 1.

B. Limits on top-squark pair production

Derived limits on squark pair production from the razor variables in the T2bW*, T2tb, and T2tt scenarios are presented in Fig. 15 and compared in Fig. 16. As in the case of the gluino interpretation, the expected limit from the razor search improves as the number of top quarks in

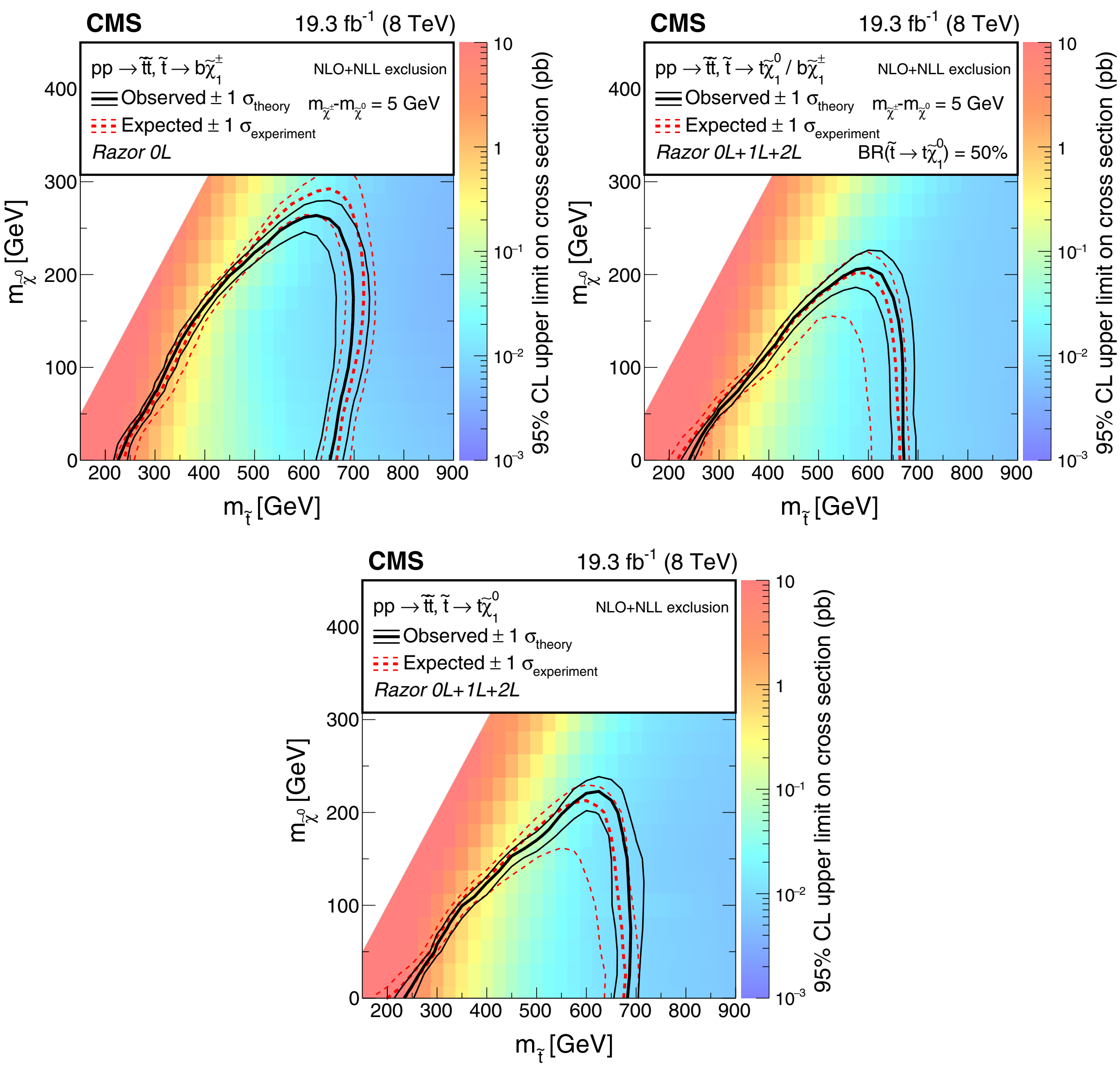

FIG. 15 (color online). Interpretation of the inclusive search with razor variables in the context of top-squark pair production models: (top panel) T2bW*, (middle panel) T2tb, and (bottom) T2tt. The limit for T2bW* is derived using only the hadronic boxes, while the limits for the remaining models are derived using all nine boxes. The meaning of the color coding and the displayed contours is explained in the caption of Fig. 13.

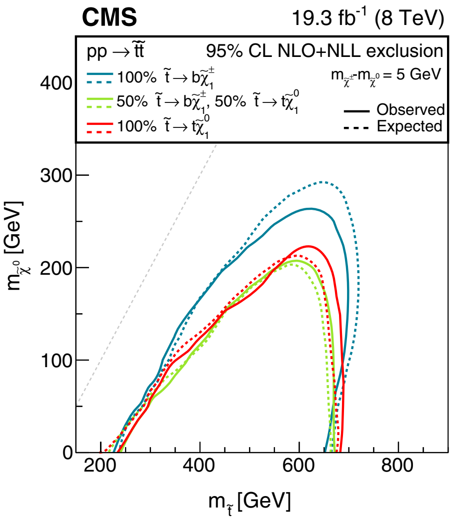

FIG. 16 (color online). Top-squark mass limit at a 95% CL., obtained for different squark pair production models with the inclusive razor analysis in the context of the natural SUSY spectrum of Fig. 1.

the decay topology decreases. For a LSP mass of 100 GeV, top-squark mass values larger than 400 GeV and smaller than 650 GeV are excluded in all three top-squark branching fraction scenarios.

Within the considered scenarios, a top-squark decay to a chargino (neutralino) is topologically similar to a bottom-squark decay to a neutralino (chargino). In the limit of degenerate charginos and neutralinos, the decay products of the chargino are generically too soft to be detected and this correspondence is exact. However, for large mass differences between the squarks and the chargino, the chargino decay products may be boosted enough to become observable, breaking the correspondence. For the models with the intermediate decay to charginos, there is a migration of reconstructed events from the low-background 2b-Jet box to the high-background MultiJet box and a consequently weaker limit with respect to the simplified model without decays to charginos.

A stronger limit on top-squark pair production is derived by combining the hadronic boxes of the razor search with the results of the exclusive single-lepton analysis [19]. The exclusive single-lepton search is conservatively assumed to only have sensitivity when both top squarks decay to a top quark and a neutralino. Figure 17 (top panel) presents the combined result obtained for the scenario where the top squark only decays to a top quark and the lightest neutralino. For a LSP mass of 100 GeV, the combination improves the constraint on the top-squark mass from 660 to 730 GeV. This result provides the most stringent limit on this specific simplified model.

Figure 17 (bottom panel) presents a more generic limit on the top-squark mass. We consider two decay modes for the top squark, as indicated in Fig. 1. We scan the relative

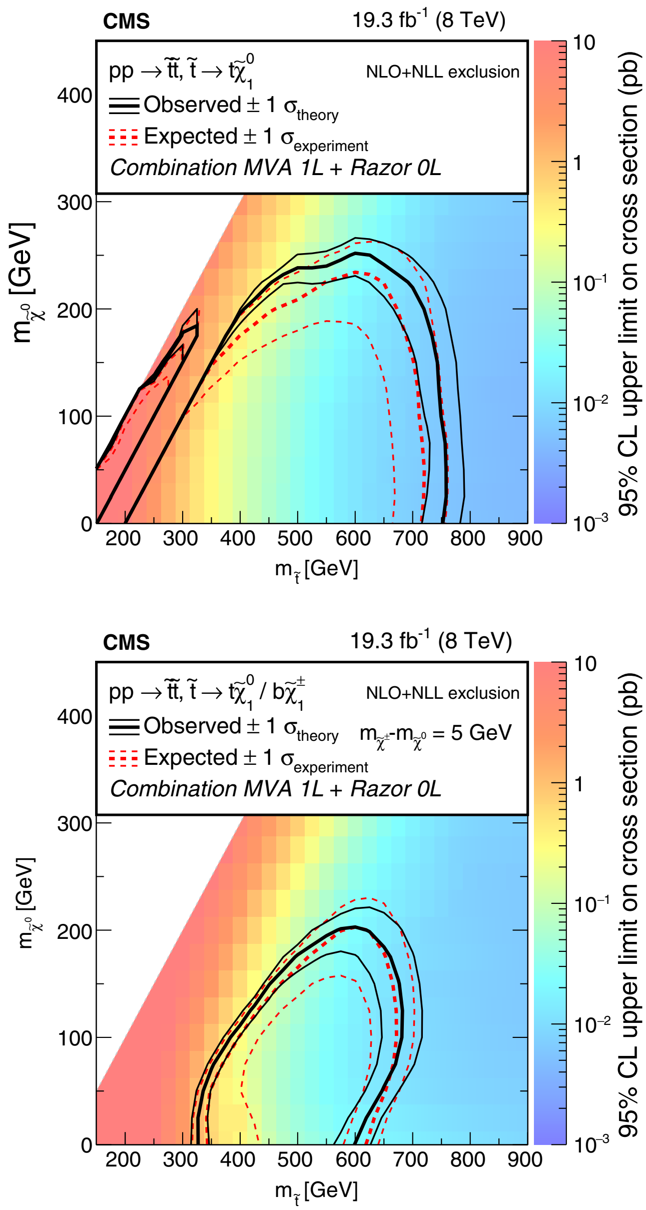

FIG. 17 (color online). Top-squark mass limit at a 95% CL., obtained by combining the result of the hadronic razor boxes with the result of Ref. [19] for (top panel) T2tt and (bottom panel) independent of the branching fraction choice. The meaning of the color coding and the displayed contours is explained in the caption of Fig. 13.

branching fractions, assuming that no other decay mode is allowed. The largest excluded cross section (that is, the worst upper limit) is found for each choice of the top-squark and neutralino mass. A branching-fraction-independent limit is derived by comparing the worst-case exclusion to the corresponding top-squark pair production cross section. In this manner, top squarks decaying to the two considered decay modes are excluded at a 95% confidence level for mass values > 400 GeV and < 645 GeV, assuming a neutralino mass of 100 GeV. Unlike other simplified model interpretations, this interpretation is not based on a specific choice of branching fractions. While a residual model dependence is present because only two decay modes are considered, this result is more general than previous constraints.

IX. SUMMARY

We present a search for supersymmetric particles using proton-proton collision data collected by CMS in 2012 at $\sqrt{s} = 8$ TeV. The data set size corresponds to an integrated luminosity of 19.3 fb^{-1}. We consider events with at least two jets, at least one of which is identified as a b-tagged jet, and study the event distribution in the razor variables (M_{R}, R^2). The data are classified according to the muon, electron, jet, and b-tagged jet multiplicities. No significant excess is observed with respect to the standard model background expectations, derived from a fit to the data distribution in low-M_{R} and low-R^2 sidebands.

The inclusive razor search is translated into 95% confidence level exclusion limits on the masses of the gluino and the top squark, in the context of simplified "natural" SUSY models. For a neutralino mass of 100 GeV and depending on the branching fractions, the pair production of gluinos and top squarks in multibottom, multitop, and mixed top-plus-bottom quark topologies is excluded for gluino masses up to 1310 GeV and top-squark masses up to 660 GeV. Using the combined likelihood of the hadronic boxes of the razor search and the single-lepton channels of the exclusive top-squark search [19], the exclusion bound on the top-squark mass is extended to 730 GeV for a top squark decaying to a top quark and to a neutralino of mass 100 GeV. Again assuming the neutralino mass to be 100 GeV, top squarks decaying to the two considered decay modes are excluded at a 95% confidence level for mass values between 400 and 645 GeV, independent of the branching fractions.

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