PROCEEDINGS OF SCIENCE

Inclusive Searches for Supersymmetry using the CMS detector

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Two inclusive searches for Supersymmetry at CMS using the full luminosity of 19.5 fb^{-1} of data collected until the end of 2012 at a center of mass energy of 8 TeV are discussed here. The first analysis requires three charged light leptons, thereby suppressing the Standard Model background, and a b-tagged jet as well as missing transverse energy. It is targeted at natural SUSY with light third generation squarks. The second discussed analysis probes the fully hadronic final state, which typically has the highest signal branching fraction but also a large Standard Model background, which is modeled using the data events. In both analyses the observed data are in good agreement with the Standard Model background-only expectations. Competitive signal cross section limits have been calculated and interpreted using various simplified model spectra.

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1. Search for Supersymmetry with multi-leptons and a b-tagged jet

Multiple searches for New Physics have been carried out at the CMS experiment [1] and constrain the phasespace of Supersymmetry. Of particular interest is the production of third generation squarks, which should be lighter the more natural SUSY is and lead to top- or bottom quarks in the final state. B-tagged jets are a powerful tool to gain sensitivity to natural SUSY scenarios and to reduce Standard Model background. In this analysis [2] at least one b-tag, three isolated light leptons, electrons or muons, and missing transverse energy (MET) are required. The analysis is sensitive to gluino pair-production, where third generation squarks are created in the cascades, or to direct third generation squark pair-production.

The three lepton selection is sensitive to signal final states that have rather low branching fractions, but this also significantly reduces the Standard Model background. The remaining background is dominated by WZ production, and ZZ, $t\bar{t}+W$, $t\bar{t}+Z$, and $t\bar{t}+H$ contribute further. Monte Carlo simulation is used to estimate these backgrounds. A different source of background comes from non-prompt or misidentified leptons mainly from b-decays in top-quark production, but also from Z+jets or WW+jets events. This background is estimated using a data sideband region, where one of the three leptons is not isolated. The probability as a function of the lepton p_T for non-prompt leptons to pass the isolation criteria is measured in a QCD data control sample and is close to 10% (5%) for electrons (muons). This probability is used to extrapolate from the side band to the signal region, an uncertainty of 30% is applied to incorporate the intrinsically different b-jet spectrum in the signal selection compared to the QCD dominated control region.

Di-lepton triggers are employed to select the data sample used in this analysis. Offline, three isolated leptons i.e. electrons or muons with at least $p_T > 10$ GeV and $|\eta| < 2.4$ are required, the leading lepton must have at least $p_T > 20$ GeV to ensure maximal trigger efficiency. At least two particle-flow reconstructed jets with $p_T > 30$ GeV and $|\eta| < 2.4$ are required, at least one of these must be b-tagged. The b-tagging is around 70% efficient at a mis-tag rate of less than 1%. Non b-tagged jets within a cone of $\Delta R < 0.4$ around a lepton candidate are removed. Finally, the scalar sum of jet transverse momenta $H_T$is required to be $H_T > 60$ GeV and $E_T^{\text{miss}} > 50$ GeV. Instead of further optimizing this selection for specific signal scenarios, 60 orthogonal signal regions are defined, as summarized in Tab. 1.

The signal regions are split into categories depending on wether or not two leptons of same flavor and opposite charge can be combined so that the invariant mass is consistent with a Z-boson within 15 GeV. The events are classified either „On-Z" or „Off-Z". The observed event yields in

Variable	Baseline selection	Signal search regions		
Lepton sign/flavor	3 e/μ	On-Z		Off-Z
$N_{\text{b-jets}}$	≥ 1	1	2	≥ 3
N_{jets}	≥ 2	2 – 3		≥ 4
H_T [GeV]	≥ 60	60 – 200		≥ 200
E_T^{miss} [GeV]	≥ 50	50 – 100	100 – 200	≥ 200

Table 1: Selection and definition of the 60 different signal regions. For $N_{\text{b-jets}} \geq 3$ no extra jet multiplicity binning is used.

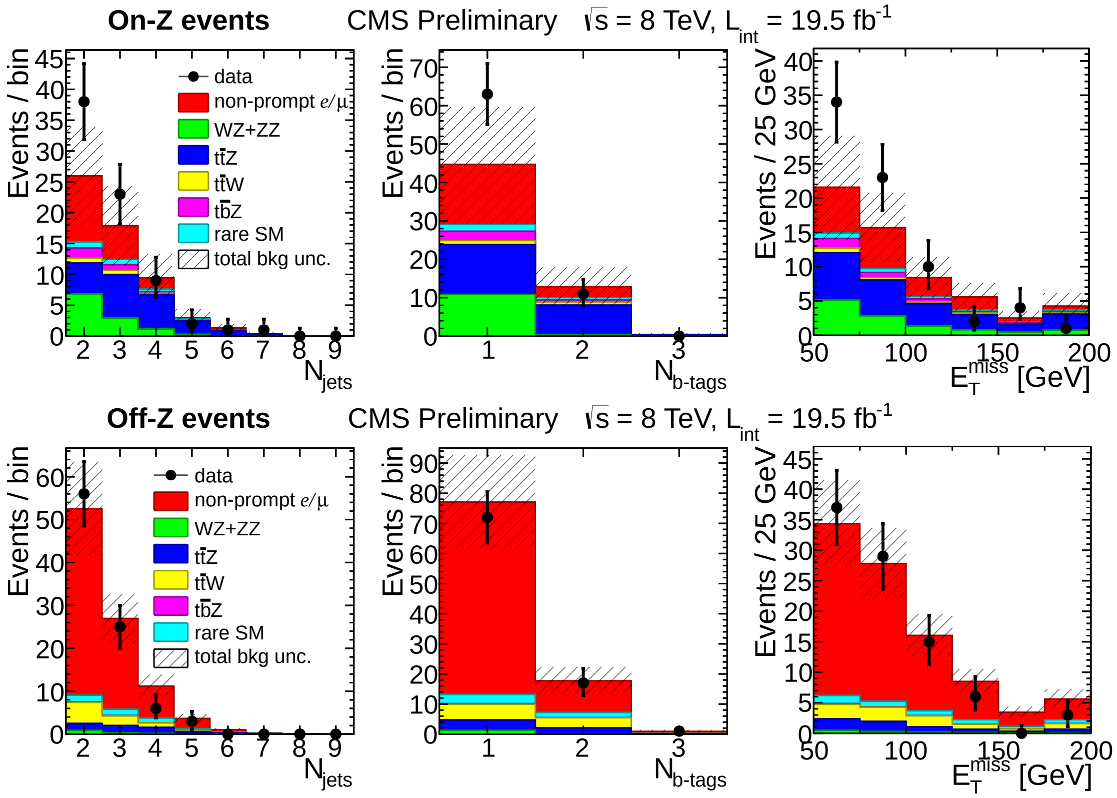

Figure 1: Observed data events compared to the Standard Model background expectation as a function of the $N_{\text{b-jets}}$, N_{jets}, and E_T^{miss} for events including a same-flavor opposite-charge di-lepton pair consistent with the Z-boson mass (top) and for events inconsitent with a Z-decay (bottom).

both categories are compared to the Standard Model expectation in Fig. 1 for the $N_{\text{b-jets}}$, N_{jets}, and E_T^{miss} variables that are also used to categorize the signal search channels.

Good agreement between the Standard Model background expectation and the data can be observed in the search channels. The channel with the largest discrepancy is a channel in the On-Z selection with 30 observed and 15.0 ± 4.5 expected events corresponding to a 1.9 σ excess. Cross-checks indicate that a statistical fluctuation is the most plausible explanation. In order to achieve maximal sensitivity to a wide range of possible signal models a simultaneous multi-bin fit is performed to obtain upper limits on the cross-section times branching fraction of a given model.

Cross section limits have been calculated using the CLs method at 95% confidence level (CL) assuming NLO+NLL signal cross sections. The results are interpreted in several simplified model scenarios. In Fig. 2a, b limits for gluino-pair production with subsequent decay $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ via an off-shell and an on-shell top squark are shown. Gluino masses up to 975 (900) GeV in case of very heavy top squarks, and up to 1000 GeV across the range of top squark masses from 250 to 800 GeV for $\text{m}(\tilde{\chi}_1^0) = 50$ GeV can be excluded in this scenario. Sbottom-pair production with subsequent decay $\tilde{b} \to tW\tilde{\chi}_1^0$ and $\text{m}_{\tilde{\chi}_1^0}/\text{m}_{\tilde{\chi}_1^\pm} = 0.5$ is shown in Fig. 2c. Here, sbottom masses up to 575 GeV are excluded for 25 $<\text{m}(\tilde{\chi}_1^0) < 150$ GeV. In Fig. 2d sbottom-pair production with subsequent decay $\tilde{b} \to bZ\tilde{\chi}_1^0$ is shown. Here, the mass difference $\text{m}(\tilde{\chi}_2^0)$- $\text{m}(\tilde{\chi}_2^0)$ is set to 110 GeV, so that only the

$\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$ decay and not the $\tilde{\chi}_2^0 \to H\tilde{\chi}_1^0$ decay is allowed. In this scenario the $\tilde{b}_1$ mass is excluded up to 450 GeV for 100 <m($\tilde{\chi}_1^0$) < 125 GeV. More interpretations can be found in [2].

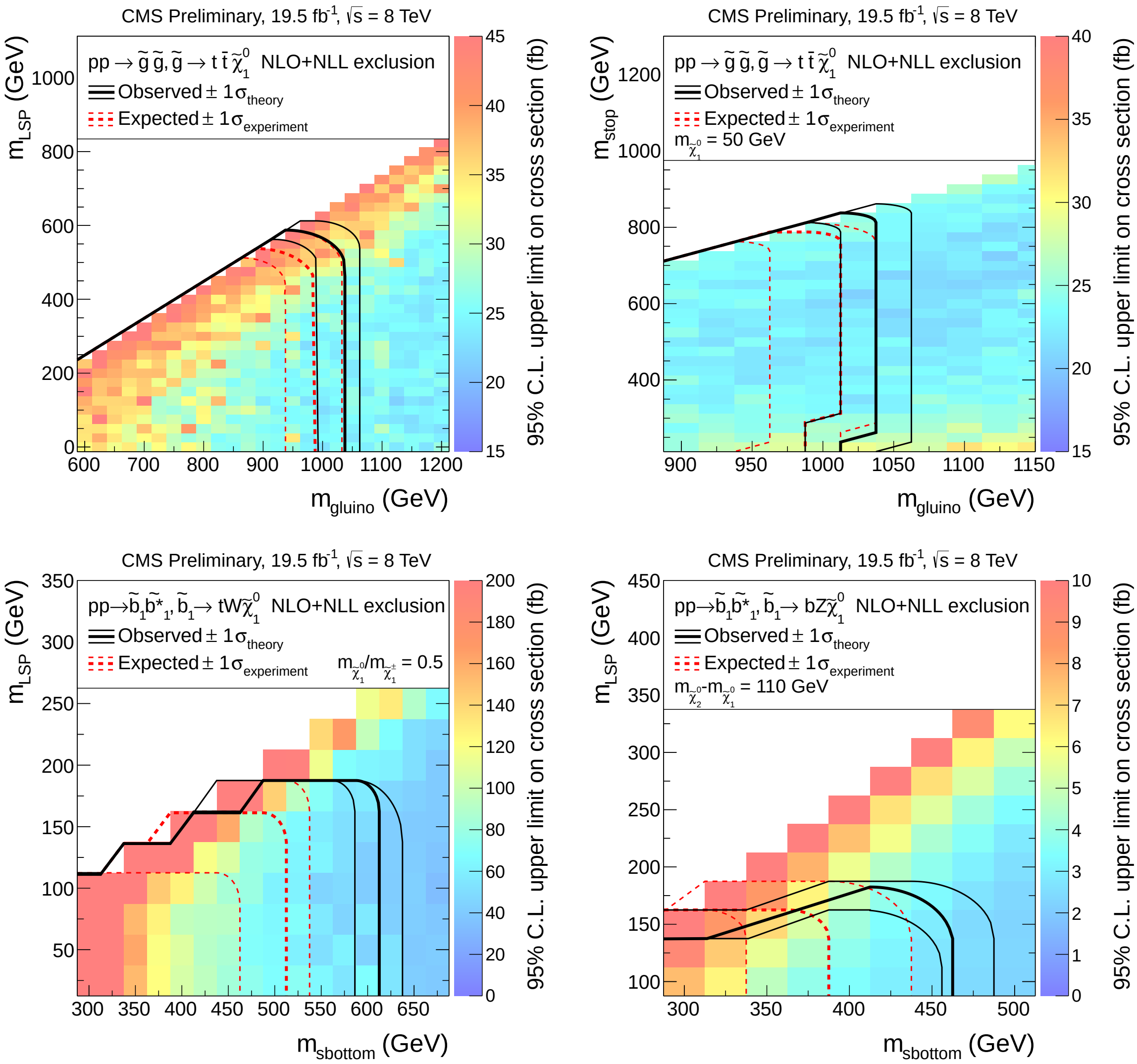

Figure 2: Observed CLs cross-section limits at 95% CL for gluino-pair production with subsequent decay $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ via an off-shell (a) and an on-shell top squark (b), for sbottom-pair production with subsequent decay $\tilde{b} \to tW\tilde{\chi}_1^0$ and $m_{\tilde{\chi}_1^0}/m_{\tilde{\chi}_1^\pm} = 0.5$ (c), and for sbottom-pair production with subsequent decay $\tilde{b} \to bZ\tilde{\chi}_1^0$ (d). The solid black (red) contours show the observed (expected) exclusions assuming NLO+NLL signal cross sections, along with one standard deviation theory (experimental) uncertainties.

2. Search for Supersymmetry with jets and missing transverse energy

The presented analysis of the fully hadronic final state with missing transverse energy [3] is a generic search for Supersymmetry with little model assumptions using 19.5 fb^{-1} of $\sqrt{s} = 8$ TeV data. The analysis requires at least three jets with transverse momentum $p_T > 50$ GeV and $|\eta| < 2.5$. The scalar sum of the jets transverse momenta H_T is required to be $H_T > 500$ GeV and $\not{H}_T$, the absolute value of the vectorial sum of the jets p_T, to be > 200 GeV. The used event triggers utilize the same variables and are measured to be $> 99\%$ efficient. In order to suppress the QCD multijet background events are rejected in which $\not{H}_T$ is aligned with one of the leading three jets in the transversal plane. Further, events containing isolated electrons or muons with $p_T > 10$ GeV are rejected to suppress $W, t\bar{t}$, and Z events with leptons in the final state, as well as events affected by instrumental effects, particles from non-collision sources, or containing poorly reconstructed kinematic variables.

Rather than to optimize the selection for a specific signal topology, 36 statistically exclusive signal regions are defined using the jet multiplicity, the H_T, and the $\not{H}_T$ variables. The analysis thereby maintains sensitivity to a variety of signal scenarios, from short cascade decays with few but high energetic jets and $\not{H}_T$; to long gluino decay cascades with many, but lower energetic jets and little $\not{H}_T$.

The main aspect of this analysis is the precise estimation of the Standard Model background, to which QCD multijet production, $Z \to \nu\bar{\nu}$, and $t\bar{t}$ and W processes contribute. The signal region includes the $t\bar{t}$ and W events if the leptons in the final state are not reconstructed, are out of acceptance, fail the isolation requirements, or are hadronically decaying τ-leptons. The accompanying neutrinos enable these events with not detected leptons to pass the $\not{H}_T$ threshold. Hadronically decaying $t\bar{t}$, W, and Z processes are negligible but are still covered by the QCD background estimation. All backgrounds are extracted from the collected data, and are validated in control regions or corrected by Monte Carlo simulation as discussed in the following.

The QCD multijet background is most relevant for signal regions with little $\not{H}_T$ but large H_T. QCD events have no intrinsic missing transverse energy but contribute due to jet resolution and mismeasurements and semileptonic heavy quark decays. This background is modeled using the data by the „Rebalance & Smear" method: In a first step, the momenta of all jets with $p_T > 10$ GeV are varied within the jet p_T dependent resolution, so that the event balances and the missing transverse energy vanishes. These rebalanced events can be compared to generator-level QCD simulation. Contamination from non-QCD events is negligible because of the large QCD multijet cross section. In a second step the jets of the rebalanced events are smeared according to the jet energy resolution as derived from multijet MADGRAPH events including heavy flavor. The main uncertainties arise from the shape of the jet energy response functions, the heavy flavor contribution, and the pileup and are of the order of 100%. The method has been validated on QCD multijet simulation.

The „lost lepton" background from semi-leptonically decaying $t\bar{t}$ and W events, including leptonic τ-decays, where a lepton is not detected and the accompanying neutrino creates the $\not{H}_T$, is estimated using a data control sample with exactly one isolated muon. To suppress new physics contaminating this control sample the transverse mass of the muon and the missing transverse energy is required to be $m_T < 100$ GeV. This sample is then corrected for the m_T cut inefficiency and the muon reconstruction and isolation efficiency, and then weighted to take into account the probability that an electron or a muon is not reconstructed, or not isolated, or not within the acceptance. The necessary electron and muon efficiencies have been determined in bins of the jet multiplicity, H_T, and $\not{H}_T$ using simulation. The method has been successfully tested on simulation. The dominant systematic uncertainties arise from the statistics of the muon control sample. Possible differences of the lepton efficiencies from simulation to those measured on the Z-peak in data are taken into account.

The hadronically decaying τ-leptons from $t\bar{t}$ and W events are predicted using the same isolated muon control sample as used before. The muon transverse momenta is replaced by hadronic and not-detectable energy according to a tau response template and added to the jet-multiplicity, $H_T$and $\not{H}_T$ of the event, respectively. The response template for τ-leptons decaying to hadrons and neutrinos is created using $t\bar{t}$ and W simulation. As for the QCD method, the same seed event is used several times by sampling the response template. The method has been validated on simulation. The main systematical uncertainties arise from the statistics of the control sample, as well as from the muon acceptance and τ-jet response function.

The remaining background from invisible $Z \to \nu\bar{\nu}$+jets events is relevant at low jet multiplicities. Here, the similarity to the γ-jets production is utilized. The photon is removed from the event and H_T and $\not{H}_T$ are recalculated. The events are than reweighted taking into account the difference in the production cross section, and the photon reconstruction efficiency and kinematic acceptance. $Z \to \mu^+\mu^-$ and γ-jets data events are used to constrain the theoretical uncertainty on the Z/γ production ratio, leading to an uncertainty of the order of 20%. Additional uncertainties arise from the photon reconstruction and isolation efficiencies and the subtraction of non-prompt photons from QCD production in the control sample.

The observed event yields for the 36 signal regions are compared to the estimated total Standard Model expectation in Fig. 3 in bins of jet multiplicity, H_T, and $\not{H}_T$. Overall, good agreement can be observed. The results from all search regions are combined, taking into account all uncertainties and possible correlations. Cross section limits have been calculated with the CLs method at 95% CL. In Fig. 4 the results are interpreted in the context of simplified models for gluino-pair and squark-pair production. The squarks are forced to decay directly into the lightest neutralino and a jet, while the gluinos decay via an offshell squark into the lightest neutralino and two jets. The neutralino and the squark or gluino masses are scanned. In these scenarios squark masses < 0.75 TeV and gluino masses < 1.1 TeV can be excluded for neutralino masses < 200 GeV.

References

[1] The CMS Collaboration, „The CMS experiment at the CERN LHC”, **JINST** 3:S08004, 2008.

[2] The CMS collaboration, „Search for supersymmetry in pp collisions at $\sqrt{s} = 8$ TeV in events with three leptons and at least one b-tagged jet”, CMS-PAS-SUS-13-008, 2013.

[3] The CMS collaboration, „Search for New Physics in Multijets and Missing Momentum Final State in pp collisions at $\sqrt{s} = 8$ TeV”, CMS-PAS-SUS-13-012, 2013.

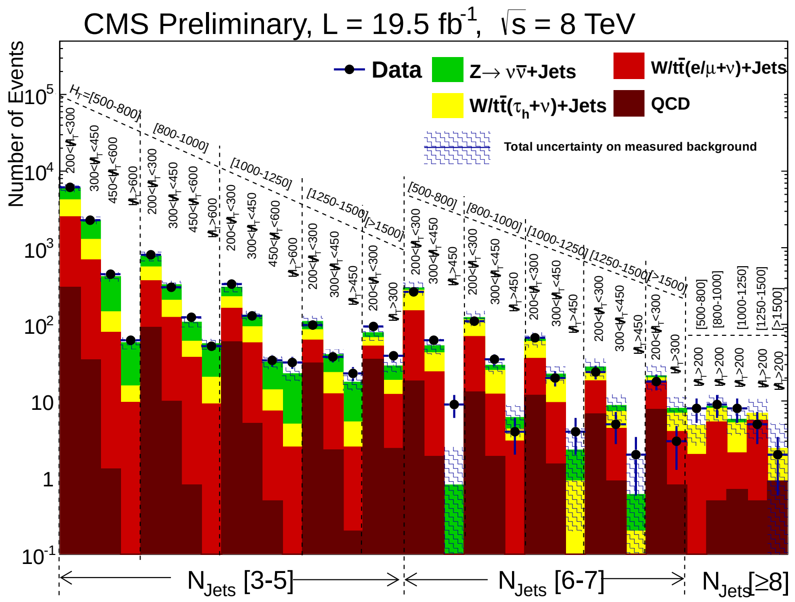

Figure 3: Summary of the observed number of events in the 36 exclusive search regions defined by the jet multiplicity, H_T and $\not{H}_T$ compared to the Standard Model background expectation as estimated using data-driven methods.

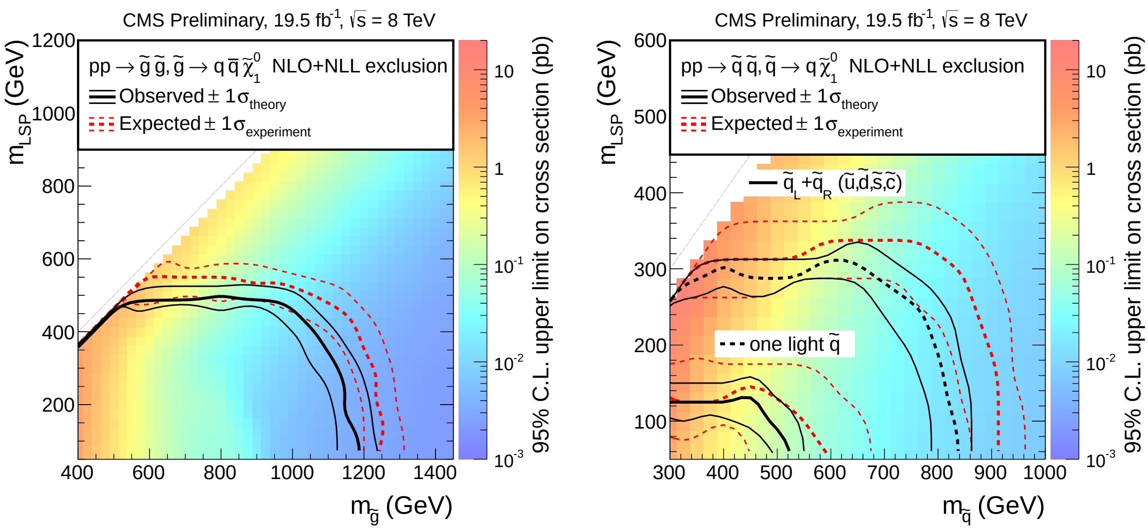

Figure 4: Observed and expected exclusion contours at 95% CL in the squark mass versus gluino mass plane for (left) $\tilde{g}\tilde{g}$ and (right) $\tilde{q}\tilde{q}$ production within the framework of simplified models. For the $\tilde{q}\tilde{q}$ production the corresponding exclusion contours are shown for two different signal cross section assumptions: The upper set of curves corresponds to the scenario when the first two generations of squarks ($\tilde{u}_L$,$\tilde{u}_R$,$\tilde{d}_L$,$\tilde{d}_R$,$\tilde{c}_L$,$\tilde{c}_R$,$\tilde{s}_L$,$\tilde{s}_R$) are degenerate and light, while the lower set corresponds to only one light flavor accessible squark, e.g. ($\tilde{u}_L$,$\tilde{u}_R$).