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# Experimental SUSY overview

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We report on recent results from the ATLAS and the CMS Collaborations on searches for supersymmetry based on data proton-proton collision data at $\sqrt{s} = 13$ TeV collected at the Large Hadron Collider during the Run 2 period.

*The Eighth Annual Conference on Large Hadron Collider Physics-LHCP2020*
*25-30 May, 2020*
*online*



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PoS(LHCP2020)166

## 1. Introduction

Supersymmetry (SUSY) [1]-[4] provides us with a plethora of possible beyond the standard model (SM) signatures and scenarios making a very attractive theory. SUSY postulates the existence of the lightest superpartner (LSP) if a new symmetry, namely the R-parity is invoked [5]-[6]. The LSP is a suitable dark matter (DM) candidate [6] and in most models it is chosen to be the lightest neutralino ($\tilde{\chi}_1^0$). Phenomenologically this results in SUSY particles produced in pairs, while the LSP is stable and evading direct detector interaction, resulting into large missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$) as an experimental signature. Recent SUSY search results are reported based on data collected during the Run 2 of the LHC corresponding to a total integrated luminosity of $\approx$ 140/fb from the ATLAS [7] and the CMS Collaborations [8].

## 2. Strong production

As gluinos ($\tilde{g}$) and squarks ($\tilde{q}$) carry color charge, they can be produced via the strong interaction with the highest production cross-section among the SUSY production mechanisms. Related searches cover a rather broad class of inclusive signatures with abundant decay scenarios[1]. Strong production searches typically are categorized according to the number of leptons in the final state, the jet multiplicities ($n_{\mathrm{jet}}$), the b-tag jets and the presence of, usually large, $p_{\mathrm{T}}^{\mathrm{miss}}$. Several more kinematic variables are also exploited, like the scalar sum of the transverse momentum ($p_{\mathrm{T}}$), the masses of the jets ($H_{\mathrm{T}}$ and $m_{\mathrm{jet}}$ respectively) or the $p_{\mathrm{T}}^{\mathrm{miss}}$ significance ($Sp_{\mathrm{T}}^{\mathrm{miss}}$). $Sp_{\mathrm{T}}^{\mathrm{miss}}$ in particular tests the hypothesis how compatible the total transverse momentum is with non-interacting particles as it quantifies the degree to which the $p_{\mathrm{T}}^{\mathrm{miss}}$ is genuine.

### 2.1 Gluino searches

A recent zero lepton result from ATLAS [9] that considers large $p_{\mathrm{T}}^{\mathrm{miss}}$, multi $n_{\mathrm{jet}}$ and b-tag jets with large $p_{\mathrm{T}}$ optimizes the $Sp_{\mathrm{T}}^{\mathrm{miss}}$ by taking into account the resolution of the individual reconstructed objects. The major backgrounds are multijet production from QCD processes, $t\bar{t}$ production, and W boson + jets production. The main background is estimated from a lower $n_{\mathrm{jet}}$ control region (CR) from a $Sp_{\mathrm{T}}^{\mathrm{miss}}$ template as it should be mostly uncorrelated with $n_{\mathrm{jet}}$. Gluinos lighter than 2 TeV for a massless $\tilde{\chi}_1^0$ are excluded (Fig. 1).

In the CMS one lepton plus $p_{\mathrm{T}}^{\mathrm{miss}}$ analysis [10] the presence of initial state radiation (ISR) jets is exploited with the use of the $m_{\mathrm{jet}}$ and the transverse mass ($m_{\mathrm{T}}$). Given that $m_{\mathrm{jet}}$ and $m_{\mathrm{T}}$ are mostly uncorrelated, the $t\bar{t}$ background at high $m_{\mathrm{T}}$ can be estimated from the $m_{\mathrm{jet}}$ from a low-$m_{\mathrm{T}}$ CR. Scenarios with $\tilde{g}$ masses up to about 2.1 TeV are excluded for $\tilde{\chi}_1^0$ masses up to 700 GeV, whereas the highest excluded $\tilde{\chi}_1^0$ mass is about 1.2 TeV (Fig. 2, left, middle).

Another all hadronic CMS search [11] focuses on $\tilde{g}$ decaying to Z bosons incorporating also the next-to-lightest SUSY particle ($\tilde{\chi}_2^0$) while the $\tilde{\chi}_2^0$ and the $\tilde{\chi}_1^0$ are mixed states of the neutral Higgs and the gauge bosons. This search has been motivated by scenarios that preserve *naturalness* (that is the need for a minimal fine tuning of the SM in order to solve the gauge hierarchy problem) by introducing large $\Delta m$ between the neutralinos and the charginos ($\tilde{\chi}_1^{\pm}$), resulting in final states with vector bosons and $p_{\mathrm{T}}^{\mathrm{miss}}$ [12]. Such final states can be contained in a single large radius reconstructed

[1]Given the attention they have drawn, direct top squark pair production ($\tilde{t}$) searches usually form a separate category.

jet, while the signal regions (SR) and the CR are defined in bins of the mass of the leading and the trailing jets; $\tilde{g}$ lighter that 1.9 TeV are excluded for a massless $\tilde{\chi}_1^0$ (Fig. 2, right).

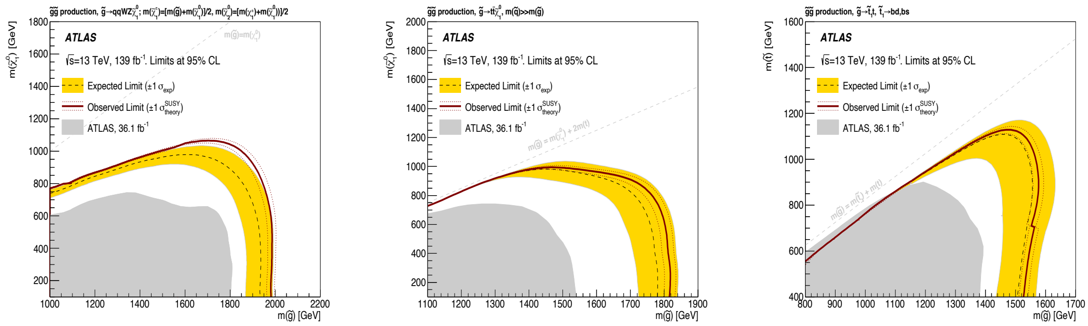


**Figure 1:** Exclusion limits at 95% confidence limit (CL) with the ±1 standard deviation (s.d.) uncertainty bands from ATLAS $\tilde{g}$ searches [9]. Left: Models with W/Z bosons mediated $\tilde{g}$ decays. Middle: For a $t\bar{t}$ plus $p_{\mathrm{T}}^{\mathrm{miss}}$ decay scenario. Right: For a stop-mediated $\tilde{g}$ decayed scenario with RPV couplings.

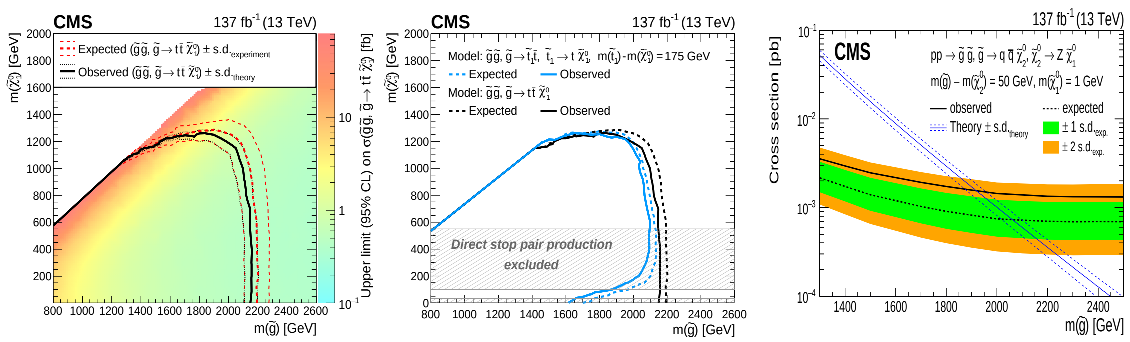


**Figure 2:** Exclusion limits at 95% CL and ±1 s.d. uncertainty bands from CMS $\tilde{g}$ searches [10]-[11]. Left and middle: Interpretation in the T1tttt (left) and the T5tttt models. Right: Limits on the T5ZZ model.

## 2.2 Stop searches

Searches for third generation stop ($\tilde{t}$) pair production have been motivated mostly from naturalness arguments [13]-[14]. The $\Delta m(\tilde{t},\tilde{\chi}_1^0)$ defines the kinematically allowed decays, namely two, three or four body decays. Of particular interest is the top corridor where the $\Delta m$ $(\tilde{t},\tilde{\chi}_1^0)$ is very close or equal to the top quark mass, and as such the produced $t\bar{t}$ is at rest and has very similar kinematic properties like the dominant SM $t\bar{t}$ background.

A zero lepton analysis from ATLAS [15] targets the two, three and four body decay scenarios by optimizing different variables like the $Sp_{\mathrm{T}}^{\mathrm{miss}}$ and the $m_{\mathrm{T}}$. Moreover, ISR sensitive variables, like the ratio of $p_{\mathrm{T}}^{\mathrm{miss}}$ and $p_{\mathrm{T}}$ of ISR jets are also used to increase the efficiency across the top corridor. Use of b-tagging and angular variables helps to reject mismeasured $p_{\mathrm{T}}^{\mathrm{miss}}$ and SM background. Stop quarks with masses below 1.2 TeV are excluded for a massless $\tilde{\chi}_1^0$ (Fig. 3).

The need for novel ideas has led to new proposed variables, like the *topness* that quantifies how well an event can be reconstructed under a dileptonic top quark hypothesis. This is exploited for example in the one lepton plus $p_{\mathrm{T}}^{\mathrm{miss}}$ final state analyses from both ATLAS and CMS [16]-[17] and are further optimized by using a large number of SR with several signal-sensitive variables, like the $m_{\mathrm{T}}$ or the $p_{\mathrm{T}}^{\mathrm{miss}}$. Among the most important background sources is mismeasured $p_{\mathrm{T}}^{\mathrm{miss}}$ and also the so called *lost lepton* background, i.e., when one lepton is misidentified or misreconstructed. Stop masses up to 1.2 TeV are well excluded with the limits weakening close to the diagonal (Fig. 4).

Two or even three leptons complement the above searches and often target more complex models, like $\tilde{\chi}_1^{\pm}$-mediated or on-shell Higgs/Z boson scenarios [18]-[19]. Variables like the $m_{\mathrm{T2}}$ that present a kinematic endpoint for background events even in the presence of two neutrinos in the event can be very useful to suppress background. The main backgrounds come from one, two and three lepton SM sources, like $t\bar{t}$ dileptonic and semileptonic decays and and are estimated from data. Results from those searches are shown in Fig. 5 (left and middle).

In R-parity violated scenarios, experimental signatures that depend on the RPV couplings can give final states with multi b jets, light stops and sbottoms [20]. Such scenarios with small $p_{\mathrm{T}}^{\mathrm{miss}}$ and zero leptons have not been covered extensively at the LHC, but are probed by a recent ATLAS analysis setting limits on stop decaying exclusively to a $\tilde{\chi}_1^{\pm}$ and a b quark [21]. (Fig. 5, right).

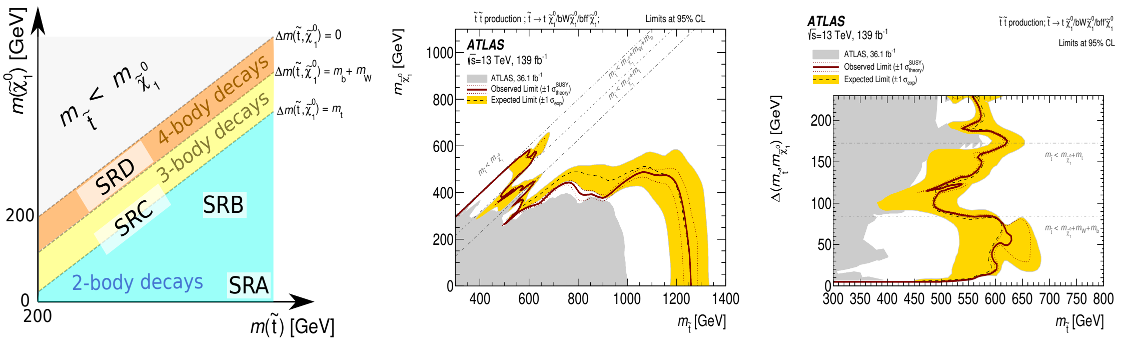


**Figure 3:** Left: The kinematically allowed decays as a function of the $\Delta m(\tilde{t},\tilde{\chi}_1^0)$. Observed and expected limits at 95% CL as a function on the $m(\tilde{t},\tilde{\chi}_1^0)$ (middle) and $\Delta m(\tilde{t},\tilde{\chi}_1^0)$ mass planes (right). All plots from [15].

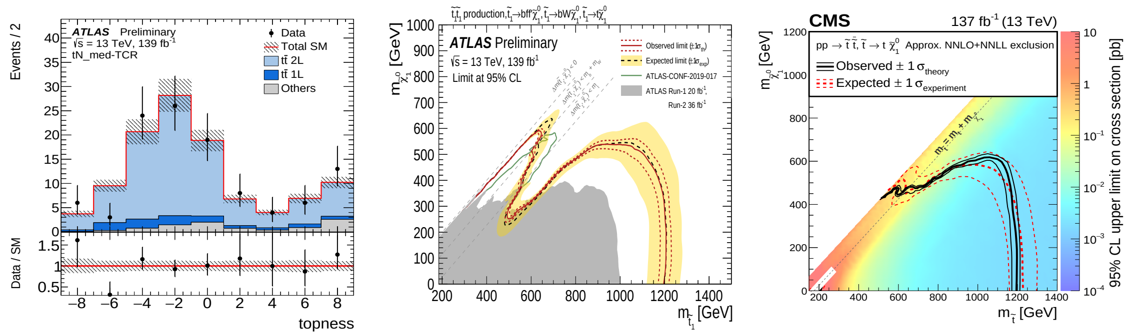


**Figure 4:** Distribution of the topness variable (left) as well as expected and observed results at 95% CL in the $(\tilde{t},\tilde{\chi}_1^0)$ mass plane from ATLAS (middle) and CMS (right). Plots from [16]-[17].

## 3. Electroweak searches

Electroweak searches are limited by the small production cross-section and low particle momenta. On the positive side, one can expect very clean signatures with $p_{\mathrm{T}}^{\mathrm{miss}}$ and multi leptons that

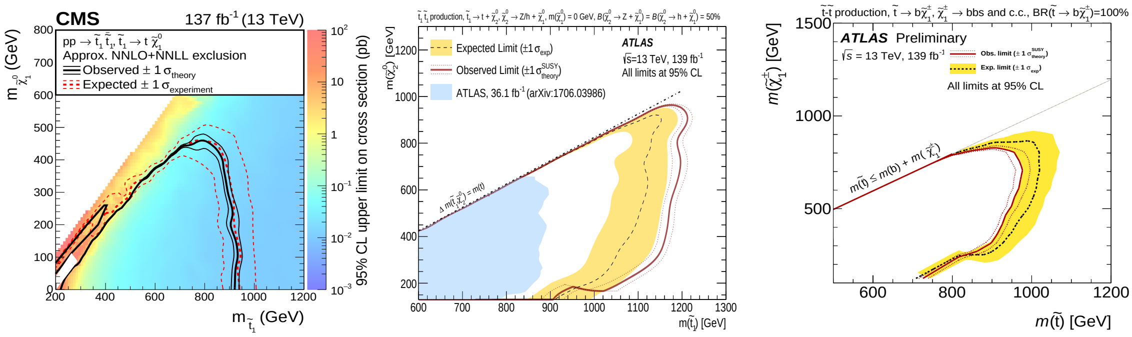


**Figure 5:** Results from the two lepton stop analysis from CMS (left), two and three leptons with H/Z bosons search from ATLAS (middle) and multi b jets in RPV search from ATLAS (right). Plots from [18]-[21].

not many SM processes can give. Many different scenarios have been explored so far, including direct chargino/neutralino models, gauge mediated or direct WIMP production etc. Of particular interest are R-parity conserved models where the LSP could have undergone annihilation-production interactions with SM particles giving the observed DM relic density, assuming coannihilation models of the stau ($\tilde{\tau}$) and the $\tilde{\chi}^0_1$ [22]-[23]. If the $\Delta m(\tilde{\tau},\tilde{\chi}^0_1)$ is also small, the predicted relic DM can be consistent with the measured one. However, the compressed region is very challenging experimentally, thus exploiting the presence of ISR jets becomes important. Because of the created recoil, the decayed low $p_{\mathrm{T}}$ products are boosted, and hence the signal acceptance is increased, a model that was investigated in a recent CMS search with low $p_{\mathrm{T}}$ taus [24]. Several handles exploiting the low $p_{\mathrm{T}}$ tau kinematic properties were used to enhance signal efficiency, in the end yielding sensitivity in a region where classic chargino/neutralino searches fail to. That is demonstrated in Fig. 3 where the sensitivity is compared against another chargino/neutralino mediated stau lepton analysis.

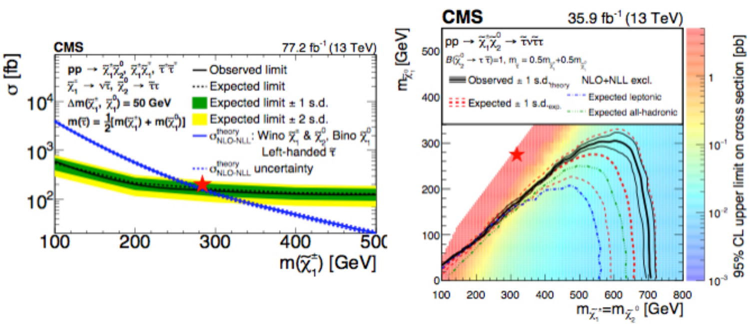


**Figure 6:** Comparison of the electroweak + ISR with low $p_{\mathrm{T}}$ stau leptons search against a more inclusive chargino/neutralino CMS analysis. The red asterisk denotes the same point on the chargino/neutralino mass plane and is illustrating that more specific and targeted topologies can help reaching corners of the phase space that are otherwise not accessible. Plots are taken from [24]-[25].

## 4. Summary and future prospects

In the landscape of SUSY searches, very stringent limits have already been set in many SUSY models. In particular, gluino masses even larger than 2 TeV are well excluded, and although for chargino and boson mediated decays limits are weaker, these lie well above 1 TeV. With the High Luminosity LHC (HL-LHC) we expect to reach gluino masses even above 3 TeV [26]. For third generation stop searches, stops lighter than 1.2 TeV are well excluded for low $\tilde{\chi}_1^0$ masses, but the limits get weaker in more compressed regions of the phase space given the low transverse momenta of the final state objects. At the HL-LHC however we expect to be able to exclude stops with masses up to 2 TeV. Regarding the electroweak searches, the stronger limits are for slepton mediated decays that exclude charginos between 0.6-1.1 TeV, followed by the boson mediated ones that exclude charginos of 0.4-0.7 TeV, while we have even weaker limits for compressed regions and direct stau pair production. Current experimental constraints from ATLAS and CMS can be seen in some of the summary plots in Fig. 7.

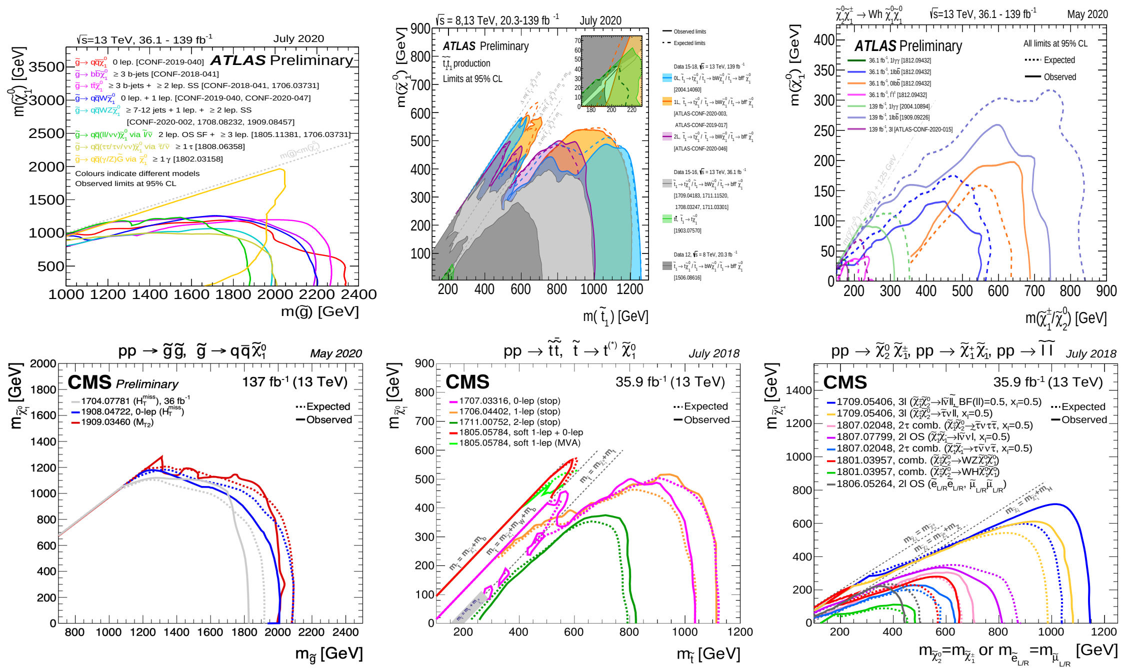


**Figure 7:** Summary plots on limits obtained by ATLAS (top row) and CMS (bottom row) for $\tilde{g}$ pair (left column), $\tilde{t}$ pair (middle column) and electroweak searches (right column). Plots from [27]-[28].

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