

CORNERING NATURAL SUSY WITH $\sqrt{s} = 13$ TeV DATA

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Naturalness arguments for weak-scale supersymmetry favour supersymmetric partners of top quarks and Higgsinos with masses not too far from those of their Standard Model counterparts. The increase in the center of mass energy of the proton-proton collisions gives us a unique opportunity to extend the sensitivity of the production of these supersymmetric particles at the Large Hadron Collider. This talk presents recent ATLAS and CMS results from searches for direct stop, sbottom and electroweakino pair production using 2015+2016 data at $\sqrt{s} = 13$ TeV. These searches include several final states with leptons, jets and missing transverse momentum.

1 Introduction

Supersymmetry (SUSY) is one of the most favorable extensions of the Standard Model (SM). It is a generalization of space-time symmetries that predicts new bosonic partners for the fermions and new fermionic partners for the bosons of the SM. If R -parity is conserved, then SUSY particles (called sparticles) are produced in pairs and the lightest supersymmetric particle (LSP) is stable and represents a possible dark-matter candidate. The scalar partners of the left- and right-handed quarks, the squarks \tilde{q}_L and \tilde{q}_R , mix to form two mass eigenstates \tilde{q}_1 and \tilde{q}_2 ordered by increasing mass. Superpartners of the charged and neutral electroweak and Higgs bosons also mix to produce charginos ($\tilde{\chi}^\pm$) and neutralinos ($\tilde{\chi}^0$) also called Electroweakino (EWKino). Naturalness suggests that gluinos should not be too heavy, stops should be light ($\leq \sim 1$ TeV) while higgsinos must be below 350 GeV.

This document summarises the ATLAS¹ and CMS² searches for the third generation superpartners (stops and sbottoms) as well as the searches for compressed EWKino production. The word compressed represents the cases where the mass difference between the next to lightest supersymmetric particles (NLSP) and the LSP are small, leading to soft final state products.

2 Searches for stop pair production

The variety of spectra that the supersymmetric particles can have, requires dedicated searches to cover the different regions of the two-dimension (2D) mass plane $m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$. Figure 1 illustrates

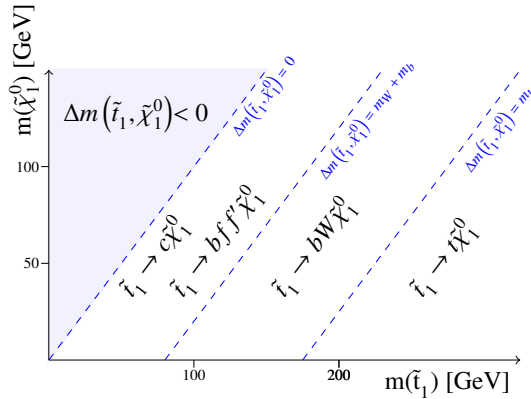


Figure 1 – A sketch of the two dimensional mass plane $m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$ with the decay topologies considered in each region³.

the different decay topologies that both ATLAS and CMS consider to cover these regions. According to that figure, the 2D plane can be divided in three regions:

- High mass ($\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0} > m_t$): This region is characterized from highly energetic final production objects leading to boosted topologies;
- Intermediate mass ($\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \leq m_t$): This region is covered by examining the three-body-decays of $\tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0$;
- Compressed ($\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0} < m_W + m_b$): This region is explored by examining either the four-body-decays of $\tilde{t}_1 \rightarrow bff\tilde{\chi}_1^0$ or $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$. It is one of the most challenging regions due to the very soft products of the decays, the high background rates that need to be controlled and due to the tagging of the c - quark.

Both ATLAS and CMS have dedicated searches for direct stop-pair production with decays into $\tilde{t} \rightarrow t\tilde{\chi}_1^0$. The decay products of the $t\bar{t}$ system in the all-hadronic decay mode can often be reconstructed as six distinct jets. The jet reconstruction is performed using the anti- k_t clustering algorithm with a distance parameter of $R = 0.4$. The signal models of high Δm involve the production of highly boosted top quarks. In such cases, it is possible to reconstruct the top quark decay products within a single large-radius jet. The hadronic decay products of the W bosons may be reconstructed in a similar manner. ATLAS and CMS use reclustered jets of $R = 1.2$ and 0.8 respectively.

2.1 Search for a Scalar Partner of the Top Quark in the Jets+ E_T^{miss} Final State at $\sqrt{s} = 13$ TeV with the ATLAS detector

These searches⁴ consist of two complementary analyses, one targeting the high Δm region, while the other probes the case where the mass difference between the \tilde{t} and the $\tilde{\chi}_1^0$ is of the $\mathcal{O}(m_t)$. The former analysis relies on the number of t - and W -tagged reconstructed jets, the minimum and maximum transverse mass between the two b -tagged jets and the missing transverse momentum, ($m_T^{b,min}$), the magnitude of the missing transverse moment (E_T^{miss}), the opening angle between the two b -tagged jets ($\Delta R(b,b)$) and the transverse mass ($m_{T2}^{\chi^2}$) which is constructed from the direction of magnitude of the E_T^{miss} in the transverse plane as well as the direction of two top quark candidates reconstructed using a χ^2 method. The latter analysis ($\Delta m \sim m_t$) requires an Initial State Radiation (ISR) jet and employs the Recursive Jigsaw Reconstruction technique⁵. According to this technique, each event is divided into an ISR hemisphere and a sparticle hemisphere, where the latter consists of the pair of candidate top squarks. Objects are

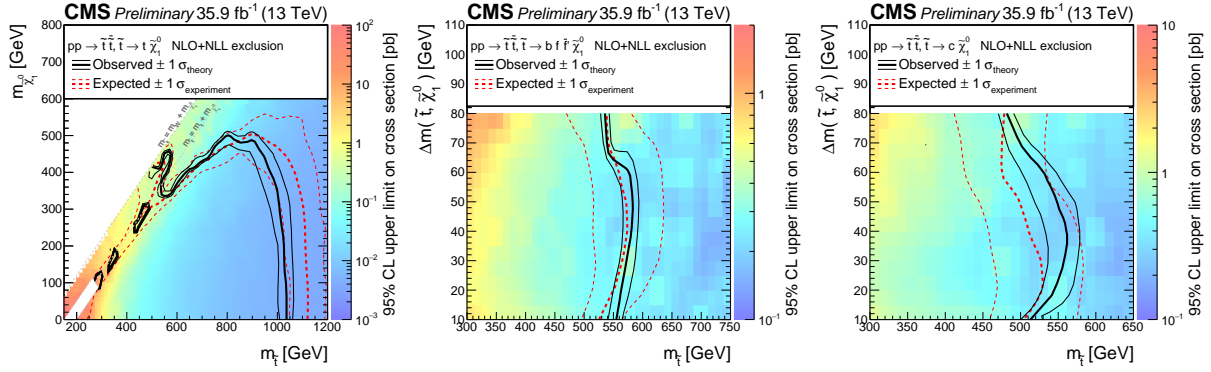


Figure 3 – Left: Exclusion limits at 95% CL for simplified models of top squark pair production in the pure $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ (left), $\tilde{t}_1 \rightarrow b f \tilde{\chi}_1^0$ (middle) and $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ (right) decay scenarios. The solid black curves represent the observed exclusion contours and the bands corresponding to the theory uncertainty on the cross section. The dashed red curves indicate the expected exclusion contour and the $\pm 1\sigma$ with experimental uncertainty ⁶.

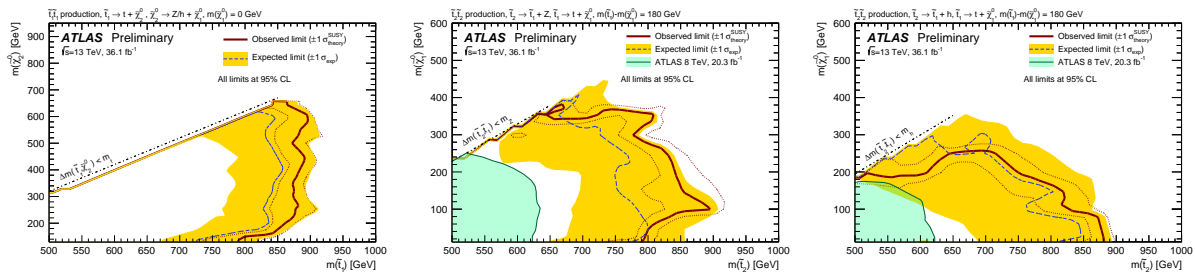


Figure 4 – Left: Exclusion limits at 95% CL from the analysis on the masses of the \tilde{t}_1 and $\tilde{\chi}_2^0$, for a fixed $m_{\tilde{\chi}_1^0} = 0$ GeV, assuming $\text{BR}(\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0) = 0.5$ and $\text{BR}(\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0) = 0.5$. The dashed line and the shaded band are the expected limit and its $\pm 1\sigma$ uncertainty, respectively. The thick solid line is the observed limit for the central value of the signal cross-section. Middle: Exclusion limits at 95% CL from the analysis on the masses of the \tilde{t}_2 and $\tilde{\chi}_1^0$, for a fixed $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 180$ GeV, assuming $\text{BR}(\tilde{t}_2 \rightarrow Z\tilde{t}_1) = 1$ (middle) and $\text{BR}(\tilde{t}_2 \rightarrow h\tilde{t}_1) = 1$ (right) ⁷.

3 Complementary models with top squarks

This section is dedicated to the ATLAS and CMS searches targeting cascade decays of stop-pair production.

3.1 Search for direct top squark pair production in events with a Higgs or Z boson, and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

This analysis ⁷ presents a search for direct top squark pair production with the Higgs and/or Z bosons appearing in the stop decay chains. In specific, the two models considered are (i) $\tilde{t}_1 \rightarrow t\tilde{\chi}_2^0 \rightarrow h/Z\tilde{\chi}_1^0$ and (ii) $\tilde{t}_2 \rightarrow h/Z\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$. The first model is interesting in its own right since it shows that new physics directly couples to the SM Higgs/Z bosons while the second model can provide additional sensitivity in the region $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m_t$.

The models involving a Z boson in the top squark decays have been examined in a three-lepton plus a b-tagged jet signature. The dominant backgrounds in this search are $t\bar{t}Z$ and multi-boson production. The normalization of these backgrounds is obtained by fitting the yield to the observed data in two CRs and then extrapolating this yield to the SRs. The top squark decays involving a Higgs boson have been studied in the one-lepton plus four b-tagged jets final-state. The dominant background contribution is coming from $t\bar{t}$ and again this contribution has been normalized to data in a dedicated CR. Both searches contain three overlapped SRs each, targeting different mass splits ($\Delta m(\tilde{t}, \tilde{\chi}_1^0)$). The statistical interpretation of the results can be seen in Figure 4.

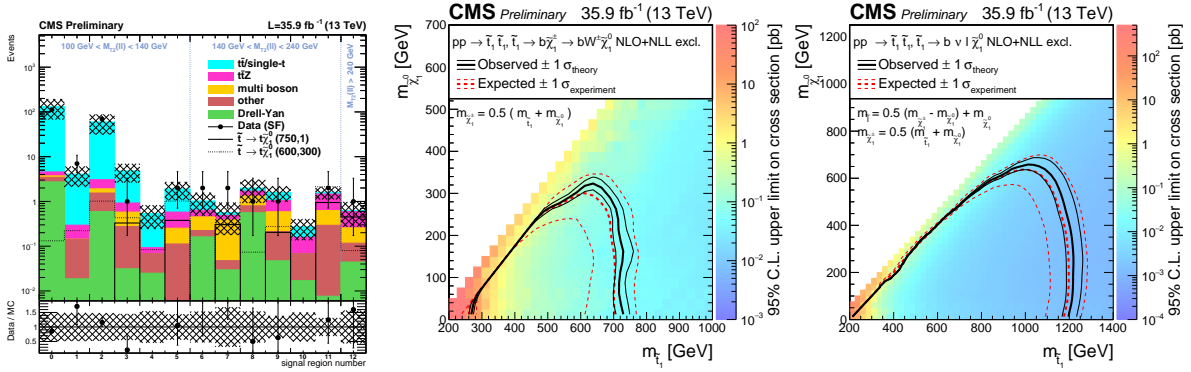


Figure 5 – Left: Observed and SM yields in the two-lepton search regions. Middle: Expected and observed limits at 95% CL for the chargino decay mode $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0$ and right for the cascade-decay mode $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu \rightarrow \ell\tilde{\chi}_1^0$ ⁸.

3.2 Search for direct pair production in the dilepton final state at $\sqrt{s} = 13$ TeV with the CMS experiment

These searches⁸ have been designed to target cascade decays of stop-pair production ($\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow W^\pm\tilde{\chi}_1^0$ and $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu \rightarrow \ell\tilde{\chi}_1^0$) and they are based on the selection of opposite-sign (OS) lepton pairs (electrons or muons). The main search variables in this analysis is the transverse mass⁹ (m_{T2}) constructed with two different ways, either considering only the two-leptons and the vector of E_T^{miss} or by using the two-leptons, the two b -tag jets and the E_T^{miss} .

The background processes from SM processes entering in the search regions are coming from single- t and $t\bar{t}$ production followed by top quark pair production in association with a Z , W , or a Higgs boson and Drell-Yan and di- or multi-boson production (WW , WZ , ZZ , WWW , WWZ , WZZ and ZZZ). For these backgrounds dedicated CRs have been constructed which have been used to normalize the MC predictions to data. Figure 5 (left) shows the predicted backgrounds and observed yields in each search region in the same-flavor (SF) OS channel. The shaded band covers the systematic uncertainties. The middle one shows the expected and observed limits at 95% CL for the decay mode $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$ (assuming that the $\tilde{\chi}_1^\pm$ mass is halfway between the \tilde{t} and $\tilde{\chi}_1^0$ masses) while the one on the right shows the statistical interpretation for the “cascade decay” mode $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu \rightarrow \ell\tilde{\chi}_1^0$.

4 Searches for bottom squark pair production

The following two searches have been performed by the CMS experiment and target the direct sbottom-pair production.

4.1 Search for direct production of bottom and top squark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV with the CMS detector

Similarly to the other analyses presented in this talk, there are two dedicated searches¹⁰, one targeting the non-compressed region ($\Delta m(\tilde{b}_1, \tilde{\chi}_1^0) > 150$ GeV) and another search for the compressed ($\Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 150$ GeV). The main discriminant variables in the high mass region are the scalar sum of the transverse momenta of the two leading jets (H_T) and the boost-corrected contranverse mass¹¹ (m_{CT}). For processes with two identical decays of heavy particles, $\tilde{b} \rightarrow b\tilde{\chi}_1^0$ the m_{CT} distribution is characterized by an endpoint defined by $m(\tilde{b})$ and $m(\tilde{\chi}_1^0)$, which for the topology in question is at $(m(\tilde{b})^2 - m(\tilde{\chi}_1^0)^2)/m(\tilde{b})$ (see left Figure 6). The philosophy for the design of the compressed SRs is based on the requirement of an ISR jet recoiling against the vector of the missing transverse momentum. The compressed SRs are then binned in E_T^{miss}

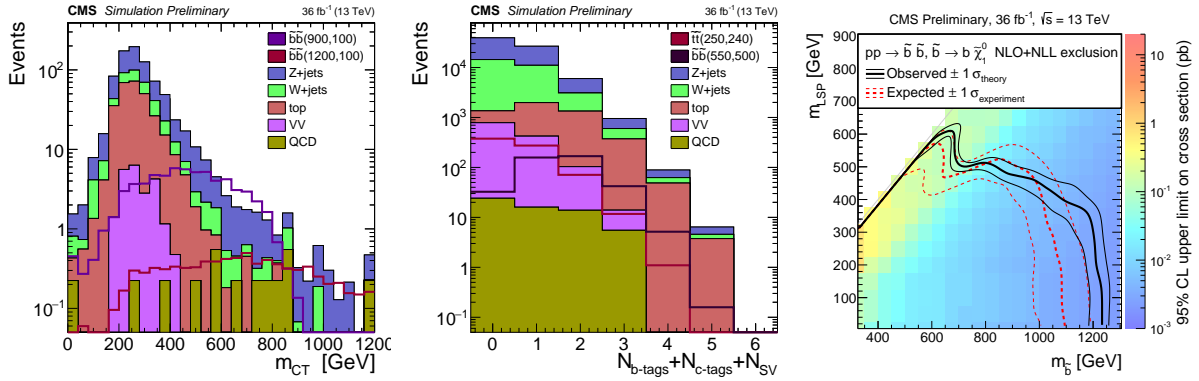


Figure 6 – Left: Distribution of m_{CT} ; Middle: Distributions of the combined b –, c –tagged jet, and SV multiplicities; Right: The 95% CL limits on the cross section, assuming 100% BR for the decay of the sbottom quark to b –quark and $\tilde{\chi}_1^0$.

and the b/c –tagged jet multiplicities. The distribution of the combined b –, c –tagged jet, and secondary vertex (SV) multiplicities at preselection level can be seen in Figure 6 middle plot.

The right plot of Figure 6 shows the statistical interpretation of the results based on a simplified model of sbottom quark pair production decaying to b –quark and $\tilde{\chi}_1^0$.

4.2 Search for Excess Higgs production in diphoton final states using the razor variables at $\sqrt{s} = 13$ TeV with the CMS detector

In the Minimal Supersymmetric Standard Model (MSSM) Higgs bosons may be produced through the cascade decays of heavier sparticles. This search¹² targets the direct sbottom pair production where the sbottoms decay through $\tilde{b} \rightarrow b\tilde{\chi}_2^0 \rightarrow H\tilde{\chi}_1^0$ and the study has been performed in the $H \rightarrow \gamma\gamma$ decay mode and in association with at least one jet. The selected events are categorized into four mutually exclusive categories. An event is categorized as “HighPt” if the p_T of the selected Higgs candidate is larger than 110 GeV. Otherwise, if the event contains two b –tagged jets whose invariant mass is between 76 GeV and 106 GeV, or between 110 GeV and 140 GeV, it is categorized as “ $H(\gamma\gamma) - H/Z(bb)$ ”. The remaining events are categorized as “HighRes” and “LowRes” if the diphoton mass resolution estimate σ_M/M is smaller or larger than 0.85%, respectively. These four categories are then subdivided further based on the razor variables¹³ M_R and R^2 .

There are two main classes of background events that pass the search selection criteria: SM Higgs production and non-resonant QCD production, with either two promptly produced photons or one prompt photon and one jet that is mistakenly identified as a photon. The SM Higgs background is estimated from the MC simulation, while the non-resonant background is predicted using a data-driven fit to the diphoton mass distribution.

Figure 7 shows the statistical interpretation of these searches. The figure on the left shows the observed significance in units of standard deviations per search region while the one on the right shows the results in terms of limits on the production cross-section times branching-ratio for bottom squark pair production decaying to a Higgs boson, a bottom quark and the LSP.

5 Searches for compressed Electroweakinos

Naturalness imposes constraints on the masses of higgsinos which are expected to be light and most likely have a compressed mass spectrum. The following search has been performed from the CMS experiment and targets EWKino production in nearly degenerated mass spectrum ($\Delta m = m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} - \tilde{\chi}_1^0 < 40$ GeV) by employing very soft leptons.

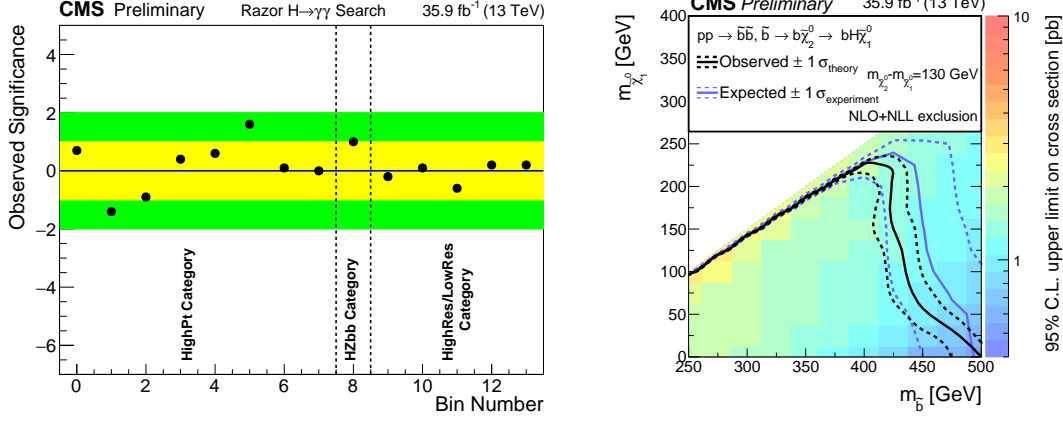


Figure 7 – Left: Observed significance in units of standard deviations per search region. The yellow and green bands represent the 1σ and 2σ regions, respectively. Right: The observed 95% confidence level (C.L.) upper limits on the production cross section for bottom squark pair production decaying to a bottom quark, a Higgs boson, and the LSP are shown. The solid and dotted black contours represent the observed exclusion region and its 1σ bands, while the analogous blue contours represent the expected exclusion region and its 1σ bands¹².

5.1 Search for new physics in events with two low momentum opposite-sign leptons and missing transverse energy at $\sqrt{s} = 13$ TeV with the CMS experiment

The phase space of this search¹⁴ is defined in the low lepton transverse momentum ($p_T > 3.5$ GeV) regime by imposing an upper limit of 30 GeV on the leading lepton p_T . To suppress contributions from the non-prompt and SM background processes a series of preselection cuts is applied. These requirements include the selection of OS pairs, moderate E_T^{miss} and the presence of at least one jet in the event which acts as an ISR jet for boosting the system. The events satisfying the preselection requirements are then binned according to the dilepton invariant mass and E_T^{miss} .

The main background contributions resulting in two prompt-leptons, like $t\bar{t}$, DY+jets and dibosons have been estimated by defining CRs (enriched in each of these processes) which are close to the SR and then using a Transfer Factor (calculated from Monte Carlo) to extrapolate these contributions to the SRs. The non-prompt lepton contribution has been estimated using a “tight to loose” method¹⁵.

The dilepton invariant mass distributions for $E_T^{miss} > 200$ GeV and > 250 GeV can be seen in Figure 8, left and middle plots respectively. The results have been interpreted in the context of direct $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ simplified models and assuming pure Wino cross sections (right Figure 8).

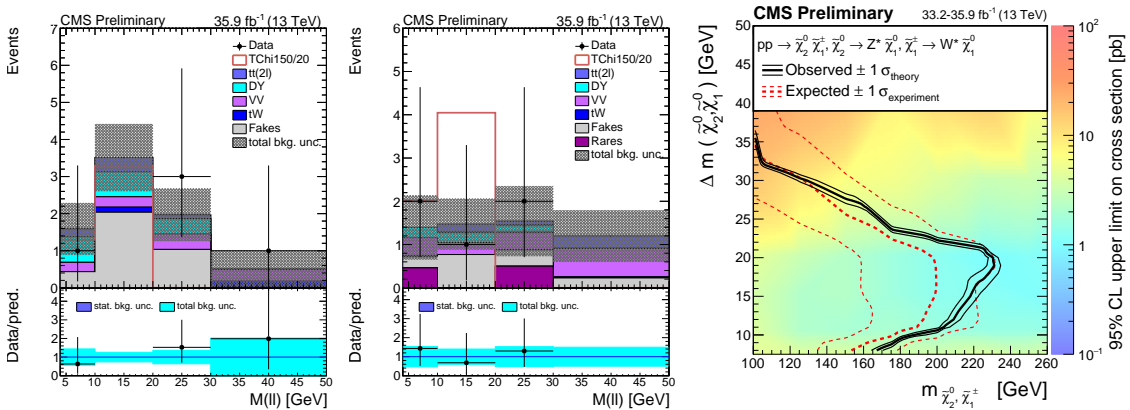


Figure 8 – Left: Electroweakino search region for $200 < E_T^{miss} < 250$ GeV; Center: Electroweakino search region for $E_T^{miss} > 250$ GeV; Right: Statistical interpretation of a simplified model of EWKino production¹⁴.

6 Acknowledgments

I would like to thank my colleagues in ATLAS and CMS Collaborations for their hard work in producing the results in this note, and to the organizers of Moriond EWK 2017 for a fruitful conference.

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