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

A.G. PETRIDIS, on behalf of the ATLAS and CMS collaborations
School of Physical Sciences, Physics Building, The University of Adelaide,
SA 5005 AUSTRALIA

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.

ATL-PHYS-PROC-2017-058
24 May 2017

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 $\tilde{q}_{\rm L}$ and $\tilde{q}_{\rm R}$, 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 ATLAS [1] and CMS [2] 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 $m_{\tilde{t}} - m_{\tilde{\chi}^0_1}$. Figure 1 illustrates

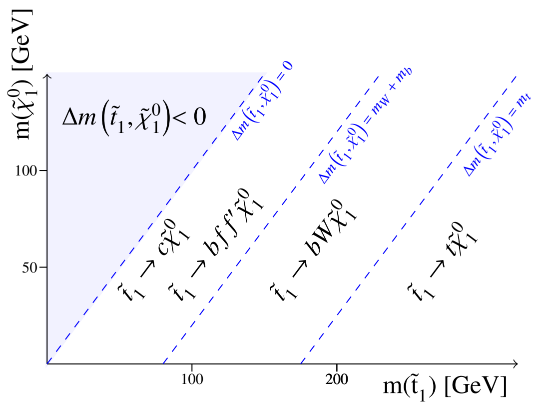

Figure 1 – A sketch of the two dimensional mass plane $m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$ with the decay topologies considered in each region [3].

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 ($\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0} < m_t$): This region is covered by examining the three-body-decays of $\tilde{t}_1 \to bW\tilde{\chi}_1^0$;
- 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 $\tilde{t}_1 \to bff\tilde{\chi}_1^0$ or $\tilde{t}_1 \to c\tilde{\chi}_1^0$. 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 $\tilde{t} \to t\tilde{\chi}_1^0$. 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 searches [4] 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 E_T^{miss}, the opening angle between the two $b-$tagged jets ($\Delta\mathrm{R(b, b)}$) and the stransverse 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 recontructed 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 technique [5]. 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 grouped together based on their proximity in the lab frame's transverse plane by minimizing the reconstructed transverse masses of the ISR system and sparticle system simultaneously over all choices of object assignment. Based on this assignment a series of observables are constructed as the jet multiplicities in the two hemispheres, the transverse mass between the entire sparticle system (including the invisible part) and the E_T^{miss} (m_S), the p_T of the ISR system in the CM frame, the azimuthal angle between the ISR system and the E_T^{miss} in the CM frame and the ratio of the E_T^{miss} to the p_T of the ISR system in the CM frame, R_{ISR} (This ratio is proportional to the ratio of the $\tilde{\chi}_1^0$ and $\tilde{t}$ masses).

The dominant backgrounds in the former analysis arise from $Z(\nu\nu) + jets$ followed by $t\bar{t}Z$ (where $Z \rightarrow \nu\nu$) while for the latter from $t\bar{t}$. All these backgrounds have been normalized to the data in Control Regions (CR) enriched in such events. Figure 2 shows the expected SM events and the observations in each Signal Region (left) while the middle and right ones show the statistical interpretation based on two simplified models, direct stop-pair production and gluino-pair production.

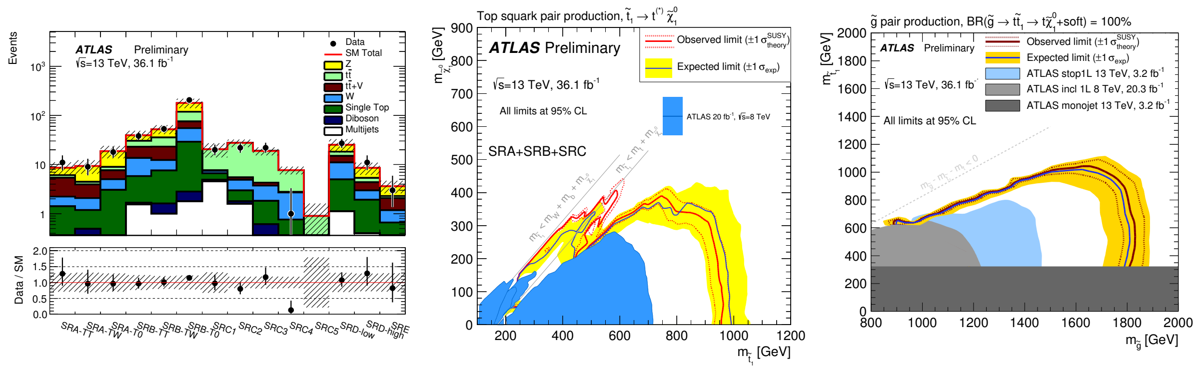

Figure 2 – Left: A comparison of the Stanadard Model expected yields and observed events in the Signal Regions (left). Center: the statistical interpretation based on a simplified model of stop-pair production ($\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$). Right: statistical interpretation based on a simplified model of gluino-pair production ($\tilde{g} \rightarrow t\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$) [4].

2.2 Search for direct top squark pair production in the all-hadronic final state in proton-proton collisions at $\sqrt{s}$ =13 TeV with the CMS detector

These searches [6] are divided in two categories. The first (second) category targets high (low) Δm scenarios and consists of multiple disjoint regions which are then combined to produce the final result. To target signal models with moderate values of Δm, in the low-$m_T(b_{1,2}, E_T^{miss})$ region, the presence of at least one "resolved-top" ($N_{res} \geq 1$) and $N_j \geq 7$ to benefit from the potential of ISR in signal events is required. The resolved-top category is an alternative way of reconstructing top quarks and recovering sensitivity in the low p_T top region. Event samples are then subdivided according to the number of $b-$tagged jets and different E_T^{miss} thresholds. A similar subdivision in N_b and E_T^{miss} is performed for events in the high-$m_T(b_{1,2}, E_T^{miss})$ region with $N_j \geq 7$ but containing no top or W objects. The signal models with larger values of Δm and sufficiently boosted top quarks or W bosons are covered by subdividing the high-$m_T(b_{1,2}, E_T^{miss})$ region into regions that require the presence of at least one recontructed top ($N_t \geq 1$), reconstructed W ($N_W \geq 1$), or resolved top. These regions do not have any further N_j requirement and are subdivided into disjoint SRs according to N_b, E_T^{miss} and the multiplicities of the top and W objects. There are in total fifty one disjoint regions.

The low Δm region is explored by examining the four-body-decays of stop production and it is based on the ISR approach. A novel soft $b-$tagging algorithm based on the presence of a secondary vertex has been developed for recovering $b-$tagged jets below $p_T < 20$ GeV. This analysis consists from fifty three disjoint SRs which are combined for the final result. Figure 3 shows the statistical interpretation of the results.

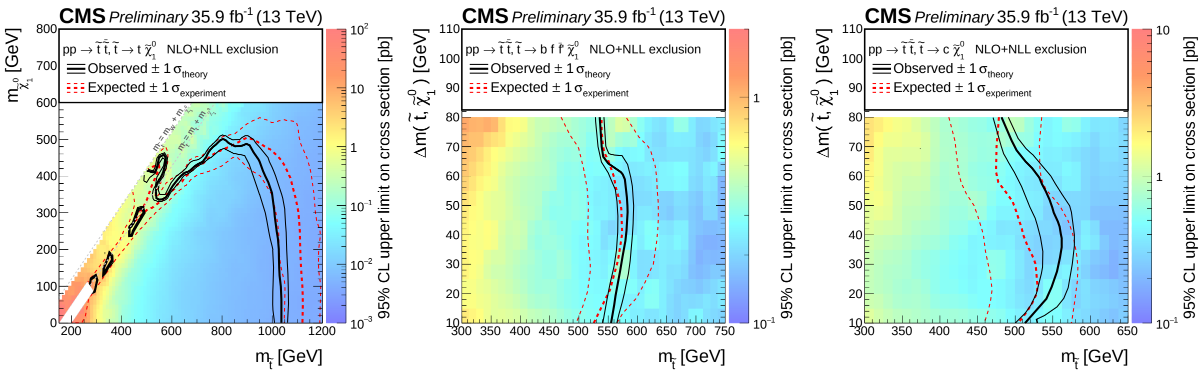

Figure 3 – Left: Exclusion limits at 95% CL for simplified models of top squark pair production in the pure $\tilde{t}_1 \to t\tilde{\chi}^0_1$ (left), $\tilde{t}_1 \to bff\tilde{\chi}^0_1$ (middle) and $\tilde{t}_1 \to c\tilde{\chi}^0_1$ (right) decay scenarios. The solid black curves represent the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

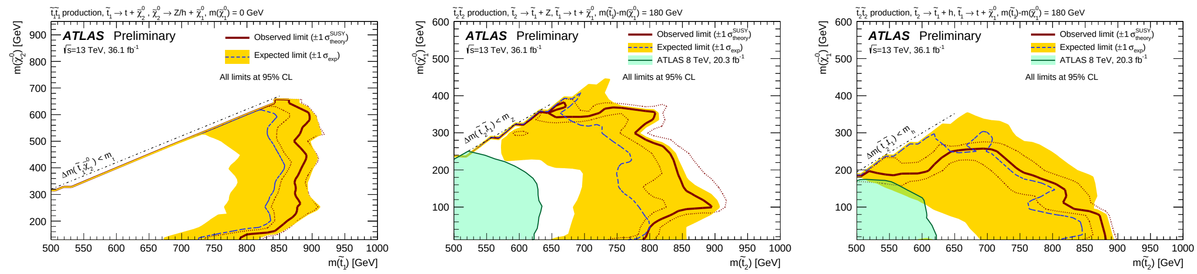

Figure 4 – Left: Exclusion limits at 95% CL from the analysis on the masses of the $\tilde{t}_1$ and $\tilde{\chi}^0_2$, for a fixed $m_{\tilde{\chi}^0_1} = 0$ GeV, assuming BR($\tilde{\chi}^0_2 \to Z\tilde{\chi}^0_1$)=0.5 and BR($\tilde{\chi}^0_2 \to h\tilde{\chi}^0_1$)=0.5. The dashed line and the 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 $\tilde{\chi}^0_1$, for a fixed $m(\tilde{t}_1) - m(\tilde{\chi}^0_1) = 180$ GeV, assuming BR($\tilde{t}_2 \to Z\tilde{t}_1$)=1 (middle) and BR($\tilde{t}_2 \to h\tilde{t}_1$)=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) $\tilde{t}_1 \to t\tilde{\chi}^0_2 \to h/Z\tilde{\chi}^0_1$ and (ii) $\tilde{t}_2 \to h/Z\tilde{t}_1 \to t\tilde{\chi}^0_1$. 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 $\Delta m(\tilde{t}_1, \tilde{\chi}^0_1) \sim m_t$.

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 bacgkrounds 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 ($\Delta m(\tilde{t}, \tilde{\chi}^0_1)$). The statistical interpretation of the results can be seen in Figure 4.

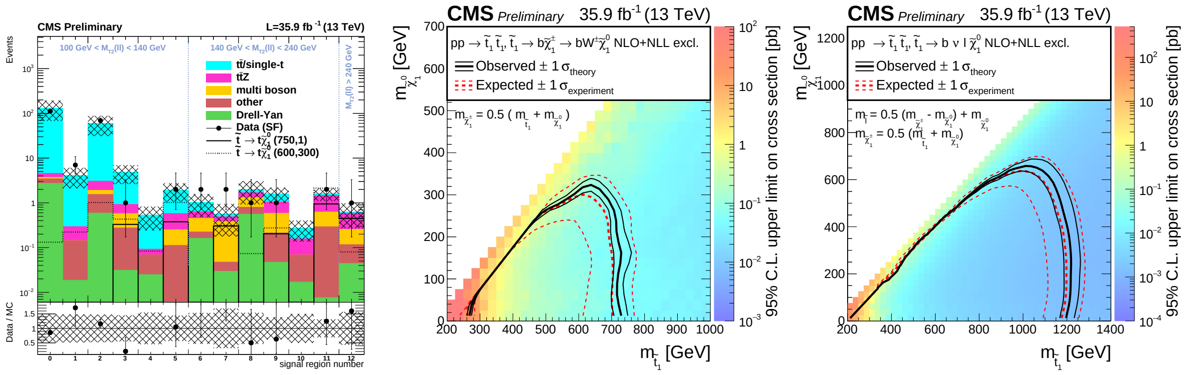

Figure 5 – Left: Observed and SM yields in the two-lepton search regions. Middle: Expected and observed limits at 95% CL for the chargino decay mode $\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm} \rightarrow W\tilde{\chi}_1^0$ and right for the cascade-decay mode $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}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

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

These searches [8] 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 stransverse mass [11] (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 $\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}$ 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 searches [9], 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 contransverse mass [10] (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} 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.

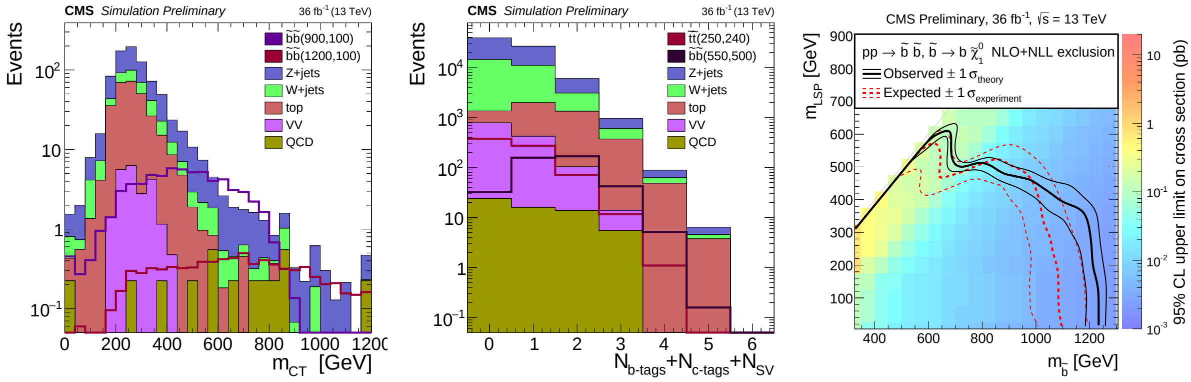

Figure 6 – Left: Distribution of m_{CT}; Middle: Distributions of the combined $b-$, $c-$tagged jet, and SV multiplicities; Right: The 95% CL limits on the cross section, assuming 100% BR for the decay of the sbottom quark to $b-$quark and $\tilde{\chi}^0_1$ [9].

The right plot of Figure 6 shows the statistical interpretation of the results based on a simplified model assuming 100% BR for the decay of the sbottom quark to $b-$quark and $\tilde{\chi}^0_1$.

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 search [12] targets the direct sbottom pair production where the sbottoms decay through $\tilde{b} \to b\tilde{\chi}^0_2 \to H\tilde{\chi}^0_1$ and the study has been performed in the $H \to \gamma\gamma$ 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 variables [13] 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 ($\Delta m = m_{\tilde{\chi}^\pm_1/\tilde{\chi}^0_2} - \tilde{\chi}^0_1 < 40$ GeV) by employing very soft leptons.

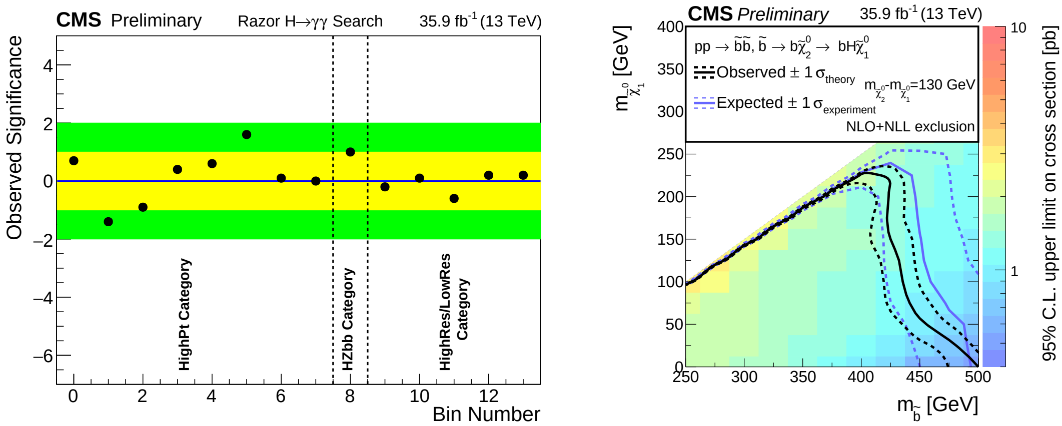

Figure 7 – Left: Observed significance in units of standard deviations per search region. The yellow and green bands represent the 1σ and 2σ regions, respectively. Right: The observed 95% confidence level (C.L.) upper limits on the production cross section for bottom squark pair production decaying to 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 bands [12].

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 search [14] 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” method [15].

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).

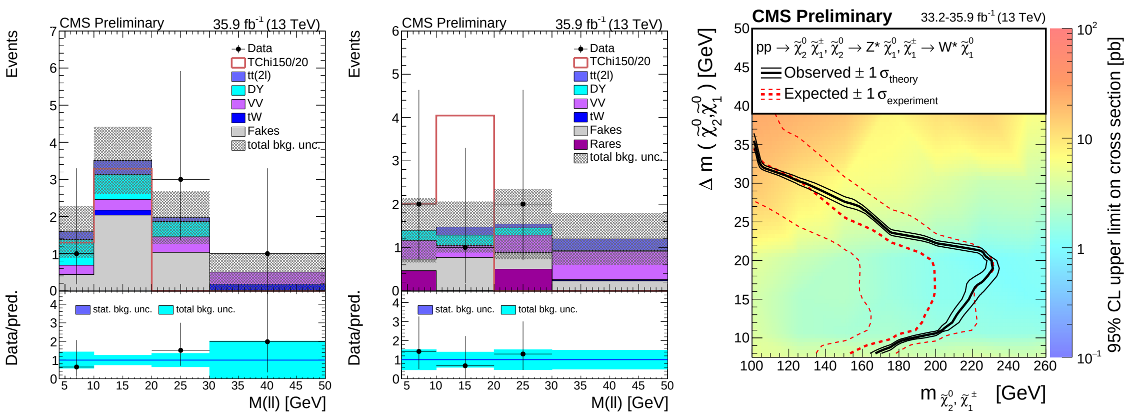

Figure 8 – Left: Electroweakino search region for 200< E_T^{miss} <250 GeV; Center: Electroweakino search region for E_T^{miss} >250 GeV; Right: Statistical interpretation based on a simplified model of EWKino production [14].

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.

References

1. ATLAS Collaboration, 2008 JINST 3 S08003
2. CMS Collaboration, 2008 JINST 3 S08004
3. ATLAS Collaboration, *ATLAS Run 1 searches for direct pair production of third-generation squarks at the Large Hadron Collider*, Eur. Phys. J. C75 (2015) 510
4. ATLAS Collaboration, ATLAS-CONF-2017-020 (2017)
5. P.Jackson, C. Rogan, M. Santoni, *Sparticles in motion: Analyzing compressed SUSY scenarios with a new method of event reconstruction*, *Phys. Rev.* D **95**, 2017 (035031).
6. CMS Collaboration, CMS-SUS-16-049 (2017)
7. ATLAS Collaboration, ATLAS-CONF-2017-019 (2017)
8. CMS Collaboration, CMS-SUS-17-001 (2017)
9. CMS Collaboration, CMS-SUS-16-032 (2017)
10. D. Tovey, *Supersymmetric particle mass measurement with boost-corrected constransverse mass*, JHEP 03 (2010) 030.
11. H.-C. Cheng and Z. Han, *Minimal Kinematic Constraints and m(T2)*, JHEP 12 (2008) 063.
12. CMS Collaboration, CMS-SUS-16-045 (2017)
13. CMS Collaboration, *Search for supersymmetry with razor variables in pp collisions at* $\sqrt{s} = 7\ TeV$, *Phys. Rev.* D **90**, (2014) (112001)
14. CMS Collaboration, CMS-SUS-16-048 (2017)
15. CMS Collaboration, *Search for new physics with same-sign isolated dilepton events with jets and missing transverse energy at the LHC*, JHEP 06 (2011) 077.