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# *Stop into Stau: Search for Scalar Top Quarks Decaying into Scalar Tau Leptons with ATLAS at $\sqrt{8} = 8$ TeV.*

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# Summary

The Standard Model (SM) describes the properties of the all known elementary particles and their electromagnetic, weak and strong quantum interactions. Matter is composed of half-integer spin particles, called *fermions*, which are divided into six *quarks* $(u, d, c, s, t, b)$, which can only be found confined into hadrons, and six *leptons* $(\nu_e, e, \nu_\mu, \mu, \nu_\tau, \tau)$. The interactions between these particles are mediated by spin-1 *bosons*: the weak force is carried by the massive $Z$ and $W^\pm$ bosons, while the photon $\gamma$ and the gluons $g$ are responsible for the electromagnetic and strong forces, respectively. The particles of the theory gain their mass through the spontaneous electroweak symmetry breaking described by the Higgs mechanism, which has been confirmed by the observation of the Higgs boson in 2012.

In the last decades the Standard Model has revealed itself very successful in predicting the behaviour of subatomic particles. However, the SM is a theory far from being complete since it does not include gravity and does not provide any explanation of the nature of Dark Matter and Dark Energy, which together compose about 95% of the Universe. Physicists have worked on possible extensions of the SM in order to solve these shortcomings. One promising theory is Supersymmetry (SUSY), which extends the SM allowing symmetry transformations that interchange fermions with bosons and predicts a super partner for each SM particle.

Since no supersymmetric particle has been experimentally observed yet, SUSY, if it exists, must be a broken symmetry and the masses of the superpartners are thought to be much larger than those of the SM particles. The mechanism behind the supersymmetry breaking is not known at the moment and in some models all the SUSY breaking terms are added directly to the Lagrangian. In contrast to this approach, other supersymmetric models assume the existence of a *hidden sector* where the SUSY breaking is generated and it is then transmitted to the *visible sector* composed by the SM particles and their superpartners. In particular, in the *Gauge Mediated Supersymmetry Breaking* (GMSB) model, a set of supersymmetric fields that couple directly to the *hidden sector* transmits the SUSY breaking to the *visible sector* through quantum loops in gauge interactions.

If Supersymmetric particles exist, they can be produced in very energetic proton collisions. The production cross section for supersymmetric particles is larger for those that couple strongly to the matter constituents, such as gluinos and squarks, with the scalar top quark pair cross section of an order of magnitude smaller than the other two generations of squarks. However, the requirement of a low level of fine tuning necessary for Supersymmetry to provide a solution for the *hierarchy problem*, together with a large Yukawa coupling and large off-diagonal terms in the mass mixing matrix, constrains the masses of top squarks below the TeV scale in many SUSY models and so these particles may be produced at the Large Hadron Collider (LHC).

The LHC is a two-ring superconducting, circular proton or heavy-ion collider located at CERN in Geneva. While the LHC is designed to operate at a proton-proton centre-of-mass energy of $\sqrt{s} = 14$ TeV, the delivered energy was $\sqrt{s} = 7$ TeV during 2010 and 2011, $\sqrt{s} = 8$ TeV during 2012 and $\sqrt{s} = 13$ TeV in 2015 and 2016. The proton beams cross each other in four sections of the LHC, where particle detectors are placed in order to study the products of the collisions. The "A Toroidal LHC ApparatuS" (ATLAS) is one of these experiments and it is designed to primarily study the Electroweak Symmetry Breaking and the Higgs Mechanism, precisely measure the SM parameters and look for new physics beyond the SM.

This thesis presents a SUSY analysis in a particular scenario arising from the GMSB mechanism that assumes a massless gravitino $\tilde{G}$ as lightest supersymmetric particle, a stau lepton $\tilde{\tau}$ as next-to-lightest supersymmetric particle and the top squark $\tilde{t}$ as the lightest among the quark superpartners. The analysis is performed using the data collected by ATLAS at a centre-of-mass energy $\sqrt{s} = 8$ TeV during 2012 data taking, for a total of 20.3 fb$^{-1}$ of integrated luminosity of $p$–$p$ collisions. In the model considered, the only open decay channel of the top squark is the three body decay $\tilde{t} \to b\tilde{\tau}\nu_{\tau}$, followed by the decay $\tilde{\tau} \to \tau\tilde{G}$, while the other supersymmetric particles are assumed to have very large masses and they do not contribute to the top squark decay chain.

The final state of this search is characterised by the presence of two tau leptons, two jets that contain a $b$-hadron and particles that escape detection such as neutrinos and gravitinos. The analysis is split into three orthogonal sub-channels that consider the cases with both taus decayed leptonically (*lep-lep*), with one hadronically decaying tau and a muon or an electron in the final state (*lep-had*) or two hadronically decaying tau leptons (*had-had*), respectively. Such final states can be realised also by Standard Model processes that represent the backgrounds to this search..

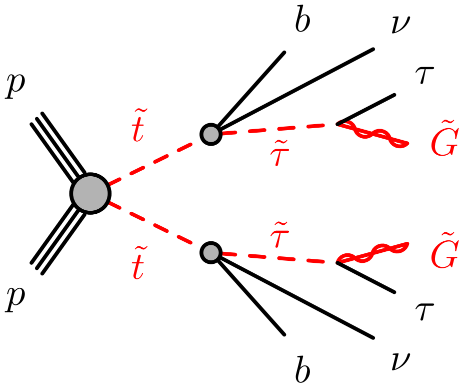

Figure S.1: Diagram showing the top squark pair production in $p-p$ collisions followed by the decay $\tilde{t} \to \tilde{\tau}b\nu_{\tau}$ and $\tilde{\tau} \to \tau\tilde{G}$.

Monte Carlo simulations are used to model the kinematics of the $\tilde{t} \to \tilde{\tau}$ signal, which depend on the unknown top squark mass $m_{\tilde{t}}$ and tau slepton mass $m_{\tilde{\tau}}$, and of the Standard Model processes.

For each channel, a number of statistically independent *Signal regions* is defined by applying specific kinematic cuts on the physics objects in the final states in order to achieve good discrimination between the signal and background. Among several kinematic variable, the *stransverse mass* $m_{\mathrm{T2}}$, provides the best discrimination power as shown in Fig. S.2. The presence of physics beyond the Standard Model would manifest itself via an excess of observed events with respect to the SM-only expectation. In order to precisely estimate the number of expected SM events in the signal regions, a normalisation fit to the major background sources is performed in *control regions*, which are designed to enhance the selection of single particular SM background processes and reduce to a negligible fraction the signal acceptance. For each channel, a simultaneous fit of the major background processes normalisation, which takes into account the associated systematic uncertainties,

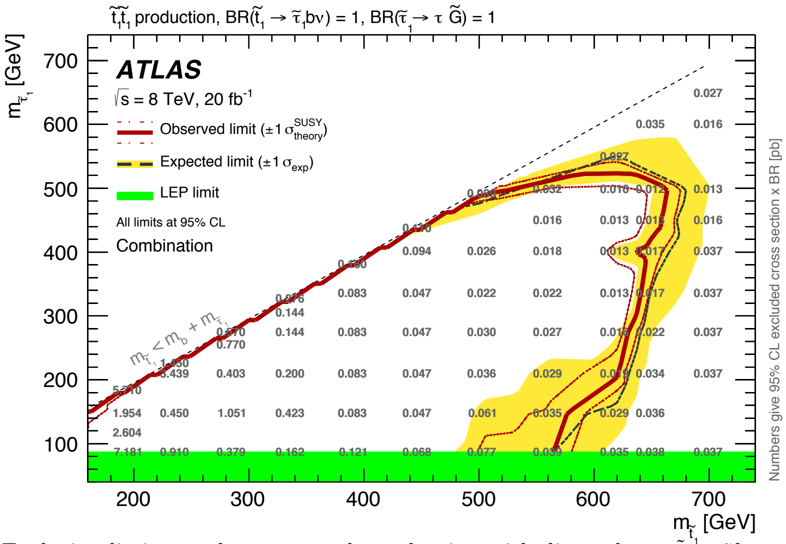

Figure S.3: Exclusion limits on the top squark production with direct decay $\tilde{t} \rightarrow \tilde{\tau} b \nu_\tau$ and $\tilde{\tau} \rightarrow \tau \tilde{G}$ at $\sqrt{s} = 8$ TeV. The limits on the $\tilde{t} \rightarrow \tilde{\tau}$ production cross section in pb are reported for each signal hypothesis.

is performed and the resulting estimates are validated in dedicated *validation regions*, designed to be enriched in SM background processes and kinematically similar, but still orthogonal, to the signal regions. The number of observed data events in the signal regions is found to be compatible with the SM-only hypothesis, hence the results of the search are interpreted as exclusion limits on the production cross section of the $\tilde{t} \rightarrow \tilde{\tau}$ model considered. In Figure S.3, the solid red line shows the observed exclusion limit at 95% CL in the $(m_{\tilde{t}}, m_{\tilde{\tau}})$ plane and for each signal hypothesis, the upper limit on the production cross section in picobarns is reported. The three channels have good complementarity in covering the simplified model parameter space and top squark masses up to 650 GeV are excluded depending on the scalar tau lepton mass.

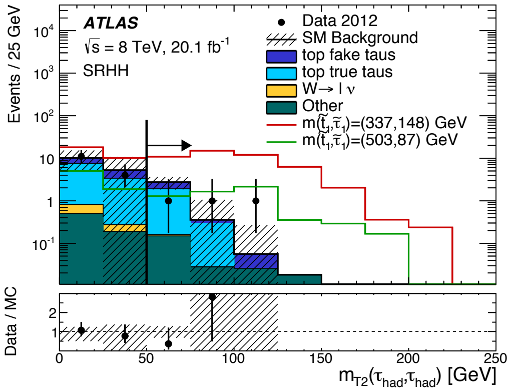

Figure S.2: Distribution of $m_{\mathrm{T2}}$ in the *had-had* signal region for the observed data, SM expectation and a $\tilde{t} \rightarrow \tilde{\tau}$ model at $\sqrt{s} = 8$ TeV.

At the end of Run-1, a long technical stop, known as the *Long Shutdown 1* (LS1), took place in order to prepare LHC and its experiments to record $p-p$ collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. The ATLAS experiment underwent several upgrades, modifications and refurbishment of detector elements with the aim to improve the acceptance, efficiency and performance in recording high quality data during Run-2. One of the major upgrades of the ATLAS Inner Detector (ID) consisted in the insertion of a new layer of the Pixel detector, the Insertable B-Layer (IBL), designed to significantly improve the tracking performance. The

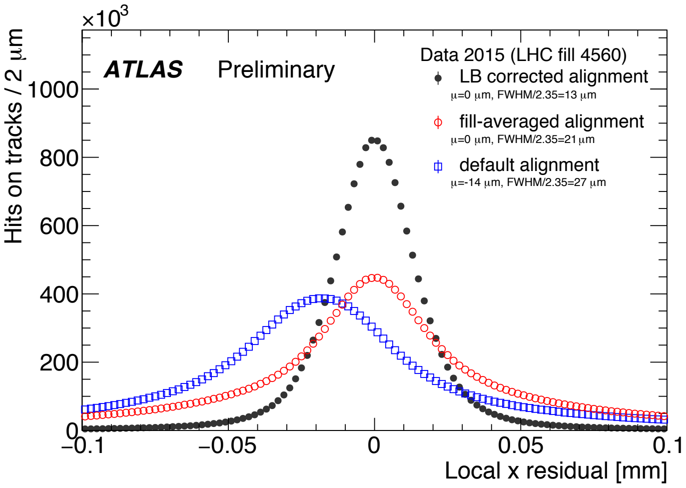

Figure S.4: The IBL local-$x$ $(r\phi)$ track-to-hit unbiased residual distributions obtained with a baseline alignment corrections (blue), with run-by-run corrections (red) and with within-run dynamic corrections (black).

insertion of a new detector causes a major change in the geometry of the experiment, which needs to be precisely assessed in order to reconstruct tracks at the design resolution.

The technique used in the ATLAS ID to measure the position of the sensitive elements is the *track-based Inner Detector Alignment*. Such method consists of calculating the corrections to an assumed ATLAS ID geometry by minimising a $\chi^2$ function which depends on the tracks parameters and on the position and orientation of the ID sensitive elements. This thesis presents the alignment of the ATLAS Inner Detector during the LS1, using cosmic ray data for the first commissioning, and for early Run-2 data taking, showing the final alignment performed at the end of 2015 campaign. During the ATLAS commissioning period with cosmic ray data, it has been observed that the IBL detector structure deforms assuming a parabolic shape whose magnitude $M$ depends linearly on the operating temperature $T$ with a slope $dM/dT = -10.6 \pm 0.7$ $\mu$m/K. Since small changes in temperature can cause sizeable displacements of the active elements that would undermine the quality of reconstructed tracks, the framework of the ID Alignment has been improved to include an additional degree of freedom that models such deformation, together with the possibility to calculate the corrections at a much smaller time granularity to correct for distortions happening during the data taking. The effect of such time-dependent correction is shown in Fig. S.4, where it is shown that the track-to-hit residual distribution gets significantly narrower, indicating the recovery of the IBL design resolution. This novel approach changes the computation of the ATLAS Inner Detector geometry which is not anymore fixed during the collection of data originating from $p-p$ collisions in Run-2, but is dynamically computed to account for smaller time-scale detector deformations.