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Searches for squark- and gluino-production in hadronic final states with the ATLAS detector

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Weak-scale supersymmetry is one of the best motivated and studied extensions of the Standard Model. The recent increase in the centre-of-mass energy of proton–proton collisions at the Large Hadron Collider gives a unique opportunity to extend the sensitivity to production of supersymmetric particles. We present several ATLAS results on searches for supersymmetric squarks and gluinos, including third generation squarks produced directly or via the decay of gluinos. The searches involve final states containing jets (possibly identified as coming from b-quarks), missing transverse momentum and no leptons. They are performed on $3.2\,\mathrm{fb}^{-1}$ proton–proton data collected in 2015 at $\sqrt{s} = 13\,\mathrm{TeV}$. The limits obtained in these searches extend the ones obtained during Run-1 of the LHC significantly.

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1. Introduction

Supersymmetry (SUSY) [1, 2, 3] is a popular extension to the Standard Model. Through the addition of supersymmetric partner fields to those of the Standard Model, SUSY could provide the solution to the hierarchy problem as well as offer a candidate dark matter particle. For these reasons, it is the target of a broad programme of searches at the Large Hadron Collider (LHC).

In this paper, we describe several searches performed on 3.2 fb^{-1} of $\sqrt{s} = 13$ TeV data collected by the ATLAS detector [4] in 2015. Should SUSY exist, the sparticles with the highest production cross-section are squarks and gluinos. In case R parity, defined through the quantum number $R = (-1)^{3(B-L)+2s}$, with B and L baryon and lepton number and s spin, is conserved, these particles are always produced in pairs and will decay in one or more steps into quarks and the lightest SUSY particle (LSP). The LSP typically is the lightest neutralino $\tilde{\chi}_1^0$. The signatures of such events involve jets, missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) and possibly leptons. In this paper, decays without leptons are targeted. Depending on the decay mode, the final state may contain one or more b jets; in particular with decays of the third-generation squarks $\tilde{b}$ and $\tilde{t}$ this will be the case. Example decays are shown in figs. 1 and 4.

With the increased production cross-section at $\sqrt{s} = 13$ TeV, early Run-2 searches have focused on pair production of gluinos, squarks, stops and sbottoms. All these searches followed a simple analysis strategy, at times in contrast with the corresponding Run-1 analysis. Standard Model background estimation techniques are similar to the ones previously used.

Irreducible background contributions are estimated through a semi-data-driven technique using dedicated control regions in which the background predictions are normalised. The obtained normalisation factors are validated in dedicated validation regions. This method allows for the cancellation of uncertainties in the background estimation through the use of transfer factors $N_{\mathrm{CR}}^{\mathrm{data}}/N_{\mathrm{CR}}^{\mathrm{MC}} = N_{\mathrm{SR}}^{\mathrm{data}}/N_{\mathrm{SR}}^{\mathrm{MC}}$, where the labels CR and SR refer to control and signal regions respectively. Minor backgrounds are estimated directly from their Monte Carlo simulation. Finally, any reducible backgrounds in each analysis are estimated using data-driven methods.

2. Inclusive searches for squarks and gluinos

The production of squarks or gluinos will lead to a cascade decay into Standard Model particles. Inclusive searches target models in which only the four lightest squarks are accesible and their mass states are degenerate. The final state targeted will thus involve many high-p_{T} jets, a large amount

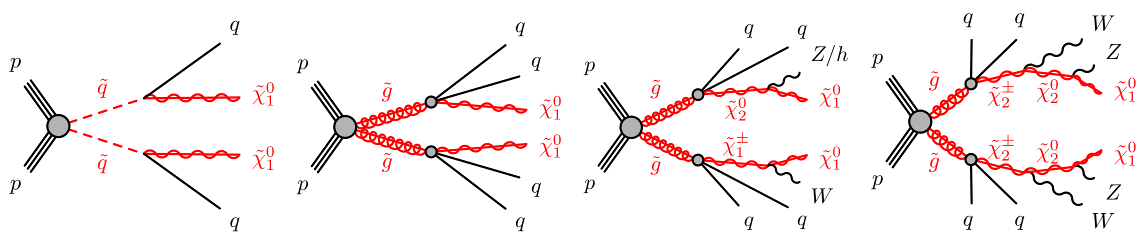

Figure 1: Feynman diagrams for the inclusive production of squarks and gluinos. No distinction between quark flavours and between particles and antiparticles is made.

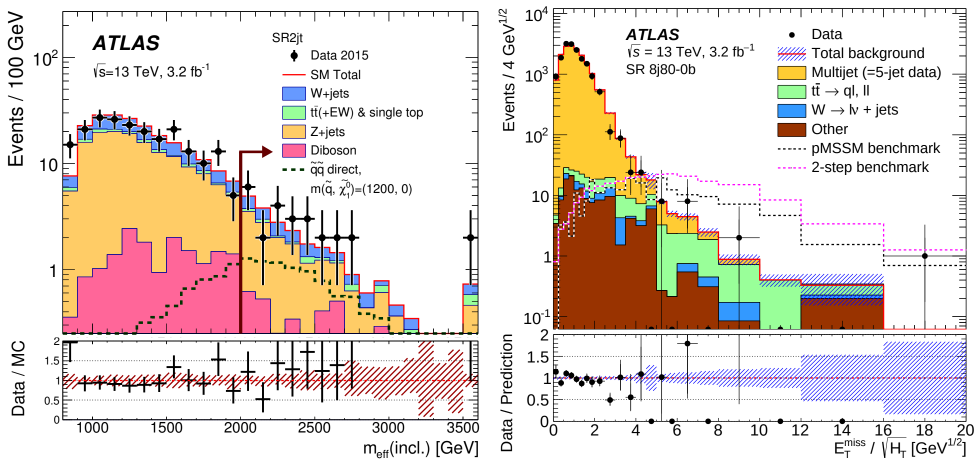

Figure 2: Signal region distributions for the 2-jet region SR2jt from the 0-lepton analysis (in m_{eff}) [5] and the 8-jet signal region SR8j80-0b, which selects 8 jets with a $p_{\text{T}} > 80\,\text{GeV}$ and no b jets, from the multijet analysis (in $E_{\text{T}}^{\text{miss}}/\sqrt{H_{\text{T}}}$) [7]. Example SUSY models are overlaid in dotted lines.

of missing transverse momentum, and possibly leptons. The searches described in this paper use the fully hadronic final state. More complex cascade decays of squarks and gluinos through the second-lightest neutralino $\tilde{\chi}_2^0$ will lead to Z and h bosons being produced. Decays through an intermediate chargino $\tilde{\chi}_1^{\pm}$ will result in W bosons in the final state. All these decays are shown in fig. 1. Depending on the number of intermediate particles, the decays are referred to as *direct*, *one-step* or *two-step* decay models.

The *0-lepton analysis* [5] primarily targets the direct production of squarks and gluinos, although it is also sensitive to one-step gluino decays. Final states with ≥ 2 to ≥ 6 jets are used. In order to be sensitive to a wide range of sparticle masses, multiple signal regions are defined. Selection criteria applied are the jets' p_{T}, the missing transverse momentum $E_{\text{T}}^{\text{miss}}$ and the *effective mass* $m_{\text{eff}} = E_{\text{T}}^{\text{miss}} + \sum_i |p_{\text{T}}^{(i)}|$, where the sum runs over the jets. The effective mass correlates strongly with the mass of the initial SUSY particle in case of massless neutralinos [6]. In addition, the ratio $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}$ is used to suppress the Standard Model QCD background. Remaining backgrounds estimated from control regions are Z+jets, W+jets, single-top and $t\bar{t}$ production.

The *multijet analysis* [7] targets longer cascade decays, primarily of gluinos. It requires ≥ 7 to ≥ 10 jets, and in addition divides the signal regions by the number of b jets in the event. The discriminating variables are similar to the 0-lepton analysis, but unlike the hard selections used to reject QCD a cut on the $E_{\text{T}}^{\text{miss}}$ significance $E_{\text{T}}^{\text{miss}}/\sqrt{H_{\text{T}}}$, where H_{T} is the sum of the jets' p_{T}, is used. As a consequence, the QCD multijet background is no longer negligible in the signal region. It is estimated from templates derived at lower jet multiplicites. The shape of the distribution is assumed not to change at higher multiplicities. That assumption is validated in dedicated validation regions.

In total, the 0-lepton analysis defines seven overlapping signal regions. The multijet analysis defines two sets of overlapping regions: one of nine regions with jets with a $p_{\text{T}} > 50\,\text{GeV}$, the other of six regions with jets with a $p_{\text{T}} > 80\,\text{GeV}$. Two example distributions are shown in fig. 2.

Neither of the analyses observes a significant excess over the Standard Model expectation. Limits on various models are set that extend beyond the previously obtained results. These limits

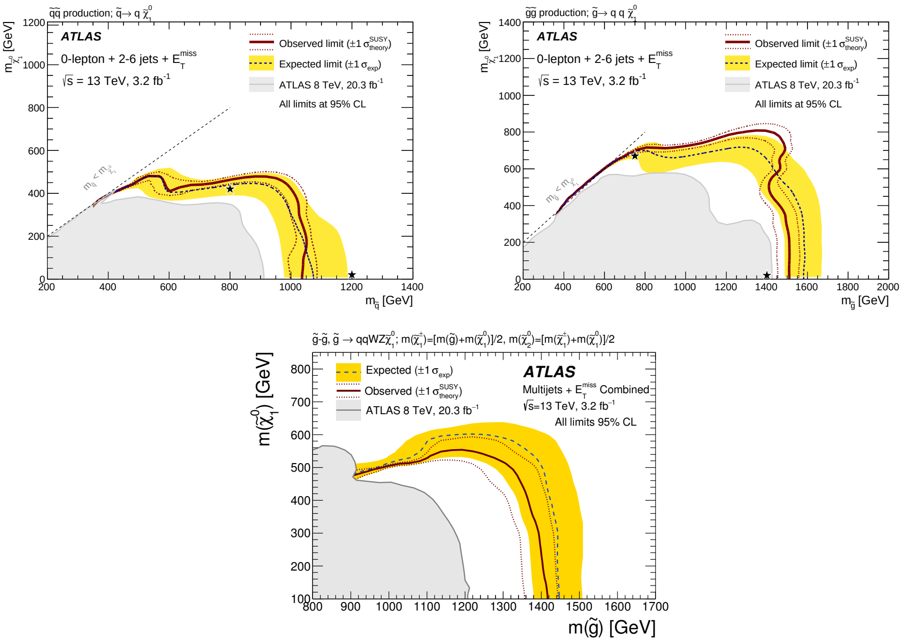

Figure 3: Observed (solid) and expected (dashed) 95% CL exclusion curves for the direct production of squarks (left) [5], direct gluino decays (middle) [5] and two-step gluino decays (right) [7]. The previous 8 TeV limits are shown in grey.

are shown in fig. 3. Assuming massless neutralinos, gluinos are excluded up to a mass of 1.5 TeV. For squarks, the corresponding limit is approximately 1050 GeV.

3. Searches for third-generation squarks

The production of a third-generation squark, whether directly or in a decay chain, leads to the production of Standard Model b or t quarks. As such, analyses that target these squarks exploit the presence of b jets in the final state. The particular selection strategy varies depending on the exact decay targeted in the analysis and further relies on the kinematic properties of the selected events. The targeted decays are shown in fig. 4. The decay models of gluinos through $\tilde{b}$ and $\tilde{t}$ are referred to as the *Gbb* and *Gtt* model, respectively.

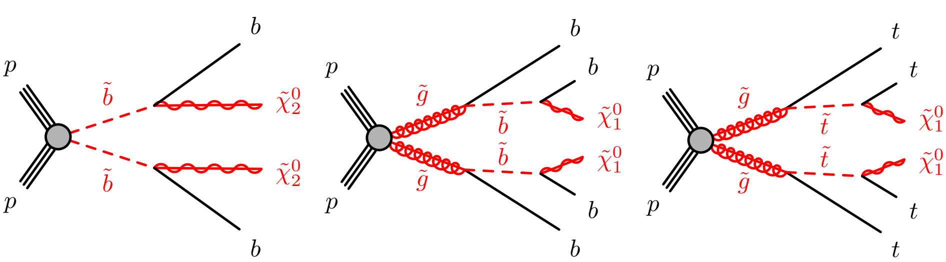

Figure 4: Feynman diagrams for the third-generation models targeted. The two models on the right are the *Gbb* and *Gtt* model.

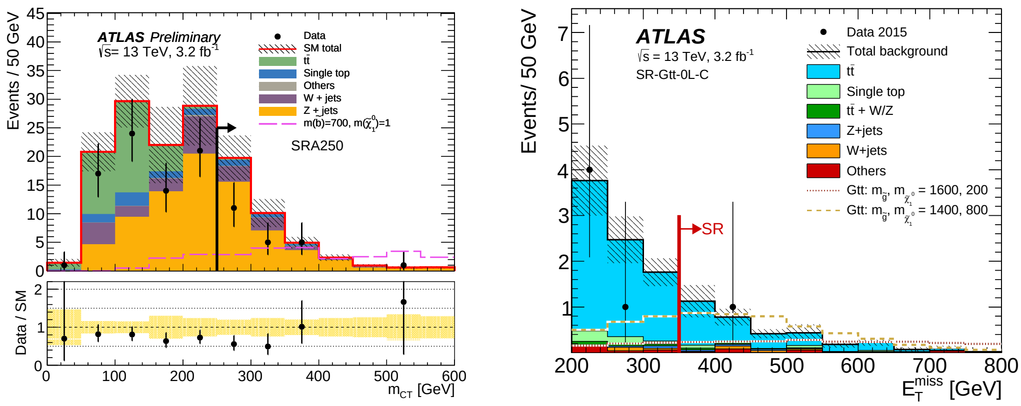

Figure 5: The distribution of the contransverse mass m_{CT} for the region SRA of the 2 b-jet analysis (left) [8] and of $E_{\mathrm{T}}^{\mathrm{miss}}$ for the Gtt-0L-C region of the 3 b-jet analysis (right) [10].

The *2 b-jet analysis* [8] targets pair production of $\tilde{b}$ squarks. The dominant background is $t\bar{t}$ production, which is suppressed by a selection based on the *contransverse mass*. Defined as $m_{\mathrm{CT}}^2 = [E_{\mathrm{T}}(v_1) + E_{\mathrm{T}}(v_2)]^2 - [\mathbf{p}_{\mathrm{T}}(v_1) - \mathbf{p}_{\mathrm{T}}(v_2)]^2$, where $v_{1,2}$ are the visible products in the decay chain, it has an endpoint at 135 GeV for $t\bar{t}$ events [9]. For $\tilde{b}$ quark production the endpoint is at $m_{\mathrm{CT}}^{\mathrm{max}} = (m_{\tilde{b}_1}^2 - m_{\tilde{\chi}_1^0}^2)/m_{\tilde{b}_1}$.

Two sets of signal regions are defined: one for large and one for small differences between $m_{\tilde{b}}$ and the LSP mass. For large mass differences a selection on m_{CT} is used; for small mass differences the recoil against an ISR jet is exploited. With new ATLAS Insertable B-Layer, the light-jet rejection has improved by a factor 2 for the same b-tagging efficiency.

Gluino decays through $\tilde{b}$ and $\tilde{t}$ are the target of the *multi b-jet analysis* [10]. Two signal regions without leptons that also use the contransverse mass are defined. In addition, selections are used on the minimum transverse mass between any of the b jets and the missing transverse momentum $m_{\mathrm{T}}^{\mathrm{min}}(b\text{-jets}, E_{\mathrm{T}}^{\mathrm{miss}})$, which has an endpoint for semileptonic $t\bar{t}$ events. A one-lepton region with a selection on the number of high-mass large-radius jets is used to target the Gtt model. All three signal regions are combined in one likelihood fit to further improve the reach of the analysis. Two example distributions are shown in fig. 5.

Neither analyis observed a significant excess over the Standard Model expectation. Limits on $\tilde{b}$ pair-production and on the Gtt model are shown in fig. 6.

4. Conclusions

The first 3.2 fb^{-1} of collected proton–proton data at $\sqrt{s} = 13$ TeV allowed the ATLAS collaboration to further explore the SUSY parameter space. Strong limits that significantly extended the corresponding Run-1 results were set. Projections made by the ATLAS collaboration [11] indicate that with the amount of data expected to be collected in 2016, the collaboration can prepare to explore larger masses and processes with lower cross-sections. These data will allow us to shed further light on whether SUSY is realised in nature, or not.

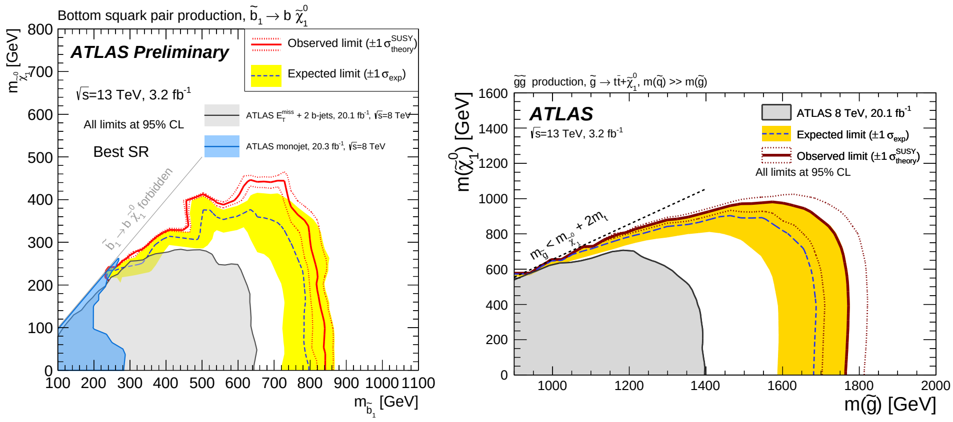

Figure 6: Observed (solid) and expected (dashed) 95% CL exclusion curves for the direct production of $\tilde{b}$ squarks (left) [8] and of gluinos decaying through $\tilde{t}$ (right) [10]. Previous 8 TeV limits are also shown.

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