Search for New Physics at $\sqrt{s} = 7$ TeV in Hadronic Final States with Missing Transverse Energy and Heavy Flavor

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A search for supersymmetric particles in events with large missing transverse momentum, heavy flavor jet candidates and no leptons ($e, \mu$) in $\sqrt{s} = 7$ TeV proton-proton collisions is presented. In a data sample corresponding to an integrated luminosity of 0.83 fb$^{-1}$ recorded by the ATLAS experiment at the Large Hadron Collider, no significant excess is observed with respect to the prediction for Standard Model processes. Model-independent production cross section upper limits are provided in the context of simplified models as well as conventional limits.

I. INTRODUCTION

Supersymmetry (SUSY) is one of the most compelling theories to describe physics beyond the Standard Model (SM). In the framework of a generic $R$-parity conserving minimal supersymmetric extension of the SM, the MSSM, SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable. The colored superpartners of the right-handed and left-handed quarks, squarks ($\tilde{q}$) and gluinos ($\tilde{g}$), are expected to be copiously produced via the strong interaction at the Large Hadron Collider (LHC). The partners of the right-handed and left-handed quarks, $\tilde{q}_R$ and $\tilde{q}_L$, can mix to form two mass eigenstates. These mixing effects are proportional to the corresponding fermion masses and therefore become important for the third generation. In particular, large mixing can yield sbottom ($\tilde{b}_1$) and stop ($\tilde{t}_1$) mass eigenstates that are significantly lighter than other squarks. Consequently, $\tilde{b}_1$ and $\tilde{t}_1$ could be produced with large cross sections at the LHC. Direct $\tilde{g}$ pair production or $\tilde{g} \tilde{g}$ production with subsequent $\tilde{g} \rightarrow \tilde{b}_1 b$ or $\tilde{g} \rightarrow \tilde{t}_1 t$ decays result in complex final states consisting of missing transverse momentum (its magnitude is referred to as $E_T^{\text{miss}}$ in the following) and several jets. Among these jets, $b$-quark jets ($b$-jets) are expected.

SUSY is searched for in final states involving $E_T^{\text{miss}}$, energetic jets, of which at least one must be identified as a $b$-jet and no isolated leptons ($e$ or $\mu$). The search is based on pp collision data at a center-of-mass energy of 7 TeV recorded by the ATLAS experiment at the LHC in 2011. The total data set used corresponds to an integrated luminosity of 0.83 fb$^{-1}$.

Two phenomenological MSSM scenarios are considered where the first and second generation squark masses are set above 2 TeV. In the first scenario, the $\tilde{b}_1$ is the lightest squark, $m_{\tilde{g}} > m_{\tilde{b}_1} > m_{\tilde{\chi}_1^0}$, and the branching ratio for $\tilde{g} \rightarrow \tilde{b}_1 b$ decays is 100%. Sbottoms are produced via gluino-mediated processes or via direct pair production and they are assumed to decay exclusively via $\tilde{b}_1 \rightarrow b \tilde{\chi}_1^0$, where $m_{\tilde{\chi}_1^0}$ is fixed at 60 GeV. The interpretation of the results is presented as a function of the gluino and light sbottom masses.

The second MSSM-like scenario is defined in the context of the general simplified models: all squarks including $b_1$ are heavy, gluino-pair production is the only kinematically allowed process and gluinos decay (off-shell) into $b\bar{b}\tilde{\chi}_1^0$ final states. Here the results are interpreted in a $(m_{\tilde{g}}, m_{\tilde{b}_1})$ plane. These results are generalized to any new physics process where gluino-like particles decay into $b\bar{b}$ and a weakly interacting massive particle.

II. SIMULATION AND EVENT SELECTION

Simulated event samples are used to determine the detector acceptance, the reconstruction efficiencies and the expected event yields. Details can be found in Ref. For the background, the following Standard Model processes are considered:

- $t\bar{t}$ and single top production
- $W(\rightarrow \ell \nu)+$jets, $Z/\gamma^*(\rightarrow \ell^+\ell^-)+$jets (where $\ell = e, \mu, \tau$) and $Z(\rightarrow \nu\bar{\nu})++$jets production
- Di-boson ($WW$, $WZ$ and $ZZ$) production, which is found to be negligible.

For the QCD background, no reliable prediction can be obtained from leading-order Monte Carlo simulation. A data-driven method is used as discussed in Section IV.

Events are selected at the trigger level by requiring one jet with high $p_T$ and large missing transverse momentum. The selection is fully efficient for events containing at least one jet with $p_T > 130$ GeV and $E_T^{\text{miss}} > 130$ GeV. Only jets with $p_T > 20$ GeV and within $|\eta| < 2.8$ are retained. Candidates for $b$-jets are identified among jets with $p_T > 50$ GeV using a secondary vertex with a tagging efficiency of 50% (1%)
for $b$-jets (light flavor or gluon jets) in $t\bar{t}$ events in simulation. A lepton veto is applied to electrons (muons) with $p_T > 20$ GeV (10 GeV) and $|\eta| < 2.47 (2.4)$.

The effective mass, $m_{\text{eff}}$, is defined as the scalar sum of $E_T^{\text{miss}}$ and the transverse momenta of the three leading jets. Events are required to have $E_T^{\text{miss}}/m_{\text{eff}} > 0.25$. In addition, the smallest azimuthal separation between the $E_T^{\text{miss}}$ direction and the three leading jets, $\Delta \phi_{\text{min}}$, is required to be larger than 0.4 to reduce the amount of QCD background. Full selection details can be found in Ref. [6].

III. SIGNAL REGION OPTIMIZATION

Phenomenological models describe well-motivated, SM-like production and decay processes, and the kinematics are determined by a small number of parameters (masses). Both SUSY scenarios considered in this analysis result in 4 $b$-jet + $E_T^{\text{miss}}$ final state signatures. The simplified model kinematics are determined to first order by the mass difference between the gluino and the neutralino. This simplicity motivates the choice of this model for signal region optimization studies, with cross-checks to ensure the results are relevant to the gluino-squark on-shell cascade case.

Signal region optimization consists of an $n$-dimensional significance maximization procedure to produce a set of optimal selections which were then iteratively reduced in number while ensuring broad-based sensitivity was retained. Four signal regions were chosen to represent good compromises among mass plane coverage, sensitivity, and practical concerns such as background control regions. They are characterized by the minimum number of $b$-jets required (1,2) and by the $m_{\text{eff}}$ threshold (500, 700 GeV).

IV. BACKGROUND ESTIMATION AND SYSTEMATIC UNCERTAINTIES

Events from $t\bar{t}$ production represent the largest background component in all four signal regions. The Monte Carlo prediction is validated by a data-driven estimate which relies on 1-lepton control regions with similar kinematic selections to those of the signal regions [6]. The normalization determined in these control regions (corrected for non-$t\bar{t}$ contamination) is then transferred to the signal regions.

The Monte Carlo estimation of the $W/Z$ background is validated with a combined fit of $t\bar{t}$ and $W/Z$ background components to the distribution of the number of $b$-tagged jets in a 0-lepton control region defined by reversing the $m_{\text{eff}}$ cut. The total systematic uncertainty on the Monte Carlo prediction is estimated to be between $\pm 30\%$ and $\pm 35\%$ depending on the final selection, and is dominated by the jet energy scale, theoretical, and $b$-tagging efficiency uncertainties [3].

The remaining QCD background in the signal regions is estimated with a data driven procedure. The technique [8,9] used is to smear the momentum of jets in clean data events with low $E_T^{\text{miss}}$ to generate "pseudoevents" with potentially large $E_T^{\text{miss}}$ values. The method was validated by comparing data and pseudoevents distributions in QCD enriched control regions obtained by reversing the cut on $\Delta \phi_{\text{min}}$. The uncertainty of $50\%$ is dominated by the dependency of the smearing function on the flavor composition of the low $E_T^{\text{miss}}$ sample [5].

V. RESULTS

Good agreement between data and Monte Carlo prediction is observed in the $m_{\text{eff}}$ distribution (Figure 1) for the signal regions with two $b$-tags. A similar level of agreement is observed for signal regions with one $b$-tag.

The observed and predicted event yields in the four signal regions are given in Table I. The SM predictions agree with the observed number of events in all four signal regions.

95% C.L. exclusion limits are derived using the $CL_s$ [8] method, while the power constrained limit (PCL) [9] method is used for comparison with previous ATLAS results. For each scenario, the signal region resulting in the best expected exclusion limit is used. In Figure 2 the observed and expected exclusion regions are shown in the $(m_{\tilde{g}}, m_{\tilde{\chi}})$ plane for $\tilde{g}$ production.
TABLE I: Summary observed and expected event yields in the four signal regions. The selections differentiating the regions are given after the region name in the format (n b-tag(s), m_{eff} cut in GeV).

| Sig. Reg. | Data | Top | W/Z | QCD | Total |
|-----------|------|-----|-----|-----|-------|
| 3JA (1,500) | 361 | 221^{+68}_{-62} | 121 ± 61 | 15 ± 7 | 356_{-92}^{+103} |
| 3JB (1,700) | 63 | 37^{+15}_{-12} | 31 ± 19 | 1.9 ± 0.9 | 70_{-24}^{+22} |
| 3JC (2,500) | 76 | 55^{+25}_{-22} | 20 ± 12 | 3.6 ± 1.8 | 79_{-25}^{+28} |
| 3JD (2,700) | 12 | 7.8^{+4.5}_{-2.9} | 5 ± 4 | 0.5 ± 0.3 | 13.0_{-5.6}^{+5.6} |

FIG. 2: Observed and expected 95% C.L. exclusion limits in the (m_{b_1}, m_{\chi^0_1}) plane. The neutralino mass is set to 60 GeV. The result is compared to previous ATLAS and CDF results. Exclusion limits from the CDF and D0 experiments on direct sbottom pair production are also shown.

The hypothesis that the lightest squark \( \tilde{b}_1 \) is produced via gluino-mediated or direct pair production and decays exclusively via \( \tilde{b}_1 \rightarrow b \chi^0_1 \). Gluino masses below 720 GeV are excluded for sbottom masses up to 600 GeV. This search extends the previous ATLAS exclusion limit by about 130 GeV [10].

Results are also interpreted in the context of simplified models. In this case, all the squarks are heavier than the gluino, which decays exclusively into three-body final states (\( b\bar{b}\chi^0_1 \)) via an off-shell sbottom. The exclusion limits obtained on the \((m_{\tilde{g}}, m_{\chi^0_1})\) plane are shown in Figure 3 as well as \( \sigma \times BR \) upper limits. Neutralino masses below 200-250 GeV are excluded for gluino masses in the range 200-660 GeV, if \( \Delta M(\tilde{g} - \chi^0_1) > 100 \) GeV.

VI. CONCLUSIONS

A search for SUSY in final states with missing transverse momentum, b-jets and no isolated leptons in pp collisions at 7 TeV is presented. No excess above the expectation from SM processes is found. The results are used to exclude parameter regions in various R-parity conserving SUSY models.

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