PROCEEDINGS OF SCIENCE

Searches for mono-X at the LHC

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If Dark Matter interacts weakly with the Standard Model it can be produced at the LHC and identified via initial state radiation (ISR) of the incoming partons. The signature left in the detector is that of the ISR particle (jet, photon, Z or W) recoiling off of the invisible Dark Matter particles, resulting in a large momentum imbalance. Similar signatures result from the compactification of extra spatial dimensions in the Arkani-Hamed, Dimopoulos, and Dvali model resulting in a Kaluza-Klein tower of massive graviton modes. The mono-X signature is also sensitive to a large class of SUSY models. The document summarises results from searches for new physics in final states containing a single jet, photon, W or Z boson, top quark and missing transverse energy studied by the ATLAS and CMS experiments at the LHC.

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PoS(DIS2014)116

1. Introduction

Events containing a jet or a photon and an imbalance in transverse momentum (E_T^{miss}) in the final state constitute a clean and distinctive signature in searches for new physics at hadron colliders. These signatures have been proposed and studied [1–6] as a discovery signal for many new physics scenarios, including the production of weakly interacting massive particles (WIMPs) as candidates for dark matter (DM), supersymmetry (gravitinos), large extra dimensions (LED) in the framework of the model proposed by Arkani-Hamed, Dimopoulos, and Dvali (ADD) and Unparticle production [7].

The presence of a non-baryonic DM component in the Universe is inferred from the observation of its gravitational interactions [8], although its nature is otherwise unknown. A WIMP with mass m_χ in the range between 1 GeV and a few TeV is a plausible candidate for DM. It could be detected via its scattering with heavy nuclei, the detection of cosmic rays (energetic photons, electrons, positrons, protons, antiprotons, or neutrinos) from annihilation in astrophysical sources, or via $\chi\chi$ pair production at colliders where the WIMPs do not interact with the detector and the event is identified by the presence of an energetic jet or a boson from initial-state radiation (ISR). The interaction of WIMPs with standard model (SM) particles is assumed to be driven by a mediator with mass at the TeV scale and described using a nonrenormalizable effective theory with several operators. The vertex coupling is suppressed by an effective cutoff mass scale $M_\star \sim M\sqrt{g_1 g_2}$, where M is the mass of the mediator and g_1 and g_2 are the couplings of the mediator to the WIMP and the SM particles, respectively. DM candidates are assumed to be Dirac fermions and different operators with scalar, vector, axial-vector, and tensor structure are considered.

The ADD model for LED [9] explains the large difference between the electroweak unification scale $\mathscr{O}(10^2$ GeV) and the Planck scale $M_{Pl} \sim \mathscr{O}(10^{19}$ GeV) by postulating the presence of n extra spatial dimensions of size R, and defining a fundamental Planck scale in $4+n$ dimensions, M_D, given by $M_{Pl} \sim M_D^{2+n} R^n$. An appropriate choice of R for a given n allows a value of M_D at the electroweak scale. The extra spatial dimensions are compactified, resulting in a Kaluza-Klein tower of massive graviton modes. At hadron colliders, these graviton modes may escape detection and can be produced in association with an energetic jet, leading to a monojet signature.

In gauge mediated SUSY breaking (GMSB) scenarios [10–12], the gravitino $\tilde{G}$ (spin–$\frac{3}{2}$ super partner of the graviton) is often considered the lightest supersymmetric particle (LSP) and a potential candidate for DM. Its mass is related to the SUSY breaking scale $\sqrt{F}$ and M_{Pl} via $M_{\tilde{G}} \propto F/M_{Pl}$. At hadron colliders, the cross sections for associated production of a gravitino and a squark ($pp \to \tilde{G}\tilde{q}+X$) or a gravitino and a gluino ($pp \to \tilde{G}\tilde{g}+X$) become relevant [13]. These cross sections depend on $m_{\tilde{G}}$ as $\sigma \sim 1/m_{\tilde{G}}^2$ and therefore provide the means to determine a lower bound on $m_{\tilde{G}}$. The decay of the gluino or squark into a gravitino and a gluon ($\tilde{g} \to \tilde{G}g$) or a gravitino and a quark ($\tilde{q} \to \tilde{G}q$), respectively, dominates and the final state is characterised by the presence of a pair of gravitinos that escape detection and an energetic jet, leading to a monojet topology.

Other searches for mono-X can also be sensitive to WIMP pair production, as well as to other DM-related models. In particular, theories postulating that the Higgs field can interact to other fundamental particles which might escape detection can be tested with searches for an *invisible* Higgs decay performed in mono-W or mono-Z signatures. At a mass of 125 GeV, the invisible branching fraction, $\mathrm{BR_{inv}} = \mathrm{BR}(H \to \text{invisible})$, of the Higgs is especially sensitive to new particles at electroweak scale. Many extensions to the SM, such as SUSY [14] or extra dimension models [15] postulate the existence of such invisible particles. Searches for mono top events, in which a potential DM particle is produced in association with a top quark, are also performed to explore the case where these new particles favour coupling to massive SM particles, such as the top quark [16].

Finally, monojet signatures have also been used to explore compressed scenarios of SUSY decays. In the case of the top squark, if $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} < m_W + m_b$, the dominant decay mode can be a decay to a charm quark and the LSP ($\tilde{t} \to c + \tilde{\chi}_1^0$), which proceeds via a loop decay. The corresponding final state is characterised by the presence of two jets from the hadronization of the charm quarks and E_T^{miss} from the two undetected LSPs. Low jet multiplicities selections can be used to explore a compressed scenario.

2. Searches in mono-jet final states

Searches in events with a very energetic jet and large E_T^{miss} have been performed by both the ATLAS and CMS experiments. The ATLAS collaboration reports results on 4.7 fb^{-1} of data recorded at $\sqrt{s} = 7$ TeV [3] and on 10.5 fb^{-1} of $\sqrt{s} = 8$ TeV data recorded in 2012 [4]. Events are selected with no more than two jets with $p_T > 30$ GeV and $|\eta| < 4.5$. In order to reject events coming from the production of W or Z bosons in association with jets, the events are required to have no electrons or muons in the final state. Several overlapping signal regions are defined by symmetric lower cuts in E_T^{miss} and p_T of the leading jet, with values of 120 GeV, 220 GeV, 350 GeV and 500 GeV. The dominant SM background contributions are normalized using scale factors determined from control region samples in data. Figure 1 shows the E_T^{miss} distribution fot the signal region defined by a cut on the E_T^{miss} and on the p_T of the leading jet at 120 GeV for the 2012 analysis, along with some characteristic distributions for DM, ADD and gravitino+squark/gluino models. The CMS collaboration has perfomed a similar analysis, both with $\sqrt{s} = 7$ TeV [5] and $\sqrt{s} = 8$ TeV [6] collision data. This analysis is performed in different signal regions defined by the threshold in $E_T^{miss} > 250, 300, 350, 500, 450, 550, 550$ GeV, and a fixed cut on the leading jet $p_T > 110$ GeV. A veto on events with more than two jets with p_T above 30 GeV and $|\eta| < 4.5$ is also in place, along with the veto on events with reconstructed leptons. The main backgrounds are also estimated with data-driven methods. The E_T^{miss} distribution from data and the expected backgrounds after all selection criteria and a E_T^{miss} cut of 250 GeV is found in Figure 2. Some representative signal distributions for DM, ADD and Unparticles are also shown.

The results of both experiments are translated into limits on the parameters of the ADD LED model. ATLAS sets 95% confidence level (CL) lower limits on M_D versus n. M_D values below 4.2 TeV for $n = 2$ and 2.5 TeV for $n = 6$ are excluded. CMS excludes M_D values below 5.1 TeV for $n = 2$ and 2.9 TeV for $n = 6$, for 95% CL. Furthermore, CMS provides limits at next-to-leading order on M_D values below 5.7 TeV for $n = 2$ and 3.1 TeV for $n = 6$. The same results can be translated into limits in the suppression scale $M*$ for WIMP pair production for all operators, probed as a function of the WIMP mass m_χ. ATLAS sets limits on the suppression scale at 90% CL for different operators. For the vector spin-independent operators, values for $M*$ below 687 GeV and 173 GeV are excluded for m_χ equal to 1 GeV and 1.3 TeV respectively. Values for $M*$ below 687 GeV and 110 GeV (1353 GeV and 240 GeV) are excluded for the axial-vector (tensor) operator, for m_χ equal to 1 GeV and 1.3 TeV respectively. CMS places 90% CL limits on the suppression

PoS(DIS2014)116

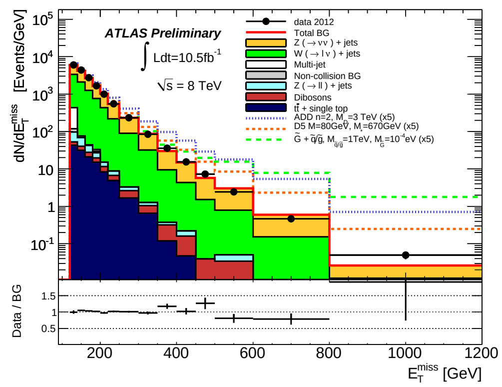


Figure 1: Measured leading E_T^{miss} distribution in the signal regions compared to the predictions for SM backgrounds. Only statistical uncertainties are shown. For illustration purposes, the impact of different ADD, WIMP, and GMSB scenarios are included.

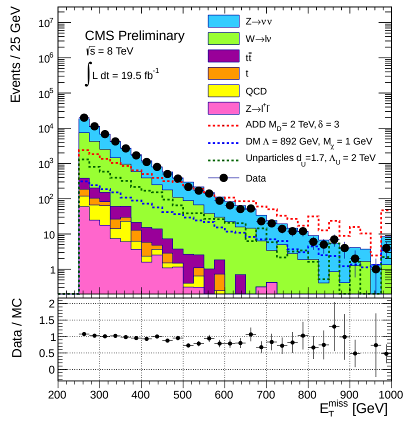
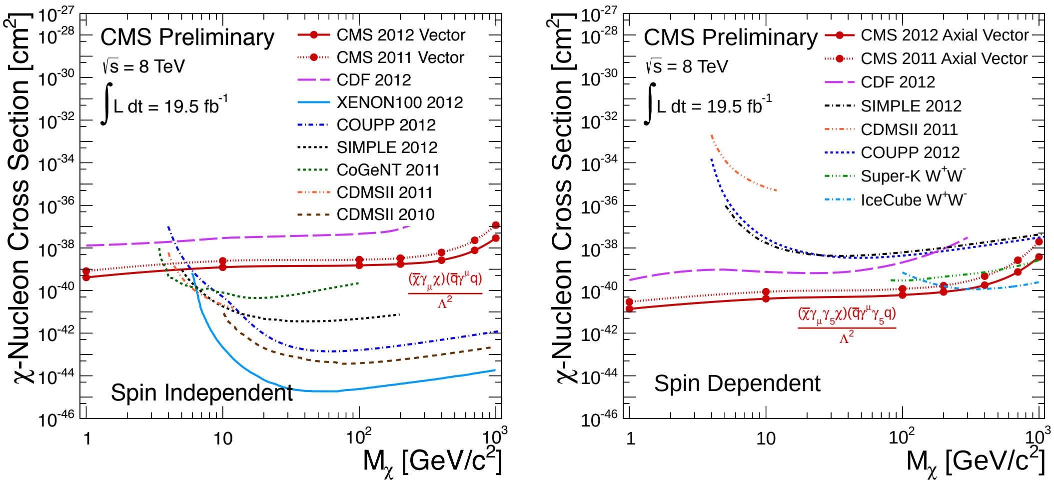


Figure 2: Missing transverse momentum E_T^{miss} after all selection cuts for data and SM backgrounds. Representative signal distributions for dark matter, ADD and Unparticles are also overlaid. Events with E_T^{miss} > 1 TeV are included in the overflow bin.

scale too. For the vector spin-independent operators, values for $M*$ below 892 GeV and 428 GeV are excluded for m_χ equal to 1 GeV and 1 TeV respectively. For the axial-vector spin-dependent operator, values for $M*$ below 913 GeV and 312 GeV are excluded for m_χ equal to 1 GeV and 1 TeV respectively. In the effective operator approach, the bounds on $M*$ for a given m_χ can be converted to bounds on WIMP–nucleon scattering cross sections, $\sigma_{\chi,N}$, which are probed by direct DM detection experiments. For the vector operator CMS excludes $\sigma_{\chi,N}$ below 4.1×10^{-40} cm^2 and 2.9×10^{-38} cm^2, for m_χ equal to 1 GeV and 1 TeV respectively. For the axial-vector operator CMS excludes $\sigma_{\chi,N}$ below 1.4×10^{-41} cm^2 and 3.8×10^{-39} cm^2, for m_χ equal to 1 GeV and 1 TeV respectively. These limits are shown in Figure 3, along with results from direct DM detection experiments, for illustration.

The ATLAS monojet results are also translated into limits on the cross section for the associated production of gravitinos with squarks or gluinos in the final state. Figure 4 shows the 95% CL limit on the gravitino mass as a function of the squark mass for degenerate squark/gluino masses. 95% CL lower bounds on the gravitino mass in the range between 3×10^{-4} and 3×10^{-5} eV are set on the squark and gluino masses. The limits on the gravitino mass can be translated into a limit on the SUSY breaking scale $\sqrt{F}$. Values of $\sqrt{F}$ below 640 GeV are excluded at 95% CL.

A search for direct top squark pair production in the decay channel to a charm quark and the lightest neutralino ($\tilde{t} \to c + \tilde{\chi}_1^0$) has been done, using 20.3 fb^{-1} of collision data at $\sqrt{s} = 8$ TeV recorded by the ATLAS experiment [17]. The analysis is carried out in different signal regions according to the final state jet multiplicity. Given the relatively small mass difference (Δm), both the transverse momenta of the two charm jets and the E_T^{miss} are too low to extract this signal from the large multijet background. The event selection can make use of the presence of ISR jets to identify signal events. To reconstruct the compressed scenario of this decay, small Δm, an approach following closely a monojet selection, where events with low jet multiplicity and large E_T^{miss} are selected, is performed. No excess above the SM background expectation is observed. The results



(a) (b)

Figure 3: Comparison of CMS 90% CL upper limits on the DM-nucleon cross section versus DM mass for (a) spin-independent and (b) spin-dependent interactions. For illustration, the results are compared with previous mono-jet and mono-photon results at colliders and results from direct detection experiments. References to all these results are cited in the CMS note [6].

are interpreted in the context of direct pair production of top squarks and presented in terms of exclusion limits in the ($m_{\tilde{t}}$, $m_{\tilde{\chi}^0_1}$) plane. Top squark masses up to 230 GeV are excluded for a neutralino mass of 200 GeV by the monojet-like selection alone. These exclusion limits are shown in Figure 5.

3. Searches in mono-photon final states

Searches in the mono-photon final state are a priori less sensitive compared to those in the monojet channel, however they allow to access a different final state, providing an independent cross check of the monojet results. The CMS experiment has reported results from a search in the final state containing a photon and E_T^{miss} [21]. The data used in this analysis correspond to an integrated luminosity of 5.0 fb^{-1} collected in pp collisions at $\sqrt{s}$ =7 TeV. The observed event yield agrees with SM expectations. Using models for production of DM particles, 90% CL upper limits of 13.6–15.4 fb on χ production in the photon-plus-missing-transverse-energy state are set. These provide very sensitive upper limits for spin-dependent χ–nucleon scattering for χ masses between 1 and 100 GeV. For models with 3–6 LED, their data exclude extra-dimensional Planck scales between 1.65 and 1.71 TeV at 95% CL. In the case of ATLAS, the search for a energetic photon and missing transverse energy is performed in pp collisions data at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 4.6 fb^{-1} [22]. Good agreement is observed between the data and the SM predictions. Upper limits at 95% CL on the parameters of ADD LED are set. Limits on M_D between 1.74 and 1.87 TeV (for different values of n) are set. Limits on $M*$ are also extracted from both the ATLAS and the CMS analyses, though not as stringent as their mono-jet counterpart.

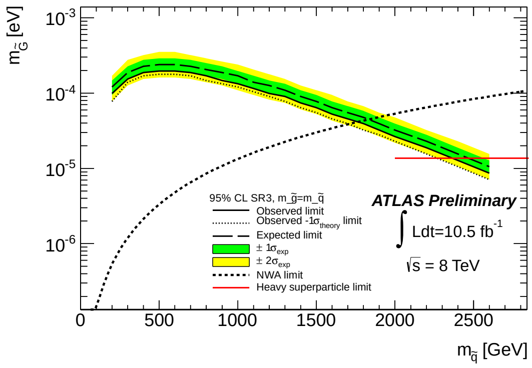


Figure 4: Observed and expected 95% CL lower limits on the gravitino mass as a function of the squark mass for degenerate squark/gluino masses. The solid red line denotes the current limit from LEP [30] on the gravitino mass assuming very heavy squarks/gluino.

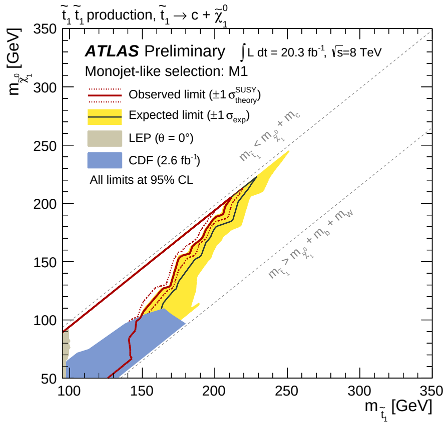


Figure 5: Exclusion plane at 95% CL as a function of top squark and neutralino masses for the monojet-like analysis. The observed and expected upper limits from this analysis are compared to previous results from Tevatron [18, 19] experiments, and from LEP [20] experiments at CERN with squark mixing angle $\theta^0 = 0$.

4. Searches in mono-Z, mono-W and mono-t

At the LHC, the ATLAS and CMS collaborations have searched for invisible Higgs decays in the ZH associated production channel, with the Z boson decaying to leptons [23–25]. The ATLAS collaboration has reported an observed (expected) 95% CL exclusion limit $\mathrm{BR}_{\mathrm{inv}}$ >0.65(0.84) using full 2011 and 2012 data; whereas the CMS collaboration observed (expected) exclusion limit is $\mathrm{BR}_{\mathrm{inv}} > 0.75\ (0.91)$. Searches for the invisible decays in the WH associated production have also been performed by both experiments. The CMS collaboration performed a search in the leptonic final state of the W-boson [26]. In this analysis vector and axial-vector couplings of the DM model are considered. The limits on the effective parameter $M*$ are between 300 and 1000 GeV for different strengths of the coupling to up- an down-type quarks, for both the vector and the axial-vector couplings. A search for mono-W and mono-Z events based on the hadronic decay products of the bosons has been done by the ATLAS collaboration [27]. To complement the effective field theory models, limits are calculated for a simple DM production theory with a light mediator, the Higgs boson. The upper limit on the cross section of Higgs boson production through WH and ZH modes and decay to invisible particles is 1.3 pb at 95% CL for $m_H = 125$ GeV. Figure 6 shows the upper limit of the total cross section of WH and ZH processes with $H \to \chi\bar{\chi}$, normalized to the SM next-to-leading order prediction for the WH and ZH production cross section (0.8 pb for $m_H = 125$ GeV), which is 1.6 at 95% CL for $m_H = 125$ GeV. Finally, the CMS collaboration has done a search on mono-Z, where the Z-boson decays into a par of b-quarks [28]. There, an upper limit at the 95% CL of 1.82 (with an expected limit of 1.99) is placed on the ratio of the product of the ZH production cross section times the Higgs invisible branching fraction, with respect to the expected ZH production cross section of a SM Higgs boson.

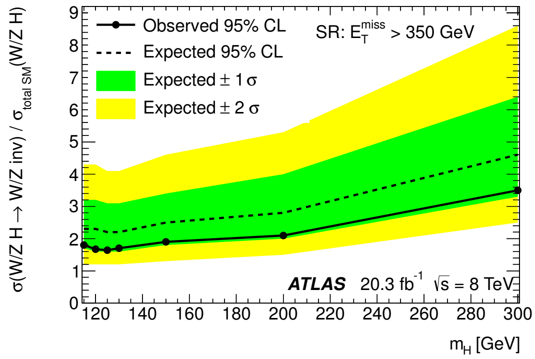


Figure 6: Limit on the Higgs boson cross section for decay to invisible particles divided by the cross section for decays to SM particles as a function of the Higgs mass, m_H, at 95% CL, derived from the signal region with $E_T^{miss} > 350$ GeV.

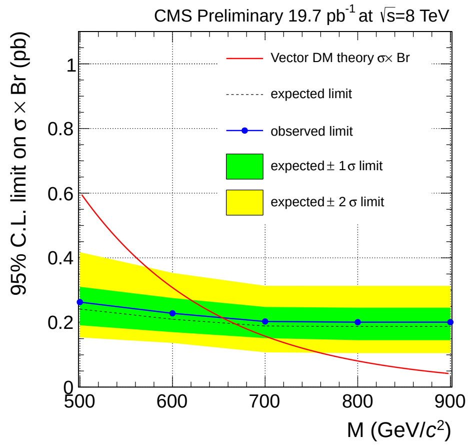


Figure 7: The 95% CL expected and observed CL_s limits as a functions of the mass of the DM candidate for the vector DM model. The theory cross section is also shown with a red solid line.

The CMS experiment has also performed a search for new physics in monotop final states [29], which contain a single top quark and large missing transverse energy induced by a WIMP particle. The measurement is performed using 19.7 fb^{-1} of $\sqrt{s} = 8$ TeV pp collision data, collected by the CMS detector. No evidence of new physics is observed in this case either, so exclusion limits on the mass of DM candidates are quoted at 95% CL. Scalar and vectorial dark matter particles with masses below 327 GeV and 655 GeV respectively, are excluded. These results are shown in Figure 7.

5. Conclusions

This contribution summarises the results of searches for new phenomena in events with a jet, a photon, a boson or a top quark and missing transverse momentum in the final state, obtained from proton-proton collision data at centre of mass energies of 7 TeV and 8 TeV, by both the ATLAS and the CMS experiments. Given the good agreement between SM predictions and data observation, the results presented here have been translated into improved limits of several physics models beyond the SM, including LED, WIMP pair production, Higgs boson decays into invisible particles and the production of gravitinos in a gauge mediated SUSY breaking model. The analyses listed here will have an important role in the Run II physics program for the LHC and the ATLAS and CMS detector. The mono-X signatures will remain a favoured search for new physics. Moreover, with the increase of collision energy, a new phase space will be explored.

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PoS(DIS2014)116