ATLAS prospects for New Physics using neutrino-like signatures

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Abstract.
Many possible extensions to the Standard Model predict new particles and heavy neutrinos. Standard Model neutrinos are invisible to detectors at colliders but they are indirectly detected using the event Missing Transverse Energy $\not\!\!E_T$. Some of the new stable particles are also invisible to detectors and are detected through their $\not\!\!E_T$. In this paper, we discuss how ATLAS is using the $\not\!\!E_T$ signatures from standard neutrinos or from new particles to prepare for the analysis of the first fb^{-1} of good data at 14 TeV in view of discovering new physics beyond the Standard Model.

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1. INTRODUCTION

The Standard Model of particle physics is a remarkable theory which is able to account for all experimental observations in particle physics. However, there are fundamentally unresolved problems in the Standard Model and it is well understood today that it's not the ultimate theory, and that we have to go beyond. A big number of theoretical models has thus been proposed, the most popular so far being supersymmetry (SUSY). Alternatives to SUSY including Grand Unified Theories, theories with extra dimensions, etc, have nevertheless been developed. Searches for evidence of these new models in ATLAS are classified into searches by signatures following the particles in the event final state: electrons, muons, jets, neutrinos... Detecting a neutrino with the same efficiency as the other standard particles in the event requires a detector size of 10^{15}meters, *i.e.* 10 000 times bigger than the sun-earth distance. So, $\not\!\!E_T$ is used to infer the presence of the standard neutrino in the event. $\not\!\!E_T$ results also from any possible new stable particle that doesn't interact with the detector. This paper reviews the use of $\not\!\!E_T$ from standard neutrinos and exotic particles in the prospective studies performed by the ATLAS collaboration on the discovery potential of New Physics. Only results which were public at the time of the conference are shown, thus based on Monte-Carlo simulations at the design centre of mass energy of 14 TeV. Most of these results are published in the reference [1]. This paper is arranged as following: ATLAS detector performances are introduced in the first section. Searches for new physics using standard neutrinos are shown in W'$\rightarrow$lepton+ν and $Z' \rightarrow \tau\tau$ analysis where neutrinos are respectively, partially used through $\not\!\!E_T$ and fully used when their 4-vector are constrained by the event topol-

TABLE 1. Expected jet rejections and identification efficiencies at the ATLAS detector.

Identifying	Jet rejection	Efficiency
Photons	few$\times 10^3$	80%
Electrons	$\sim 10^5$	60%
B-jets	~ 100	60%
$\tau \rightarrow$hadrons	few hundreds	50%

ogy. Then, a SUSY search and Arkani-Hamed–Dimopoulos–Dvali (ADD) Graviton [4] examples where $\not{E}_T$ is induced by stable new particles are presented. Some analysis without $\not{E}_T$ are also presented through searches of new heavy netrinos.

2. ATLAS DETECTOR

The ATLAS detector is a general multi-purpose detector which is described in detail in [1]. It comprises a silicon-based tracking system, electromagnetic and hadronic calorimeters and a muon spectrometer system. Together, these systems provide powerful identification as well as jet reconstruction capabilities, summarized in Table 1. The reconstruction resolutions of the ATLAS detector, described in detail in [1] are briefly summarized in Table 2 as a function of the total energy E or the transverse momentum p_T of the corresponding object.

The neutrino momentum information can be inferred partially from the energy imbalance in the detector, since the total transverse momentum of the event has to add up to zero. In ATLAS, the standard $\not{E}_T$ is reconstructed from the energy deposits in calorimeter cells which survive a noise suppression procedure. Calibration to cell energies is done using global cell-level weights depending on the energy density (referred to as global calibration) and/or calibration weights for the reconstructed physics object that the cell is assigned to (referred to as refined calibration). Corrections for muons in events and the energy loss in dead materials are applied. The resolution on $\not{E}_T$ depends on the resolutions on the associated jets, muons, electrons... and their multiplicity in the event. The average resolutions of $\not{E}_T$ as expected in the W' decays are: 18 GeV and 25 GeV for 1 TeV and 2 TeV W' decaying to muon-neutrino and 10 GeV and 14 GeV for 1 TeV and 2 TeV W' decaying to electron-neutrino, respectively (Figure 1)

3. NEUTRINO-LIKE SIGNATURES

In this section, we show analyses using $\not{E}_T$ as signature. $\not{E}_T$ is induced either by a standard neutrino, in W'$\rightarrow$lepton+ν or in $Z' \rightarrow \tau\tau$, or induced by new particles which don't interact with ATLAS, in Lightest Supersymmetric Particles or in ADD Graviton.

TABLE 2. Expected reconstruction performance of detector subsystems of the ATLAS experiment.

detector subsystem	performance
Tracker	Si pixels, strips + TRT (pid) $\sigma/p_T \approx 5\times10^{-4} p_T \oplus 0.01$
EM calorimeter	Lead and liquid Argon (LAr) $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.007$
Hadronic calorimeter	Fe+scintillator / Cu+LAr $\sigma/E \approx 50\%/\sqrt{E} \oplus 0.03$
Combined muons	2% at 50 GeV to 10% at 1 TeV

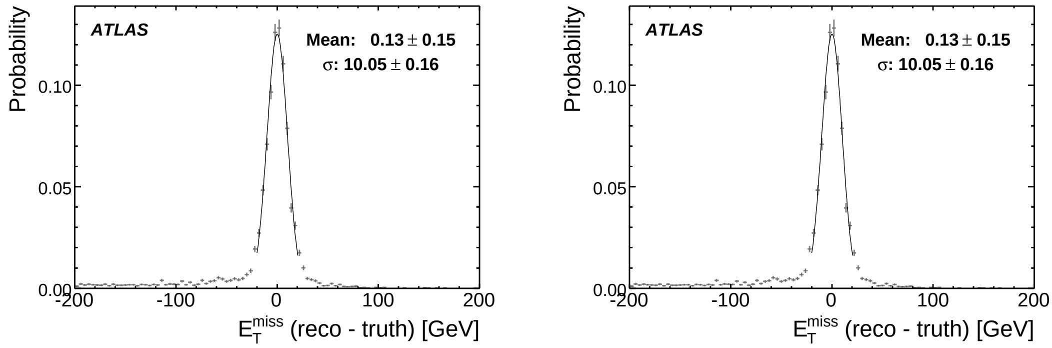

FIGURE 1. $\not{E}_T$ resolutions in a 1 TeV W': (left) decaying to electron + neutrino, (right) decaying to muon + neutrino

3.1. $\not{E}_T$ from Standard neutrinos

3.1.1. $\not{E}_T$ and transverse mass: W'

Several New Physics scenarios include heavy charged gauge bosons, W', that are able to decay into a charged lepton plus a neutrino. Here, only information in the transverse plan are known about the neutrino. As in the case of the SM W boson, the *transverse mass* m_T, defined as $m_T = \sqrt{2 p_T \not{E}_T (1 - \cos\Delta\phi(\ell, \not{E}_T))}$, helps to extract the W'. W' events are required to have exactly one, isolated, high-p_T lepton (electron or muon), a large amount of missing transverse energy $\not{E}_T$ (over 50 GeV) and most of their $\not{E}_T$ should come from the lepton and the neutrino *i.e.*, they should have low jet activity. These cuts are very effective to reduce the dijet and $t\bar{t}$ backgrounds. The main remaining background is the off-shell, high-m_T tail of the SM W boson, which has a falling m_T distribution, while the expected signal would have a Jacobian edge at the mass of the W' boson, which can be exploited by keeping events with $m_T > 0.7 m_{W'}$. Figure 2 shows the m_T distribution of two $m_T^{W'}$ signals with different masses and the backgrounds after all selection criteria. Figure 2 (right) shows the 5σ required luminosities to dicover a W'. For a 1 TeV W', 10pb^{-1} of collected data are enough to discover it. To reach W' masses up to 3 TeV, 1fb^{-1} of collected data are needed[1]. The theoretical uncertainties (renormalization/factorization scales and PDF's) are $\pm 8\%$ on a K-factor of 1.37 for all W' masses. The effect of all systematic uncertainties on the 5σ luminosity for W' is shown in the right plot of Figure 2.

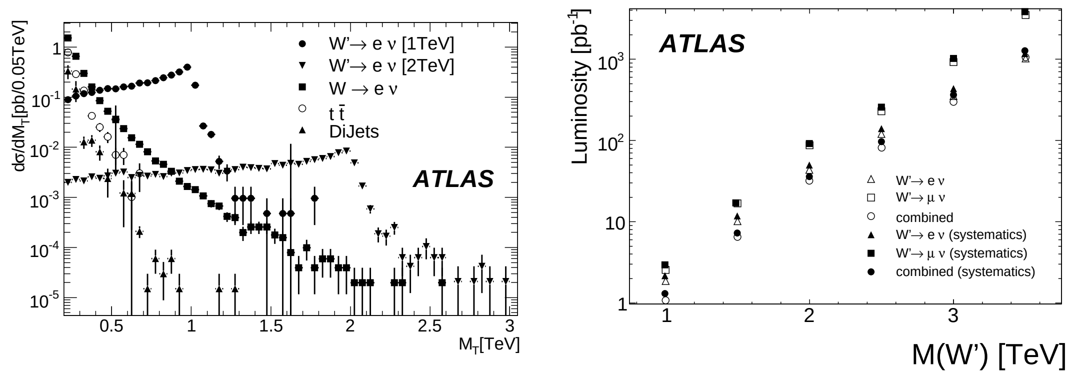

FIGURE 2. Discovery potential of W'. (Left), invariant mass of the W' and W , $t\bar{t}$ and Dijets backgrounds in electron channel. (Right), luminosity needed for 5σ discovery as a function of the W' mass.

3.1.2. Kinematic constraints on neutrinos in Z' $\rightarrow \tau^+\tau^-$

High mass resonances could decay into pairs of tau leptons, each of which, in turn, can decay hadronically or leptonically producing neutrinos in the final state. All decay modes (lepton-hadron, hadron-hadron, lepton-lepton) have been studied and used in a combined search. Event selection is based on $\not{E}_T$ cuts, an upper bound on the transverse mass and the scalar sum of the transverse momentum of potential decay products, and a b-jet veto.

Although neutrinos are always present in these decays, the *collinear approximation*, i.e. assuming that the final state leptons have the same direction that their parent tau leptons, allows a good reconstruction of the resonance's invariant mass. Figure 3(left) shows the expected distribution of the reconstructed mass for a Z'_{SSM} after 1fb^{-1} of collected data, along with the main backgrounds for this type of search [1].

However, when the visible leptons are back-to-back, the above approximation breaks down. In such cases, the *visible mass*, defined as the invariant mass of the (four-) vector sum of the momenta of the identified visible decay products of the two taus and the missing transverse momentum, provides a good discriminator for this search. Although the signal-to-noise ratio is much smaller in this case than when the collinear approximation can be applied, the number of events used is much larger. Figure 3(right) shows the integrated luminosity needed for 3 and 5σ evidence using a combination of these two methods, and of all decay channels [1]. A Z'_{SSM} with a mass up to 1.2 TeV could yield a 5σ significance with about 1fb^{-1} of data.

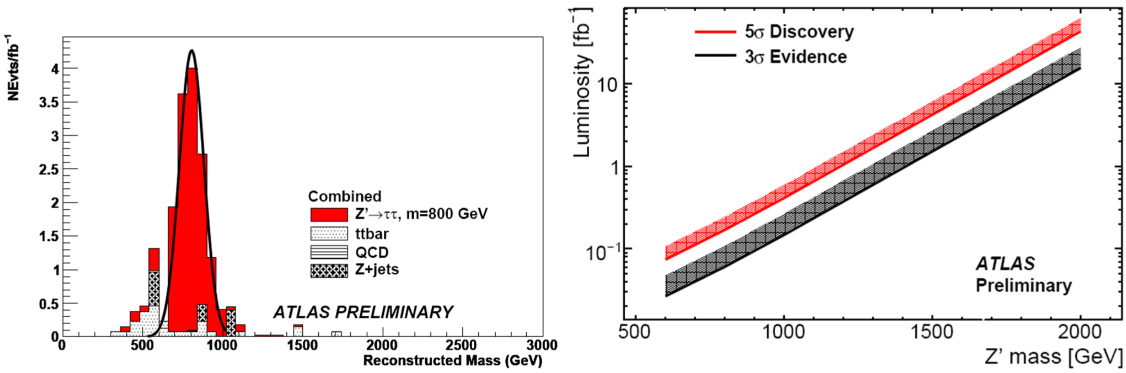

FIGURE 3. (Right), reconstructed mass distributions, for all $\tau\tau$ final states and $m(Z') = 800$ GeV, for 1 fb^{-1} of data, using the collinear approximation. (Left) luminosity required for 3σ evidence or 5σ discovery (all $\tau\tau$ channels combined) as a function of the mass of the Z' resonance, including a 20% systematic uncertainty.

3.2. $\not{E}_T$ from New Stable Particle

Here, signal events don't contain standard neutrinos. $\not{E}_T$ is induced by new particles which don't interact with the detector. Events with similar topologies to the signal but where $\not{E}_T$ is induced by standard neutrinos, are considered as a source of background.

3.2.1. $\not{E}_T$ from Lightest Supersymmetric Particles

At the LHC, the production of sparticles is dominated by strongly interacting particles, namely squarks and gluinos. Therefore, even though supersymmetry comes in many flavours depending on its breaking mechanism (minimal SUGRA, GMSB, AMSB, split SUSY,...) as soon as we assume that R-parity is conserved, there is a common topology for most SUSY events which is the following: high transverse energy jets, coming from the decays of the squarks or gluinos, leptons, from the decays of the subsequent gauginos, and missing transverse energy from the escape of the Lightest Supersymmetric Particle (LSP). The production cross sections then primarily depend on the masses.

For selecting SUSY events, a number of powerful observables have been designed in addition to the missing transverse energy: mainly the effective mass M_{eff}, the transverse sphericity (S_T) and the transverse mass M_T.

$$M_{eff} = \sum_{i=1}^{4} p_T^{jet,i} + \not{E}_T \; [+ \sum_{i=1} p_T^{lep,i}]$$

where the sums run respectively over the four highest p_T jets within $|\eta| < 2.5$ and over all the identified leptons.

$$S_T = \frac{2\lambda_2}{\lambda_1 + \lambda_2}$$

where λ_1 and λ_2 are the eigenvalues of the 2×2 sphericity tensor $S_{ij} = \sum_k p_{ki} p^{kj}$.

$$M_T^2(\mathbf{p}_T^\alpha, \mathbf{p}_T^{miss}, m_\alpha, m_\chi) = m_\alpha^2 + m_\chi^2 + 2(E_T^\alpha \not{E}_T - \mathbf{p}_T^\alpha . \mathbf{p}_T^{miss})$$

where $E_T^\alpha = \sqrt{(\mathbf{p}_T^\alpha)^2 + m_\alpha^2}$, $\not{E}_T = \sqrt{(\mathbf{p}_T^{miss})^2 + m_\chi^2}$, α is some visible particle and the parameter m_χ is the mass of the invisible particle, which is usually assumed to be zero.

The baseline event selection is then the following: at least 4 jets of at least 50 GeV transverse energy (at least one jet must have $p_T > 100$ GeV); $\not{E}_T > 100$ GeV; $\not{E}_T > 0.2 M_{eff}$ (this is against Gaussian fluctuations of the $\not{E}_T$ measurement); $S_T > 0.2$ (this selection is efficient against QCD background); exactly 0 or 1 or 2 identified leptons (electrons or muons). Additional criteria are, in the no lepton case: the angle in the transverse plane between the three most energetic jets and the missing transverse energy ($\Delta\phi(j, \not{E}_T)$) must be greater than 0.2; in the 1 or 2 lepton case, the transverse mass of any lepton and the missing transverse energy must be greater than 100 GeV.

Indeed, the backgrounds to fight are, on the one hand, the QCD multijet events with their huge cross section, especially in the no-lepton case, in which instrumental effects can fake missing energy. The $\Delta\phi(j, \not{E}_T)$ selection is meant to reduce this type of background. On the other hand, there are the lower cross section top quark pairs, W and Z with additional jets events in which the presence of at least one neutrino implies some real missing transverse energy. In this case, it is the transverse mass selection which is used to lower the background level.

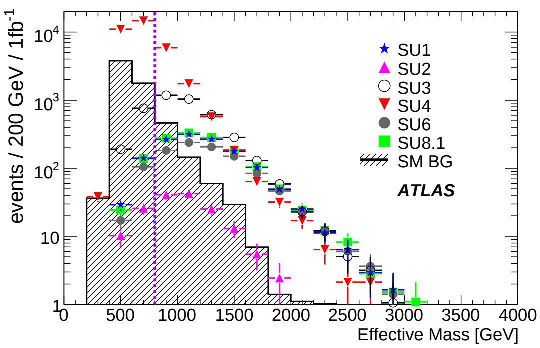

FIGURE 4. M_{eff} distribution for all SUSY benchmark points inside Minimal SUGRA and the total Standard Model background after the full baseline selection with a lepton veto.

Figure 4 shows, for 1 fb^{-1} of well understood data, the effective mass distribution for each benchmark point and for the sum of all standard model backgrounds after the baseline selection with a lepton veto. There is clearly a very high sensitivity for all points, except the one labeled SU2 (situated in the focus point region where the lightest neutralino has a large higgsino component) for which the cross section is dominated by direct gaugino production.

3.2.2. $\not{E}_T$ in ADD Gravitons

There are several models with extra-dimensions, corresponding to different assumptions on the structure and size of extra-dimensions and the kind of particles allowed to propagate into them. In the first Arkani-Hamed–Dimopoulos–Dvali (ADD) type of models [4], which exhibit factorized geometry, and where the extra-dimensions form a compact manifold, only gravity propagates in the extra-dimensions, while matter is confined to a 4D brane. In the simplest channels, the graviton would be produced together with a gluon, a Z boson or a photon. As the graviton interacts only gravitationally and extra dimensions are open for it, it will not interact with the detector, giving rise to a missing transverse energy in the event. This $\not{E}_T$ can be very large, far beyond 1 TeV. The Graviton + jet channel has been studied in the past [5] and the study has never been updated. The signal cross-section has been implemented in ISAJET using an effective theoretical approach. The generated events have been investigated using the ATLAS fast simulation program[6]. The study has been done for 100fb^{-1} of collected data. It showed that the reach in the fundamental scale is possible up 9 or 6 TeV for 2 or 4 extra-dimensions, respectively.

4. SIGNATURES WITHOUT $\not{E}_T$

4.1. Heavy neutrinos

Here, we discuss a prospective analysis about a model that produces new neutrinos which does't necessarily induce a $\not{E}_T$. In Left-Right symmetric models, which address the non-zero neutrino mass and baryogenesis, incorporate three heavy right-handed Majorana neutrinos (N_e, N_μ, N_τ). Some of them also introduce right-handed heavy bosons (W_R and Z'). Figure 5 shows a possible decay in one such model, where the W_R boson decays into a lepton and a Majorana neutrino N_ℓ, which ultimately produces a lepton and two jets. Since all final state particles can be reconstructed, it is possible in this model to reconstruct both the N_ℓ and the W_R masses. Selection cuts similar to those used in the LQ search allow a strong reduction of the expected backgrounds also in this case; Figure 6(left) shows the reconstructed mass of N_ℓ, after cuts, for two possible scenarios: one with $m_{W_R} = 1.8$ TeV and $m_{N_e} = m_{N_\mu} = 300$ GeV, denoted as `LRSM_18_3`, and one with $m_{W_R} = 1.5$ TeV and $m_{N_e} = m_{N_\mu} = 500$ GeV, labeled as `LRSM_15_5` [1].

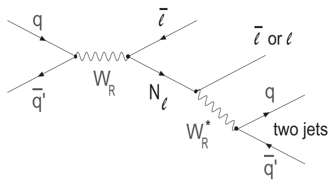

FIGURE 5. Feynman diagram for W_R boson production and its decay to a Majorana neutrino N_ℓ.

Figure 6 (right) shows the expected significance of this search for the same scenarios; triangles correspond to `LRSM_18_3`, while squares represent `LRSM_15_5`. Solid/hollow markers show the significance when systematic uncertainties are in-

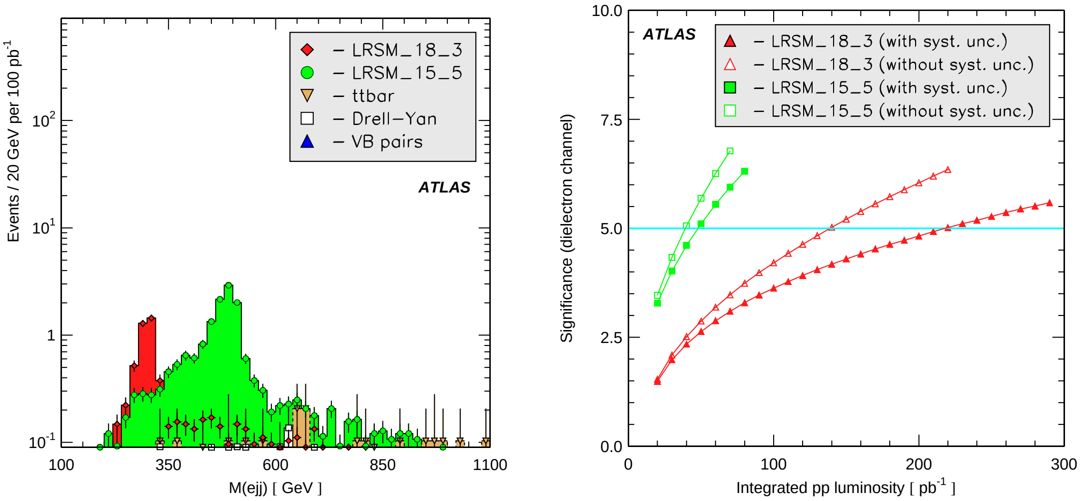

FIGURE 6. (Left): distribution of reconstructed invariant mass for N_e candidates in background and signal events after background suppression. (Right), Expected signal significance versus integrated luminosity for two mass hypotheses for the N_e neutrino and the W_R boson.

cluded/excluded. As shown, for these mass values, a 5σ significance could be reached with less than 150 pb^{-1} and 40 pb^{-1} of collision data, respectively.

5. SUMMARY

The standard neutrinos are invisible to detectors but they are indirectly detected through their induced $\not{E}_T$. Some of the new stable particles are also invisible to detectors and are detected through their $\not{E}_T$. We discussed how ATLAS is using the $\not{E}_T$ signatures from standard neutrinos or from new particles to prepare for the analysis of the first fb^{-1} of good data at 14 TeV in view of discovering new physics beyond the Standard Model. When possible, the neutrino 4-momentum is constrained by the event kinematics to build the needed invariant mass. Otherwise, only the transverse mass or the effective mass is used in the New Physics search Early observation of New Physics using $\not{E}_T$ signatures is possible with the ATLAS detector at LHC with only few 10pb^{-1}.

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