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Search for dark matter produced in association with a hadronically decaying vector boson in pp collisions at √s = 13 TeV with the ATLAS detector

ATLAS Collaboration

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Search for dark matter produced in association with a hadronically decaying vector boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

A search is presented for dark matter produced in association with a hadronically decaying W or Z boson using 3.2 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the Large Hadron Collider. Events with a hadronic jet compatible with a W or Z boson and with large missing transverse momentum are analysed. The data are consistent with the Standard Model predictions and are interpreted in terms of both an effective field theory and a simplified model containing dark matter.

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Dark matter is the dominant component of matter in the universe, but its particle nature remains a mystery. Searches for a weakly interacting massive particle (WIMP), denoted by χ, and for interactions between χ and Standard Model (SM) particles are a central component of the current set of dark-matter experiments.

At particle colliders, dark-matter particles may be produced in pairs via some unknown intermediate state. While in many models direct detection experiments have the greatest sensitivity for dark-matter masses m_χ between 10 and 100 GeV, searches for dark matter at particle colliders are most powerful for lower masses [1–3]. The final-state WIMPs are not directly detectable, but their presence can be inferred from the recoil against a visible particle [1]. Two example processes are shown in Figure 1.

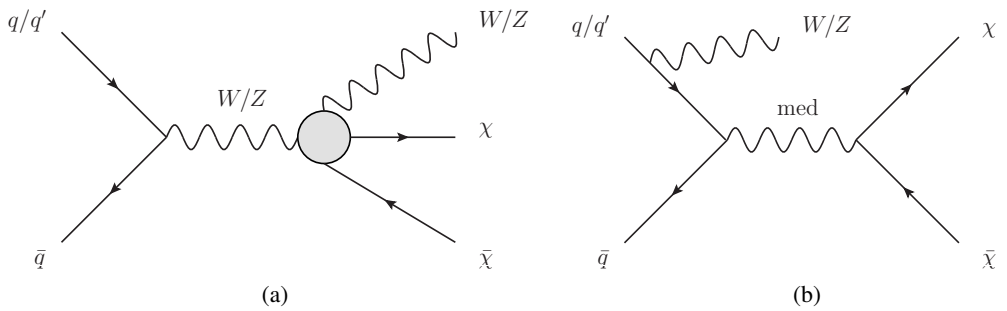


Figure 1: Pair production of WIMPs ($\chi\bar{\chi}$) in proton–proton collisions at the LHC in association with a vector boson (V, meaning W or Z) via two hypothetical processes: (a) production via an effective $VV\chi\chi$ interaction or (b) via a simplified model which includes an s-channel mediator.

The Tevatron and LHC collaborations have reported limits on the cross section of $p\bar{p} \to \chi\bar{\chi} + X$ and $pp \to \chi\bar{\chi} + X$, respectively, where X is a hadronic jet [1–3], a photon (γ) [4, 5], a W/Z boson [6, 7], or a Higgs boson [8, 9]. In many cases, results are reported in terms of limits on the parameters of an effective field theory (EFT) formulated as a four-point contact interaction [10–18] between quarks and WIMPs. For such models, the strongest limits come from data in which the recoiling object is a jet. In other models, however, the interaction is between dark matter and vector bosons [19], such that the primary discovery mode would be in final states such as those analysed here, where the recoiling object is a W or Z boson.

In this letter, a search is reported for the production of a W or Z boson decaying hadronically (to $q\bar{q}'$ or $q\bar{q}$, respectively) and reconstructed as a single massive jet in association with large missing transverse momentum from the undetected $\chi\bar{\chi}$ particles in data collected by the ATLAS detector from pp collisions with centre-of-mass energy $\sqrt{s} = 13$ TeV. This search is sensitive to WIMP pair production, as well as to other dark-matter-related models which predict invisible Higgs boson decays (WH or ZH production with $H \to \chi\bar{\chi}$).

The ATLAS detector [20] at the LHC covers the pseudorapidity[1] range $|\eta| < 4.9$ and the full azimuthal angle ϕ. It consists of an inner tracking detector surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and an external muon spectrometer incorporating large superconducting

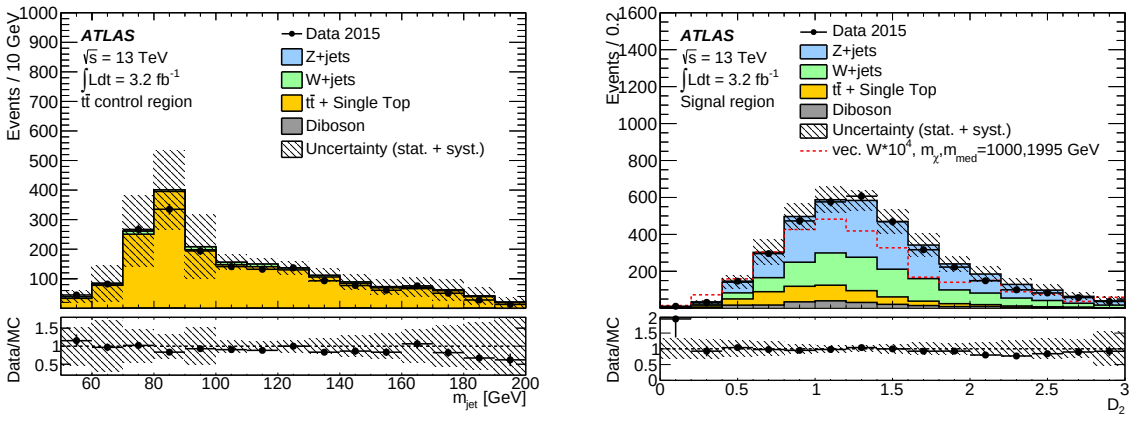
[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Polar coordinates (r, ϕ) are used in the transverse (x, y) plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

toroidal magnets. A two-level trigger system is used to select interesting events to be recorded for subsequent offline analysis. Only data for which beams were stable and all subsystems described above were operational are used. Applying these requirements to pp collision data, recorded during the 2015 LHC run, results in a data sample with a time-integrated luminosity of 3.2 fb^{-1}. The systematic uncertainty of 2.1% in the luminosity is derived following the same methodology as that detailed in Ref. [21].

Three non-exclusive categories of jet candidates are built, each using the anti-$k_\perp$ clustering algorithm [22]. Two categories use clusters of energy deposits in calorimeter cells seeded by those with energies significantly above the measured noise and calibrated at the hadronic energy scale [23]. They are distinguished by their radius parameters; jets with radius parameter of 1.0 (0.4) are referred to as *large-R jets (narrow jets)*. Large and narrow jets can share a fraction of their energy deposits. A third type of jet candidate is reconstructed from inner-detector tracks using the anti-$k_\perp$ algorithm with $R = 0.2$, referred to as *track jets*. Large-R jets are trimmed [24] to remove energy deposited by pile-up jets, the underlying event, and soft radiation. In this process, the constituents of large-R jets are reclustered using the $k_\perp$ algorithm [25, 26] with a distance parameter of 0.2, and subjets with transverse momentum p_{T} less than 5% of the large-R jet p_{T} are removed. Large-R jets are required to satisfy $p_{\mathrm{T}} > 200$ GeV and $|\eta| < 2.0$. These large-R jets are intended to capture the hadronic products of both quarks from the decay of a W or Z boson, while the narrow jets and track jets are helpful in background suppression. The internal structure of the large-R jet is characterized in terms of two quantities: D_2 [27, 28], which identifies jets with two distinct concentrations of energy [29, 30], and m_{jet}, which is the calculated invariant mass of the jet. Narrow jets are required to satisfy $p_{\mathrm{T}} > 20$ GeV for $|\eta| < 2.5$ or $p_{\mathrm{T}} > 30$ GeV for $2.5 < |\eta| < 4.5$. Track jets are required to satisfy $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.5$. For both the large-R and narrow jets, jet momenta are calculated by performing a four-vector sum over these component clusters, treating each topological cluster [23] as an $(E, \vec{p})$ four-vector with zero mass, and are calibrated to the hadronic scale. For narrow jets, the direction of $\vec{p}$ is given by the line joining the reconstructed vertex with the barycentre of the energy cluster. The missing transverse momentum $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$ is calculated as the negative of the vector sum of the transverse momenta of reconstructed jets, leptons, and those tracks which are associated with the reconstructed vertex but not with any jet or lepton. A closely related quantity, $\mathbf{E}_{\mathrm{T,no}\mu}^{\mathrm{miss}}$, is calculated in the same way but excluding reconstructed muons. A third variant, $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$, is the missing transverse momentum measured using inner detector tracks. The magnitudes of the three missing-tranverse-momentum variants are denoted by $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T,no}\mu}^{\mathrm{miss}}$, and $p_{\mathrm{T}}^{\mathrm{miss}}$, respectively. Electrons, muons, jets, and $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$ are reconstructed as described in Refs. [23, 31–33], respectively.

Candidate signal events are selected by an inclusive $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger that is more than 99% efficient for events with $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV. Events triggered by detector noise and non-collision backgrounds are rejected as described in Ref. [34]. In addition, events are required to satisfy the requirements of $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV, no reconstructed electrons or muons, and at least one large-R jet with $p_{\mathrm{T}} > 200$ GeV, $|\eta| < 2.0$, m_{jet} and D_2 consistent with a W or Z boson decay as in Ref. [35]. To further suppress backgrounds from multijet and $t\bar{t}$ production, events are required to satisfy $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV, a minimum azimuthal angular distance, $\Delta\phi$, of 0.6 between the $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$ and the nearest narrow jet, and $\Delta\phi(\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) < \pi/2$. Within a fiducial volume defined at parton level by similar selection requirements (except those on D_2 and $p_{\mathrm{T}}^{\mathrm{miss}}$), the reconstruction efficiency for the signal models described above varies from 38% to 49%.

The dominant source of background events is $Z \to \nu\bar{\nu}$ production in association with jets. A secondary contribution comes from the production of jets in association with a leptonically decaying W or Z boson in which the charged leptons are not identified or the τ leptons decay hadronically. The third major background contribution comes from top-quark pair production. The kinematic distributions of these three



(a) (b)

Figure 2: Pane (a) Distribution of m_{jet} in the data and for the predicted background in the top-quark control region. Pane (b) Distribution of jet substructure variable D_2 in the data and for the predicted background in events satisfying all signal region requirements other than those on D_2. Also shown is the distribution for the simplified model with a vector-boson mediator, scaled by a factor of 10^4 for given values of m_χ and m_{med}, the mediator mass.

largest backgrounds are estimated using simulated event samples but the normalization is determined using control regions where the dark-matter signal is expected to be negligible. Each control region requires $E_{\text{T}}^{\text{miss}} > 200$ GeV and $p_{\text{T}}^{\text{miss}} > 30$ GeV as well as one large-R jet satisfying the substructure requirement on D_2 as applied in the signal region. The Z boson control region requires exactly two muons with dimuon invariant mass $66 < m_{\mu\mu} < 116$ GeV. The W boson (top quark) control region requires exactly one muon, and zero (at least one) b-tagged track jet not associated with the large-R jet. Validation of the reconstruction of hadronic W boson decays with large-R jets is performed in the top-quark control region, as shown in Figure 2, which also presents the distribution of the D_2 substructure variable. Other sources of background are diboson production and single-top-quark production. The contribution to the signal region from multijet production is negligble.

Samples of simulated W+jets and Z+jets events are generated using Sherpa 2.1.1 [36]. Matrix elements are calculated for up to two partons at next-to-leading order (NLO) and four partons at leading order (LO) using the Comix [37] and OpenLoops [38] matrix element generators and merged with the Sherpa parton shower [39] using the ME+PS@NLO prescription [40]. The CT10 [41] PDF set is used in conjunction with dedicated parton shower tuning developed by the Sherpa authors. The W/Z production rates are normalized to a next-to-next-to-leading order (NNLO) calculation [42]. The production of $t\bar{t}$ and single-top processes, including s-channel, t-channel and Wt production is modelled with the Powheg-Box v2 generator [43–45] interfaced to Pythia6.428 [46]. In these generators the CT10 and CTEQ6L1 [47] PDF sets are used, respectively. Top-quark pair production is normalized to NNLO with next-to-next-to-leading-logarithm corrections [48] in QCD while single-top processes are normalized at NLO [49, 50] in QCD. The diboson (WW, WZ, ZZ) processes are simulated using Sherpa 2.1.1 with the CT10 PDF and normalized at NLO [51, 52] in QCD. The multijet process is described using samples simulated with Pythia8.186 [53] and the NNPDF2.3LO [54] PDF at leading order in QCD; these multijet samples were used to develop the background estimation strategy but not for the final background prediction.

Samples of simulated $W\chi\bar{\chi}$ and $Z\chi\bar{\chi}$ events are generated using MadGraph5_aMC@NLO [55], and the

underlying event and parton showering are simulated with Pythia8.186 [53]. Two theoretical models are used as benchmarks: a seven-dimensional $VV\chi\chi$ EFT [19] model (V meaning W or Z) and a vector-mediated simplified model [56]. The strength of the EFT interaction is controlled by a mass scale, $M_\star$, and the strength of the simplified model interaction is controlled by the product of the couplings of the mediator to the SM and the dark matter (DM) particles, $g_{\mathrm{SM}}g_{\mathrm{DM}}$. The EFT model samples were generated with $M_\star = 3000$ GeV, and the simplified model samples were generated with couplings $g_{\mathrm{SM}} = 0.25$ and $g_{\mathrm{DM}} = 1$. The samples were generated as a function of dark-matter particle mass m_χ for the EFT model and in a grid of mediator mass m_{med} and m_χ for the simplified model.

Major sources of systematic uncertainty are uncertainties in the modelling of large-R jet observables, which have a 5–13% impact on the expected background and signal yields, and the energy scale of the narrow jets, which contribute a 1–5% uncertainty to the expected yields. Other sources of uncertainty include theoretical uncertainties in the simulated event samples used to model the background processes (1–10%), parton distribution functions (10–15%), and lepton reconstruction and identification efficiencies (up to 2%).

A profile-likelihood fit [57] to the $E_{\mathrm{T}}^{\mathrm{miss}}$ ($E_{\mathrm{T,no}\mu}^{\mathrm{miss}}$) distribution in the signal region (control regions) is used to constrain the W boson, Z boson, and $t\bar{t}$ backgrounds and extract the signal strength, μ, for each model as an overall normalization factor for the signal prediction. Besides the signal strength, three overall normalization factors for the W boson, Z boson, and $t\bar{t}$ backgrounds are parameters in the fit. The diboson and single-top backgrounds are estimated from simulation, and the multijet background is negligible. The likelihood function is defined as the product of Poisson distributions over all bins in $E_{\mathrm{T}}^{\mathrm{miss}}$ and $E_{\mathrm{T,no}\mu}^{\mathrm{miss}}$, and the likelihood is simultaneously maximized over the signal and control regions.

Variations of the expected signal and background to allow for their systematic uncertainties are described with nuisance parameters constrained by Gaussian probability distribution functions, and correlations across signal and background processes and regions are taken into account.

A background-only ($\mu = 0$) fit, shows no deviation from SM predictions, and Figures 3 and 4 show kinematic distributions after the profile-likelihood fit. The floating background-normalization parameters are consistent with unity within one standard deviation. Tables 1 and 2 show the expected event yields after applying the signal selection and the background normalization scale factors, respectively. The values in these tables are estimated for the background-only hypothesis.

Upper limits at 95% confidence level (C.L.) on μ are calculated using the CL_s method [58]. For the $VV\chi\chi$ EFT model, these limits are translated into constraints on the mass scale, $M_\star$. Figure 5(a) shows the limit on the mass scale, $M_\star$, in the EFT model, as a function of m_χ. Figure 5(b) shows the limits on the signal strength, μ, for a vector-mediated simplified model generated with couplings $g_{\mathrm{SM}} = 0.25$ and $g_{\mathrm{DM}} = 1$ in the plane of m_χ and m_{med}.

In conclusion, this Letter reports ATLAS limits on dark-matter production in events with a hadronically decaying W or Z boson and large missing transverse momentum. These limits from 3.2 fb^{-1} of 13 TeV pp collisions at the LHC improve on earlier ATLAS results. No statistically significant excess is observed over the Standard Model prediction.

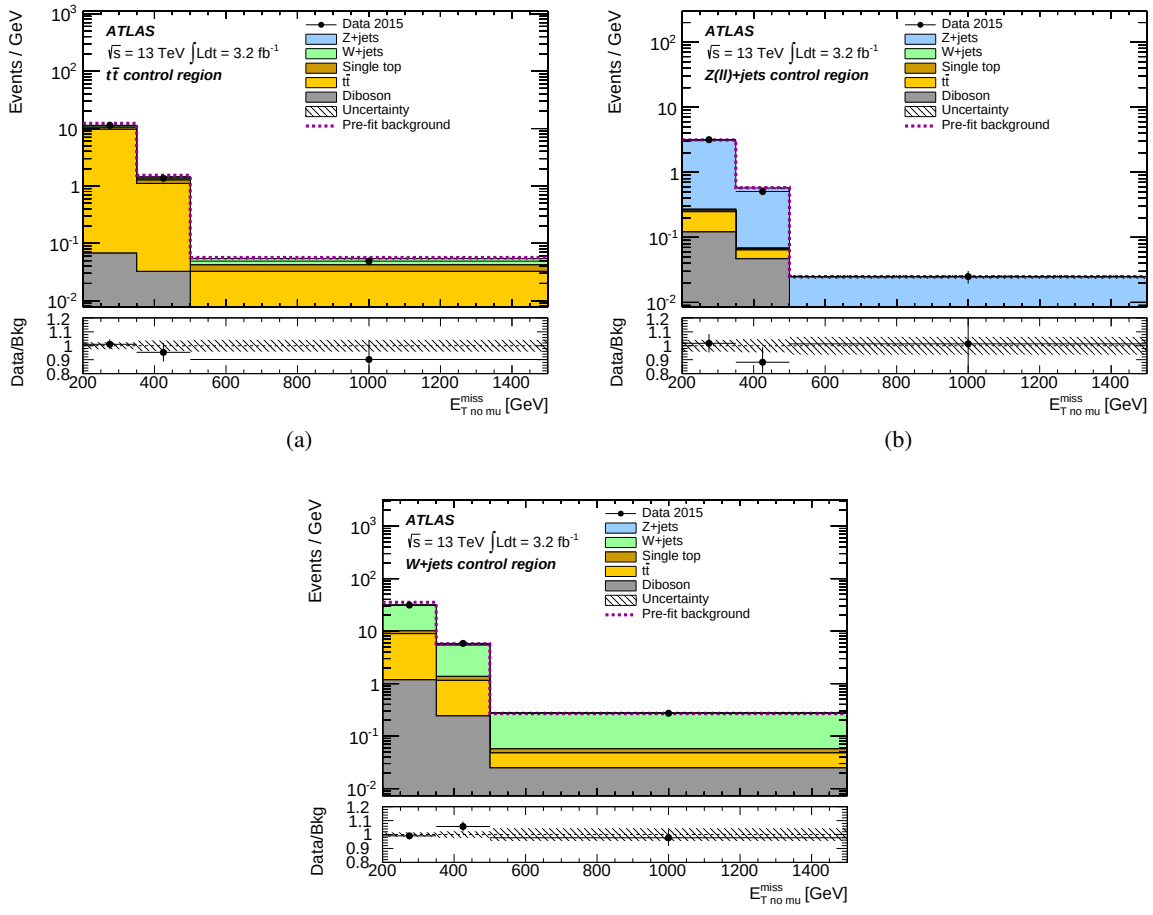


Figure 3: The $E_{\mathrm{T,no}\mu}^{\mathrm{miss}}$ distribution of the events in the control regions after the profile-likelihood fit to the data under the background-only hypothesis. Pane (a) shows the $t\bar{t}$ control region, pane (b) shows the Z+jets control region, and pane (c) shows the W+jets control region. The total background prediction before the fit is shown as a dashed line. The inset at the bottom of each plot shows the ratio of the data to the total post-fit background. The hatched bands represent the total uncertainty in the background.

Table 1: Predicted and observed number of events in the signal region. The yields and uncertainties of the backgrounds are shown after the profile-likelihood fit to the data under the background-only hypothesis. For comparison, the expected yield in the $VV\chi\chi$ EFT model with $M_\star = 600$ GeV and $m_\chi = 500$ GeV is 10.1 ± 0.4 events.

Process	Events
Z+jets	544 ± 33
W+jets	275 ± 24
$t\bar{t}$ and single-top	211 ± 19
Diboson	89 ± 12
Total Background	1120 ± 47
Data	1121

Table 2: Background normalization factors relative to the initial theoretical prediction, extracted from the profile-likelihood fit under the background-only hypothesis.

Process	Normalization Factor
Z+jets	1.01 ± 0.16
W+jets	0.90 ± 0.16
$t\bar{t}$	0.91 ± 0.18

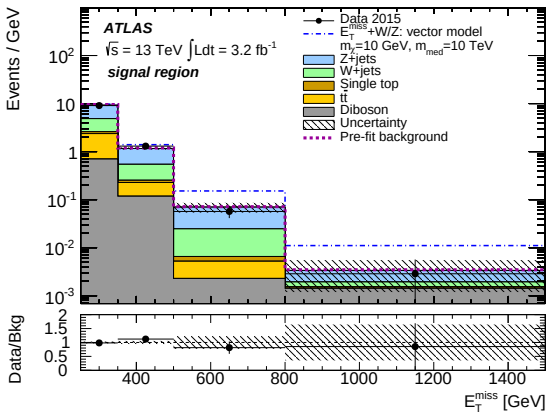
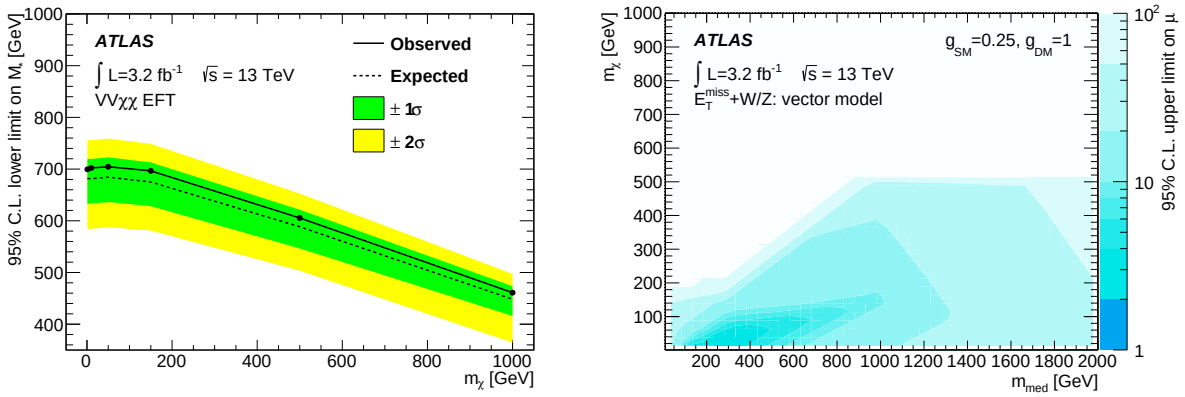


Figure 4: The $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution of the events in the signal region after the profile-likelihood fit to the data under the background-only hypothesis. The inset shows the ratio of the data to the total background. Also shown is the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution for the simplified model with a vector-boson mediator, scaled by a factor of 10^4 for $m_\chi = 10$ GeV and $m_{\mathrm{med}} = 10$ TeV. The total background before the fit is shown as a dashed line. The hatched bands represent the total uncertainty in the background.



(a) (b)

Figure 5: Pane (a) shows the limit on the mass scale, $M_\star$, of the $VV\chi\chi$ EFT model. Pane (b) shows the observed limit on the signal strength, μ, of the vector-mediated simplified model in the plane of the dark-matter particle mass, m_χ, and the mediator mass, m_{med}; white areas indicate an upper limit at $\mu \geq 100$.

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