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Search for non-resonant production of semi-visible jets using Run~2 data in ATLAS

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Search for non-resonant production of semi-visible jets using Run 2 data in ATLAS

The ATLAS Collaboration

Semi-visible jets, with a significant contribution to the event's missing transverse momentum, can arise in strongly interacting dark sectors. This results in an event topology where one of the jets can be aligned with the direction of the missing transverse momentum. The first search for semi-visible jets produced via a t-channel mediator exchange is presented. The analysis uses proton-proton collisions with an integrated luminosity of 139 fb^{-1} and a centre-of-mass energy of 13 TeV, collected with the ATLAS detector during the Run 2 of the LHC. No excess over Standard Model predictions is observed. Assuming a coupling strength of unity between the mediator, a Standard Model quark and a dark quark, mediator masses up to 2.7 TeV are excluded at the 95% confidence level. Upper limits on the coupling strength are also derived.

1 Introduction

Collider searches for dark matter (DM) have often focussed on scenarios in which DM particles are produced in association with heavy Standard Model (SM) particles or photons or jets. However, no experimental evidence confirming the existence of DM has been found so far. Several proposed models [1–4] include a strongly coupled dark sector, giving rise to unexplored collider-event topologies, and thus motivating the present search.

A feature of the strongly coupled dark sector is the so-called 'dark shower' (DS), emulating the QCD parton shower. Since the DS contains families of dark quarks which bind into dark mesons at energies lower than the dark confinement scale, the subsequent hadronisation can give rise to flavour-diagonal and off-diagonal π_{d} and ρ_{d} mesons, with spin 0 and 1 respectively. Depending on the flavour content of the dark shower, these dark mesons can be stable or can decay back into the SM particles.

The models described above are particularly useful as event-topology generators, and depending on the fraction of stable dark hadrons among all dark hadrons in the event, denoted as R_{inv}, different experimental signatures can arise. If this fraction is unity, the signature would consist of missing transverse momentum, the magnitude referred to as $E_{\mathrm{T}}^{\mathrm{miss}}$, produced along with a jet (or jets) from the SM sector, resembling the monojet signature. On the other hand, if the fraction is zero, the signature would resemble QCD multijet events with no intrinsic missing transverse momentum. This signature is often referred to as a 'dark jet' [5]. Semi-visible jet (SVJ) [6, 7] signatures arise when the fraction has intermediate values, resulting in jets geometrically encompassing dark hadrons.

A search for SVJ signatures in the s-channel production mode has been presented by the CMS Collaboration [8], and excludes mediator masses up to 5.1 TeV, depending on other signal parameters. This Letter presents a first search for t-channel production of SVJs using the full LHC Run 2 dataset of 13 TeV proton–proton collisions with an integrated luminosity of 139 fb^{-1} recorded by the ATLAS experiment. Searches for t-channel production modes probe a broad class of non-resonant signals.

In the t-channel production mode, a scalar mediator, Φ, acts as a portal between the SM and dark sectors. It couples to a SM quark and a dark quark, and mediates the production of dark quarks, which then hadronise to stable and unstable dark hadrons through the DS process described above and shown in Figure 1.

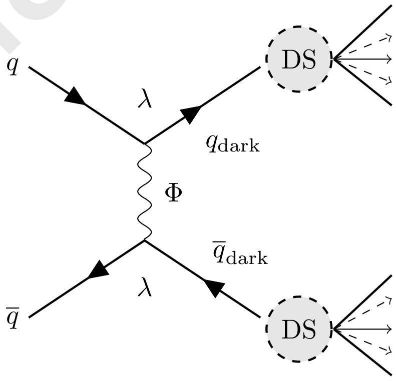

Figure 1: A diagram illustrating the production of semi-visible jets via a t-channel mediator, Φ, producing a pair of dark quarks, labelled q_{dark}. DS denotes the dark shower which produces a final state consisting of SM hadrons and dark hadrons, governed by the R_{inv} fraction. The coupling strength of the q–q_{dark}–Φ interaction is denoted by λ.

At the leading order, the two SVJs are produced back-to-back and the direction of the missing transverse momentum ($\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$) is aligned with one of the two reconstructed jets. A boost due to additional jets leads to signatures with the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ not necessarily pointing in the direction of one of the two SVJs, since both of them contribute to the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$. Events in which the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is aligned with a jet typically contain a mismeasured jet, and are usually discarded. This search, however, considers an inclusive fiducial phase space and thus is complementary to existing searches that have focussed on phase-space regions that suppress background contributions arising from mismeasured jets.

2 ATLAS detector

The ATLAS experiment [9] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile hadron calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision chambers for tracking and fast detectors for triggering. A two-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions. An extensive software suite [10] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Signal and background event simulation

Signal events were modelled at the leading order (LO) in QCD, using the MadGraph5_aMC@NLO [11] event generator to calculate matrix elements (ME) with up to two extra partons at the leading order. The NNPDF3.0lo [12] parton distribution function (PDF) set was used. The mediator mass was varied within the range 1–5 TeV in 0.5 TeV steps. The Hidden Valley (HV) module [13] of Pythia 8 [14] was used to shower the ME-level event and produce dark hadrons, using the NNPDF2.3lo [12] PDF set and the A14 set of tuned parameters [15]. The MLM [16] jet matching scheme, with the matching parameter set to 100 GeV, was employed.

A detailed description of the HV module is beyond the scope of this Letter, and the HV parameter settings adopted here provide a simple way to generate this mostly unexplored collider-event topology. The mass of the dark quark was set to 10 GeV, the flavour-diagonal π_{d} and ρ_{d} meson masses were set to 10 GeV and 20 GeV respectively, and the off-diagonal π_{d} and ρ_{d} meson masses were set to 4.99 GeV and 9.99 GeV

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[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 upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

Table 1: Summary of generators used to simulate background processes, along with the PDF, parton shower and tune used.

Process	Generator	ME order	PDF	Parton shower	Tune
W/Z+jets	SHERPA 2.2.11 [24, 25]	NLO (up to 2 jets)	NNPDF3.0NNLO [12]	SHERPA MEPS@NLO	SHERPA
$t\bar{t}$	POWHEG BOX v2 [26–28]	NLO	NNPDF3.0NLO [12]	PYTHIA 8.230 with NNPDF2.3LO	A14 [15]
Single top	POWHEG BOX v2	NLO	NNPDF3.0NNLO	PYTHIA 8.230 with NNPDF2.3LO	A14
Multijet	PYTHIA 8.230 [14]	LO	NNPDF2.3LO [12]	PYTHIA 8.230	A14
Diboson	SHERPA 2.2.1	NLO (up to 2 jets)	NNPDF3.0NNLO	SHERPA MEPS@NLO	SHERPA

respectively. The number of flavours in the HV module was set to unity. This implies that flavour diagonal π_d and ρ_d mesons decay promptly into off-diagonal stable dark π_d and ρ_d pairs, and to SM quarks, following a five-flavour scheme, due to portal interactions of the mediator which couples the SM sector to the dark sector [17]. These choices are based on Refs. [7, 18] and kinematic considerations for enabling the relevant decays. The general topology of the signal events shows negligible sensitivity to the chosen mass values.

The branching fraction of unstable dark mesons decaying to stable dark mesons is taken as the R_{inv} fraction defined above, and is a free parameter of the model. The signal samples were generated with R_{inv} values of 0.1, 0.2, 0.4, 0.6, 0.8, and 0.9 for each simulated mediator mass value. The PYTHIA 8 HV α_{dark} coupling was chosen to be running at one-loop, and the dark QCD confinement scale value was set to 6.5 TeV, based on Ref. [18]. Another free parameter in the model is the strength of the coupling connecting the SM and DM sectors (shown as λ in Figure 1). The nominal samples were generated with $\lambda = 1$, although λ can be varied up to 4π [19, 20]. The cross-section scales as λ^4 without having any impact on the kinematic distributions, or on the validity of the model, if the mediator mass is 2.5 TeV or higher. At lower mediator masses, there are stronger contributions from resonant production of the mediator as well.

Simulated event samples were used to describe the main background processes – W/Z+jets, $t\bar{t}$, single top, multijet, and diboson – as listed in Table 1. The Monte Carlo (MC) generated samples were processed through a detailed ATLAS detector simulation [21] based on GEANT4 [22]. Additional simulated inelastic proton–proton collisions generated using PYTHIA 8 with the A3 set of tuned parameters [23] and NNPDF2.3LO PDF set were overlaid on each simulated hard-scatter event to model the effects of additional collisions in the same or neighbouring bunch crossings (referred to as ‘pile-up’). The simulated events were then reconstructed and analysed using the same procedure and software as used for data events.

4 Event and object selection

This analysis uses 139 fb^{-1} of data from 13 TeV proton–proton collisions with 25 ns bunch spacing collected by ATLAS from 2015 to 2018. The data were subjected to quality requirements [29], including the removal of events recorded when relevant detector components were not operating correctly. Events for this search were selected with the un-prescaled $E_{\text{T}}^{\text{miss}}$ trigger with the lowest threshold [30]. In 2015, a threshold of 70 GeV was used; this was subsequently raised to cope with increasing effects from pile-up as the LHC achieved higher luminosities, reaching 110 GeV during the 2016–2018 data-taking period. The $E_{\mathrm{T}}^{\mathrm{miss}}$ in the trigger is based only on calorimetric measurements and does not include any reconstructed muons, so the muons behave similarly to invisible particles in this trigger. Events must have at least one reconstructed vertex with at least two associated tracks with $p_{\mathrm{T}} > 500$ MeV. The vertex with the highest sum of the squared transverse momenta of associated tracks is taken as the primary vertex.

Particle-flow (PFlow) jets are constructed using the anti-k_t algorithm [31, 32] with a radius parameter of $R = 0.4$, using charged constituents associated with the primary vertex and neutral PFlow constituents as inputs [33]. Jets are calibrated to the particle-level scale using a sequence of corrections, including pile-up subtraction and energy and angular calibrations [34]. Events are required to have at least two jets within $|\eta| < 2.8$, the leading jet is required to have $p_{\mathrm{T}} > 250$ GeV, and other jets are required to have $p_{\mathrm{T}} > 30$ GeV. To suppress jets originating from pile-up collisions, requirements on the jet-vertex tagger [35] discriminant are applied to jets with p_{T} below 60 GeV. Events are also required to have at least one jet within $\Delta\phi = 2.0$ of the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ direction. The distance between the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ direction and the closest jet decreases with higher R_{inv} fractions. Jets are identified as b-jets if they pass the 77% efficiency working point of the DL1r algorithm [36]. The b-jet-tagging performance has a strong dependence on the jet p_{T}. The efficiency drops from 65% for a b-jet p_{T} of around 500 GeV to 10% for a p_{T} of around 2 TeV. Estimated from MC simulation, the corresponding mistag rate of charm jets drops from 15% to 2% over the same p_{T} interval, and that of light-flavour jets remains at the level of 1% [36]. Events with two or more b-jets are vetoed to reduce $t\bar{t}$ background contributions. A tighter veto cannot be applied because the signal topology contains some fraction of jets which originate from b-quarks.

Events with jets containing anomalous energy depositions due to coherent noise or electronic noise bursts in the calorimeter [37, 38] are removed, but this has a negligible effect on the signal efficiency. Non-collision backgrounds, e.g. energy depositions in the calorimeters due to muons of beam-induced or cosmic-ray origin, are suppressed by imposing an additional selection criterion on the leading jet: the ratio of the jet charged-particle fraction to the maximum fraction of the jet energy collected by a single calorimeter layer, $f_{\mathrm{ch}}/f_{\mathrm{max}}$, is required to be larger than 0.1. Events are rejected if they contain a selected jet pointing in the direction where tile calorimeter modules were disabled, or where other detector errors were present. The non-collision backgrounds contribution is found to be negligible after these requirements.

Hadronically decaying τ-lepton candidates are formed by using a Recurrent Neural Network algorithm which combines information from the calorimeters and inner tracking detectors, and they are required to have one or three associated tracks [39]. Any events with such a τ-lepton candidate with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$ are rejected. Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter that are associated with charged-particle tracks reconstructed in the inner detector. Electrons are required to fulfill 'tight likelihood' identification criteria as well as calorimeter- and track-based isolation criteria [40]. Muon candidates are reconstructed by combining inner-detector tracks with muon spectrometer tracks or energy deposits in the calorimeters consistent with the passage of muons. Muons are required to fulfil 'medium' identification criteria as well as calorimeter- and track-based isolation criteria [41]. Electrons and muons are required to satisfy $p_{\mathrm{T}} > 7$ GeV and be within the tracking volume $|\eta| < 2.5$. Electrons are also required not to be in the transition region $1.37 < |\eta| < 1.52$ between the barrel and endcap EM calorimeters.

An overlap removal procedure is applied to avoid ambiguities in reconstructing the objects specific to this final state. Firstly, any electron which shares a track with a muon is rejected. Any jet whose angular distance ΔR from an electron is less than 0.2 is removed, as is any which has fewer than three tracks and lies within $\Delta R = 0.4$ of a muon. Finally, electrons and muons within $\Delta R = 0.4$ of the remaining jets are discarded.

The missing transverse momentum vector, $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is reconstructed as the negative vector sum of transverse momenta of all selected objects, as well as tracks compatible with the primary vertex but not matched to any of those objects; this last contribution is called the 'soft term' [42]. The magnitude of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is referred to throughout this Letter as the missing transverse momentum, denoted by $E_{\mathrm{T}}^{\mathrm{miss}}$. Events with offline $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV are selected in order to ensure that the trigger is fully efficient. If muons are selected in the event, the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is recalculated, considering muons to be invisible, to mimic an invisibly decaying W or Z boson, in order to have a consistent definition of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ in the signal and control regions. The lepton and jet momentum scales and resolutions, the lepton reconstruction, identification, and isolation efficiencies, the b-jet identification efficiency, and the trigger efficiency in the simulation are corrected to match those measured in data.

5 Analysis strategy

After the preselection of events with $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV and at least two jets, with at least one being within $\Delta\phi = 2.0$ of the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ direction, the signal region (SR) is defined with $E_{\mathrm{T}}^{\mathrm{miss}} > 600$ GeV and $H_{\mathrm{T}} > 600$ GeV, where H_{T} is the scalar sum of the p_{T} of jets in the event. As mentioned earlier, events with at most one b-jet are selected in SR. The reason for this is twofold: signal events with higher mediator masses and R_{inv} fractions typically have high $E_{\mathrm{T}}^{\mathrm{miss}}$, and the background contribution from mismeasured multijet events becomes subdominant. Events with any electrons or muons passing the $p_{\mathrm{T}} > 7$ GeV requirement are discarded in the SR selection. The dominant background contributions are then from processes with real $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, namely W/Z+jets, diboson and semileptonic top-quark processes. The background from $t\bar{t}$ and W+jets arises either because an electron or a muon is not observed (because it has $p_{\mathrm{T}} < 7$ GeV, fails the identification requirement, or is produced outside the central region of the detector) or because a hadronically decaying τ-lepton is misidentified as a jet.

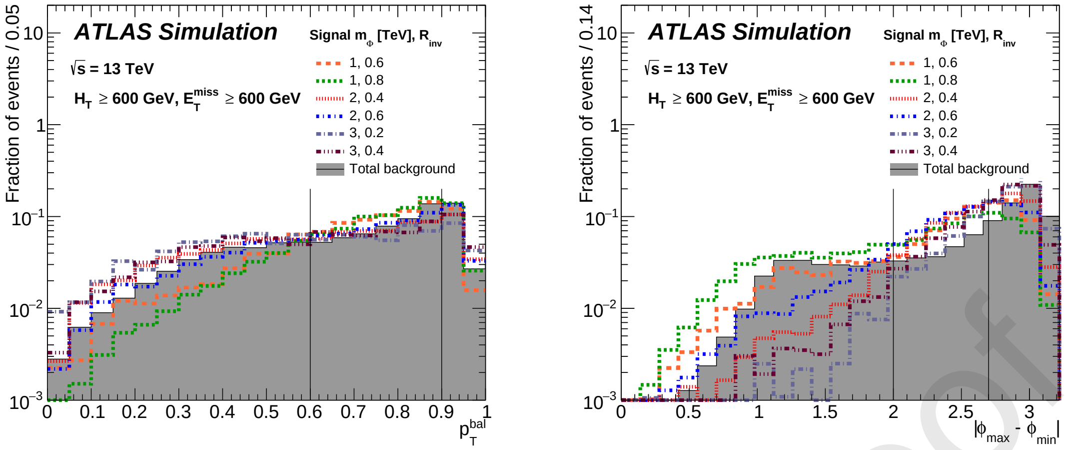
In order to estimate the backgrounds resulting from these processes, control regions (CRs) with the same $E_{\mathrm{T}}^{\mathrm{miss}}$ and H_{T} requirements as the SR are defined using muons. The 1L CR requires exactly one muon and no b-tagged jet. The 1L1B CR requires exactly one muon as before, but also exactly one b-tagged jet. Finally, the 2L CR requires two oppositely charged muons with the pair's invariant mass lying between 66 GeV and 116 GeV, and no b-tagged jets. The 1L CR is dominated by W+jets events, the 1L1B CR is dominated by semileptonic $t\bar{t}$ and single-top-quark processes as well as W+heavy-flavour jets processes, and the 2L CR almost exclusively contains Z+jets events. The CRs have negligible signal contamination.

The search then makes use of two other key observables, which are found to be largely uncorrelated:

1. the p_{T} balance between the jets closest (j_1) and farthest (j_2) in azimuth from the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ direction, denoted by $p_{\mathrm{T}}^{\mathrm{bal}}$ and defined using the two-dimensional p_{T} vectors:

$$p_{\mathrm{T}}^{\mathrm{bal}} = \frac{|\vec{p}_{\mathrm{T}}(j_1) + \vec{p}_{\mathrm{T}}(j_2)|}{|\vec{p}_{\mathrm{T}}(j_1)| + |\vec{p}_{\mathrm{T}}(j_2)|},$$

2. the azimuthal separation between j_1 and j_2 as defined above, denoted by $|\phi_{\max} - \phi_{\min}|$.



(a)

(b)

Figure 2: Shape comparisons of the (a) $p_{\mathrm{T}}^{\mathrm{bal}}$ and (b) $|\phi_{\max} - \phi_{\min}|$ distributions of the total background before the fit and six signal predictions for representative mediator masses and invisible fractions in SR. The solid vertical lines show how these distributions are subsequently divided to form the nine-bin grid.

Figure 2 compares the shapes of the signal and total background $p_{\mathrm{T}}^{\mathrm{bal}}$ and $|\phi_{\max} - \phi_{\min}|$ distributions in the SR. There are distinct distribution shape differences between the total background and the different signal benchmark points, and these are utilised in designing the fit strategy. The $|\phi_{\max} - \phi_{\min}|$ distribution is divided into three bins covering < 2, 2–2.7, and > 2.7, and the $p_{\mathrm{T}}^{\mathrm{bal}}$ distribution is divided into three bins covering < 0.6, 0.6–0.9, and > 0.9.

Although the simulated signals mostly populate the higher part of the $p_{\mathrm{T}}^{\mathrm{bal}}$ and $|\phi_{\max} - \phi_{\min}|$ ranges, these regions also have larger background contributions and both have less signal sensitivity than the lower part of the $|\phi_{\max} - \phi_{\min}|$ distribution. The nine bins are defined identically in the SR and CRs. The yields in these bins of $p_{\mathrm{T}}^{\mathrm{bal}}$ and $|\phi_{\max} - \phi_{\min}|$ are treated as the observables used in the fit described in Section 6.

For the two sensitive observables chosen above, mostly good agreement between data and MC predictions is observed in the various CRs. However, since no independent CR for multijet processes can be established, an additional low-$E_{\mathrm{T}}^{\mathrm{miss}}$ multijet reweighting region (MJRR) for multijet processes is defined by requiring $E_{\mathrm{T}}^{\mathrm{miss}}$ to be between 250 GeV and 300 GeV with the same $H_{\mathrm{T}} > 600$ GeV requirement as in the SR and CRs. In this MJRR, the $p_{\mathrm{T}}^{\mathrm{bal}}$ bins in the range $2.7 < |\phi_{\max} - \phi_{\min}| < 3.2$ are found to be multijet-rich. In these bins, the contribution from multijet processes is estimated by subtracting the other predicted SM process yields from the data event yield after applying the scale factors obtained for these backgrounds in Section 6. The differences observed between this predicted multijet yield and MC predictions for multijet processes determine the reweighting factors which are applied to the other $|\phi_{\max} - \phi_{\min}|$ bins in the same $p_{\mathrm{T}}^{\mathrm{bal}}$ range. This reweighting factors range from 2 to 2.4 for different $p_{\mathrm{T}}^{\mathrm{bal}}$ ranges. Tests showed that using different bin-ranges causes only small changes in those factors, and their values also remained compatible when derived from ranges of lower or higher $E_{\mathrm{T}}^{\mathrm{miss}}$ values. A fit is initially performed using both SRs and CRs to extract the multijet reweighting factors. Once the reweighting factors are derived, the final CR-SR simultaneous fit described in Section 6 is performed after accounting for the obtained factors.

6 Statistical analysis and background estimation

In order to estimate the signal strength, as well as to better determine the individual yield N_i^{bg} of the i-th background having a probability distribution function P_i, a simultaneous binned maximum-likelihood function fit is performed on the product of all P_i and the nine bin yields, using MC templates, by including both the SR and the corresponding CRs (1L, 1L1B, and 2L). This provides a way to search for the signal while simultaneously improving the background prediction in the SR. The normalisation factors k_i^{SF} for the individual backgrounds are allowed to float and are determined from the fit:

$$\mathcal{L}(\mu,\theta) = \prod_{j \in 36 \text{ bins}} \text{Poisson}(N_j^{\text{obs}} | \mu N_j^{\text{sig}}(\theta) + \sum_{i \in \text{bg}} k_i^{\text{SF}} \times N_{i,j}^{\text{bg}}(\theta)) \times f^{\text{constr}}(\theta)$$

where N_j^{obs} is the observed total yield, $N_j^{\text{sig}}(\theta)$ is the total predicted signal yield, and $N_{i,j}^{\text{bg}}(\theta)$ is the predicted background yield for the i-th background. The signal strength μ is given by the ratio of the measured to predicted signal cross-section. All the systematic uncertainties discussed in Section 7 are propagated into the simultaneous fit as different nuisance parameters (NPs), denoted by θ. The term $f^{\text{constr}}(\theta)$ represents the product of the Gaussian constraints applied to each of the nuisance parameters, and is defined as

$$f^{\text{constr}}(\theta) = \prod_{k=1}^{M} G_k(\theta)$$

where G_k is the standard normal distribution, and M is the total number of systematic uncertainty sources. The MC templates are allowed to vary within their shape uncertainty, and the NPs representing the systematic uncertainties are correlated across bins and signal and control regions unless stated otherwise. The fit finds the set of values of the unknown parameters μ and θ that maximises $\mathcal{L}$. The profile-likelihood ratio is used as the test statistic, and upper limits on the contribution of events from new physics are computed by using the modified frequentist approach CL_s based on asymptotic formulas at 95% confidence level [43]. It should be noted that μ is allowed to take negative values in the fit, and CL_s deals with this value by considering a different likelihood ratio than that which would be utilised for positive-definite μ values. The different likelihood ratio then corrects for any over-constraining of the limits. The fit also finds the uncertainty in μ by taking into account the correlations between all sources of uncertainty. The post-fit scale factors for different background processes are listed in Table 2. The normalisation scale factors have a correlation of 20% between the top-quark and W+jets processes, 14% between W+jets and Z+jets processes, and 5% between top-quark and Z+jets processes.

Table 2: Scale factors for each background process obtained from the simultaneous fit using the SR, 1L CR, 1L1B CR and 2L CR. 'Top processes' denotes merged contributions from $t\bar{t}$ and single top-quark processes. The quoted uncertainties include statistical and systematic uncertainties. As can be seen, the multijet process normalisation factor is close to unity after the multijet reweighting procedure. The W+jets and Z+jets process scale factors are primarily driven by the dedicated control regions and they are close to unity as well.

Process	k^{SF}
Z+jets	1.18 ± 0.05
W+jets	1.09 ± 0.04
Top processes	0.64 ± 0.04
Multijet	1.10 ± 0.04

7 Systematic uncertainties

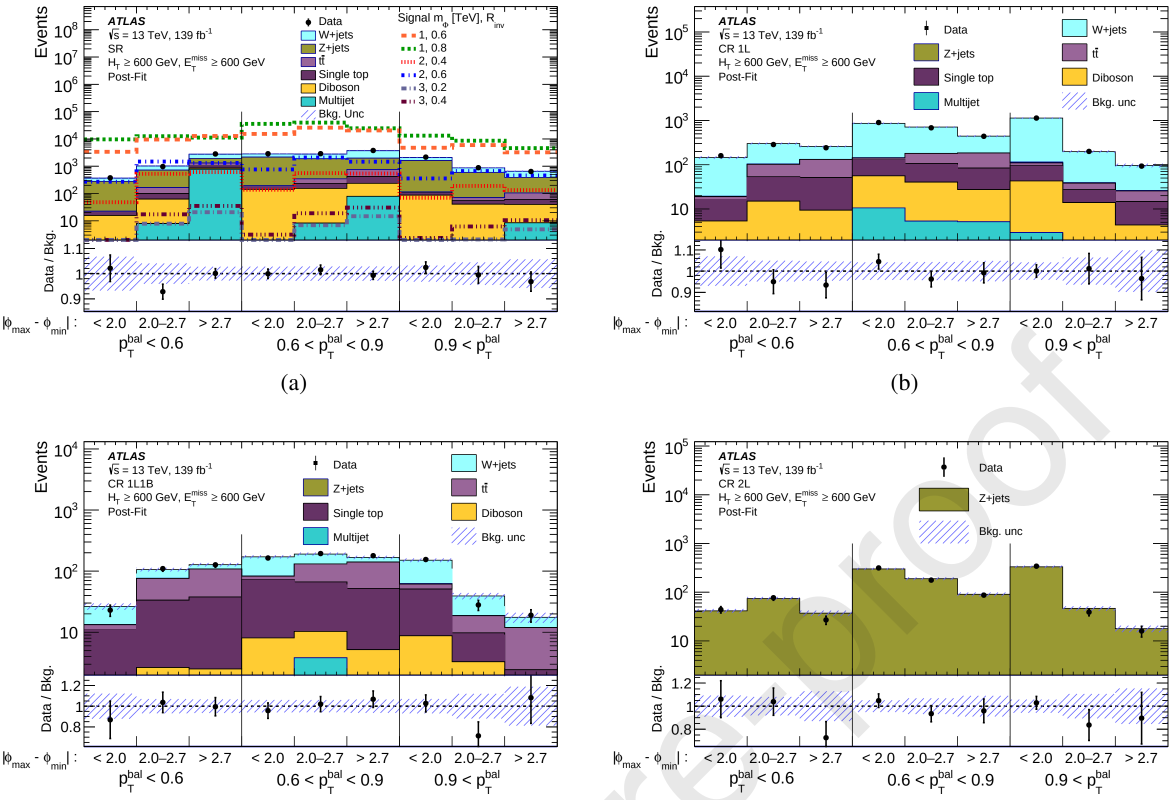
Systematic uncertainties in the signal and background yields and shapes result from experimental uncertainties and theoretical modelling effects. Except the luminosity uncertainty, all the other uncertainties are shape uncertainties, but eventually they are translated to 9-bin yields. The experimental ones are due to the jet energy scale (JES) and resolution (JER) [44], computation of the $E_{\mathrm{T}}^{\mathrm{miss}}$ soft term [42], flavour-tagging performance [45], rescaling of simulation to match the pile-up profile in data, and an uncertainty in the luminosity estimation. The uncertainty in the combined 2015–2018 integrated luminosity is 1.7% [46], obtained using the LUCID-2 detector [47] for the primary luminosity measurements. The luminosity uncertainty is applied to background processes that are normalised to theoretical predictions and to the signal cross-section parameters in the fit. Uncertainties in the reconstruction, identification, isolation [40, 48, 49] and trigger efficiencies [50] of muons, electrons and τ-leptons and in their energy scale and resolution are also considered.

Theoretical uncertainties common to the MC samples are due to renormalisation and factorisation scale choices, and also the choice of PDF set and value for the strong coupling constant α_{s}. These uncertainties were assessed from the effect of varying the scales, the PDFs, and the value of α_{s}. Additionally, initial- and final-state radiation scale uncertainties were assessed for $t\bar{t}$ and single-top processes, and were taken to be uncorrelated. For $t\bar{t}$ and tW processes, alternative predictions were obtained by using aMC@NLO as the matrix element generator, also interfaced to Pythia 8.230, or by using the same matrix element generator Powheg Box v2, but interfaced instead to Herwig 7 [51, 52] for the modelling of the parton shower, hadronisation, and underlying event. The differences are treated as systematic uncertainties in the modelling of these processes. Because the fit is performed using the same H_{T} requirement in the CRs and the SR, and the observables most sensitive to signal are largely insensitive to the p_{T} of the top quark, no additional uncertainty related to the modelling of the top quark's p_{T} is considered. The difference between using the diagram-subtraction and diagram-removal schemes [53] to remove the overlap between the tW and $t\bar{t}$ processes is also considered. The W+jets samples were split into heavy- and light-flavour subprocesses, and since the MC prediction was found to underestimate the former by about a factor of 1.3 [54], an additional 30% normalisation uncertainty is assigned to the heavy-flavour samples. Scale variations are treated as uncorrelated between the W+jets heavy- and light-flavour subprocesses.

An additional uncertainty from the reweighting procedure is also considered for the multijet modelling, and is conservatively assessed to be 100% for each of the bins, except those used to obtain the reweighting factors as described at the end of Section 5. This uncertainty is treated as fully uncorrelated between the bins, and was checked in an intermediate-$E_{\mathrm{T}}^{\mathrm{miss}}$ validation region of 300–600 GeV with the same $H_{\mathrm{T}} > 600$ GeV requirement. The agreement of the data with the sum of the predicted background indicates no additional mismodelling of the multijet background beyond the quoted uncertainty.

8 Results

The post-fit yields for all nine bins are shown in Figure 3 of the three CRs and the SR separately, and listed in Table 3. Overall, good agreement between data and SM predictions is observed for all the bins. The post-fit distributions of the H_{T}, $E_{\mathrm{T}}^{\mathrm{miss}}$, $|\phi_{\mathrm{max}} - \phi_{\mathrm{min}}|$ and $p_{\mathrm{T}}^{\mathrm{bal}}$ observables are shown in Figure 4 for the SR. Again, excellent agreement of data with SM background predictions is seen for all the observables, which also indicates the absence of any effect beyond the SM. The largest post-fit effects on the shapes of discriminating observables are signal modelling uncertainties of up to 8%, Z+jets modelling uncertainties



(a) (b)

(c) (d)

Figure 3: The post-fit yields in the nine bins of the ($p_T^{\text{bal}}, |\phi_{\text{max}} - \phi_{\text{min}}|$) grid are shown for the (a) SR, (b) 1L CR, (c) 1L1B CR, and (d) 2L CR. Data are compared with background predictions, and six signal predictions covering a representative mediator mass and invisible fraction range are overlaid in the SR. Figure (a) shows a background-only fit in the SR. The uncertainties include all systematic and statistical components.

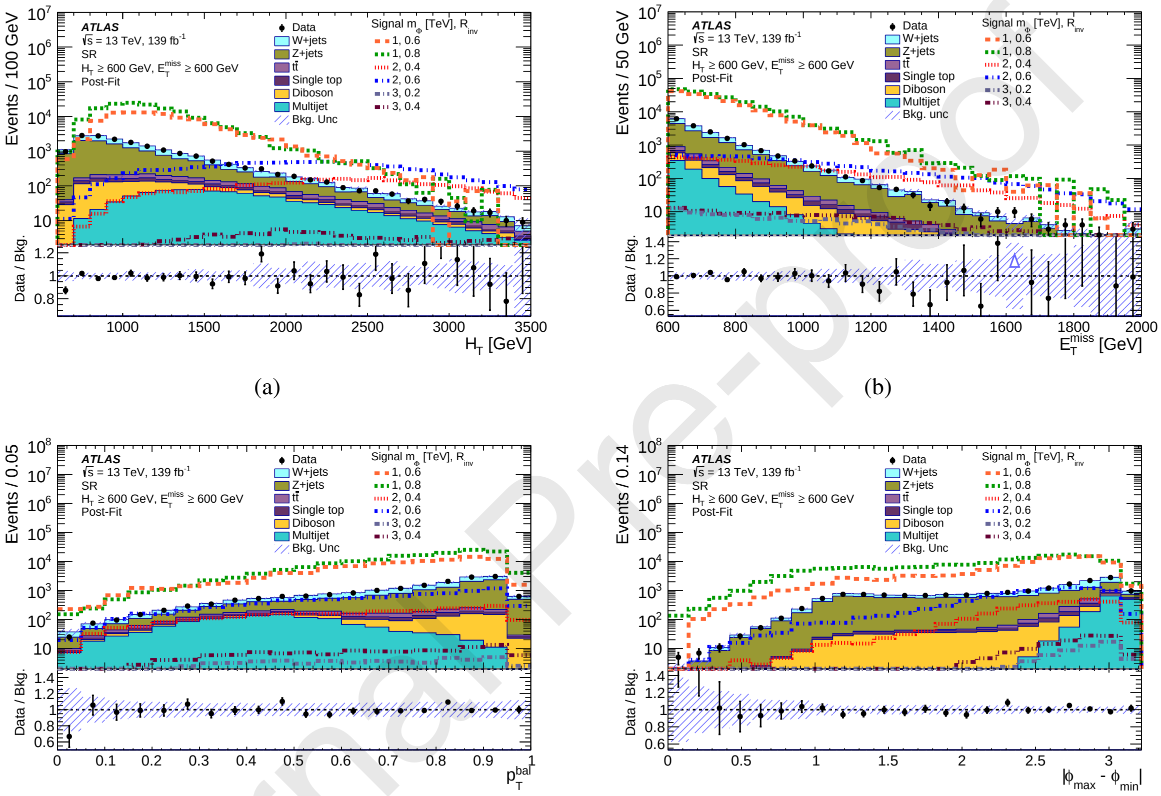
of up to 7%, and top-quark process modelling uncertainties of up to 4%. The rest of the contributions are less than 2%. The total data yield can be translated into a model-independent cross-section limit in this SR.

Upper limits on the contribution of events from new physics are computed by using the modified frequentist CL$_s$ approach based on asymptotic formulas at 95% confidence level (CL) [43, 55], and are given in terms of the signal strength, μ, defined previously. For upper limits with values of $\mu \leq 1$, the nominal cross-section is excluded, while for upper limits with $\mu > 1$, no such conclusion can be obtained. The limits on the signal model are presented in two different ways. The 95% CL exclusion limit plots for limits on the cross-section as a function of mediator mass and R_{inv} values are shown in Figure 5. The observed limits increase from 2.4 TeV for R_{inv} of 0.2 to 2.7 TeV for R_{inv} of 0.8. The observed exclusions tend to be slightly stronger than the expected ones due to a slight deficit in data in individual SR bins and the fit's preference of a negative signal yield to improve the data agreement. The exclusion confidence levels decrease at higher mediator masses as the distributions of the discriminating observables, e.g. $|\phi_{\text{max}} - \phi_{\text{min}}|$, become more background-like in shape and with lower yields. The signal acceptance in the SR decreases for lower mediator masses, opposing the effect of rapidly increasing signal event rates. The systematic uncertainties weaken the limits by about 25%.

Table 3: Post-fit yields from the background-only fit, including pre-fit contributions of different signal benchmark points. Dashes refer to components that are negligible or not applicable. The total uncertainties include statistical and systematic uncertainties.

Process	SR	CR 1L	CR 1L1B	CR 2L
Z+jets	8 490 ± 260	11.6 ± 1.4	2.2 ± 0.6	1 120 ± 40
W+jets	5 820 ± 300	3 190 ± 170	351 ± 41	-
$t\bar{t}$	920 ± 70	350 ± 29	304 ± 24	-
Single top	533 ± 47	358 ± 29	290 ± 25	-
Multijet	850 ± 100	28 ± 11	7.7 ± 3.1	-
Diboson	757 ± 10	187 ± 9	34.5 ± 2.8	-
Total bkg.	17 370 ± 280	4 120 ± 100	990 ± 35	1 120 ± 40
Data	17 388	4 136	999	1 124
Signal:				
$m_\Phi = 1$ TeV, $R_\text{inv} = 0.6$	101 000 ± 23 000	-	-	-
$m_\Phi = 1$ TeV, $R_\text{inv} = 0.8$	160 000 ± 40 000	-	-	-
$m_\Phi = 2$ TeV, $R_\text{inv} = 0.4$	2 800 ± 600	-	-	-
$m_\Phi = 2$ TeV, $R_\text{inv} = 0.6$	8 900 ± 2 000	-	-	-
$m_\Phi = 3$ TeV, $R_\text{inv} = 0.2$	59 ± 13	-	-	-
$m_\Phi = 3$ TeV, $R_\text{inv} = 0.4$	126 ± 29	-	-	-

Additionally, the nominal signal cross-sections for each signal mass point, obtained with $\lambda = 1$, can be scaled by λ^4 for mediator masses larger than 2.5 TeV. For each mediator mass point, the limit on the cross-section is obtained, and the corresponding λ is calculated. This λ value corresponding to the cross-section upper limit is presented for the SR in Figure 6. It can be seen that for lower mass points, the nominal cross-sections are excluded, whereas for higher mass points only higher values of cross-sections can be excluded. The advantage of this representation is that it sets stringent limits on the signature in general for a wide range of λ values, and can help in recasting this analysis for future model predictions.



(a) (b)

(c) (d)

Figure 4: The post-fit distributions of (a) H_{T}, (b) $E_{\mathrm{T}}^{\mathrm{miss}}$, (c) $p_{\mathrm{T}}^{\mathrm{bal}}$, and (d) $|\phi_{\max} - \phi_{\min}|$ are shown for the SR. Data are compared with background predictions, and six signal predictions covering a representative mediator mass and invisible fraction range are overlaid. The uncertainties include all systematic and statistical components. The last bin in (a) and (b) contains the overflow.

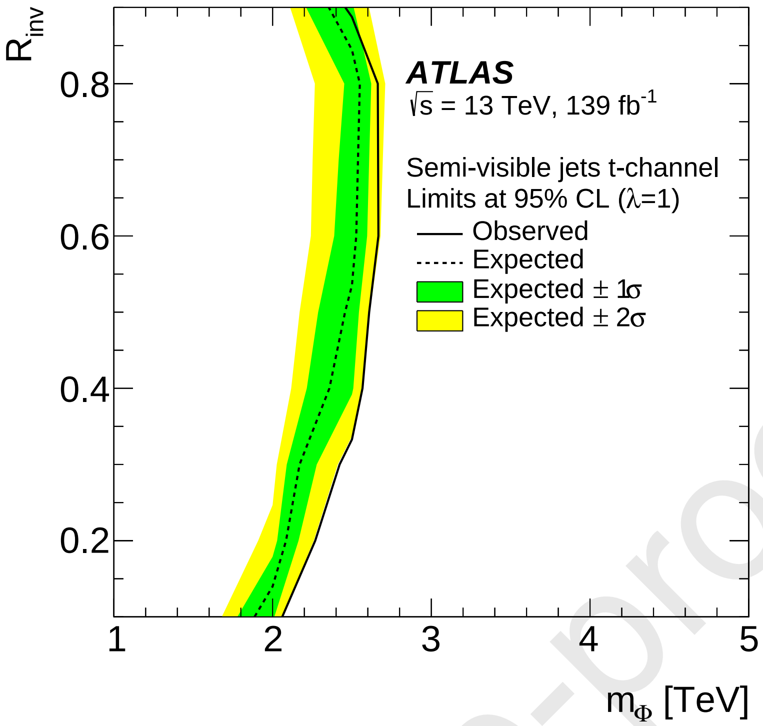


Figure 5: The expected and observed exclusion contours at 95% CL for semi-visible jets signal as a function of mediator mass m_{Φ} on the horizontal axis and R_{inv} on the vertical axis. The solid black line is observed limit as a function of the mediator mass and R_{inv}.The green and yellow shaded bands correspond to the expected one and two standard deviation uncertainties, respectively, with the expected central value shown by the black dashed line.

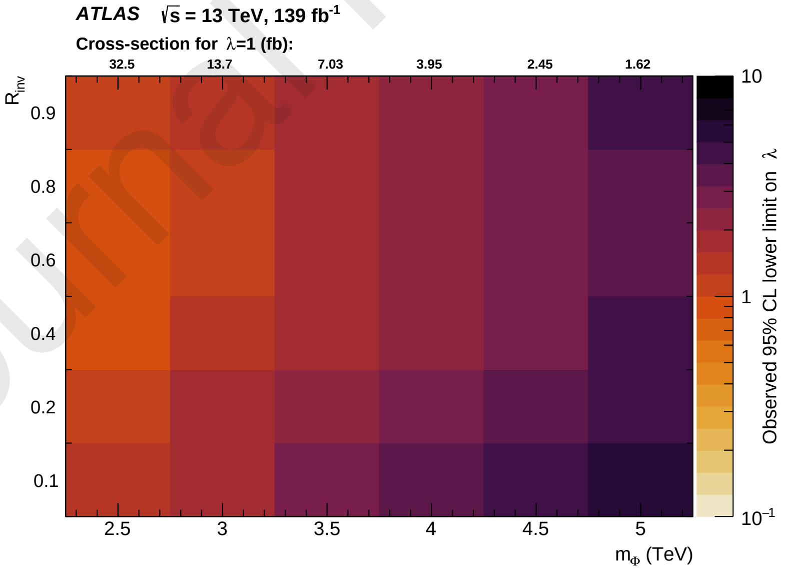


Figure 6: The grid shows the observed 95% CL lower limit on λ with m_{Φ} on the horizontal axis, R_{inv} on the vertical axis. Shown above each m_{Φ} column is the predicted cross-section in fb for that specific mass value as a reference. As the nominal signal cross-sections for each signal mass point, obtained with $\lambda = 1$, can only be scaled by λ^4 for mediator masses larger than 2.5 TeV, so only mediator masses starting from 2.5 TeV are shown.

9 Conclusions

A first search is performed for semi-visible jets in the t-channel production mode using 139 fb^{-1} of data collected from $\sqrt{s} = 13$ TeV proton-proton collisions by the ATLAS experiment at the LHC. Semi-visible jets arise in the strongly interacting dark sector, where dark quarks are produced and their hadronisation generates jets where dark hadrons are interspersed with SM hadrons in the jet, leading to a novel collider signature. The search considers mediator masses in the range 1–5 TeV and a stable-dark-hadron fraction, R_{inv}, of 0.1–0.9. The observed yields are in agreement with the SM background expectations in the signal region defined by $E_{\text{T}}^{\text{miss}} > 600$ GeV and $H_{\text{T}} > 600$ GeV. A total of 17388 data events are observed in the SR, which can be translated into a model-independent cross-section upper limit relevant to the acceptance of this specific signal region selection. The 95% confidence-level upper limits on the mediator mass vary from 2.4 TeV to 2.7 TeV, depending on the value of R_{inv}. They are translated into upper limits on the coupling strength between the mediator, a Standard Model quark and a dark quark.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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