



Letter

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

The ATLAS Collaboration ^{*}

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ABSTRACT

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_T^{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 re-

ferred 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 Fig. 1.

At the leading order, the two SVJs are produced back-to-back and the direction of the missing transverse momentum (\vec{p}_T^{miss}) is aligned with one of the two reconstructed jets. A boost due to additional jets leads to signatures with the \vec{p}_T^{miss} not necessarily pointing in the direction of one of the two SVJs, since both of them contribute to the \vec{p}_T^{miss} . Events in which the \vec{p}_T^{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.

^{*} E-mail address: atlas.publications@cern.ch.

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)	NNPDF 3.0NNLO [12]	SHERPA MEPS@NLO	SHERPA
$t\bar{t}$	POWHEG BOX v2 [26–28]	NLO	NNPDF 3.0NLO [12]	PYTHIA 8.230 with NNPDF 2.3LO	A14 [15]
Single top	POWHEG BOX v2	NLO	NNPDF 3.0NNLO	PYTHIA 8.230 with NNPDF 2.3LO	A14
Multijet	PYTHIA 8.230 [14]	LO	NNPDF 2.3LO [12]	PYTHIA 8.230	A14
Diboson	SHERPA 2.2.1	NLO (up to 2 jets)	NNPDF 3.0NNLO	SHERPA MEPS@NLO	SHERPA

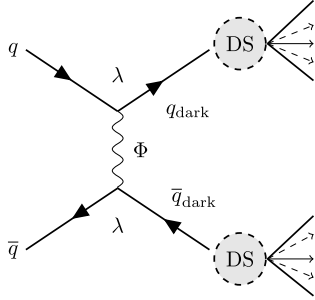


Fig. 1. A diagram illustrating the production of semi-visible jets via a t -channel mediator, Φ , producing a pair of dark quarks, labelled q_{dark} . DS denotes the dark shower which produces a final state consisting of SM hadrons and dark hadrons, governed by the R_{inv} fraction. The coupling strength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

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 Tm 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.

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 $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

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 NNPDF 3.0LO [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 NNPDF 2.3LO [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 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 Fig. 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 NNPDF 2.3LO 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_T^{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_T^{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 $p_T > 500$ 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_r 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 $p_T > 250$ GeV, and other jets are required to have $p_T > 30$ 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}_T^{miss} direction. The distance between the \vec{p}_T^{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, $f_{\text{ch}}/f_{\text{max}}$, 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 $p_T > 20$ 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 $p_T > 7$ 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}_T^{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}_T^{miss} is referred to throughout this Letter as the missing transverse momentum, denoted by E_T^{miss} . Events with offline $E_T^{\text{miss}} > 250$ GeV are selected in order to ensure that the trigger is fully efficient. If muons are selected in the event, the \vec{p}_T^{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}_T^{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 $E_T^{\text{miss}} > 250$ GeV and at least two jets, with at least one being within $\Delta\phi = 2.0$ of the \vec{p}_T^{miss} direction, the signal region (SR) is defined with $E_T^{\text{miss}} > 600$ GeV and $H_T > 600$ 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_T^{miss} , and the background contribution from mismeasured multijet events becomes subdominant. Events with any electrons or muons passing the $p_T > 7$ GeV requirement are discarded in the SR selection. The dominant background contributions are then from processes with real \vec{p}_T^{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 $p_T < 7$ 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_T^{miss} and H_T requirements as the SR are defined using muons. The 1 L 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 2 L 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 1 L 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 2 L 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}_T^{miss} direction, denoted by p_T^{bal} and defined using the two-dimensional p_T vectors:

$$p_T^{\text{bal}} = \frac{|\vec{p}_T(j_1) + \vec{p}_T(j_2)|}{|\vec{p}_T(j_1)| + |\vec{p}_T(j_2)|},$$

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

Fig. 2 compares the shapes of the signal and total background p_T^{bal} and $|\phi_{\text{max}} - \phi_{\text{min}}|$ 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.

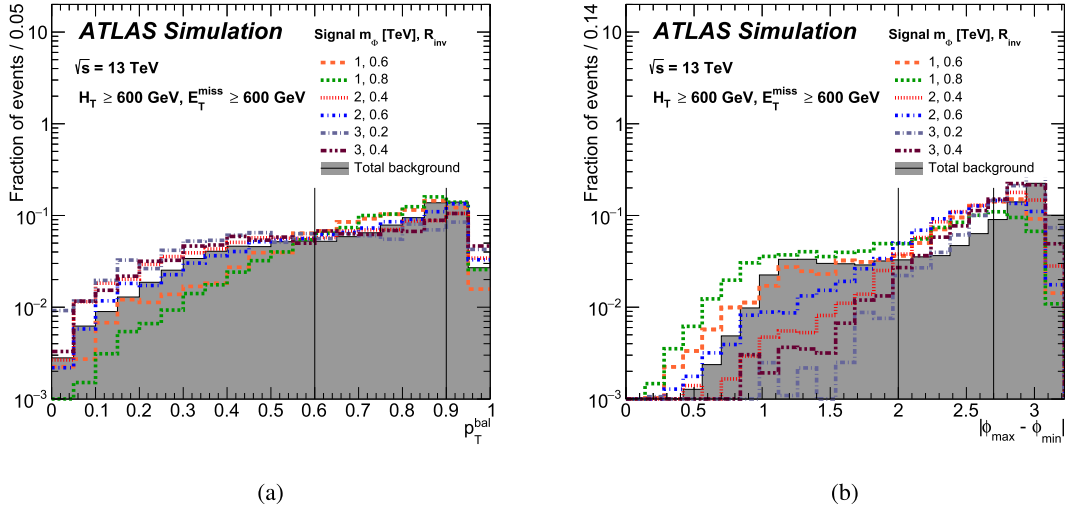


Fig. 2. Shape comparisons of the (a) p_T^{bal} and (b) $|\phi_{\text{max}} - \phi_{\text{min}}|$ distributions of the total background before the fit and six signal predictions for representative mediator masses and invisible fractions in SR. The solid vertical lines show how these distributions are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

The $|\phi_{\text{max}} - \phi_{\text{min}}|$ distribution is divided into three bins covering < 2 , 2 – 2.7 , and > 2.7 , and the p_T^{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_T^{bal} and $|\phi_{\text{max}} - \phi_{\text{min}}|$ ranges, these regions also have larger background contributions and both have less signal sensitivity than the lower part of the $|\phi_{\text{max}} - \phi_{\text{min}}|$ distribution. The nine bins are defined identically in the SR and CRs. The yields in these bins of p_T^{bal} and $|\phi_{\text{max}} - \phi_{\text{min}}|$ 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_T^{miss} multijet reweighting region (MJRR) for multijet processes is defined by requiring E_T^{miss} to be between 250 GeV and 300 GeV with the same $H_T > 600$ GeV requirement as in the SR and CRs. In this MJRR, the p_T^{bal} bins in the range $2.7 < |\phi_{\text{max}} - \phi_{\text{min}}| < 3.2$ 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 $|\phi_{\text{max}} - \phi_{\text{min}}|$ bins in the same p_T^{bal} range. This reweighting factors range from 2 to 2.4 for different p_T^{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_T^{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 (1 L, 1L1B, and 2 L). 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.

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_T^{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 estima-

Table 2

Scale factors for each background process obtained from the simultaneous fit using the SR, 1 L CR, 1L1B CR and 2 L 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 multi-jet 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

tion. 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 uncertain-

ties 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_T^{miss} validation region of 300–600 GeV with the same $H_T > 600$ 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.

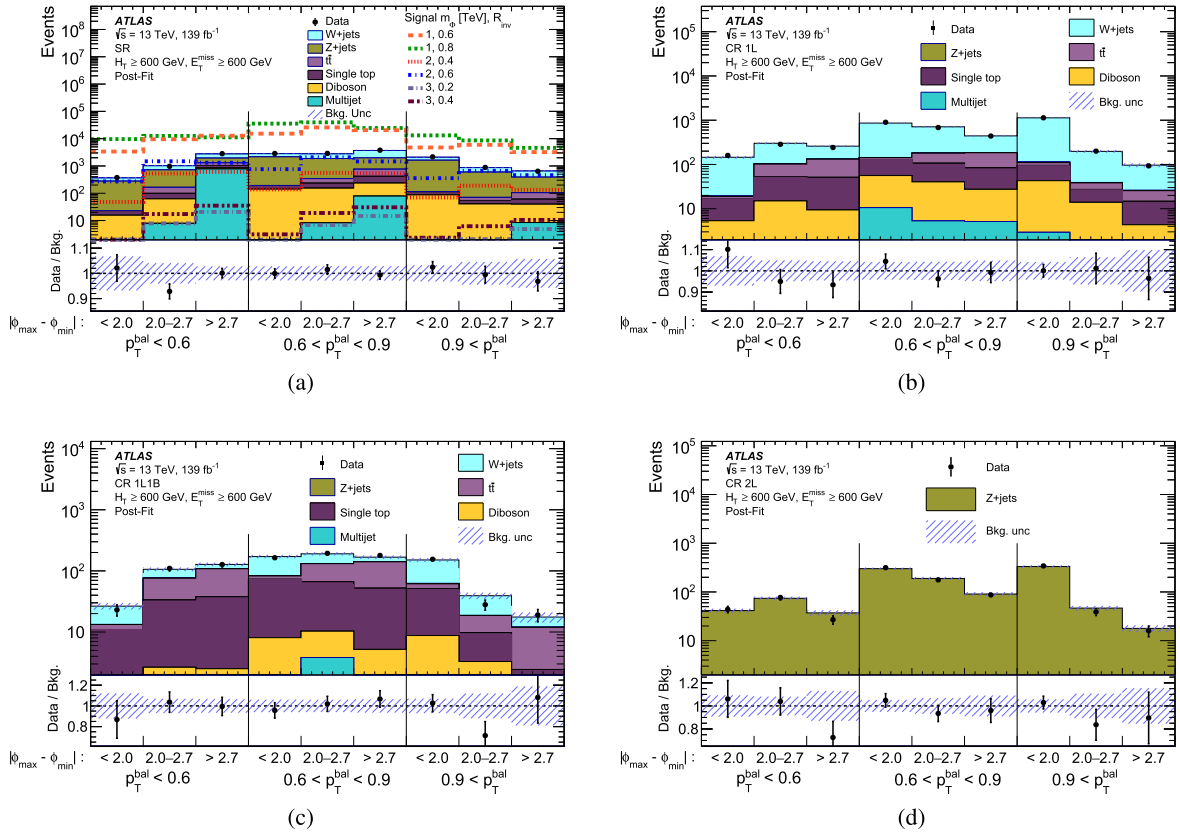


Fig. 3. The post-fit yields in the nine bins of the $(p_T^{\text{ball}}, |\phi_{\text{max}} - \phi_{\text{min}}|)$ grid are shown for the (a) SR, (b) 1 L CR, (c) 1L1B CR, and (d) 2 L CR. Data are compared with background predictions, and six signal predictions covering a representative mediator mass 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.

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 1 L	CR 1L1B	CR 2 L
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	-	-	-

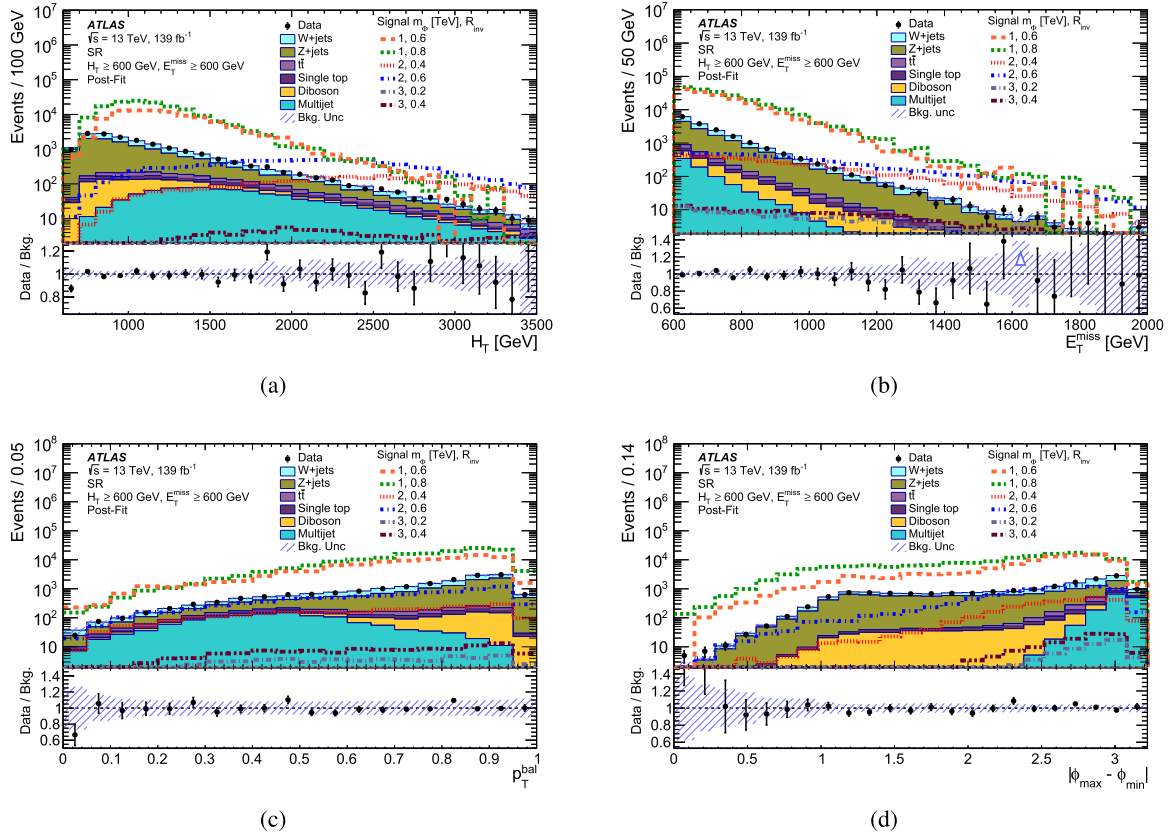


Fig. 4. The post-fit distributions of (a) H_T , (b) E_T^{miss} , (c) p_T^{bal} , and (d) $|\phi_{\text{max}} - \phi_{\text{min}}|$ are shown for the SR. Data are compared with background predictions, and six signal predictions covering a representative mediator mass and invisible fraction range are overlaid.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

8. Results

The post-fit yields for all nine bins are shown in Fig. 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_T^{miss} , $|\phi_{\text{max}} - \phi_{\text{min}}|$ and p_T^{bal} observables are shown in Fig. 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 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.

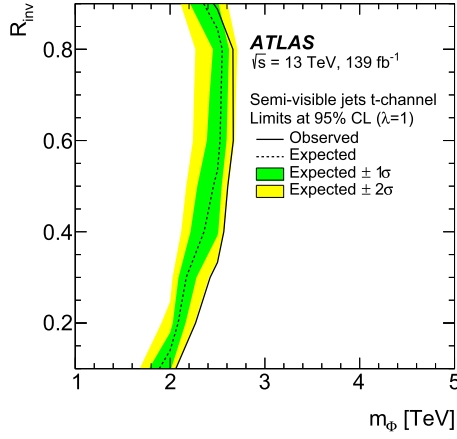


Fig. 5. The expected and observed exclusion contours at 95% CL for semi-visible jets signal as a function of mediator mass m_ϕ on the horizontal axis and R_{inv} on the vertical axis. The solid black line is observed limit as a function of the mediator mass and R_{inv} . The green and yellow shaded bands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

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 Fig. 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%.

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

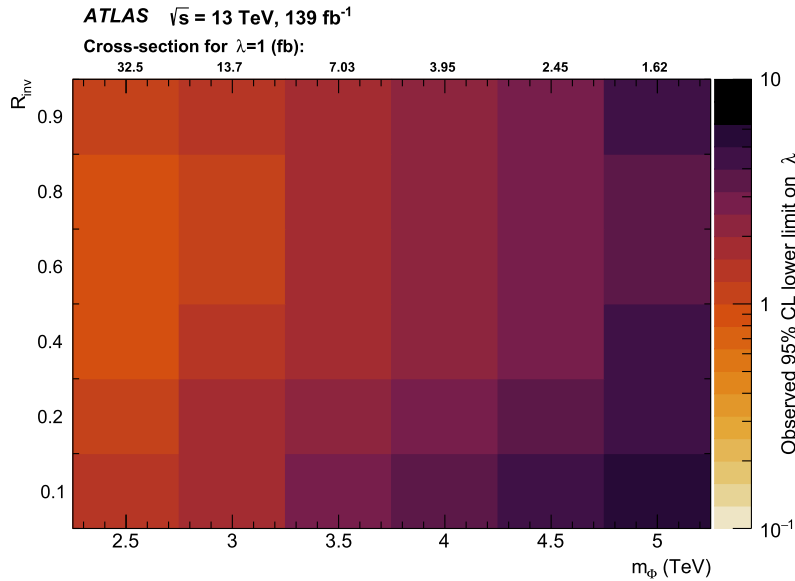


Fig. 6. The grid shows the observed 95% CL lower limit on λ with m_ϕ on the horizontal axis, R_{inv} on the vertical axis. Shown above each m_ϕ column is the predicted cross-section in fb for that specific mass value as a reference. As the nominal signal cross-sections for each signal mass point, obtained 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.

λ value corresponding to the cross-section upper limit is presented for the SR in Fig. 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.

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.

Declaration of competing interest

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.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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The ATLAS Collaboration

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M.J. Basso ^{156a, [id](#)}, C.R. Basson ^{102, [id](#)}, R.L. Bates ^{59, [id](#)}, S. Batlamous ^{35e}, J.R. Batley ^{32, [id](#)}, B. Batool ^{141, [id](#)},
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 D. Bencheikroun ^{35a, [id](#)}, F. Bendebba ^{35a, [id](#)}, Y. Benhammou ^{151, [id](#)}, M. Benoit ^{29, [id](#)}, J.R. Bensinger ^{26, [id](#)},
 S. Bentvelsen ^{114, [id](#)}, L. Beresford ^{48, [id](#)}, M. Beretta ^{53, [id](#)}, E. Bergeaas Kuutmann ^{161, [id](#)}, N. Berger ^{4, [id](#)},
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 K. Tsur ^{118, [id](#)}, D. Tsybychev ^{145, [id](#)}, Y. Tu ^{64b, [id](#)}, A. Tudorache ^{27b, [id](#)}, V. Tudorache ^{27b, [id](#)}, A.N. Tuna ^{36, [id](#)},
 S. Turchikhin ^{38, [id](#)}, I. Turk Cakir ^{3a, [id](#)}, R. Turra ^{71a, [id](#)}, T. Turtuvshin ^{38, [id](#), [y](#)}, P.M. Tuts ^{41, [id](#)}, S. Tzamarias ^{152, [id](#), [e](#)},
 P. Tzanis ^{10, [id](#)}, E. Tzovara ^{101, [id](#)}, F. Ukegawa ^{157, [id](#)}, P.A. Ulloa Poblete ^{137c,137b, [id](#)}, E.N. Umaka ^{29, [id](#)}, G. Unal ^{36, [id](#)},
 M. Unal ^{11, [id](#)}, A. Undrus ^{29, [id](#)}, G. Unel ^{160, [id](#)}, J. Urban ^{28b, [id](#)}, P. Urquijo ^{105, [id](#)}, G. Usai ^{8, [id](#)}, R. Ushioda ^{154, [id](#)},
 M. Usman ^{108, [id](#)}, Z. Uysal ^{21b, [id](#)}, L. Vacavant ^{90b, [id](#)}, V. Vacek ^{132, [id](#)}, B. Vachon ^{104, [id](#)}, K.O.H. Vadla ^{125, [id](#)},
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 M. Vandenbroucke ^{135, [id](#)}, E.R. Vandewall ^{121, [id](#)}, D. Vannicola ^{151, [id](#)}, L. Vannoli ^{57b,57a, [id](#)}, R. Vari ^{75a, [id](#)},
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C. Vittori ^{36, [id](#)}, I. Vivarelli ^{146, [id](#)}, V. Vladimirov ¹⁶⁷, E. Voevodina ^{110, [id](#)}, F. Vogel ^{109, [id](#)}, P. Vokac ^{132, [id](#)}, Yu. Volkotrub ^{86a, [id](#)}, J. Von Ahnen ^{48, [id](#)}, E. Von Toerne ^{24, [id](#)}, B. Vormwald ^{36, [id](#)}, V. Vorobel ^{133, [id](#)}, K. Vorobev ^{37, [id](#)}, M. Vos ^{163, [id](#)}, K. Voss ^{141, [id](#)}, J.H. Vosseveld ^{93, [id](#)}, M. Vozak ^{114, [id](#)}, L. Vozdecky ^{95, [id](#)}, N. Vranjes ^{15, [id](#)}, M. Vranjes Milosavljevic ^{15, [id](#)}, M. Vreeswijk ^{114, [id](#)}, R. Vuillermet ^{36, [id](#)}, O. Vujanovic ^{101, [id](#)}, I. Vukotic ^{39, [id](#)}, S. Wada ^{157, [id](#)}, C. Wagner ¹⁰³, J.M. Wagner ^{17a, [id](#)}, W. Wagner ^{171, [id](#)}, S. Wahdan ^{171, [id](#)}, H. Wahlberg ^{91, [id](#)}, M. Wakida ^{111, [id](#)}, J. Walder ^{134, [id](#)}, R. Walker ^{109, [id](#)}, W. Walkowiak ^{141, [id](#)}, A. Wall ^{128, [id](#)}, T. Wamorkar ^{6, [id](#)}, A.Z. Wang ^{170, [id](#)}, C. 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¹ Department of Physics, University of Adelaide, Adelaide; Australia² Department of Physics, University of Alberta, Edmonton AB; Canada³ (a) Department of Physics, Ankara University, Ankara; (b) Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye⁴ LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France⁵ APC, Université Paris Cité, CNRS/IN2P3, Paris; France⁶ High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America

- ⁷ Department of Physics, University of Arizona, Tucson AZ; United States of America
- ⁸ Department of Physics, University of Texas at Arlington, Arlington TX; United States of America
- ⁹ Physics Department, National and Kapodistrian University of Athens, Athens; Greece
- ¹⁰ Physics Department, National Technical University of Athens, Zografou; Greece
- ¹¹ Department of Physics, University of Texas at Austin, Austin TX; United States of America
- ¹² Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan
- ¹³ Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain
- ¹⁴ ^(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; ^(b) Physics Department, Tsinghua University, Beijing; ^(c) Department of Physics, Nanjing University, Nanjing; ^(d) School of Science, Shenzhen Campus of Sun Yat-sen University; ^(e) University of Chinese Academy of Science (UCAS), Beijing; China
- ¹⁵ Institute of Physics, University of Belgrade, Belgrade; Serbia
- ¹⁶ Department for Physics and Technology, University of Bergen, Bergen; Norway
- ¹⁷ ^(a) Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; ^(b) University of California, Berkeley CA; United States of America
- ¹⁸ Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany
- ¹⁹ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland
- ²⁰ School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom
- ²¹ ^(a) Department of Physics, Bogazici University, Istanbul; ^(b) Department of Physics Engineering, Gaziantep University, Gaziantep; ^(c) Department of Physics, Istanbul University, Istanbul; Türkiye
- ²² ^(a) Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá; ^(b) Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia
- ²³ ^(a) Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; ^(b) INFN Sezione di Bologna; Italy
- ²⁴ Physikalisches Institut, Universität Bonn, Bonn; Germany
- ²⁵ Department of Physics, Boston University, Boston MA; United States of America
- ²⁶ Department of Physics, Brandeis University, Waltham MA; United States of America
- ²⁷ ^(a) Transilvania University of Brasov, Brasov; ^(b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; ^(c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; ^(d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; ^(e) University Politehnica Bucharest, Bucharest; ^(f) West University in Timisoara, Timisoara; ^(g) Faculty of Physics, University of Bucharest, Bucharest; Romania
- ²⁸ ^(a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic
- ²⁹ Physics Department, Brookhaven National Laboratory, Upton NY; United States of America
- ³⁰ Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina
- ³¹ California State University, CA; United States of America
- ³² Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom
- ³³ ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) iThemba Labs, Western Cape; ^(c) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; ^(d) National Institute of Physics, University of the Philippines Diliman (Philippines); ^(e) University of South Africa, Department of Physics, Pretoria; ^(f) University of Zululand, KwaDlangezwa; ^(g) School of Physics, University of the Witwatersrand, Johannesburg; South Africa
- ³⁴ Department of Physics, Carleton University, Ottawa ON; Canada
- ³⁵ ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; ^(b) Faculté des Sciences, Université Ibn-Tofail, Kénitra; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; ^(d) LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; ^(e) Faculté des sciences, Université Mohammed V, Rabat; ^(f) Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco
- ³⁶ CERN, Geneva; Switzerland
- ³⁷ Affiliated with an institute covered by a cooperation agreement with CERN
- ³⁸ Affiliated with an international laboratory covered by a cooperation agreement with CERN
- ³⁹ Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America
- ⁴⁰ LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France
- ⁴¹ Nevis Laboratory, Columbia University, Irvington NY; United States of America
- ⁴² Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark
- ⁴³ ^(a) Dipartimento di Fisica, Università della Calabria, Rende; ^(b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy
- ⁴⁴ Physics Department, Southern Methodist University, Dallas TX; United States of America
- ⁴⁵ Physics Department, University of Texas at Dallas, Richardson TX; United States of America
- ⁴⁶ National Centre for Scientific Research “Demokritos”, Agia Paraskevi; Greece
- ⁴⁷ ^(a) Department of Physics, Stockholm University; ^(b) Oskar Klein Centre, Stockholm; Sweden
- ⁴⁸ Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany
- ⁴⁹ Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany
- ⁵⁰ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany
- ⁵¹ Department of Physics, Duke University, Durham NC; United States of America
- ⁵² SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom
- ⁵³ INFN e Laboratori Nazionali di Frascati, Frascati; Italy
- ⁵⁴ Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany
- ⁵⁵ II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany
- ⁵⁶ Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
- ⁵⁷ ^(a) Dipartimento di Fisica, Università di Genova, Genova; ^(b) INFN Sezione di Genova; Italy
- ⁵⁸ II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany
- ⁵⁹ SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom
- ⁶⁰ LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France
- ⁶¹ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America
- ⁶² ^(a) Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; ^(b) Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; ^(c) School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; ^(d) Tsung-Dao Lee Institute, Shanghai; China
- ⁶³ ^(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany
- ⁶⁴ ^(a) Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; ^(b) Department of Physics, University of Hong Kong, Hong Kong; ^(c) Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China
- ⁶⁵ Department of Physics, National Tsing Hua University, Hsinchu; Taiwan
- ⁶⁶ IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France
- ⁶⁷ Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain
- ⁶⁸ Department of Physics, Indiana University, Bloomington IN; United States of America
- ⁶⁹ ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy
- ⁷⁰ ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy
- ⁷¹ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano; Italy
- ⁷² ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli; Italy
- ⁷³ ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia; Italy
- ⁷⁴ ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy
- ⁷⁵ ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy

- 76 ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy
- 77 ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy
- 78 ^(a) INFN-TIFPA; ^(b) Università degli Studi di Trento, Trento; Italy
- 79 Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria
- 80 University of Iowa, Iowa City IA; United States of America
- 81 Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America
- 82 Istinye University, Sariyer, Istanbul; Türkiye
- 83 ^(a) Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; ^(b) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(c) Instituto de Física, Universidade de São Paulo, São Paulo; ^(d) Rio de Janeiro State University, Rio de Janeiro; Brazil
- 84 KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
- 85 Graduate School of Science, Kobe University, Kobe; Japan
- 86 ^(a) AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow; ^(b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland
- 87 Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland
- 88 Faculty of Science, Kyoto University, Kyoto; Japan
- 89 Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan
- 90 ^(a) L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; ^(b) CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France
- 91 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina
- 92 Physics Department, Lancaster University, Lancaster; United Kingdom
- 93 Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom
- 94 Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia
- 95 School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom
- 96 Department of Physics, Royal Holloway University of London, Egham; United Kingdom
- 97 Department of Physics and Astronomy, University College London, London; United Kingdom
- 98 Louisiana Tech University, Ruston LA; United States of America
- 99 Fysiska institutionen, Lunds universitet, Lund; Sweden
- 100 Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain
- 101 Institut für Physik, Universität Mainz, Mainz; Germany
- 102 School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom
- 103 Department of Physics, University of Massachusetts, Amherst MA; United States of America
- 104 Department of Physics, McGill University, Montreal QC; Canada
- 105 School of Physics, University of Melbourne, Victoria; Australia
- 106 Department of Physics, University of Michigan, Ann Arbor MI; United States of America
- 107 Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America
- 108 Group of Particle Physics, University of Montreal, Montreal QC; Canada
- 109 Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany
- 110 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany
- 111 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan
- 112 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America
- 113 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands
- 114 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands
- 115 Department of Physics, Northern Illinois University, DeKalb IL; United States of America
- 116 ^(a) New York University Abu Dhabi, Abu Dhabi; ^(b) University of Sharjah, Sharjah; United Arab Emirates
- 117 Department of Physics, New York University, New York NY; United States of America
- 118 Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan
- 119 Ohio State University, Columbus OH; United States of America
- 120 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America
- 121 Department of Physics, Oklahoma State University, Stillwater OK; United States of America
- 122 Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic
- 123 Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America
- 124 Graduate School of Science, Osaka University, Osaka; Japan
- 125 Department of Physics, University of Oslo, Oslo; Norway
- 126 Department of Physics, Oxford University, Oxford; United Kingdom
- 127 LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France
- 128 Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America
- 129 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America
- 130 ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; ^(b) Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Departamento de Física, Universidade de Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); ^(g) Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal
- 131 Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic
- 132 Czech Technical University in Prague, Prague; Czech Republic
- 133 Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic
- 134 Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom
- 135 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France
- 136 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America
- 137 ^(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; ^(b) Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago; ^(c) Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena; ^(d) Universidad Andres Bello, Department of Physics, Santiago; ^(e) Instituto de Alta Investigación, Universidad de Tarapacá, Arica; ^(f) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile
- 138 Department of Physics, University of Washington, Seattle WA; United States of America
- 139 Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom
- 140 Department of Physics, Shinshu University, Nagano; Japan
- 141 Department Physik, Universität Siegen, Siegen; Germany
- 142 Department of Physics, Simon Fraser University, Burnaby BC; Canada
- 143 SLAC National Accelerator Laboratory, Stanford CA; United States of America
- 144 Department of Physics, Royal Institute of Technology, Stockholm; Sweden
- 145 Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America
- 146 Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom
- 147 School of Physics, University of Sydney, Sydney; Australia
- 148 Institute of Physics, Academia Sinica, Taipei; Taiwan
- 149 ^(a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi; ^(c) University of Georgia, Tbilisi; Georgia

- ¹⁵⁰ Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel
¹⁵¹ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel
¹⁵² Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece
¹⁵³ International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan
¹⁵⁴ Department of Physics, Tokyo Institute of Technology, Tokyo; Japan
¹⁵⁵ Department of Physics, University of Toronto, Toronto ON; Canada
¹⁵⁶ ^(a) TRIUMF, Vancouver BC; ^(b) Department of Physics and Astronomy, York University, Toronto ON; Canada
¹⁵⁷ Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan
¹⁵⁸ Department of Physics and Astronomy, Tufts University, Medford MA; United States of America
¹⁵⁹ United Arab Emirates University, Al Ain; United Arab Emirates
¹⁶⁰ Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America
¹⁶¹ Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden
¹⁶² Department of Physics, University of Illinois, Urbana IL; United States of America
¹⁶³ Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia; Spain
¹⁶⁴ Department of Physics, University of British Columbia, Vancouver BC; Canada
¹⁶⁵ Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
¹⁶⁶ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany
¹⁶⁷ Department of Physics, University of Warwick, Coventry; United Kingdom
¹⁶⁸ Waseda University, Tokyo; Japan
¹⁶⁹ Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel
¹⁷⁰ Department of Physics, University of Wisconsin, Madison WI; United States of America
¹⁷¹ Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
¹⁷² Department of Physics, Yale University, New Haven CT; United States of America

- ^a Also affiliated with an institute covered by a cooperation agreement with CERN.
^b Also at An-Najah National University, Nablus; Palestine.
^c Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
^d Also at Center for High Energy Physics, Peking University; China.
^e Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
^f Also at Centro Studi e Ricerche Enrico Fermi; Italy.
^g Also at CERN, Geneva; Switzerland.
^h Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
ⁱ Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.
^j Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
^k Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
^l Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
^m Also at Department of Physics, California State University, Sacramento; United States of America.
ⁿ Also at Department of Physics, King's College London, London; United Kingdom.
^o Also at Department of Physics, Stanford University, Stanford CA; United States of America.
^p Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
^q Also at Department of Physics, University of Thessaly; Greece.
^r Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
^s Also at Hellenic Open University, Patras; Greece.
^t Also at Institució Catalana de Recerca i Estudis Avançats, ICREA, Barcelona; Spain.
^u Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
^v Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
^w Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
^x Also at Institute of Particle Physics (IPP); Canada.
^y Also at Institute of Physics and Technology, Ulaanbaatar; Mongolia.
^z Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
^{aa} Also at Institute of Theoretical Physics, Ilija State University, Tbilisi; Georgia.
^{ab} Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
^{ac} Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
^{ad} Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
^{ae} Also at Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
^{af} Also at Technical University of Munich, Munich; Germany.
^{ag} Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
^{ah} Also at TRIUMF, Vancouver BC; Canada.
^{ai} Also at Università di Napoli Parthenope, Napoli; Italy.
^{aj} Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
^{ak} Also at Washington College, Chestertown, MD; United States of America.
^{al} Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
^{*} Deceased.