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Search for quantum black hole production in lepton + jet final states using proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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A search for quantum black holes in electron + jet and muon + jet invariant mass spectra is performed with 140 fb^{-1} of data collected by the ATLAS detector in proton-proton collisions at $\sqrt{s} = 13$ TeV at the Large Hadron Collider. The observed invariant mass spectrum of lepton + jet pairs is consistent with Standard Model expectations. Upper limits are set at 95% confidence level on the production cross section times branching fractions for quantum black holes decaying into a lepton and a quark in a search region with invariant mass above 2.0 TeV. The resulting quantum black hole lower mass threshold limit is 9.2 TeV in the Arkani-Hamed-Dimopoulos-Dvali model, and 6.8 TeV in the Randall-Sundrum model.

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I. INTRODUCTION

Quantum black holes (QBHs) are predicted in low-scale quantum gravity models [1–3] that offer solutions to the mass hierarchy problem of the Standard Model (SM) by lowering the scale of quantum gravity (M_{D}) from the high Planck scale ($\sim 10^{16}$ TeV) to the TeV region (1–10 TeV). In these new physics scenarios, gravity becomes strong, and quantum effects are relevant. In models with large extra dimensions such as the Arkani-Hamed-Dimopoulos-Dvali (ADD) model [1,2], the gravitational field is allowed to propagate in n extra dimensions ($n = 6$ in our analysis), while all SM fields are localized in the usual four-dimensional space-time. There are also warped scenarios, such as the Randall-Sundrum model (RS1) [3], in which a single warped extra dimension ($n = 1$) separates two three-dimensional branes by some distance. Gravitons can propagate in this warped dimension, and the effective Planck scale on the three-dimensional brane is determined by the curvature of the extra dimension, also referred to as the warp factor. These models postulate conservation of total angular momentum, color, and electric charge in the production and in the decay of QBHs [4–6]. The behavior of QBHs with masses near M_{D} decaying into two-particle final state is distinct from that of the semiclassical black holes [7] that decay into a multiparticle final state via Hawking radiation [8–11] (thermal decay). Two-particle final states make up 51% (74%) of all possible QBH decays in the ADD (RS1) model [6].

The QBH models can be tested at the Large Hadron Collider (LHC) up to 13 TeV. In this paper, a search for QBHs decaying into a single electron (e) or a single muon (μ), and a quark producing a jet is undertaken. The QBHs are postulated to be produced near the low-scale M_{D}. One expects in strong-gravity interactions that angular momentum, electric charge, and color are conserved. It is less clear that global symmetries such as baryon or lepton number of the SM need to be conserved in strong-gravity interactions. While in high Planck-scale gravity in four dimensions the baryon number violation is bound to be very small [6], the baryon number violation in low-scale gravity in higher dimensions is less constrained and could cause a sizeable impact on observables. Therefore, a search for QBH production that violates SM global symmetries provides a possible way to examine low-scale gravity phenomena. In the absence of a coherent and reliable Feynman diagram technique for the quantum black hole description, the easiest and most accurate way to visualize the QBH production mechanism would be a set of partonic 2-to-2 scattering processes,

$$uu \to \bar{d}\ell^{+}, \qquad ud \to \bar{u}\ell^{+}, \qquad \bar{d}\,\bar{d} \to d\ell^{+}, \tag{1}$$

and the respective charge conjugates. Only these six electric charge initial states ($\pm 4/3$, $\pm 2/3$, $\pm 1/3$) can result in a lepton-quark or lepton-antiquark pair in the final state. Here, the u and d symbols denote all up and down quark flavors and ℓ—all charged leptons excluding τ-lepton, which is not considered in the analysis. In this way, all quark flavors are possible in both the initial and the final state in Eq. (1). The angular momentum of the QBH is entirely due to the spin states of the incoming partons.

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The initial orbital angular momentum is assumed to be negligible because of the small impact parameter in the parton-parton collision. The model/generator makes no attempt to convert a classical impact parameter to quantized orbital angular momentum. Final states with lepton plus quark (antiquark) can only have either the spin 0 or the spin 1. Thus, only QBHs with these spin states can contribute to the cross section of the considered process. Color is conserved in the interaction, but QBH has color, and thus the final state has color, so the beam remnant has the corresponding anticolor.

A previous search for QBHs in the lepton + jet channel was performed in proton-proton (p-p) collisions at a center-of-mass energy of $\sqrt{s} = 8$ TeV by ATLAS [12]. The combined 95% confidence level upper limit on the QBH production cross section with threshold mass above 3.5 TeV was found to be 0.18 fb. This limit constrains the threshold mass of QBH, which was found to be above 5.3 TeV in the ADD model. QBHs have also been sought in the dijet, dilepton, and photon + jet channels by both ATLAS and CMS at center-of-mass energies of 7 TeV [13–15], 8 TeV [16–20], and 13 TeV [21–27]. These LHC results with different final states use the same QBH model/generator, so results can be compared. In general, the QBH searches in the lepton + jet final-state are less sensitive than in the dijet searches (at the same QBH threshold mass). On the other hand, the limits obtained in the lepton + jet events are stronger than those with photon + jet and dilepton final states. Different final states supplement each other because they search for QBHs with different quantum numbers. In addition, the lepton + jet model-independent limits can constrain some other models violating the baryon-lepton global symmetry.

II. ATLAS DETECTOR

The ATLAS experiment [28] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a nearly 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 [29], 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 end cap 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 tracking chambers and fast detectors for triggering. A two-level trigger system [30] 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 [31] 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.

III. DATASETS AND SIMULATED EVENT SAMPLES

The results described in this paper use p-p collision data collected by ATLAS at $\sqrt{s} = 13$ TeV during 2015–2018 in stable beam conditions and with all detector systems operating normally [32]. The event quality is checked to remove events with noise bursts or coherent noise in the calorimeters. Events in the electron channel are required to pass at least one of two single-electron triggers [33]: the first requires a transverse momentum (p_{T}) threshold of 60 GeV, and the second has looser identification criteria and a p_{T} threshold of 120 or 140 GeV, depending on the data-taking period. Events in the muon channel are recorded using a single-muon trigger [34] with a transverse momentum (p_{T}) requirement of at least 50 GeV. The integrated luminosity of the dataset is determined to be $140.1 \pm 1.2\ \mathrm{fb}^{-1}$ [35], obtained using the LUCID-2 detector [36] for the primary luminosity measurements.

Background events with a high-p_{T} lepton and one or more jets arise from electroweak processes including vector boson production with additional jets (W/Z + jets), dibosons (WW, WZ and ZZ), top-quark pair ($t\bar{t}$) and single-top-quark production, and multijet processes including nonprompt leptons from leptonic hadron decays and jets misidentified as leptons.

Monte Carlo (MC) simulation is used to model the expected contributions of various SM processes as well as possible QBH signals. A full description of the MC simulated event samples used is given below and summarized in Table I. The expected contributions of the SM backgrounds reported in Table I are taken from MC simulation, either directly or adjusted by the fit to data in dedicated control regions. The multijet background is

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upward. 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 I. The event generators used for simulation of the signal and background processes. The acronyms ME and PS stand for matrix element and parton shower. The top-quark mass is set to 172.5 GeV.

Process	ME generator and ME PDFs	PS, PDFs, nonperturbative effect
$W/Z+$jets	Sherpa 2.2.1, NNPDF3.0NLO	Sherpa 2.2.1, NNPDF3.0NLO
$t\bar{t}$	POWHEG BOX, NNPDF3.0NLO	PYTHIA 8.230, NNPDF2.3LO, EvtGen 1.6.0
Single-top s-channel, tW	POWHEG BOX, NNPDF3.0NLO	PYTHIA 8.230, NNPDF2.3LO, EvtGen 1.6.0
Single-top t-channel	POWHEG BOX, NNPDF3.04fNLO, MadSpin	PYTHIA 8.230, NNPDF2.3LO, EvtGen 1.6.0
Diboson, semileptonic decay	Sherpa 2.2.1, NNPDF3.0NLO	Sherpa 2.2.1, NNPDF3.0NLO
Diboson, fully leptonic decay	Sherpa 2.2.2, NNPDF3.0NLO	Sherpa 2.2.2, NNPDF3.0NLO
QBH signal, ADD, RS1	QBH 3.0, CTEQ6L1	PYTHIA 8.205, CTEQ6L1, EvtGen 1.2.0

measured directly in data. In this case the events collected by a set of unprescaled single-lepton triggers with different p_{T}-thresholds are used.

$W/Z+$jets and diboson samples [37,38] are simulated with the Sherpa generator [39]. The $W/Z+$jets, and semileptonically decaying diboson samples, are simulated with Sherpa 2.2.1, while the fully leptonic diboson processes are simulated with Sherpa 2.2.2. In the Sherpa samples the additional hard parton emissions [40] are matched to parton showers based on Catani–Seymour dipole factorization [41]. The NNPDF3.0NLO [42] set of parton distribution functions (PDFs) and a dedicated set of tuned parameters developed by the Sherpa authors are used [39]. The matching of the matrix element to the parton shower [43–46] is employed for the various jet multiplicities, which are then merged into an inclusive sample using an improved CKKW (Catani-Krauss-Kuhn-Webber) procedure [45] that is extended to next-to-leading-order (NLO) accuracy using the MEPS@NLO prescription [44]. The virtual QCD correction for matrix elements at NLO accuracy is provided by the OpenLoops library [47,48]. The $W/Z+$jets (diboson) simulations are calculated for up to two (one) additional partons at NLO and up to four (three) additional partons at Leading Order (LO). The $W/Z+$jets processes are normalized to a next-to-next-to-leading-order (NNLO) cross section prediction [49]. The diboson processes are normalized to the NNLO cross section prediction [50] as well.

The production of $t\bar{t}$ [51] and single-top tW [52] and s-channel [53] events is modeled using the POWHEG BOX [54–56] v2 generator at NLO with the NNPDF3.0NLO PDF set. The single-top t-channel [57] is modeled with POWHEG BOX in the four-flavor scheme with the NNPDF3.04fNLO PDF set. The events are interfaced with PYTHIA 8.230 [58] using the A14 tune [59] and the NNPDF2.3LO PDF set [60]. The h_{damp} parameter[2] is set to 1.5 times the top-quark mass [61]. The $t\bar{t}$ inclusive production cross section is corrected to the theory prediction at NNLO in QCD, including the resummation of next-to-next-to-leading logarithmic (NNLL) soft-gluon terms calculated using Top++2.0 [62]. The tW inclusive cross section is corrected to the theory prediction calculated at NLO in QCD with NNLL soft-gluon corrections [63,64]. The MadSpin [65] generator is used to preserve top-quark spin correlations in the t channel of the single-top background. The EvtGen 1.6.0 [66] package is applied for the modeling of c- and b-hadron decays.

The simulated QBH signal event samples are obtained from the QBH 3.0 generator [67], which uses the CTEQ6L1 leading-order PDF set [59,68]. The parton showering and hadronization are performed in PYTHIA 8.205, using the CTEQ6L1 PDF set and the A14 tune. The QCD factorization scale for the PDFs is set to the inverse gravitational radius [67]. The QBH simulation assumes massless parton interaction and conserves total angular momentum. The threshold mass, M_{th}, is set equal to M_{D}. For the ADD QBH signal, the number of extra dimensions is $n=6$ (total number of dimensions $D=10$). For the RS1 QBH signal, a single extra dimension is assumed leading to a total of five dimensions. The ADD (RS1) samples for both leptonic channels are generated with M_{th} from 2 TeV to 9.5 (7.5) TeV with steps of 0.5 TeV (the same as in Ref. [12]). A quantum black hole is not a particle, so it does not have a single mass or width. The generator produces a distribution of QBH masses (with no additional mass smearing). The QBH mass is required to be in range of 1–3 M_{D} to ensure that the QBHs are produced in the region in which expected quantum effects are important, and that a region of possible thermal decay is excluded. The decay products have exactly the energy and momentum of the produced black hole. Unlike particles produced in quantum field theory, the black hole is produced in a nonperturbative gravity model. The cross sections predicted by the QBH 3.0 event generator [67] are used in the determination of the model-dependent limits for the signal processes. Processes with a quark pair in the initial state have at least 2 orders of magnitude higher cross sections than those with antiquark pairs in the initial state.

All simulated event samples include the effect of multiple p-p interactions in the same or neighboring bunch crossings. These effects are collectively referred to as pileup. The simulation of pile-up collisions is performed

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[2] The h_{damp} parameter controls the p_{T} of the first additional emission beyond the leading-order Feynman diagram in the parton shower and therefore regulates the high-p_{T} emission against which the $t\bar{t}$ system recoils.

with PYTHIA 8.186 using the ATLAS A3 set of tuned parameters [69] and the `NNPDF2.3LO` PDF set and weighted to reproduce the average number of pile-up interactions per bunch crossing observed in data. The generated background events are passed through a full detector simulation [70] based on GEANT4 [71]. Simulated QBH event samples are produced with a fast parametrization of the calorimeter response [72], while GEANT4 is used for the other detector systems.

IV. EVENT RECONSTRUCTION AND OBJECT IDENTIFICATION

For an event to be considered, at least one p-p interaction vertex with at least two tracks must be reconstructed. The primary vertex is chosen to be the vertex with the highest summed p_{T}^2 of tracks with transverse momentum $p_{\mathrm{T}} > 0.4$ GeV that are associated with the vertex [73].

Two identification levels are defined for leptons and jets, referred to as "`Baseline`" and "`Signal`," with `Signal` objects being a subset of `Baseline`. The `Baseline` requirement provides a higher selection efficiency for leptons and jets when calculating missing transverse momentum and resolving ambiguities between overlapping physics objects (see below in this section). The leading lepton passing the `Signal` selection is matched to the lepton that triggered the event.

Electron candidates are reconstructed using energy clusters in the EM calorimeter which are matched to a track of Inner Detector (ID) track, and they are calibrated as described in Ref. [74]. `Baseline` electron candidates are required to have $|\eta| < 2.47$ in order to pass through the fine-granularity region of the EM calorimeter and be outside the range $1.37 < |\eta| < 1.52$ corresponding to the transition region between the barrel and end cap EM calorimeters. They should also satisfy `Loose` identification criteria and have $p_{\mathrm{T}} > 10$ GeV. The trajectory of `Baseline` electrons must be consistent with the primary vertex to suppress electrons originating from pileup. Therefore, the tracks associated with `Baseline` electrons must have a longitudinal impact parameter relative to the primary vertex (z_0) such that $|z_0 \cdot \sin\theta| < 0.5$ mm. `Signal` electrons are defined as `Baseline` candidates that have $p_{\mathrm{T}} > 30$ GeV and satisfy the `Tight` identification and `HighPtCaloOnly` isolation requirements [74]. The track associated with each `Signal` electron must have a transverse impact parameter significance $|d_0/\sigma(d_0)| \leq 5$.

`Baseline` muon candidates are reconstructed in the region $|\eta| < 2.5$ by matching ID tracks to tracks reconstructed in the Muon Spectrometer, and they are calibrated *in situ* using $Z \rightarrow \mu\mu$ decays [75]. `Baseline` muon candidates are required to have $p_{\mathrm{T}} > 10$ GeV. They have to satisfy a set of requirements on the quality of the tracks defined as `Medium` [75] and to pass a requirement on the longitudinal impact parameter $|z_0 \cdot \sin\theta| < 0.5$ mm. `Signal` muons are defined as `Baseline` candidates that have $p_{\mathrm{T}} > 30$ GeV, pass a requirement on the significance of transverse impact parameter $|d_0/\sigma(d_0)| \leq 3$, and satisfy `HighPt` muon identification requirements [75] and a track-based isolation criterion. For the isolation requirement, the summed p_{T} of tracks (with $p_{\mathrm{T}} > 0.4$ GeV) originating from the primary vertex within a cone of radius $\Delta R = 0.2$ around the muon, but excluding the muon candidate track itself, has to be less than 1.25 GeV. A bad-muon veto for the `HighPt` muons is applied. An event is rejected when `Signal` muon has a large relative error of charge over momentum (q/p) associated with the track. The veto requirement is changing from 2.5σ to 2.0σ depending on the muon η for the muon $p_{\mathrm{T}} \leq 1$ TeV, and is linearly tightened to 1σ for muons with $p_{\mathrm{T}} \geq 5$ TeV. The σ is the average expected error on the (q/p) as a function of the muon p_{T} and η.

The anti-k_t algorithm [76] with distance parameter $R = 0.4$ implemented in the FastJet library [77] is used to reconstruct jets up to $|\eta| = 4.9$ from massless clusters of energy depositions in the calorimeter [78] (EMTopo jets). Jets are then calibrated as described in Refs. [79,80]. `Baseline` jets are required to have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.8$. Events are vetoed if they contain jets induced by calorimeter noise or noncollision background, according to criteria described in Ref. [81]. Additional jets that arise from pile-up interactions are rejected by applying a dedicated track-based selection (Jet Vertex Tagger [82]), based on classifying the tracks associated with the jet as pointing or not pointing to the primary vertex. The jet candidates passing all the above requirements are called `Baseline` jets. `Signal` jets are defined as `Baseline` candidates that have $p_{\mathrm{T}} > 30$ GeV.

Jets containing b-flavored hadrons, used only for the estimation of some backgrounds, are identified in the region $|\eta| < 2.5$ by the MV2c10 algorithm [83], which makes use of the impact parameters of tracks associated with the candidate jet, the positions of reconstructed secondary vertices and their consistency with the decay chains of such hadrons. For the working point chosen for this analysis, such jets are identified with an average efficiency of 77% in simulated $t\bar{t}$ events [84], corresponding to rejection factors of 110, 4.9 and 15 for jets originating from light quarks or gluons, charm quarks and τ leptons, respectively.

The efficiencies of the electron and muon trigger, reconstruction, identification and isolation, the jet b-tagging and Jet Vertex Tagging, and the pile-up rejection are taken into account in every simulated event by applying the respective weights that correct for deficiencies in the MC description of those efficiencies [74,75,78,81,82,84].

To avoid reconstruction of a single detected object as multiple leptons or jets, an overlap removal procedure is applied to `Baseline` leptons and jets. First, jet candidates are discarded if they are within $\Delta R < 0.2$ of an electron. Second, electron candidates are discarded within $\Delta R < 0.4$

of the remaining jets. Finally, muon candidates are discarded if they are within $\Delta R < 0.4$ of a remaining jet with at least three tracks of $p_{\mathrm{T}} > 500$ MeV; if this jet has less than three tracks, it is discarded and the muon is kept instead.

The missing transverse momentum (whose magnitude is denoted $E_{\mathrm{T}}^{\mathrm{miss}}$) is defined as the negative vector sum of the transverse momenta of all identified objects (electrons, photons, muons, jets and τ-leptons) and an additional soft term. The overlap removal between baseline objects is applied before computing $E_{\mathrm{T}}^{\mathrm{miss}}$. The soft term is constructed from all tracks associated with the primary vertex but not with any physics object. Fully calibrated electrons, muons, photons, jets, hadronically decaying τ-leptons and charged-particle tracks are used to reconstruct $E_{\mathrm{T}}^{\mathrm{miss}}$ [85,86].

V. EVENT SELECTION AND BACKGROUND ESTIMATION STRATEGY

The event selection is designed to be efficient for true electron + jet and muon + jet final states. For candidate signal events, $p_{\mathrm{T}} > 130$ GeV is required for both the highest p_{T} (leading) lepton and the highest p_{T} jet. The invariant mass of this lepton + jet pair, m_{inv}, is required to be greater than 2.0 TeV in the signal region. A veto on subleading leptons with $p_{\mathrm{T}} > 10$ GeV is applied. Subleading jets in the event are required to have $p_{\mathrm{T}} < 130$ GeV. These selection requirements are summarized in Table II.

The dominant background in both channels is the $W +$ jets process in which the W boson decays leptonically. In the electron + jet channel, the second largest background is events with nonprompt and misidentified (fake) leptons. It mostly originates from multijet production processes when one of the jets is misidentified as a lepton. In the muon channel, this background source is less than 0.5% of the total background in the signal region (SR). Its contribution is 4 times smaller than the single-top background and 10 times smaller than the total uncertainty on the sum of all the other background contributions in the SR: it is therefore considered to be negligible in the muon + jet channel. There are also contributions from $Z +$ jets events in which one lepton is not detected; from diboson processes in which at least one boson decays leptonically; as well as from $t\bar{t}$ and single-top-quark production, in which the W boson from the top-quark decays leptonically.

The background yields for $W/Z +$ jets and $t\bar{t}$ processes in the SR are estimated using dedicated control regions (CRs) and confirmed in validation regions (VRs). The control (validation) regions enriched with $W/Z +$ jets and $t\bar{t}$ backgrounds are designated as WCR (WVR), ZCR (ZVR) and TCR (TVR), respectively. They are orthogonal to each other. There are different CRs and VRs in the electron + jet and muon + jet channels. Definitions of all regions are given in Table II. The CRs/VRs are defined using m_{inv} requirements and additional selections to increase the purity of the corresponding background (last three rows in Table II). The signal contamination estimated for the CRs is less than 0.3% for the ADD signal with $M_{\mathrm{th}} = 5$ TeV. This M_{th} value is considered since lower masses were excluded by the previous analysis at 8 TeV [12]. An additional validation region, SVR, is used to verify the agreement of the background with data in a phase space that is closer to the SR. The SVR uses the same selections as the SR but with lower m_{inv} (see Table II). The WVR and TVR are the subsets of SVR because extra requirements are applied to define WVR and TVR selections in addition to the SVR selection. The ZVR is orthogonal to SVR because two `Signal` leptons are required in ZVR.

The multijet background for the electron channel is estimated using the data-driven *Matrix Method* described in Ref. [87]. Two parameters of the method (real and fake efficiencies, r and f) are evaluated using the MC simulated samples of the $W/Z +$ jets background and the data samples. Events in the samples are selected with looser object requirements with respect to the `Baseline` selection to enrich the selected events with nonprompt electrons and nonelectron objects identified as electrons. The *Matrix*

TABLE II. Definitions of the control, validation and signal regions. Note, that "· · ·" means that this criterion is not applied. Two same-flavor opposite-sign (SFOS) leptons satisfying the `Signal` selection criteria are required in the $Z +$ jets control and validation regions, while `Signal` and `Baseline` stand for the corresponding sets of the lepton and jet selection criteria.

Event selection	WCR (WVR)	ZCR (ZVR)	TCR (TVR)	SR (SVR)
m_{inv} [TeV]	1.0–1.5 (1.5–2.0)	1.0–1.5 (1.5–2.0)	1.0–1.5 (1.5–2.0)	>2.0 (1.5–2.0)
Leading lepton, p_{T} [GeV]	`Signal`, >130	`Signal`, >130	`Signal`, >130	`Signal`, >130
Subleading leptons, p_{T} [GeV]	`Baseline`, <10	SFOS, >30	`Baseline`, <10	`Baseline`, <10
Leading jet, p_{T} [GeV]	`Signal`, >130	`Signal`, >130	`Signal`, >130	`Signal`, >130
Subleading jets, p_{T} [GeV]	`Signal`, <130	`Signal`, <130	`Signal`, <130, $N \geq 3$	`Signal`, <130
Number of b-tagged jets	0		≥ 2	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>60			
$m_{\ell^+\ell^-}$ [GeV]		70–110		

Method uses *tight* and *loose* selection. The *tight* selection corresponds to the `Signal` requirement. In contrast to *tight*, the *loose* selection uses the `Loose` identification and does not apply the isolation requirement.

The r value is the fraction of the electron candidates passing the *tight* requirements and matched to a generated electron, with respect to the electron candidates passing *loose* selection and matched also to a generated electron. The f value is the fraction of the electron candidates passing the *tight* requirements, but not matched to any generated electron (fake), with respect to the candidate electrons passing the *loose* selection and not matched to any generated electron. The r and f efficiencies and their uncertainties are estimated as a function of lepton p_{T} and η, and they cover all regions. The r and f efficiencies are a part of the fake/nonprompt lepton background's estimation toolset [88] that is developed using data and MC simulations and is validated in data. Estimation of the r and f uncertainties is described in Sec. VII. The number of events with fake electrons (N_{multijet}) selected with the *tight* requirement is estimated as

$$N_{\mathrm{multijet}} = \frac{f}{r-f}(r(N_l + N_t) - N_t), \qquad (2)$$

where N_t is the total number of electron candidates passing the *tight* selection in the data sample. N_l is the number of electron candidates that pass the *loose* selection and fail the *tight* requirements in the data.

All background processes (and signal sources when they are included in the fit) except the multijet are estimated using MC simulated events. The control regions are used to constrain the freely floating $W+\mathrm{jets}$, $Z+\mathrm{jets}$ and $t\bar{t}$ background normalization factors, which are obtained independently for the electron and muon channels. The normalizations for the multijet, diboson and single-top backgrounds are allowed to vary, but only within their uncertainty ranges.

VI. STATISTICAL ANALYSIS

A QBH signal is sought in the m_{inv} distributions in the electron + jet and muon + jet channels as well as in their combination. The statistical interpretation of the results is performed using the profile likelihood method implemented in the HistFitter framework [89]. The likelihood function is a product of the probability density functions of the binned m_{inv} distributions, with one for each region contributing to the fit. The number of events in each of the bins in the given regions is described using a Poisson distribution, the mean of which is the sum of the expected contributions from all background and signal sources. Systematic uncertainties described in Sec. VII are added into the fit as nuisance parameters. They are assumed to follow Gaussian distributions whose widths are determined from the size of the corresponding uncertainty. Normalization factors are free-floating parameters in the fit. All the fit parameters are determined by maximizing the product of the Poisson probability functions and the constraints on the nuisance parameters.

The combination of the electron and muon channels was made by merging the electron and muon samples in the data and in the MC simulation. The combined channel (lepton + jet) is fitted independently from the electron and muon channels. Two types of fits are performed as detailed below.

A *model-independent* fit compares the data event yield in the SR with the SM background estimate and its uncertainties, to test for possible contribution of any non-SM signal in the SR. As a first step, a *background-only* fit is performed, where the normalization and shape fit of the backgrounds is adjusted to match the data in the three control regions simultaneously. The resulting distributions are extrapolated into the signal region to correct the expected shapes and yields of the corresponding backgrounds. The extrapolation of the adjusted distributions and nuisance parameters is also checked in the VRs by means of comparison to data and total yield of the SM background. In a second step, any non-SM signal is sought in the SR. The possible contribution of a signal is scaled by a freely floating normalization factor of the dummy signal added in the SR. The significance of a possible excess of observed events over the SM prediction is quantified by the one-sided probability, p_0, of the background alone to fluctuate to the observed number of events or higher, by using the asymptotic formula described in Ref. [90]. The presence of a non-SM signal would manifest itself as a small p_0 value. In the absence of an excess over the SM expectation, upper limits on the cross section of any non-SM signal are estimated.

In a *model-dependent* fit, an ADD or RS1 signal is included in the SR, and its yield is scaled by a freely floating signal normalization factor. In the absence of any significant excess above the SM background prediction, limits are evaluated with the modified frequentist $\mathrm{CL_S}$ method [91]. The background normalization factors and nuisance parameters are determined simultaneously in the CRs and in the SR. The bin width over m_{inv} in the SR is optimized to obtain good fit performance and stability for all QBH threshold masses used in the analysis. The 2 TeV width was found to be the best bin size.

Acceptance and efficiency are estimated with the use of the simulated QBH signal event samples. Acceptance is calculated at the generation level as the fraction of events passing the signal requirements. Efficiency is the fraction of events passing the signal requirements at the reconstruction level with respect to the generation-level signal requirements. The product of acceptance and efficiency (Acc × Eff) of the signal selection does not depend on the QBH threshold mass within their uncertainties. The Acc × Eff is also consistent for both models (ADD and RS1). The average values of Acc × Eff are equal to $(66.5 \pm 0.4)\%$ and $(67.1 \pm 0.4)\%$ in the electron and muon channels, respectively.

The suppression of the additional jet activity in the event due to the vetoing of subleading jets with $p_T > 130$ GeV leads to a better separation between the signal and SM background processes. However, the constraint distorts the acceptance and efficiency of the signal extraction from the background, since the QBH signal is calculated at LO + PS accuracy in QCD, while the largest SM backgrounds, $V +$ jets, are generated with NLO + PS precision. Thus, the comparison of signal with background may be distorted in the fit, leading to an over-optimistic estimate of upper limits on $\sigma \times Br$. The effect of the higher order QCD radiation in the QBH production yield is evaluated as a correction factor, R_c. The R_c is obtained using the $W/Z +$ jets samples, since the events have a color structure in the final state similar to that of the signal and are generated at higher order accuracy. Hence, the R_c quantifies the overestimate in signal acceptance and efficiency due to use of the veto on the high-p_T subleading jets at LO MC generated events.

The R_c is defined as the ratio of the number of events passing the signal selection without and with the requirement on the subleading jet activity (see Table II). The ratios are calculated separately for $W +$ jets and $Z +$ jets events, and the average of the two is used as the R_c correction factor. The maximal difference between corrections obtained with the $W +$ jets and $Z +$ jets samples is used as the systematic uncertainty on the R_c factor. Statistical uncertainties in the $W/Z +$ jets samples are also included in the R_c total uncertainty. The uncertainty on R_c was added to the total systematic uncertainty in the fit. The QCD correction for the electron + jet and muon + jet final-states combination is calculated as the weighted average. The R_c correction factors in the electron and muon channels and their combination are given in Eq. (3), respectively:

$$\langle R_c\rangle^{\mathrm{ele}} = 0.36 \pm 0.02, \qquad \langle R_c\rangle^{\mathrm{muo}} = 0.39 \pm 0.04,$$
$$\langle R_c\rangle^{\mathrm{comb}} = 0.37 \pm 0.02. \tag{3}$$

The R_c factors are consistent between the electron, muon and combined channels and are used to correct the signal MC Acc × Eff in the limit setting procedure.

VII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties are evaluated for all signal and background predictions and include experimental uncertainties on detector measurements as well as modeling uncertainties and the effect of limited statistics of MC simulation. The systematic uncertainties of all backgrounds are extrapolated from the control regions into the validation and signal regions in the background-only fit. The background uncertainties are practically the same in all types of fit. The expected QBH signal and its uncertainties are estimated for the ADD and RS1 models in the model-dependent fit. The relative systematic uncertainties for the SM background and a representative signal (ADD, $M_{\mathrm{th}} = 6.0$ TeV) in the SR are represented in Table III. The resulting uncertainty in the total background differs from the sum in quadrature of the single sources because of correlations.

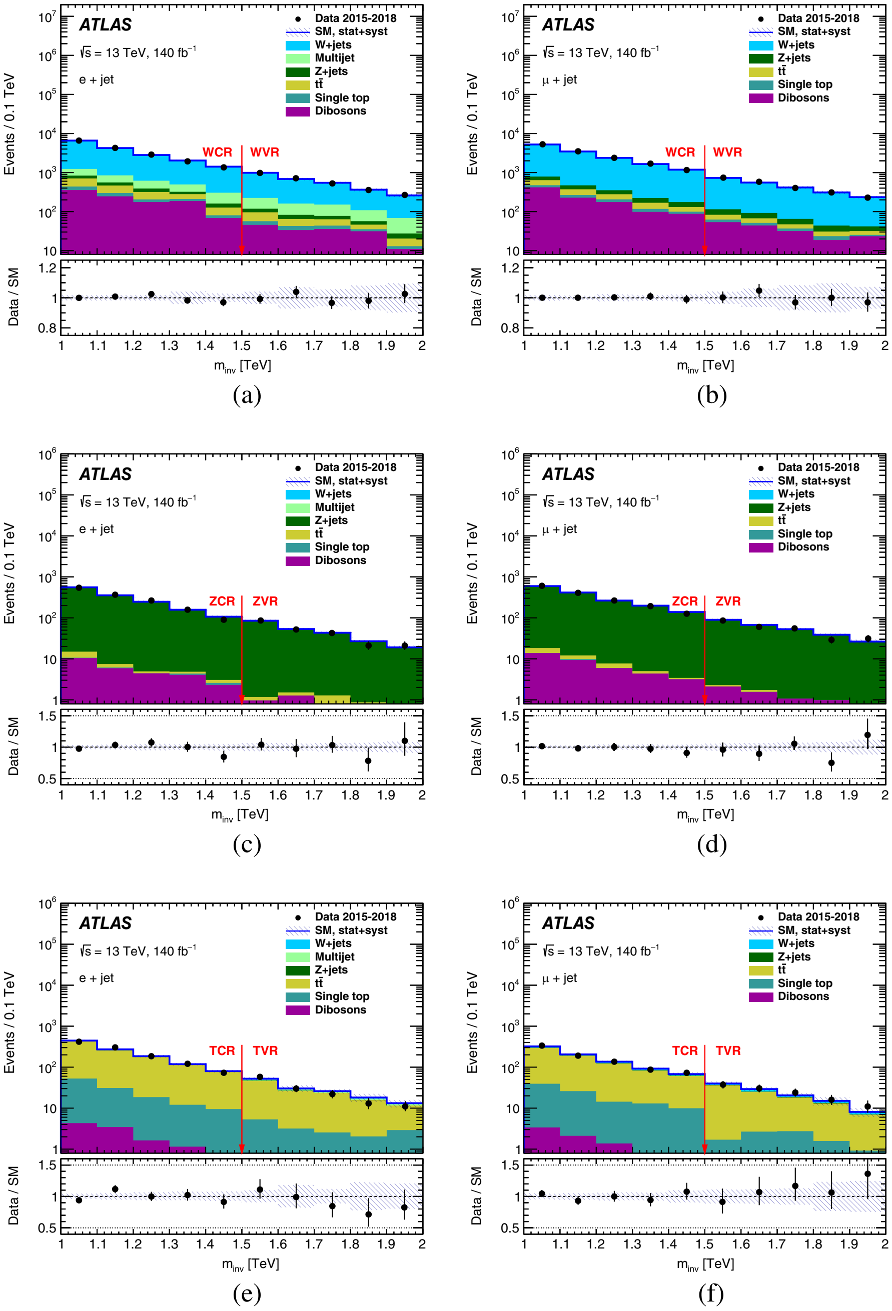
TABLE III. The relative systematic uncertainties (in %) on the SM background in the SR are estimated in the background-only fit; and systematic uncertainties on the ADD signal are estimated for the QBH with $M_{\mathrm{th}} = 6.0$ TeV in the model-dependent fit. Lepton modeling combines all the types of experimental uncertainties for the electrons or muons. All the uncertainties shown are obtained independently for the electron and muon channels. The relative statistical errors on the data (in %) are also shown.

	Electron + jet		Muon + jet	
Source	Background	Signal	Background	Signal
JER	2.4	1.9	2.4	1.6
JES	0.7	0.4	0.6	0.5
Lepton modeling	2.8	0.6	3.6	1.7
Pileup	0.7	0.6	0.8	1.0
Luminosity	0.5	0.7	0.5	0.7
$W +$ jets normalization	1.1		1.1	
$W +$ jets modeling	0.5		0.6	
$Z +$ jets normalization	0.3		0.3	
$Z +$ jets modeling	0.3		0.3	
$t\bar{t}$ normalization	0.2		0.4	
MC statistics	1.6	0.6	1.5	0.7
Multijet estimation	1.4			
Total uncertainty	4.6	2.4	5.1	2.7
Statistical errors of data	2.1		2.7	

Experimental uncertainties reflect the accuracy of the experimental measurements of jets and leptons. The jet energy scale (JES) and resolution (JER) uncertainties are derived as a function of the p_T and η of the jet. They are determined using a combination of data and simulation, through measurements of the jet p_T balance in dijet, $Z +$ jets and $\gamma +$ jets events [80]. The uncertainties in scale and resolution of the electron energy [74] and muon momentum [75] are propagated to the measured event yield. Systematic uncertainties in the measurements of the electron [33,74] and muon [75] identification, reconstruction, isolation, and triggering efficiencies as well as in the pile-up jet identification using the jet vertex tagger algorithm [82] are also propagated to the measured m_{inv} distributions.

The uncertainty in the m_{inv} spectrum due to pileup is estimated by varying the average number of pile-up events in the simulation to account for the differences between the values of the measured and predicted total inelastic cross section used in the pile-up simulation [92]. The impact of the luminosity uncertainty on the SM background is estimated by varying the integrated luminosity combined over 2015–2018 within its uncertainty of 0.83% [35].

Modeling uncertainties on the $W/Z+$ jets backgrounds are calculated as follows. The PDF uncertainties propagated to the m_{inv} distribution are estimated using the nominal PDF set and a set of 100 PDF replicas for `NNPDF3.0NNLO` [42]. The impact of the $\alpha_s(m_Z)$ uncertainty on the background is estimated by varying $\Delta\alpha_s(m_Z) = \pm 0.002$. The impact of missing higher order calculations is evaluated using seven-point variations of the factorization and renormalization scales in the cross section calculations. The scales are independently varied upward and downward by a factor



(a) (b)

(c) (d)

(e) (f)

FIG. 1. The distributions of events over the invariant mass of the leading lepton and the leading jet are shown after the *background-only* fit. The data (points with error bars) and SM backgrounds (solid histograms) are shown in (a), (c), and (e) for the electron + jet channel and in (b), (d), and (f) for the muon + jet channel. The normalizations extracted from the fit in the CRs are applied in the full m_{inv} range. (a),(b) The WCR and WVR. (c),(d) The ZCR and ZVR. (e),(f) The TCR and TVR. The lower panels show the ratio of the number of events observed in the data to the fitted total background. The hatched bands represent the total relative uncertainty in the background estimate.

TABLE IV. The observed number of data events, the fitted background events in the SVR and the SR for the *background-only* fit and the number of background events expected from the MC background samples in the electron + jet and muon + jet channels. The errors shown for the "Expected events" are statistical and systematic uncertainties summed in quadrature.

	SVR electron + jet	SVR muon + jet	SR electron + jet	SR muon + jet
Observed data	9053	5504	2319	1359
Fitted events	8900 ± 320	5380 ± 200	2290 ± 110	1386 ± 70
$W +$ jets	5590 ± 270	4190 ± 200	1290 ± 70	1087 ± 54
Multijet	1670 ± 200		570 ± 47	
$Z +$ jets	646 ± 73	439 ± 27	199 ± 17	131 ± 13
$t\bar{t}$	527 ± 10	351 ± 7	109 ± 5	69 ± 5
Single top	143 ± 7	112 ± 5	31 ± 2	28 ± 2
Dibosons	335 ± 22	289 ± 14	94 ± 9	72 ± 8
Expected events	9390 ± 340	5260 ± 220	2647 ± 94	1303 ± 55
$W +$ jets	6090 ± 270	4080 ± 210	1654 ± 65	1016 ± 48
Multijet	1690 ± 210		577 ± 38	
$Z +$ jets	598 ± 85	408 ± 23	186 ± 18	122 ± 12
$t\bar{t}$	546 ± 14	366 ± 7	109 ± 6	71 ± 5
Single top	141 ± 7	104 ± 4	29 ± 2	28 ± 2
Dibosons	327 ± 23	298 ± 12	92 ± 10	66 ± 8

of 2, excluding simultaneous variations in opposite directions. The envelope of the resulting variations as a function of m_{inv} is taken as the size of the associated systematic uncertainty. All aforementioned modeling uncertainties are combined in quadrature and represented in Table III as "$W/Z +$ jets modeling." Total modeling (theoretical) uncertainties are not estimated for the $t\bar{t}$, single-top and diboson samples because they are small backgrounds. The uncertainties in the normalization of the $W/Z +$ jets and $t\bar{t}$ backgrounds from the fitting procedure are shown in Table III as well as uncertainties from the limited MC statistics of the background simulated samples.

The uncertainties in the multijet background are related to the estimate of the f and r parameters (Δf and Δr) as well as to statistical errors in the total number N_t of *tight* electron candidates (ΔN_t) and in the total number N_l of *loose* electron candidates (ΔN_l). The Δf and Δr uncertainties are estimated for different ($\eta - p_{\mathrm{T}}$) regions by varying the requirements used in the event selection [87]. All these uncertainties are combined in quadrature and reported in Table III.

Systematic uncertainties described in this section are added into the fit as nuisance parameters where they can be pulled and constrained. After the fit all systematic uncertainties are pulled by less than 0.7 of a standard deviation. The errors of nuisance parameters are constrained within $\pm 0.5\sigma$ in comparison with their initial values.

VIII. RESULTS

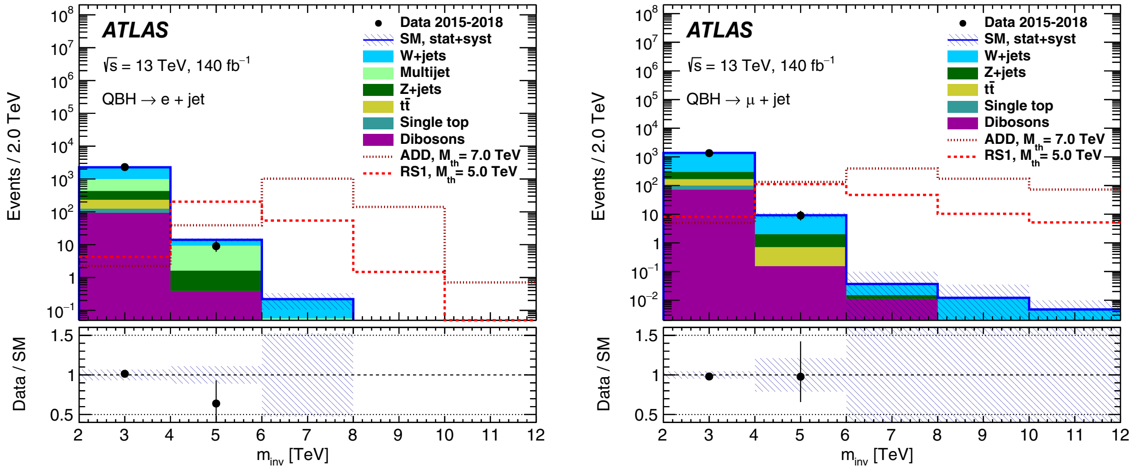
In the *background-only* fit, the normalization factors of the $W +$ jets, $Z +$ jets and $t\bar{t}$ background processes are consistent with unity within uncertainties. Differences of normalization factors from unity are $\leq 5\%$ in all cases. The m_{inv} distributions of events in the WCR, ZCR, TCR and corresponding validation regions after the *background-only* fit are shown in Fig. 1. There is good agreement between the data and the SM background in all CRs and VRs.

The comparison of the post-fit background yields with the data in the SVR and SR is represented in Table IV. The pre-fit background yields expected in the MC are shown in the bottom part of Table IV. There is agreement between the data ("Observed data") and the total SM background ("Fitted events") within 1σ in all regions. The errors include both statistical and systematic uncertainties.

The difference between expected and fitted yields of $W +$ jet background in the electron channel in Table IV is ~10% in SVR and ~20% in SR, with the $W +$ jet normalization factor close to unity (1.01 ± 0.02), since the pre-fit $W +$ jet background in the electron channel has a visible slope relative to data. The $W +$ jet distribution is fitted to data in CRs where both the slope and the normalization are adjusted. The slope elimination is a result of simultaneous pulls of several nuisance parameters. The main contributors are five parameters that tune the $W +$ jet yields in the 5-bin WCR in the likelihood fit. The total uncertainty includes statistical errors, uncertainties on normalization and slope elimination, and nuisance parameters related to objects, detector, and modeling.

The m_{inv} distributions after the *background-only* fit shown in Fig. 2 have good agreement between the data and the SM background in the SR in both the electron + jet and the muon + jet channels. The differences between the data and background are within 1σ. The highest invariant mass of a lepton + jet pair reconstructed in the electron (muon) channel is 4.74 TeV (4.96 TeV).

The *model-independent* fit is performed simultaneously in the WCR, ZCR, TCR and a single-bin SR to test for a



(a) (b)

FIG. 2. The distributions of events over the invariant mass of the leading lepton and the leading jet in the SR for data (points with error bars) and for SM backgrounds (solid histograms) after the *background-only* fit are shown in (a) the electron + jet and (b) the muon + jet channels. The normalizations extracted from the fit in the CRs are applied in the full m_{inv} range including the SR. The sum of the systematic uncertainties and the statistical errors due to the limited size of the fitted MC samples is shown by the hatched area. The lower panels show the ratios of the number of events observed in the data to the fitted total background. The hatched band represents the total relative uncertainty in the background estimate. Two examples of QBH signals normalized to the predicted cross section are overlaid.

non-SM signal contribution. The possible contribution of signal events is scaled by a freely floating signal normalization factor. No significant excess above the SM background prediction is observed in either of the channels. The *model-independent* upper limit on the cross section times branching fraction ($\sigma \times Br$) is estimated at 95% confidence level (CL) for the production of a non-SM signal.

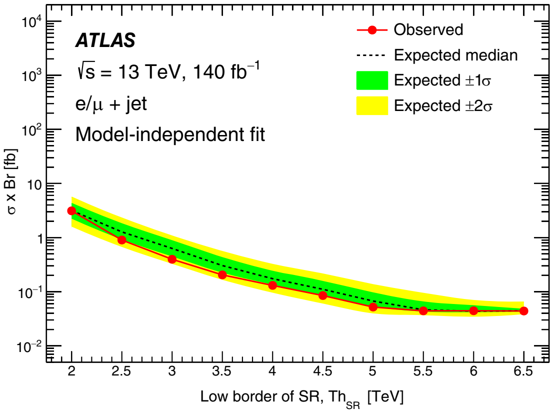


FIG. 3. The 95% CL *model-independent* upper limits on $\sigma \times Br$ for the non-SM signal production with decay into lepton + jet (combined channel). The limits take into account statistical and systematic uncertainties. Circles along the solid red line indicate the lower border of the SR (threshold of SR, $\mathrm{Th}_{\mathrm{SR}}$), above which the observed limit is computed. The expected limits are shown by the dashed line. The $\pm 1\sigma$ and $\pm 2\sigma$ bands of expected limits are shown in green and yellow, respectively. The limits are obtained with pseudoexperiments.

Figure 3 shows the upper limits on the $\sigma \times Br$ (circles along the solid red line) integrated above the lower threshold of the SR (events with $m_{\mathrm{inv}} > \mathrm{Th}_{\mathrm{SR}}$) for the lepton + jet channel (combined channel of electron + jet and muon + jet).

In the *model-dependent* fit, the 5-bin m_{inv} distributions of signal and backgrounds in the SR are fitted simultaneously with background in three CRs. The number of ADD (RS1) signal events is scaled by a freely floating signal normalization factor. The background normalization factors are also determined simultaneously in the fit in the CRs, and they are consistent with those of the *background-only* fit. There is no evidence of a QBH signal at any M_{th} in both models. Figure 4 shows the 95% CL upper limit on the cross section times branching fraction[3] ($\sigma \times Br$) as a function of M_{th} for the combined lepton + jet channel for the production of a QBH in the ADD and RS1 models. The limits are obtained using pseudoexperiments with a spacing of 0.5 TeV in M_{th}, and they are linearly interpolated between the points.

The lower limits on M_{th} for ADD and RS1, upper limits on $\sigma \times Br$ at the M_{th} mass point limits and model-independent upper limits on $\sigma(m_{\mathrm{inv}} > 5\ \mathrm{TeV}) \times Br$ are shown in Table V. Accounting for QCD radiation effects in the QBH production using the R_c correction factor leads to more stringent limit estimates than without it. Future QBH lepton + jet analyses have the potential to explore higher

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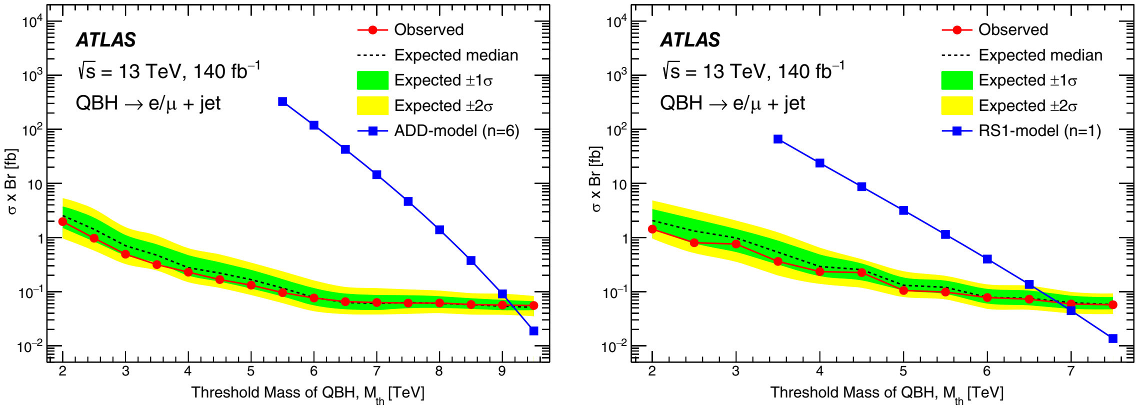
[3] There are six QBH states that can decay to lepton + jet. As each state has a different production cross section and branching fraction, the limits set an effective limit which is a sum over all possible QBH states.



(a) (b)

FIG. 4. The combined 95% CL upper limits on $\sigma \times Br$ as a function of M_{th} for QBH production at $M_{\mathrm{th}} = M_{\mathrm{D}}$ with decay into lepton + jet for (a) ADD (extra dimensions $n = 6$) and (b) RS1 (extra dimensions $n = 1$). The limits take into account statistical and systematic uncertainties. Circles along the solid red line indicate the mass M_{th} of the signal where the observed limit is computed. The expected limits are shown by the dashed line. The $\pm 1\sigma$ and $\pm 2\sigma$ bands are shown in green and yellow, respectively. The theoretically predicted $\sigma \times Br$ for the QBH production and decay is shown as the solid blue curve with squares. The limits are obtained with pseudoexperiments.

TABLE V. The lower limits on M_{th} and the upper limits on $\sigma \times Br$ at these mass points for QBHs decaying to a lepton and jet in the ADD and RS1 models. The model-independent upper limits on $\sigma \times Br$ are shown at $m_{\mathrm{inv}} > 5$ TeV.

	ADD	ADD	RS1	RS1	Model-independent
Channel	$\sigma \times Br$ [fb]	M_{th} [TeV]	$\sigma \times Br$ [fb]	M_{th} [TeV]	$\sigma(m_{\mathrm{inv}} > 5\ \mathrm{TeV}) \times Br$ [fb]
Electron + jet	0.091	9.0	0.099	6.6	0.095
Muon + jet	0.083	9.0	0.087	6.7	0.084
Combined	0.056	9.2	0.061	6.8	0.052

QBH mass ranges and lower QBH production cross section values once hard QCD radiation effects are included in the QBH event generation model.

IX. CONCLUSION

The ATLAS detector at the LHC has been used to search for new phenomena in the lepton + jet invariant mass spectrum. The search is performed with 140 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV, recorded during 2015–2018. The observed invariant mass spectrum of lepton + jet pairs is consistent with SM expectations. Upper exclusion limits are set on the cross section times branching fraction for quantum black holes decaying to a lepton and a quark in a search region with invariant mass above 2.0 TeV. The resulting lower mass threshold limits in the ADD (RS1) models with six (one) extra dimensions at the 95% CL are 9.2 (6.8) TeV. The obtained limits show a factor of 3.5 improvement with respect to the previous model-independent upper limit on $\sigma \times Br$ [12]. The obtained limit on the QBH threshold mass for the ADD model is 3.9 TeV higher compared to the previous ATLAS result in this channel at 8 TeV [12]. The obtained limit on the QBH M_{th} for the RS1 model is determined for the first time in the lepton + jet decay mode.

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