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Search for the exclusive W boson hadronic decays $W^\pm \to \pi^\pm\gamma$, $W^\pm \to K^\pm\gamma$ and $W^\pm \to \rho^\pm\gamma$ with the ATLAS detector

The ATLAS Collaboration

A search for the exclusive hadronic decays $W^\pm \to \pi^\pm\gamma$, $W^\pm \to K^\pm\gamma$ and $W^\pm \to \rho^\pm\gamma$ is performed using up to 140 fb^{-1} of proton-proton collisions recorded with the ATLAS detector at a center-of-mass energy of $\sqrt{s} = 13$ TeV. If observed, these rare processes would provide an unique test bench for the quantum chromodynamics factorization formalism used to calculate cross sections at colliders. Additionally, at future colliders, these decays could offer a new way to measure the W boson mass through fully reconstructed decay products. The search results in the most stringent upper limits to date on the branching fractions $\mathcal{B}(W^\pm \to \pi^\pm\gamma) < 1.9\times10^{-6}$, $\mathcal{B}(W^\pm \to K^\pm\gamma) < 1.7\times10^{-6}$, $\mathcal{B}(W^\pm \to \rho^\pm\gamma) < 5.2\times10^{-6}$ at 95% confidence level.

The W boson predominantly decays hadronically into a quark-antiquark pair that manifests as a pair of jets. In rare cases, the quark pair gives rise to one or a few hadrons. Examples include decays with a meson $M^{\pm}$ and a photon in the final state, of the form $W^{\pm} \rightarrow M^{\pm}\gamma$ [1, 2], and fully hadronic decays such as $W^{\pm} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}$ [2]. These decays offer a unique opportunity to study both the high energy/weakly coupled and low energy/strongly coupled regimes of quantum chromodynamics (QCD) in a single process. In particular, radiative decays are a test bench for the QCD factorization framework [3–6] which allows the calculation of cross sections of processes at hadron colliders through the separation of perturbative and non-perturbative elements. The importance of these decays in this context arises from the fact that higher order corrections constitute small contributions, since they scale with Λ_{QCD}/m_W [1], where Λ_{QCD} denotes the QCD energy scale. Furthermore, these exclusive decays could be explored as a new way to measure the W boson mass [7, 8]. The experimental precision of the W boson mass measurement is currently inferior to that of the Standard Model prediction [9]. This measurement has been performed in the past exclusively through leptonic decays of the W boson ($W \rightarrow \ell\nu$), with often large systematic uncertainties associated with the incomplete kinematics due to the presence of the neutrino. At future colliders beyond the HL-LHC [10], the aforementioned exclusive hadronic decays could enable a W boson mass measurement with a fully reconstructed, high resolution final state.

As a result of their importance, there are multiple theoretical predictions for the branching fractions of these decays [1, 8, 11–13]. These span orders of magnitude and experimental input is required to shed light on this puzzle. To date, these decays have remained largely unexplored, and no exclusive hadronic decay of the W boson has been observed. The most stringent upper limits at 95% confidence level (CL) are $\mathcal{B}(W^{\pm} \rightarrow \pi^{\pm}\gamma) < 7.0 \times 10^{-6}$ by the CDF Collaboration [14], $\mathcal{B}(W^{\pm} \rightarrow D_s^{\pm}\gamma) < 6.5 \times 10^{-4}$ by the LHCb Collaboration [15], and $\mathcal{B}(W^{\pm} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}) < 1.01 \times 10^{-6}$ by the CMS Collaboration [16]. Upper limits on $W^{\pm} \rightarrow \pi^{\pm}\gamma$ have also been published by the UA2 and CMS Collaborations [17, 18].

This Letter reports a search for $W^{\pm} \rightarrow \pi^{\pm}\gamma$, $W^{\pm} \rightarrow K^{\pm}\gamma$ and $W^{\pm} \rightarrow \rho^{\pm}\gamma$. The latter two decays have not been previously searched for by other experiments. The leading-order Feynman diagrams representing the three decay processes are shown in Fig. 1. The most recent predictions for the branching fractions are $(4.0 \pm 0.8) \times 10^{-9}$, $(3.3 \pm 0.7) \times 10^{-10}$, and $(8.7 \pm 1.9) \times 10^{-9}$, respectively [1]. The analysis presented here uses up to 140 fb^{-1} of proton-proton (pp) collision data at the center-of-mass energy of $\sqrt{s} = 13$ TeV collected by the ATLAS experiment between 2015 and 2018. The analysis is enabled by novel experimental techniques: a dedicated trigger targeting final states with a single hadron, a non-parametric background modeling method, and the unconventional use of photon triggers and τ-lepton reconstruction algorithms to target the $\rho^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ decay. In fact, a τ lepton decays into $\pi^{\pm}\pi^{0}$, via an intermediate $\rho^{\pm}$, 25.5% of the time [19]. The limited ATLAS particle identification capabilities for high momentum hadrons do not allow discrimination between $W^{\pm} \rightarrow K^{\pm}\gamma$ and $W^{\pm} \rightarrow \pi^{\pm}\gamma$. The two processes are collectively referred to as $W^{\pm} \rightarrow \pi^{\pm}/K^{\pm}\gamma$ in the following and distinguished when necessary.

ATLAS [20] is a multipurpose particle detector at the LHC with cylindrical geometry and a near 4π coverage in solid angle. It consists of an inner tracking detector surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer with three toroidal superconducting magnets. The inner tracking detector (ID) covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking (TRT) detectors. Liquid-argon (LAr) sampling calorimeters provide electromagnetic energy measurements with high granularity. A steel and 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 electromagnetic and hadronic energy measurements up to $|\eta| = 4.9$. A two-level trigger system is used to select events. The first-level trigger, implemented in hardware, uses a subset of the detector information to accept events at a rate below 100 kHz.

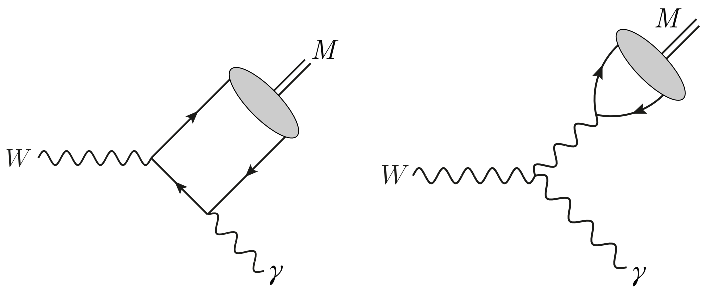


Figure 1: Leading-order Feynman diagrams for the radiative decays $W \to M\gamma$ with $M = \{\pi, K, \rho\}$. The fermion lines represent quarks, the gray blobs represent the meson bound state.

A software-based trigger, part of the ATLAS software suite [21], further reduces the accepted event rate to 1 kHz on average.

The main backgrounds are multijet and mis-reconstructed $Z \to e^+e^-$ events, in which one electron is mis-reconstructed as a photon and the other electron is mis-reconstructed as a meson candidate. Multijet events are modeled with a data-driven method described in Ref. [22] and employed in previous ATLAS analyses [23–26]. Monte Carlo (MC) simulation is used to model the $Z \to e^+e^-$ and signal processes. Events are generated at next-to-leading order precision in QCD with Powheg Box v1 [27] using the CT10 [28] set of parton distribution functions (PDFs). The parton shower, hadronization and underlying event are modeled with Pythia8 [29] (version 8.243 for $W^\pm \to \pi^\pm\gamma$, 8.244 for $W^\pm \to K^\pm\gamma$ and $W^\pm \to \rho^\pm\gamma$, 8.186 for $Z \to e^+e^-$) configured according to the AZNLO tune [30] using the CTEQ6L1 PDF set [31]. In $W \to M\gamma$ events, the W boson is decayed isotropically and events are reweighted to match the theoretically predicted angular distribution [32]. For the W boson production cross section the ATLAS measurement of (185 ± 6) nb is used [33]. The detector response is simulated with a Geant4-based [34] ATLAS framework [35]. The effect of additional interactions in the same and neighboring bunch crossings (pileup) is modeled by overlaying simulated inelastic pp events generated by Pythia8 with the A3 tune [36] and the NNPDF2.3lo PDF set [37]. MC events are reweighted so that the distribution of the average number of interactions per bunch crossing matches the one in the data. Only events recorded during stable beam conditions, and for which all relevant components of the detector were operational, are considered [38].

Two orthogonal event selections are defined, 1) *track-photon*, optimized for $W^\pm \to \pi^\pm\gamma$ and $W^\pm \to K^\pm\gamma$, reconstructing the charged meson as a track, and 2) *tau-photon*, targeting $W^\pm \to \rho^\pm\gamma$. In the tau-photon selection, the meson candidate is reconstructed as a hadronic τ lepton (τ_{had}) taking into account both the charged and neutral $\rho^\pm$ meson decay products. The track-photon selection offers supplementary sensitivity to $W^\pm \to \rho^\pm\gamma$ events that are partially reconstructed, because the π^0 is not explicitly identified. Two sets of triggers are used to record events: a track-photon trigger for the track-photon selection and a di-photon trigger for the tau-photon selection. The track-photon trigger was derived from τ-lepton triggers [39] and modified to select $W^\pm \to \pi^\pm\gamma$ events. This trigger was activated in 2016 and collected a dataset of 137 fb^{-1}. It requires a photon with transverse momentum $p_{\text{T}} > 25$ GeV (35 GeV in 20% of the dataset) and one isolated ID track with $p_{\text{T}} > 30$ GeV associated with a topological cluster of calorimeter cells [40] with transverse energy $E_{\text{T}} > 25$ GeV. The invariant mass of the track and photon is required to be greater than 50 GeV and the ratio between the energy deposition in the calorimeter matched to the track and the track transverse momentum $E_{\text{T}}/p_{\text{T}}$ is required to lie within 0.4 and 0.85 to limit the trigger rate for background processes. This trigger has 58% efficiency for selecting $W^\pm \to \pi^\pm\gamma$ events in the phase space of interest. While the requirement on $E_{\text{T}}/p_{\text{T}}$ is efficient for $W^\pm \to \pi^\pm/K^\pm\gamma$, it significantly reduces the acceptance for $W^\pm \to \rho^\pm\gamma$ events. Consequently, a di-photon trigger [41] that requires two photons with $p_{\text{T}} > 35$ GeV and $p_{\rm T} > 25$ GeV, respectively, is employed to recover sensitivity to $W^{\pm} \rightarrow \rho^{\pm}\gamma$ events. The di-photon trigger sensitivity to $W^{\pm} \rightarrow \rho^{\pm}\gamma$ derives from the production of two collimated photons in the decay chain $\rho^{\pm} \rightarrow \pi^{\pm}\pi^{0}$, $\pi^{0} \rightarrow \gamma\gamma$. The efficiency of this trigger for events selected by the tau-photon selection requirements is 43%. The $p_{\rm T}$ requirements of the analysis are mainly driven by the high $p_{\rm T}$ thresholds of the triggers, which are necessary in order to limit the high background rate from multijet events.

Tracks are reconstructed from hits in the ID, as described in Ref. [42], and are required to have $p_{\rm T} > 33$ GeV and to be within the acceptance of the ID. Tracks must also satisfy the "Tight Primary" quality criteria detailed in Ref. [43], in order to reject displaced tracks not directly produced in pp collisions and to reduce backgrounds from random combinations of hits. Furthermore, the sum of transverse momenta of tracks within a cone of $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.2$, excluding the candidate track, is required to be less than 14% of its $p_{\rm T}$, hence imposing low hadronic activity surrounding the selected meson, and suppressing contributions from tracks associated to jets. The $p_{\rm T}$ and isolation requirements were optimized for a maximum significance of $W^{\pm} \rightarrow \pi^{\pm}\gamma$ over the multijet background for the subset of data with a W boson invariant mass between 75 GeV and 85 GeV.

Photon candidates are reconstructed from variable-size topological clusters in the LAr calorimeter [44]. Identification is performed using a multivariate discriminant trained on shower shape variables to reject background from hadronic jets [45]. The "Tight" criterion described in Ref. [45] is used. Photons with $|\eta| > 2.37$ are discarded, since they are outside of the acceptance of the first layer of the LAr calorimeter, employed in photon-π^{0} discrimination. Photon candidates in the transition region between the barrel and endcap are also excluded, since performance is degraded in this region due to a substantial amount of inactive material in front of the active layers of the calorimeter. In order to be considered for the track-photon (tau-photon) selection, photons are required to have $p_{\rm T} > 30$ GeV or $p_{\rm T} > 35$ (36) GeV, depending on the trigger being used. Both selections reduce contributions from jets faking photons by requiring that the sum of transverse energies of calorimeter clusters not associated to the photon candidate but within a cone of $\Delta R = 0.4$ is less than 2.45 GeV + $0.022 \times p_{\rm T}(\gamma)$ and the sum of transverse momenta of tracks within a cone of $\Delta R = 0.2$, excluding possible conversion tracks, is less than 5% of $p_{\rm T}(\gamma)$.

The $\tau_{\rm had}$ reconstruction [46, 47] considers only visible decay products and is seeded by jets built by combining calibrated calorimeter clusters. Charged constituents are reconstructed by matching tracks within $\Delta R < 0.2$ of the $\tau_{\rm had}$ direction to calorimeter clusters using a particle-flow approach, while neutral constituents ($\pi^{0}_{\rm cand}$) are reconstructed from clusters surrounding the charged candidates. Mis-reconstructed $\pi^{0}_{\rm cand}$, arising from $\pi^{\pm}$ cluster remnants or noise, are rejected using a multivariate discriminant. Five $\tau_{\rm had}$ classes are defined according to the number of $\pi^{\pm}$ and π^{0} and the migration across classes is mitigated by a second multivariate discriminant. Mis-reconstructed $\tau_{\rm had}$ are suppressed using an identification algorithm based on a recurrent neural network [48]. $\tau_{\rm had}$ objects with exactly one $\pi^{\pm}$ and one π^{0} as constituents are used to reconstruct $\rho^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ candidates in the $W^{\pm} \rightarrow \rho^{\pm}\gamma$ decay. The $\tau_{\rm had}$ reconstruction algorithm is well suited for the prompt $\rho^{\pm}$ decay as the latter is indistinguishable from one produced in the τ decay $\tau^{\pm} \rightarrow \rho^{\pm}\nu_{\tau}$ besides a small displacement of the π track due to the decay length of the τ lepton. The candidate $\rho^{\pm}$ meson is required to have $p_{\rm T} > 30$ GeV. On average, a $\rho^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ decay will be contained in a narrower angular cone than a hadronic jet, and as such the angular distance $\Delta R_{\tau_{\rm had}}$ is required to be less than 0.065. Additionally, a requirement of $\log(|d_0|/\text{mm}) < -1.2$, where d_0 stands for the transverse impact parameter of the track, is used. This ensures that the charged particle originates from the interaction region, rather than from the decay of a tau lepton or another long lived particle. The specific values of the selections were chosen following simultaneous optimization for the maximum significance of $W^{\pm} \rightarrow \rho^{\pm}\gamma$ over the multijet background.

The $Z \to e^+e^-$ background suppression in the track-photon selection is based on the expected different behavior between an electron and a charged hadron in terms of the ratio between the transverse energy deposited in the hadronic and electromagnetic calorimeters (hadronic leakage), and the amount of transition radiation generated in the TRT. The latter one is used to construct a likelihood discriminant employed in electron versus charged-hadron discrimination, which is defined in Ref. [49]. Typically, electrons are expected to generate larger levels of transition radiation and to have very low hadronic leakage, compared to charged hadrons. In the tau-photon selection, the $Z \to e^+e^-$ background is suppressed by applying requirements on the properties of the τ_{had} object and its constituents. As in the track-photon case, the amount of radiation produced in the TRT by the τ_{had} track is exploited. τ_{had} objects with a low value of $E_{\text{T}}^{\tau_{\text{had}}}/p_{\text{T}}^{\pi^\pm}$ are excluded, since mis-reconstructed electrons have, on average, lower $E_{\text{T}}^{\tau_{\text{had}}}$ than $\rho^\pm$ candidates. A multivariate discriminant trained on τ_{had} calorimeter shower shape variables and track properties to discriminate between hadronic tau lepton decays and electrons [50] is employed. Differences in the kinematic topology between a single electron mis-reconstructed as a τ_{had} and a $\rho^\pm$ decay are also exploited. In the case of the electron, the direction of the τ_{had} object is defined solely by the electron, and as such the charged track will be closer in ΔR to the τ_{had} axis. A lower limit is thus imposed on $\Delta R_{\tau_{\text{had}}}$.

The decay products of the signal processes are generated back-to-back in the laboratory frame. Therefore, in both selections, events with low $\Delta\phi(M, \gamma)$ are excluded. Furthermore, in the track-photon selection, if both the meson and the photon are reconstructed in the endcap regions, the photon and meson candidates are required to have $\eta(M) \times \eta(\gamma) \geq 0$. A W boson candidate in the track-photon selection is formed by the highest p_{T} photon and meson, while in the tau-photon selection the meson and photon candidate pair with with the largest $\Delta\phi$ is selected. A detailed list of the selection criteria used is provided in the Supplemental Material of this Letter. The track-photon selection efficiency (including the trigger selection) is 5.0% for $W^\pm \to \pi^\pm\gamma$, 5.5% for $W^\pm \to K^\pm\gamma$ and 0.5% for $W^\pm \to \rho^\pm\gamma$. The higher $W^\pm \to K^\pm\gamma$ efficiency compared to $W^\pm \to \pi^\pm\gamma$ originates from the differences in nuclear interaction properties for pions and kaons which create small differences for variables used in the trigger selection (mainly the track $E_{\text{T}}/p_{\text{T}}$) and in the $Z \to e^+e^-$ background suppression. The efficiency of the tau-photon selection for $W^\pm \to \rho^\pm\gamma$ is 0.3%, half that of the track-photon signal region (SR) selection but compensated by a higher background rejection. The contribution of $W^\pm \to \pi^\pm\gamma$ and $W^\pm \to K^\pm\gamma$ events surviving the tau-photon selection requirements is negligible, with a number of predicted events $< 10^{-8}$ for each process. The contribution of $W^\pm \to \tau^\pm\nu$ events is also negligible, suppressed by the requirements on the photon including its separation from the τ_{had} in the transverse plane.

The background is dominated by the multijet component, which is modeled using a non-parametric data-driven technique [22]. This method models the most important features of the background in a dataset defined by a relaxed version of the event selection, the Generation Region (GR). In the track-photon selection, the GR is defined by relaxing the requirements on the p_{T} and isolation of the track, as well as the isolation requirements on the photon. In the case of the tau-photon selection, the GR is constructed by relaxing the requirements on $p_{\text{T}}(\tau_{\text{had}})$, $\Delta R_{\tau_{\text{had}}}$ and $\log(|d_0|)$ of the τ_{had} track. Data events in the GR are used to construct templates of the variables needed to describe the kinematics of the decay products and object properties, such as isolation. Templates use up to three dimensions to capture the most relevant correlations across variables. Multijet pseudo-events are generated by ancestral sampling of the templates. Details of the sampling sequences employed can be found in the Supplemental Material of this Letter. Following the sampling procedure, compound kinematic variables, such as the W boson invariant mass, can be calculated for each generated pseudo-event. The process of factorizing the n-dimensional probability density function of the background into the product of lower dimension distributions dilutes the features of resonant contributions, such as the small $Z \to e^+e^-$ background. These contributions are not described by the model and need to be considered separately. Other resonant processes such as $Z \to \tau\tau$ and $W/Z \to qq$

were found to have a negligible impact on the sensitivity. Possible small contributions from non-resonant background processes are absorbed by the background modelling method. The set of produced multijet pseudo-events is normalized to the number of observed data events in GR and it is subject to the full set of selection requirements which define the Signal Region (SR). Validation regions (VRs) are defined by applying only one of the SR requirements to events in the GR. Good compatibility is found between the data and the background prediction in these VRs, verifying the correct modeling of the most important correlations in the data sample.

The discriminating variable used to quantify the presence of signal is the candidate W boson invariant mass. In the track-photon selection, the shapes of the $m(W^{\pm} \to \pi^{\pm}\gamma)$ and $m(W^{\pm} \to K^{\pm}\gamma)$ distributions are modeled with the same functional form, a sum of two Voigt functions multiplied by a sigmoid-like efficiency curve obtained by fitting MC event distributions in the SR. A single Voigt function is used for $m(W^{\pm} \to \rho^{\pm}\gamma)$ in the tau-photon selection as no goodness-of-fit improvement is observed by using two. The efficiency curve describes the variation of acceptance as a function of the candidate W boson invariant mass. In the track-photon selection, the $m(W^{\pm} \to \rho^{\pm}\gamma)$ shape is obtained by smoothing the MC events with a Gaussian kernel density estimator (KDE). The resulting W boson mass resolution is 2.7% for $W^{\pm} \to \pi^{\pm}/K^{\pm}\gamma$; 3.1% for $W^{\pm} \to \rho^{\pm}\gamma$ in the track-photon selection, and 2.9% in the tau-photon selection. In both selections, the multijet and $Z \to e^{+}e^{-}$ predictions are also KDE-smoothed.

The presence of a signal is quantified using a binned maximum likelihood fit. The mass range between 60 GeV and 110 GeV is used for both selections. The background normalization is determined in the fit. Systematic uncertainties associated with the shape of the multijet background are implemented through a moment morphing technique [51]. Background shape variations are obtained through modifications of the nominal sampling procedure by shifting the photon p_{T} and by deforming the $\Delta\phi(M,\gamma)$ distribution. These effects are propagated to the W boson invariant mass shape resulting in a shift and a skewness variation, respectively. A third variation is directly obtained through a multiplicative transformation of the candidate W boson invariant mass by a linear function. These variations provide complementary modes of deformation of the nominal background shape. Each variation is controlled in the fit by a nuisance parameter. The pre-fit magnitude of the variation is chosen to be large enough so that the corresponding parameters are constrained by the data in the fit. Larger variations were found to produce compatible results.

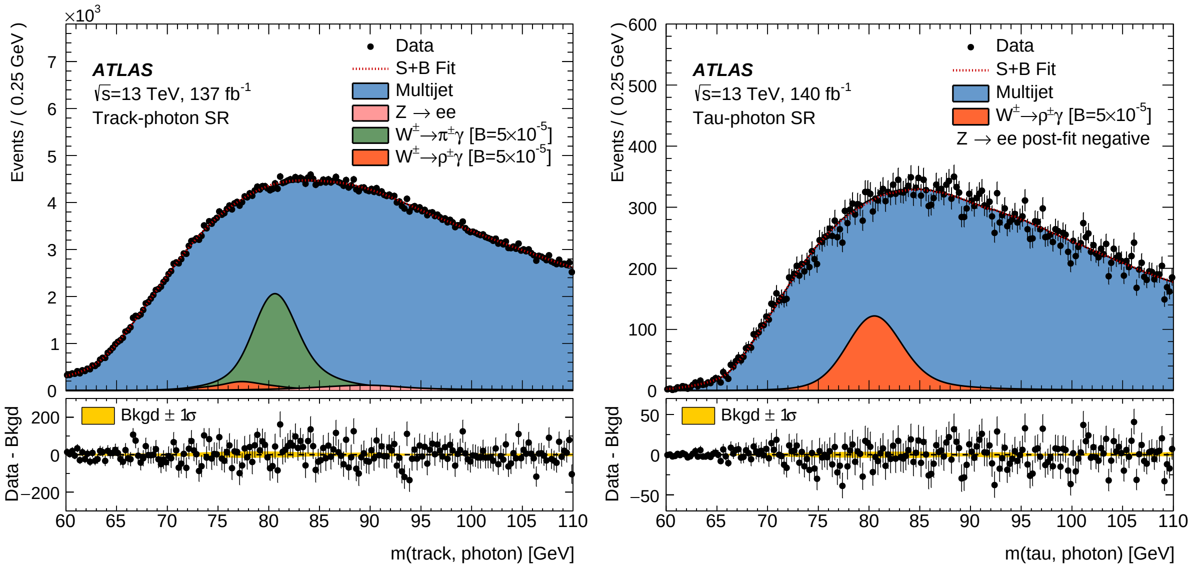
In the track-photon category, uncertainties are similar in size for all three signal processes. The impact of uncertainties in terms of normalization variation is described in the following. Trigger efficiency calibration uncertainties are estimated by factorizing the photon and track components and amount to 0.6% and 3.6%, respectively. The uncertainty for the track component of the trigger is derived by correcting and smearing the leading track $E_{\mathrm{T}}/p_{\mathrm{T}}$ according to the results of Ref. [52]. The impact of energy scale and resolution effects [53] is found to be below 1%. Sources of uncertainty associated with photon identification and isolation efficiencies [54] account for a 2% normalization variation, and those associated with track efficiency amount to approximately 1%. The estimated uncertainty associated with the correction of the pileup profile in simulated events is 2.2%.

In the tau-photon category, the trigger efficiency uncertainty is 10%, determined by comparing data and simulated $Z \to \tau(\mu\nu\nu)\tau_{\mathrm{had}}$ events selected by a muon-photon trigger that uses the same photon selection criteria used by the di-photon trigger chosen for $W^{\pm} \to \rho^{\pm}\gamma$. Energy resolution and scale uncertainties associated with the calorimeter response amount to 6%. A 5.5% uncertainty is associated with pileup modeling. The combined impact of reconstruction, identification and isolation efficiency uncertainties for τ_{had} is 13%, and 2% for photons.

In both track-photon and tau-photon categories, signals are subject to a 3.3% uncertainty associated with the $pp \to W$ cross section [33]. The acceptance uncertainty associated with renormalization and factorization scale variations is estimated conservatively due to statistical fluctuations as 6.2% in the track-photon SR and 6.5% in the tau-photon SR. The uncertainty on the integrated luminosity is 0.83% [55].

A simultaneous fit is performed including both track-photon and tau-photon SRs. The inclusion of both SRs better constrains the $W^\pm \to \rho^\pm\gamma$ signal strength parameter. The $W^\pm \to \pi^\pm\gamma$ and $W^\pm \to K^\pm\gamma$ contributions in the tau-photon SR are negligible and not included in the fit. Uncertainties and background normalization parameters are not correlated across SRs due to the large difference in phase space, except for those associated with the W boson production cross section and the integrated luminosity.

The expected number of $W^\pm \to \pi^\pm\gamma$ ($W^\pm \to K^\pm\gamma$) events in the track-photon SR is 5.0 ± 0.4 (0.45 ± 0.04), assuming the previously quoted branching fraction 4.0×10^{-9} (3.3×10^{-9}) and including both statistical and systematic uncertainties. The expected number of $W^\pm \to \rho^\pm\gamma$ events, with a branching fraction of 8.7×10^{-9}, is 1.18 ± 0.10 in the track-photon SR and 0.72 ± 0.14 in the tau-photon SR. The result of a signal-plus-background fit is shown in Fig. 2, with the $W \to M\gamma$ contributions overlaid. The number of observed events is reported in Table 1.



(a) (b)

Figure 2: Distributions of the candidate W boson invariant mass in the (a) track-photon SR and (b) tau-photon SR. In the top panel data (black points) are compared to the signal-plus-background model after a fit. The $W^\pm \to \pi^\pm\gamma$ and $W^\pm \to \rho^\pm\gamma$ distributions corresponding to an arbitrarily large branching fraction of 5×10^{-5} are shown overlaid. The lower panel displays the difference between the number of data and background events. The error bars account only for the statistical uncertainty. The yellow band displays the background systematic uncertainty.

No significant excess with respect to the background prediction is observed in the data. Upper limits obtained using the asymptotic approximation of the profile likelihood test statistic described in Ref. [56] and the modified frequentist confidence level $\mathrm{CL_S}$ [57] are reported in Table 2. When computing the $W^\pm \to \pi^\pm\gamma$ upper limit, $W^\pm \to \rho^\pm\gamma$ is profiled, and vice-versa. The $W^\pm \to K^\pm\gamma$ upper limit is produced in the same manner, conservatively replacing $W^\pm \to \pi^\pm\gamma$ with $W^\pm \to K^\pm\gamma$. The systematic uncertainties

Table 1: Number of expected and observed events in the signal regions extracted from the signal-plus-background fit. All uncertainties described in the text are included. $W^{\pm} \to \pi^{\pm}/K^{\pm}\gamma$ represents the sum of $W^{\pm} \to \pi^{\pm}\gamma$ and $W^{\pm} \to K^{\pm}\gamma$ contributions.

	Number of events	
	Track-photon SR	Tau-photon SR
Multijet	632000 ± 2200	43200 ± 600
$Z \to e^{+}e^{-}$	6100 ± 1500	-200 ± 400
$W^{\pm} \to \pi^{\pm}/K^{\pm}\gamma$	1000 ± 800	–
$W^{\pm} \to \rho^{\pm}\gamma$	-100 ± 400	-90 ± 240
Data	638962	42918

result in a deterioration of the obtained upper limit by +42% for $W^{\pm} \to \pi^{\pm}\gamma$ and $W^{\pm} \to K^{\pm}\gamma$ and +59% for $W^{\pm} \to \rho^{\pm}\gamma$. The dominant systematic uncertainties are the ones associated with the modeling of the shape of the multijet background: the sole inclusion of signal uncertainties degrades the upper limit by +1% for $W^{\pm} \to \pi^{\pm}\gamma$ and $W^{\pm} \to K^{\pm}\gamma$ and +6% for $W^{\pm} \to \rho^{\pm}\gamma$. The combined track-photon and tau-photon fit improves the observed (expected) upper limit on $W^{\pm} \to \rho^{\pm}\gamma$ by 18% (7%) compared to a tau-photon-only fit. The inclusion of the tau-photon selection has negligible impact on the $W^{\pm} \to \pi^{\pm}\gamma$ and $W^{\pm} \to K^{\pm}\gamma$ upper limits.

Table 2: Expected and observed upper limits on the $W^{\pm} \to \pi^{\pm}\gamma$, $W^{\pm} \to K^{\pm}\gamma$, and $W^{\pm} \to \rho^{\pm}\gamma$ branching fractions.

	95% CL upper limits	
Branching fraction	Expected $\times 10^{-6}$	Observed $\times 10^{-6}$
$\mathcal{B}(W^{\pm} \to \pi^{\pm}\gamma)$	$1.2^{+0.5}_{-0.3}$	1.9
$\mathcal{B}(W^{\pm} \to K^{\pm}\gamma)$	$1.1^{+0.4}_{-0.3}$	1.7
$\mathcal{B}(W^{\pm} \to \rho^{\pm}\gamma)$	$6.0^{+2.3}_{-1.7}$	5.2

These results improve the previous upper limit on $\mathcal{B}(W^{\pm} \to \pi^{\pm}\gamma)$ [14] by approximately a factor of four and provide first upper limits on $\mathcal{B}(W^{\pm} \to K^{\pm}\gamma)$ and $\mathcal{B}(W^{\pm} \to \rho^{\pm}\gamma)$. This work provides relevant input for the design of future collider experiments, where exclusive hadronic decays of the W boson could potentially be observed for the first time. Future $e^{+}e^{-}$ colliders are expected to deliver a clean sample of $O(10^{8})$ $W^{+}W^{-}$ events [58], which would allow access to the $W^{\pm} \to D_{s}^{\pm}\gamma$ and $W^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}$ decays according to current SM predictions [1, 2, 8, 16]. Future hadron colliders are projected to produce $O(10^{12})$ W bosons [59], which would translate to thousands of $W^{\pm} \to \pi^{\pm}\gamma$ and $W^{\pm} \to \rho^{\pm}\gamma$ decays and hundreds of $W^{\pm} \to K^{\pm}\gamma$ decays. In both cases, the observation of these channels pose significant experimental challenges both in terms of trigger strategy and background discrimination. Thus, careful detector optimization is required in order to access these signatures, and exploit them as a new way to measure the W boson properties and to probe the QCD factorization formalism. The novel experimental techniques presented in this Letter are an initial step towards the observation of these decays in future facilities, which are currently being planned.

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Supplemental material

Full event selection

The complete set of selection requirements which defines the track-photon and tau-photon Signal Regions (SR) can be found in Table 3 and Table 4, respectively. Background enriched regions are defined for use in the background modelling and its validation. The Generation Region (GR) includes the object and event level requirements listed in the tables, as well as the requirements devised in order to suppress the background from $Z \to e^+e^-$ events. Validation regions (VR) are defined by applying one of the SR requirements to the events in the GR, as summarised in the tables.

Table 3: Summary of the track-photon selection. Photon calorimeter isolation and photon track isolation are imposed by requiring that the sum of transverse energies of calorimeter clusters not associated to the photon candidate but within a cone of $\Delta R = 0.4$ is less than 2.45 GeV $+ 0.022 \times p_{\mathrm{T}}(\gamma)$ and the sum of transverse momenta of tracks within a cone of $\Delta R = 0.2$, excluding possible conversion tracks, is less than 5% of $p_{\mathrm{T}}(\gamma)$, respectively. Track isolation is imposed by requiring that the sum of transverse momenta of tracks within $\Delta R = 0.2$, excluding the candidate track, is less than 14% of its p_{T}.

Baseline selection
Photon requirements: $p_{\mathrm{T}} > 30$ GeV or $p_{\mathrm{T}} > 35$ GeV, dependent on specific trigger $\lvert\eta\rvert < 2.37$, excluding $1.37 < \lvert\eta\rvert < 1.52$ *Tight* identification [45]
Track requirements: $p_{\mathrm{T}} > 30$ GeV, $\lvert\eta\rvert < 2.5$ *Tight Primary* identification [43]
Event requirements: $\eta(M) \times \eta(\gamma) \geq 0$ if track and γ in endcap ($\lvert\eta(M)\rvert > 1.5$ and $\lvert\eta(\gamma)\rvert > 1.37$) $\Delta\Phi(M, \gamma) > \pi/2$
$Z \to e^+e^-$ suppression requirements: TRT electron likelihood discriminant $\leq$ 10% [49] or TRT electron likelihood discriminant $>$ 10% if hadronic leakage $>$ 3%
GR selection: baseline + $Z \to e^+e^-$ suppression requirements **VR1 selection:** GR + $p_{\mathrm{T}}(M) > 33$ GeV **VR2a selection:** GR + Photon calorimeter isolation **VR2b selection:** GR + Photon track isolation **VR3 selection:** GR + Track isolation **SR selection:** all requirements

Table 4: Summary of the tau-photon selection. Photon calorimeter isolation and photon track isolation are imposed by requiring that the sum of transverse energies of calorimeter clusters not associated to the photon candidate but within a cone of $\Delta R = 0.4$ is less than 2.45 GeV + $0.022 \times p_{\mathrm{T}}(\gamma)$ and the sum of transverse momenta of tracks within a cone of $\Delta R = 0.2$, excluding possible conversion tracks, is less than 5% of $p_{\mathrm{T}}(\gamma)$, respectively.

Baseline selection
Photon requirements: $p_{\mathrm{T}} > 36$ GeV $\lvert\eta\rvert < 2.37$, excluding $1.37 < \lvert\eta\rvert < 1.52$ *Tight* identification Photon calorimeter isolation Photon track isolation
Tau requirements: $h^{\pm}\pi^{0}$ decay mode $p_{\mathrm{T}} > 26$ GeV $\lvert\eta\rvert < 2.5$, $1.37 < \lvert\eta\rvert < 1.52$ *Medium* identification working point [48]
Event requirements: $\Delta\Phi(\tau_{\text{had-vis}}, \gamma) > 2$
$Z \to e^{+}e^{-}$ suppression requirements: *Tight* electron-tau discriminant working point [50] $E_{T}(\tau)/p_{T}(\text{trk}) > 2.4$ $\Delta R_{\tau}^{\max} > 0.036$ TRT electron likelihood discriminant < 0.9
GR selection: baseline + $Z \to e^{+}e^{-}$ suppression requirement **VR1 selection:** GR + $p_{\mathrm{T}}(\tau_{\text{had-vis}}) > 30$ GeV **VR2 selection:** GR + $\Delta R_{\tau}^{\max} < 0.065$ **VR3 selection:** GR + $\log(\lvert d_{0}(\tau_{\text{had-vis}})\rvert) < -1.2$ **SR selection:** all requirements

Multijet background modeling

Multijet pseudo-events are generated through ancestral sampling using multi-dimensional PDFs. Each pseudo-event is fully described by the meson and photon four-vectors and by the additional variables used in selection criteria applied to GRs that define SRs. The sampling procedures used to generate multijet pseudo-events in the track-photon and tau-photon selections are detailed below and illustrated in Fig. 3. The candidate meson is described in terms of the object used to reconstruct it i.e. a track and a hadronic τ lepton in the track-photon and tau-photon selections, respectively.

Track-photon

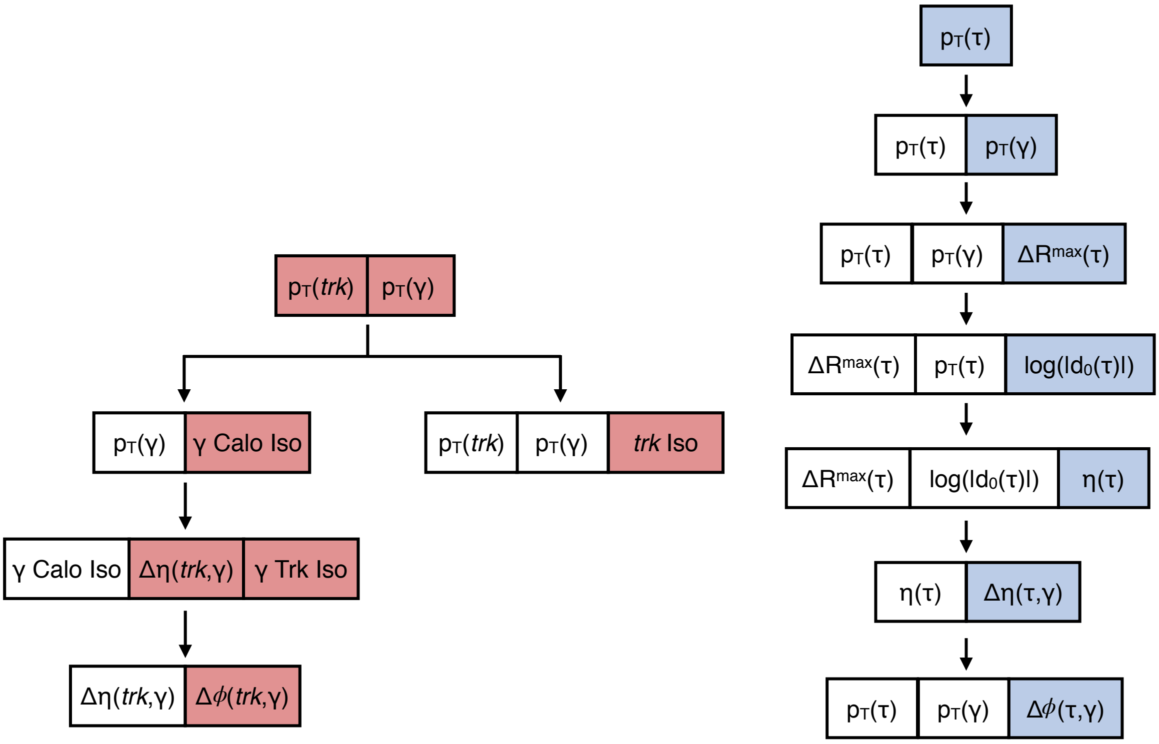
1. $p_{\mathrm{T}}(trk)$ and $p_{\mathrm{T}}(\gamma)$ are sampled simultaneously from a two-dimensional template.
2. Track isolation is described in bins of $p_{\mathrm{T}}(\gamma)$ and $p_{\mathrm{T}}(trk)$ using a three-dimensional template. Given the values sampled in step 1, the template is projected along the track isolation and a value of track isolation is randomly sampled.
3. Photon calorimeter isolation is described in bins of $p_{\mathrm{T}}(\gamma)$. A value for photon calorimeter isolation is sampled from the bin corresponding to the $p_{\mathrm{T}}(\gamma)$ value sampled in step 1.
4. $\Delta\eta(trk,\gamma)$ and photon track isolation are described in bins of photon calorimeter isolation using a three-dimensional template. $\Delta\eta(trk,\gamma)$ and photon track isolation are sampled simultaneously from the two-dimensional projection corresponding to the photon calorimeter isolation value obtained in the step 3.
5. $\Delta\phi(trk,\gamma)$ is described in bins of $\Delta\eta(trk,\gamma)$ using a two-dimensional template. Based on the value of $\Delta\eta(trk,\gamma)$ obtained in step 4, the template is projected along the $\Delta\phi(trk,\gamma)$ and a value for $\Delta\phi(trk,\gamma)$ is sampled.
6. $\eta(trk)$ and $\phi(trk)$ are sampled independently from the corresponding one-dimensional templates.

Tau-photon

1. $p_{\mathrm{T}}(\tau)$ is sampled from the corresponding one-dimensional template.
2. $p_{\mathrm{T}}(\gamma)$ is sampled from the distribution obtained projecting the two-dimensional template of $p_{\mathrm{T}}(\gamma)$, $p_{\mathrm{T}}(\tau)$ along $p_{\mathrm{T}}(\gamma)$ using the value of $p_{\mathrm{T}}(\tau)$ obtained in step 1.
3. $\Delta R_{\tau}^{\mathrm{max}}$, defined as the ΔR between the pion track associated to the τ and the τ axis, is described in bins of $p_{\mathrm{T}}(\tau)$ and $p_{\mathrm{T}}(\gamma)$. Using the values of $p_{\mathrm{T}}(\tau)$ and $p_{\mathrm{T}}(\gamma)$ previously obtained, the three-dimensional distribution is projected along ΔR and a value for ΔR is sampled.
4. $\log(|d_0(\tau)|)$, where d_0 is defined as the track transverse impact parameter of the τ track, is sampled as a function of $p_{\mathrm{T}}(\tau)$ and $\Delta R_{\tau}^{\mathrm{max}}$ using the same technique described in step 3.
5. $\eta(\tau)$ is sampled as a function of $\log(|d_0(\tau)|)$ and $\Delta R_{\tau}^{\mathrm{max}}$ using the same technique described in the previous step.
6. $\Delta\eta(\tau,\gamma)$ is sampled from the projection of the two-dimensional distribution of $\Delta\eta(\tau,\gamma)$ and $\eta(\tau)$ using $\eta(\tau)$ obtained in the previous step.

7. $\Delta\phi(\tau, \gamma)$ is sampled from the projection of the three-dimensional template of $\Delta\phi(\tau, \gamma)$, $p_{\mathrm{T}}(\tau)$, $p_{\mathrm{T}}(\gamma)$ defined by the values previously obtained.

8. $\phi(\tau)$ is sampled independently from the corresponding one-dimensional template.



(a) (b)

Figure 3: Graphical representation of the sampling sequence used in the generation of multijet pseudo-events in the (a) track-photon selection, (b) tau-photon selection. Variables not shown explicitly are sampled in a factorized, uncorrelated manner from one-dimensional templates. Groups of two(three) variables represent two(three)-dimensional templates. Arrows are used to show the sequential order of steps in the sampling. Variables are highlighted with color at the step in which they are defined for each pseudo-candidate.

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The ATLAS Collaboration

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