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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. These rare processes provide a test bench for the quantum chromodynamics factorization formalism used to calculate cross sections at colliders, as well as a probe of W boson coupling to quarks and a new way to measure the W boson mass through fully reconstructed decay products. The search results in the most stringent upper limit 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 can give rise to one or a few hadrons as, for example, in $W^{\pm} \rightarrow M^{\pm}\gamma$ with $M = \{\pi, K, \rho, D, D_s, B\}$ and $W^{\pm} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}$. These exclusive decays provide a probe of the W boson coupling to different generations of quarks, new direct channels for the measurement of the W boson mass [1, 2] and sensitivity to both the weakly and strongly coupled regimes of quantum chromodynamics (QCD). In particular, radiative decays are a test bench for the QCD factorization framework [3]. At present, exclusive W boson decays have not been measured and theoretical calculations are affected by large uncertainties. For example, the branching fraction $\mathcal{B}(W^{\pm} \rightarrow \pi^{\pm}\gamma)$ is reported in the literature as between 10^{-7} and 10^{-9} [2–6]. The most stringent upper limits at 95% confidence level (CL) are $\mathcal{B}(W^{\pm} \rightarrow \pi^{\pm}\gamma) < 7.0 \times 10^{-6}$ and $\mathcal{B}(W^{\pm} \rightarrow D_s^{\pm}\gamma) < 1.3 \times 10^{-3}$ by the CDF Collaboration [7, 8], and $\mathcal{B}(W^{\pm} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}) < 1.01 \times 10^{-6}$ by the CMS Collaboration [9]. Upper limits on $W^{\pm} \rightarrow \pi^{\pm}\gamma$ have also been published by the UA2 and CMS Collaborations [10, 11].

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 [3]. 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, and utilizes a dedicated trigger for $W^{\pm} \rightarrow \pi^{\pm}\gamma$ and $W^{\pm} \rightarrow K^{\pm}\gamma$ events and τ lepton reconstruction algorithms for $W^{\pm} \rightarrow \rho^{\pm}\gamma$. 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.

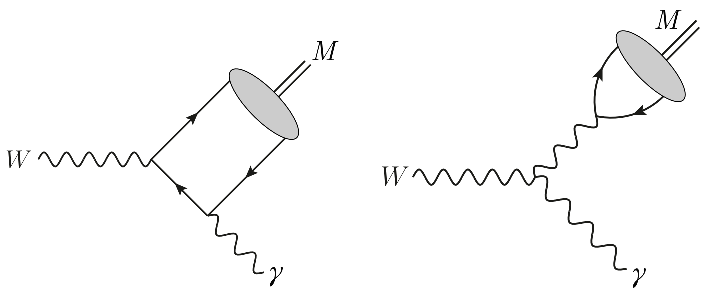

Figure 1: Leading-order Feynman diagrams for the radiative decays $W \rightarrow M\gamma$ with $M = \{\pi, K, \rho\}$. The fermion lines represent quarks, the gray blobs represent the meson bound state.

ATLAS [12] 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. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic 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 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. A software-based trigger, part of the ATLAS software suite [13], further reduces the accepted event rate to 1 kHz on average.

The main backgrounds are multijet and mis-reconstructed $Z \to e^+e^-$ events. Multijet events are modeled with a data-driven method described in Ref. [14] and employed in previous ATLAS analyses [15–18]. 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 [19] using the CT10 [20] set of parton distribution functions (PDFs). The parton shower, hadronization and underlying event are modeled with Pythia8 [21] configured according to the AZNLO tune [22] using the CTEQ6L1 PDF set [23]. In $W \to M\gamma$ events, the W boson is decayed isotropically and events are reweighted to match the theoretically predicted angular distribution [24]. For the W boson production cross section the ATLAS measurement of (185 ± 6) nb is used [25]. The detector response is simulated with a Geant4-based [26] ATLAS framework [27] 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 [28] and the NNPDF2.3lo PDF set [29]. 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 [30]. Two event selections, found to be orthogonal, are defined: track-photon, optimal for $W^\pm \to \pi^\pm\gamma$ and $W^\pm \to K^\pm\gamma$, and 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. 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. Track-photon triggers are derived from τ-lepton triggers [31] and modified to select $W^\pm \to \pi^\pm\gamma$ events. These triggers were activated in 2016 and collected a dataset of 137 fb^{-1}. They require 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 [32] 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 last requirement, efficient for $W^\pm \to \pi^\pm/K^\pm\gamma$, is found to reduce the $W^\pm \to \rho^\pm\gamma$ acceptance. Consequently, a di-photon trigger [33] that requires two photons with $p_{\text{T}} > 35$ GeV and $p_{\text{T}} > 25$ GeV, respectively, is employed to recover sensitivity to $W^\pm \to \rho^\pm\gamma$ events. The di-photon trigger sensitivity to $W^\pm \to \rho^\pm\gamma$ derives from the production of two collimated photons in the decay chain $\rho^\pm \to \pi^\pm\pi^0$, $\pi^0 \to \gamma\gamma$.

Tracks are reconstructed as described in Ref. [34], and are required to have $p_{\text{T}} > 30$ GeV, $|\eta| < 2.5$ and satisfy the “Tight Primary” criteria detailed in Ref. [35]. Photon candidates are reconstructed from variable-size topological clusters in the LAr calorimeter [36]. The candidates are required to be within the region of acceptance of the ID ($|\eta| < 2.37$), to be able to associate the electromagnetic clusters with tracks and separate photons and electrons. The photon candidates in the barrel/endcap transition region ($1.37 < |\eta| < 1.52$) are excluded. Photon candidates are required to pass the “Tight” photon identification criteria [37]. The τ_{had} reconstruction [38, 39] considers only visible decay products and is seeded by jets built by combining calibrated calorimeter clusters. Charged constituents are reconstructed by matching tracks to the calorimeter clusters using a particle-flow approach, while neutral constituents (π^0_{cand}) are reconstructed from clusters surrounding the charged candidates. Mis-reconstructed π^0_{cand}, arising from $\pi^\pm$ cluster remnants or noise, are rejected using a multivariate discriminant. Five τ_{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 τ_{had} are suppressed using an identification algorithm based on a recurrent neural network that provides 75% efficiency for true τ_{had} and 3% for mis-reconstructed τ_{had} [40]. The τ_{had} object is used to reconstruct $\rho^\pm \to \pi^\pm\pi^0$ candidates in the $W^\pm \to \rho^\pm\gamma$ decay. The τ_{had} reconstruction algorithm is well suited for the prompt $\rho^\pm$ decay as the latter is indistinguishable from one produced in the

τ decay $\tau \to \rho\nu_\tau$ (25% branching fraction) besides a small displacement of the π track due to the decay length of the τ lepton.

In the track-photon selection, photons are required to have $p_\mathrm{T} > 30\,\mathrm{GeV}$ or $p_\mathrm{T} > 35\,\mathrm{GeV}$, depending on the trigger, and tracks are considered as meson candidates. Although the track-photon selection is designed to select $W^\pm \to \pi^\pm/K^\pm\gamma$ events, it also offers some efficiency to $W^\pm \to \rho^\pm\gamma$ events which are partially reconstructed, as the π^0 is not explicitly identified. The highest p_T photon and meson constitute the candidate W boson if the difference in azimuthal angle $\Delta\phi(M,\gamma)$ is larger than $\pi/2$. If both the meson and the photon are reconstructed in the endcap regions ($|\eta(M)| > 1.5$ and $|\eta(\gamma)| > 1.37$) the photon and meson candidates are required to have $\eta(M) \times \eta(\gamma) \geq 0$, to suppress multijet background.

The $Z \to e^+e^-$ background, in which one electron is mis-reconstructed as a photon and the other electron is mis-reconstructed as a meson candidate, is suppressed as follows: if the probability that the meson candidate is an electron based on TRT information exceeds 10%, the hadronic leakage of the energy deposit matched to the meson track is required to be at least 3%. The hadronic leakage is defined as the ratio between transverse energy deposited in the hadronic and electromagnetic calorimeters. Electrons are suppressed as the associated hadronic leakage is smaller than for hadrons.

The requirements listed above and applied to the track-photon selection define the Generation Region (GR). The track-photon signal region (SR) is defined by adding three requirements to the GR selection criteria: $p_\mathrm{T}(M) > 33\,\mathrm{GeV}$; the sum of transverse energies of calorimeter clusters not associated to the photon candidate but within a cone of $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$ is required to be less than $2.45\ \mathrm{GeV} + 0.22 \times p_\mathrm{T}(\gamma)$ (photon calorimeter isolation) and the sum of transverse momenta of tracks within a cone of $\Delta R = 0.2$, excluding possible conversion tracks, is required to be less than 5% of $p_\mathrm{T}(\gamma)$ (photon track isolation); and the sum of transverse momenta of tracks within a cone of $\Delta R = 0.2$, excluding the meson candidate track, is required to be less than 14% of $p_\mathrm{T}(M)$ (meson isolation). Both isolation requirements reduce the contribution of photon and meson candidates faked by jets, and meson p_T and isolation requirements maximize the sensitivity to $W^\pm \to \pi^\pm\gamma$. The track-photon SR 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 small differences between pions and kaons for variables used in the trigger selection, mainly the track $E_\mathrm{T}/p_\mathrm{T}$, and in the $Z \to e^+e^-$ background suppression. In the phase space defined by the track-photon SR requirements, the track-photon trigger has a 58% efficiency for selecting $W^\pm \to \pi^\pm\gamma$ events.

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. For example, in the track-photon selection, the first step is sampling $p_\mathrm{T}(M)$ and $p_\mathrm{T}(\gamma)$ from a two-dimensional template, and the second step is sampling the track isolation from a three-dimensional $p_\mathrm{T}(M)$-$p_\mathrm{T}(\gamma)$-isolation template using the $p_\mathrm{T}(M)$ and $p_\mathrm{T}(\gamma)$ determined in the first step. The set of produced multijet pseudo-events is normalized to the number of observed data events and it is subject to the SR selection requirements. Validation regions (VRs) are defined by applying only one of the SR requirements at a time on top of the GR selection. 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 multijet model does not describe small resonant background contributions such as $Z \to e^+e^-$, as their specific features and correlations are not reproduced by the multijet-dominated templates.

The tau-photon GR is defined as follows: photons are required to be isolated (as in the track-photon SR) and have $p_{\mathrm{T}} > 20$ GeV with at least one photon satisfying $p_{\mathrm{T}} > 36$ GeV. The candidate ρ meson (τ_{had}) must have $p_{\mathrm{T}} > 26$ GeV and exactly one $\pi^{\pm}$ and one π^{0} as constituents. The τ_{had}-photon pair must satisfy $\Delta\phi > 2$. In case more than one pair can be formed, the one with the largest $\Delta\phi$ is selected. The $Z \rightarrow e^{+}e^{-}$ background is highly suppressed by applying requirements on the τ_{had} object and its constituents: the "Tight" criterion of the electron-veto algorithm described in Ref. [41]; ΔR between the τ_{had} axis and the $\pi^{\pm}$ track larger than 0.036; $E_{\mathrm{T}}^{\tau_{\mathrm{had}}}/p_{\mathrm{T}}^{\pi^{\pm}} > 2.4$; and the probability that the $\pi^{\pm}$ is an electron based on TRT information less than 90%. The numerical values of the last three requirements are obtained by simultaneous optimization of the $W^{\pm} \rightarrow \rho^{\pm}\gamma$ significance. The tau-photon SR is defined by a triplet of criteria simultaneously optimized to maximize the sensitivity to $W^{\pm} \rightarrow \rho^{\pm}\gamma$: $p_{\mathrm{T}}(\tau_{\mathrm{had}}) > 30$ GeV; the maximum distance between the τ_{had} axis and the charged pion track $\Delta R_{\tau_{\mathrm{had}}} < 0.065$; and $\log(|d_0|/\mathrm{mm}) < -1.2$, where d_0 represents the transverse impact parameter of the charged pion track in the τ_{had} object expressed in mm. The $W^{\pm} \rightarrow \rho^{\pm}\gamma$ efficiency of the tau-photon SR (including the trigger selection) is 0.3%, half than that of the track-photon SR but compensated by a higher background rejection. The di-photon trigger efficiency with respect to the SR requirements is 43% for $W^{\pm} \rightarrow \rho^{\pm}\gamma$ events. The contribution of $W^{\pm} \rightarrow \pi^{\pm}\gamma$ and $W^{\pm} \rightarrow K^{\pm}\gamma$ events in the tau-photon SR is negligible, with a number of predicted events $< 10^{-8}$ for each process. The background composition is dominated by the multijet component, modeled using the data-driven technique previously described. The VRs are defined following the same strategy as in the track-photon case and show good compatibility between data and the background prediction.

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 $m(W^{\pm} \rightarrow \pi^{\pm}\gamma)$ and $m(W^{\pm} \rightarrow K^{\pm}\gamma)$ distributions are modeled with the same shape, 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 $m(W^{\pm} \rightarrow \rho^{\pm}\gamma)$ 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 $m(W^{\pm} \rightarrow \rho^{\pm}\gamma)$ 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 $W^{\pm} \rightarrow \pi^{\pm}/K^{\pm}\gamma$; 3.1% for $W^{\pm} \rightarrow \rho^{\pm}\gamma$ in the track-photon selection, and 2.9% in the tau-photon selection. In both selections, the multijet and $Z \rightarrow e^{+}e^{-}$ 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 multijet background normalization is determined in the fit. Systematic uncertainties associated with the shape of the multijet background are implemented through a moment morphing technique [42]. 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. [43]. The impact of energy scale and resolution effects [44] is found to be below 1%. Sources of uncertainty associated with photon identification and isolation efficiencies [45] 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 [25]. 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 in the integrated luminosity is 0.83% [46].

A simultaneous fit is performed including both track-photon and tau-photon SRs. The inclusion of both SRs allows to better constrain 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), considering both statistical and systematic uncertainties. The expected number of $W^{\pm} \to \rho^{\pm}\gamma$ events 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.

Table 1: Number of 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

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. [47] and the modified frequentist confidence level CL_{S} [48] 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 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%

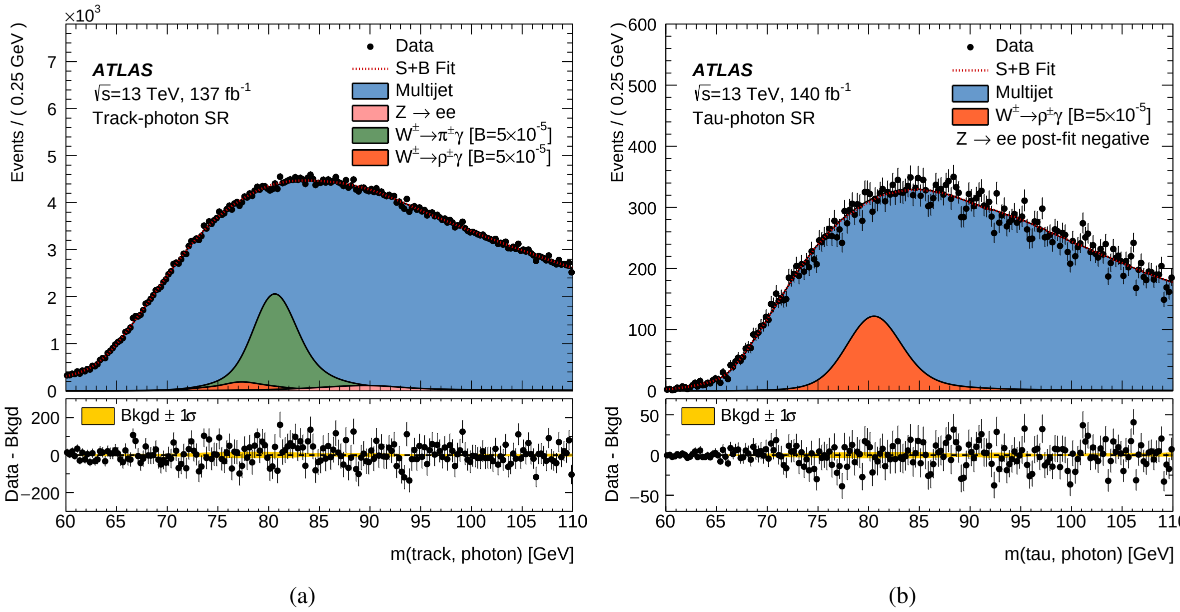

Figure 2: Distributions of the candidate W boson invariant mass in the (a) track-photon SR and (b) tau-photon SR. In the top panel data (black points) are compared to the signal-plus-background model after a fit. The $W^{\pm} \to \pi^{\pm}\gamma$ and $W^{\pm} \to \rho^{\pm}\gamma$ distributions corresponding 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.

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 $\mathcal{B}(W^{\pm} \to \pi^{\pm}\gamma)$ [7] by approximately a factor of four and provides first upper limits on $\mathcal{B}(W^{\pm} \to K^{\pm}\gamma)$ and $\mathcal{B}(W^{\pm} \to \rho^{\pm}\gamma)$. They also pave the way for a direct W mass measurement and stricter tests of theoretical predictions based on the QCD factorization approach, both possible with future larger datasets.

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Supplemental material

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.

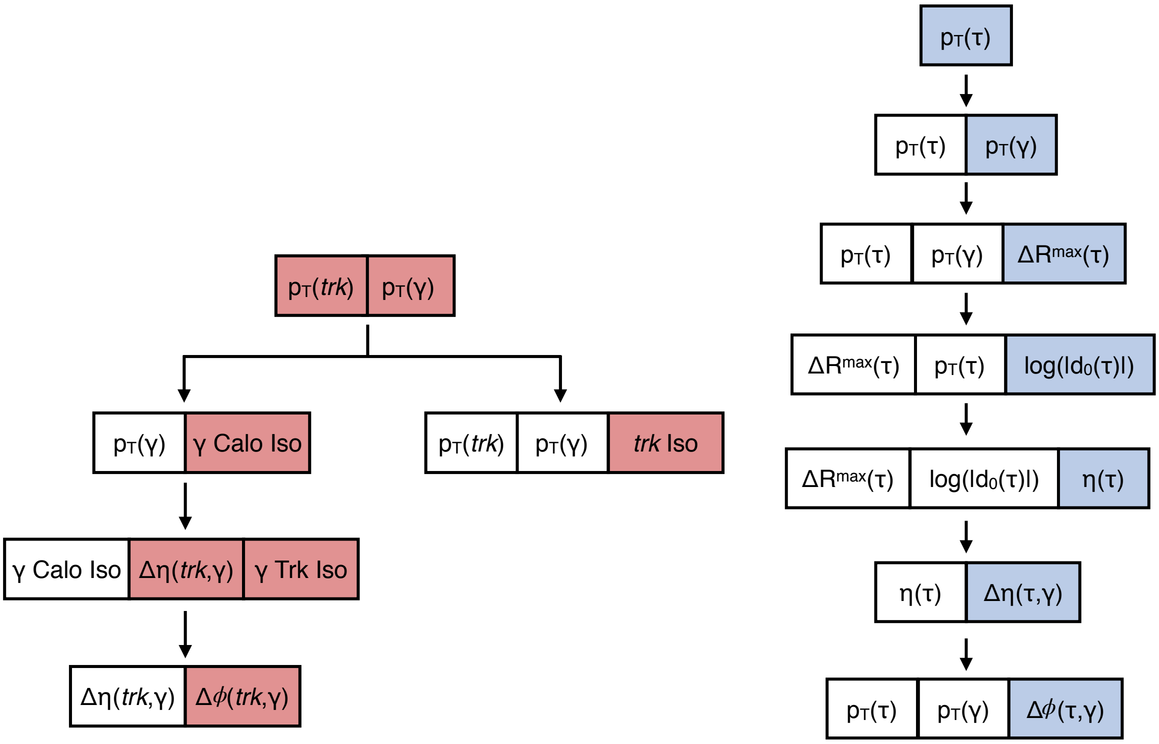
Track-photon

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. $\Delta R_{\tau}^{\max}$, 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 $\Delta R_{\tau}^{\max}$ using the same technique described in step 3.
5. $\eta(\tau)$ is sampled as a function of $\log(|d_0(\tau)|)$ and $\Delta R_{\tau}^{\max}$ 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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