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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

G. Aad *et al.*[*]
(ATLAS Collaboration)

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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 a 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 $\mathcal{B}(W^{\pm} \to \pi^{\pm}\gamma) < 1.9 \times 10^{-6}$, $\mathcal{B}(W^{\pm} \to K^{\pm}\gamma) < 1.7 \times 10^{-6}$, $\mathcal{B}(W^{\pm} \to \rho^{\pm}\gamma) < 5.2 \times 10^{-6}$ at 95% confidence level.

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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 $W^{\pm} \to M^{\pm}\gamma$ [1,2], and fully hadronic decays such as $W^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}$ [2]. These decays offer a unique opportunity to study both the weakly and 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 nonperturbative elements. The importance of these decays in this context arises from the fact that higher order corrections constitute small contributions, since they scale with $\Lambda_{\mathrm{QCD}}/m_W$ [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 ($W \to \ell\nu$), 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 $\mathcal{B}(W^{\pm} \to \pi^{\pm}\gamma) < 7.0 \times 10^{-6}$ by the CDF Collaboration [14], $\mathcal{B}(W^{\pm} \to D_s^{\pm}\gamma) < 6.5 \times 10^{-4}$ by the LHCb Collaboration [15], and $\mathcal{B}(W^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}) < 1.01 \times 10^{-6}$ by the CMS Collaboration [16]. Upper limits on $W^{\pm} \to \pi^{\pm}\gamma$ have also been published by the UA2 and CMS Collaborations [17,18].

This Letter reports a search for $W^{\pm} \to \pi^{\pm}\gamma$, $W^{\pm} \to K^{\pm}\gamma$, and $W^{\pm} \to \rho^{\pm}\gamma$. 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 nonparametric background modeling method, and the unconventional use of photon triggers and τ-lepton reconstruction algorithms to target the $\rho^{\pm} \to \pi^{\pm}\pi^{0}$ 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

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[*] Full author list given at the end of the Letter.

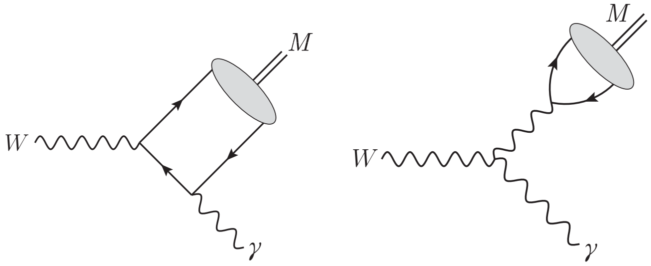


FIG. 1. Leading-order Feynman diagrams for the radiative decays $W \to M\gamma$ with $M = \{\pi, K, \rho\}$. The fermion lines represent quarks, the gray blobs represent the meson bound state.

between $W^\pm \to K^\pm\gamma$ and $W^\pm \to \pi^\pm\gamma$. The two processes are collectively referred to as $W^\pm \to \pi^\pm/K^\pm\gamma$ 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 end cap 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 [21], further reduces the accepted event rate to 1 kHz on average.

The main backgrounds are multijet and misreconstructed $Z \to e^+e^-$ events, in which one electron is misreconstructed as a photon and the other electron is misreconstructed 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 $W^\pm \to M\gamma$ 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 diphoton 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 $p_{\mathrm{T}} >$ 25 GeV (35 GeV in 20% of the dataset) and one isolated ID track with $p_{\mathrm{T}} > 30$ GeV associated with a topological cluster of calorimeter cells [40] with transverse energy $E_{\mathrm{T}} > 25$ 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 $E_{\mathrm{T}}/p_{\mathrm{T}}$ 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 $E_{\mathrm{T}}/p_{\mathrm{T}}$ 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 diphoton trigger [41] that requires two photons with $p_{\mathrm{T}} > 35$ GeV and $p_{\mathrm{T}} > 25$ GeV, respectively, is employed to recover sensitivity to $W^\pm \to \rho^\pm\gamma$ events. The diphoton trigger sensitivity to $W^\pm \to \rho^\pm\gamma$ derives from the production of two collimated photons in the decay chain $\rho^\pm \to \pi^\pm\pi^0$, $\pi^0 \to \gamma\gamma$. The efficiency of this trigger for events selected by the tau-photon selection requirements is 43%. The p_{T} requirements of the analysis are mainly driven by the high p_{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 $p_{\mathrm{T}} > 33$ 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_T, hence imposing low hadronic activity surrounding the selected meson, and suppressing contributions from tracks associated with jets. The p_T and isolation requirements were optimized for a maximum significance of $W^\pm \to \pi^\pm\gamma$ 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 $p_\mathrm{T} > 30$ GeV or $p_\mathrm{T} > 35(36)$ 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 $2.45\ \mathrm{GeV} + 0.022 \times p_\mathrm{T}(\gamma)$ 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 $p_\mathrm{T}(\gamma)$.

The τ_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 τ_had direction to calorimeter clusters using a particle-flow approach, while neutral constituents (π^0_cand) are reconstructed from clusters surrounding the charged candidates. Misreconstructed 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. Misreconstructed τ_had are suppressed using an identification algorithm based on a recurrent neural network [48]. τ_had objects with exactly one $\pi^\pm$ and one π^0 as constituents are 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 $\tau^\pm \to \rho^\pm\nu_\tau$ 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 $p_\mathrm{T} > 30$ GeV. On average, a $\rho^\pm \to \pi^\pm\pi^0$ decay will be contained in a narrower angular cone than a hadronic jet, and as such the angular distance $\Delta R_{\tau_\mathrm{had}}$ is required to be less than 0.065. Additionally, a requirement of $\log(|d_0|/\mathrm{mm}) < -1.2$, 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 $W^\pm \to \rho^\pm\gamma$ 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 $E_\mathrm{T}^{\tau_\mathrm{had}}/p_\mathrm{T}^{\pi^\pm}$ are excluded, since misreconstructed electrons have, on average, lower $E_\mathrm{T}^{\tau_\mathrm{had}}$ 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 misreconstructed 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 $\Delta R_{\tau_\mathrm{had}}$.

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 end cap 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 the largest $\Delta\phi$ is selected. A detailed list of the selection criteria used is provided in the Supplemental Material [51] 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_T/p_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 nonparametric 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 $p_T(\tau_{\text{had}})$, $\Delta R_{\tau_{\text{had}}}$, 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 pseudoevents are generated by ancestral sampling of the templates. Details of the sampling sequences employed can be found in the Supplemental Material [51] of this Letter. Following the sampling procedure, compound kinematic variables, such as the W boson invariant mass, can be calculated for each generated pseudoevent. 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 nonresonant background processes are absorbed by the background modeling method. The set of produced multijet pseudoevents is normalized to the number of observed data events in the 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 sigmoidlike 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 [52]. 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 prefit 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_T/p_T according to the results of Ref. [53]. The impact of energy scale and resolution effects [54] is found to be below 1%. Sources of uncertainty associated with photon identification and isolation efficiencies [55] 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

$Z \to \tau(\mu\nu\nu)\tau_{\text{had}}$ events selected by a muon-photon trigger that uses the same photon selection criteria used by the diphoton 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% [56].

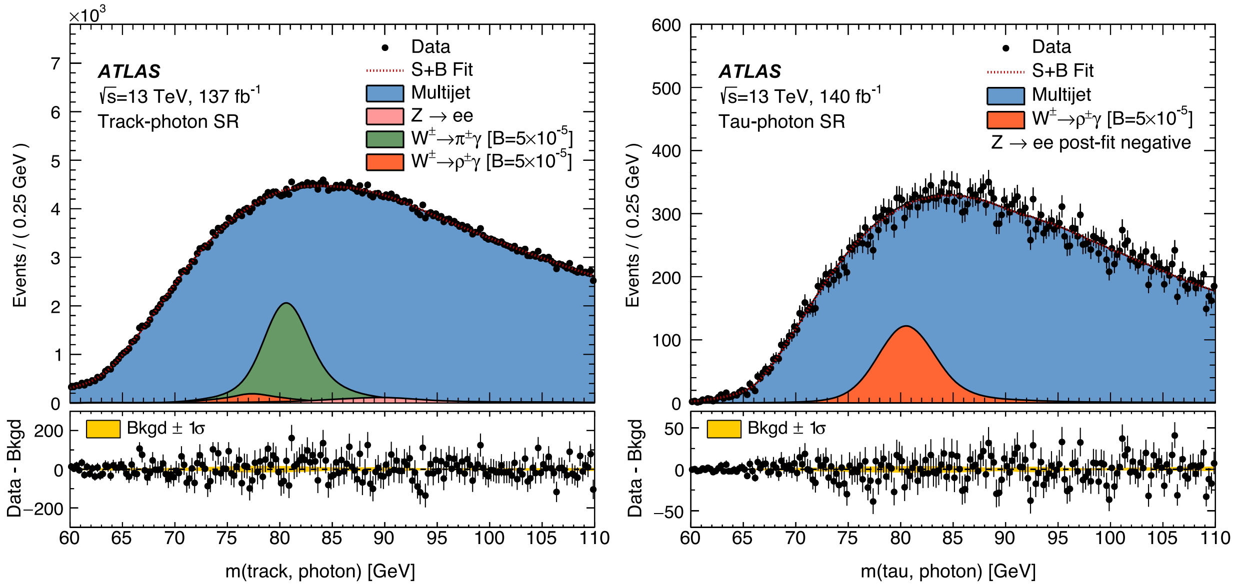
A simultaneous fit is performed including both track-photon and tau-photon SRs. The inclusion of both SRs better constrains the $W^\pm \to \rho^\pm\gamma$ signal strength parameter. The $W^\pm \to \pi^\pm\gamma$ and $W^\pm \to K^\pm\gamma$ contributions in the tau-photon SR are negligible and not included 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 $W^\pm \to M\gamma$ contributions overlaid. The number of observed events is reported in Table I.

TABLE I. 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	$632\,000 \pm 2200$	$43\,200 \pm 600$
$Z \to e^+e^-$	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	638 962	42 918

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. [57] and the modified frequentist confidence level CL_S [58] are reported in Table II. When computing the $W^\pm \to \pi^\pm\gamma$ upper limit, $W^\pm \to \rho^\pm\gamma$ is profiled, and vice-versa. The $W^\pm \to K^\pm\gamma$



(a)

(b)

FIG. 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.

TABLE II. 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

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% 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.

These results improve the previous upper limit on $\mathcal{B}(W^\pm \to \pi^\pm\gamma)$ [14] by approximately a factor of 4 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 $\mathcal{O}(10^8)$ W^+W^- events [59], 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 $\mathcal{O}(10^{12})$ W bosons [60], 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 poses 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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T. R. Wyatt,[101] B. M. Wynne,[52] S. Xella,[42] L. Xia,[14c] M. Xia,[14b] J. Xiang,[64c] M. Xie,[62a] X. Xie,[62a]
S. Xin,[14a,14e] A. Xiong,[123] J. Xiong,[17a] D. Xu,[14a] H. Xu,[62a] L. Xu,[62a] R. Xu,[128] T. Xu,[106] Y. Xu,[14b] Z. Xu,[52]
Z. Xu,[14c] B. Yabsley,[147] S. Yacoob,[33a] Y. Yamaguchi,[154] E. Yamashita,[153] H. Yamauchi,[157] T. Yamazaki,[17a]
Y. Yamazaki,[85] J. Yan,[62c] S. Yan,[126] Z. Yan,[25] H. J. Yang,[62c,62d] H. T. Yang,[62a] S. Yang,[62a] T. Yang,[64c]
X. Yang,[36] X. Yang,[14a] Y. Yang,[44] Y. Yang,[62a] Z. Yang,[62a] W-M. Yao,[17a] Y. C. Yap,[48] H. Ye,[14c] H. Ye,[55]
J. Ye,[14a] S. Ye,[29] X. Ye,[62a] Y. Yeh,[96] I. Yeletskikh,[38] B. Yeo,[17b] M. R. Yexley,[96] P. Yin,[41] K. Yorita,[168]
S. Younas,[27b] C. J. S. Young,[36] C. Young,[143] C. Yu,[14a,14e,ll] Y. Yu,[62a] M. Yuan,[106] R. Yuan,[62b] L. Yue,[96]
M. Zaazoua,[62a] B. Zabinski,[87] E. Zaid,[52] Z. K. Zak,[87] T. Zakareishvili,[149b] N. Zakharchuk,[34] S. Zambito,[56]
J. A. Zamora Saa,[137d,137b] J. Zang,[153] D. Zanzi,[54] O. Zaplatilek,[132] C. Zeitnitz,[171] H. Zeng,[14a] J. C. Zeng,[162]
D. T. Zenger Jr.,[26] O. Zenin,[37] T. Ženiš,[28a] S. Zenz,[94] S. Zerradi,[35a] D. Zerwas,[66] M. Zhai,[14a,14e] B. Zhang,[14c]
D. F. Zhang,[139] J. Zhang,[62b] J. Zhang,[6] K. Zhang,[14a,14e] L. Zhang,[14c] P. Zhang,[14a,14e] R. Zhang,[170] S. Zhang,[106]
S. Zhang,[44] T. Zhang,[153] X. Zhang,[62c] X. Zhang,[62b] Y. Zhang,[62c,5] Y. Zhang,[96] Y. Zhang,[14c] Z. Zhang,[17a]
Z. Zhang,[66] H. Zhao,[138] T. Zhao,[62b] Y. Zhao,[136] Z. Zhao,[62a] A. Zhemchugov,[38] J. Zheng,[14c] K. Zheng,[162]
X. Zheng,[62a] Z. Zheng,[143] D. Zhong,[162] B. Zhou,[106] H. Zhou,[7] N. Zhou,[62c] Y. Zhou,[7] C. G. Zhu,[62b] J. Zhu,[106]
Y. Zhu,[62c] Y. Zhu,[62a] X. Zhuang,[14a] K. Zhukov,[37] V. Zhulanov,[37] N. I. Zimine,[38] J. Zinsser,[63b]
M. Ziolkowski,[141] L. Živković,[15] A. Zoccoli,[23b,23a] K. Zoch,[61] T. G. Zorbas,[139] O. Zormpa,[46]
W. Zou,[41] and L. Zwalinski[36]

(ATLAS Collaboration)

[1]*Department of Physics, University of Adelaide, Adelaide, Australia*
[2]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[3a]*Department of Physics, Ankara University, Ankara, Türkiye*
[3b]*Division of Physics, TOBB University of Economics and Technology, Ankara, Türkiye*
[4]*LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France*
[5]*APC, Université Paris Cité, CNRS/IN2P3, Paris, France*
[6]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*
[7]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[8]*Department of Physics, University of Texas at Arlington, Arlington, Texas, USA*
[9]*Physics Department, National and Kapodistrian University of Athens, Athens, Greece*
[10]*Physics Department, National Technical University of Athens, Zografou, Greece*
[11]*Department of Physics, University of Texas at Austin, Austin, Texas, USA*
[12]*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
[13]*Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain*
[14a]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
[14b]*Physics Department, Tsinghua University, Beijing, China*
[14c]*Department of Physics, Nanjing University, Nanjing, China*
[14d]*School of Science, Shenzhen Campus of Sun Yat-sen University, Guangzhou, China*
[14e]*University of Chinese Academy of Science (UCAS), Beijing, China*
[15]*Institute of Physics, University of Belgrade, Belgrade, Serbia*
[16]*Department for Physics and Technology, University of Bergen, Bergen, Norway*
[17a]*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA*
[17b]*University of California, Berkeley, California, USA*
[18]*Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*
[19]*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[20]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[21a]*Department of Physics, Bogazici University, Istanbul, Türkiye*
[21b]*Department of Physics Engineering, Gaziantep University, Gaziantep, Türkiye*
[21c]*Department of Physics, Istanbul University, Istanbul, Türkiye*
[22a]*Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá, Colombia*
[22b]*Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia*
[23a]*Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna, Italy*
[23b]*INFN Sezione di Bologna, Bologna, Italy*
[24]*Physikalisches Institut, Universität Bonn, Bonn, Germany*
[25]*Department of Physics, Boston University, Boston, Massachusetts, USA*

[26]*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
[27a]*Transilvania University of Brasov, Brasov, Romania*
[27b]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[27c]*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*
[27d]*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania*
[27e]*National University of Science and Technology Politechnica, Bucharest, Romania*
[27f]*West University in Timisoara, Timisoara, Romania*
[27g]*Faculty of Physics, University of Bucharest, Bucharest, Romania*
[28a]*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
[28b]*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
[29]*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
[30]*Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina*
[31]*California State University, Fresno, California, USA*
[32]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[33a]*Department of Physics, University of Cape Town, Cape Town, South Africa*
[33b]*iThemba Labs, Western Cape, South Africa*
[33c]*Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa*
[33d]*National Institute of Physics, University of the Philippines Diliman (Philippines), Quezon city, Philippines*
[33e]*University of South Africa, Department of Physics, Pretoria, South Africa*
[33f]*University of Zululand, KwaDlangezwa, South Africa*
[33g]*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
[34]*Department of Physics, Carleton University, Ottawa, Ontario, Canada*
[35a]*Faculté des Sciences Ain Chock, Université Hassan II de Casablanca, Casablanca, Morocco*
[35b]*Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco*
[35c]*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
[35d]*LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco*
[35e]*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
[35f]*Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco*
[36]*CERN, Geneva, Switzerland*
[37]*Affiliated with an institute covered by a cooperation agreement with CERN*
[38]*Affiliated with an international laboratory covered by a cooperation agreement with CERN*
[39]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
[40]*LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
[41]*Nevis Laboratory, Columbia University, Irvington, New York, USA*
[42]*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
[43a]*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
[43b]*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Cosenza, Italy*
[44]*Physics Department, Southern Methodist University, Dallas, Texas, USA*
[45]*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
[46]*National Centre for Scientific Research "Demokritos", Agia Paraskevi, Greece*
[47a]*Department of Physics, Stockholm University, Stockholm, Sweden*
[47b]*Oskar Klein Centre, Stockholm, Sweden*
[48]*Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
[49]*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[50]*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
[51]*Department of Physics, Duke University, Durham, North Carolina, USA*
[52]*SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[53]*INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
[54]*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
[55]*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
[56]*Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
[57a]*Dipartimento di Fisica, Università di Genova, Genova, Italy*
[57b]*INFN Sezione di Genova, Genova, Italy*
[58]*II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
[59]*SUPA— School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[60]*LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
[61]*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*

[62a]*Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics,*
University of Science and Technology of China, Hefei, China
[62b]*Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE),*
Shandong University, Qingdao, China
[62c]*School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE),*
SKLPPC, Shanghai, China
[62d]*Tsung-Dao Lee Institute, Shanghai, China*
[62e]*School of Physics and Microelectronics, Zhengzhou University, China*
[63a]*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[63b]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[64a]*Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China*
[64b]*Department of Physics, University of Hong Kong, Hong Kong, China*
[64c]*Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology,*
Clear Water Bay, Kowloon, Hong Kong, China
[65]*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
[66]*IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France*
[67]*Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona, Spain*
[68]*Department of Physics, Indiana University, Bloomington, Indiana, USA*
[69a]*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
[69b]*ICTP, Trieste, Italy*
[69c]*Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy*
[70a]*INFN Sezione di Lecce, Lecce, Italy*
[70b]*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
[71a]*INFN Sezione di Milano, Milano, Italy*
[71b]*Dipartimento di Fisica, Università di Milano, Milano, Italy*
[72a]*INFN Sezione di Napoli, Napoli, Italy*
[72b]*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
[73a]*INFN Sezione di Pavia, Pavia, Italy*
[73b]*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
[74a]*INFN Sezione di Pisa, Pisa, Italy*
[74b]*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
[75a]*INFN Sezione di Roma, Rome, Italy*
[75b]*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
[76a]*INFN Sezione di Roma Tor Vergata, Rome, Italy*
[76b]*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
[77a]*INFN Sezione di Roma Tre, Rome, Italy*
[77b]*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
[78a]*INFN-TIFPA, Povo, Italy*
[78b]*Università degli Studi di Trento, Trento, Italy*
[79]*Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck, Austria*
[80]*University of Iowa, Iowa City, Iowa, USA*
[81]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
[82]*Istinye University, Sariyer, Istanbul, Türkiye*
[83a]*Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil*
[83b]*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
[83c]*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
[83d]*Rio de Janeiro State University, Rio de Janeiro, Brazil*
[84]*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
[85]*Graduate School of Science, Kobe University, Kobe, Japan*
[86a]*AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow, Poland*
[86b]*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
[87]*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
[88]*Faculty of Science, Kyoto University, Kyoto, Japan*
[89]*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
[90]*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
[91]*Physics Department, Lancaster University, Lancaster, United Kingdom*
[92]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[93]*Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics,*
University of Ljubljana, Ljubljana, Slovenia
[94]*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*

[95]*Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
[96]*Department of Physics and Astronomy, University College London, London, United Kingdom*
[97]*Louisiana Tech University, Ruston, Louisiana, USA*
[98]*Fysiska institutionen, Lunds universitet, Lund, Sweden*
[99]*Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
[100]*Institut für Physik, Universität Mainz, Mainz, Germany*
[101]*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[102]*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
[103]*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
[104]*Department of Physics, McGill University, Montreal, Quebec, Canada*
[105]*School of Physics, University of Melbourne, Victoria, Australia*
[106]*Department of Physics, University of Michigan, Ann Arbor, Michigan, USA*
[107]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
[108]*Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada*
[109]*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
[110]*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
[111]*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
[112]*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
[113]*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands*
[114]*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
[115]*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
[116a]*New York University Abu Dhabi, Abu Dhabi, United Arab Emirates*
[116b]*University of Sharjah, Sharjah, United Arab Emirates*
[117]*Department of Physics, New York University, New York, New York, USA*
[118]*Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan*
[119]*The Ohio State University, Columbus, Ohio, USA*
[120]*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
[121]*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
[122]*Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic*
[123]*Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA*
[124]*Graduate School of Science, Osaka University, Osaka, Japan*
[125]*Department of Physics, University of Oslo, Oslo, Norway*
[126]*Department of Physics, Oxford University, Oxford, United Kingdom*
[127]*LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France*
[128]*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
[129]*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
[130a]*Laboratório de Instrumentação e Física Experimental de Partículas— LIP, Lisboa, Portugal*
[130b]*Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
[130c]*Departamento de Física, Universidade de Coimbra, Coimbra, Portugal*
[130d]*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
[130e]*Departamento de Física, Universidade do Minho, Braga, Portugal*
[130f]*Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain*
[130g]*Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*
[131]*Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic*
[132]*Czech Technical University in Prague, Prague, Czech Republic*
[133]*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
[134]*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
[135]*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[136]*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
[137a]*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
[137b]*Millennium Institute for Subatomic Physics at High Energy Frontier (SAPHIR), Santiago, Chile*
[137c]*Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena, La Serena, Chile*
[137d]*Universidad Andres Bello, Department of Physics, Santiago, Chile*
[137e]*Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile*
[137f]*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[138]*Department of Physics, University of Washington, Seattle, Washington, USA*
[139]*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
[140]*Department of Physics, Shinshu University, Nagano, Japan*
[141]*Department Physik, Universität Siegen, Siegen, Germany*

[142]*Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada*
[143]*SLAC National Accelerator Laboratory, Stanford, California, USA*
[144]*Department of Physics, Royal Institute of Technology, Stockholm, Sweden*
[145]*Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA*
[146]*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
[147]*School of Physics, University of Sydney, Sydney, Australia*
[148]*Institute of Physics, Academia Sinica, Taipei, Taiwan*
[149a]*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
[149b]*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
[149c]*University of Georgia, Tbilisi, Georgia*
[150]*Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
[151]*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
[152]*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[153]*International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
[154]*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
[155]*Department of Physics, University of Toronto, Toronto, Ontario, Canada*
[156a]*TRIUMF, Vancouver, British Columbia, Canada*
[156b]*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
[157]*Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
[158]*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
[159]*United Arab Emirates University, Al Ain, United Arab Emirates*
[160]*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
[161]*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
[162]*Department of Physics, University of Illinois, Urbana, Illinois, USA*
[163]*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain*
[164]*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
[165]*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*
[166]*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
[167]*Department of Physics, University of Warwick, Coventry, United Kingdom*
[168]*Waseda University, Tokyo, Japan*
[169]*Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel*
[170]*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
[171]*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
[172]*Department of Physics, Yale University, New Haven, Connecticut, USA*

[a] Deceased.
[b] Also at Department of Physics, King's College London, London, United Kingdom.
[c] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[d] Also at Lawrence Livermore National Laboratory, Livermore, USA.
[e] Also at TRIUMF, Vancouver, British Columbia, Canada.
[f] Also at Department of Physics, University of Thessaly, Volos, Greece.
[g] Also at An-Najah National University, Nablus, Palestine.
[h] Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
[i] Also at University of Colorado Boulder, Department of Physics, Colorado, USA.
[j] Also at Department of Physics, Westmont College, Santa Barbara, USA.
[k] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
[l] Also at affiliated with an institute covered by a cooperation agreement with CERN.
[m] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
[n] Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.
[o] Also at Università di Napoli Parthenope, Napoli, Italy.
[p] Also at Institute of Particle Physics (IPP), Canada.
[q] Also at Borough of Manhattan Community College, City University of New York, New York, New York, USA.
[r] Also at National Institute of Physics, University of the Philippines Diliman (Philippines), Quezon City, Philippines.
[s] Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
[t] Also at Department of Physics, Stanford University, Stanford, California, USA.
[u] Also at Centro Studi e Ricerche Enrico Fermi, Rome, Italy.
[v] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
[w] Also at Technical University of Munich, Munich, Germany.
[x] Also at Yeditepe University, Physics Department, Istanbul, Türkiye.

[y] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
[z] Also at CERN, Geneva, Switzerland.
[aa] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece.
[bb] Also at Hellenic Open University, Patras, Greece.
[cc] Also at Center for High Energy Physics, Peking University, Beijing, China.
[dd] Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France.
[ee] Also at Department of Physics, California State University, Sacramento, Sacramento, California, USA.
[ff] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
[gg] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[hh] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
[ii] Also at Washington College, Chestertown, Maryland, USA.
[jj] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco.
[kk] Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia.
[ll] Also at University of Chinese Academy of Sciences (UCAS), Beijing, China.
[mm] Also at Faculty of Physics, Sofia University, "St. Kliment Ohridski," Sofia; Bulgaria.