General relativistic simulations of the quasi-circular inspiral and merger of charged black holes: GW150914 and fundamental physics implications

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We perform general-relativistic simulations of charged black holes targeting GW150914. We show that the early inspiral is most efficient for detecting black hole charge through gravitational waves and that GW150914 places only weak constraints on the charge-to-mass ratio, Q/M < 0.4. Our work applies to electric and magnetic charge, and to theories with black holes endowed with U(1) (hidden or dark) charges. With our results, we place an upper bound on the deviation of the so-called theory of MOdified Gravity (MOG) from general relativity in the dynamical, strong-field regime.

Introduction According to the “no-hair” conjecture [1–6], general relativistic black holes are described by four parameters: mass, angular momentum, electric and magnetic charge. It is assumed, often implicitly, that astrophysical black holes have negligible charge because of the expectation that they would quickly discharge due to the interaction with a highly conducting gaseous environment or by the spontaneous production of electron-positron pairs [7–11]. However, observational data unequivocally supporting this expectation are currently absent, and any existing constraints depend crucially on the assumptions of the models employed (e.g. [12, 13]). Gravitational-wave observations offer a model-independent path to constraining the charge of astrophysical black holes. The electromagnetic fields influence the spacetime, altering the gravitational-wave emission compared to an uncharged binary. These deviations are accurately modeled in Einstein-Maxwell theory, and are potentially detectable by LIGO-Virgo and future gravitational-wave observatories.

In this letter, we initiate a robust program for constraining black hole charge by combining LIGO-Virgo observations with novel numerical relativity simulations. Our focus here is on event GW150914 [14]. Using the event’s sky location and the calibrated LIGO noise, we compute the mismatch (defined later) between the uncharged case and various charged ones. The observed signal-to-noise ratio sets a threshold mismatch above which two waveforms are distinguishable [24–27]. Hence, assuming that the observed waveform is described by uncharged, non-spinning black holes, we find the minimum charge that would be detectable by LIGO.

For uncharged binaries, when black hole spin is neglected and the mass-ratio is fixed, knowing one “mass” parameter determines the entire gravitational waveform. We will use here the chirp mass $\mathcal{M}$ [28]. In the case of inspirals of charged binaries, this parameter can be degenerate with the charge itself [29–32]. This can be understood as follows: In Newtonian physics, gravity and electromagnetism are both central potentials, so the electrostatic force can be accounted for by introducing an effective Newton constant $\lambda G$. Consider two bodies with mass $m_1$, $m_2$ and charge $q_1 = \lambda_1 m_1$, $q_2 = \lambda_2 m_2$ ($\lambda$ being the charge-to-mass ratio); the dynamics of the system is indistinguishable from one with uncharged bodies with gravitational constant $\tilde{G} = (1 - \lambda_1 \lambda_2)G$. Since the relationship between chirp mass and gravitational-wave frequency evolution involves Newton’s constant, introducing charges corresponds to rescaling the chirp mass while keeping $G$ fixed. This degeneracy is broken by electromagnetic radiation reaction and the field self-gravity.

Adopting the effective Newton constant approach, previous studies [29–33] constructed Newtonian-based waveforms by considering the Keplerian motion of two charged bodies and accounting for loss of energy via quadrupolar emission of gravitational waves and dipolar emission of electromagnetic ones. The authors of [30] computed the bias in the binary parameters due to the charge-chirp mass degeneracy. With similar tools, [33] performed a full Bayesian analysis with Gaussian noise to place preliminary constraints on charge using events in the first gravitational wave transient catalog [34]. Alternatively, the dipole can be constrained directly by adding a $-1\text{PN}$ (Post-Newtonian) term to describe the loss of energy due to dipole emission [33], as first done for modified theories of gravity [35]. In [35, 36], it was found that the dipole can be constrained more effectively in the inspiral (also noted in [29, 32] with explicit reference to charges). One of the main limitations of these (post-)Newtonian methods is that they strictly apply only to the early inspiral. However, binaries like GW150914 are in the regime where numerical relativity simulations are necessary for accurate modeling [14]. Therefore, existing constraints on black hole charge in events where only a few orbits to merger have been detected are at best preliminary. Moreover, the effective Newton constant approach does

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1 The possibility that GW150914 involved charged black holes has been invoked [15–17] to explain the observation of a coincident electromagnetic signal by Fermi-GBM [18, 19]. This association is debated as others satellites did not detect the event [20–23].
not capture the physics in cases when only one of the two components is charged, and when the dipole moment vanishes these previous approaches do not treat quadrupole electromagnetic emission. This is very important because as we demonstrate here, it is binaries with near vanishing dipole moment that place that weakest constraint on black hole charge.

A second avenue for constraining black hole charge is through the ringdown signal. In the context of mergers of charged black holes, this was first studied in [29, 32] in the limit of small charge, using the method of geodesic correspondence. Via a Fisher matrix analysis, it was noticed that the ability to constrain charge depends strongly on the signal-to-noise ratio, so GW150914 cannot be used to place strong bounds on the charge-to-mass ratio \( \lambda \) of the final black hole. However, as the authors remarked, these results should be considered only as qualitative, since higher-order terms in \( \lambda \) were neglected.

Instead of using approximations, here we solve the full non-linear Einstein-Maxwell equations, extracting accurate gravitational waves to overcome the shortcomings of previous approaches. We perform numerical-relativity simulations of black holes with (1) same charge-to-mass ratio (that we will indicate with \( \lambda_+^+ \)) (2) same charge-to-mass ratio but opposite sign (\( \lambda_-^- \)), and (3) only one charged black hole (\( \lambda_0^+ \)). Einstein-Maxwell theory has no intrinsic scale, so our simulations scale with the total ADM (Arnowitt-Deser-Misner) mass of the system \( M \) [37]. Thus, we can explore arbitrary chirp masses with each simulation. We compute the mismatch between gravitational waveforms generated by charged and uncharged binaries with a range of different masses to account for the degeneracy: black hole charge is constrained when the mismatch is larger than a value set by the signal-to-noise ratio [24–27] for all possible values of the chirp mass.

An important advantage of our approach is that it furnishes a first-principles calculation based on fundamental theories, and does not rely on particular models. As a result, the mathematical formulation we employ has direct fundamental physics applications. Examples are dark matter theories (e.g., dark electromagnetism [30, 38–40], or mini-charged particles [29, 41–44]). These theories allow black holes to be highly charged, since neutralization arguments do not apply. Moreover, with a duality transformation [45], our work also constrains black hole magnetic charge (e.g., from primordial magnetic monopoles [46, 47]).

Furthermore, our research targets theories of gravitation where gravity is also mediated by a vector field, like the scalar-tensor-vector gravity developed in [48] to explain “dark matter” phenomenology without dark matter. This theory (also known with the acronym “MOG” – MOdified Gravity), has been widely studied in the past and can pass several tests, such as Solar System ones [49] (see also [48, 50–58]; for a summary of the formulation, assumptions, and successes of the theory, see [53]). MOG features a scalar field that makes gravity stronger by increasing Newton’s constant and a Proca field that counteracts this effect in the short range. When considering systems much smaller than the galactic scale, the vector field can be considered massless and the scalar field becomes constant and modifies Newton’s constant to \( G_{\text{eff}} = G(1 + \alpha) \). According to MOG, a body with mass \( M \) has a gravitational charge \( Q \) that is associated with the vector field and is proportional to \( M \). Moffat’s prescription sets the constant of proportionality to \( \sqrt{\alpha G_{\text{eff}}/(1 + \alpha)} \) so that the theory satisfies the weak equivalence principle [59]. In this limit, MOG differs mathematically from Einstein-Maxwell theory only in using \( G_{\text{eff}} \) instead of \( G \), and when \( \alpha = 0 \) the theory becomes general relativity. This rescaling gives rise to the same degeneracy in the chirp mass and \( G \) that we discussed above in the case of electromagnetism: in geometrized units, MOG solutions with mass \( M_{\text{MOG}} \) and gravitational constant \( G_{\text{eff}} = 1 \) are equivalent to Einstein-Maxwell solutions with mass \( M = M_{\text{MOG}}(1+\alpha) \) and \( G = 1 \). Hence, by scanning through all possible values of the mass, a constraint on the charge-to-mass ratio translates in this theory to a constraint on \( Q/M = \sqrt{\alpha/(1 + \alpha)} \).

The results of this work depend on two basic assumptions: 1) Einstein-Maxwell theory is the correct description of charged black holes at the energy, length, and time scales we are investigating; 2) GW150914 is accurately modeled by waveforms from uncharged, non-spinning binary black holes with mass ratio 29/36. Furthermore, motivated by the fact that GW150914 was consistent with non-rotating black holes [60], in this first study, we do not vary the spin. In addition, we fix the mass ratio to 29/36—the value inferred for GW150914 [14]. We will relax these assumptions in future work. To reduce the parameter space, we only consider black holes with the same charge-to-mass ratio bracketing the possibilities. This choice also ensures the applicability of our results to modified theories of gravity where the charge-to-mass-ratio represents a coupling constant (as in MOG), in which case only systems with the same charge-to-mass ratio are relevant (in the limit we discussed above).

**Methods** We employ the Einstein Toolkit [61–64] to solve the coupled Einstein-Maxwell equations in the 3 + 1 decomposition of four-dimensional spacetime [37, 65–68]. We report the general features of our approach here and leave the details for the Supplemental Material.

We performed simulations with charge-to-mass ratio \( \lambda \in \{0.01, 0.05, 0.1, 0.2, 0.3\} \) with like or opposite charge for the two black holes (cases that we will designate as \( \lambda_+^+ \) and \( \lambda_-^- \), where the superscript and subscript indicate the sign of the charge of the primary and the secondary, respectively), and only one charged black hole (\( \lambda_0^+ \)). These cases are supplemented by an uncharged one (\( \lambda_0^0 \)), a convergence study, and by simulations with \( \lambda_0^+ = 0.4 \), \( \lambda_0^0 = 0.35 \), and \( \lambda_0^0 = 0.35 \).
The initial data are generated with TwoChargedPunctures [69], which solves the constraint equations [67] adopting an extended Bowen-York formalism [70–72] we developed in [69]. We fix the initial coordinate separation to 12.1 M. We choose the black hole initial linear momenta to yield a quasi-circular inspiral using a 2.5PN estimate after rescaling G to \( \tilde{G} \).

We evolve the spacetime and electromagnetic fields with the open-source and well-tested Lean and ProcaEvolve codes [73–75]. Lean implements the Baumgarte-Shapiro-Shibata-Nakamura formulation of Einstein’s equation [76, 77], while ProcaEvolve evolves the electromagnetic vector potential with a constraint-damping scheme. The evolution is on Carpet [78] grids where the highest resolution is approximately \( M/65 \), with \( M \) being the binary ADM mass [37]. We extract gravitational waves based on the Newman-Penrose formalism [75, 79], adopting the fixed-frequency integration method [80]. We decompose the signal into \( -2 \) spin weighted spherical harmonics, and focus on the dominant \( \ell = 2, m = 2 \) gravitational wave mode.

Two waveforms are considered experimentally indistinguishable if their mismatch is smaller than \( 1/(2\rho^2) \) [24–27], with \( \rho \) being the signal-to-noise ratio. For GW150914, \( \rho = 25.1 \) [60], so the threshold mismatch above which two signals are distinguishable is approximately \( 8 \times 10^{-4} \). We calculate the mismatch between strains \( h_1 \) and \( h_2 \) as \( 1 - \max O(h_1, h_2) \), where \( O(h_1, h_2) \) is the overlap between the two signals (see Supplemental Material), and the maximum is evaluated with respect to time-shifts, orbital-phase shifts and polarization angles [27, 81]. The overlap calculation is performed in the frequency domain. We consider LIGO’s noise curve at the time of GW150914 detection, and adopt the GW150914 inferred sky location. For the uncharged signal, we set a source frame ADM mass \( M = 65 M_\odot \) and a luminosity distance of 410 Mpc, corresponding to cosmological redshift of \( \approx 0.09 \) [82]. In the Supplemental Material we discuss how different choices for these parameters affect the results. To account for the charge-chirp mass degeneracy, we compute the mismatch between gravitational waves from uncharged black holes and the ones from charged systems with different chirp masses \( M \). To change the chirp mass, we rescale \( M \) by a factor that we indicate with \( M/M_{00} \), where \( M_{00} \) is the chirp mass of the uncharged simulation. We estimate the error on the mismatch by comparing simulations at different resolutions.

**Results and Discussion** The mismatch between a charged and the uncharged binary grows with the charge-to-mass ratio \( \lambda \). So, we may place an upper bound on the charge by finding the value of \( \lambda \) at which the minimum mismatch (as we vary the chirp mass) is larger than \( 8 \times 10^{-4} \). We find that GW150914 constrains \( \lambda \) to be

\[
\lambda^+ < 0.4, \quad \lambda^- < 0.2, \quad \lambda^0 < 0.35.
\]

In our simulations we always endow the more massive black hole with positive charge. Since the mass asymmetry of the system is small, we expect our conclusions to remain the same in the opposite case. The simulation with \( \lambda^+ = 0.35 \) confirms this expectation: the computed minimum mismatch differs by 10% from the \( \lambda^+ = 0.35 \) case. Thus, the effect of the mass asymmetry is small.

![FIG. 1. Mismatch between the strains from uncharged black holes and from charged ones with chirp mass rescaled by \( M/M_{00} \)].](image)

In Figure 1, we show the mismatch between the uncharged simulation and charged ones as a function of the rescaling factor \( M/M_{00} \) for the chirp mass. The figure has three sets of curves. Solid curves represent the mismatch computed on the entirety of the signal (i.e., all frequencies are included). In the top panels, these curves have minima below the threshold mismatch (horizontal solid line) for some value of \( M/M_{00}\text{min} \). Thus, gravitational waves from these charged configurations are indistinguishable from the signal that we adopt as true for GW150914. The opposite holds in the bottom panels. Therefore, under the assumptions of our study, GW150914 is compatible with involving charged black holes with \( Q/M \) up to about 0.3. The noise curve
adopted plays an important role: if instead of the realistic one, we consider the Zero-Detuned-High-Power noise curve [83], the mismatch increases by a factor of about 3, making the top panels in Figure 1 incompatible with the observation, and hence distinguishable. Thus, it is important to use the realistic noise in these calculations.

Figure 1 reports two additional sets of curves: dashed lines, representing the mismatch computed including frequencies below 55 Hz, and dotted ones for frequencies above 55 Hz. In other words, the dashed and dotted curves are the mismatch that would be computed if we had detected only the inspiral or only the plunge and merger phases. The frequency of 55 Hz marks conventionally the end of the inspiral phase [84]. Including a larger range of frequencies, decreases the minimum mismatch (from dashed lines to solid). Hence, previous studies focusing only on the inspiral overestimate the mismatch and the bias in the extracted chirp mass.

GW150914 and the solid ones are the strains from the charged simulations, rescaled and shifted to maximize the overlap. The plot shows that the greatest difference between charged and uncharged black holes arises in the earlier inspiral. Thus, signals that stay for a longer duration in LIGO-Virgo bands allow for stronger constraints on the charge. All waveforms in Figure 2 have mismatch with GW150914 larger than $8 \times 10^{-4}$, hence the corresponding charge configurations are incompatible with GW150914.

One of the reasons why the merger+ringdown phase of the signal is not as informative as the inspiral is that the properties of the final black holes do not depend strongly on the initial charge configuration. In all our simulations, the mass of the final black hole is the same to within 1\% ($M_{\text{final}} \approx 0.96 M$), and the dimensionless spin differs by at most 6\% ($a_{\text{final}}/M_{\text{final}} \approx 0.66$). In particular, in our opposite charge cases, the final mass and spin have sub-percent differences with respect to the uncharged case, and, as expected from relativistic estimates, the case with same charge has a lower spin [85]. This result agrees with [29, 32]: a large charge or a large signal-to-noise ratio is required to extract the charge information from the ringdown.

Our full non-linear study supports previous results that were obtained with parametrized methods. Constraints on the dipolar gravitational-wave emission were placed in [35, 36] using Fisher matrix analysis based on phenomenological waveform models. Translated into an upper bound on the normalized electric dipole, the constraint becomes $\zeta = |\lambda_1 - \lambda_2|/\sqrt{1 - \lambda_1 \lambda_2} \lesssim 0.31$ [29, 33]. Our work shows that $\zeta < 0.3$ (from the case with $\lambda_2 = 0.3$). However, our work goes further by placing a constraint on the individual black hole charge.

Our results can also be applied to the so-called theory of MOdified Gravity (MOG) [86]. At scales relevant for compact binary mergers, this theory replaces Newton’s constant $G \rightarrow G_{\text{eff}}$, and postulates the existence of a gravitational charge $Q = \sqrt{\alpha G_{\text{eff}}/(1 + \alpha)} M$. The difference in Newton’s constant is degenerate with a change in chirp mass, which we thoroughly explored. Figure 1 shows that when $\lambda_+ = 0.4$ no matter how the chirp mass is changed, it is not possible to reconcile GW150914 with the merger of charged black holes with $\lambda_+ = 0.4$. Hence, our study directly constrains $\alpha \lesssim 0.19$. This implies that the theory cannot deviate much from general relativity in the strong field.

**Conclusions** In this letter, we presented fully self-consistent general relativistic simulations of the inspiral and merger of charged non-spinning black holes with mass ratio 29/36. We considered cases where both black holes are charged with the same charge-to-mass ratio ($\lambda_+^+$), opposite charge-to-mass ratio ($\lambda_+^-$), and only one black hole charged ($\lambda_0^+$). By comparing waveforms from uncharged systems to those from charged ones, we addressed the charge-chirp mass degeneracy and derived
the following constraints for GW150914:
\[ \lambda_+^+ < 0.4, \quad \lambda_-^+ < 0.2, \quad \text{and} \quad \lambda_0^+ < 0.35. \]  
(2)

We found that the early inspiral is the most constraining part of the signal for charge (Figures 1, 2). So, low-mass binaries, having more orbits in LIGO-Virgo bands, will likely yield tighter bounds on black hole charge. Our full non-linear analysis confirms that it is challenging to constrain charge from the ringdown phase of merging charged black holes [29, 32].

The bounds found in this study do not apply only to electric charge, but they can be directly translated to constraints on modified theories of gravity and exotic astrophysical scenarios, e.g., dark matter models [29], or primordial magnetic monopoles [46]. In this work, we applied our findings to Moffat’s scalar-vector-tensor gravity (SVTG or MOG) [48] and constrained its \( \alpha \) parameter to \( \alpha < 0.19 \). Note that \( \alpha = 0 \) is general relativity. Applications to lower-mass black hole binary detections may be able to constrain this theory significantly in the strong field, dynamical regime.

In addition to assuming that Einstein-Maxwell theory is the correct description of charged black holes and that GW150914 is accurately described by waveforms from uncharged, non-spinning binary black holes with mass ratio 29/36 and mass \( M = 65 M_\odot \), our results hold under the assumption that spin and mass-ratio play a secondary role. Moreover, we only considered systems where both black holes have the same charge-to-mass ratio. In the future, we will address these limitations by exploring spinning black holes, different mass-ratios, and asymmetric charge-to-mass ratio.

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Supplemental material

Details of the numerical methods We generate constraint-satisfying initial data with TwoChargedPunctures, which can build arbitrary configurations of charged binary black holes. The values of the initial black hole linear momenta are chosen to yield a quasi-circular inspiral. To do so, we first use a 2.5 post-Newtonian expression to determine the values required to generate a quasi-circular inspiral in the uncharged case. Next, for given charge-to-mass ratios \( \lambda_1 \) and \( \lambda_2 \), we rescale \( G \) to \( \tilde{G} \), by multiplying the linear momenta with \( \sqrt{1 - \lambda_1 \lambda_2} \) (since they are proportional to \( \sqrt{G} \)). For the initial orbital separation chosen, and the charge-to-mass ratios explored, this choice yields near quasi-circular inspirals: estimating the eccentricity with the method described in the Appendix of [87], the maximum eccentricity after the first orbit is 0.005, except in the \( \lambda_+^+ \) case, where it is 0.014. Our experiments show that our method for setting the initial black hole linear momenta must be modified to achieve very low eccentricity in simulations with black holes that have close to extremal and opposite charges (i.e., large \( \lambda_\pm \)), in which case eccentricity-reduction methods or more sophisticated post-Newtonian expansions that include the electromagnetic fields may be required.

For the time integration of the Einstein-Maxwell equations we use the method of lines with a fourth-order Runge-Kutta scheme. The spacetime evolution is performed adopting sixth-order finite-differences with the Lean code [74], which is based on the Baumgarte-Shapiro-Shibata-Nakamura (BSSN) formulation [76, 77] of the Einstein equations, and exploits the puncture approach for the black-hole singularities. Apparent horizons are located with AHFinderDirect [88, 89], and their physical properties [90, 91] are computed with QuasiLocalMeasuresEM—a version of QuasiLocalMeasures [92] we extended to implement the formalism of quasi-isolated horizons in full Einstein-Maxwell theory [69]. Maxwell’s equations are evolved also using sixth-order finite differences with the ProcaEvolve code [75], which is designed to keep the magnetic field divergenceless. We adopt the Lorenz gauge for the electromagnetic sector, and the \( 1 + \log \) and \( \Gamma \)-freezing gauge conditions for the lapse function and shift vector [93–95]. To improve the stability of the evolution, we add seventh-order Kreiss-Oliger dissipation [96] to all evolved variables. Both Lean and ProcaEvolve are part of the Canuda open-source suite [73] and have already been tested and used in previous studies (e.g. [74, 75]).

We employ Carpet [78] for moving-box adaptive mesh-refinement, and use nine refinement levels. The outer boundary is placed at 1033 \( M \) where we impose outgoing-wave boundary conditions. We performed selected simulations with outer boundary twice as far, and found that all reported quantities are invariant with the outer boundary location to within one part in 10\(^8\).

The extraction of gravitational and electromagnetic waves is performed at ten different spatial radii in the
range (45.19 \, M, 192.74 \, M). In this work we report quantities at the extraction radius 111.69 \, M. We checked that our results do not depend on the extraction radius, and small differences from different radii are taken into account in our error budget. We remove the first period from the extracted signals as it contains junk radiation from the initial data [97, 98].

We calculate the mismatch between strains \( h_1 \) and \( h_2 \) as [27, 81]

\[
mismatch(h_1, h_2) = 1 - \max \mathcal{O}(h_1, h_2),
\]

with the maximum evaluated with respect to time-shifts, orbital-phase shifts and polarization angles. Here, \( \mathcal{O}(h_1, h_2) \) is the overlap between \( h_1 \) and \( h_2 \)

\[
\mathcal{O}(h_1, h_2) = \frac{(h_1, h_2)}{\sqrt{(h_1, h_1)(h_2, h_2)}},
\]

with \((h_1, h_2)\) being the two-detector noise-weighted inner product between the two signals in the frequency domain \( h_1(f) \) and \( h_2(f) \), [99]

\[
(h_1, h_2) = \sum_{\text{Hanford Livingston}} \left[ 4 \operatorname{Re} \int_{f_{\text{min}}}^{f_{\text{max}}} \frac{\tilde{h}_1(f)\tilde{h}_2^*(f)}{S_n(f)} \, df \right],
\]

where \( S_n(f) \) is the power spectral noise, and an asterisk denotes complex conjugation. We pad numerical waveforms with zeros so that all frequency series have the same length. We apply a Tukey window to the time series before taking the discrete Fourier transforms so that the signal goes smoothly to zero. We consider three choices for the combination \((f_{\text{min}}, f_{\text{max}})\): (20, 1024) Hz to include the entire signal; (20, 55) Hz to take into account only the “inspiral” (at least six orbits) and (55, 1024) Hz for the plunge and post-merger phases (corresponding to approximately the last two cycles). We choose these frequencies following the LIGO-Virgo collaboration in identifying the first part as inspiral, and the second is what LIGO-Virgo further splits in intermediate + merger and ringdown [84]. This second group of frequencies is in the most sensitive range for LIGO. The lowest frequency in our simulations is approximately 23 Hz. For \( S_n(f) \), we employ the calibrated noise registered in coincidence with GW150914 (downloaded from the Gravitational Waves Open Science Center [100]). We use the inferred sky location of the source (right ascension: 8 h, declination: \(-70^\circ\), UTC time: 09:50:45.39 September 14 2015) and the corresponding gravitational-wave antenna pattern of the two detectors [60].

**Error budget and convergence** Our simulations exhibit excellent conservation of total energy, total angular momentum, and total charge. Summing up the mass of the final black hole, and the energies carried away by gravitational and electromagnetic waves, we find the initial ADM energy to within 1 part in \( 2 \times 10^4 \). Similarly, angular momentum is conserved to within 1 part in \( 7 \times 10^4 \). In these calculations we also extrapolate waves to spatial infinity following [95] and include all harmonic modes up to \( l = 8 \). Results are nearly invariant if a finite extraction radius is considered instead.

For energy and angular momentum radiated we use the Newman-Penrose scalars [101, 102]. Charge is conserved to a high degree of accuracy: if \( Q_1, Q_2 \) are the initial horizon charges and \( Q_{\text{final}} \) the final black hole charge computed by QuasiLocalMeasures [69], we find that

\[ |Q_{\text{final}} - (Q_1 + Q_2)|/(|Q_1| + |Q_2|) \leq 2 \times 10^{-5}. \]

For the case \( \lambda_+^2 = 0.3 \) we performed a convergence study by considering resolutions 25% higher \((M/81)\) and lower \((M/52)\) compared to the canonical one. Among our cases, \( \lambda_+^2 = 0.3 \) exhibits the highest velocities, and strongest emission of energy and angular momentum in gravitational and electromagnetic waves. The high-resolution simulation is also used to provide an estimate for the error of the standard resolution simulations. The conserved quantities reported in the previous paragraph improve by a factor of \( \approx 2 \) for the simulation at higher resolution.

We show convergence more formally in Figure 3, where we report the absolute value of the difference of \( h_{+2}^{\text{XX}} \) between different resolutions (and similarly for \( h_{-2}^{\text{XX}} \)). Early on we observe the well-known resolution-dependent high-frequency noise [103, 104] due to reflection/diffraction phenomena across refinement-level boundaries. After an initial noise-dominated phase, the difference between the two higher resolution simulations (orange dashed curve) becomes smaller than the one between the two lower-resolution runs (blue solid line), demonstrating self-convergence.

We estimate the error of the mismatch by finding the maximum mismatch between the simulation with standard resolution and the one with higher resolution with respect to changing the extraction radius, the cutoff frequency for the fixed-frequency integration, and the amount of signal cropped at the beginning of the simulation to remove “junk” radiation. We find an error of \( 1.5 \times 10^{-4} \) for the total signal, \( 3 \times 10^{-5} \) for the lower frequency, and \( 2 \times 10^{-4} \) for the high frequency. These numbers are well below the LIGO GW150914 threshold mismatch of \( 8 \times 10^{-4} \) for distinguishing two different waveforms. The minimum of the mismatch when only considering high frequencies alone is of the same order as our error, which explains why the dotted curves in Figure 1 are noisier compared to the other ones. This systematic error in our simulation prevents us from estimating what signal-to-noise ratio would be needed to extract charge information from the ringdown phase (see dotted lines in Figure 1).

To confirm that the mismatch we compute is due to the presence of charge and not the residual initial eccentricity, we use EccentricFD [105]–a non-spinning frequency-domain, inspiral-only template available in PyCBC [106, 107]. Focusing on the inspiral (up to 55 Hz),
we find that the values of eccentricity we measure in our simulations (≈ 0.005) produce mismatches that are at least one order of magnitude smaller than the ones we reported in the main text. Even for the largest eccentricity we measure (0.014), the computed mismatch remains subdominant (≈ 2 × 10⁻⁴). Therefore, this assures us that for the large values of λ in our survey, the mismatch is due to black hole charge and not to the initial eccentricity.

Confidence levels In the main text, we represent GW150914 as an uncharged binary black hole with total mass 65 M⊙, at a luminosity distance of 410 Mpc, and use for the signal-to-noise ratio ρ the value 25.1 These are the most probable parameters for the event according to the Bayesian analysis performed by the LIGO-Virgo collaboration [60]. Moreover, we adopted as threshold mismatch for distinguishing two signals the standard choice of 1/(2ρ²). Using Equation (18) in [108] (with one degree of freedom k = 1 since we compare charged configurations with an uncharged one, and maximize the overlap over all other parameters), a mismatch of 1/(2ρ²) corresponds to a 68% confidence level. The most probable parameters represent neither the worst nor the best case scenario for distinguishing black hole charge. The worst-case-scenario is when both the number of gravitational wave cycles in LIGO’s sensitivity band and the signal-to-noise ratio are minimized: for GW150914 this happens when the distance is 570 Mpc and the total mass is 69.5 M⊙, which are the largest values in LIGO’s 90% confidence levels. The minimum signal-to-noise ratio reported by LIGO is ρ = 23.4. Even under these conditions, our constraint on λ^+ remains unchanged, but for the λ^+ = 0.4 case, the threshold mismatch for distinguishing charge must reduce to 6.8 × 10⁻⁴, making the confidence level of our constraint (based on Equation (18) in [108]) 61%.

FIG. 3. Self-convergence of the plus and cross polarization of the strain for simulations with λ^+ = 0.3. The blue solid (orange dashed) lines are the absolute value of the difference between the strain at medium and low (high and medium) resolution. In the bottom panel we rescale the difference between the high and medium resolutions assuming sixth order convergence, i.e., by a factor of (1 + t)^6 ≈ 3.8, where 1.25 is the ratio between the resolutions.
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