

Braking Protons at the Electron-Ion Collider: From Invisible Meson Decay to New Physics Searches

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We investigate the sensitivity of the Electron-Ion Collider (EIC) to invisible final states in coherent exclusive electroproduction. The characteristic signal is a forward proton with reduced energy and little additional detector activity. Using the excellent particle detection capabilities and kinematics reconstruction at the EIC, we argue that backgrounds can be strongly suppressed. While our analysis applies to various states, we specifically focus on vector and pseudoscalar particles: (i) neutral mesons [$P = \pi^0, \eta^{(\prime)}, V = \rho^0, \omega, \phi$], whose invisible standard model decays are extremely suppressed, and (ii) gluon-coupled axionlike particles (ALPs) decaying invisibly to a dark sector. With the baseline detector and a conservative residual-background estimate, the EIC can improve the sensitivity to invisible η, η', ω , and ϕ decays by factors of about 4–40 and probe invisible ρ^0 decays for the first time. With further background reduction and optimized detector performance, the projected sensitivity may reach branching fractions as small as 4×10^{-11} . In addition, under the same conditions, the EIC would directly probe invisibly decaying ALPs with the couplings up to $f_a \sim 10^5$ GeV and masses in the range 0.1–2 GeV.

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Introduction—The upcoming Electron-Ion Collider (EIC) [1,2], to be built at Brookhaven National Laboratory, will collide electrons of up to 18 GeV with protons of up to 275 GeV (or nuclei from deuterons to uranium), eventually reaching annual integrated luminosities $\mathcal{L}_{\text{int}} = 100 \text{ fb}^{-1}$. Its physics program is primarily devoted to unraveling the partonic structure of nucleons and nuclei, but its kinematic reach and detector capabilities also make it a powerful laboratory for searches for rare and exotic processes, offering sensitive probes of physics beyond the standard model (SM) [3–27].

A distinctive feature of the EIC relevant for this work is its far-forward detector (FFD) system [28,29], which covers the forward-going protons ($\eta_{p'} > 4.5$) up to very large pseudorapidities. This provides capabilities for exploring various signatures involving such protons.

Coherent exclusive electroproduction with the invisible final state X ,

$$p(p_p) + e^-(p_e) \rightarrow p(p_{p'}) + e^-(p_{e'}) + X(p_X), \quad (1)$$

stands out as an especially promising target.

We consider two cases for the particle X . First, we take it to denote the SM neutral mesons $\{\pi^0, \eta, \eta', \rho^0, \omega, \phi, \dots\}$. Such mesons are short-lived and decay visibly within the SM [30]. However, invisible decay channels arise naturally in many extensions involving hidden sectors [31–38], including scenarios with decays to sterile neutrinos [39] or to particles that can accommodate the dark matter relic density [40–44]. Second, we identify X with a new, beyond-the-SM particle that can be copiously produced in ep collisions and evades detection as well. For example, it could be a new spin-0 or spin-1 particle, which is coupled to hadrons and is either long-lived or decays into a dark sector.

If such invisible channels exist, the process in Eq. (1) would lead to a significant loss of proton energy with no accompanying detector activity. Current limits on invisible branching ratios of SM mesons [45,46] leave ample room for the EIC to achieve major improvements. In this Letter, we propose a missing-proton-energy (MPE) search strategy

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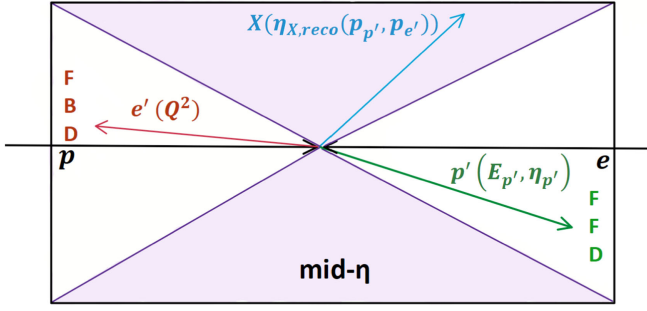


FIG. 1. An illustration of the EIC missing-proton-energy (MPE) search in $e + p \rightarrow e' + p' + X$ events. Without relying on reconstructing X , its pseudorapidity η_X is indirectly extracted $[\eta_{X,\text{reco}}(p_{p'}, p_{e'})]$ from the kinematics of outgoing states p' and e' . The latter are reconstructed by the far-forward (FFD) and central (mid- η)/far-backward (FBD) detectors if the event's Q^2 , $E_{p'}$, $\eta_{p'}$ fall under detectability ranges (see Table I). Events with $|\eta_X| < 4$ are within the fully detector-instrumented region; thus, visible X can be vetoed, leaving only invisible states. See text for details.

at the EIC, see Fig. 1, based on the efficient tagging of the forward proton by the FFD and on reconstructing the full event kinematics by additionally seeing the scattered electron. This provides significant background suppression and enables broad parameter space exploration. The uniqueness of the MPE over other missing energy searches at the EIC, such as the missing-electron-energy search in Ref. [22], is its sensitivity to X particles with hadronic interactions. This has important consequences both for the rare invisible meson decays and beyond the standard model (BSM) searches.

Regarding X , we focus for concreteness on the pseudoscalar case (see Fig. 2), with mesons $P = \{\pi^0, \eta, \eta'\}$ and the axionlike particles (ALPs) a that couple to the SM primarily via gluons, see Eq. (3) below. In addition, we also provide our results for the case of a vector meson $V = \{\rho^0, \omega, \phi\}$.

Our calculation of the coherent electroproduction cross sections for pseudoscalar states is based on the framework developed in the companion work [47] and can also be validated by a data-driven method. Our results, summarized in Table II and Fig. 3, show that the same experimental analysis can improve the sensitivity to invisible η, η', ω , and ϕ decays by factors of about 4–40 with the baseline detector and conservative background estimate, with substantially stronger reach under optimized benchmark assumptions, while also probing previously unexplored ALP parameter space. Supplemental Material [48] provides

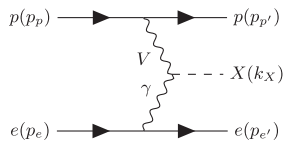


FIG. 2. Feynman diagram for the electroproduction $ep \rightarrow epX$ with $X = \pi^0, \eta^{(\prime)}, a$ in the $V\gamma$ -fusion channel, with $V = \rho^0, \omega, \phi$, see Ref. [47] and text for details.

details on the kinematics of the signal processes, as well as on simulations and background estimates.

Detector description—The first experiment being constructed at the EIC is the Electron-Proton/Ion Collider (ePIC) detector. It contains elements of high-resolution tracking, electromagnetic and hadronic calorimetry, Cherenkov and time-of-flight particle identification, and beam-line detectors for tagging exclusive processes [51]. The EIC environment is effectively pileup-free, enabling straightforward timing- and vertex-based object reconstruction in the main detector. The EIC may operate with a broad range of the incoming proton and electron energies $E_p = 41, 100\text{--}275$ GeV, $E_e = 5\text{--}18$ GeV. In addition to ePIC, there is a growing interest in building a second detector at the EIC. It would be complementary to ePIC for discovery confirmation between two independent experiments, but with potentially different technologies to additionally focus on other measurements [52,53].

Considering the scattering process in Eq. (1), we use the electron transferred momentum $Q^2 \equiv -(p_e - p_{e'})^2$ and pseudorapidity $\eta_{e'}$, as well as the outgoing proton's energy $E_{p'}$ and pseudorapidity $\eta_{p'}$ to characterize the measured electron e' and proton p' . Crucially, the exclusive electroproduction of hadronically interacting particles prefers $E_{e'} \approx E_e$ [47].

In ePIC, the e' may be reconstructed by one of the two detectors: by the central detector, or by the far-backward detector (FBD). The coverage of the central detector is given by $|\eta_{e'}| < 4$, while the FBD coverage is often defined in terms $10^{-3} < Q^2(E_{e'}, \eta_{e'})/(1 \text{ GeV}^2) < 0.1$. However, the FBD range does not accurately characterize the reconstruction efficiency for the particular kinematics $E_{e'} \approx E_e$, which is the case for the process in Eq. (1). There, it is additionally limited by $-7.5 < \eta_{e'} < -5.5$, and even inside this domain, the e' particles have a small reconstruction efficiency [2,54]. This is crucial not only for MPE but also for studying any coherent exclusive hadroproduction events at the EIC, including the standard model channels.

However, this limitation may be mitigated by optimized FBD instrumentation. To illustrate its potential, we examine the potential reach of an “upgraded FBD” in addition to the current instrumentation, under which we assume unit electron reconstruction efficiency in the window $Q^2 > 10^{-3} \text{ GeV}^2$, $\eta_{e'} < -4.2$.

On the proton side, the FFD system covers the proton-going direction to large pseudorapidities, with dedicated off-momentum proton tagging. In the current ePIC layout, protons with a momentum greater than 40% of the beam momentum can be reconstructed with $\approx 100\%$ efficiency for $\eta_{p'} > 4.5$ in the instrumented sections. The latter region could be extended with the second interaction region proposed in Ref. [55]. Besides the recoil proton, all other visible particles are reliably reconstructed by the mid- η detector for $|\eta| < 4$.

Reconstructing e', p' , it is possible to indirectly reconstruct the kinematics of X or its decay products even if they

are not detected (which covers both the signal and background cases); in particular, the reconstructed pseudorapidity $\eta_{X,\text{reco}}(p_{e'}, p_{p'})$ reproduces the true η_X with a relative resolution of about 5%.

Background categories and proposed selection—SM channels with neutrinos in the final state, for example, decays of intermediate resonances into $\nu\bar{\nu}$, give an irreducible contribution to the MPE events. Their cross sections are suppressed by the Fermi coupling and by phase space, and the expected yield over a full EIC run is well below one event; quantitative estimates are given in Supplemental Material [48]. The dominant concern is therefore reducible background from processes that may mimic an invisible signature.

We group these backgrounds into two main classes: (1) Beam-related and instrumental: accidental overlaps (e.g., beam-gas collisions), particles traversing small uninstrumented gaps in fiducial acceptance, or rare reconstruction failures. (2) Leakage of visible states: events of the type Eq. (1) in which the state X is visible but not detected. This can occur either when X (or its decay products) is produced at large pseudorapidity, $\eta_X \gtrsim 4$, where the detector coverage is incomplete as described above, or when X lies in the fully instrumented region $|\eta_X| < 4$ but its decay products fail to be reconstructed because of finite detection efficiency.

A reliable determination of the first class of background requires detector runs; here we only outline general handles such as tight timing and vertex matching, global vetoes on additional activity in central and forward detectors, and the exclusion of events with elasticlike kinematics, for example $|\mathbf{p}_{T,e'}| \simeq |\mathbf{p}_{T,p'}|$. Further discussion is provided in Supplemental Material [48].

Regarding the second class, we construct a selection to control the leakage of visible states without relying on any specific nature for X (see Table I). The key ingredients are (i) reconstruction of e' and p' with good energy and angular resolution; in what follows, we assume unit reconstruction efficiency for e' and p' within the specified domain; (ii) requiring $|\eta_{X,\text{reco}}| < 4$ for the indirectly reconstructed pseudorapidity of the missing final state, for the event to be in the instrumented region; and (iii) a veto on any additional reconstructed activity besides e' and p' .

Two distinct selections are summarized in Table I. The baseline choice corresponds to an early EIC running configuration with $(E_p, E_e) = (100, 10)$ GeV and considering the e' detection solely by the central detectors. Additionally, to illustrate the impact of upgrading the FBD, we consider the baseline selection with the upgraded FBD added, baseline_{FBD}. The optimal selection uses lower beam energies $(E_p, E_e) = (41, 5)$ GeV and assumes unit e' reconstruction efficiency independently of its kinematics, to illustrate the maximal possible reach of the EIC, see Supplemental Material [48].

Going forward, the selection efficiency could be further optimized using modern machine-learning techniques [56,57].

TABLE I. Two kinematic selection criteria of the outgoing proton p' , electron e' , and X from the process of Eq. (1), and backgrounds assumptions. For the baseline setup, in Fig. 3, we also include the sensitivity assuming the upgraded FBD setup, which allows for the reconstruction of e' in the domain $\eta_{e'} < -4.2$, $Q^2 > 10^{-3}$ GeV².

Selection	Baseline	Optimal
E_p, E_e	(100,10) GeV	(41,5) GeV
p', X	$\eta_{p'} > 4.5, 0.5 < E_{p'}/E_p < 0.9, \eta_X < 4$	$ \eta_X < 4$
e'	$ \eta_{e'} < 4$	...
Bkg	0 (bg,free), Eq. (2) (bg,cons)	0

Background suppression—To quantify the residual background after applying our selections, we generated samples of representative processes with visible final states X (such as $\pi^0 \rightarrow \gamma\gamma$, $\rho^0 \rightarrow \pi^+\pi^-$, $\phi \rightarrow K\bar{K}$, and $\gamma^* \rightarrow \ell^+\ell^-$) and propagated them through a fast simulation of the ePIC detector response using the baseline energy configuration $(E_p, E_e) = (100, 10)$ GeV. The fast simulation includes beam energy spread, angular divergence, transport through the beam line, and the currently understood acceptances and resolutions. It has been benchmarked against full-simulation studies performed for other physics channels [58,59].

The quoted estimate concerns leakage of the simulated visible final states and is conservative for this background class: we use relatively high veto thresholds while machine-background studies are ongoing, and the reconstruction does not yet combine information from all ePIC subsystems. Machine-induced and accidental backgrounds are a separate category that requires detector-specific studies with finalized geometry, digitization, and reconstruction. Optimized thresholds and combined reconstruction, tighter fiducial cuts, and additional forward instrumentation are expected to reduce visible-state leakage further; details are given in Supplemental Material [48].

In the simulation, we classify events according to the true pseudorapidity of X : either $|\eta_X| < 4$, where the detector is fully instrumented, or $\eta_X > 4$, where only partial or no coverage is available. For events with $|\eta_X| < 4$, the rejection is limited by the efficiency of the global veto in the instrumented region. For the dominant $\pi^0 \rightarrow \gamma\gamma$ background, full vetoing requires an inefficiency $\lesssim 10^{-9}$. Requiring that at least one photon be absorbed in the electromagnetic calorimetry leads to an effective depth of order ten radiation lengths, which is satisfied in ePIC for $|\eta_X| < 4$.

We find in simulated events that decay products rarely escape without producing detectable signals in the tracking and/or calorimeter systems, for both nonmuonic and muonic final states, where the latter rely on deposits in the hadronic calorimeters with > 4 hadronic interaction lengths. Depending on the process, the probability of missing all visible activity in this region is $10^{-5} - 10^{-3}$, mostly driven by near-edge events with $\eta_X \simeq 4$.

The corresponding conservative estimate of the background yield is

$$N_{\text{bg,cons}} \sim 9 \times 10^4, \quad (2)$$

mainly dominated by $\rho^0 \rightarrow \pi^+\pi^-$, $\gamma^* \rightarrow \mu^+\mu^-$, and bremsstrahlung producing a photon. Further details are provided in Supplemental Material [48].

For events with $\eta_X > 4$, contamination of the signal region requires both that all visible final states escape detection in uninstrumented or partially instrumented regions and that the event be misreconstructed as having $|\eta_{X,\text{reco}}| < 4$. The latter probability is already small and can be further reduced by tightening the $\eta_{X,\text{reco}}$ requirement or improving the indirect reconstruction of X . We therefore assume that the dominant background comes from the $|\eta_X| < 4$ region, with the estimate given in Eq. (2).

Given the discussion, we present projected sensitivities considering background assumptions: the conservative estimate Eq. (2), and the background-free hypothesis $N_{\text{bg}} = 0$. To estimate the reach, we require $\sum_X N_X \times \text{BR}(X \rightarrow \text{inv}) > 2\sqrt{N_{\text{bg}}}$ for the former scenario, and $\sum_X N_X \times \text{BR}(X \rightarrow \text{inv}) > 3$ for the latter, where $N_X = \mathcal{L} \times \sigma_{\text{sel}}$, with σ_{sel} being the production cross section of the X particle after imposing the selection from Table I.

The pseudoscalar case—Let us now study the implications of our analysis for the case of invisible decays of pseudoscalar states. These include invisible decays of $P = \pi^0, \eta, \eta'$, as well as of hadronically coupled ALPs a . We focus on the model of gluonic ALPs:

$$\mathcal{L}_a \supset \frac{\alpha_s}{4\pi} \frac{a}{f_a} G^{\mu\nu} \tilde{G}_{\mu\nu} + i g_{a\chi} a \bar{\chi} \gamma^5 \chi, \quad (3)$$

where $\tilde{G}_{\mu\nu} \equiv (1/2)\epsilon_{\mu\nu\rho\sigma} G^{\rho\sigma}$, χ is a dark sector particle, and the ALP mass m_a is taken to be a free parameter. Motivated by the QCD axion [60–63] and its phenomenological implications [64–74], as well as by the axion quality problem [75–78], ALPs with masses much larger than the QCD axion $m_a^2 \gg (m_\pi f_\pi / f_a)^2$, with f_a the ALP decay constant, have been considered. Such heavy variants arise in models addressing the strong CP problem [79–96], and have been the focus of extensive theoretical and experimental studies [15, 19, 97–128]. Moreover, we are interested in the regime where $\text{BR}(a \rightarrow \chi\bar{\chi}) \approx 1$ and the ALP does not decay visibly inside the detector, which is satisfied for most values of $g_{a\chi}$ due to the relatively small width to visible states $\Gamma_{a \rightarrow \text{vis}} \ll m_a \sim \Gamma_{a \rightarrow \chi\bar{\chi}} / g_{a\chi}^2$ [107, 128, 129].

There are two contributions to MPE at the EIC in this model: decays of the on-shell ALP $X = a \rightarrow \text{inv}$ or of pseudoscalar mesons $X = P \rightarrow \text{inv}$, occurring via off-shell ALPs (i.e., $P - a$ mixing), with the main production diagrams of X particles shown in Fig. 2. Detailed cross-section calculations and kinematics analysis, used in this Letter, are performed in Ref. [47]. Namely, our calculation of the meson coherent electroproduction cross sections is based on

TABLE II. Current experimental bounds on invisible decays of different mesons and the branching ratios the EIC can probe. We consider the baseline and optimal selections defined in Table I; for optimal, we assume zero background, $N_{\text{bg}} = 0$. A dash “...” in the last column indicates that the corresponding baseline sensitivity does not improve the current bound.

M	$\text{BR}(M \rightarrow \text{inv})_{\text{current}}$	$\text{BR}(M \rightarrow \text{inv})_{\text{EIC}}$
π^0	4.4×10^{-9} [45]	...(baseline _{bg,cons}) ...(baseline _{bg,free}) 2×10^{-10} (optimal)
η	1.1×10^{-4} [46]	2×10^{-5} (baseline _{bg,cons}) 9×10^{-8} (baseline _{bg,free}) 1×10^{-9} (optimal)
η'	2.1×10^{-4} [46]	5×10^{-5} (baseline _{bg,cons}) 2×10^{-7} (baseline _{bg,free}) 4×10^{-9} (optimal)
ρ^0	No bound	4×10^{-7} (baseline _{bg,cons}) 2×10^{-9} (baseline _{bg,free}) 4×10^{-11} (optimal)
ω	7.3×10^{-5} [134]	2×10^{-6} (baseline _{bg,cons}) 1×10^{-8} (baseline _{bg,free}) 3×10^{-10} (optimal)
ϕ	1.7×10^{-4} [134]	7×10^{-6} (baseline _{bg,cons}) 4×10^{-8} (baseline _{bg,free}) 3×10^{-9} (optimal)

a gauge-invariant extension of data-constrained photoproduction amplitudes [130–133] to the full $2 \rightarrow 3$ kinematics of Eq. (1), appropriate for the low- Q^2 regime relevant for this search. We then construct the ALP production amplitude following the description of Refs. [107, 128, 129].

The signal cross section, namely single-pseudoscalar production, can eventually be validated using meson decays into well-measured visible channels, thereby reducing the theoretical uncertainty on the signal yield. This approach is viable in our case thanks to the reliable reconstruction of the final-state system X and the good invariant-mass resolution for all visible states. Notably, such a robust data-driven strategy can also facilitate precision measurements of rare standard model meson decays.

The EIC reach for invisible decays of pseudoscalar and vector mesons, assuming that only a single meson species contributes to the signal yield [which is often true for particular parameters of the model Eq. (3)], is summarized in Table II. Under the conservative background assumption and for the baseline ePIC setup, the EIC will be able to improve the reach of invisible decays of $\eta^{(\prime)}$ (ω, ϕ) mesons by up to a factor of $\simeq 5$ (20–40), and, for the first time, explore invisible decays of ρ^0 mesons. Reducing the background would improve the reach by a factor of about 200. Upgrading the FBD detector would add a factor of 2–5, depending on the

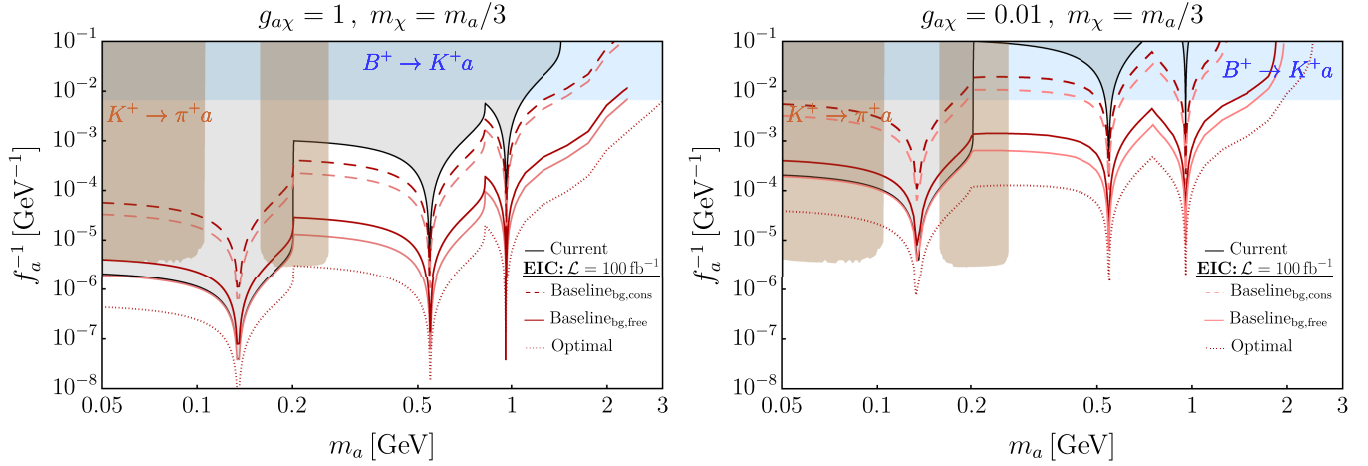


FIG. 3. The EIC sensitivity to the model of invisibly decaying ALPs [see Eq. (3)] in the $\{m_a, f_a^{-1}\}$ plane, for $g_{a\chi} = 1$ (0.01) on the left (right) panel. The left (right) panel is dominated by invisible meson (ALP) decay. We use the baseline selection under conservative [Eq. (2)] and background-free assumptions (dashed and solid red lines), as well as the optimal selection (red dotted line). Current bounds from invisible flavorless meson [45,46] (black), kaon [49] (brown region) and B -meson decays [50] (turquoise region) are also presented. For the baseline setup, the darker curves assume a setup from Table I, while the lighter curves assume an upgraded FBD detector.

meson. Relative to the $\text{baseline}_{\text{FBD}}$ benchmark, the optimal selection would further improve the sensitivity by a factor of approximately 5–25, depending on the meson, and would additionally allow a search for invisible π^0 decays.

For the π^0 channel, the optimal setup probes somewhat lower $\sqrt{s_{\gamma^*p}}$ values, where our production framework discussed in Ref. [47] is less robust and subject to large uncertainties. However, this can be systematically studied by using visible π^0 decays of the same kinematics, which will be collected at the EIC.

The EIC probes the sum of the on-shell and off-shell ALP contributions in a complementary way, without the ability to disentangle them within a single energy run. The on-shell ALP signal yield scales as $\text{BR}(a \rightarrow \text{inv})/f_a^2$, while the off-shell ALP yield scales as $g_{a\chi}^2/f_a^2$. Combining this with $\Gamma_{\text{vis}} \ll \Gamma_{a \rightarrow \chi\chi}/g_{a\chi}^2$, we find that the on-shell ALP production is the main probe for small values of $g_{a\chi}$, while the off-shell ALP dominates for $g_{a\chi} \sim \mathcal{O}(1)$. In addition, the ALP mass reach of the two contributions is different as the off-shell production can probe masses above the mother meson at the $\mathcal{O}(10 \text{ GeV})$ scale, see Supplemental Material [48].

We present the combined sensitivity of the two contributions (on-shell and off-shell) on the $\{m_a, f_a^{-1}\}$ plane for $g_{a\chi} = 1$ (0.01), as well as corresponding bounds, shown in the left (right) panel of Fig. 3, see Supplemental Material [48] for details. In particular, the off-shell (on-shell) process dominates the sensitivity for $g_{a\chi} = 1$ (0.01). Furthermore, we derive the bounds from meson invisible decays resulting from current experimental results on $K \rightarrow \pi + \text{inv}$ from NA62 [49] and $\eta^{(\prime)} \rightarrow \text{inv}$ from NA64h [46] (black region). Additionally, we show the current bounds inferred from the measurements $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ [135] (brown region) and $B^+ \rightarrow K^+ \nu\bar{\nu}$ [50,136–138] (turquoise region).

If an MPE excess were observed, varying the beam energies could help distinguish signal contributions despite the limited missing-mass resolution. Over $\sqrt{s} = 28\text{--}140 \text{ GeV}$, both the event rate and the missing-energy distribution $E_X = E_p + E_e - E_{p'} - E_{e'}$ depend on the missing-particle mass; for example, under the baseline selection the π^0 rate is about three times the η' rate [47]. A dedicated analysis is left for future work.

Outlook—We have introduced the missing-proton-energy strategy for invisible final states produced in coherent electroproduction at the EIC. Even with the baseline detector and conservative background assumptions, it substantially improves the sensitivity to invisible pseudoscalar- and vector-meson decays and probes new ALP parameter space. Such sensitivities usually require dedicated experiments, while no approved high-statistics program currently targets comparable reach across the η , η' , ρ^0 , ω , and ϕ channels. Production uncertainties can be reduced by normalizing to visible decays measured in the same topology.

Improved background rejection, optimized far-backward electron reconstruction, and a complementary second detector could extend the reach and help distinguish meson and ALP contributions [52,53,139]. The same strategy applies to other hadronically coupled invisible states, including spin-0, spin-1, and millicharged particles, and can be combined with missing-electron-energy searches when both hadronic and leptonic interactions are present [22]. It may also be adapted to future lepton-hadron facilities with different energies or beam species [126,140–143].

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Data availability—The approach that supports the findings of this article, as well as the framework needed to reproduce the results are discussed in the companion paper [47].

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